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FOREWORD

For the last 50 years, the conference of the Italian Association of Theoretical and Applied Mechanics has been an important meeting place for scientists working in the field of general, fluid, solid and structural mechanics, as well as mechanics for machines and mechanical systems.

The aim of the meeting is to promote an exchange of ideas and expertise among the participants, to stimulate interest in novel research topics, and to share the most recent scientific results in the field. The conference's topics are related to all aspects of scientific research in mechanics, including theoretical, computational and experimental techniques and technological applications. The meeting also covers new multidisciplinary approaches.

The XXIV Conference of the Italian Association of Theoretical and Applied Mechanics (AIMETA 2019) was organized with the support of the Sapienza Università di Roma and held in Rome, Italy, on 15th-19th September 2019.

There were five plenary lectures covering different areas of the conference: Chiara Daraio (Division of Engineering and Applied Science, California Institute of Technology, Pasadena, CA, USA), Massimo Ruzzene (School of Aerospace Engineering Georgia Institute of Technology, Atlanta, GA, USA), Anna Pandolfi (Politecnico di Milano, Italy), Roberto di Leonardo (Sapienza Università di Roma, Italy), and Paolo Carafa (Sapienza Università di Roma, Italy).

About 400 contributions were presented at the conference's four thematic sessions and 15 mini-symposia.

The Organizing Committee

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PLENARY LECTURES

Mechanics of robotic matter

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Architected materials (aka. metamaterials) blur the boundaries between what is conventionally defined a structure and a material in mechanics. More recently, the use of active and/or responsive materials as constitutive elements in architected materials blurs the boundaries between robots and materials as we know them. Rapidly evolving 3D manufacturing approaches now allow fabrication of objects with almost arbitrary architecture, different constitutive properties and ad-hoc pre-stress distribution, opening the door to new functionalities. For example, architected sheets of responsive materials can morph into relatively complex three-dimensional shapes. In this talk, I will discuss recent progress in the design of micro- and macro-scale, nonuniform materials that can bend into freeform objects, in response to environmental stimuli, prestress or with simple application of point loads. Engineering the distribution of residual stresses, stiffness gradients and/or cut patterns, we control the material's bending and buckling, at both local and global scales. The designed distribution of responsive materials in the sheets provides a time-dependent control of the developing shapes. Programming 2D sheets into rigid, 3D geometries expands the potential of existing manufacturing tools for efficient and versatile production of 3D objects. Finally, I show how the use of responsive materials, like shape memory polymers and liquid crystal elastomers, allows creating new, passive soft robots.

Metastructures for wave and vibration control: internal resonances, edge states and quasi-periodicity

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Beyond the mere notion of a material, metastructures draw their unique characteristics from their finite size and the existence of interfaces. The resulting structural assemblies feature unprecedented performance in terms of stress wave mitigation, wave guiding, acoustic absorption, and vibration isolation.

The talk illustrates the frequency-selective properties of periodic metastructures, which result in their ability to direct waves in preferential direction and attenuate vibrations at certain frequencies. Such properties are observed in complex structural lattices, and in structural components equipped with periodic arrays of adaptive electromechanical resonators. The presentation will also introduce basic concepts that govern the onset of localized, interface wave modes. Specifically, spring-mass systems, lattices, and plates with internal resonators will be presented as part of a framework that seeks for mechanical lattices that exhibit one-way, edge- bound, defect-immune, wave motion. Finally, quasi-periodic structural assemblies are introduced as configurations that support vibration confinement in systems that are not ordered, but are described by deterministic property distributions. Results for beam and plate structures with quasiperiodic arrangements of grounding springs and lumped masses are presented to illustrate the unique dynamic behavior characterized by a multitude of highly localized modes of vibration.

OTM: combining optimal transportation theory and meshless discretization for the simulation of general solid and fluid flows

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Keywords: meshfree methods, optimal transportation theory, diffusion, fracture.

The optimal transportation meshfree (OTM) method has been developed for simulating general solid and fluid flows, including fluid-structure interaction [1]. The approach combines materi-al-point sampling and max-ent meshfree interpolation [2] with concepts from optimal transpor-tation theory. The OTM method generalizes the Benamou–Brenier differential formulation of the of optimal mass transportation [3] to problems including arbitrary geometries and constitu-tive behavior. The method enforces exactly mass transport and essential boundary conditions, conserves linear and angular momentum, and is free from tension instabilities. The OTM meth-od has been proved to be predictive when combined with eigenerosion methods [4] in the simu-lation of dynamic fracture [5]. Innovative particle methods based on OTM have been devel-oped recently for the solution of advection-diffusion problems, by approximating the density of the diffusive species by Dirac measures [6]. Relying on the optimal transport theory and in al-ternative to traditional schemes formulated in linear spaces, the method hybridizes elements of a Galerkin approximation with those of an updated Lagrangian approach. The time discretiza-tion of the diffusive step is based on the Jordan-Kinderlehrer-Otto (JKO) variational principle [7]. The JKO functional characterizes the evolution of the density as a competition between the Wasserstein distance (which penalizes departures from the initial conditions) and entropy (which tends to spread the density and it make uniform over the domain), and is regarded as a functional of an incremental transport map which rearranges the density over the time step. The resulting update is geometrically exact with respect to advection and volume. In applica-tions, the JKO functional is discretized in space using one discretization for the density and an-other discretization for the incremental transport map. By exploiting the structure of the Euler-Lagrange equations, which are linear in the density, the density is treated as a measure and coherently approximated as a collection of Diracs. A few examples will demonstrate the ap-plicability of the approach. The work has been developed in collaboration with Bo Li (Case University, OH), Livio Fedeli and Michael Ortiz (Caltech, CA and Bonn University, Germany).

References

[1] Li, B., Habbal,F., Ortiz, M. Optimal transportation meshfree approximation schemes for fluid and plastic flows. Int. J. Numer. Meth. Eng. ***83****:1541–1579 (2010).*

[2] Arroyo, M., Ortiz, M. Local maximum-entropy approximation schemes: a seamless bridge between finite elements and meshfree methods. Int. J. Numer. Meth. Eng. ***65****:2167-2202, (2006).*

[3] Benamou JD, Brenier Y. A computational fluid mechanics solution to the Monge–Kantorovich mass transfer problem. Numerische Mathematik, ***84****:375–393 (2000).*

[4] Pandolfi, A., Ortiz, M. An eigenerosion approach to brittle fracture. Int. J. Numer. Meth. Eng. ***92****:694-714 (2012).*

[5] Li, B., Pandolfi, A., Ortiz, M. Material-point erosion simulation of dynamic fragmen-tation of metals. Mechanics of Materials, ***80****:288-297 (2015).*

[6] Fedeli, L., Pandolfi, A., Ortiz, M. Geometrically-exact time-integration mesh-free schemes for advection-diffusion problems derived from optimal transportation theory and their connection with particle methods. Int. J. Numer. Meth. Eng. ***112****:1175-1193 (2017).*

[7] Jordan, R., Kinderlehrer, D., Otto, F. Free energy and the Fokker-Planck equation. Physica D, ***107****:265-271 (1997).*

The statistical and fluid mechanics of swimming bacteria

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Dense suspensions of swimming bacteria display striking motions that appear extremely vivid when compared to the thermal agitation of colloidal particles of comparable size. These suspensions belong to a broader class of non-equilibrium systems that are now collectively referred to as active matter. Fundamental research in the physics of active matter investigates the basic principles governing non equilibrium phenomena such as self-propulsion, collective behavior and rectification. From a more engineering point of view, however, active particles could potentially provide the active "atoms" of a new class of smart materials with unique response characteristics. Using advanced 3D optical imaging, micromanipulation and microfabrication tools, we study complex phenomena in active matter using direct and quantitative methods. I will review our recent work in this direction, from the fluid and statistical mechanics of bacterial movements in structured environments to the use of genetically modified bacteria as propellers for micromachines or as a "living" paint that can be controlled by light.

MG

General Mechanics

Correlation between fracto-emissions and statistical seismic precursors in the case of low-magnitude earthquakes

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Keywords: TeraHertz pressure waves, Fracto-emissions, Earthquake precursors

High-frequency pressure waves (up to TeraHertz, 10^12 Hz), produced by mechanical instabilities at the nano-scale, can trigger fracto-emission signals in the form of Acoustic Emission AE, Electromagnetic Emission EME, and Neutron Emission NE [1]. The same phenomenon can take place during the early stages of a seismic event. Cracking is a multi-scale phenomenon within the earthquake preparation zone [2,3], nano-cracks coalesce to form larger ones, and the preparation area shrinks until coinciding with the quake epicentre. At the same time, pressure wave frequencies vary from THz for fracture at the nano-scale up to the simple Hz at the kilometre scale, which is the typical frequency of seismic oscillations. In this framework, fracto-emissions can represent a promising tool in seismology, not only for their monitoring capabilities during the earthquake, but also for their forecasting potentialities before the event [2,3].

Another important seismic precursor is represented by the temporal variation of *b*-value, a sort of statistical parameter deriving from the magnitude-frequency relation proposed by Gutenberg and Richter [4], that is also successfully applied to study the cracking process. In general terms, the fracture moves from nano to macrocracks and the *b*-value decreases from about 1.5 in the initial stages to 1.0 or less approaching the final collapse. In seismology values of unity are commonly related to an incoming seismic event: i.e. an earthquake is often preceded by a *b*-value decrement in the weeks to few days before the quake occurrence.

Since July 2013, an in-situ experimental campaign has started at a gypsum mine located in Northern Italy, revealing the strong seismic forecasting potentialities of the fracto-emissions by means of a dedicated monitoring platform and a multi-modal statistical analysis. In particular, AE, EME, and NE tend to anticipate the next seismic swarm peak with an evident and chronologically ordered shifting of about one day, three-four days, and one week, respectively [2,3].

On the other hand, the *b*-value trend, estimated for all the major seismic swarms observed during the in-situ monitoring, shows a decrement to values below 1.0 approximately two days before the swarm peak occurrence.

References

[1] Carpinteri A., Lacidogna G., Manuello A. (Editors), Acoustic, Electromagnetic, Neutron Emissions from Fracture and Earthquakes. Springer, 2015.
[2] Carpinteri A., Borla O. (2017): Fracto-emissions as seismic precursors. Engineering Fracture Mechanics, 177, 239-250.
[3] Carpinteri A., Borla O. (2018): Acoustic, electromagnetic, and neutron emissions as seismic precursors: The lunar periodicity of low-magnitude seismic swarms", Engineering Fracture Mechanics, DOI:10.1016/j.engfracmech.2018.04.021.
[4] Richter CF, (1958) Elementary Seismology (W.H. Freeman, San Francisco and London 1958).

On constitutive choices for growth terms in binary fluid mixtures

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Keywords: fluid mixtures, constitutive relations, wave propagation.

In the present paper we present the thermodynamic system of balance equations for a binary mixture of fluids such as the system of a single fluid, in addition to that pertinent to the relative motion, using a mere change of variables [1]. Next, we follow [2] to recognize all the thermo-mechanical fields as defined in the motion of the mixture as a whole and in the diffusive motion, so as to verify the three metaphysical principles of [3] and, further, we assume that the entropy flux is not equal to the heat flux divided by the temperature [4].

Furthermore, we recover the kinetic energy theorem for the binary mixture directly from the mechanical equations in order to propose the expressions of growths for the body by minimizing the production or destruction of mass and linear momentum: the different proposals take into account the essential features of classical models of two-phase mixture of fluids in the presence of production terms capable of describing the effects of diffusion, virtual inertia, inviscid inertial drag, and so on (see, e.g., [5, 6, 7]).

Finally, we consider two examples, such as the superfluid helium and a mixture of Euler fluids, and study the propagation of small vibrations near an undisturbed state of equilibrium for the mixture to verify the influence of the growth terms on the linear solutions.

References

[1] G. Capriz, Alcune osservazioni sulla termomeccanica delle miscele binarie. *Rivista Matematica Univ. Parma*, **16**, 63-71, 1990.

[2] C. Truesdell, Sulle basi della termomeccanica. *Rend. Accad. Naz. Lincei*, **8**, 158-166, 1957.

[3] C. Truesdell, Thermodynamics of diffusion. In *Rational Thermodynamics*, Lecture 5. McGraw-Hill, New York, 1969.

[4] I. Müller, On the entropy inequality. *Arch. Rational Mech. Anal.*, **26**, 118-141, 1967.

[5] G. Capriz, P. Giovine, On effects of virtual inertia during diffusion of a dispersed medium in a suspension. *Arch. Rational Mech. Anal.*, **98**, 115-122, 1987.

[6] P. Giovine, Sulla dinamica di una miscela di due fluidi comprimibili e non miscibili. *Rend. Mat. Acc. Lincei*, **1** (9), 377-385, 1990.

[7] P. Giovine, F. Oliveri, Wave features related to a model of compressible immiscible mixtures of two perfect fluids. *Acta Mechanica*, **96**, 85-96, 1993.

Experimental analysis on bedforms produced on a particle bed

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Keywords: Bedforms, Granular Materials, Failure.

The formation of ripple over a saturated sand bed has been the object of a recent work [1]. They study the role of turbulence in sediment resuspension in absence of mean shear. Following this idea, we do something simpler and carry out an experiment to study bedform in a water tank with a particle bed. This is one of the activity of the project "Theoretical, numerical and experimental analysis of elastic and acoustic waves in a fluid-saturated aggregate of particles" supported by Office of Naval Research (ONR-Global, London).

A pressure gradients is generated in fluid saturated particle bed by a plate oscillating in the water above the bed surface. Because the flow is oscillatory, there is no mean shear stress on the bed and no force within it. However, fluctuations in pressure and shear stress occur and, consequently, a heap develops over the bed. In this new experiment [2], we show failure of the bed induced by a gradient pressure that is able to lift particle from the bed and this, essentially, creates a heap below the oscillating plate. These vertical pressure gradients facilitates particle displacement in its interior and transport at and near its surface.

References

[1] *Johnson, B.A., "Turbulent Boundary Layers and Sediment Suspension Absent Mean Flow-Induced Shear", PhD Dissertation. Cornell University, (2016)*

[2] *La Ragione, L., Laurent, K., Jenkins, J.T., Bewley, P. G., "Bedforms Produced on a Particle Bed by Vertical Oscillations of a Plate", under review (2018)*

MF

FLUID MECHANICS

An Aerostatic Pad with Internal Pressure Compensation

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Keywords: aerostatic pad, active compensation, feedback pressure control.

Because of their almost zero friction and wear, aerostatic pads are used in applications were very precise positioning are requested, e.g, medical equipment, measuring and machine tool [1]. However, when compared to their hydrostatic and rolling counter parts, air bearings exhibit low specific stiffness and poor damping. Using compensation methods represents a solution to increase air bearings performance [2]. It is possible to distinguish passive and active compensation methods. The classification of these two methods depends on the type of energy which is exploited to compensate for air gap variations. Active compensation solutions need external sources of energy, e.g., actuators, sensors and digital controller. Conversely, passive compensated systems use only the energy associated with the pressurized air supplied to the system.

This paper presents a new actively controlled pad with a feedback pressure control. The proposed compensation system was inspired by a larger scale solution proposed by Raparelli et al. [3, 4]. The proposed solution consists in the integration of a conventional air pad with a regulating valve similar to that presented in [3, 4]. To make it possible the integration on the pad, some parts of the valve was modified. These changes allowed valve dimensions to be reduced of about 35% keeping the same working principle. The performance of the system has been tested in static conditions to obtain the characteristic curve of the active pad. Experimental results demonstrate that the static stiffness of the bearing can be increased up to the 75% at the cost of little reduction of the load capacity.

References

1. *Lentini, L., Moradi, M., Colombo, F.: A Historical Review of Gas Lubrication: From Reynolds to Active Compensations. Tribology in Industry. 40, 165–182 (2018).*
2. *Raparelli, T., Viktorov, V., Colombo, F., Lentini, L.: Aerostatic thrust bearings active compensation: Critical review. Precision Engineering. 44, 1–12 (2016).*
3. *Raparelli, T., Viktorov, V., Manuello Bertetto, A., Trivella, A.: Air bearing with pneumatic active control. In: Proceedings of the first 2000 AIMETA International Tribology Conference. pp. 693–700 (2000).*
4. *Belforte, G., Raparelli, T., Viktorov, V., Trivella, A.: Analysis of steady and transient characteristics of pneumatic controlled air bearing. In: 5th JFPS International Symposium on Fluid Power. S. Yokota (2002).*

An investigation about polygonal steady vortices

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Keywords: two-dimensional vortex dynamics, steady vortices, polygonal vortices

A class of steady solutions of two-dimensional, inviscid, incompressible Euler equations involving uniform polygonal vortices [1] is investigated. The vorticity takes the uniform (and constant) value ω inside a polygonal domain P, while it vanishes outside, and the vortex rotates about its center of vorticity (assumed on the origin) without changing the shape of its boundary. The aim of the present analysis lies in finding the boundary ∂P, as well as its rotation speed Ω.

The proposed approach is based on Complex Analysis and, in particular, uses the Schwarz function $\boldsymbol{\Phi}$ of the boundary ∂P ($\boldsymbol{\Phi}$ is the conjugate $\overline{\boldsymbol{x}}$ of $\boldsymbol{x}$ in any $\boldsymbol{x} \in \partial P$ and it is analytically continued in a suitable neighbourhood of that curve, see [2]). The induced (conjugate) velocity is related to this function [3] by means of a Cauchy integral $\boldsymbol{C}$:

$$\overline{\boldsymbol{u}}(\boldsymbol{x}) = \frac{\omega}{2\boldsymbol{i}} \left[\chi_P(\boldsymbol{x})\, \overline{\boldsymbol{x}} - \boldsymbol{C}(\boldsymbol{x}) \right] \qquad \text{with:} \qquad \boldsymbol{C}(\boldsymbol{x}) = \frac{1}{2\pi\boldsymbol{i}} \int_{\partial P} d\boldsymbol{y}\, \frac{\boldsymbol{\Phi}(\boldsymbol{y})}{\boldsymbol{y} - \boldsymbol{x}} \tag{1}$$

in which χ_P holds 1 inside P, 0 outside and $1/2$ on the boundary ∂P. Equation (1) represents a significant improvement of the Biot-Savart law, in order to analytically handle the kinematics and the dynamics of uniform vortices.

Assume that the vortex P is steady. At a given time $t > 0$ any point $\boldsymbol{x} \in \partial P(t)$ is the image of a point $\boldsymbol{\xi} \in \partial P(0)$ through the relation $\boldsymbol{x} = \boldsymbol{\xi}\, e^{\boldsymbol{i}\Omega t}$ (notice that this relation has a purely geometrical meaning: it should be not confused with the flow, which behaves in a more complicated way also on the vortex boundary). By inserting this relation inside the above form of the velocity, it is found that the initial Schwarz function satisfies the nonlinear eigenvalue [$\lambda = \Omega/(\omega/2)$] problem

$$\left[\left(\lambda - \frac{1}{2} \right) \boldsymbol{\Phi}(\boldsymbol{\xi}) + \boldsymbol{C}(\boldsymbol{\xi}) \right] + \frac{d\boldsymbol{\Phi}}{d\boldsymbol{\xi}}(\boldsymbol{\xi}) \left[\left(\lambda - \frac{1}{2} \right) \boldsymbol{\xi} + \overline{\boldsymbol{C}(\boldsymbol{\xi})} \right] = 0\ . \tag{2}$$

The main difficulty in the analytical handling of the problem (2) is due to the presence of the unknown boundary $\partial P(0)$ as domain of integration of the integral $\boldsymbol{C}$. In the present analysis it is overcame by enforcing suitable regularity hypotheses on the Schwarz function outside P and using classical results [4] about its integral representation on the vortex boundary. In particular, polygonal solutions of the problem (2) are approximated by assuming a polynomial behaviour of $\boldsymbol{\Phi}$ at infinity: a polygonal vortex with n sides is obtained by taking $\boldsymbol{\Phi}(\boldsymbol{\xi}) \sim \boldsymbol{\xi}^{n-1}$ as $\boldsymbol{\xi} \to \infty$. More details will be given in the talk.

References

[1] *Saffman, P.G., Vortex Dynamics, Cambdridge University Press, Cambdridge* (1992).
[2] *Davis, P.J., The Schwarz Function and its Applications, Carus Mathematical Monographs, No.* 17*, The Mathematical Association of America, Buffalo, New York* (1974).
[3] *Riccardi, G., A complex analysis approach to the motion of uniform vortices, Ocean Dynamics, vol.* 68-2*, pages* 273-293 (2018).
[4] *Muskhelishvili, N.I., Singular Integral Equations, P. Noordhoff N.V., Groningen, Holland* (1953).

The dynamics of fluid in nanoporous media.

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Keywords: porous lyophobic systems, intrusion/extrusion dynamics,

Hydrophobic nanotextured surfaces, also known as superhydrophobic surfaces, have a wide range of technological applications, including self-cleaning, anti-moisture, anti-icing and anti-fogging materials, friction/drag reduction, and many more. The accidental complete wetting of surface textures, which *destroys* superhydrophobicity, and the opposite process of recovery are two crucial processes that can prevent or enable the technological applications mentioned before. Porous lyophobic materials can be used for energy storage and dissipation, and shock absorption, depending on the hysteresis of the pressure-volume curve in intrusion/extrusion cycles. These examples show how controlling the intrusion/extrusion of liquids in/from lyophobic pores may enable a wide range of engineering applications of textured surface and porous media. Key to this objective is the understanding of the dynamics of a fluid in corrugations and its dependence on the morphology, geometry and chemistry of the pores.

The theoretical investigation of the intrusion/extrusion of liquids in/form hydrophobic (nano)pores is challenging because the process is typically characterized by (large) free energy barriers. In other words, in order to enters in/exits from the (nano)pores the liquid has to overcome a barrier. This barrier is responsible, for example, of the well known metastability of the Cassie-Baxter and Wenzel states [1]. Special techniques must be used in these cases known as *methods for rare events*. These techniques, originally developed in the field of chemistry and molecular physics, were recently extended to investigate the dynamics of confined fluids [2]. Standard techniques neglect liquid inertia, i.e. they assume that the liquid enters in/exits from the (nano)pores so slowly that its meniscus can achieve the equilibrium morphology at each degree of progress of the process. In fluid dynamics it is well known that inertia forces can play a key role depending on the value of the Womersley number. However, in nanofluidics *thermal fluctuations*, which are neglected in continuum fluid dynamics (Navier-Stokes) equation, plays a central role in presence of free energy barriers and this might alter the relative importance of inertial *vs* viscous forces *vs* thermal forces.

In this work we performed advanced atomistic simulations of the intrusion and extrusion of a liquid from a nanopore of $\sim$ 30 nm. We show that there are pressure regimes in which the effect of inertia is negligible on the wetting path and kinetics, and other where inertia, though non dominant, alters the wetting/dewetting mechanism significantly. Our results reconcile theory and experiments [3] and open new avenues for the *in silico* design of textured surfaces and porous systems with tailored intrusion/extrusion properties for novel nanofluidic technologies.

References

[1] *Lafuma, A., Quéré, D., "Superhydrophobic states", Nature Materials,* **2***, pages 457-460 (2003).*

[2] *Giacomello, A., Chinappi, M., Meloni, S., Casciola, C. M., "Metastable Wetting on Superhydrophobic Surfaces: Continuum and Atomistic Views of the Cassie-Baxter–Wenzel Transition", Physical Review Letters,* 22*, pages 226102 (2012).*

[3] *Lv, P., Xue, Y., Liu, H., Shi, Y., Xi, P., Lin, H., Duan, H., "Symmetric and asymmetric meniscus collapse in wetting transition on submerged structured surfaces", Langmuir,* 31*, pages 1248-1254 (2015).*

Numerical study on the flow field generated by a double-orifice synthetic jet device

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Keywords: Active flow control, Synthetic jet actuators, Twinjets

In the last few years Synthetic Jet (SJ) actuators have shown their full potential in controlling and manipulate an incoming crossflow. Indeed, these devices have been able to control separated flows over aerodynamic bodies, delay or anticipate transition to turbulence, suppress or enhance turbulence and control liquid jets and sprays. In many applications arrays of SJ actuators or multiple-orifice (or multi-slot) devices are preferred to single-orifice/single-slot actuators. Multi-orifice strategies have been often employed for the control of separated flows, in order to cover the entire spanwise length of the flow to be controlled or to introduce a spanwise modulation of the control. Moreover, such devices are also employed in cooling applications, since multiple-orifice devices exhibit a larger heat dissipation with respect to a single, centred orifice one.

Despite this fact, a great part of the studies concerning the design of a SJ actuator have been based on single-slot or single-orifice configurations. As a consequence, the present work is focused on the interaction between the jets generated by a multiple-orifice actuator. In particular, the external flow field generated by a double-orifice SJ actuator is investigated. The analyzed actuator is sealed at one side by an elastic diaphragm, which is composed of a piezoelectric disk and a flexible shim, and connected to the external environment via two circular orifices. The numerical setup matches the flow parameters of the experiments and the preliminary numerical simulations reported in [1].

A series of numerical simulations are carried out, varying the distance between the orifices. The computational domain includes the entire cavity, the orifices, and the external environment. Differently from [1], the investigation focuses on the development of the external flow field, rather than on the vortex motion near the exit plane and within the cavity. The instantaneous flow field is characterized by the presence of two, in-phase, zero-net-mass-flux jets. These jets become turbulent, converge towards each other and merge. The characteristics of the flow are strongly dependent on the distance between the orifice centers and their momentum [2]. It is important to find a scaling law for the merging point streamwise position as a function of these parameters, since jet merging is responsible for circulation cancellation and could be detrimental for flow control applications. Time-averaged flow fields are obtained, and their features are compared with the (time-averaged) characteristics of three-dimensional, continuous twinjets [3]. Moreover, time and phase-averaged velocity fields and fluctuations are compared with those of single-orifice actuators.

Finally, spectral analysis of probes (located along the jets trajectories) and dynamic mode decomposition (DMD) are used to investigate the inner shear-layer interactions and recognize shifts in the dominant frequency along the streamwise direction. The latter analyses are useful to detect the vortical motions which are responsible of the jet convergence, of the entrainment of external fluid and of the far-field behaviour of the jet.

References

[1] Chiatto, M., Capuano, F., & de Luca, L., "Numerical and experimental characterization of a double-orifice synthetic jet actuator", Meccanica, 53(11-12), pp. 2883-2896.
[2] Watson, M., Jaworski, A. J., & Wood, N. J., "A study of synthetic jets from rectangular and dual-circular orificies", Aeronautical Journal, 2003, 107(1073), pp. 427-434.
[3] Harima, T., Fujita. S. & Osaka, H., "Turbulent properties of twin circular free jets with various nozzle spacing", In: Engineering Turbulence Modelling and Experiments 6. Elsevier Science BV, pp. 501-510, 2005.

How to design nanoporous materials that dewet

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Keywords: nanoporous materials, liquid extrusion, hydrophobicity

In this work we explore by means of experiments, theory, and molecular dynamics the effect of pore morphology on the spontaneous extrusion of liquids from lyophobic nanopores [1]. Understanding and controlling this phenomenon is of importance for displacing nanoconfined liquids, e.g., in nanofluidic applications, drug delivery, and oil extraction. Qualitatively different extrusion behaviors were observed in high-pressure water intrusion and extrusion experiments on porous materials with similar nominal diameter and hydrophobicity: macroscopic capillary models and molecular dynamics simulations were the key to understand that the possibility of achieving extrusion, i.e., to dewet the pores after completely wetting them, is connected to the internal morphology of the pores and, in particular, to the presence of small-scale roughness or pore interconnections. Additional experiments with mercury confirmed that this mechanism is generic for nonwetting liquids and is connected to the pore topology. The present results suggest a rational way to design heterogeneous systems for energy and nanofluidic applications in which the extrusion behavior can be controlled via the pore morphology.

References

[1] *Amabili, M., Grosu, Y., Giacomello, A., Meloni, S., Zaki, A., Bonilla, F., Faik, A. and Casciola, C.M., "Pore Morphology Determines Spontaneous Liquid Extrusion from Nanopores," ACS Nano,* **Vol 13**, *page 1728-1738 (2019).*

A parametric study of sap flow in xylem vessels and sap-feeding insect foregut

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Keywords: Xylem Sap Flow, Sap Viscosity, Slip Boundary Condition

The study of sap flow in xylem and sap-feeding insect foregut is important to understand the nutrition of plants and insects and can shed light on the transmission of xylem limited pathogens that cause dangerous plant diseases worldwide. The model frequently used in literature ([1, 2]) for xylem-sap flow in vessels is the Poiseuille law, where the vessel is approximated with a smooth circular straight pipe, the flow is laminar and the fluid has the same characteristics of the water. However, this model leads to inconsistencies in the evaluation of the xylem sap tension (see e. g. [3]). In particular, the flow should occur under significant negative pressures, which could trigger nucleation and cavitation of the fluid, preventing the sap from flowing and the insect from feeding. On the other hand, the actual pressures in the plant vassels and in the insect foreguts has never been measured, since instruments would trigger cavitation in plant vassels or kill the insect. Therefore, a theoretical model is necessary for the evaluation of xylem sap tension, but the Poiseuille model must be overcome, relaxing some of the assumptions on the fluid viscosity and on the boundary conditions. The low content of nutrients suggested that the fluid viscosity is the same of water ([4, 5]), but the viscosity was never directly measured. Schenk et. al. [6] suggested that the presence of surfactants in xylem can trigger the formation of nanobubbles, affecting the fluid viscosity. Moreover, some slip at the microchannel walls occurs when wall surface are hydrophobic [7]. In view of these issues, we use the analitical solution proposed by Wu et. el. [8], to perform a parametric study of the pressure gradient necessary to drive the flow in a microchannel with slip boundary condition, varying the viscosity and the slip lenght The aim of this study is to evaluate more realistic pressure gradients, estimate the viscosity and slip lenght influence, and identify possible working condition of xylem sap flow and sap-feeding insect suction.

References

[1] *Andersen, P.C., Brodbeck, B.V. and Mizell R.F., Feeding by the leafhopper, H. C., in relation to xylem fluid chemistry and tension, J Insect Physiol,* **38(8)**, *611-622 (1992).*

[2] *Novotny, N. and Wilson. M.R., Why are there no small species among xylem-sucking insects?, Evol Ecol,* **11(4)**, *419-437 (1997)*

[3] *Kim, W., Mechanics of xylem sap drinking, Biomed Eng Lett,* **3(3)**, *144-148 (2013).*

[4] *Nobel, P.S., Biophysical plant physiology and ecology, WH Freeman and company, (1983)*

[5] *Terra, W.B., Evolution of digestive systems of insects, Annu Rev Entomol,* **35(1)**, *181-200 (1990)*

[6] *Schenk, H. J., Espino, S., David R. M., Nima, N., Aissa Y. T. D., Joseph M. M., Papahadjopoulos-Sternberg, B., Yang, J., Zuo, Y. Y., Steppe, K., and Jansen, S., Xylem surfactants introduce a new element to the cohesion-tension theory, Plant Physiol,* **173(2)**, *1177-1196 (2017)*

[7] *Tretheway, D. C. and Meinhart, C. D., Apparent fluid slip at hydrophobic microchannel walls, Phys Fluids,* **14(3)**, *L9-L12 (2002)*

[8] *Wu, Y. H., Wiwatanapataphee B. and Maobin H., Pressure-driven transient flows of Newtonian fluids through microtubes with slip boundary, Physica A Stat Mech Appl,* **387(24)**, *5979-5990 (2008)*

Non-Botzmann distributions in a hypersonic flows past a sphere

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Keywords: State to State kinetics; thermochemical non-equilibrium; hypersonic flows.

Numerical investigations of high enthalpy flows is important to design new space and hypersonic vehicles. Indeed, at hypersonic speed, such that experienced during an atmospheric entry, a strong shock wave forms in front of the vehicle; through this wave kinetic energy is converted into internal energy of molecules among different degrees of freedom (translational, rotational, vibrational and electronic) causing also dissociation and ionization. Speed can be so high that some of the characteristic times of internal modes and chemical reactions are of the same order of the fluid dynamic characteristic time, thus the flow is in thermochemical non-equilibrium.

A classical approach to thermochemical non-equilibrium is the multi-temperature model proposed by Park [1] assigning a single temperature to translational and rotational modes (translational temperature) and supposing a Boltzmann distribution for vibrational levels at a different temperature (vibrational temperature). In order to take into account the important effects that vibration has on chemical reactions, reactions rate coefficients are modeled by using the Arrhenius law with a controlling temperature that is a weighted geometric mean of the translational and vibrational ones. However, supposing Boltzmann distributions is a strong assumption that if not verified can lead to a wrong evaluation of reaction rates, strongly depending on high energy levels. In order to overcome this limitation, we implemented in a 2D axial-symmetric finite volume solver of the Navier-Stokes equations the so called State to State (StS) approach [2]. Such model determines the distribution of internal states by considering each vibrational level as a separated species that evolves according to vibrational-translational and vibrational-vibrational energy exchanges, thus allowing to take into account the effects that high energy levels have on dissociation rates. However, the higher accuracy of the StS approach implies a huge computational cost. To overcome this obstacle we adopted an MPI-CUDA approach allowing us to obtain speed-up values of a single GPU against a single core CPU of about 150 [2].

In order to compare the predictive capabilities of the Park and StS models, we considered a hypersonic flow past a sphere whose condition are given in Ref. [3]. We found that, with respect to the Park model, the StS approach predicts a stand-off distance that is in better agreement with experimental findings. Such behavior is due to non-Boltzmann distributions that lead to different reaction rates of oxygen dissociation, thus showing the importance of a detailed StS kinetics when dealing with high enthalpy flow in thermochemical non-equilibrium [3].

References
[1] Chul Park, Nonequilibrium Hypersonic Aerothermodynamics, John Wiley & Sons, (1990).
*[2] F. Bonelli, M. Tuttafesta, G. Colonna, L. Cutrone, and G. Pascazio, "An MPI-CUDA approach for hypersonic flows with detailed state-to-state air kinetics using a GPU cluster," Computer Physics Communications **219**, 178–195 (2017).*
[3] G. Colonna, F. Bonelli and G. Pascazio, "Impact of a fundamental molecular kinetics on macroscopic properties of high-enthalpy flows: the case of hypersonic atmospheric entry." Under review for Physical review Fluids

An experimental investigation on micro-hydropower generation

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Keywords: hydropower generation; laboratory tests; renewable energy.

The aim of this work is to investigate the use of the Pump as Turbine (PAT) technology to produce energy in a sustainable way, at a relatively small scale. PATs represent a smart solution which enables to obtain pressure regulation and electrical energy production, significantly reducing both design and maintenance costs if compared to traditional turbine [1]. Nevertheless, their performance curves are generally not provided from manufacturers and investigation of such issue is of great importance.

Energy generation from domestic and urban water supply systems has been tackled by exploiting an experimental facility available in the *Laboratory of Hydraulics and Maritime Constructions* of the Università Politecnica delle Marche (Ancona, Italy). The facility has been equipped with a recovered/recycled pump (now used as a turbine), a feed pump, two flowmeters and three pressure gauges (Fig.1a). A bypass pipe has been added to cooperate with the regulating valves, simulating the PAT application to typical Water Distribution Networks (WDN), and to properly adjust water head and flow rate entering the turbine. A transparent PVC pipe has also been installed downstream of the PAT, with the aim to visualize the vortices generated at the PAT exit, mainly due to turbulence generation and cavitation phenomena at specific regimes. A set of four pressure taps has been located at the PAT exit to investigate possible pressure variations induced by such vorticity generation. To measure the output power, the torque and the specific speed induced by the water flowing in the PAT, a test bench has also been used.

Tests are mainly focused on understanding the main characteristics of the pump when working in the traditional way (direct mode) or as turbine (reverse mode). Another goal is that of mimicking a real-world application and estimating the actual energy production at the different tested regimes, i.e. varying both hydrodynamic (water discharge and pressure) and mechanical (braking/torque and impeller speed). Preliminary results, e.g. mechanical power generated with changing water discharge (Fig.1b), will be discussed at the conference.

a) 

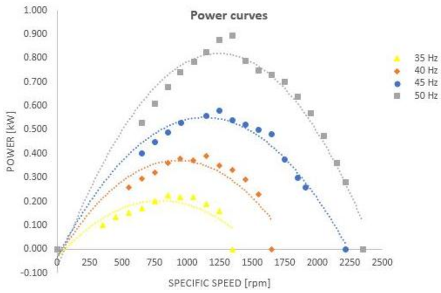
b) 

Figure 1 a) Experimental setup, b) Generated power curve.

References

[1] Rossi, M., Righetti, M, Renzi, M., "Pump-as-Turbine for energy recovery applications: the case study of an aqueduct" Energy Procedia, vol. 101, no. September, pp. 1207–1214, 2016.

Numerical simulation of flow separation in a truncated ideal contour nozzle

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Keywords: Hybrid RANS/LES, flow separation, compressible flows.

Detached eddy simulation of an over-expanded nozzle flow is carried out at a Reynolds number, based on the nozzle throat diameter and the stagnation chamber properties, equal to 1.75×10^7. During the start-up phase of rocket nozzles, an overexpanded flow is encountered, with a shock induced separation located inside of the nozzle. This non-stationary flow, characterized by a self-sustained shock oscillation, induces local unsteady loads on the nozzle wall as well as global off-axis forces, which are the most excessive experienced by the engine's operation cycle [1]. Despite the several studies in the last decades, a physical understanding is still lacking. Detailed numerical simulations can be very helpful, due to the higher amount of data they can provide. However, the Reynolds number of this kind of flow is too high to carry out a large eddy simulation, therefor a hybrid RANS/LES [2] technique has been adopted to simulate the separated flow in the nozzle. The geometry under investigation is a sub-scale truncated ideal contour (TIC) nozzle, which has been tested at the University of Texas at Austin [3]. In this study the analysis has been focused on the unsteady pressure signature on the nozzle wall. The classical Fourier spectral analysis has been conducted to investigate how the energy content of the pressure oscillation is distributed in frequency. The comparison with the experimental data is rather good: the power spectra are characterized by a large bump in the low frequency range (linked to the shock movement), a broad and high amplitude peak at high frequencies (the trace of the shear layer) and a high and narrow peak at an intermediate frequency. The analysis of the Fourier azimuthal pressure modes indicates that this intermediate-frequency peak belongs to the first (non-symmetrical) pressure mode and therefore it should be linked to the side-load generation.

References

[1] *Hadjadj, A. and Onofri, M., Nozzle Flow Separation, Shock Waves (2009) 19: 163*

[2] *Philippe R. Spalart, Detached Eddy Simulation, Annual Review of Fluid Mechanics 2009 41:1, 181-202*

[3] *Brian W. Donald, Woutijn J. Baars, Charles E. Tinney, and Joseph H. Ruf, Sound Produced by Large Area-Ratio Nozzles During Fixed and Transient Operations, AIAA Journal, Vol. 52, No. 7 (2014), pp. 1474-1485.*

Dynamics of a bubble moving through a liquid

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Keywords: cavitation, bubble dynamics, Rayleigh-Plesset equation

Cavitation is a topic of great interest in the field of high-speed hydrodynamic devices [1]. The study of development and evolution of vapour/gas bubbles inside a liquid, consequent to the dynamic generation of low-pressure field, is a fundamental tool to improve the knowledge of the phenomenon, and elaborate proper countermeasures [2]. Thus, the search for a better understanding of crucial aspects of bubble dynamics has received increasing attention.

In previous papers [3, 4] the authors derived from first principles and refined a model for the radial and translational dynamics of a spherical bubble, rising due to gravity through an inviscid liquid. The obtained formulation extends the famous Rayleigh-Plesset equation for the time evolution of the bubble radius, and is based on the hypothesis that the motion of translation would not significantly affect the bubble shape.

The present study consists in another step of a path finalised to investigate, with proper analytical methods, hydrodynamic cavitation. It is aimed, eventually, to predict the bubble motion, when the bubble lies in a prescribed flow, as it would be in the presence of hydrodynamic devices. Although this could induce significant bubble deformations, the simplifying assumption of dealing with a spherical bubble is maintained here, in view of the facts that: i) in many cases the spherical shape of the bubble proves to be stable against pressure perturbations; ii) important features of bubble behaviour under the action of a pressure disturbance (as the sound generation) can be studied by neglecting its deformations. Moreover, results of the present investigation can then be adopted as a reference when the task of studying the evolution of a non-spherical bubble is undertaken.

The present method closely follows the formulation developed for the study of the rising bubble, although it is suitable to deal with problems of three-dimensional dynamics of the bubble. The motion, within a fluid at rest, of a bubble in a plane parallel to the gravity field is study here, as a first step to investigate the behavior of the bubble when subject to transport of a background two-dimensional flow field.

References

[1] Franc, JP, Michel, JM, *Fundamentals of Cavitation*, Kluwer Academic Publishers, Dordrecht (2004).

[2] Brennen, CE, *Cavitation and Bubble Dynamics*, Cambridge University Press, Cambridge (2013).

[3] De Bernardis, E, Riccardi, G, (2016) Dynamics of a bubble rising in gravitational field, Commununications in Applied and Industrial Mathematics 7-1, 48-67.

[4] Riccardi, G, De Bernardis, E, (2016) Dynamics and acoustics of a spherical bubble rising under gravity in an inviscid liquid, Journal of the Acoustical Society of America 140-3, 1488-1497.

Exact Classical Nucleation theory for nucleation of vapour between hydrophobic plates

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Keywords: Vapour Nucleation, Hydrophobic Confinement, Nanofluidics

When liquid water is confined by nanometric hydrophobic surfaces, the combined effect of hydrophobicity and geometric confinement favours the evaporation of the liquid phase and the formation (nucleation) of vapour bubbles [1]. This peculiar behaviour holds great importance in a number of fields spanning from surface physics to engineering and biology. In order to name a few phenomena in which confinement-induced drying plays a major role we may recall the unusual robustness of superhydrophobicity at the nanoscale [2], the remarkable properties hydrophobic nanoporous materials [3] and self-assembly mechanisms of biological molecules [4].

In the present contribution we focus our attention on the formation of vapour between two parallel infinite hydrophobic plates. This simple geometry constitutes a minimal example of the accelerated drying induced by hydrophobic confinement and a widely studied model for the study of nanoconfined nucleation [4-6].

Previous studies on the subject have been showing how, as the confinement between the plates approaches the nanometer, the results of molecular simulations seem to deviate (in terms of nucleation free energies and mechanisms) from those of simple, classical, capillary-based vapour nucleation models. Non-classical effects, including elusive line tension contributions and nanoscale phenomena have been invoked as the cause of such deviations [5-6].

In this contribution an exact Classical Nucleation Theory for the nucleation of vapour beetween two hydrophobic plates is formulated, including line tension effects. Comparison with available Molecular Dynamics simulations allows us to critically discuss the relevance of nonclassical and nanoscale contributions and the role of the triple line tension for the dewetting of planar hydrophobic plates.

References

[1] *Debenedetti P.G.,"Metastable liquids: concepts and principles". Princeton University Press, Princeton (1996)*

[2] *Giacomello, A., Schimmele, L., Dietrich, S., "Perpetual superhydrophobicity". Soft Matter,* **12**, *pages 8927-8934 (2016)*

[3] *Tinti, A., Giacomello, A., Grosu, Y., Casciola, C.M., "Intrusion and extrusion of water in hydrophobic nanopores". Proc. Natl. Acad. Sci. USA,* **114(48)**, *pages E10266–E10273 (2017)*

[4] *Berne, B.J., Weeks, J.D., Zhou, R,"Dewetting and hydrophobic interaction in physical and biological systems". Annual Review of Physical Chemistry,* **60** *pages 85-103 (2009)*

[5] *Sharma, S. , Debenedetti, P.G., "Evaporation rate of water in hydrophobic confinement". Proc. Natl. Acad. Sci. USA* **109(12)** *pages 4365–4370, (2012)*

[6] *Remsing, R.C., Xi, E., Vembanur, S., Sharma, S., Debenedetti, P.G., Garde, S., Patel, A.J., "Pathways to dewetting in hydrophobic confinement". Proc. Natl. Acad. Sci. USA,* **112(27)** *pages 8181–8186, (2015)*

Preliminary design of variable pitch systems for Darrieus wind turbine using a genetic algorithm based optimization procedure

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Keywords: Vertical Axis Wind Turbine, Variable Pitch Systems, Optimization.

In recent years, the research in the field of Vertical Axis Wind Turbines (VAWT) has increased significantly because of the capability of these wind energy systems to work with omni-directional wind with no yaw mechanism. However, VAWTs are commonly affected by a dynamic stall condition that influences both aerodynamic and structural performances. This phenomenon is typically induced by a steep variation of the angle of attack of the blades during the turbine motion, increasing the noise and reducing the fatigue life of mechanical components. A consolidated strategy to delay the dynamic stall, increasing the power, contemplates consists in a dynamic variation of the blade pitch angle.

In literature, both active and passive variable-pitch systems have been presented to reproduce an assigned variable-pitch law. An active variable-pitch system changes the blade pitch angle continuously during the turbine rotation by using actuators that modify the blade aerodynamic layout, achieving the desired angle of attach (typically, the current max-lift angle). An active system commonly assumes blades actuated by pushrods driven by a central cam, which produces a pre-scheduled pitch variation. A major issue of such systems is a capped amplitude of the pitch variation, as it is fixed by the cam geometry. A passive variable-pitch system is conceived to remove this issue. In this case the pitch angle is directly modified by a combination of aerodynamic forces and inertial loads acting on the blade. However, the set-up of passive variable-pitch mechanisms presented in literature results quite complex; moreover, a relatively high thickness of blade cross-section is often required with a direct impact on the VAWT overall scale.

In the present paper, two preliminary designs of variable pitch systems are proposed, the first one is based on an active approach while the second is passive. The active pitch system is characterized by the following components: an eccentric point with respect to the main rotational axis, which relative position varies dynamically during the turbine motion by means of two linear actuators; an additional linear actuator that induces a variation of the current distance between a specific hinge on the airfoil chord and the eccentric point. An optimization procedure based on a binary genetic algorithm is performed to determine actuators stroke variation during the turbine motion to reply an a-priori known, effective variable-pitch law.

The alternate passive system is conceived to be mounted externally to the main VAWT structure (ground fixed) in order to allow the implementation also in small scale VAWT systems characterized by a limited airfoil thickness. In this case the blades are hinged at a quarter of chord to allow a pitch variation; a pin mounted on a rear point along the chord at the blade bottom is left free to slide into a curved (circular) slot cut out from the shield disk. The pin end is then constrained to follow the radial profile of an external loop during the turbine rotation. The conformation of the external loop has been determined using a genetic algorithm to replicate the kinematics of a previously achieved optimal pitch law.

Free topology generation of thermal protection system for reusable space vehicles using integral soft objects

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Keywords: Thermal Protection System, Integral Soft Objects, Re-Entry vehicles

The conceptual design of next generation Reusable Space Vehicles (RSVs) for manned and unmanned space missions is currently overstressed. Newly introduced mission requirements demand for RSVs with advanced features as gliding re-entry, reusability, and low-g landing on conventional runways, even though limited economic budgets and short turnaround times interval are highly envisaged. As a consequence, conceptual design routinely contemplates trade-off processes among non-linear conflicting design objectives, while satisfying, at the same time, a number of constraints functions [1]. For instance, the design of the Thermal Protection System (TPS) of RSVs performing a lifting re-entry, requires a mandatory compromise between the maximum allowed peak heating, and the integrated heat load. This scenario also involves the choice and distribution of specific thermal protections materials (TPMs) to shield the vehicle from the aerodynamic heating and minimize the vehicle mass. Typically, the capability to resolve and capture objectives and constraints may lead to many design variables involved in the vehicle design. Therefore, the adoption of an efficient parameterization represents the only viable approach in a conceptual design phase. Within this multidisciplinary framework, we intend to promote and test a proprietary SBISO (Skeleton-Based Integral Soft Object) methodology, originally developed for free topology generation and optimization of self-stiffened aerospace structures [2], to allow a free topology generation and design of a vehicle TPS. The basic idea is to define thermal shield models that can be controlled through special mathematical objects (i.e., SBISO primitives). These objects or "agents" can be arbitrarily placed on a flat grid and then left free to interact with each other according to specific rules with the purpose to enable a highly sensitive, powerful and arbitrary assignation of different insulating materials, each one dynamically linked with its own thickness map. To make this desirable scenario possible, the SBISO agents are applied on the topological (invariant) map associated to the current instance of the aerodynamic shape. Parametric objects are organized in different clusters; the first one is devoted to the arbitrary mapping of different types of insulating materials on the aerodynamic surface with no topological constraints (this means that different materials could be potentially placed in whichever sequence or alternance, for example, banded, spotted, or any combination), while the remaining clusters of SBISO primitives model the continuous thickness maps specific for each material. A major advantage derived by SBISO methodology is that a high degree of complexity can be managed through a relatively small number of decoupled parameters that do not have to undergo any functional constraint to remain self-consistent. In the present context, this circumstance is likely to produce very positive effects in an optimization procedure called to explore and manage a huge variety of configurations (shape and properties) of the space vehicle.

References

[1] *Dominic, D., Erwin, M., "Optimization of entry-vehicle shapes during conceptual design". Acta Astronautica,* ***Vol*** *94(1), page 198-214. (2014).*

[2] *Iuspa, L., Free topology generation of self-stiffened panels using skeleton-based integral soft objects. Computer & Structures 158, 184-210, (2015).*

Microfluidics for cavitation enhanced endothelial permeability

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Keywords: Microfluidics, Cavitation, Ultrasound.

In drug delivery, therapeutical agents are most often injected systemically in the circulation raising concern for uptake efficiency at target tissues. Indeed, large molecule permeation through the endothelial barrier lining the blood vessels is a necessary and difficult step [1]. Here we report on our recent multidisciplinary efforts to fabricate a microfluidic chip endowed with a living endothelial layer (blood-vessel-on-a-chip) to study cavitation enhanced endothelial permeability (Figure 1, left). The endothelium is grown under physiological shear stress conditions and let maturate under flow in order to form well developed junctions between neighboring cells. A biological barrier that prevents diffusion of large solutes from the vessel to the central tissue compartment is then formed. To permeabilize the barrier, stabilized microbubbles (MBs) are injected in the vessel and irradiated with ultrasound (US). The protocol results in the transient formation of gaps between cells that temporarily increase the permeability of the endothelium (Figure 1, right). Crucial for clinical applications, after irradiation a compact endothelium reforms, recovering the barrier biological functionality. In the talk fabrication and bio-functionalisation issues and the related microfluidics will be addressed touching upon the idea of the so-called organs-on-a-chip expected to pave new avenues for high precision medicine.

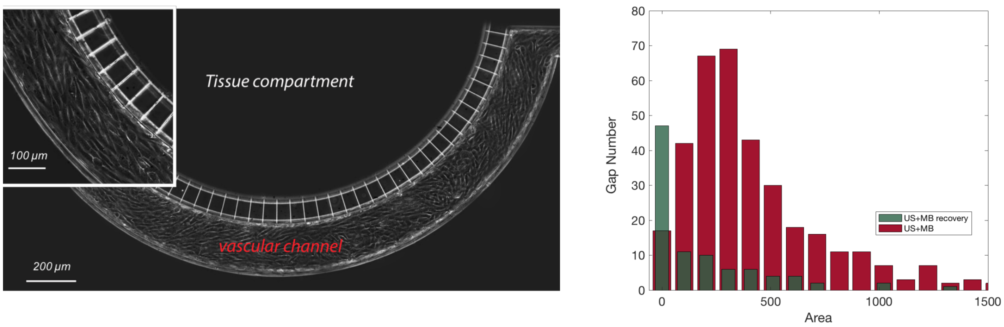

Figure 1. Left, artificial vascular channel with endothelial layer. Right, gap opening under USMB irradiation and recovery 40 min after irradiation (area in px units).

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References

[1] G. Peruzzi, G. Sinibaldi, G. Silvani, G. Ruocco, C.M. Casciola, "Perspectives on Cavitation Enhanced Endothelial Layer Permeability", Colloids and Interfaces B: biointerf. 2018.

Droplet homogeneous nucleation in two-way coupled turbulent flows

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Keywords: droplet nucleation, multiphase turbulent flow, two-way coupling regime

Homogeneous nucleation of liquid droplets in hot vapour stream, mixing with a cooler and dry external environment, occurs in many technological applications which could benefit from a better understanding of such multi-physics turbulent flows. Many experiments [1, 2] using DBP or water as condensing species, investigated the sensitivity of nucleation rates to the underlying turbulent flow. Some numerical simulations, RANS/LES [3, 4] and DNS [5], have been carried out, but a steam jet DNS is still missing despite the multitude of experiments and its relevance for applications.

The nonlinear interplay between homogeneous nucleation and turbulent fluctuations within a multiphase flow, leads to a non-trivial physical situation, where it is crucial to take into account cross-coupling phenomena. Classical Nucleation Theory (CNT) prescribes rates and critical diameters at which droplets nucleate, strongly depending on the local thermodynamical state. DNS allows to capture without any modelling the underlying turbulence, while additional effects such as the disperse phase back-reaction are accounted in the so called two-way coupling regime. In the low Mach number formulation, a full description of the droplet nucleation in turbulent steam jets is addressed through DNS accounting for the small droplets under the point-particle approximation including all the coupling effects i.e. mass, momentum and energy transfer between the different phases. Each conservation equation has a singular source term, regularized and time-delayed, in a physically consistent way [6].

During the talk, the relevance of the effects arising in the two-way coupling regime will be discussed. Because of the particles back-reaction on the thermodynamics, we are able to account for the whole effect of the phase change process. Moreover, following a Lagrangian description of the disperse phase dynamics, each particle trajectory is drawn and every observable can be fully characterized from a statistical point of view, contrary to the approaches adopted in literature [3, 5].

References

[1] *Lesniewski, T.K. and Friedlander, S.K. "Particle nucleation and growth in a free turbulent jet", Proc. Royal Soc. A*, **454**(1977), 2477–2504 (1998).

[2] *Lim, S., Cha, J., Lee, H., Kim, T. and Shin, W.G. "Understanding the condensation process of turbulent steam jet using the PDPA system", Int. J. Multiph. Flow*, **98**, 168–181 (2018).

[3] *Di Veroli, G.Y. and Rigopoulos, S., "Modeling of aerosol formation in a turbulent jet with the transported population balance equation-probability density function approach", Phys. Fluids*, **23**(4), 043305 (2011).

[4] *Pesmazoglou, I., Kempf, A.M. and Navarro-Martinez, S., "Aerosol nucleation in a turbulent jet using Large Eddy Simulations", Chem. Eng. Sci.*, **116**, 383–397 (2014).

[5] *Zhou, K., Attili, A., Alshaarawi, A. and Bisetti, F., "Simulation of aerosol nucleation and growth in a turbulent mixing layer", Phys. Fluids*, **26**(6), 065106 (2014).

[6] *Gualtieri, P., Picano, F., Sardina, G. and Casciola, C.M., "Exact regularized point particle method for multiphase flows in the two-way coupling regime", J. Fluid Mech.*, **773**, 520–561 (2015).

On the stability of Subsonic Impinging Jets

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Keywords: Impinging Jet, Compressible flow, Stability Analysis

The study of impinging jets is relevant to heating and cooling processes because they may enhance the local heat transfer by more than an order of magnitude, compared to classical wall boundary layers [1]. Recent investigations and experiments have been focused to maximise the heat transfer efficiency of impinging jets. Different techniques have been proposed [2]; in particular, it has been demonstrated that the use of a pulsating inlet with an appropriate pulsation frequency can result in a 40% enhancement of heat transfer compared to a non-pulsating configuration. Such effect is related to the enlargement of the generated toroidal vortices which cause higher wall shear stresses [3]. The mechanism underlying the generation of these larger vortex rings at a specific frequency is still unclear and the explanation of the effects of pulsation on heat transfer is still an open question. In this work we focus on a subsonic impinging round jet confined between two walls with a nozzle-to- plate distance of h/D = 5. We first perform a DNS of the jet at Ma = 0.8 and Re = 3300 (fig. 1a) and analyse the characteristics of the resulting flow fields, including dominant frequencies and the heat transfer at the wall. In a second step we perform a global stability (fig. 1b) and sensitivity analysis: the characteristics and the nature of the resulting unstable modes will be presented and the effect of the instability on the heat flux at the target plate will be analysed. A comparison between the eigenfrequency of the dominant modes and the optimal inlet pulsation will be presented and possible adjoint-based control strategies based on linear stability analysis will be discussed.

(a) (b)

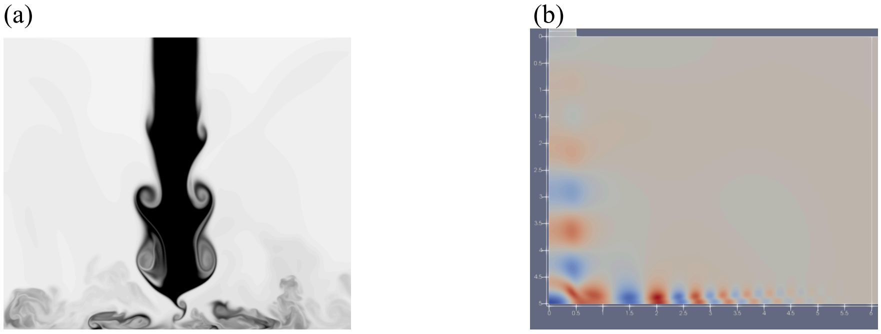

Figure 1: (a) Snapshot of DNS at Ma = 0.8 and Re = 3300: temperature field. (b) Leading unstable eigenmode at M a = 0.8 and Re = 2500: real part of the pressure field.

References
[1] *Martin, H., "Heat and Mass Transfer between Impinging Gas Jets and Solid Surfaces" Advances in Heat Transfer, Vol. 13, page 1-60, (1977)*
[2] *Janetzke, T., Doctoral dissertation, TU Berlin (2010)*
[3] *Wilke, R., Doctoral dissertation, TU Berlin (2017)*

Jet-Flat Plate Interaction: Wall Pressure Coherence Modeling

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Keywords: Jet Noise, Wall Pressure Fluctuations, Installation Effects

An important challenge for the future aicraft design is the reduction of the interior noise, which influences both comfort and health indices of the passengers, pilots and attendants. This annoyance is the product of several noise sources: the propulsion system, high speed flow over the vehicle surfaces and the operations of on board system. Nowadays the noise produced by the propulsion system, in particular considering the Jet engines in installed configuration, becomes an important aspect of investigation for the new generation of ultra high bypass ratio (UHBPR) engines. The increase of the nozzle diameter will bring about more aggressive close-coupled configuration leading to an increase of the pressure load on the wing and the fuselage surface, causing panel stress and vibrations. In order to clarify this issues several studies have been carried out to investigate the wall pressure fluctuations induced by non compressible and compressible jet flows over a flat plate, varying the jet initial conditions (see among: [2, 3, 4]) and providing also a preliminary coherence modeling using the Corcos' exponential fit. This model is usually used to predict the coherence functions in non compressible flows, but at high subsonic Mach numbers it provides a quite good fit for a short frequencies range [4], lacking the prediction of the low frequency region which is of particular interest for the possible connection with the structural modes. Furthermore with the aim to provide a complete prediction of the wall pressure coherence functions induced by a compressible jet flow over a flat plate, the authors modified the Efimitsov model [1] normally used for the classical Turbulent Boundary Layer. In this work a mathematical model able to reconstruct the wall pressure coherences over a flat plate will be provided using as input only the nozzle exhaust diameter (D) and the jet Mach number (M_j). This analysis, that concerns also the assessment of the model, is carried out in streamwise direction, downstream of the jet impact point over the plate surface and for different radial positions of the flat plate (H).

References

[1] Efimtsov B. M. Model of a field of pseudonic turbulent wall pressures and experimental data. Sov. Phys. Acoust. 28, 289292.(1982)

[2] Di Marco A., Mancinelli M., Camussi R. Pressure and velocity measurements of an incompressible moderate Reynolds number Jet interaction with a tangential flat plate. Journal of Fluid Mechanics 770:247-272. (2015)https://doi.org/10.1017/jfm.2015.149

[3] Meloni S., Di Marco A., Mancinelli M., Camussi R. Reynolds numbers effect on wall pressure fluctuations induced by a subsonic jet on a tangential flat plate. FIV (Toronto)(2018).

[4] Meloni S., Di Marco A., Mancinelli M., Camussi R. Exp Fluids (2019) 60: 48. https://doi.org/10.1007/s00348-019-2696-3

Numerical simulation of shock - boundary layer interaction using a shock fitting technique for unstructured grids.

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Keywords: shock-fitting, boundary layer, interaction.

Shock-wave/boundary-layer interactions [1] occurring within a high speed flow can greatly affect the performance of a vehicle or a propulsion system due to the presence of large recirculation regions, intense local heating and a loss of efficiency of the aerodynamic control surfaces.

In the proposed paper we will be mainly concerned with different test cases involving shock-wave/boundary-layer interactions. In this abstract we show results for shock-induced separation on a compression ramp in hypersonic laminar flow. The numerical simulations have been performed using both a state-of-the-art shock-capturing code and a novel shock-fitting algorithm [2], both working on 2D unstructured triangular grids. The shock-fitting technique consists in identifying the shock as a polygonal curve, which is treated as an internal boundary by a CFD code, and computing the shock motion and the shock-upstream and shock-downstream states according to the Rankine-Hugoniot equations. We will show that shock-fitting allows to overcome most of the numerical troubles incurred by shock-capturing schemes when used on unstructured grids. These include: the finite shock-thickness (often spanning several mesh intervals) that characterizes captured shock-waves and the spurious disturbances that pollute the shock-downstream regions even when fine grids are used. The comparison between the pressure distribution obtained using the same CFD code, working both in shock-capturing and shock-fitting mode, is shown in figures 1 and 2. More details about this simulation and other test-cases (e.g. biconvex transonic airfoil) involving different kinds of shock/boundary-layer interactions will be discussed and analyzed in the full paper.

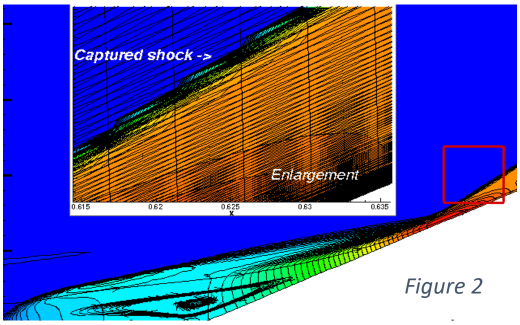

Figure 2

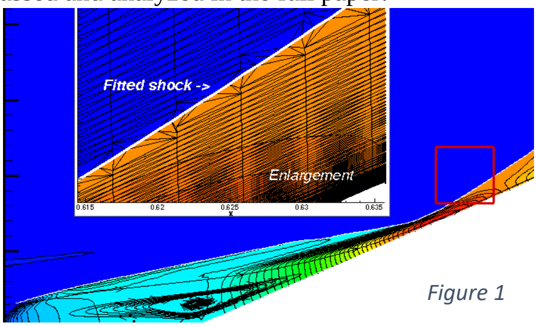

Figure 1

References

[1] Babinsky H.,Harvey J., Shock Wave-Boundary-Layer Interactions, Cambridge University Press (2011).

[2] Paciorri R., Bonfiglioli A., "A shock-fitting technique for 2D unstructured grids". Computers and Fluids, Vol.38 ,no.3, page 715-726 (2009).

Flow regimes and mixing in micro-mixers

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Keywords: micro-mixers, flow regimes and mixing, experiments and DNS

Micro-mixers and micro-reactors, constituted by micro-channels of width $\leq$ 1 mm, in which two fluid streams are fed through inlet branches and mix and possibly react in the outlet channel, are interesting for several engineering applications. They offer, e.g., continuous operation and high heat transfer capacity due to the very high surface to volume ratio. Efficient mixing is fundamental to have high reaction yield. The main issue is to obtain efficient mixing at low Reynolds numbers (laminar flow).

The simplest and most studied configuration is the so-called T-mixer, in which the inlet channel axis is perpendicular to that of the main channel. Despite the very simple geometry and the laminar flow conditions, significanlty different and complex flow regimes occur in T-mixers when increasing the Reynolds number, Re: stratified, steady symmetric (vortex), steady asymmetric (engulfment), periodic asymmetric and periodic symmetric regimes. The characterization and eventually the control of these regimes and of their onset is crucial because they can lead to largely different degrees of mixing. Indeed, mixing remarkably increases with the onset of the steady engulfment and keeps increasing monotonically with Re until the periodic symmetric regime takes place, in which the mixing efficiency dramatically drops. The present work first summarizes a systematic and synergic experimental and numerical analysis of the flow regimes and mixing occurring for increasing Re in T-shaped micro-mixers operated by a single fluid ([1]). Quantitative comparisons with recent experimental velocity measurements carried out by using particle image velocimetry are also provided.

Then, a modification of the T geometry obtained by tilting downward the inlet channels respect to the mixing channel (arrow-shaped micro-mixer) is considered. This configuration is interesting from a practical viewpoint, because it leads to an onset of the engulfment regime, and thus to an increase of mixing, at Reynolds numbers significantly lower than for T-mixers. This effect becomes more pronounced by increasing the tilting angle α. However, for α larger than some critical value (between $15°$ and $20°$ for the configuration investigated in [2]) a significant drop of mixing is observed already within the steady engulfment regime, which is not present for T-mixers and for low tilting angles. This is due to a change of flow topology, i.e. the presence of a unique vortical structure at the center of the mixing channel instead of two co-rotating ones, typical of the engulfment regime in T-mixers ([2]). It is shown in the present work that also the flow dynamics in the periodic unsteady regimes is significantly influenced by the tilting angle α and this once again has a strong impact on mixing. It appears that moderate values of α (around $10°$) lead to the best mixing performances.

References

[1] *Mariotti, A., Galletti, C., Mauri, R., Salvetti, M.V., Brunazzi, E., "Steady and unsteady regimes in a T-shaped micro-mixer: Synergic experimental and numerical investigation". Chemical Engineering Journal* **341**, *page 414-431 (2018).*

[2] *Mariotti, A., Galletti, C., Brunazzi, E., Salvetti, M.V. "Steady flow regimes and mixing performance in arrow-shaped micro-mixers", Physical Review Fluids,* **034201** *(2019).*

Turbulent pipe flow laden with elastic chains

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Keywords: Elastic chains, turbulent pipe, turbulence modulation

In the last decades, a lot of studies have been devoted to the investigation of inertial spherical particle in turbulent flows [1, 2, 4], whilst few works deals with fibers despite their importance in nature and human applications. Here we present results of simulations of turbulent pipe flow laden with strings of tracers interacting elastically. The dynamics of each single tracer composing the string follows the classical Rouse model derived for polymeric chains [5]. The main physical parameters are the number of links, N_ℓ, the characteristic relaxation time of the non-linear elastic links, τ_ℓ, the maximum link extension and the equilibrium length of the chain in absence of the flow. A recent work [6], addresses the dynamics of these elastic chains in two dimensional turbulent flow in a squared double periodic domain, observing strong preferential accumulation of the chains, depending on their physical features. Our aim is to investigate the dynamics of these elastic chains in a turbulent pipe flow and its dependence on the physical parameters. The implications of the observed behaviour of the chains in wall turbulence will be discussed with particular aim at turbulent drag reduction applications, typically addressed in the context of simple dumbbell models which neglects the multi-link nature of the polymers [3].

References

[1] *Balachandar, S. and Eaton, J. K, "Turbulent dispersed multiphase flow", Annual Review of Fluid Mechanics,* **42**, *111-133 (2010).*

[2] *Battista, F., Gualtieri, P., Mollicone, J.-P., Casciola, C.M., "Application of the Exact Regularized Point Particle method (ERPP) to particle laden turbulent shear flows in the two-way coupling regime", International Journal of Multiphase Flow,* **101**, *113-124 (2018).*

[3] *De Angelis, E., Casciola, C.M. and Piva, R., "DNS of wall turbulence: dilute polymers and self-sustaining mechanisms", Computers & Fluids,* **31**, *4-7 (2002).*

[4] *Gualtieri, P., Battista, F. and Casciola, C.M., "Turbulence modulation in heavy-loaded suspensions of tiny particles", Physical Review Fluids,* **2**, *034304 (2017).*

[5] *ttinger, H.C., Stochastic processes in polymeric fluids: tools and examples for developing simulation algorithms, Springer, New York (1996).*

[6] *Picardo, J.R., Vincenzi, D., Pal, N. and Ray, S.S., "Preferential Sampling of Elastic Chains in Turbulent Flows", Physical Review Letters,* **121**, *244501 (2018).*

Wall turbulence modification as predicted by the Exact Regularised Point Particle method

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Keywords: *Turbulence modulation, Drag increasing, Particles*

In wall bounded particle laden flows when the mass flow rate of the disperse phase and of the carrier fluid are comparable a significant inter-phase momentum exchange occurs (two-way coupling regime). Under these conditions a substantial alteration of the turbulent fluctuations is observed.

Many numerical attempts to predict the flow modification are available in the literature even though the results do not indicate a clear effect of the particles on the fluid. Some numerical simulations show that turbulence intensities were increased for small mass loading but the inverse behaviour is observed for higher loadings while others report an overall drag reduction due to the particles.

In this contribution we present new results of a particle laden turbulent pipe flow in the two-way coupling regime exploiting a novel momentum coupling method named Exact Regularised Point Particle (ERPP) approach [1, 2] which overcomes the typical difficulties of the Particle In Cell approach. In the ERPP, the momentum coupling is achieved in a physically consistent manner. The local flow disturbance produced by each small particle is described in closed form by an exact unsteady Stokes solution. In the extended contribution we will fully document the turbulence modulation and, by exploiting the axial mean momentum equation, we will give reason of the observed drag increase.

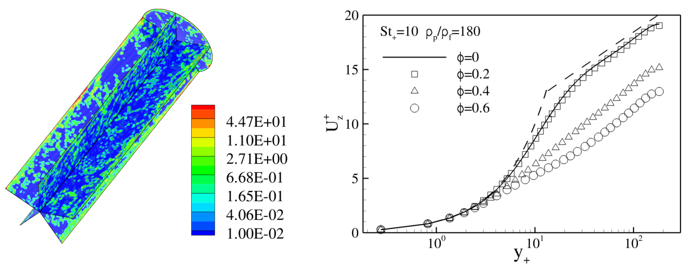

Figure 1: Left panel: instantaneous feedback-forcing field on the carrier phase. Right panel: semi-logarithmic plot of the normalised mean velocity profile, $U^+ = \langle u_z \rangle / u_*$ with u_* the friction velocity, as a function of the normalised wall distance $y^+ = (R - r)/y_*$ being y_* the wall unit. Solid line: uncoupled case (no back-reaction); symbols data at $St_+ = 10$ and different mass loading.

References

[1] *F. Battista, J.-P. Mollicone, P. Gualtieri, R. Messina, and CM. Casciola. "Exact regularized point particle (erpp) method for particle-laden wall-bounded flows in the two-way coupling regime." Submitted to Journal of Fluid Mechanics, 2019.*

[2] *P. Gualtieri, F. Picano, G. Sardina, and CM. Casciola. "Exact regularized point particle method for multiphase flows in the two-way coupling regime." Journal of Fluid Mechanics,* **773***:520–561, 2015.*

MSS

SOLID AND STRUCTURAL MECHANICS

Titolo: Mitigazione delle vibrazioni nelle costruzioni mediante dispositivo di protezione passiva del tipo Magnetic Flexural Damper

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Parole chiave: Protezione passiva, smorzamento.

Fenomeni naturali e attività umane possono essere origine di forze tali da provocare vibrazioni nelle costruzioni [1]; le costruzioni vibrando dissipano energia che, se non opportunamente controllata, può comportare uno stato di sollecitazione del materiale tale da anticiparne il degrado, nonché il danneggiamento della costruzione, per effetto del fenomeno della fatica.

Il presente studio riporta i risultati della sperimentazione di un sistema in grado di ridurre le vibrazioni indotte da azioni esterne sulle costruzioni, con particolare riferimento agli edifici ed ai ponti.

Il dispositivo considerato è uno smorzatore a massa accordata [2] del tipo "Magnetic Flexural Damper", assimilabile ad un oscillatore semplice ad un grado di libertà composto da una massa magnetica che si può muovere in un'unica direzione (orizzontale o verticale) oscillando davanti ad una lamina metallica ed inducendo un campo magnetico che genera uno smorzamento regolabile mediante la distanza piastra-magnete; il dispositivo è collegato al sistema da "proteggere" tramite una struttura di supporto in alluminio.

Per la progettazione del dispositivo è stato sviluppato un software in Matlab validato effettuando una modellazione agli elementi finiti ed analizzando il comportamento meccanico del dispositivo mediante l'ausilio del programma ad elementi finiti COMSOL Multiphysics.

L'efficacia del dispositivo progettato è stata verificata sperimentalmente, attenuando le vibrazioni su un modello di una costruzione sottoposto ad oscillazioni libere.

I risultati sperimentali evidenziano la validità dei modelli teorici applicati [3] e l'efficacia del dispositivo ai fini della riduzione della risposta strutturale sia in termini di accelerazione che di spostamento, come anche le potenzialità dello smorzatore ad essere applicato nella riduzione di vibrazioni, oltre che negli edifici, in altre costruzioni data la sua versatilità.

Riferimenti

[1] Paz, M., International Handbook of Earthquake Engineering, Springer Science Business Media Dordrecht (1994).

[2] Connor, J.J., Introduction to Structural Motion Control, Prentice Hall (2002).

[3] Christopoulos, C., Filiatrault, A., Principles of Passive Supplemental Damping and Seismic Isolation, Multimedia Cardano (2006).

Brittle crack initiation from a circular hole: From FFM theory to experiments

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Keywords: Crack onset, biaixial loading, Finite Fracture Mechanics.

The coupled criterion of Finite Fracture Mechanics (FFM) is employed to investigate brittle crack initiation from a circular hole in an infinite slab subjected to remote biaxial loading. Depending on the loading conditions and on the ratio between the crack advance and the hole radius, the crack propagation could reveal to be either unstable (positive geometries), or stable (negative geometries). Furthermore, it is shown that stable paths could follow unstable paths and vice-versa, leading to locally positive/globally negative or locally negative/globally positive configurations. Finally, for each configuration discussed above, the FFM predictions are compared successfully with the experimental data available in the literature [1] and/or recently carried out [2-3], restricting the analysis to the nucleation/failure stress, for the sake of simplicity.

References

[1] Carter, B.J., Lajtai, E.Z. and Yuan Y., "Tensile fracture from circular cavities loaded in compression", Int. J. Fract., ***57****, 221–236 (1992).*

[2] Torabi, A.R., Etesam, S., Sapora, A. and Cornetti, P., "Size effects on brittle fracture of Brazilian disk samples containing a circular hole", Eng. Fract. Mech. ***186****, 496–503 (2017).*

[3] Sapora, A., Torabi, A.R., Etesam, S., Cornetti, P. "Finite Fracture Mechanics crack initiation from a circular hole", Fatigue Fract. Eng. Mater. Struct. ***41****, 1627–1636 (2018).*

Diffraction and reflection of antiplane shear waves in a cracked couple stress elastic material

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Keywords: Couple stress; Wave diffraction; Rayleigh waves

We investigate the effect of a semi-infinite rectilinear crack on diffraction and reflection of antiplane shear waves in an elastic solid with microstructure. Waves are induced by moving shear traction vectors applied at the faces of the crack. The material behavior is described by the indeterminate theory of couple stress elasticity considering micro inertia. This elastic constitutive model accounts for the material microstructure and it is a special case of the micropolar theory; it was developed by Koiter [3] for the quasi-static regime and later extended by Eringen [1] to include dynamic effects. The full-field solution is obtained through integral transforms and the Wiener-Hopf technique [5] and it may be used as a bulding block to solve general wave propagation problems in a cracked half-space in antiplane deformation. The solution differs significantly from the classical result given in [2] for isotropic elastic materials. Indeed, unlike classical elasticity, antiplane shear Rayleigh waves are supported in couple stress materials [4]. A complicated wave pattern appears which consists of entrained waves extending away from the crack, reflected Rayleigh waves, localized waves irradiating from and body waves scattered by the crack-tip. Wave diffraction and interference brings an important contribution to the stress intensity factors originally presented in [6] in the static framework. Resonance is triggered when the applied loading is fed *into* the crack-tip at Rayleigh speed and this result is confirmed by the evaluation of the energy release rate.

References

[1] A. C. Eringen, "Theory of micropolar elasticity". In *Microcontinuum field theories*, pages 101–248. Springer, 1999.
[2] L. B. Freund, *Dynamic fracture mechanics*. Cambridge Monographs on Mechanics and Applied Mathematics. Cambridge university press, Cambridge, 1990.
[3] W. Koiter, "Couple-stress in the theory of elasticity". In *Proc. K. Ned. Akad. Wet*, volume 67, pages 17–44. North Holland Pub, 1964.
[4] A. Nobili, E. Radi, and A. Vellender, "Diffraction of antiplane shear waves and stress concentration in a cracked couple stress elastic material with micro inertia". *Journal of the Mechanics and Physics of Solids*, 124:663 – 680, 2019.
[5] B. Noble, *Methods based on the Wiener-Hopf technique for the solution of partial differential equations, International Series of Monographs on Pure and Applied Mathematics. Vol. 7.* Pergamon Press, New York, 1958.
[6] E. Radi, "On the effects of characteristic lengths in bending and torsion on mode III crack in couple stress elasticity". *International Journal of Solids and Structures*, 45(10):3033–3058, 2008.

Corrosion fatigue investigation on the possible collapse reasons of Polcevera Bridge in Genoa

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Keywords: Cable-stayed Bridge; Corrosion Fatigue; Very-High Cycle Fatigue.

On August 14th, 2018, a few spans of the cable-stayed viaduct crossing the Polcevera river (Genoa, Italy) collapsed, causing tens of fatalities along with considerable material damage and hundreds of people displaced. The viaduct, as well as many others belonging to the national road network, was built in the second half of the last Century, and has been in service for over fifty years.

In the present paper, a possible scenario is proposed to put into evidence how the combined effect of fatigue at very high number of cycles [1] and corrosion [2] could have been responsible for the sudden failure of one of the strands and the subsequent collapse of the so-called balanced system conceived by the designer Morandi [3].

The analysis accounts for an actual estimation of the heavy lorries traffic and load spectrum, as well as the European standards [4] prescription for the fatigue damage accumulation assessment. In addition, the effective construction phases of the viaduct are considered. The structural analysis is carried out by means of analytical models, in order to simplify the structure complexity without prejudice to the description of the most relevant aspects of the structural behavior.

The purpose of the present study is not to identify responsibility among the different actors involved with the infrastructure collapse, aspect to be addressed by the Italian magistracy. On the other hand, the main goal is to warn the scientific community and the public administrations that the combined effects of low amplitude fatigue and corrosion can be dangerously underestimated, and that the existing asset of last Century bridges deserves special attention in this respect.

References

[1] Bathias C., Paris P.C., Gigacycle Fatigue in Mechanical Practice, Marcel Dekker, New York, (2005).

[2] Lotsberg I., Fatigue Design of Marine Structures, Cambridge University Press, Cambridge (2016).

[3] Morandi R., "Viaducto sobre el Polcevera, en Genova – Italia", Informes de la Construcción, ***21****(200), 57-88, (1968).*

[4] Nussbaumer A., Borges L., Davaine L. Fatigue Design of Steel and Composite Structures, ECCS – European Convention for Constructional Steelwork, Ernst & Sohn, Berlin, (2011).

An Analytical Algorithm for Statics and Dynamics of High-rise Buildings

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Keywords: Tall buildings, Analytical formulation, Preliminary design.

In the design of high-rise buildings, it is important to reduce the stresses due to horizontal loads, such as wind and earthquakes, in order to minimize lateral displacements.

To this purpose, different types of resisting elements are employed, such as braced frames and closed- or open-sections shear walls [1], to give stability, rigidity and, at the same time, to guarantee lightness and versatility to the construction. These typologies of vertical bracings are ideal for hosting elevators, stairs and technological facilities, but they should not exceed 35-40 storeys.

For higher buildings, more complex systems are used, that employ outrigger and belt truss systems. These structures, connecting the central core with columns placed along the perimeter of the building, are generally made up of one- or two-storey-high steel truss beams, which provide high flexural stiffness and induce tension-compression actions in the columns. These systems decrease the stress due to bending moment inside the core and also contribute to minimize the lateral displacements of the building.

Such configurations can be analyzed using a semi-analytical approach [2], in which only three degrees of freedom per storey are taken into account. Using this method, the bending and the torsional behaviour of the structure can be studied at the same time.

This solution proves to be as general as possible in order to study any type of vertical bracings, as well as open-sections shear walls, outrigger systems, framed-tubes, spatial truss systems (diagrid structures), provided that the stiffness matrix is known.

For this reason, an analytical code, called General Algorithm [3], has been developed to perform static, dynamic and buckling analyses in computational times reasonable more quickly than that obtained by the FEM software programs.

The effectiveness of this analytical code has been verified in some case studies of high-rise buildings carried out in recent years by the authors.

References

[1] *Lacidogna, G., "Tall buildings: Secondary effects on the structural behaviour", Proceedings of the Institution of Civil Engineers. Structures and Buildings,* **170**, *391-405 (2017).*

[2] *Carpinteri, A., Lacidogna, G. and Nitti, G., "Open and closed shear-walls in high-rise structural systems: Static and dynamic analysis", Curved and Layered Structures,* **3**, *154-171 (2016).*

[3] *Nitti, G., Lacidogna, G. and Carpinteri, A., "Tall buildings subjected to horizontal loading: Analysis of two case studies by an in-house numerical code" in Proceedings of 23rd Conference of the Italian Association of Theoretical and Applied Mechanics, Salerno (Italy), 4-7 September 2017,* **1**, *292-300 (2017).*

Investigation into the benefits of coupling a frame structure with a rocking rigid block

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Keywords: Visco-elastic coupling, rocking rigid block, gain coefficients and maps.

After the pioneering work [1] that examined the stability of a standalone slender block subject to a base motion, several papers analysed the dynamics of rigid blocks. In recent years many studies have regarded the coupling of rigid block with other mechanical system in order to protect the block from overturning [2]. It is not frequent the use of rocking rigid block as protecting device of other kinds of structures. Recently some authors have considered a rigid coupling between a frame and a rocking wall, in order to improve the seismic behaviour of the frame [3].

This paper analyses the linear visco-elastic coupling of a frame structure and a rigid block aimed at improving the dynamic behaviour of the frame. A two-degree of freedom linear system is used as model for a multi-story frame structure. A visco-elastic device connects the block to one of the lower stories of the frame structure. The nonlinear equations of motion of the coupled-system are obtained by a Lagrangian approach and successively numerically integrated to analyze the behaviour of the coupled system. Simulations are performed using both harmonic and seismic excitation as forcing term. An extensive parametric analysis is performed and the results are summarized in gain maps. The maps show the ratio between the maximum displacements or drifts of the coupled and uncoupled systems in different planes of the systems parameters. Results of the numerical simulations show that there are wide regions of the parameters where the coupling is effective.

Experimental simulations are performed to verify the effectiveness of such a coupling. A scale shear-type 2 d.o.f frame coupled with an aluminum rigid block is sinusoidally forced by an electro-dynamic long-stroke shaker. The systems response, in terms of displacements, measured by no-contact and currently expensive optical/laser sensors, is real-time processed in the LabView Environment. Preliminary results confirm the capacity of the block to improve the dynamic response of the coupled system with respect to the uncoupled one.

References

[1] *G.W. Housner, The behavior of inverted pendulum structures during earthquakes. Bulletin of the Seismological Society of America,53(2):404-417. (1963).*

[2] *G. Simoneschi and A.M. de Leo and A. Di Egidio, "Effectiveness of oscillating mass damper system in the protection of rigid blocks under impulsive excitation." Engineering Stuctures, 137:285-295. (2017).*

[3] *N. Makris and M. Aghagholizadeh, "The dynamics of an elastic structure coupled with a rocking wall." Earthquake Engineering and Structural Dynamics, 46:945-954. (2017).*

Base isolation systems for structures subject to anomalous dynamic events

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Keywords: base isolation systems, dynamic nonlinear analysis, finite element method.

A base isolation system is investigated which is suitable for structures subject to dynamic events characterized by high intensity and critical values of frequency content. The analyzed base isolation system is defined as high damping hybrid seismic isolator since it is realized by the assembly in series of a lead rubber bearing isolator and a friction slider isolator characterized by a high friction coefficient. A nonlinear dynamic analysis is performed for a base isolated structure characterized by irregularity in plan. The base isolation system is designed to cope with extreme dynamic events in terms of peak ground acceleration and in terms of frequency content. A nonlinear dynamic analysis is performed for the considered base isolated structure by investigating the time history of the base shear and the time history of the base displacement of the superstructure for the different analyzed dynamic events. The characteristic features of the presented base isolation system are compared with the ones of a traditional lead rubber bearing base isolation system for the dynamic protection of structures. The advantages of the illustrated high damping hybrid base isolation system are shown to be useful for the safeguard of structures under extreme dynamic events in terms of peak ground acceleration and frequency content.

References

[1] De Angelis, F., Cancellara, D., Dynamic analysis and vulnerability reduction of asymmetric structures: fixed base vs base isolated system, COMPOSITE STRUCTURES, Vol. 219, pp. 203-220, 2019.

[2] Cancellara, D., De Angelis, F., Dynamic assessment of base isolation systems for irregular in plan structures: response spectrum analysis vs nonlinear analysis, COMPOSITE STRUCTURES, Vol. 215, pp. 98-115, 2019.

[3] Cancellara, D., De Angelis, F., Assessment and dynamic nonlinear analysis of different base isolation systems for a multi-storey RC building irregular in plan, COMPUTERS AND STRUCTURES, Vol. 180, pp. 74–88, February 2017.

[4] De Angelis, F., Taylor, R.L., An Efficient Return Mapping Algorithm for Elastoplasticity with Exact Closed Form Solution of the Local Constitutive Problem, ENGINEERING COMPUTATIONS, Vol. 32, Issue 8, pp. 2259 - 2291, 2015.

[5] De Angelis, F., Taylor, R.L., A Nonlinear Finite Element Plasticity Formulation without Matrix Inversions, FINITE ELEMENTS IN ANALYSIS AND DESIGN, Vol. 112, pp. 11-25, 2016.

[6] Cancellara, D., De Angelis, F., Nonlinear dynamic analysis for multi-storey RC structures with hybrid base isolation systems in presence of bi-directional ground motions, COMPOSITE STRUCTURES, Vol. 154, pp. 464–492, 2016.

[7] Cancellara, D., De Angelis, F., A base isolation system for structures subject to extreme seismic events characterized by anomalous values of intensity and frequency content, COMPOSITE STRUCTURES, Vol. 157, pp. 285–302, 2016.

Dynamic analysis of base isolation systems for irregular in plan structures

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Keywords: dynamic nonlinear analysis, base isolation systems, finite element method.

A dynamic nonlinear analysis is discussed for irregular in plan structures with base isolation systems. In the present investigation different base isolation systems have been analyzed. They are realized by considering different types of elastomeric isolators actuated in parallel with friction sliders. The mechanical performance of the base isolation systems is analyzed in order to regularize the dynamic behavior of irregular in plan structures. A three-dimensional base isolated structure characterized by strong irregularity in plan is considered subject to dynamic events. In the analysis bi-directional ground motions have been adopted. The base isolated structure is investigated by a nonlinear finite element analysis. The dynamic behavior of the base isolated structure is assessed and a comparative analysis is discussed between the traditional fixed base structure and the structure base isolated by the considered base isolation systems.

References

[1] De Angelis, F., Cancellara, D., Dynamic analysis and vulnerability reduction of asymmetric structures: fixed base vs base isolated system, COMPOSITE STRUCTURES, Vol. 219, pp. 203-220, 2019.

[2] Cancellara, D., De Angelis, F., Dynamic assessment of base isolation systems for irregular in plan structures: response spectrum analysis vs nonlinear analysis, COMPOSITE STRUCTURES, Vol. 215, pp. 98-115, 2019.

[3] Cancellara, D., De Angelis, F., Assessment and dynamic nonlinear analysis of different base isolation systems for a multi-storey RC building irregular in plan, COMPUTERS AND STRUCTURES, Vol. 180, pp. 74–88, February 2017.

[4] De Angelis, F., Taylor, R.L., An Efficient Return Mapping Algorithm for Elastoplasticity with Exact Closed Form Solution of the Local Constitutive Problem, ENGINEERING COMPUTATIONS, Vol. 32, Issue 8, pp. 2259 - 2291, 2015.

[5] De Angelis, F., Taylor, R.L., A Nonlinear Finite Element Plasticity Formulation without Matrix Inversions, FINITE ELEMENTS IN ANALYSIS AND DESIGN, Vol. 112, pp. 11-25, 2016.

[6] Cancellara, D., De Angelis, F., Nonlinear dynamic analysis for multi-storey RC structures with hybrid base isolation systems in presence of bi-directional ground motions, COMPOSITE STRUCTURES, Vol. 154, pp. 464–492, 2016.

[7] Cancellara, D., De Angelis, F., A base isolation system for structures subject to extreme seismic events characterized by anomalous values of intensity and frequency content, COMPOSITE STRUCTURES, Vol. 157, pp. 285–302, 2016.

Scaling of creep behaviour in metallic materials: Theoretical aspects and experimental evidence

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Keywords: Creep, Scaling effects, Crack growth, Incomplete self-similarity, Fractals.

Scaling effects governing the creep behaviour at elevated temperature of smooth and notched metallic specimens are investigated by applying dimensional analysis and fractal modeling to experimental results taken from the literature [1,2]. The correlation between the applied stress σ and the rupture time t_R in smooth specimens is examined emphasizing the strong analogy with the Wöhler's law for fatigue. The observed specimen-size effects on the σ-t_R curves [1] are interpreted in terms of incomplete self-similarity [3] and fractal weakening (lacunarity) of the specimen reacting cross-section [4]. By using a fracture mechanics approach, the effects of macroscopic defects on creep crack growth are studied by analogy with the Paris law [5-6] . Predictions of creep crack growth are discussed in the framework of Linear Elastic and Time Dependent Fracture Mechanics, being the crack growth rate d*a*/d*t* correlated respectively with the stress-intensity factor *K* and the creep *C**-parameter [7-8]. Crack-size effects on creep crack growth rate experimental curves [2] are examined on the basis of self-similarity considerations [3], and geometrically interpreted in terms of fractal tortuosity of the crack profile. In all cases scale-invariant creep laws are deduced by a renormalization procedure [4].

References

[1] Goldhoff R. (1963) "Stress concentration and size effects in a Cr-Mo-V steel at elevated temperatures". Proceedings of the Institution of Mechanical Engineers, 178, 19-32.

[2] Tabuchi M., Kubo K., Yagi K. (1991) "Effect of specimen size on creep crack growth rate using ultra-large CT specimens for 1 Cr-Mo-V steel". Engineering Fracture Mechanics, 40, 311-321.

[3] Barenblatt, G.I. (1996) "Scaling, Self-similarity and Intermediate Asymptotics". Cambridge University Press, Cambridge, UK.

[4] Carpinteri A. (1994) "Scaling laws and renormalization groups for strength and toughness of disordered materials". Int. J. Solids Struct., 31, 291-302.

[5] Carpinteri An., Spagnoli A. (2004) "A fractal analysis of size effect on fatigue crack growth". International Journal of Fatigue, 26, 125-133.

[6] Paggi M., Carpinteri A. (2009) "Fractal and multifractal approaches for the analysis of crack-size dependent scaling laws in fatigue". Chaos, Solitons and Fractals, 40, 1136-1145.

[7] Landes J.D., Begley J.A. (1976) "A fracture mechanics approach to creep crack growth". ASTM Special Technical Publication, 590, 128-148.

[8] Saxena A., Tabuchi M., Yagi K. (1994) "Crack growth under small scale and transition creep conditions in creep-ductile materials". ASTM Special Technical Publication 1207, 481-497.

Numerical investigations on infilled frames and predictive formulae

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Keywords: Infilled frames, Numerical model, Interpolation formulae.

Infilled frames are one of the most commonly used structural systems worldwide. In the practical structural analysis, infill walls are not included in the numerical models. In this way, their stiffness and strength contribution as well as their interaction with the load-bearing elements of the frame are fully neglected. However, it was observed [1-4] that masonry infill walls can have a significant effect on the structural performance of RC frames under seismic actions. The widespread neglect of the contributions of these elements can be attributed, in part, to difficulties associated with the modelling, and, in part, to the scatter that pervades the available published results [4,5].

In this paper, numerical investigations on the behaviour of single-storey infilled frames are carried out, with focus on local interaction among the panel and the surrounding primary RC elements. A numerical finite element model of infilled frame, where the masonry panel is assumed homogeneous and isotropic, is analysed. Considerations about the friction influence at the frame-infill interface allowed to neglect the friction and to use a simple interface model working only by normal contact forces of compression, like [6]. The numerical model is validated by experimental evidences provided by literature. Parametric analyses are carried out and interpolation formulae capable to predict the frame-infill contact lengths are determined. An analytical model of equivalent diagonal strut is also formulated in the elastic range and an interpolation formula for the strut width is obtained. The proposed approach is found to provide the best fitting of the numerical results among literature models [4].

References

[1] Mehrabi, A. B., Benson Shing, P., Schuller, M. P., and Noland, J. L., "Experimental evaluation of masonry-infilled RC frames," Journal of Structural engineering, 122.3, page 228-23, (1996).

[2] Mehrabi, A. B., and Shing, P. B., "Finite element modeling of masonry-infilled RC frames," Journal of structural engineering, 123(5), page 604-613, (1997).

[3] Calvi, G. M., and Bolognini, D., "Seismic response of reinforced concrete frames infilled with weakly reinforced masonry panel," Journal of Earthquake Engineering, 5(02), page 153-185,(2001).

[4] Ghosh, A. K., and Amde, A. M., "Finite element analysis of infilled frames," Journal of Structural Engineering, 128(7), page 881-889, (2002).

[5] Asteris, P. G., Antoniou, S. T., Sophianopoulos, D. S., and Chrysostomou, C. Z., "Mathematical macromodeling of infilled frames: state of the art," Journal of Structural Engineering, 137(12), page 1508-1517, (2011).

[6] Cavaleri, L., and Di Trapani, F., "Prediction of the additional shear action on frame members due to infills," Bulletin of Earthquake Engineering, 13(5), page 1425-1454, (2015).

Fractality and size effect in fatigue damage accumulation: Comparison between Paris and Wöhler perspectives

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Keywords: Size Effect, Fatigue Limit, Fatigue Threshold, Fractals.

Fatigue life assessment can be carried out according to two well-known approaches. The first is based on the so-called Paris' law [1] that express the sub-critical crack growth rate as a function of the stress-intensity factor range. The second is based on Wöhler's curve [2] that relates the applied stress range with the number of cycles to failure. Both approaches exhibit scale effects, which can be explained in the framework of dimensional analysis and intermediate asymptotics concepts.

More recently, the application of fractal geometry concepts provided an alternative way to obtain similar scaling laws [3]. In this new framework, it is possible to conceive that the propagating crack of the Paris formulation is characterized by an invasive fractal roughness, whereas in the Wöhler context the material ligament is provided with a lacunar fractal, in order to account for cross-sectional weakening due to inherent defects. In particular, scaling laws are found for the fatigue threshold ΔK_{th} and fatigue limit $\Delta\sigma_{fl}$. The former increases with the crack length, whereas the latter decreases with the specimen size [4].

The fractal formulations for the two approaches are presented and put in comparison. Subsequently, the size effects represented by the two fractal formulations are compared with some recent results available in the literature [5, 6].

References

[1] *P. Paris, F. Erdogan (1963) A critical analysis of crack propagation laws. Journal of Basic Engineering Transaction ASME **85**, 528–534.*
[2] *A. Wöhler (1870) Über die Festigkeitsversuche mit Eisen und Stahl. Zeitschrift für Bauwesen **20**, 73–106*
[3] *M. Paggi, A. Carpinteri (2009) Fractal and multifractal approaches for the analysis of crack-size dependent scaling laws in fatigue. Chaos, Solitons and Fractals **40**, 1136–1145.*
[4] *A. Carpinteri, F. Montagnoli (2018) Scaling and fractality in fatigue crack growth: Implications to Paris' law and Wöhler's curve. Procedia Structural Integrity (In printed).*
[5] *U. Zerbst, M. Vormwald, R. Pippan, H.P. Gänser, C. Sarrazin-Baudoux, M. Madia (2016) About the fatigue crack propagation threshold of metals as a design criterion – A review. Engineering Fracture Mechanics, **153**, 190-243.*
[6] *Y. Furuya (2010) Size effects in gigacycle fatigue of high-strength steel under ultrasonic fatigue testing. Procedia Engineering, **2**, 485-490.*

Möbius kaleidocycles as "torquegrity" linkages

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Keywords: kaleidocycle; infinitesimal mechanism; stiffening effect.

The term "tensegrity" was coined by Buckminster Füller to refer to a structure whose integrity is assured by tensioned members, usually cables, prestressed by matching a few "floating" compression struts. Matrix analysis [1] shows that, although structures of this kind are statically indeterminate, states of self-stress can impart first order stiffness to every mode of inextensional deformation that they can sustain.

There are conceptual analogies between tensegrities and a new class of linkages presented in [2]. Each element of this class is a closed chain of any number $N \geq 7$ of identical bars with ends coupled by revolute hinges, whose axes are skew lines forming a critical acute twist angle, and can be continuously everted much like the rings of six regular tetrahedra called kaleidocycles [3]. The hinge orientation induces a nonorientable topology equivalent to the topology of a threefold Möbius band and, because of this, in [2] chains of this type have been called Möbius Kaleidocycles. Although a closed chain of N links should have $N - 6$ internal degrees of freedom according to the classical mobility rule, Möbius Kaleidocycles appear to exhibit a single degree of freedom whatever the number N, in this specific geometry.

From the analysis of the kinematic and static matrixes, we recognize that, at the critical twist angle for the hinge axes, the system admits one state of self-stress which can impart first order stiffness to all the possible modes of motion that leave unchanged the relative position of the hinges in each link, except one mode constituting the finite mechanism associated with the everting motion. This state of self-stress can be obtained by manufacturing the hinges in one or more links with a twist angle slightly different from the critical one and forcibly closing the chain. Since the resulting state of stabilizing self-stress is dominated by the torsion of the bars which constitute the links, in the analogy with tensegrities we propose to designate Möbius Kaleidocycles as "*torquegrity*" linkages, as a portmanteau of "*torque-induced-integrity*".

References

[1] Pellegrino, S., and Calladine, C.R.; "Matrix analysis of statically and kinematically indeterminate frameworks", Intern. Journal of Solids and Structures, ***22****(4),409–428 (1986).*
[2] Schönke, J., and Fried, E., "Single degree of freedom everting ring linkages with nonorientable topology", Proceedings of the National Academy of Sciences of the United States of America ***116****(1), 90-95 (2019).*
[3] Schattschneider. D., "Creating kaleidocycles and more". In Senechal, M., and Fleck, G., eds, "Shaping space. A polyhedral approach", Chap. 1, 57–60. Birkhauser, Basel (1988).

Smart beam element approach for LRPH device

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Keywords: smart displacement, LRPH, distributed plasticity.

LRPH (Limited Resistance Rigid Perfectly Plastic Hinge) device is a special steel device mainly usable to join beam elements of plane or spatial steel frames covered by patent n. 102017000088597 at the Italian Ministry of Economic Development and identified in the In-ternational Patent System with the number PCT/IB2018/055766. In the framework of moment (rigid) connection, the main fundamental innovation of LRPH consists in the mutual inde-pendence of its own resistance and stiffness features. The device is constituted by a sequence of three steel elements of limited length bounded by two parallel steel plates joined up with the connected structure elements. The cross-sections of the three steel elements are classical I sections with appropriate wing and web thicknesses obtained by the solution of suitable op-timal design problem. Therefore, the overall device shows piecewise discrete geometric and mechanical features. In order to implement this device in a frame-oriented code for the de-sign of both 2D and 3D frame structures, it is necessary to adopt a suitable model based on a non-uniform cross section beam element. The latter element should be able to reproduce the elastic and plastic behavior of the device. Recently, in the literature it has been proposed a new inelastic beam element, belonging to the displacement based approach and formulated for uniform beams, based on variable displacement shape functions, whose analytic expres-sions are prone to updating (smart) in accordance to the plastic deformation evolution in the beam element. Aim of the paper is to utilize the relevant smart displacement beam element approach and extend it to the case of non-uniform beams to evaluate the nonlinear behavior of the LRPH device. The obtained results confirm the efficacy and the feasibility of the smart displacement beam element opening the way of implementing LRPH device in a FEM code.

References

[1] *Benfratello, S., Cucchiara, C., Palizzolo, L., Tabbuso, P., "Fixed strength and stiffness hinges for steel frames" AIMETA 2017 - Proceedings of the 23rd Conference of the Italian Association of Theoretical and Applied Mechanics,* ***1****, page 1287-1296.*

[2] *Benfratello, S., Palizzolo, L., "Limited resistance rigid perfectly plastic hinges for steel frames", International Review of Civil Engineering,* ***8****(6), page 286-298 (2017).*

[3] *Pantò, B., Rapicavoli, D., Caddemi, S., Caliò, I., "A smart displacement based (SDB) beam element with distributed plasticity", Applied Mathematical Modelling,* ***44****, page 1339-1351 (2017).*

A reliable approach for plastic strain evaluation at the shakedown limit

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Keywords: Shakedown behaviour, transient phase, plastic deformations.

A new formulation devoted to the measurement of reliable limit values for the plastic deformations occurring in the transient phase of a structure in elastic shakedown conditions is proposed. Without losing in generality, reference is made to elastic perfectly plastic frame structures subjected to any quasi-static load history appertaining at a given admissibility load domain.

The formulation consists in the search for the optimal self-stress values that maximize a chosen measures of the plastic deformations occurring in the transient phase of the shakedown. The typical self-stress field can be obtained as the elastic response of the structure to an assigned field of plastic strains respecting the ductility limit behaviour of the relevant material.

The proposed formulation substantially differs from the known usual approaches based on bounding techniques (see, e.g. [1-3]) or other new techniques based on a special scanning method [4].

In detail, once known the shakedown load domain of the relevant structure, a sufficiently high number of plastic deformation fields can be generated, and correspondingly an analogous number of self-stress fields can be determined by solving some appropriate elastic analysis problems. Consequently, a subset of stress fields can be identified respecting the plastic admissibility for the structure. Finally, the maximum value of the chosen measure of the plastic strains appertaining at the obtained subset provide a reliable evaluation of the limit inelastic behaviour of the structure during the transient phase that comes before the final shakedown.

The effected applications are related to plane steel frames and some useful comparisons with the results obtainable by performing an elastic plastic analysis confirm the good reliability of the proposed approach.

References

[1] *Polizzotto, C., "A unified treatment of shakedown theory and related bounding techniques" S.M. Archives, **7**(1), 19-75 (1982).*

[2] *Giambanco, F., Palizzolo, L., "Computation of bounds on chosen measures of real plastic deformation for beams" Computers and Structures, **61**(1), 171-182 (1996).*

[3] *Giambanco, F., Palizzolo, L., "Optimal bounds on plastic deformations for bodies constituted by temperature-dependent elastic hardening material" Journal of Applied Mechanics, **64**(3), 510-518 (1997).*

[4] *Atkočiūnas, J., Liepa, L., Gervytė, A., Merkevičiūtė, D., "The scanning method for analysing the residual displacements of the framed structures at shakedown" Computers and Structures, **207**, 148-154 (2018).*

Preliminary experimental results of shaking table tests on MDOF structure equipped with non-conventional TMD

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Keywords: non-conventional TMD, shaking table tests, dynamic response

The use of tuned mass damper (TMD) to attenuate structural vibrations has been largely studied in past years [1]. Typically, it consists of a small auxiliary mass attached to the main structure by means of a linear (with elastic or viscoelastic behavior) or nonlinear connection (with plastic or friction behavior). It is well known that conventional TMD works effectively but it seems not robust for structural parameters variations and fails when dealing with non-stationary inputs, especially of impulsive character.

Recent studies have demonstrated that TMD control performances and robustness can be strongly enhanced by increasing its mass, i.e. realizing a non-conventional TMD. In case of frame structures, a way to apply this concept is to use masses already present in the structure to be converted into tuned masses, realizing segmented upper stories or sliding roof systems, which are isolated from the substructure and act as TMD. A non-conventional TMD is suitable for new constructions as well as for retrofitted ones since its impact on the structure is minimal, not requiring additional weight. Among the literature reports, only few regard experimentation on non-conventional TMD applied for inter-story isolation [2, 3].

The present memory illustrates preliminary experimental results of shaking table tests conducted on a frame structure equipped with non-conventional TMD. The objective of the experiments is to investigate the dynamic response and control performances in case of seismic actions. The reference physical structural model consists of a 4-story steel frame structure. The non-conventional TMD is realized by isolating the top story mass (fourth floor) and connecting it to the substructure (3-storys) with two high damping rubber bearings (HDRB) placed in series. Different configurations are investigated: 1) the reference 4-story structure, 2) the segmented 3-story structure, 3) the 3-story structure with the support plane for the HDRB, 4) the 3-story structure equipped with the non-conventional TMD. Simple input motion conditions, such as white noise and sine sweep signals, are utilized to investigate the dynamic response, through pseudo-frequency response functions, in the various configurations. Dynamical behaviors qualitatively different emerge from each case and allow to highlight useful considerations for control purposes.

References

[1] *Soong, T. T., Dargush, G. F., Passive energy dissipation systems in structural engineering, John Wiley & Sons, 1997.*

[2] *De Angelis, M., Perno, S., Reggio, A., "Dynamic response and optimal design of structures with large mass ratio TMD", Earthquake Engineering & Structural Dynamics,* ***41****(1), 41-60 (2012).*

[3] *Reggio, A., De Angelis, M., "Optimal energy-based seismic design of non-conventional Tuned Mass Damper (TMD) implemented via inter-story isolation", Earthquake Engineering & Structural Dynamics,* ***44****(10), 1623-1642 (2015).*

Exact homogenization and redesign requirements in composites reinforced with monoclinic/trigonal helically wound fibres

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Keywords: Wire strand; Composites; Homogenization

The mechanical performances of reinforced composites, at different scales, are strongly influenced by the stress transferred at the matrix-fibre interfaces and at any material discontinuity surface. For example, the mechanical performances of cord/rubber composites are heavily compromised by fatigue and delamination phenomena occurring at cord-rubber and ply-interfaces, rubber as well as polymeric matrices being mainly vulnerable to the accumulation of deviatoric energy [1]. In the present contribution, by introducing the coupling between torsion and tensile loads in twisted cords [2], we provide a model characterized by an enriched cord-matrix mechanical interplay able to theoretically explain and predict actual stress distributions at the basis of the onset of delamination and fatigue-guided phenomena experimentally observed in such composites [3]. By exploiting exact solutions for compound cylinders made of an isotropic core and concentric monoclinic/trigonal hollow layers, a one-to-one correspondence is established between the elastic moduli of an equivalent anisotropic cylinder and stiffness and geometrical parameters governing the local mechanical behaviour of helically arranged wires obeying the classical Costello's rope theory [4]. At the end, to show the effectiveness and the relevance of the theoretical findings for the applications, Finite Element results for rubber/cord composite units under prescribed boundary conditions are presented to highlight the discrepancies, in terms of mechanical behaviour, between standard approaches and the proposed model enriched with the homogenized monoclinic/trigonal cords.

References

[1] *Sokolov, S.L.,. "Prediction of the Fatigue Life of Pneumatic Tires", Journal of Machinery Manufacture and Reliability,* ***39*** *(5), 66-73, (2010).*
[2] *Fraldi, M., Cowin, S.C., "Chirality in the torsion of cylinders with trigonal symmetry", Journal of Elasticity,* ***69****, 121-148, (2002).*
[3] *Turner, J.L., Ford, J.L.,. "Interply behavior exhibited in complimentary composite laminates", Rubber Chemistry and Technology,* ***55****, 1079-1094, (1982).*
[4] *Costello, G., "Mechanical models of helical strands". Applied Mechanics Reviews,* ***50****, 1-14, (1990).*

A dimensionally reduced formulation for the peridynamics of thin films

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Keywords: reduced peridynamics, thin films

In the framework of bond-based peridynamics [1] we propose a dimensionally reduced model for thin films, that is capable of retaining information about failures occurring through the thickness while highly reducing the computational times. Unlike classical continuum mechanics, peridynamics accounts for non-local interactions and the resulting structure of the balance of linear momentum is an integral equation. This fact renders peridynamics very well-suited for modelling fractures. Such integral equations, in fact, do not require continuity of the displacement and stress fields. Peridynamic models for 2D elements have been proposed by several authors [2, 3], although such models do not take into account the possibility of a crack propagation through the thickness, as they only consider in-plane stretching and dynamic tearing.
In this work, we specialise the analysis to peridynamics of plates experiencing through-thickness Mode-I delamination. This is achieved by taking into account a discontinuous displacement field, and by subsequently, dimensionally reducing the model. This procedure generates a hierarchy of terms characterising the energy stored inside the thin film. Examples are then shown to depict the mechanical behaviour of a thin film under bending.

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References

[1] *Silling, S.A., "Reformulation of elasticity theory for discontinuities and long-range forces", Journal of Mechanics and Physics of Solids,* **48**, *page 175-209 (2000).*

[2] *Silling, S.A., Bobaru, F., "Peridynamic modeling of membrane and fibers", International Journal of Non-Linear Mechanics,* **40**, *page 395-409 (2005).*

[3] *Taylor, M., Steigmann, D.J., "A two-dimensional peridynamic model for thin plates," Mathematics and Mechanics of Solids,* **20**, *page 998-1010 (2014).*

Hybrid structural optimization for applications in large-span civil structures

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Keywords: design optimization, topology optimization, bio-inspired civil structures

Structural optimization aims to identify the optimal material arrangement within a structure in order to maximize its strength-to-weight ratio under prescribed loading conditions and constraints, in a way to guarantee the required bearing capacity by making the most efficient use of the available material [1, 2]. The governing principle of this strategy are highly inspired by nature, in which a great variety of living structures have optimized their shape through the millennia for adapting to the changes of the environmental mechanical stimuli, by exhibiting forms that recall those assumed by some non-living systems under the action of known physical forces. On these bases, the present work introduces a new hybrid strategy that combines a structural optimization [3] approach, here defined as *Galilei's Design Optimization* (GDO) in honour of one of the first scientists who debated this problem, with topology optimization (TO) [1, 2]. The GDO is essentially based on the bio-inspired concept that, in every section and element of a load-carrying structure, the work rate is maximized and the highest stress always equates the yield stress of the material reduced by a safety factor. Hence, the coupled procedure first provides the optimal material distribution in the topological domain of an assigned system, and then optimizes its internal structural elements by implementing GDO by means of a parametric algorithm. In this way, the optimized design of the structure is performed at two hierarchical levels. This procedure has been suitably employed for large-span civil structures like roofings, with the aim of obtaining particularly slender architectures that can represent a possible solution to the problem of protecting archaeological excavations without impacting the scenario. To this purpose, a first application example of an optimized roofing is reported for the case of "Villa Augustea" ruins, located near Naples in Italy. However, the generality of the proposed procedure allows to envisage several applications in which different geometries and structural typologies can be built up thanks to a fully parametric approach. For this reason, it is believed that further developments of the GDO/TO coupled strategy can allow to blend an efficient use of the materials and the construction techniques with the intuition and creativity of designers in conceiving innovative engineering architectures.

References

[1] *Bendsoe, M.P.A, Sigmund, O., "Topology Optimization: Theory, Methods and Applications, Springer, Lyngby (Denmark), 2002.*

[2] *Nemat-Nasser, S., Hori, M., "Micromechanics: Overall Properties of Heterogeneous Materials" (2nd Ed.), North-Holland, Amsterdam (Holland), 1999.*

[3] *Spillers, W.R., MacBain, K.M., "Structural Optimization", Springer, Newark (New Jersey-USA), 2009.*

JKR, DMT and more: gauging adhesion of randomly rough surfaces

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Keywords: adhesion, surface roughness, multi-asperity theory.

In the past years, the community of tribologists has shown growing interest in the adhesion between rough bodies. The contact mechanics of several engineering applications is indeed strongly affected by interfacial adhesive interactions. New technological challenges, such as the more and more sought-after downsizing of nano and micro electro mechanical systems, forced to model surface interactions accurately.

The classical adhesion theories, i.e. the Derjaguin, Muller & Toporov (DMT) theory [1] and the Johnson, Kendall & Roberts (JKR) theory [2], allow estimating adhesion between elastic smooth spheres.

In this work, we present a brief overview of the main models aimed at estimating adhesion in presence of surface roughness, ranging from DMT to JKR based solutions. Typically, a DMT based solution consists in solving the contact problem neglecting the effect of adhesion on surface deformations but simply scaling the total load by a tensile attractive contribution. In a JKR based solution, it is necessary to model surface deformations due to adhesion, which can lead to elastic instabilities and hysteresis phenomena. Although the aforementioned phenomena are widely detected in experimental investigations [3, 4], very few models are able to capture them [5].

We have extended a recent multi-asperity contact model, the Interacting and Coalescing Hertzian Asperities (ICHA) model, to the adhesive case in the limit of the DMT and JKR theories. In the ICHA model, the major shortage of the original Greenwood and Williamson theory is overcome (i) by including the elastic coupling between asperities and (ii) taking into account the coalescence of merging contact regions.

Results are compared with analytical, numerical and experimental data taken from the literature finding a very good agreement. Some numerical experiments are also carried out to show loading-unloading hysteretic loops which occur with soft materials with high surface energy.

References

[1] Derjaguin, B. V., Muller, V. M., & Toporov, Y. P. "Effect of contact deformations on the adhesion of particle"s. Journal of Colloid And Interface Science, 53(2), 314–32. (1975).

[2] Johnson, K. L., Kendall, K., & Roberts, A. D. "Surface Energy and the Contact of Elastic Solids". Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 324(1558), 301–313. (1971).

[3] Guduru, P. R., & Bull, C. "Detachment of a rigid solid from an elastic wavy surface: experiments". Journal of the Mechanics and Physics of Solids, 55(3), 473-488. (2007).

[4] Kesari, H., Doll, J. C., Pruitt, B. L., Cai, W., & Lew, A. J. "Role of surface roughness in hysteresis during adhesive elastic contact". Philosophical Magazine Letters, 90(12), 891–902. (2010).

[5] Carbone, G., Pierro, E., & Recchia, G. "Loading-unloading hysteresis loop of randomly rough adhesive contacts". Physical Review E, 92(6), 062404 (2015).

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MECHANICS OF MACHINES AND MECHANICAL SYSTEMS

A new pneumatic pad controlled by means of an integrated proportional valve

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Keywords: aerostatic pad, active compensation, proportional valve.

Aerostatic air bearings have the advantages of supporting loads with no friction and wear and for this feature they are extensively adopted in metrology as they allow very precise motion.

The possibility of integrating an active component increases the performance of the aerostatic pads, which can be designed in order to obtain an infinite stiffness or to improve stability.

In [1,2] the authors developed a prototype of active pad controlled by means of digital valves and Arduino board. A shortcoming of this prototype was a small amplitude oscillation of the pad supply pressure due to the opening and closing of the digital valve. In order to overcome this problem a new prototype was designed making use of a proportional valve. This paper shows the first experimental tests together with the numerical model.

References

[1] Colombo F, Maffiodo D, Raparelli T. Active Gas Thrust Bearing With Embedded Digital Valves and Backpressure Sensors, Tribology Transactions 2016; DOI: 10.1080/10402004.2016.1213344

[2] Maffiodo D, Colombo F, Raparelli T. Open and closed loop control of an active air bearing with digital valves, Proceedings of the XXIII Conference of the Italian Association of Theoretical and Applied Mechanics, Salerno, Italy, September 2017

Oral exostoses and congruence of the contact in the temporo-mandibular joint

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Keywords: contact mechanics; bone remodeling; congruence measure.

In this paper the correlation between the formation of oral exostoses and contact disfunctions in the temporo-mandibular joint (TMJ) are investigated. The mechanics of contact is studied by taking into account the functional matrix hypothesis (FMH) by Moss [1], the spatial matrix hypothesis (SMH) [2-3] and the law of bone remodelling by Wolff [4]. Furthermore, the insurgence of oral exostoses can be related also with parafunctional activities such as bruxism [2-3]. The aim of the paper is to demonstrate that oral exostoses can grow up in response to mechanical loads disfunctions and non-uniformities during mechanical contact [5]. A case study of a buccal maxillary exostosis was considered. After excluding malocclusions and tumors the 2D images from a cranial computerized tomography were used to reconstruct the 3D model of the patient's skull, obtaining a 3D triangular mesh. The analysis of contact disfunctions was performed by calculating the joint congruence, according to the elastic foundation contact model (EFCM) by Winkler and to the studies of Conconi et al. [6–8]. Comparing the two buccal sides of the maxilla, with and without neoformations, in terms of load distributions and congruence measure, the results show a non-uniform distribution of the loads on the two sides of the jawbones, with a higher contact load on the side where the exostosis grew up [9]. Thus, the congruence measure and the analysis of contact load distribution allow to predict the risk of neoformations.

References

[1] Moss, M.L., "The functional matrix hypothesis revisited. 1. The role of mechanotransduction," Am. J. Orthod. Dentofac. Orthop, ***112****, 8–11 (1997).*
[2] Singh, G.D., "Spatial matrix hypothesis," Brit. Dent. J. ***202(5)****, 238-239 (2007).*
[3] Singh, G.D., "On Growth and Treatment: the Spatial Matrix hypothesis,". In: Growth and treatment: A meeting of the minds. McNamara JA Jr (ed.) Vol 41, Craniofacial Growth Series, Ann Arbor, USA, 197-239 (2004).
[4] Wolff, J., The Law of Bone Remodelling, Springer, Berlin/Heidelberg, Germany (1986).
[5] Pearson, O.M., Lieberman, D.E., "The Aging of Wolff's "Law": Ontogeny and Responses to Mechanical Loading in Cortical Bone," Yearb. Phys. Anthropol., ***47****, 63–99 (2004).*
[6] Conconi, M., Leardini, A., Parenti-Castelli, V., "Joint kinematics from functional adaptation: A validation on the tibio-talar articulation," J. Biomech, ***48****, 2960–2967 (2015).*
[7] Conconi, M., Parenti-Castelli, V., "A sound and efficient measure of joint congruence," Proc. Inst. Mech. Eng. Part H J. Eng. Med., ***228****, 935–941 (2014)*
[8] Conconi, M., Halilaj, E., Parenti-Castelli, V., Crisco, J.J., "Is early osteoarthritis associated with differences in joint congruence?," J. Biomech., ***47****, 3787–3793 (2014)*
[9] Valigi, M.C., Logozzo, S., "Do Exostoses Correlate with Contact Disfunctions? A Case Study of a Maxillary Exostosis," Lubricants, ***7(2)****, 15 (2019).*

Mechatronic Design of a Robotic Arm to Remove Skins by Wine Fermentation Tanks

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Keywords: Confined spaces with pollution, winemaking sector, robotics.

The mechatronic design of a robotic arm to remove skins by wine fermentation tanks was developed, along with the building and testing of a first prototype, within the frame of the BRIC 2015 national research project on the confined spaces, which was funded by INAIL (National Institute for Insurance against Accidents at Work). The main motivation of this research is to avoid workers accident when operating inside confined spaces with pollution, as in the case of wine fermentation tanks. In fact, commonly, the removal of skins requires the entrance into the tank through the manhole access and the successive task of the worker by the inside, in order to push the skins out. Probably, this is the most labor-intensive aspects of winemaking and consequently, great care should be taken when entering a tank that has just finished fermentation due to the danger of asphyxiation from the residual carbon dioxide.

Thus, acquired the design specifications by the industrial environment, in terms of shape and size of the most common wine fermentation tanks, the kinematic synthesis of a tendon-driven mechanism was formulated and then, developed the mechatronic design of a new robotic arm that is the subject of this paper. In particular, the tendon-driven mechanism of this 3R (Three-Revolute) robotic arm is one time redundant, since has 3 d.o.f.s in the horizontal plane, and it is also provided of specific hooks that are installed along a suitable chain transmission system with 1 d.o.f. Therefore, the removal of the skins from the wine fermentation tank can be performed by the robotic arm of Fig.1, because of the combination of two joint effects, the closing motion of the 3R planar mechanism, along with the action of the moving hooks to harvest the skins.

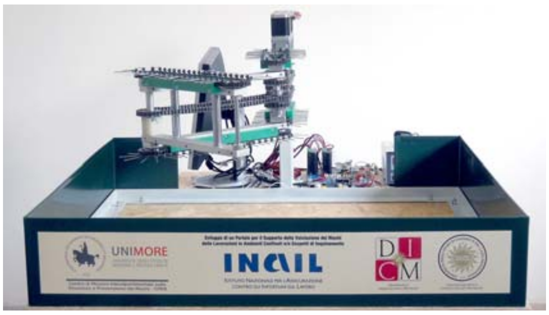

Fig. 1 - Robotic arm prototype to remove skins by wine fermentation tanks.

Kinematic Analysis of Slider-Crank/Rocker Mechanisms via the Bresse and Jerk Circles

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Keywords: Kinematic analysis, slider-crank/rocker mechanisms, Bresse and jerk circles.

The kinematic analysis of planar mechanisms can be developed by means of both graphical and analytical methods, as widely described in several text books [1-2]. Currently, the traditional graphical methods are applied by using two-dimensional CAD systems or solid modeling systems, while the analytical methods can be found in commercially available programs or specific user-written computer programs in a high-level language can be created.

However, the kinematic analysis of planar mechanisms based on Bresse's circles is less common, especially when they are computed and plotted by making use of the computer, even if, they provide a better physical understanding of the motion and its velocity and acceleration vector fields. In fact, these geometric loci intersect each other at both centers of the instantaneous rotation and acceleration, which are also the centers of two corresponding circular vector fields.

Sometime, even jerk and jounce vector fields are of great interest to understand the kinematic performance of a given planar mechanism [3], but also for synthesis purposes, as in the case of dwell mechanisms, which find several applications, such as rock crushers, mechanical presses, machine tools, packaging machines, assembly lines, and others of the manufacturing process.

Similarly to Bresse's circles and the acceleration center, the zero-normal and zero-tangential jerk circles represent interesting and useful geometric loci to better understand and visualize the jerk vector field that is also circular around the jerk center. A first formulation based on the use of the instantaneous geometric invariants and aimed to represent and analyze different geometric loci, including jerk's circles, was proposed in [4] for centered slider-crank mechanisms.

This paper deals with a more general formulation for the kinematic analysis of offset slider-crank/rocker mechanisms that allows the calculation and plot of both pairs of the Bresse and jerk circles, with the aim to analyze their properties for the most significant mechanism configurations. The proposed algorithm is still based on the use of the instantaneous geometric invariants, since representing the most powerful method to obtain the algebraic equations of the above mentioned geometric loci with respect to the canonical system of the coupler link.

Moreover, particular attention will be devoted to the analysis and proof of the most significant degenerate cases of the Bresse and jerk circles, as when referring to the asymptotic and dead-point configurations of different types of slider-crank/rocker mechanisms.

References

[1] Waldron, K.J., Kinzel, G.L. and Agrawal, S.K. "Kinematics, Dynamics, and Design of Machinery", 3rd edition, John Wiley & Sons Inc., Chichester (UK), 2016.

[2] Di Benedetto, A., Pennestrì, E., "Introduzione alla Cinematica dei Meccanismi", Casa Editrice Ambrosiana, Milan, Vol.1,2,3, 1999. (in Italian)

[3] Figliolini, G. and Lanni, C., "Jerk and jounce relevance for the kinematic performance of long-dwell mechanisms", 15th IFToMM World Congress, Krakow, Poland, 2019. (submitted)

[4] Figliolini, G. and Lanni, C., "Geometric loci for the kinematic analysis of planar mechanisms via the instantaneous geometric invariants", in MEDER: Proc. of the 4th IFT0MM Symposium on Mechanism Design, Gasparetto A. & Ceccarelli M. (Eds.), Springer, Cham (CH), 184-192 (2018).

Numerical and experimental analysis of small scale horizontal-axis wind turbine in yawed conditions

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Keywords: wind energy, yaw, wind turbines

In wind farms a considerable amount of production losses are due to the presence of wakes: therefore, in order to optimize the efficiency, many control strategies have been conceived and tested recently [1]. Among the most important methods investigated for wind farm control, yawing seems to be one of the most effective. Anyway, this topic has mostly been treated by an energetic point of view: there is still a lack of studies focusing on yaw effects on mechanical and vibrational behavior of wind turbines.

On these grounds, this work is devoted to yawed wind turbines and a comparison is conducted between experimental data, collected in wind tunnel tests on a small scale turbine, and aeroelastic numerical models.

The experimental setup is composed by a 2 meters diameter wind turbine equipped with accelerometers, load cells and tachometers in order to collect vibration, thrust and rotational speed data. With this arrangement, tests have been performed in a closed loop, open chamber wind tunnel, at University of Perugia. The wind turbine has been subjected to steady wind time series and its mechanical behavior has been studied for yaw angles of $\pm 45°$, $\pm 22.5°$ and $0°$.

As concerns simulations, a model is implemented using the FAST software by NREL. The simulations with FAST model are performed with the same wind speed and yaw angles as the experimental wind tunnel tests.

The first step of this study is comparing thrust coefficients (C_t) from experimental tests and numerical models. Since the FAST code tends to overestimate the thrust, further studies are conducted about blade deflections, vibrations and tower shadows. The study of experimental thrust depending on the azimuth angle in different yaw configurations revealed that, for vanishing yaw angles, the thrust force has the highest oscillations. This behavior can be ascribed to tower blockage effect and blade deflections. As the distance between these two elements reduces, with respect to wind direction, the effect of decelerated air upstream the tower increases. Under this circumstance, an outlook on vibration power spectrum is accomplished. From this it can be showed that 3P (blade passing) frequency, induced by tower blockage [2], decreases in correspondence of higher yaw angle, demonstrating that tower blockage has a lower effect. In addition, for wind speed lower than 10 m/s at $0°$ yaw, thrust oscillations decrease because of the correspondingly lower blade deflection.

Some additional test with FAST software have been performed with flexible blade in order to reproduce more faithfully the real behavior of turbine for what concerns vibration spectra.

This study confirms that vibrational behavior of turbines is strongly affected by yaw angle and that there is a relation between the shape of thrust power spectrum and oscillations of this force, caused by tower interaction and blade deflections.

References

[1] M. S. Adaramola and P. Krogstad. Experimental investigation of wake effects on wind turbine performance. *Renewable Energy*, 36(8):2078–2086, 2011.

[2] D. S. L. Dolan, S. Member, P. W. Lehn, and S. M. Ieee. Simulation Model of Wind Turbine 3p Torque Oscillations due to Wind Shear and Tower Shadow. pages 2050–2057, 2006.

Field vibrational analysis of a full scale horizontal-axis wind turbine in actual operating conditions

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Keywords: wind turbine, vibrations, structural health, identification

Wind farm operation reliability is becoming a key asset for the final success of wind energy conversion systems in the grid-parity energy market. As a result experimental methods for characterising the vibrational behaviour of wind turbines in real operating conditions are going to play a fundamental role in order to improve the correct estimation of the RUL (Remaining Useful Life) of the components as well as the whole system.
For this reason in present work a new experimental approach for the identification of the most important mechanical parameters through field acceleration measurements has been developed and tested through on a full scale three bladed machine. The main goal of the identification procedure was to give the correct estimation of important vibration parameters of the structure and the machine as for example:

- the tower structural eigenfrequencies;
- the structural damping;
- the key parameters for the gearbox (the number of teeth, the meshing frequencies, etc...);
- the electromechanical couplings frequencies.

The experimental measuring campaign has been performed on a three bladed wind turbine with a rated power of 200 kW and a rotor diameter of 29 m operating in an on-shore complex site. The site complexity has made more challenging the identification process due to added noise and unsteadiness induced by the gusty wind. The experimental setup included three accelerometers on the nacelle (two for the tower and one for the gearbox) and up to four sensors on along the tower. The structural eigeinfrenquencies has been studied through machine emergency stops [1].
The drive-train and the electromechanical coupling have been studied under running conditions with different wind speeds. Some fundamental signal processing techniques such as Short Time Fourier Transform (STFT) and Order Tracking has been successfully applied for the gear parameters identification [2].
Results demonstrate that the experimental data post-processing can represents a fruitful and quick approach for defining the most important structural and dynamic parameter even when the full details of the machine (i.e. the tower geometry, the gearbox layout, the number of teeth for the gears, etc...) are not available.

References

[1] A. Hu, J. Zhao, and L. Xiang. Output-only modal analysis of wind turbine tower based on vibration response under emergency stop. *ISA transactions*, 80:411–426, 2018.

[2] N. Sawalhi and R. B. Randall. Gear parameter identification in a wind turbine gearbox using vibration signals. *Mechanical Systems and Signal Processing*, 42(1-2):368–376, 2014.

Static balancing of an Exechon-like parallel mechanism

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Keywords: static balancing, gravity compensation, Parallel Kinematics Machine.

A statically balanced mechanism has invariant total potential energy, hence no motor actions being required for resting in any assumable configuration. Static balancing is typically achieved by installing passive (i.e. unactuated) devices, the most common being counterweights and springs. It can considerably reduce the energy consumption of a mechanism whenever the dynamic loads characterizing its typical tasks are comparable to the gravity loads of its own moving members [1]. Numerous applications operating under such working conditions can be found, e.g. Parallel Kinematics Machines (PKMs) and surgical robots.

This study focuses on the gravity compensation of mechanisms with an Exechon-like architecture. The Exechon tripod is a PKM implemented by several machine tool manufacturers [2]. It features hybrid serial-parallel kinematics: a 3-DOF moving platform is driven by 2-UPR and 1-SPR legs, i.e. with universal (U), revolute (R), spherical (S), and actuated prismatic (P) joints (Fig. 1); a 2-DOF spherical wrist, connected to the platform, controls the spindle orientation. A variant with a 3-DOF wrist has been also developed as a reconfigurable fixturing system. The platform kinematics can be described by means of a linkage connecting the platform to the fixed base and consisting of a PR serial joint sequence followed by a planar RPPR closed chain [2].

An approximate balancing solution for the Exechon is presented (Fig. 1). It consists of a fourth passive leg derived from [2]. *Link-A* is connected by a P joint to the platform, and by a U joint to the coupler of a parallelogram that replaces the RPPR chain. The device requires a minimum of four zero-free-length springs. Three springs connect the coupler to the fixed base, the platform and *link-A*, respectively. The fourth one is included in an auxiliary RRRR linkage connecting the platform and *link-A*. The effectiveness of the developed device is verified through simulations with a multibody software (ADAMS). The numerical results confirm a significant reduction in the static motor actions throughout the complete workspace.

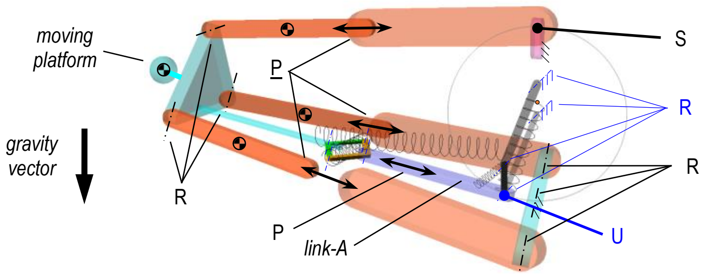

Figure 1: Statically balanced Exechon tripod.

References

[1] *Martini, A., Troncossi, M., Carricato, M. and Rivola, A., "Static balancing of a parallel kinematics machine with Linear-Delta architecture: theory, design and numerical investigation," Mechanism and Machine Theory,* ***90****, 128-141 (2015).*

[2] *Zoppi, M., Zlatanov, D. and Molfino, R., "Kinematics Analysis of the Exechon Tripod," in Proceedings of ASME IDETC/CIE 2010, Montreal, Canada, August 15-18, 1-6 (2010).*

Analysis of agricultural machinery to reduce the vibration to the operator seat

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Keywords: Experimental Dynamic Substructuring, Vibrations, Agricultural Machinery.

In the research framework of acoustic and vibration problems, the vibrations produced by the agricultural machinery have a relevant position, assuming indeed a double role: firstly, the vibrations due to the soil irregularity and to the operation of the machinery are transmitted to the seat of the tractor's operator, inducing comfort and safety problems [1]; secondly, they are always combined with annoying sound emission, encountering the limitations imposed by the international and national regulations. The control of noise and vibration on the operator is of interest of the National Institute for Insurance against Accidents at Work (INAIL). Despite the study of the tractor dynamics and the induced vibrations have been deeply investigated in the literature [2], relatively few works deal with the influence of the agricultural machinery in the transmission of vibration.

The objective of this work is to investigate the effect of mounted, semi-mounted and trailed machinery on the vibrations transmitted to the tractor's operator introducing a simplified model of an agricultural machine, considering not only the DoFs (degrees-of-freedom) relative to the tractor but also the ones relative to the machinery.

Moreover, a model of the three points linkage between the tractor and the machinery and a model of the hitch for trailed machinery are proposed [3]. The dynamic substructuring [4] is exploited to couple the model of the tractor with the machinery through the linkage system. The linkage systems are modeled by finite elements methods and reduced by the Craig-Bampton method [5]. The reduced order models are used to perform a frequency based coupling of the substructures. In order to evaluate the effects of the suspension systems, several models of tractors are considered in the analysis.

Eventually, the transmissibility from the wheels to the operator's seat is investigated, focusing on the influence of the tractor suspensions in the vibration transmission. The numerical results are compared to experimental test, according to the standard ISO 5008, in order to validate the approach.

References

[1] *Bovenzi, M. and Betta, A., "Low-back disorders in agricultural tractor drivers exposed to whole-body vibration and postural stress", Applied ergonomics,* **25***, pp. 231-241 (1994).*

[2] *Servadio, P. and Belfiore, N. P., "Influence of tyres characteristics and travelling speed on ride vibrations of a modern medium powered tractor Part I: Analysis of the driving seat vibration", Agricultural Engineering International: CIGR Journal,* **15***, pp. 119-131 (2013).*

[3] *Brunetti, J., D'Ambrogio, W. and Fregolent, A., "Transmission of vibrations between towed and towing agricultural machines", in Proc. ISMA 2018, Leuven (Belgium), (2018).*

[4] *de Klerk, D., Rixen, D. J. and Voormeeren, S., "General framework for dynamic substructuring: history, review and classification of techniques", AIAA journal,* **46***, pp. 1169-1181 (2008).*

[5] *Craig, R. and Bampton, M., "Coupling of substructures for dynamic analyses", AIAA journal,* **6***, pp. 1313-1319 (1968).*

Experiments on efficiency and durability of DLC-coated gear

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Keywords: Gear pitting, Gear efficiency, DLC-coatings

In recent times, Diamond Like Carbon coatings (DLC) have been successfully applied in high performance applications, such as transmissions for motorsport vehicle, in order to increase gear performance. In particular, DLC coatings are characterized by very low friction coefficient, therefore they are supposed to be useful in reducing power dissipation and in preventing scuffing failure.

In this work, an experimental investigation on gear coatings is shown; coated and uncoated spur gear pairs are compared in terms of efficiency on a dedicated test rig. The role of all possible combinations of WC/C coating and underlaying layer is investigated; in particular, WC/C coating is applied on quenched, nitrided and carburised gear samples.

Efficiency of the gear pair is measured by means of two torque transducers for varying angular velocity and load; at the same time dynamic transmission error is measured, in order to investigate vibration-efficiency dependency for uncoated and coated gears.

On the same test bench, the most promising solution (in terms of coating - thermal treatment combination) is tested for pitting durability in comparison with an uncoated gear pair.

References

[1] *M. Kalin, J. Viintin, "The tribological performance of DLC-coated gears lubricated with biodegradable oil in various pinion/gear material combinations", Wear, 259 7-12, page 1270-1280, (2005)*

[2] *M. Andersson, M. Sosa, U. Olofsson, "The effect of running-in on the efficiency of superfinished gears", Tribology International, 93 A, page 71-77, (2016)*

[3] *J.C. Jiang, W.J. Meng, A.G. Evans, C.V. Cooper, "Structure and mechanics of W-DLC coated spur gears", Surface and Coatings Technology, 176-1, page 50-56, (2003)*

An Inverse Dynamics Approach based on the Fundamental Equations of Constrained Motion and on the Theory of Optimal Control

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Keywords: Forward and Inverse Dynamics, Udwadia-Kalaba Equations, Optimal Control Theory.

In this investigation, a new algorithm for the nonlinear control of mechanical systems is developed. The method proposed in this paper can be used for the forward and inverse dynamics of nonlinear mechanical systems. For this purpose, the Udwadia-Kalaba equations, also known as the fundamental equations of constrained motion, are combined with the feedback control strategy resulting from the theory of optimal control. In forward dynamics problems, the fundamental equations of constrained motion allow for explicitly calculating the generalized constraint forces associated with a nonlinear set of kinematic constraints. Furthermore, in inverse dynamic problems, the Udwadia-Kalaba equations can be effectively used for computing the generalized control forces that impose a prescribed dynamic behavior to the mechanical system under consideration. In this dual case, the desired dynamic behavior is described in terms of nonlinear algebraic equations that play the role of the kinematic joints encountered in the problems of direct dynamics. Conversely, it is shown in this work that the mathematical tool of the optimal control theory can be employed for the practical design of an effective compensation controller that improves the performance of the nonlinear control laws devised by using the fundamental equations of constrained motion. Employing the new approach proposed in this paper, the compensation controller designed by using the theory of optimal control is fully integrated into the nonlinear set of control laws obtained considering the general form of the Udwadia-Kalaba equations. The method developed in this paper is tested by means of numerical experiments. For this purpose, the nonlinear dynamic equations of a physical pendulum are used in order to exemplify the analytical developments carried out in this work and for assessing in a straightforward manner the performance of the proposed methodology.

MS01

INTERFACE MODELS AND PHASE-FIELD APPROACHES FOR FRACTURE AND DAMAGE MECHANICS

Modelling of sliding fracture mode in strengthened structures

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Keywords: CZM, DIC, composite.

Adhesive junctions have become widely adopted for structural applications in the field of Industrial, Automotive, Naval and Aerospace Engineering.

In the field of Civil Engineering, composites are frequently used for rehabilitating existing structures with external Fiber Reinforced Polymer (FRP) reinforcements [1-2]. The application of this technique to constructions requires the prediction of the failure modes of the strengthened structures.

No specific standards are available to experimentally evaluate the FRP maximum stress corresponding to end debonding, except for semi-empirical formulae proposed by the American ACI 440.2R-08, the European fib T.G. 9.3 and the Italian CNR-DT 200 R1/2013.

Within this context, sliding fracture mode of concrete specimens, reinforced with pultruded GFRP, were experimentally investigated by the authors, by means of shear tests performed at the Design Machine Laboratory of the University of Salerno. Traditional equipment and non contact (*Digital Image Correlation*) technique were included in the experimental layout.

Starting from the experimental data, the *J*-integral and the specimens' fracture toughness were evaluated. Subsequently, a cohesive law was indirectly modelled using the theoretical approach proposed by Rice [2-3].

References

[1] Ascione, L., Berardi, V.P., "Anchorage device for FRP laminates in the strengthening of concrete structures close to beam-column joints", Composites Part B: Engineering, ***42(7)****, pp. 1840-1850, (2011).*

[2] Perrella, M., Berardi, V.P., Cricrì, G., "A novel methodology for shear cohesive law identification of bonded reinforcements", Composites Part B: Engineering, ***144****, pp. 126-1334, (2018).*

[3] Lepore, M.A., Perrella, M., "From test data to FE code: a straightforward strategy for modelling the structural bonding interface", Frattura ed Integrità Strutturale, ***39****, pp. 191-201, (2017).*

Damaging of FRCM composites through a micro-scale numerical approach

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Keywords: Interface damaging, FRCM composites, numerical modelling

The retrofitting of existing masonry structures with innovative, effective and sustainable materials is an active research field in structural engineering. In this framework, in the last decades, great attention has moved towards cementitious composite materials, such as fiber-reinforced cementitious mortars (FRCMs), made with a fiber textile mesh embedded within mortar layers. The mechanical behavior of such a kind of strengthening material has been investigated through many experimental works and analytical approaches. The experimental evidence highlighted its advantages in terms of mechanical properties and its compatibility with the masonry substrates [1].

Direct tensile tests carried out on FRCM specimens have shown an inelastic constitutive behavior, mainly due to the mortar cracking and the slippage of the fibers along the load direction. These failure mechanisms depend on the type of mortar and fibers and also on the joining between the two materials constituting the composite. Thus, micro-mechanical analyses can significantly help in a correct modeling of the FRCM response.

The work aims to suggest a micro-scale numerical model that considers both the cracking phenomena and the debonding occurrence between the two constituents, through the implementation of interface elements. These latter are modeled according to the theoretical method, as provided in [2]. The numerical model is based on an incremental strain-based approach within the plane-stress two-dimensional formulation. The damaging of the FRCM representative element is detected through the stress analysis on the interfaces. The numerical model is validated with available benchmarking experimental results [3]. Furthermore, the shear behavior of the same representative element is investigated. Validation results confirm soundness and consistency of the proposed modeling approach and highlight the tensile and shear behavior of FRCM composites.

References

[1] *Nerilli, F., Ferracuti, B., "Investigation on the FRCM-masonry bond behaviour, in Proceedings of 9th Int Conf on Fibre-Reinforced Polymer (FRP) Compos in Civil Eng, 2018, 90-97, 2018.*

[2] *Alfano G., Marfia S., Sacco E., "A cohesive damage-friction interface model accounting for water pressure on crack propagation, Comput Methods Appl Mech Eng,* **196**, *192-209 (2006).*

[3] *Carozzi, F.G, Poggi, C., "Mechanical properties and debonding strength of Fabric Reinforced Cementitious Matrix (FRCM) systems for masonry strengthening, Compos Part B-Eng ,* **70**, *215-230 (2015).*

Material internal lengths in the multi-cracking process of fiber-reinforced composites

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Keywords: variational model, fiber-reinforced composites, damage and plasticity.

Composite materials consisting of strengthening short fibers embedded in a surrounding brittle matrix (e.g., fiber-reinforced concretes) usually exhibit ductile failure, which is characterized by a stress-hardening phase of micro- and multi-cracking, followed by a stress-softening stage of micro-crack opening. Within each crack, bridging fibers enhance the strength, and improve the ductility.

The aim of this talk is to present a variational model capable of describing the composite failure process, and to focus on the key rule played by three different internal length on the evolution of cracks. The model schematizes the composite as a mixture of two phases coupled by elastic bonds, which account for brittle matrix and elasto-plastic reinforcement. A damage scalar field accounts for the opening and propagation of fractures in the brittle matrix, according to the phase-field approach to fracture, and a plastic strain field describes the evolution of inelastic deformations within the reinforcement phase. Proper internal energies are associated to the two phases and to the coupling bonds. Since damage and plastic energies incorporate non-local contributions, they introduce internal lengths. The length of the brittle phase is related to the size of the process zone accompanying the micro-fracture process, and it depends on the size of the matrix aggregates. The internal length of the reinforcement phase accounts for the size of the plastic localization zone which describes macro-cracks, and it depends on the fibers length. A third characteristic length arises from the elastic energy coupling the displacement fields of the two phases. It controls the distance between adjacent micro-cracks and it depends on the size of matrix-to-fibers stress transfer zone around each micro-crack. Attention is focused on the influence of these three characteristic lengths on the process of micro-crack patterning and on the evolution of macro-fractures. Several cracking scenarios are investigated, depending on the different values assigned to the internal lengths.

Finally, analytical estimates and numerical solutions show the model capability of describing the different stages of the failure evolution.

Fatigue effects in elastic materials with variational damage models: A vanishing viscosity approach

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Keywords: Fatigue; Gradient-damage models; Vanishing-viscosity.

Inspired by the models recently introduced in [1], we consider the problem of the existence of quasistatic evolutions for a family of gradient damage models which take into account fatigue, that is the process of weakening in a material due to repeated applied loads. The main feature of these models is the fact that damage is favoured in regions where the cumulation of the elastic strain (or other relevant variables, depending on the model) is higher. To prove in [2] the existence of a quasistatic evolution, we follow a vanishing viscosity approach based on two steps: we first let the time-step τ of the time-discretisation and later the viscosity parameter ϵ go to zero. As $\tau \to 0$, we find ϵ-approximate viscous evolutions; then, as $\epsilon \to 0$, we find a rescaled approximate evolution satisfying an energy-dissipation balance.

References

[1] *Alessi R., Vidoli S., and De Lorenzis L., "A phenomenological approach to fatigue with a variational phase-field model: The one-dimensional case", Engineering Fracture Mechanics,* **190***, page 53–73, (2018).*

[2] *Alessi R., Crismale V., and Orlando G., "Fatigue Effects in Elastic Materials with Variational Damage Models: A Vanishing Viscosity Approach", J Nonlinear Sci, (2018). https://doi.org/10.1007/s00332-018-9511-9.*

Minimisation and Ambrosio-Tortorelli approximation of the Griffith energy with Dirichlet boundary condition

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Keywords: brittle fracture, phase-field approximation, minimisation

In [2] we prove a Γ-convergence approximation *à la* Ambrosio-Tortorelli for Griffith-type energies with either Dirichlet boundary condition or a mild fidelity term, such that minimisers are *a priori* not even in $L^1(\Omega;\mathbb{R}^n)$.

Moreover, in [3] and [4] we show existence of weak and strong minimisers, respectively, for the Griffith energy under Dirichlet boundary condition.

These results are obtained by studying fine properties of $GSBD$ functions, introduced by Dal Maso in [1].

References

[1] *Dal Maso, G., "Generalised functions of bounded deformation" in J. Eur. Math. Soc. (JEMS), 15 (2013)*

[2] *Chambolle, A. and Crismale, V., "A density result in $GSBD^p$ with applications to the approximation of brittle fracture energies", In press on Arch. Ration. Mech. Anal. (2018)*

[3] *Chambolle, A. and Crismale, V., "Compactness and lower semicontinuity in $GSBD$", To appear on J. Eur. Math. Soc. (JEMS).*

[4] *Chambolle, A. and Crismale, V., "Existence of strong solutions for the Dirichlet problem for the Griffith energy", Preprint (2018).*

Adhesive interfaces under shear load: a fracture mechanics model

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Keywords: adhesion, friction, fracture mechanics

The interplay between adhesion and friction plays a fundamental role in tribology as it affects different fields of engineering. Understanding the mechanism for dissipation is indeed crucial for structural damping as well as to develop bioinspired adhesive solutions. The first linear elastic fracture mechanics model for adhesion and friction interaction dates back to the seminal work of Savkoor & Briggs [1], who extended the JKR model to the presence of tangential load. Nevertheless their model suggested a greater reduction of contact area with respect to what was observed experimentally. Later Johnson [2] and Waters and Guduru [3] adopted a phenomenological mode-mixity function to account for the interface frictional dissipation. All the previous models hypothesize the contact shrinks in an axisymmetric fashion, which is in contrast with the experimental observation [3,4]. In this work [5,6] we extended the elliptical JKR model by Johnson and Greenwood [7] to accommodate also the tangential shearing of the contact area, where the contact edge is represented as an external crack under mixed-mode (I opening, II in-plane and III antiplane shearing). The derived model has been extensively validated against experimental results giving an excellent agreement not only in terms of overall contact area but also in terms of evolution of the shape of contact patch.

References

[1] Savkoor, A.R. , Briggs, G.A.D., (1977). The effect of a tangential force on the contact of elastic solids in adhesion. Proc. R. Soc. Lond. A 356, 103–114.

[2] Johnson KL, 1996, Continuum mechanics modeling of adhesion and friction. Langmuir 12:4510{4513.

[3] Waters JF, Guduru PR, (2010), Mode-mixity-dependent adhesive contact of a sphere on a plane surface. Proc R Soc A 466:1303{1325.

[4] R. Sahli, G. Pallares, C. Ducottet, I. E. Ben Ali, S. Al Akhrass, M. Guibert, and J. Scheibert, Proceedings of the National Academy of Sciences of the USA 115, 471 (2018).

[5] Papangelo, A., & Ciavarella, M. (2019). On mixed-mode fracture mechanics models for contact area reduction under shear load in soft materials. Journal of the Mechanics and Physics of Solids, 124, 159-171.

[6] A. Papangelo, J. Scheibert, R. Sahli, G. Pallares, M. Ciavarella, (2019), Shear induced contact area anisotropy explained by a fracture mechanics model. To be Submitted

[7] Johnson, K. L., & Greenwood, J. A. (2005). An approximate JKR theory for elliptical contacts. Journal of Physics D: Applied Physics, 38(7), 1042.

Derivation of linear elasticity for multi well energies

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Keywords: Nonlinear elasticity, Interfaces, Crystals

Linear elasticity can be rigorously derived from finite elasticity under the assumption of small loadings in terms of Gamma-convergence. This was first done in the case of one-well energies with super-quadratic growth [3], using the well-known rigidity estimate of Friesecke, James, and Müller [4], and later generalised to different settings, in particular to the case of multi-well energies where the distance between the wells is very small (comparable to the size of the load) [5, 1]. The case when the distance between the wells is independent of the size of the load was studied in [2]. In this context linear elasticity can be derived by adding to the multi-well energy a singular higher order term which penalises jumps from one well to another. In this talk we discuss the derivation of linear elasticty from multi-well discrete models, under different assumptions on the geometry of the crystals and on the scaling of the coefficients. We show that the role of the singular perturbation term is played in this setting by interactions beyond nearest neighbours.

References

[1] *Agostiniani, V., Blass, T. and Koumatos, K., From nonlinear to linearized elasticity via Γ-convergence: The case of multiwell energies satisfying weak coercivity conditions, Math. Models Methods Appl. Sci.,* **25**, *1–38, (2015).*

[2] *Alicandro, R., Dal Maso, G., Lazzaroni, G. and Palombaro, M., Derivation of a linearised elasticity model from singularly perturbed multiwell energy functionals, Arch. Ration. Mech. Anal.,* **230**, *1–45, (2018).*

[3] *Dal Maso, G., Negri, M., and Percivale, D., Linearized elasticity as Γ-limit of finite elasticity, Set-Valued Analysis,* **10**, *165–183, (2002).*

[4] *Friesecke, G., James, R.D. and Müller, S., A theorem on geometric rigidity and the derivation of nonlinear plate theory from three-dimensional elasticity, Comm. Pure Appl. Math.,* **55**, *1461–1506, (2002).*

[5] *Schmidt, B., Linear Γ-limits of multiwell energies in nonlinear elasticity theory, Continuum Mech. Thermodyn.,* **20**, *375–396, (2008).*

Fracture modelling of a GFRP adhesive connection by an imperfect soft interface model

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Keywords: cohesive fracture, interface model with damage, beam-to-column connection.

The connections in FRP structures are commonly made using bolted connections, akin to those used in steel structures. In fact, some FRP profiles manufacturers and design guidelines stipulates that bonded connections should not be allowed for primary load bearing components, where failure of the connection could lead to progressive collapse or unacceptable risks. The main reason for the prohibition of bonded connections is lack of knowledge about and experience with the performance of such connections. Recently, several experimental investigations were performed by some of the authors [1-2] to assess the strength and stiffness of GFRP beam-to-column connection showing that their overall performance can equal and surpass the performance of similar bolted connections in FRP structures. The next step consists to develop a predictive numerical model of the structure behavior in order to make a comparison with experimental results, in terms of ultimate bending moment, as well as to analyze the role played by several features. The model proposed has been successfully validated in further studies on brick-mortar interfaces [3]. The model is derived by an asymptotic analysis, due to the thickness of the adhesive layer, of a composite structure made of two elastic solids bonded together by a third thin one, which has a nonlinear behavior. The adhesive is micro cracked by adopting a Kachanov-type model [4]. The model is implemented in Comsol Software. The model assumptions are adjusted with the experimental investigations lead on the adhesive (tensile and shear tests, CT-scans). Experimental results are also used to identify the normal and tangential adhesive stiffness in taking into account the initial damage of the interface. Finally a simulation of the bonded GFRP structure is proposed and simulation results are successfully compared to experimental tests.

References
[1] Ascione F, Lamberti M, Razaqpur AG, Spadea S. Strength and stiffness of adhesively bonded GFRP beam-column moment resisting connections. Compos Struct 2017;160:1248–57.
[2] Ascione F, Lamberti M, Razaqpur AG, Spadea S. Pseudo-ductile failure of adhesively joined GFRP beam-column connections: An experimental and numerical investigation. Compos Struct 2018;200:864–873.
[3] Sevostianov, I., Kachanov, M., "On some controversial issues in effective field approaches to the problem of the overall elastic properties", Mech Mater, 105, 69-93 (2014)
[4] Raffa, M.L., Lebon, F., Rizzoni, R., "Derivation of a model of imperfect interface with finite strains and damage by asymptotic techniques. Application to masonry structures", Meccanica (2017), https://doi.org/10.1007/s11012-017-0765-3.

Mixed-Mode delamination with large displacement modeling of fiber-bridging

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Keywords: Delamination, Mixed-Mode, Fiber-Bridging.

While widely and successfully used for the modeling of delamination, cohesive models are known to exhibit intrinsic flaws when used in the presence of large interface openings. In particular, it is known that only co-linear models, i.e. where tractions are aligned with the opening vector, can preserve angular momentum [1]. However, co-linear models are too simple to reproduce the complex fracture energy evolution with mode-ratio that is usually observed in many composites. On the other hand, restricting the analysis to the initial, small opening separation process, would be overly conservative, since for many composite materials, interfaces exhibit additional and significant resistance resources due to crack bridging, which can be activated only when large openings take place [2]. Depending on the nature of the interface and of the joined materials, these additional strength mechanisms can be due, e.g., to fibrillation or fiber bridging.

According to several authors, fiber-bridging in composite materials can be observed under both Mode I and Mode II loading conditions. However, large relative sliding occurring under Mode II conditions can be treated with standard cohesive models, without incurring in the geometric flaws mentioned above. In contrast, under Mode I conditions, growing normal relative displacements soon compromise the interface rotational equilibrium.

In this work, the isotropic damage cohesive model formulated in [3] is extended to account for large openings and for the presence of large-scale bridging or interfacial fibrillation. In the presence of small openings, the considered cohesive model is particularly suited to treat mixed-mode delamination with variable mode ratios, since no a-priori assumptions are made on the shape of the failure locus in terms of fracture energy and since it allows for different forms of the traction-separation law in the pure modes. When the normal component of the relative displacement becomes large, the transition from small to large openings with the onset of the bridging mechanism is modeled by replacing the classical interface element with a fibril element, transmitting co-linear tractions and endowed with a constitutive behavior such that no discontinuity in the dissipated energy or in the cohesive tractions is introduced.

Several tests with large openings confirm the accuracy of the proposed model.

References

[1] Ottosen, N., Ristinmaa, M., Mosler, J., "Fundamental physical principles and cohesive zone models at finite displacements", Int. J. Solids Struct. ***53****, 70–79 (2015).*

[2] Dàvila, C.G., Rose, C.A., Camanho, P.P., "A procedure for superposing linear cohesive laws to represent multiple damage mechanisms in the fracture of composites", Int. J. Fract., ***158****, 211-223 (2009).*

[3] Confalonieri, F., Perego, U., "A new framework for the formulation and validation of cohesive mixed-mode delamination models",Int. J. Sol. Stru., doi:10.1016/j.ijsolstr.2018.12.032 (2019)

Peridynamic Ericksen's Bars

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Keywords: Peridynamics; Nonlinear elasticity; Non-convex energy.

The static states of a peridynamic nonlinear-elastic bar of *finite* length, stretched in a hard device, are investigated. The nonlocal character of peridynamics requires that the edge conditions shall be defined on a boundary layer with the same thickness of the horizon, which can affect the solution in the bar interior. The approach is variational and it is based upon the assumption that the energy is a function of the relative displacement between particles within the horizon, not weighted by the inverse of their relative distance as in Dayal and Bhattacharya [1]. This implies a weak interaction between neighboring points that allows for discontinuities in the displacement field.

In particular, we assume a non-monotone constitutive relation associated with a non-convex strain energy density, which is the counterpart for the case of peridynamics of the classical model in nonlinear elasticity proposed by Ericksen [2]. We find [3] that, at a micro-scale of the same order of the length of the horizon, the displacement field is characterized by the orderly formation of undulations and discontinuities, while at the macroscopic level the stress vs. elongation graph is a sequence of strain hardening and softening branches. Such complex response is triggered at the bar ends where the boundary layer effect, similarly to the linear elastic case, produces the formation of noteworthy displacement jumps that depend upon the length of the horizon. The equilibrium path, found numerically with a pseudo-arc-length continuation method, becomes unstable above a certain elongation. Convexification of the strain energy density provides solutions that are very different because, unlike in Ericksen's model, re-arrangements of material phases along the bar are prevented by the nonlocal nature of peridynamics. Results from this work can be used to interpret the complex phenomena of localization of inelastic strain in slip bands, as experimentally observed in ductile metallic bars, or to provide a continuum description of complex hierarchical structures with interacting long-range crosslinkers, as in biological systems.

References

[1] Dayal, K., Bhattacharya, K., "Kinetics of phase transformations in the peridynamic formulation of continuum mechanics". J. Mech. Phys. Solids ***54 (9)****, 1811-1842, 2006.*

[2] Ericksen, J.L., Equilibrium of bars. Journal of Elasticity, ***5(3-4)****, 191-201, 1975.*

[3] Aguiar, A.R., Royer-Carfagni, G.F. and Seitenfuss, A.B., Wiggly strain localizations in peridynamic bars with non-convex potential. International Journal of Solids and Structures ***138 (1)****, 1-12, 2018.*

[4] Aguiar, A.R., Royer-Carfagni, G.F. and Seitenfuss, A.B., Boundary layer effects in a finite linearly elastic peridynamic bar. Latin American Journal of Solids and Structures ***15 (10)****, 1-14, 2018.*

An experimental and numerical study to evaluate the crack path under mixed mode loading on PVC foams.

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Keywords: Sandwich Structures, PVC foam, Crack Path.

Being able to provide outstanding performances under out-of-plane loading, sandwich structures offer great flexibility and a variety of solutions for lightweight structural systems. In spite of their wide structural effectiveness, sandwich panels can however be affected by macroscopic and microscopic damage phenomena, which might produce catastrophic failure modes. As a consequence, the in-depth understanding of the propagation of internal macro-cracks in the core and the delamination at face/core interfaces is a topic of great computational interest. Moreover, the capability to link sophisticated numerical models with physical properties of the materials that can be actually measured by simple lab tests is fundamental for actual engineering applications.The characterisation of the core fracture toughness in Mixed Mode loading is particularly relevant because foam cracking strongly reduces the capacity of the sandwich structures to carrying loads [2]. To this end, PVC foams typically used as inner core in structural application were considered over a range of foam densities (from 100 to 200 kg/m^3). Firstly, the fracture toughness properties of the investigated foams have been measured under Mode I loading condition by using the Single Edged Notch Bending (SENB) test procedure, according to ASTM D5045-14. These results have been compared with the ones arising from three-point bending tests on Semi-Circular Bend (SCB) specimens [2]. Subsequently, Asymmetric Semi-Circular Bend (ASCB) specimens have been tested in order to generate all range of mixed fracture modes. According to this setup, the position of the left or right support has been varied to simulate different levels of Mixed Modes loading. Following a methodology previously employed by Marsavina et. al [2] for polyurethane (PUR) foams, the mostly recognized fracture criterions have been considered and their capability to compute the crack propagation angles in PVC foams have been evaluated. The crack path occurred on the ASCB samples have been used to test the accuracy of the response provided by a mechanical model developed by the authors [3]. The same model was employed to describe a macro-crack propagation in the core of a sandwich structure.

References

[1] *Carlsson, L.A., G.A. Kardomateas, "Structural and Failure Mechanics of Sandwich Composites", Solid Mechanics and its Applications, ed. S.D.H.L.N. York. Vol. 121. (2011).*

[2] *Marsavina, L., Linul, E., Voiconi, T., Constatinescu, D.M., Apostol, D.A., "On the crack path under mixed mode loading on PUR foams" Frattura ed Integrità Strutturale,* ***9****, page444-453 (2015).*

[3] *Funari, M.F, Greco, F., Lonetti, P., Spadea, S., "A numerical model based on ALE formulation to predict crack propagation in sandwich structures" Frattura ed Integrità Strutturale,* ***13****, page277-293 (2019).*

A Phase field approach of damage evolution in partially saturated porous media

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Keywords: Phase field, Partial saturation, Poromechanics

Phase field models have been successfully applied to damage evolution and fracture propagation in brittle materials. The primary advantage of phase field modeling lies in the alleviation of pathological mesh dependencies by facilitating regularizations on the evolution of the phase field parameter. The effectiveness of this approach in the context of damage-gradient modeling of fracture has been demonstrated by [1]. This approach has been drawn into the framework of mechanics of porous media by several authors [2], [3], [4]. However, to the best of our knowledge only recently has this approach been extended to the case of partially saturated media [5]. In the current study, assuming that the porous media is composed of a wetting fluid(liquid water), a non-wetting fluid(wet air) and a deformable porous skeleton, the variational approach to damage proposed by [6] and implemented as damage-gradient models for brittle fracture by [1] within the finite element code based on FEniCS Library [7] is extended to the analysis of partially saturated porous continua. The variational forms of the governing equations are derived and appropriate boundary conditions are imposed in the context of a one-dimensional test. Further developments of this work will be devoted to the extension of this approach to the phase field theory of partially saturated porous media proposed by [8]. In this case, in addition to the damage variable, the saturation degree will be considered as another phase field parameter.

References

[1] *Marigo, J.-J., Maurini, C., and Pham, K., An overview of the modelling of fracture by gradient damage models, Meccanica,* **Vol 51**, *Issue 12, page 3107-3128 (2016).*

[2] *Miehe, C., and Mauthe, S., Phase field modeling of fracture in multi-physics problems. Part III. Crack driving forces in hydro-poro-elasticity and hydraulic fracturing of fluid-saturated porous media, Computer Methods in Applied Mechanics and Engineering,* **Vol 304**, *page 619-655 (2016).*

[3] *Chukwudozie, C., Bourdin, B., and Yoshioka, K., A variational phase-field model for hydraulic fracturing in porous media, Computer Methods in Applied Mechanics and Engineering,* **Vol 347**, *page 957-982 (2019).*

[4] *Mikelic, A., Wheeler, M.F., and Wick, T., Phase-field modeling of a fluid-driven fracture in a poroelastic medium, Computational Geosciences,* **Vol 19**, *Issue 6, page 1171-1195 (2015).*

[5] *Cajuhi, T., Sanavia, L., and De Lorenzis, L., Phase-field modeling of fracture in variably saturated porous media, Computational Mechanics,* **Vol 61**, *Issue 3, page 299-318 (2018).*

[6] *Pham, K., and Marigo, J.-J., Approche variationnelle de lendommagement : I. Les concepts fondamentaux, Comptes Rendus Mecanique,* **Vol 338**, *Issue 4, page 191-198 (2010).*

[7] *Logg, A., Mardal, K.-A., and Wells, G.N., Automated Solution of Differential Equations by the Finite Element Method, Springer-Verlag Berlin Heidelberg (2012).*

[8] *Sciarra, G., Phase field modeling of partially saturated deformable porous media, Journal of the Mechanics and Physics of Solids,* **Vol 94**, *page 230-256 (2016).*

A numerical model for the adhesive behaviour of elastic membranes

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Keywords: adhesion, membrane, 3D

Adhesion is a topic that has attracted great interest in the mechanics community in recent years. The recent development of novel theories coming from nano-tribology, theoretical mechanics and bio-adhesion presented new mechanical problems, which often involve a non-trivial structures and constitutive properties. One problem which needs to be faced is the adhesive behaviour of a membrane adhered to a substrate. These structures are usually studied using one dimensional models, which involve 1D tapes or symmetrical geometries in conjunction with adhesive theories as the JKR theory. This approach is oversimplified for many practical problems since the adhesive behaviour of several complex two-dimensional structures is still poorly explained. To address this issue, we introduce a three-dimensional model which combines a lattice framework, a finite element approach and a 3D cohesive zone model. We have modelled different geometrical and elastic features of the membrane to describe the adhesive behaviour of complex structures (Figure 1). We have obtained empirical results which are in good agreement with the numerical model. We have shown that the interface and the shape of the membrane are two major rulers of the maximal achievable adhesive force.

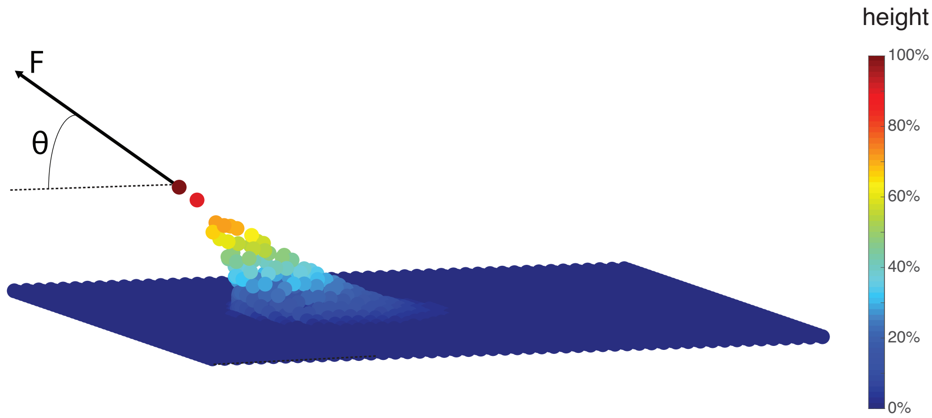

Figure 1) Schematic representation of a peeling test. A membrane is pulled by a force F at an angle θ in a single point. Colours indicate the normalized elevation of the corresponding point

Numerical strategies for J2 phase-field models regularizing shear fracture

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Keywords: J2 phase-field, variational approach, gradient-damage

Variational models of quasi-static cracks evolutions are based on the minimization of an energy functional composed of a bulk term, *i.e.*, the elastic energy of the sound material, and a surface energy term à la Griffith, together with proper irreversibility conditions to avoid material interpenetration [1]. The free-discontinuity problem can be approximated by an elliptic two-fields energy functional [2]. One field is representative of the displacement of any material point of the body, whereas the other is similar to a scalar damage field (or phase-field). In the regularized energy functional, the original surface fracture term is replaced by a bulk term depending not only on the phase-field variable itself but also on its gradient (non-local model). Within this framework, alternative formulations depending on the underlying fracture mechanisms and irreversibility conditions exists, mostly differing for what concern the elastic energy bulk term, [3].

In this work, the attention is focused on those models rigorously regularizing shear fractures, [5]. In these models only the deviatoric part of the strain elastic energy is assumed to drive the cracks evolutions and therefore penalized by the phase-field whereas the hydrostatic part is unaffected by damage [4]. As a result, the kinematics associated with material damage is that associated only with deviatoric deformations: micro-fractured shear bands form and coalesce in mode II cracks, according to the von Mises-Hencky-Hüber (or J2) failure criterion.

Contrary to the original isotropic phase-field fracture model, such J2 failure models own some numerical issues. In fact, since inelastic strains are isochoric, fully damaged material points exhibit an elastic behaviour similar to an incompressible elastic material. The numerical difficulties are exacerbated if low order finite elements are used. Here, two possible strategies are investigated in order to circumvent these issues: selective reduced integration or mixed displacement-pressure formulation. Several numerical examples are presented and convergence results discussed, in order to assess the numerical procedures and to highlight the capabilities of different solution strategies.

References

[1] *G. A. Francfort, J.-J. Marigo, Revisiting brittle fracture as an energy minimization problem, J. Mech. Phys. Solids.* ***46*** *(1998) 1319-1342.*

[2] *B. Bourdin, G. A. Francfort, J.-J. Marigo, Numerical experiments in revisited brittle fracture, J. Mech. Phys. Solids.* ***48*** *(2000) 797-826.*

[3] *F. Freddi, G. Royer-Carfagni, Regularized variational theories of fracture: A unified approach, J. Mech. Phys. Solids.* ***58*** *(2010) 1154-1174.*

[4] *G. Lancioni, G. Royer-Carfagni, The variational approach to fracture mechanics. a practical application to the french panthéon in paris, Journal of Elasticity.* ***95*** *(2009) 1-30.*

[5] *A. Chambolle, S. Conti, G. A. Francfort, Approximation of a Brittle Fracture Energy with a Constraint of Non-interpenetration, Arch. Rational Mech. Anal.* ***228*** *(2018) 867-889.*

Interphase model and phase-field approach for strain localization

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Keywords: phase-field, interphase, softening

Quasi-brittle materials subjected to a high level of mechanical solicitations see the development in relatively narrow zone of micro-cracks that coalesce into stress free cracks. In this work, the problem of strain localization in elastoplastic materials exhibiting softening has been approached by applying the interphase model [1] together with the phase-field theory [2-3]. In particular, the narrow zone where strains concentrate, usually named process zone or localization band, is kinematically modeled using the interphase model, while the phase-field variable is introduced to regularize the contact strains at the interface between the plastic strain band and the surrounding material. This corresponds to diffuse the interphase in the volume of the solid body.
The formulation of the problem has been developed in a classical way using the principles of thermodynamics. A key point consists in a Reuss/Sachs type homogenization of the inelastic contact strains through a weak Dirac delta function which takes the shape of the Mumford-Shah functional. The introduction of this kinematical hypothesis consistently leads to the complete set of the governing equations for a localized body.
The model has been tested by means of analytical and numerical applications. The results show that the introduced strain regularization does not affect substantially the structural behavior, also the model can be easily used to replicate experimental results.
The application of the proposed model may involve different contexts as the strain localization in soil mechanics, plastic hinge formation in reinforced concrete frames and delamination in composite materials. It should be noted that the calibration of model parameters for the comparison between numerical end experimental results can be performed easily, since no additional mechanical parameters are needed with respect to those that characterize the elastoplastic behavior.

References

[1] *Fileccia Scimemi, G., Giambanco, G., and Spada, A. "The interphase model applied to the analysis of masonry structures.", Computer Methods in Applied Mechanics and Engineering,* **279**, *pages 66-85 (2014).*

[2] *Miehe, C., Hofacker, M., and Welschinger, F. "A phase field model for rate-independent crack propagation: Robust algorithmic implementation based on operator splits.", Computer Methods in Applied Mechanics and Engineering,* **199**, *pages 2765-2778 (2010).*

[3] *Ambati, M., Gerasimov, T. and De Lorenzis, L. "Phase-field modeling of ductile fracture", Computational Mechanics,* **55**, *pages 1017-1040 (2015).*

Measurement of cohesive laws from mixed bending-tension tests

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Keywords: delamination, cohesive zone model, experimental testing

The mixed bending-tension (MBT) test was proposed by Macedo *et al.* [1] to assess the mode I interlaminar fracture toughness of composite laminates with very low bending stiffness and strength. Specimens obtained from such laminates may fail in bending prior to delamination growth, when tested using the double cantilever beam test [2]. In the MBT test, the specimen with a pre-implanted delamination is adhesively bonded to two metal bars and then loaded in opening mode (Fig. 1).

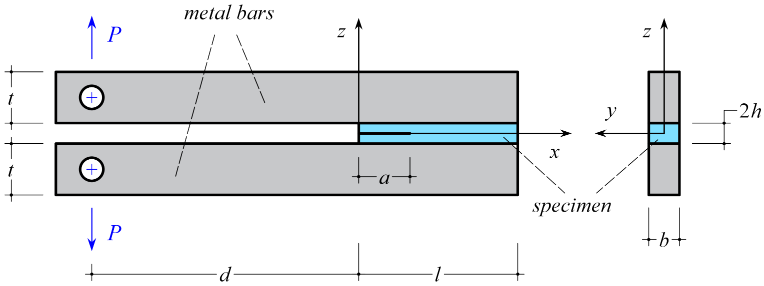

Figure 1: Scheme of the MBT test: (a) side view; (b) cross section.

Bennati *et al.* [3] developed a mechanical model of the MBT test, where the two separating parts of the specimen are connected by a cohesive interface with bilinear traction-separation law. Accordingly, the specimen response can be subdivided into three stages: (i) linearly elastic behaviour, (ii) progressive material damage, and (iii) crack propagation. The theoretical predictions were in good agreement with the experimental results by Macedo *et al.* [1] in the linearly elastic stage. Instead, only qualitative agreement was obtained for the subsequent stages.

Here, we upgrade the previous model by introducing a piece-wise linear, discontinuous traction-separation law for the cohesive zone [4]. We show how the global response of the specimen depends on the cohesive law parameters. Besides, we present an operative procedure to determine the cohesive law parameters based on the test measures.

References

[1] *Macedo, F.S., Pereira, A.B., and de Morais, A.B., Mixed Bending-Tension (MBT) test for mode I interlaminar and intralaminar fracture, Compos. Sci. Technol.,* **72**, *1049–1055 (2012).*

[2] *ASTM D5528–13, Standard Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites, ASTM International, West Conshohocken, PA (2013).*

[3] *Bennati, S., Fisicaro, P., Taglialegne, L., and Valvo, P.S., "An elastic interface model of the mixed bending-tension (MBT) test" in Proceedings of the 22nd National Congress of the AIMETA, Genoa, Italy, 14–17 September 2015, pages 479–487.*

[4] *Valvo, P.S., Sørensen, B.F., and Toftegaard, H.L., "Modelling the double cantilever beam test with bending moments by using bilinear discontinuous cohesive laws" in Proceedings of the 20th Int. Conference on Composite Materials, Copenhagen, Denmark, 19-24 July 2015, (2015).*

Multiple crack localization and debonding mechanisms for thin thermal coating films

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Keywords: Strain localization, Interface, Debonding.

Three and four points bending tests carried out on small scale beams with a thin thermal coating, used as thermal barrier to a superalloy structural substrate, have shown complex failure mechanisms [1]. The dominating failure mechanism observed is the competition between of two fracture mechanisms. First the formation, on the external coating surface, of tensile cracks, which grows in number and propagates in the interior of the coating up to reach the substrate interface. Then, the tensile cracks can pass through the interface or, more likely, a debonding shear mechanism may develops along the interface between the coating (typically a ceramic-type material with quasibrittle constitutive behavior) and the high strength superalloy substrate. The final failure mechanism shows the fragmentation, with subsequent expulsion of small pieces the coating barrier film, which leave the superalloy undercoated and then exposed to the very high temperature variation. Very high temperature variations can be dangerous not only for the development of high thermal strains, but mostly for possible solid phase changes induced in the superalloy.

The present paper analyzes the mechanical problem of the nonlinear behavior thin film on a stiff substrate adopting a computational approach. Namely, incremental 2D nonlinear finite element simulations are adopted, modeling the stiff superalloy as a thermo-elastic material. The coating films are generally realized with ceramic-like materials, therefore it is constitutively modeled as quasibrittle material with a nonlocal elastic-damage constitutive relation [2]. The nonlocal elastic damage model allow to reproduce the formation of damage localization in a mesh-objective way. The formation and propagation of cracks between the coating film and the superalloy substrate is modeled by a zero-thickness cohesive-frictional mechanical interface [3-4].

The overall formulation has been implemented in an open source nonlinear finite element program and a number of 2D simulations have been carried out. A discussion on the amplitude and distance between the surface cracks is presented. The correlation between mechanical properties of the materials and of the interface, together with the influence of the thickens of the coating are analyzed.

References

[1] *Peng J., Xueling F., Yongle S., Dingjun L., Tiejun W., Bending-driven failure mechanism and modelling of double-ceramic-layer thermal barrier coating system, Int. J. Solids Structures,* **130-131***, page 11-20 (2018).*

[2] *Borino G., Failla B., Parrinello F., A Symmetric nonlocal damage theory, Int. J. Solids Structures,* **40***, 3621-3645 (2003).*

[3] *Parrinello F., Failla B., Borino G., Cohesive-frictional interface constitutive model, Int. J. Solids Structures,* **46***, 2680-2692 (2009).*

[4] *Parrinello, F., Marannano, G., Borino, G., A thermodynamically consistent cohesive-frictional interface model for mixed mode delamination, Eng. Fract. Mechanics,* **153***, 61-79 (2016).*

Progressive damage in quasi-brittle solids

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Keywords: damage, regularization, convex constraints

Regularized damage models have become increasingly popular in the last decades for dealing with problems in Mechanics suffering from spurious mesh sensitivity induced by strain softening [1]. Among them, classical approaches rely upon use of gradient enhancements or integral averaging operators that provide globally smoothed solutions by enforcing a greater regularity on either strains or internal variables that are no longer defined at the quadrature point level.

In the present communication emphasis is placed on the so-called Thick Level Set (TLS) approach to quasi-brittle fracture [2], whereby progressive damage in a solid body takes place in a region of prescribed thickness defined as a function of the distance to the undamaged portion of the domain under consideration. In particular, we show that damage evolution in the structure can be followed using an implicit representation of the damage field supplemented with convex constraints that allows the continuous tracking of the position of a moving layer where the transition between the damaged and undamaged material occurs.

Numerical results for representative test cases will be presented to show the model capabilities.

References

[1] *Francfort, G.A., Marigo, J.J., Revisiting brittle fracture as an energy minimization problem, Journal of the Mechanics and Physics of Solids (1998)* ***46****:1319–1342.*

[2] *Moës, N., Stolz, C., Bernard, P., and Chevaugeon, N., A level set based model for damage growth: The thick level set approach, International Journal for Numerical Methods in Engineering (2011)* ***86****:358-380.*

Cohesive-frictional interface in an equilibrium based finite element formulation

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Keywords: HEE, equilibrium, frictional contact, hybrid.

The interface element and the cohesive zone models are powerful tools for the analysis of delamination, crack propagation and frictional contact problems in the finite element formulations. The interface cohesive models are generally developed in intrinsic formulation, which considers a penalty stiffness, assumed as an elastic behaviour, in both the initial condition of the sound material and in the residual frictional behaviour of the cracked one.

The extrinsic interface is instead defined with an initial rigid behaviour, such as a rigid-damage cohesive zone model (CZM), and its implementation require specific non-standard numerical formulation. The discontinuous Galerkin method is applied in classic displacement based formulations together with extrinsic interface, in [1, 2] for the numerical analysis of delamination phenomenon and for the analysis of crack propagation.

In the present paper the extrinsic interface, with rigid-damage model, is developed in the framework of hybrid equilibrium element, instead of standard displacement based finite element formulation. The hybrid equilibrium formulation belongs to the class of stress based approaches and the weak form solution of the elastic-static problem is given in the form of stationary condition of the complementary energy functional. The formulation considered in the present paper for the stress based solution of the elastic static two-dimensional problem is the same proposed in [3], where the stress fields are independently defied for each finite element. The inter-element equilibrium condition and the boundary equilibrium condition are applied by following the classical hybrid formulation, considering independent side displacement fields as interfacial Lagrangian variable.

The rigid cohesive frictional CZM is developed in the rigorous thermodynamic framework of damage mechanics [4, 5] and is defined as embedded interface at the hybrid equilibrium element sides. The numerical simulations of delamination and frictional contact problems are performed and the results are compared with the solution of classic displacement based formulations.

References

[1] Mergheim, J., Kuhl, E., Steinmann, P., 2004. A hybrid discontinuous galerkin/interface method for the computational modelling of failure. Communications in Numerical Methods in Engineering 20 (7), 511-519.

[2] Nguyen V, 2014. Discontinuous galerkin/extrinsic cohesive zone modeling: Implementation caveats and applications in computational fracture mechanics. Engineering Fracture Mechanics 128 (C), 37-68.

[3] Parrinello, F., 2013. Restraining approach for the spurious kinematic modes in hybrid equilibrium element. Computational Mechanics 52 (4), 885-901.

[4] Parrinello, F., Failla, B., Borino, G., 2009. Cohesive-frictional interface constitutive model. Int. J. Solids Structures 46 (13), 2680-2692.

[5] Parrinello, F., Marannano, G., Borino, G., 2016. A thermodynamically consistent cohesive-frictional interface model for mixed mode delamination. Eng.Frac.Mech.153, 61-79.

Theory of multiple peeling of hyperelastic strips

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Keywords: multiple peeling, nonlinear hyperelasticity

Understanding the mechanics at the base of peeling processes that occur at the adhesive interface of film-substrate systems has found wide interest in the scientific literature of the last decades. It in fact represents a necessary step toward the comprehension of adhesion/de-adhesion phenomena characterizing a wide range of biological structures at different length scales as well as involved in many industrial, robotic and biomedical applications. Starting from the work by Kendall [1], in which an energy-based approach was adopted for modelling the single peeling of a thin adhesive film from a rigid substrate, several theoretical and experimental studies have been conducted to analyze the delamination of tape-like elements by taking into account the role played by the roughness or compliance of the substrate and by pretension, bending stiffness or multiple arrangements of the strips [2]. On this ground, the Authors generalize the linear theory of multiple peeling [2] by involving finite strains and nonlinear hyperelasticity of the adhesive strips and by including the effect that a pre-stretch, eventually stored in their adhering or free portions, can exert on the process. By focusing on a symmetrical V-shaped system comprising neo-Hookean elements, peeling onset and its quasi-static progression are analytically described, gaining closed-form solutions in particular cases. In this way, some remarkable and previously unseen results are revealed and theoretical confirmations of experimental evidences are obtained. In particular, maximum adhesion strength is shown to occur for an initially flat configuration of the tapes and to increase with the prestretch in their adhering tracts. Delamination process is found to start at lower values of critical pull-off force with respect to standard linearly elastic formulations, and studying the evolution of the detaching regions then leads to predict the progressive achievement of asymptotic limits for both pulling loads and peeling angles. Deviations toward asymmetrical detachment configurations are additionally investigated, thus demonstrating that the critical pulling load remains unchanged, similarly to what happens in limit analysis for perfectly plastic structures, in which a unique limit multiplier can be associated to different collapse mechanisms. Finally, the case of a flat strip with both adherent and free tracts differently prestressed is analyzed, so finding that the optimality condition, e.g. the maximum critical pull-off force, is always attained as the whole system is uniformly prestretched, the analytical approach also allowing to identify an incompatibility-instability region in the prestretches' phase space. It is felt that the proposed model might be adopted to gain new insights into the mechanisms governing the adhesion capabilities of biomechanical anchorage structures, as well as to guide the design of novel artificial (e.g. biomimetic) devices, in which geometry, hyperelasticity and prestress can be exploited to optimize the adhesion strength for applications to soft robotics and materials engineering.

References

[1] *Kendall, K., Thin-film peeling-the elastic term, Journal of Physics D: Applied Physics (1975).*
[2] *Pugno, N. M., The theory of multiple peeling, International Journal of Fracture (2011).*

Layered phase field approach to shells

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Keywords: Fracture, Shells, Phase-field.

Fracture is one of the most commonly encountered failure modes of engineering materials and structures. Prevention of cracking-induced failure is, therefore, essential to save lives and contain costs and should be considered a social commitment. However, the understanding of nucleation and propagation of complex crack patterns in real structures is still an open problem, for which traditional techniques are unable to provide satisfactory results. In this field, the variational formulation of fracture mechanics as an energy minimisation problem opened new perspectives; in particular, the phase field approach to fracture revealed to be a versatile and powerful tool for the investigation of crack problems.

Despite the widespread use of plates and shells in engineering applications, the failure mechanisms of these kind of structures are quite poorly understood. As a matter of fact, few attempts have been devoted to the formulation and applications of the phase field approach to plates and shells [1], [2]. In this contribution an alternative phase field formulation is proposed, which relies on the subdivision of the thin (or slender) solid into several layers. In this way, while the mechanical behaviour of the solid is governed by classical theories of plates and shells, the phase field equation has to be satisfied within each layer, that is, in a domain with reduced dimension. The proposed procedure is validated and critically examined through comparisons with a full 3D approach.

References

[1] *Amiri, F., Millan, D., Shen Y., Rabczuk T. and Arroyo M., "Phase-field modeling of fracture in linear thin shells" Theoretical and Applied Fracture Mechanics, 69, 102-109, 2014.*

[2] *Kiendl, J., Ambati, M., De Lorenzis L., Gomez, H. and Reali A.,"Phase-field description of brittle fracture in plates and shells" Computer Methods in Applied Mechanics and Engineering, 312, 374-394, 2016.*

The role of damage poromechanics in the modeling of interfaces in production/injection wells

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Keywords: well integrity, micro-annulus, zonal isolation

The leakage of contaminating and greenhouse fluids is often observed in sites of gas production or storage. Such upward migration of fluids, which poses an environmental hazard, is typically concentrated in production/injection wells, as a consequence of the formation of circumferential cracks (the so-called "micro-annulus") at the interfaces of cement sheath with the steel casing and the rock formation, respectively [4]. In these phenomena, the importance of the coupling between fluid flow and mechanical damage is shown by the crucial role played by the pressure of leaking fluids in the debonding at well interfaces.

In view of these considerations, we presented new poroelastic laws to model fluid-induced damage in interfaces [2]. This model offered some advantages with respect to other previous laws for pressurized interfaces, as demonstrated by its better performance in reproducing the main behavioural features of the response of water-pressurized fractures in concrete.

More recently, our poromechanics modeling of localized damage has been extended, e.g. by taking into account the interface porosity preexisting to damage. Also our formulation of the well problem, with interfaces subjected to displacement discontinuities and fluid pressures, has been further generalized, in order to employ the corresponding semi-numerical solution method for the analysis of available laboratory tests on full-scale physical models of wells [1, 3]. The main objective of these new computations is to investigate the performance of low-strength and low-stiffness expansive cements in contrasting the crack formation and in closing damaged interfaces, also in combination with the confinement action due to the surrounding rock formation.

References

[1] *Boukhelifa, L., Moroni, N., James, S., Le Roy-Delage, S., Thiercelin, M. J., and Lemaire, G., "Evaluation of Cement Systems for Oil and Gas Well Zonal Isolation in a Full-Scale Annular Geometry". Society of Petroleum Engineers (2005).*

[2] *Callari, C., Fasano, V., "Analisi del danneggiamento di pozzi esistenti in siti di stoccaggio di CO2" in Proceedings of Conference "Problemi attuali e prospettive nell'ingegneria delle strutture" Maratea, 26-27 settembre 2013, page 239-244, Pellegrini Editore, Cosenza (2014)*

[3] *Jackson, P. B., and Murphey, C. E. "Effect of Casing Pressure on Gas Flow Through a Sheath of Set Cement". Society of Petroleum Engineers, page 215-224, (1993)*

[4] *Nelson, E.B., and Guillot, D., Well Cementing, Schlumberger (2006).*

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COMPOSITES IN CIVIL ENGINEERING

Bistable cantilever shells for vibration energy harvesting

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Keywords: bistable composite shell; nonlinear vibration energy harvesting; reversible snap-through.

Given the almost ubiquitous nature of vibrational energy in mechanical systems, in the last two decades the field of vibration based energy harvesting has received growing attention. Most of the initial research focused on linear resonant vibration harvesters, which exploit resonance to amplify the input motion to drive a transducer to produce electrical power. More recently, the introduction of nonlinearity to increase the operational frequency range has been considered. One type of nonlinear system of particular interest is the bistable one, due to its capacity for high output power when it snaps through from one stable state to another providing large-amplitude motions across a wide range of input frequencies [1]. A variety of architectures of bistable systems for energy harvesting have been investigated for suitability. Recently the design and manufacturing of cantilever shells with prescribed multistable capabilities was addressed in [2] where two manufactured demonstrators were discussed.

On the basis of the preceding works, a bistable cantilever laminated composite shells is here considered. The cantilever shell undergoes harmonic base excitation and several objectives are pursued: The dynamic analysis of the cantilever composite shell whose design was conceived under static loading conditions; the dynamic snap-through between remarkably distinct equilibrium configurations; the identification of the nonlinear dynamic regimes and bifurcations triggering reversible snap-through (see Figure 1). The numerical validation of the results is shown via FE simulations and equivalent reduced Duffing-Holmes oscillators.

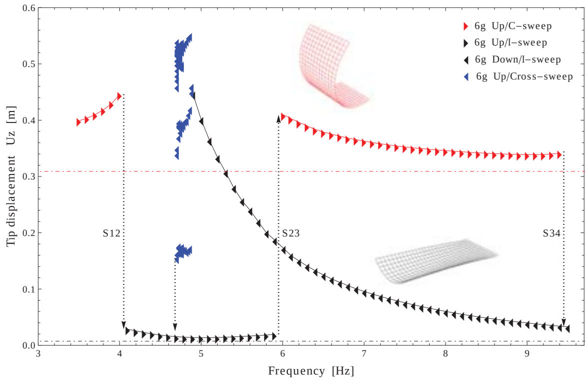

Figure 1: Reversible snap-through path under base excitation up and down frequency sweep.

References

[1] *Chiacchiari, S., Romeo, F., McFarland, D.M., Bergman, L.A., Vakakis A.F., Vibration energy harvesting from impulsive excitations via a bistable nonlinear attachment, Int. J. Non-Linear Mech.,* **94***, pp. 84-97 (2017).*

[2] *Brunetti, M., Kloda, L., Romeo, F., Warminski, J., Multistable cantilever shells: Analytical prediction, numerical simulation and experimental validation, Composites Science and Technology,* **165***, pp. 397-410 (2018).*

Interface laws for multi-physic composites

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Keywords: Composites, Interfaces, Multi-physic materials.

In the last decades, the interest in bonded structures, obtained by assembling different parts made of possibly different materials to compose a unique structure, is strongly increased. In the present work we focus our attention to a specific type of composite, constituted by two media, called the adherents, bonded together with a thin interphase layer, called the adhesive. We assume that the composite constituents are made of different multi-physic materials with highly contrasted constitutive properties. The study considers a generic multi-physic coupling in a very general framework and can be adapted to well-known multi-physic behaviors, such as piezoelectricity, thermo-elasticity, as well as to multifield microstructural theories, such as micropolar elasticity. The analysis has been carried out by means of asymptotic expansions method. This technique has been applied to the rigorous derivation of simplified models for complex assemblies, presenting thin interphases, in the field of linear elasticity [1] as well as in piezoelectricity, taking into account other physical interactions [2]. The asymptotic methods allow to replace the adhesive layer with a two-dimensional surface, the so-called imperfect interface, with non-classical transmission conditions between the two adherents. By defining a small parameter ε, associated with the thickness and constitutive properties of the middle layer, we perform an asymptotic analysis. We assume that the middle layer thickness depends linearly on ε, while the multi-physic stiffness ratios between the adherents and the adhesive depend on ε^p. We identify three critical exponents p, corresponding to different imperfect interface models: $p = 1$, the soft (also called lowly-conducting) multi-physic interface model; $p = 0$, the hard (also called moderately-conducting) multi-physic interface model; $p = -1$, the rigid (also called highly-conducting) multi-physic interface model. Following the approach by [1], we characterize the order zero and higher order transmission problems. Finally, a general multi-physic interface model has been developped, and numerically tested through the finite element method. In particular, in the framework of piezoelectricity, we compare the results obtained by modeling the adhesive as an interphase, having a thin finite thickness, with the results obtained with the general multi-physic interface model.

References
[1] *Rizzoni R., Dumont S., Lebon F., and Sacco E. Higher order models for soft and hard elastic interfaces, Int. J. Solids Struct.* **51***(23-24), 4137-4148 (2014).*
[2] Serpilli M., Mathematical modeling of weak and strong piezoelectric interfaces, J. Elasticity **121***(2), 235-254 (2015).*

Analytical model to study the bond behavior of FRCM-masonry joints tested using single-lap and hinged beam tests

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Keywords: Beam test, Fiber Reinforced Cementitious Matrix (FRCM), Cohesive Material Law (CML)

In the last decades, composite materials have been proven to be an excellent solution for strengthening and retrofitting existing reinforced concrete (RC) and masonry structures.

Within this category of materials, those comprising a high strength fiber textile embedded in an inorganic matrix, generally referred to as fiber reinforced cementitious matrix (FRCM) or textile reinforced mortar (TRM), showed good behavior at (relatively) high temperature and good compatibility with the substrate. This last feature, as well as the partial reversibility of the strengthening/retrofitting intervention, made these composites popular for applications on heritage buildings.

Despite of some advantages associated with the use of an inorganic matrix, the bond behavior between the matrix and the embedded fiber textile still needs investigation. Indeed, failure of externally bonded FRCM composites comprising one layer of textile generally occurs due to debonding at the matrix- fiber interface.

Direct-shear and beam test set-ups were proposed to study the bond behavior of FRCM-substrate joints.

In this paper, an analytical model is proposed to describe the debonding process at the matrix-fiber interface of a PBO FRCM composite. The analytical model assumes a matrix-fiber zero-thickness interface and the interfacial behavior is modeled by a trilinear cohesive material law (CML). The analytical results are compared with experimental outcomes of single-lap and hinged beam tests of FRCM-masonry joints.

References

[1] Alecci, V., Focacci, F., Rovero, L., Stipo, G., De Stefano, M. "Extrados strengthening of brick masonry arches with PBO-FRCM composites: experimental and analytical investigations", Composite Structures, Vol. 149, page 184-196 (2016).

[2] Carlonii, C., Santandrea, M., Imohamed, I. A. O., "Determination of the interfacial properties of SRP strips bonded to concrete and comparison between single-lap and notched beam tests", Engineering Fracture Mechanics, Vol. 186, page 80-104 (2017).

[3] Gartner, A., Douglas, E. P., Dolan, C. W., Hamilton, H. R. "Small beam bond test method for CFRP composites applied to concrete", Journal of Composites for Construction, Vol. 15, page 52-61 (2011).

Basalt-based FRP composites as strengthening of reinforced concrete members: experimental and theoretical insights

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Keywords: Basalt-FRP, debonding failure, strengthening of RC structures

In the field of civil engineering, the retrofitting of existing reinforced concrete structures is a fundamental task. In the last decades, the strengthening of inflected concrete members, such as beams or slabs, through the use of fiber-reinforced polymer (FRP) composites, leaded to promising and interesting results. Indeed, unidirectional FRP sheets, applied on the traction side of the members, entail an improvement of both strength (ultimate limit state) and stiffness (serviceability limit state) of the structure. The experimental evidence, together with analytical and numerical approaches, highlighted the effectiveness of such a kind of strengthening system. Nevertheless, many applications concern the use of traditional FRP made with carbon fibers or glass fibers.

Recently, the attention of the scientific community and of the producers has moved towards ecologically sustainable materials. In this framework, basalt fibers are a good alternative to traditional fibers, exhibiting also good mechanical properties. Moreover, basalt-based FRPs (BFRPs) have proved an adequate efficiency in terms of mechanical performance and economic sustainability [1].

The work aims to investigate the effectiveness of BFRP composites as strengthening material for beam-like concrete structural elements. The non-linear flexural response of beams strengthened with BFRPs is investigated. An analytical approach, based on the evaluation of the cross-section moment-curvature relationship, that also considers the tension stiffening phenomenon, is developed and applied to a number of study cases. Neverthless, typical failure modes involve also the FRP-concrete end-debonding. This latter occurs as a brittle mechanism that jeopardises the ductility demand required in the structural design concept, becoming a critical issue. In this framework, results of a wide experimental program based on push-pull double shear tests on BFRP-concrete specimens [2] are presented, by proposing suitable correction coefficients for improving the effectiveness of some available technical design rules when BFRP are adopted [3].

References

[1] *Nerilli, F., Monaldo, E., Vairo, G., "Basalt-based fiber-reinforced materials and structural applications in civil engineering", Composite Structures,* **214***, 246-263 (2019).*

[2] *Nerilli, F., Vairo, G., "Experimental investigation on the debonding failure mode of basalt-based FRP sheets from concrete", Composites Part B:Engineering,* **153***, 205-216, (2018)*

[3] *Nerilli, F., Monaldo, E., Vairo, G., "Effectiveness of some technical standards for debonding analysis in FRP-concrete systems", Composites Part B:Engineering,* **160***, 254-267 (2019).*

Numerical modeling of accelerated ageing weathering cycles in masonry strengthened with composites

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Keywords: Salt Crystallization; FRCM; FRP

Rising damp and salt crystallization are acknowledged as major factors of environmental degradation of porous materials like masonry. Additionally, composite strengthening systems (e.g. FRP and FRCM) have been widely applied on historic masonry buildings, given their poor structural performance.

However, the durability of these strengthening systems bonded to masonry is still scarcely known. Indeed, although few laboratory tests have been recently carried out to this aim, very limited information is generally available.

In this study, the multiphase numerical model developed in [1], which accounts for salt transport and crystallization, is implemented together with ad hoc boundary conditions and a restart analysis procedure to simulate weathering cycles of FRP- and FRCM-strengthened masonry specimens. The multiphase model is then used to gain more in-depth knowledge on the different processes of environmental degradation in these strengthening systems.

References

[1] *Castellazzi, G., Colla, C., de Miranda, S., Formica, G., Gabrielli, E., Molari, L., and Ubertini, F. "A coupled multiphase model for hygrothermal analysis of masonry structures and prediction of stress induced by salt crystallization," Construction and Building Materials,* ***41****, 717–731 (2013).*

A comparison between GFRP adhesive and bolted connection made of a tubular column and a built-up beam: an experimental investigation

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Keywords: GFRP, Adhesive and bolted connection, strength and stiffness.

Fibre reinforced polymer (FRP) materials are being increasingly considered as an alternative to traditional materials for civil engineering structural applications due to their high tensile strength and resistance to aggressive environment, lightweight, and quick installation time. Presently, pultrusion is the preferred method than other manufacturing methods for continuous FRP profiles with constant cross-section, such as hollow sections, angles, I-beams and channel, all being suitable for framing and building applications.

With regard to frames structures, efforts to develop suitable connection systems for GFRP elements started in the nineties when I-shaped sections were used as beams and columns in most cases following steel construction practices. However, these connections exhibit brittle failure manner such as, for example, the detachment of the column flange from the web and the delamination in the heel of the top angles. Recently, the present research group have performed a number of experimental investigations [1] aiming at demonstrating the structural effectiveness of adhesive connections between pultruded I-profiles. The test results show that bonded connections, if properly designed and constructed, possess high strength, at least comparable to the one of bolted connection. There are reasons to believe that bonded connections can achieve higher performance compared to bolted connections in FRP composite structures. Firstly, it is well known that the holes made in structural members cause stress concentration and also increase the risk of moisture penetration within the matrix-fibre interface. There are few experimental or numerical results available to assess their strength, stiffness and overall performance. To fill this gap in knowledge, the objective of this paper is to experimentally characterize the behaviour of an adhesive GFRP connection between a tubular profile (column) and a built-up beam composed of U-profiles. With respect to previous studies, the choice of tubular profiles for the beam and the column is motivated by the increased torsional stiffness and resistance to distortions, as well as the greater available surface for adhesion.

The connection is tested under static and cyclic loads to investigate both its static and fatigue performance. Furthermore, the mechanical response of the connection under static load is compared to the behaviour of an analogous bolted connection, demonstrating its great potential in terms of strength and stiffness.

References

[1] Ascione, F., Lamberti, M., Razaqpur, A.G., Spadea, S. "Strength and stiffness of adhesively bonded GFRP beam-column moment resisting connections". Compos Struct, Vol. 160, 1248–57 (2017).

Numerical Modelling of GFRP Reinforced Thin Concrete Slabs

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Keywords: GFRP bar, RC slab, finite element modelling, bond, concrete compressive law, mesh dependency

With the development of new glass fiber reinforced polymer (GFRP) bars for RC structures, their application extends simultaneously. The non-corrosive nature of GFRP bars enables maximal lowering of the concrete cover, thus making them very suitable as a reinforcement in thin RC plate elements. Such thin members are usually prefabricated and used as façade panels, pavement or components of sandwich panels. Along with experimental studies, the finite element (FE) numerical modeling represents very useful tool for assessing and predicting the structural member behavior. Proper choice of material constitutive models and strategy of concrete/bar bond implementation always presents challenge when dealing with numerical FE modelling of RC structures. This study considers FE modelling of thin GFRP RC slabs' flexural behavior under three-point bending test setup. It uses direct bond approach, that is, explicit simulation of the bond-slip effect between concrete and reinforcing bars. For this purpose, the experimental bond-slip law was used, obtained from the pull-out test having the same GFRP bar, same concrete cover and similar concrete properties as simulated RC slab. Since the slab failed for concrete crushing, the study assesses the importance of concrete compressive model selection on the numerical analysis results. Two different models were employed in the numerical analysis, in combination with three FE mesh densities. The main differences between the models comprise post-peak capacity and mesh dependency. The FE modelling strategy developed in the study was shown successful in reproducing the experimental outcome. Both concrete models showed convergence tendency when refining the mesh, whereas only one of them succeeded to reproduce the experimental results.

Optimal epoxy dilution for epoxy-coated Textile Reinforced Mortar (TRM): an experimental perspective

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Keywords: TRM, interphase adhesion, coating optimization

In this work, the effect of epoxy coating dilution on the mechanical performance of epoxy-coated alkali-resistant glass (ARG) fabric embedded in a lime-based mortar is studied experimentally. The composite mechanical behaviour is assessed in uni-axial tensile tests, according to the ICC [1] guidelines. Epoxy is diluted in acetone and several concentrations, namely 10%, 25%, 50%, 75% and 90%, are considered in an attempt to define a decay law for strength, ductility and dissipated energy at failure. Digital Image Correlation (DIC) is employed to investigate the crack pattern evolution. Surprisingly, although epoxy-coating promotes a striking improvement of the composite mechanical performance with respect to the uncoated specimens [2], epoxy dilution appears to little affect the global response, even at very low concentrations. Indeed, it appears that epoxy resin is able to uniformly impregnate the bundles of the yarns in a very thin layer, still preserving its contribution to the mechanical performance. In fact, wettability of the yarns plays a fundamental role in the mechanical performance of the laminate for it antagonizes telescopic failure. Besides, alongside a marginal reduction in terms of strength and ductility of the laminates, dilution strongly promotes the ease of application, as a result of the resin viscosity being sharply reduced. Most remarkably and contrarily to common expectation, the specific energy dissipated at failure exhibits a maximum point, whence an optimal dilution ratio seems to exists which best balances intrephase strength and ductility. Some consideration regarding optimal design and cost optimization are also provided.

References

[1] *ICC-Evaluation Service, "Acceptance criteria for masonry and concrete strengthening using fiber-reinforced cementitious matrix (FRCM) composite systems" Whittier, CA, (2013)*

[2] *Messori, M., Nobili, A., Signorini, C., Sola, A., "Mechanical performance of epoxy coated AR-glass fabric Textile Reinforced Mortar: Influence of coating thickness and formulation" Composites Part B-Engineering,* **149** *page 135-143, (2018)*

Numerical-parametric analysis of debonding phenomena in FRCM-strengthened masonry elements

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Keywords: Masonry, FRCM, Shear Test.

The application of composite materials as structural strengthening requires the use of special adhesives. The choice of the adhesive depends on several factors, one in particular is related to the characteristics of the support (concrete, masonry or wood). There are many types of natural and synthetic adhesives: the most suitable adhesives for composite materials are based on epoxy resin; adhesive-based on mortar are currently the topic of several researches in order to ensure sustainability and to use renewable technologies also in the field of civil engineering [1].

The aim of this paper is providing a contribution regarding numerical study of adhesion problems of FRCM (Fiber Reinforced Cementitious Matrix) strengthening system. Using software based on Finite Element Method (FEM), single-lap shear bond tests have been performed implementing bond-slip laws available for masonry supports and inorganic matrix systems. The numerical model used in the simulations includes two types of reinforcements: PBO-FRCM and FLAX-FRCM, applied on masonry support. FRCM (cement-based composites) are nowadays widely used in the reinforcement of existing structures [2-3]; unfortunately, the guidelines for the qualification of FRCM systems are not yet operational, as there are no design criteria available, if not for standard applications. Consequently of this, numerical analyses have been carried out considering debonding law provided by the Guidelines CNR-DT 200 R1/2013 [4]; different parametric analyses have been allowed in order to compare computational and experimental results with Guidelines predictions.

For the purpose of the work, the parameters analyzed were the bond length, the bilinear bond strength - slip and the bond interface between reinforcement-support and reinforcing fiber-matrix. In the end, all the results highlighted the different debonding mechanisms observed during the experimental analyzes, both for the reinforcement system PBO-FRCM and Flax-FRCM applied to masonry support, mainly due to the loss of adhesion.

References

[1] R. S. Olivito, R. Codispoti, O.A. Cevallos, Bond behavior of Flax-FRCM and PBO-FRCM composites applied on clay bricks: Experimental and theoretical study, Composite Structures, Volume 146, 20 June 2016, Pages 221-231.
[2] O.A. Cevallos, R.S. Olivito, Effects of fabric parameters on the tensile behaviour of sustainable cementitious composites, Composites Part B: Engineering, Volume 69, February 2015, Pages 256-266, ISSN 1359-8368.
[3] O.A. Cevallos, R.S. Olivito, R. Codispoti, L. Ombres, Flax and polyparaphenylene benzobisoxazole cementitious composites for the strengthening of masonry elements subjected to eccentric loading, Composites Part B: Engineering, Volume 71, 15 March 2015, Pages 82-95, ISSN 1359-8368
[4] CNR-DT 200/R1/2013, Istruzioni per la Progettazione, l'Esecuzione ed il Controllo di Interventi di Consolidamento Statico mediante l'utilizzo di Compositi Fibrorinforzati.

Evaluation of the tensile response of FRCM composites on the basis of the fiber-matrix bond properties

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Keywords: FRCM, cracking, cohesive material law.

Fiber reinforced cementitious matrix (FRCM) composites are usually mechanically characterized by means of tensile and bond tests [1]. The load responses provided by tensile tests are typically constituted of three phases, namely the uncracked, cracking, and fully cracked phase [1]. During the uncracked phase, which ends when the applied stress attains the matrix tensile strength, the composite behaves elastically. During the cracking phase, multiple cracks form in the matrix and the behavior of the specimens is governed by the shear stress acting at the fiber-matrix interface. During the fully cracked phase the width of the cracks increases and the applied load is carried mainly by the textile.

The bond behavior of FRCM composites is generally investigated using single-lap shear test set-ups, which allow for the evaluation of the stress-transfer mechanism within the matrix, at the matrix-substrate interface, and at the matrix-fiber interface. Within the framework of fracture mechanics, Focacci et al. [2] calibrated a cohesive material law (CML) that describes the bond behavior between the poliparafenilenbenzobisoxazole (PBO) fibers and the embedding matrix of a PBO-FRCM composite on the basis of the experimental results provided by D'Antino et al. [3].

In this paper, the PBO fiber-matrix CML calibrated in [2] is introduced in an analytical model of FRCM composite tensile tests in order to verify if it allows the cracking process to be accurately predicted. The results of the model are compared with corresponding experimental results of tensile tests of the same PBO-FRCM composite employed to calibrate the CML [2]. The experimental cracking process is evaluated with the digital image correlation (DIC) technique and the comparison between the analytical and the experimental results is performed in terms of load response and distance and opening of cracks.

References

[1] *Carozzi, F. G., Bellini, A., D'Antino, T., de Felice, G., Focacci, F., Hojdys, L., Laghi, L., Lanoye, E. Micelli, F., Panizza, M., Poggi, C., "Experimental investigation of tensile and bond properties of Carbon-FRCM composites for strengthening masonry elements", Composites Part B,* ***128****, 100-179 (2017).*

[2] *Focacci, F., D'Antino, T., Carloni, C., Sneed, L. H., Pellegrino, C., "An indirect method to calibrate the interfacial cohesive material law for FRCM-concrete joints" Materials & Design,* ***128****, 206-217 (2017).*

[3] *D'Antino, T., Carloni, C., Sneed, L. H., Pellegrino, C., "Matrix-fiber bond behavior in PBO FRCM composites: a fracture mechanics approach", Eng. Fract. Mech.* ***117****(02), 94-111 (2014).*

On the experimental behaviour of adhesive junctions

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Keywords: CZM, DIC, composite.

Adhesively bonded connections are widely used in several fields of Engineering, like as Automotive, Naval, Aerospace and Civil Engineering [1-2], due to the development of high-strength structural adhesives.

Several authors have investigated the behaviour of adhesive junctions in composite structures, by performing experimental and theoretical studies. The obtained results have shown that the failure mechanisms of these connections are markedly influenced by surface preparation, curing process, joint geometry and test setup.

No specific standards or guidelines are available at now in Industrial and Civil field to experimentally evaluate the constitutive law of adhesive interface.

Within this context, mode II behaviour of end-notch-flexure (ENF) specimens was studied by the authors, via shear tests performed at the Design Machine Laboratory of the University of Salerno, based on both traditional equipment and non contact (*Digital Image Correlation*) technique.

Starting from the experimental data, the specimens' fracture toughness and the corresponding adhesive interface's cohesive law [2-3] were evaluated.

References

[1] Ascione, L., Berardi, V.P., "Anchorage device for FRP laminates in the strengthening of concrete structures close to beam-column joints", Composites Part B: Engineering, ***42(7)****, pp. 1840-1850, (2011).*

[2] Perrella, M., Berardi, V.P., Cricrì, G., "A novel methodology for shear cohesive law identification of bonded reinforcements", Composites Part B: Engineering, ***144****, pp. 126-1334, (2018).*

[3] Lepore, M.A., Perrella, M., "From test data to FE code: a straightforward strategy for modelling the structural bonding interface", Frattura ed Integrità Strutturale, ***39****, pp. 191-201, (2017).*

An inter-element fracture approach for the analysis of concrete cover separation failure in FRP reinforced RC beams

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Keywords: concrete cover separation, cohesive interface model, inter-element fracture.

In the present work, an innovative finite element (FE) approach for simulating cover separation failure in RC beams with externally bonded strengthening (e.g. FRP) systems is proposed. Several experimental and theoretical studies have clearly shown that externally bonded FRP composites can be successfully used to improve the structural performances of concrete members [1-2], although an important issue concerning the reliability and the safety of this strengthening method is the occurrence of potential brittle failures of FRP systems, which may significantly reduce their effectiveness [3]. In this regard the present paper deals with a novel numerical framework for the collapse analysis of reinforced concrete (RC) structures strengthened with FRP plates, based on an inter-element fracture approach for concrete, used in combination with an embedded truss model for taking into account the interaction between concrete cracks and tensile steel rebars and additional mixed-mode cohesive elements along the adhesive/concrete (AC) and adhesive/plate (AP) material interfaces. The reliability and the effectiveness of the proposed fracture approach have been shown by means of comparisons with available experimental results and the numerical model has been exploited for predicting the load-carrying capacity and the related failure mode of real-scale retrofitted RC elements. The proposed model, developed in a 2D finite element setting and implemented within a commercial software with programming capabilities [4], represents an innovative and versatile numerical tool able to analyse in an effective manner all the main failure mechanisms in FRP/concrete systems due to multiple crack initiation, propagation and coalescence, unlike for most existing models. In particular, the adopted inter-element approach dramatically simplifies the simulation of complex fracture phenomena [5].

References

[1] *Triantafillou, T. C., Plevris, N., "Strengthening of RC beams with epoxy-bonded fibre-composite materials", Materials and Structures,* ***25****, 201-211 (1992).*
[2] *Rabinovitch, O., "Fracture-mechanics failure criteria for RC beams strengthened with FRP strips—a simplified approach", Composite Structures,* ***64****, 479-492 (2004).*
[3] *Bruno, D. Greco, F., Lo Feudo, S., Nevone Blasi, P., "Multi-layer modeling of edge debonding in strengthened beams using interface stresses and fracture energies", Engineering Structures,* ***109****, 26-42 (2016).*
[4] *Comsol AB, Comsol Multiphysics Physics Builder Manual (2018).*
[5] *De Maio, U., Fabbrocino, F. Greco, F., Leonetti, L., Lonetti, P., "A study of concrete cover separation failure in FRP-plated RC beams via an inter-element fracture approach", Composite Structures,* ***212****, 625-636 (2019).*

Fiber-reinforced brittle-matrix composites: Discontinuous phenomena and optimization of the components

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Keywords: Fiber-reinforced composites; Bridged Crack Model; Ductile-to-brittle transition.

In the field of Fracture Mechanics of fiber-reinforced composites, the problem of minimum reinforcement and catastrophic (snap-back) or hyper-strength structural behavior is investigated, in order to improve the material design through an optimization of the components. A Non-linear Fracture Mechanics approach [1] makes it possible to analyze the composite post-cracking behavior and, unlike the classical strength theory, to explain certain discontinuous phenomena, that are experimentally verified, such as the size-scale effects or the snap-back and snap-through instabilities [2].

In particular, the fundamental secondary-phase role played by the fiber volume fraction is investigated by means of the Bridged Crack Model [1], and through an experimental comparison, in order to highlight how the fracture toughness of the brittle matrix is improved by means of the fiber bridging action affecting the matrix micro- and macro-cracks, so as to prevent their coalescence, opening and growth. These bridging toughening mechanisms are due to debonding, sliding and frictional pulling-out between the matrix and the high-resistance fibres, or to yielding of the low-resistance ductile fibres.

Moreover, the effect of the size scale is found to be fundamental for the global structural behaviour, which can range from ductile to catastrophic simply with the variation of a dimensionless brittleness number, N_P, which is a function of the toughness of the matrix, of the yielding or slippage limit of the reinforcement, of the volume fraction of the reinforcement, and of the characteristic structural size [1].

References
[1] *Carpinteri, A., 1984. "Stability of fracturing process in RC beams". Journal of Structural Engineering ASCE, 110: 544-558.*
[2] *Bosco, C., Carpinteri, A., 1995. "Discontinuous constitutive response of brittle matrix fibrous composites". Journal of the Mechanics and Physics of Solids, 43:261-274.*

A numerical algorithm for contact behaviour at ITZ of concrete at the mesoscale

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Keywords: concrete, elasto-plasto-damage, interfacial transition zone.

Abstract. *The present work is aimed at proving the soundness of a contact numerical algorithm for the correct simulation of the slip between aggregate and cement paste in the interfacial transition zone (ITZ) that typically characterizes cementitious composites at the mesoscale. The model is supposed to follow an elasto-plasto-damaged formulation in function of two invariants of the deviatoric stress tensor and in line with non-associated plasticity [1]. ITZ is therefore characterized mechanically in analogy with the surrounding cement paste [2-3] but with different yield function and plastic potential, so accounting for its lower stiffness and different compactness.*
Numerical solid models of cubic specimens tested in compression take advantage of a numerical algorithm for the random distribution of the aggregates in the cement matrix, according to the criterion of maximum packing of particles [4].
Results are provided in terms of damage patterns and compared with the failure mechanisms of the tested samples, in order to prove the capability of the model to predict crack initiation and propagation within the composite material.

REFERENCES

[1] P. Menétrey, K.J. Willam, Triaxial failure criterion for concrete and its generalization. *ACI Structural Journal*, **92(3)**, 311–318, 1995.

[2] G. Mazzucco, G. Xotta, B. Pomaro, V.A. Salomoni, F. Faleschini, Elastoplastic-damaged meso-scale modelling of concrete with recycled aggregates. *Composites Part B-Engeneering*, **140**, 145–156, 2018.

[3] G. Mazzucco, B. Pomaro, V.A. Salomoni, C.E. Majorana, Apex control within an elasto-plastic constitutive model for confined concretes. *Mathematics and Computers in Simulation*, **162**, 221–232, 2019.

[4] G. Mazzucco, B. Pomaro, V.A. Salomoni, C.E. Majorana, Numerical modeling of ellipsoidal inclusions, Construction and Building Materials, **167**, 317–324, 2018.

Bond behaviour and reinforcement of masonry arches with PBO and carbon based TRM systems: testing and modelling

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Keywords: TRM, experimental testing, analytical model

Textile Reinforced Mortar (TRM) constitutes a novel perspective for the reinforcement of both RC and masonry structures, [1], and reasonably, it will be employed extensively in the next future. Some TRM systems show higher compatibility with structures belonging to the cultural heritage due to the presence of lime as a primary binder in the mortar admixture and mineral fibres instead of organic-based, [2, 3]. In TRM, the textile embedded in the matrix undergoes both axial strains and slip since fibre constituting bundles are imbued in the mortar only partially, and no chemical bonding can be activated, [4]. Other aspects influence the tensile capacity and the efficacy of a TRM to adhere to a substrate, e.g. textile layout, fibre-bundle cross-section, the tensile strength of mortar. In [5], it is shown that some relation between the bonding of TRM and substrate mechanical properties can also be found. Thus, additional experimental investigation is crucial to gain reliable acceptance criteria for materials and design methods.

Here, an experimental investigation and a viable modelling strategy are reported. Carbon- and PBO-based TRM systems, both coupled with a cement-based mortar, were tested through double shear tests. The test apparatus, two separated bricks connected through two reinforcement jackets, provides adequate alignment and reproduce the way the TRM system works. Then, 1:2 scale masonry arches reinforced at the extrados were tested under a vertical point force at a quarter of span. To represent the contribution offered by the reinforcement in the arch, the bond behaviour (load-displacement) recorded during double shear tests has been transformed into a force-rotation of the hinge prevented by the reinforcement. This is employed in the four-bar linkage model, which represents the four-hinge mechanism activated during tests on arches, as a "delaying function" of the rotation of the inner hinge. Good agreement is found between the analytical model and experimental evidence, refinements to the model are currently under investigation.

References

[1] *Kouris, L., Triantafillou, T., "State-of-the-art on strengthening of masonry structures with textile reinforced mortar (TRM)," Construction and Building Materials,* ***188****, page1221-1233 (2018).*

[2] *Misseri, G., Rovero, L., Stipo, G., Barducci, S., Alecci, V. and De Stefano, M., "Experimental and analytical investigations on sustainable and innovative strengthening systems for masonry arches," Composite Structures,* ***210,*** *page526-537 (2019).*

[3] *Monaldo, E., Nerilli, F. and Vairo, G., "Basalt-based fiber-reinforced materials and structural applications in civil engineering," Composite Structures,* ***214****, page246-263(2019).*

[4] *Carozzi, F.G., Colombi, P., Fava, G. and Poggi, C. "A cohesive interface crack model for the matrix–textile debonding in FRCM composites," Composite Structures,* ***143****, page230-241(2016).*

[5] *Ceroni, F., Salzano, P., "Design provisions for FRCM systems bonded to concrete and masonry elements," Composites Part B: Engineering,* ***143****, page230-242(2018).*

Phase-field modelling of the pseudo-ductile response of hybrid laminates

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Keywords: hybrid composites, phase-field, variational approach

A possible strategy to provide the composite with a ductile failure response is to consider novel composite architectures where fibres of different stiffness and ultimate strain values are combined (hybridisation) [1]. In a tensile test, failure occurs first in the fibres with lowest ultimate strain inducing a stress relaxation (a decrement of stress at fixed global mean strain for the hybrid composite). The remaining high elongation fibres are proportioned to sustain the total load up to failure. By optimising the quantity and type of fibres, a ductile to failure response can be achieved.

In this work we present a 2D extension of the simplified 1D phase-field formulation [2, 4] to capture the main feature of the UD hybrid composites [3]. The brittle behaviour of the two materials is determined through the minimisation of an energy functional defined on two fields, i.e., the displacement and the damage fields, establishing an energetic competition between the elastic energy release and material damage localised in fracture surfaces. Moreover at the interface level a nonlinear cohesive interface law is assumed. Fracture mechanisms are carried out by parametric analyses of the different failure mechanisms of the laminates. The models is capable to reproduce and describe at the same time failure within the material and delamination at the interface level according to experimental observations.

References

[1] *G. Czél, M.R. Wisnom, Demonstration of pseudo-ductility in high performance glass/epoxy composites by hybridisation with thin-ply carbon prepreg, Compos. Part A Appl. Sci. Manuf.* ***52*** *(2013) 23–30.*

[2] *J.-J. Marigo, C. Maurini, K. Pham, An overview of the modelling of fracture by gradient damage models, Meccanica.* ***51*** *(2016) 3107-3128.*

[3] *R. Alessi, J. Ciambella, A. Paolone, Pseudo-ductile response of hybrid composites with cohesive interfacial law, Meccanica.* ***52*** *(2017) 1079-1091.*

[4] *R. Alessi, F. Freddi, Phase-field modelling of failure in hybrid laminates, Composite Structure.* ***181*** *(2016) 9-25.*

Freezing and Thawing Durability of High Performance Fiber Reinforced Concrete: an experimental investigation

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Keywords: HPFRC, steel fibers, mechanical properties.

High-performance fiber reinforced concrete (HPFRC) is currently being used in the civil construction field for strengthening existing members [1] and for controlling opening cracks in new ones [2]. Although in literature there are many studies focused on the evaluation of the HPFRC mechanical properties varying the matrix composition and/or the type and quantity of the fibers [3,4], a lack of knowledge exists for what concerns durability.
The present paper deals with freezing and thawing durability of an HPFRC containing short steel fibers. In details, three different concrete mixtures were examined varying the steel fiber volume fraction: 0%, 1.25% and 2.50%, while the High Performance Concrete (HPC) adopted was a commercial one.
In this study, the dynamic moduli (transversal, longitudinal and torsional) and tensile strength of the HPFRCs mentioned were determined showing the influence of freeze and thaw cycles.
The latter were performed according to UNI 7087-2017. More in details, five prismatic specimens per each concrete mixture were subjected to 75 freeze-thaw cycles while other three specimens were selected as reference samples. The durability evaluation was determined adopting the *Impact Resonance Method* (IRM) provided by the ASTM C215. Finally, all prismatic specimens were tested under four-point bending to evaluate the influence of the freeze/thaw cycles on the flexural behavior of mixtures under investigation.
The experimental results showed that increasing the steel fiber volume fraction the tensile strength increased while the effect of freeze and thaw cycles is negligible.

References

[1] Martinola, G., Meda, A., Plizzari, G. A., Rinaldi, Z. "Strengthening and repair of RC beams with fiber reinforced concrete". Cement and Concrete Composites, Vol. 32(9), 731-739 (2010).
[2] Tiberti, G., Minelli, F., Plizzari, G. A., Vecchio, F. J. "Influence of concrete strength on crack development in SFRC members". Cement and Concrete Composites, 45, 176-185 (2014).
[3] Caggiano, A., Folino, P., Lima, C., Martinelli, E., Pepe, M. "On the mechanical response of Hybrid Fiber Reinforced Concrete with Recycled and Industrial Steel Fibers". Construction and Building Materials, Vol. 147, 286–295 (2017).
[4] Caggiano, A., Gambardelli, S., Martinelli, E., Nesticò, N, Pepe, M.. "Experimental characterization of the post-cracking response in Hybrid Steel/Polypropylene Fiber-Reinforced Concrete". Construction and Building Materials, Vol. 125, 1035–1043 (2016).

Investigation of microscopic instabilities in fiber-reinforced composite materials by using multiscale modeling strategies

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Keywords: microscopic stability analysis, multiscale failure models, fiber-reinforced composites.

Fiber micro-buckling is a frequent failure mode in fiber-reinforced composite materials subjected to prevalent compression along the fiber direction. Indeed, this failure mode may lead to a sensible decrease in their strength, especially if subjected to multi-axial loading conditions [1], inducing also micro-crack initiation and propagation, which ultimately cause their premature collapse [2].

Several studies have shown that instability phenomena in composite materials must be studied at both micro- and macro-scales, in order to capture all possible instability modes [3]. It follows that a detailed model is usually required, resulting in a huge time of the related simulations [4]. To increase the computational efficiency, different multiscale strategies have been proposed (see, for instance, [5]), which are able to overcome the limitations of first-order homogenization schemes, implicitly assuming well-separated spatial scales and periodic arrangement of failure mechanisms.

In this work, the efficacy of two multiscale models for the instability-induced failure analysis of composite materials is investigated, with special reference to locally periodic microstructures under large deformations, for which the micro-to-macro scale length ratio is much larger than zero.

The first multiscale model is a semi-concurrent model, by which the macroscopic constitutive response is computed “on the fly”, whereas the latter one is a hybrid hierarchical/concurrent model, based on a multi-level domain decomposition method, according to which a numerical homogenization scheme is used only for the regions not directly influenced by local failures.

Finally, the numerical accuracy of such multiscale models is assessed via comparisons with direct simulations, also highlighting the role of boundary effects on the overall structural response.

References

[1] Nestorović, M.D. and Triantafyllidis, N., “Onset of failure in finitely strained layered composites subjected to combined normal and shear loading”, J Mech Phys Solids, ***52****, 941-974 (2004).*

[2] Greco, F., Leonetti L., Medaglia, C.M., Penna, R. and Pranno, A., “Nonlinear compressive failure analysis of biaxially loaded fiber reinforced materials”, Compos B Eng, ***147****, 240-251 (2018).*

[3] Michel, J.C., Lopez-Pamies, O., Ponte Castañeda, P. and Triantafyllidis, N., “Microscopic and macroscopic instabilities in finitely strained fiber-reinforced elastomers”, J Mech Phys Solids, ***58****, 1776-1803 (2010).*

[4] Greco, F., Leonetti, L., Luciano, R. and Nevone Blasi, P., “Effects of microfracture and contact induced instabilities on the macroscopic response of finitely deformed elastic composites”, Compos B Eng, ***107****, 233-253 (2016).*

[5] Nezamabadi, S., Potier-Ferry, M., Zahrouni, H. and Yvonnet, J., “Compressive failure of composites: a computational homogenization approach” Compos Struct, ***127****, 60-68 (2015).*

MS03

MECHANICS AND MATERIALS (GMA)

A microstructural model of the human cornea: Cross-link interaction between collagen fibrils

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Keywords: collagen microstructure, human cornea trusswork, keratoconus

Keratoconus is a progressive non-inflammatory disorder of the human cornea that alters the shape of the lens dramatically from sphere to conus through a localized thinning. The refractive consequences of keratoconus are irregular astigmatism, strong myopia, and a marked loss of vision. From the macroscopic point of view, keratoconic corneas present a conical curvature, which induces ruptures and abnormal deposition of chemical species. Microscopically, keratoconus is associated with degenerative changes in the organization of the reinforcing collagen fibrils of the cornea, which are embedded into an isotropic matrix of elastin and proteoglycans [1].

The particular microstructure of the collagen suggests that the macroscopic changes of the geometry in the keratoconus pathology are related to the weakening of the bonds (crosslink) between the collagen fibrils. It is generally acknowledged that corneal fibrils assume a complex yet smooth configuration to provide general confinement to the intraocular pressure (IOP) [2].

In a first attempt to develop a physically based model of keratoconus onset and progression, in the present contribution, we present a simplified model of the collagen microstructure of the human cornea [3]. The model consists of a trusswork that describes the two sets of fibrils and the hypothesized crosslinks connecting the fibrils. The model disregards the actual stochastic nature of the fibril distribution, the spatial organization and regularity of collagen, the presence of hierarchical structures, and the mechanical contribution of the matrix. Clearly, the model does not pretend to deliver a quantitative estimate of the deformation and the stress within a keratoconus cornea, but it tries to understand the function of the different components of the fibril network in the preservation of the quasi-spherical configuration of the cornea. We analyze the mechanical response of the system according to the type of interlacing and on the stiffness of the bonds. Results show that the weakening of transversal bonds is associated with a marked increase in the deformability of the system. In particular, the deterioration of transversal bonds can justify the loss of stiffness of the stromal tissue resulting in localized thinning and bulging typically observed in keratoconus corneas.

References

[1] *Ambekar, R., Toussaint, K.C., Johnson, A.W., The effect of keratoconus on the structural, mechanical, and optical properties of the cornea, Journal of the Mechanical Behavior of Medical Biomaterials* **4***, 223–236 (2011).*

[2] *Daxer, A., Fratzl, P., Collagen fibril orientation in the human corneal stroma and its implication in keratoconus, Investigative Ophthalmology & Visual Science* **38***, 121–129 (1997).*

[3] *Pandolfi, A., Gizzi, A., Vasta, M., A microstructural model of crosslink interaction between collagen fibrils in the human cornea, Philosophical Transactions of the Royal Society A, 20180079 (2019) doi.org/10.1098/rsta.2018.0079.*

Mechanoluminescence in scintillators

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Keywords: Mechanoluminescence, Scintillating materials, Finite elasticity, Configurational forces

Scintillating materials produce photons when they are hit by radiations like γ-rays and for this reason are used in high-energy physics, to detect particle collisions, or in medical imaging. A continuum model for scintillation in inorganic crystals was obtained and studied into [1]-[3].

Scintillation is an example of Radioluminescence: however there are materials which may exhibit Electroluminescence (photon emission when acted by an electric field) or Mechanoluminescence (photon emission by elastic deformation, fracture or scratch) [4]-[7]. These phenomena are cross-correlated and since they modify the photon production we need to understand the role of the various causes of photon production.

As we did for scintillation in [1] we obtain a continuum with microstructure model for Mechanoluminescence, which allows to understand from a phenomenological point of view the relation between mechanical stress and scintillation efficiency, as it was done experimentally *e.g.* in [6].

References

[1] *Daví, F., "A continuum theory of scintillation in inorganic scintillating crystals", European Physics Journal B, Volume **92**, 1, 16, (2019)*

[2] *Daví, F., "Existence, decay time and light yield for a reaction diffusion-drift equation in the continuum physics of scintillators' in Proceedings of the Conference on Harnack's inequalities and nonlinear operators, Cortona, Italy, June 19th-23th, 2017. INDAM Conference Proceedings, Springer (2019)*

[3] *Daví, F., "Decay time estimates by a Continuum model for Inorganic Scintillators", Crystals, **9**(1), 4, (2019)*

[4] *Bünzli, J.-C. G., W. Ka-Leung, "Lanthanide mechanoluminescence", Journal of Rare Earths **36**, 1–41, (2018)*

[5] *Chandra, B.P., "Acoustic and photon emissions during mechanical deformation of coloured alkali halide crystals", J. Phys. D: Appl. Phys., **1**(7), 117–123, (1984)*

[6] *Reynolds, G.T., Austin, R.H., "Mechanoluminescence of plastic scintillation counters", Journal of Luminescence **92**, 79–82, (2001)*

[7] *Tantot, A., Santucci, S., Ramos, O., Deschanel, S., Verdier, M.-A., Mony, E., Wei, Y., Ciliberto, S., Vanel, L., and Di Stefano, P. C. F. , "Sound and Light from Fractures in Scintillators", PHYSICAL REVIEW LETTERS (PRL) **111**, 154301 (2013)*

[8] *Gayshana, V. , Boyarintsev, A., Gektin, A. , Zosim. D., "Mechanical deformation effect on CsI(Tl) scintillators efficiency", Nuclear Instruments and Methods in Physics Research, A**505** 97–100, (2003)*

A potential for strain gradient plasticity simulations free from unexpected interruptions of plastic flow under non-proportional loading

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Keywords: Higher-order strain gradient plasticity, cyclic plasticity, non-proportional loading

Higher-order (HO) strain gradient plasticity (SGP) theories allow for modelling size effects in small-scale metal plasticity, with focus on the capability to predict the increased hardening and yield stress (strengthening) due to plastic strain gradients [1]. These SGP theories employ HO boundary conditions to impose constraints on plastic flow due to dislocations blockage. Since Fleck et al. [2], it is known that "non-incremental" SGP theories may suffer an "elastic gap" due to their specific prescription of the HO dissipation. The elastic gap is an unexpected purely elastic incremental response occurring when suddenly changing loading path, including variation in the HO boundary conditions [3, 4]. It is known that dissipative HO stresses lead to strengthening as observed on experiments. Regarding energetic HO stresses, strengthening is predicted only by resorting to a less-than-quadratic defect energy [4]; however, in this case, SGP predicts anomalous cyclic behavior with inflection points where strain gradients are small [4, 5]. In this work we first show that in cyclic plasticity an elastic gap may occur also without HO dissipation if a less-than-quadratic defect energy is employed. Mainly, we propose a mixed energetic/dissipative plastic HO potential to predict both strenghtening and a reliable cyclic response free from elastic gaps. The features of the new formulation, that can be employed in any HO SGP theory, are demonstrated by referring to Gurtin 2004 theory [6, 4, 7], which is based on the use of Nye's dislocation density tensor as primal HO kinematic variable.

References

[1] *Fleck, N.A. and Hutchinson, J.W., Strain gradient plasticity, Adv Appl Mech,* **33**, *295-361 (1997).*

[2] *Fleck, N.A., Hutchinson, J.W., and Willis, J.R., Strain gradient plasticity under non-proportional loading, Proc R Soc A,* **470**, *20140267 (2014).*

[3] *Willis, J.R., Some forms and properties of models of strain-gradient plasticity, J Mech Phys Solids,* **123**, *348-356 (2019).*

[4] *Panteghini, A. and Bardella, L., Modelling the torsion of thin metal wires by distortion gradient plasticity, J Mech Phys Solids,* **78**, *467-492 (2015).*

[5] *Al-Naaman, S.A., Nielsen, K.L. and Niordson, C.F., An investigation of back stress formulations under cyclic loading, Mech Mater,* **130**, *76-87 (2019).*

[6] *Gurtin, M.E., A gradient theory of small-deformation isotropic plasticity that accounts for the Burgers vector and for dissipation due to plastic spin, J Mech Phys Solids,* **52**, *2545-2568 (2004).*

[7] *Bardella, L. and Panteghini, A., On the role of higher-order conditions in distortion gradient plasticity, J Mech Phys Solids,* **118**, *293-321 (2018).*

Micropolar approach to electromagnetic coupling in liquid crystals

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Keywords: Liquid crystals; micromorphic continua; electromagneto-elastic coupling

Classical continuum theories of nematic liquid crystals are based on a physical model which accounts for molecular orientation by introducing an internal degree of freedom, the ”director”. The mathematical approach of the mechanical model relies on a constitutive dependence on gradients of the director variable [1, 2]. An alternative approach has been introduced on the basis of the micromorphic continuum theory [3]. In this case the orientational molecular properties are modeled by the microstructural deformation. The extension to electro-magneto-elastic coupling has been recently reformulated in order to obtain explicit expressions for polarization and magnetization in terms of the microstrain tensor, avoiding to introduce generic constitutive equations for these quantities [4].

In the present work we apply this micropolar approach to investigate electromagnetic properties of nematic liquid crystals. The general model is outlined accounting for Maxwell equations and deriving an explicit form of the magnetic induction. A relevant phenomenon, concerning layered nematic structures, is the ”Freedericksz transition”. It implies the existence of a not null critical value of magnetic or electric field beyond which the deformed configuration arises breaking the original uniform molecular orientation at equilibrium. In the classical ”director” approaches, the critical fields are related to dielectric and magnetic parameters which are independent on molecular deformation and inertial properties. Differently, the present micropolar model accounts for microdeformation and microinertia parameters in representing dielectric and magnetic effects via polarization and magnetization [5].

In particular we consider here a homeotropic structure of a liquid crystal layer and analyze the effects of an applied electric potential V on the threshold value H_c of the magnetic field for a Freedericksz transition. The analysis of the corresponding boundary value problem allows to show that, in addition to the dependence on elastic parameters and electric quadrupole, H_c turns out to be enhanced by the absolute value of V. Moreover, it is shown that the trivial solution of null molecular deformation is admitted together with a not uniform incremental magnetic field for $V \neq 0$. Finally, a numerical solution of the problem shows that an hysteresis behavior occurs just behind the threshold field, which is compatible with a first order transition, experimentally observed in similar problems.

References

[1] *Leslie, F.M., Some constitutive equations for liquid crystals, Arch. Rat. Mech. Anal.* **28**, *265-283 (1968)*

[2] *Ericksen, J.L., Equilibrium theory of liquid crystals, Advances in Liquid Crystals* **2**, *233-298 (1976)*

[3] *Eringen, A.C., Microcontinuum Field Theories II - Fluent Media, Springer-Verlag, New York (2001)*

[4] *Romeo, M., Micromorphic continuum model for electromagnetoelastic solids, Z.A.M.P.,* **62**, *513-527 (2011)*

[5] *Romeo, M., Micropolar nematic model for polarized liquid crystals, Continuum Mech. Thermodyn,* **30**, *207-219 (2018)*

One-way and two-way shape memory polymers: phenomenological model and comparison with experimental data

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Keywords: shape memory polymers, constitutive modeling, material characterization.

Thermally-triggered shape memory polymers (SMPs) attract significant attention thanks to advantageous properties such as low cost, low weight, high deformability, biocompatibility, and, overall, to their thermo-responsive response [1]. The latter, known as "one-way shape memory effect", describes the capability of the polymer, deformed in a temporary configuration, in recovering the original permanent shape when exposed to a thermal stimulus. Such a response is however non-reversible, since an external mechanical force is required to set again the temporary shape, after any shape memory cycle. By contrast, certain classes of thermally-triggered SMPs possess also the so-called "two-way shape memory effect" that may be described as the capability of a reversible shape-effect between two different configurations under a cooling-heating cycle. Despite the importance of such classes of SMPs for the development of innovative applications as actuators, artificial muscles, and self-locomotion robotics, few modeling papers are available from the literature.

The present work proposes a new constitutive model to describe the one-way and two-way shape memory effect in semi-crystalline networks. The phenomenological model, formulated in a finite strain framework, is based on parameters with a clear and direct physical interpretation and measurability and is simple to implement. Model predictions are validated on experiments on crosslinked poly(ε-caprolactone) materials synthesized in [2]. The obtained results allow to discuss the effect of crosslink density, heating/cooling rate, and thermal strains on material shape memory response. Model extensions to other shape memory behaviors will be also discussed.

References

[1] *Leng, J., Lan, Y., Liu, X., Du, S., "Shape-memory polymers and their composites: Stimulus methods and applications," Journal of Engineering Materials and Technology, Trans. ASME,* **56**, *1077-1135 (2011).*

[2] *Pandini, S., Baldi, F., Paderni, K., Messori, M., Toselli, M., Pilati, F., Gianoncelli, A., Brisotto, M., Bontempi, E., Riccò, T., "One-way and two-way shape memory behaviour of semi-crystalline networks based on sol-gel crosslinked poly(ε-caprolactone)," Polymer,* **54**, *4253-4265 (2013).*

Different spider silk junctions as a tool to improve the structure efficiency of spider's orb web.

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Keywords: Spider Webs, Spider Silk, Multi-functionality.

Spider webs are fascinating structures to many scientists. They have been under study during the last decades because of their role in inspiring smart technologies, owing to their remarkable mechanical properties. These are, for example, the capability to absorb a huge amount of kinetic energy, to bear high wind loads and to be robust [1]. The mechanisms that stay under these features must be understood in order to design structures and materials with superior mechanical properties. In this work, we present various aspects that contribute to the mechanical features of the spider's orb web. In particular, starting from the mechanical properties of a single silk thread, we present the mechanical properties of the spider webs anchorages to external surfaces [2] and the role of different junctions among threads, which we show to be composed of different types of silk [3][4]. The behaviour of these structures under load is here presented using both the theory of the multiple peeling [5] and experimental data. Thus, the mechanical behaviour and multifunctionality of various structures within the webs (junctions, anchorages, glue droplets and single thread) are presented highlighting their role in the increase of the performances of the entire web. This bottom-up process in building natural structures with a single starting material could be helpful in design complex artificial structures with enhanced mechanical performances.

References
[1] Cranford, S.W., Tarakanova, A., Pugno, N.M. and Buehler, M. J., Nonlinear material behaviour of spider silk yields robust webs, Nature, 482, 72-76 (2012)
[2] Pugno, N.M., Cranford, S.W., Buehler, M.J., Synergetic Material and Structure Optimization Yields Robust Spider Web Anchorages, small, 9, 2747-2756(2013)
[3] Meyer, A., Pugno, N.M.,Cranford, S.W., Compliant threads maximize spider silk connection strength and toughness, J. R. Soc. Interface, 11, 20140561 (2013)
[4] Pugno, N.M., The Egg of Columbus for Making the Worlds Toughest Fibres, PLOS ONE, 9, 185-193, e93079 (2014)
[5] Pugno, N.M., The theory of multiple peeling, Int J Fract, 171, 185-193 (2011)

Effective constitutive behavior of heterogeneous materials comprising bimodular phases

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Keywords: bimodular constitutive response, composite materials, intraphase non-linearity

Materials exhibiting different constitutive response in tension and in compression are called bimodular and, in the elastic regime, they can be modelled as piecewise linear, resulting in a subclass of the conewise linear elastic materials [1]. Many materials employed for engineering applications behave as bimodular [2] (e.g., concrete, biological gels, graphite, NiTi SMAs, fiber-reinforced composites, microcracked materials). Bimodularity effects are generally faced by addressing the macroscopic bimodular constitutive response of materials comprising constituents that locally exhibit a linear elastic behavior. This is the case of layered materials such as fiber-reinforced composites [3], whose homogenized response is bimodular due to interphase non-linearity sources (e.g., unilateral contact, microscale instabilities, microvoids asymmetric response). On the other hand, bimodularity features could be exploited for designing novel microstructured materials, by conceiving composite materials comprising bimodular phases. Nonetheless, how point-wise bimodularity impacts on the overall material response has to be retained a challenging open task. In this framework, computational methods can be useful to understand the effect of intraphase constitutive non-linearities induced by the tension/compression transition of local material stiffness. In this study, the effective behavior of heterogeneous materials comprising bimodular phases is investigated via a computational homogenization approach. Proposed numerical results, obtained via an iterative finite-element scheme, highlight that the local bimodularity leads to a macroscopic constitutive response more complex than that of local phases. By referring to different microstructures and by considering a broad range of triaxial strain-based conditions, coupling effects between hydrostatic and deviatoric states are highlighted, revealing an unconventional macroscale material response, opening to possible smart applications. Finally, proposed results furnish useful indications towards the definition of effective strategies for analytical nonlinear homogenization schemes.

References

[1] *Curnier, A., et al., Conewise linear elastic materials. J Elasticity,* **37**, *1–38 (1994).*
[2] *Jones, R.M.. Stress-strain relations for materials with different moduli in tension and compression. AIAA Journal,* **15(1)**, *16–23 (1977).*
[3] *Bert, C.W., Models for fibrous composites with different properties in tension and compression. J Eng Mat Technol,* **99(4)**, *344–349 (1977).*

Identification of non-local continua for beam-lattice materials

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Keywords: beam-lattices, non-local elasticity, frequency band structure.

It is well known that the identification of non-local continua for beam-lattices may present some drawbacks mainly in the energetic consistency of the equivalent continuum model (see for reference [1-3]). To overcome these problems enhanced continualization technique has been proposed providing good approximations of both the boundary layer effects and the frequency band structure of 1D beam lattices with lumped mass [4]. In this framework such approach is developed to 2D/3D lattices through a proper extension of the non-local pseudo differential down-scaling law. In this way the difference equation of motion of the Lagrangian system is properly transformed in a pseudo-differential equation equivalent to differential equation of infinite order. Moreover, it will be shown that the equivalent continuum governed by this field equation exhibits a frequency band structure overlapping with that of the Lagrangian model. Finally, some examples will be presented in which the capabilities of the identified continuum in describing both the static response and the frequency band structure together with the polarization vectors are emphasized.

References

[1] *Merkel A., Tournat V., Gusev V., "Experimental Evidence of Rotational Elastic Waves in Granular Phononic Crystals", Physical Review Letters,* ***107****, 225502 (2011).*

[2] *Bacigalupo A., Gambarotta L., "Wave propagation in non-centrosymmetric beam-lattices with lumped masses: discrete and micropolar modelling", International Journal of Solids and Structures,* ***118-119****, 128-145 (2017).*

[3] *Bacigalupo A., Gambarotta L., "Dispersive wave propagation in two-dimensional rigid periodic blocky materials with elastic interfaces", Journal of the Mechanics and Physics of Solids,* ***102****, 165-186 (2017).*

[4] *Bacigalupo A., Gambarotta L., "Generalized micropolar continualization of 1D beam lattices", International Journal of Mechanical Sciences, in press (2019).*

A dynamic homogenization approach for modelling hybrid piezoelectric nanogenerators

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Keywords: Energy scavenging; ZnO nanorods; Multi-field homogenization

Energy scavenging, from green and sustainable energy resources, is increasingly attracting the attention of researchers and industries in several engineering fields. The main aim is capturing the energy, naturally available in the environment, and converting it into electrical energy. Emerging applications, such as in flexible/strechable micro and nano electronics, biomedical monitoring, wearable technology, micro and nano robotics and extreme technology, require devices of smaller and smaller size and high performances.

In this framework, we investigate hybrid piezoelectric nanogenerators, made up with Zinc oxyde nanorods [1], embedded in a polymeric matrix, and grown on a flexible polymeric support. The ZnO nanorods are arranged in clusters, forming nearly regular distributions, so that periodic topologies can be realistically assumed. It is well established that, in the context of multi-field problems involving complex composite topologies, a very valuable tool is resorting to generalized homogenization approaches [2-4]. Thus, we propose a dynamic multi-field asymptotic homogenization approach, for the static and dynamic characterization of such microstructured periodic devices, [5]. A set of applications is proposed considering nanogenerators based on three different working principles. Both extension and bending nanogenerators are, indeed, analysed, considering either extension along the nanorods axis, or orthogonally to it. The study of the wave propagation is, also, exploited to comprehend the main features of such piezoelectric devices in the dynamic regime.

References

[1] *Wang, Z. L., Song, J., "Piezoelectric nanogenerators based on zinc oxide nanowire arrays". Science,* **312***(5771), 242–246 (2006).*

[2] *Francfort, G. A., "Homogenization and linear thermoelasticity". SIAM Journal on Mathematical Analysis,* **14***(4), 696-708 (1983)*

[3] *Abdessamad, Z., Kostin, I., Panasenko, G., Smyshlyaev, V. P., "Homogenization of thermoviscoelastic KelvinVoigt model". Comptes Rendus Mcanique,* **335***(8), 423-429 (2007).*

[4] *Fantoni, F. Bacigalupo, A., Paggi, M., "Multi-field asymptotic homogenization of thermopiezoelectric materials with periodic microstructure". International Journal of Solids and Structures,* **120***, 31-56 (2017).*

[5] *De Bellis M. L., Bacigalupo A., Zavarise G., "Characterization of hybrid piezoelectric nanogenerators through dynamic asymptotic homogenization", submitted, http://arxiv.org/abs/1902.04010, 2019*

Quasicrystalline multilayered metamaterials: negative refraction and self-similar Bloch-Floquet spectrum

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Keywords: Quasicrystalline laminates, negative refraction, Kohmoto's invariant

The problem of an antiplane wave obliquely incident at the interface between an elastic substrate and a laminate is investigated. The considered multilayered media possess a quasicrystalline structure, generated according to the Fibonacci substitution rules [1]. The substrate-laminate system is studied combining the transfer matrix method to the normal mode decomposition technique [2]. The diffraction angles associated with the transmitted modes are estimated by means of the space averaging procedure of the Poynting vector [3]. It is shown that, with respect to a periodic classical bilayer [4], on the one hand, beyond a certain frequency threshold, high order Fibonacci laminates can provide negative refraction for a wider range of angles of incidence, on the other, they allow negative wave refraction at lower frequencies. The performed numerical results illustrate that the Bloch-Floquet spectrum corresponding to this class of laminates has a self-similar layout linked to the specialisation of the Kohmoto's invariant, a function of the frequency that was recently studied by the authors for periodic one-dimensional quasicrystalline-generated waveguides [5]. This function is able to explain two types of scaling occurring in dispersion diagrams. The obtained results represent an important advancement towards the realisation of multilayered quasicrystalline metamaterials.

References

[1] *Gei, M., Waves in quasiperiodic structures: stop/pass band distribution and prestress effects, Int. J. Solids Struct.,* **47***, 3067-3075, (2010).*

[2] *Morini, L., Eyzat, Y., Gei, M., Negative refraction in quasicrystalline multilayered metamaterials, J. Mech. Phys. Solids,* **124***, 282-298, (2019).*

[3] *Willis, J.R., Negative refraction in a laminate, J. Mech. Phys. Solids,* **97***, 10-18, (2016).*

[4] *Srivastava, A., Metamaterial properties of periodic laminates, J. Mech. Phys. Solids,* **96***, 252-263, (2016).*

[5] *Morini, A., Gei, M., Waves in one-dimensional quasicrystalline structures: dynamical trace mapping, scaling and self-similarity of the spectrum, J. Mech. Phys. Solids,* **119***, 83-103, (2018).*

A semi-analytical homogenisation procedure for the study of actuation in hierarchical dielectric laminated composites at finite strains

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Keywords: Dielectric laminated composites; electromechanical actuation; homogenisation.

We focus on the layout optimisation of hierarchical laminated composites that can be profitably employed to enhance the actuation performance of electrostatically-activated soft dielectric transducers [1]. In particular, we study the behaviour of a rank-two laminate constituted by ideal dielectric phases obeying nonlinear elasticity. This actuation response is evaluated by coupling two rank-one problems: the first one is concerned with the two-phase microstructure constituting the so-called *core*; the second one, at the mesoscopic scale, involves the core and a third homogeneous phase. Concerning the microscale rank-one problem, we adopt for the core the analytical form of the effective free energy density obtained by Spinelli and Lopez-Pamies [2] for isochoric neo-Hookean elasticity. Hence, we solve the whole problem by imposing the macroscopic boundary prescriptions and the electro-mechanical continuity conditions at the laminate interfaces.

We analytically simplify at lowest terms the resulting set of nonlinear equations, thus obtaining a partly uncoupled system, which, as a main novelty with respect to the literature, is unaffected by the local Lagrangian multipliers ensuing from the assumed isochoric deformation. We demonstrate the computational efficiency of our procedure by studying two different composites previously investigated in [1, 3]. Moreover, on the basis of sensitivity analyses with respect to the micro- and meso-structural parameters, we provide new layouts able to optimise the actuation stretch.

Finally, we study a rank-one composite in which we remove the constraint of isochoric deformation in the softer phase, and consider contrast up to the limit of a void phase. We highlight the non-trivial effects of this further degree of freedom on the effective response, both by discussing the homogenisation procedure and by determining the layouts in which it plays a relevant role. For these layouts, in the case of a void phase, we demonstrate the large inaccuracy of the results obtained by taking the limit of vanishing neo-Hookean elastic modulus in the softer phase for the fully incompressible rank-one laminate.

References

[1] *Tian, L., Tevet–Deree, L., deBotton, G. and Bhattacharya, K., Dielectric elastomer composites, J. Mech. Phys. Solids,* **60***, 181-198 (2012).*

[2] *Spinelli, S.A. and Lopez-Pamies, O., Some simple explicit results for the elastic dielectric properties and stability of layered composites, Int. J. Eng. Sci.,* **88***, 15-28 (2015).*

[3] *Gei, M. and Mutasa, K.C.K., Optimisation of hierarchical dielectric elastomer laminated composites, Int. J. Nonlinear Mech.,* **106***, 266-273 (2018).*

Locally Resonant Materials for energy harvesting at small scale

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Keywords: phononic crystals, dispersion spectrum, homogenization

Locally Resonant Materials (LRMs) have generated much interest in the recent years thanks to their peculiar properties with respect to wave propagation. They gain their unusual dynamic behavior from the design of low dimensional heterogeneities which allows for the presence of the so-called band gaps, i.e. finite frequency regions where waves, for one or more wave vector directions, are evanescent and thus cannot propagate through the LRM.
By considering the similarities with the quantum mechanics potential step, Yang et al. [1] have demonstrated that inside a band gap the phenomenon of tunneling occurs, i.e. the group velocity of a pulse traveling through a LRM increases linearly with its thickness. Furthermore, in [2], resonant tunneling through two barriers divided by a cavity and constituted by a pair of identical sonic crystals is also shown, confirming the analogy with the quantum mechanics field.
In this contribution, the same idea is further developed by considering mechanical waves propagating through two or more LRM barriers, focusing the attention on what happens inside the material placed between each barriers and studying the possibility of therein localizing the strain energy generated by propagating waves.
Dispersion analyses are usually numerically carried out by imposing Bloch-Floquet's periodic conditions on the unit cell [3-4]. Nevertheless, for frequencies such that the wavelength would be much larger than the lattice constant, one can predict the band gap formation by considering an effective equivalent medium, as e.g. in [5]. Both the cited methods are thus used for characterizing the dynamic behavior of the LRMs considered.
The resonant tunneling of mechanical waves could be of interest for the design of vibration energy harvesting generators that could localize in one or more points mechanical waves coming from different sources, combining and enhancing the energy carried by them.

References

[1] *Yang, S., Page, J.H., Liu, Z., Cowan, M.L., Chan, C.T. and Sheng, P., "Ultrasound Tunneling through 3D Phononic Crystals" Physical Review Letters,* **88***(10), (2002).*

[2] *Van Der Biest, F., Sukhovich, A., Tourin, A., Page, J.H., Van Tiggelen, B.A., Liu, Z. and Fink, M., "Resonant tunneling of acoustic waves through a double barrier consisting of two phononic crystals" Europhysics Letter,* **71***(1), pp. 63-69 (2005).*

[3] *Comi, C. and Driemeier, L., "Wave propagation in cellular locally resonant metamaterials" Latin American Journal of Solids and Structures,* **15***(4), pp. 1-15 (2018).*

[4] *Moscatelli, M., Ardito, R., Driemeier, L., Comi, C., "On 2D and 3D band-gap structure in cellular locally resonant materials" in Proceedings of GIMC XXII - GMA IX, Ferrara, Italy, 13-14 September 2018, page 11, (2018).*

[5] *Comi, C., Marigo, J.J., "Homogenization approach and Bloch-Floquet theory for band-gap prediction in 2D locally resonant metamaterials", Preprint (2019).*

Mechanics of chemo-mechanical stimuli responsive soft polymers

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Keywords: Polymers, Responsive Materials, Mechanophores.

Responsive materials, often obtained by designing the molecular structure of polymers or gels, respond through detectable physical changes to esternal stimuli such as chemical (pH), temperature variation, light, mechanical stress, etc. [1].
In our study we propose a micromechanics-based model, rooted in the statistical approach to the network conformation of polymeric materials, to predict the mechanical response of polymers with embedded mechanophores molecules. The knowledge of the evolution of the chains conformation described through the distribution function $\varphi(\boldsymbol{r})$ ($\boldsymbol{r}$ being the end-to-end polymer chain's vector) when external stimuli (chemical and/or mechanical) act on the material, allows to determine the deformation and stress state of the material. In general, the energy of the system is obtainable by adding up the contributions of the active chains (i.e. connected chains), as [2]

$$\Psi = \int_{\Omega} \varphi(\boldsymbol{r})\psi(\boldsymbol{r}) \ \ d\Omega = \langle \varphi(\boldsymbol{r})\psi(\boldsymbol{r}) \rangle \tag{1}$$

where $\psi(\boldsymbol{r})$ is the energy per single chain and $\langle \blacksquare \rangle$ indicates the integration over the chains configuration space. When a volume fraction ϱ of active molecules (mechanophores), exist in the network, once activated their effect can be detected, because of some chemical of physical changes occurring in the material. The case of physical effect, such as when a conformation change occurs, is particularly interesting because it induces a deformation of the material at the macroscale (Fig. 1). In the general case of mechanophores sensible to both chemical and mechanical stimuli, the energy per unit volume becomes:

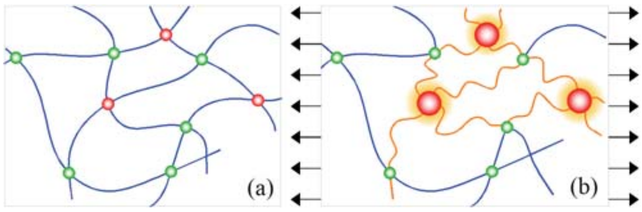

Fig. 1. Effect of mechanophore activation on the network's chains

$$\Psi = \langle \varphi(\boldsymbol{r})[(1-\varrho)\psi(\boldsymbol{r}) - h(\boldsymbol{F}, C_s) \ \ \varrho \ \ \psi_{sw}] \rangle + (1-\varrho)\Psi_{mix} \tag{2}$$

where h indicates the fraction of activated mechanophores, ψ_{sw} is the mechanophores' activation energy and Ψ_{mix} is the energy of mixing per unit volume when a fluid (carrying the pH change) enters into the polymer, while C_s is its concentration [3].
The micromechnical model, formulated within the finite deformation framework, has been implemented in a FE code enabling to simulate smart responsive materials or to design the material's microstructure according to the desired functionality.

References

[1] *Wei, M., Gao, Y., Li, X., Serpe, M. J.. "Stimuli-responsive polymers and their applications". Polymer Chem.,* ***8****(1), 127–143 (2017).*
[2] *Vernerey, F.J., Long, R., Brighenti, R. "A Statistically-Based Continuum Theory for Polymers with Transient Networks". J. Mech. Phys. Sol.,* ***107*** *(2017), 1–20 (2017).*
[3] *Brighenti, R., Artoni, F., Cosma, M. P. "Mechanics of materials with embedded unstable molecules". Int. J. Sol. Struct.,* ***162****, 21–35 (2019).*

Shear wave propagation in transformation-based periodically perforated systems

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Keywords: wave propagation, cloaking, Helmholtz equation

The problem of the propagation of out of plane shear waves through doubly periodic perforated regions is considered and a recursive geometric transformation is applied. The application of a radial geometric transformation in each unit cell maps the initial isotropic annulus domains into annulus domains, which have radially anisotropic and inhomogeneous elastic material properties, namely mass density and stiffness tensor. The model generalizes the techniques used for cylindrical cloaking devices to periodic or semi periodic systems [1]-[2].

Dispersion diagrams and transmission properties for wave propagating through a transformed interface have been analyzed using the finite element method in COMSOL Multiphysics and semi-analytical multiple expansion method [3].

The invariances of the governing Helmholtz equation and the eigenfrequencies are demonstrated, while folding transformation is shown to lead to an anomalous resoncance effect. Geometric transformation can be used to tune dispersion and filtering properties for both normal and oblique incidence, including negative refraction and full transmission or reflection.

References

[1] *Brun, M., Guenneau, S. and Movchan, A. B., "Achieving control of in-plane elastic waves", Applied Physics Lettters,* **94***, 061903, (2009)*

[2] *Norris, A. N. and Shuvalov, A. L., "Elastic cloaking theory", Wave Motion,* **48***, 525-538, (2011)*

[3] *Poulton, C. G., McPhedran R. C., Movchan, N. V. and Movchan A. B., "Convergence properties and flat bands in platonic crystal band structures using the multipole formulation", Waves in Random and Complex Media,* **20***, 702-716, (2010)*

Analytical bounds for the pull-in voltage of carbon nanotubes

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Keywords: Pull-in voltage, Nanocantilever, van der Waals interactions.

Carbon nanotubes (CNTs) display a number of attractive electronic and mechanical properties that are currently exploited in a wide variety of industrial applications, such as sensors, nanoactuators, memory devices, switches, high frequncy nanoresonators and nanotweezers. Due to their tiny size they indeed display ultra-low mass and very high resonance frequency as well as the capability to carry huge electrical currents and to sustain high current densities. These properties, in conjunction with the significant progress recently made in the fabrication of carbon nanostructures, allow CNTs to become essential components in the fabrication of enhanced nano-electromechanical systems (NEMS)

An accurate determination of the stable actuating range and the pull-in instability threshold is a crucial issues for designing reliable CNT based NEMS. Despite the amount of numerical or approximated investigations, analytical models and closed form expressions for pull-in instability analysis of CNT still appears to be limited. An analytical methodology for assessing accurate lower and upper bounds to the pull-in parameters of an electrostatically actuated micro- or nanocantilever has been provided in two previous works [1, 2], taking into consideration the contributions of flexible support and compressive axial load.

In the present work, attention is paid to investigate the pull-in phenomenon in CNT with circular cross-section, by considering the proper expressions of the electrostatic and van der Waals forces per unit length acting on a CNT, as well as the significant reduction of the pull-in voltage induced by the charge concentration at the free end [3]. Two-side accurate analytical estimates of the pull-in parameters of a carbon nanotube switch clamped at one end under electrostatic actuation are provided by considering the effects of van der Waals interactions and charge concentration at the free end. The problem is governed by a fourth-order nonlinear boundary value problem, according to the Eulero-Bernoulli beam theory. Two-side estimates on the deflection are first derived, then very accurate lower and upper bounds to the pull-in voltage and deflection are obtained as functions of the geometrical and material parameters. The analytical predictions are then found to agree remarkably well with the numerical results provided by the shooting method.

References

[1] Radi E., Bianchi G., di Ruvo L., "Upper and lower bounds for the pull-in parameters of a micro- or nanocantilever on a flexible support". International Journal of Non-Linear Mechanics, ***92****, 176-186 (2017).*

[2] Radi E., Bianchi G., di Ruvo L., Analytical bounds for the electromechanical buckling of a compressed nanocantilever. Applied Mathematical Modelling, ***59****, 571-572 (2018).*

[3] Ke C.H., "Electromechanical properties and applications of Carbon nanotube nano-cantilevers" in Voiculescu I., Zaghloul M. (Eds.) Nanocantilever beams, modeling, fabrication and applications, pp. 195-220 (2016).

The coupling of bioelectrical and mechanical phenomena

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Keywords: Bioelectricity, electrochemomechanics, finite volume method

In [1], Pietak and Levin have investigated the role of bioelectricity in pattern regulation by developing a finite volume-based multiphysics simulator referred to as the BioElectric Tissue Simulation Engine (BETSE). In particular, in [1], the dynamics of bioelectricity are described in terms of the spatiotemporal evolution of the electric potential, and the relevant ion concentrations, over a network of cells interacting with each other and with their environment through their plasma membrane.

In the present contribution, the BETSE platform is augmented to account for the mechanical interactions between cells, which arise from bioelectrical ion fluxes. On the basis of the electrochemomechanical theories developed in the last decade (see, e.g., [2, 3, 4, 5], and references therein), the electrostatic forces and osmotic pressure, respectively generated by voltage and concentration gradients across the cell membranes, are employed to determine the mechanical stress through equilibrium. Then, the deformation field of the cell cluster is obtained by assuming isotropic elasticity. The whole electrochemomechanical process is in principle coupled, as the deformation may trigger the opening of mechano-sensitive ion channels, ultimately leading to a reshaping of the spatial ion fluxes and membrane potential patterns within the cell network.

References

[1] *Pietak, A. and Levin, M., "Exploring instructive physiological signaling with the bioelectric tissue simulation engine", Frontiers in Bioengineering and Biotechnology, 4:55 (2016).*

[2] *Hong, W., Zhao, X., and Suo, Z., "Large deformation and electrochemistry of polyelectrolyte gels", Journal of the Mechanics and Physics of Solids, 58.4:558-577 (2010).*

[3] *Cha, Y. and Porfiri, M., "Mechanics and electrochemistry of ionic polymer metal composites", Journal of the Mechanics and Physics of Solids, 71:156-178 (2014).*

[4] *Dorfmann, L. and Ogden, R. W., "Nonlinear electroelasticity: material properties, continuum theory and applications", Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 473.2204: 20170311 (2017).*

[5] *Leronni, A. and Bardella, L., "Influence of shear on sensing of ionic polymer metal composites", European Journal of Mechanics - A/Solids, in press.*

Machine learning techniques for the design of smart metamaterials

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Keywords: Acoustic metamaterials, surrogate optimization, machine learning.

Recently, an increasing research effort has been dedicated to analyse transmission and dispersion properties of periodic acoustic metamaterials with local resonators [1]. In this framework, particular attention has been focused on optimizing the amplitude, center frequency of selected stop, and pass bands in the Floquet-Bloch spectrum [2]. Potential novel applications of this research field are in the design of smart tunable mechanical filters and directional waveguides. The present study deals with the maximization of low-frequency band gaps by defining a multi-purpose objective function. Specifically the feasibility and effectiveness of Radial Basis Function networks and Quasi Monte Carlo methods for the interpolation of the objective functions are discussed, with reference to different typologies of beam lattice metamaterials. The discussion is technically motivated by the high computational effort often needed for an exact evaluation of the actual objective functions in parametric optimization problems, when using iterative solution algorithms. By replacing such functions with surrogate objective functions, well-performing suboptimal solutions can be obtained with a smaller computational effort [3,4]. Numerical results demonstrate the effective potential of the proposed approach. Directions of current research involving the additional use of machine learning techniques are presented.

References

[1] Bigoni D., Guenneau S., Movchan A.B., Brun M., "Elastic metamaterials with inertial locally resonant structures: application to lensing and localization," Physical Review B ***87****, article ID: 174303 (2013).*

[2] Bacigalupo A., Lepidi M., Gnecco G., Vadalà F., Gambarotta L., "Optimal design of the band structure for beam lattice metamaterials," Frontiers in Materials, ***6:2*** *(2019).*

[3] Bacigalupo A., Gnecco G., "Metamaterial filter design via surrogate optimization," Journal of Physics: Conference Series, ***1092****, article ID: 012043 (2018).*

[4] Lin C., Lee Y.H., Schuh J.K., Ewoldt R.H., Allison J.T., "Efficient optimal surface texture design using linearization," Advances in Structural and Multidisciplinary Optimization, Springer, pp. 632-647 (2017).

Finite bending of beams with anticlastic effect: analytical model, experimental test and FE modeling

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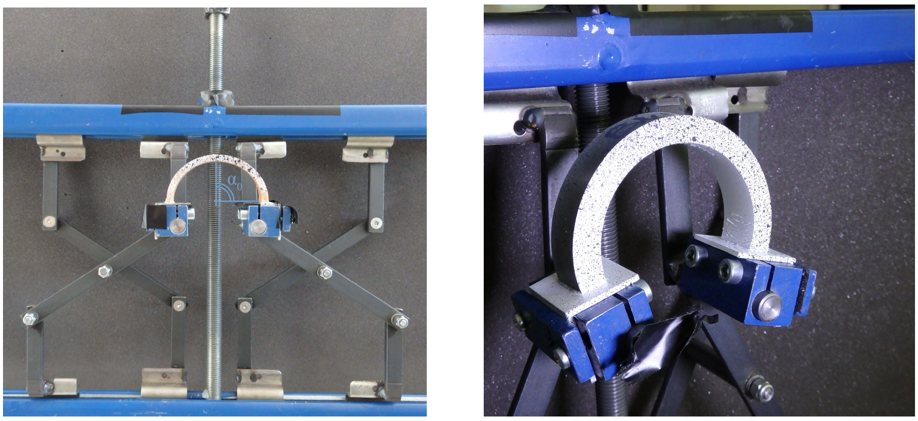
Keywords: Finite elasticity, anticlastic effect, experimental pure-bending;

A recent model of a bent solid in finite elasticity appears in Literature [1]. Making reference to a compressible Mooney-Rivlin material, such a model is able to describe properly the anticlastic effect arising in a bent beam made of a rubber-like material.

An experimental device is here presented (see Figure 1) aimed at simulating pure bending. In particular, the device lets the specimen free to exhibit its own elastic retaining force. Accordingly, the bent sample assumes the shape of an arc of circumference. With the aid of a DIC optical monitoring system, the experimental displacement field is acquired during the deformation process varying the angles α_0 imposed at the final beam cross sections.



(a) (b)

Figure 1: Experimental pure bending device.

For different rubber specimens, based on a theoretical model [2], both compression and tensile tests have been performed in order to properly characterize the constitutive parameters. Once the constitutive parameters have been found, by means of non-linear fitting experimental data, a FE model has been carried out in order to reproduce the experimental test. A good agreement is found among analytical, experimental and numerical results, thus showing the reliability of the proposed experimental device together with the consistency of the basic hypotheses of the theoretical model.

References

[1] *Lanzoni, L., Tarantino, A. M., "Finite anticlastic bending of hyperelastic solids and beams", Journal of Elasticity,* **131**, *137-170 (2018).*

[2] *Lanzoni, L., Tarantino, A.M., "Equilibrium configurations and stability of a damaged body under uniaxial traction", ZAMP,* **66** *, 171-190 (2015).*

Acoustic dispersion properties of beam lattice meta-materials with viscoelastic resonators

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Keywords: Periodic meta-materials, viscoelastic coupling, complex-valued band structure.

Beam lattice materials are characterized by a periodic microstructure realizing a geometrically regular pattern of elementary cells. In these materials, the acoustic dispersion properties governing the free propagation of bulk waves can be studied by formulating parametric lagrangian models in combination with the Floquet-Bloch theory. Among the others, a major theoretical and applied mechanical issue is the wave filtering in the low-frequency oscillation range [1,2]. Specifically, the propagation inhibition can be achieved by the parametric design of the cellular microstructure targeted at opening band gaps at specific center frequencies [3]. To this purpose, a general dynamic formulation for determining the dispersion properties of acoustic meta-materials based on a beam lattice framework equipped with local resonators is presented. The local resonances are realized by tuning periodic auxiliary masses, viscoelastically coupled with the beam lattice microstructure. The viscoelastic coupling is derived by a mechanical formulation based on the Boltzmann superposition integral, whose kernel is approximated by a Prony series [4,5]. Therefore, the free propagation of damped waves is governed by integral-differential equations of motion. Applying the bilateral Laplace transform, differential equations of motion with frequency-dependent coefficients are obtained. Then, the complex-valued branches characterizing the dispersion spectrum are parametrically analyzed. Moreover, the spectra corresponding to Taylor series approximations of the equation coefficients are investigated. The standard dynamic equations with linear viscous damping are recovered at the first-order approximation. Increasing approximation orders determine non-negligible spectral effects, including the occurrence of pure-damping spectral branches.

References

[1] Vadalà, F., Bacigalupo, A., Lepidi, M., Gambarotta, L., "Bloch wave filtering in tetrachiral materials via mechanical tuning," Composite Structures, ***201****, 340-351 (2018).*

[2] Bacigalupo, A., Gambarotta, L., Lepidi, M., Vadalà, F., "Acoustic waveguide filters made up of rigid stacked materials with elastic joints," Meccanica, in press (2019).

[3] Bacigalupo A., Lepidi M., Gnecco G., Vadalà F., Gambarotta L., "Optimal design of the band structure for beam lattice metamaterials," Frontiers in Materials, ***6:2*** *(2019).*

[4] Fabrizio, M., Morro, A. Mathematical problems in linear viscoelasticity. Siam (1992).

[5] Krushynska, A., Kouznetsova, V., Geers, M. "Visco-elastic effects on wave dispersion in three-phase acoustic metamaterials," J. of the Mechanics and Physics of Solids, ***96****, 29-47 (2016).*

Experimental analysis of topological pumping in phononic plates

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Keywords: Topological pumping; Phononic waveguide; Edge Waves.

Topological waveguides have gained a lot of attention within the research community, due to their ability to manipulate acoustic [1] and electromagnetic waves. Indeed, the combination of topological properties and phononic crystals has led to a new field of study know as *Topological Mechanics* [2]. In this context, elastic waveguides have been designed in analogy with quantum systems in order to guarantee defect immune and lossless energy transmission along desired wave propagation paths, even in presence of sharp bends [3].

Recent discoveries about topological modes in quasi-crystals opened new promising possibilities to manipulate elastic waves. That is, leveraging higher order topological properties in lower dimensional physical systems [4]. Boundary modes are observed in 1D quantum lattices, in which the modulation parameters are projected from a 2D space leveraging sinusoidal functions. The shape of these modes (left or right localized) is topological, since it can be parametrized by the modulation phase. When this parameter is varied along a temporal or spatial dimension, the localized modes migrate to the opposite boundary, therefore achieving a topological pump.

In this work, we investigate topological pumping in elastic structures. Specifically, modulated plates under simply supported conditions are considered as reference case-study, in which a sinusoidal elasticity profile is defined along one direction. This modulation is characterized by inherit topological properties which guarantee the formation of an edge mode. When the modulation phase is varied along the second spatial dimension, the topological mode migrates from the left-bottom to right-top corners, therefore achieving a pump for elastic waves. Theoretical results are extended to square wave thickness profiles and validated experimentally, proving robust energy transmission in a broadband range of frequencies.

The present study provide a relatively simple way to manipulate elastic waves, which can be particularly relevant for several applications involving mechanical vibrations, among which structural health monitoring and energy harvesting.

References

[1] *R. Fleury, A. B. Khanikaev, and A. Alu, "Floquet topological insulators for sound," Nature communications,* **7**, *11744 (2016).*

[2] *S. D. Huber, "Topological mechanics," Nature Physics,* **12**, *621 (2016).*

[3] *M. Miniaci, R. K. Pal, B. Morvan, and M. Ruzzene, "Experimental observation of topologically protected helical edge modes in patterned elastic plates," Phys. Rev. X,* **8**, *031074 (2018).*

[4] *Y. E. Kraus, Y. Lahini, Z. Ringel, M. Verbin, and O. Zilberberg, "Topological states and adiabatic pumping in quasicrystals," Physical review letters,* **109**, *106402 (2012).*

The effects of a large elastic mismatch on the decohesion of thin films from substrates

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Keywords: interfaces; mixed-mode fracture; soft materials substrates.

The decohesion of coatings, thin films, or layers used to protect or strengthen technological and structural components causes the loss of their functions. This failure mechanism occurs at very different scales in structural and technological components such as sandwich structures, thermal barrier coatings, electronic packages, soft electronics and protective polymer coatings applied to metals. In these applications new material combinations are used which have an exceptionally large mismatch of the elastic constants, e.g. epoxy/polymeric foam; Al/PMMA; Au/PDMS.

Analytical and semi-analytical 2D solutions have been derived for the energy release rate and mode-mixity phase angle of an edge-delamination crack between a thin layer and an infinitely deep substrate [1]. The thin layer is subjected to general edge loading: axial and shear forces and bending moment. The solutions are based on the derivations in [2-4].

The fracture parameters are presented in terms of elementary crack tip loads and are applicable to general edge loading. They apply to a wide range of material combinations, with a large mismatch of the elastic constants. Isotropic materials with Dundurs' parameters $-1 \le \alpha \le 1$ and $-0.4 \le \beta \le 0.4$ are considered in order to describe also stiff layers on soft substrates ($\alpha \approx 1$) and soft layers on stiff substrates ($\alpha \approx -1$), and to account for the mismatch in the volumetric stiffnesses of the layer and substrate ($\beta \ne 0$).The effects of crack tip shear on the fracture parameters is accounted for. For stiff layers over soft substrates, e.g. metal/elastomer or epoxy/polymeric foam, the effects of material compressibility ($\beta \ne 0$) are weak and the assumption of substrate incompressibility is accurate; for other combinations, including soft layers over stiff substrates, e.g. polymer/metal, the effects may be relevant and problem specific. The solutions are applicable to edge- and buckling-delamination of thin layers bonded to thick substrates, to mixed-mode fracture characterization test methods, and as benchmark cases.

References

[1] *Massabò, R., Ustinov, K., Barbieri L., Berggreen, C, Fracture mechanics solutions for interfacial cracks between compressible thin layers and substrates, Coatings, 2019, 9, 152; doi:10.3390/coatings9030152.*

[2] *Ustinov, K. On separation of a layer from the half-plane: Elastic fixation conditions for a plate equivalent to the layer. Mech. Solids 2015, 50, 62–80*

[3] *Li, S.;Wang, J.; Thouless, M.D. The effects of shear on delamination in layered materials. J. Mech. Phys. Solids 2004, 52, 193–214*

[4] *Barbieri, L.; Massabò, R.; Berggreen, C. The effects of shear and near tip deformations on interface fracture of symmetric sandwich beams. Eng. Fract. Mech. 2018, 201, 298–321.*

Numerical modelling of fracture in self-healing nacre-like materials

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Keywords: Fracture, Self-healing, Bio-inspired materials

In recent years, many efforts have been devoted to emulate in artificial materials features observed in biological materials with improved mechanical properties, e.g. an increase of maximum strength and fracture toughness. Two of the most studied cases are self-regeneration and nacre-like structures [1].

Self-healing is a characteristic property of biological materials to regenerate their micro traumas if subjected to stress and fatigue, allowing to delay the final failure and to increase fracture toughness. Similarly, natural nacre has a peculiar brick-and-mortar structure leading to an increase of its maximum strength and toughness. Both systems have been studied in natural and in artificial materials [2] to find new smart solutions. In order to verify the properties of each architecture and to identify the optimal design for a practical application, further theoretical studies and numerical models are required to understand the behaviour of these materials during fracture propagation and near failure.

We investigate in numerical simulations fracture phenomena in self-healing and nacre-like materials by implementing these properties into a Random Fuse Model and a Lattice Spring Model, which have been widely studied in the literature [3]. We highlight typical effects due to self-healing, showing that it can increase the maximum material strength but can also lead to a more catastrophic failure. We show how self-healing can be combined with an optimized nacre-like structure to obtain a synergetic improvement of fracture toughness and other global mechanical properties of the material.

References

*[1] B. Ji, H. Gao, "Mechanical properties of nanostructure of biological materials", J.Mech. Phys. Solids **52**, 1963 (2004)*
*[2] S.R. White, N.R. Sottos, P.H. Geubelle, J.S. Moore, M.R. Kessler, S.R. Sriram, E.N. Brown, S. Viswanathan, "Autonomic healing of polymer composites", Nature **409**, 794 (2001)*
*[3] M.J. Alava, P.K.V.V. Nukala, S. Zapperi, "Statistical models of fracture", Advances in Physics **55**, 349 (2006)*

Development of a Data Reduction Method for Composite Sandwich Face/Core Fracture Characterization under Mode III loadings

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Keywords: Debonding, Interface, Fracture Toughness

Sandwich structures are key-enablers for lightweight structural applications because of their superior stiffness/weight and strength/weight ratios compared with traditional metallic concepts. One of the most severe type of in-service damage in a composite sandwich structure is the lack of adhesion between the face sheets and core known as a "debond" [1]. Therefore, the fracture characterization of the face/core surface is fundamental to predict the remaining life of a damaged sandwich structure when all the three types of opening-crack modes are present at the debond front.

The aim of this work consists in developing a reliable Data Reduction Method for a novel test rig [2], which is inspired by the rig designed in [3] for unidirectional composites. The test rig is capable to carry out fracture characterization tests on pre-delaminated composite sandwich specimens subjected to external anti-plane shear loadings. The scope is to apply boundary conditions and design the specimen geometry in order to induce an anti-plane stress state as uniform as possible along the debond front. In this way, it is possible to measure a value for the interface fracture toughness under a nearly pure Mode III state.

Theoretical and numerical analyses of the specimen enable the understanding of how specimen geometrical parameters and loads introduction influence stresses and Energy Release Rate (ERR) distributions along the debond front.

The theoretical model considers the delaminated arms as short beams subjected to anti-plane shear loadings. A 3D finite element model accurately describes the local stress fields. The ERR is extracted from the numerical model using a displacement correlation technique showed in [1].

Numerical analyses show an intrinsic coupling between Mode II and Mode III stress fields in the region close to the lateral free-surfaces of the specimen. This mixed-mode state can be mitigated introducing longitudinal cuts to the specimen. Moreover, the data reduction method would only define the average value of the ERR distribution along the debond front.

References

[1] C. Berggreen, B. C. Simonsen, K. K. Borum. "Experimental and Numerical Study of Interface Crack Propagation in Foam-cored Sandwich Beams". Journal of Composite Material, ***Vol. 41****, No. 4/2007.*

[2] P. Sabbadin, C. Berggreen, B.N. Legarth, "Development of a Mode I/II/III Test Fixture for Composite Laminates and Sandwich Face/Core Fracture Characterization", in Proceedings of 12th International Conference on Sandwich Structures, Lausanne, 19 August 2018, pp. 35-37.

[3] B. D. Davidson, F. O. Sediles. "Mixed mode I-II-III delamination toughness determination via shear-torsion-bending test". Composites Part A-applied Science and Manufacturing - 2011, ***Vol 42(6)****, pp. 589-603.*

Computational Modeling of Architected Electrodes for High Performance Batteries

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Keywords: Lithium ion batteries computational modeling multiscale modelling

The aim of the present work is predicting the performance of batteries with complex architected electrodes, ultimately tailoring the response of innovative electro chemical cells.

The basic principle of Li-ion batteries lies in the electrochemical-potential-driven redox reaction that occurs at the boundary between storage material (typically active particles for porous electrodes) and electrolyte, which leads to the intercalation of lithium ions. The limiting factor of this process is not solely related to electrochemical affinities, but is influenced by architectural and mechanical features of the electrodes. Theoretical and computational modeling of these issues were reviewed in [1].

A multiscale compatible approach, which relies on the fundamental balance laws (mass, momentum and charge, using Maxwell's equations in quasi-static sense) and a rigorous thermodynamic settings, was proposed in [2]. In this study, new electrode architectures are investigated. The role of the geometry on the electro-chemo-mechanical response of the battery is studied through a number of numerical analyses, using either commercial codes (Abaqus) or high performance computing open libraries (deal.ii).

A 2D plane battery model is considered first with homogenous electrodes and a liquid electrolyte [3]. The analyses have been extended to 3D with image-based realistic reconstruction of RVEs of porous electrodes and high performance computing simulations.

References

[1] *D. Grazioli, M. Magri, and A. Salvadori. Computational modeling of Li-ion batteries. COMPUT MECH, 58(6):889?909, 2016.*

[2] *A. Salvadori, R.M. McMeeking, D. Grazioli, and M. Magri. A coupled model of transport-reaction-mechanics with trapping. part I - small strain analysis. J MECH PHYS SOLIDS, 114:1?30, 2018.*

[3] *Magri M., Boz B., Dev T. and Salvadori A. A numerical study of the influence of electrode morphology in the electro-chemo-mechanical response of Li-ion batteries. submitted, 2019.*

Mechanobiology of plant morphogenesis and crawling locomotion

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Keywords: engineering mechanobiology, morphogenesis, locomotion

Both in the plant and animal kingdoms biological living systems are able to exhibit interesting and complex behaviors by means of relatively simple mechanisms which represent a great source of inspiration for many fields, such as soft-robotics, biomedical engineering and material science. Motivated by this kind of applications, we focused our research activity on the mechanobiology of plant morphogenesis and crawling locomotion.

Indeed, robotic locomotion research has recently considered crawling and burrowing animals, whence many research projects on bio-inspired metameric (soft) robots [2, 3]. As a matter of fact, many species such as earthworms, caterpillars, sea cucumbers and snails move using peristalsis which is a locomotion mechanism consisting of a series of wave-like muscle relaxation and contraction which propagate along the body [5]. In this regard, it has been shown that, under the assumption of small deformations, peristaltic waves provide the optimal actuation solution in the ideal case of a periodic infinite system, and that this is approximately true, modulo edge effects, for the real, finite length system [1].

In addition to this, also the mechanics and morphogenesis of rapidly elongating plant organs (e.g., shoots and roots) have recently started inspiring the soft-robotics community [4]. Indeed, as well known, plants exhibit different kinds of interesting behaviors during their growth, which can be broadly classified into two classes: tropisms and nastic movements.The former (such as gravitropism, phototropism, thigmotropism, etc.) are movements triggered by environmental cues (e.g., gravity, light, touch, etc.), they are dependent on the direction of the stimulus itself and are mainly the result of differential growth. The latter (such as the closing of stomata at night) are non-directional responses to external stimuli (e.g., temperature, humidity, light irradiance, touch, etc.).
Our aim is to study the mechanical effects of competing tropic movements in the steady morphologies of plant organs and, to this end, we propose a 3D rod-like model for growing plant shoots.

References

[1] *Agostinelli, D., Alouges, F. and DeSimone, A., "Peristaltic Waves as Optimal Gaits in Metameric Bio-Inspired Robots", Frontiers in Robotics and AI,* **Vol** *5, (2018).*

[2] *Menciassi, A., Accoto, D., Gorini, S., and Dario, P., "Development of a biomimetic miniature robotic crawler", Auton. Robots,* **Vol** *21, page 155163, (2006)*

[3] *Fang, H., Li, S., Wang, K. W., and Xu, J., "Phase coordination and phase-velocity relationship in metameric robot locomotion", Bioinspir. Biomimet. (2015).*

[4] *Sadeghi, A., Mondini, A., Del Dottore, E., Mattoli, V., Beccai, L., Taccola, S., Lucarotti, C., Totaro, M. and Mazzolai, B., "A plant-inspired robot with soft differential bending capabilities", Bioinspir. Biomimet.,* **Vol** *12, N. 1, (2016).*

[5] *Quillin, K., "Kinematic scaling of locomotion by hydrostatic animals: ontogeny of peristaltic crawling by the earthworm lumbricus terrestris", J. Exp. Biol.* **Vol** *202, pages 661-674, (1999).*

Smart helical structures inspired by the pellicle of euglenids

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Keywords: euglenoid pellicle, morphing structures, bio-inspired structures, shape control

We discuss a new concept for a reconfigurable structure bio-inspired by the cell wall architecture of euglenids, a family of unicellular protists, and based on the relative sliding of adjacent strips. Uniform sliding turns a cylinder resulting from the assembly of straight and parallel strips into a cylinder of smaller height and larger radius, in which the strips are deformed into a family of parallel helices. We examine the mechanics of this cylindrical assembly, in which the interlocking strips are allowed to slide freely at their junctions, and compute the external forces (axial force and axial torque at the two ends, or pressure on the lateral surface) necessary to drive and control the shape changes of the composite structure. Despite the simplicity of the structure, we find a remarkably complex mechanical behaviour that can be tuned by the spontaneous curvature or twist of the strips.

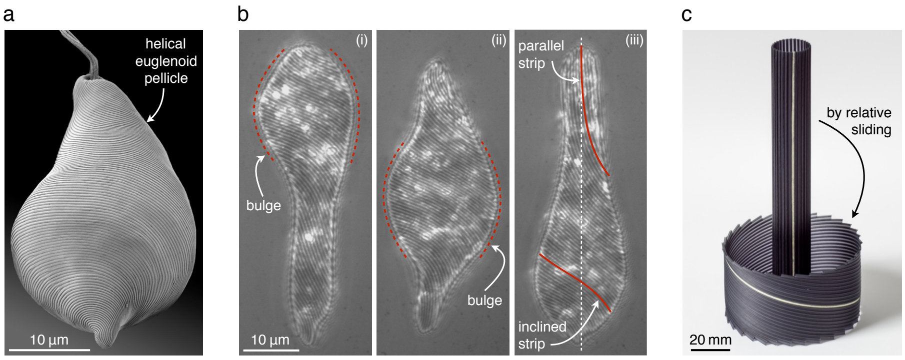

Figure 1: (a) A scanning electron micrograph of *Eutreptia pertyi* showing helically arranged pellicle strips, adapted from [3]. (b) Three micrographs of *Euglena gracilis* executing metaboly between a microscope slide and a cover slip. Observation via brightfield reflected light microscopy reveals the reconfiguration of the striated pellicle concomitant with cell body deformations. (c) A 3d-printed structure with interlocking strips reminiscent of the shape morphing mechanism of euglenids.

References

[1] *Noselli, G., Arroyo, M., DeSimone, A.: Smart helical structures inspired by the pellicle of euglenids, J. Mech. Phys. Solids* **123**, *234–246, 2018.*

[2] *Arroyo, M., DeSimone, A.: Shape control of active surfaces inspired by the movement of euglenids, J. Mech. Phys. Solids* **62**, *99–112, 2014.*

[3] *Leander, B.S., Witek, R.P., Farmer, M.A.: Trends in the evolution of the euglenid pellicle, Evolution* **55**, *2215–2235, 2001.*

A coupled model of transport-reaction-thermo-mechanics with trapping

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Keywords: Chemo-transport-thermo-mechanics, finite strains

A fully coupled model for mass and heat transport, mechanics, and chemical reactions with trapping extends the one proposed in [1]. It is rooted in non-equilibrium rational thermodynamics stating balance laws for mass, linear and angular momentum, energy, and entropy. Thermodynamic restrictions are identified, based on the classical strain decomposition and on the definition of the Helmholtz free energy. Constitutive theory and chemical kinetics are studied in order to finally write the governing equations for the multi-physics problem. The field equations are solved numerically with the finite element method, stemming from a three-fields variational formulation. Three case-studies on vacancies redistribution in metals, hydrogen embrittlement, and the charge-discharge of active particles in Li-ion batteries demonstrate the features and the potential of the proposed model.

References

[1] *Salvadori A., McMeeking R.M., Grazioli D., Magri M., A coupled model of transport-reaction-mechanics with trapping. Part I - small strain analysis, J MECH PHYS SOLIDS, vol 114, 1-30, (2018)*

Spatially constrained growth triggers tumour vessels tortuosity

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Keywords: buckling, tumour capillaries, volumetric growth

Solid tumours have the ability to assemble their own vascular network for optimizing their access to the vital nutrients. These new capillaries are morphologically different from normal physiological vessels. In particular, they have a much higher spatial tortuosity forcing an impaired flow within the peritumoral area [1]. This is a major obstacle for the efficient delivery of antitumoral drugs. This work proposes a morpho–elastic model of the tumour vessels. A tumour capillary is considered as a growing hyperelastic tube that is spatially constrained by a linear elastic environment, representing the interstitial matter. We assume that the capillary is an incompressible neo–Hookean material, whose growth is modeled using a multiplicative decomposition of the deformation gradient.

We study the morphological stability of the capillary by means of the method of incremental deformations superposed on finite strains, solving the corresponding incremental problem using the Stroh formulation and the impedance matrix method. The incompatible axial growth of the straight capillary is found to control the onset of a bifurcation towards a tortuous shape. The post-buckling morphology is studied using a mixed finite element formulation in the fully nonlinear regime. The proposed model highlights how the geometrical and the elastic properties of the capillary and the surrounding medium concur to trigger the loss of marginal stability of the straight capillary and the nonlinear development of its spatial tortuosity [2].

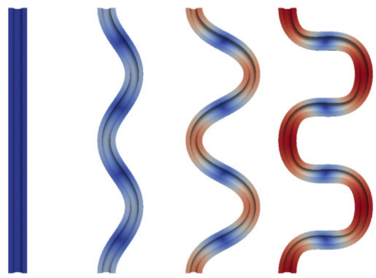

Figure 1: Buckled morphology of the tumour capillary resulting from the numerical simulation of the proposed model.

References

[1] E. Bullitt, D. Zeng, G. Gerig, S. Aylward, S. Joshi, J. K. Smith, W. Lin, and M. G. Ewend, "Vessel tortuosity and brain tumor malignancy: a blinded study," *Academic radiology*, vol. 12, no. 10, pp. 1232–1240, 2005.

[2] D. Riccobelli and P. Ciarletta, "Morpho-elastic model of the tortuous tumour vessels," *International Journal of Non-Linear Mechanics*, vol. 107, pp. 1–9, dec 2018.

Mechanical model of fiber morphogenesis in the liver

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Keywords: collagen fibers, growth, morphogenesis.

Cirrhosis of the liver is one of the major cause of death in the western world. It is characterized by excessive accumulation of extracellular matrix proteins in the liver tissue, including collagen fibers, in a process known as fibrosis. To date there is only a limited number of studies modeling the microcirculation of the liver, and none considers the presence of localized fibrous tissue. We build on the modeling approach in [1], where the poromechanical formulation of a perfusion problem in biological tissues is based on a species diffusion model. We especially focus on the fibrotic regions, and on the interactions between the underlying solid matrix and blood flow. The liver tissue is constituted of "lobules" which are basic functional structures approximately in the shape of hexagonal prisms. Blood enters the lobules via the portal tracts and is drained via the centrilobular vein [2]. The lobule tissue contains a dense network of capillary-like vessels (the sinusoids), surrounded by hepatic cells. Fibrosis consists in a progressive pattern formation of fiber bundles which develop along the perisinusoidal regions, during a process lasting even decades. According to the conjecture that identifies the portal mesenchymal cells as the precursors of fibroblasts (the cells producing fibers), we propose a model of fiber growth and recruitment based on fibroblast diffusion and aggregation inside the lobule. Starting from the seminal paper [3] about the theory of mesenchymal morphogenesis for generating patterns in biology, we derive a thermodynamically consistent model of cell diffusion and tissue growth, using the principle of virtual powers. Our numerical simulations of a fibrotic lobule suggest that regions of hypo-perfusion arise. Moreover, through simulations we can predict which fibrotic pattern evolution adversely affects blood perfusion the most.

References

[1] *A. Tatone, F. Recrosi, R. Repetto and G. Guidoboni, "From species diffusion to poroelasticty and the modeling of lamina cribrosa", J. Mech. Phys. Solids* **124**, *849-870, (2019)*

[2] *A. Bonfiglio, K. Leungchavaphongse, R. Repetto and J. H. Siggers, "Mathematical modeling of the circulation in the liver lobule", Journal of Biomechanical Engineering* **132** *(11), (2010)*

[3] *G. F. Oster, J. D. Murray and A. K. Harris, "Mechanical aspects of mesenchymal morphogenesis", J. Embryol. exp. Morph.* **78**, *83-125, (1983)*

Modeling approach and finite element analyses of a shape memory epoxy-based material

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Keywords: shape memory polymer, thermo-mechanical model, finite element.

Shape memory polymers (SMP) are appealing for many innovative devices targeted towards different fields: biomedical, aerospace, construction engineering, purely aesthetic, etc. [1]. With the rise of 3D printing, the interest in (SMP) for engineering applications has grown even more. However, the lack of effective approaches to tailor shape memory effect and then include its modelling in the design process of a real component could hinder the potential advantages associated with an easier and cheaper production of smart devices.

To this aim here, a series of structurally related epoxy resins were prepared as model systems for the investigation of the shape memory response, tailoring their thermo-mechanical response and describing their strain evolution under triggering stimuli with a thermo-viscoelastic model. Following the approach by Diani et al. [2,3], the shape memory behavior on epoxy resin was modeled through the definition of linear viscoelastic parameters, in combination with the general time-temperature reduction scheme. Specifically, this translates into the definition of a (hyper)elastic response enriched with a Prony series to implement time dependency and a William-Landel-Ferry (WLF) equation to implement temperature dependency.

While the (hyper)elastic response parameters are found with a standard fitting procedure on tension tests, finding the correct parameters for the Prony series might be challenging. For this reason, an ad-hoc optimization process was coded in Mathworks Matlab environment: proper guess values are created and then a chain of constrained optimizers (such as genetic, particle swarm, pattern search and different non-linear programming algorithms) with smart evolving boundaries looks for the right set of parameters.

The ability to correctly predict strain history and shape transitions with a finite element model was evaluated on a case study for self-deployment of a folded tubular structure. Tubular specimens were tested and the model was used to reproduce the switching from a temporary folded six-pointed star shape to their original cylindrical shape. Overall, this approach proved to be a very effective way to simulate complex shape memory responses in time and temperature domains, for which standard Dynamic mechanical analyses (DMA) and tensile test are sufficient to calibrate material parameters for Finite element implementation.

References

[1] *Karger-Kocsis, J., and Kéki, S., "Review of Progress in Shape Memory Epoxies and Their Composites," Polymers (Basel)., 10(1), pp. 1–38 (2017)*

[2] *Diani, J., Gilormini, P., Frédy, C., and Rousseau, I., "Predicting Thermal Shape Memory of Crosslinked Polymer Networks from Linear Viscoelasticity," Int. J. Solids Struct., 49(5), pp. 793–799 (2012)*

[3] *Arrieta, J. S., Diani, J., and Gilormini, P., "Experimental and Modelling Studies of the Shape Memory Properties of Amorphous Polymer Network Composites," Smart Mater. Struct., 23 (2014)*

A computational method integrating the phase-field approach and homogenization to simulate damage in fibre-reinforced materials

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Keywords: Phase field approach to damage, homogenization, nonlinear finite element method.

The simulation of damage and failure in heterogenous materials with microstructure is challenging from the computational point of view, due to the need of resolving nonlinear phenomena taking place over very different length scales. The phase-field approach to fracture appears to be very promising in simulating complex fracture patterns and damage evolution in homogenous materials or in laminates. However, its further development to address multi-scale problems is still open research direction. In this work, a novel multi-scale phase field approach to damage is proposed for the simulation of the nonlinear mechanical response of heterogenous composites made of a brittle matrix and reinforced by stiffer linear elastic fibres. To this aim, under the assumption of scales separation, first-order computational homogenization is exploited to identify the constitutive elastic tensor of a representative volume element at the meso-scale, depending on the level of damage. At the macro-scale, on the other hand, damage is supposed to evolve according to the phase-field approach, which ensures mesh independency of the formulation through its nonlocality.

The proposed formulation, implemented in the research finite element analysis programme FEAP, leads to a concurrent formulation integrating computational homogenization and the phase-field approach to damage, in each finite element integration point. To reduce the associated computation cost, an acceleration strategy is proposed based on the concept of the so-called look-up tables.

Numerical examples involving fibre-reinforced composites with different shapes and volumetric content of the reinforcement are proposed, to prove the ability of the methodology to simulate failure phenomena typically observed in experiments. In situ tensile tests performed in the MUSAM-Lab of the IMT School for Advanced Studies Lucca, with a tensile stage placed within a scanning electron microscope, are used as benchmark for comparison.

Viscoelastic experimental characterization of flax-based composites

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Keywords: viscoelasticity, bio-composites, flax

There have been many authors reporting experimental results about the mechanical characterization of bio-based composites [1, 2]. All the previous works unanimously agreed on the need to evaluate both modulus and inelastic strain to fully describe its response. Despite some efforts on the experimental characterization of natural fiber composites [3], a recognized procedure to fully characterize their mechanical properties has not been defined yet, as well as a consolidated material model. This work presents an experimental characterization of the mechanical behavior of unidirectional composites based on flax fibers and (bio-)epoxy resins. The study primarily targets the viscoelastic and the pseudo-plastic response. Specimens have been produced through a Light Resin Transfer Moulding process and tested in pure monotonic tension, cyclic tension, and creep. The effect of the strain rate has also been investigated. This is found to have a strong influence due to the very high creep sensitivity of the material. Finally, the intra-laminate variability of the mechanical properties has been highlighted. Results reveal that the mechanical properties of flax-based composites might show either good repeatability or high dispersion, based on the supplier quality of the rough materials. However, results indicate a defined transition strain level between the initial elastic modulus E_1 and the secondary modulus E_2, alongside a strain-based failure criterion. Tests about cyclic loads further evidenced that the full characterization of bio-composites passes through the estimation of the viscous response of the material, as proposed in [4]. In fact, the behavior of flax bio-composites is found to be both viscoelastic, being highly dependent from the strain rate, and viscoplastic, since the inelastic strain is found to accumulate when strains exceed 0.1%. Interesting results are found observing that there is a significant portion of the inelastic strain which recovers over time. Further, creep is found to highly influence the inelastic strain accumulation even at ambient temperatures.

References

[1] Libo Yan, Nawawi Chouw, and Krishnan Jayaraman. Flax fibre and its composites - A review. *Composites Part B: Engineering*, 56:296–317, 2014.

[2] Zia Mahboob and Habiba Bougherara. Fatigue of flax-epoxy and other plant fibre composites: Critical review and analysis. *Composites Part A: Applied Science and Manufacturing*, 109(March):440–462, 2018.

[3] G. Mattei and A. Ahluwalia. A new analytical method for estimating lumped parameter constants of linear viscoelastic models from strain rate tests. *Mechanics of Time-Dependent Materials*, pages 1–9, apr 2018.

[4] C. Poilâne, Z. E. Cherif, F. Richard, A. Vivet, B. Ben Doudou, and J. Chen. Polymer reinforced by flax fibres as a viscoelastoplastic material. *Composite Structures*, 112(1):100–112, 2014.

Metamaterials with extreme elastic response

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Keywords: Metamaterials, tensegrity cells, elastic response

In this work we analyze a metamaterial sheet constituted by a periodic pattern of tensegrity cells. In particular, we fix the geometrical and mechanical properties of a cell through an optimization mass problem satisfying the restrictions arising from the material failure and stability conditions, both for the whole system and the single member. Interestingly we obtain on optimal dimension of the internal microstructure of the metamaterial. We also analyze the properties of this material by determining the analytical dependence of the (macro) tangent moduli on the applied loads. In the case of compressive load conditions we obtain that the shear stiffness of this optimized lattice is very small in comparison to the other elastic moduli with a strong dependence on the applied load. This behavior suggests to employ the proposed scheme as tunable isolation system.

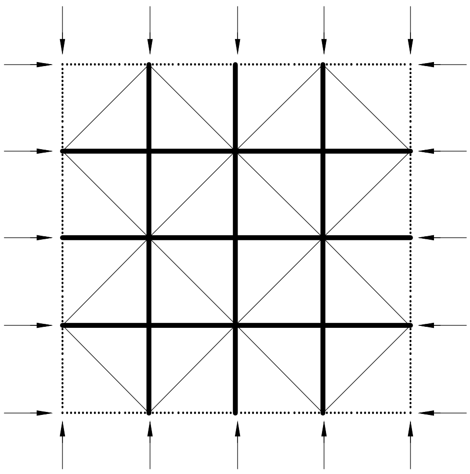

Figure 1: Scheme of a planar lattice under biaxial compressiva load condition

References

[1] *De Tommasi, D., Maddalena, F., Puglisi, G., Trentadue, F., Fractality in selfsimilar minimal mass structures,, Journal of the Mechanics and Physics of Solids,* **107***, 433-450, (2017).*

[2] *De Tommasi, D., Puglisi, G., Trentadue, F., Elastic response of an optimal tensegrity-type metamaterial,, Frontiers in Materials,* **6***, doi:10.3389/fmats.2019.00024, (2019).*

[3] *Fraternali, F., Carpentieri, G., Amendola,A., Skelton, R.E., Nesterenko, V.F., Multiscale tunability of solitary wave dynamics in tensegrity metamaterials,, Applied Physics Letters,* **105***, 201903, (2014).*

[4] *Cummer, S.A., Christensen, J. Alú, A., Controlling sound with acoustic metamaterials,, Nat. Reviews, Materials,* **1***, 16001, (2016).*

Discrete homogenization procedure for estimating the mechanical properties of non-local nets and pantographic structures

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Keywords: Discrete homogenization, Microstructure, Non-local materials.

The characterization of the mechanical response of complex materials, like tissues, woven composites, fibre networks etc. often requires multilevel analyses, since the micro structure strongly influences the observable behaviour. Existing approaches can be subdivided essentially into equivalent continuum or multiscale models. Often non-local continuum models are needed, see for instance [1]. The choice of the appropriate non-local model and of its physical parameters must rely on the experimental or numerical consideration of the real microstructure of the material. Asymptotic homogenization techniques can be effectively used for obtaining simplified continuum models, since they can be expanded up to the required order able to include the desired physical effects. In the case of lattice microstructures (networks, pantographic structures, tissues,...), discrete homogenization appears particularly useful [2, 3]. The purpose of the work is to extend the method to general, unbalanced, lattice systems, periodic or quasi-periodic, discussing the forms obtained for the constitutive relations and for the microrotations. Also, it will be discussed cases for which an higher order model is predicted by the homogenization procedure. The presentation will be restricted to a 2D case. Although not specifically presented, the procedure will be set within a framework ready for analysing the geometrical non linear case. Numerical simulations of planar deformations through FEM models with high continuity will be used for validating the obtained results.

References

[1] *F. dell'Isola, M. Cuomo, L. Greco and A. Della Corte, Bias extension test for pantographic sheets: numerical simulations based on second gradient shear energies, Journal of Engineering Mathematics, (2016).*

[2] *D. Caillerie, A. Mourad and A. Raoult, Discrete homogenization in graphene sheet modeling, Journal of Elasticity, (2006), 84, pp. 33-68.*

[3] *C. Boutin and S. Hans, Homogenisation of periodic discrete medium: Application to dynamics of framed structures, Computers and Geotechnics, (2003), 30, pp. 303-320.*

Device influence in single molecule isotensional experiments

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Keywords: single molecule force spectroscopy (SMFS), macromolecules unfolding, device stiffness

Mechanical forces at molecular level play a crucial role in a wide range of biological phenomena [1]. The ongoing innovation in Single Molecule Force Spectroscopy (SMFS, Fig 1a) techniques such as Atomic Force Microscopy pulling experiments opened up the possibility of investigating the force-induced unfolding and conformational transitions in macromolecules [2]. We study in the framework of Statistical Mechanics the influence of the device stiffness and temperature in Single Molecule Force Spectroscopy experiments. The results of [3, 4] are extended to systems with more general energy functions. We derive fully analytical expressions for the folding-unfolding process of a macromolecule modeled as a chain of discrete bistable elements [5] reproducing known experimental effects (Fig 1b).

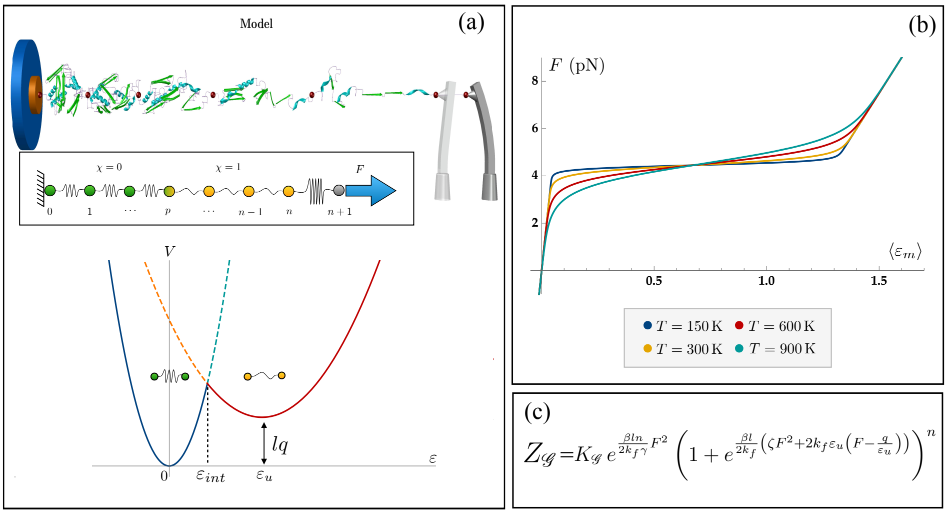

Figure 1: (a) Scheme of a SMFS experiment, one-dimensional chain with a device subject to an external force, sketch of the potential energy associated to each element of the macromolecule. (b) Force-extension curves for variable values of the temperature. (c) Partition function in the Gibbs ensemble.

References

[1] *Goriely A., The Mathematics and Mechanics of Biological Growth, Springer, New York, (2017).*
[2] *De Tommasi D., Puglisi G., Saccomandi G., Multiscale mechanics of macromolecular materials with unfolding domains, J. Mech. Phys. Solids,* **78***, 154-172 (2015).*
[3] *Puglisi G., Florio G., Unveiling the influence of device stiffness in single macromolecule unfolding, Scientific Reports 9, 4997 (2019)*
[4] *Bellino L., Puglisi G., Florio G., On the influence of device handle in single-molecule experiments, ArXiv: 2748873, (2019)*
[5] *Puglisi G., Truskinovsky L., Mechanics of a Discrete Chain with Bi-Stable Elements, J. Mech. Phys. Solids,* **48***, 1-27 (2000).*

Thermodiffusion in periodic materials: dynamic asymptotic homogenization and complex frequency band structure

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Keywords: thermo-diffusivity, damped wave propagation, Floquet-Bloch theory

Composite materials with periodic microstructures subjected to thermo-diffusive phenomena are of interest for the fabrication of many renewable energy devices and energy harvesters [1, 2]. In the context of battery devices, thermo-diffusive phenomena involving Solid Oxide Fuel Cells (SOFCs)-like periodic materials are investigated in the present work in the dynamic regime [3].

By means of a first-order multi-field asymptotic homogenization procedure, generalized down-scaling relations are obtained and the field equations for a first-order thermo-diffusive homogenized continuum are derived. The closed form of the overall constitutive tensors [4] and inertial terms of the equivalent multi-field continuum are derived in terms of periodic perturbation functions and relative quantities characterizing the microstructure. Damped wave propagation within the periodic heterogeneous medium in presence of thermodiffusion phenomena is investigated in accordance to Floquet-Bloch theory. In this regard, complex frequency band structure of the periodic medium is determined. Specifically, generalized Christoffel equations defined on the periodic cell, together with Floquet-Bloch boundary conditions, are numerically resolved and complex frequency spectrum associated to free waves propagation is obtained.

Finally, dispersion functions of the homogenized medium are determined and their approximation is derived in closed form through perturbative analysis. Accuracy of such dispersion functions is tested by means of a comparison with acoustic branches obtained from the heterogeneous model via Floquet-Bloch theory.

References

[1] *Nowacki, W., "Dynamical problems of thermodiffusion in solids. 1" in Bull. Polish Acad. Sci. Tech. Sci,* **22***, page 55-64 (1974).*

[2] *Nowacki, W., "Dynamical problems of thermodiffusion in solids. 2" in Bull. Polish Acad. Sci. Tech. Sci,* **22(3)***, page 205-211 (1974).*

[3] *Bove, R., Ubertini, S., Modeling solid oxide fuel cells: methods, procedures and techniques, Springer Science & Business Media, (2008).*

[4] *Bacigalupo, A., Morini, L., and Piccolroaz, A., "Multiscale asymptotic homogenization analysis of thermo-diffusive composite materials" in International Journal of Solids and Structures,* **85***, page 15-33 (2016).*

Poro-mechanical analysis of a biomimetic scaffold for osteochondral defects

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Keywords: Osteochondral defects, Biomimetic scaffolds, Porous media mechanics.

Scientific advances in our knowledge of biomaterials, stem cells, growth and differentiation factors, and biomimetic environments have created unique opportunities to fabricate tissues in the laboratory from combinations of engineered extracellular matrices (scaffolds), cells, and biologically active molecules. Tissue engineering scaffolds hold great promise for treating various degenerative diseases or trauma consequences.

In this work we derive a mathematical model for the description of a tissue scaffold starting from the works in [1,2] and considering the scaffold as a biphasic porous material. Cells and the extracellular matrix constitute the solid skeleton of the scaffold, which is completely filled with interstitial fluid. As we deal with soft materials, we formulate the problem in the context of finite displacements, to account for large deformations in the material.

Due to the complexity of the modeling framework, a systematic understanding of the role of the parameters governing the equations is of paramount importance. To this aim, we simulate a stress-relaxation experiment and perform a parametric study to investigate the influence of the solid skeleton stiffness and permeability on the mechanical response of the scaffold.

The mathematical model and its computational implementation provide an effective tool to investigate the mechanical behavior of bio-inspired scaffolds and can help in tailoring ad hoc devices. In addition, the model could be used to estimate the forces and physical constraints to which the cells that populate the scaffold are subjected, contributing to the understanding of the cellular mechanical environment.

References

[1] Mascheroni, P., Carfagna, M., Grillo, A., Boso, D. P., and Schrefler, B. A., "An avascular tumor growth model based on porous media mechanics and evolving natural states", Mathematics and Mechanics of Solids, ***23(4)****, 686–712 (2018)..*

[2] Grillo, A., Prohl, R., & Wittum, G., "A poroplastic model of structural reorganisation in porous media of biomechanical interest", Continuum Mechanics and Thermodynamics, ***28(1–2)****, 579–601 (2016).*

Propagazione di onde flessionali all'interno di reticoli periodici e manipolazione del loro comportamento dinamico

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Parole chiave: metamateriali, reticoli prestressati, rifrazione negativa.

Obiettivo del lavoro è stato lo studio della propagazione delle onde flessionali all'interno di reticoli periodici di travi, per capire come la propagazione di un'onda sia influenzata dalla microstruttura del materiale [1] e per modificarne il percorso nel modo desiderato [2].
Si sono analizzati reticoli periodici costituiti da travi con massa uniformemente distribuita, libere di deformarsi sia assialmente che flessionalmente. I reticoli sono stati studiati utilizzando la formulazione esatta di Floquet-Bloch per le oscillazioni libere, permettendo di ottenerne le proprietà dispersive. Osservando le superfici di dispersione si sono ottenute informazioni significative sui regimi di onde stazionarie in corrispondenza dei punti nei quali il gradiente delle superfici risulta nullo (punti sella), nei "punti di Dirac" e sull'anisotropia dinamica dei reticoli. Lo studio delle oscillazioni libere in un reticolo periodico infinito con la teoria di Floquet-Bloch, ha permesso di predire il comportamento dello stesso reticolo soggetto ad una forzante puntuale (forza o momento). I reticoli forzati sono stati studiati numericamente attraverso il software ad elementi finiti COMSOL Multiphysics. Si è osservato come al variare della frequenza della forzante la risposta del reticolo si modichi notevolmente ma in accordo con quanto previsto dall'analisi di Floquet-Bloch.

La comprensione della propagazione delle onde ha permesso inoltre di creare dei reticoli in grado di poter canalizzare e manipolare il loro percorso [2]. A tal fine si è sfruttata la diversa risposta a un segnale dei reticoli generati con travi con proprietà meccaniche differenti, per generare delle interfacce. Il modo più interessante e semplice trovato per generare le interfacce è stato quello di introdurre uno stato di prestress nelle travi. L'aspetto importante del metodo proposto è che gli stati di prestress possono essere facilmente rimossi o modificati al fine di regolare con continuità le caratteristiche di propagazione del mezzo. Scegliendo opportunamente il valore del prestress, in base alla frequenza della forzante, è stato possibile creare delle interfacce che causano la riflessione totale, la rifrazione negativa oppure la canalizzazione all'interno di percorsi voluti di un'onda, prefigurando la possibilità di realizzare lenti piatte o di schermare un oggetto. I risultati ottenuti possono essere utilizzati nella realizzazione di metamateriali progettati per filtrare la propagazione delle onde, generate da sollecitazioni che agiscono con frequenze assegnate.

References

[1] Bordiga, G., Cabras, L., Bigoni, D. and Piccolroaz, A., "Free and forced wave propagation in a Rayleigh-beam grid: flat bands, Dirac cones, and vibration localization vs isotropization", International Journal of Solids and Structures, ***161****, pages 64-81 (2019).*

[2] Bordiga, G., Cabras, L., Piccolroaz, A. and Bigoni, D., "Prestress tuning of negative refraction and wave channeling from flexural sources", Applied Physics Letters, ***114*** *(2019).*

Theory and prediction of strength in BCC High Entropy Alloys up to 1900K

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Keywords: dislocations, plasticity, multi-scale modeling

Body-centered-cubic (BCC) high entropy alloys show exceptional strengths up to 1900K [1]. They are characterized by Mo, Nb, Ta, V, W, Cr, often combined with Ti, Zr, Hf [2], occupying BCC lattice sites at random. Few such alloys have been tested. Fundamental understanding of the mechanisms originating such exceptional behaviour is crucial to formulate theories enabling combinatorial search over the immense compositional space. We introduce a new holistic, parameter-free strengthening theory of screw and edge dislocations in BCC alloys [3,4]. In contrast with screw-controlled pure BCC metals, in non-dilute BCC alloys both edge and screw dislocations are pinned [5] due to strong local energy fluctuations [3]. Both screw and edge dislocations assume wavy/kinked minimum-energy configurations where dislocation segments of characteristic length ζ_c are pinned at low-energy sites. Three strengthening regimes are found in screws: (1) low-temperature, Peierls-barrier controlled strength; (2) intermediate-temperature strength, due to kink migration over barriers scaling with solute/dislocation interaction; (3) high-temperature strength, scaling with energy of vacancy and self-interstitials forming after unpinning of cross-kinks. Edge dislocation strengthening (scaling with misfit volumes and elastic moduli) is controlled at all temperatures by glide of the ζ_c segments across the large energy barriers due to energy fluctuations. Theory captures quantitatively and qualitatively experiments in a vast range of alloy compositions and temperatures (Fe-Si, Nb-Mo, Nb-W; high entropy Ti-Nb-Zr-based and Nb-Mo-Ta-W-V alloys). Screws control strength of non-dilute binaries and Ti-Nb-Zr-based alloys. The exceptional high-temperature strengthening in Nb-Mo-Ta-W-V alloys is controlled by edge dislocations, due to much larger ($\sim$3 eV) energy barriers created by solute/edge dislocation interaction. This holistic theory of strengthening in BCC alloys rationalizes and captures experiments on BCC alloys. A reduced form of the theory enables combinatorial search for stronger alloys, opening avenues for materials discovery.

References

[1] *Senkov, O. N., Wilks, G. B., Scott, J. M., Miracle, D. B., Mechanical properties of Nb25Mo25Ta25W25 and V20Nb20Mo20Ta20W20 refractory high entropy alloys. Intermetallics,* **19***, 698-706 (2011).*

[2] *Miracle, D. B., Senkov, O. N., A critical review of high entropy alloys and related concepts. Acta Materialia,* **122***, 448-511 (2017).*

[3] *Maresca, F., Curtin, W. A., Mechanistic Origin of High Retained Strength in Refractory BCC High Entropy Alloys up to 1900K. Under review, arXiv:1901.02100 (2019)*

[4] *Maresca, F., Curtin, W. A., Theory of Screw Dislocation Strengthening in Random BCC Alloys from Dilute to High-Entropy Alloys. Under review (2019)*

[5] *Mompiou, F., Tingaud, D., Chang, Y., Gault, B., Dirras, G., Conventional vs harmonic-structured β-Ti-25Nb-25Zr alloys: A comparative study of deformation mechanisms. Acta Materialia,* **161***, 420-430 (2018).*

Effective elastic properties of media containing coalescing holes

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Keywords: Cylindrical pores; irregular cross-section; bipolar coordinates;

A recent study about the temperature and heat flux distributions around two nonconductive (separate or intersecting) circular holes in a plane system recently appeared in Literature [1]. These results have been used to construct the second-rank resistivity contribution tensor which allows assessing the effective thermal properties of a composite including circular inhomogeneities.

Here, that study is extended to assess the overall elastic properties of an isotropic elastic matrix with two separate circular cavities or a cavity obtained by the union of two circles of generally different diameters (Figure 1).

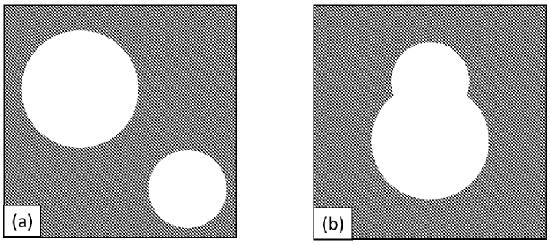

Figure 1. (a) two separate circular holes, (b) cross-section formed by two coalesced circular holes of generally different radii.

The problem is formulated in terms of stress functions expressed in Fourier series or Fourier transforms. Reference is made to bipolar cylindrical coordinates [2]. Once the displacement field $\boldsymbol{u}$ has been calculated, the extra strain $\Delta\varepsilon$ due to the inhomogeneity is assessed according to

$$\Delta\varepsilon = \frac{1}{2V}\int_{\partial V}\left(\boldsymbol{un}+\boldsymbol{nu}\right)dS, \tag{1}$$

being $\boldsymbol{n}$ the normal vector and V the volume reference. Finally, the extra strain is used to assess the fourth-rank compliance contribution tensor varying the size of the circular arcs.

References

[1] *Lanzoni, L., Radi, E. and Sevostianov, I., "Effect of cylindrical fibers, with cross-sections formed by two circular arcs, on the overall conductivity of a composite" International Journal of Solids and Structures, **138**, 264-276, (2018).*

[2] *Jeffery, G.B., "Plane stress and plane strain in bipolar co-ordinates" Philos. Trans. R. Soc. London, Ser. A, **221**, 265-293 (1921).*

Deformability analysis and improvement in stretchable electronics systems through Finite Element Analysis

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Keywords: stretchable electronics, FEM, optimization.

Stretchable electronics devices and stretchable electro-textiles are emerging classes of electrical systems that allow completely new applications for electrical devices, such as unobtrusive sensing of specific vital signs with devices conformable to human skin. These systems employ a combination of extremely deformable substrates with electrically conductive inks printed on their surface, on which components are connected: here, the absence of solid metal as conductive material greatly enhances the deformability of these systems without the need to hinder unobtrusiveness of the devices. Although being able to sustain high deformation, however, the presence of rigid components on such systems heavily affects their achievable deformation due to strain concentrations at near the interconnection area. In order to improve stretchability under these conditions, a combination of research on materials for conductive inks and optimization of the employed layout is needed. Especially for the latter, Finite Element modelling is very useful, since it gives the possibility to locate critical regions based on stress and strain maps calculated starting from the applied boundary and loading conditions.[1,2]

In this work, the authors show the application of this strategy to improve mechano-electrical performance of the system under uniaxial tension by modelling and then modifying the overall stiffness of specific sample regions. Depending on the specific need, different strategies have been adopted to intervene on stiffness changes, namely overall material removal or addition from specific sample regions and laser cutting to induce local stiffness changes.

This work shows that, in particular, a simple technique such as laser cutting can be used to tailor the local material parameters at a deeper level, thus allowing decrease in stiffness gradients and a general enhancement of electrical performances under high levels of uniaxial deformation of the sample, as also predicted in the FE analyses.

References

[1] Mosallaei M, Jokinen J, Honkanen M, Iso-Ketola P, Vippola M, Vanhala J, Kanerva M, Mäntysalo M. "Geometry analysis in screen-printed stretchable interconnects". IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 8, no. 8, pp. 1344-1352, (2018).

[2] Mosallaei, M, Jokinen, J, Kanerva, M and Mäntysalo, M, "The Effect of Encapsulation Geometry on the Performance of Stretchable Interconnects," Micromachines, vol. 9, 645 (2018).

Effects of in-homogeneous interphase zone on the shear modulus of a periodic particulate composite containing hollow spherical inclusions.

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Keywords: elasticity, composite materials, interphase.

To estimate the elastic properties of a particulate composite manufactured with hollow spheres surrounded by graded interphase dispersing in a matrix, some micromechanical models have been proposed in the past years using different approaches. For an accurate prediction of the properties of composite, parametric investigations have been performed in the literature to analyse the effects of inclusion wall thickness, inclusion diameter, volume fraction, interphase properties etc.

This study aims to understand how the shear modulus of a particulate composite manufactured by hollow microspheres surrounded by graded interphases and dispersing in a matrix depends on the elastic and geometric properties of the interphase zone and inclusion.

Assuming a radial power law behavior for the shear modulus in the in-homogenous interphase, the analytical elastic solutions of the two problems of a single composite sphere with traction or displacement boundary conditions, are used to determine shear modulus and obtained in the framework of the elasticity theory. By using the energetic composite sphere assemblage model based on the Hashin-Shtrikman (HS) variational approach [1] the shear elastic bounds are obtained.

The explicit analytical formulae are compared with a previous study concerning solid spheres [2] and the case without inclusions, corresponding to a periodic particulate with the presence of holes in the matrix with graded interphase around the holes. Either hard or soft interphases surrounding the hollow spheres are taken into account for analyzing the effective properties of composites.

The numerical results are compared with the results obtained with different theoretical predictions present in the literature with particular attention to the case with thin thickness of the inclusion walls [3]. These investigations permit us to highlight how the geometric and constitutive properties of constituents in composite materials play an important role in predicting the shear modulus bounds of particle-reinforced composites as so as the interphase zone properties.

References

*[1] Hashin, Z., Shtrikman, S., "A variational approach to the theory of the elastic behaviour of polycrystals," J. Mech. Phys. Solids, **10**; 343–352 (1962).*

*[2] Sburlati, R., Cianci, R. and Kashtalyan, M. "Hashin's bounds for elastic properties of particle-reinforced composites with graded interphase," International Journal of Solids and Structures **138**, 224-235 (2018).*

*[3] Bardella, L., Sfreddo A., Ventura, C., Porfiri, M., Gupta, N. "A critical evaluation of micromechanical models for syntactic foams," Mechanics of Materials, **50**, 53-69 (2102).*

Design and experimental validation of auxetic metamaterials with ultra-wide bandgap

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Keywords: phononic crystals; tunable bandgap; periodic structures.

Metamaterials are special structured materials ad-hoc designed to obtain properties usually non existing in standard materials. Two meaningful examples are auxetic materials [1] with negative Poisson's ratio and phononic crystals with wide-band gap that filter elasto-acoustic wave transmission [2]. The paper is focused on innovative periodic structures, which join the two above mentioned features, with possible applications at the macro- and at the micro-scale, typically for innovative microsystems.

The most popular feature of auxetic structures is, in fact, that they can expand in the direction perpendicular to an externally exerted tension thus showing an equivalent negative Poisson's ratio. In addition, they enhance material properties related to negative Poisson's ratio, such as increased shear modulus, indentation resistance, fracture toughness, energy absorption, porosity/permeability variation with strain and synclastic curvature. On the other hand, periodic structures may exhibit bandgaps, i.e. portions of frequency domain in which there is no propagation of waves. Such phenomena are well known when dealing with electro-magnetic wave transmission. Recently, a growing interest emerged in the mechanical counterpart, namely elastic or acoustic waves [3]. Applications of such periodic structures in the elastic and acoustic domains span all the mechanical frequency domain ranging from very high frequency (i.e. heat conduction) to very low frequency (i.e. seismic insulation). Generally, the widest the bandgap, the most robust the wave attenuation around a certain frequency, therefore all the applications take advantages from very wide bandgaps.

The proposed periodic structures are specifically designed to obtain a significant auxetic behavior along with an ultra-wide, subwavelength bandgap [4]. The most interesting feature is the possibility of exploiting auxetic deformation in order to obtain a mechanically tunable bandgap. The macro-scale metamaterial is characterized by a fully three-dimensional geometry; conversely, for the micro-scale case, a 2D design is considered, showing full compatibility with the typical micromachining process for microsystems. The paper presents the theoretical explanation of the mechanical behavior of such metamaterials and the numerical analyses via FEM. Finally, the peculiar features are proved by means of experimental tests.

References

*[1] Bruggi, M., Zega, V., Corigliano, A., "Synthesis of auxetic structures using a micropolar material model," Structural and multidisciplinary optimization, **Vol. 55**, 1 (2017).*
*[2] D'Alessandro, L., Belloni, E., Ardito, R., Corigliano, A., Braghin, F., "Modeling and experimental verification of an ultra-wide bandgap in 3D phononic crystals," Applied Physics Letters, **Vol. 109**, 221907 (2016).*
[3] LaudeV. Phononic Crystals: Artificial Crystals for Sonic, Acoustic, and Elastic Waves. De Gruyter, New York (2015).
*[4] D'Alessandro, L., Zega, V., Ardito, R., Corigliano, A., "3D auxetic single material periodic structure with ultra-wide tunable bandgap," Scientific Reports, **Vol. 8**, 2262 (2018)*

Experimental characterisation of buckling-driven delamination growth in four-point bending tests

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Keywords: Composite laminate, delamination buckling, four-point bending test.

Delamination cracks in composite laminates may originate from manufacturing defects, low-energy impacts, and many other causes. Once present, a delamination crack may propagate due to local buckling producing high interlaminar stresses at the crack front [1]. To investigate this phenomenon, many authors have suggested carrying out four-point bending tests on composite laminated specimens with mid-span, through-the-width delamination cracks [2, 3, 4]. In previous work, we developed an analytical solution for an elastic-interface model of such a test [5].

Herein we present the results of an experimental campaign aimed at validating the abovementioned mechanical model. A 300 x 400 mm^2 laminated plate was manufactured using quasi-unidirectional carbon-fibre fabric and epoxy resin by Microtex Composites for a total of 16 plies and a nominal thickness of 4.8 mm. Ten 220 x 13 mm^2 specimens were cut from the plate to conduct four-point bending tests according to the ASTM standard [6]. A 40 mm long artificial delamination was created at the mid-span of each specimen by introducing a thin layer of polytetrafluoroethylene (PTFE) between the second and third plies.

The experimental tests were conducted using the facilities of the Multi-scale Analysis of Materials Laboratory (MUSAM-Lab) at IMT. A Zwick-Roell universal testing machine with 10 kN load cell was used for displacement control with a rate of 1 mm/min. The Correlated Solution kit for 2D Digital Image Correlation (DIC) was employed to measure the full-field displacement and the delamination length during the test. Snapping instability was observed, followed by crack propagation. Plots of the load vs. crack opening displacement and delamination length have been obtained and compared to the theoretical predictions of our previous model.

References

[1] *Bolotin, V.V., "Delaminations in composite structures: Its origin, buckling, growth and stability", Composites Part B,* ***27****, 129–145 (1996).*

[2] *Kardomateas, G.A., "Snap buckling of delaminated composites under pure bending", Composites Science and Technology,* ***39****, 63–74 (1990).*

[3] *Kinawy, M., Butler, R., and Hunt, G.W., "Bending strength of delaminated aerospace composites", Philosophical Transactions of the Royal Society A,* ***370****, 1780–1797 (2012).*

[4] *Gong, W., Chen, J., and Patterson, E.A., "An experimental study of the behaviour of delaminations in composite panels subjected to bending", Compos. Struct.,* ***123****, 9–18 (2015).*

[5] *Bennati, S., Dardano, N., Valvo, P.S., "An elastic-interface model for buckling-driven delamination growth in four-point bending tests", in Proceedings of AIMETA 2017, Salerno, Italy, 4-7 September 2017, p. 2107–2118.*

[6] *ASTM D7264/D7264M-15, "Standard Test Method for Flexural Properties of Polymer Matrix Composite Materials".*

On the role of interatomic potentials for carbon nanostructures

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Keywords: molecular mechanics, graphene, carbon nanotubes, non-linear mechanics

In the atomistic models of nanomaterials, the most interesting and controversial ingredients are without any doubt the interatomic potentials, because the expressive features of the models themselves depend nearly exclusively on them. This applies to all nanomaterials and also to those based on carbon, such as graphene and nanotubes. And, of course, it also involves the continuum models identified starting from atomistic formulations, because they willy-nilly incorporate strengths and weaknesses of the selected potentials. Obviously, the most interesting and questionable aspects emerge when we investigate highly non-linear phenomena, such as buckling or fracture behavior, but there are difficulties even in a linearized context, if the most known potential, namely that of Brenner, fails blatantly in precision in determining even the elastic constants [1]. Behind these facts there are also difficulties in communication between the Solids Mechanics and Solid State Physics, because the dialogue between these two disciplines takes place through concepts such as stress, deformation, stiffness but also average operators, not always shared cultural heritage. Given the above, the proposed work aims to examine some interatomic potentials [2] [3] [4] based only on short-range interactions, sufficiently simple to be a basis for both the identification of non-linear continuum models and for an effective implementation with Finite Elements. These potentials are either of literature or of a new conception, and have been subjected to a calibration procedure in order to define the elastic constants well and to capture ultimate stresses and deformations of graphene, both in zigzag configuration and in armchair configuration, with adequate precision. In addition, they also take into account the flexural stiffness of the graphene sheets. All the proposed parameterizations are compared with the *ab-initio* results present in the literature. In addition, the false problem of graphene auxeticity in armchair configuration [5] is addressed, demonstrating how, contrarily to the *ab-initio* methods, this is only a product of molecular dynamics and of some potentials.

References

[1] *S. Gamboa, G.L.Vignoles, J-M Leyssale, On the prediction of graphene's elastic properties with eactive empirical bond order potentials, Carbon:* **89***, pp. 176-187, (2015).*

[2] *F.H.Stillinger, T.A.Weber, Computer simulation of local order in condensed phases of silicon, Psysical Review B,* **31***, no. 8, pp. 5262-5271 (1985).*

[3] *W.H.Duan, Q.Wang, K.M.Liew, X.Q.He, Molecular Mechanics modeling of carbon nanotube fracture, Carbon:* **45***, pp. 1769-1776 (2007).*

[4] *S.L.Mayo, B.D. Olafson, W.A.Goddard III, DREIDING: a generic force field for molecular simulations, J. Phys. Chem.,* **94***, pp. 8897 -8909 (1990)*

[5] *J-W Jiang, T.Chang, X.Guo, H.S. Park, Intrinsic Negative Poisso's Ratio for Single-Layer Graphene, Nanoletters,* **16***, pp. 5286-5290 (2016).*

Necking of carbon nanotubes: a 1D continuum approach

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Keywords: Necking, Generalized continua, Nanomechanics.

In a preceding paper [1], some of the authors proposed a 1D model able to describe the necking phenomenon in nanostructures. There the model was used for the analysis of graphene sheets by assuming a Morse modified potential for the atoms interactions.

This presentation is aimed to exploit that model for the analysis of the necking that can happen in carbon nanotubes subjected to severe tension (see e.g. [2]).

Following [1], the first step is the choice of a Representative Elementary Volume (REV) for the nanotube. Two cases are examined: a) the REV is made up by six atoms and only the stretch and angular variation energies are considered; b) eight more atoms are added to the REV in order to take into account also the dihedral energy. The Cauchy-Born procedure is adopted for the construction of the continuum model and a number of different choices of the interatomic potential are made in order to assess their role in the predictive capabilities of the model.

Some cases are studied and for each one of them the trivial (nonlinear) equilibrium path is determined, that exhibits a limit point. A bifurcation that describes the necking is determined along the trivial path. The postbuckling behaviour is then studied. The analyses are performed for both the armchair and zigzag arrangements of the atoms.

The numerical results obtained are discussed pointing out some relevant questions like the auxetic behaviour of the armchair nanotubes and the snap-back that characterise the bifurcated equilibrium path.

References

[1] H. Aminpour, N. Rizzi, On the Modelling of Carbon Nano Tubes as Generalized Continua, in Generalized Continua as Models for Classical and Advanced Materials, (Holm Altenbach and Samuel Forest, Editors), Springer International Publishing Switzerland 2016, ISBN 978-3-319-31719-9 ISBN 978-3-319-31721-2 (eBook) DOI 10.1007/978-3-319-31721-2

[2] S. Zhang and T. Zhu, Atomic geometry and energetics of carbon nanotube neck- ing, Philosophical Magazine Letters, Vol. 87, No. 8, August 2007, 567?574.

Printing of non-Euclidean hydrogel plates

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Keywords: hydrogels, shape morphing, 4D printing

Hydrogels are soft elastic materials that can change shape as a consequence of swelling, which can be triggered by a variety of non-mechanical stimuli. Some polymer gels are biocompatible and they have analogies with living tissues, making them attractive for biomedical applications. Currently there is a growing interest in developing 4D printing techniques [1], where the form and function of the material evolve after it is 3D-printed.

We develop a photolitography-based printing technique that allows to fabricate stimuli-responsive hydrogels capable of morphing into programmed shapes. By combining simulations [2] and experiments, we demonstrate how complex equilibrium shapes emerge from the interaction among simple building blocks. Finally we present preliminary results concerning transient shape control of non-Euclidean plates [3].

References

[1] *Campbell, T.A., Tibbits, S., Garrett, B., The Programmable World, Scientific American,* **202***, 1-15, 2014*

[2] *Lucantonio, A., Nardinocchi, P., Teresi, L., Transient analysis of swelling-induced large deformations in polymer gels, JMPS,* **61***, 205-218, 2013*

[3] *Klein, Y., Efrati, E., Sharon, E., Shaping of elastic sheets by prescription of non-Euclidean metrics, Science,* **315***, 1116-1120, 2007.*

Periodic spectra of canonical quasicrystalline metamaterials

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Keywords: Metamaterial, Phononic crystal, Fibonacci structure.

The Floquet-Bloch spectrum of a family of one-dimensional two-phase periodic structured rods generated by a quasicrystalline sequence -such as the Fibonacci recursion rule- is characterised by self-similar stop/pass band layouts and scaling phenomena [1,2]. These properties are governed by an invariant function of the circular frequency, the Kohmoto's invariant, which can be represented as a surface in a suitable three-dimensional space. In general, the traces of the transmission matrices of the family of rods identify orbits on the Kohmoto's surface [2,3]. For particular frequencies, named *canonical frequencies*, the orbits are closed. The condition for the existence of these frequencies is that a particular ratio between the constitutive parameters of the two phases composing the waveguide is a rational number. We show that for these canonical structures the dynamic spectrum is periodic and that the scaling of this spectrum at increasing generation index of the relevant sequence can be determined analytically performing a linearisation of the orbit concerned. We also show that for frequencies that are not canonical, there are two types of stop bands for the same rod, i.e. regular and ultrawide. Experiments confirming the theoretical predictions have been performed on finite-size specimens.

References

[1] *Gei, M., Wave propagation in quasiperiodic structures: stop/pass band distribution and prestress effects, International Journal of Solids and Structures 47, 3067-3075 (2010).*

[2] *Morini, L., Gei, M., Waves in one-dimensional quasicrystalline structures: dynamical trace mapping, scaling and self-similarity of the spectrum, Journal of the Mechanics and Physics of Solids 119, 83-103 (2018).*

[3] *Morini, L., Eyzat, Y., Gei, M., Negative refraction in quasicrystalline multilayered metamaterials, Journal of the Mechanics and Physics of Solids 124, 282-298 (2019).*

Loss of ellipticity and localization in prestressed beam lattices

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Keywords: lattice dynamics; prestress; localization

The quest for wave channeling and manipulation has driven a strong research effort on topological and architected materials, capable of propagating localized electromagnetical or mechanical signals. With reference to an elastic structural grid, which elements can sustain both axial and flexural deformations, it is shown that material interfaces can be created with structural properties tuned by prestress states to achieve total reflection, negative refraction, and strongly localized signal channeling. On the other hand, prestress states can induce the loss of ellipticity of the structural constitutive response, leading to localization phenomena at both the macroscopic and the microscopic scales. These phenomena are explored in this work and a connection between the microstructural properties of the elastic grid and the effective properties of the equivalent continuum is made.

References

[1] *Bordiga, G., Cabras, L., Piccolroaz, A., Bigoni, D., Prestress tuning of negative refraction and wave channeling from flexural sources, Applied Physics Letters,* **114***, 041901 (2019).*

Solid-fluid interaction and Biot's theory for consolidated, fully-saturated granular material

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Keywords: Acoustic waves, Biot model, Granular material.

We study the qualitative and quantitative features of velocities and attenuation of compressional waves in a fully-saturated granular material. Acoustic waves in porous saturated materials find a proper description in the theory proposed by Biot [1] [2] where two longitudinal waves and a transverse wave are predicted. The theory is based upon a system of dynamics equations where both fluid and solid phase are considered and their relative interaction.
We focus on a fully saturated granular materials made of identical elastic particles surrounding by a compressible fluid in a consolidate condition. We aim to improve the Biot's model by including a particle fluid interaction [3] that will modify some of the terms presented in the theory. The passage of a compressible wave induces the fluid in the pores to interact with the particles. This interaction is governed by a lubrication model in which the elasticity of the particles and the fluid is modelled by single springs. The integration over all possible interaction springs provides the force between a typical pair. Next we move from a local force interaction to the average stress of the aggregate that gives a frequency dependent overall moduli of the particles immersed in a fluid [4] [5]. These moduli in a natural way will enter in the Biot's model and modify it with excellent comparison with experimental data.

References

[1] *M. A. Biot, "Theory of propagation of elastic waves in a fluid-saturated porous solid. I. Low-frequency range." J. Acoust. Soc. Am. 28, 168178 (1956)..*

[2] *M. A. Biot, "Theory of propagation of elastic waves in a fluid-saturated porous solid. II. Higher frequency range." J. Acoust. Soc. Am. 28, 179-191 (1956)..*

[3] *G. Recchia, J. T. Jenkins, L. La Ragione, "Storage and loss moduli in an ideal aggregate of elastic disks, with lubricated contacts", in "Micro to MACRO Mathematical Modelling in Soil Mechanics". eBook ISBN 978-3-319-99474-1; Hardcover ISBN 978-3-319-99473-4. Series ISSN 2297-0215. Edition Number 1 (2018).*

[4] *L. La Ragione, G. Recchia, J. T. Jenkins, "A micro-mechanical model for the Biot theory of acoustic waves in a fully saturated granular material", Proceedings of Meetings on Acoustics, Vol. 35, 005001 (2018).*

[5] *L. La Ragione, G. Recchia, J. T. Jenkins, "Particle-fluid interaction and Biot's theory for an unconsolidated granular material", Journal of the Acoustical Society of America, under review (2019).*

Influence of sunlight on the durability of laminated glass panes

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Keywords: Laminated glass, polymers, durability.

The design of laminated glass structures needs detailed knowledge of the mechanical behavior of interlayer materials, either through the direct modeling of composite glass panes or using practical expressions based on simplified methods. However, the polymer interlayer is responsible for not linear, time and temperature dependent deformation of the structural elements that causes also dependence from load history. The peculiarity of interlayer properties impacts also on the functionality of procedures like cold lamination bending or cold bending and, most of all, on the durability of structural elements. As it is known, polymer materials are sensitive to weathering actions, particularly to solar radiation [1, 2, 3]; the modification of mechanical properties of the interlayer can affect the structural response of laminated glass units [4, 5, 6, 7].

In this paper the consequences of solar radiation on the behavior of laminated glass interlayer are experimentally evaluated. In general, it seems that the modification of interlayer behavior is not linearly dependent on the exposition time, as if UV was responsible for opposite effects connected to different changes in the material structure.

The parameters of constitutive model of interlayer material, based on linear viscoelasticity and thermo-rheological simplicity, are tuned based on the experimental behavior of the laminated glass beams tested in creep in different temperature conditions. The possibility of determining some damage parameters that accounts for the modification attained by interlayer while exposed to solar radiation, is investigated.

References

[1] El-Din, N.M.Ss., Sabaa M.W., "Thermal degradation of poly(vinyl butyrral) laminated safety glass", Polymer Degradation and Stability 47(2), page 283-8 (1995).

[2] Saad, G.R., El-Shafee, E., Sabaa, M.W., "Dielectric and mechanical properties in the photodegradation of poly(vinyl butyral) films", Polymer Degradation and Stability 47(2), page 209-15 (1995).

[3] Liu, R., He, B., Chen, X., "Degradation of poly(vinyl butyral) and its stabilization by bases" Polymer Degradation and Stability 93(4), page 846-53 (2008).

[4] Ensslen, F., "Tragverhalten von bewitterten Verbund-Sicherheitsglas-Scheiben", Stahlbau 16(8), page 582-90 (2007).

[5] Louter, C., Belis, J., Veer, F. and Lebet, J.P., "Durability of SG-laminated reinforced glass beams: Effects of temperature, thermal cycling, humidity and load-duration", Construction and Building Materials 27, page 280–292 (2012).

[6] Serafinavicius, T., Lebet, J-P., Louter, C., Kuranovas, A., Lenkimas, T. "The effects of environmental impacts on durability of laminated glass plates with interlayers (SG, EVA, PVB)" In: Louter C, Bos F, Belis J, Lebet J-P, editors. Challenging glass 4 & COST action TU0905 final conference. Losanna: CRC PRESS-TAYLOR & FRANCIS GROUP; (2014).

[7] Andreozzi, L., Briccoli Bati, S., Fagone, M., Ranocchiai, G., Zulli, F., "Weathering action on thermo-viscoelastic properties of polymer interlayers for laminated glass", Construction and Building Materials 98, page 757-766 (2015).

A resonant metasurface for Love waves

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Keywords: Love waves; Metamaterials; Metasurfaces; GRIN Lenses

Elastic metamaterials comprise a broad class of artificially engineered media designed to control the propagation of elastic waves at sub-wavelength scales. This unique ability stems from the presence of resonant inclusions embedded in an elastic matrix which affect the wave propagation at specific frequency ranges. Elastic metasurfaces are a special class of metamaterials, realized by arranging an array of resonant structures at the free surface of the medium or at an interface between two media. Metasurfaces of vertical resonators over an elastic half-space have been successfully utilized to control the propagation of in plane surface waves, i.e., Rayleigh waves, for various applications across different length scales, as wave guiding [1], [2] or wave filtering [3], [4].

In this talk, we present an extension of the metasurface concept to Love waves, anti-plane surface waves existing in semi-infinite layered media [5]. We investigate the interaction between Love waves and a metasurface of horizontal oscillators deriving an original analytical solution for its dispersion relation. By tuning the mass and the frequency of the resonators we achieve full control of the Love wave phase velocity, and thus on the related metasurface refractive index. We exploit the ability of manipulating the metasurface refractive index to design gradient index lenses (i,e. Luneburg and Maxwell lenses) for Love waves redirection. We analyse the performance of the designed lenses using full 3D FE simulations confirming the analytical predictions. Our work can serve as a guide for advanced Love wave-based devices and sensors as well as for the design of meter-scale barriers for low frequency vibrations attenuation [6].

References

[1] Addouche, M., Al-Lethawe, M. A., Elayouch, A., Khelif, A. Subwavelength waveguiding of surface phonons in pillars-based phononic crystal. AIP Adv. 4, 124303 (2014).
[2] Al Lethawe, M., Addouche, M., Benchabane, S., Laude, V., Khelif, A. Guidance of surface elastic waves along a linear chain of pillars. AIP Adv. 6, (2016).
[3] Benchabane, S., Khelif, A., Rauch, J. Y., Robert, L., Laude, V. Evidence for complete surface wave band gap in a piezoelectric phononic crystal. Phys. Rev. E - Stat. Nonlinear, Soft Matter Phys. 73, 065601 (2006).
[4] Colombi, A., Colquitt, D., Roux, P., Guenneau, S., Craster, R. V. A seismic metamaterial: The resonant metawedge. Sci. Rep. 6, 27717 (2016).
[5] Palermo, A., Marzani, A. Control of Love waves by resonant metasurfaces. Sci. Rep. 8, 7234 (2018).
[6] Palermo, A., Krödel, S., Marzani, A., Daraio, C. Engineered metabarrier as shield from seismic surface waves. Sci. Rep. 6, 39356 (2016).

Multiscale analysis of materials with anisotropic microstructure as micropolar continua

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Keywords: Multiscale, Anisotropic materials, Finite element method

Multiscale procedures are often adopted for the continuum modeling of materials composed of a specific micro-structure. Generally, in mechanics of materials only two-scales are linked. In this work the original (fine) micro-scale description, thought as a composite material made of matrix and fibers/particles/crystals which can interact among them, and a scale-dependent continuum (coarse) macro-scale are linked via an energy equivalence criterion [1, 2]. In particular the multiscale strategy is proposed for deriving the constitutive relations of anisotropic composites with periodic microstructure and allows us to reduce the typically high computational cost of fully microscopic numerical analyses. At the microscopic level the material is described as a lattice system while at the macroscopic level the continuum is a micropolar continuum, which provides orientation as a degree of freedom (other than classical displacements). The derived constitutive relations account for shape, texture and orientation of inclusions as well as internal scale parameters, which account for size effects even in the elastic regime in the presence of geometrical and/or load singularities [2-5].
Applications of this procedure concern polycrystals, wherein an important descriptor of the underlying microstructure gives the orientation of the crystal lattice of each grain, fiber reinforced composites [5], as well as masonry-like materials [2-3]. In order to assess the efficiency of the proposed multiscale strategy, some numerical finite element simulations, with elements specifically performed for micropolar media, are presented. The performed simulations, which extend several parametric analyses earlier performed [3], involve two-dimensional media subjected to combined shear and compression loads, both in the linear and non-linear framework. Computational performances are investigated and compared with classical benchmarks from the published literature and new applications leading to novel multiscale analysis are shown.

References

[1] Trovalusci, P. and Masiani, R. "Non-linear micropolar and classical continua for anisotropic discontinuous materials". Int J Solid Struct, ***40,*** *1281–1297 (2003).*

[2] Trovalusci, P. and Masiani, R. "A multi-field model for blocky materials based on multiscale description", Int J Solid Struct, ***42****, 5778–5794 (2005).*

[3] Leonetti, L., Fantuzzi, N., Trovalusci, P., Tornabene, F. "Scale effects in orthotropic composite assemblies as micropolar continua: A comparison between weak and strong-form finite element solutions", Materials, ***12****, 758 (2019).*

[4] Fantuzzi, N., Leonetti, L., Trovalusci, P., Tornabene, F. "Some Novel Numerical Applications of Cosserat Continua", Int J Comput Methods, ***15****, 1850054.*

[5] Sansalone, V., Trovalusci, P., Cleri, F. "Multiscale modeling of materials by a multifield approach: Microscopic stress and strain distribution in fiber-matrix composites", Acta Mat, ***54****, 3485–3492 (2006).*

Homogenization of polycristalline composites with thin interfaces using a Fast Statistical Homogenization Procedure (FSHP)

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Keywords: Statistically-based Homogenization, Random Multiphase Structure, CMC

Several materials adopted in various engineering applications exibit a random multiphase structure. In particular, Ceramic Matrix Composites (CMC) play a relevant role in this context. CMC materials show a great variety of internal structures, such as short or long-fibers, layered composite materials, particle and functionally graded materials, polycrtstalline materials with grain boundaries or thin/thick interphases between grains [1]. In this work, we focus the attention on random polycrystalline materials with thin interfaces. These interfaces can play the role of a matrix in which the polycrystals are embedded. In CMC materials, a key aspect is the evaluation of appropriate mechanical properties to be adopted for the study of their behaviour. However, in the case of materials with random multiphase structure, the lack of periodicity makes it difficult to perform homogenization process, with particular reference to the possibility of identifying a representative volume element (RVE), that is not known *a priori*. To overcome this problem, a statitically-based homogenization procedure has been developed in [2] for random bi-phases materials with circular inclusions. The main problem of this procedure is the high number of simulations required to identify the RVE and the homogenized moduli. In [3] the procedure has been integrated and implemented in a so called Fast Statistical Homogenization Procedure (FSHP) using Virtual Element Method (VEM), making possible to easily perform high number of analyses. The recently proposed VEM [4], is an extension of Finite Element philosophy with many advantages: possibility to use very general polygons with rather general shapes; capabilities of using hanging nodes, that permit local refinements and coupling different degree elements; robustness to distorsion of the elements; perfect coupling with FEM elements; accuracy because the stiffness matrix is computed in precision machine; easy to implement. Through FSHP with VEM, several parametric analyses have been performed and RVE size with related mechanical parameters have been identified.

References

[1] *Sadowski, T., Marsavina, L., Multicale modelling of two-phase Ceramic Matrix Composites, Comput Mater Sci,* **50**, *1336–1346 (2011).*

[2] *Trovalusci, P., Ostoja-Starzewski, M., De Bellis, M.L., Murrali, A., "Scale-dependent homogenization of random composites as micropolar continua", Eur J Mech A/Solids,* **49**, *396–407 (2015).*

[3] *Pingaro, M., Reccia, E., Trovalusci, P., Masiani, R., Fast statistical homogenization procedure (FSHP) for particle random composites using virtual element method, Comput Mech, 1–14 (2019).*

[4] *Beirao Da Vega, L., Brezzi, F., Marini, L.D., "Virtual Elements for Linear Elasticity Problems", SIAM J Numer Anal,* **51**, *794–812 (2013).*

Robust design of thin magneto-elastic actuators

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Keywords: magneto-rheological elastomers, inverse problem, pde constrained minimization

Magneto-rheological elastomers are a class of materials whose deformation can be controlled by applying an external magnetic field. They are usually produced by dispersing ferromagnetic or paramagnetic particles in a soft elastomeric matrix. The application of the magnetic field can either be used to orient the particles when the elastomer is still un-cured or to deform the composite once the matrix has become solid [1, 2]. This peculiar property arises from the combination of magnetic susceptibility of the embedded particles and the large elastic compliance of the polymeric matrix, and allows the design of magnetic robots which can crawl and even swim, controlled remotely [3]. In this work, we study the inverse design problem which arises when producing thin magneto-rheological actuators with bespoken deformed shapes. By using a nonlinear model for thin magneto-elastic rods recently proposed in [4], we formulate the inverse problem as a pde constrained minimization whose solution gives to the optimal distribution of the particles necessary to achieve the desired shape. The same problem is extended to control multiple deformed configuration which would allow a controlled motion of the actuator to be realised.

References

[1] *Stanier, D. C., Ciambella, J. & Rahatekar, S. S. Fabrication and characterisation of short fibre reinforced elastomer composites for bending and twisting magnetic actuation. Compos. Part A Appl. Sci. Manuf. 91, 168–176 (2016).*

[2] *Ciambella, J., Stanier, D. C. & Rahatekar, S. S. Magnetic alignment of short carbon fibres in curing composites. Compos. Part B Eng. 109, 129–137 (2017).*

[3] *Lum, G. Z. et al. Shape-programmable magnetic soft matter. Proc. Natl. Acad. Sci. 113, E6007–E6015 (2016).*

[4] *Ciambella, J., Favata, A. & Tomassetti, G. A nonlinear theory for fibre-reinforced magneto-elastic rods. Proc. R. Soc. A Math. Phys. Eng. Sci. 474, 20170703 (2018).*

Evaluation of piezoelectric energy harvester based on flag-flutter

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Keywords: Piezoelectric, Energy Harvester, Flag-Flutter, Aeroelastic, Fluid-Structure Interaction

From the last few decades, piezoelectric materials are widely used in the field of micro/nano-electromechanical systems. With the recent advancements in compact and portable electronic technology, power sources have been evolved too. For such portable electronic devices, it is necessary to have their own power source rather than relying on external batteries that has limited lifespan and in some cases their replacement is problematic as well i.e., wireless sensors for suborbital missions. In these conditions, piezoelectric materials play a vital role as an alternative source of power supply to drive microelectronic devices. The effect of electromechanical and fluid-surface interaction is an important phenomenon in piezoelectricity for characterizing smart structures, energy harvesters, integration of sensors and actuators for structural health monitoring specially for aerospace industry.

In this research, the harvester will absorb energy from airflow, thanks to the fluid-structure interaction (FSI) and convert it into useful electrical energy. To analyze FSI, it is important to consider the whole dynamics of the system formed by the structure and the flow i.e., aeroelastic system rather than considering them as two different systems. This coupling, from the mathematical point of view, happens because the natural boundary condition of the structure is defined by the flow pressure which is mutually influenced by the structure. This leads to a very complex phenomenon that is intrinsically un-stationary and it is no longer possible to study it by considering the structure and the flow separately. The aeroelastic system remains stable up to a critical velocity of the flow known as flutter velocity which depends on the flowing media and the mechanical properties of the surrounded system. After this particular velocity the aeroelastic system is no longer stable in its unperturbed condition. The system can no longer be considered as linear anymore and stable oscillations arises, the so-called Limit Cycle. Indeed, the interaction of the fluid in the form of airflow with structure i.e., airfoil will transfer oscillations to the piezoelectric which will result in energy harvesting.

In the present work, the possibility to extract energy by means of piezoelectric transduction from a post-critical aeroelastic behavior, as the Limit Cycle Oscillation (LCO), is investigated both numerically and experimentally. A suitable designed aeroelastic device based on the use of piezoelectric components and operating thanks to the flag-flutter phenomenon is presented. The presented harvester will be studied from both the numerical and the experimental point of view. Indeed, harvesting performances, flutter boundaries, aeroelastic modes, and Limit Cycle Oscillations (LCOs) amplitudes predicted by the different models, are compared with experimental data provided by wind tunnel tests.

They have numerous applications in the field of aerospace engineering because of their voltage dependent actuation. Furthermore, it will be shown that the overall system is suitable for energy harvesting and can be utilized to drive microelectronics i.e., wireless sensors in sub-orbital missions, launchers, space vehicles and in various aerospace applications.

An adaptive peridynamic model for dynamic fracture analysis in brittle materials

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The most common way of discretizing peridynamics is a meshfree method which makes use of a Cartesian grid of nodes. However, this contributes to a difficulty when a very dense grid spacing for a localized area is required. In this study, a way to handle this issue, by developing a multi-grid peridynamic model, is introduced. A new strategy to couple peridynamic grids with different grid spacing is devised. The method is free of ghost forces in static cases; moreover, it can cope with spurious wave reflections in dynamic cases thanks to its proper discretization scheme. One of the appealing features of this method is that it does not lead to any loss of volume (corresponding to the non-uniform discretization) at the interface between different grids. In this study, an efficient algorithm is designed to develop a new adaptive grid refinement technique in peridynamics using the proposed coupling strategy. This enables the peridynamic solver to increase the resolution of the analysis only in the critical zones. The performance of the approach in terms of accuracy and efficiency for some benchmarks as well as multi-physics thermomechanical problems, including crack propagation in brittle materials, is investigated. We compare the solutions of the proposed method with those of a standard peridynamic model, which employs uniform discretization, and show that the same accuracy can be achieved at a much smaller computational cost.

MS04

MODELLING AND ANALYSIS OF SMALL-SCALE STRUCTURES

Effective stiffness of Carbon NanoTube fibers under tension and bending

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Keywords: Carbon NanoTubes, tensile response, bending response, effective stiffness.

Because of their high tensile strength and electrical and thermal conductivities, at lower density than classical materials, Carbon NanoTubes (CNTs) have been perceived as a very promising material for applications in nano-engineering. Due to their flexibility, fibers composed of a high number of CNTs can be used as sensory fibers, medical catheters, and energy devices. For applications of this kind, the assessment of the flexural response is a crucial point, which is attracting the growing interest of researchers. The bending response of microscopic CNT bundles and macroscopic fibers has been extensively experimentally investigated, demonstrating that this is intermediate between the limit cases of perfect coupling, in which the fiber behaves as a homogeneous rod, and decoupled behavior, where the constituent NTs can freely slide one another [1]. Some authors have exploited the theory of layered beams to propose simplified models for the bending response of CNT fibers, but these are characterized by very restrictive assumptions. In particular, the bundle length is considered equal to that of the constituent NTs, while this is usually several orders of magnitude higher.

A micromechanically-motivated model is here presented to interpret the response under pure traction and bending of circular fibers composed of a great number of CNTs (of the order of 10^6-10^8 in the cross section), arranged in a square lattice, whose length are much less than that of the fiber. The model accounts for the shear coupling of the CNTs along their lateral surface, due to the van der Waals forces that provide the cohesion of the fiber. The most important characteristic of the model is that it considers the offset of the CNTs placed on contiguous longitudinal lines. The bending response has been studied by considering a generic bending plane, inclined with respect to the lattice vectors. In this case, the springing apart of the NTs allows their mobility in longitudinal direction, providing an internal re-arrangement under the applied deformation that is determined through energy minimization.

Based on an accurate evaluation of the load state of the individual CNTs, the internal actions in the whole fiber are evaluated. Remarkably, it is demonstrated that uniform axial strain is associated with constant tensile normal force and null bending moment, while a constant-curvature deformation corresponds to null axial force and constant bending moment. Consequently, the CNT fiber behaves as a continuous homogeneous beam with constant stiffness [2], which turns out to be dependent on mechanical and geometrical parameters of the bundle and of the constituent CNTs. The obtained results are in good qualitative agreement with the experimental findings [1].

References

[1] Adnan, M., Pinnick, R., Tang, Z., Taylor, L. W., Pamulapati, S. S., Royer-Carfagni, G., and Pasquali, M., "Bending behavior of CNT fibers and their scaling laws".Soft Matter, ***14(41)****, pages 8284-8292, (2018).*

[2] Galuppi, L., Pasquali, M., Royer-Carfani, G., "Bending response of Carbon NanoTube bundles", submitted (2019).

Influence of hot-spot location on fretting fatigue crack path and lifetime estimation

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Keywords: Al 7075-T651 aluminium alloy, fretting fatigue, hot-spot location.

Fretting is a contact phenomenon affecting metallic structural components that are subjected to vibrations or small oscillatory movements. In such conditions, microcracks may nucleate in correspondence to the contact zone and, consequently, propagate due to the presence of a cyclic fatigue loading, thus resulting in the fatigue failure of the components [1]. As a matter of fact, microcracks are frequently observed in the stress concentration regions, after few hundred cycles. Moreover, it is important to take into account the multiaxial nature of the stress field evaluated in a region distant 4 to 5 times the material mean grain size from the contact surface.

In the present paper, a new methodology for estimating both crack path and lifetime of metallic structural components under constant amplitude fretting fatigue loading is proposed. Such a methodology is based on the joint application of:

(i) the multiaxial fatigue criterion by Carpinteri et al. [2] for metallic structures under multiaxial constant amplitude fatigue loading, in high-cycle fatigue regime;

(ii) the critical direction method by Araújo et al. [3];

(iii) the Theory of the Critical Distance by Taylor [4], in the form of the Line Method.

Firstly, the proposed methodology is verified by examining the experimental results reported in Ref. [5], related to experimental tests carried out by using two cylindrical fretting pads pushed against a dog bone specimen, where pads and specimen are made of Al 7075-T651 aluminium alloy.

Then, a parametric study related to the hot-spot location (starting from the trailing edges and moving inside the contact surface) is performed in order to evaluate its influence on both crack path and fatigue life.

References

[1] Vantadori, S., Fortese, G., Ronchei, C., Scorza, D., "A stress gradient approach for fretting fatigue assessment of metallic structural components," International Journal of Fatigue, 101, 1-8 (2017).

[2] Carpinteri, A., Spagnoli, A., Vantadori, S., "Multiaxial fatigue assessment using a simplified critical plane-based criterion," International Journal of Fatigue, 33, 969-976 (2011).

[3] Araújo, J.A., Almeida, G.M.J., Ferreira, J.L.A., da Silva, C.R.M., Castro, FC., "Early cracking orientation under high stress gradients: The fretting case," International Journal of Fatigue, 100, 611-618 (2017).

[4] Taylor, D., The theory of critical distances: a new perspective in fracture mechanics, Elsevier, Oxford, UK (2007).

[5] Vázquez, J., Navarro, C., Domínguez, J., "Two dimensional versus three dimensional modelling in fretting fatigue life prediction," Journal of Strain Analysis, 51, 109–117 (2016).

Experimental investigation on structural vibrations by a new shaking table

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Keywords: vibration mitigation; structural design; tuned liquid dampers.

The purpose of this work is to perform experimental investigations on structural vibrations by using a novel shaking table developed by our team at the laboratory of mechanics of the department of industrial engineering of the University of Salerno. The possible sources of excitation for civil structures are both environmental (earthquake, wind, waves, differential subsidence, thermal gradients) and anthropic (pedestrian traffic on walkways, vehicular traffic on viaducts, operating machines) [1]. These phenomena are undesirable, so one of the challenges for structural engineering is to find new techniques and devices capable of protecting structures from excessive stress and ensure full habitability. Our idea is to test devices for vibration mitigation and seismic devices for slender parametric structures [2, 3]. We designed a new shaking table capable of supporting the different types of structures we want to study. The goal of our experimental investigation is to test tuned liquid damper (TLD) for mitigating vibration in a vertical irregular three-story structure. This structure is made of aluminium bars for the floors and harmonic steel for the beams [4]. The shaking table is made of a solid block of aluminium weighing around 130 kg. On both sides of the frame there are Hiwin guides, with two carriages each, on which a sled made of bosh sections is mounted. The vibrating table is actuated by means of an electrodynamic shaker of Brüel & Kjær piloted by the wave generator Textronix Arbitrary Function Generator AFG320, amplified by the power amplifier Brüel & Kjær - Type 2732. Brüel & Kjær Type 4371 accelerometers have been installed on each floor of the structure in order to acquire the acceleration time history. After creating a 3dof lumped-mass model for evaluating the natural frequencies of the system and validating these data by a hammer impact test, we were able to set the sloshing frequency of the TLD by method proposed by Housner [5]. The dynamical behaviour of the structure was studied by positioning, for the same frequency of the input signal, the TLD on each floor, in order to analyse the responses to the different configurations. Experimental results have demonstrated the excellent ability of a TLD to mitigate vibrations under resonance conditions when appropriately sized.

References

[1] *Ewins, D. J., MODAL TESTING theory, practise and application, Research Studies Press LTD, Baldock, Hertfordshire, England (2000).*

[2] *Krishnamoorthy, A., "Finite Element Method of Analysis for Liquid Storage Tank Isolated with Friction Pendulum System," Journal of Earthquake Engineering,* **1**, *11 (2018).*

[3] *De Simone, M.C., Guida, D., "Dry Friction Influence on Structure Dynamics," in Proceedings of of the 5th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Crete, Greece, 25-27 May 2015, page 4483-4491,*

[4] *Pabarja, A., Vafaei, M., Alih, S. C., Yatim, M. Y. M. and Osman, S. A., "Experimental study on the efficiency of tuned liquid dampers for vibration mitigation of a vertically irregular structure," Mechanical Systems and Signal Processing,* **114**, *page 84-105 (2019).*

[5] *Housner, G. W., "The dynamic behavior of water tanks," Bulletin of the seismological society of America,* **53(2)**, *page 381-387, (1963).*

Thermally induced vibrations of slender beams at the nanoscale

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Keywords: thermally-induced vibration, nano-beams, moderately large deflections.

Vibrations induced by fast varying thermal gradients were first investigated by Boley [1] with respect to the case of beams operating in micro-gravity extra-atmospheric environment. Indeed, spacecrafts and orbiting satellites crossing from the earth's shadow into sunlight experience rapid changes in the thermal loading due to the solar radiation, which is responsible of time dependent bending moments and transverse shear forces on appendages and booms, which typically are very long, lightweight structures, having high flexibility with low frequency and damping characteristic [2]. At small scales, in the fields of Micro-Electro-Mechanical Systems (MEMS) and Nano-Electro-Mechanical Systems (NEMS), thermally-induced vibrations have been observed in beam-shaped resonators after thermal shocks due to laser heating [3]. Hence, a correct comprehension of the phenomenon, that could not be correctly analyzed if the inertia effect and the coupling between temperature and strain fields are not taken into account [4], is of practical interest for applications, from the macroscale down to the nanoscale. With this idea in mind, the proposed contribution is focused on the theoretical and numerical analysis of cantilevers modeled using Rayleigh beam theory undergoing thermally-induced vibration. The equations of motion are written under the hypothesis of moderately large deflections taking into account the thermo-mechanical coupling and the interplay among thermal conductivity, longitudinal modulus of elasticity and mass density, with the aim to optimize the mechanical response and investigate the role played, at the nanoscale, by nonlocal effects on the dynamics of cantilevers and slender beams.

References

[1] Boley, B.A., Thermally induced vibrations of beams, *Journal of the Aerospace Sciences* **23**, 179–181 (1956).

[2] Kong, C., Park, H., Lee, H., Study on comparison of atmospheric and vacuum environment of thermally-induced vibration using vacuum chamber, *International Journal of Aeronautical and Space Sciences*, **11**(1), 26-30 (2010).

[3] Sun, Y., Fang, D., Saka, M., Soh, A. K. Laser-induced vibrations of micro-beams under different boundary conditions, *International Journal of Solids and Structures*, **45**(7-8), 1993-2013 (2008).

[4] Manolis, G.D., Beskos, D.E. Thermally induced vibrations of beam structures, *Computer Methods in Applied Mechanics and Engineering*, **21**, 337–355 (1980).

Change of buckle patterns in micro-structures

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Keywords: micro-structures, auxetic materials, buckling modes

Many structures at a micro level present regular patterns which can be represented by assemblages of thin-plates. The behaviour of such structures is strongly affected by instability phenomena which can be studied analytically only in very simple cases. In fact, in the vast majority of problems, the analysis of these models needs to be conducted numerically.

In particular auxetic materials are characterised by high energy absorption and fracture resistance and can be found in nature, as it is the case of many honeycomb structures at the macro or at the micro scale, or can be manufactured with the aid of modern technologies. The current capabilities of manufacture allows to adapt auxetic materials to different needs and experimental and numerical work carried out by Bertoldi et al. [1] has shown that mechanical instabilities in periodic porous structures can induce a complete reorganisation of the material from the original configuration.

In this framework, it is well-known that the non-linearity of the modelling introduces the possibility of non-unique relationships between the loading applied to the structure and the corresponding deformations modes, including the buckling failure mode. If only one non-linear 'loading path' is possible then the calculations carried out in the modelling are unique and lead to the 'correct' engineering description of the thin-walled structure. Nevertheless, in many cases there could be 'multiple loading paths' and it is very possible that the results from the non-linear modelling will be non-unique and the results from the modelling could lead to erroneous results. The work in stability carried out in the past decades has shown that significant changes in the deformation modes of many micro-structures can occur suddenly despite very low stress [2-4].

The existence of a multiplicity of equilibrium paths at or near the critical load level obviously has important consequences for any numerical nonlinear stability analysis. In the present work it is shown that reliable predictions based on initial post-buckling behaviour, which are so successful in the simple case of distinct bifurcation points may turn out to be quite difficult to achieve in the case of many micro-structures and this fact can be also correlated to the phase transitions from auxetic to non-auxetic and vice versa, which have been recently pictured on the basis of a new single cell model [5].

References

[1] Bertoldi K, Reis PM, Willshaw S, Mullin T. Negative poisson's ratio behaviour induced by an elastic instability. Adv. Mater. 2010; 22: 361–366..

[2] Stein M. The phenomenon of change in buckle patterns in elastic structures. NASA technical report R-39, 1959.

[3] Supple WJ. On the change of buckle pattern in elastic structures. Int.. J. Mech. Sci. 1968; 10: 737-745.

[4] Schaeffer D, Golubitsky M. Boundary Conditions and Mode Jumping in the Buckling of a Rectangular Plate. Comm. Math. Phys. 1979; 69: 209-236.

[5] Hunt GW, Dodwell TJ. Complexity in phase transforming pin-jointed auxetic lattices. Proc. R. Soc. A – Math. Phys. Eng. Sci. 2019; 475(2224):20180720.

Nonlocal mechanics of curved beams

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Keywords: Curved beams; Nonlocal elasticity; NEMS.

Curved structures are basic structural components of Nano-Electro-Mechanical-Sistems (NEMS) [1, 2, 3] whose design requires appropriate modelling of scale effects [4].

In the present study, the size-dependent static behaviour of slender curved elastic beams is investigated by stress-driven nonlocal continuum mechanics, adopted for straight structures in [5, 6]. Unlike formulations of local elasticity, axial strains and flexural curvatures are outputs of integral convolutions involving axial and bending interaction fields and appropriate attenuation functions. The stress-driven integral model for curved beams is shown to be equivalent to a differential problem with constitutive boundary conditions.

The new methodology is illustrated by examining exact nonlocal responses of curved structures of applicative interest, such as nano-sensors and nano-actuators.

Peculiar properties, merits and implications of the new proposal are illustrated in comparison with strategies available in literature.

References

[1] *Wang, Q., Arash, B., A review on applications of carbon nanotubes and graphenes as nano-resonator sensors, Computational Material Science,* **82***, 350-360 (2014).*

[2] *Voiculescu, I., Zaghloul, M., Nanocantilever beams: modeling, fabrication, and applications, CRC Press, (2015).*

[3] *Teik-Cheng, L., Nanosensors: theory and applications in industry, healthcare and defense, CRC Press, (2016).*

[4] *Farajpour, A., Ghayesh, M.H. and Farokhi, H., A review on the mechanics of nanostructures, International Journal of Engineering Science,* **133***, 231-263 (2018).*

[5] *Romano, G., Barretta, R., Nonlocal elasticity in nanobeams: the stress-driven integral model, International Journal of Engineering Science,* **115***, 14-27 (2017).*

[6] *Barretta, R., Diaco, M., Feo, L., Luciano, R., Marotti de Sciarra, F., Penna, R., Stress-driven integral elastic theory for torsion of nano-beams, Mechanics Research Communications,* **87***, 35-41 (2018).*

Bending and buckling of Timoshenko nano-beams in stress-driven approach

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Keywords: Nonlocal stress-driven model, stubby nano-beams, shear deformation theories.

The theoretical treatment of structures having very small size, such as nano-beams, requires suitable models different from those provided by the local continuum theory. Many researchers, coming from engineering areas where local models are widespread, have made extensive use of nonlocal models derived from local ones. Above all, the Euler-Bernoulli beam model traditionally used in local theory has also been extended to treat nonlocal problems, originating many nonlocal Euler-Bernoulli beam models. Following this approach, in recent years, many advances have been made for nonlocal beams [1]. Romano and Barretta [2] have proposed a stress-driven model able to provide closed-form solutions to many nano-beam problems. Specifically, the stress-driven model has been adopted for bending of functionally graded nano-beams, buckling, axisymmetric nanoplates and nonlocal thermoelastic behavior. Recently, a stress-driven local-nonlocal mixture [3] has been applied to the bending problem of Timoshenko nano-beams. In this work, a modified total potential energy functional is derived for stress-driven non-local model of Timoshenko beam subject to transverse load and/or critical axial load. The modified functional includes expressions representing the constitutive boundary conditions, which are a peculiarity of the adopted stress-driven approach. The Euler equations of the modified functional are the governing equations of the stress-driven non-local problem. Instead of solving directly the Euler equations, approximate solutions are searched by imposing the stationary condition of the modified functional through the Ritz method. In order to validate the method, the proposed numerical solutions are compared with closed-form expressions, in load cases where closed-form solutions are available. Finally, the proposed numerical method is used for determining the buckling load of non-local Timoshenko beam. In the conference presentation, further applications of the proposed method to local-nonlocal mixture and higher-order shear deformation beam theories will be illustrated.

References

[1] Fernández-Sáez, J., Zaera, R., Loya, J.A. and Reddy, J.N., "Bending of Euler-Bernoulli beams using Eringen's integral formulation: A paradox resolved", International Journal of Engineering Science, ***99****, pages 107-116 (2016).*
[2] Romano, G. and Barretta, R., "Nonlocal elasticity in nanobeams: the stress-driven integral model", International Journal of Engineering Science, ***115****, pages 14-27 (2017).*
[3] Barretta, R., Caporale, A., Faghidian, S.A., Luciano, R., Marotti de Sciarra, F. and Medaglia, C.M., "A stress-driven local-nonlocal mixture model for Timoshenko nano-beams", Composites Part B: Engineering, ***164****, pages 590-598 (2019).*

Emergence of velocity strengthening and weakening behaviour in viscoelastic materials

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Keywords: Friction, Viscoelasticity, Numerical model

Over the years, the frictional properties of rubber materials have been investigated in depth. The knowledge of rubber-surface interactions when sliding occurs is a topic of great interest in the scientific community, especially in the automotive sector. To study friction coefficients of viscoelastic materials, we developed a numerical code using a 1D spring block model. This model was used to study the macroscopic frictional properties of hierarchical and 2D systems [1–6]. The Amontons-Coulomb law used in [1–4] was replaced with rate and state equations. These equations were introduced to analyse the behaviour of friction coefficients as a function of the sliding velocity and time. In addition, the Kelvin–Voigt model was introduced to study the frictional properties of viscoelastic and mixed materials in which the number of viscoelastic interactions was changed.

We observed that the increment of the viscoelasticity of the material allows a reduction of the static friction coefficient. This effect is caused by an increment of the damping force. Dynamic friction coefficients decrease increasing the viscoelasticity of the system, leading to think that viscoelastic systems dissipate less than the elastic one. To confirm this the energy dissipated by the systems was calculated and the results show a decrease of dissipated energy with viscoelasticity. Dynamic friction coefficient presents also the onset of a minimum in systems with a high percentage of viscoelastic interactions caused by creep mechanisms.

References

[1] *G. Costagliola, F. Bosia, and N. M. Pugno, "Hierarchical Spring-Block Model for Multiscale Friction Problems", ACS Biomater. Sci. Eng., vol. 3, no. 11, pp. 2845–2852, (2017).*

[2] *G. Costagliola, F. Bosia, and N. M. Pugno, "A 2-D model for friction of complex anisotropic surfaces", J. Mech. Phys. Solids, vol. 112, pp. 50–65, (2018).*

[3] *G. Costagliola, F. Bosia, and N. M. Pugno, "Static and dynamic friction of hierarchical surfaces", Phys. Rev. E, vol. 94, no. 6, pp. 1–10, (2016).*

[4] *G. Costagliola, F. Bosia, and N. M. Pugno, "Tuning friction with composite hierarchical surfaces", Tribol. Int., vol. 115, pp. 261–267, (2017).*

[5] *R. Capozza and N. Pugno, "Effect of surface grooves on the static friction of an elastic slider", Tribol. Lett., vol. 58, no. 3, p. 35, (2015).*

[6] *N. M. Pugno, Q. Yin, X. Shi, and R. Capozza, "A generalization of the Coulomb's friction law: From graphene to macroscale", Meccanica, vol. 48, no. 8, pp. 1845–1851, (2013).*

Mechanics of interconnected microfibres for the treatment of spinal cord injuries

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Keywords: microfibres, junction, tensile test.

Decades of intense research activities brought an advanced knowledge of spinal cord injury. However, several mechanisms regarding the lesion are still unknown, and this lack avoids the development of an effective treatment for the pathology [1]. Neurofibres [2] is a Horizon 2020 FET PROACTIVE project, aiming to develop and test a device composed of bio-functionalised electro-conducting microfibres for the regeneration of the damaged spinal cord tissue. Once implanted, the device will bridge the injured area and the material, the shape and the stimuli imposed will permit the regrowth of the axons [3]. The device is an array of interconnected microfibres, which must undergo the typical loads and movement of the spinal cord [4], and endure the chemical and biological attacks of the surrounding host tissue [5].

This work is focused on the mechanical characterisation of the interconnected microfibres. The aim is to evaluate the effect of different fibre junctions in the electronic system and thus to characterise their mechanical behaviour outside and inside the neural tissue. First, two interconnected microfibres and arrays of tens microfibres were tested. Tensile tests were performed on the various type of microfibres, joined with different methods. The fracture energy [6] of each type of junction was calculated. Furthermore, the mechanical performance of the device was examined in a spinal cord tissue matrix, mimicking the typical loads supported by the spinal cord.

The results obtained were used to develop an analytical and a numerical model of the device under tensile stresses. Analytical calculations and numerical simulations were performed on single and interconnected fibres, modeled as systems of springs. The effective mechanical parameters were obtained.

The experimental characterisation combined with analytical and numerical models provides a complete description of the electronic system itself and the system embedded in the human spinal cord. The obtained results can be exploited to study the behaviour of the system in the neural tissue and to enable the identification of critical and dangerous conditions.

References

[1] Gazdic, M., Volarevic, V., Harrell, C., Fellabaum, C., Jovicic, N., Arsenijevic, N., Stojkovic, M., "Stem cells therapy for spinal cord injury", International journal of molecular sciences, 19.4, 159-172, 2018.
[2] www.neurofibres.eu
[3] Alves-Sampaio, A., García-Rama, C., Collazos-Castro, J.E., "Biofunctionalized PEDOT-coated microfibers for the treatment of spinal cord injury", Biomaterials, 89, 98–113, 2016.
[4] Harrison, D.E., Cailliet, R., Harrison, D.D., Troyanovich, S.J., Harrison, S.O., "A review of biomechanics of the central nervous system—Part III: spinal cord stresses from postural loads and their neurologic effects", Journal of manipulative and physiological therapeutics, 22.6, 399-410, 1999.
[5] M.T. Fitch, J. Silver, "CNS injury, glial scars, and inflammation: Inhibitory extracellular matrices and regeneration failure", Experimental neurology, 209.2, 294–301, 2008.
[6] Pugno, N.M., "Nano-friction, stick-slip and pull-out forces in nanotube-multiwalls-composites and-bundles", Journal of the Mechanical Behavior of Materials, 18.4, 265-282, 2007.

Shear effects in elastic nanobeams

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Keywords: Nanobeams, Shear effects, Nonlocal elasticity.

The beam theories dealing with mechanical problems affected by size effects, nowadays widely used in the context of nano-devices such as actuators or sensors, have received a renewed attention in the last decades (see e.g. [1] and reference therein). Nonlocal approaches in the elastic realm have been proposed in the relevant literature to handle such size effects which render the classical theories unable to describe diffusive phenomena related to the behavior at a nano-scale structural level. The key idea of those nonlocal models which, among others, are classified as nonlocal integral ones is to introduce at constitutive level some internal material parameters able to describe macroscopically phenomena arising within the micro-structure of the constituent material. In this context a model proposed by the authors in [2] and recently applied to solve some benchmark beam problems [3], namely the strain-difference based nonlocal integral model of Eringen-type, is here considered to investigate on the shear effects on nano-beams in bending. The followed rationale resembles the ones of Reddy [4] and Polizzotto [5] within a local elastic treatment and is here rephrased with reference to the quoted nonlocal elastic integral model. The peculiarities of the solution in terms of deflection, stress distribution and shear warping of the nano-beam cross-section are discussed. Few cases of statically determinate and undeterminate nano-beams under different loading and boundary conditions are addressed. A warping function, suitably fixed, allows to range from a nonlocal Euler-Bernoulli-type nanobeam to a nonlocal Timoshenko-type one, passing through the so-called Reddy-type beam [4]. The results, confirming the well known "small is stiffer" phenomena, seam very effective to overcome some recently debated paradoxes [6] introducing some attractive novelties in the description of normal and shear stress distributions at the nano-beam cross section opening the way to future fruitful investigations in the addressed research field.

References

[1] *Wang Q., Arash B., "A review on applications of carbon nanotubes and graphenes as nano-resonator sensors. " Comput. Mater. Sci.,* **82***, 350-360 (2014).*

[2] *Polizzotto C., Fuschi P., Pisano A.A., "A nonhomogeneous nonlocal elasticity model." Eur. J. Mech. A/Solids,* **25***, 308-333 (2006).*

[3] *Fuschi P., Pisano A.A., Polizzotto C., "Size effects of small-scale beams addressed with a strain-difference based nonlocal elasticity theory." Int. J. Mech. Sci,* **151***, 661-671 (2019).*

[4] *Reddy J.N., "Nonlocal theories for bending, buckling and vibration of beams." Int. J. Eng. Sci,* **45***, 288-307 (2007).*

[5] *Polizzotto C., "From the EulerBernoulli beam to the Timoshenko one through a sequence of Reddy-type shear deformable beam models of increasing order." Eur. J. Mech. A/Solids,* **53***, 62-74 (2015).*

[6] *Challamel N., Reddy J.N., Wang C.M., "Eringen′s stress gradient model for bending of nonlocal beams." J. Eng. Mech,* **142***, doi: 10.1061/(ASCE)EM.1943-7889- 0001161 (2016).*

MS05

THEORETICAL AND APPLIED BIOMECHANICS (GBMA)

Cardiac fluid dynamics in prolapsed and repaired mitral valve

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Keywords: Fluid dynamics, mitral valve repair, direct numerical simulation.

Fluid dynamics drive myocardial adaptation during cardiovascular disease and after surgical therapy. We study patients with normal volumetric and deformation cardiac measures after mitral valve repair (MVR) for severe mitral regurgitation. We aim to study the feasibility to detect early development of left ventricular (LV) dysfunction using non-invasive computation of LV hemodynamic forces. Geometry of LV and MV are extracted from 4D-transesophageal echocardiography and fluid dynamics is reproduced by a dedicated approach to direct numerical simulation (DNS) that includes flow-tissue interaction for the MV leaflet [1]. For this study we used the actual pre and post MV and LV individually for each patients (Figure 1). The hemodynamic force and energy dissipation are calculated in patients after conventional MVR and after reparation with NeoChord procedure (NC). Results display an increase of energy dissipation with respect to similar healthy conditions; this effect, that reduces efficiency of the LV, is due to the deviation of the mitral jet that gives rise to an irregular vortex that is more unstable and breaks down quickly. Such an increase of energy dissipation is commonly associated with a reduction of the hemodynamic systolic impulse [2]. The assessment of blood flow after MV repair is feasible and can identify subclinical LV dysfunctions that influence the long-term clinical outcome [3]. The reliability of DNS in this clinical scenario opens the possibility of comparing different surgical options before they are effectively performed.

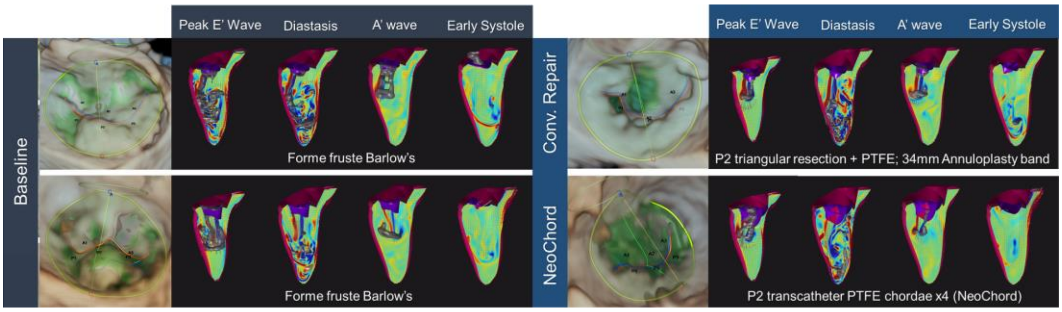

Figure 1. Example of flow field comparison between pre-surgery (Baseline) and after repair in conventional and Neochord procedures.

References

[1] *Collia, D., Vukicevic M., Meschini V., Zovatto L., Pedrizzetti G., "Mitral valve modelling and dynamics for left ventricular flow in prospective clinical application," In preparation.*

[2] *Rushmer, R.F., "Initial Ventricular Impulse. A potential key to cardiac evaluation," Circulation 1964 10.1161/01.CIR.29.2.268.*

[3] *Pedrizzetti G, La Canna G, Alfieri O, Tonti G. The vortex - an early predictor of cardiovascular outcome. Nature Reviews Cardiology 2014; 11:545–53.*

Electromechanics of active soft tissues: Competing mechanisms of stress and stretch contributions to electrical diffusivity

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Keywords: active electromechanics, finite elasticity, stress-assisted diffusivity.

Soft excitable media represent complex nonlinear systems which are often electrochemical. They typically couple several multi-physical factors and support nonlinear bioelectrical waves propagation. Such complex dynamics enforce large mechanical deformations of the underlying medium (mechano-electric feedback–MEF). Studying the spatiotemporal dynamics of excitation waves in soft active media is of paramount importance in the understanding of a large class of processes underlying pathophysiological behaviors. Processes related to MEF have a fundamental role in a wide variety of passive physical systems: corrosion, rock anisotropy, glass transition, dissolution phenomena, electromigration, hydrogen trapping, as well as swelling effects. Clear evidence for the existence of such a coupling in biological systems has also been recently observed in strain-dependent oxygen diffusivity in cartilage, and in transcription factors within the cell nucleus. Regarding the specific context of active biological media, connections forming gap junctions in excitable cells, e.g. cardiomyocytes, have been recently discussed in terms of their mechano-sensitive properties [1]. Furthermore, a quantitative analysis of the specific effects of stretch into connexins in terms of hemichannels has been experimentally verified in many different cellular preparations.

In this contribution, we present a novel formulation for the description of soft active deformable media within the context of coupled reaction-diffusion-mechanics systems and employ nonlinear cardiac dynamics as a main motivating example [2, 3]. We discuss the concept of stress-assisted diffusion (SAD) comparing its effect with the more adopted stretch-activated current (SAC) contribution. We show that an anisotropic and inhomogeneous diffusivity is naturally induced by mechanical deformations in the case of SAD and not for SAC, thus affecting the nonlinear dynamics of the spatiotemporal excitation wave as experimentally observed. Besides, the present formulation can recover and generalise a large class of electromechanical models [4] studying the plausibility of specific choices in the model parameter space. Our assessment is conducted for stretched tissues, focusing on appropriate physical indicators as conduction velocity, propagation patterns and spiral dynamics, and also carefully identifying conditions leading to the stability of the coupled system.

References

[1] *Lenarda, P., Gizzi, A., Paggi, M., A modeling framework for electro-mechanical interaction between excitable deformable cells. European Journal of Mechanics A - Solids* **72***, 374–392 (2018).*

[2] *Cherubini, C., Filippi, S., Gizzi, A., Ruiz-Baier, R., A note on stress-driven anisotropic diffusion and its role in active deformable media, Journal of Theoretical Biology* **430***, 221–228 (2017).*

[3] *Loppini, A., Gizzi, A., Ruiz-Baier, R., Cherubini, C., Fenton, F.H., Filippi, S., Competing mechanisms of stress-assisted diffusivity and stretch-activated currents in cardiac electromechanics, Frontiers in Physiology* **9***, 1714 (2018).*

[4] *Brandstaeter, S., Gizzi, A., Fuchs, S.L., Gebauer, A.M., Aydin, R.C., Cyron, C.J., Computational model of gastric motility with active-strain electromechanics. ZAMM* **98***, 2177–2197 (2018)*

An experimental-computational approach to elucidate principles of tensional homeostasis in soft tissue

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Keywords: mechanobiology, growth, remodeling

In living tissues, cells apparently exhibit a natural tendency to establish or maintain by means of mechano-regulated growth and remodeling some preferred "homeostatic" mechanical state. This inherent property of various soft biological tissues is called tensional homeostasis [1]. Most mathematical and computational models of soft tissue growth and remodeling are facing the challenge to specify the mechanical and mathematical properties of tensional homeostasis [2]. Unfortunately, these remain poorly understood so far.

To close this important gap in our understanding of soft tissue mechanobiology, we developed a combined experimental and computational framework. It consists on the one hand of an experimental set-up where collagen gels seeded with living cells (e.g., fibroblasts), so-called tissue equivalents, are subjected to well-controlled biaxial loading and their stress-strain response is measured dynamically so that the specific nature of tensional homeostasis in higher dimensions can be examined. This experimental set-up is complemented by a novel micromechanical computational model, where individual biological cells and matrix fibers are represented as discrete objects so that different hypotheses for interactions between them can be developed and tested systematically, with the overall objective of unraveling the micromechanical foundations of tensional homeostasis.

In this talk we will present first results of our combined experimental-computational framework for studying tensional homeostasis. On the experimental side, we will report observed relations between cell density and amplitude of the homeostatic stress and the observed response of tissue equivalents to various biaxial perturbations of a given homeostatic state. On the simulation side, we will present computational evidence on micromechanical mechanisms that are likely to play key roles in tensional homeostasis

The combined experimental-computational framework introduced here can form a starting point for a detailed exploration of mechanical and mathematical principles governing tensional homeostasis in higher dimensions.

References

[1] *Cyron, C.J., Humphrey, J.D., "Growth and remodeling of load-bearing biological soft tissues", Meccanica,* **52***, 645-664 (2017).*

[2] *Braeu, F.A., Aydin, R.C., Cyron, C.J., "Anisotropic stiffness and tensional homeostasis induce a natural anisotropy of volumetric growth and remodeling in soft biological tissues", Biomechanics and Modeling in Mechanobiology, Epub ahead of print (2018).*

A patient-specific mechanical modeling of metastastic femurs.

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Keywords: Bone constitutive description, fracture risk assessment, image-based finite-element modeling

Computed tomography-based finite element (FE) models were widely used to assess the femur mechanics [1]. In case of metastatic femurs, the usually-adopted linearly-elastic constitutive description leads to model the metastasis as a pseudo-healthy tissue, neglecting any specific material property of metastasis, as well as the biomechanical interaction between the lesion and the surrounding tissue. Experimental evidence showed that the metastatic tissue is characterized by a porous solid matrix with interstitial fluids, that induces mechanical alterations in the bone adjacent to the metastasis. Such an aspect is fundamental for describing growth and remodelling processes [2]. As such, a refinement of local constitutive description for the metastasis is necessary to obtain a comprehensive understanding of femoral mechanical behavior and to identify failure scenarios, as well as to detect localized effects. In this work a novel computational modeling strategy based on a FE formulation to describe the mechanical response of metastatic femurs is presented. A clinical case related to a patient with both femurs affected by multiple metastases is numerically analyzed [3]. Healthy bone tissue and metastases were described by a linearly poroelastic approach. The bone-metastasis interaction was modelled through a Gaussian-shaped graded transition of material properties in the bone around the metastasis. A progressive damage procedure was implemented by a displacement-driven incremental approach and considering both a stress- and a strain-based failure criterion. The proposed approach showed significant differences in fracture loads, fracture mechanisms, and damage patterns than a purely elastic formulation (i.e., with metastasis modelled as a pseudo-healthy tissue), revealing also its capability in identifying stress/strain localization mechanisms within the metastasis strictly related to mechanobiological stimuli driving onset and evolution of the lesion. The proposed strategy is a first attempt towards the development of effective computational tools for addressing fracture risk assessment and patient-specific treatments in case of metastatic femurs, contributing to overcome some limitations of actual clinical standards.

References

[1] *Falcinelli, C., et al., "Multiple loading conditions analysis can improve the association between finite element bone strength estimates and proximal femur fractures: a preliminary study in elderly women," Bone,* **67**, *71–80 (2014).*

[2] *Cyron, C., et al., "Growth and remodeling of load-bearing biological soft tissues," Meccanica,* **52**, *645-664 (2017).*

[3] *Falcinelli, C., et al., "Mechanical behavior of metastatic femurs through patient-specific computational models accounting for bone-metastasis interaction," J. Mech. Behav. Biomed.,* **93**, *9-22 (2019).*

The effect of Line Patterns on Intracellular ATP concentration in Vascular Endothelial Cells

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Keywords: Endothelial Cells, ATP, cell migration

The migration of endothelial cells (ECs) is critical for various processes including vascular wound healing, tumor angiogenesis, and the development of viable endovascular implants. EC migration is regulated by intracellular ATP and recent observations in our laboratory on ECs cultured on line patterns - surfaces where cellular adhesion is limited to 15 m-wide lines that physically confine the cells - have demonstrated very different migration behavior from cells on control unpatterned surfaces. Specifically, while ECs on unpatterned surfaces exhibit random motion in the absence of flow and persistent directed motion under flow, cells on line patterns both in the presence and absence of flow exhibit three distinct migration phenotypes: a) *running*– cells are polarized and migrate continuously and persistently on the adhesive lines with possible directional changes, b) *undecided*– cells are elongated and exhibit periodic changes in the direction of their polarization and minimal net migration, and c) *tumbling*-like – cells migrate persistently for a certain amount of time but then stop and round up for a few hours before spreading again and resuming migration.

We hypothesize that the three migration phenotypes on patterns reflect differences in intracellular ATP profiles. Specifically, we propose that running ECs have sufficiently high ATP concentrations at all time in order to elongate, polarize, and migrate. In contrast, we suggest that undecided ECs have an intermediate level of ATP concentration that is sufficiently high for cell spreading but not for sustained polarization and migration. Finally, tumbling-like cells are thought to have low levels of intracellular ATP during the rounding-up phase but manage to "recharge their batteries" so that ATP levels recover sufficiently for the cells to eventually elongate, polarize, and migrate. To test this hypothesis, we have developed a mathematical model that describes the time evolution of intracellular ATP concentration.

The computations provide the time dynamics of both EC length and intracellular ATP concentration. The results demonstrate that depending on the parameter values adopted for the simulations, the different hypothesized intracellular ATP profiles can indeed be obtained. Thus, for certain parameter values, we observe a rapid and sustained increase in ATP concentration, corresponding to the hypothesized behavior for running cells. For other parameter values, the ATP concentration remains within an intermediate range throughout, presumably reflecting undecided cells. Finally, for part of the parameter space, we obtain an initial drop in the concentration followed by recovery, as suggested for tumbling-like cells. The results are consistent with the notion that changes in intracellular ATP modulate the phenotype of EC migration on line patterns.

Future work will focus on providing experimental evidence for the involvement of ATP as well as on extending the modeling to include cellular polarization and migration.

Exploring THz Protein Vibrations by means of Modal Analysis: All-Atom vs Coarse-Grained Model

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Keywords: Protein Vibrations, Terahertz Range, HIV-1 Protease

It is strongly believed among the scientific community that protein dynamics constitutes the fundamental link existing between structure and function. Analyzing the characteristics of protein vibrations is then essential for understanding the complex mechanisms hidden behind protein biological functionality. Indeed, by means of modal analysis, it has been shown that low-frequency vibrational modes are strictly related to protein conformational transitions [1].

In the last years, some of the authors made use of an all-atom mechanical model, treating proteins like elastic lattice structures, in order to investigate the vibrational modes and the natural frequencies by means of modal analysis [2,3]. In particular, low-frequency modes were found to involve the whole protein structure and occur in the so-called terahertz (THz) range.

Vibrations at THz frequencies, especially around or below 1 THz, were also detected experimentally on lysozyme [2] and Na^+/K^+-ATPase [4] powder samples by means of Raman spectroscopy technique using modern ultra-low frequency (ULF) filters. Modal analysis results were then useful for associating possible protein motions to the obtained Raman peaks.

In order to focus mostly on low-frequency vibrations occurring in the THz frequency range, a coarse-grained model is then proposed, which aims at modeling only the protein backbone, considering just the coordinates of C_α atoms. In this way, a deeper comprehension of the slowest motions is achieved, by comparing the results arising from all-atom and coarse-grained calculations both in terms of eigenmodes and natural frequencies. In particular, in this contribution the case of HIV-1 protease, whose activity is pivotal for the HIV life-cycle, is investigated.

References

[1] Tama, F., Sanejouand, Y. H., "Conformational change of proteins arising from normal mode calculations", Protein Engineering, 14, 1-6, (2001).
[2] Carpinteri, A., Lacidogna, G., Piana, G., Bassani, A., "Terahertz mechanical vibrations in lysozyme: Raman spectroscopy vs modal analysis", Journal of Molecular Structure, 1139, 222-230, (2017).
[3] Carpinteri, A., Piana, G., Bassani, A., Lacidogna, G., "Terahertz vibrational modes in Na/K-ATPase", Journal of Biomolecular Structure and Dynamics, 37, 256-264, (2019).
[4] Lacidogna, G., Piana, G., Bassani, A., Carpinteri, A., "Raman spectroscopy of Na/K-ATPase with special focus on low-frequency vibrations", Vibrational Spectroscopy, 92, 298-301, (2017).

Protein Conformational Changes: What can Geometric Nonlinear Analysis tell us?

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Keywords: Protein Conformational Changes, Geometric Nonlinear Analysis, Mechanical Instability

Protein functioning is usually associated to conformational changes. For example, a large conformational transition, triggered by ATP-binding, occurs in kinesin heads when it walks along microtubules, hemoglobin exhibits a structural rearrangement when switching from the deoxy- to the oxy-state, etc. In the last decades, several researches have shown that conformational changes depend on the protein intrinsic flexibility and that the low-frequency modes, arising from the application of modal analysis to protein elastic network models, are strictly related to the conformational transition [1].

Several efforts have been also made in order to understand the actual pathways followed by proteins during these transitions [2]. The problem is usually linearized, under the assumption of small displacements. In the same way, the forces that could trigger the conformational change have been investigated by means of linear theories, such as the perturbation-response scanning (PRS) method, which aims at evaluating the relative changes in the protein coordinates when a perturbation is applied at single residues [3,4].

Although good results could be generally obtained by linear theories like PRS, in this contribution, we question whether the assumption of small displacements involved within the conformational change is reliable. In particular, we investigate the influence of geometric nonlinearities, by applying both linear and (geometric) nonlinear analysis to the protein elastic model and comparing the outcomes in terms of force profiles. Eventually, from the results regarding the conformational change of HIV-1 protease, we show that the displacements should not be considered small *a priori* and that some mechanical instability may occur during the conformational transition.

References

[1] Tama, F., Sanejouand, Y. H., "Conformational change of proteins arising from normal mode calculations", Protein Engineering, 14, 1-6, (2001).
[2] Moon, K. K., Jernigan, R. L., Chirikjian, G. S., "Efficient Generation of Feasible Pathways for Protein Conformational Transitions", Biophysical Journal, 83, 1620-1630, (2002).
[3] Atilgan, C., Gerek, Z. N., Ozkan, S. B., Atilgan, A. R., "Manipulation of Conformational Change in Proteins by Single-Residue Perturbations", Biophysical Journal, 99, 933-943, (2010).
[4] Liu, J., Sankar, K., Wang, Y., Jia, K., Jernigan, R. L., "Directional Force Originating from ATP Hydrolysis Drives the GroEL Conformational Change", Biophysical Journal, 112, 1561-1570, (2017).

Computational engineering for the heart: a multi-physics model for medical support

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Keywords: Hemodynamics, Multi-physics model, Fluid structure interaction

It has been estimated that, overall, cardiovascular disorders (CVD) cost the EU economy 210 billion per year and this expenditure will at least triple by 2050 owing to the ageing of the population and a growing percentage of it accessing advanced medical care [1]. Progress in medical research, over the last decades, has improved the prognoses for CVDs but, unfortunately, the advances have come to a halt because of increasing risk factors (obesity, physical inactivity, diabetes and smoking) that are strongly correlated to CVD [1]. In order to revert this unfavourable trend innovative tools are needed for the improvement of treatment outcomes without increasing, concurrently, the medical costs. The combination of computational engineering and medical research provides fundamental contributions in this direction by producing data driven virtual models capable of refining the analysis power and adding predicting capabilities to the existing diagnostic tools.

Nevertheless, producing a computational model of the heart is a very challenging task since it needs to account for the complex deforming geometries, the mechanics and properties of the biological tissues, which are anisotropic and nonlinear, along with the pulsatile, transitional and turbulent character of the flow, the strong fluid/structure interaction and their connection with the electrophysiological system. To this aim, we have developed and validated a fluid-structure-electrophysiology interaction (FSEI) code, which is based on the Navier-Stokes solver AFiD, a structure solver based on the interaction potential approach, the immersed boundary method [2] and a bidomain electrophysiology model that can account for the different cellular models of the various portions of the heart. The main novelty of our approach is that, for the first time, the resulting multi-physics model can cope simultaneously with the electrophysiology of the myocardium, its active contraction and passive relaxation, the dynamics of the valves (aortic and mitral) and the hemodynamics in the whole left heart, thus including ventricle, atrium and the first tract of the aorta. All these models are three-way coupled with each other thus capturing the fully synergistic physics, which makes the computational model a predictive tool for virtually testing new prosthetic devices and surgical procedures.

References

[1] Mittal, R., Seo, J. H., Vedula, V., Choi, Y. J., Liu, H., Huang, H. H., Jain, S., Younes, L., Abrahamd, T., and George, R. T.. Computational modeling of cardiac hemodynamics: Current status and future outlook. Journal of Computational Physics, 305:10651082, 2016.

[2] Meschini, V., de Tullio, M., Querzoli, G., and Verzicco, R.. Flow structure in healthy and pathological left ventricles with natural and prosthetic mitral valves. Journal of Fluid Mechanics, 834:271307, 2018.

Computational strategy for non-affine kinematics of collagen fibers in arterial mechanics

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Keywords: Non-linear finite-element formulation, non-affine kinematics, arterial mechanics

Cardiovascular diseases are the leading cause of death worldwide but their aetiology is debated and the therapeutic approaches, as well as the diagnosis are still based on the definition of risk parameters mainly evaluated on the own experience of clinicians, and, furthermore they still have an high percentage of failure [1]. In this framework, computational models have been recently proved useful to provide novel insights into aortic biomechanics [2], allowing to furnish helpful indications towards more effective clinical assessment.

With the aiming of understanding physiological and pathological processes to improve diagnosis and therapy, the multiscale structurally-motivated approach for tissue constitutive description, recently proposed by some of the authors [3], has been integrated in a computational procedure allowing the mechanical analyses of arterial segments via a non-linear finite-element formulation, to allow the use of this refined constitutive description towards fully-personalized clinical applications. In fact, such a multiscale structural approach has been proved to be effective for describing the non-affine kinematics of collagen fibers on simple case studies, but it has never been employed in finite element simulations. In detail, the anisotropic and non-linear elastic mechanical response of arterial tissue is computationally treated via FE strategies. The constitutive response of aortic tissue is modelled via a multi-scale approach integrating: (i) the non affine fiber kinematics, addressed via the Eshelby's inclusion problems theory [3]; (ii) the non-linear behaviour of collagen fibers [4]; (iii) the real morphological data of the aortic tissue [5].

This work presents a novel computational model that captures the complexity of the load-induced micro-structural morphological changes. Furthermore, the proposed framework, providing data about the stress and strain patterns at the different length scale of the arterial tissue, can open to clarify the aetiology of the aneurysms and the patho-physiological remodelling mechanisms.

References

[1] *Kelly, B., et al., "Promoting cardiovascular health in the developing world: a critical challenge to achieve global health", National Academies Press, (2010).*

[2] *Gasser, T.C., "The Biomechanical Rupture Risk Assessment of Abdominal Aortic Aneurysms - Method and Clinical Relevance", Biomedical Technology, Springer, page 233-253, (2018).*

[3] *Morin, C., et al., "Non-affine fiber kinematics in arterial mechanics: a continuum micromechanical investigation",ZAMM - Journal of Applied Mathematics and Mechanics,* **98-12***, page 2101-2121, (2018).*

[4] *Maceri, F., et al., "A unified multiscale mechanical model for soft collagenous tissues with regular fiber arrangement", Journal of Biomechanics,* **43-2***, page 355-363, (2010).*

[5] *Witold, K., et al. "A comprehensive study of layer-specific morphological changes in the microstructure of carotid arteries under uniaxial load", Acta biomaterialia, page 342-351, (2017).*

Effects of the rate-dependence properties and fluid-structure interactions on the failure of brain tissue mimicking hydrogels

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Keywords: hydrogel; rate-dependent fracture; poroelasticity

Synthetic materials commonly replace tissues in biomechanical research, finding applications in several fields, included surgical training and tissue engineering. A composite hydrogel, obtained from the combination of Polyvinyl Alcohol (PVA) and Phytagel, has been proposed as brain tissue surrogate and showed excellent mimicking of the mechanical response of the brain in compression and indentation tests [1].

Brain tissue is a strongly heterogeneous material, identifiable as a porous hyper-viscoelastic medium filled with cerebrospinal fluid, which in turns interacts with the solid network, determining complex rate-dependent effects [2]. Several models have been proposed in the literature to simulate the viscous behaviour of the brain [3,4], and extended knowledge on the failure mechanisms of biphasic materials can be obtained from recent studies on the fracture of hydrogels [5]. Compression tests have been widely used to characterise the rate-dependency of the brain tissue. In addition, wire cutting tests have been used as a mean to test the fracture behaviour of soft solids, such as foodstuffs, and also applied to measure the fracture resistance of elastic gelatine gels [6].

In the present study, the fracture behaviour of the composite hydrogel is studied in the framework of a viscous hyperelastic model, in which the solid structure interacts with the incompressible fluid. Specific attention is devoted to the rate-dependent effects determined by this biphasic model on the fracture behaviour of the hydrogel. Experimental data from wire cutting tests, at various strain rates, are presented and compared with finite element analyses.

References

[1] *Forte, A.E., Galvan, S., Manieri, F., Rodriguez y Baena, F. and Dini, D., "A Composite Hydrogel for Brain Tissue Phantoms", Mater. Des.,* ***112****, 227–238 (2016).*

[2] *Forte, A.E., Gentleman, S.M. and Dini, D., "On the Characterization of the Heterogeneous Mechanical Response of Human Brain Tissue", Biomech. Model. Mechanobiol.,* ***16****, 907–920 (2017).*

[3] *Miller, K., "Constitutive Model of Brain Tissue Suitable for Finite Element Analysis of Surgical Procedures", J. Biomech.,* ***32****, 531-537 (1999).*

[4] *Franceschini, G., Bigoni, D., Regitnig, P. and Holzapfel, G.A., "Brain Tissue Deforms Similarly to Filled Elastomers and Follows Consolidation Theory", J. Mech. Phys. Solids,* ***54****, 2592–2620 (2006).*

[5] *Mao, Y. and Anand, L., "A Theory for Fracture of Polymeric Gels", J. Mech. Phys. Solids,* ***115****, 30–53 (2018).*

[6] *Forte, A.E., D'Amico, F., Charalambides, M.N., Dini, D. and Williams, J.G., "Modelling and Experimental Characterisation of the Rate Dependent Fracture Properties of Gelatine Gels", Food Hydrocoll.,* ***46****, 180–190 (2015).*

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Insights on the receptor dynamics and the spreading of cells

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Keywords: *Finite strain mechanics, chemo-transport-mechanics, receptor dynamics.*

Recent publications [1, 2] unveiled the multi-physics interactions that preside receptors relocation on a lipid membrane and provided a rationale to the evolution in time of some quantities of interest for the protein dimerization process that were formerly observed experimentally. In spite using a surrogated mechanics allowed identifying limiting factors with significant accuracy, the quantitive evaluation of mechanical measures remained questionable.

In the present work receptor dynamics is coupled to large strain mechanics to simulate the relocation of proteins on endothelial cells. Fully coupled mass and momentum balance laws, accompanied by thermodynamically derived constitutive laws, are written in weak form and discretized via the finite element method. High performance computations are carried out afterwards, making use of the open-source library deal.ii (dealii.org).

Novel in vitro experimental investigations on the spreading of endothelial cells on a substrate enriched with polilisin validated the numerical simulations. Co-designed experiments and modeling thus allows shading new insights on both the receptor dynamics and the physical mechanisms that govern the spreading of cells.

References

[1] *Salvadori A., Damioli V., Ravelli C., Mitola S., Modeling and Simulation of VEGF Receptors Recruitment in Angiogenesis, Mathematical Problems in Engineering, vol. 2018, Article ID 4705472, 10 pages, 2018.*

[2] *Damioli V., Salvadori A., Beretta G.P, Ravelli C., Mitola S., Multi-physics interaction drive VEGFR2 relocation on endothelial cells, Scientific Reports 7, Article number:16700(2017), 01 December 2017.*

Failure mechanisms of osteonal structures: a computational approach

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Keywords: osteon, interlamellar areas, fracture micromechanics

Bone is a multi-scale composite material with a complex and hierarchical internal architecture. As a result, the fracture mechanism prediction within a bony structure results unavoidably complicated. Nonetheless, a deep knowledge of the osseous microstructure reveals necessary because the nature of the bone constituent elements at the microscale influences its macroscopical mechanical behavior [1]. As a matter of fact, alterations in the local bone properties, mainly induced by age and/or occurence of diseases, can lead to drastic variations in the overall mechanical response.

In the last decades, several finite element-based models have been developed to predict the bone mechanical behaviour, even if only few studies focused on micromechanical aspects [1, 2]. At the microscale level, cortical bone presents structural units called osteons, which are in turn formed by concentric, approximately cylindrical lamellae, delineated by weak interfaces [2]. Many investigations are based on the assumption of linearly elastic, isotropic and homogeneous osteon properties, but it results in a rough approximation, given the bone microstructural complexity. Even less works treated the interlamellar areas as actual interfaces. Therefore, the present study aims to furnish a more accurate and detailed numerical modeling of the single osteonal structure. The model takes into account for the different orientations of the mineralized collagen fibrils constituting each lamella (important feature for the overall mechanical properties), as well as it describes the thin interlamellar areas as elastic layers characterized by the absence of any constitutive symmetry. These features are coupled to a brittle damage constitutive aspect, in order to simulate the progressive fracture at the lamellar level. Damage process is modelled by considering the possibility of both an interlaminar and an intralaminar failure. The model reliability is assessed by mimicking the experiments carried out in [3], concerning the bending behavior of osteons. The proposed modeling approach is able to account for different microstructural arrangements at the osteonal level, for instance related to the aging, and it could lead to useful indications on microscale failure mechanisms of bone structures that can be adopted for defining refined up–to–macroscale descriptions of bone mechanical response.

References

[1] *Giner, E., Arango, C., Vercher, A., Fuenmayor, F. J., Numerical modelling of the mechanical behaviour of an osteon with microcracks, J Mech Behav Biomed Mater,* **37***, 109-124 (2014).*

[2] *Nobakhti, S., Limbert, G., Thurner, P. J., Cement lines and interlamellar areas in compact bone as strain amplifiers–Contributors to elasticity, fracture toughness and mechanotransduction, J Mech Behav Biomed Mater,* **29***, 235-251 (2014).*

[3] *Ascenzi, A., Baschieri, P., Benvenuti, A., The bending properties of single osteons, J Biomech,* **23(8)***, 763-771 (1990).*

Chemo-mechanical modelling of arterial tissues

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Keywords: arterial physiopathology, multiscale constitutive modeling, cell-cell signaling pathways.

Modeling of arterial physiopathology needs the introduction of multi-field mechanisms, driven by the complex interplay between mechanics and cell-cell signaling pathways [1]. The former is affected by the multiscale hierarchical arrangement of tissue constituents, while the latter involves molecular transport mechanisms.

This work presents a novel chemo-mechano-biological computational modeling strategy for arterial multiphysics, by introducing biochemically-motivated remodeling laws associated with physiopathological mechanisms. The aim is to develop an effective strategy for describing tissue physiopathological remodeling associated with alterations in tissue biochemical environment, that determine an imbalance from the homeostasis. A multiscale constitutive description of arterial tissues is integrated with a mechanistic modeling of cell-cell signaling pathways (involving molecular transport phenomena in the arterial thickness) and with biochemically-motivated remodeling laws of tissue structural features [3]. Accordingly, arterial multiphysics response can be investigated from a novel and unexplored perspective, by straight accounting for local, non-homogeneous, and fine variations of histological and biochemical properties.

The biochemical activity of matrix metalloproteinases, transforming growth factors-beta and interleukines on tissue remodeling is specifically addressed. The effects of a physiopathological mechanism that includes macrophages infiltration, intimal thickening and a healing phase are investigated, highlighting the corresponding influence on the arterial compliance. As a remarkable result, changes in arterial mechanics are described as a consequence of alterations in tissue biochemical environment and cellular activity, allowing also to incorporate the protective role of autoimmune responses and of pharmacological treatments [4].

References

[1] *Michel, J.B. et al., "Topological Determinants and Consequences of Adventitial Responses to Arterial Wall Injury". Arterioscler. Thromb. Vasc. Biol.* **27***, 1259–1268 (2007).*

[2] *Aparício, P.et al., "A novel chemo-mechano-biological model of arterial tissue growth and remodelling", J. Biomech.* **49***, 2321–2330 (2016).*

[3] *Marino, M. et al., "A chemo-mechano-biological formulation for the effects of biochemical alterations on arterial mechanics: the role of molecular transport and multiscale tissue remodelling. J. R. Soc. Interface* **14***(136), 20170615 (2017).*

[4] *Dai, J. et al., "Long term stabilization of expanding aortic aneurysms by a short course of cyclosporine a through transforming growth factor-beta induction", PloS one,* **6** *,e28903 (2011).*

Comparison of mechanical properties among different chitin-based structures of the spider *Harpactira curvipes*

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Keywords: Spider, chitin, nanoindentation.

Chitin is one of the most widespread polysaccharides in nature[1] and it is the basis of many biological structures[2]. This material appears in various parts of the spider exoskeleton, such as fangs, paws, cuticle and hairs[3][4]. These structures accomplish different functions with remarkable efficiency and mechanical properties, thanks to the multi-functionality of the chitin[5]. Therefore, here we investigate in depth the mechanical properties of different body parts of the spider *Harpactira curvipes*. By means of imaging (SEM and AFM) and nanoindentation techniques, a mapping of the variations in the elastic modulus and hardness in the different sections is achieved and we compare the results to thus explain how these properties change within the spider's body[6]. From a broader perspective, this characterization is of interests because it could help to improve understanding of how the same basic material can be used to reach distinguishing mechanical characteristics and properties in different structures to better adapt biomechanical functions to their specific biological needs. The physical insights of this work are potentially important to investigate the properties of chitin and to find possible inspiration for the design of materials with advanced mechanical properties.

References

[1] Rinaudo, M., "Chitin and chitosan: Properties and applications", Science Direct, Vol. 31, page 603-632 (2006)

[2] Meyers, M.A., Chen, P., Lin, A.Y. and Seki, Y.,"Biological materials: Structure and mechanical properties", Progress in Materials Science, Vol. 53, page 1-206 (2008)

[3] Bar-On, B., Barth, F.G., Fratzl, P. and Politi, Y., "Multiscale structural gradients enhance the biomechanical functionality of the spider fang", Nature Communications, Vol. 5, page 1-8 (2014)

[4] Politi, Y., Priewasser, M., Eckhard, P., Zaslansky, P., Hartmann, J., Siegel, S., Li, C., Barth, F.G. and Fratzl, P., "A Spider's Fang: How to Design an Injection Needle Using Chitin-Based Composite Material", Materials Views, Vol. 22, page 2519-2528 (2012)

[5] Zumber, M., Zia, K.M. and Barikani, M., "Chitin and Chitosan Based Blends, Composites and Nanocomposites" in Advance in Natural Polymers, Springer, Berlin (2013)

[6] Labonte, D., Lenz, A. and Oyen, M.L., "On the relationship between indentation hardness and modulus, and the damage resistance of biological materials", Acta Biomaterialia, Vol. 57, page 373-383 (2017)

A comprehensive multiscale model of the cardiovascular system

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Keywords: computational hemodynamics, closed-loop multiscale cardiovascular model, baroreflex

Numerous mathematical models of the cardiovascular system have been proposed [1, 2], both to further explore the physiological behaviour of circulation and support medical developments. In this context, we present a closed-loop multiscale model, which has the advantage to integrate into a single framework the fundamental characteristics of the cardiovascular system: the arterial wave propagation, the complex dynamics of cardiac valves, the short-term baroreflex mechanism, a well-organised structure of micro-circulation groups and venous return, and the unstressed volumes. The main goal of this work is to effectively simulate each portion of the cardiovascular system.

Large-medium arteries are described through the 1D mass and momentum equations, considering the vascular tapering and branching, and the anisotropic non-linear viscoelastic behaviour of the arterial walls [3]. The rest of circulation is represented through a proper combination of resistances, compliances and inductances, standing for the viscous, elastic and inertial effects, respectively. Both the contractility of the cardiac chambers and the non-ideal behaviour of cardiac valves are modelled. A short-term baroreflex model is included to guarantee homeostasis.

As shown in Fig.1a, pressure waves correctly propagate along the arterial tree, with systolic pressures increasing, diastolic pressures decreasing, pressure signals delaying and steepening along the aorta. Valvular flow rates in Fig.1b are also in agreement with literature data, with reverse flows as valves close. This model well mimics the expected hemodynamics and can be used for different applications (e.g., cardiac pathologies, orthostatic variations, exercise conditions, etc...).

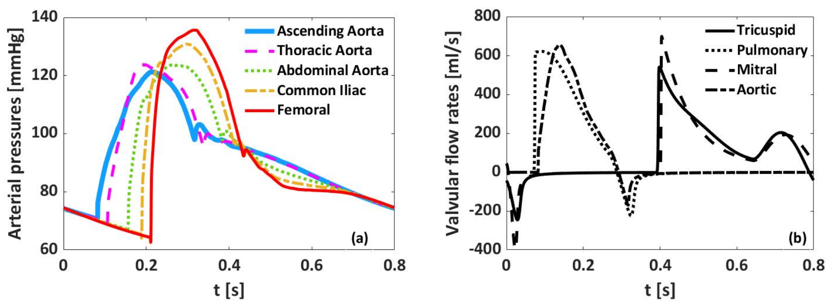

Figure 1: Pressures along the arterial tree (a) and valvular flow rates (b) at 75 bpm.

References

[1] *Shi, Y., Lawford, P., and Hose, R., "Review of zero-D and 1-D models of blood flow in the cardiovascular system", Biomed. Eng. Online,* **10***, 33 (2011).*

[2] *Blanco, P.J., and Feijóo, R.A., "A dimensionally-heterogeneous closed-loop model for the cardiovascular system and its applications", Med. Eng. Phys.,* **35***, 652–667 (2013).*

[3] *Scarsoglio, S., Gallo, C., and Ridolfi, L., "Effects of atrial fibrillation on the arterial fluid dynamics: a modelling perspective", Meccanica,* **53***, 3251-3267 (2018).*

Integrated microCT-uniaxial loading protocol to investigate the structure of biological fibrous tissues under increasing levels of strain

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Keywords: biological fibrous tissue, microCT, strain

Hierarchical microstructure of load-bearing biological tissues is optimized for their specific anatomical position and inherent function [1]. Anterior Cruciate Ligament (ACL) in human knee joint is a strong fibrous tissue that acts as a primary restrain against translations in the sagittal plane. When injured, ACL cannot self-repair and it is usually replaced by a biological graft via surgery. This study aimed to investigate the relation between structure and function in biological fibrous tissues, primary focusing on ACL. A deep knowledge of structure-function relationship - concerning both this ligament and the grafts commonly used to replace it - could explain possible alterations of joint biomechanics after surgery and support the development of optimized treatments. In order to achieve this objective, a dedicated setup was designed and developed to acquire the 3d volumetric fibrous microstructure of human ACL samples under increasing level of mechanical strain.

A commercial microCT system (Bruker Skyscan 1176, nominal resolution 9 μm) was specifically used to acquire 3d tissue structure. An experimental device for uniaxial tensile test was designed and developed to fit the internal dimensions of the scanner. The device was composed of two clamps for ligament grasping, a screw-driven linear guide for ligament elongation, a load cell to measure reaction force and a tubular framework. An aluminium-zinc alloy was used for this part, due to its high mechanical resistance and low x-ray attenuation. Contrasting agents containing high Z element were necessary to enhance imaging [2]; different formulations were tested to optimize the contrast protocol without affecting the mechanical behaviour of the tissues. After cyclic preconditioning, a pre-scan force-strain curve was acquired to determine the free ligament length, so that both the toe and linear behaviour of fibre bundles were highlighted. The ACL was scanned at 6 different strain steps between 1-8%; a 6-minute waiting period was considered between each step.

Force-strain curves were obtained together with ACL images, which allowed to highlight volumetric strain within the sample and perform estimation on volumetric structural adaptations, including fibre bundles uncrimping, reorienting, tensioning and defibrillation. This integration of micro-structure and function is crucial to better understand physiological and pathological phenomena in biological fibrous tissues and contribute in optimizing ligament replacement.

References

[1] *Zhang, Z., Zhang, Y. and Gao, H., "On optimal hierarchy of load-bearing biological materials", Proceedings of the Royal Society B: Biological Sciences, Vol 278,1705, page 519-525, 2011*

[2] *Balind, R., Lowe, T. and Shearer T., "Optimal contrast agent staining of ligaments and tendons for x-ray computed tomography", Plos One, Vol 11,4, 2016*

Comparison between numerical and MRI data of ascending aorta hemodynamics in a circulatory mock loop

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Keywords: ascending thoracic aortic hemodynamics, CFD simulation, in-vitro 3D PC-MRI data.

Hemodynamic forces play an important role in the initiation and progression of cardiovascular diseases such as in case of ascending thoracic aortic aneurysm [1]. A 3D flow magnetic resonance imaging (3D PC-MRI) technique has been proposed as a clinical tool able to provide, in-vivo in a non-invasive manner, hemodynamic information. However, MRI suffers of spatial and temporal resolution limitations and it is not able to provide quantitative flow descriptors, such as wall shear stresses, with a sufficient accuracy. In the last years, merging of MRI with computational fluid dynamics (CFD) has been proposed to provide clinical information at patient-specific level. Indeed, CFD enables the investigation of pressure and flow field at a time and space resolution unachievable by any in-vivo measurement. However, different sources of uncertainties are present in CFD models, as e.g. inflow/outflow boundary conditions and modeling of the vessel wall compliance properties. These uncertainties may affect the accuracy of the output quantities of interest. In-vivo 3D PC-MRI data can be used to provide patient-specific boundary conditions to numerical simulations as well as for comparison against numerical results, to provide a cross validation. A framework integrating in-vivo 3D PC-MRI data into the numerical simulation of a healthy thoracic aorta was presented in [2]. The simulations were carried out with the open-source code Simvascular and the MRI data were used to provide/calibrate inlet and outlet boundary conditions, to evaluate the elastic properties of the vessel walls and to validate the simulation results. The integration was all in all successful, but some discrepancies between numerical results, although calibrated, and in-vivo data were observed. These discrepancies can be ascribed to limitations of CFD models, but also to inaccuracies in MRI data due to the difficulty in characterizing in in-vivo experiments rotation and translation movements of the inlet section.

The aim of the present work is to provide a similar integration of simulations with MRI data obtained by a fully controlled and sensorized circulatory mock loop for 3D-printed aortic models. This experimental set up, whose details are given in a companion submitted abstract, allows a few uncertainties in measurements to be eliminated: the flow rate is controlled and it is exactly the same for each cardiac cycle, the model is fixed and the wall model properties are known. In this way, clearer indications on the accuracy and possible improvements of CFD models could be obtained.

References

[1] *Capellini K., Vignali E., Costa E., et al, "Computational fluid dynamic study for aTAA hemodynamics: an integrated image-based and radial basis functions mesh morphing approach", J Biomech Eng,* **140(11)***, 111007 (2018)*

[2] *Boccadifuoco, A., Mariotti, A., Capellini, K., Celi, S. and Salvetti, M.V., "Validation of numerical simulations of thoracic aorta hemodynamics: comparison with in vivo measurements and stochastic sensitivity analysis", Cardiovasc Eng Technol,* **9(4)***, page 688-706, (2018).*

Leaflet kinematics of artificial aortic valves: implications on turbulence levels and cell damage

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Keywords: immersed-boundary, fluid-structure-interaction, hemolysis.

Considerable improvements in artificial heart valve design have been made in the last years, providing optimized mechanical and bio-prosthetic devices. The success of a new prosthesis is defined by several factors that contribute to achieve an adequate performance in the short and long term, guaranteeing also durability. Hemodynamics plays a crucial role in order to ensure the best possible clinical outcomes for patients undergoing heart valve replacement, and is strictly related to the leaflet kinematics of the valve.

The prostheses are passive structures immersed in the blood flow, their leaflet kinematics being affected by the interaction with the flow and inertial properties of the structure. Depending on the geometrical features of the devices and material properties, one can obtain non-physiological flow patterns with transition to turbulence, that are characterized by increased levels of shear stress on blood particles and high flow resistance. This in turn can induce fluttering on the leaflets, enhanced structural loading and high leaflet tip velocities.

In order to better understand this complex fluid-structure interaction problem, we effectively employ numerical simulations to accurately predict the flow patterns downstream different available aortic devices. A versatile immersed boundary method [1] is adopted to simulate the interaction of rigid and deformable valve leaflets with the incoming flow. Realistic geometries for three valves (bi- and tri-leaflet mechanical, bio-prosthetic) and ascending aorta are considered under pulsatile flow conditions.

Leaflet kinematics in the three cases is provided in terms of time-dependent geometric orifice area, identifying different opening and closing behavior of the valves and related hydrodynamic stresses and turbulence levels. Particular attention is paid to investigate the effect that little construction details may have on both the leaflet kinematics and fluid dynamics.

In order to evaluate blood damage, a high-fidelity hemolysis model is adopted, based on a coarse-grained description of the erythrocyte membrane spectrin cytoskeleton [2]. In this way, under the hydrodynamic loadings, the instantaneous shape distortion of the cells and consequent damage along their trajectories are evaluated, assessing the different propensity of the prostheses to thromboembolic complications.

References

[1] *M.D. de Tullio and G. Pascazio, "A moving-least-squares immersed boundary method for simulating the fluid-structure interaction of elastic bodies with arbitrary thickness", Journal of Computational Physics, **325**, page 201-225 (2016).*

[2] *H.M. Ezzeldin, M.D. de Tullio, M. Vanella, S.D. Solares, and E. Balaras, "A Strain-Based Model for Mechanical Hemolysis Based on a Coarse-Grained Red Blood Cell Model", Annals of Biomedical Engineering, **43**, page 1398-1409 (2015).*

Fluid-structure interaction within a ventricular assist device: a novel immersed-boundary/isogeometric framework

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Keywords: Immersed boundary method, deformable capsule transport, paracorporeal ventricle

Predicting the elastic response of a membrane under hydrodynamic loads has great relevance for many biological applications. In this work we present a computational method designed to accurately reproduce the mutual interaction between a thin membrane and an incompressible fluid. The fluid motion is resolved in a parallel environment with a pressure projection method on a Cartesian grid. The immersed membrane is modeled as a NURBS surface, and the elastic response is obtained from a displacement-based Isogeometric analysis relying on the Kirchhoff-Love shell theory [1]. Fluid and shell solvers exchange data through a direct-forcing immersed-boundary approach; the required boundary conditions are imposed at the fluid-solid interface with a dynamic forcing, as proposed in [2].

First, the proposed method is validated against data available in literature [3] for biological capsules transport at intermediate Reynolds numbers ($Re \approx 10 - 100$). The model reproduces the transport of an elastic capsule flowing in a pressure-driven channel within the inertial flow regime. The shell stiffness plays a crucial role in the transport dynamics because the elastic response of the membrane affects the capsule migration mechanism. Numerical investigation on biological cells transport are increasingly exploited to explore the possibilities of indirect cells manipulation for sorting or probing purposes.

Furthermore, the flow field inside a Pneumatic Ventricular Assist Device (PVAD) is investigated. Similar devices are primarily used to provide mechanical circulatory support to a single ventricle as temporary bridge to transplant. The design investigated herein consists of a pneumatically driven pump which delivers the required blood mass flow by means of a pulsatile membrane separating two doomed chambers. On the computational side, the model presents several challenges in terms of heavy added-mass effect and buckling/wrinkling motion of the membrane. The accurate replication of membrane displacement and blood flow field can lead to improvements of the device performances as well as provide haemolysis predictions based on simple transport models.

References

[1] *Kiendl, J. et al., Isogeometric shell analysis with Kirchhoff-Love elements, Computer Methods in Applied Mechanics and Engineering,* **198***, page 49-52 (2009).*

[2] *de Tullio, M. D., Pascazio, G., "A moving-least-squares immersed bound- ary method for simulating the fluid-structure interaction of elastic bodies with arbitrary thickness", Journal of Computational Physics,* **325***: page 201-225 (2016).*

[3] *Schaaf, C., Stark, H. Inertial migration and axial control of deformable capsules, Soft Matter,* **13***, page 3544-3555 (2017).*

MRI-based numerical simulation of right ventricle fluid mechanics

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Keywords: intracardiac flows, computational fluid dynamics, magnetic resonance imaging

The analysis of intracardiac blood flow patterns can significantly contribute to improve the understanding and treatment of cardiovascular disease [1]. In contrast to the abundant literature on the left side of the heart, there is currently a significant lack of knowledge about the right ventricle (RV) fluid mechanics, both in healthy and diseased conditions.

This work presents a comprehensive framework for the numerical simulation of right heart flows based on magnetic resonance imaging (MRI) data and an immersed boundary technique. The RV kinematics is preliminarily reconstructed from multi-slice MRI datasets, i.e. short-axis and longitudinal contours of the RV walls with temporal resolution of 30 phases per cardiac cycle. Commercial software with feature-tracking capabilities (QStrain) is used to extract the time history of the endocardium contours. A time-continuous representation of the entire RV geometry is then obtained using image-registration algorithms, particularly the Large Deformation Diffeomorphic Geometric Mapping (LDDMM) framework combined with an atlas-based approach [2]. The developed method has proved to be able to provide a rather good representation of the complex RV contraction pattern, including the clinically relevant longitudinal shortening. The RV kinematics is finally fed to an in-house computational fluid dynamics solver based on a robust immersed boundary method [3], which is used to carry out fully-resolved direct numerical simulations of several cardiac cycles.

Results are reported for patient-specific geometries in both healthy and congenital heart disease (CHD) cases, with particular reference to Tetralogy of Fallot (ToF). In this form of CHD, patients suffer from chronic pulmonary insufficiency after repair and eventually require pulmonary valve replacement. Differences between the normal and ToF cases are discussed, in terms of overall flow features, kinetic energy of flow components, and influence of pulmonary valve regurgitation on the pumping efficiency. It is expected that such a computational framework will contribute to develop better clinical indications for the long-term care of CHD patients.

References

[1] *Bermejo, J., Martínez-Legazpi, P., and del Álamo, J. C., The Clinical Assessment of Intraventricular Flows, Annual Review of Fluid Mechanics,* ***47****, 315–342 (2015).*
[2] Deformetrica. `https://www.deformetrica.org`
[3] *Vanella, M., Balaras, E., A moving-least-squares reconstruction for embedded-boundary formulations, Journal of Computational Physics,* **228***, 6617–6628 (2009).*

Growth-induced remodelling in mechanics of solid tumors

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Keywords: Poromechanics - Tumor growth - Remodelling

The macroscopic nonlinear behavior of growing soft tissues results from different chemo-mechanical interactions occurring, at different scales, among interstitial fluids and evolving solid constituents, described by adopting a thermodynamically consistent poro-hyperelastic framework [1, 2]. In this context, the kinetics of heterogeneous growth is traced through large deformations and mixture-based multiphase models [3], apt to describe how the different biological species including cells, extra-cellular constituents and metabolites diffusing through the fluids exchange mass and forces within constrained environments. In these complex systems, the modelling of the leading interactions and feedback mechanisms governing the growth fate is diriment to evaluate how mechanical stresses influence the physiological events at the tissue level and, in turn, in which way the dynamics of tissue growth affects the remodelling of tissue properties at the continuum scale. In the case of solid tumors, abnormally high residual stresses generate from impairments between healthy and cancer cell mitosis, leading the latter to hyper-proliferate in confined districts [4]. Nonlinear (soft) poroelasticity allows to highlight how tumor development is strongly affected by the level of mechanical stress, stress gradients and interstitial fluid pressure (IFP), that, as well-known, alter cells intrinsic rates via specific mechano-transduction signaling and rule the nutrients movement towards the periphery of the tumor aggregates, in this way promoting cancer cells invasion and central apoptosis [5]. Growth-induced stresses so alter the intra-tumoral micro-environment, the deformation of solid matrix due to the activity of aggressive cells potentially causing a significant deviation of local tissue properties from the native ones. The *in vivo* characterization of intra-tumoral compression and evolutionary remodelling can thus help to envisage potential mechanically-based strategies for cancer treatment via precise medicine, e.g. by selectively targeting tumor districts with dynamic stimuli *ad hoc* designed on the basis of the tumor-specific mechanical response, also to find possible effects on cells programs. To this aim, the relation among nonlinear elastic moduli, inelastic deformation and prestress describing how growth irreversibly determines the adaptation of tangent properties is studied, by investigating growth-induced material heterogeneities and anisotropies and by also looking at possible applications for bio-inspired materials.

References

[1] *M. Fraldi and A. R. Carotenuto, "Cells competition in tumor growth poroelasticity," Journal of the Mechanics and Physics of Solids, vol. 112, p. 345-367, (2018).*

[2] *G. Sciumé, S. Shelton, W. Gray, C. Miller, F. Hussain, M. Ferrari, P. Decuzzi and B. Schrefler, "Tumor Growth Modeling from the Perspective of Multiphase Porous Media Mechanics," Mol Cell Biomech., vol. 9, no. 3, pp. 193-212, (2012).*

[3] *S. C. Cowin and L. Cardoso, "Mixture theory-based poroelasticity as a model of interstitial tissue growth," Mechanics of Materials, no. 44, pp. 47-57 (2012).*

[4] *S.-L. Xue, B. Li, X.-Q. Feng and H. Gao, "Biochemomechanical poroelastic theory of avascu-lartumor growth," Journal of the Mechanics and Physics of Solids, no. 94, pp. 409-432, (2016).*

[5] *T. Stylianopoulos and al., "Causes, consequences, and remedies for growth-induced solid stress in murine and human tumors," PNAS, vol. 109, no. 38, p. 1510115108, (2012).*

Development of a fully controllable real-time pump to reproduce left ventricle physiological flow

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Keywords: Pulsatile pump, in-vitro haemodyinamic simulation, left ventricle

Experimental methods offer the ability to recreate physical state and conditions in a controlled environment in terms of input and output variables. In the context of the cardiovascular system, mock circulatory systems (MCSs) are important experimental tools to provide information such as blood flow and pressures at different locations that, currently, can be difficult to be measured clinically. In literature several types of MCS were proposed for fluid dynamic investigation of different vascular districts as well as to test new medical devices [1]. However, these MCSs suffer the main drawback of being not fully controllable for flow reproduction waveform in terms of times and amplitudes of the physiological heart cycle [2].
The aim of this work is to present a custom pulsatile pump system with the advantage of a full flexible flow waveform definition. The system was composed by a piston actuated by a servomotor and controlled by a real-time processor. Our system can reproduce the entire ventricular waveform, including both the aortic and mitral flow profiles. The core of our workflow is mainly based on a B-spline interpolation algorithm where the set of the physiological parameters can be modified directly by the user. In particular, the platform permits to independently set: stroke volume (SV), heart frequency (HF), systole/diastole duration ratio and physiologic flow peaks values and the relative time positions. To demonstrate the versatility and to validate the waveform reproduction, three different profiles were imposed and the corresponding flow was measured through an ultrasound flow meter positioned at the output of the pump. The three profiles were chosen to mimic three common waveforms of the left ventricle in a normal state (p_1) and in case of severe cardiac insufficiency (p_2) and cardiac fibrillation (p_3). For p_1 a dataset from literature was used [3]; p_2 and p_3 were obtained by reducing the SV from 75 to 20 ml and by increasing the HF from 70 bpm to 120 bpm, respectively. The maximum root mean square error (E_{RSM}) between the ideal and the measured profile was evaluated as a percentage of the flow range considered over 50 cycles. The E_{RSM} were 2.3%, 1.6% and 5.1% for p_1, p_2 and p_3, respectively. The performance validation was considered to be satisfactory, even for low amplitude and high frequency profiles, as the error values were always contained within the transducer accuracy range (2-6 %).

References

[1] *Toninato, R., Salmon, J., Susin, F.M., Ducci, A., Burriesci, G., Physiological vortices in the sinuses of Valsalva: An in vitro approach for bio-prosthetic valves. J Biomech.,* **Vol 49**, *(2016)*

[2] *Mechoor, R., Schmidt, T., Kung, E., A Real-Time Programmable Pulsatile Flow Pump for In Vitro Cardiovascular Experimentation, ASME. J Biomech Eng.,* **Vol 11**, *(2016)*

[3] *Capellini, K., Vignali, E., Costa, E., et al. Computational Fluid Dynamic Study for aTAA Hemodynamics: An Integrated Image-Based and Radial Basis Functions Mesh Morphing Approach, ASME. J Biomech Eng.,* **Vol 11**, *(2018)*

Hyperelasticity and instability in soft-tensegrity structures for cell mechanics

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Keywords: cell mechanics, nonlinear tensegrity systems, multicellular models

In the last decades, several evidences have shown that tensegrity principles can effectively explain many aspects of the mechanical behaviour of living cells. According to an idea proposed by Ingber in 1980s, the cytoskeleton behaves as a tensegrity unit providing internal forces transmission, shape and elastic stiffness to the cell through the storing of prestress within its protein constituents, mainly actomyosin microfilaments and microtubules [1]. In most of the literature applications, tensegrity systems consist of a set of linearly elastic cables under (pre)tension interconnected to rigid or extremely small contracting, eventually buckling, struts under (pre)compression [1]. However, when adopting tensegrity systems for describing cell mechanics, these standard hypotheses have to be necessarily overcome in the light of the large displacements and nonlinear deformations exhibited by the cytoskeletal network during cells *in vivo* activities or in response to mechanical solicitations, with possible coupling of severe contractions and buckling in microtubules [2]. On these bases, the Authors provide a novel 30-element hyperelastic and buckling soft-strut cellular tensegrity model, involving both constitutive and geometrical nonlinearities, which allows to gain further qualitative and quantitative insights into the cell mechanics under different types of loading conditions [2]. In this way, prestress-guided mechanisms of overall elasticity modulation, size tuning, energy storing/releasing, microstructural kinematics and instability-mediated configurational switching are analytically and numerically derived. Finally, the capability of the cellular tensegrity paradigm to give different macroscopic deformability as a function of the internally stored prestretch level, is employed for building up finite element models of multicellular clusters inhabited by both healthy and tumour cells, which in fact have been found to exhibit a discrepancy of about 70% in terms of elastic stiffness, and hence possible in-frequency separated resonance-like responses when subjected to ultrasound-induced mechanical oscillations [3]. The harmonic response of clusters of tensegrity-like cells is then studied under the action of low intensity ultrasounds to the aim of investigating the possibility to perform targeting and selective attack of cancer cells in tumour masses by means of in-frequency tuned mechanical actions such as to induce focused destruction of malignant units, e.g. via fatigue-like phenomena, without compromising the healthy neighbours.

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[1] D.E. Ingber, N. Wang, and D. Stamenović. Tensegrity, cellular biophysics, and the mechanics of living systems. *Rep.Prog.Phys.*, 2014.

[2] M.Fraldi, S.Palumbo, A.R.Carotenuto, A.Cutolo, L.Deseri, and N.Pugno. Buckling soft tensegrities: fickle elasticity and configurational switching in living cells. *J.Mech.Phys.Solids*, 2019.

[3] M. Fraldi, A. Cugno, L. Deseri, K. Dayal, and N. M. Pugno. A frequency-based hypothesis for mechanically targeting and selectively attacking cancer cells. *J.R.Soc.Interface*, 2015.

Measuring in-vivo, loaded knee kinematics through dynamic MRI

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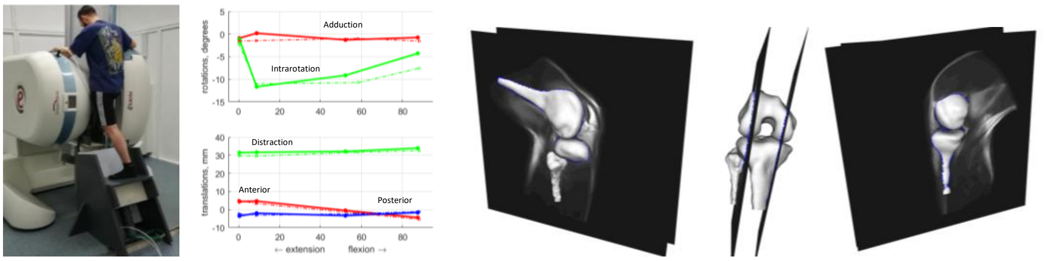
Keywords: Knee Kinematics, Dynamic MRI, 2D/3D Registration

Understanding normal and impaired musculoskeletal function during motion is a high radiological, biomechanical and clinical priority [1]. Understating the joint kinematics under loads is a fundamental step. Actual measurement techniques are however invasive or imprecise [2]. Dynamic magnetic resonance imaging (DMRI) represents an edging technology that may overcome these limitations, providing a way to record the motion of articular structures non-invasively [3].
This work presents a combination of MRI scanner (0.25 T G-Scan Brio, Esaote), MRI compatible rig (fig. 1.a), MR dynamic sequence (2D-HYCE S Gradient Echo), and postprocessing software (a 2D/3D registration algorithm based on edge detection and ICP registration) that makes it possible to measure the tibio-femoral relative motion in-vivo, under physiological loading conditions and over 90° of knee flexion.
To evaluate the accuracy of the measurement process, tibio-femoral kinematics was first evaluated through four static 3D MRIs taken roughly at 0°, 10°, 60° and 90° of flexion. From these static scans, simulated DMRI data was reconstructed and the tibio-femoral kinematics was evaluated through the proposed approach. The comparison of the two motions (fig 1.b) results in a maximum mean rotation and translation errors of 1.89° (flexion) and 1.43 mm (distraction), respectively. Preliminary investigations with real DMRI data confirm the applicability of the proposed approach (fig 1.c).



(a) (b) (c)

Figure 1: a) The scanner with the rig during dynamic, loaded test. b) Comparison of the tibio-femoral kinematics obtained from 3D static MRI (dotted) and simulated DMRI (continuous). c) Preliminary results from real DMRI.

References
*[1] Storheim, K, Zwart, J-A., "Musculoskeletal disorders and the Global Burden of Disease study" Ann RheumDis, **73**, page 949-950, (2014).*
[2] Masum, M. A., et al., "A Review: Techniques for Kinematic Analysis of Knee Joints," Australian Biomedical Engineering Conference (ABEC), Camberra, Australia, May, (2014).
*[3] Borotikar, B., et al., "Dynamic MRI to quantify musculoskeletal motion: A systematic review of concurrent validity and reliability, and perspectives for evaluation of musculoskeletal disorders", PloS one, **12** (12) e0189587, (2017).*

A numerical model based on Kalman filtering for data assimilation of turbulent flows in heart valves applications

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Keywords: Data Assimilation, Kalman Filter, Heart Valves

The clinical relevance of 4D Phase Contrast Magnetic Resonance Imaging for blood flow in the ascending aorta is limited by spatial and temporal resolution which are insufficient for detailed assessment of flow related parameters such as turbulent kinetic energy (TKE) or viscous shear stress (VSS). Data Assimilation (DA) technique can help to enhance the quality of these parameters. The technique consists in combining sparse and noisy measurement data (observed data) with a numerical (forward) model in order to obtain an improved prediction of the true state of the system.

In the past decades Kalman filter [1] has proven to be a mature and well developed algorithm for DA in a wide range of research fields. Computation of an appropriate filter is based on the covariances of the uncertainties of the measurement and the forward model. These covariances are typically not known a priori, such that an appropriate design of a Kalman filter requires modelling.

First, we propose to consider the voxel-based observed data as the result of an averaging of the true state over the voxel size. Such data can be interpreted as an LES-filtered flow field (Large Eddy Simulation) and the corresponding covariance matrix as the subgrid scale term. Second, the numerical forecast given by the forward model can be decomposed in an expectation value (averaging over time or phase) and its fluctuations. Such expected values can be interpreted as a RANS (Reynolds Averaged Navier–Stokes) flow field and the corresponding covariance matrix as the Reynolds stresses. This allows us to use the rich theory of turbulent flow, RANS and LES models to design an appropriate Ensemble Kalman filter [2].

The forward model, used to provide the numerical forecast, comprises a finite-element solver for the full elastodynamics equations of the structure (vessels and heart valves) and a finite-difference flow solver for the Navier–Stokes equations for the Direct Numerical Simulation (DNS) of turbulent flows. The two solvers are coupled with an immersed boundary method where the fluid velocities and the mechanical responses of the structure are transferred between the fluid grid and the structural mesh by a variational approach, [3].

At any update time, our DA algorithm applies a correction to the forecast based on a set of observed data and the covariances of the observations and the forecast itself. The resulting 4D flow field is then used to quantify the TKE in the wake of the aortic valve. Furthermore, it will provide detailed information on characteristic flow patterns in the ascending aorta and VSS in the bulk flow.

These results will be presented for different configurations of increasing complexity in order to validate the proposed methodology.

References

[1] *Kalman, R. E., "A New Approach to Linear Filtering and Prediction Problems" Transactions of the ASME-Journal of Basic Engineering,* **82** *(Series D), page 35-45 (1960).*

[2] *Evensen, G., "The Ensemble Kalman Filter: theoretical formulation and practical implementation," Ocean Dynamics,* **53***, page 343-367 (2003).*

[3] *Nestola, M. G. C., Becsek, B., Zolfaghari, H., Zulian, P., De Marinis, D., Krause, R., & Obrist, D., "An immersed boundary method for fluid-structure interaction based on overlapping domain decomposition," arXiv preprint arXiv:1810.13046 (2018).*

Undulatory locomotion of an elastic body in granular media: a comparison between FEM-DEM simulations and Resistive Force Theory

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Keywords: Undulatory locomotion, Resistive Force Theory, FEM-DEM simulation.

Undulatory locomotion is a common and powerful strategy used in nature at different biological scales by a broad range of living organisms [1], from flagellated bacteria to prehistoric snakes. Their movement inside a *"flowable"* material is a complex phenomenon. By taking inspiration from this strategy we aim to model locomotion in a granular medium with the objective of providing more insights to design robots for soil exploration. Granular locomotion is relatively still not well understood, compared to other kinds of motion, and thus it still remains as an open and challenging field. Firstly, we approach this phenomenon by performing a combined Finite Element and Discrete Element analysis of a slender body immersed in a layer of mono-disperse frictionless spherical particles. We present a parametric study where the propulsion of the body is numerically observed. Our results show that the slender body reaches a steady state velocity after a transitory period, based on the applied boundary conditions.

Further, we analytically derive the Lagrange's equations of motion [2] of a discrete multi-bar system subjected to following and viscous forces, thus emulating the granular environment. The forces exchanged between the locomotor and the environment, according to the Resistive Force Theory [3], play a crucial role in improved comprehension of granular motion. Another essential feature of the model is the strategy adopted for generating a propulsive wave [4] and, thus, controlling the system. The two approaches, despite the different physical hypothesis, show a good agreement both qualitatively and quantitatively.

References

[1] N. Cohen and J. H. Boyle, "Swimming at low Reynolds number: a beginners guide to undulatory locomotion," *Contemporary Physics*, vol. 51, no. 2, pp. 103–123, 2010.

[2] D. T. Greenwood, *Classical dynamics*. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1997.

[3] J. Gray and G. Hancock, "The propulsion of sea-urchin spermatozoa," *Journal of Experimental Biology*, vol. 32, no. 4, pp. 802–814, 1955.

[4] M. Sfakiotakis and D. P. Tsakiris, "Biomimetic centering for undulatory robots," *International Journal of Robotics Research*, vol. 26, no. 11-12, pp. 1267–1282, 2007.

A Genetic Algorithm for the Estimation of Viscoelastic Parameters of Biological Samples manipulated by MEMS Tweezers

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Keywords: MEMS Microgripper, Viscoelastic Characterization, Genetic Algorithms.

In this paper, a novel technique for the viscoelastic characterization of biosamples is presented. The measuring tool consists of MEMS-technology based tweezers that are used, in general, to perform micromanipulation tasks. A mechanical model is developed for the nonlinear dynamics of the microsystem, composed of the tweezers and the sample to be analyzed. The Maxwell liquid drop constitutive law is considered for the sample. The identification of the viscoelastic parameters is performed by implementing a genetic algorithm.

References

[1] *Mijailovic, A. S., Qing, B., Fortunato, D., Van Vliet, K. J., 2018. Characterizing viscoelastic mechanical properties of highly compliant polymers and biological tissues using impact indentation. Acta biomaterialia 71, 388–397.*
[2] *Backman, D. E., LeSavage, B. L., Shah, S. B., Wong, J. Y., 2017. A robust method to generate mechanically anisotropic vascular smooth muscle cell sheets for vascular tissue engineering. Macromolecular bioscience 17 (6).*
[3] *Zhang, W. et al, 2018. Effect of in vitro storage duration on measured mechanical properties of brain tissue. Scientific reports 8 (1), 1247.*
[4] *Addae-Mensah, K. A., Wikswo, J. P., 2008. Measurement techniques for cellular biomechanics in vitro. Experimental biology and medicine 233 (7), 792–809.*
[5] *Rodriguez, M. L., McGarry, P. J., Sniadecki, N. J., 2013. Review on cell mechanics: experimental and modeling approaches. Applied Mechanics Reviews 65 (6), 060801.*
[6] *Chen, K., Yao, A., Zheng, E. E., Lin, J., Zheng, Y., 2012. Shear wave dispersion ultrasound vibrometry based on a different mechanical model for soft tissue characterization. Journal of Ultrasound in Medicine 31 (12), 2001.*
[7] *Lim, C., Zhou, E., Quek, S., 2006. Mechanical models for living cellsa review. J. of biomechanics 39 (2), 195–216.*
[8] *Johnson, M. L., Faunt, L. M., 1992. Parameter estimation by least-squares methods. In: Methods in enzymology. Vol. 210. Elsevier, pp. 1–37.*
[9] *Kohandel, M., Sivaloganathan, S., Tenti, G., 2008. Estimation of the quasi- linear viscoelastic parameters using a GA. Mathematical and Computer Modelling 47 (3-4), 266–270.*
[10] *Di Giamberardino, et al., 2018. New mems tweezers for the viscoelastic characterization of soft materials at the microscale. Micromachines 9 (1).*

A single integral approach to fractional-order non-linear hereditariness

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Keywords: non-linear hereditariness, fractional calculus, quasi-linear model

In this study a non-linear approach to the hereditariness of complex materials and soft matter [1,2,3] is faced within the context of fractional differential calculus. The non-linear dependence of the creep (relaxation) function on the level of stress (strain) observed in experimental tests conducted at the Bio/NanoMechanics for Medical Sciences Lab of Palermo University on ligaments and tendons of the human knee has been discussed with a multiplicative decomposition of the material characteristic function [4]. This approach, followed by a proper non-linear transform of the material state variables yields a Volterra convolution in terms of the transformed variables and a non-linear model involving fractional-order operators with specified relations among the integro-differentiation orders has been obtained. Some numerical examples showing that for prescribed strain (stress) history the material stress function (strain function) may be predicted either using the relaxation function and/or its non-linear equivalent creep function has been reported in the paper.

References

[1] *Fung Y.C., Skalak R. Biomechanics: Mechanical Properties of Living Tissues. J Biomech Eng 1981;103:231.*

[2] *Provenzano P.P., Lakes R.S., Corr D.T., Vanderby R., "Application of nonlinear viscoelastic models to describe ligament behavior" Biomech Model Mechanobiol, 1:4557. 2002.*

[3] *Pioletti D.P, Rakotomanana L.R., "On the independence of time and strain effects in the stress relaxation of ligaments and tendons" J Biomech, 33:172932, 2000.*

[4] *Bologna E., Lopomo N., Marchiori G., Zingales M. "A non-linear sthocastic approach of ligaments and tendons fractional-order hereditariness" submitted to Probabilistic Engineering Mechanics, CSM8.*

MS06

SHELL AND SPATIAL STRUCTURES

Active tensegrity shells of energy efficient buildings

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Keywords: Tensegrity Structures; Dynamic Solar Façades; Energy Efficient Buildings.

Tensegrity structures are prestressable truss structures, which are obtained by connecting compressive members (bars or struts) through the use of pre-stretched tensile elements (cables or strings). Motivated by nature, where tensegrity concepts appear in every cell, in the microstructure of the spider silk, and in the arrangement of bones and tendons for control of locomotion in animals and humans, engineers have only recently developed efficient analytical methods for exploiting tensegrity concepts in engineering design [1-2].

Recent studies have investigated the use of tensegrity structures for the construction of active solar façades of Energy Efficient Buildings [3-4]. Optimal daylighting in buildings can be achieved, for example, through effective shading devices ensuring optimal illumination levels according to the time of the day and the season. The present work aims to design, model and control active solar façade based on tensegrity units that support solar panels and/or sound-proof panels. We propose a tensegrity solution for the actuated façade panels of the well-known Al Bahar Towers in Abu Dhabi. Designed recently by Aedas Architects, using a different technology, this is intended to mimic the shading lattice-work "mashrabiya". The elements forming the "origami" panels of the tensegrity shading screens analyzed in the present work are opened (i.e., folded) at night, and are progressively closed during daylight hours, by controlling the tension in selected cables. We simulate the dynamics of the tensegrity shading screens through an in-house developed code that handles a rigidity constraint on the deformation of the bars. We present numerical results illustrating the mechanics of the proposed tensegrity solar façade and its morphing capabilities, which require minimal storage of internal energy, and reduced operation costs (due to lighter friction between parts), as compared, for instance, to the piston-actuated technology adopted by Aedas Architects.

References

[1] *Skelton RE, de Oliveira MC. Tensegrity Systems. New York: Springer Science+Business Media, 2009.*

[2] *Skelton RE, Fraternali F, Carpentieri G, Micheletti A. Minimum mass design of tensegrity bridges with parametric architecture and multiscale complexity. Mech Res Commun 2014; 58: 124-132*

[3] *Fraternali F, De Chiara E, Skelton RE. On the use of morphing and wind stable tensegrity structures for shading facades of smart buildings. Smart Mater Struct 2015; 24, 105032 (10pp).*

[4] *Cimmino, M.C., Miranda, R., Sicignano, E., Ferreira, A. J. M.; Skelton, R. E., Fraternali, F. Composite solar façades and wind generators with tensegrity architecture. Compos Part B-Eng 2016, doi: 10.1016/j.compositesb.2016.09.077*

A new quadrilateral implicit G^1-conforming shell element

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Keywords: G^1 conforming shell element, G^1 continuity, Gregory Patch

A new strategy to design implicit G^1-conforming finite elements for the analysis of Kirchhoff-Love shells are presented. In particular in this contribution only the quadrilateral element based on the bi-cubic Gregory patch [1, 2] is presented.

The proposed element accounts for the edge rotations of the Kirchhoff-Love shell model implicitly at the element formulation. The key-idea consists in generating the rational Gregory approximant by means of the control of the configuration of the boundary ribbons of the element (patch), generalizing the idea proposed in [4]. The G^1-conformity is directly accounted at the element level in the assembly of the global stiffness, analogously to [3].

The Gregory Patch is an useful tool to design G^1-conforming elements on general C^0-conforming unstructured meshes. But due to the rational enhancement the second derivatives at the corners of the elements present finite discontinuities, that prevent the elements from passing the bending patch test. These discontinuities are removed by means of a constrained Gregory Patch formulation (indicated by CG^1-formulation) by means of the Lagrange multiplier method.

In this way, the rational conforming space collapses into a conforming rearrangement of the original polynomial space. Resuming, the rational Gregory Patch is suitable to assemble the global stiffness accounting the G^1-continuity implicitly, successively the vanishing of the discontinuities on the second cross derivative (at the corners of the elements) are enforced at the local element via Lagrange Multipliers formulation.

The proposed CG^1-formulation design robust Kirchhoff-Love shell elements that pass the bending patch test and present optimal rate of convergence on general unstructured meshes.

References

[1] *Farin, G., Curves and surfaces for CAGD: A practical guide, The Morgan Kaufmann Series in Computer Graphics. Morgan Kaufmann, 5 edition, (2001).*

[2] *Gregory, J.A., Smooth interpolation without twist constraints, Computer Aided Geometric Design, page 71-87 (1974).*

[3] *Greco, L., Cuomo, M. and Contrafatto, L., A quadrilateral G^1-conforming finite element for the Kirchhoff plate model, Computer Methods in Applied Mechanics and Engineering,* **346**, *page 913-951 (2019).*

[4] *Cuomo, M. and Greco, L., An implicit strong G^1-conforming formulation for the analysis of the Kirchhoff plate model, Continuum Mechanics and Thermodynamics, https://doi.org/10.1007/s00161-018-0701-3 (2018).*

R-Funicularity of analytical shells

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Keywords: funicular analysis, analytical shells, form finding

The interest of studying funicularity of shell structures stands in their ability to carry applied loads mainly by membrane actions. This property is governed by the structural form, the actual configuration of applied loads and boundary conditions represented by the presence and effectiveness of shell supports. The term funicular shell has been generally related to some particular solutions of the equilibrium equation pertaining to the membrane theory of shells. For instance a shell with a uniform and isotropic state of compressive stress, is the one proposed in 1961 by Ramaswamy [1]. Therein the membrane equilibrium problem is discussed and some interesting approximated solutions, having different analytical expressions known from the Prandtl's membrane analogy.
A huge number of shell forms can be obtained numerically, either by solving the equilibrium equation associated to the membrane theory of shells or by alternative numerical approaches such as the Force Density Method or the Thrust Network Analysis [2]. All these solutions start from the hypothesis of pure membrane behavior. However if one is interested in solving the complete elastic shell problem over the initial shape found (analytically or numerically), then bending behavior arises, depending on the boundary conditions and the ratio between membrane and bending stiffness. For this reason a re-definition of shell funicularity has been recently proposed by some of the authors [3], namely *relaxed funicularity* or *R-funicularity*, in order to assess the goodness of the initial shape. In a previous work R-funicularity has been used to analyze the shape of form-found shells. In this work we propose to verify the solutions proposed in [1]. The interest in this subject is because after Ramaswamy's work, many concrete shells of that form have been realized, supposing a complete funicular behavior.

References

[1] *Ramaswamy, G. S., "Design and construction of a new shell of double curvature", in Proceedings of the Symposium on Shell Research, Delft, Nederland, 1961, North Holland Publishing Co. Amsterdam, page 102-115, (1961).*

[2] *Marmo, F., Rosati, L., "Reformulation and extension of the thrust network analysis", Computers & Structures,* **182***, page 104-118, (2017).*

[3] *Gabriele, S., Varano, V., Tomasello, G., Alfonsi, D.,"R-Funicularity of form found shell structures", Engineering Structures,* **157***, page 157-169, (2018).*

Towards an effective modelling of timber gridshells: staged construction, R-Funicularity, continuum modelling

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Keywords: gridshell, funicularity, discrete homogenization

A nonlinear staged construction analysis is adopted to simulate the forming process of timber gridshell [1], paying particular attention to the modelling of the cylindrical joints connecting the orthogonal laths. Cylindrical joints enable the initially flat lattice to be formed into a doubly curved gridshell shape; therefore, a stated in [2], accurate modelling of the joints is a crucial aspect when simulating the forming process of active bending timber gridshells. The effect of joint modelling on the final gridshell shape is thus investigated. Another important parameter influencing the gridshell shape is the orientation of laths of the initially flat lattice.

Then, an equivalent continuum of the gridshell selected is proposed through two different constitutive identification procedures, based on a flat and a curved REV, respectively. Having an equivalent continuum of a gridshell could be advantageous for better understanding of the global mechanical behaviour of the gridshell, in relation with its final shape. In the literature equivalent continua are used to evaluate the global buckling load of the gridshell [3], or for design purposes, as done for the Mannheim Multihalle one [1]. Furthermore, an equivalent continuum model could be used for exploring, in a more efficient way, a design space of target shapes or, once the shape is fixed, to study the optimal directions of the grid lines, with respect to the principal lines of the surface. Several approaches to identify an equivalent continuum have been developed in the literature, as referenced in [4]. In this work, the identification procedure is based on a variational approach. The efficiency of the identification procedure is validated through numerical comparisons. Using an equivalent continuum definition, the final geometry of the grid shells obtained from different lath orientations, is analysed in order to assess how laths orientation affects the structural shape in terms of *funicularity*. The R-Funicularity method presented in [5] is used for such purpose.

References

[1] *E. Happold, W.I. Liddell, Timber lattice roof for the Mannheim Bundesgartensschau, The Structural Engineer,* **53***, no. 3, pp. 99-135 (1975).*

[2] *B. D'Amico, A. Kermani, H. Zhang, Form finding and structural analysis of actively bent timber grid shells, Engineering Structures:* **81***, pp. 195-207 (2014).*

[3] *S. Malek, T. Wierzbicki, and J. Ochsendorf, Buckling of spherical cap gridshells: A numerical and analytical study revisiting the concept of the equivalent continuum, Eng. Struct.,* **75***, pp. 288-298 (2014).*

[4] *V. Gioncu, Buckling of Reticulated Shells: State-of-the-Art, Int. J. Space Struct.,* **10***, no. 1, pp. 146 (1995)*

[5] *S. Gabriele, V. Varano, G. Tomasello, D. Alfonsi, R-Funicularity of form found shell structures, Engineering Structures:* **157***, pp. 157-169, (2018).*

Stability evaluation by Digital Image Correlation of a masonry vault prototype under loading

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Keywords: Digital Image Correlation, Masonry Vault, Additive Manufacturing

The new attention to masonry structures evidenced their continuous potential to be an actual architectural and engineering solution. The increasing interest in analysing ancient masonry vaults, built in the past all over the world, gave back today a renovated necessity to propose this kind of structures for the covering of new sustainable buildings. At the same time the stability condition of ancient and new masonry vaults represent a fascinating and crucial area of research.

In the present paper different funicular structures have been analyzed in order to compare them to identify the best shape and the best hole pattern.

The first goal is to propose a form finding design for latticed masonry shells starting from a given topology and obtaining the optimized grid in term of stiffness and stability. The shape of the vaults is reached through the changing of some chosen parameters such as shallowness ratio (SR) and hole pattern in the vault [1,2]. Global structural stability analysis has been made varying the slenderness, the SR, through different load-cases and constrain conditions[3,4].

In the present paper, a **scaled prototype** of this vault typology is realized with the help of additive manufacturing. The prototype has been subjected to different loading configurations and analyzed by **Digital Image Correlation** (DIC) in order to observe the deformation pattern of the vaults during the increasing force application. The experimental test were performed in order to correlate the numerical evidence to the experimental data.

References

[1] *Richardson, J. N., Adriaenssens, S., Coelho, R. F., & Bouillard, P. "Coupled Form FInding and Grid Optimization Approach for SIngle Layer Grid Shells". Engineering Structures* ***Vol. 52****, 230-239 (2013).*

[2] *Manuello, A.;Bazzucchi, F.; Carpinteri, A.. "Step-by-step stability analysis of shallow grid shells: Buckling versus snap-through" IASS 2016 Tokyo Symposium: Spatial Structures in the 21st Century, Tokyo 26-30 September 2016.*

[3] *Bazzucchi, F.; Manuello, A.; Carpinteri, A.. "Instability load evaluation of shallow imperfection-sensitive structures by form and interaction parameters" European Journal of Mechanics. A, Solids.* ***Vol. 66,*** *201-211, (2017).*

[4] *Bazzucchi, F.; Manuello, A.; Carpinteri, A.. Interaction between snap-through and Eulerian instability in shallow structures In: International Journal of Non-linear Mechanics.* ***Vol.*** *88,*

On the straight-helicoid to spiral-ribbon transition in thin elastic ribbons

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Keywords: Thin ribbons, Sadowsky functional, microstructure

Thin ribbons are usually modeled as unstretchable plates endowed with the Kirchhoff bending energy. The first treatment of thin ribbons can be found in the seminal work of Sadowsky [2], who proposed to model a ribbon as a thin rod whose strain energy depends on the curvature and the torsion of the axis. A formal justification of the Sadowsky's energy was given by Wunderlich [3] also by means of a parametrization of the deformed configuration of the ribbon as a ruled surface. A rigorous justification based on variational convergence was given in [1].

A ribbon model starting from the Kirchhoff bending energy was derived in [4] using mechanical arguments. The inextensibility of the ribbon leads to a non convex constraint. As a consequence, the usual energy energy-minimization procedure may fail to select equilibria. Indeed, what may happen is that a minimizing sequence of isometric deformation may have a limit that does not satisfy the constraint $\det \mathbf{K} = 0$. This difficulty is resolved by introducing a relaxed energy which automatically accounts for the fine scale oscillations and, as a consequence, is defined also for symmetric tensor having determinant different from zero.

Using this model, we study the equilibrium of a thin elastic strip subject to combined twist and traction. As a result, we recover two types of equilibrium states: the straight-helicoid and the spiral-ribbon. We also identify the critical value of the twist at which the transition from one state to another takes place for a prescribed traction.

References

[1] L. Freddi, P. Hornung, M.G. Mora, R. Paroni: A corrected Sadowsky functional for inextensible elastic ribbons. *J. Elasticity* **123** (2016), 125–136.

[2] M. Sadowsky: Ein elementarer Beweis für die Existenz eines abwickelbaren Möbiuschen Bandes und die Zurückführung des geometrischen Problems auf ein Variationsproblem. *Sitzungsber. Preuss. Akad. Wiss.* 1930 – Mitteilung vom 26. Juni, 412–415.

[3] W. Wunderlich: Über ein abwickelbares Möbiusband, *Monatshefte für Mathematik* **66** (1962), 276–289.

[4] R. Paroni and G. Tomassetti: Macroscopic and Microscopic Behavior of Narrow Elastic Ribbons, *Journal of Elasticity* (2018), https://doi.org/10.1007/s10659-018-09712-w.

Pressure field correlation for buildings with hyperbolic paraboloid roofs: results of wind-tunnel tests.

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Keywords: wind-tunnel tests, correlation structure, hyperbolic paraboloid roof.

The aerodynamics of roofs with a hyperbolic paraboloid shape is almost neglected by codes. However, this shape is commonly used to cover large spans through tensile structures or light shells. Due to their lightness and size, these structures are very sensitive to wind, that may produce very complex pressure distributions. The correlation structure of wind-induced pressure fields plays therefore a relevant role, because it affects the resultant forces to be included in the design of structural elements, at different scales, and this aspect has not yet been fully explored in the scientific literature for this shape. Based on experimental tests performed in the CRIACIV boundary-layer wind-tunnel in Prato (Italy) on in-scale models, this paper investigates, as a part of a wider research, the correlation structure of the pressure field on buildings with a hyperbolic paraboloid roof. Namely, the loss of correlation of the experimental pressure distribution on a sample model is described by evaluating the effective pressure coefficients on regions of increasing size around significant points of the roof, for different angles of incidence of the wind.

References

[1] *Rizzo, F., D'Asdia, P., Ricciardelli, F., Bartoli, G., "Characterization of pressure coefficients on hyperbolic paraboloid roofs", Journal of Wind Engineering and Industrial Aerodynamics,* ***102****, 61–71 (2012).*

[2] *Rizzo, F., Sepe, V.,"Static loads to simulate dynamic effects of wind on hyperbolic paraboloid roofs with square plan", Journal of Wind Engineering And Industrial Aerodynamics,* ***137****,46-57 (2015).*

[3] *Rizzo, F., Sepe, V., Vasta, M.,"Correlation structure of wind-tunnel pressure fields for a hyperbolic paraboloid roof" in Proceedings of AIMETA 2017 - XXIII Conference of the Italian Association of Theoretical and Applied Mechanics, Salerno, Italy, 4-7 September 2017, 462-471, ISBN 978-889-42484-7-0 (2017).*

[4] *Rizzo, F., Ricciardelli, F., "Design approach of wind load for hyperbolic paraboloid roof with circular and elliptical plan", Journal of Engineering Structures,* ***139****, 153-169 (2017)*

[5] *Rizzo F., Barbato M., Sepe V., "Peak factor statistics of wind effects for hyperbolic paraboloid roofs", Engineering Structures,* ***173****, 313-330 (2018)*

Equilibrium analysis of a sail vault in Livorno's Fortezza Vecchia through a modern reworking of the stability area method

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Keywords: Masonry dome, Fortezza Vecchia in Livorno, Limit Analysis.

The 'Fortezza Vecchia' in Livorno is a maritime castle of great historical interest. Although its oldest parts date back to the Middle Ages, the castle was substantially reshaped in the 16th century by Giuliano and Antonio the Elder da Sangallo, who enlarged it. The modifications performed took into account the nature of the site and the pre-existing medieval structures [1]. The aim of the present paper is to refer about a preliminary study of the mechanical response of an interesting sail vault covering a quadrilateral room located in the Cavaniglia bastion of Fortezza Vecchia.

In particular, admissible stress fields within the vault have been determined by considering the weights of the vault itself and the overlying soil layers. The analysis has been performed by means of a re-visitation of the stability area method, an interesting historical method proposed by Durand-Claye. Originally designed for masonry arches, in 1880 [2], the French scholar extended it to domes of revolution, provided the dome is subdivided into several lunes, obtained by ideally sectioning the dome with meridian planes. Durand-Claye's contribution consists in applying his method to each lune, considered as an independent arch of varying width.

In previous contributions the authors re-elaborated Durand-Claye's method in order to assess the stability of masonry domes of revolution subject to symmetrical load distributions. The method has been suitably extended in order to assess the stability of an entire dome by assuming nil tensile hoop forces. Indeed, in the general case, vanishing of the stability area of a single lune may not correspond to a kinematically admissible collapse mechanism for the entire dome. Hence, the stability area is examined by searching for any limit distributions of the internal forces leading to a corresponding mechanism for the dome considered as a whole [3]. In the present contribution, the reworked Durand-Claye method, implemented in an expressly developed numerical tool, is used to estimate the safety level of the sail vault in the Fortezza Vecchia under vertical loads. Determination of the vault's geometric safety factor, together with the admissible distributions of internal forces within the vault itself, represents a first basic step in its safety assessment.

References

[1] Ulivieri, D., Fortezza Vecchia in Livorno, Nexus Netw J (2014) 16:675–697.
[2] Durand-Claye A., Vérification de la stabilité des voûtes et des arcs. Applications aux voûtes sphériques, Annales des Ponts et Chaussées, 19, I sem., 416-440, 1880.
[3]Aita D., Barsotti R., Bennati S., A modern reinterpretation of Durand-Claye's method for the study of equilibrium conditions of masonry domes. AIMETA 2017 - Proceedings of the XXIII Conference The Italian Association of Theoretical and Applied Mechanics, L. Ascione, V. Berardi, L. Feo, F. Fraternali and A. M. Tralli (eds.), Gechi Edizioni, Mediglia (MI), Salerno, Italy, 4-7 September 2017, 1459-1471, 2017.

Self-stress analysis of tensegrity structures using Distributed Static Indeterminacy (DSI) and the nodal degrees

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Keywords: tensegrity structures, distributed static indeterminacy, nodal degree.

The analysis of the feasible self-stress states of tensegrity structures with multiple independent self-stress modes is a crucial step in the design of such structures [1]. In seeking of solutions of the form-finding problem for a tensegrity structure with an assigned geometrical configuration, the most difficult aspect is the evaluation of the internal forces in the elements that are consistent both with symmetry properties of the structure and with the unilateral behavior of the elements, i.e. the cables must be in tension and the struts in compression [2].

This paper proposes a novel approach for the grouping scheme of the elements, taking into account both the Distributed Static Indeterminacy (DSI) [3] and the total degrees of the nodes of an element [4].

The feasible self-stress identification is first formulated through a Singular Value Decomposition (SVD) of the equilibrium matrix, and subsequently, through a further SVD of a suitable matrix whose first columns represent the independent self-stress modes and whose last columns are vectors conforming to the unilateral and symmetry properties of the elements and deriving from the adopted grouping scheme.

Several two-dimensional [2] and three-dimensional tensegrity structures [5] were investigated to assess the validity and the accuracy of the proposed method.

References

[1] Zhang, J. Y., Ohsaki, M., Tensegrity Structures (2015).

[2] Koohestani, K., "Automated element grouping and self-stress identification of tensegrities", Eng. Comput., ***32****, page 1643-1660 (2015).*

[3] Zhou, J., Chen, W., Zhao, B. and Dong, S., "A feasible symmetric state of initial force design for cable-strut structures", Arch. Appl. Mech., ***87****, page 1385–1397 (2017).*

[4] Perfect, H., Biggs, N. L., Lloyd, E. K. and Wilson, R. J., Graph Theory, Math. Gaz. (2007).

[5] Fraddosio, A., Marzano, S., Pavone, G. and Piccioni, M. D., "Morphology and self-stress design of V-Expander tensegrity cells", Compos. Part B Eng., ***115****, page 102–116 (2017).*

New computational Limit Analysis approaches for structural optimization problems

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Keywords: computational Limit Analysis (LA), large-scale truss-frame structures, structural optimization problems

In this paper, two recently developed algorithms for the computational Limit Analysis of large-scale 3D truss-frame structures are outlined as useful tools for structural design and optimization purposes. Specifically, they are developed toward characterizing the structural collapse state, which can be considered in selecting the optimum geometrical configuration within appropriate form-finding procedures. The first algorithm, starting from [1], is able to trace a fully exact evolutive piece-wise linear elastoplastic response of the structure [2], up to plastic collapse, by reconstructing the true sequence of activation of made-available plastic joints (as a generalization of plastic hinges). The second algorithm is based on a kinematic iterative approach [3] and is able to determine collapse load multiplier and plastic mechanism in subdued computational time [4]. A rather impressive performance is achieved, in truly precipitating from above on the collapse load multiplier, by rapidly adjusting to the sought collapse mode, in very few iterations. The two algorithms could be conceived separately or all together, based on their own peculiarities, to set down a very efficient procedure toward ruling structural optimization problems based on form-finding quests relying on LA interpretations and concepts.

References

[1] Cocchetti G, Maier G (2003) Elastic-plastic and limit-state analyses of frames with softening plastic-hinge models by mathematical programming. *International Journal of Solids and Structures*, 40(25):7219–7244.

[2] Ferrari R, Cocchetti G, Rizzi E (2016) Limit Analysis of a historical iron arch bridge. Formulation and computational implementation. *Computers and Structures*, 175(15 October 2016):184–196, doi: 10.1016/j.compstruc.2016.05.007.

[3] Zhang P, Lu M, Hwang K (1991) A mathematical programming algorithm for limit analysis. *Acta Mechanica Sinica*, 7(3):267–274.

[4] Ferrari R, Cocchetti G, Rizzi E (2018) Effective iterative algorithm for the Limit Analysis of truss-frame structures by a kinematic approach. *Computers and Structures*, 197(15 February 2018):28–41, doi:10.1016/j.compstruc.2017.11.018.

Design and Control of Minimum Energy Adaptive Structures

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Keywords: adaptive structures, minimum energy, active structural control

The construction industry is the largest consumer of raw materials and most of the environmental impacts of structures are embodied into load-bearing systems [1]. Civil structures are usually designed to meet strength and deformation requirements to withstand rare events such as earthquakes and strong winds which in practice occur very rarely. Most structures are thus over-designed during their service life. Instead, structures could be adaptive to counteract the effects of external loads through sensing and actuation.

A new optimum design methodology for adaptive structures has been formulated by Senatore et al. [2]. The main objective is the minimization of the whole-life energy which encapsulates material and operational energy minimization. Instead of relying only on passive resistance through material mass, an actuation system is optimally integrated to alter the flow of internal forces and to change the shape of the structure. The internal forces are controlled to achieve stress homogenization and the shape is changed to control deflections or to morph the structure into optimal shapes as the load changes [3]. To ensure the embodied energy saved this way is not used up to by actuation, the adaptive solution is designed to cope with ordinary loading events using only passive load bearing capacity whilst relying on active control to counteract larger events with a smaller probability of occurrence. Extensive numerical simulations show that the whole-life total energy could be reduced by up to 70% when the design is stiffness governed (e.g. slender structures, strict deflection limits) [4]. A large scale prototype was successfully tested demonstrating the feasibility [5].

Structural adaptation allows a much more efficient utilization of material resources, thus lowering environmental impact. Adaptive structures can be extremely slender while still being capable of reducing deflections at the expense of a small amount of operational energy. This allows for taller and more slender buildings resulting in increased floor area via reduction of structural cores as well as longer span bridges and self-supporting roof systems. Combining these aspects is unique in structural engineering.

References

[1] S. Kaethner and J. Burridge, "Embodied CO2 of structural frames," *The structural engineer,* vol. 90, no. 5, p. 33-40, 2012.

[2] G. Senatore, P. Duffour and P. Winslow, "Synthesis of Minimum Energy Adaptive Structures," *Structural and Multidisciplinary Optimization.* https://doi.org/10.1007/s00158-019-02224-8, 2019.

[3] A. Reksowardojo, G. Senatore and I. F. C. Smith, "Actuator layout optimization for adaptive structures performing large shape changes," *Lecture Notes in Computer Science,* vol. 10863, 2018.

[4] G. Senatore, P. Duffour and P. Winslow, "Energy and Cost Analysis of Adaptive Structures: Case Studies," *Journal of Structural Engineering (ASCE),* vol. 144, no. 8, p. 04018107, 2018.

[5] G. Senatore, P. Duffour, P. Winslow and C. Wise, "Shape Control and Whole-Life Energy Assessment of an "Infinitely Stiff" Prototype Adaptive Structure," *Smart Materials and Structures,* vol. 27, no. 1, p. 015022, 2018.

Modular foldable and deployable structures and new forms therefore

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Keywords: foldable plate structures; scissor-like structures; angulated bars.

Most of modular kinetic structure thought at the scale of architectural components are the so-called scissor-like structures which emerged in the '70s [1]. Each module is a 4R - planar closed linkage, i.e. a closed chain of four rigid bodies connected by means of four revolute joints whose axes meet at infinite. Meanwhile, supported by custom construction possibilities, the research on kinetic computational origami is now fervent, its fields of application are wide, while constructed architectural examples are lacking [2]. These are also linkages, precisely they are 4R- spherical linkages, which are closed chains where however the four revolute joints have axes meeting at a real point. As the definitions suggests, there are analogies between 4R- spherical and planar linkages. Interestingly, however, such connections have been practically unexplored both at the morphological and at the structural levels.

We set up and discuss such a relationship. The classification of the single linkages is based over the reciprocal distance between the joints and related symmetry, as by the classical Grashof's criterium: we consider the links as rigid bodies whose motion in constrained to certain reciprocal rotations by the distance, either linear or angular in case of planar or spherical mechanisms respectively, between the connecting joints. Similarly, symmetry rules applied to the distance between the joints govern the possible combinations of different linkages [3].

We present therefore mechanisms that have been previously separately developed in the two forms; and we also present mechanisms which are novel in one form, but which are here obtained by the simple translation of the shared symmetry rules from one form to the other, further extending previous research [4] to comprise in particular angulated scissor elements with their retractable motion [5] of their arrangements and their novel foldable plates counterpart.

References

[1] F. Escrig, Modular, ligero, transformable: un paseo por la arquitectura ligera móvil, Universidad de Sevilla,Sevilla (2012).

[2] Miura, K. et al. (eds.), Origami6, American Mathematical Society (2017).

[3] Beatini, V., "Symmetry-Based Transformable and Foldable Plate Structures". ASME. J. Mech. Des. 139(7), pp. 072301—12, 2017.

[4] Beatini V, Morphology of kinetic architectural structures by means of bar and plate 4R-linkages," in Nexus 2018, Relationships Between Architecture and Mathematics, Pisa. Turin: Kim Williams Editors, 2018.

[5] C. Hoberman, "Radial Expansion/Retraction Truss Structures", US patent 5,024,031, 1991. (year of publication).

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VEHICLE DYNAMICS

Front wheel patter instability of motorcycles in straight braking manoeuvre

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Keywords: motorcycle dynamics; stability analysis; front wheel patter; self–excited vibration.

The front wheel of a motorcycle during heavy braking in straight motion can lock before reaching the maximum longitudinal braking force, a problem affecting especially performances of road racing motorcycles, which is preceded by a self–excited vibration referred to as front wheel patter. Aim of the present study is the identification of the actual switching mechanism to instability together with its governing parameters.

A minimal model of the front assembly of a motorcycle is proposed, and its stability in equilibrium configurations is studied via eigenvalue analysis. The sensitivity with respect to all its governing parameters is analyzed by means of stability maps and the self–excitation mechanism is explained with the aid of energy balance analysis and phase–diagrams [1], comparing the results to those existing in the literature [2] and to numerical simulations obtained from a full motorcycle multibody model.

Similarly to chattering at the rear wheel [3], also in this case the key role in the switching mechanism to instability is played by the local dependency of the longitudinal ground force by the downforce. It gives rise to a non–conservative restoring force and to an asymmetric stiffness matrix in the equations of motion, which potentially raises to a critical value the phase–lag between the non–stationary components of longitudinal ground force and slip. Beyond this limit the energy flux is reversed, with the external braking force feeding the oscillating system.

Sensitivity analysis has clarified which, among other parameters, are the most influential ones on patter vibration: the travelling speed, increasing which can have strong destabilizing effects, and the front suspension damping. In case of very stiff elements and assemblies, as for racing motorcycles, patter vibration has been found to be mainly associated to pitch of the main frame, rather than to fork pivotting with respect to the frame itself. In these conditions, the front suspension damping has a strong destabilizing effect, enhanced primarily by the presence of Coulomb friction in dampers and/or forks.

References

[1] *Kroger M., Neubauer M., Popp K. Experimental investigation on the avoidance of self–excited vibrations. Phil. Trans. of the Royal Society A 366 (2008): 785–810.*

[2] *Sharp R.S., Giles C.G. Motorcycle front wheel patter in heavy braking. Proceedings, 8th International Symposium of Dynamics of Vehicles on Roads and Tracks (IAVSD), 1983; Cambridge MA, USA: 578–590.*

[3] *Sorrentino S., Leonelli L. A study on the stability of a motorcycle wheel–swingarm suspension with chain transmission. Vehicle System Dynamics 55-11 (2017): 1707–1730.*

T.R.I.C.K. Real Time. A tool for the real-time onboard tyre performance evaluation.

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Keywords: Tire road interaction, Driver assistance, Performance evaluation.

Real-time knowledge of the tire's behavior is a fundamental prerequisite for using electronic controls in vehicle dynamics, which are rapidly increasing their complexity and, consequently, the required accuracy from the measurement systems.

Some examples of new products from the automotive industry are driver assistance (ADAS) and roadside units, (RSU) receivers installed on the road infrastructure capable of collecting vehicle data, with the purpose of monitoring the status of the road. Moreover, thanks to the low connection latency offered by the 5g network, interconnected vehicles will be able to passively communicate and apply autonomous driving strategies with the aim of avoiding road accidents [1].

Typically, the tire characterization is performed offline with expensive equipment that obtain data on which, subsequently, the parameters of models such as Pacejka [2] or Dugoff [3] are identified. For the identification of parameters from on-board measurements, sensors that are not available in standard vehicles, such as the dynamometer hub, are required.

The UniNa vehicle dynamics research group has developed a tool called TRICK [4] that estimates the quantities necessary to identify the model from the processing of CAN channels normally available in telemetry. The forces developed by the tyres are derived from the equilibrium equations, while the tyre slips from the kinematics equations [5].

The work presented concerns the redesign of the TRICK tool, which has been made capable of working in real time, providing data to both the driver and the control systems. Issues related to the on-board instrument calibration procedure, noise filtering and interface development were addressed.

References

[1] *Cheng, X., Chen, C., Zhang, W. and Yang, Y., "5G-Enabled Cooperative Intelligent Vehicular (5GenCIV) Framework: When Benz Meets Marconi" in IEEE Intelligent Systems, vol. 32, no. 3, pp. 53-59, (2017).*
[2] *Pacejka, H.B., "Tyre and Vehicle Dynamics," Butterworth-Heinemann, Oxford UK (2006).*
[3] *Dugoff, H., Fancher, P., and Segel, L., "An Analysis of Tire Traction Properties and Their Influence on Vehicle Dynamic Performance," SAE Technical Paper 700377 (1970).*
[4] *Farroni, F., "TRICK-tire/road interaction characterization & knowledge-A tool for the evaluation of tire and vehicle performances in outdoor test sessions," in Mech. Syst. Signal Process. 72, pp. 808–831, (2016).*
[5] *Guiggiani, M., "The Science of Vehicle Dynamics," Springer, Netherlands (2014).*

Preliminary implementation of model-based algorithms for truck tire characterizations from outdoor sessions

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Keywords: tire-road interaction, model-based, performance evaluation

The tire behaviour optimization is crucial for the definition of the best setup of the whole vehicle; in fact, its interface with the ground is constituted by the sum of small surfaces in which tire-road interaction forces are exchanged. The fundamental role that in the last years tires have played in automotive industry and the growing need to reproduce with a high level of detail the phenomena concerning with vehicle dynamics have given a strong impulse to the research in the field of vehicle systems and modelling [1].

This paper focuses on the possibility to modify and extend the use of a pre-existing tool for tires' forces estimation to the heavy vehicles field, such as Truck, Bus, Agro and OTR. The tool developed by the UniNa Vehicle Dynamics research group, represents a customization of Trick Tool [2] software, able to predict truck tires behaviour, based on standard sensors and signals acquired from the vehicle CAN bus. This enables to study vehicle dynamics and tires characteristics using the truck as a moving lab. The final processing tool, named TRICK4TRUCK, returns a sort of "virtual telemetry" that includes forces and slips, evaluated on the basis of equilibrium and kinematics equations, useful to provide tire-road interaction characteristics and to predict and simulate the real tire behaviour. This tool can be an important instrument for the interaction curves identification based on models such as the Pacejka's MF one [3][4]. After some brief notes about the basics of heavy vehicle dynamics and tire-road interaction, the developed tool and procedures are presented, highlighting their features and their critical issues, describing the path followed for the realization and discussing results and possible application field.

References

[1] Guiggiani, M., "The Science of Vehicle Dynamics", Springer, Netherlands, (2014).

[2] Farroni, F., "TRICK - tire/road interaction characterization & knowledge - A tool for the evaluation of tire and vehicle performances in outdoor test sessions" in Mech. Syst. Signal Process. 72, pp. 808–831, (2016).

[3] Alagappan, A. V., Rao, K. V. N., Kumar, R. K., "A comparison of various algorithms to extract Magic Formula tyre model coefficients for vehicle dynamics simulations" in Vehicle System Dynamics, 53(2), (2014).

[4] Pacejka, H.B., "Tyre and Vehicle Dynamics," Butterworth-Heinemann, Oxford UK (2006).

Experimental activity for the analysis of tires tread responses at different conditions with a dynamic dial indicator

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Keywords: Vehicle Dynamics - Non-Destructive analysis - Tire characterization.

The knowledge of tires tread viscoelastic behaviour plays a fundamental role in automotive to optimize vehicle performance and safety. These properties are usually characterized by means of Dynamic Mechanical Analysis [1] which implies the testing of compound sample that can be obtained by destroying the tire of interest or manufactured in different condition respect to the final product provided by tiremakers.

Nowadays, the non-destructive analysis procedures are an attractive solution. These techniques are essentially advantageous for being employed in testing the whole tire, allowing the analysis of a great number of them without affects costs.

The purpose of this work is the experimental analysis of the tire tread response, in different working condition, evaluated by a dynamic dial indicator [2] considering the measured displacement values of the device. Experimental tests have been carried out on different tread compounds and, being the tire performance strictly affected by the working temperature, additional tests have been performed by heating and cooling each sample in a range of interest [3][4]. Moreover, the effects of aging on a tire has been studied.

The comparison of the testing activity results shows the reliability of the dynamic dial indicator to capture the tires tread different behaviour within the operating condition of interest. These encouraging results lead to next step of the research activity which will focus on the evaluation of properties characterizing the hysteretic behaviour of tires.

References

[1] K. P. Menard, Dynamic mechanical analysis: a practical introduction. CRC Press, 2008.

[2] F. Farroni, A. Sakhnevych, and F. Timpone, "Physical modelling of a dynamic dial indicator for the non-destructive evaluation of tire tread viscoelastic characteristics," in Lecture Notes in Engineering and Computer Science, 2016.

[3] F. Farroni, D. Giordano, M. Russo, and F. Timpone, "TRT: Thermo racing tyre a physical model to predict the tyre temperature distribution," Meccanica, 2014.

[4] F. Farroni, F. Timpone, and A. Sakhnevych, "An Evolved Version of Thermo Racing Tyre for Real Time Applications," in Lecture Notes in Engineering and Computer Science: Proceedings of The World Congress on Engineering 2015, 2015.

A physical-analytical model for friction hysteretic contribution estimation between tyre tread and road asperities

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The numerical prediction of rubber friction properties is a great challenge from the modelling point of view. In many applications such as tyres, sealing systems, conveyor belts, the observed friction process arises from complex mechanisms occurring at the interface rubber/substrate [1].

During the sliding contact between two deformable bodies, the friction main contributions can be accountable in adhesive and hysteretic causes [2]. The adhesive contribution is related to the formation and breaking of the adhesive bridges in the real contact points inside the nominal contact region, instead the hysteretic contribution is related to the deformation cycles that result in energy losses due to the viscoelastic behaviour of the bodies. Due to these mechanisms, a frictional force is generated during the relative sliding between two bodies. As concerns the hysteretic contribution, previous studies [3] showed that even in the absence of adhesion in the contact region, the contact pressure is distributed in a non-symmetrical manner causing a force of resistance that opposes the motion.

In this paper, a physical-analytical model is developed to calculate the friction hysteretic component of a tyre tread elementary volume in sliding contact with road asperities. In this study, the road macroscale is only considered. The shape of the asperity is modelled as the osculating sphere [3]. The model is based on the energy balance between the work done by the friction force component and the energy dissipated in the material due to hysteresis. The compound viscoelastic properties are defined in terms of storage and loss moduli by means D.M.A. experimental tests. The internal dissipated energy is evaluated considering the stress and strain field calculated by Hamilton formulation [4].

Finally, some consideration about further model improvements are made regarding the introduction of a complete road spectrum (PSD) and the material modelling by fractional derivative algorithms.

References

[1] Heinrich, G., Kluppel, M., "Rubber friction, tread deformation and tire traction", Elsevier, 2008.

[2] Lang, A., Kluppel, M., "Influences of temperature and load on the dry friction behaviour of tire tread compounds in contact with rough granite", Elsevier, 2017.

[3] Aleksandrov, V. M., I. G. Goryacheva, and E. V. Torskaya. "Sliding contact of a smooth indenter and a viscoelastic half-space (3D problem)." Doklady Physics. Vol. 55. No. 2. MAIK Nauka/Interperiodica, 2010.

[4] Carputo, F., Farroni, F., Genovese, A., Sakhnevych, A., and Timpone, F., "An Analysis on stress field distribution of a deformable rubber specimen due to indentation", AIMETA, Salerno, 2017.

[5] Hamilton, G. M. (1983) Explicit equations for the stresses beneath a sliding spherical contact. roc. I. Mech. E., 197C, 53-59. [205]

Torque Vectoring Control for fully electric Formula SAE cars

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Keywords: Torque Vectoring Control, Driver Model, Fully Electric Vehicle, Formula SAE

Fully electric vehicles with individually controlled powertrains can achieve significantly enhanced vehicle response, in particular by means of Torque Vectoring Control (TVC) [1,2]. By imposing an uneven distribution of the torque demand between the left and right side of the vehicle, a direct yaw moment can be generated and appropriately exploited to improve vehicle performance and to reduce laptime. This paper presents a TVC strategy for a Formula SAE (FSAE) fully electric vehicle, the "T-One" car designed by "UninaCorse E-team" of the University of Naples "Federico II", featuring four in-wheel motors.
The developed TVC strategy consists of: i) a reference generator that calculates the target yaw rate in real time based on the current values of steering wheel angle and vehicle velocity, in order to follow a desired optimal understeer characteristic; ii) a high-level controller which generates the overall traction/braking force and yaw moment demands based on the accelerator/brake pedal and on the error between the target yaw rate and the actual yaw rate (measured with an Inertial Measurement Unit, IMU); iii) a control allocator which outputs the reference torques for the individual wheels [1]. Specific details will be provided in the full paper.
To assess the effectiveness of the proposed TVC strategy, a Matlab-Simulink double-track vehicle model was implemented, featuring non-linear (Pacejka) tyres. A driver model was implemented to work out the brake/accelerator pedal inputs and steering wheel angle input needed to follow a generic trajectory [3]. In a first implementation of the model, a "figure of eight" trajectory was adopted, consistently with the "skid-pad" test of the FSAE competition [4]. Results are promising as the vehicle with TVC achieves up to ≈ 3% laptime savings with respect to the vehicle without TVC, which is deemed significant and potentially crucial in the context of the FSAE competition.

References

[1] Lenzo, B., Sorniotti, A., De Filippis, G., Gruber, P., Sannen, K.,"Understeer characteristics for energy-efficient fully electric vehicles with multiple motors", EVS29 Proceedings, Montreal, Quebec, 19-22 June 2016.

[2] De Novellis, L., Sorniotti, A., Gruber, P., "Driving modes for designing the cornering response of fully electric vehicles with multiple motors", Mechanical System and Signal Processing, 64- 65, 2005.

[3] Braghin, F., Cheli, F., Melzi, S. Sabbioni, E., "Race driver model", Computers and Structures 86, 1503-1516, 2008.

[4] Formula Sae rules, last accessed 21 February 2019: https://www.fsaeonline.com/content/2017-18%20FSAE%20Rules%209.2.16a.pdf

On the implementation of an innovative temperature-sensitive version of Pacejka's MF in vehicle dynamics simulations

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Keywords: **tire/road interaction**, **advanced MF model**, **performance/temperature relationship**

The characterization and reproduction of tire behaviour for vehicle modelling is a topic of particular interest both for real-time driving simulations and for offline performance optimization algorithms. In such contexts, the Pacejka's Magic Formula (MF) tire model [1] represents a standard that gained in the last 25 years a role of high relevance due to its low computational request and attitude to allow an efficient parameterization for a wide range of tires working conditions.

Nevertheless, the original MF formulation was conceived with the aim to provide tire/road interaction forces and moments as a function of vertical load, longitudinal and lateral slip, and inclination (or camber) angle; such variables are fundamental but not totally satisfying in the description of the complex multi-physical phenomena occurring at tire/road interface [2].

In particular, the relationship between interaction forces and the cited input variables is highly influenced by further effects, linked to tire temperature, tread wear, compound viscoelastic characteristics and road roughness. Among these, the influence that the thermal conditions of the different layers constituting the global thickness of tires have on the friction and on their stiffness characteristics, is highly significant and definitely not negligible in case a full reliability of the vehicle dynamics simulations is required, especially in motorsport applications [3][4].

The paper illustrates the basic concepts linked to the development of a novel version of a MF-based formulation, able to take into account uncommon factors affecting tire/road interaction. Once described the structure and the parameters identification process [5], some results obtained with the MF-evo employed in a simulative loop with a thermal model are reported.

References

[1] Pacejka, H.B., "Tyre and Vehicle Dynamics", Butterworth-Heinemann, Oxford UK (2006).
[2] NHTSA, "The Pneumatic Tire", National Highway Traffic Safety Administration 2006).
[3] Farroni, F., Russo, M., Sakhnevych, A., Timpone, F., TRT EVO: Advances in real-time thermodynamic tire modeling for vehicle dynamics simulations. Proceedings of IMECHE, Part D: Journal of Automobile Engineering, 233(1), 121–135 (2019).
[4] Farroni, F.,Lamberti, R., Mancinelli, N., Timpone, F., TRIP-ID: A tool for a smart and interactive identification of Magic Formula tyre model parameters from experimental data acquired on track or test rig, Mechanical Systems and Signal Processing 102, 1-22 (2018)

Towards T.R.I.C.K. 2.0 – A tool for the evaluation of the vehicle performance through the use of an advanced sensors system

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Keywords: Tire-Road Interaction, Vehicle Modeling, Performance Evaluation .

In the last years, the tire technological development has played a fundamental role in motorsport and in automotive industry. The tire contact patch forces have a great influence on the vehicle behaviour, so their correct estimation is a crucial task to understand how to improve the car performance[1]. In order to identify the tire interaction characteristic it is also necessary to use a procedure that allows the correct evaluation of the sideslip angles in the different operating conditions [2].

This paper presents an evolution of the T.R.I.C.K. tool [3] developed by the UniNa vehicle dynamics research group. In the first version of this tool an 8 DOF vehicle model has been implemented and, starting from the experimental data acquired, the T.R.I.C.K. calculates the interaction forces and the tire slips using the equilibrium equations [4].

Using more car parameters and further data obtained from track sessions and dedicated tests, in the presented release of the tool, new formulations have been developed for a more accurate calculation of the tire-road forces [5]. The effectiveness of the treatments is assessed using experimental data and the simulator outputs.

The T.R.I.C.K. 2.0 allows, depending on the availability of additional vehicle data and acquisition sensors, to estimate the interaction forces with different and more accurate methodologies than the kinematics equations, while retaining very reduced simulation times. In this way it is possible to carry out a more precise study of vehicle dynamics with the possibility of investigating and significantly improving performance.

References

[1] Dakhlallah, J., Glaser, S., Mammar, S., Sebsadji, Y., "Tire-road forces estimation using extended Kalman filter and sideslip angle evaluation", American Control Conference 2008, IEEE, pages. 4597-4602 (2008).

[2] Chindamo, D., Lenzo, B., Gadola, M., "On the vehicle sideslip angle estimation: a literature review of methods, models, and innovations", Applied Sciences ***8****(3), page 355 (2018).*

[3] Farroni, F., "T.R.I.C.K.-Tire/Road Interaction Characterization & Knowledge **-** *A tool for the evaluation of tire and vehicle performances in outdoor test sessions", Mech. Syst. Signal Process.* ***72****, pages 808–831, (2016).*

[4] Guiggiani, M., The Science of Vehicle Dynamics, Springer, Netherlands (2018).

[5] Fischer, D., Isermann, R., "Mechatronic semi-active and active vehicle suspensions", Control engineering practice ***12****(11), pages 1353-1367(2004).*

On the torque steer problem for front-wheel-drive electric cars

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Keywords: Torque steer, Torque vectoring, vehicle dynamics

Beyond the well-known benefits of electric and hybrid powertrains in terms of environmental impact, the peculiar torque curve of electric motors for automotive applications offers extensive opportunities for improved vehicle dynamics control, such as yaw moment control through the application of different tractive forces across the axle: the so-called torque vectoring [1]. This is made possible for instance by fitting an independent motor on each wheel of a drive axle.

On the other side, whenever torque vectoring is achieved on the front axle it can give birth to the so called torque steer effect: an undesirable influence of tractive or braking torque on the steering [2]. This is perceived by the driver as a “tugging or pulling sensation in the steering wheel, or a veering of the vehicle from the intended path” [3]. The steering feedback and self-aligning properties, often considered a vital portion of the feedback required for safe and intuitive driving control [4, 5], are thus jeopardized, especially under heavy acceleration. This is very similar to what can be experienced on front-wheel-drive cars featuring a high torque-to-weight ratio, often requiring the adoption of a LSD or active differential device in order to optimize traction capabilities [6].

The paper presents an approach to the torque steer problem on high-performance electric and hybrid vehicles, where the effects of suspension and steering geometry as well as tyre contact patch load variation are taken into account and various design solutions are proposed as an improvement. The VI-grade® software tools for vehicle dynamics analysis are adopted, also in co-simulation with Matlab-Simulink® whenever an active control strategy is used. The impact on steering feedback quality is assessed through a testing campaign carried out on a state-of-the-art driving simulator.

References

[1] *De Novellis, L.; Sorniotti, A.; Gruber, P. (2014). Wheel torque distribution criteria for electric vehicles with torque-vectoring differentials. IEEE Transactions on Vehicular Technology, 63(4),6656947, pp. 1593-1602.*

[2] *Woo, S., Park, S., Oh, Y. (2007). Solution for the torque steer problem of a front-wheel drive car with a high torque engine in vehicle development stages. 14th Asia Pacific Automotive Engineering Conference Hollywood, California, USA, August 5-8, 2007.*

[3] *Wikipedia on the torque steer effect: https://en.wikipedia.org/wiki/Torque_steer*

[4] *R.S. Sharp: Vehicle dynamics and the judgement of quality (pp. 87-96), in J.P. Pauwelussen: Vehicle performance – understanding human monitoring and assessment. Swets & Zeitlinger, 1999.*

[5] *Gritti, G.; Peverada, F.; Orlandi, S.; Gadola, M. at al. (2017). Mechanical steering gear internal friction: effects on the drive feel and development of an analytic experimental model for its prediction. Proc. of the Intl. Joint Conf. on Mechanics, Design Eng. & Adv. Manufacturing (JCM), Catania, Italy.*

[6] *Gadola, M.; Chindamo, D.; Lenzo, B. (2018). On the Passive Limited Slip Differential for High Performance Vehicle Applications. Proc. of the 14th International Symposium on Advanced Vehicle Control (AVEC 18), Beijing, July 16-20, 2018.*

Analysis of multiscale theories for viscoelastic rubber friction

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Keywords: Viscoelasticity – Sliding Contact – Friction

Rubber friction plays a fundamental role in the study of the tire-road interaction and still represents a topic of discussion for both academics and manufacturing companies, especially with the introduction of the concept of multiscale roughness [1,2].

Taking into account that the road surface is a hard substrate, the two contributions to rubber friction can be considered to be (i) hysteretic phenomena deriving from time dependent viscoelastic deformations of the rubber by means the substrate asperities and (ii) adhesive effects.

From modelling point of view, the estimation of each contribution represents a great challenge, and both aspects contain inevitable empirical constants. For example, hysteretic friction could be in principle computed by a full multiscale Persson's theory [1,3], but this ultimately contains a choice of arbitrary cutoff, and the full multiscale theory can be in most cases simplified [4]. The adhesive contribution, instead, remains fundamentally empirically described by fitting functions and parameters [5], and it is still a challenge to recognize the importance of the two contributions, despite considerable progress [5]. In this work, an analysis of the results obtained with the different formulations is proposed with particular reference to the empirical constants variability.

References

[1] Persson, Bo NJ. "Theory of rubber friction and contact mechanics." The Journal of Chemical Physics 115.8 (2001): 3840-3861.

[2] Putignano, C., G. Carbone, and D. Dini. "Mechanics of rough contacts in elastic and viscoelastic thin layers." International Journal of Solids and Structures 69 (2015): 507-517.

[3]Lorenz, Boris, et al. "Rubber friction on road surfaces: Experiment and theory for low sliding speeds." The Journal of chemical physics 142.19 (2015): 194701.

[4] Ciavarella, Michele. "A simplified version of Persson's multiscale theory for rubber friction due to viscoelastic losses." Journal of Tribology 140.1 (2018): 011403.

[5] Tolpekina, T. V., & Persson, B. N. J. (2019). Adhesion and Friction for Three Tire Tread Compounds. Lubricants, 7(3), 20.

Safe and secure control of swarm of vehicles by small-world theory

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Keywords: Autonomous vehicle, platoon control, swarm behavior, small world theory, complex networks.

The present paper investigates a new paradigm to control a swarm of moving individuals, based on the introduction of few random long-range communications in a queue dominated by short-range car-following dynamics [1]. The theoretical approach adapts the small-world theory[2, 3], originally proposed in social sciences, to the investigation of these networks. It is shown that the controlled system exhibits properties of higher synchronization and robustness with respect to communication failures. The considered application to a vehicle swarm shows how safety and security of the related traffic dynamics is strongly increased, diminishing the collision probability even in the presence of a hacker attack [4] to some connectivity channels.

References

[1] Du, D.Z. P. P. M., An Introduction to Traffic Flow Theory, 2014, p. 36.
[2] Milgram, S., "The Small-World Problem," Psychology Today, vol. 1, no. 1, pp. 61-67, 1967.
[3] Watts, D. J., Strogatz, S. H., "Collective dynamics of 'small-world' networks," Nature magazine, vol. 393, pp. 440-442, 1998.
[4] Harris, M., "Researcher Hacks Self-driving Car Sensors", IEEE Spectrum, available online.

Optimal control of autonomous vehicle for safe maneuvering

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Keywords: Autonomous vehicle, Variational control, Safety.

Autonomous vehicle (AV) represents the main step towards intelligent transportation systems, a field of research of great current interest. The state of the art is still far from the total reliability and the absence of a clear and uniform legislation for self-driving car could delay the entering in the world of mass transportation system [1-3]. Responsibility in case of accident, ethical issues and decision making have a key role in the advanced frontiers of autonomous vehicle. Objective elements for evaluating the safety level of the autonomous vehicle is becoming an issue in this field.

The goal of this paper is to produce a robust obstacle avoidance control as first step of an ongoing research project of the Mechatronic and Vehicle Dynamic Lab of Sapienza, by investigating the following steps: (i) a new method of control for a complex mechanical systems, named Feedback Local Optimality Principle FLOP [4] and (ii) the definition of an objective crash avoidance parameter, i.e. a KPI related to the safe effectiveness of the guidance controller.

The FLOP method is here adopted to control a bike model vehicle, testing different crash scenarios: crossroad, car fender bender and pedestrian crossing. In order to avoid the crash, the FLOP method manages the obstacle avoidance maneuverer with carriage limits using the velocity obstacle technique [5]. Accidents cannot always be avoided because the requested manoeuvre to skip the obstacle can belong to a set of states that are not reachable by the system. Here, a statistical analysis is done to characterize the system safety thought two quality indexes, one related to crash probability and the other related to the kinetic energy involved in unavoidable crashes. The results prove the robustness of FLOP control showing same performances in different scenarios with a sharp transition between no-crash area and 100% crash area.

References

[1] Y. Zhang et al., "Hybrid Trajectory Planning for Autonomous Driving in Highly Constrained Environments", IEEE Access, 2018, vol. 6, pp. 32800-32819.

[2] Febbo, H., Liu, J., Jayakumar, P., Stein, J. L., & Ersal, T., "Moving obstacle avoidance for large, high-speed autonomous ground vehicles", Proceedings of the American Control Conference, 2017, 5568-5573.

[3] Liu, J., Jayakumar, P., Stein, J. L., & Ersal, T. (2018), "A nonlinear model predictive control formulation for obstacle avoidance in high-speed autonomous ground vehicles in unstructured environments", Vehicle System Dynamics, 2018, 56(6), 853-882.

[4] G. Pepe, D. Antonelli, L. Nesi & A. Carcaterra, "FLOP: Feedback Local Optimality Principle", under review on "International Journal of Control"

[5] Snape, J., Van Den Berg, J., Guy, S. J., & Manocha, D., "The hybrid reciprocal velocity obstacle", IEEE Transactions on Robotics, 2011, 27(4), 696-706.

A new approach in swarm robotic control, moving in complex environment

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Keywords: swarm robotics, optimal control, nonlinear dynamic.

The field of swarm and cooperative robotics, and the more general field of multi-agent dynamic systems is an active field of research that has been popular for more than two decades. A robotic swarm system consists of autonomous robots with local detection and communication capabilities, lacking centralized control or access to global information, located in a potentially unknown environment that performs a collective action. Swarms remind often system organizations met in nature, in which a large number of agents perform complex collective behaviors, although originated by relatively simple agent-agent interactions. This is the case, for example, of the shoals of fish, flocks of birds, and humans in a societal organization [1]. The growing interest in multi-agent dynamic systems and particularly in robot swarms is due to the rich possibilities of applications in several fields, including agriculture, health, defense and others. Of particular engineering interest today are the applications involving teams of unmanned air, ground, space or marine and submarine vehicles [2]. In general, the concepts of swarm robotics are appropriate for spatially distributed tasks that benefit from easy and robust scalability, where the addition or removal of elements to the swarm can increase or decrease some performances but does not compromise the global ability to perform the desired task. This work proposes a novel approach for robot swarm control, named Feedback Local Optimality Principle – FLOP [3]. The method strategy is based on the Pontryagin's optimal control theory, modified to produce a feedback control. To this aim, a local optimality principle is considered, instead of the global one, dividing the cost function into many sub-intervals, i.e. reducing the time horizon into which the optimization is performed. The FLOP method, thanks to the ability to deal with nonlinear systems and to locally vary the shape of the cost function, succeeds in controlling the swarm to perform different tasks, e.g. reaching an assigned target, avoiding external obstacles and internal collisions. This new technique permits to reproduce the advantages of the bioinspired system opening intriguing possibilities for advanced robotics. The algorithm allows to optimize the robot swarm formation according to the environment and to identify optimal trajectories that maximize the average speed of the swarm and reduce the fuel consumption [4].

References

[1] R. Olfati-Saber, "Flocking for multi-agent dynamic systems: algorithms and theory," IEEE Transactions on Automatic Control, vol. 51, no. 3, pp. 401-420, 2006.
[2] Yan,R.,Zhou,Y.,Shi,Z.,Zhong,Y."Formation tracking of unmanned aerial vehicle swarm systems with predefined formation reference and switching topologies" 2016 14th International Conference on Control, Automation, Robotics and Vision, ICARCV 2016
[3] G. Pepe, D. Antonelli, L. Nesi & A. Carcaterra, "FLOP: Feedback Local Optimality Principle", under review on International Journal of Nonlinear Control
[4] L. Nesi, D. Antonelli, G. Pepe & A. Carcaterra, "Fast moving of a population of robots through a complex scenario" NODYCON 2019, Rome, 17-20 February 2019.

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NOVEL APPROACHES IN COMPUTATIONAL MECHANICS (GIMC)

Simulations of ophthalmologic tests and corneal refractive surgery

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Keywords human cornea; fluid-solid interaction; air puff test; refractive power

We illustrate recent applications of a code developed ad hoc to model the biomechanics of the human cornea. Among several clinical applications, here we model the air puff test, a contactless tonometer commonly used in ophthalmology to estimate the intraocular pressure exerted on the posterior surface of the cornea by the aqueous humor [1]. The test consists in a rapid and localized air pulse hitting the external surface of the cornea, provoking a temporary change of the corneal curvature. The sequence of configurations assumed by the cornea are recorded in images. A sound mechanic model of the test may lead to the estimation of the material properties of the corneal tissues [2]. The air puff test is a coupled problem characterized by the interaction between a solid (the cornea) and a fluid (the aqueous humor). The correct model of the test requires numerical tools based on fluid-structure interaction algorithms. In this study we use a staggered approach, based on different discretization of solid and fluid domains: finite element and a particle based meshless method [3, 4]. The results of the simulations are in a good agreement with the experiments, confirming the effectiveness of the numerical approach. The same code has been used to model a few common refractive surgical procedures (PRK, LASIK, SMILE) considering patient-specific geometries. The topological and geometrical modifications induced by the procedures, and the different resulting loading conditions, leading to contact and sliding between newly created surfaces inside the cornea, required an important elaboration of the discretization of the solid parts. The numerical models have been validated against several patient specific geometries, providing a satisfactory correspondence with the clinical observations.

References

[1] Pandolfi,A. and Manganiello, F. "A model for the human cornea: constitutive formulation and numerical analysis." BMMB 5.4(2006):237-246.

[2] Ariza-Gracia, M., Á., et al. "A predictive tool for determining patient-specific mechanical properties of human corneal tissue." CMAME 317 (2017): 226-247.

[3] Montanino, A., et al., "Modelling with a meshfree approach the cornea-aqueous humor interaction during the air puff test." JMBBM 77(2018):205-216.

[4] Montanino, A., et al., " A 3D fluid-solid interaction model of the air puff test in the human cornea " Submitted to JMBBM.

Large rotation finite element analysis of 3D beams based on incremental rotation vector and exact strain measures

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Keywords: 3D finite rotations, rotation vector, geometrically nonlinear analysis, 3D beams, path-independence, singularity-free.

Different strategies based on rotation vector and exact strain measure have been proposed over the years for analysing flexible bodies undergoing arbitrary large rotations. To avoid the singularity of the vector-like parametrisation, the interpolation of the incremental rotation vector [1] is the standard approach in this context, even if this leads to path-dependence and instability, i.e. errors accumulate step by step. It is also non objective, although strain invariance and path-independence are obtained with h and p refinement [2]. Corotational approaches [3] are immune to these drawbacks, but the geometrically exact model is achieved by mesh refinement. In this work, we develop a novel strategy which uses the incremental nodal rotation vectors to define corotational nodal rotations, which are then interpolated for the evaluation of the nonlinear strains. This choice makes the approach singularity-free, allows for additive updates within each increment and preserves for any mesh and interpolation the main features of the continuum problem: rotational variables, strain invariance, exact strain measure, path-independence and symmetric stiffness matrix for conservative loads. This last property is a consequence of the direct differentiation in compact form of the relation between local and global rotations, which also makes it possible a straightforward definition of the internal forces and the tangent stiffness for interpolations of generic order [4]. As a side development, we show how the common approach of interpolating incremental vectors can be made stable by a simple updating procedure based on corotational rotations to be carried out at the end of each increment in order to avoid cumulative errors. Geometrical exact beams are considered as demonstrative example.

References

[1] *Ibrahimbegović A., "On the choice of finite rotation parameters", Computer Methods in Applied Mechanics and Engineering* **149***, page 49-71 (1997)*

[2] *Crisfield M.A., Jelenić G., "Objectivity of strain measures in the geometrically exact three-dimensional beam theory and its finite-element implementation", Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences,* **455***, page 1125-1147 (1999).*

[3] *Battini J.M., Pacoste C., "Co-rotational beam elements with warping effects in instability problems," Computer Methods in Applied Mechanics and Engineering,* **191***, page 1755 - 1789 (2002).*

[4] *Ritto-Correa M., Camotim, D., "On the differentiation of the Rodrigues formula and its significance for the vector-like parameterization of Reissner-Simo beam theory," International Journal for Numerical Methods in Engineering,* **55***, page 1005-1032 (2002).*

Virtual Elements with curved edges in structural mechanics

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Keywords: structural mechanics, polygonal meshes, exact geometry

The Virtual Element Method (VEM) was introduced in [1, 2] as a generalization of the Finite Element Method that allows for general polygonal and polyhedral meshes. Polytopal meshes can be very useful for a wide range of reasons, including meshing of the domain (such as cracks) and data (such as inclusions) features, automatic use of hanging nodes, moving meshes, adaptivity. By avoiding the explicit construction of the local basis functions, Virtual Elements can easily handle general polygons/polyhedrons without the need of an overly complex construction.
The scope of the present talk is to present Virtual Elements with curved faces, introduced in [3] and further developed in [4]. Indeed, all the VEM papers in the literature make use of polygonal and polyhedral meshes, i.e. with straight edges and faces. On the other hand, as recognized in the finite element (FEM) literature, expecially for high order methods the approximation of the domain by facets introduces an error that can dominate the analysis. This issue has lead, for example, to the development of non affine isoparametric FEM elements and to Isogeometric Analysis.
In the context of Virtual Elements, one can exploit the peculiar construction of the method that (1) does not need an explicit expression of the basis functions and (2) is directly defined in physical space, i.e. no reference element is used. This allows to define discrete spaces also on elements that are curved in such a way to exactly represent the domain of interest. The needed ingredient is a (piecewise regular) parametrization of the boundary of the domain. Somehow, the present case fits very naturally into the Virtual Element setting. Numerical tests in the realm of small deformation elasticity and inelasticity will be shown in this talk. The subject of this talk is in collaboration with the authors appearing in [3, 4].

References

[1] *L. Beirão da Veiga, F. Brezzi, A. Cangiani, G. Manzini, L. D. Marini, A. Russo, "Basic principles of virtual element methods", Math. Models Methods Appl. Sci., 23:199214 (2013).*
[2] *L. Beirão da Veiga, F. Brezzi, L. D. Marini, A. Russo, "The Hitchhikers Guide to the Virtual Element Method", Math. Models Methods Appl. Sci., 24:15411573 (2014).*
[3] *L. Beirão da Veiga, A. Russo, G. Vacca. "The Virtual Element Method with curved edges", Math. Mod. Numer. Anal., DOI 10.1051/m2an/2018052*
[4] *E: Artioli, L. Beirão da Veiga, F. Dassi. "A first developement of Virtual elements with curved edges in structural mechanics", in preparation.*

Mixed formulations for material constraints in transversely isotropic elasticity: theoretical and computational results

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Keywords: Anisotropic materials, Incompressibility, Mixed variational formulations

Material responses in engineering applications are often associated with internal constraints due to, for instance, the presence of overstiff directions (i.e., stiff fibers) and/or small/negligible volumetric deformations (i.e., matrix incompressibility). In this case, the accuracy and robustness of numerical simulations are affected by anisotropic or volumetric-locking effects. To overcome this issue, mixed formulations based on a Hu-Wahizu-type functional can be developed [1, 2]. The starting point is the decomposition of the full kinematic field in a penalized contribution, which contains the deformation mode associated with material constraint, and the complementary part. If this kinematic decomposition respects energetically-orthogonality, the associated mixed variational formulation is energetically decoupled (ED). Therefore, the balance of linear momentum (BLM) does not explicitly depend on the overstiff material behavior. The volumetric-deviatoric split introduced in isotropic elasticity leads to ED mixed variational formulations, and thus the bulk modulus doesn't appear explicitly in the BLM. On the other hand, the determination of energetically-orthogonal anisotropic deformation modes is still an open issue.

This works presents the theoretical derivation of energetically-orthogonal deformation modes in transversely isotropic linear elasticity. Starting from the representation of transversely isotropic tensors offered by the Walpole's basis [3], a projector operator is built such to satisfy two criteria: the projected strain is representative of the total elongation along material preferred direction; the projected strain is energetically-orthogonal to the complementary one. It is also proved that the projected strain contains the full volumetric deformation at hand. ED mixed variational formulations are thus introduced for the treatment of strong transversely isotropic anisotropies and/or incompressibility. The computational performances of different mixed formulations for unidirectional fiber-reinforced materials are discussed by means of a number of numerical tests. Different degrees of anisotropy and incompressibility are explored. The accuracy and error convergence behaviors obtained for ED formulations are compared with the ones of non-ED approaches for different values of material parameters. Pure-bending and Cook's membrane benchmark tests are addressed, together with applications which investigate the bias-extension test of a woven fabric and a punch test with soft rubber materials reinforced by steel fibers.

References

[1] *Auricchio, F., Scalet, G., Wriggers, P., "Fiber-reinforced materials: finite elements for the treatment of the inextensible constraint", Comput Mech* **60***, pages 905-922 (2017).*

[2] *Ralofoson, F., Grieshaber, B.J., Reddy, B.D., "Finite element approximation for near incompressible and near-inextensible transversely isotropic bodies", Int J Numer Methods Eng* **117***, pages 693–712 (2019).*

[3] *Bellini, C., Federico, S., "Green-Naghdi rate of the Kirchhoff stress and deformation rate: the elasticity tensor", Z. Angew. Math. Phys. ZAMP* **66***, pages 1143–1163 (2015).*

Extended Virtual Element Method for the Membrane Problem with Field Singularities and Discontinuities

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Keywords: virtual element method; X-FEM; membrane

Among the many stabilized Galerkin finite element formulations proposed in the literature, the recently proposed Virtual Element Method (VEM) [1] stands out for its capability of dealing with very general polygonal or polytopal meshes, in which the basis functions are are not known explicitly within the problem domain (hence, virtual). The bilinear form on each element is decomposed into two parts, by means of suitably defined elliptic projectors: a consistent term, exactly reproducing a the first-order polynomial space, and an additional term ensuring stability. In this contribution, we propose a first-order extended virtual element method (X-VEM) to treat singularities and crack discontinuities that arise in the mambrane problem. The approach herein draws from the development of the extended finite element method for fracture problems [2], in which the discrete space is augmented by means of additional basis functions that capture the main features of the exact solution. A similar approach is pursued in the proposed X-VEM formulation with a few notable extensions. To suitably represent singularities and discontinuities in the discrete space, we extend the standard virtual element space with an additional contribution consisting of the product of virtual nodal basis functions with so-called enrichment functions. For discontinuities, the enrichment function is the generalized Heaviside function across the crack and for singularities it is a weakly singular function that satisfies the Laplace equation. For the membrane problem with a discontinuity, we project the virtual basis functions onto affine polynomials over the two partitions of elements cut by the discontinuity. For the membrane problem with a singularity, we devise an extended projector that maps functions lying in the extended virtual element space onto affine polynomials and the enrichment function. Numerical experiments are performed on quadrilateral and polygonal meshes for the problem of an L-shaped domain with a corner singularity and the problem of a cracked membrane under mode III loading. Obtained results show the accuracy and demonstrate optimal rates of convergence in both L2 norm and energy of the proposed method.

References

[1] Beirao da Veiga, L., Brezzi, F., Cangiani, A., Manzini, G., Marini, L.D., Russo, A., "Basic Principles of the Virtual Element Method", Mathematical Models and Methods in Applied Sciences, 23(1), 2013.

[2] Moes, N., Dolbow, J., Belytschko, T., "A finite element method for crack growth without remeshing", International Journal for Numerical Methods in Engineering, 46(1), 1999.

A fully-explicit Lagrangian Finite Element Approach for the simulation of 3D fluid-structure interaction problems

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Keywords: fluid-structure interaction, explicit coupling, PFEM

In the present work, fluid-structure interaction (FSI) problems are solved with a partitioned explicit approach. Partitioned approaches are particularly interesting for the reuse of existing software for both fluid and structure sub-problems; furthermore, explicit methods can be advantageous in real engineering problems characterized by fast dynamics and high degree of nonlinearity.

The fluid sub-problem is solved with an explicit version of the Particle Finite Element Method (PFEM) [1], while the solid sub-problem is solved with a standard finite element approach. Thanks to its Lagrangian nature, the PFEM can efficiently deal with free surface flows and large displacements of the fluid-solid interface [e.g.1, 2]. The fast remeshing algorithm, typically used to overcome the possible large distortion of the fluid mesh, has been coupled with a novel efficient mesh smoothing technique to guarantee a regular fluid mesh with a reasonably large stable time increment. SIMULIA Abaqus/Explicit has been used for the solution of the structural domain.

The Abaqus co-simulation engine has been used to couple the fluid and solid domains using a GC Domain Decomposition approach [3]. The two sub-problems are solved independently and then they are linked at the interface using a Lagrange multiplier technique. The proposed method allows for different time-steps in the two subdomains and for non-conforming meshes at fluid-solid interfaces. Moreover, this approach guarantees a strong and explicit coupling at the interfaces [4].

Large scale 3D tests will be presented to validate the proposed approach and to confirm that the proposed method can be appealing for applications in a variety of engineering problems.

References

[1] *Cremonesi, M., Meduri, S., Perego, U. and Frangi, "A. An explicit Lagrangian finite element method for free-surface weakly compressible flows" Comp. Particle Mech.* **4***, page 357-369 (2017)*

[2] *Oñate, E., Idelsohn, S.R., del Pin, F. and Aubry, R. "The Particle Finite Element Method. An Overview" Int J Computational Method* **1***, page 267-307 (2004)*

[3] *Combescure, A. and Gravouil, A. "A time-space multi-scale algorithm for transient structural nonlinear problems" Mecanique et Industries* **2***, page 43-55 (2001)*

[4] *Meduri, S., Cremonesi, M., Perego, U., Bettinotti O., Kurkchubasche, A. and Oancea, V. "A partitioned fully explicit Lagrangian finite element method for highly nonlinear fluid-structure interaction problems" Int J Numer Meth Eng* **113***, page 43-64 (2018)*

MEMS resonators: numerical modeling

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Keywords: MEMS, resonators, modeling.

Quartz crystals were considered the frequency-reference industrial standard in the past century. Recently MEMS resonators entered this market as a possible solution to the increasing request of size reduction and integrability, but still need to be improved in terms of thermal drift and quality factor *Q*. The thermal drift of the natural frequency of resonators is related to the intrinsic temperature dependence of the elastic constants [1] and of the other thermal properties of silicon, on the doping level [2] and on the orientation of the resonator with respect to the silicon wafer. On the other side, the rather low thermoelastic quality factor is a strong limit for practical applications. A known strategy for improving *Q* consists in adding slots along the beams to reduce heat conduction. Regrettably, slots may also sensibly increase the frequency drift in temperature [3].
A comprehensive study of the behavior of MEMS resonators in terms of frequency stability and *Q* for different orientations and doping levels is needed to provide a powerful tool for the design of MEMS resonators. We collect the material properties of single crystal silicon with different levels of doping from the literature and we develop a custom Finite Element tool to compute the natural frequency and the quality factor of MEMS resonators under varying temperature conditions and arbitrary material parameters. We aim at proving that for a given level of doping and resonant mode type (e.g. bending-mode) the material orientation has a strong impact on the thermal drift and a clear minimum can be achieved. This value is essentially independent of the mode-order and geometric dimensions. On the other side, the impact of material orientation on the *Q* value is minimal, and the rather low *Q* is an intrinsic limitation. By adding slots in the deformable arms of the resonators we increase the *Q* while keeping the same intrinsic low thermal drift. By optimizing the geometry of the slots and the orientation of the structure through the CMA-ES (Covariance Matrix Adaptation Evolution Strategy) evolutionary algorithm for nonlinear non-convex black-box optimization problems, it is in fact possible to significantly increase the *Q* while keeping the same intrinsic minimum thermal drift obtained for the specific doping.
Two prototypes have been fabricated through the epi-seal encapsulation process proposed by researchers at the Robert Bosch Research and Technology Center in Palo Alto and then demonstrated in a close collaboration with Stanford University. Testing is ongoing in order to validate the theoretical findings here presented.

References

[1] Varshni, Y. P., "Temperature dependence of the elastic constants" Phys. Rev. B, 2, 3952-3958 (1970).
[2] Jakkola, A. et all., "Design rules for temperature compensated degenerately n-type doped silicon MEMS resonators" J. Microelectromech. Syst., 24, 1832-1839 (2015).
[3] Zega, V., Frangi, A., Guercilena, A., Gattere, G., "Analysis of Frequency stability and thermoelastic effects for slotted tuning fork MEMS resonators" Sensors, 18, 2157, (2018).

Virtual Element Methods for Elasticity Problems

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Keywords: VEM, Elasticity Problems, Mixed Methods

The Virtual Element Method (VEM) is a new technology for the approximation of partial differential equation problems. VEM was born in 2012, see [1], and shares the same variational background of the Finite Element Method (FEM).

In the framework of 2D elasticity problems, we first present a family of Virtual Element schemes based on the Hellinger-Reissner variational principle, see [2, 3]. As it is well-known, imposing both the symmetry of the stress tensor and the continuity of the tractions at the inter-element is typically a great source of troubles in the framework of classical Galerkin schemes. We exploit the great flexibility of VEM to present alternative methods, which provide symmetric stresses, continuous tractions and are reasonably cheap with respect to the delivered accuracy. VEMs reach this goal by abandoning the local polynomial approximation concept, a feature originally used to design conforming Galerkin schemes on general polytopal meshes, see [1]. We then present a new VEM scheme based on a dual hybrid formulation of the linear elastic problem, see [4]. Here, *a priori* locally self-equilibrated stresses are employed, while the displacement field is essentially required only on the mesh skeleton and serves as a Lagrange multiplier for the traction continuity.

In this talk, we detail the ideas which led to the design of our schemes, we state the theoretical results, and we present several numerical tests to assess the actual computational performance of the our approach. Finally, we discuss some possible future extensions.

References

[1] *Beirão da Veiga, L., Brezzi, F., Cangiani, A., Manzini, G., Marini, L. D., Russo, A., "Basic principles of Virtual Element Methods", Math. Models Methods Appl. Sci., 23, pp. 119–214, (2013).*

[2] *Artioli, E., de Miranda, S., Lovadina, C., Patruno, L., "A stress/displacement Virtual Element method for plane elasticity problems", Computer Methods in Applied Mechanics and Engineering, 325, pp. 155–174, (2017).*

[3] *Artioli, E., de Miranda, S., Lovadina, C., Patruno, L., "A Family of Virtual Element Methods for Plane Elasticity Problems Based on the Hellinger-Reissner Principle", Computer Methods in Applied Mechanics and Engineering, 340, pp. 978-999, (2018).*

[4] *Artioli, E., de Miranda, S., Lovadina, C., Patruno, L., "A dual hybrid Virtual Element Method for plane elasticity problems", ESAIM: Mathematical Modelling and Numerical Analysis, submitted.*

Reduced Order Modelling for geometric non-linearities in MEMS

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Keywords: MEMS, Model Order Reduction, Nonlinear dynamics

Micro-Electro-Mechanical-Systems (MEMS) are experiencing an explosive growth and pose new challenges also from the numerical simulation viewpoint. Even if MEMS are typically actuated in the linear regime, there is however an increasing interest in investigating their nonlinear response also for commercial applications. Typically, the analysis of these devices if performed with the Finite Element Method, which generates a large-scale second order differential system of equations. Moreover, in order to minimise power consumption and to give better resolution, these devices are near-vacuum encapsulated and often feature large quality factors. The analysis of a large scale dynamical system with a large Q is often prohibitive in terms of computational effort by means of standard finite element. One of the possible way to treat this kind of problems is using a suitable Reduced Order Model (ROM).
In [1] a review of reduced order modelling for nonlinear geometric structures is presented. Geometrical nonlinearities can be addressed resorting to classical techniques and in particular great attention has been devoted to the computation of Nonlinear Normal Modes [2]. Taking inspiration from these contributions, we develop a simplified technique for investigating the primary resonance and internal resonances of non-linear systems under harmonic excitation. When the response becomes non-linear, also on the basis of experimental observations, MEMS oscillate with a form which is still very similar to the linear mode but higher order modes, which respond quasi-statically, can modify the distribution of stresses introducing *local small* modifications in the displacement field. The issue of static condensation has been debated in a number of contributions [1], especially with applications to plate or shell structures in which axial and membrane modes have been successfully condensed into the equations for bending modes. However, the use of these concepts for generic large solid-like models with no clear distinction between these types of modes is still under investigation. Our aim is to derive a ROM with very few DOFs (typically 2 or 1) which should reproduce the non linear Frequency Response Curve (FRF) of the main resonance. The model should also allow to address the nonlinear interaction of the main mode with other "spurious" modes associated, for instance, to internal resonances or autoparametric excitation. As model problems to validate our approach we will consider the standard hardening clamped-clamped beam, a shallow arch showing softening behaviour and internal resonance and a real MEMS gyroscope. Particular attention will be devoted to the comparison between standard integration techniques and the ROM proposed in terms of computational effort.

References

[1] *M.P. Mignolet, A. Przekop, S.A. Rizzi, S.M. Spottswood, A review of indirect/nonintrusive reduced order modeling of nonlinear geometric structures, Journal of Sound and Vibration, vol. 332, pp. 24372460, (2013).*

[2] *L. Renson, G. Kerschen, B. Cochelin, Numerical computation of nonlinear normal modes in mechanical engineering, Journal of Sound and vibration, vol. 364, pp.177,206, (2016)*

A posteriori error estimation for the VEM based on stress recovery

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Keywords: Error estimation, VEM, Stress-recovery

The Virtual Element Method is a recently developed discretization scheme which is rapidly attracting the interest of the scientific community [1] due to its elegance and flexibility. One of the peculiarities which greatly contributed to the success of the VEM approach, is its ability to allow the use of polygonal elements. Such characteristic makes the VEM approach particularly well suited for all such problems in which the possibility to adopt elements of arbitrary shape is an advantage such as crack propagation [2] and mesh adaptivity [3].

One of the drawback of VEM in its displacement based formulation, is the fact that a projector operator needs to be built in order to allow the calculation of the strain field and, thus, the stress field. Such operator leads to an undesirable loss of information. A stress recovery procedure based on complementary energy minimization (RCP), which allows to avoid the introduction of the projection operator in the calculation of the stress field, has been presented in [4]. In its simplest version, despite its name, the procedure does not requires the creation of patches and can be seen as an efficient alternative to the classical VEM projection operator.

Inspired by the results presented in [3], in this work the RCP based stress recovery procedure proposed in [4] is used in order to provide error estimates for plane elasticity problems. Such error estimates are obtained by comparing the stress field evaluated by means of the standard VEM projector and that obtained by means of RCP.

Proceeding in such a way, error estimates can be simply and efficiently obtained and might be used, for instance, to drive an automatic mesh refinement process. The obtained numerical results confirm the soundness of the proposed approach.

References

[1] Beirão da Veiga, L., Brezzi, F., Cangiani, A., Manzini, G., Marini, L. D., & Russo, A. "Basic principles of virtual element methods", Mathematical Models and Methods in Applied Sciences, ***23****, 199-214,(2013).*

[2] Artioli, E., Marfia, S., Sacco, E. "A Virtual Element Method approach for 2D fracture mechanics problems", in Proceedings of GIMC-GMA 2018 , Ferrara, 13-14 September 2018, ***6****, (2018).*

[3] Chi, H., da Veiga, L. B., & Paulino, G. H.," A simple and effective gradient recovery scheme and a posteriori error estimator for the Virtual Element Method (VEM)", Computer Methods in Applied Mechanics and Engineering, ***347****, 21-58, (2019).*

[4] Artioli, E., de Miranda, S., Lovadina, C., Patruno, L. "An equilibrium-based stress recovery procedure for the VEM", International Journal for Numerical Methods in Engineering, ***117****, 885-900, (2018).*

Multi-physical interactions drive VEGFR2 and integrin relocation on endothelial cells

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Keywords: *Chemo-transport-mechanics, receptor dynamics, angiogenesis*

Angiogenesis, the process of new blood vessel formation from pre-existing ones, plays a pivotal role in physiologic and pathologic conditions. Specifically, tumor angiogenesis is modulated by the interaction between distinct membrane receptors, expressed by endothelial cells (ECs), and ligands produced by the tumor cells and adsorbed onto the extracellular matrix (ECM). The Vascular Endothelial Growth Factor Receptor-2 (VEGFR2) is the main mediator of angiogenesis. It binds different ligands. These immobilized factors represent a persistent stimulus for the otherwise quiescent ECs, drive directional EC migration and proliferation, eventually leading to new blood vessel growth.
The complex biophysical mechanisms of angiogenesis include the mechanical behavior of the cell. Integrins are membrane receptors that connect surrounding ECM to the cytoskeleton, and are the main responsible of the remodeling of the cytoskeleton itself. Such a binding triggers the propagation of intracellular signaling cascades that affect further the mechanical response of the cell.
Although biochemical pathways that follow the VEGFR2 and integrins activation are well established, knowledge of the dynamics of receptors on the plasma membrane and their interactions with the mechanics of ECs remains limited [1, 2].
Co-designing in vitro experiments and numerical simulations allows identifying how ligands stimulation induces the polarization of VEGFR2/β_3 complex in cell protrusions and in the basal aspect in ECs plated on a ligand-enriched ECM. Understanding and predicting the effects of the formation of bioactive VEGFR2β_3 integrin complexes on the mechanical response of ECs is a further target of the present work. Identifying the laws that regulate polarization opens new perspectives toward developing innovative anti-angiogenic strategies through the modulation of EC activation.

References

[1] *Salvadori A., Damioli V., Ravelli C., Mitola S., Modeling and Simulation of VEGF Receptors Recruitment in Angiogenesis, Mathematical Problems in Engineering, vol. 2018, Article ID 4705472, 10 pages, 2018.*

[2] *Damioli V., Salvadori A., Beretta G.P, Ravelli C., Mitola S., Multi-physics interaction drive VEGFR2 relocation on endothelial cells, Scientific Reports 7, Article number:16700(2017), 01 December 2017.*

An inter-element VEM approach for cohesive fracture

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Keywords: cohesive fracture, virtual element method, inter-element approach.

This work presents an innovative *inter-element* approach for cohesive fracture problems based on Virtual Element Method.

The Virtual Element Method (VEM) is a recently introduced methodology to approximate partial differential equations [1]; it is a Galerkin method which can be considered as an evolution of the Finite Element Method (FEM). VEM is able to naturally manage mesh complexities, such as polytopal shapes and hanging nodes, or problems with high continuity requirements. Differently from standard FEM, shape functions are not *explicitly* known and thus they are called *virtual*; however, the available information on them is sufficient to form the discrete variational form of the problem at hand.

In line with so called *inter-element* approaches to problems of 2D fracture mechanics [2], a new methodology is proposed which makes use of linear eleastic virtual elements for the bulk portion of the fracturing medium [3], exploiting adaptive remeshing to develop a fracture tracking and evolution control algorithm. Cohesive damage/friction interface 1D linear elements are employed to model crack branches [4]. A classical arc-length continuation method is used in conjunction with the nonlinear structural solver in order to model the whole initiation and advancement fracturing process.

The analysis will assess accuracy and efficiency by comparison with established techniques [5].

References

[1] *Beirão da Veiga, L., Brezzi, F., Cangiani, A., Manzini, G., Marini, L. D. and Russo, A.*, Basic principles of virtual element methods. *Math. Models Methods Appl. Sci.*, 23(1) (2013) pp.199–214.

[2] *Moës, N., Dolbow, J., and Belytschko, T.*, *A finite element method for crack growth without remeshing*, Int. J. Num. Meth. Engrg. **46** (1999), pp.131–150.

[3] *Artioli, E., Beirão da Veiga, L., Lovadina, C., and Sacco, E.*, *Arbitrary order 2D virtual elements for polygonal meshes: Part I, elastic problem*, Comp. Mech. **60** (2017), pp.355–377.

[4] *Alfano, G., Marfia, S., and Sacco, E.*, *A cohesive damage-friction interface model accounting for water pressure on crack propagation.*, Comp. Meth. Appl. Mech. Engrg. **196** (2006), pp.192–209.

[5] *Moës, N., Belytschko, T.*, *Extended finite element method for cohesive crack growth*, Eng. Frac. Mech. **69** (2002), pp.813–833.

A mixed membrane finite element for masonry structures

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Keywords: Mixed formulation, Discontinuous interpolation, Continuum damage mechanics

The prediction of the mechanical response of masonry structures represents a challenging and still open research topic in computational mechanics. In fact, reliable numerical procedures are needed in safety assessment and evaluation of repair/strengthening interventions, especially related to the preservation of architectural heritage and historical buildings.

Currently, numerical strategies aiming at the analysis of complex real structures are mainly based on the use of phenomenological/macromechanical constitutive laws for masonry material in conjunction with the finite element method. Attention is here focused on the latter aspect, i.e. on the formulation of a finite element capable to capture distinctive features of the mechanical behavior of masonry structures, such as strain localization, even adopting coarse meshes.

Resorting to mixed finite elements to overcome well-known limitations of displacement-based formulations (e.g., see [1]), a promising approach consists in the adoption of a Hu–Washizu-type variational principle with a strain field approximation that is piecewise discontinuous over suitable element subdomains. In fact, that approach has been initially proven to be an effective strategy in beam problems (e.g., see [2, 3]), and then has been generalized to membrane problems in the framework of standard materials [4]. The present work addresses a further generalization of the mixed finite element presented in [4] to membrane problems involving a continuum damage mechanics material model, as needed for masonry structures (e.g., see [5, 6]).

Some peculiar computational aspects related to strain softening behavior are discussed. Specifically, an element state determination procedure based on Newton's method is proposed to solve compatibility and constitutive equations at the element level. Moreover, typical regularization techniques for guaranteeing mesh-objectivity are integrated in the present approach.

Structural scale applications are carried out for assessing accuracy, robustness and effectiveness of the proposed finite element and comparing its performances with other available displacement-based formulations.

References

[1] *Nodargi, N.A., "An overview of mixed finite elements for the analysis of inelastic bidimensional structures", Arch. Comput. Methods Eng., (2018).*

[2] *Spacone, E., Filippou, F. C., and Taucer, F. F., "Fibre beam-column model for non-linear analysis of R/C frames: Part I. Formulation", Earthq. Eng. Struct. Dyn.,* **25***, 711–725 (1996).*

[3] *Taylor, R. L., Filippou, F. C., Saritas, A. and Auricchio, F., "A mixed finite element method for beam and frame problems", Comput. Mech.,* **31***, 192–203 (2003).*

[4] *Nodargi, N. A., Bisegna, P., "A novel high-performance mixed membrane finite element for the analysis of inelastic structures", Comput. Struct.,* **182***, 337–353 (2017).*

[5] *Pelà, L., Cervera, M., and Roca, P., "An orthotropic damage model for the analysis of masonry structures", Constr. Build. Mater.,* **41***, 957–967 (2013).*

[6] *Gatta, C., Addessi, D., and Vestroni, F., "Static and dynamic nonlinear response of masonry walls", Int. J. Solids Struct.,* **155***, 291–303 (2018).*

Isogeometric collocation methods for the nonlinear dynamics of three-dimensional Timoshenko beams

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Keywords: Isogeometric collocation; Nonlinear dynamics; Timoshenko beams.

Isogeometric collocation (IGA-C) is a new computational method proposed in [1] which keeps the computational attributes of isogeometric analysis, such as high-order accuracy, robustness, geometric capabilities and, at the same time, gains increased efficiency due to the elimination of numerical quadrature (and associated issues) due to the direct discretization of the strong form of the differential problem.

In spite of being a relatively new technology, IGA-C has been successfully applied to several structural problems. The majority of these studies has been conducted so far in the geometrically linear regime. After the recent extension of the method to the nonlinear static problem of three-dimensional Timoshenko beams [2, 3], in this talk we discuss a further advancement of the method addressing the dynamic formulation. The configuration manifold of a Timoshenko beam undergoing finite motions involves the Lie group $\mathrm{SO}(3)$ used to describe the (finite) rotation of each beam cross section. Most of the computational complexities originate from the presence of such a non-additive and non-commutative rotation group which makes geometric consistency a fundamental requirement for the entire formulation. By employing the incremental rotation vector to describe the evolution of finite rotations, we discuss how in an IGA-C framework geometric consistency can be guaranteed in all the key operations (i.e. linearization of the governing equations, initialization and update procedures) for both explicit [4] and implicit schemes. A series of numerical applications are also presented to assess the capabilities of the formulations.

References

[1] *Auricchio, F., Beirão da Veiga, L., Hughes, T.J.R., Reali, A., Sangalli, G., "Isogeometric collocation methods", Math. Models Methods Appl. Sci.,* **20**, *page 2075-2107 (2010).*

[2] *Marino, E., "Isogeometric collocation for three-dimensional geometrically exact shear-deformable beams", Comput. Methods Appl. Mech. Eng.,* **307**, *page 383-410 (2016).*

[3] *Marino, E., "Locking-free isogeometric collocation formulation for three-dimensional geometrically exact shear-deformable beams with arbitrary initial curvature", Comput. Methods Appl. Mech. Eng.,* **324**, *page 546-572 (2017).*

[4] *Marino, E., Kiendl, J., De Lorenzis, L., "Explicit isogeometric collocation for the dynamics of three-dimensional beams undergoing finite motions", Comput. Methods Appl. Mech. Eng.,* **343**, *page 530-549 (2019).*

Mesoscale prediction of insulating mortar thermal properties

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Keywords: meso-scale, random distribution, insulating mortar

Mortar is a brittle composite material whose constitutive behaviour is strictly depending on the physical and mechanical properties of its constituents. A variety of scientific researches is devoted to the numerical prediction of the homogenised properties of composite materials by means of meso-scale analysis. Usually, each component of the heterogeneous composite is individually modelled. The distribution of the components inside a Representative Volume Element (RVE) is randomly generated, following different approaches. Therefore, the analysis is concentrated on a finite sample, whose spatial discretisation is usually performed by the FE method. Other approaches are based on lattice element models [1, 2].

The paper concerns the numerical prediction of the equivalent thermal properties of innovative insulating materials by means an homogenisation technique at the mesoscale. The same strategy was applied in the prediction of the mechanical properties of concrete in a recent work of the authors [3]. The numerical description of the mesoscale structure of the heterogeneous material and of the heat flux is attained by using a random method that allocates at each Gauss point of the RVE finite element discretization a specific phase of the mixture, depending on the volume fractions of the components. Therefore, the model does not consider the physical size of the components. The mesh independency is quickly obtained just by means of relatively coarse meshes of the RVE. Moreover, the randomness of the generation of the micro structure does not affect the overall properties of the mixture. The equivalent thermal conductivity is accurately predicted. The numerical predictions are compared with experimental measures on different innovative mixtures, with different lime or cement binder and various grain size assortment. The porous aggregate used in the mixture to obtain the insulating properties is volcanic ash, obtained by recycling Etna pyroclasts. The influence of an air entraining agent was also studied. The method is suitable for a straightforward application in multiscale analysis.

References

[1] *Benkemoun, N., Ibrahimbegović, A. and Colliat, J.-B., "Anisotropic constitutive model of plasticity capable of accounting for details of meso-structure of two-phase composite material", Computers and Structures,***90-91***, page 153-162, (2012)*

[2] *Nikolić, M., Karavelić, E., Ibrahimbegovic, A. and Miščević, P., "Lattice Element Models and Their Peculiarities", Archives of Computational Methods in Engineering,***25(3)***, page 753-784, (2018)*

[3] *Contrafatto, L. , Cuomo, M. and Gazzo, S., "A concrete homogenisation technique at meso-scale level accounting for damaging behaviour of cement paste and aggregates", Computers and Structures,***173** *page 1-18, (2016)*

Implicit G^1-conforming plate elements

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Keywords: plate element, G^1 continuity, Gregory Patch

A family of quadrilateral and triangular G^1-conforming finite elements, based on the Gregory patch [2, 1], suitable for the analysis of the Kirchhoff plate model are analyzed. These elements present cubic control of the normal derivative along the sides and therefore be combined among themselves and with side beams [4, 3]. The coupling strategy are based on the formulas of the Bézier degree elevation. Using the Bézier extraction, G^1-conforming hierarchic refinement can be designed for these elements.

A rational enhancement of the base-polynomial spaces, known in the CAGD-literature as Gregory Patch, useful to design G^1-conforming elements on general C^0-conforming unstructured meshes is presented. The second derivatives at the corners of the rational approximant present finite discontinuities, that prevent the elements from passing the bending patch test. These discontinuities are removed using a constrained version of the Gregory Patch, obtained imposing their suppression via Lagrange multipliers. This strategy is indicated by CG^1-formulation.

In this way, the rational conforming space collapses into a conforming rearrangement of the original polynomial space. The proposed CG^1-formulation design triangular and/or quadrilateral elements that pass the bending patch test, present optimal rate of convergence on general unstructured meshes and are easy to assemble together.

References

[1] *Farin, G., Curves and surfaces for CAGD: A practical guide, The Morgan Kaufmann Series in Computer Graphics. Morgan Kaufmann, 5 edition, (2001).*

[2] *Gregory, J.A., Smooth interpolation without twist constraints, Computer Aided Geometric Design, page 71-87 (1974).*

[3] *Greco, L., Cuomo, M. and Contrafatto, L., A quadrilateral G^1-conforming finite element for the Kirchhoff plate model, Computer Methods in Applied Mechanics and Engineering,* **346**, *page 913-951 (2019).*

[4] *Cuomo, M. and Greco, L., An implicit strong G^1-conforming formulation for the analysis of the Kirchhoff plate model, Continuum Mechanics and Thermodynamics, https://doi.org/10.1007/s00161-018-0701-3 (2018).*

Predicting the constitutive response of heterogeneous materials via machine learning

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Keywords: machine learning, data-driven mechanical response, composite materials

In the paradigm of data-intensive science, supervised machine learning techniques are largely exploited in order to discover inherent rules and gain hidden insights, grounded on massive amounts of data [1]. Automated detection of constitutive equations for complex systems and governing equations for given physical phenomenonae are of great importance in applied sciences [2].

The present work shows that data-driven techniques can be efficiently exploited in order to identify the macroscopic, effective mechanical response of heterogeneous, non linear elastic materials. From a collection of data sets of stress-strain couples that sample the constitutive response of the composite material, machine learning shows good performances in predicting the overall material properties depending upon the distribution of the forming constituents. In particular, a feed forward neural network has been validated in order to predict the effective mechanical behavior of truss structures.

Such intelligent material model opens new promising chances for implementing accurate concurrent simulations in the analysis of large scale heterogeneous structures, also in the case of three-dimensional and non linear, history-dependent loading scenarios. Incorporating different types of simulations across different length scales may provide efficient, high-fidelity means for new materials design and manufacturing [3].

References

[1] *Mitchell, T.M., Machine learning, McGraw-Hill, Portland (1997).*

[2] *Kirchdoerfer, T., Ortiz, M., "Data-driven computational mechanics" in Computer Methods in Applied Mechanics and Engineering,* **304***, page 81–101 (2016).*

[3] *Wang, K., Sun, W., "A multiscale multi-permeability poroplasticity model linked by recursive homogenizations and deep learning" in Computer Methods in Applied Mechanics and Engineering,* **334***, page 337–380 (2018).*

Enhanced beam formulations with cross-section warping under large displacements

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Keywords: Thin-walled beam, Warping, Large displacements

Beam models are commonly used for the analysis of large scale structures because of their computational efficiency in reproducing the structural response. However, most beam formulations used in engineering practice are based on the assumption of rigid body cross-section and fail in correctly describing the response of thin-walled structures. Indeed, the mechanical behavior of thin-walled beams is significantly influenced by warping of the cross-sections, which causes multi-axial stress/strain interaction and leads to complex nonlinear responses, even under ordinary load conditions. Starting from the pioneering work by Vlasov [1], many authors have proposed enriched formulations which extend classic beam theories and account for warping deformations of the cross-section, aiming at capturing interaction of axial force and bending moments with shear and torsional effects. However, many of them are based on specific kinematic and/or constitutive assumptions that limit their range of application and prevent generalization to complex case studies.

This work explores the adoption of two different approaches for the analysis of thin-walled structures, both based on enriched beam theories that include out-of-plane cross-section warping, being the in-plane deformations neglected. First approach relies on a three-dimensional beam finite element [2] based on a four-field mixed formulation, where cross-section warping displacement is included as additional independent field to the standard cross-section rigid-body displacements, strains, and stresses and is interpolated with the definition of specific shape functions: along the element axis and over the general cross-section. Geometric nonlinearity is included through a corotational approach that considers the coupling between axial and torsional stress/strain components, know as Wagner effect. As opposed to the first approach, a simpler but coarse descriptor of warping displacement field is adopted in the second approach [3], assuming *a priori* the warping profile over the cross-section [1]. Geometric nonlinearity is included by adopting nonlinear hyperelastic relations to describe the generalized cross-section constitutive response and account for Wagner term. In this case, the nonlinear equilibrium equations of an enriched beam model are solved through a finite differences procedure.

For selected specimens, modal decompositions and step-by-step incremental analyses are conducted under small and large displacements, comparing the results obtained for both models with analytical solutions and experimental outcomes. Advantages and disadvantages of each approach are discussed.

References

[1] *Vlasov, V.Z., Thin-Walled Elastic Beams, Monson, Jerusalem (1961).*

[2] *Di Re, P., Addessi, D. and Filippou, F.C., "Mixed 3D beam element with damage plasticity for the analysis of RC members under warping torsion", J Struct Eng ASCE,* **44**, *04018064 (2018).*

[3] *Lofrano, E., Paolone, A. and Ruta, G., "A numerical approach for the stability analysis of open thin-walled beams", Mechanics Research Communications,* **48**, *76-86 (2013).*

An orthotropic multi-surface elastic-damaging-plastic model with regularized XFEM interfaces for wood structures

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Keywords: XFEM, wood mechanics, Plasticity

Wood is an extraordinary natural composite material exhibiting a pronounced orthotropic behavior, and markedly different properties along the parallel and transverse-to-the grain directions. It also displays a strongly non-linear response, almost elastic-plastic under compression and elastic-damaging under tension and shear [1].

Restoration and development of smart wooden based elements are gaining an increasing interest in the building industry. In this context, the computational challenge is to develop numerical constitutive models that account for the complex, strongly non-linear, nature of wood behavior.

In the present contribution, we develop a novel constitutive model obtained by coupling the non-smooth multi-surface plasticity model, developed by Schmidt and Kaliske [2] for compressive failure modes, with the orthotropic damage model proposed by Sandhaas et al. [3, 4] for tensile/shear failure modes. Joints are modeled with a regularized version of the eXtended Finite Element Method (XFEM) [5] that allows to model the development of the crack process zone [6], while ensuring mesh-size independent results and a smooth continuous-discontinuous transition.

Numerical and experimental results are compared for validation purposes.

References

[1] Persson, K., "Micromechanical modelling of wood and fibre properties", Lund University, Department of Mechanics and Materials (2000).

[2] Schmidt, J., and Kaliske, M., "Zur dreidimensionalen Materialmodellierung von Fichtenholz mittels eines Mehrflächen-Plastizitätsmodells", Holz als Roh-und Werkstoff, **64**, 393-402 (2006).

[3] Sandhaas, C., Van de Kuilen, J.W.G., "Material model for wood", Heron, **58**, 171-191 (2013).

[4] Orlando, N., Taddia, Y., Benvenuti, E., Pizzo, B., Alessandri, C., "End-repair of timber beams with laterally-loaded glued-in rods: Experimental trials and failure prediction through modelling", Construction and Building Materials, **195**, 623-637 (2019)

[5] Benvenuti, E., "A regularized XFEM framework for embedded cohesive interfaces", Computer Methods in Applied Mechanics and Engineering, **197**, 4367-4378 (2008).

[6] Murata, K., Nagai, H., Nakano, T., "Estimation of width of fracture process zone in spruce wood by radial tensile test", Mechanics of Materials, **43**, 389-396 (2011).

FE model updating: sensitivity, reliability and regularization issues

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Keywords: model updating, model reduction, masonry buildings

Combining ambient vibration monitoring and finite element (FE) modelling through suitable model updating procedures allows for obtaining an estimate of the boundary conditions and mechanical material properties of engineering structures [1]. Application of FE model updating to historical buildings is relatively recent and involves the solution of a constrained minimum problem, whose objective function is generally expressed as the discrepancy between experimental and numerical quantities, such as natural frequencies and mode shapes [2], [3].

The paper presents an algorithm for FE model updating based on the construction of local parametric reduced-order models embedded in a trust-region scheme and implemented in NOSA-ITACA, a non-commercial FE code developed by the authors [4], [5], [6]. The algorithm exploits the structure of the stiffness and mass matrices and the fact that only a few of the smallest eigenvalues have to be calculated. This new procedure enables to compute eigenvalues and eigenvectors cheaply and thus to solve the minimum problem very efficiently. Besides reducing the overall computation time of the numerical process and enabling the accurate analysis of large scale models with little effort, the proposed algorithm allows for getting information on both the reliability of the solution and its sensitivity to noisy experimental data. Some case studies are presented and discussed and the adoption of regularization techniques to recover meaningful solutions investigated.

References

[1] Mottershead, J.E., Friswell, M.I. , "Model updating in structural dynamics: a survey", Journal of Sound and Vibration, ***167****(2), 347-375 (1993).*

[2] Bautista-De Castro, Á., Sánchez-Aparicio, L. J., Ramos, L. F., Sena-Cruz, J., and González-Aguilera, D., "Integrating geomatic approaches, Operational Modal Analysis, advanced numerical and updating methods to evaluate the current safety conditions of the historical Bôco Bridge", Construction and Building Materials, ***158****, 961-984 (2019).*

[3] Ferrari, R., Froio, D., Rizzi, E., Gentile, C., and Chatzi, E. N., "Model updating of a historic concrete bridge by sensitivity-and global optimization-based Latin Hypercube Sampling", Engineering Structures, ***179****, 139-160 (2019).*

[4] Girardi, M., Padovani, C, Pellegrini, D., Porcelli, M., and Robol, L., "Finite element model updating for structural applications", arXiv:1801.09122 [math.NA] (2018).

[5] Girardi, M., Padovani, C., Pellegrini, D, Porcelli, M., and Robol, L., "FEA for masonry structures and vibration-based model updating using NOSA-ITACA" in proceedings of the 10th International Masonry Conference, Milan, July 9-11 2018, G. Milani, A. Taliercio and S. Garrity (eds.) (2018).

[6] Girardi, M., Padovani, C., Pellegrini, D., and Robol. L., "A model updating procedure to enhance structural analysis in the FE code NOSA-ITACA" to appear in Journal of Performance of Constructed Facilities, post print arXiv:1902.03949 [cs.CE] (2019).

A Virtual Element approach for in plane Cosserat elasticity

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Keywords: virtual element method, Cosserat continuum, micropolar continua

A large number of engineering materials are strongly characterized by nonlocal constitutive response such as materials with a granular, fibrous, or lattice structure. Classical continuum models, that does not incorporate internal length scales, suffer various problems in numerical computations [1].
The Cosserat continuum, that belongs to the class of micromorphic continua [2, 3], is able to retain memory of an inherent microstructure, providing an enriched constitutive behaviour, with respect to the classical Cauchy continuum. The main characteristic of the linear Cosserat elastic theory is that each material point is equipped with a microstructure, so that is can both translate and rotate, thus resulting in additional strains and stresses: besides the classical components, micropolar ones include curvatures (work conjugate to couple stresses) and skew-symmetric strains (work conjugate to skew-symmetric stresses).
In this work, we propose a Virtual Element Method (VEM) for solving boundary value problems in 2D linear isotropic Cosserat elasticity. The recently proposed VEM [4, 5], represents an extension of Finite Element philosophy to deal with very general polygons with rather general shapes, including non convex ones, polyhedra in three dimensions with curved faces, hanging nodes, and so on. Following the basic idea of the method, here, the displacement and rotation fields are decomposed into a polynomial space (consistency term), either linear or quadratic, and a remaining non-polynomial space (stabilization term) is suitably approximated. The label virtual depends on the fact that the basis functions are not explicitly known. Different applications are proposed [6, 7], ranging from a patch test, properly conceived for micropolar continua, to various engineering applications. The obtained results are in good agreement with reference solutions, confirming the capability of the proposed elements in modelling the expected responses.

References

[1] *Trovalusci, P. (Ed.), "Materials with Internal Structure. Multiscale and Multifield Modeling and Simulation", Springer Tracts in Mechanical Engineering,* **18**, *109–131 (2016).*
[2] *Eringen, A.C., "Microcontinuum field theories", Springer-Verlag, New York, (1999).*
[3] *Trovalusci, P., "Molecular Approaches for Multifield Continua: origins and current developments", CISM, Courses and Lectures,* **556**, *211–278 (2014).*
[4] *Beirao Da Vega, L., Brezzi, F., Marini, L.D., "Virtual Elements for Linear Elasticity Problems", SIAM J Numer Anal,* **51**, *794–812 (2013).*
[5] *Pingaro, M., Reccia, E., Trovalusci, P., Masiani, R., Fast statistical homogenization procedure (FSHP) for particle random composites using virtual element method, Computational Mechanics, 1–14 (2019).*
[6] *Providas, E. and Kattis, M. A., "Finite element method in plane Cosserat elasticity", Comput Struct,* **80**, *2059–2069 (2002).*
[7] *Fantuzzi, N., Leonetti, L., Trovalusci, P., Tornabene, F., "Some Novel Numerical Applications of Cosserat Continua", Int J Comp Meth-Sing,* **15**, *(2018)*

Numerical prediction of genesis and evolution of orographies in films wrinkling on 3D-shaped substrata

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Keywords: wrinkling, thin films, numerical modeling.

The proposed contribution is focused on wrinkles of thin metal films generated and driven by mechanical or thermal-induced stresses [1]. Wrinkles have recently found unforeseeable applications in surprising ways in many emerging fields since this process offers potential to generate planar and non-planar surfaces patterned in 1–100μm pitch range with height features at nanoscale over areas of square centimeters [2]. Thus, wrinkles formation could be formidable bottom-up process if the fabrication will become full a predictable and governable nano-micro-technology. However, full prediction is still a challenging ambition [3]. In fact, as a matter of fact, the intrinsic nonlinear nature of the mechanical response of these systems and the complex interaction occurring at the interface between thin layer and elastically inhomogeneous substrates require extremely expensive computational times and limit the use of closed-form solutions and thumb rules, especially if some symmetries and shape regularities of the overall constructs are lost [4]. To contribute to overcome these obstacles in modeling compliant film wrinkling in non trivial cases of interest, a new hybrid analytical-numerical (Finite Element-based) strategy is here proposed to drastically reduce the computational costs of in-silico simulations and to gain both qualitative and quantitative results for predicting wrinkle profiles, including onset and progressive evolution of wrinkling films nano-orographies.

References

*[1] Sun, Y., Choi, W.M., Jiang, H., Huang Y.Y. and Rogers J.A. "Controlled buckling of semiconductor nanoribbons for stretchable electronics", Nature Nanotechnology, **1**, 201-207, (2006).*

[2] Hutchinson, J.W., Mechanics of thin films and multilayer. Technical University of Denmark (1996.).

*[3] Bowden, N., Brittain, S., Evans, A. G., Hutchinson J.W. and Whitesides G.M.," Spontaneous formation of ordered structures in thin films of metals supported on an elastomeric polymer", Nature,**393**, 146–149, (1998).*

*[4] Cai, S, Breid, D, Crosby, AJ., Suo, Z, Hutchinson JW,."Periodic patterns and energy states of buckled films on compliant substrates", Journal of the Mechanics and Physics of Solids, **59**, 5, 1094-1114, (2011).*

A numerical study on explicit vs implicit time integration of the Vermeer-Neher constitutive model

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Keywords: subsidence modelling, Vermeer-Neher, implicit time integration.

Abstract. *In the oil and gas industry, subsidence modelling aims to predict the deformation of the ground surface induced by hydrocarbon withdrawal from underground reservoir rocks. In reason of environmental and operational implications associated to subsidence, energy companies make a firm commitment to providing accurate estimates and reliable forecasts. This goal can be achieved through numerical simulations with advanced constitutive models accounting for soil/rock plasticity and creep, such as the model proposed by Vermeer and Neher in 1999. Several different implementations of this model have been proposed in the literature, including explicit and semi-implicit time integrations, but a clean and consistent fully implicit formulation is still missing. In this work, in the line of the classical approach for the modified Cam-Clay model, a fully implicit backward-difference integration is proposed and validated. The derivation of the consistent stiffness matrix is also described in detail, together with its validation strategy. The model has also been implemented in a commercial code for finite element analysis through a user-defined material subroutine. We show the expected advantages of the implicit formulation in terms of stability with respect to the explicit formulation. The examples include studies at material point level and at field scale for a case study of subsidence above a synthetic gas reservoir.*

An approach for making attractive the symmetric BE analysis of plane elastic problems

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Keywords: symmetric BEM, complex variables, boundary integration.

Collocation BE models allow a description of plane elastic problems more compact than standard FE models and an equally accurate evaluation of both displacement and stress fields [1]. However, the same BE models provide boundary variables systems, lacking in symmetry and sign-definiteness also if small and fully populated. These missing features cause troubles when FE and BE models have to be coupled or when a BE dynamic analysis is performed. To preserve the proprieties of the continuum model, symmetric BE models have been proposed considering boundary integral equations associated with static and kinematic distributed sources, interpolating sources distributions and boundary fields with the same shape functions [2]. In this way the boundary variables system become symmetric but its entries result from heavy and complicated double boundary integrations containing a large number of terms, especially when high order shape functions are used, generically oriented domains are analyzed and highly singular fundamental solutions are involved. All these integration troubles, often separately tackled by using numerical or analytical techniques, have hindered the diffusion of the symmetric BEMs and their corresponding computer codes. It is clear that the best solution could be the use of a unified integration procedure able to build the boundary system avoiding the differences of numerical accuracy that can derive from a mixed use of analytical and numerical integration and ensuring a fast assembling of the boundary system. In this work a symmetric BE model for plane elasticity is implemented introducing a novel strategy based on a complex variable analytical integration procedure able to provide accurate and concise results for both overlapping and separate integration domains. It avoids the tedious and large algebraic manipulations required by the integration in the real plane and includes a special integration rule combined with a preliminary regularization process to cancel the singular boundary terms of the kernels thanks to the continuity of the shape functions. So doing, only two analytical expressions, one for generically oriented and one for aligned/parallel integration domains, are necessary to build the boundary system knowing the relative location of boundary elements. These formulas prove compactness of the results and advantages of the regularization technique while some numerical tests show accuracy and effectiveness of the proposed computational strategy for symmetric BEM.

References

[1] *Vable, M., "An algorithm based on the boundary element method for problems in engineering mechanics", International Journal for Numerical Methods in Engineering* ***21****, 9, 1625-1640 (1985).*

[2] *Sirtori, S., Maier, G., Novati, G., Miccoli, S., "A Galerkin symmetric boundary-element method in elasticity: formulation and implementation", International Journal for Numerical Methods in Engineering,* ***35****, 2, 255-282 (1994).*

Multi-scale and multi-physics computational analyses of the DTT magnet system

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Keywords: Computational mechanics, Fusion magnets, multi-scale approaches

In the context of controlled thermonuclear fusion, the Divertor Tokamak Test (DTT) is an experimental fusion reactor to be built in Italy, at the ENEA Frascati research centre. According to the objectives set by the European Fusion Roadmap, in order to scale up from purely experimental devices to the first prototype of grid-connected fusion machines, a reactor must be built that specifically adresses the issues of power and exhaust handling. Only a thorough investigation of several confgurations of the component that extracts energy from the reaction chamber, named "divertor", will ensure a confident extrapolation of data from the ITER experimental reactor to the EU-DEMO grid-connected reactor.

The DTT machine will host fusion reactions in a high-temperature plasma (an average value of $\langle T_\mathrm{e} \rangle = 6.2\,\mathrm{keV}$, roughly $72 \times 10^6\,\mathrm{K}$), that will be confined by intense magnetic fields ($6\,\mathrm{T}$ at the plasma core). The magnetic system that generates such fields is therefore a crucial component of the machine, and it comprises eighteen Toroidal Field Coils (TFCs), six Poloidal Field Coils (PFCs), a Central Solenoid (CS) and several finer-control coils. All of the TFC, PFC and CS coils are superconductive, operate at $4.5\,\mathrm{K}$, and have the requirement of confining at least two kinds of plasma topologies, namely the single-null and the double-null conformations. Numerous steps were taken in order to obtain a design that is magnetically consistent with the plasma requirements on the one hand, while remaining structurally compliant on the other.

This work presents the analyses performed to assess the performance of the magnet system. After a process of cool-down to the operating cryogenic temperatures, the coils will be energised and will experience electromagnetic forces that vary with the plasma scenario. To tackle the inherent complexity of the analyses, different multi-scale and multi-physics approaches have been employed, both at a simplified theoretical level and at an in-detail, FEM-supported level. These approaches include: the search for a reduced-stress design for the toroidal coils, which are sturctures that must withstand intense electromagnetic loads; a consistent magnetic field computation, taking into account the contribution of the whole magnet system; numerical homogenisation of material properties, to allow faster three-dimensional computational analyses; fatigue evaluation, since some of the magnets are operated in pulsed regime; structural topology optimisation, to attain an optimal distribution of the mass of the support structures. The broad scope of the study is intended not only to assess a specific design of the magnet system, but also to individuate and methodologically characterise some focal design aspects.

A full orthotropic bond-based peridynamic formulation for linearly elastic solids

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Keywords: Non-local lattice, Peridynamics, Orthotropy, Micropolar, Elasticity

An original full orthotropic model for in plane linear elasticity is proposed in the micropolar peridynamic analysis framework. The analytical formulation is derived from the definition of a specific microelastic energy function for micropolar nonlocal lattices which allows to obtain, for the first time, an orthotropic bond-based model characterized by four independent elastic moduli.
An important feature of the model is that the bond properties, i.e. the elastic constants, are continuous functions of the bond orientation in the principal material axes. The introduction of the bond shear stiffness and the definition of a bond shear deformation measure which accounts for particle's rotation, on one hand eliminates the restriction of two independent constants that affects other bond-based orthotropic peridynamic formulations, and on the other makes the model suitable in predicting the mechanical behavior of a wide variety of Cauchy orthotropic materials undergoing homogeneous and non-homogeneous deformations. The accuracy of the proposed model in linear elasticity has been verified through simulating uniaxial extension test of a composite lamina with a central circular hole and natural frequency analyses considering different orientations of the principal material reference system.

References

[1] *Diana, V., Casolo, S., A bond-based micropolar peridynamic model with shear deformability: Elasticity, failure properties and initial yield domains. International Journal of Solids and Structures 2019;* **160***:201 231.;*

[2] *Silling, S.. Reformulation of elasticity theory for discontinuities and long-range forces. Journal of the Mechanics and Physics of Solids ;***48***(1):175209 (2000).*

[3] *Ostoja-Starzewski, M.. Lattice models in micromechanics. Applied Mechanics Review ASME ;***55***(1):3560 (2002).*

Well balanced ALE Finite Volume schemes on moving nonconforming meshes for non-conservative hyperbolic systems

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Keywords: Nonlinear hyperbolic equations, Finite Volume methods, Arbitrary-Lagrangian-Eulerian methods

In this talk I will present the results of my PhD thesis and some recent advances on those topics.

My PhD thesis presents a novel second order accurate direct Arbitrary-Lagrangian-Eulerian (ALE) Finite Volume scheme for nonlinear hyperbolic systems, written both in conservative and non-conservative form, whose peculiarities are the nonconforming motion of interfaces, the exact preservation of equilibria and the conservation of angular momentum. It is especially well suited for modeling vortical flows affected by strong differential rotation: in particular, the novel combination with the well balancing make it possible to obtain great results for challenging astronomical phenomena as the rotating Keplerian disk. A large set of tests shows the greatly reduced dissipation and the significant improvements of the new scheme compared with well established software for astrophysical fluid dynamics.

A new HLL-type and a novel Osher-type flux have been formulated: they are able to maintain up to machine precision the equilibrium between pressure gradient, centrifugal force and gravity force that characterizes the Euler equations with gravity, and correspondingly capture with high accuracy even small perturbations. Moreover, to ensure a high quality of the moving mesh for long computational times, I have introduced a new and fully automatic nonconforming treatment of the sliding interfaces that appear due to the differential rotation.

In addition, it has been shown that the introduced techniques can be easily extended also to other contexts, such as steady vortex flows in the shallow water equations or complex free surface flows in compressible two-phase models, and a preliminary analysis on how to increase the accuracy of the method by exploiting the conservation of the angular momentum.

The methods developed during the thesis have been recently extended to higher order of accuracy, to the Galerkin Discontinuous framework and to more complex space–time moving geometry.

References

[1] *E. Gaburro, M. Dumbser, M.J. Castro, Direct Arbitrary-Lagrangian-Eulerian finite volume schemes on moving nonconforming unstructured meshes, Computers & Fluids, vol. 159, p. 254-275, 2017.*

[2] *E. Gaburro, M.J. Castro, M. Dumbser, Well balanced Arbitrary-Lagrangian-Eulerian finite volume schemes on moving nonconforming meshes for the Euler equations of gasdynamics with gravity, Monthly Notices of the Royal Astronomical Society, vol. 477(2), p. 2251-2275, 2018.*

[3] *E. Gaburro, M.J. Castro, M. Dumbser, A well balanced diffuse interface method for complex nonhydrostatic free surface flows. Computers & Fluids, vol. 175, p. 180-198, 2018.*

[4] *E. Gaburro, W. Boscheri, S. Chiocchetti, C. Klingenberg, V. Springel, M. Dumbser, High order direct ALE schemes on moving Voronoi meshes with changing connectivity, manuscrit available on my web site, 2019.*

Solid-shell finite element and isogeometric models for nonlinear analysis and design of elastic shells using Newton, Koiter and Koiter-Newton solution strategies

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Keywords: shells, composites, geometrically nonlinear analysis, buckling, large deformation.

This work aims at developing a reliable and efficient numerical framework for the analysis and the design of slender elastic shells, in particular when composite materials are adopted, taking account of the geometrically nonlinear behaviour. Different aspects of this challenging topic are tackled: discretisation techniques [1], numerical solution strategies [2] and optimal design [3]. The important advantages of using a mixed solid model for analysing shell structures over traditional shell models and the implications of this on the performances of the solution strategies are discussed. A mixed solid-shell model is introduced for making the Koiter method an effective tool for analysing imperfection sensitive structures. Its quick predictions are exploited to develop a stochastic optimisation strategy for the layup of composite shells, able to take account of the worst geometrical imperfection. The benefits of the mixed formulation in the Newton iterative scheme are extended to any displacement-based finite element model by means of a novel strategy, called Mixed Integration Point. An efficient implementation of the novel Koiter-Newton method is proposed, able to recover the equilibrium path of a structure accurately with a few Newton iterations, combining an accurate Koiter predictor with the reduced iterative effort due to a mixed formulation. The solid-shell discrete model is reformulated, following the isogeometric concept, by using NURBS functions to interpolate geometry and displacement field on the middle surface of the shell in order to take advantage of their high continuity and of the exact geometry description. The approach is made accurate and efficient in large deformation problems by combining the Mixed Integration Point strategy with a suitable patch-wise reduced integration. The resulting discrete model proves to be much more convenient than low order finite elements, especially in the analysis of curved shells undergoing buckling. This is shown by means of an efficient isogeometric version of the Koiter analysis.

References

[1] *Leonetti L., Liguori F., Magisano D., Garcea G., "An efficient isogeometric solid-shell formulation for geometrically nonlinear analysis of elastic shells", Computer Methods in Applied Mechanics and Engineering,* **331***, page 159 - 183 (2018).*

[2] *Magisano D, Leonetti L, Garcea G. "How to improve efficiency and robustness of the Newton method in geometrically non-linear structural problem discretized via displacement-based finite elements", Computer Methods in Applied Mechanics and Engineering,* **313***, page 986 - 1005 (2017).*

[3] *Liguori F.S., Madeo A., Magisano D., Leonetti L., Garcea G., "Post-buckling optimisation strategy of imperfection sensitive composite shells using Koiter method and Monte Carlo simulation", Composite Structures,* **192***, page 654 - 670 (2018).*

MS09

MECHANICS AND GEOMETRY

Mechanics of surface growth: stability of 1D and 2D treadmilling systems

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Keywords: surface growth, actin treadmilling, stability

Actin growth is a fundamental biophysical process [1] and it is, at the same time, a prototypical example of diffusion-mediated surface growth. We consider a coupled chemo-mechanical, growth model [2] encompassing both material accretion and ablation.

We first study a one dimensional example. A rod-like element composed of actin monomers is fixed at one end and connected to an elastic device at the other. The mechanical behaviour of the rod, the diffusion of free actin monomers in a surrounding solvent and the kinetic growth laws at the accreting/ablating ends are accounted for. The constitutive behaviour of actin is prescribed in fairly general terms by mainly requiring that the elastic strain energy density of the material be convex. The existence of treadmilling solutions, characterized by a constant length of the continuously evolving body, is investigated. It is shown that the present model admits at most one such solution and that it is always stable.

We conclude by extending the model to a two dimensional geometry, discussing the stability of circularly symmetric treadmilling solutions of an annulus of actin with the inner boundary fixed. This example is motivated by in vitro experiments (see e.g. [3]) investigating the onset of actin mediated motion observed in bacterium Listeria Monocytogenes [4].

References

[1] *Theriot, J. A., "The Polymerization Motor", Traffic,* **1***, pages 19-28 (2000).*

[2] *Tomassetti, G., Cohen, T. and Abeyaratne, R., "Steady accretion of an elastic body on a hard spherical surface and the notion of a four-dimensional reference space", Journal of the Mechanics and Physics of Solids,* **96***, pages 333-352 (2016).*

[3] *Cameron, L. A., Footer, M. J., van Oudenaarden, A. and Theriot, J. A., "Motility of ActA protein-coated microspheres driven by actin polymerization", Proc Natl Acad Sci USA,* **96***, pages 4908-4913 (1999).*

[4] *Prost, J., Joanny, J.-F., Lenz, P. and Sykes, C., "The Physics Of Listeria Propulsion", in "Cell Motility", Springer, New York (2008).*

Deformation Transfer and Elasticity

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Keywords: nonlinear elasticity, target metric, morphing.

Deformation transfer is a technique widely used in computer animation: the goal is to acquire the motion of a given character, the source, and use that information to animate a different character, the target [1].

Here, we frame this problem within the theory of nonlinear elasticity with large distortions [2]: our goal is to develop a reliable mathematical tool to probe the metric change between a pair of shapes of a same material body, and then use this information to deform likewise a different body. To pursue this goal, we exploit the notions of target metric, non Euclidean plates [3] and non-linear distortions, which have been widely used to describe shape formation.

Our method is based on two steps: at first, we transport the metric information gauged from a body A onto a different body B [4]; then, basing on this transported metric, we define a target metric which is used to morph the body B. The configuration which is effectively realized by B is the one that minimizes the distance, measured through the elastic energy, between the target metric and the actual one.

Of paramount importance is the compatibility of the target metric, a feature that can be measured by evaluating the Riemann curvature associated to it [5]: if the target metric is compatible, the motion mapping is perfect, in the sense that the body B will deform exactly as the body A.

We present some worked example of morphing mapping for 3D bodies and 2D surfaces.

References

[1] R. W. Sumner, J. Popovi, "Meshes Deformation Transfer for Triangle Meshes", Proceedings of SIGGRAPH (2014).
[2] P. Nardinocchi, L. Teresi, V. Varano, "The elastic metric: A review of elasticity with large distortions, International Journal of Non-Linear Mechanics", vol 56, page 34–42 (2013).
[3] Y. Klein, E. Efrati, E. Sharon, "Shaping of elastic sheets by prescription of non-Euclidean metrics", Science vol 315, page 1116–1120 (2007).
[4] F. Milicchio, V. Varano, S. Gabriele, L. Teresi, P. Puddu, P. Piras, "Parallel transport of local strains", Computer Methods in Biomechanics and Biomedical Engineering: Imaging &Visualization (2018).
[5] P. G. Ciarlet, An Introduction to Differential Geometry with Applications to Elasticity, Springer (2005).

Exploiting mechanical nonlinearities to sequentially inflate multiple soft actuators

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Keywords: mechanical nonlinearities, elastic inflatable actuators, soft robotics

Soft actuators are used as active components in soft or semi-soft robots. The complexity and, thus, the amount of tasks that a soft robot can perform, depends on the number of actuators installed in the body of the robot [1].

Elastic inflatable actuators are very common soft actuators for robotic applications. A basic inflatable structure can be designed in order to elongate, contract, bend or twist upon inflation. Those actuators consist of rubber structures having inner cavities filled with fluid, whose pressurization deforms the overall structure into a useful configuration [2].

The main disadvantage of such actuators is that each cavity needs to be individually connected to a dedicated pressure source. A high number of actuators corresponds to a same amount of tethers, which not only increases the complexity of the pressure control system (multiple valves and fluidic connectors) but it also creates a physical obstacle to the motion of the robot.

To overcome this issue and decrease the number of tethers, we took advantages of the mechanical nonlinearities caused by the hyperelasticity of rubber [3] to generate a predetermined sequence of inflation of multiple interconnected soft actuators.

Balloon-like actuators, characterized by thin inflatable membranes, undergo a snap-through instability at a certain pressure value corresponding to a very fast volume growth. When two or more of such actuators are interconnected, the instability causes a local fluid transfer between actuators generating an inflation sequence.

The actuation sequence of multiple nonlinear actuators is determined by analytically computing the static equilibrium configurations at each inflation step. In a subsequent step we implemented in the model the hysteresis cycle between inflation and deflation and pressure drops caused by passive flow restrictors.

With this approach, we built a semisoft robotic tetrapod, where each limb is composed of two contracting soft actuators inflating in a predetermined sequence in order to perform a step motion. The number of tethers is decreased from 8 to 1. The same principle is applied to two bending actuators to create a nonreciprocal motion, inspired to the one of biological cilia.

References

*[1] Kim, S., Laschi, C. and Trimmer, B., "Soft robotics: A bioinspired evolution in robotics" Trends in Biotechnology. **31**, 287–294 (2013).*

*[2] Gorissen, B., Reynaerts, D., Konishi, S., Yoshida, K., Kim, J-W. and De Volder, M., "Elastic Inflatable Actuators for Soft Robotic Applications" Advanced Materials, **29**, 1604977 (2017).*

[3] Müller, I., Strehlow, P. and Marder, M., Rubber and Rubber Balloons: Paradigms of Thermodynamics, Springer-Verlag, New York (2004).

Instability and Landau theory of a confined stretchable thin elastic sheet

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Keywords: Buckling, phase transitions, singularity theory

A growing or compressed thin elastic sheet adhered to a rigid substrate can exhibit a buckling instability, forming an inward hump. What is the critical force at which the collapse occurs? How are the geometric features of the hump at the transition related to the material constants and to the geometry of the system? [1] We show that the strip morphology depends on the delicate balance between the compression energy and the bending energy so that the instability is a first order phase transition between the adhered solution and the buckled solution whose main control parameter is related to the sheet stretchability [2, 3]. Furthermore, compressibility is the key assumption which allows us to resolve the apparent paradox of an unbounded pressure exerted on the external wall by a confined flexible loop. We show that it is possible to construct a Landau-like expansion of the energy of these systems, whose mathematical justification is based on singularity theory, so that the analysis of the phase transitions and of their stability becomes particularly transparent.

References

[1] *De Pascalis, R., Napoli, G., Turzi, S., "Growth-induced blisters in a circular tube", Physica D,* **283***, page 1-9 (2014).*

[2] *Napoli, G., Turzi, S., "Snap buckling of a confined thin elastic sheet", P. Roy. Soc. A - Math. Phys.,* **471***, page 2183 (2015).*

[3] *Napoli, G., Turzi, S., "The delamination of a growing elastic sheet with adhesion", Meccanica,* **52***, page 3481-3487 (2017).*

From Föppl–von Kármán plates to enhanced one-dimensional rods: the role of compatibility

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Keywords: Föppl–von Kármán plates, enhanced rod models, compatibility, non-locality

The Föppl–von Kármán model [2] is customarily adopted to describe the large deflections of thin elastic plates or shells. Because of the smallness parameter given by the thickness, such a model is intrinsically 2D. We here intend to consider Föppl–von Kármán-like strips endowed with a further smallness parameter, namely the width. Being thin and slender at the same time, such bodies can be naturally described on having recourse to 1D continua. Besides the classical beam models, in the literature are often adopted the so-called models *à la* Sadowski, usually generated starting from plate models (see [3] and references therein).

We here deduce a 1D model of elastic rods enhanced by additional kinematical descriptors that keep explicit track of the compatibility condition requested in the 2D or 3D parent continua, that in the classical models are identically satisfied after the dimensional reduction. This enhanced model allows to describe some phenomena of preeminent importance even in 1D bodies, such as formation of singularities and localization of the elastic energy (d-cones, elastic folds, etc.), otherwise inaccessible by the classical 1D models. Indeed, these phenomena are expression of a complex interaction between elasticity and geometry having an intrinsically 2D character, the compatibility conditions being the formal expression of such interaction. In the Föppl–von Kármán model, *e.g.*, the compatibility condition descends from the Gauss Theorema Egregium and expresses the relation between membrane deformations and variation of Gaussian curvature and identifies those changes of configuration that are energetically favorable. On the other hand, since the limit process involves two smallness parameters (thickness and width of the strip), it is reasonable that, at least for some values of their ratio, the limit problem keeps track of its 2D origin, somehow inheriting the compatibility condition.

In our reduced model, the 2D compatibility condition enters by means of a *non-locality* induced by a convolution integral over all the domain, whose cutoff radius can be analytically determined. Moreover, if the inextensibility condition prevails, analytical solutions can be obtained. Numerical solutions are instead in order in the fully non-local model.

References

[1] Brunetti, M., Favata, A., Vidoli, S., From Föppl–von Kármán plates to enhanced one-dimensional rods: the role of compatibility. *In preparation*.

[2] P.G. Ciarlet, *Mathematical Elasticity: Theory of Plates*, North-Holland, 1997

[3] Freddi, L., Hornung, P., Mora, M.G. and Paroni, R., One-dimensional von Kármán models for elastic ribbons, Meccanica, 53, 2, 659-670 (2018)

Programmed shape-shifting in beams and shells via swelling and shrinking

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Keywords: swelling, polymer gels, shape-shifting

Swelling and shrinking of polymer gels has been widely used as a driving force for changing the shape of materials. In response to different stimuli, the solvent uptake or release inside the cross–linked network could be changed, resulting in reversible volumetric expansion or shrinkage. When beams and plates are involved, the deformative process may induce, if appropriately programmed, curving of an originally flat structure and storage of stretching and bending energies. The programming strategies are based on the generation of appropriate stresses inside the materials which can result in bending torques and axial forces. The first ones induce out-of-plane bending [1] whereas the second out-of-plane buckling [2].
Swelling and shrinking processes corresponding to solvent uptake and release can determine that stress gradient in bilayered structures. These latter can be designed in terms of geometrical and material characteristics in such a way to get the desired curving, under solvent uptake/release. The appropriate design is typically based on multiphysics modeling of the stress-diffusion problem [3]. Granted for the distinguished shape of beams and plates, approximate methods have also been proposed to describe the final shape of beam-like structures under swelling [4]. However, the same methods have been rarely applied to the analysis of structures which are far from being flat at the beginning of the process as well as far from being dry.
The aim of the present work is to investigate the above phenomena. We start getting explicit formulae for swelling/shrinking induced curving of a beam. In particular, for initially curved beams, we also aim to distinguish the curvature-driven morphing from the swelling/shrinking one through an analysis of the competing elastic energy storage corresponding to the two mechanisms. We also aim to extend the analysis to (narrow) strips of polymer (plate-like structures). In this case, it is well known that spherical and cylindrical shape are taken under swelling/shrinking, mainly depending on geometrical characteristics of the structure. The question we would aim to answer is: can we drive the structure towards a different shape, with respect to the one naturally taken, through an appropriate design of the material composing the structure?

References

[1] *Egunov, A.I., Korvinkb, J.G. and Luchnikov, V.A., Polydimethylsiloxane bilayer films with an embedded spontaneous curvature; Soft Matter,* **12**, *45-52 (2016).*

[2] *Pezzulla, M., Shillig, S.A., Nardinocchi, P. and Holmes, D.P., Morphing of geometric composites via residual swelling; Soft Matter,* **11**, *5812-20 (2015).*

[3] *Lucantonio, A., Nardinocchi, P. and Teresi, L., Transient analysis of swelling-induced large deformations in polymer gels; J. Mech. Phys. Solids,* **61**, *205-218 (2013).*

[4] *Lucantonio, A., Nardinocchi, P. and Pezzulla, M., Swelling-induced and controlled curving in layered gel beams; Proc. R. Soc. London, Ser. A,* **470** *(2014).*

Geometry and mechanics of narrow ribbons from a three-dimensional prospective

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Keywords: ribbons, nonlinear elasticity, wrinkling

Geometrically, a narrow ribbon is a slender structural element with a parallelepiped shape with one side much longer than another that, in turn, is much longer than the remaining side. Narrow ribbons when subjected to particular deformations exhibit fine-scale ‘corrugations’ or ‘wrinkles’, while in other cases they simply deform ‘isometrically’. In this talk we shall analyze the ‘wrinkling’ behavior starting from a nonlinear three-dimensional elastic model of the ribbon. The talk is based on joint works with L. Freddi, P. Hornung, M.G. Mora, and G. Tomassetti, [1-5].

References

[1] L. Freddi, P. Hornung, M.G. Mora, R. Paroni, Generalised Sadowsky theories for ribbons from three-dimensional nonlinear elasticity, submitted 2018.
[2] R. Paroni, G. Tomassetti, Macroscopic and microscopic behavior of narrow elastic ribbons, J. Elasticity, DOI: https://doi.org/10.1007/s10659-018-09712-w, 2018.
[3] L. Freddi, P. Hornung, M.G. Mora, R. Paroni, One-dimensional von Kàrmàn models for elastic ribbons, Meccanica 53, 659–670, 2018.
[4] L. Freddi, P. Hornung, M.G. Mora, R. Paroni, A variational model for anisotropic and naturally twisted ribbons, SIAM Journal on Mathematical Analysis 48, 3883–3906, 2016.
[5] L. Freddi, P. Hornung, M.G. Mora, R. Paroni, A corrected Sadowsky functional for inextensible elastic ribbons, J. Elasticity 123, 125–136, 2016.

A neutrally stable shell in a Stokes flow: a rotational Taylor's sheet

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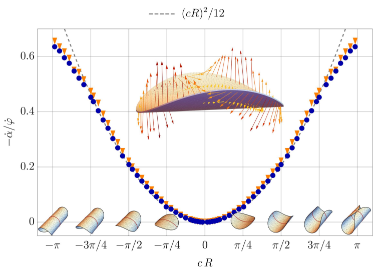
Keywords: morphing structures, fluid-structure interaction, motility

In a seminal paper [1] of 1951, Taylor studied the interactions between a viscous fluid and an immersed flat sheet which is subjected to a travelling wave of transversal displacement. The net reaction of the fluid over the sheet turned out to be a force in the direction of the wave phase-speed. This effect is a key mechanism for the swimming of micro-organisms in viscous fluids. Much more recently [2] studied the nonlinear deformations of pre-stressed circular shells. Suitably chosen pre-stress fields lead to shells having a connected one-dimensional set of neutrally-stable equilibria. Moving the actual shell shape along this one-dimensional set is extremely cheap as the shell tangent stiffness vanishes: the resulting motion is a sequence of cylindrical shapes differing by a precession of the axis of maximal curvature.

Here we merge these results to study the interactions between a viscous fluid and an immersed cylindrical shell subjected to a continuous precession of its axis of maximal curvature. We demonstrate that, despite the net force acting on the shell vanishes, the resultant torque does not. The described shell deformation constitutes the rotational analogous of the Taylor's sheet, where the translational swimming velocity is replaced by an angular velocity. A similar mechanism can be used to maneuver in viscous fluids.



Rotational swimming velocity $\dot{\alpha}$ for a circular shell generated by the precession velocity of the curvature axis $\dot{\varphi}$ (numeric), for different values of the curvature.

The results from the low Reynolds, motility problem naturally suggest further interesting research questions, involving whether relaxing the low Reynolds number hypothesis might allow for additional swimming strategies. These would entail exploiting phenomena such as instabilities of thin structures, as bistable clamped tails, or pulsatile motions, and a numerical study would require taking into account the elastic response of the structure, using reduced models or finite-element shell models [3], as well as a full Navier-Stokes solver for the fluid problem.

References

[1] *Taylor, G.I., "Analysis of the swimming of microscopic organisms", Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences,* **209**, *page 447-461 (1951).*

[2] *Hamouche, W., Maurini, C., Vidoli, S. and Vincenti, A., "Multi-parameter actuation of a neutrally stable shell: a flexible gear-less motor", Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences,* **473** *(2017).*

[3] *J. S. Hale, M. Brunetti, S.P.A. Bordas, and C. Maurini, "Simple and extensible plate and shell finite element models through automatic code generation tools", Computers & Structures,* **209**, *page 163-181 (2018).*

Elasto-active instabilities of spherical shells

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Keywords: dehydration, instabilities, shells

We study dehydration processes in homogeneous and inhomogeneous spherical hydrogel shells. Particularly, dehydration processes drive the high power mechanisms used by many natural systems, such as the fern sporangium and the sphagnum moss, to throw away their spores [1, 2]. The reproduction of these mechanisms in a Lab by means of artificial devices requires the knowledge of the determinants of the process.
With this aim, we study dehydration processes in gel spheres confining water-filled cavities, by tuning local inhomogeneities in the cavity's walls and show as different mechanical instabilities can be driven changing a few material parameters.
The dynamics of dehydration in a hydrogel body with a closed cavity is a challenging multiphysics and computational problem which has been partially investigated in [3] with reference to a cubic microcapsule. Therein, the suction occurring during the dehydration process determined the inwards bending of the capsule's walls and put the water inside the capsule under tension up to a threshold value known as cavitation value. In spherical capsules, a snapping mechanism occurs corresponding to a sharp pressure change inside the cavity with small volume change (see figure 1).

The analysis represents a first step towards the occurrence of instability mechanisms into arrays of spherical microcavities embedded into a soft matrix .

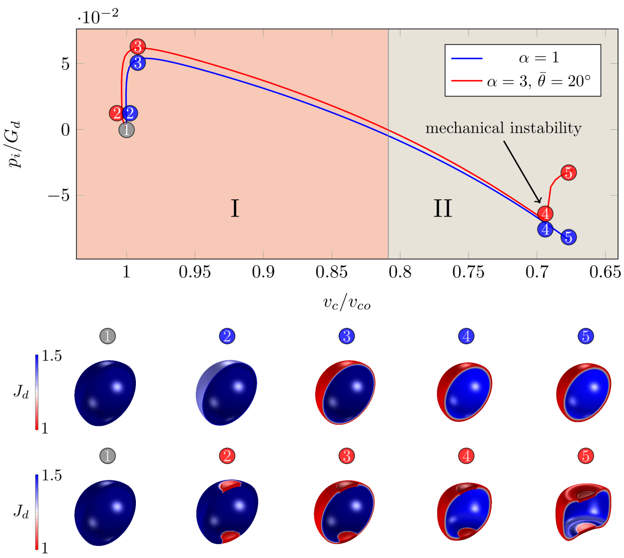

Figure 1: Dehydration induced instability of the inhomogeneous spherical shell.

References
[1] *X. Noblin, N. O. Rojas, J. Westbrook, C. Llorens, M. Argentina and J. Dumais, Science, 2012, 335, 1322.*
[2] *Whitaker, Dwight L., and Joan Edwards. Science 329.5990 (2010): 406-406.*
[3] *Curatolo, Michele, Paola Nardinocchi, and Luciano Teresi. Soft matter 14.12 (2018): 2310-2321.*

Elastic metrics in soft beams and shells

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Keywords: shells, swelling, soft mechanics

Soft polymeric beams and shells morph into a variety of shapes when subjected to mechanical as well as chemical actions. When the driving force of the morphing process is related to the diffusion of a solvent within the polymer, the mechanical and dynamical response of the soft structure can be set and studied within the context of a fully three-dimensional nonlinear stress-diffusion model[1]. However, understanding the essence of the mechanical behaviour through approximate beam and/or shell model can represent a breakthrough in the comprehension of morphing processes driven by diffusion when these structures are involved, as structural beam and shell models consent to analytically discuss the problem and evidence the determinants of the process.
Starting from [2], where it has been observed and shown as *the choice of elastic energies for thin plates and shells is an unsettled issue with consequences for much recent modeling of soft matter*, we discuss how the choice is still more complex when swelling phenomena take place in the structure. Indeed, in that case the three-dimensional modeling requires an energetic characterization of the process which is typically based on neo-Hookean or Gent elastic energy, at most augmented by anisotropic components [3]. On the other hand, the formulation of approximate beam and shell models requires a coherent identification of stretching and bending components of the energy functional. Through a few examples of swelling-induced deformations in thin beam-like and shell-like bodies, it will be shown as different choices based on different elastic metrics differs in the prediction of the basic mechanical behaviour of the body.

References

[1] *Lucantonio, A., Nardinocchi, P., Teresi, L. "Transient analysis of swelling-induced large deformations in polymer gels", J. Mech. Phys. Solids,* **61**, *205-218 (2013).*

[2] *Wood, H.G., Hanna, J.A. "Contrasting bending energies from bulk elastic theories", Soft Matter,* **15**, *2411-2417 (2018).*

[3] *Nardinocchi, P., Teresi, L. "Actuation performances of anisotropic gels", J. Appl. Phys.* **120**, *215107 (2016).*

The ellipse of crack-tip flexibility for the partitioning of fracture modes

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Keywords: fracture mode partitioning, virtual crack closure technique, ellipse of elasticity

A crack in a solid body will generally propagate according to a combination of the three basic fracture modes (I or opening, II or sliding, and III or tearing). Thus, the energy release rate, G, will be the sum of three modal contributions, G_{I}, G_{II}, and G_{III} [1]. In the finite element context, the virtual crack closure technique (VCCT) is widely used to calculate the energy release rate and its modal contributions [2]. Accordingly, G is related to the work done by the forces, $\mathbf{r}$ and $-\mathbf{r}$, applied at the crack-tip nodes to close up the crack, once propagated by a finite length, Δa (Fig. 1a).

In I/II mixed-mode fracture problems, the crack-tip relative displacement, $\Delta\mathbf{s} = [\Delta u, \Delta w]^T = \mathbf{F}\mathbf{r}$, where $\mathbf{F}$ is the crack-tip flexibility matrix. The conic section associated to $\mathbf{F}$ turns out to be an ellipse, Γ, named the *ellipse of crack-tip flexibility* (Fig. 1b), similar to Culmann's ellipse of elasticity [3]. The ellipse of crack-tip flexibility helps visualise the relationship between the crack-tip force, $\mathbf{r}$, and relative displacement, $\Delta\mathbf{s}$, whose directions correspond to conjugate diameters [4]. Furthermore, the ellipse can be used to decompose the crack-tip force vector, $\mathbf{r}$, into energetically orthogonal components, which enable a physically consistent partitioning of fracture modes [5].

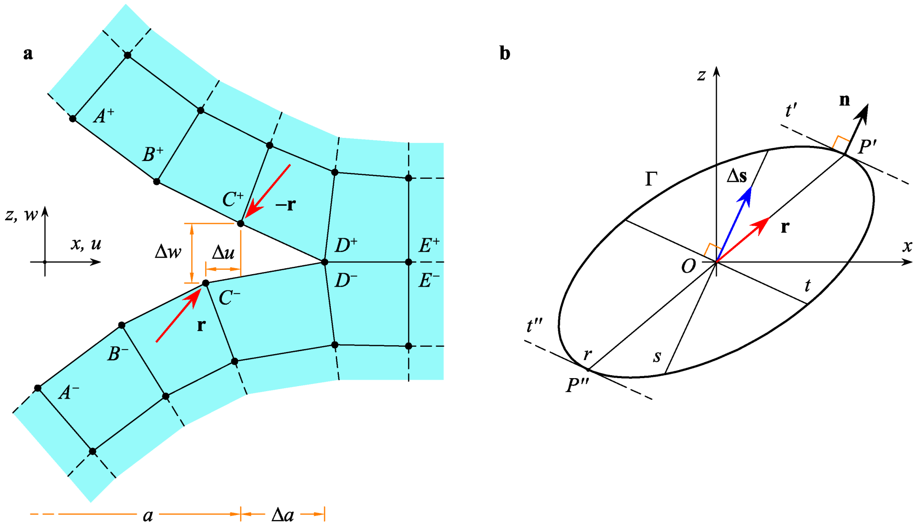

Figure 1: (a) virtual crack closure; (b) ellipse of crack-tip flexibility.

References
[1] *Sun, C.T., and Jin, Z.-H., Fracture Mechanics, Academic Press, Waltham, MA (2012).*
[2] *Krueger, R., Virtual crack closure technique: History, approach, and applications, Applied Mechanics Reviews,* **57***, 109–143 (2004).*
[3] *Culmann, K., Die graphische Statik, 2nd edn. Meyer & Zeller, Zurich (1875).*
[4] *Valvo, P.S., A revised virtual crack closure technique for physically consistent fracture mode partitioning, International Journal of Fracture,* **173***, 1–20 (2012).*
[5] *Valvo, P.S., A further step towards a physically consistent virtual crack closure technique, International Journal of Fracture,* **192***, 235–244 (2015).*

MS10

Dynamics and Stability of Mechanical Systems (GADeS)

Wave dynamics of spatial tensegrity structures

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Keywords: Tensegrity Structures; Compact Wave Dynamics; Stiffening Response

The dynamics of strongly nonlinear metamaterials is attracting increased attention from many research sectors including acoustics, aerospace and mechanical engineering, medical diagnosis and sound control [1]-[2]. A number of studies available in the to-date literature have shown that elastically hardening discrete systems formed by lumped masses connected by nonlinear springs support compressive solitary waves and the unusual reflection of waves on material interfaces [3], while elastically softening systems support the propagation of rarefaction solitary waves under initially compressive impact loading [4]. Solitary wave dynamics has been proven to be useful for the construction of a variety of novel acoustic devices. These include: acoustic band gap materials; shock protector devices; acoustic lenses; and energy trapping containers, to name some examples (refer, e.g., to [2] and references therein). Ordinary engineering materials typically exhibit either elastic stiffening (e.g., crystalline solids), or elastic softening (e.g., foams). More puzzling is the nonlinear response of structural lattices based on tensegrity units, which may gradually change their elastic response from stiffening to softening through the modification of mechanical, geometrical, and prestress variables [3]-[5]. The present study investigates the propagation of mechanical waves in tensegrity lattices with elastic stiffening response. The presented results highlight that such systems support compressive solitary waves and the unusual reflection of waves on material interfaces [3]. The analyzed structures may serve as actuators or sensors generating and/or receiving solitary waves from host media, with the aim of targeting localized defects or monitoring the mechanical properties of materials and structures [6].

References

[1] *Lu, M.H., Feng, L., Chen,Y.F., 2009. Phononic crystals and acoustic metamaterials, Mater. Today 12, 34-42.*

[2] *Brunet, T., Leng, J., Mondain-Monva, O., 2013. Soft acoustic metamaterials. Science, 342, 323-324.*

[3] *F., Senatore, L., Daraio, C., 2012. Solitary waves on tensegrity lattices. J.Mech. Phys. Solids 60, 1137-1144.*

[4] *Herbold, E. B., Nesterenko, V. F., 2012. Propagation of rarefaction pulses in discrete materials with strain-softening behavior. Phys. Rev. Lett. 110, 144101.*

[5] *Amendola, A., Nava, E.H., Goodall, R., Todd, I., Skelton, R.E., Fraternali, F., 2015. On the additive manufacturing and testing of tensegrity structures. Compos. Struct. 131,66-71.*

[6] *Daraio, C., Fraternali, F., 2013. "Method and Apparatus for Wave Generation and Detection Using Tensegrity Structures", US Pat. No. 8,616,328, granted on December 31, 2013.*

Periodic orbits of a bouncing mass on a flexible hinged-hinged beam

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Keywords: Bouncing balls, periodic solutions, flexible beam

We investigate the periodic orbits of a ball repeatedly bouncing on a flexible beam with hinged-hinged boundary conditions. The impact is described by the simple model presented in [1]. Between successive impacts of the ball, the beam profile and the ball trajectory follow a free dynamics; the beam profile is either known (in absence of ball-beam coupling) or governed by the usual beam equation on which we impose hinged-hinged boundary conditions (in presence of coupling); the ball follows the usual parabolic trajectory. We begin by exploring the case of a static beam, in which case a manifold of periodic solutions exists when the ball falls from rest at any point on the beam. Figure 1(a) shows the horizontal position of the ball as a function of time and figure 1(b) shows the mass trajectory (red line) for the periodic solution with initial condition at $x_0 = 0.2$.

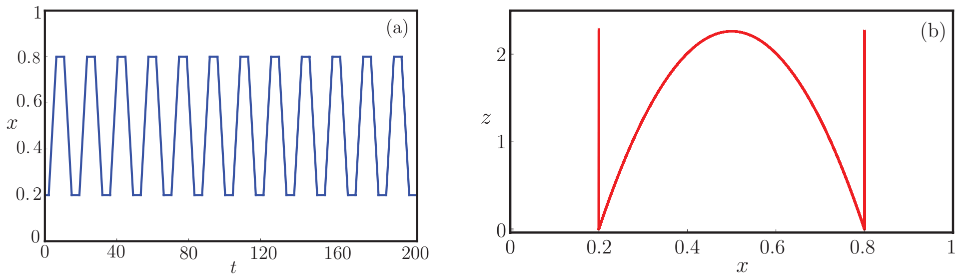

Figure 1: (a) Horizontal coordinate of the mass $x(t)$ for the case of a static beam with $x_0 = 0.2, h = 2.27243$ and (b) trajectory of the mass (red line), $(x(t), z(t))$.

In the following step, we consider a beam vibrating with a known time dependence and with a given frequency, (either taken as a free parameter or coincident with one of the beam's eigenfrequencies). We see that orbits starting close to a given periodic orbit remain close to it. Suitable phase-space projections show evidence of multiple periodic motion in a wide range of the beam's frequency. Finally, we examine the case of a fully coupled system, in which the vibration modes of the beam are affected by the impacts.

References

[1] *Demeio, L., and Lenci, S., Dynamic analysis of a ball bouncing on a flexible beam, J. of Sound and Vibration,* **441**, *page 152-164 (2018).*

Condition monitoring of wind turbine gearboxes through on-site measurement and vibration analysis techniques

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Keywords: wind energy, vibration, condition monitoring

Condition monitoring of wind turbine gearboxes has attracted an impressive amount of attention in the wind energy literature [1]. This happens on one side for practical issues: it is estimated that wind turbines unavailability time is of the order of the 3% of the lifetime [2] and that gearbox damages account for at least the 20% of it. On the other side, the condition monitoring of gear-based mechanical systems undergoing non-stationary operation is scientifically challenging.

On these grounds, the present work is devoted to the diagnosis of gearbox damages through a novel approach, designed exclusively for this study, based on on-site measurements and data post-processing. The main point of this method is the relatively easy repeatability, also for wind turbine practitioners, and its low impact on wind turbine operation: actually, the measuring site is not the gearbox, but it is instead the tower. Longitudinal and transversal accelerations are measured inside the tower at 7 and 2 meters above the ground.

A real test case has been considered: a multi mega-watt wind turbine sited in Italy and owned by the Renvico company (www.renvicoenergy.com). Measurements have been collected at the target wind turbine, where the fault was supposed (on the grounds of oil particle counting) to be occurring, and at two reference wind turbines, that were supposed to be healthy. The data have been subsequently processed through a multivariate Novelty Detection algorithm in the feature space. The application of this algorithm is justified by univariate statistical tests of variance (ANOVA) on the time-domain features selected (root mean square, skewness, kurtosis, peak value, crest factor) and by a visual inspection of the dataset via Principal Component Analysis.

The main result of this work is that the novelty index [3] based on time-domain features (as for example the Mahalanobis distance), computed from the accelerometric signals acquired inside the turbine tower, proves to be suitable to highlight a damaged condition in the wind turbine gearbox, which can be then successfully monitored.

This system is non-invasive with respect to wind turbine operation and the results of this study support that it can, in principle, enable to monitor also the damage evolution in time, establishing the foundations for further works on prognostics, which could optimize the wind turbines maintenance regimes, ensuring higher reliability and minimal down times.

References

[1] *Feng, Y., Qiu, Y., Crabtree, C.J., Long, H., Tavner, P.J. "Monitoring wind turbine gearboxes", Wind Energy,* **16(5)**, *728-740*

[2] *Tchakoua, P., Wamkeue, R., Ouhrouche, M., Slaoui-Hasnaoui, F., Tameghe, T.A., Ekemb, G. "Wind turbine condition monitoring: State-of-the-art review, new trends, and future challenges", Energies,* **7**, *25952630*

[3] *Worden, K., Manson, G., Fieller, N.R.J. "Damage detection using outlier analysis", Journal of Sound and Vibration,* **229(3)**, *647667*

A procedure for Damage Identification in a steel truss

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Keywords: Damage identification, Steel structures, Stochastic Subspace Identification

Vibration based damage detection methods are typically used in Structural Health Monitoring to keep track of the deterioration and identify the presence of damage in civil structures by monitoring features extracted from their vibration response [1-3].

This paper addresses the problem of identifying structural damage affecting one element of a steel truss. The purpose is to detect damages and defects in relation to their magnitude, location and extension. A planar model of a damaged steel truss is used to illustrate the procedure.

The direct problem is addressed by FEM, proposing the local stiffness of a damaged truss element. A modal identification was first implemented to obtain dynamic characteristics: natural frequencies, damping ratio and mode shape. The global modes were identified by operative modal analysis (OMA).

Damage is described as a reduction of the truss cross section, and defined in terms of its magnitude, extent and position. Moreover, a damaged element stiffness matrix has been derived and implemented within of a classical FEM procedure to obtain a numerical model used to generate a pseudo-experimental dynamic structural response under environmental noise. Then, an Output-only modal analysis (Stochastic Subspace Identification [4]) will be carried out to extract and identify the main modal parameters related to both damage and undamaged truss system. Damage index will be defined to evaluate the effectiveness of the proposed procedure.

References

[1] C. Zhang, L. Cheng, J. Qiu, H. Ji, J. Ji, Structural damage detections based on a general vibration model identification approach, *Mechanical System and Signal Processing*, 123, 316-332, 2019.

[2] F. Magalhaes, A. Cunha, E. Caetano, Vibration based structural health monitoring of an arch bridge: From automated OMA to damage detection, *Mechanical Systems and Signal Processing*, 28, 212-228, 2012.

[3] M. Dohler, F. Hille, L. Mevel, W. Rucker, Structural health monitoring with statistical methods during progressive damage test of S101 Bridge. *Engineering Structures*, 69, 183-193, 2014.

[4] A. Deraemaeker, E. Reynders, G. De Roeck, J. Kullaa, Vibration-based structural health monitoring using output-only measurements under changing environment. *Mechanical Systems and Signal Processing*, 22, 34-56, 2008.

Stability analysis of parametrically excited gyroscopic systems

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Keywords: stability, Floquet theory, gyroscopic effects, Timoshenko beam.

Stability analysis of parametrically excited gyroscopic systems is a topic of both theoretical interest and practical importance in rotor dynamics. The role played by gyroscopic terms in this problem, however, has not been deeply investigated yet: actually, most studies that can be found in the literature contain wrong conclusions (periodic critical solutions with destabilizing effects caused by gyroscopic terms, as for instance in [1, 2]), due to an improper application of classical Bolotin's method [3]. In the present work, therefore, a novel contribution is given aimed at clarifying gyroscopic effects on the stability of parametrically excited rotor systems, also considering and analysing the contextual and not negligible role played by both external (non– rotating) and internal (rotating) damping distributions.

As case–study giving rise to a set of coupled differential Mathieu–Hill equations with both gyroscopic and damping terms, a balanced shaft is considered, modelled as a spinning Timoshenko beam loaded by oscillating axial end thrust and twisting moment, carrying additional inertial elements. After discretization of the equations of motion into a set of coupled ordinary differential Mathieu–Hill equations, stability of Floquet solutions is studied via harmonic balance method [4]. A numerical algorithm is then developed for computing global stability thresholds in presence of both gyroscopic and damping terms. The adopted formulation and numerical algorithm are suitable for application to a more general category of gyroscopic systems, including complex shape rotors in those cases in which properly condensed finite element models are available.

The influence on stability of the main characteristic parameters of the shaft is analyzed with respect to frequency and amplitude of the external loads on stability charts in the form of Ince–Strutt diagrams. As a result, it has been demonstrated that gyroscopic terms produce substantial differences in both critical solutions and stability thresholds: the former are generally non–periodic limited–amplitude functions, and modifications induced on stability thresholds consist of shifts and merging of unstable regions, depending on the separation of natural frequencies into pairs of forward and backward values.

References

[1] *Ng Y.T., Lam K.Y., Reddy J.N. Parametric resonance of a rotating cylindrical shell subjected to periodic axial loads, Journal of Sound and Vibration 214-3 (1998): 513–529.*

[2] *Liew K.M, Hu Y.G., Ng T.Y., Zhao X. Dynamic stability of rotating cylindrical shells subjected to periodic axial loads, International Journal of Solids and Structures 43 (2006): 7553– 7570.*

[3] *Bolotin V.V. The dynamic stability of elastic systems. Holden–Day, San Francisco, 1964.*

[4] *Yakubovich V.A., Starzhinskii V.M. Linear differential equations with periodic coefficients. Wiley, New York, 1975.*

The relaxation function in viscoelasticity: some non-classical thermodynamically admissible examples

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Keywords: Materials with memory, Viscoelasticity, Regular and singular relaxation functions

The model of viscoelastic body is considered. Specifically, a body is termed *viscoelastic* whenever its mechanical response is determined not only by the present status but also on its past *history*. The *classical* viscoelasticity evolution problem is modelled via the linear integro-differential equation

$$u_{tt} = G(0)u_{xx} + \int_0^t \dot{G}(t-\tau)u_{xx}(\tau)d\tau + f, \tag{1}$$

in which the kernel G represents the relaxation function, u indicates the displacement while the history of the material as well as an external force, if present, are included in the term f. The classical model, when a one-dimensional isotropic and homogeneous viscoelastic body is considered, prescribes that the kernel G satisfies the conditions:

$$G \in L^1(0,T) \cap C^2(0,T), \quad \dot{G} \in L^1(\mathbb{R}^+) \ , \ G(t) = G_0 + \int_0^t \dot{G}(s)\, ds \ , \ G(\infty) = \lim_{t\to\infty} G(t) \tag{2}$$

where $G(\infty) > 0, \dot{G}(t) < 0, \ddot{G}(t) > 0, \forall t > 0$. The attention is focussed on the relaxation function G aiming to consider cases in which requirements it satisfies are weaker than (2).

Specifically, the case of G unbounded at the initial time $t = 0$ when $\dot{G} \notin L^1(\mathbb{R}^+)$ is studied [1, 2, 3]. When a magneto-viscoelasticity material is considered, coupling the magnetic effects with the viscoelastic behaviour, both the regular classical case [4, 5] as well as the singular one [7] are considered. A different generalisation of interest is G continuous, but not derivable [6].

References

[1] S. Carillo, V. Valente and G. Vergara Caffarelli, *A linear viscoelasticity problem with a singular memory kernel: an existence and uniqueness result*, D.I.E., **Vol. 26**, pp. 1115-1125, (2013).

[2] S. Carillo, *Singular kernel problems in materials with memory*, Meccanica, **Vol. 50**, pp. 603-615, (2015).

[3] S. Carillo, *A 3-dimensional singular kernel problem in viscoelasticity: an existence result*, Atti Accad. Peloritana Pericolanti, Cl. Sc. Fis., Mat. e Nat., **Vol. 96** (S2), A1 (2018).

[4] S. Carillo, V. Valente, G. Vergara Caffarelli, *A result of existence and uniqueness for an integro-differential system in magneto-viscoelasticity*, Appl. Anal.,**Vol. 90**, pp. 1791-1802, (2011).

[5] S. Carillo, V. Valente, G. Vergara Caffarelli, *An existence theorem for the magneto-viscoelastic problem* Disc. Cont. Dyn. Sys. S. , **Vol. 5 (3)**, pp. 435-447 (2012).

[6] S. Carillo, M. Chipot, V. Valente, G. Vergara Caffarelli, *On weak regularity requirements of the relaxation modulus in viscoelasticity*, arXiv:**1811.06723**, (2019).

[7] S. Carillo, M. Chipot, V. Valente, G. Vergara Caffarelli, *A magneto-viscoelasticity problem with a singular memory kernel*, Non Anal. B: Real World App., **Vol. 35C**, pp. 200-210 (2017).

An efficient computational strategy for nonlinear time history analysis of seismically base-isolated structures

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Keywords: time-integration method, phenomenological model, base-isolated structure

Nonlinear time history analysis represents the most appropriate structural analysis procedure to accurately analyze seismically base-isolated structures since their dynamic response is typically governed by a system of coupled nonlinear ordinary differential equations of the second order in time [1]. The selection of a suitable time integration method, required to numerically integrate the nonlinear equilibrium equations, as well as of a phenomenological model, required to accurately describe the hysteretic behavior of each seismic isolation bearing, plays a crucial role in performing such analyses. Indeed, both the time integration method and the phenomenological model directly affect the accuracy of the results and the computational burden of the analyses. This paper proposes an efficient computational strategy obtained by combining an explicit structure-dependent time integration method and a novel phenomenological model. In particular, the proposed time integration method, belonging to the Chang's family of explicit methods [2], has excellent accuracy and stability properties, does not require iterative procedures and, consequently, does not suffer from convergence issues. The proposed hysteretic model, belonging to the more general class of uniaxial phenomenological models developed by Vaiana et al. [3], has an algebraic nature since the device restoring force, representing the output variable of the model, is computed by solving an algebraic equation; in addition, it is based on a set of only three parameters having a clear mechanical significance, and it can be easily implemented in a computer program. Numerical accuracy and computational efficiency of the proposed computational strategy are assessed by performing several nonlinear dynamic analysis on base-isolated structures and comparing the results with those obtained by employing the Newmark's constant average acceleration method and the celebrated Bouc-Wen model [4].

References

[1] *Wilson, E., Three-Dimensional Static and Dynamic Analysis of Structures, 3rd edn., Computers and Structures Inc, Berkeley, CA, USA (2002).*

[2] *Chang, S-Y., Family of structure-dependent explicit methods for structural dynamics, Journal of Engineering Mechanics, ASCE,* **140***(6), page 1-7 (2014).*

[3] *Vaiana, N., Sessa, S., Marmo, F. and Rosati, L., A class of uniaxial phenomenological models for simulating hysteretic phenomena in rate-independent mechanical systems and materials, Nonlinear Dynamics,* **93***(3), page 1647-1669 (2018).*

[4] *Nagarajaiah, S., Reinhorn, A.M. and Constantinou, M.C., Nonlinear dynamic analysis of 3-D base-isolated structures, Journal of Structural Engineering, ASCE,* **117***(7), page 2035-2054 (1991).*

Assessing the sensitivity on state-space variables through anisometric integrity measures

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Keywords: Basins of attraction, dynamical integrity, anisometric measures.

The description of the local behaviour through estimation of equilibria and their eigenvalues, Lyapunov exponents and bifurcation analyses does not suffice to unveil the nature of a system with competing solutions. Indeed, the possible occurrence of multistability requires the computation of basins of attraction, by definition, the sets of possible initial conditions assuring specific responses [1]. However, the computation of basins of attraction is useless without classifying and quantifying both size and shape of the domains. In this perspective, the meaning of the dynamic integrity is to predict the robustness of the attractors by means of different measures applied to their respective basins. Coexisting in-well and out-of-well bounded solutions interacts bringing to a mutual erosion of basins. Thus, a basin loses its safety, i.e. a desired dynamical response, if it presents a highly intertwined structure and/or it is characterized by fractal boundaries.

In order to improve and generalize the more adopted existing integrity measures, namely the local integrity measure and the integrity factor, their anisometric conjugates have been recently introduced [2]. Non-equidistant measures account for inhomogeneous sensitivities of the dynamical system to the state-space variables. Perturbations act differently between different coordinates in phase-space, e.g. a more pronounced susceptibility can be observed on velocity rather than to displacement. Standard integrity measures fail to catch this sensibility leading less confident and targeted identification of safe regions. Anisometric measures require anisometric parameters. They are ratios between the sensibilities along different directions on the phase-space. The anisometric parameters can be a priori fixed or can be deduced from the analysis of basins. The latter approach requires a large computational effort and an ad hoc efficient hybrid-parallel implementation. Nevertheless, it resolves for the different sensitivity of the system to specific perturbations as result of the evolution of anisometric parameters.

This work aims at extracting useful information on the stability of a Duffing-like oscillator by performing multiple anisometric integrity measures. We found that the rate of change of the safe area in the anisometric parameter is an index of interwinding tongues. Furthermore, the sequential evaluation of anisometric integrity measures provides useful insights on the conformation of the phase-space whereas sudden variations of the anisometric grade predicts the change in the orientation of the basin.

References

[1] *Chudzik, A., Perlikowski, P., Stefanski, A., and Kapitaniak, T., "Multistability and rare attractors in Van der Pol-Duffing oscillator", International Journal of Bifurcation and Chaos,* ***21****:1907–1912, (2011).*

[2] *Belardinelli, P., Lenci, S., and Rega, G., "Seamless variation of isometric and anisometric dynamical integrity measures in basins's erosion", Communications in Nonlinear Science and Numerical Simulation,* ***56****:499–507, (2018).*

Mechanical energy transport and acoustic wave polarization in beam lattices through asymptotic perturbation methods

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Keywords: beam lattice, energy transport, perturbation methods.

The free propagation of elastic waves through periodic microstructures is generally accompanied by a transfer of mechanical energy [1]. The present study focuses on the energy transport related to dispersive waves propagating through the bidimensional microstructure of non-dissipative beam lattices [2]. The dynamic equations governing the linear dynamics of the periodic cell are reduced to the minimal space of lagrangian nodal coordinates. Within the framework of linear elasticity, multi-coupled interactions among adjacent cells are considered [3]. The linear eigenproblem characterizing the free undamped propagation of harmonic wave is formulated according to the Floquet-Bloch theory. The complete eigensolution associates the real-valued dispersion functions of the propagating elastic waves with the corresponding complex-valued waveforms. First, nondimensional quantities (*polarization factors*) are introduced to qualitatively distinguish and quantitatively assess the linear wave polarization, according to a proper energetic criterion [4]. Second, a vector variable related to the periodic cell is presented to describe the directional flux of mechanical energy, in analogy to the Umov-Poynting vector related to the material point in solid mechanics [5]. The physical-mathematical relations among the energy flux, the velocity of the energy transport and the group velocity are recognized. A multiparametric perturbation methods is employed to asymptotically approximate the wave polarization factors and the mechanical energy fluxes, up to the desired approximation order and independently of the model dimension. Finally, all the theoretical developments are successfully applied to the prototypical beam lattice characterized by a periodic tetrachiral microstructure. The possible physical occurrence and the proper mathematical treatment of pathological conditions (singularities) in the perturbation based solutions are discussed both for the fundamental dispersion properties (frequencies and waveforms) and for the derived dispersion quantities (energy fluxes and velocities).

References

[1] Biot, M.A., "General theorems on the equivalence of group velocity and energy transport" Physical review ***105****(4), pp.1129-1137 (1957).*

[2] Langley, R., "A transfer matrix analysis of the energetics of structural wave motion and harmonic vibration" Proc. of the Royal Society of London A ***452****(1950), pp.1631-1648 (1996).*

[3] Romeo, F., Luongo, A. "Invariant representation of propagation properties for bi-coupled periodic structures," Journal of Sound and Vibration, ***257****(5), 869-886 (2002).*

[4] Gattulli, V., Lepidi, M., "Localization and veering in the dynamics of cable-stayed bridges." Computers & Structures, ***85****(21-22), pp.1661-1678 (2007).*

[5] Bacigalupo, A., Lepidi, M., "Acoustic wave polarization and energy flow in periodic beam lattice materials" Int. J. Solids and Structures, ***147****, pp.183-203 (2018).*

Diffusion in finely mixed materials, the role of Fokker-Planck and Fick laws

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Keywords: Fick's diffusion law; Fokker-Planck diffusion law; homogenization

Diffusion in inhomogeneous media is often modeled by means of Fick's equation

$$c\frac{\partial u}{\partial t} = \nabla \cdot (D(x)\nabla u)\,, \tag{1}$$

where u is the scalar density field and D is the diffusivity coefficient, that is a positive scalar or more in general a matrix. The coefficient $c > 0$ represents a capacity. It is known in the literature [1,2] that an alternative, in some cases closer to physical reality, is Fokker-Planck's equation

$$c\frac{\partial u}{\partial t} = \nabla \cdot \nabla(D(x)u)\,. \tag{2}$$

In this talk, we report on some recent results concerning the interplay of the two models in cases when they interact in a finely mixed environment. This means that the the regions where either equation applies are interspersed, and however the coefficients D and c may oscillate. Our approach essentially relies on the methods of homogenization theory of partial differential equations and is aimed at gaining a clearer insight on the applicability of the two models.

References

[1] *Andreucci, D., Cirillo, E.N.M., Gabrielli D., Colangeli M., "Fick and Fokker-Planck Diffusion Law in Inhomogeneous Media" Journal of Statistical Physics,* **174***, page 469–493 (2019).*

[2] *van Milligen, B.Ph., Bons, P.D., Carreras, B.A., Sánchez, R.: On the applicability of Fick's law to diffusion in inhomogeneous systems. Eur. J. Phys.* **26***, page 913-–925 (2005).*

Rubber-Layer Roller Bearings (RLRB) for base isolation: the non-linear dynamic behavior

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Keywords: *non-linear vibrations, viscoelastic damping, rolling contact.*

In this study we focus on the non-linear dynamic behavior of a two degree of freedom mechanical system, in which a simple superstructure (mass-spring system) is subjected to seismic base excitation. In order to provide a certain degree of base isolation, a non-linear viscoelastic Rubber-Layer Roller Bearing (RLRB) [1] is interposed between the ground and the superstructure (see Fig. 1). The viscoelastic contact mechanics between the rigid cylinders and the rubber layer is firstly investigate, allowing to determine the non-linear damping behavior of the RLRB device. Then, the non-linear dynamics of the whole system is studied in the framework of periodic excitations. We show the effect of both the excitation frequency, the relaxation time of the RLRB viscoelastic material, and the rigid cylinder distance. Indeed, depending on the specific parameters, the operating condition of the system may lay on the descending portion of the damping curve, thus entailing strongly non-linear vibrational behavior. Moving from these results, we performed an extensive study by reproducing numerically the ground vibration of the Central Italy 2016 earthquake main shock [2]. By opportunely tuning the viscoelastic and geometrical parameters of the RLRB device, we optimized the RLRB damping behavior with respect to the maximum value and root-mean-square value of the absolute acceleration of the superstructure. Further, by comparing the non-linear system performance to that of an equivalent linear system (where the non-linear viscoelastic rolling damping is replaced by a linear viscous one), we show that significantly advantages can be achieved by relying on non-linear RLRB damping.

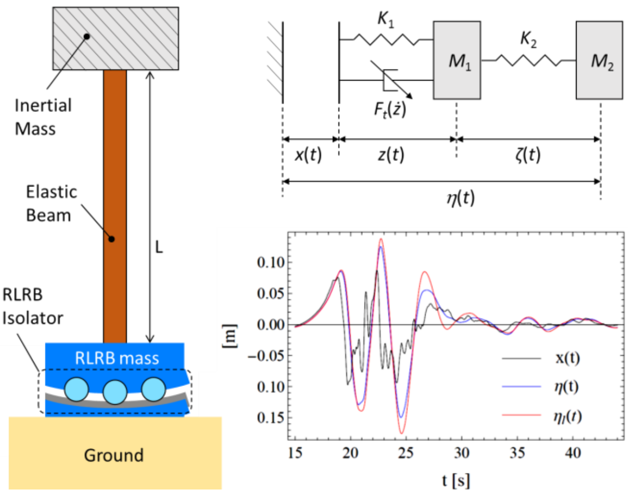

Figure 1 – The physical and lumped parameters systems, together with the optimized superstructure displacement

References
[1] *Menga, N., Foti, D., & Carbone, G. (2017). Viscoelastic frictional properties of rubber-layer roller bearings (RLRB) seismic isolators. Meccanica, 52(11-12), 2807-2817.*
[2] *Istituto Nazionale di Geofisica e Vulcanologia. Website: http://itaca.mi.ingv.it/ - Event ID: 20161030_0000029*

A closed form solution for the buckling of orthotropic Reddy plate and prismatic plate structures

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Keywords: Piola- Kirchhoff stress tensor, Stability Reddy plate, Levy-type approach.

A closed-form solution based on the Reddy third-order shear deformation plate theory is proposed for the buckling of both flat and stiffened plates, with simply supported on two opposite edges. The equations governing the critical behaviour considering the full Green-Lagrange strain tensor and the second Piola-Kirchhoff stress tensor are derived using the principle of minimum potential energy. The general Levy-type approach is employed, and the accuracy and effectiveness of the proposed formulation is validated through direct comparison with analytical and numerical results available in the literature. The parametric analyses performed for different geometrical ratios show that the von Kármán hypothesis holds only for thin flat plates whereas it can significantly overestimate buckling loads for stiffened plates, for which the buckling mode entails comparable in-plane and out-of-plane displacements.

References

[1] Reddy, JN. Theory and Analysis of Elastic Plates and Shells. 2nd ed. Boca Raton: CRC Press, FL. 2007.

[2] Reddy JN. A simple higher-order theory for laminated composite plates, Trans. ASME J. Appl. Mech. 51, 1984: 745–752.

[3] Ruocco E, Mallardo V. Buckling analysis of Levy-type orthotropic stiffened plate and shell based on different strain–displacement models. Int J Non-Linear Mech 50, 2013: 40–47.

[4] Ruocco E, Reddy JN. Shortening Effect on Buckling Behavior of Reddy Plates and Prismatic Plate Structures,Int J Struct Stab and Dynamics 4, 2019:1-21

A probabilistic framework for non-linear dynamic seismic risk assessment of historic non-isolated masonry towers

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Keywords: non-linear dynamic, probabilistic framework, masonry towers.

A great part of the Italian built heritage is constituted of historic masonry towers. Such structures, due to their intrinsic slenderness, are prone to seismic risk and, like every historic structure, exhibit many constructive aspects which are difficult to be estimated from a numerical point of view. Among the most common: the restraint condition at their base is not exactly clear as they are often embedded in other buildings (such as churches bell-towers); the material behavior can't be simply identified as the masonry walls are often multi-leaf, made of three layers, each one with different mechanical characteristics, etc. In this paper, with the aim to include most of the sources of uncertainties, to assess the seismic risk of historic masonry towers a probabilistic approach is presented. The probabilistic framework, originally introduced by Gusella [1], is herein discussed through a specific case study: the Torre Grossa of San Gimignano [2].

In a first part of the paper some experimental results, accelerations of some level of the tower under ambient noise, are employed to identify a numerical model. Subsequently the identified numerical model is employed to perform non-linear time history analyses which constitute the basis for the evaluation of the tower collapse probability.

References

[1] *Gusella V. Structural failure and stochastic discrete process of random events. An application to seismic vulnerability analysis of an historic building. Structural Safety 1991; 11:13-28.*
[2] *Bartoli G., Betti M., Giordano S. In situ static and dynamic investigations on the "Torre Grossa" masonry tower. Engineering Structures 2013; 52: 718-733.*

Analytic frequency-response curves of a novel geometrically exact beam model

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Keywords: Geometrically exact beam, frequency-response curves, method of multiple scales.

With the aim to answer to the question about what is the correct notion for curvature to adopt in constitutive relationships, a geometrically exact beam model is deduced in [1] by stipulating a relation between one- and three-dimensional formulations, and the possibility to derive a hierarchy of approximated models from it is explored in [2]. A simplified model concerning only transverse displacements is analyzed in [3] and a total lagrangian finite element approach is proposed in [4] to numerically integrate the whole set of partial differential equations of motion. The present contribution, following [5], is focused on analytical developments, based on the method of multiple scales [6]. In particular, to draw the frequency-response curves, the exact partial differential equations are analyzed around frequencies corresponding to certain natural bending modes. Findings, whenever possible, are compared with existing literature results.

References

[1] E. Babilio and S. Lenci. On the notion of curvature and its mechanical meaning in a geometrically exact plane beam theory. *Int J Mech Sci*, 128-129:277–293, 2017.

[2] E. Babilio and S. Lenci. The role of parameters of smallness in deduction of approximated theories for deterministic dynamics of beams. *MATEC Web Conf*, 83, 2016.

[3] E. Babilio and S. Lenci. Consequences of different definitions of bending curvature on nonlinear dynamics of beams. *Procedia Eng*, 199:1411–1416, 2017.

[4] E. Babilio and S. Lenci. A simple total-lagrangian finite-element formulation for nonlinear behavior of planar beams. *Proc ASME Des Eng Tech Conf*, 2018. DETC2018-85622. Quebec City, Quebec. August 26-29, 2018.

[5] L. Kloda, S. Lenci, and J. Warminski. Nonlinear dynamics of a planar beamspring system: analytical and numerical approaches. *Nonlinear Dynamics*, 94(3):1721–1738, 2018.

[6] A.H. Nayfeh. *Perturbation methods*. Physics textbook. John Wiley & Sons, 2000.

Dynamic analysis of tower buildings based on a reduced-order Timoshenko beam model

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Keywords: Modal properties, Timoshenko beam, Tower buildings.

Tower buildings are very complex systems from a structural point of view. Their detailed design requires the formulation of three-dimensional (3-D) finite element models. Mono-dimensional reduced models are extremely useful in the preliminary design of a new building, as well as for a simplified assessment of the building performances (e.g., wind-induced response). Based on reduced models, simplified analytical procedures for the estimate of their modal properties have been proposed in the literature [1, 2, 3].

The authors have introduced an equivalent shear-shear-torsional beam model able to reproduce, in an approximate way, the dynamic behaviour of 3-D shear-type structures [4, 5]. However, slender buildings may involve significant global flexural deformation. Thus, a continuous equivalent Timoshenko linear beam model embedded in a 3-D space has been recently formulated [6]. The constitutive law of the beam is defined based on the equivalence of the elastic energy of the building generic cell with the strain energy of the equivalent Timoshenko beam. A coupled elastic law is thus obtained, with coefficients defined as functions of the stiffness of the different elements connecting the rigid floors delimiting the sample cell. The proposed equivalent model is able to describe mixed behaviours, including Euler-Bernoulli and shear-type models as limit cases.

In this paper, the ability of the equivalent Timoshenko beam model in reproducing the dynamic characteristics of tower buildings, including natural frequencies and mode shapes, is investigated. Dealing with symmetric structures, the modal properties of the equivalent beam are estimated analytically. When the disposal of the resisting elements is non-symmetric, the boundary value problem for the modal analysis of the equivalent beam is solved numerically. The dynamic characteristics of the equivalent model are compared with numerical results from detailed finite element models of the building.

References

[1] *Chajes, M.J., Zhang, L., and Kirby, J.T. "Dynamic analysis of tall building using reduced-order continuum mode," Journal of Structural Engineering ASCE, **122(11)**, 1284-1291 (1996).*

[2] *Zalka, K.A. "A simplified method for calculation of the natural frequencies of wall-frame buildings," Engineering Structures, **23(12)**, 1544-1555 (2001).*

[3] *Malekinejad, M., Rahgozar, R. "A simple analytic method for computing the natural frequencies and mode shapes of tall buildings," Applied Mathematical Modelling, **36**, 3419-3432 (2012).*

[4] *Piccardo, G., Tubino, F. and Luongo, A., "A shear–shear torsional beam model for nonlinear aeroelastic analysis of tower buildings." Z. Angew. Math. Phys. (ZAMP), **66(4)**, 1895-1913 (2014).*

[5] *Piccardo, G., Tubino, F. and Luongo, A. "Equivalent nonlinear beam model for the 3-D analysis of shear-type buildings: Application to aeroelastic instability," Int. J. Nonlinear Mech., **80**, 52-65 (2016).*

[6] *Piccardo, G., Tubino, F. and Luongo, A. "Equivalent Timoshenko linear beam model for the static and dynamic analysis of tower buildings," Applied Mathematical Modelling, **71**, 77-95 (2019).*

On the influence of drag force modeling in long-span suspension bridge flutter analysis

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Keywords: aeroelastic flutter; suspension bridge; Akashi Kaikyo bridge.

Flutter stability analysis of long-span bridges is usually conducted as a damped complex eigenvalue analysis, where the aeroelastic (self-excited or motion-dependent) forces acting on the bridge deck are expressed as linear functions of deck's displacements and velocities [1]. In most practical applications, among the general three aeroelastic forces of drag, lift, and pitching moment, only the latter two are of interest, the former being of little importance for dynamic stability. However, it has been shown [2] that, for very long-span bridges like the case of the Akashi Kaikyo bridge – the current world record for a single span – all the three components must be taken into account to correctly predict the flutter wind velocity.

The present study aimed at investigating the role played by the description of the drag component on the predicted flutter velocity (and frequency) of very long-span suspension bridges. The Akashi Kaikyo bridge was selected as a benchmark. To the purpose, a detailed finite element model of the central span of the bridge was implemented in ANSYS. The user-defined element *Matrix 27* [3] was incorporated in the model to define the nodal aeroelastic forces by means of element aerodynamic stiffness and damping matrices. Flutter analyses were thus run considering the following descriptions of the wind aerodynamic actions:

1) lift, moment and drag all unsteady (motion-dependent);
2) lift and moment unsteady, drag steady (motion-independent);
3) lift and moment unsteady, no drag.

The finite element results were compared with those obtained by an *in-house* MATLAB code based on a semi-analytic continuum model. The latter includes flexural-torsional second-order effects induced by steady drag force in the bridge equations of motion, in addition to the unsteady lift and moment actions.

For the analyzed case, the results confirmed that including the drag force is, in facts, necessary to correctly estimate the flutter velocity, but also indicated that good predictions can be obtained by combining steady drag together with unsteady lift and moment: in fact, flutter analyses in the cases 1) and 2) gave comparable results.

References

[1] *Scanlan, R.H., "Developments in aeroelasticity for the design of long-span bridges", in: T. Miyata, et al. (Eds.), Long-Span Bridges and Aerodynamics, Proceedings of the International Seminar Bridge Aerodynamics Perspective, Kobe, March 1998, Springer, Tokyo (1999).*

[2] *Miyata, T., et al., "New findings of coupled-flutter in full model wind tunnel tests on the Akashi Kaikyo Br.", Proceedings of the International Conference on Cable-Stayed and Suspension Bridges, Vol. 2, Deauville, France (1994).*

[3] *Hua, X.G., et al., "Flutter analysis of long-span bridges using ANSYS", Wind and Structures, **10**(1), 61-82 (2007).*

On the influence of the wind static force on linear galloping of shallow flexible cables

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Keywords: Cables, galloping, static swing

The linear aeroelastic behavior of horizontal, suspended, shallow, iced cables is analyzed via a continuous model taking into account both external and internal damping [1, 2]. Quasi-steady aerodynamic forces are considered, including the static contribution (i.e., mean wind force). This latter induces a rotation of the cable (static swing) around the line connecting the suspension points, together with a deformation of the initial equilibrium profile under self-weight [3].

First, by using perturbation methods, the nontrivial equilibrium configuration is determined as a nonlinear function of the wind velocity. Then, the motion is linearized around the nontrivial equilibrium and, consequently, the spectral properties of the cable, as modified by the static forces, are analyzed by exactly solving a coupled boundary value problem. In particular, the behavior of the cable close to the crossover points is investigated. Finally, the wind critical value at which bifurcation takes place is determined by solving a boundary value problem in the complex field.

Numerical investigations are carried out to detect the influence of the static force on the aeroelastic phenomenon, both in non-resonance and in-resonance cases.

References

[1] *Foti, F. and Martinelli, L., "A unified analytical model for the self-damping of stranded cables under aeolian vibrations", Journal of Wind Engineering and Industrial Aerodynamics,* **176***, 225-238 (2018).*

[2] *Ferretti M., Zulli D. and Luongo A., "A continuum approach to the nonlinear in-plane galloping of shallow flexible cables", Advances in Mathematical Physics, Article ID 6865730 (2019).*

[3] *Luongo A., Zulli D. and Piccardo G., "A linear curved-beam model for the analysis of galloping in suspended cables", Journal of Mechanics of Materials and Structures,* **2***(4), 675-694 (2007).*

Experimental study on large amplitude vibrations of a circular cylindrical shell subjected to thermal gradients.

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Keywords: shells, nonlinear vibrations, thermal gradients

The large amplitude vibrations of thin polymeric cylindrical shell subjected to thermal gradient across the thickness direction are experimentally analyzed. The temperature gradient effects on the shell dynamic behavior are investigated.

Shells are widely used in many fields of Structural Engineering. In the middle of the XX century, in particular thanks to the aerospace industry, a great effort was done in order to understand the dynamic behavior of this kind of structures (see [1]). Recent works on shells, such as [2], confirm the great interest of the scientific community on that complex subject, that is far from being fully known.

In this paper, taking advantage of the test setup and findings of [3-5], a shell that carries a top mass and clamped on its base, has been harmonically excited in the longitudinal direction.

When the structure is axially excited by a harmonic forcing with forcing frequency close to the natural frequency of the first axisymmetric vibration mode, the interaction between the top mass and the shell leads to a parametric excitation and instability arises: a severe top mass dynamic phenomena occurs (saturation of the axial acceleration) and large lateral vibrations take place (see [6]).

The aim of the present research is to clarify the role of the temperature gradient in emphasizing the nonlinear dynamics of the shells when subjected to a resonant forcing.

References

[1] A. W. Leissa, Vibration of Shells. Washington, D.C.: Governament Printing Office, 1993.

[2] M. Amabili, Nonlinear mechanics of shells and plates in composite, soft and biological materials. Cambridge University Press, 2018.

*cylindrical shell under axial harmonic load", Int. J. Nonlinear Mech., **94**, 417-440 (2017).*

[3] Gelman, L., Harish Chandra, N., Kurosz, R., Pellicano, F., Barbieri, M., Zippo, A., Novel spectral kurtosis technology for adaptive vibration condition monitoring of multi-stage gearboxes, Insight: Non-Destructive Testing and Condition Monitoring, 58 (8), pp. 409-416 (2016), DOI: 10.1784/insi.2016.58.8.409.

[4] Zippo, A., Barbieri, M., Iarriccio, G., Pellicano F., "Nonlinear vibrations of circular cylindrical shells with thermal effects: an experimental study", Nonlinear Dynamics, (in press) (2019). https://doi.org/10.1007/s11071-018-04753-1.

[5] A. Zippo, M. Barbieri, and F. Pellicano, "Temperature gradient effect on dynamic properties of a polymeric circular cylindrical shell," Compos. Struct., 2019. https://doi.org/10.1016/j.compstruct.2019.02.098

*[6] Pellicano, F., Barbieri, M., Zippo, A., Strozzi, M., "Experiments on shells under base excitations", J. Sound Vib., **369**, 209-227 (2016).*

Experimental identification of dynamic properties of a composite plate with smart materials

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Keywords: Experimental, Composite structures, smart materials

Innovations in structures and new materials are nowadays pointing out through lighter structures that are replacing traditional designs and materials: structures made of composite materials and metal alloys are more and more used in many industrial fields from aerospace industry to automotive industry, together with smart materials that allow to control and modify the dynamic properties of the structures as piezoceramic macro fiber composites (MFC) patches or electroactive polymers. Experimental studies in nonlinear dynamics play a key role and have an important implication to validate numerical and theoretical models and to highlight and discover complex behaviors of mechanical systems and structures [1].
The effect of the combination of electroactive polymers within a composite plate has been experimental studied and results will be presented; the incorporation of soft materials [2], like rubbers, biomaterials or polymers, in composite structure makes more important to provide experimental results due to the intrinsic nonlinear properties and their innovative applications. This study profits from previous works and experimental techniques [3-5] investigated by the present research group to deeply analyze the dynamic properties of a composite plate combined with smart materials in three configurations: I) a single carbon fiber composite plate, II) a composite plate with piezoceramic (MFC) actuator and sensor patches and III) a composite plate with MFC patches and variable stiffness polymeric layer. A comparison in the three configurations will be presented and results shown.

References

[1] A. Zippo, G. Ferrari, M. Amabili, M. Barbieri, F. Pellicano, Active vibration control of a composite sandwich plate, Composite Structures, Vol. 128, 2015, Pages 100-114, https://doi.org/10.1016/j.compstruct.2015.03.037.

[2] Marco Amabili, Nonlinear vibrations of viscoelastic rectangular plates, Journal of Sound and Vibration, Volume 362, 2016, Pages 142-156, https://doi.org/10.1016/j.jsv.2015.09.035

[3] Gelman, L., Harish Chandra, N., Kurosz, R., Pellicano, F., Barbieri, M., Zippo, A., Novel spectral kurtosis technology for adaptive vibration condition monitoring of multi-stage gearboxes, Insight: Non-Destructive Testing and Condition Monitoring, 58 (8), pp. 409-416 (2016), DOI: 10.1784/insi.2016.58.8.409

[4] Zippo, A., Barbieri, M., Iarriccio, G., Pellicano F., Nonlinear vibrations of circular cylindrical shells with thermal effects: an experimental study, Nonlinear Dynamics, (in press) (2019). https://doi.org/10.1007/s11071-018-04753-1.

[5] Antonio Zippo, Marco Barbieri, Francesco Pellicano, Temperature gradient effect on dynamic properties of a polymeric circular cylindrical shell, Composite Structures, Vol. 216, 2019, Pages 301-314. https://doi.org/10.1016/j.compstruct.2019.02.098

Vibrations of circular cylindrical shells under random excitation and thermal gradients

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Keywords: Shells, Random vibration, Synchronization

The present paper is focused on the random vibrations of circular cylindrical shells subjected to thermal gradients across the shell thickness; the investigation is fully experimental. The topic is of practical interest in many engineering fields such as: Aerospace, Automotive, Civil, Nuclear. Indeed, in real environments the excitations are likely non deterministic, moreover, extreme thermal conditions can cause differences of temperature inside and outside the shell, e.g. thermal exchangers. Due to the importance of the subject the literature on shell vibration is extremely wide, it is not analyzed here for the sake of brevity; however, it is to note that the number of papers containing experimental results is not large.
When a system is excited with random forcing one generally expects a random response of the system, the statistical properties of the random response are correlated with the forcing through the transfer function in the case of linear systems, or more complicated relationships in the case of nonlinear systems. However, in some particular conditions (e.g. internal resonances, parametric resonances, ...) the presence of a nonlinearity in the systems can give rise to a surprising phenomenon, said synchronicity or entrainment (see [1,2]), which consists in a response made of a combination of random and harmonic signals.
In this work a shell subjected to a random base excitation is analyzed experimentally, the excitation is random (flat or limited frequency band). The work take advantage from previous setup and experimental techniques [3-5] developed by the present research team. The phenomenon of synchronicity is clearly observed for some particular thermal conditions: a strong transfer of energy from a broad band excitation signal to an almost harmonic response is experimentally observed, confirming the general findings of refs. [1,2].

References

[1] *Ibrahim R. A. and Roberts J. W., Broad Band Random Excitation of a two-degree-of-freedom autoparametric coupling, J. of Sound and Vibration 44(3), 335-348 (1976)*
[2] *R. V. Jensen, Synchronization of randomly driven nonlinear oscillators, Physical Review E, 58(6), 6907-6910, 1998.*
[3] *Zippo, A., Barbieri, M., Pellicano, F. Experimental analysis of pre-compressed circular cylindrical shell under axial harmonic load International Journal of Non-Linear Mechanics, 94, pp. 417-440 (2017).*
[4] *Zippo, A., Barbieri, M., Iarriccio, G., Pellicano F., Nonlinear vibrations of circular cylindrical shells with thermal effects: an experimental study, Nonlinear Dynamics, (in press) (2019).* https://doi.org/10.1007/s11071-018-04753-1.
[5] *Gelman, L., Harish Chandra, N., Kurosz, R., Pellicano, F., Barbieri, M., Zippo, A., Novel spectral kurtosis technology for adaptive vibration condition monitoring of multi-stage gearboxes, Insight: Non-Destructive Testing and Condition Monitoring, 58 (8), pp. 409-416 (2016), DOI: 10.1784/insi.2016.58.8.409.*

Perturbation solutions of nonlinear taut strings travelled by a moving force

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Keywords: Moving-load problems, Nonlinear dynamics, Perturbation techniques

Moving-load problems are very important in several engineering systems. The moving force model is still widely used in both scientific and technical field for its relevance and ease of use; it is often sufficient to deal with problems of practical interest. The nonlinear behavior induced by moving loads has been addressed in several areas (e.g, [1], [2]) but rarely for nonlinear taut strings.

The taut string is an idealized model of cable with evanescent sag. It is quite accurate when the natural length of the cable is smaller than the distance between the suspension points (i.e., prestressed cables). In engineering problems the geometric non-linearity of taut strings is usually addressed for specific objectives such as the possibility of overcoming the critical velocity (e.g., [3]), otherwise it is usually neglected. On the other hand, the dynamics of nonlinear strings seems important to applied mathematics (e.g., [4]). Similar problems are dealt with in the field of traveling tensioned strings.

Classic perturbation solutions are able to describe weakly nonlinear dynamics only [5], characterized by low values of the parameters governing the problems, i.e. the coefficient of cable elasticity, the magnitude of the load and its speed. A change of variable involving the nonlinear quasi-static response allows to overcome the problem by defining new equations of motion in an incremental dynamic variable. Fulfilling the hypothesis of loading velocity far enough from the critical value, this work studies the dynamic behavior of the system in terms of the dynamic increment variable, even in the presence of strong nonlinearities, through different time scales (as, e.g., in the Multiple Scale Methods). A perturbation solution in the framework of the WKB approximation is being developed; comparisons with numerical solutions are performing using literature values for the model parameters.

References

[1] *Mamandi, A., Kargarnovin, M., Younesian, D., "Nonlinear dynamics of an inclined beam subjected to a moving load," Nonlinear Dynamics,* **60**, *277-293 (2010).*

[2] *Wang, L., Rega, G., "Modelling and transient planar dynamics of suspended cables with moving mass," International Journal of Solids and Structures,* **47**, *2733-2744 (2010).*

[3] *Gavrilov, S., "Nonlinear investigation of the possibility to exceed the critical speed by a load on a string," Acta Mechanica,* **154**, *47-60 (2002).*

[4] *Kang, Y., Lee, M., Jung, I., "Stabilization of the Kirchhoff type wave equation with locally distributed damping," Applied Mathematics Letters,* **22**, *719-722 (2009).*

[5] *Ferretti, M., Piccardo, G., Luongo, A., "Weakly nonlinear dynamics of taut strings traveled by a single moving force," Meccanica,* **52**, *3087-3099 (2017).*

Vortex-shedding phenomenon of a highly tapered circular cylinder

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Keywords: Vortex-induced vibrations, Wind tunnel experiments, Tapered circular cylinders

Vortex-induced vibrations (VIVs) caused by wind are known since ancient times and constitute the main component of the across-wind response of slender structures. Lock-in phenomenon (e.g., [1]) usually happens in lightweight and low-damped structures, violating the Strouhal law over a specific range of wind speed and leading to oscillations of remarkable amplitude. In 1983 Vickery and Basu [2] proposed a fluid-elastic model able to predict the across-wind response of structures with circular cross-section, successfully reproducing the lock-in phenomenon. This model has subsequently been adopted by several codes of practice to evaluate the structural response to VIV. While this model has been adequately verified for prismatic structures (although considerable uncertainties remain in its application, e.g. [3]), not many are the works focused on tapered structures, including tapered circular cylinders. Concerning realistic Reynolds numbers for civil structures, the most complete and documented work about non-prismatic structures remains the one developed by Vickery and Clark [4] in 1975.

The present paper presents the results of a study conducted on a 1.5 m tall tapered circular cylinder (8% of taper ratio), carried out by both an extensive wind tunnel campaign and through the implementation of a suitable analytical model. The VIV response of the model has been investigated using a purposely mounted accelerometer mounted inside the wind tunnel model, a hot-wire anemometer placed at four different heights in the wake behind the model and through the installation of four rings of pressure sensors around the bottom third of the structure. In uniform smooth flow conditions, the maximum experimental response occurs when the shedding frequency at almost one quarter of the height of the structure is equal to the natural frequency of the model. The measured drag coefficients are lower than values reported in the literature for circular cylinders at those Reynolds numbers. The results are critically discussed and the outcome of a detailed numerical implementation of the Vickery-Basu model [3] – suitably calibrated to simulate the results dictated by the physics of the wind tunnel campaign – is presented.

References

[1]. *Scruton, C. and Flint, A.R., "Wind-excited oscillations of structures" in Proc Inst Civ Eng* ***27*** *(4): 673–702 (1964).*

[2]. *Vickery, B. J. and Basu, R. I., "Across-wind vibrations of structures of circular cross-section. Part I. Development of a mathematical model for two-dimensional conditions", J Wind Eng Ind Aerod 12: 49-73 (1983).*

[3]. *Pagnini, L.C. and Piccardo, G., "A generalized gust factor technique for evaluating the wind-induced response of aeroelastic structures sensitive to vortex-induced vibrations" J. Fluids Struct 70: 181-200 (2017).*

[4]. *Vickery, B. J. and Clark, A. W., "Lift or across-wind response of tapered stacks" J Struct Div-ASCE 98(ST1): 1-20 (1972).*

A simple model for predicting the nonlinear dynamic behavior of elastic systems subjected to friction

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Keywords: non-linear dynamics, stick-slip motion, friction dampers

The stick-slip phenomenon is a jerking motion that may occur when two objects are forced to slide with friction over each other. There are many situations in which this motion can be observed in practice, for example, between the components of different kinds of seismic protection systems, such as the slabs of some friction dampers or the sliding elements of some base isolation systems [1-3]. Such systems are generally designed to work in a smooth and flawless manner. However, it cannot be excluded that in particular situations undesired jerking motions may develop. These kinds of situations are widespread in all areas of engineering and may result in very complex nonlinear dynamic behavior even when only a small number of degrees of freedom are involved.

Over the years, several investigations have been conducted to better understand the dynamic behavior of systems in which two components are forced to slide with friction over each other, the ultimate objective being to identify conditions that may disrupt their proper functioning and optimize their performance. The body of literature on this particular topic may be subdivided into two main categories. The first is represented by numerical studies performed by means of finite element models. The second approach, to which this work belongs, is conducted via simplified models which regard the considered system as a mechanical system endowed with a small number of degrees of freedom.

A simple scheme for problems of this kind consists of a rigid block connected elastically to a rigid support, while its base is in contact with a moving rough surface. Both the support and surface can be assigned a prescribed motion. Despite its apparent simplicity, this model can provide some useful indications on the main features of many interesting physical systems. This contribution illustrates an analytical study conducted to better understand the nonlinear dynamic behavior of systems of this kind, with the objective of identifying the conditions that may disrupt their proper functioning. In particular, the equations of motion are solved analytically, the sticking and sliding phases are studied, the influence on the solution of some of the system main parameters is investigated, and some typical long-term responses of the system are discussed. Lastly, some results obtained by means of an expressly developed numerical procedure are illustrated.

References

[1] Chopra, A.K., "Dynamics of Structures: Theory and Applications to Earthquake Engineering", Prentice Hall Inc, Upper Saddle River, N.J., 4th ed., (2011).

[2] Soong, T.T., Constantinou, M.C., "Passive and active structural vibration control in civil engineering", Springer-Verlag GmbH, Wien, Austria, (1994).

[3] Grigorian, C., Popov, E., "Energy dissipation with slotted bolted connections", Earthquake Engineering Research Center, University of California, Richmond, CA, Report No. UCB/EERC-94/02, (1994).

Substructuring using NNMs of nonlinear connecting elements

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Keywords: Substructure coupling, Nonlinear Normal Modes, Nonlinear connection

Dynamic substructuring represents one of the most used tool in engineering to design very complex structures and, preliminarily, to analyse their response in different situations. This procedure was first outlined by Craig and Bampton [1] and then improved during the following years [2], thus now it can be implemented for the resolution of many kinds of problems, either in coupling of substructures to get the behaviour of the coupled system (direct problem) or in decoupling the whole system to analyse in detail one of its subcomponents (inverse problem). It is very efficient since only the dynamic information of the subsystems at the connecting points are needed to obtain reliable results. Moreover, it allows to represent each substructure with a differet type of model that can be experimental, theoretical or numerical. Classical substructuring methods are well assessed for linear problems. However, in real cases nonlinearities can play a significant role, thus some modifications are necessary to account for the nonlinear behaviour in the substructuring scheme.

The objective of this work is to study what happens when two linear systems are connected through a nonlinear junction, as it can be for two beams with a joint. In order to account for the substructure nonlinearities, Nonlinear Normal Modes (NNMs) are used. They were introduced by Rosenberg [3] and they represent the periodic response of a conservative nonlinear system which is characterized by energy dependent frequency and amplitudes. The proposed method looks for the NNMs of the nonlinear connecting element, and use them to perform a modal reduction of the sustructure. The NNMs of the complete structure are obtained by coupling the two linear substructures with the nonlinear connecting one [4]. This work focuses in analysing lumped parameters models, thus having finite number of linear and nonlinear modes. This model represents a broad range of situations, in which the systems are approximated by a truncated set of modes. Furthermore, some analyses are performed considering more than one connection between the two substructures being coupled. This is closer to the real case considering that in general the conjunction between structures happens in more than one point. The results obtained with this method will be compared with the benchmark data for the complete structure to prove its reliability and efficiency.

[1] R. Craig, M. Bampton, Coupling of substructures for dynamic analysis, AIAA Journal 6 (7).

[2] D. de Klerk, D. J. Rixen, S. N. Voormeeren, General Framework for Dynamic Substructuring: History, Review, and Classification of Techniques, AIAA journal 46 (5).

[3] R. M. Rosenberg, The normal modes of nonlinear n-degree-of-freedom systems, Journal of applied Mechanics 29 (1) (1962) 7–14.

[4] R. J. Kuether, M. S. Allen, Nonlinear modal substructuring of systems with geometric nonlinearities, in: 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 2013, p. 1521.

Flexural torsional buckling of micro-structured beams

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Keywords: Equivalent beam model, Micro-structured beam, Buckling analysis.

A one-dimensional equivalent beam model, embedded in a three-dimensional space, is developed for buckling analysis of beam-like structures [1,2], i.e. grilled cylinder, made by a periodic and specifically designed three-dimensional assembly of beams.

It is assumed that the micro-structure is composed of two families of beams, one of which is parallel to the cylinder axis and the other belonging to the cross-section plane. The arrangement of the second families of beams consists in a rectangular pattern reinforced by diagonal bracing elements.

The equivalent Timoshenko beam model is developed via a direct approach, and the constitutive law is deduced through an energy equivalence [3,4]. This latter takes into account for the prestress effect by means of a geometric term, representing the work done by the pretension of the fundamental state in the second order component of the deformation. The formulation of the constitutive law generalizes the results shown in [5] for the case of uniform compression of beam-like structures.

Also the warping of the cross-section caused by shear is taken into account in the equivalent model by defining a suitable corrective factor of the true cross-section area.

The bifurcation analysis for the case of uniformly and not-uniformly compressed micro-structured beams, under different boundary conditions, is then addressed and numerical results concerning the equivalent model are compared with 3D finite element analyses. Results given by the equivalent model are shown to be in a good agreement with that obtainable via much more cumbersome finite-element analyses. Different buckling modes [6], including local, Timoshenko- and Euler-like, are detected as a function of mechanical and geometrical parameters of the grilled cylinder. Finally, some conclusions and perspectives are drawn.

References

[1] *Noor, A. K., "Continuum modeling for repetitive lattice structures", Applied Mechanics Reviews, 41(7), page 285-296, (1988).*

[2] *Tollenaere, H., Caillerie, D., "Continuous modeling of lattice structures by homogenization", Advances in Engineering Software, 29(7-9), page 699-705, (1998).*

[3] *Luongo, A., Zulli, D., Mathematical Models of Beams and Cables, Wiley, Hoboken (2013).*

[4] *Piccardo, G., Tubino, F., Luongo, A., "Equivalent Timoshenko linear beam model for the static and dynamic analysis of tower buildings", Applied Mathematical Modelling, **71**, 77–95 (2019).*

[5] *Ferretti, M., "Flexural torsional buckling of uniformly compressed beam-like structures", Continuum Mechanics and Thermodynamics, **30**(5), 977-993, (2018).*

[6] *Pignataro, M., Rizzi, N., Luongo, A., Bifurcation, Stability and Postcritical Behaviour of Elastic Structures, Elsevier, Amsterdam (1990).*

Static and dynamic responses of micro-structured beams

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Keywords: Equivalent beam model, Micro-structured beam, Linear analysis.

A one-dimensional equivalent beam model, embedded in a three-dimensional space, is developed for static and dynamic analyses of beam-like structures. These are grilled cylinders, i.e. micro-structured bodies, made by a periodic and specifically designed three-dimensional assembly of beams.

The micro-structure of the cylinder is composed of two families of beams: (i) those parallel to its axis; (ii) those lying in the plane of the cross-section. These latter are arranged in a rectangular orthogonal pattern which, moreover, is reinforced through bracing diagonal elements, thus entailing the in-plane indeformability of the cross-section.

A Timoshenko beam model (coarse model) is formulated in the framework of the direct 1D approach, while the constitutive law is determined by a homogenization procedure [1-3]. A linear constitutive equation is obtained, with axial force coupled with bending and shear force coupled with torsion. The assumption of rigid cross-section is analogous to that of paper [4], where a tower building model is considered as a periodic system with rigid floors connected by deformable vertical elements.

In order to consider the warping of the cross-section caused by shear, the concept of shear factor, or shear area, is introduced; accordingly, a corrective factor of the true cross-section area is determined, which springs from equating the elastic potential energy of the refined model and that of the coarse model, once the same macroscopic displacement is given.

The limits of applicability of the equivalent model are discussed with reference to the linear static and dynamic responses of some micro-structured beams, taken as case-studies, for which both analytical and numerical tools are used. Numerical results obtained by the equivalent model are compared with 3D finite element analyses, in order to show to effectiveness of the former.

References

[1] *Luongo, A., Zulli, D., Mathematical Models of Beams and Cables, Wiley, Hoboken (2013).*

[2] *Noor, A. K., "Continuum modeling for repetitive lattice structures", Applied Mechanics Reviews,* ***41****(7), page 285-296, (1988).*

[3] *Tollenaere, H., Caillerie, D., "Continuous modeling of lattice structures by homogenization", Advances in Engineering Software,* ***29****(7-9), page 699-705, (1998).*

[4] *Piccardo, G., Tubino, F., Luongo, A., "Equivalent Timoshenko linear beam model for the static and dynamic analysis of tower buildings", Applied Mathematical Modelling,* ***71****, 77–95 (2019).*

Linear spatial galloping analysis of shallow cables via a continuum model

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Keywords: Shallow cables, Galloping, Continuous model analysis.

Cables are weakly damped light structures, and therefore prone to galloping. This aeroelastic phenomenon is triggered by a wind flow acting on cylinders of non-circular cross-sections, as shallow iced cables. The structure is modeled as a self-excited dynamical system, in which the excitation is represented, in the linear field and according to the quasi-static theory, by forces proportional to the structural velocity.

When the system possesses just one degree of freedom (d.o.f.) [1], the critical velocity is determined by the condition the total damping is zero. When, however, the system has more than one d.o.f. [1,2], an eigenvalue analysis has to be carried out. Such an analysis is not so easy when an analytical model is employed. In contrast, such a model is useful to obtain closed-form expressions, able to throw light on the bifurcation mechanism.

In this work a linear continuous one-dimensional model of cable [3], embedded in the three-dimensional space, is adopted. The aim is to generalize the results of [2], in which coupled translation galloping of sectional models of beams or strings, roughly describing along- and cross-wind motion interactions, is addressed. Generalization is referred to the following aspects: (i) a cable is considered, in which in-plane and out-of-plane frequencies are mutually related; (ii) a continuous model is adopted, in which coupling involves more than two modes of the finite-dimensional system.

The cable is assumed to be externally and internally damped, according to the Rayleigh model, and the aerodynamic forces are described through the quasi-static theory. The exact galloping modes are determined through a semi-analytical approach, by solving a coupled two-field linear boundary value problem. Then, in order to obtain qualitative information on the role of the out-of-plane component, a perturbation procedure is applied to investigate galloping in non-resonant, 1:1 resonant and 1:1:1 resonant conditions, reproducing all the occurrence for a shallow cable spectrum. It is found that coupling can lead to critical velocities either lower or higher than those predicted by the simplified planar model. Moreover, the character real or complex of the galloping mode is discussed.

References

[1] Blevins, Robert D., Flow-induced vibration, Van Nostrand Reinhold Co., New York (1977).
*[2] Luongo, A., Piccardo, G., "Linear instability mechanisms for coupled translational galloping", Journal of sound and vibration, **288**(4-5), page 1027-1047, (2005).*
[3] Luongo, A., Zulli, D., Mathematical Models of Beams and Cables, Wiley, Hoboken (2013).

The inverse problem of train load evaluation from measurements of the rail response

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Keywords: Inverse problems, Train loads, strain measurements

There is a growing interest from the railway administration in the safety standards of the ralway transport; among the various issues which concern the safety, one important point is to control the weight of travelling trains, in particular freight trains. This paper deals with the solution of the inverse problem of determining the weight of a train using the measurements of the response of a railway to the passing train. In particular, it is convenient to acquire the rail response through measurements of strains of the rail; to this scope fiber optic strain gauges are used since they are a measurement system which is quite a low cost, easy to set up and readable from a distance.

First, the direct problem is solved: the response of the rail due to travelling loads is investigated. The model of the rail is the one-dimensional Euler-Bernoulli beam with constant geometrical and mechanical properties, resting on a linear elastic foundation with viscous damping and subjected to a Dirac delta load travelling at constant speed. Under these assumptions an analytical expression of the solution is obtained, which permits to describe the sensitivity of the response to the main mechanical parameters. Since strains are the measured quantities in the experimental campaign, the time-histories of curvatures are derived and overall compared to their experimental counterpart, showing the ability of the model to describe the real phenomenon. It can therefore be a reliable interpretative model to be used in the successive identification phase.

As a second step, the inverse problem of identifying the time-history of loads for a given time-history of measured strains is addressed. The solution of the inverse problem is set up as a minimization problem where the objective function is based on the difference between the experimental and the model response time-histories. Notwithstanding the direct problem is linear, the inverse problem based on the observed response quantities is strongly nonlinear and the solution is pursued by numerical techniques, which must take into account the ill-conditioning character of the problem.

The procedure proposed is finally applied to experimental strains recorded on the foot of a rail on a stretch of line run by freight trains moving with low constant speed. The identified time-hystories of loads furnishes an optimal estimate of the train weights; for a selected number of trains, these weights are compared to those declared by the carrier, providing satisfactory results.

References

[1] Pau, A., Vestroni, F., Duca, E., Platini, M., Identification of freight train loads using time-histories of rail strains, 12th World Conference on Railway Research, Tokyo, 2019

Design of a membrane structure subjected to blast load

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Keywords: blast, membrane structure, fast dynamics

The use of light membrane structures is continuously growing, thanks to their many interesting characteristics: lightness, easiness and velocity of installation, adaptability, ability to cover large empty spaces etc. Membrane structures include tenso-structures, which are self-standing membranes whose form is determined by the equilibrium of self-stresses (form-finding), and tendo-structures, that have a bearing skeleton constituted by light metallic elements to which the membrane is attached. From an engineering point of view, in the design of these structures dead loads and seismic loads have almost no influence, while the most important external actions are those due to non conservative loads (atmospheric water, snow), and to the interaction with air flow. Strong wind is one of the main cause of failure of these structures.

In petrochemical facilities tendo-structures, employed for temporary uses, need to resist to vapor cloud explosions that can happen in the vicinity of the tent. Such explosions generate a blast wave characterized by a peak pressure and by an impulse energy, that, upon impact, interacts with the structure yielding fast dynamic actions [1]. Although the metallic skeleton usually has a vibration period much greater than the duration of the blast, the same is not true for the tent, whose eigenperiods are of the same order or even smaller than the duration of the blast. The analysis of the structure response needs then to accurately account for the interaction between the fluid and the membrane.

Very few analyses of this type are present in the literature, and even fewer are the experimental evidences. Designers can employ simplified procedures like those recommended by the API 756 [2], that suggest to perform dynamic analyses for a range of simplified load conditions. It appears, however, that the actions on the structure are largely overestimated, and, in addition, the effects of the wave passing through the membrane are not analysed, while they can be critical for the safety assessment of the employees working within the facility.

The paper aims to give contributions on some of the open questions indicated. Within the simplified models proposed by API 756, a comparison will be presented between the response of the structure disregarding the dynamic behaviour of the external membrane, and the response calculated considering the interaction between the membrane and the metallic frame. An implicit non linear fast dynamic analysis will be carried out, with consideration on the stability of the time step.

Similar procedures can be used for light tenso-structres subjected to strong wind, since the wind pressure on the membrane strongly depends on the shape of the membrane, which is, on its own, strongly influenced by the loads. A procedure suggested in [3] will be used for generating non stationary wind actions.

References

[1] *Ngo, T., Mendis, P. and Gupta, A., "Blast Loading and Blast Effects on Structures - An Overview," EJSE Special Issue: Loading on Structures (2007).*

[2] *American Petroleum Institute, API Recommended Practice 756 - Management of Hazards Associated with Location of Process Plant Tents, (2014).*

[3] *Solari, G. and Piccardo, G., "Probabilistic 3D turbulence modeling for gust buffeting of structures," Probabilistic Engineering Mechanics,* **16***, page 73-86 (2001).*

Dynamic substructuring with time variant interface due to sliding friction

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Keywords: Dynamic Substructuring, Time-variant Interface, Friction.

Although dynamic substructuring is typically applied to time-invariant systems [1], an interesting subset of time variant systems is represented by those built from time-invariant component subsystems subjected to time-variant coupling conditions. For such systems, the classical techniques developed for time invariant systems can be adapted with few modifications. Typical examples of such time variant systems are those encountered in contact problems (e.g. when a sliding velocity exists between two contacting bodies). The analysis of contact problems in the framework of dynamic substructuring can provide interesting results with relatively low computational effort. For instance, the macroscopic analysis of the time-frequency behaviour of bodies in relative sliding with friction can benefit of the substructuring approach. Since time-variant coupling conditions are involved, the time domain approach is the most appropriate.

The general framework for dynamic substructuring can be extended to time-variant coupling conditions. Specifically, time-variant coupling conditions due to a sliding contact are considered by introducing time dependent compatibility and equilibrium conditions. The sliding contact can be without or with friction. With friction, the set of degrees of freedom to which equilibrium conditions apply includes tangential directions at the contact interface, which are not considered in the compatibility conditions because of sliding. This is in fact a non collocated interface as defined in decoupling problems [2, 3]. In previous works [4, 5] the problem was tackled using both primal and dual assembly in the time domain. Singularity problems arising in dual assembly were avoided by revisiting the forward increment Lagrange multipliers method [6]. Furthermore a time-frequency approach was developed to obtain the Time Dependent Frequency Response Functions (TD-FRFs) using dual assembly.

In this paper, the proposed approaches, previously applied to lumped parameters models, are extended to a simple finite element model composed by two beams in sliding contact, under the assumption that the relative sliding motion at the contact interfaces is known a-priori.

References

[1] *de Klerk, D., Rixen, D. J., Voormeeren, S., "General Framework for Dynamic Substructuring: History, Review, and Classification of Techniques", AIAA Journal,* **46***, pp 1169-1181 (2008).*

[2] *Voormeeren, S. N., Rixen, D. J., "A Family of Substructure Decoupling Techniques Based on a Dual Assembly Approach", Mech. Syst. Sig. Proc.,* **27***, pp. 379-396 (2012).*

[3] *D'Ambrogio, W., Fregolent, A., "Inverse dynamic substructuring using direct hybrid assembly in the frequency domain", Mech. Syst. Sig. Proc.g,* **45***, pp. 360-377 (2014).*

[4] *Brunetti, J., D'Ambrogio, W., Fregolent, A., "Dynamic Substructuring with a Sliding Contact Interface" in Dynamics of Coupled Structures, Vol 4, pp. 105-116, Springer, Cham (2018).*

[5] *Brunetti, J., D'Ambrogio, W., Fregolent, A., "Contact problems in the framework of dynamic substructuring" in Proceedings of ISMA 2018, pp. 3987-3998 (2018).*

[6] *Carpenter, N. J., Taylor, R. L., Katona, M. G., "Lagrange constraints for transient finite element surface contact", Int. J. Numer. Methods Eng.,* **32***, pp. 103-128, (1991).*

Vibrations reduction of rail noise barriers with hysteretic absorber

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Keywords: noise barriers, high speed railway, hysteretic vibration absorber.

Noise barriers for high-speed train lines are subjected to strong vibrations due to fluid pressure generated by moving trains [1]. The pressure dynamic signal is characterized by two main impulses, corresponding to the head and tail of the train, connected by oscillations of minor amplitude. The barriers, generally made of steel cantilever beams and panels of metal, concrete, or transparent material, sustain a large number of oscillation cycles with the passage of each train and become vulnerable to fatigue.

In the vibration suppression field, it is common to connect the structure to be protected with an attachment, which has the role of absorbing part of the vibration energy of the excited primary structure, thus reducing vibration reduction. Different kinds of attachments have been suggested in recent years [2-4]. In this study a strategy is proposed to reduce the barrier vibrations by attaching a hysteretic vibration absorber to each column. The absorber is made of a light mass on rubber elements; it has the great advantage to combine in one element the elastic and dissipative characteristics of the device.

For the numerical investigations the barrier is modelled as a generalized single degree of freedom system and the hysteretic absorber is described by the Bouc-Wen model. An optimal tuning of the hysteretic vibration absorber is necessary, due to the dependence of the stiffness and dissipative properties of nonlinear device on the oscillation amplitude. The design of the vibration absorber, calibrated to behave around the 1:1 internal resonance condition, is illustrated and the sensitivity analysis of its constitutive parameters is carried out for the optimal tuning with the train passage. To assess the effectiveness of the absorber in the mitigation of the vibration of the barrier, a performance index evaluated on the base of the rms of the response is considered. An investigation varying the train speed is carried out to evaluate the robustness of the control system to reduce the barrier vibrations. The results show that the absorber effectively reduces the amplitude and the number of vibration cycles in a wide range of train velocities. Experimental tests are underway and the results obtained till now look like encouraging on the effectiveness of hysteretic absorbers.

References

[1] Evangelista, L., Vittozzi, A., Silvestri, G., "Theoretical-experimental evaluation of the noise barriers behavior on high speed lines" Ingegneria Ferroviaria (2009).
*[2] Vakakis, A.F., "Intentional utilization of strong nonlinearity in structural dynamics" Procedia Engineering, **199**, 70-77 (2017).*
*[3] Carpineto, N., Lacarbonara, W., Vestroni, F., "Hysteretic tuned mass dampers for structural vibration mitigation", Journal of Sound and Vibration, **333** (5), 1302-1318 (2014).*
*[4] Casini, P., Vestroni, F., "Nonlinear resonances of hysteretic oscillators", Acta Mechanica, **229** (2), 939 - 952 (2018).*

Homogenization of composite media with highly conductive inclusions

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Keywords: Homogenization, unfolding technique, diffusion problems

We study, via homogenization technique, the thermal properties of a composite material made up of a hosting medium in which a periodic array of nano-particles is inserted. The microscopic inclusions are assumed to be perfect heat conductors (i.e. they have infinite thermal conductivity). Indeed, in practical applications, the heat conductivity of the inclusions is far larger than the one of the hosting medium. These models are becoming increasingly important in the last years, due to the appearance in the market of nano-engineered composite materials, produced with the purpose of increasing the overall thermal conductivity. For example, this is the case in the packaging of electronic devices, in which a rubber is used to encapsulate them and the need of an efficient heat dispersion justifies the insertion of highly conductive inclusions into the rubber itself.

From a mathematical point of view, the problem reduces to a heat equation satisfied by the temperature u_ε in the hosting medium, while on the boundary of the inclusions (i.e. on the interface between the two different conductive phases) u_ε is assumed to be constant with respect to the space variable and determined by a heat balance on the inclusions, taking into account the heat flux entering the inclusions themselves. More precisely, on each interface $\Gamma_{\varepsilon i}$, the temperature satisfies the non standard boundary condition $\lambda u_{\varepsilon t} = \frac{1}{\varepsilon^3}\int_{\Gamma_{\varepsilon i}} K\nabla u_\varepsilon \cdot \nu_\varepsilon d\sigma$, where λ is a strictly positive constant, proportional to the specific heat capacity, K takes into account the diffusion properties of the hosting medium and ε represents the characteristic length of the nano-particles.

The purpose of this investigation is to give a theoretical motivation of heuristic models used by engineers in applications (see, for instance, [1, 2, 3, 4]).

References

[1] *Ebadi-Dehaghani, H., Nazempour, M., "Thermal conductivity of nanoparticles filled polymers", Smart Nanoparticles Technology,* **23***, page 519-540, (2012).*

[2] *Kemaloglu, S., Ozkoc, G., Aytac, A., "Thermally conductive boron nitride/sebs/eva ternary composites:processing and characterisation", Polymer Composites (Published online on www.interscience. wiley.com, 2009, Society of Plastic Engineers), page 1398-1408, (2010).*

[3] *Phromma, W., Pongpilaipruet, A., Macaraphan, R., "Preparation and Thermal Properties of PLA Filled with Natural Rubber-PMA Core-Shell/Magnetite Nanoparticles", European Conference; 3rd, Chemical Engineering, Recent Advances in Engineering, Paris, (2012).*

[4] *Shahil, K. M., Balandin, A. A., "Graphene-based nanocomposites as highly efficient thermal interface materials", Graphene Based Thermal Interface Materials, page 1-18, (2011).*

Experimental and numerical response analysis of a unilaterally constrained SDOF system under harmonic base excitation

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Keywords: Impact dynamics, Experimental tests, Numerical model.

The pounding between adjacent systems can occur in different situations typical of civil engineering (base-isolated structures with limited seismic gap [1], equipment [2,3] or bridges). The acceleration spikes, produced by the impact, can damage acceleration-sensitive equipment or lead to severe structural damage. These side effects can be mitigated inserting dissipative and deformable shock absorbers (bumpers) between the colliding systems, thus reducing the impact stiffness. In this work, the problem was studied considering a base-isolated single-degree-of-freedom (SDOF) system impacting against two symmetrically arranged bumpers, under harmonic base excitation [4-6]. Using a shaking table, a parametric experimental laboratory campaign was carried out, in which different values of peak table acceleration, total gap (distance between mass and bumpers) amplitude and different types of bumpers were considered. From the examination of some of the experimental results, it was possible to identify different scenarios that can occur varying the investigated parameters. These scenarios were found also numerically using a simplified nonlinear model, described in terms of dimensionless parameters. Although the model does not include all the nonlinearities involved in the real problem, some of the observations emerged analyzing the numerical results have found confirmation in the experimental outcomes.

References

*[1] Polycarpou, P. C., Komodromos, P., "On poundings of a seismically isolated building with adjacent structures during strong earthquakes", Earthq Eng Struct Dyn, **39**(8), 933-940 (2010).*

*[2] Reggio, A., De Angelis, M., "Optimal design of an equipment isolation system with non-linear hysteretic behavior", Earthq Eng Struct Dyn, **42**, 1907-1930 (2013).*

*[3] Reggio, A., De Angelis, M., "Combined primary-secondary system approach to the design of an equipment isolation system with High-Damping Rubber Bearings", J Sound Vib, **333**, 2386-2403 (2014).*

*[4] Andreaus, U., De Angelis, M., "Nonlinear dynamic response of a base-excited SDOF oscillator with double-side unilateral constraints", Nonlinear Dyn, **84**, 1447-67 (2016).*

*[5] Andreaus, U., Baragatti, P., De Angelis, M., Perno, S., "A Preliminary Experimental Study About Two-Sided Impacting SDOF Oscillator Under Harmonic Excitation", J Comput Nonlin Dyn, **12**, 061010 (2017).*

*[6] Andreaus, U., Baragatti, P., De Angelis, M., Perno, S., "Shaking table tests and numerical investigation of two-sided damping constraint for end-stop impact protection", Nonlinear Dyn, **90**, 2387-421 (2017).*

Dispersion features in a model of elastic bar with microcracks derived from a generalized continuum formulation

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Keywords: multiscale-multifield model, wave propagation, damage effects

In contemporary technological applications wide interest is devoted to microstructured materials, characterized by the existence of an internal structure represented by material length parameters, accounting for the distance between particles, the size of a grain, the length and distance of microcracks, etc., that introduce a scale-dependence in the model governing equations. The mechanical modeling of microstructured continua meets the main difficulty in accounting for the microscopic features through suitable constitutive laws. This often calls for the need of non-classical (generalized) continuum descriptions that can be considered as non-local models due to the presence of internal length parameters and dispersion properties in wave propagation [1]. Within the class of implicit non-local models, a multiscale approach has been presented and described in [2]. The method consists in the description of the mechanical behavior of a continuum model, i.e. the macromodel, and of a complex lattice model, representing the micromodel. The field variables at the two material scales are linked via an energy equivalence criterion. The obtained model is characterized by the presence of more field descriptors than the classical continuum, allowing to retain the memory of the fine organization of the material. The presence of the microstructure plays an important role when the dynamical behavior of these materials is investigated, especially in nowadays applications where high frequency excitations are commonly used. In fact, when excitation wavelengths are comparable with microstructure length, dispersion effects due to the microstructure reveal the multiscale nature of the material [3]. Within this framework, a model of monodimensional bar of elastic material with distributed stationary microcracks, derived from a generalized continuum formulation [2], has been investigated in terms of free wave as well as forced wave propagation. The ensuing, coupled, balance equations give rise to a higher-order dispersion wave equation as a function of the standard macro-displacement and of the additional micro-displacement describing the microcracks. The analysis of the dynamical response of the bar allows us to critically discuss the influence of the micromodel descriptors, representing cracks density and length. The modification of these parameters entails description of bars under different levels of damage, and proves to be able to meaningfully alter shape, velocity, and actual occurrence of propagating waves, with also significant distorting effects of the macro-displacement response

References

[1] *Trovalusci, P., "Molecular approaches for multifield continua: origins and current developments", in Multiscale Modeling of Complex Materials, 211-278, Springer (2014).*

[2] *Trovalusci, P., Varano, V., and Rega, G., "A generalized continuum formulation for composite materials and wave propagation in a microcracked bar", Journal of Applied Mechanics,* **77***(6), 061002–1/11 (2010).*

[3] *Berezovski, A., Engelbrecht, J., Salupere, A., Tamm, K., Peets, T., and Berezovski, M., "Dispersive waves in microstructured solids", International Journal of Solids and Structures,* **50***(11-12), 1981-1990 (2013).*

Modal asynchronicity in a simply-supported beam with a cantilever extension

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Keywords: modal asynchronicity, localisation, continuous system.

It is well-known that linear systems commonly experience synchronous modal oscillations. Modal synchronicity implies that all material points reach their maxima/minima at the same instants of time, so that in time the motion is fully characterised by a harmonic function, namely $f_i(\mathbf{r}, t) = f_i(\mathbf{r}) \sin(\omega_i t + \phi_i)$, where ω_i stands for the *i*-th natural frequency.

Nevertheless, it has been observed that such properties might no longer be valid, provided the so-called *conditions for modal asynchronicity* are met. This feature is evident when localised vibrations occur. For such modes, a part of the structure is at rest, which is equivalent to say that on that part at least one frequency is null. Following this line of though, localised modes have been found in a number of discrete linear systems, such as the ones referred to in [1]. A continuous beam under varying normal force has also been regarded [2]. In the latter one, when localisation was imposed in the form of quasi-Bessel modes, it was not possible to guarantee continuity of rotation at the boundary between the localized vibration region and the one at rest. In other words, it was not an exact example of asynchronous mode, although it was asynchronous from an engineering point of view, since displacements were very small in a part of the structure.

In this work, we seek for a continuous system that exhibits a truly exact asynchronous mode. With this in mind, we address a simply-supported beam with a cantilever extension, with a TMD attached in a certain position. Such a system is described by three differential equations, with 12 boundary conditions and 12 unknowns. After conditions for modal asynchronicity are imposed, so that the cantilever part does not move, the system is reduced to eight unknows and nine boundary conditions. The remaining condition is imposed by properly choosing the TMD's mass or stiffness, this leading to the searched asynchronous mode. Finally, we return to the general system, in order to determine the order number of such a mode; the lower it is, the more relevant its role will be in a typical forced dynamical analysis.

The analytical results are all validated with the aid of finite-element models. The most relevant asynchronous mode found is the third one in the general system. By the way, the TMD and the beam oscillate with the same frequency, but in antiphase. This yields null rotation and moment at the support on the cantilever's side, which are the necessary conditions for modal localisation in this system.

References:
[1] Lenci, S., Mazzilli, C.E.N., "Asynchronous free oscillations of linear mechanical systems: a general appraisal and a digression on a column with a follower force", International Journal of Non-Linear Mechanics, vol. 94, pp. 223-234, 2017.
[2] Mazzilli, C.E.N., Ribeiro, E.A.R., "Asynchronous modes of beams on elastic media subjected to varying normal force: continuous and discrete models", in IUTAM Symposium 'Exploiting Nonlinear Dynamics for Engineering Systems', Novi Sad, Serbia, July 2018.

Optimal positioning of piezoelectric plates in a rotating beam to suppress vibrations in case of bi-modal excitation

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Keywords: PZT, Bi-modal, Rotating Beam

Vibration suppression systems are often crucial to extend the life cycle of the structures in several engineering fields. In fact vibrations reduce the life-cycle of the components and accelerate the cracks propagation. During the last decades several passive and active vibration damping systems have been investigated in order to reduce vibrations. The passive systems are the most commonly used but their efficiency is low in case of dynamic loads. On the other hand, the active damping systems may overcome this problem but their cost and implementation are more critical. Since the external forces acting on a rotating blade may excite several vibrational modes simultaneously, an active multi-modal damping device could enhance the damping action. The piezoelectric (PZT) actuators seem to be the most promising for such applications but their positioning plays a crucial role [1, 2]. The piezoelectric materials show high resolution, large bandwidth, fast dynamic and can be used both as sensors and actuators therefore many researchers investigated their implementation to suppress vibrations in mechanical components. A novel strategy for bi-modal vibrations damping in non-rotating cantilever beams, based on the optimal placement of piezoelectric elements, was proposed in [3, 4]. In this paper, several combinations of bi-modal excitations have been considered for a rotating cantilever beam. The paper offers new design charts for optimizing the positions of the piezoelectric actuators. Finally, FEA (Finite Element Analysis) has been used to validate the results obtained by the theoretical approach.

References

[1] *Crawley, E.F., De Luis, J., "Use of piezoelectric actuators as elements of intelligent structures", AIAA journal,* **25***, page 1373–1385 (1987).*

[2] *Barboni, R., Mannini, A., Fantini, E., Gaudenzi, P., "Optimal placement of PZT actuators for the control of beam dynamics", Smart Materials and Structures,* **9***, 110 (2000).*

[3] *Botta, F., Dini, D.,; Schwingshackl, C., di Mare, L., Cerri, G., "Optimal Placement of Piezoelectric Plates to Control Multimode Vibrations of a Beam", Advances in Acoustics and Vibration,* **2013***, art no. 905160 (2013).*

[4] *Botta, F., Scorza, A, Rossi, A., "Optimal Piezoelectric Potential Distribution for Controlling Multimode Vibrations", Applied Sciences,* **8(4)***, 551 (2018).*

Optimal sensors placement for damage detection of beam structures

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Keywords: Vibrating 1-D uncertain continua, Damage detection, Sensors placement

Safety assessment of existing structures is a crucial task of many engineering field. Within this framework, dynamic approaches - mainly concerned with output-only techniques - have been proved useful to locate and quantify structural damages. When attention is paid to "early warning" systems, able to activate specific protocols, a robust identifiability of dynamics features of the structure plays a key role. Despite this increasing interest, structural health monitoring is often addressed in engineering practice relying on simplified rules, where sensors network is established *a priori*.

Among the approaches dedicated to sensors placement, we may cite the one proposed in [1], based on improved genetic algorithms, and the work in [2] where attention is paid in searching the weakest part of the structure in a random context. Several methods for optimal sensors placement were studied and compared for a suspended bridge in [3].

This paper is dedicated to the identifiability of vibrating uncertain beam structures. In [4], a perturbation method has been proposed by some of the authors to derive the asymptotic eigensolution up to the second order. Then, the statistics of the random parameter have been obtained by means of an objective function minimizing the difference among analytical and experimental fractiles of the eigenvalues. Starting from this model, we here propose a technique for obtaining an optimized solution of sensors placement. The proposed approach aims at exploiting the closed-form asymptotic solution of the inverse problem to compare more combinations of number and placement of the sensors. These comparisons must be intended as an investigation on the minimum number of sensors beyond which monitoring accuracy (evaluated by an error function measuring the deviation from the exact solution) increases less than a 'small' predetermined threshold. As the asymptotic nature of the research pattern, the performance of the proposed placement optimization technique has a low computational effort. The capabilities and efficiency of the technique are shown through a parametric analysis on a sample case study: a simply supported beam with a random parameter ruling the evolution of a quasi-localized damage. The relevant results are presented and discussed, showing which conditions (sensors network) properly characterizes the beam dynamics.

References

[1] *Guo, H.Y., Zhang, L., Zhang, L.L. and Zhou, J.X., Optimal placement of sensors for structural health monitoring using improved genetic algorithms, Smart Materials and Structures,* **13***(3), 528–534 (2004).*

[2] *He, H., Xu, H., Wang, X., Zhang, X. and Fan, S., Optimal Sensor Placement for Spatial Structure Based on Importance Coefficient and Randomness, Shock and Vibration,* **2018***, 1–14 (2018).*

[3] *Meo, M. and Zumpano, G., On the optimal sensor placement techniques for a bridge structure, Engineering Structures,* **27***(10), 1488 – 1497 (2005).*

[4] *Lofrano, E., Paolone, A. and Vasta, M., Identification of Uncertain Vibrating Beams through a Perturbation Approach, ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering,* **2***(2), 1–11 (2016).*

Shaking table testing of a tuned mass damper inerter (TMDI)-equipped SDOFs and nonlinear dynamic modelling under harmonic excitations

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Keywords: Tuned mass damper inerter, shaking table testing, nonlinear dynamic model

This paper presents preliminary experimental results from a novel shaking table testing campaign investigating the dynamic response of a 2DOF system with a grounded inerter under harmonic excitation and contributes a nonlinear dynamic model to characterise the behaviour of the test specimen.

In its ideal form, the inerter [1] is a weightless mechanical element generating a force proportional to the relative acceleration between its two terminals by a constant termed inertance. Several relatively small-scale inerter devices have been prototyped over the years achieving inertance with two or more orders of magnitude larger than the device physical mass tailored for vehicle engineering applications. Recently, numerous analytical and computational studies showed the potential of inerters for mitigating seismically induced vibrations in large-scale civil engineering applications. Nevertheless, few experimental tests have been undertaken thus far to verify the feasibility of inerter-based vibration control for civil engineering applications.

To this end, herein, a damped 2DOF physical model is built on a shaking table consisting of a primary mass connected to ground through an elastomeric isolator and a secondary mass connected to primary mass through a second elastomeric isolator. The model is representative of a primary system featuring a tuned mass damper (TMD) vibration absorber. The physical model is further equipped with a flywheel-based rack-and-pinion inerter prototype device which connects the secondary mass to ground. The resulting system resembles the tuned mass damper inerter (TMDI) configuration with grounded inerter analytically discussed and numerically assessed in [2-3]. The physical prototype is tested on the shake table under sine-sweep excitation with increasing and with decreasing frequencies and for various intensities. Preliminary results are reported from the experimental parametric analysis evaluating the influence of excitation amplitude and inertance on the dynamic response of the TMDI-equipped SDOF system. Furthermore, the nonlinear behaviour of the inerter and of both the isolators are identified and a nonlinear numerical model able to capture the experimental data is defined and computationally verified.

References

[1] *Smith, M.C., "Synthesis of mechanical networks: the inerter", IEEE Transactions on automatic control,* **47***(10), 1648-1662 (2002).*

[2] *Laurentiu, M., Giaralis, A., "Optimal design of a novel tuned mass-damperinerter (TMDI) passive vibration control configuration for stochastically support-excited structural systems", Probabilistic Engineering Mechanics,* **38***, 156-164 (2014).*

[3] *Pietrosanti, D., De Angelis, M. and Basili, M., "Optimal design and performance evaluation of systems with Tuned Mass Damper Inerter (TMDI)", Earthquake Engineering and Structural Dynamics,* **46***(8), 1367-1388 (2017).*

A novel characterization method of brake lining materials to squeal noise propensity

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Keywords: friction noise, squeal, brakes.

Disc brake systems are a technology widely adopted within the automotive and rail industry, especially when high performance is needed. The frictional interaction between the brake disc and the pads is responsible for friction-induced vibrations [1], leading often to fastidious noise emissions such as squeal [2] and creep groan [3]. In the last decades, many efforts have been addressed to brake noise, considered as a major issue in terms of customer dissatisfaction. The source of this phenomenon is attributed to unstable friction-induced vibrations due to the contact between two solids in relative motion. In particular, the same frictional system can lead to different contact scenarios such as stable sliding, with low amplitude friction vibrations, unstable sliding with mode coupling instability or macroscopic stick-slip response of the system [4]. Local contact phenomena occurring at the contact interface, and resulting in friction noise, can be responsible for the triggering of the dynamic instability.

This work proposes a new method for characterizing friction lining materials, by measuring the friction noise coming from the contact between different pad materials and a disc rotor; the propensity of lining materials to trigger the squeal instability is analysed by comparing the friction noise generated by the investigated materials under identical boundary conditions. The whole analysis is performed by means of a dedicated experimental setup (TriboAir), developed in order to reproduce and investigate the system frictional response under well-controlled boundary conditions and no parasite noise. A laser vibrometer is used to detect local contact vibrations without interfering with the contact itself. A parametrical analysis has been carried out with the aim of highlighting the influence of the main parameters on the generated friction noise. Finally, when testing the same lining materials on a full brake disc system, the measured friction noise indexes resulted to be strongly correlated with the squeal occurrence, validating the proposed characterization method for the squeal propensity of the lining material.

References

[1] *G. Sheng, Friction-Induced Vibrations and Sound; Principles and Applications. CRC Press Inc., 2008.*

[2] *J. Brunetti, F. Massi, W. D'Ambrogio, and Y. Berthier, "A new instability index for unstable mode selection in squeal prediction by complex eigenvalue analysis," Journal of Sound and Vibration, vol. 377, pp. 106–122, 2016.*

[3] *A. Lazzari, D. Tonazzi, G. Conidi, C. Malmassari, A. Cerutti, and F. Massi, "Experimental evaluation of brake pad material propensity to stick-slip and groan noise emission," Lubricants, Article vol. 6, no. 4, 2018, Art no. 107, doi: 10.3390/lubricants6040107.*

[4] *D. Tonazzi, F. Massi, L. Baillet, J. Brunetti, and Y. Berthier, "Interaction between contact behaviour and vibrational response for dry contact system," Mechanical Systems and Signal Processing, vol. 110, pp. 110-121,2018.*

Modeling and identification of carbon nanotube/polymer beams nonlinear dynamic behavior

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Keywords: nanocomposites, experimental frequency response, softening/hardening nonlinearity, identification

Due to the reinforcement effect and the superior damping capacity provided by carbon nanotubes (CNT) integrated in lightweight polymer systems, CNT nanocomposites are being widely used as structural material for dynamic devices in several engineering fields [1]. In this work, the peculiar nonlinear dynamic behavior of nanocomposite cantilever beams is experimentally investigated, modeled and identified. Nanocomposite cantilevers are subject to a transverse harmonic base excitation near the primary resonance of their lowest bending modes to obtain the frequency-response curves. The experimentally observed dynamic response of the nanocomposite beams exhibits two concurrent nonlinearities, softening at low amplitudes and hardening at larger amplitudes. While the hardening behavior is justified by the stiffness-augmenting nonlinear bending curvature effect, the softening-type nonlinearity is attributed to the stiffness-degrading CNT/polymer stick-slip, i.e., an energy dissipation phenomenon occurring at the CNT/matrix interfaces [2] whereby the frictional sliding of polymer chains on the CNTs causes both energy dissipation and loss of stiffness. To derive the equation of motion of the cantilevers exhibiting the hardening nonlinearity, the nonlinear, inextensible Euler-Bernoulli beam theory and the Galerkin discretization method are employed. In addition, to model the softening behavior due to the nanostructural stick-slip energy dissipation, the reduced-order equation of motion is modified by introducing a modal restoring force, shaped up according to a model of hysteresis mimicking the Bouc-Wen model [3]. A genetic-type algorithm is employed for the identification of the coefficients of the proposed reduced-order equation of motion. Subsequently, a pseudo-arclength path following scheme is implemented to construct the frequency-response curves. The agreement between the predicted frequency-response curves and those experimentally obtained corroborates the capability of the proposed model to capture the nonlinear softening-hardening response exhibited by the nanocomposite cantilevers.

References

[1] Li, X., Song, M., Yang, J., Kitipornchai, S., Primary and secondary resonances of functionally graded graphene platelet-reinforced nanocomposite beams. Nonlinear Dynamics, 1-20 (2018).
[2] Suhr, J., Koratkar, N. A., Energy dissipation in carbon nanotube composites: a review. Journal of Materials Science, 43(13), 4370-4382 (2008).
[3] Formica, G., Talò, M., Lanzara, G., Lacarbonara, W. Parametric identification of carbon nanotube nanocomposites constitutive response. Journal of Applied Mechanics (2018). doi:10.1115/1.4042137.

Asymptotic analysis of the nonlinear dynamic response of hysteretic oscillators based on a general class of phenomenological models

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Keywords: Hysteretic oscillators, Method of multiple scales, Phenomenological models

The method of multiple scales is adopted to investigate the dynamic response of a general family of nonlinear hysteretic oscillators whose constitutive behaviour is governed by a phenomenological model. In the context of the multiple scales strategy [1] for the asymptotic analysis of nonlinear resonance behaviour one of the key points of the formulation is the integration of the hysteretic response from a differential model to obtain piece-wise closed-form representations of the different branches. In particular, this is the case with the well-known Bouc-Wen model and its modified versions (*e.g.*, see [2]). Due to the highly nonlinear nature of the hysteretic response, this often leads to additional approximations in the problem formulation besides those that are typical of asymptotic approximations [3].

This limitation is overcome in the present work by adopting the phenomenological model proposed in [4], where the hysteretic response of the so-called exponential model, which matches the response of Bouc-Wen models, can be expressed analytically. Such a model belongs to a class of uniaxial models formulated to accurately simulate hysteretic phenomena in rate-independent mechanical systems and materials requiring only one history variable. Thus, the present investigation can be considered sufficiently general and of broad applicability.

Several numerical examples will be provided in order to study the response of the hysteretic oscillator in terms of frequency responses, and to evaluate its sensitivity to the main constitutive parameters. The frequency response obtained in closed form allows one to carry out the stability analysis together with a parametric study leading to behaviour charts characterising multi-valued softening/hardening responses or single-valued, quasi-linear responses.

References

[1] *Nayfeh, A., Mook, D., Nonlinear Oscillations, John Wiley & Sons, New York (1995).*

[2] *Casalotti, A., Lacarbonara, W., "Tailoring of pinched hysteresis for nonlinear vibration absorption via asymptotic analysis", International Journal of Non-Linear Mechanics,* **94***, 59–71 (2017).*

[3] *Lacarbonara, W., Nonlinear Structural Mechanics, Springer, New York (2013).*

[4] *Vaiana, N., Sessa, S., Marmo, F., Rosati, L., "A class of uniaxial phenomenological models for simulating hysteretic phenomena in rate-independent mechanical systems and materials", Nonlinear Dynamics,* **93***, 1647–1669 (2018).*

An appraisal of modelling strategies for assessing aeolian vibrations of transmission lines

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Keywords: Aeolian vibrations, Cable dynamics, Overhead power lines

Suspended conductors and guard wires of overhead power lines are prone to Aeolian Vibrations, triggered by the alternate shedding of vortices in the cable wake. Aeolian vibrations typically occur under ligth to moderate winds and are characterized by small-amplitude flexural oscillations in the cross-wind direction. Vibration frequencies can be in the broad range of 3-200 Hz.. Whenever not contrasted, aeolian vibrations can induce wear damage and fatigue failures [1]. Passive control devices (e.g. Stockbridge dampers [2]), hence, are often installed along the line spans.

The current technical approach to the assessment of aeolian vibrations is based on the Energy Balance Method (EBM) [1] and relies on the knowledge of the natural frequencies and modes of the line. Under the simplifying assumption of mono-modal vibrations, for each frequency, the vibration amplitude is evaluated by imposing the balance between the power imparted by the wind to the vibrating cable and the power dissipated within the structure. The latter, in turns, can be regarded as the sum of the power dissipated in the control devices and in the cables (self-damping [3]). The reliability of the EBM results can be strongly affected by the criteria adopted to define the input data (i.e. the wind power) as well as by the modelling assumptions adopted to model the dynamics of the line. The aim of the present paper is to investigate, within an unitary theoretical framework, the effect of different modelling strategies on the outcomes of the EBM.

In this work, the line spans are modelled through a dynamic substructuring approach: the mechanical impedance matrix of each structural element (e.g. the cables) is defined through a continuum approach and then assembled to lumped components (e.g. the dampers) to obtain the impedance of the overall system. Natural frequencies and modal shapes are then determined through a forced vibration method, which allows to easily handle non-proportional damping, typical for the problem at study. By taking advantage of the inherent modularity of the proposed approach, different structural models to describe both the cables and the passive damping devices are implemented. Several different strategies to model the self-damping of the cables are also considered for comparison purposes. The proposed formulation is then applied, within the framework of the EBM, to estimate the aeolian vibration amplitude of some well documented power lines, for which experimental data are available in the literature.

References

[1] *EPRI, Transmission Line Reference Book: Wind-Induced Conductor Motion, Palo Alto Ca (USA) (2006).*

[2] *Foti, F., Martinelli, L., "Hysteretic behaviour of Stockbridge dampers: Modelling and parameter identification", Mathematical Problems in Engineering,* **Vol. 2018**, *Article ID. 8925121 1-17 (2018).*

[3] *Foti, F., Martinelli, L., "An enhanced unified model for the self-damping of stranded cables under aeolian vibrations", Journal of Wind Engineering,* **182**, *72-86 (2018).*

On the modelling of the hysteretic behaviour of wire rope isolators

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Keywords: Wire rope isolators, Base isolation, Wire rope modelling

Wire rope isolators are made of two parallel retaining plates or bars, connected through a metallic cable (wire rope). The cable is often arranged in a nearly-helical shape, altough different geometric configurations can also be adopted. Due to their good performances as vibration isolators and shock absorbers, the wire rope isolators have been widely employed in industrial applications to support equipment and secondary structures [1]. Applications of this technology to the seismic isolation of lightweight civil structures have also been envisaged and some research on this subject is recently surfacing in the literature [2].

The dynamic behaviour of wire rope isolators is strongly affected by both geometric and material non-linearities. The latter are mainly due to the peculiar hysteretic bending behaviour of metallic cables. Relative displacements between the wires of the cable, indeed, can occur during flexural vibrations, depending on the value of the vibration amplitude. These internal sliding phenomena are associated with frictional dissipation, which makes the dynamic response of the device inherently non-holonomic.

The typical approach adopted in the literature to characterize the hysteresic behaviour of wire rope isolators (see e.g. [1]) is based on semi-empirical phenomenological models. These models allow to characterize the response of the devices with respect to simple loading cases (typically along a set of three coordinate direction, i.e. the vertical, pitch and roll directions [1,2]).

A different modelling approach is pursued in this work. The proposed model is based on a beam-like description of the wire rope and on a nonlinear formulation of the cross sections cyclic bending behaviour. At the cross-sectional level, the mechanical behaviour of the wire rope is described by extending the mechanical formulation for the hysteretic bending of stranded cables developed in [3], which has been recognized as adequate to represent the local behaviour mainly controlled by interwire sliding processes. The hysteretic cross-sectional model is then implemented within a corotational beam finite element, to fully account for the geometric non-linearities which characterize the response of the device. The performances of the proposed model are assessed through extensive comparisons with the results of well documented experimental tests of the literature.

References

[1] *Tinker, M.L., Cutchins, M.A., "Damping phenomena in a wire rope vibration isolation system", Journal of Sound and Vibration,* **157**, *7-18 (1992).*

[2] *Vaiana, N., Spizzuoco, M., Serino, G., "Wire rope isolators for seismically base-isolated lightweight structures: Experimental characterization and mathematical modeling", Engineering Structures,* **140**, *498-514 (2017).*

[3] *Foti, F., Martinelli, L., "Hysteretic behaviour of Stockbridge dampers: Modelling and parameter identification", Mathematical Problems in Engineering,* **Vol. 2018**, *Article ID. 8925121 1-17 (2018).*

Bistable nonlinear energy sink robustness analysis for multi-mode energy dissipation

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Keywords: bistable nonlinear energy sink; nonlinear vibration absorbers; impulsive excitation.

Nonlinear vibration absorbers, designed to resonate for a broad frequency band, have received considerable attention in the last decade [1]. Their main advantage with respect to their linear counterpart, i.e. the tuned mass damper (TMD), is that they are able to interact with more than one resonant mode of the primary system. In particular, the bistable nonlinear energy sink (BNES), consisting of a small mass connected to the primary system by a cubic nonlinear and a negative linear springs, is able to exhibit unique dynamical characteristics. Its main feature consists in possessing a double well potential, which enables it to have very different dynamic regimes, depending on the energy level. Namely, it performs linear in-well motion al low energy, chaotic intra-well motions at middle energy levels and 1:1 modal interaction at high energy [2].

Following a recent study of the authors [3], in this work, the robustness of the bistable nonlinear energy sink for the mitigation of impulsive excitation of a two-degree-of-freedom (DOF) primary system is assessed. The performance of the BNES at high energy level are analytically estimated by the identification of slow invariant manifolds, i.e. high dimensional surfaces relating the absorber vibration amplitude to the primary system one. In-well dynamical efficiency is also analytically evaluated exploiting its almost linear nature, while for the analysis of the chaotic regimes combined analytical-numerical methods are utilized. The robustness assessment is performed varying the distance in frequency between the two modes of the primary system, in order to study the different behavior of the BNES for close or distant primary system natural frequencies.

A comparative analysis between the BNES and the TMD is eventually performed. The comparison hinges on the TMD and BNES different capabilities to enlarge their frequency bandwidth: the latter, by increasing damping, the former, by increasing nonlinearity in presence of small damping. The obtained results illustrate that analytical techniques can be successfully used to estimate performance of the BNES, while interacting with multi-DOF primary systems. Optimal energy ranges of efficiency for the BNES are identified and explicit formula for their rapid identification are provided. The comparative analysis shows that the performance of the two absorbers is not significantly different. This suggests that the choice between the BNES or the TMD in a practical engineering application should be guided by the technological requirements of the specific application at hand.

References

[1] *Vakakis, A.F., Gendelman, O., Energy pumping in nonlinear mechanical oscillators: part II–resonance capture, Journal of Applied Mechanics,* **68***, page 42-48 (2001).*

[2] *Manevitch L.I., Sigalov G., Romeo F., Bergman L. A., Vakakis A., Dynamics of a linear oscillator coupled to a bistable light attachment: analytical study, J. Appl. Mech.,* **81***, page 041011 (2014).*

[3] *Habib G., Romeo F., The tuned bistable nonlinear energy sink, Nonlinear Dynamics,* **89***, page 179-196 (2017).*

Optical flow dynamic measurements with high-speed camera on a small-scale steel frame structure

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Keywords: image analysis dynamic measurements, high-speed camera, feature tracking.

The tremendous advances in high-resolution and high-speed cameras have allowed improving optical measurement techniques enabling extraction of dynamic characteristics of vibrating structures [1-3]. These techniques turned out to be particularly useful for vibration observations as they are contactless and they don't interfere with the structural response (as indeed is the case of accelerometers installed on a light-weight set-up, with non-negligible additional masses).

The paper reports the results of an experimental campaign, carried out to verify the accuracy of the dynamic displacements measurement obtained with a high-speed camera and the Hybrid Lagrangian Particle Tracking software [4], a software based on the solution of the Optical Flow equation [5]. The experimental setup includes a 4-dof small-scale steel frame structure excited on a shaking table, a high-speed camera able to record images of the motion and five accelerometers. From images, a two-dimensional moving field is recorded and the absolute and relative displacements are determined. Confidence in the novel developed measuring methodology is determined by direct comparison with acceleration measurements and numerical prediction of a structural model. Compared to the numerical displacements, the image analysis measurements turned out to be sufficiently accurate and the second derivatives of the acquired data are compatible with the direct accelerometer measures.

References

[1] *Baqersad, J., Poozesh, P., Niezrecki, C., Avitabile, P., "Photogrammetry and optical methods in structural dynamics - A review", Mechanical Systems and Signal Processing", **86**, 17-34 (2017).*

[2] *Ferrer, B., Espinosa, J., Pérez, J., Ivorra, S., Mais, D., "Optical scanning for structural vibration measurement", Research in Nondestructive Evaluation, **22**, 61-75 (2011).*

[3] *Trebunˇa, F., Hagara, M., "Experimental modal analysis performed by high-speed digital image correlation system", Measurement, **50**, 78-85 (2014).*

[4] *Shindler L, Moroni M, Cenedese A., "Using optical flow equation for particle identification and velocity prediction in particle tracking", Applied Mathematics and Computation, **218**, 8684-8694 (2012).*

[5] *Moroni M., Cenedese A., "Comparison among feature tracking and more consolidated velocimetry image analysis techniques in a fully developed turbulent channel flow", Measurement Science and Technology, **16**, 2307-2322 (2005).*

Non-linear Features in Structural Control

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Keywords: control law, nonlinearity, structural control

Kolovsky [1] published 20 years ago a book linking nonlinear dynamics with the broad technological area of vibration protection.

The last two decades have seen the suggestion of devices for passive control and the introduction of innovative schemes for semiactive and active control. The former items often come with equivalent linearized approximations, while the latter technology is mainly applied to linear systems, with control laws either linear or nonlinear.

A critical discussion of modelling versus implementation and design is addressed by this contribution. The main finding is to outline the gap between technical solutions and that would appear as a sound mechanical idealization.

References

[1] Kolovsky M.Z., "Nonlinear dynamics of active and passive systems of vibration protection, Foundation of Engineering Mechanics, Springer Verlag, 1999.

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STOCHASTIC MECHANICS AND PROBABILITY IN ENGINEERING

Stochastic seismic assessment of bridge networks by matrix-based system reliability method

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Keywords: system reliability, bridge network, stochastic optimization

Infrastructure systems represent an important role for economic activity and emergency response after a disaster, such as an earthquake. In these infrastructures, bridges are important components but are often considered the weak link because of their vulnerability to hazards. Indeed, the structural damage of a bridge can create a disconnection in a network or can reduce its functionality. For this reason, a probabilistic approach is a natural environment in which to analyze a complex network and to carry out in risk/loss assessment and decision-making processes. This problem presents various computational challenges and usually, the sampling-based approaches are used to account the uncertainty [1]. In this contribution, a non-sampling based approach is proposed. The main challenging is to compute the probability of complex system events by simple matrix calculations.
In general, the matrix-based system reliability (MSR) approach is applicable to general system events including series, parallel, cut-set and link-set systems and provide the system failure probability to facilitate an optimization [2].
The MSR method is able to describe component failure probabilities by vectors and also estimating the probabilities of complex system events with parameters sensitivities through efficient matrix calculations.
With this method, it is possible to quantify the reliability of the system under seismic action [3]. Furthermore with MSR method is possible to compute the probability of disconnection between each city and also estimate the conditional probabilities of component failures given the system failure. By means of conditional probabilities, it is possible to numerically quantify the disconnection events produced by damage or collapse of bridges. Finally, it is possible to evaluate the minimum risk path with a linear programming optimization. The problem of linear stochastic programming exhibits some similarity that can be found to evaluate the collapse of truss structures [4].

References

[1] Guikema, S., and Gardoni P. "Reliability estimation for networks of reinforced concrete bridges." Journal of Infrastructure Systems 15.2: 61-69 (2009).
[2] Song, J., and Kang W.-H.. "System reliability and sensitivity under statistical dependence by matrix-based system reliability method." Structural Safety 31.2: 148-156 (2009).
[3] Kang, W.-H., Song J. and Gardoni, P., "Matrix-based system reliability method and applications to bridge networks." Reliability Engineering & System Safety 93.11 1584-1593 (2008).
[4] Caddemi, S., Ricciardi G., and Saccà C. "Limit analysis of structures with stochastic strengths by a static approach." Meccanica 37.6 : 527-544 (2002).

Influence of user-defined parameters using Stochastic Subspace Identification (SSI).

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Keywords: OMA, SSI, damping estimation

Operational Modal Analysis (OMA) is nowadays the most used technique to test structure under ambient excitation, for structural health monitoring, for acceptance test and for model updating.

In Operational Modal Analysis, the modal parameters are obtained only from the measured data using ambient vibration as unknown input (wind load, micro-tremors, traffic) and without any artificial excitation applied on the structure. Conversely, in classical Experimental Modal Analysis (EMA), modal parameters are evaluated by applying a measured input on the system and measuring the response of the system.

The advantage of OMA technique is that it can be used to test big scale structures, impossible to test using artificial excitation, and provides a modal model under operating conditions, meaning within true boundary conditions, actual force and vibration levels. Other advantages of OMA are the velocity and cheapness to make the tests, and the possibility to find close-spaced modal shapes.

One of the most used methods in OMA is the Stochastic Subspace Identification (SSI) [1], it relies on an elegant mathematical framework and robust linear algebra tools to identify the state-space matrix from raw data. As a result, non-linear optimization problems are avoided. Moreover, the use of well-known tools from numerical linear algebra, such as SVD and LQ decomposition, leads to a numerically very efficient implementation.

To obtain accurate modal parameters estimations, especially damping ratios, some user-defined parameters need be properly set [2].

In this paper, two user-defined parameters for damping estimation using Data-Driven Stochastic Subspace Identification (DD-SSI) method are investigated: the number of block rows in Hankel matrix and the selection of the length of the data acquired used in the identification process. In order to establish a standardization on the use of those parameters for reliable system parameters identification, a sensitivity analysis have been conducted on both laboratory models and real scale buildings vibration data.

References

[1] *Van Overschee, P. and De Moor, B.: Subspace Identification for Linear Systems: Theory – Implementation – Applications, Dordrecht, The Netherlands, Kluwer Academic Publishers, (1996).*

[2] *Rainieri, C., & Fabbrocino, G. (2014). "Influence of model order and number of block rows on accuracy and precision of modal parameter estimates in stochastic subspace identification", International Journal Lifecycle Performance Engineering,* ***Vol****. 1(4), 317–334 (2014).*

Analysis of linear elastic cracked structures with uncertain-but-bounded depths

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Keywords: uncertain-but-bounded damage, cracked structures, dynamic structural response

The present paper deals with the dynamic response of linear elastic structures with cracked members [1]. For a realistic prediction of the mechanical response of such structures, the unavoidable uncertainty affecting the cracked members has to be taken into account. To this aim, the crack depths have been modeled as uncertain-but-bounded variables [2]. The objective of the study is the evaluation of the time-varying upper and lower bounds of the response of a truss structure with multiple cracks with uncertain interval depths subjected to a deterministic excitation.

The analysis is performed by adopting a finite element approach where the crack in a member is modeled by introducing a local compliance that produces a discontinuity of the displacements in correspondence of the cracked section [3]. The compliance of the cracked member is determined by simply adding the compliance of the intact element to the overall compliance due to the crack.

In order to provide the bounds of the response, an approach originating from [4,5], which requires the derivation of the bounds of the interval eigenvalues evaluated as solution of two suitable deterministic eigenvalue problems, is followed. A preliminary analysis is conducted to provide the two commonest combinations of the bounds of the interval uncertainties over the time of interest via a pseudo-static sensitivity approach [6].

The proposed procedure is validated through numerical tests on truss-like structures. The accuracy is evidenced by the excellent agreement between the response bounds calculated by the present approach compared with the exact bounds derived via a combinatorial procedure.

The application of the method can be straightforwardly extended to frame-like structures with uncertain damage.

References

[1] Okamura, H., Watanabe, K., and Takano T., "Deformation and strength of cracked member under bending moment and axial force", Eng Fract Mech, ***Vol. 7(3)****, 531-539 (1975).*

[2] Moore, R.E., Interval Analysis, Prentice-Hall, Englewood Clifffs (1966).

*[3] Gentilini, C.,Ubertini F., and Viola, E., "Probabilistic analysis of linear elastic cracked structures with uncertain damage", Prob Eng Mech,****Vol. 20****, 307-323 (2005).*

[4] Sofi, A.,Muscolino G., and Elishakoff, I., "Natural frequencies of structures with interval parameters", J Sound Vib, ***Vol. 347****, 79-95 (2015).*

[5] Muscolino G., and Santoro, R., "Dynamics of multiple cracked prismatic beams with uncertain-but-bounded depths under deterministic and stochastic loads", J Sound Vib, ***Vol. 443****, 717-731 (2019).*

[6] Muscolino G., Sofi, A., and Giunta, F., "Dynamics of structures with uncertain-but-bounded parameters via pseudo-static sensitivity analysis", Mech Syst Signal Pr, ***Vol .11****, 1-22 (2018).*

Optimal design of a U-OWC nonlinear wave energy harvester

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Keywords: Statistical Linearization, U-OWC, Genetic Algorithms.

This work deals with the development of an algorithm identifying the optimal geometrical configuration of a U-Oscillating Water Column wave energy harvester [1]. As classical oscillating water column systems, it is composed by a water column and an air chamber equipped with a Power Take-Off (PTO) system (usually a Wells turbine). However, it includes also an additional vertical duct located in the wave beaten. This duct allows increasing the inertia of the device, which is utilized for tuning the eigen-period of the U-OWC to a desired period. The dynamics of a U-OWC is governed by the two coupled nonlinear integro-differential equations describing, respectively, the water column oscillations (x) and the air pressure (p_c) variations,

$$M(x)\ddot{x} + C(\dot{x},x)\dot{x} + x + \frac{1}{\rho g}(p_c - p_{atm}) + \frac{b_2}{g b_1}\int_{-\infty}^{t} K(t-\tau)\dot{x}(\tau)d\tau = \frac{\Delta p^{(D)}}{\rho g}$$

and

$$C_p(x)\dot{p}_c - C_x(p_c)\dot{x} + K_p(p_c)p_c = 0,$$

where it is seen that nonlinear mass, damping and stiffness terms appear. These equations have no closed-form solution. Therefore, time-consuming numerical approaches are employed to obtain the response of the system. In addition to that, the system parameters are geometry dependent and must be determined by solving a related boundary value problem according to the linear water wave theory [2]. These facts pose significant challenges during the design process, when a number of possible configurations must be analyzed.

To cope with this problem we propose an analysis based on Genetic Algorithms (GAs) [3], that are stochastic search techniques finding iteratively a solution from an initial population of vectors via operations of selection and recombination. For solving efficiently the optimization problem, a semi-analytical approach is adopted to compute the hydrodynamic parameters of the U-OWC and the statistical linearization technique [4] is utilized for estimating to the U-OWC response. The GA is used for selecting some U-OWC geometrical parameters under the assumption that the system is exposed to the action of a given (fixed) sea state. In this context, the algorithm objective function is the electrical power produced by the Wells turbine. The proposed method is validated against Parameter Sweep (PS). It is shown that it is able to find the global maximum of the power and reduces considerably, more than ten times, the computational time with respect to the PS.

References

[1] P. Boccotti, "On a new wave energy absorber," Ocean Eng., vol. 30, no. 9, pp. 1191–1200, 2003.

[2] G. Malara F. Arena, Response of U-Oscillating Water Column arrays: semi-analytical approach and numerical results, Renewable Energy, vol. 138, pp. 1152-1165, 2019.

[3] J.H. Holland, Adaptation in natural and artificial systems: an introductory analysis with applications to biology, control, and artificial intelligence, MIT press, 1992.

[4] J.B. Roberts, P.D. Spanos, Random Vibration and Statistical Linearization, Dover Publications, Mineola, New York, USA, 2003.

Dealing with uncertainties in structural dynamic identification and damage detection of cable stayed footbridges

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Keywords: Uncertainty Quantification, Bayesian Inverse Problem, Operational Modal Analysis

Structural identification is a very important task especially in all those countries characterized by significant architectural and historical heritage and strongly vulnerable infrastructures subjected to degradation with time and to natural hazards, e.g. seismic and wind loads.
Structural response of existing constructions is usually estimated using suitable numerical models that are driven by a set of geometrical and/or mechanical parameters that are usually unknown and/or affected by different levels of uncertainties. Some of these information can be obtained by experimental tests but it is practically impossible to obtain all the required data for reliable response estimations. For these reasons it is current practice to calibrate some of the significant unknown and/or uncertain geometrical and mechanical parameters using measurements of the actual response (static and/or dynamic) and solving an inverse structural problem [1].
The identification of structural dynamic characteristics (e.g. natural frequencies, mode shapes and damping ratios) is usually carried out by means of monitoring data provided by Ambient Vibration Tests (AVT). Ambient vibration sources include wind, seismic micro tremors, pedestrian and traffic, which are not deterministic and can be only described by random processes. In the Operational Modal Analysis (OMA) technique this input excitation is not measured and it is assumed to be a stationary white noise [2]. Nevertheless these ambient vibrations can be very far to be stationary: therefore, tools are therefore needed to take into account all these sources of uncertainties.
In this paper a new robust framework to be used in structural identification is proposed in order to have a reliable numerical model that can be used both for random response estimation and for structural health monitoring (SHM). First a tentative FE model of the existing structural system is developed and updated using probabilistic Bayesian framework. Second, virtual samples of the structural response affected by random loads are evaluated. Third, these virtual samples are used as "virtual experimental response" in order to assess the effect of the signal sampling parameters on the estimation of structural modal features. Finally, the information given by the measurement uncertainties are used to assess the capability of vibration based damage identification methods [3]. The obtained results will be crucial to follow the structural performance and reliability in - time (SHM) and to develop suitable damage detection procedures to be used in a early warning framework.

References

[1] *Marwala,T., Finite-element-model Updating Using Computational Intelligence Techniques, Springer-Verlag, London, (2010)*

[2] *Brincker, R., Introduction to Operational Modal Analysis, Wiley-Blackwell, (2015).*

[3] *Rytter, A., Vibrational Based Inspection of Civil Engineering Structures, Ph.D.-Thesis University of Aalborg, April 20, (1993).*

An innovative ambient identification method

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Keywords: Operational Modal Analysis, Hilbert Transform, Analytical.

Ambient modal identification, also known as Operational Modal Analysis (OMA), aims to identify the modal properties of a structure based on vibration data collected when the structure is under its operating conditions, i.e., no initial excitation or known artificial excitation. This procedure for testing and/or monitoring historic buildings, is particularly attractive for civil engineers concerned with the safety of complex historic structures. However, since the external force is not recorded, the identification methods have to be more sophisticated and based on stochastic mechanics [1].

In this context, this contribution will introduce an innovative ambient identification method based on applying the Hilbert Transform [2, 3], to obtain the analytical representation of the system response in terms of the correlation function. In particular, it is worth stressing that the analytical signal is a complex representation of a time domain signal: the real part is the time domain signal itself, while the imaginary part is its Hilbert transform. Several numerical examples will be presented to show the accuracy of the proposed procedure, and comparisons with data from virtual experiments of multi-degree-of-freedom systems will be used to assess the reliability of the approach.

References

[1] *Barone, G., Marino, F. and Pirrotta, A., "Low stiffness variation in structural systems: identification and localization", Structural Control and Health Monitoring,* ***15****, 450-470 (2008).*

[2] *Cottone, G., Pirrotta, A. and Salamone, S. "Incipient Damage Identification through Characteristics of the Analytical Signal Response", Structural Control and Health Monitoring,* ***15****, 1122-1142 (2008).*

[3] *Lo Iacono, F., Navarra, G. and Pirrotta A., "A Damage Identification procedure based on Hilbert transform: experimental validation", Structural Control and Health Monitoring,* ***19****, 146-160 (2012).*

Speeding up the stochastic linearisation for systems controlled by non-linear passive devices

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Keywords: stochastic linearisation, passive control devices, spectral moments

The response of structures under dynamic loadings is often improved by introducing passive control devices, such as Fluid Viscous Dampers, Tuned Mass Dampers, Tuned Liquid Column Dampers, Non-linear Energy Sinks. These devices can operate through the dissipation of the input energy or by changing the dynamic characteristics of the main structure at which they are attached, thus involving several different physical mechanisms. Nevertheless, the large-scale use and design of these devices have been limited by the computation difficulties due to the presence of inherent non-linearities in constitutive laws. To overcome this limitation it is common to replace non-linear equations of motion of a system equipped with a passive device with linear equivalent ones by using well-established procedures as Stochastic Linearisation Techniques (SLT) [1]. The conditions of equivalence may be established in order to preserve some response quantities in statistical sense, when passing from the non-linear to the equivalent linear system. Most of SLT operate recursively, since the values of the equivalent linear parameters implicitly depend on response statistics. Hence, the computational burden required for the analyses increases. Moreover, calculations are very often carried out only numerically, since analytical solutions for response statistics are available only for a limited class of problems. Recently, an analytic closed-form model for PSD functions of stochastic representations of earthquake loads coherent to response spectra suggested by seismic codes has been proposed [2] and analytical approximate expressions of statistical quantities of the response, such as the first spectral moments, have been derived [3, 4]. In this study, the aforementioned findings have been exploited in order to speed up the convergence of the recursive algorithms in SLT procedure by setting a starting point closer to the final value. Analytic solutions and numerical applications have been carried out on both Single- and Multi-Degree-Of-Freedom structural systems in order to assess the validity of the proposed approach and its ability in reducing the computational effort approaching the design procedure of passive control devices coherently with the provisions of seismic building codes.

References

[1] *J.B. Roberts and P.D. Spanos, Random Vibration and Statistical Linearization, Wiley, New York, USA, 1990*

[2] *G. Barone, F. Lo Iacono, G. Navarra, A. Palmeri, A novel analytic model of power spectral density function coherent with earthquake response spectra, in Proceedings of UNCECOMP 2015, 25th-27th May 2015, Crete, Greece, (2015).*

[3] *V. Artale, G. Navarra, A. Ricciardello, G. Barone, "Exact closed-form fractional spectral moments for linear fractional oscillators excited by a white noise", ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering,* **3***(3). doi: 10.1115/1.4036700, (2017).*

[4] *G. Navarra, F. Lo Iacono and M. Oliva, "Probabilistic optimal design of passive control devices coherently with seismic codes response spectra", in AIMETA 2017 - Proceedings of the 23rd Conference of the Italian Association of Theoretical and Applied Mechanics, (2017).*

TMD optimal position in 3D frames excited by gaussian noises

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Keywords: passive control, optimal placement, TMD

Tuned mass damper (TMD) is the most well-known and widely used passive control device to mitigate structural vibrations in civil and mechanical engineering. Several configurations have been proposed and installed all over the world on real structures, such as bridges, tall buildings, wind turbines and so on [1].

An extensive literature exists on the design of the optimal parameters (i.e. damping, stiffness and mass ratio) of TMDs installed on structures excited by random loadings [2]. Only a few studies have been carried out on the optimal position of the TMD, yet most of them consider multi-storey shear-type structures [3].

In this paper, the effectiveness of the unidirectional TMD is analysed considering the influence of its position in three dimensional structures excited by white and coloured Gaussian noises. In particular, the stochastic dynamic response of an one-storey 3d building controlled by an unidirectional TMD has been determined in closed-form as a function of the epicentral direction of the ground excitation, the direction of motion of the device, and its position relative to the frame centre of mass. The analysis is performed under the assumption of negligible axial deformations of beams and columns and floor diaphragm rigid in its own plane while flexible in bending, so that the frame motion is determined by three degrees of freedom, i.e. translations in two orthogonal directions, and rotation about the geometric vertical axis.

The proposed mathematical model enables predicting the optimal parameters and location of the TMD, and the resultant stochastic dynamic response of the primary structure in closed-form, with no further requirements for implementing numerical optimisation algorithms. Finally, sensitivity analyses have been performed to evaluate the influence of changes in mechanical and geometrical characteristics of the primary structure on the model results, thus identifying its range of validity.

References

[1] *Housner, G., Bergman, L., Caughey, T., Chassiakos, A., Claus, R., Masri, S., Skelton, R., Soong, T., Spencer, B., Yao, J., "Structural Control: Past, Present, and Future", Journal of Engineering Mechanics,* **123***(9), 897–971, (1997).*

[2] *Asami, T., Nishihara, O., Baz, A.M., "Analytical Solutions to H∞ and H2 Optimization of Dynamic Vibration Absorbers Attached to Damped Linear Systems", Vib Acoust.,* **123***(2), 284-295, (2002).*

[3] *Chen, G., Wu, J., "Optimal Placement Of Multiple Tune Mass Dampers For Seismic Structures", J. Struct. Eng.,* **127***, 1054-1062, (2001).*

Comparison of surrogate models for handling uncertainties in SHM of historic buildings

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Keywords: surrogate models, structural health monitoring, historic buildings.

Structural Health Monitoring systems, complemented by Operational Modal Analysis techniques, represent valid tools to assist post-earthquake structural assessment [1]. This task can be achieved by exploiting monitoring data in conjunction with a building's Finite Element Model for response simulation [2,3]. The availability of experimental data from Ambient Vibration Tests or long-term dynamic monitoring is of aid for getting accurate knowledge of the building and reducing the uncertainty related to the parameters characterizing the building's modal behavior. Monitoring records can be used for the FE model calibration and updating, or for tracking the uncertain parameters' evolution due to material's aging or damage. Especially in the case of masonry historic buildings, where the computational burden of FEM simulations is large, surrogate modelling can be used to bypass the numerical model when performing damage localization or continuous model updating.
In this context, surrogate models consist of statistical tools for regression analysis that give a numerical estimate of modal characteristics (natural frequencies and modal displacements) as a function of the uncertain mechanical parameters of the structure [4]. The accuracy of the surrogate model can strongly influence the results of damage localization or model updating. For this reason, in this paper different metamodels are compared such as: quadratic response surface method (RSM), Kriging model and Random Sampling High Dimensional Model Representation (RS-HDMR).
The surrogate models are built with reference to a 41 m high civic tower located in the city of Perugia, Italy, named *Torre degli Sciri*. The tower is equipped with a long-term dynamic monitoring system that continuously provides data since December 2107. The tower is made of stone masonry, has a quadrangular cross-section and is incorporated into a building aggregate.
The results of modal parameters estimation obtained with the different investigated surrogate models, allow to compare their performance and accuracy and give an insight into the advantages and disadvantages of their use for damage assessment of historic buildings.

References
[1] Saisi, A., Gentile, C., Guidobaldi, A., "Post-earthquake continuous dynamic monitoring of the Gabbia Tower in Mantua, Italy", Construction and Building Materials, ***81****, 101-112.*
[2] Di Paola, M., Iacono, F.L., Navarra, G., Pirrotta, A., "Impulsive tests on historical structures: The dome of Teatro Massimo in Palermo", Open Construction and Building Technology Journal ***10****(Suppl 1: M7), 122-135, (2016).*
[3] Ubertini, F., Cavalagli, N., Kita, A., Comanducci, G., "Assessment of a monumental masonry bell-tower after 2016 Central Italy seismic sequence by long-term SHM", Bulletin of Earthquake Engineering, ***16****, 775-801, (2018).*
[4] Garcìa-Macìas E., Castro-Triguero R., Friswell M.I., Adhikari S., Sàez A., "Metamodel-based approach for stochastic free vibration analysis of functionally graded carbon nanotube reinforced plates", Composite Structures, ***152****, 183-198, (2016).*

Is it true that the higher is the number of plies, the safer is a brittle laminate?

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Keywords: laminates, brittle materials, redundancy, robustness.

Motivation for this study arises from the optimization of brittle glass in challenging architectural works. When glass is used in structural applications, the common belief is that lamination is always beneficial, thanks to stress redistribution after breakage of one of more plies. It is well known that, for-plastic materials, the more numerous are the elements in which the structure is divided, the higher is the improvement in structural reliability [1]. This principle is always assumed even more so for brittle materials, although plastic adaptations are not possible.
The “failure modes” approach [1] is here used to obtain the retro-cumulative functions of plate strength for brittle laminated plates composed by a variable number of plies under in-plane or out-of-plane bending. Two limit conditions are considered based upon the ability of the interlayers at transferring shear stresses among the plies: the layered behaviour and the monolithic behaviour. For the sake of comparison, material strength is characterized by different statistics *à la* Weibull [2], implying either a volume size effect or a size effect related to the tensile surface area, as in the case of structural glass [3]. A log-normal normal statistics is also considered, for the sake of comparison, to model materials that do not exhibit size effect.
For the same maximum stress in the sound state, lamination is beneficial under any circumstances for plate made by a material with volume size effect. The same is true for area size effect only if the plate is in-plane loaded, otherwise lamination leads to an increasing of the surface area subject to tensile stress. In this latter case, stress redistribution can counterbalance this negative effect only for the extreme lower quantiles of the plate strength distribution. When no size effect is present, the gain from lamination is only appreciable on the left-hand-size tail of the retro-cumulative function, regardless of the type of loading.
These findings do not confirm the common belief that increasing the number of plies leads to a safer design. One should consider the structural reliability as a whole and compare, on a statistical basis, what is the real gain obtainable through lamination in terms of probability of survival under the applied design load, in order to define the optimal number of plies for any specific application.

References

[1] *Melchers, R.E., Beck, A.T., Structural Reliability Analysis and Prediction – Third Edition, John Wiley & Sons Ltd, Hoboken NJ-USA, (2018).*
[2] *Weibull, W., “A statistical theory of the strength of materials”, Ingenirsvetenskapsakademiens Handlingar, **151**, page 1-45, (1939).*
[3] *Pisano, G., and Royer Carfagni, G., “The statistical interpretation of the strength of float glass for structural applications”, Construction and Building Materials, **98**, page 741-756, (2014).*

Stress-driven approach for stochastic analysis of noisy non-local beam

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Keywords: integral formulation, random vibrations, eigen-analysis
Several structures, such as micro/nano-devices, long-fiber reinforced composites, beam with external patches, exhibit a mechanical behavior that cannot be described by classical local continuum model. For these structural elements, since the long-range interactions cannot be neglected, it is needed the introduction of an enriched mechanical model that takes into account these nonlocal effects. For this reason, during the last decades, several scientific efforts have been dedicated to the formulation of various nonlocal mechanical models [1–5]. Among these formulations, the stress-driven approach has been recently developed [6, 7]. In addition to overcome some limitations and paradoxes of the classic integral nonlocality, such recent integral model allows to obtain some closed-form solutions. Specifically, for bending problems, the stress-driven formulation provides the analytical solutions in terms of transverse displacement for several static cases [8]. In this work the stress-driven approach is used to perform the stochastic dynamic analysis of nonlocal beams. The natural frequencies and the eigenfunctions of nonlocal Euler-Bernoulli beam are evaluated, and the Power Spectral Density function of the displacement response due to a Gaussian white noise input is provided for different values of the nonlocal parameters. Such kind of problem is of interest for the applications of nano- and micro-beams as actuators and sensors where stochastic analysis is needed to reproduce the real load cases and and the size effect causes the nonlocal mechanical behavior.

References

[1] *Kröner, E., Elasticity theory of materials with long-range cohesive forces, Int J of Solids Struct,* **3**, *pages 731-742, (1967).*

[2] *Eringen, A.C., Linear theory of nonlocal elasticity and dispersion of plane waves, Int J of Eng Sci,* **10**, *pages 425-435, (1972).*

[3] *Polizzotto, C., Non local elasticity and related variational principles, Int. J. of Solids Struct,* **38**, *pages 7359-7380, (2001).*

[4] *Di Paola, M., Zingales, M., Long-range cohesive interactions of non-local continuum faced by fractional calculus, Int. J. of Solids Struct,* **45**, *pages 5642-5659, (2008).*

[5] *Alotta, G., Failla, G., Pinnola F. P., Stochastic Analysis of a Nonlocal Fractional Viscoelastic Bar Forced by Gaussian White Noise, ASCE-ASME J. of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering,* **3(3)***:030904-030904-7, (2017).*

[6] *Romano, G., Barretta, R., Diaco, M., Marotti de Sciarra F., Constitutive boundary conditions and paradoxes in nonlocal elastic nano-beams, Int J Mech Sci,* **121**, *pages 151-156, (2017).*

[7] *Romano, G., Barretta, R., Nonlocal elasticity in nanobeams: the stress-driven integral model, Int J of Eng Sci,* **115**, *pages 14-27, (2017).*

[8] *Barretta, R., Čanadija, M., Feo, L., Luciano, R., Marotti de Sciarra, F., Penna, R., Exact solutions of inflected functionally graded nano-beams in integral elasticity, Composites Part B,* **142**, *pages 273-286, (2018).*

Fracture of beams with random field properties: fractal and Hurst effects

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Keywords: Griffith's fracture criterion, random fields, fractal-and-Hurst effects.

The classical problem of peeling a beam off a substrate is studied through a re-examination of Griffith's fracture criterion in the presence of multiscale random properties [1]. Four types of wide-sense stationary Gaussian random fields of the vector {Young's modulus E, surface energy density γ} are considered: Ornstein–Uhlenbeck, Matérn, Cauchy, and Dagum. The latter two allow decoupling of the fractal-and-Hurst effects [2]. The need to actually include the fractal-and-Hurst properties is motivated by the richness of temporal and spatial phenomena in the real world: geophysics, atmosphere, biology, and economy. In particular, fracture mechanics provides stepping-stone models to studies of many critical phenomena in geomechanics, where long cracks like fault lines in geologically unstable areas are relevant in geotechnical and foundation engineering.

The variance of the crack driving force G with any given type of random field in terms of the covariances of E and γ, under either fixed-grip or dead-load conditions, is calculated. In view of the non-linear relationship between the random field vector RF {E, γ} and the crack driving force G, the exact variance function of energy and its release rate is evaluated by a recently established probability transformation method (PTM) [3-4]. This investigation is complemented by a study of the stochastic crack stability, which involves a stochastic competition between potential and surface energies. Also, the Obreimoff experiment is treated through the evaluation of the probability density function of the critical crack length. Overall, we find that, for Cauchy and Dagum models, the introduction of fractal-and-Hurst effects strongly influences the fracture mechanics results. However, even if Cauchy and Dagum models represent a more realistic scenario of RFs, given the same covariance on input, the response on output is strongest for Matérn, then Ornstein–Uhlenbeck, then Cauchy and finally Dagum model.

References

[1] Ostoja-Starzewski, M., Microstructural Randomness and Scaling in Mechanics of Materials, CRC Press, Boca Raton, (2008).
[2] Gneiting, T., Schlather, M., "Stochastic models that separate fractal dimension and the Hurst effect", SIAM, 46, 269-282, (2004).
[3] Falsone, G., Settineri, D., "Explicit solutions for the response probability density function of linear systems subjected to random static loads", Probabilistic Engineering Mechanics, 33, 86-94, (2013).
[4] Falsone, G., Laudani, R., "A probability transformation method (PTM) for the dynamic stochastic response of structures with non-Gaussian excitations", Engineering Computations, 35, 1978-1997, (2018).

Laplace’s method of integration in the Path Integral approach for the probabilistic response of nonlinear systems

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Keywords: Path Integral, Laplace’s method, Probability density function.

In this paper the nonstationary response of a class of nonlinear systems subject to broad-band stochastic excitations is examined. A version of the Path Integral (PI) approach is developed for determining the evolution of the response Probability Density Function (PDF). Specifically, the PI approach [1], utilized for evaluating the response PDF in short time steps based on the Chapman-Kolmogorov equation, is here employed in conjunction with the Laplace’s method of integration [2]. In this manner, an approximate analytical solution of the integral involved in this equation is obtained, and the repetitive integrations generally required in the conventional numerical implementation of the procedure can be circumvented.

The proposed approach is developed for one-dimensional nonlinear systems under modulated white noise. Further, extension to nonlinear oscillators subject to separable evolutionary broad-band processes is provided, relying on the approximate model of the system response amplitude as a one-dimensional Markov process [3]. Applications to three different nonlinear systems is considered. Specifically, results pertinent to a first-order nonlinear system, a Duffing oscillator, and a Van der Pol oscillator are presented. Analyses are carried out for several broad-band excitations and degree of nonlinearities. Appropriate comparisons with Monte Carlo simulation data are presented, demonstrating the efficiency and accuracy of the proposed approach.

Notably, considering the non-negligible computational cost required by the classical application of the Path Integral method, especially for higher-dimensional systems, the proposed approach could offer some advantages for an efficient analytical, albeit approximate, evaluation of the involved integrals.

References

[1] Bucher, C., Di Matteo, A., Di Paola, M., Pirrotta, A., “First-passage problem for nonlinear systems under Lévy white noise through path integral method”, Nonlinear Dynamics, ***85****, 1445-1456 (2016).*

[2] Bender, C.M., Orszag, S.A., Advanced Mathematical methods for scientists and Engineers I: Asymptotic methods and perturbation theory, Springer, New York (1999).

[3] Kougioumtzoglou, I.A., Spanos, P.D., “Response and First-Passage Statistics of Nonlinear Oscillators via a Numerical Path Integral Approach”, Journal of Engineering Mechanics, ***139****, 1207-1217 (2013).*

Estimation of masonry texture and mechanical characteristics by means of thermographic images

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Keywords: Masonry, Thermal Imaging, Experimental tests

When dealing with the estimation of mechanical characteristics of masonry belonging to existing building, one of the problems the structural engineering has to face is that the masonry panels are covered with plaster. In the case of historical and monumental buildings, the plaster may host frescos, and therefore they can not be removed to study the masonry. It would be therefore valuable to have a method to estimate the behaviour of the masonry in such situations, using non-destructive techniques [1].

In preceding works, the authors have proposed to use thermal images taken with a infra-red camera in order to recover information on the texture of the masonry panels. It has been moreover shown that by applying reconstruction techniques it is possible to enhance the quality of the images and achieve a better representation of the texture [2, 3].

In this paper, we present the results obtained in a test campaign designed to refine the technique, to explore its limits and capabilities and to validate the obtained results. Three samples with different textures have been used. The textures adopted are: periodic, quasi-periodic and random. The samples have dimensions 750 mm $\times$ 750 mm, are made from blocks obtained by bricks with dimensions 250 mm $\times$ 120 mm $\times$ 55 mm and with mortar joints having thickness 10 mm. The samples have been covered with plaster having thickness 10 mm. Thermographic images of the samples have been taken, the textures have been identified and compared with those obtained with photographic images and eventually the mechanical characteristic have been estimated numerically by means of "test-window" approach [2]. In order to validate the obtained results, the masonry samples have been also tested in laboratory.

The effect of the uncertainties in the parameters involved in the reconstruction of texture from thermographic image, such has the upper and lower bound of temperature range and the properties of the kernel used in the image enhancement algorithm, have been studied in order to assess their influence on the estimated mechanical characteristics.

References

[1] *Titman, D.J., "Applications of thermography in non-destructive testing of structures," NDT & E International,* **34***, page 149-154 (2001)*

[2] *Cluni, F., Costarelli, D.,Minotti, A.M. and Vinti, G.,"Enhancement of thermographic images as tool for structural analysis in earthquake engineering", NDT & E International,* **70***, page 60-72 (2015)*

[3] *Cluni, F., Gusella, V. and Vinti, G., "Characterization of elastic properties of masonry through digital imaging techniques applied to thermographic images" in Proceedings of Eighth Conference on Computational Stochastic Mechanics (CSM 8), Paros (GR), June 10-13, (2018)*

Temperature dependent fractional viscoelastic material under stochastic agencies.

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Keywords: fractional viscoelasticity, temperature variation, stochastic process

Nowadays polymeric materials or composites with polymeric matrices are widely used in a very wide range of applications such as aerospace, automotive, biomedical and also civil engineering. From a mechanical point of view, polymers are characterized by high viscoelastic properties and high sensitiveness of mechanical parameters from temperature. Analytical predictions in real-life conditions of mechanical behaviour of such a kind of materials is not trivial for the intrinsic hereditariness that imply the knowledge of all the history of the material at hand in order to predict the response to applied external loads. If temperature variations are also present in the materials, a reliable evaluation of the response may be performed only if the variations of the material parameters with the temperature are taken into account. In [1, 2] the response of a fractional viscoelastic material subjected to stochastic temperature process and under deterministic loads has been faced up. In this work we study the problem of a fractional viscoelastic materials subjected to deterministic temperature history and forced by a stochastic load. It is shown that, if interpreted in the correct way, the Boltzmann superposition principle is still valid for such a kind of system and its application leads to a generalized form of the well known fractional viscoelastic constitutive laws. Moreover, by means of a proper discretization approach [3], it is possible the evaluate the response of the system also when the load is a stochastic process in order to perform Monte Carlo simulations.

References

[1] *Alotta, G., Colinas-Armijo, N., "Analysis of fractional viscoelastic material with mechanical parameters dependent on random temperature", ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering, 3(3), 030906, (2017).*

[2] *Colinas-Armijo, N., Di Paola, M., Di Matteo, A.,"Fractional viscoelastic behaviour under stochastic temperature process", Probabilistic Engineering Mechanics, 54, page 37-43, (2018).*

[3] *Colinas-Armijo, N., Di Paola, M., "Step-by-step integration for fractional operators ", Communications in Nonlinear Science and Numerical Simulations, 59, page 292-305, (2018).*

Exact solutions to the dynamic analysis of beams with periodically attached resonators

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Keywords: continuous-discrete systems, resonators, vibration attenuation.

Beams coupled with periodically attached resonators represent a new and challenging concept for vibration attenuation. Typically, they are modeled as a continuous-discrete system, where resonators are mass-spring subsystems coupled with a continuous beam. The continuous-discrete model has been applied to sandwich beams with embedded resonators [1], beams carrying beam-like resonators [2], elastic metamaterial beams [3]. Different resonators have been designed with the purpose of attenuating structural wave propagation over wide frequency ranges [1]-[3].

Most frequently, solutions for beams with periodically attached resonators have been sought in the frequency domain using the transfer matrix approach. Also, homogeneization techniques based on defining an equivalent mass per unit length have been used [1] or the Galerkin technique in presence of non-linearities [3].

With the present study a comprehensive framework is introduced to calculate the dynamic response of linearly-elastic beams with periodically attached resonators. The key is to show that a mass-spring subsystem modeling a resonator can be reverted to an equivalent external constraint whose reaction on the beam depends only on the displacement of the attachment point, through a suitable equivalent stiffness. This leads to derive the response of the whole system using the motion equations of the beam only. Specifically, the beam equations will be solved by a generalized function approach to handle the discontinuity of the response variables at the attachment points of the resonators [4]. In this context, exact frequency response functions will be obtained; exact modal frequency and impulse response functions will be also obtained, by a complex modal superposition approach on deriving suitable orthogonality conditions for the modes. The approach is formulated for periodically-spaced resonators but can readily be extended to continuously-distributed resonators, again starting from a pertinent equivalent stiffness. Continuously-distributed resonators are of great interest to attenuate structural wave propagation in beams over a wide frequency range.

References

[1] *Chen, J.S., Sharma, B., Sun, C.T., Dynamic behavior of sandwich structure containing spring-mass resonators, Composite Structures,* **Vol**, *93, page 2120-2125 (2011).*

[2] *Xiao, Y., Wen, J., Wang, G., Wen, X., Theoretical and experimental study of locally resonant and Bragg band gaps in flexural beams carrying periodic arrays of beam-like resonators, Journal of Vibration and Acoustics,* **Vol** *135, 041006 (2013).*

[3] *Casalotti, A., El-Borgi, S., Lacarbonara, W., Metamaterial beam with embedded nonlinear vibration absorbers, International Journal of Non-Linear Mechanics,* **Vol** *98, page 32-42 (2018).*

[4] *Failla, G., An exact modal analysis approach to vibration analysis of structures with mass-spring subsystems and rotational joints, Journal of Sound and Vibration,* **Vol** *438, page 191-219 (2019).*

Probabilistic assessment of surrogate capacity surfaces of Reinforced Concrete sections

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Keywords: Ultimate Limit State; Reinforced Concrete; Capacity Surface

Determination of the Ultimate Limit State (ULS) domains of reinforced concrete cross sections subject to axial force and biaxial bending is a conventional procedure based on a deterministic description of the involved constitutive parameters, namely, strength, yield and ultimate strain of concrete and of the reinforcement bars. Their definition is based on probability density functions so that the assumed characteristic values present a code-specified exceedance probability. The conventional nature of such capacity domains consists in the fact that the failure probability of the cross section is not constant within the capacity surface [1]. In particular, the failure probability relevant to load conditions in which the bending moments are negligible turns out to be close to the code-specified exceedance probability. On the contrary, load conditions in which bending is significant present a failure probability far smaller than the prescribed value because of the correlation between the constitutive parameters. For this reason, the actual capacity of the section is underestimated for most of the points of the capacity surface.
The latter aspect introduces the possibility of replacing the ULS boundary by surrogate capacity surfaces, which are computationally more efficient than the classic algorithms to perform ULS capacity checks [2], as long as their failure probability does not exceed the code-prescribed value.
The present research presents a probabilistic assessment of a surrogate formulation of the capacity surface based on the Minkowski sum of ellipsoids [3] in order to determine their failure probability. To this end, a fully probabilistic model is adopted for describing the constitutive parameters by means of correlated random variables. Then, the first-order failure probability of a discretized set of points belonging to the surrogate surface is computed by a First-Order Reliability Method (FORM). Finally, the failure probability is compared with the corresponding values evaluated for the boundary of the classic ULS domain.
The presented result concern two common typologies of cross sections, namely, rectangular and L-shaped sections, with increasing values of the reinforcement area in order to investigate the applicability of the proposed surrogate formulation.

References

[1] *Sessa, S., Marmo, F., Vaiana, N., Rosati, L., "Probabilistic assessment of axial force – biaxial bending capacity domains of reinforced concrete sections", Meccanica, Under review.*

[2] *Magisano, D., Liguori, F.S., Leonetti, L., Garcea, G. "Minkowski plasticity in 3D frames: Decoupled construction of the cross-section yield surface and efficient stress update strategy", International Journal for Numerical Methods in Engineering,* **116***(7), 435-464 (2018).*

[3] *Sessa, S., Marmo, F., Rosati, L., Leonetti, L., Garcea, G., Casciaro, R. "Evaluation of the capacity surfaces of reinforced concrete sections: Eurocode versus a plasticity-based approach", Meccanica,* **53***(6), 1493-1512 (2018).*

Explicit assessment of the forced vibration of multi-cracked beams with uncertain damage intensity

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Keywords: Dynamic response, Generalised functions, concentrated damage.

Damage in beams can strongly affect their dynamic properties and consequently their response. On the other hand, the correct evaluation of the damage intensity is a problem of difficult solution. For these reasons, exploring the variability of the dynamic response in damaged beams considering the damage intensities as uncertain parameter is a useful contribution to assess the safety of structures. Classic approaches require to treat damage as concentrated rotational springs, where continuity conditions have to be enforced, and to perform re-analyses varying the damage intensities in a desired range. In this paper, two main improvements to this procedure are provided. The first contribution is the use of an efficient solution [1] which employs generalised functions to compute the dynamic properties of a damaged beam for a limited number of damage configurations; such a method avoids the enforcement of continuity conditions at the cracked sections. Then, an explicit continuous expression of such dynamic properties as a function of the damage intensities is proposed by employing the Sherman and Morrison formula. The proposed explicit approach is verified and applied for the evaluation of the dynamic properties of damaged beams; then, via modal superposition, the variability of the response associated to time histories is assessed as well as frequency-response curves for single and multi-cracked beams subjected to forced vibraions.

References

[1] *Cannizzaro, F., De Los Rios, J., Caddemi, S., Caliò, I., and Ilanko, s., "On the use of a roving body with rotary inertia to locate cracks in beams," Journal of Sound and Vibration,* ***Vol****, 425(7) page 275-300 (2018).*

MS12

Recent Advances and Challenges in Structural Mechanics and Engineering

Koiter method and solid-shell finite elements for postbuckling optimisation of variable angle tow composite structures

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Keywords: variable angle tow laminates, postbuckling optimisation, Koiter method.

The stiffness-tailoring capability of Variable Angle Tow (VAT) laminates gives enhanced freedom to design thin-walled structures. One key advantage of tow steering is the ability to redistribute stresses improving buckling performance, leading to reduction in material weight and costs. The aim of this work is to optimise the initial postbuckling behaviour of a recently proposed VAT composite wingbox [1]. The optimisation process is based on a fibre path parameterisation. It involves seeking the stacking sequence that minimises the displacements occurring in the postbuckling regime. This problem is solved by coupling the multi-modal Koiter asymptotic approach implemented within a solid-shell Finite Element [2] environment through stochastic optimisation strategies [3]. Results obtained regarding different optimisation scenarios show a much improved performance for the buckling and postbuckling response of the wingbox with respect to the initial VAT design. Additionally, manufacturing constraints are readily included in the optimisation program. The possibility of performing an efficient and robust optimisation process of a complex structure with a multi-modal Koiter asymptotic approach is demonstrated, showing its viability as a design tool for buckling dominated structures. A parametric study regarding the influence of steering radii shows that overcoming the current manufacturing constraint on minimum radius is worthy of investigation.

References

[1] *Oliveri V., Peeters D., Clancy G. J., Jones D., O'Higgins R. M., Weaver P. M., "Design, optimization and manufacturing of a unitized carbon fiber/thermoplastic wingbox structure", International Journal for Numerical Methods in Engineering,* **38***, page 3653-3673 (1995)*

[2] *Magisano D., Leonetti L., Garcea G., "Koiter asymptotic analysis of multilayered composite structures using mixed solid-shell finite elements", Composite Structures,* **191***, page 296-308 (2016).*

[3] *Liguori F.S., Madeo A., Magisano D., Leonetti L., Garcea G., "Post-buckling optimisation strategy of imperfection sensitive composite shells using Koiter method and Monte Carlo simulation," Composite Structures,* **192***, page 654 - 670 (2018).*

Equilibrium of the von Mises truss in nonlinear elasticity

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Keywords: von Mises truss; finite elasticity; equilibrium.

The problem analyzed in this work is classically known as the von Mises truss (Fig. 1), referring to the scientist who first analyzed its structural stability [1]. Recently, formulations including two degrees of freedom for the apex node were developed [2]. Nevertheless, the equilibrium solutions were derived considering large nodal displacements, moderately small axial components of strain and a linear elastic constitutive law. Instead, in this work, a fully nonlinear finite theory for the von Mises truss is derived [3]. Both displacements and deformations are large and the rods are regarded as hyperelastic bodies composed of a general homogeneous compressible isotropic material. Under the assumption of homogeneous deformations, the boundary-value problem is formulated and the relations governing the equilibrium of each body are derived. The global equilibrium of the apex node of the truss in the deformed configuration is then written and the stability of the solutions is assessed through the energy criterion. An application to Mooney-Rivlin materials in case of vertical load reveals that asymmetrical configurations are unstable. Therefore, the instability phenomenon occurs as a snap-through and no bifurcation takes place.

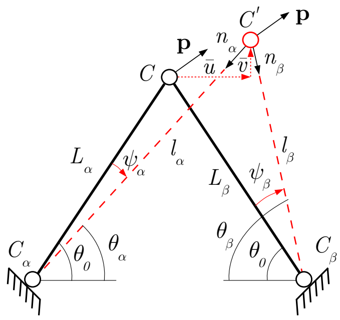

Figure 1: von Mises truss

References

[1] *Mises, R., "Über die stabilitätsprobleme der elastizitätstheorie". ZAMM-Journal of Applied Mathematics and Mechanics/Zeitschrift für Angewandte Mathematik und Mechanik,* **3(6)**, *406-422 (1923)*

[2] *Kwasniewski, L., "Complete equilibrium paths for Mises trusses", International Journal of Non-Linear Mechanics,* **44(1)**, *19-26 (2009)*

[3] *Pelliciari, M. and Tarantino, A.M., "Equilibrium paths for von Mises trusses in finite elasticity", Journal of Elasticity, (in press)*

Bending of beams in finite elasticity and some applications

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Keywords: anticlastic bending; finite elasticity, Mooney-Rivlin material.

The 2D Rivlin solution concerning the finite bending of a prismatic solid has been recently extended by accounting for the complete 3D displacement field [1]. In particular, the relationship between the principal and transverse (anticlastic) deformation of a bent solid has been investigated, founding the coupling relationships among three kinematic parameters which govern the problem. Later, based on the formulation reported in [1], and making reference to a (hyper)elastic material, the formulation has been extended to slender beams by introducing some simplifying assumptions [2]. This leads to a challenging relation between the external bending moment m and the curvature R_0^{-1} of the longitudinal axis, which involves both the constitutive and geometric parameters of the beam. This relation can be viewed as a generalization of the *Elastica* [3].

However, such a relationship can be simplified through a series expansion, thus obtaining a reliable moment-curvature relation as follows [4]:

$$m(s) = \frac{4(a+b)(a+4b+3c)}{a+3b+2c}\frac{1}{R_0(s)} + O(R_0^{-3}(s)), \qquad r(s) = \frac{a+3b+2c}{b+c}R_0(s), \tag{1}$$

being a, b, c the constitutive parameters involved in the stored energy function according to a compressible Mooney-Rivlin material, whereas r denotes the anticlastic radius of the cross section [1]. In eqn $(1)_1$ the radius of curvature R_0 depends on the curvilinear abscissa s describing the beam axis in its deformed configuration. The rotation θ of the beam cross section follows from the derivative of the curvature with respect abscissa s, i.e. $\theta'(s) = R_0^{-1}(s)$. Thus, the axial and vertical components of the displacement field and the rotation of the beam cross section are found to be coupled in a set of three equations in integral form, which is handled in an iterative procedure in order to analyse elastic structures exhibiting deformations and displacements both large.

Some basic structural schemes under both dead and live loads are here investigated, thus assessing the deformed configuration and the arising internal forces into the beam. It is found that the magnitude of the external loads strongly affects the qualitative distribution of the axial and shear forces and the bending moment in the inflexed beam, giving rise to a solution which completely differs to that corresponding to infinitesimal strains and small displacements.

References

[1] *Lanzoni, L. and Tarantino, A.M., "Finite Anticlastic Bending of Hyperelastic Solids and Beams" J. Elasticity, 131(2), (2018).*
[2] *Tarantino, A.M., Lanzoni, L. and Falope, Federico Oyedeji, The Bending Theory of Fully Nonlinear Beams, Springer, (2019).*
[3] *Frisch-Fay, R., Flexible bars. Butterworths, London (1962).*
[4] *Lanzoni, L., Tarantino, A.M., "The bending of beams in finite elasticity," Submitted.*

Modeling of carbon and polyester elastomeric isolators in unbounded configuration by using an efficient uniaxial hysteretic model

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Keywords: hysteretic model, fiber reinforced isolators, unbounded isolators.

This paper presents the application of a recently developed uniaxial phenomenological model to low-cost Fiber Reinforced Elastomeric Isolators (FREIs) in unbounded configuration. Prototypes under study represent the subject of a previous experimental investigation performed at the University of Naples Federico II [1], through which polyester FREIs demonstrated a very effective performance in comparison with carbone ones. A stable roll-over behavior was detected up to very large displacements (γ=300%) both under monotonic and cyclic loading protocol. An accurate analytical model was also provided for preliminary design of the devices. In the present study, an uniaxial rate-independent hysteretic model [2] is proposed and calibrated in order to be employed in earthquake analysis problems of seismically base isolated structures. In particular, such a model, requiring only five parameters to be calibrated from experimental tests, is able to accurately reproduce the complex hysteretic behavior displayed by the tested FREIs as the result of combined rubber behavior and roll-over process. A satisfactory approximation is obtained up to 100% shear deformation, whereas a larger scatter comes out in the case of larger deformations. The paper also demonstrates that a very effective an easy to use calibration process is needed in order to accurately reproduce the experimental behavior of the tested seismic isolators. Furthermore, by implementation of the proposed hysteretic model, significant advantages arise in terms of reduced computational effort and processing time with respect to other accurate models available in the literature.

References

[1] Losanno, D., Madera Sierra, I., Spizzuoco, M., Marulanda, J., Thomson, P., "Experimental assessment and analytical modeling of novel fiber-reinforced isolators in unbounded configuration", Composite Structures, ***212****, 66-82 (2019)*

[2] Vaiana, N., Sessa, S., Marmo, F., Rosati, L., "An accurate and computationally efficient uniaxial phenomenological model for steel and fiber reinforced elastomeric bearings", Composite Structures, ***211****, 196-212 (2019)*

A novel structural resilience index: definition and applications to frame structures

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Keywords: Resilience, robustness, kinematic matrix

Resilience is the ability to undergo disruptive events without suffering complete failure and minimizing undesirable consequences thereof. Though various indicators that are helpful to qualitatively describe these design desiderata have been proposed [1, 2, 3], it is still challenging to develop quantitative measures and indicators in order to identify them from a quantitative point of view [4, 5]. They have been conceived as to be useful in comparing and classifying the resilience of different structures.

In this talk we propose a novel rational and deterministic structural resilience index, based on a worst-case disruptive event, and making use of a minimalistic kinematics-based mechanical description. Differently from the previously mentioned approaches, the metrics herein discussed is based on the kinematic matrix, which accounts for the connections and the constraints of the elements composing the structural system. Particular emphasis is given to the computation of such a new structural resilience index for a generic frame structure, it being possible without the use of automated algorithms and an analytic expression of it has been achieved in terms of the numbers of ports (modules) and floors. First of all, keeping fixed the number of modules, the resilience index decreases as the number of floors increases. Secondly, keeping fixed the number of floors, the resilience index increases as the number modules increases. Finally, we notice that the case with infinite floors has a lower resilience index with respect to case of infinite modules, which is, as expectable, more resilient.

References

[1] *Cennamo, C., Cennamo, G.M., Chiaia, B.M., 2012. Robustness-oriented de-sign of a panel-based shelter system in critical sites. Journal of ArchitecturalEngineering 18, 123139*

[2] *De Biagi, V., 2016. Structural behavior of a metallic truss under progressivedamage. International Journal of Solids and Structures 82, 5664.*

[3] *Beeby, A., 1999. Safety of structures, and a new approach to robustness. Struc-tural Engineer 77.*

[4] *Balas, G.J., Doyle, J.C., 1994. Robustness and performance trade-offs in con-trol design for flexible structures. IEEE Transactions on control systemstechnology 2, 352361.*

[5] *Spencer Jr, B., Sain, M., Won, C.H., Kaspari, D., Sain, P., 1994. Reliability-based measures of structural control robustness. Structural Safety 15, 111129.*

Energetic and geometric criteria for defining shear-deformable beam models

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Keywords: Shear flexibility, Center of twist, Center of shear

We discuss the energetic and geometric consistency of a one-dimensional (1D) beam model based on the Saint-Venant three-dimensional (3D) solution of a beam-like solid, with a focus on the effects associated with shear stresses.

The energetic approach is pursued by enforcing the equivalence of the elastic energy of the 3D solid model and the related 1D beam model. The geometric criterion is based on the analysis of the 3D displacement field of the beam-like solid and its comparison with the one pertaining the 1D beam model.

Each approach allows one to define a flexibility operator, one providing the elastic energy of the solid and the other yielding the kinematic parameters of the free end section of the beam-like solid assumed to be a cantilever. To this end we consider an intrinsic expression of the stress and displacement fields of the solid due to a shear force acting at an arbitrary point of the end section.

While the evaluation of the elastic energy is simply based on the Saint Venant solution, the definition of a kinematic model requires some additional hypotheses. First of all, in order to remove the arbitrariness of the rigid body displacements without conflicting with Saint Venant's hypothesis of free warping, a weak formulation of the constraint at the root section is considered, following a strategy recently proposed in the literature [2]. Moreover, we assume the transverse displacements of the point where the shear force is applied to represent the whole 3D displacement field of the original beam-like solid.

It is shown that such specific kinematic hypotheses provide a geometric model of the beam that is consistent with the energetic one, as proved by the coincidence of the relevant flexibility operators. Actually a unique shear flexibility tensor can be introduced, having both an energetic and a kinematic meaning, and explicitly involving the point where the shear force is supposed to act.

Furthermore, the vanishing of the shear-torsion coupling allows one to identify the center of twist as the point of the cross section where the shear force must be applied in order to ensure a condition of pure flexure. Consequently, the center of twist assumes the role of center of shear both in an energetic and a kinematic sense and it is recognized as the unique point providing the uncoupling between shear and torsion, overcoming the traditional energetic/kinematic dualism.

References

[1] *Paradiso, M., Marmo, F. and Rosati, L., "Consistent derivation of a beam model from the Saint Venant's solid model", Int. J. Solids Struct.,* **159***, 90–110 (2019).*

[2] *Serpieri, R., "On the Equivalence of Energetic and Geometric Shear Factors Based on Saint Venant Flexure", J. Elast.,* **116***, 115–160 (2014).*

[3] *Sokolnikoff, I.S., Mathematical Theory of Elasticity, McGraw-Hill, New York (1946).*

[4] *Weinstein, A.S., "The center of shear and the center of twist", Q. Appl. Math.,* **5***, 97–99 (1947).*

Steel-glass based bracings for the seismic retrofitting of the hystorical monuments

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Keywords: laminated glass, seismic retrofitting, hybrid element.

Laminated glass, composed by glass plies bonded by polymeric interlayers, is used for structural purposes thanks to its safe *post-glass-breakage* response: the shards remain attached to the polymer, imparting to the assembly a certain cohesion and avoiding injuries due to catastrophic collapse. Thanks to the tension stiffening of interlayer due to the contact with the glass shards, the damaged elements exhibit a residual load-bearing capacity, strongly dependent on the amount of delamination [1]. Furthermore, experimental studies [2] have demonstrated that the broken element can dissipate energy under cyclic loading, due to the cohesive polymer/glass contact.

This suggests the use of laminated glass panels to increase the load bearing capacity and ductility of existing buildings under horizontal actions, as those from an earthquake. To mitigate the intrinsic brittleness of glass, the panel may be contoured by a thin steel frame [3]. This kind of *hybrid glass-steel diaphragm* is ideal for the seismic retrofitting of historic buildings, because it meets the criteria of minimum visual impact, immediate recognizability and complete reversibility, as suggested by the modern principles of conservation and restoration [4].

The proposed solution is designed so to remain sound under moderate earthquakes, while it may break (in a ductile manner) and dissipate energy under cyclic loading under the most severe events. When glass is sound, the in-plane stiffness is governed by glass, while in the post-glass-breakage phase the load-resistant scheme is formed by a steel frame confining an infill panel, playing the role of a transparent strut diagonal, with a static scheme similar to that of a masonry infill panel. Materials and geometry have been optimized to achieve the suitable requirements in both the pre- and post-glass-breakage phases. The direct contact between metal and glass is avoided interposing a soft material and the corners shall be designed in order to prevent stress concentrations. Linear and non-linear numerical experiments have been performed to evaluate the structural response of the hybrid cell and its interactions with the existing structure.

References

[1] D'Ambrosio, G., Galuppi, L., Royer Carfagni, G. "A simple model for the post-breakage response of laminated glass under in-plane loading", submitted, (2019).

*[2] Freddi, F., Royer Carfagni, G., Silvestri, M., "Full-scale experiments for point-fixing frameless laminated glass", Composite Structures, **154**, 600-615, (2016).*

[3] D'Ambrosio, G., Galuppi, L., Royer Carfagni, G., "Pre- and post-glass-breakage response of shear-resistant hybrid steel-glass bracings for the preservation of historical buildings", in preparation, (2019).

*[4] Barou, L., Oikonomopoulou, F., Bristogianni, T., Veer, F., Nijsse, R., "Structural glass. A new remedial tool for the consolidation of historic structures", Heron, **63(1/2)**, 159-198, (2018).*

Use, effectiveness and long term reliability of MR dampers for seismic protection of framed structures

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Keywords: magnetorheological damper, semi-active control, ageing effects.

The implementation, operation and efficacy of semi-active (SA) structural control systems based on the adoption of magnetorheological (MR) devices are still object of research. For a such system, generally a complex electronic equipment is required to acquire then elaborate then generate signals to properly command the smart devices in real time [1]. Given this, the effectiveness of these control systems in reducing the seismic response of structures is often called into question. And one wonders about the performance of these systems in the long term, i.e. when called to respond to seismic actions after many years since their installation. Will the devices be ready to respond? Is their dissipative capacity still that exhibited before their installation?

This work attempts to present a comprehensive description and offer suitable solutions for a number of specific aspects that characterise the implementation of SA control systems. Authors also highlight undesired and unavoidable effects and provide insights on the way to reduce their incidence. The performance of such system is then showed via a shaking table test of a full-scale steel structure [2-3]. These tests allowed to measure the actual short-term effectiveness of this system. After 10 years of inactivity of those MR devices, these have been subjected characterization tests once again [4], in order to assess the evolution of their mechanical behaviour over time and the decay of performance. The long-term response in terms of readiness, dissipative capacity and reaction force was measured, leading to positive conclusions about the reliability of the control system after years of inactivity.

References

[1] Chu, S.Y., Soong, T.T., Reinhorn, A.M., Helgeson, R.J., Riley, M.A., 2002. Integration issues in implementation of structural control systems, J. Struct. Control, 9, 31–58.

[2] Dolce, M., Ponzo, F. C., Di Cesare, A., Ditommaso, R., Moroni, C., Nigro, D., Serino, G., Sorace, S., Gattulli, V., Occhiuzzi, A., Vulcano, A. and Foti, D. (2008), "Jet-pacs Project: Joint Experimental Testing on Passive and Semiactive Control Systems", Proc. 14th World Conference on Earthquake Engineering, Beijing, China.

[3] Caterino, N., Spizzuoco, M., Occhiuzzi, A. "Shaking table testing of a steel frame structure equipped with semi-active MR dampers: comparison of control algorithms", Smart Structures and Systems, Techno-Press, 15(4), 2015, pp. 963-995.

[4] Caterino, N., Spizzuoco, M., Occhiuzzi, A., Ageing effects due to inactivity for magnetorheological seismic dampers: a 10-years experimental investigation, Smart Mater. Struct. 27(6), 2018, Article number 067001.

Dynamic behavior of unreinforced and FRCM reinforced full-scale masonry arches

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Keywords: Masonry; Arches; Dynamic tests; FRCM reinforcement

Masonry arches, one of the most iconic architectural and structural elements of historical constructions, show a pronounced seismic vulnerability, entailing the risk of losing important parts of our architectural and cultural heritage. Thus, the problem of the dynamic behavior of masonry arches and vaults has gained increasing interest in recent years. Anyway, the literature on this important research topic is still quite limited [1], especially for what concerns the case of reinforced masonry arches.
The above motivates the present study, that concerns experimental full-scale dynamic tests on unreinforced and GFRCM-reinforced Apulian tuff masonry arches. For the experiments, a test bench expressly designed and built has been used. Masonry arches have been dynamically excited by a harmonic base motion with fixed amplitude and increasing frequency. During the tests, the dynamic response of the examined arches has been experimentally investigated in terms of accelerations of the instrumented points of the arches and of base shear and base displacements.
The preliminary experimental results obtained are discussed in the light of some theoretical works about the dynamic of masonry arches [2-4]. Moreover, the amplification of the base motion, the damage and possible collapse modes, and the effect of the interaction between FRCM reinforcements and the masonry structures are examined.

References

[1] V. Giamundo, G.P. Lignola, G. Maddaloni, F. da Porto, A. Prota, G. Manfredi, Shaking table tests on a full-scale unreinforced and IMG retrofitted clay brick masonry barrel vault, Bull. Earthquake Eng., 14 (2016) 1663-1693.
[2] I.J. Oppenheim, The masonry arch as a four-link mechanism under base motion, Earthq. Eng. Struct. D. 21 (1992) 1005-1017.
[3] P. Clemente, Introduction to dynamics of stone arches, E Earthq. Eng. Struct. D. 27 (1998) 513-522.
[4] L. De Lorenzis, M. DeJong, J. Ochsendorf, Failure of masonry arches under impulse base motion, Earthq. Eng. Struct. D. 36 (2007) 2119-2136.

In-plane shear compression tests on Timber-Framed Pisé panels

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Keywords: Rammed Earth, Timber Reinforcement, in-plane shear-compression behaviour.

Attaining the sustainability of human activities has become an inescapable challenge. There is the rapidly arising need for a “cradle to cradle” approach, in which any kind of process must return the materials involved to their original source. This way of thinking guarantees that the next generations will have the same amount of resources as we have today, so that their consumption can be sustainable.

In this context, traditional materials, such as raw earth, are re-garnering interest. Since ancient times, earth has been used as a construction material in several forms (adobe, wattle and daub, rammed earth). Although it is considered one of the first building materials, its mechanical characteristics have been delineated only relatively recently: both its local response, at the microstructural level, and global response, at the panel level, are still the subject of debate within the scientific community [1].

Cooperative research carried out at the universities of Pisa and Minho has contributed to updating the rammed earth building technique. Inspired by a traditional Italian reinforcement technique known as *case baraccate* [2], herein we propose a composite element formed by rammed earth panels reinforced by a timber frame. The paper focuses mainly on assessing the mechanic response of the TFP (Timber Framed Pisé panel). As the scientific literature contains very few studies regarding the mechanical behaviour of composite structures like those proposed here, the study necessarily began with a series of experimental tests in order to collect some results on the capacity and stiffness of TFP elements under vertical and horizontal loads.

Four 1:2 scale TFP elements are loaded quasi-statically in a shear-compression test. The vertical load is kept constant at a value determined by assuming the TFP elements to be part of the ground-level load-bearing walls of a medium-sized residential building. A monotonically increasing horizontal load is then applied to the first specimen, while a cyclic loading protocol is adopted in the other three until critical damage of the specimens occurs. The experimental results are illustrated and compared to those available in the literature [3] on both reinforced and unreinforced elements. In order to better understand TFP’s mechanical response, the experimental results are compared with theoretical ones obtained via simplified schemes based on limit analysis while accounting for the interaction between the rammed earth and timber frame.

References

[1] *Houben, H., Guillad, H., Earth Construction: A comprehensive guide, Intermediate Technology Publications, Michigan (1994)*

[2] *Vivenzio, G., Istoria e teoria de tremuoti in generale. E in particolare di quelli della Calabria, e di Messina del 1783. Stamperia Regale, Napoli (1783)*

[3] *Miccoli, L., Drougkas, A., Müller, U., “In-plane behaviour of rammed earth under cyclic loading: Experimental testing and finite element modelling”, Eng. Str.,* ***125****, 144-152 (2016)*

Curved and twisted beam models for aero-elastic analysis of wind turbine blades undergoing large displacements

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Keywords: wind turbine blades, beam-like structures, geometrically exact models

New methods are continually being sought to improve wind turbine performance by capturing more energy, alleviating loads, and developing lighter, yet more resistant structures, all with the ultimate goal of lowering the cost of energy [1]. As several studies have shown, such goal is likely to be achieved through the use of advanced materials, a design that optimizes aerodynamic and structural performance and suitable load control techniques. One promising passive load control approach is bend-twist coupling (BTC) of the blades. This method offers the potential of 'shaping' the power curve and reducing fatigue damage to the horizontal axis wind turbines (HAWT) due to its effects on the blades' aero-elastic behavior. This can be achieved by sweeping the shape of the blades (geometric coupling) or by changing the orientation of the composite blade's fibers (material coupling), as demonstrated by successful results in several research programs [2].

BTC and the continuous increase in the size and flexibility of HAWT blades make the interaction between the aerodynamics, inertial loads and structural elasticity ever more important, and the modeling and prediction of their aero-elastic behavior ever more challenging. For the structural part of this modeling, schematizing the blades as beam-like elements currently provides the best compromise between computational efficiency and accuracy of results. However, it is worth noting that, due to their slenderness and high flexibility, modern blades are likely to undergo large displacements during operation. Moreover, the nonlinear geometric coupling between bending and torsion can have important effects on the stability and operational lifespan of the entire wind turbine. In addition, non-classical effects, such as transverse shear deformation, in- and out-of-plane cross-sectional warping, as well as elastic couplings due to material properties may prove to be important for structures of this kind [3]. Thus, the development of a suitable model for curved and twisted blades undergoing large displacements which accounts for all those factors is a fundamental step for accurate aero-elastic modeling of modern HAWT blades.

The present work addresses the modeling of the mechanical behavior of HAWT blades. In particular, after an introduction to the possible approaches for curved and twisted beam-like structures, a suitable model for the problem at hand is proposed. The model is based on a so-called geometrically exact approach, which allows for three-dimensional strain and stress determination. It can be used to analyze large deflections under prescribed loads, as well as aero-elastic stability, provided a suitable aerodynamic model is added.

References

[1] Wiser, R., Jenni, K., et al, "Forecast wind energy costs and cost drivers: the views of the world's leading experts", LBNL 1005717, (2016).

[2] Ashwill, T.D., Kanaby, G., et al, "Development of the swept twist adaptive rotor (STAR) blade", in 48th AIAA Aerospace Sciences Meeting, Orlando, FL, (2010).

[3] Hodges, D.H., "Unified approach for accurate and efficient modeling of composite rotor blades dynamics", Journal of the American Helicopter Society, 60, 011001, (2015).

The Non-Smooth Dynamics of multiple leaf masonry walls of the Arquata del Tronto fortress

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Keywords: Masonry, Multiple Leaf Walls, Non-Smooth Contact Dynamics method.

The present paper investigates from an advanced numerical point of view the progressive damage of the Arquata del Tronto medieval fortress, after a long sequence of strong earthquakes that struck central Italy in 2016, plunging the area into chaos for several months [1].

The fortress, which is a typical example of Umbrian-Marchean Apennines fortified architecture of the XIII century, is mainly made by calcareous stone masonry walls made of multiple leafs, which can be prone to disintegration under strong dynamic actions. The fortress is in a strategical position, located on the border between the Ascoli and Norcia's administrations, and was damaged but left standing by the magnitude 6.0 earthquake event occurred in August 2016 that flattened the town center. The medieval fortress lost *chemin de ronde* and was one of the few buildings in the town to remain still standing after the main shock. It was then severely damaged by further quakes that rattled the region in October 2016, demonstrating a not proper transverse bond for most of the masonry walls.

An advanced numerical model is here utilized to have an insight into the modalities of progressive damage and the behavior of the structure under strong nonlinear dynamic excitations, namely a Non-Smooth Contact Dynamic method (NSCD) [2] adopting a full 3D detailed discretization.

In the NSCD method, the fortress is schematized as a system of rigid blocks, undergoing frictional sliding and perfect plastic impacts. The structure exhibited a complex dynamic behavior, because of the geometrical nonlinearity and the non-smooth nature of the contact laws, with a focus on the possible non-smooth nature of the dynamic response, which can come commonly just before and during the collapse.

Harmonic oscillations applied to the basement of the fortress is considered first, and a systematic parametric study is done, aimed at correlating the global vulnerability to the amplitude and frequency of the excitation. Also, from the numerical results, both the role played by the actual geometry and the insufficient resistance of the constituent materials are envisaged, showing a good match with actual crack patterns and collapses observed after the seismic sequence. Finally, the numerical analyses provide a valuable picture of the actual behavior of the fortress, thus giving useful hints for the reconstruction and future effective strengthening interventions.

References

[1] *Poiani, M., Gazzani, V., Clementi, F., Milani, G., Valente, M. and Lenci, S., "Iconic crumbling of the clock tower in Amatrice after 2016 center Italy seismic sequence: advanced numerical insight", in proceeding of CINPAR 2018 - XIV International Conference on Building Pathology and Constructions Repair, Florence, Italy, June 20-22, 2018.*

[2] *Chetouane, B., Dubois, F., Vinches, M. and Bohatier, C., "NSCD discrete element method for modelling masonry structures," Int J. Numer Methods Eng,* ***64****, 65-94 (2005).*

A simplified inhomogeneous beam-like model for the dynamic analysis of multi-storey buildings

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Keywords: Beam-like Model, Dynamic Analysis, Rayleigh-Ritz method.

The analysis of multi-storey frames by means of equivalent models, introduced in the last century [1], is still a current subject since it allows drastically containing the required computational burden. Aiming at simulating the static and dynamic behaviour of entire buildings, some recent studies have been devoted to formulate beam-like models based on the equivalence of framed structures to continuum beam elements [2, 3]. The simplified beam-like approaches proposed in the literature usually make reference to uniform homogeneous elements.

In the present research a simple inhomogeneous beam-like model, suitable for the representation of buildings that do not have uniform mass and stiffness distribution along their height is proposed.

The model takes into account the floor deformability by means of floor stiffness reducing coefficients. Asymmetric distribution of stiffness within the floors, which leads to torsional effects, are also taken into account.

The equations of motion of the proposed spatial unsymmetrical beam-like model are derived through the application of Hamilton's principle. The linear dynamic behaviour of the inhomogeneous beam-like element is then evaluated by discretizing the continuous model according to a Rayleigh-Ritz approach based on a suitable number of modal shapes of uniform shear- torsional beam models.

In spite of the simplicity of the proposed beam like model, accurate results have been obtained. In particular, frequencies and modes of vibration of the proposed beam-like model have been compared to the correspondent results of multi-storey buildings, evaluated by means of 3D FEM modelling approach, showing a very good correspondence.

The capability of the proposed equivalent inhomogeneous beam model to approximate the dynamic response to seismic ground motion of spatial frames is also investigated.

References

*[1] Chajes, M., Romstad, K. and McCallen, D., "Analysis of multiple-bay frames using continuum model", Journal of Structural Engineering ASCE, **119**(2), pp. 522-546 (1993).*

[2] Piccardo, G., Tubino, F. and Luongo, A., «Equivalent nonlinear beam model for the 3-D analysis of shear-type buildings: Application to aeroelastic instability", International Journal of Non-Linear Mechanics, vol. 80, pp. 52-65, (2016).

*[3]Piccardo, G., Tubino, F. and Luongo, A., "Equivalent Timoshenko linear beam model for the static and dynamic analysis of tower buildings", Applied Mathematical Modelling, vol. **71**, pp. 77-95, (2019).*

Dynamic identification and damage detection on masonry buildings using shaking table tests

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Keywords: Confined Masonry, Shaking Table Tests, Dynamic identification

In the year 2016 Central Italy have been struck by a series of massive earthquakes of significant intensity, highlighting the need to improve the knowledge on the the dynamic behavior of masonry structures excited by ground motions in order to develop useful design solutions to mitigate the seismic vulnerability. For this reason, a research program aimed at improve the dynamic performance of masonry structures by using confined masonry technique was started. A shaking table experimental investigation has been carried out on both unreinforced and confined masonry building models at the ENEA laboratory in Casaccia, Rome, in order to compare the dynamic behavior of the two different construction types.

The masonry models modal parameters characterization has been obtained from full-scale Ambient Vibration Tests (AVT) outside and inside the shaking table using classical contact sensors [1]. It is well known that the dynamic identification of a model fixed on a shaking table is a crucial task, due to the interaction between the complex dynamic actuators system and the model itself producing similar effects to the well known soil–structure interaction problem [2, 3]. For this reason the experimental modal parameters of the two masonry models outside the table have been compared to those obtained when the structural model is bound to the table and subjected to random loads having almost white noise characteristics.

The dynamic investigation was then extended to gather information on the possible influence of the damage patterns observed in the two models on changes in the modal parameters (both natural frequencies and mode shapes). To this purpose, a reference seismic input motion characterized by significant intensity in all the three directions has been used as input and a series of seismic tests have been carried out increasing the amplitudes of the chosen reference acceleration records. At the end of each seismic test, a dynamic characterization test has been carried out applying a white noise random load.

The obtained results can be crucial for both calibrating reliable numerical models to be used for static and dynamic non linear analysis and for assessing the ability of the modal parameters to be used as damage detection and localization indexes.

References

[1] *Brincker, R., Introduction to Operational Modal Analysis, Wiley-Blackwell, (2015).*

[2] *Pitilakis, D., Iliou K., and Karatzetzou, A., Shaking table tests on a stone masonry building: modeling and identification of dynamic properties including soil-foundation-structure interaction, International Journal of Architectural Heritage,* **12-6**,*1019-1037 (2018).*

[3] *Trombetti, T.L., Conte J.P.,Shaking Table Dynamics: Results from a Test-Analysis Comparison Study, Journal of Earthquake Engineering,* **6-4**,*513-551 (2002).*

Cyclic uniaxial testing and constitutive modelling of cementitious composite materials

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Keywords: cementitious composites; cyclic testing; constitutive modelling.

Innovative cementitious composite materials are drawing considerable interest due to their substantially improved mechanical properties, as compared to ordinary cement-based materials: among the others, higher tensile strength, tensile strain hardening, flexural strength, fracture toughness [1] and resistance to fatigue. Their enhanced ductility appears to be promising and particularly suited to structural applications under severe dynamic loading conditions (earthquake, impact, blast) [2]. Accurate constitutive models to simulate the dynamic behaviour of cementitious composites are hence needed, as well as corresponding appropriate testing protocols for their experimental characterisation [3].

In this study, the response of cementitious composites to cyclic uniaxial loadings has been investigated. Cyclic response is essential to understand the effects of unloading and reloading on the material, to examine how it behaves in the transition from tension to compression and to characterise its properties in terms of energy dissipation and strain-rate sensitivity. Different loading schemes have been considered, including reversed cyclic tension/compression loadings, in order to identify the complete stress-strain curve and the transition behaviour, which can occur, for instance, under seismic, fatigue and wind loads. Monotonic quasi-static tension and compression tests have been also performed, to provide a benchmark for the evaluation of the envelope curve of cyclic response.

The experimental campaign was carried out on cylindrical specimens, a standard geometry in compression testing of cement-based materials. Several series of homothetic specimens (height to diameter ratio fixed as 2) with different dimensions were tested, to evaluate the influence of scale effects. Variability and reproducibility of the testing results have been taking into account by employing a minimum number of three specimens per loading condition. All the tests were performed, under deformation-controlled regime, on an MTS servo-hydraulic testing machine with 250 kN load cell. The testing machine was customised with accessories designed to meet specific test requirements, avoiding instability and bending moments during the alternating phases of uniaxial compression and tension. Linear variable displacement transducers (LVDT) and strain gauges were used to measure vertical displacements and lateral deformations, respectively. The results obtained experimentally represent a reliable basis for the development of constitutive models suited to numerical simulation.

References

[1] *Restuccia, L., Reggio, A., Ferro, G.A., Kamranirad, R., "Fractal analysis of crack paths into innovative carbon-based cementitious composites", Theoretical and Applied Fracture Mechanics,* ***90****, 133-141, 2017.*

[2] *Yoo, D. Y., Banthia N. "Mechanical properties of ultra-high-performance fiber-reinforced concrete: A review", Cement and Concrete Composites,* ***73****, 267-280, 2016.*

[3] *Kesner, K.E., Billington, S.L., Douglas K.S. "Cyclic response of highly ductile fiber-reinforced cement-based composites", ACI Materials Journal,* ***100****(5), 381-390, 2003.*

Effects of in- and out-of-plane nonlinear modelling of masonry infills on the seismic response of r.c. framed buildings

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Keywords: nonlinear modelling of masonry infills, r.c. infilled framed buildings, seismic analysis.

Reinforced concrete (r.c.)-framed buildings with unreinforced masonry infills (MIs) suffered severe damage and in some cases collapse during recent earthquakes (e.g. L'Aquila, 1999), related to the influence of the MIs. The types of damage observed for the MIs are usually a combination of, or an interaction between, in-plane (IP) and out-of-plane (OoP) mechanisms. Specifically, the IP drift ratio is generally reduced at the upper storeys of buildings, where the OoP drift ratio increases due to an increase of seismic acceleration, while significant OoP damage may also take place at the lower storeys where the highest values of IP drift ratio are attained.

The present work is aimed at identifying the effects of IP and OoP damage of MIs on the nonlinear seismic response of r.c. framed buildings. To this end, the state secondary school De Gasperi-Battaglia of Norcia (Italy) is considered for the numerical investigation. The school is a reinforced concrete framed structure with a long-shaped rectangular plan, deriving from the ex-post structural linking of three adjacent blocks originally separated by Gerber saddles, and regular elevation, composed of a basement and three storeys above the ground level. The structure was built at the beginning of the 1960s and designed to comply with the Royal Decree Law (1939). The main infill typologies consist of: i) two leaves of clay hollow bricks, with thickness 8 cm, for some interior frames; ii) one leaf with solid bricks, with thickness 12 cm, and the other leaf similar to the previous MI, for all the exterior frames. Partial height infill walls inducing short column effects are also considered along the short side of the perimeter, where the incomplete height is attributed to window openings.

A five-element macro-model comprising four diagonal nonlinear beams and one (horizontal) central nonlinear truss for the prediction of the OoP and IP behaviour of MIs [1], respectively, is first implemented in a C++ computer code for the nonlinear dynamic analysis of r.c. infilled framed structures. In detail, cylindrical hinges are used for restraining the out-of plane rotations of the four diagonal beams in the connection points with the central element, while the out-of plane rotations of these diagonal elements are allowed in the connection joints with the frame where spherical hinges are placed. The proposed algorithm addresses the issue of nonlinear interaction by modifying stiffness and strength values of the MI in the OoP direction on the basis of simultaneous or prior IP damage. Two three-dimensional models of the test structure are subjected to biaxial spectrum-compatible accelerograms, assuming: i) bare structure with non-structural MIs; ii) infilled structure with structural MIs. The numerical results prove the good performance of the five-element macro-model in simulating IP and OoP failure mechanisms of MIs in the De Gasperi-Battaglia school, and highlight the importance of including nonlinear OoP behaviour.

References

[1] *Mazza, F., "In-plane–out-of-plane non-linear model of masonry infills in the seismic analysis of r.c.-framed buildings," Earthquake Engineering and Structural Dynamics, 10.1002/ eqe.3143, pages 1-22 (2018).*

A novel wireless sensor with energy harvesting capabilities for structural health monitoring

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Keywords: damage detection, bridge, dynamic.

The process of implementing a strategy for assessing the state of a structure is usually referred to as Structural Health Monitoring (SHM) [1]. In order to carry out this process on a real bridge, we have developed a Wireless Sensor Network (WSN) consisting of MEMS accelerometers powered by an energy harvesting system that uses both environmental vibrations of the structure as well as solar energy.

The node sensor allows the data to be processed locally and in real-time before transmitting it to a central node for storage and web uploading; in this way, efficient numerical algorithms can be implemented on the sensor to detect damage [2,3] and extract the dynamic properties of the structure, including natural frequencies, modal forms and damping ratios.

This system provides a low-cost, easy-to-install product, combined with a robust remote control and processing system for security assessment and emergency management, available for subsequent large-scale applications [4]. The results of a long-term monitoring campaign and the comparison with cabled conventional accelerometers will be reported and discussed.

References
[1] Sensor Technologies for Civil Infrastructures, Editors: Ming L. Wang Jerome P. Lynch Hoon Sohn, Woodhead Publishing (2014)
[2] Lofrano, E., Romeo, F., Paolone, A., Sensitivity Analysis and Improvement of a Pseudo-Modal Approach for Damage Localization, ASME DETC2015-46715, pp. V008T13A097 (2015).
[3] Ciambella, J., Pau, A. & Vestroni, F. Modal curvature-based damage localization in weakly damaged continuous beams. Mech. Syst. Signal Process. 121, 171–182 (2019).
[4] Bacchettini, V., Ciambella J., Ricci E., Un innovativo sistema di monitoraggio dinamico, Quaderno Comitato Tecnico Nazionale D.3 "Ponti" (2018).

High velocity impact on composite structures: modelling and experimental validation

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Keywords: High velocity impact, composite structure, damage mechanisms

The detection of damages in composite structures due to impacts is a critical issue for any structural health monitoring (SHM) strategy. As well known from experience and studied in the recent literature, the damage produced during an impact is strongly dependent upon the velocity of the impact, namely low-velocity, high-velocity and hypervelocity ranges can be identified. In this contribution the authors would like to present the outcomes of some recent research conducted at the University of Rome La Sapienza concerning the modeling of high velocity impact on composite structures having both planar and curved geomeries. In fact, especially for the high velocity range involving aeronautical case studies, the importance of curvature of composite structural elements is of paramount importance if one would like to represent accurately the real shapes of either fuselage or wing structures.

Composite structures subjected to high-velocity impacts (HVI) are likely to suffer complete perforation, eventually causing the dramatic failure of the overall system. During impacts composite targets undergo different damage and energy absorbing mechanisms. During the impact, the kinetic energy of the projectile is either absorbed or dissipated by the target via various deformation/damage mechanisms.

The paper proposes an analytical approach proposed by the authors (1) as an improvement of previous papers in literature that is able to represent the various damage mechanisms produced during the impacts and recent developments for curved geometries (2) in comparison with experimental evidences recently published in the open literature.

References

1. M. Pasquali, C. Terra, P.Gaudenzi, *Analytical modelling of high-velocity impacts on thin woven fabric composite targets*, Composite Structures, 131, 1, 2015, 951-965

2. M. Pasquali and P.Gaudenzi, *Effects of curvature on high-velocity impact resistance of thin woven fabric composite targets*, Composite Structures, 160, 2017, 349-365.

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HYDROTHERMAL AGEING OF NATURAL FIBRE POLYMER COMPOSITES

Influence of weathering and sequence of stacking on the mechanical properties of hybrid natural fibre thermoplastic composites

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Keywords: Weathering, Hybrid thermoplastic composites. Mechanical properties.

Nowadays the use of reinforced polymeric materials is widespread and the analysis of their behavior under environmental conditions, suitably simulated in the laboratory, assumes a fundamental role in order to predict their stability / durability even under severe conditions. This consideration is especially true if the attention is focused on natural fibre composites already applied in many fields [1,2] and much more sensitive to adverse environments, when exposed for a long period of time, if compared with composite materials including traditional glass or carbon fibres [3,4].

Thermoplastic composite laminates, reinforced with one or more different natural fibres (kenaf fibres, flax fabric, basalt fabric), were prepared by film-stacking and hot-pressing according to different configurations. Specimens of appropriate dimensions, cut from each sample laminate, were exposed under pre-established environmental conditions of temperature and humidity to accelerate and monitor eventual degradation phenomena by periodic mechanical tests and to assess the reliability of investigated materials even under saturation conditions by immersing specimens in water.

Specifically, evaluations of the diffusion coefficient of water and maximum absorption are performed by systematic weighing of specimens at predefined time intervals while any influence on their flexural and impact behaviour is ascertained mainly by flexural and impact properties.

Results, averaged on at least five determinations on each sample, combined with morphological/structural analyses, can provide, among other, useful information for an optimal design and manufacturing of new eco-friendly materials.

References

[1] Mochane, M.J., Mokhena, T.C., Mokhothu, T.H., Mtibe, A., Sadiku, E.R., Ray, S.S., Ibrahim, I.D., Daramola, O.O., "Recent progress on natural fibre hybrid composites for advanced applications: A review" Express Polymer Letters, ***13****, 159-198 (2019).*

[2] Stevens, C., Industrial applications of natural fibers: Structure, properties and technical applications, John Wiley and Sons (2010).

[3] Azwa, Z.N., Yousif, B.F., Manalo, A.C., Karunasena, W., "A review on the degradability of polymeric composites based on natural fibres", Materials & Design, ***47****, 424-442 (2013).*

[4] John, M.J., "Environmental degradation in biocomposites" in "Biocomposites for high-performance applications", WoodHead Publishing, 181-194 (2017).

Mechanical properties of hemp fibre based composite materials: Influence of fibre content, size and weathering

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Keywords: Bio-composites, Hemp fibre, Weathering, Mechanical properties.

In recent years, there has been a significant interest toward the use of natural fibres in development of lightweight and low environmental impact composite materials. Among these fibres, mainly acting as a reinforcement of the hosting matrix, hemp is widely considered given its good thermal and acoustic insulation, breathing and prevention of condensation, waterproofing and so on [1].

In light of these peculiarities, many works have been conducted so far on the development of hemp reinforced mortar [2], concrete [3] and cementitious [4] matrices focusing the attention not only on the ultimate performances of product and variable influencing the same but also on their durability in specific environmental conditions: aspect commonly analyzed in terms of residual properties and toughness indices of conditioned composites [5].

In this work, new building materials based on a commercial mortar modified by different amounts of hemp fibers, with average variable length, have been prepared and characterized in terms of mechanical properties and morphological aspects. Tests have been performed on newly obtained specimens and on specimens exposed in predefined environmental conditions (for example, wetting and drying under room temperature). In this latter case, evaluations of residual flexural/compression strength of weathered samples provided useful information on their durability.

References

[1] Le, A.D.T., Maalouf, C., Mai, T.H., Wurtz, E., Collet, F., "Transient hydrothermal behaviour of a hemp concrete building envelope", Energy Build, ***42****, 1797-1806 (2010).*

[2] Asprone, D., Durante, M., Prota, A., Manfredi, G., "Potential of structural pozzolanic matrix-hemp fiber grid composites", Construction and Building Materials, ***25****, 2867-2874 (2011).*

[3] Niyigena, C., Amziane, S., Chateauneuf, A., Arnaud, L., et al. "Variability of the mechanical properties of hemp concrete", ***7****, 122-133 (2016).*

[4] Sedan, D., Pagnoux, C., Smith, A., Chotard, D., "Mechanical properties of hemp fibre reinforced cement: influence of the fibre/matrix interaction", Journal of the European Ceramic Society, ***28****, 183-192 (2008).*

[5] Canti, M., "Experimental study on the physical-mechanical durability of innovative hemp-based composites for the building industry", Energy and Buildings, ***104****, 316-322 (2015).*

Masonry walls retrofitted with natural fibers under tsunami loads

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Keywords: Masonry walls, Local mechanisms, Innovative retrofit systems, Natural fibers, Tsunami.

In the last decades, several tsunamis have interested international coasts and engaged scientific awareness to the retrofit of coastal buildings against tsunami loads.

Structural design under tsunami loads is difficult to model due to the high uncertainties of the phenomenon. Also, the retrofit of structures under tsunami actions could be an innovative re-search topic for all the international coastal buildings located in areas characterized by a high tsunami risk.

Local collapse mechanisms of masonry walls, like as out of plane mechanisms [1], have an high probability due to flexural actions; a higher flexural capacity can be reached using particular retrofit systems; in particular, this paper aims to deepen the behavior of masonry walls retrofitted with innovative retrofit systems like as natural fibers applied with inorganic mortar matrices [2][3].

The effects of retrofit systems will be discussed in terms of critical inundation depth variations before and after the interventions, accounting for different geometrical parameters of masonry walls and axial loads. Therefore normalized diagrams are proposed in order to quantify the optimum composite mechanical ratio for a retrofit system design.

References

[1] *Belliazzi, S., Lignola, G.P., Prota, A., "Textile Reinforced Mortars systems: a sustainable way to retrofit structural masonry walls under tsunami loads" International journal of Masonry Research and Innovation, 3(3), pp. 200-222, 2018.*

[2] *Ramaglia, G., Lignola, G.P., Fabbrocino, F., Prota, A., "Impact of natural fibers on the ultimate behaviour of masonry elements" AIMETA 2017 - Proceedings of the 23rd Conference of the Italian Association of Theoretical and Applied Mechanics, **2**, pp. 2012-2021, 2017.*

[3] *G.P. Lignola, C. D'Ambra, A. Prota, F. Ceroni, Modelling of tuff masonry walls retro-fitted with inorganic matrix–grid composites. In proceedings 16th international brick and block masonry conference (16IBMAC), Padova, Italy, June 26-30, 2016*

Natural fibers for structural sustainable out of plane retrofit of existing masonry

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Keywords: natural fiber, ductility, strengthening systems, sustainability, existing masonry.

Recent engineering applications demonstrated the innovative strengthening systems [1] to be effective for the retrofit of existing masonry buildings [2]. Several types of constituents can be used to improve the seismic capacity of masonry elements [3] both for the fibers (synthetic or natural) and matrix (organic or inorganic). The inorganic matrix usually replaces the organic matrices due to better compatibility with the masonry substrate [4]. Conversely, fibers characterized by high mechanical performances like as: carbon, glass, steel and basalt demonstrated to be effectives for several types of masonry substrates. However, for poor masonry, like as adobe or cultural heritage they could have low efficiency due to the lower mechanical compatibility to the masonry substrate [5]. In fact, for poor masonry, high performance fibers can be replaced by more compatible systems like as natural fibers. These strengthening systems are of great interest in the practical applications due to the low costs and their sustainability. In fact, the lower costs compared to the synthetic fibers allow their diffusion in emerging regions. In this paper, the impact of matrix constituent on the structural capacity of masonry elements strengthened with natural systems has been assessed. Important results have been provided in order to improve the knowledge and encourage the development of these systems in many engineering applications.

References

[1] Lignola, G.P.; Caggegi, C.; Ceroni, F.; de Santis, S.; Krajewski, P.; Lourenço, P.B.; Morganti, M.; Papanicolaou, C.; Pellegrino, C.; Prota, A.; et al. Performance assessment of basalt FRCM for retrofit applications on masonry. Compos. Part B 2017, 128, 1–18, doi:10.1016/j.compositesb.2017.05.003.

[2] Bilotta, A.; Ceroni, F.; Nigro, E.; Pecce, M. Experimental tests on FRCM strengthening systems for tuff masonry elements. Constr. Build. Mater. 2017, 138, 114–133, doi:10.1016/j.conbuildmat.2017.01.124.

[3] Ramaglia, G.; Lignola, G.P.; Fabbrocino, F.; Prota, A. Numerical investigation of masonry strengthened with composites. Polymers 2018, doi:10.3390/polym10030334.

[4] Leone, M.; Aiello, M.A.; Balsamo, A.; Carozzi, F.G.; Ceroni, F.; Corradi, M.; Gams, M.; Garbin, E.; Gattesco, N.; Krajewski, P.; et al. Glass fabric reinforced cementitious matrix: Tensile properties and bond performance on masonry substrate. Compos. Part B 2017, 127, 196–214, doi:10.1016/j.compositesb.2017.06.028.

[5] Ramaglia, G.; Lignola, G.P.; Fabbrocino, F.; Prota, A. Numerical Modelling of Masonry Barrel Vaults Reinforced with Textile Reinforced Mortars. Key Eng. Mater. 2017, 747, 11–19, doi:10.4028/www.scientific.net/KEM.747.11.

Experimentation on lime mortars reinforced with jute fibres: mixture workability and bending resistance

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Keywords: Experimental tests, lime mortar, jute fibres, workability, bending stress

Given the high number of masonry buildings on the Italian territory, which was scenario of numerous devastating earthquakes, it is clear the importance of the restoration programming. Thanks to a renewed technique sensitivity towards sustainable interventions, it is evident that the recovery techniques to protect the historical heritage must be carried out with innovative green compound materials, such as mortars reinforced with natural fibres [1, 2].

In the current paper laboratory tests on lime mortars strengthened with raw jute fibres have been performed. Workability of the fibre-reinforced mixture has been assessed through shaking table tests and the mechanical resistance of tested 40x40x160mm standard specimens has been evaluated by three-points bending tests. Given the hygroscopic nature of jute, it has been identified the optimal water / lime ratio and the maximum water percentage absorbed by jute fibers.

From analysis results it has been derived a relationship between the water/lime ratio and the spreading of the mixture, the latter being indicative of the mortar consistency. On the other hand, from bending tests, it has been noticed an effective behaviour of fibres, which provide a cracks seam effect able to make more ductile the behaviour of investigated fibre-reinforced lime mortars.

References

[1] Formisano, A., Fabbrocino, F., Dessi, E., Chiumiento, G.,"Experimental shear tests on tuff blocks triplets with hemp fibres reinforced lime mortar" in Proceedings of the 23rd Conference of the Italian Association of Theoretical and Applied Mechanics (AIMETA 2017), Salerno, 4-7 September, pp. 2022-2028, (2017).

[2] Formisano, A., Dessì, E., Landolfo, R., "Mechanical-physical experimental tests on lime mortars and bricks reinforced with hemp" in AIP Conference Proceedings, 1906, Thessaloniki, 21-25 April, art. no. 090006, DOI: 10.1063/1.5012363,(2017).

Coffee Sikverskin Filled EPDM Composite for Roofing System

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Coffee is the most consumed drinks in the world and therefore, the most important agricultural commodity in the world. Coffee worldwide demand is second only to petroleum in global trade activity and value. The industrial production of coffee beverage requires several processing production steps. It stars with the conversion of coffee cherries into green coffee beans, and with the removal of both the pulp and hull using either a wet or dry method. The roasting of coffee beans is a very important step in coffee processing, since specific organoleptic properties (flavors, aromas, and color) are developed, and affect the quality of the coffee. The entire coffee production process causes serious environmental problems mainly related to the huge amount of solid residues generated. The main wastes that need of specific disposal options are two, the spent coffee grounds (SCG) and the coffee silverskin (CSS). In particular, SCG is the residue of the brewing process, while CSS is the by-product coming from the coffee roasting process and consists of the innermost layer of the coffee bean. CSS has high contents of fibres and minerals a marked amount of protein, polysaccharides and fats. It shows antioxidant activity probably due to the synergistic interaction among chlorogenic acids, caffeine, and melanoidins that are present in its composition. On these bases, CSS can be considered a promising waste derived resource and many research groups are focusing on its utilization as sustainable renewable energy sources (bio-mass, bio-diesel oil and bio-ethanol); and for cosmetic applications. However, CSS could find application as filler especially in polymer matrix composites. There are only few papers dealing with the use of CSS as filler in polymer but it may have promising antiaging properties due to the presence of antioxidants. The aim of this work is to design and characterize a composite material based on a thermoplastic elastomer matrix (Ethylene Propylene Diene Monomer) EPDM, filled with SSC for metal roofing system application.

After preliminary characterization of CSS (FT-IR and Scanning electron microscopy), compounds have been prepared by batch mixing and vulcanized on steel substrate. Samples have been UV aged according to ASTM D4329 – 13 and tested, before and after aging, by means of FT-IR, Shore A Hardness, tensile test and bending test. After aging, SCC filled samples show higher mechanical properties than unfilled samples, confirming the possibility to use CSS as filler in polymer matrix composites.

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MASONRY CONSTRUCTIONS: FROM MATERIAL TO STRUCTURES, MODELLING AND ANALYSIS APPROACHES

Discrete approaches and Limit Analysis for the in-plane failure analysis of historical masonry.

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Keywords: Masonry, Rigid Blocks, Micromodelling, Limit Analysis.

Despite its complexity, the accurate structural modelling of masonry still represents an active field of research, due to several practical applications in civil engineering, with special reference to the preservation and restoration of cultural heritage. The above-mentioned tasks call for very accurate analyses of masonry structures, able to capture their peculiar mechanical features in the nonlinear range. In this work a comparison of different models and techniques for the assessment of the mechanical behaviour of two-dimensional block masonry walls subjected to the static action of in-plane loads is presented. Panels are characterized by different height-to-width ratio as well as various masonry textures. Brick-block masonry, perceived as a jointed assembly of prismatic particles in dry contact, is modelled as a discrete system of rigid blocks interacting through contact surfaces unable to carry tension and resistant to sliding by friction, modelled as zero thickness elasto-plastic Mohr-Coulomb interfaces. Different approaches and numerical models are considered: Limit Analysis (LA), Discrete Element Method (DEM) and Finite Element Method (FEM). Limit Analysis is able to provide fast and reliable results in term of collapse multiplier and relative kinematism. Here a non-standard Limit Analysis (non-associative rules) is adopted [1],[2] via an own made procedure based on Non-Linear and Non-Convex Mathematical Programming, taking into account friction at interfaces, settlements of the supports, reinforcements and/or cohesion among stones. Focusing on discrete models, they represent a class of numerical models able to study the mechanical behaviour of systems made of particles, blocks or multiple bodies. Discrete element models are characterized by two components: elements, considered as infinitely rigid or deformable bodies or modelled into Finite Elements frames [3], and contacts. A numerical comparison is proposed to evaluate the field and limit of application of the different approaches.

References

[1] Baggio, C., and Trovalusci, P. (2000) Collapse behaviour of three- dimensional brick-block systems using non-linear programming. Structural Engineering and Mechanics 10, 2, 181-195.

[2] Baggio, C., and Trovalusci, P. (2016) 3D Limit Analysis of roman groin vaults. In: Brick and Block Masonry: Trends, Innovations and Challenges - Proceedings of the 16th International Brick and Block Masonry Conference, IBMAC 2016, 1023-1028.

[3] Baraldi, D., Reccia, E., and Cecchi, A. (2018) In plane loaded masonry walls: DEM and FEM/DEM models. a critical review. Meccanica, 53, 7, 1613-1628.

Thrust network analysis of masonry vaults through a constrained force density method

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Keywords: force density method, funicular analysis, vaulted structures, mathematical programming

Thrust network analysis is extensively adopted to cope with the assessment of masonry vaults and domes, especially those of historical interest, see e.g. [1, 2, 3]. Surface structures such as shells are modeled as statically indeterminate networks of vertices and edges of given topology, working exclusively in compression. The networks are subject to boundary supports and are in equilibrium with loads applied at the nodes. To assess the safety of an existing structure in the spirit of the lower bound theorem of limit analysis, a thrust network must be found whose vertices lie between the intrados and the extrados of the vault, see e.g. [4]. A minimization/maximization problem is formulated on networks of general shape adopting, as objective function, a norm of the horizontal thrusts and, as unknowns, the independent set of the so–called force densities [5], i.e. the ratio of force to length in each branch of the network. These can be found computing the Reduced Row Echelon form of the network's equilibrium matrix, see e.g. [6, 7]. A suitable set of constraints is formulated to enforce lower and upper bounds for the vertical coordinates of the vertices of the network, which are written in terms of the two sets of unknowns, along with compression–only members. Networks of minimum and maximum thrust can be efficiently retrieved through techniques of mathematical programming that are generally implemented to handle multi–constrained formulations of structural optimization [8]. Numerical simulations are shown that refer to masonry-like curved structures such as vaults and domes. Both horizontal and vertical loads are considered to validate the predictions of the proposed algorithm with respect to numerical and analytical results available in the literature of no-tension solids, see also [9].

References

[1] *O'Dwyer, D.W., "Funicular analysis of masonry vaults", Comput. Struct.,* **73***, 187–197 (1999).*

[2] *Block, P., Ochsendorf, J., "Thrust network analysis: a new methodology for three-dimensional equilibrium", J. Int. Assoc. Shell Spatial Struct.,* **48(3)***, 167–173 (2007).*

[3] *Marmo, F., Rosati, L., "Reformulation and extension of the thrust network analysis", Comput. Struct.,* **182***, 104–118 (2017).*

[4] *Ceradini, C., "La curva delle pressioni nelle volte cilindriche", Annali della Società degli Ingegneri e degli Architetti Italiani (1887).*

[5] *Schek, H.J., "The force density method for form finding and computation of general networks", Comput. Methods Appl. Mech. Eng.,* **3***, 115–134 (1974).*

[6] *Cercadillo-García, C., Fernández-Cabo, J.L., "Analytical and Numerical funicular analysis by means of the Parametric Force Density Method", J. Appl. Res. Technol.,* **14***(2), 108-124 (2016).*

[7] *Liew, A., Pagonakis, D., Van Mele, T., Block, P., "Load-path optimisation of funicular networks", Mecc.,* **53:1–2***, 279–294 (2018).*

[8] *Christensen, P., Klarbring A., An Introduction to Structural Optimization, Springer (2009).*

[9] *Como, M., Statics of Historic Masonry Constructions, Springer (2016).*

On the displacement-based analysis of collapse mechanisms in masonry structures

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Keywords: Damage model; Contact interface; Limit analysis

Limit analysis-based numerical strategies represent reliable approaches for the investigation of the collapse mechanisms and collapse multipliers of masonry structures [1].

However, limit analysis does not provide any information about the evolution of the displacement field of the structure. Therefore, limit analysis-based solutions cannot be used in the framework of displacement-based seismic assessment procedures (e.g. pushover analysis), which are the most common and widespread utilized procedures in earthquake engineering.

In this study, the possibility of conducting displacement-based analyses of collapse mechanisms in masonry structures is explored. Particularly, all the nonlinearities of the numerical model are lumped into tight zones of the structure suitably defined according to the collapse mechanism previously computed through upper-bound adaptive limit analysis [1]. Then, pushover analyses are performed, by using various nonlinear constitutive models [2]. Accordingly, the collapse mechanism is imposed to the structure and the evolution of the displacement field along with the analysis is computed.

References

[1] *Chiozzi, A., Milani, G., Grillanda, N., and Tralli, A. "A fast and general upper-bound limit analysis approach for out-of-plane loaded masonry walls," Meccanica, **53**(7), 1875–1898 (2018).*

[2] *D'Altri, A. M., de Miranda, S., Castellazzi, G., and Sarhosis, V. "A 3D detailed micro-model for the in-plane and out-of-plane numerical analysis of masonry panels," Computers & Structures, **206**, 18–30 (2018).*

Roman masonry stairways. Geometry, construction and stability

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Keywords: roman stairways, masonry, limit analysis.

This article focuses on the study of the so-called "Roman Masonry Stairways" which represent a rather common typology in historical buildings particularly in the Neapolitan area. The vaulted system of the numerous examples of Neapolitan open staircases consists of the use of the main elements of structural support, such as arches and vaults, underlining the close dialectical relationship between form and structure. Therefore, the analysis of the vaulted space is carried out in relation to functional requirements, materials and construction techniques within the articulation of the architectural figure [1].

This research proposes an interpretation of the static behavior of this type of staircase through simplifications that facilitate its analysis.

In this paper reference is made to the case study of the stairway of Palazzo Persico in Naples, whose structural analysis is carried out in the theoretical framework of the Limit Analysis as applied by Heyman to masonries [2]. The main objective of the investigation is to demonstrate the static equilibrium of this structure and to understand its mechanical behavior.

Before dealing with the analysis, the structural process was defined from different points of view, by interlocking formal, material and spatial aspects. The formal definition concerns its geometric configuration, while the material and spatial one concerns the elements that compose it and the relationship existing between them.

Specifically, the staircase in issue is characterized by a cantilevered structural system with a planimetric scheme consisting of a 45° rotated square. Its vertices are rounded off by arches of circumference along the sides of which are placed the flights. The flights are cantilevered from the walls and connected by small vaults constituting the landings, as common for these masonry vaulted staircases.

The aim of the work is to obtain an equilibrium solution that, being compatible with the loads, does not violate the limit condition of the material [3]. In other words, a solution for which there is no traction and where the compressive stresses are contained within the masonry. The structural analysis was performed taking into account the principles of limit analysis and by applying the Safe Theorem. Ultimately a static graphic analysis has been conducted.

References

[1] *Luggo, A.,"Struttura e forma: le superfici voltate nelle scale aperte napoletane" in Disegnare il tempo e l'armonia. Firenze, 2010, pp. 394-399, Alinea Editrice, ISBN 978- 88-6055-572-4.*

[2] *Heyman, J.,"The mechanics of masonry stairs", Transactions of the Built Environment, Vol. 15, WIT Press (1995).*

[3] *Como, M., "Statics of historic masonry constructions", Springer Series in Solid and Structural Mechanics, Vol. 9, New York (2017).*

On unilateral contact between rigid masonry blocks

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Keywords: Contact problems, Masonry, Foundation settlements.

The study of historic masonry buildings deals with two main issues: 1) understanding their structural behavior, by studying the possible states of equilibrium, to assess safety versus applied loads, and 2) interpreting the origin and significance of their fractures, evaluating what kind of foundation settlements gave origin to the observed pattern of cracks. As it is well known, modern theory of limit analysis of masonry structures, which has been developed mainly by J. Heyman, is the most reliable tool to understand and analyze equilibrium of masonry structures and a huge amount of works treated this subject and developed efficient numerical techniques. More recent is the interest in the study of the crack patterns induced by the movements of the masonry structure and the development of approximate numerical techniques to evaluate them.

Let us consider both an assemblage of stone blocks and a masonry body, which can be modeled as an assemblage of particles held together by the compressive stresses produced by loads. The small size of the bricks, compared to the dimensions of the body, enables it to be considered a continuum, instead of a discrete system of many individual particles. However, both in the state of incipient collapse and in presence of foundation settlements, in a masonry structure appear fractures and the body motion (or the body displacement field in the second case) represents a mechanism. Therefore, the displacement field is piecewise continuous and strong discontinuities (fractures) appear along lines, when considering the problem in 2D, or surfaces, in 3D, and these anyway actually identify separate blocks.

This contribution first addresses the problem of the unilateral contact between elastic bodies. For the sake of simplicity frictionless contact, the so-called Signorini-Fichera problem, is considered. We re-discuss two variational formulations based on the search for extreme points of quadratic forms defined on convex sets. The first is the classical one based on the minimum of the total potential energy; the second formally obtained by the Green functions of the problem has as unknowns only the contact pressures that the bodies exchange between them and with the constraints [1-3]. In the case of negligible elastic deformations, the quadratic part of the two functional vanishes and two linear functional are left which express the work of the external loads and of the constraint reactions for the imposed settlements. The discretization of the two problems leads to two dual linear programming problems. In this way, it is possible to critically discuss the obvious similarities between the limit analysis of masonry structures and the contact problem between rigid bodies and, more importantly, underline the profound differences among them.

References

[1] *Wriggers, P., Computational contact mechanics, Springer, Berlin (2006).*
[2] *Kikuchi, N., Oden, J. T., Contact problems in elasticity,SIAM (1988).*
[3] *Alliney, S., Tralli, A., and Alessandri, C., "Boundary variational formulations and numerical solution techniques for unilateral contact problems", Computational Mechanics,* ***6****(4), 247-257 (1990).*

Thrust membrane analysis of the domes of the Baia thermal baths

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Keywords: Thrust membrane analysis, Masonry domes

Based on Heymans principles of limit analysis of masonry structures [1], the Thrust Network Analysis (TNA) is a recently formulated technique for modelling stresses in masonry vaults as a discrete network of forces in equilibrium with the applied loads [2]. Although the TNA allows for analysing structures of very complicated geometry [3] subjected to both vertical and horizontal loads [4] the evaluation of membrane stresses starting from the value of branch thrust is troublesome.

For this reason, the TNA has been recently extended to properly model membrane stresses by formulating a triangular element that substitutes branch elements of the classical thrust network model. Renamed Thrust Membrane Analysis (TMA) for obvious reasons [5], this new formulation employs energetic equivalence between a triangular element and a network of three branches connecting element nodes in order to establish a relationship between membrane stresses and thrust forces within side branches. Accordingly, the proposed strategy modifies assemblage and post-processing of the TNA, although the set of equilibrium equations and the solving procedures remain unchanged. Hence, all beneficial features of the TNA are inherited by the new formulation, with the additional advantage of properly modelling membrane stresses.

After illustrating the main assumptions underlying the TMA, we report on the application of the method to the limit equilibrium analysis of the domes covering the Roman thermal baths of Baia (Naples) [6]. In particular, due to their interesting features, we present the cases of the dome of Mercury, considered to be the prototype of the celebrated Pantheon dome in Rome, and the half-destroyed dome of Diana, the biggest one in the archeological park of Baia.

References

[1] *Heyman, J., "The stone skeleton," International Journal of solids and structures,* **2***(2), 249–279, (1966).*

[2] *Marmo, F., Rosati, L., "Reformulation and extension of the thrust network analysis," Computers & Structures,* **182***, 104–118, (2017).*

[3] *Marmo, F., Masi, D., Rosati, L., "Thrust network analysis of masonry helical staircases," International Journal of Architectural Heritage,* **12***, 828–848, (2018).*

[4] *Marmo, F., Ruggieri, N., Toraldo, F., Rosati, L., "Historical Study and Static Assessment of an Innovative Vaulting Technique of the 19th century," International Journal of Architectural Heritage, DOI:10.1080/15583058.2018.1476607, (2018).*

[5] *Marmo, F., Sessa, S., Paradiso, M., Rosati, L., "Thrust Membrane Analysis of masonry vaults," Manuscript in preparation, (2019).*

[6] *Marmo, M., "Le cupole del Complesso archeologico delle Terme di Baia: la geometria degli spazi e dei fenomeni luminosi," Doctoral dissertation, University of Naples Federico II, (2019).*

Collapse of non-symmetric masonry arches with Coulomb friction: Monasterio's approach and equilibrium analysis

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Keywords: non-symmetric masonry arches, Coulomb's friction, limit analysis.

The present paper examines a challenging subject, *i.e.* the collapse analysis of non-symmetric masonry arches under the hypothesis of finite Coulomb friction.

As is well known, when the Coulomb friction is assumed to be finite, the normality rule characterizing a *standard* behaviour of the material does not hold. When a finite friction is assumed, some static admissible solutions identified by the equilibrium approach could correspond to a mechanism with relative sliding, and the collapse mechanism is not necessarily unique, except for particular cases such as symmetric arches [1, 2, 3].

The first scholar who studied in depth the collapse conditions of non-symmetric arches has been Joaquín Monasterio in his unpublished manuscript, entitled *Nueva teórica sobre el empuje de bóvedas*, an interesting text found by Santiago Huerta [4]. The approach proposed by Monasterio differentiates itself from the static one, since the starting point of his analysis concerns the *a priori* identification of some plausible collapse mechanisms, by defining the conditions required for their activation; therefore, the procedure can be placed in an upper bound framework.

A comparison between the kinematic approach proposed by Monasterio and equilibrium analysis according to Coulomb's treatment [5] is performed, by examining the collapse behavior of an arch in the presence of finite friction. Although Monasterio's criterion has only a local and not a global validity, it will be shown that also his kinematic approach allows for obtaining a chart to identify overall stability of the arch, by taking into account the critical role of the most important parameters, that is friction and arch thickness.

References

[1] *Sinopoli, A., Corradi, M. and F. Foce. 1997. A Modern Formulation for Pre-Elastic Theories on Masonry Arches, Journal of Engineering Mechanics, ASCE, 204-213.*

[2] *Sinopoli, A., Aita, D. and F. Foce. 2007. Further Remarks on the collapse of masonry arches with Coulomb Friction, Proceedings of the 5th International Conference on Arch Bridges. P. B. Lourenço, D. V. Oliveira, and Portela A. (eds.), Multicomp, Guimaraes, 2007, 649-657.*

[3] *Aita D., Barsotti R., Bennati S. 2019. Looking at the collapse modes of circular and pointed masonry arches through the lens of Durand-Claye's stability area method, Archive of Applied Mechanics. https://doi.org/10.1007/s00419-019-01526-z*

[4] *Huerta, S., Foce, F. 2003. Vault theory in Spain between XVIIIth and XIXth century: Monasterio's unpublished manuscript "Nueva teorica sobre el empuje de bovedas", Proceedings of the First International Congress on Construction History, Madrid. January 20-24, 2003, S. Huerta (ed.), Madrid: I. Juan de Herrera, ETSAM, 2003, 1155-1166.*

[5] *Coulomb C. A. 1776. Essai sur une application des règles de maximis et minimis à quelques problèmes de statique, relatifs a l'architecture. Mémoires de mathématique & de physique, présentés à l'Academie Royale des Sciences par divers savans, 7, 1773, 343-382.*

Strain based residuals limit analysis of arcs and domes

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Keywords: Limit design, masonry vault, lower bound theorem.

The masonry structures that constitutes the whole of the Cultural Heritage have been analysed by centuries by means of well-established procedures based on statics. It is well known to structural engineers that the methods based on equilibrium refers in a certain way to lower bound theorem of limit analysis [1]. The limit analysis represents a road to the evaluation of structural stability and lends itself well to the study of masonry structures, whether you want to adopt a kinematic approach [2], [3], or whether you want to adopt a static approach [4] [5].

In this work, the authors propose the study of a masonry arch through the lower bound theorem through the implementation of SBR (Static Based Residual) Method and a comparison with known results of an experimental test performed by Page [6] and an analysis with cinematic approach by Gambarotta [7]. The equilibrated stress is obtained by strain based residuals SBR approach. The SBR derive discontinuous finite elements by applying Volterra's discontinuities to element nodes. In particular, one-dimensional arc (1D) is proposed in order to introduce the SBR methodology, which is fully useful in the case of two-dimensional and three-dimensional models where it is not possible to define eigenstress basis. The application of the static theorem removes the burden of having to intuitively search for a possible mechanism of the structure, managing to derive a value of the collapse multiplier in a straight form. This involves the possibility of making the method a real procedure, lending itself very well to writing the optimization problem in the form of an algorithm. Furthermore, the SBR method yields to an effective procedure to analyse the self-equilibrated stress field of structures within the discontinuity based stress space.

References

[1] Mery, M., "Sur l'equilibre des vôute en berceau" in Annales de ponts et chaussées , Paris, 1^er^ series, 1^er^ semester, page 55-70, (1840).

[2] Tralli, A., Alessandri, C., Milani, G., "Computational Methods for Masonry Vaults: a review of recent results", The Open Civil Engineering Journal, ***8*** *272-287 (2014).*

[3] Marmo, F., Masi, D., Sessa, S., Toraldo, F., Rosati, L., "Thrust network analysis of masonry vaults subject to vertical and horizontal load", in Proceedings of the 6^th^ International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Rhodes Island, Greece,15-17 June 2017, vol. 1, 2227-2238 (2017).

[4] Block, P., Lachauer, L., "Three dimensional funicular analysis of masonry vaults", Mechanics Research Communication, ***56****, 53-60, (2014).*

[5] Fraternali, F., "A thrust network approach to the equilibrium problem of unreinforced masonry vaults via polyhedral stress functions", Mechanics Research Communication, ***37****, 198-204, (2010).*

[6] Page, J., "Load tests to collapse on to arch bridges at Preston, Shropshire and Prestwood, Staffordshire", Department of Transport, TRRL Research report 110, TRL, Crowthorne, England, (1987)

[7] Cavicchi, A., Gambarotta, L., "Two dimensional finite element upperbound limit analysis of masonry bridges", Computer and structures, ***84****, 2316-2328, (2006)*

Corotational multiscale beam finite element model for stability analysis of nonlinear masonry walls

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Keywords: Masonry walls, Stability, Multiscale approach

Under horizontal loadings, such as seismic actions, buckling phenomena can strongly affect the bearing capacity of masonry walls to gravity loads. Indeed, due to the low tensile strength of the mortar, when vertically loaded masonry members are subjected to bending moments induced by load eccentricity, out-of-plane collapse mechanisms often prevails on compressive vertical crushing [1].

Many approaches have been proposed in the last decades to simulate the progressive out-of-plane instability of masonry structural elements. In 1971, Yokel [2] proposed an analytic approach where the wall is modeled as a continuous homogeneous element, allowed to deformed only in the out-of-plane direction. By considering an eccentric monotonically increasing vertical load applied at the top and elastic no-tension material, the nonlinear equilibrium equations under large displacements are solved and the evolution of wall deflection is described. Numerical methods have been later developed, often adopting Finite Element (FE) techniques [3, 1]. These rely on the micromechanical, macromechanical or multiscale approach, distinguished for modeling and analysis scale.

This work extends the multiscale beam-to-beam FE model presented in [4] to study the out-of-plane stability of masonry walls under eccentric vertical compressive loads. The model at the macroscale considers a two-dimensional Timoshenko beam that is linked to a repetitive masonry Unit Cell (UC) at microscale. This is made by the superposition of a single linear elastic brick, a mortar joint exhibiting a damage-plastic constitutive response and, eventually, a reinforcing layer, characterized by a piece-wise linear damage-based constitutive law. As opposed to the original model formulated under the assumption of linear geometry, in this work a corotational formulation is considered for the beam at the macroscale that accounts for large nodal displacements and P-Delta effects occurring during instability phenomena. The response of eccentrically loaded masonry walls is reproduced, comparing the numerical results with experimental data and analytical solutions.

References

[1] *Bernat, E., Lluis, G., Roca, P. and Sandoval, C., "Experimental and numerical analysis of bending-buckling mixed failure of brickwork walls", Construction and Building Materials,* **43**, *1-13 (2013).*

[2] *Yokel, F.Y., "Stability and load capacity of members with no tensile strength", Journal of the Structural Division,* **97**, *1913-1926 (1971).*

[3] *Lu, M., Schultz, A.E., and Stolarski, H.K., "Application of the arc-length method for the stability analysis of solid unreinforced masonry walls under lateral loads", Engineering Structures,* **27**, *909-919 (2005).*

[4] *Addessi, D. and Sacco, E., "Homogenization of heterogeneous masonry beams", Meccanica, DOI: 10.1007/s11012-017-0758-2 (2017).*

Metamodels in nonlinear mechanics for Bayesian FEM updating of ancient high-rise masonry structures

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Keywords: Metamodel, Bayesian paradigm, Uncertainties quantification.

In order to estimate their behavior as realistic as possible, masonry structures and historical complex buildings are frequently assessed with demanding non-linear procedures, whether for static or dynamic purposes. However, uncertainties related to the epistemic and aleatory field, especially for historical masonry, can widely influence the output reliability and diminish the value of the deterministic approach (one input – one output) in a decision making workflow: for instance, the necessity for urgent structural interventions or even the possibility to close the building or civil object for safety reasons [1], [2].

This paper aims to show how these uncertainties could be quantified, based on a multi-parameter input approach, and consequently handled. In sequence, *i*) the knowledge, based on the state-of-the-art survey of the object (geometry, quality and characteristics of the materials, etc.) and scientific or engineering contents (constitutive laws, possible sources of excitation, solution methods, etc.) can be put inside a numerical model in order to find a solution for the desired output, *ii*) input parameters could be treated as variables, so that the model space could be explored for different sets of values and *iii*) a probabilistic model or distribution could be adopted for each parameter, based on previous known observations. The outputs of such a model will be of statistic nature and will have a probabilistic distribution as well: based on this data, produced by the numerical model (f.i. a finite element model), a relationship between inputs and outputs could be established in an approximated mathematical formulation, the so-called metamodel [3], [4]. In this context, the newly generated (meta)model has the following characteristics: *i*) it has been validated as the correct representation of the original model, *ii*) it is much less computationally demanding than the original model, *iii*) it establishes a direct relationship between the input parameters and the output, *iv*) it can be used both for input parameters calibration, based on new observations, and, possibly, for the risk assessment. Based on these considerations, the metamodel could be assumed as a fast and validated decision-making tool. An elucidating example is herein discussed with reference to a historic masonry tower.

References

[1] *Conde, B., Eguìa, P., Stavroulakis, G.E. and Granada, E., "Parameter identification for damaged condition investigation on masonry arch bridges using a Bayesian approach," Engineering Structures, 172, page 275-285 (2018).*

[2] *Jensen, H.A., Esse, C., Araya, V., and Papadimitriou, C., "Implementation of an adaptive meta-model for Bayesian finite element model updating in time domain," Reliability Engineering & System Safety, 160, page 174-190 (2017).*

[3] *Friedman, L.W., The Simulation Metamodel, Kluwer Academic Publisher, Norwel, Massachusetts, (1996).*

[4] *Tarantola, A., Inverse Problem Theory and methods for Model Parameter Estimation, Siam, Philadelphia, Pennsylvania, (2005).*

Orthotropic masonry-like materials

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Keywords: orthotropic masonry, anisotropic damage.

Certain materials can only withstand some types of stress. It is generally assumed that the admissible stresses must belong to a closed and convex subset K of the space of all symmetric tensors of the second order, which is called the stress range. Materials that are not resistant to traction, possibly with limited resistance to compression and shear stresses belong to this class of non-linear elastic materials. They are characterized, as well as by K, by the elasticity tensor **C**. When **C** is isotropic, the explicit solution of the constitutive equation can be obtained quite easily, as in this case the coaxiality of the stress and strain tensors allows to solve the problem in their common characteristic space [1], [2]. Nevertheless, there are several applications for which, the model turns out to be more realistic if the different properties of the material in various directions are accounted for [3]. In [4] the constitutive equation has been generalized to the case where **C** is orthotropic, a circumstance in which the characteristic space of the stress is part of the unknowns of the problem.
In this paper, a further generalization of the constitutive equation has been proposed which accounts for both the anisotropy of the stress range K and the orthotropic elasticity tensor **C.** This equation allows to better model the non isotropic masonry behaviour and to formulate non-isotropic damage laws [5],[6].

References

*[1] Lucchesi, M., Pintucchi, B., Zani, N., "Masonry-like materials with bounded shear stress" European J. Mech-A Solids, **72**, 329-340 (2018).*
*[2] Lucchesi, M., Pintucchi, B., Zani, N., "Bounded shear stress in masonry-like bodies" Meccanica, **53**, 1777-1791 (2018).*
*[3] Lourenço, P. B., Rots, J. G., Blaauwendraad J., "Continuum model for masonry: parameter extimation and validation" J. Stuct. Eng. **124**, 642-652 (1998).*
[4] Lucchesi, M., Pintucchi, B., Zani, N., "Orthotropic plane bodies with bounded tensile and compressive strength", to appear in J. Mech. Mat. Struct.(2019).
*[5] Berto, L., Scotta, R., Vitaliani, R., "An orthotropic damage model for masonry structures" Int. J. Numer. Methods Eng. **55**, 127-157 (2002).*
*[6] Lourenco, P., De Borst, R., Rots, J., "A plane stress softening plasticity model for orthotropic materials" Int. J. Numer. Methods Eng. **40**, 4033-4057 (1997).*

Failure analysis of masonry panels with an anisotropic elastic-perfectly plastic constitutive model

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Keywords: masonry, anisotropy, numerical modelling

Failure mechanisms and crack patterns characterizing the nonlinear response of masonry under both vertical and horizontal load conditions are strongly affected by its intrinsic anisotropic behaviour. Moreover, in case of ancient masonry walls, typically constituted by high strength units (stone blocks or bricks) and weak mortar, texture (i.e. the arrangement of blocks and mortar joints) is one of the key elements that determine failure morphological features. Some analogies between this material and fissured rocks can therefore be envisaged: the discontinuities of a rock mass and their orientation drive failure similarly to mortar joints in masonry walls and in both cases cohesion and friction characterize the response along these weakness planes. However, peculiar features such as interlocking due to staggered head joints and the periodic nature of masonry need to be considered and make its constitutive response more complex.

In this research work the in-plane and the out-of-plane behaviour of masonry walls are analysed. The adopted constitutive model has been formulated stemming from a pre-existing one, originally conceived to simulate the behaviour of jointed rock layers, and has been implemented in the commercial code *PLAXIS 3D* [1]. It is a three-dimensional model based on the identification of preferential orientation of failure planes, on which a Mohr Coulomb failure criterion holds in conjunction with a tensile stress cut-off. Elastic properties are derived from a relatively simple homogenization procedure [2] and geometrical characteristics of blocks as well as the effect of staggered arrangement of head joints are accounted for.

Some case-studies in which masonry is subjected to self-weight and horizontal forces for different geometrical configurations are analysed. Results are compared with both experimental evidences [3] and the numerical outcomes obtained resorting to a different constitutive model in which masonry is described as a homogenized anisotropic medium [4]. The proposed model is also adopted for the simulation of a real-scale static soil-structure interaction problem, in which the effects of a landslide occurring in proximity to a historical masonry building are studied.

The analyses aim at highlighting the capability of the model to describe the structural macroscopic behaviour in terms of collapse mechanism and collapse multiplier. In spite of its simplicity, the proposed approach is able to account for the role of texture with low computational cost and a relatively limited number of mechanical parameters, obtained from a manageable calibration procedure.

References

[1] *Lasciarrea, W. G., Amorosi, A., Boldini, D., De Felice, G. and Malena, M., "Jointed Masonry Model: a constitutive law for 3D soil-structure interaction analysis", Submitted (2018).*

[2] *De Felice, G., Amorosi, A., and Malena, M., "Elasto-plastic analysis of block structures through a homogenization method", International journal for numerical and analytical methods in geomechanics* **34***(3), page 221-247 (2010).*

[3] *Restrepo Vélez, L. F., Magenes, G., Griffith, M. C., "Dry Stone Masonry Walls in Bending Part I: Static Tests" International Journal of Architectural Heritage: Conservation, Analysis, and Restoration,* **8***(1) page 1-28 (2014).*

[4] *Malena, M., de Felice, G., "Crack pattern prediction in masonry", Journal of Mechanics of Materials and Structures. Submitted (2018).*

Sensitivity to bricks arrangement in typical nineteenth-century masonry vaults in Cagliari

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Keywords: masonry vaults, bricks arrangement, constructive techniques

In this work, masonry vaults are investigated with the purpose of evaluating the role of bricks arrangement in their mechanical behaviour and in relation to the techniques adopted for their construction.

Attention is focused on a typical typology of masonry vaults built during the nineteenth-century in the city of Cagliari. They are lowered sail vaults, obtained from the intersection of a spherical cap with a prism with a square base carved on its base, i.e. with four vertical planes. The peculiarity of these vaults is that they are built with several brick arrangements. A series of rigorous laser scanner surveys have been performed on some of these vaults in the Cagliari area, in order to obtain the effective geometry both at macro-level – the vault shape – and at micro-level – brick patterns.

As it is well known, under membrane theory assumption, stress diffusion in masonry vaults and its distribution along meridians and parallels is only a problem of equilibrium [1] and is related to the vault shape [2, 3]. Instead, the distribution of strains is related both to the vault geometry both to mechanical properties of material, therefore masonry stiffness has to be considered. The different brick patterns adopted in these vaults may play a relevant role [4].

In the work, the sensitivity to brick arrangement is evaluated. Moreover, some hypothesis about the constructive techniques that might have been used by masons are investigated: the purpose is to evaluate if these peculiar brick patterns have been adopted to facilitate the construction of the vaults.

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References

[1] *Belluzzi, O., Scienza delle Costruzioni vol.III, Zanichelli, Bologna, (1955).*

[2] *Heyman, J., "The Stone skeleton", International Journal of Solids and Structures,* **2***, page 249-279 (1966).*

[3] *Como, M., Statica delle costruzioni storiche in muratura, Aracne Editrice, Roma (2015).*

[4] *Milani, G., Cecchi, A., "Compatible model for herringbone bond masonry: Linear elastic homogenization, failure surfaces and structural implementation International Journal of Solids and Structures,* **50***,20-21, page 3274-3296 (2013).*

Impact analysis in the rocking of masonry circular arches

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Keywords: masonry, circular arch, no tension material, rocking, restitution factor, constant acceleration pulse.

Aim of the paper is the study of the rocking of the masonry arch that, hit by a horizontal impulse of acceleration, moves sideways according to a mechanism u^- defined by four hinges. The arch, once reached a maximum side displacement, inverts its motion going back, still moving along the same mechanism. At a time instant t, it reaches the zero configuration and it cannot continue its motion along u^- because all the hinges of this mechanism are now blocked. A reverse mechanism thus takes place. The arch mobilizes the new mechanism u^+ that has the "mirror" positions of the hinges of the mechanism u^-. A new impact model, alternative to the ones available in literature and pointing out all the questionable problems, is proposed in this paper. It is thus shown that impacts occur in the points where are located the hinges of this new mechanism u^+: energy losses take place at these impact points.
It is shown that the arch presents a coefficient of restitution lower than the one of the solid column, due to the existence of multiple impact sections. Furthermore, the energy dissipation increases with decreasing values of the angle of embrace of the arch. Then the arch, in its rocking motion, continues to move back and forth, slowing down, up to the stop of the motion. The paper will thoroughly analyze all the stages of motion evaluating, by means of the Principles of Impulse an d of the Angular Momentum, the coefficient of restitution, i.e. the changing, occurring at the impacts, of the kinetic energy of the arch.

Equivalent frame modelling of an unreinforced masonry building in finite element environment

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Keywords: equivalent frame model, unreinforced masonry, cultural heritage.

Equivalent frame method (EFM) is a viable modelling option for global seismic analysis of masonry buildings in comparison to more refined techniques, such as continuum finite elements (FE)[1, 2, 3]. However, said simplified method takes advantage of a building's geometric regularity, the good quality of its masonry and the floors stiffness, since these are the requirements for box-like behaviour under seismic loads. On the other hand, typical vulnerabilities in existing unreinforced masonry (URM) buildings, e.g. deformable floors, openings too close one another, poor quality masonry, isolated pillars and non-vertically aligned walls, limit the effectiveness of EFM application for their modelling.

Recently, many studies have been devoted to expanding the possibilities of applying EFM to buildings which don't meet box-behaviour hypotheses [4, 5, 6].

The paper describes the procedure for implementing an equivalent frame (EF) model of an existing URM building in Midas GEN, a finite element code otherwise purposely thought for steel and r.c. design. The equivalent frame (piers and spandrels) consists of a system of 1-D lumped plasticity beam elements, as proposed by [7]. In MIDAS Gen the definition of the frame starts from existing theoretical criteria [8, 9] adapted to the peculiar characteristics of the building.

The case study is represented by a brick-and-timber-floors palace, part of Italian cultural heritage buildings, placed just outside the old town of Noale (Venezia). Palazzo Carraro complies with the main requirements of EFM except for floors stiffness, although horizontal connections may be considered sufficient at this level of analysis.

Possibilities and limits of the specific procedure are here discussed, referring also to other state-of-the-art techniques, such as continuum models [10], implemented through the DIANA FEA code.. The paper explores the response of the EF model to different modelling choices but also its reliability in global analyses.

REFERENCES

[1] E. Quagliarini, G. Maracchini, F. Clementi, Uses and limits of the Equivalent Frame Model on existing unreinforced masonry buildings for assessing their seismic risk: a review. *Journal of Building Engineering*, **10** (3), 166-182, 2017

[2] F. Clementi, P.A. Mezzapelle, G. Cocchi, S. Lenci, Global analyses of historical masonry buildings: Equivalent frame vs. 3D solid models. *Proceedings of the International Conference of Numerical Analysis and Applied Mathematics* (ICNAAM), 2016

[3] F. Clementi, V. Gazzani, M. Poiani, S. Lenci, Assessment of seismic behaviour of heritage masonry buildings using numerical modelling. *Journal of Building Engineering*, **8** (12), 29-47, 2016

[4] R. Siano, G. Camata, V. Sepe, E. Spacone, P. Roca, L. Pelà, Finite Elements vs. Equivalent-Frame Models for URM walls' in-plane behaviour. *16th World Conference on Earthquake Engineering*, 2017

[5] Y. Nakamura, H. Derakhshan, A. Sheikh, J.M. Ingham, M.C. Griffith, Equivalent Frame Modelling of an Unreinforced Masonry Building with Flexible Diaphragms – A Case Study *Bulletin of the New Zealand Society for Earthquake Engineering,* **49** (3), 2016

[6] I. Giongo., M. Piazza, R. Tomasi, Pushover analysis of traditional masonry buildings: influence of refurbished timber-floors stiffness. In *International Conference on Structural Health Assessment of Timber Structures, Lisbon*, 2011

[7] G. Magenes, A. Della Fontana, Simplified Non-linear Seismic Analysis of Masonry Buildings, *Proceedings of the British Masonry Society,* London, 1998

[8] N. Augenti, Seismic behaviour of irregular masonry walls. *Proceedings of the 1st European Conference on Earthquake Engineering and Seismology,* Geneva (CH), 2006

[9] M. Dolce, Schematizzazione e modellazione degli edifici in muratura soggetti ad azioni sismiche. *L'Industria delle Costruzioni,* **25**, 44-57 [in Italian], 1991

[10] J. Rots, Structural masonry: an experimental/numerical basis for Practical Design Rules, Balkema, Rotterdam, 1997.

A hysteretic model with damage based on Bouc-Wen formulation

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Keywords: hysteresis, damage, masonry

Hysteresis is a well-known phenomenon involving history-dependent response of many structural (and non-structural) materials. Among the various models that can be adopted to describe it, the Bouc-Wen model [1] is certainly one of the most widely used, and it is considered the forefather of an entire class of hysteresis models. During the last decades, the original formulation was modified to take into account the effects of strength and stiffness degradation, pinching and non symmetric response [2]. Moreover, issues related to its thermodynamic admissibility were tackled [3]. This research presents a discussion on the acknowledged limits of the original Bouc-Wen model, focusing on thermodynamic admissibility and Drucker's postulate for hardening materials. The influence of the parameters β and γ (governing the shape of hysteresis cycles) is highlighted and a revised formulation of dissipated energy is proposed. Then, an enriched version of the model is introduced, in which degradation of strength and stiffness is accounted for by means of a single scalar damage variable. The effect of pinching can also be included resorting to a parallel arrangement of a nonlinear elastic element. Some considerations on its thermodynamic admissibility are briefly presented and some simple validation examples are reported to show the main features of the model. The proposed damaging model was implemented in a beam finite element [4] (within the framework of equivalent frame models) to reproduce, through lumped plastic hinges, the shear and flexural mechanisms characterizing the response of masonry panels under cyclic in-plane horizontal loads. The repeated excursions into the inelastic range are in fact responsible for both strength and stiffness degradation accompanied by energy dissipation. Some analyses were performed and the results here presented show the capability of this model to describe, at the macroscopic scale, damaging behaviour characterizing masonry structures.

References

[1] *Bouc, R., "A mathematical model for hysteresis", Acta Acustica united with Acustica* **24 (1)**, *page 16-25 (1971).*

[2] *Baber, T. T., Noori, M. N. "Random vibration of degrading, pinching systems", Journal of Engineering Mechanics* **111 (8)** *page 1010-1026 (1985).*

[3] *Erlicher, S., Bursi, O. S., "Bouc-wen-type models with stiffness degradation: thermodynamic analysis and applications", Journal of Engineering Mechanics* **134 (10)**, *page 843-855 (2008).*

[4] *Addessi, D., Liberatore, D., Masiani, R., "Force-based beam finite element (FE) for the pushover analysis of masonry buildings", International Journal of Architectural Heritage,* **9 (3)**, *page 231-243 (2015).*

Frictional behaviour of masonry interfaces: experimental investigation on two dry-jointed tuff blocks

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Keywords: Experimental interface behaviour, 3D dry-jointed masonry blocks, Shear-torsion-bending interaction

In historical masonry structures, featured by dry or weak mortar joints, limit analysis of 3D assemblages of blocks represents a useful tool for the prediction of failure mechanism and collapse load [1, 2]. Results of limit analysis, with no-tension and frictional contact interfaces, are based on the definition of accurate block interface yield domains: experimental and numerical investigations on the frictional contact conditions are required. Despite the characterization of shear behaviour of frictional contact was widely studied in the past [3, 4], limited research is available on the behaviour of dry masonry joints implying interactions among shear, bending and torsion moments [5].

This work aims to present an extensive experimental investigation conducted in order to analyse the frictional behaviour of two dry-jointed tuff blocks subjected to loading patterns reproducing several possible yield conditions. Besides providing fundamental parameters required for limit analysis formulations, the adopted testing program investigates on 3D yield domains of a single contact interface though different loading scenarios. Moreover, the experimental analysis is extended on different interface geometries, as triangular and trapezoidal ones, in order to support the modelling of more complex stereometry of masonry blocks assemblages (e.g. diagonal ribs of cross vaults) [6, 7].

The results of each test are then compared with those obtained by a numerical model based on the assumptions of rigid blocks, which interact through no-tension, featured by frictional interfaces.

References

[1] *Baggio, C., Trovalusci, P., "Limit Analysis for No-Tension and Frictional Three-Dimensional Discrete Systems," Mechanics of Structures and Machines,* **26**, *287-304 (1998).*

[2] *Orduña, A., Lourenço, P.B., "Three-dimensional limit analysis of rigid blocks assemblages. Part I: Torsion failure on frictional interfaces and limit analysis formulation ," International Journal of Solids and Structures,* **42**, *5140-5160 (2005).*

[3] *Lourenço, P.B., Ramos, L.F., "Characterization of Cyclic Behavior of Dry Masonry Joints," Journal of Structural Engineering,* **130**, *779–786 (2004).*

[4] *Vasconcelos, G., Lourenço, P.B., "Experimental characterization of stone masonry in shear and compression," Construction and Building Materials,* **23**, *3337–3345 (2009).*

[5] *Casapulla, C., Portioli, F., "Experimental tests on the limit states of dry-jointed tuff blocks," Materials and Structures,* **49**, *751–767 (2016).*

[6] *Milani, G., Simoni, M. and Tralli, A., "Advanced numerical models for the analysis of masonry cross vaults: A case-study in Italy," Engineering Structures,* **76**, *339–358 (2014).*

[7] *Intrigila, C., Nodargi, N.A. and Bisegna, P., "Square Cross Vaults on Spreading Supports," RILEM Bookseries,* **18**, *1045–1053 (2019).*

Manufacturing imperfection assessment of multi-leaf masonry panels

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Keywords: multi-leaf masonry panels, model updating, manufacturing imperfections

Structural stability is a major consideration in the design of structures. The stability is affected both by structure dimensions and by geometrical and mechanical imperfections.

The intrinsic heterogeneity of historical masonry affects its structural behaviour; the identification of the local homogeneity degradation allows to define a new design approach to take on the structural rehabilitation of multi-leaf masonry structures.

In this paper, the imperfection effects on the performances of multi-leaf masonry walls, considered as orthotropic material, are investigated using experimental and numerical approaches based on modal analysis [1, 2]. Unavoidable imperfections of workmanship, emphasized by mechanical orthotropy, affect the application of conventional design approach.

After a first identification of the dynamic parameters - such as frequencies and modal shapes, of different multi-leaf masonry panels characterized by undamaged, damaged and strengthened fill - the model updating procedure has been applied to assess the local and global modal shapes.

A Finite Element Model has been built simulating the fill by mono-dimensional element with different unidirectional stiffness between the external layers to distinguish and calibrate the local modal shapes and, then, the global response [3, 4].

The experimental and numerical data have been compared to analyse the reliability of the applied method [5]; the calibrated models have been tested through the non-linear static analysis and the results have been compared with the structural performances of the multi-leaf masonry panels subjected to the compressive loads.

References:

[1] *Da Porto, F., Valluzzi, M.R., Modena, C., "Investigations for the knowledge of multi-leaf stone masonry walls" in Proceedings of the First International Congress on Construction History, Madrid, 20th-24th January 2003, (2003).*

[2] *Da Porto, F., Valluzzi, M.R., Modena, C., "Behavior and modeling of strengthened three-leaf stone masonry walls" Materials and Structures,* ***37****(3), 184-192, (2004),*

[3] *Pina-Henriques, J., Lourenço, P.B., Binda, L., Anzani, A., "Testing and modelling of multi-leaf masonry walls under shear and compression" in Proceedings of IV International Seminar on Structure Analysis of Historic Constructions, Padova, January 2004, 299-310, (2004).*

[4] *Vintzileou, E., "Three-Leaf Masonry in Compression, Before and After Grouting: A Review of Literature" International Journal of Architectural Heritage: Conservation, Analysis, and Restoration,* ***5****(4-5), 13-538, (2011).*

[5] *Boscato, G., Reccia, E., Cecchi, A., "Non-destructive experimentation: Dynamic identification of multi-leaf masonry walls damaged and consolidated" Composites Part B: Engineering,* ***133****, 145-165, (2018).*

Thrust Surface Analysis of historical masonry pavilion vaults

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Keywords: masonry, vault, limit analysis

Masonry constructions represent the vast majority of Italian and European Architectural Heritage which needs to be preserved for future generations for its immense cultural and historical value. In spite of all the researches recently carried out [1], there are not still widely accepted approaches for studying the structural response of masonry structures, especially for the case of historic masonry vaults.

Classical Limit Analysis equilibrium approaches [2-3] aimed at the stability assessment of masonry vaults are based on the so-called "slicing technique" that reduce the vault to a system of arches, neglecting any possible three-dimensional structural behavior. This simplification could be admissible for simpler cases as barrel vaults subject to the self-weight but it could strongly underestimate the actual load-bearing capacity for vaults with complex geometries (for example, characterized by a non-smooth middle surface) or in presence of complex load conditions.

Recent studies on this issue have tried to overcome the above drawback, proposing Limit Analysis equilibrium approaches able to consider the complex three-dimensional structural behavior of masonry vaults, and thus to give a substantially better load-bearing capacity estimate [4-5-6]. In particular, in [7] the Thrust Surface Method (TSM) is proposed, an innovative application of the lower bound theorem of Limit Analysis capable of fully exploring the three-dimensional load-bearing capacity of a masonry vault having an arbitrary geometry and under an arbitrary load condition. Indeed, since the particular numerical formulation of the method, TSM can take into account not only any kind of vertical loads, but also horizontal loads like those simulating the maxima inertia effects related to seismic actions.

In the present paper, TSM is applied to the iconic case of the pavilion vault. By results, a discussion on the complex three-dimensional structural behavior and a comparison with other approaches in the literature are performed, also when horizontal forces are acting.

References

[1] *Tralli A., Alessandri C., Milani G., "Computational methods for masonry vaults: A review of recent results", Open Civ Eng J,* ***8****, pages 272-287, (2014).*

[2] *Heyman J., "The stone skeleton", Int J Solids Struct,* ***2****, page 249–79 (1966).*

[3] *Como M., Statics of Historic Masonry Constructions Third Edit., Springer, (2016).*

[4] *Block P., Ochsendorf J., "Thrust network analysis: A new methodology for three-dimensional equilibrium", J Int Assoc Shell Spat Struct,* ***48****, pages 1-7, (2007).*

[5] *Angelillo M., Babilio E., Fortunato A., "Singular stress fields for masonry-like vaults", Contin Mech Thermodyn,* ***25****, pages 423-441, (2013).*

[6] *Marmo F., Rosati L., "Reformulation and extension of the thrust network analysis", Comput Struct,* ***182****, pages 104-118, (2017).*

[7] *Fraddosio A., Lepore N., Piccioni M.D., "Thrust Surface Method: an innovative approach for the three-dimensional lower bound Limit Analysis of masonry vaults", Eng Struct, under review, (2019).*

Analysis of masonry pointed arches on moving supports: a numerical predictive model and experimental evaluations

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Keywords: masonry arches, rigid blocks, moving supports.

In this paper the topic of the vulnerability assessment of masonry rigid block arches subject to soil settlements is analyzed [1-5]. A novel numerical procedure for detecting the collapse mechanism and the limit settlement, already presented in [1] for the case of circular or segmental arches, is herein applied to the case of pointed arches.

The arch is regarded as a system of *n* rigid blocks and *n+1* interfaces, represented through a set of three links, two orthogonal to the interface and the third along the interface. Links are characterized by a rigid-cracking behaviour with respect to axial forces and a perfectly rigid behavior with respect to shear forces. The procedure finds, for any kind of settlement, the only structure kinematically compatible and in equilibrium with the applied loads. In particular, by means of the combinatorial analysis, the set of three hinges opened in the structure due to an applied settlement is identified; then, for each pattern of the three hinges and the settlement, the structure is subject to a kinematic test and, only those that are compatible are in turn statically analyzed to check if the equilibrium is verified. In so doing, only one structure is identified, which is the structure at collapse in an equilibrium condition.

The limit value of the settlement at collapse is finally computed by performing the analysis in finite displacements. The settlement is increased little by little and it is checked if the line of thrust within the profile of the arch at each incremental step still holds. The limit value of the settlement is attained when the line of thrust becomes tangent to the intrados or extrados of the arch in further joints.

The algorithm to detect the only equilibrated and kinematically compatible structure is based exclusively on the solution of linear equations relating to the equilibrium condition and, as for the kinematic condition, the assessment of the sign of the determinant of a square matrix of order 2 that is formulated in the three hinged joints. In so doing, the use of optimization techniques required in limit analysis is avoided with a consequent reduction of the algorithm complexity. Moreover its computational cost has been estimated as a 6 degree polynomial in function of the block number.

In-scale pointed arch models performed by the authors are tested considering both the horizontal and vertical movements of the left impost. Numerical models of such arches are analyzed using the procedure above and results are compared to the experimental results in order to ascertain the reliability and effectiveness of the procedure. Finally, to investigate the effects of geometry on the arch response to an impost movement, the numerical results of pointed arches are compared to the results of circular arches with same span, thickness and angle of embrace.

References

[1] Galassi S. Misseri G., Rovero L., Tempesta G., "Failure modes prediction of masonry voussoir arches on moving supports". Engineering Structures, 173, 706-17 (2018)

[2] Ochsendorf J. Masonry arch on spreading supports. Struct Eng 2006;84(2):29–34.

[3] Coccia S, Di Carlo F, Rinaldi Z. Collapse displacements for a mechanism of spreading-induced supports in a masonry arch. Int J Adv Struct Eng (IJASE) 2015;7(3):307–20.

[4] Zampieri P, Faleschini F, Zanini MA, Simoncello N. Collapse mechanisms of masonry arches with settled springing. Eng Struct 2018;156:363–74.

[5] Portioli F, Cascini L. Large displacement analysis of dry-jointed masonry structures subjected to settlements using rigid block modelling. Eng Struct 2017;148:485–96.

The role of shape irregularities on the lateral loads bearing capacity of circular masonry arches

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Keywords: masonry arch, parametric model, limit analysis.

The present contribution is aimed at assessing the effect of the shape irregularities on the collapse conditions of circular masonry arches in presence of horizontal actions. Actually, historical constructions often present structural elements characterized by irregular shapes, which could affect their bearing capacity if calculated considering their nominal geometry. Some of these irregularities can be ascribed to the arising of deformed states developed over time, or, in other cases, directly to technological construction processes. In this sense, the literature present a lack of studies about the influence of such geometrical irregularities on the strength of masonry structural elements.

In previous papers [1,2], the role of geometrical uncertainties on the structural behavior of masonry arches have been already investigated. More in detail, in these studies the uncertainties have been related to the voussoirs' stereometry, while deterministic line axes were assumed for the analyzed arch typologies. Nevertheless, it is well known that actual structures are generally characterized by irregular shapes due to construction flaws or to deformation processes [3].

In order to take into account the irregularities due to the constructive process, mainly related to the empirical design of the wooden frames known as centrings, a parametric model of a polycentric arch has been developed. The procedure allows to generate random geometries, starting from a deterministic nominal one, consisting of different circumferential arcs referred to a family of input variables and connected assuring the tangent continuity.

A limit analysis based procedure, referring to Heyman's theory, has been developed in order to evaluate the horizontal loads multiplier, which leads to the collapse condition. In this terms has been also studied the collapse state, whose statistical moments up to second order and probability density functions have been rated versus a shape parameter.

The comparison between the results for the nominal geometry and those obtained studying the irregular arches highlighted the effects of that shape uncertainties about the carrying capacity of this type of structures.

References

[1] Cavalagli, N., Gusella, V. and Severini, L., "Lateral loads carrying capacity and minimum thickness of circular and pointed masonry arches", International Journal of Mechanical Sciences, ***115-116****, 645- 656 (2016).*

[2] Cavalagli, N., Gusella, V. and Severini, L., "The safety of masonry arches with uncertain geometry", Computers and Structures, ***188****, 17-31 (2017).*

[3] De Arteaga, I. and Morer, P., "The effect of geometry on the structural capacity of masonry arch bridges", Construction and Building Materials, ***34****, 97-106 (2012).*

Static analysis of a double-cap masonry dome

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Keywords: *Masonry domes, no tension material, limit analysis.*

The present work is focused on the analysis of the double-cap dome of St. Gennaro Chapel, in Naples (Italy), whose safety and stability was the object of a heated debate among engineers in the early Eighteenth century. Technical reports dating back to that time displayed some concerns about cracks found in both the two caps and lead to different strengthening hypotheses. We consider here the problem under a modern perspective and evaluate the dome stability applying two approaches, one continuum, the other discrete. The former, originally proposed in [1] and further developed in [2], consists in searching a thrust surface entirely contained within the volume of the structure and in equilibrium with the external loads. Following the Pucher's approach, the equilibrium problem is studied with reference to projected stresses onto vault platform, partitioned in two regions, one under bi-axial regime, where both radial and circumferential stresses are compressive, and the other under uni-axial regime, with vanishing circumferential stress. The second approach is instead based on a three-dimensional rigid-block model, with a solution procedure implemented in a MATLAB-based tool [3]. Applying the two formulations to the static analysis of St. Gennaro dome, new and reliable results are obtained, extending those discussed in [4] and [5].

References

[1] M. Angelillo and A. Fortunato. Equilibrium of masonry vaults. *Lect Notes Appl Comput Mech*, 14:105–111, 2004.

[2] M. Angelillo, E. Babilio, and A. Fortunato. Singular stress fields for masonry-like vaults. *Continuum Mech Thermodyn*, 25(2-4):423–441, 2013.

[3] L. Cascini, R. Gagliardo, and F. Portioli. LiABlock_3D: A software tool for collapse mechanism analysis of historic masonry structures. *Int J Archit Herit*, 2018.

[4] E. Babilio, A. Fortunato, and M. Lippiello. Equilibrium of masonry domes: a case study. In A. Carini, G. Mimmi, and R. Piva, editors, *AIMETA 2007. Proceedings of 18*th *Congress of Italian Association of Theoretical and Applied Mechanics*, pages 1–11 (on CD–ROM). Starrylink, 2007.

[5] M. Lippiello, F. Portioli, C. Ceraldi, and R. Landolfo. Masonry domes strengthening: a comparative structural analysis. In J. Jasieńko, editor, *8th International Conference on Structural Analysis of Historical Constructions (SAHC 2012)*, pages 489–497, 2012.

Equilibrium of masonry sail vaults: the case study of a subterranean vault by Antonio da Sangallo the Elder in the "Fortezza Vecchia" in Livorno

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Keywords: masonry vaults, limit analysis, membrane theory.

The present paper addresses the problem of determining the safety level under vertical dead loads of the sail vault covering a trapezoidal room in the Cavaniglia bastion of Livorno's "Fortezza Vecchia", a medieval maritime castle eventually fortified in the 16th century by Antonio da Sangallo the Elder. The work illustrates some first results obtained by the Pisa University Research Group on Historic Masonry Construction within the framework of a research project funded by the university itself (PRA 2017, "*Architetture toscane rinascimentali: casi studio fra indagine storica, rilievo e analisi strutturale*").

The analysis is performed within the framework of the safe theorem of limit analysis by searching for statically admissible stress fields within the vault [1]. The weights of the vault and the overlying soil layers have both been considered. According to Heyman's hypotheses, it is assumed that the vault's constituent material has no tensile strength and that no sliding is allowed between its component masonry units. Among the many available solution techniques (for example, see [2]), the equilibrium problem is tackled by using the concept of *thrust surface*, which can be regarded as the middle surface of a thin shell under a membrane stress state [3]. It can be shown that if it is possible to find a thrust surface that is wholly contained within the thickness of the masonry, over which it is possible to define a stress field which is at the same time in equilibrium with the external loads and characterized by compressive principal stresses, then the structure is able to withstand the action of external loads.

Working within the framework of membrane theory of shells, we build a suitable set of explicit expressions for statically admissible stresses defined over thrust surfaces all wholly contained within the vault thickness and compatible with the peculiar vault shape, characterized by a spherical profile and trapezoidal plan. More specifically, the analysis aim at investigating how the boundary conditions assumed between the masonry sail vault and vertical walls affect the statically admissible solution and the corresponding safety factor. In this regard, different contact conditions are assumed; moreover, the intrados surface has been carefully reconstructed by laser scanner survey and approximated by means of a regular surface that allows for a relatively simple analytical description. The results obtained provide a preliminary estimate of the safety level of the vault under vertical loads.

References

[1] Heyman, J., The stone skeleton, Cambridge University Press, Cambridge (1966).
[2] Block P., Ochsendorf J., "Thrust network analysis: A new methodology for three-dimensional equilibrium", J Int Assoc Shell Spat Struct, 48: 1-7 (2007).
[3] Fortunato, A., Angelillo, M., Babilo, E., "Singular stress field for masonry-like vaults," Continuum Mechanics and Thermodynamics, 25: 423-441, (2012).

Displacement capacity of masonry structures under alternate loading

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Keywords: masonry, alternate loading, interface models

The in-plane displacement capacity under alternate loading is a key feature of the mechanical response of masonry constructions in view of seismic structural analyses [1], but is very complex to be predicted through the application of numerical models. Indeed, the very low tensile strength of the joints allows very soon for the activation of rocking mechanisms between the ashlars. This strongly influences the mechanical response under dynamic alternate loads, and may render masonry constructions capable of withstanding horizontal accelerations considerably higher than those predictable by static non-linear analyses [2].

In this work, a cohesive-frictional interface model for describing the non-linear behavior of masonry plane structures [3] is calibrated starting from experimental results. The latter concern both shear tests on triplets for characterizing interface behavior of mortar joints, and a masonry arch subject to a concentrated eccentric alternate load applied in displacement control. Then, the numerical model is used for analyzing a masonry wall with openings; among them, a large opening under a masonry arch. The structural behavior under alternate loading is discussed also in terms of displacement capacity. In particular, a parametric study is performed by varying the interfacial shear strength, in order to assess the influence of this parameter on the overall behavior of the masonry structure.

References

[1] Messali, F., Rots, J.G., "In-plane drift capacity at near collapse of rocking unreinforced calcium silicate and clay masonry piers", Engineering Structures 164, pages 183-194 (2018).

[2] Lagomarsino, S., "Seismic assessment of rocking masonry structures", Bulletin of Earthquake Engineering, 1, page 97-128 (2015).

[3] Serpieri, R., Albarella, M., Sacco, E., "A 3D microstructured cohesive–frictional interface model and its rational calibration for the analysis of masonry panels", International Journal of Solids and Structures 122-123, pages 110-127 (2017).

Experimental behaviour of historic masonry walls under compression and shear loading

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Keywords: Brickwork masonry wall; GFRP strip; FE analysis.

In Italian seismic areas brickwork or stone masonry walls are commonly present in historic buildings. In recent years, the strengthening of masonry walls with external bonded (EB) fiber reinforced polymers (FRPs) has been increased to give a tensile capacity to masonry that it is normally weak to tensile stress [1-2]. Many aspects of this strengthening method are not yet thoroughly known; in particular, the debonding mechanism of FRP strips needs to be analysed more through experimental data [3-5]. The primary object of this work was to investigate the structural behaviour and the shear strength of a single-story shear walls built with historic solid clay bricks in scale 1/3rd under in-plane loading with and without strengthening by Glass-FRP strips. In the tests described here, the model structure was subjected to precompression in the vertical direction to simulate the actual loading condition in a building subjected to racking load. Two brickwork masonry walls were tested under combined compression and shear loading; one was strengthened after damage with EB GFRP strips and then once again subjected to the same loading until failure; another one was strengthened with EB GFRP strips without damage and subjected to the same path of loading until failure. A comparison between the responses of the unreinforced and reinforced model is presented, and the failure mechanisms are discussed taking into account the delamination failure of the GFRP strips.

The behaviour of experimental walls was also analysed by theoretical FEM modelling with non-linear procedure [6], assuming both brick and truss elements, according to the macromodelling approach. The numerical modelling of GFRP reinforcement, perfectly glued to the masonry support, involves particular regard to the delamination phenomenon by the adoption of a bilinear constitutive relation characterized by brittle behaviour. Finally, a comparison between theoretical data and experimental results is shown and discussed for both un-strengthened and strengthened shear walls.

References

[1] Tomazevic, M., Earthquake-resistant design of masonry buildings, London Imperial College Press, London (1999).

[2] Turnesec, V., Cacovic, F., "Some experimental results on the strength of brick masonry walls" In: Proc. 2nd Int. Brick Masonry Conf., Stoke on Trent 1971, UK, 149-156.

*[3] Ehsani, M., Saadatmanesh, H., Velazquez-Dimas, J., "Behavior of retrofitted URM walls under simulated earthquake loading" J. Compos. Constr. ASCE, **3**(3), 134-42 (1999).*

[4] Shrive, NG., "The use of fibre reinforced polymers to improve seismic resistance of masonry" Construction and Building Materials, 20: 269-277 (2006).

*[5] Capozucca, R., "Experimental analysis of historic masonry walls reinforced by CFRP under in-plane cyclic loading" Composite Structures, **94**, 277-289 (2011).*

*[6] Lourenço, P., "Computations of historical masonry constructions, Progress in Structural Engineering and Materials" **4**(3), 301-319 (2002).*

Experimental tests and numerical modelling of traffic-induced vibrations

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Keywords: Historical building, artistic finishing, structural monitoring.

It is rather unusual that the vibrations induced by the traffic, even if heavy, cause structural damage, whereas they often provoke cracking occurrence or propagation or cumulative damage in non-structural elements. In the Cultural Heritage context, there is a great interest in determining the influence of the vibrations on artistic elements. The issue is an extremely serious and pressing problem in residential areas. It also has some connections with the building protection against low and medium-low earthquakes. In particular, historical centres have a high concentration of historical heritage that need to be protected by actions that may generate additional stress on the structures. A lot of work has been carried out with reference to the structural damage produced by traffic vibration [1-4], but very few contributions have been provided so far with reference to the damage in the historical artefacts [5]. The problem is worthy to be investigated as many historical buildings are located close to important arterial roads and the value of such buildings is often given by the historical and artistic surface coatings (frescos, mosaics, plasters, stucco, etc.) rather than by the masonry structures that bear them.

This paper represents a preliminary analysis of the vibrations produced by vehicular traffic and of their influence on the artefacts inside the buildings. In fact, such vibrations may be meaningless for the main structure, but relevant, even deleterious, especially if repeated continuously for years, on more delicate elements. Impact assessment was carried out by monitoring accelerations and injuries on plasters of two historical Palaces in Ferrara.

References

[1] *Whiffin, A.C., Leonard, D.R., "A survey of traffic-induced vibrations", Transport and Road Research Laboratory (Crowthorme),* ***VLR-418****, 1-53 (1971).*

[2] *Watts, G.R, "Traffic induced vibrations in buildings", Transport and Road Research Laboratory (Crowthorme),* ***RR-246****, 1-31 (1990).*

[3] *Crispino, M, D'Apuzzo M., "Measurement and prediction of traffic-induced vibrations in a Heritage building", Journal of Sound and Vibration,* ***246****, 319-335 (2001).*

[4] *Hao, H., Ang, T.C. and Shen, J., "Building vibration to traffic-induced ground motion", Building and Environmental,* ***Vol 36-62****, 321-336 (2007).*

[5] *Barbaro, S., Barrera, G. and Santamaria, S., "Messa a punto di una procedura teorico-sperimentale per la misura dell'impatto vibrazionale dovuto al traffico veicolare sugli edifici di interesse storico-artistico,"Quaderni di Scienza della Conservazione,* ***Vol 6****, 237-259 (2006).*

Upper bound limit analysis of quasi-periodic masonry by means of Discontinuity Layout Optimization (DLO)

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Keywords: Quasi-periodic masonry, Discontinuity layout optimization, Upper bound limit analysis

Quasi-periodic masonry consist of blocks having different size arranged in such a away that blocks having approximately the same height are aligned to form horizontal rows; anyway, the length of the blocks inside a row and the height of each row vary in each sample.

Since the masonry is not a periodic one, the usual methods available in literature to estimate the failure surface can not be used. One possible approach to overcome this difficulty is to consider the effective quasi-periodic texture at the micro-scale and estimating a hierarchy of lower- and upper-bounds of failure surface by means of essential and natural boundary conditions [1]. An alternative approach is to define an equivalent, in a statistical sense, periodic unit cell [2], for which the failure surface can be estimated using some of several methods available in literature (for example those in [3, 4]). In this paper, a different approach is proposed: the effective texture of the masonry is taken into account, and the upper bound of the failure surface is estimated by means of Discontinuity Layout Optimization (DLO) [5]. In DLO method, a great number of the possible discontinuities that can appear in the sample are considered, and the effective pattern of discontinuities at failure is estimated by minimizing a suitable function, according to usual methods of limit analysis. In particular, if the function is a linear one, it can be minimized through linear programming techniques.

The DLO appears to be more suitable than other limit analysis approaches when dealing with quasi-periodic masonry, since these are usually formulated using a representative (periodic) volume element, while DLO allows to take into account the whole masonry panel. The results here presented are, as far as the authors are aware, the first time that the DLO is applied to quasi-periodic masonry. In particular, we consider that the discontinuities can appear only in the mortar joints, according to a Mohr-Coulomb failure criterion. The results show that the failure multiplier and the associated mechanism depends on the direction of the action. Several analysis have been carried out in order to assess the influence of the mechanical and geometrical parameters.

References

[1] *Cavalagli, N., Cluni, F. and Gusella, V., "Strength domain of nonperiodic masonry by homogenization in generalized plane state," European Journal of Mechanics - A/Solids,* **30***, page 113-126 (2011)*

[2] *Cavalagli, N., Cluni, F. and Gusella, V., "Failure surface of quasi-periodic masonry by means of Statistically Equivalent Periodic Unit Cell approach," Meccanica,* **53***, page 1719-1736 (2018)*

[3] *Milani, G., "Simple lower bound limit analysis homogenization model for in- and out-of plane loaded masonry walls," Construction and Building Materials,* **25***, page 4426-4443 (2011)*

[4] *Luciano, R., Sacco, E.,"Homogenization technique and damage model for masonry," International Journal of Solids and Structures,* **34***, page 3191-3208 (1997).*

[5] *Smith, C., Gilbert, M., "Application of discontinuity layout optimization to plane plasticity problems," Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences,* **463***, page 2461-2484, (2007)*

An experimental study on the effectiveness of CFRP reinforcements applied to curved masonry pillars

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Keywords: masonry; masonry arch; CFRP reinforcements; spike anchor; delamination; curved substrates.

Carbon Fiber Reinforced Polymers (CFRP) have been more and more used in the past decades in strengthening and retrofitting interventions carried out on existing masonry buildings. The excellent mechanical performance, combined with lightness and easiness of application, justify their widespread use in the structural field.
The effectiveness of such reinforcements, demonstrated by several experimental and numerical analyses published in the literature, depends on the CFRP-to-substrate adhesion. Several techniques have been proposed in the literature to improve CFRP-to-substrate bonding properties. Among these, spike anchors demonstrated to effectively increase both the load bearing capacity and the global ductility of CFRP reinforcements bonded to masonry elements.
Most of the papers in the literature, concerning the analysis of CFRP-masonry adhesion properties of anchored or not anchored reinforcements, refer to flat surfaces; conversely, limited research is devoted to curved masonry elements (arches, vaults, etc.), despite the great interest of the technical and scientific community on this field.
The experimental results reported and synthetized in this paper represent a contribution on this field. They refer to an experimental program, partially described in [1,2], concerning anchored and not anchored CFRP sheet reinforcements bonded to both right and curved masonry pillars tested using a single lap shear test scheme. The experimental outcomes enabled to assess the effects of the curvature of the bonding surface and of the position (intrados/extrados) of the reinforcement on the mechanical behavior of the specimens.

References

[1] Rotunno T, Fagone M, Bertolesi E, Grande E, Milani G. Single lap shear tests of masonry curved pillars externally strengthened by CFRP strips. Compos Struct 2018;200:434–48. doi:10.1016/j.compstruct.2018.05.097.
[2] Rotunno T, Fagone M, Bertolesi E, Grande E, Milani G. Curved masonry pillars reinforced with anchored CFRP sheets: an experimental analysis. Submitt to Compos Struct n.d.

Vulnerability analyses of Italian masonry structures by seismic collapse mechanisms evaluation

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Keywords: collapse mechanisms, seismic vulnerability, masonry buildings.

Abstract. *In the field of risk assessment and mitigation strategies, knowledge of the vulnerability of exposed buildings is a fundamental requirement for estimating expected damage. Studies on the collapse mechanisms of masonry buildings represent a useful tool capable of describing the structural damage. In the past, the correlation between the structural typologies that characterize Italian masonry buildings, the possible mechanisms of collapse in the plane and out of the plane, and the acceleration of the ground have been investigated [1]. This work aims to study these correlations with reference to further collapse mechanisms out of the plane through the use of the kinematic theorem. In particular, the procedure provide to evaluate the horizontal mass multiplier for each out of plane mechanism considered, depending on typological characteristics of the buildings (geometries, loads, materials and technological solutions). Furthermore, the vulnerability curve in PGA relating to the investigated mechanisms is drawn up. To this purpose a buildings casuistry on the basis of typological characteristics is generated by a Monte Carlo simulation and, exploiting the SAVE procedure [2], an exhaustive sample for each vulnerability class is defined. At the end, on the basis of the relation between the PGA value and the horizontal mass multiplier, statistical correlations between PGA and damage are evaluated for each vulnerability class and each mechanism of collapse. On the basis of this parameters, a vulnerability curve for each mechanism of collapse is defined. Finally, some comparisons with empirical vulnerability curves present in the literature are proposed.*

REFERENCES

[1] Zuccaro, G.,Dato, F., Cacace, F. De Gregorio, D., Sessa, S. *Seismic collapse mechanisms analyses and masonry structures typologies: a possible correlation,* in International Journal of Earthquake Engineering, 2017.

[2] Zuccaro, G., Cacace, F. *Seismic Vulnerability Assessment based on typological characteristics, the first level procedure "SAVE"*, Soil Dyn. Earthq. Eng 69 (2015) 262-269.

Isotropic and orthotropic macromechanical models with damage for masonry

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Keywords: masonry, damage, macromechanical approach

The lively interest towards the development of accurate numerical models to predict response of masonry structures is due to their widespread in the architectural heritage of many countries and the complex mechanical behavior exhibited by masonry material. The main difficulties in modeling are related to its heterogeneous microstructure, which makes masonry global response strongly affected by shape, sizes, arrangement and mechanical properties of the constituents. Among the available modeling strategies, macromechanical models represent a fair compromise between accuracy and computational cost. These substitute the heterogeneous material with an equivalent homogeneous medium and introduce proper phenomenological constitutive law involving damage and plasticity inner variables. Despite isotropic formulations [1] are largely adopted because of their simplicity, these models neglect the directional mechanical properties characterizing masonry with regular texture, where bed joints act as plane of weakness [2]. Thus, the most accurate macromodels describe masonry as an orthotropic material by making use of proper failure criteria which account for influence of applied stresses with respect to bed joints orientation. It should be also remarked that macroscopic models based on the classical Cauchy continuum can not describe the non-symmetric shear behavior along different planes. To this end enriched continua, like the Cosserat model, should be adopted [3].
Basing on the above considerations, this work explores the use of isotropic and anisotropic macromechanical model with damage for the analysis of masonry structures. In particular, behavior of panels characterized by different masonry textures is analyzed by using an isotropic and orthotropic damage model. The first [1] introduces damage scalar variables in the constitutive law, which affect in the same way all components of the degraded stiffness matrix. Conversely, the orthotropic model adopts a tensorial damage representation, thus distinguishing between stiffness and strength properties along masonry natural axes. Both models are based on the Cauchy continuum and adopt a nonlocal integral formulation to overcome the mesh-dependency occurring in presence of strain softening behavior by introducing an internal length parameter related to the brick size. The obtained global force-displacement response curves and damage distributions are compared with experimental outcomes or results derived by detailed micromechanical analyses. The purpose is to identify cases in which the overall response can be satisfactorily captured by adopting simplified isotropic models and cases where it is required to resort to anisotropic material descriptions.

References

[1] *Gatta, C., Addessi, D. and Vestroni, F., Static and dynamic nonlinear response of masonry walls, International Journal of Solids and Structures,* **155**, *page 291-303 (2018).*

[2] *Dhanasekar, M., Page, A.W. and Kleeman, P.W., "The failure of brick masonry under biaxial stresses" in Proceedings of the Institution of Civil Engineers, page 295-313, (1985).*

[3] *Trovalusci, P. and Masiani, R., Non-linear micropolar and classical continua for anisotropic discontinuous materials, International Journal of Solids and Structures,* **40**, *page 1281-1297 (2003).*

A vulnerability investigation of ordinary masonry buildings by applying the Heyman model throught PRD method

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Keywords: Masonry · In-plane mechanism · Vulnerability curves

The objective of the present paper is to investigate global in-plane mechanisms for ordinary masonry buildings under seismic actions with the aim to assess vulnerability functions useful in the framework of risk assessment at national and regional scale.

In a previous paper [1], part of authors developed a study correlating structural-typologies, local mechanisms and ground accelerations. In this paper, the latter analysis is extended in order to explore the gap between first local and final global mechanism. Since the large amount of data to be processed, the procedure finds the compromise between modelling and numerical effort in term of computational time. For this purpose, the analysis is conducted following the Heyman approach [2] and the numerical tool chosen is the PRD method (Piecewise Rigid Displacement method) [3]. Looking for the minimum of the total potential energy of the loads, the PRD method searches the minimizer by increasing the horizontal static multiplier until the energy is not bounded from below anymore. The solution, beyond a horizontal static multiplier, allows to find a rigid macro-blocks partition of the whole domain representing the global mechanism.

The set of all ordinary masonry structures is subdivided in classes by taking into account different typologies characteristics desumed by PLINIVS database. With respect to a given vulnerability class, virtual buildings are generated and then analyzed with PRD method. Grouping all these results by classes, vulnerability curves correlating the probability of occurrence of a global in-plane mechanism and the ground acceleration are determined.

References

[1] *Zuccaro, G., Dato, F., Cacace, F., De Gregorio, D., and Sessa, S., Seismic collapse mechanisms analyses and masonry structures typologies: a possible correlation. Ingegneria Sismica, 34(4), 121-150, (2017).*

[2] *Heyman, J., The stone skeleton. International Journal of solids and structures, 2(2), 249-279, (1966).*

[3] *Iannuzzo, A., Angelillo, M., De Chiara, E., De Guglielmo, F., De Serio, F., Ribera, F., and Gesualdo, A., Modelling the cracks produced by settlements in masonry structures. Meccanica, 53(7), 1857-1873, (2018).*

Numerical analysis of the bond behavior of FRP applied to masonry curved substrates with anchor spikes

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Keywords: FRP; anchor spike; masonry curved structures.

The bond behavior of Fiber Reinforced Polymer (FRP) strengthening systems is one of the most important topic still object of investigation particularly for applications concerning curved masonry structures [1-5]. Indeed, the available studies underline that the geometry curvature and the position of the strengthening (in particular at the intrados) could lead to premature debonding failures because of tensile normal stresses developing at the FRP/masonry interface. Then, in order to improve the bond performance of FRP strengthening systems externally applied to structural supports, the use of anchor spikes has been recently proposed and experimentally investigated [6-9]. The outcomes emerged from these experimental tests underline the role of the anchor spikes in improving the bond behavior of the strengthening system and, at the same time, they also emphasize the occurrence of failure modes characterized by damages involving a deep portion of the masonry support. This behavior, different respect to the case of FRPs applied without providing anchor spikes, requires the use of numerical models able to account for both the de-cohesion phenomenon developing at the FRP/masonry interface and, in addition, the phenomena due to the interaction among the anchor spike, the FRP and the masonry.
In this paper, the author presents two different modeling strategies for the study of the debonding of FRP applied to curved masonry substrate throughout both the adhesive layer and anchor spikes. The first one is based on a simple 1D-schematization of specimens, previously proposed by the authors for applications without providing anchor spikes, based on the use of linear and nonlinear spring elements schematizing the support, the FRP, the masonry/FRP interface. Here this approach has been opportunely modified by introducing specific constitutive laws for the spring able to also

model the local failure mechanisms due to the presence of the anchor spikes. On the other hand, the second approach consists of a tri-dimensional micro-modelling FE approach where bricks, mortar joints, FRP sheet and the spike anchor have been modeled separately. A Concrete Damage Plasticity model implemented into the Abaqus software has been used for the masonry, whilst the FRP strengthening has been assumed elastic.
Both the approaches have been validated by considering experimental tests performed by the authors [5]. The obtained results presented in this paper show both the reliability of the proposed approaches to capture the experimental behavior and, moreover, their efficacy for investigating the role of anchor spikes on the bond behavior of FRP strengthening systems.

References

[1] Basilio, I. (2007). "Strengthening of arched masonry structures with composite materials." University of Minho.

[2] Grande, E., Fagone, M., Rotunno, T., Bertolesi, E., and Milani, G. (2018). "Coupled interface-based modelling approach for the numerical analysis of curved masonry specimens strengthened by CFRP." Composite Structures.

[3] Grande, E., and Milani, G. (2016). "Modeling of FRP-strengthened curved masonry specimens and proposal of a simple design formula." Composite Structures, 158.

[4] Malena, M., and de Felice, G. (2014). "Debonding of composites on a curved masonry substrate: Experimental results and analytical formulation." Composite Structures.

[5] Rotunno, T., Fagone, M., Bertolesi, E., Grande, E., and Milani, G. (2018). "Single lap shear tests of masonry curved pillars externally strengthened by CFRP strips." Composite Structures.

[6] Borri, A., Castori, G., and Corradi, M. (2011). "Intrados strengthening of brick masonry arches with composite materials." Composites Part B: Engineering.

[7] Caggegi, C., Pensée, V., Fagone, M., Cuomo, M., and Chevalier, L. (2014). "Experimental global analysis of the efficiency of carbon fiber anchors applied over CFRP strengthened bricks." Construction and Building Materials.

[8] Fagone, M., Ranocchiai, G., Caggegi, C., Briccoli Bati, S., and Cuomo, M. (2014). "The efficiency of mechanical anchors in CFRP strengthening of masonry: An experimental analysis." Composites Part B: Engineering.

[9] Fagone, M., Ranocchiai, G., and Briccoli Bati, S. (2015). "An experimental analysis about the effects of mortar joints on the efficiency of anchored CFRP-to-masonry reinforcements." Composites Part B: Engineering.

MS15

THEORETICAL, NUMERICAL AND PHYSICAL MODELLING IN GEOMECHANICS

Observation of direct shear failure of snow through image analysis

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Keywords: failure mechanics, natural material, PIV

Snow is a natural material that originates in the clouds and is composed of crystals with complex shape and variable size, depending on air temperature and excess vapor density on their surface. It falls on the ground forming the snowpack and the single crystals undergo variations in physical and mechanical properties, i.e., snow metamorphism. The knowledge of the mechanical behavior of snowpack is a key requirement to understand snow avalanche triggering processes [1]. In its most hazardous configuration, snowpack presents a weak layer in-between two more compact snow slabs.

The present contribution presents the results of a campaign performed on an artificial weak layer made of faceted ice crystals in-between two snow slabs. A specific device has been used for these tests [2]. To investigate the influence of interface, the shape of the interface between the weak layer and the slabs, flat and sawtooth-like surfaces were considered [3]. A lateral opening in the testing device allowed to perform high-speed camera recordings. The micro-mechanical processes were interpreted through image analysis techniques. In particular, the strain field during the shear loading was studied by means of digital image correlation (DIC). The failure mechanisms were interpreted through particle image velocimetry (PIV).

The tests were performed at various confinement pressures in the range 0.5 kPa to 3.3 kPa. The DIC analysis showed that, during the increase of the shear force, the deformation concentrates in some points inside the weak snow layer. When strain localization starts, vortices and jamming zones appear. A sort of disturbance is observed, characterized by a sequence of force chains collapse – formation of vortices – jamming – dissolution of vortices, similarly to what observed in sands. This phenomenon continues inside the shear band, also when failure occurs and during irreversible sliding. The experimental results proved that, as in other natural granular-type materials, such as sands, a shear band can be identified and the stresses are transmitted only by a fraction of grains through force chains [4].

References

[1] *Schweizer, J., Jamieson, J.B., Schneebeli, M., "Snow avalanche formation", Reviews of Geophysics,* **41**, *1016 (2003)*

[2] *Barbero, M., Barpi, F., Borri-Brunetto, M., Pallara, O., "An Apparatus for In Situ Direct Shear Tests on Snow", Experimental techniques,* **40**, *149–158 (2016).*

[3] *De Biagi, V., Barbero, M., Barpi, F., Borri-Brunetto, M., Podolskiy, E., "Failure mechanics of snow layers through image analysis", European Journal of Mechanics / A Solids,* **74**, *26–33 (2019)*

[4] *Tordesillas, A., Pucilowski, S., Lin, Q., Peters, J., Behringer, R., "Granular vortices: identification, characterization and conditions for the localization of deformation", Journal of the Mechanics and Physics of Solids,* **90**, *215–241 (2016)*

An elasto-plastic model for granular soils subjected to suffusion

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Keywords: Suffusion, Constitutive Modelling, Mechanical Behaviour

Seepage flow through granular medium may induce detachement, transportation and even deposition of the fine particles of a granular skeleton. This volumetric process of internal erosion is called suffusion. Recent experimental studies exploring the mechanical consequences of suffusion has stated that this phenomenon is the source of volumetric strains, strength reduction, and change in the density state, from dense to loose [1][2]. These results agree with those of several theoretical and numerical studies conduced earlier considering suffusion as particle removal [3][4]. Moreover, the macroscopic poromechanical coupling between seepage flow, suffusion and skeleton behaviour has been explored modelling suffusion history by means of a new internal variable: the suffusion induced porosity ϕ^{er}[5]. With the aim of going deeper into the macroscopic modelling of the suffusion effects on the mechanical properties of a granular medium, the present study exposes the development of an elasto-plastic model of the mechanical behaviour of a suffusive soil. An existing elasto-plastic model [6] is extended by introducing the internal variable ϕ^{er} as a hardening variable and a parametrization of the characteristic state. The modified hardening law models changes in density state, from dense to loose, during suffusion. The porosity driven characteristic state models the residual strength reduction observed and specifies the nature of the volumetric plastic strain (dilative or contractive) during suffusion. To illustrate the model abilities, numerical integrations of the elasto-plastic model are carried out for monotonic loading, under drained and oedometric conditions.

References

[1] *Chang, DS., Zhang, LM., "A stress-controlled Erosion Apparatur for Studying internal Erosion in Soils", Geotechnical Testing Journal,* **34(6)***, page 579-589 (2011).*

[2] *Ke, L., Takahashi, A., "Experimental investigations on suffusion characteristics and its mechanical consequences on saturated cohesionless soil", Soils Found.,* **54(4)***, page 713–730 (2014).*

[3] *Scholtès, L., Hicher, PY., Sibille, L., "Multiscale approaches to describe mechanical responses induced by particle removal in granular materials". C. R. Mec.* **338(10–11)***, page 627–638 (2010).*

[4] *Muir Wood, D., Maeda, K., Nukudani, E., "Modelling mechanical consequences of erosion", Géotechnique* **60(6)***, page 447–457 (2010).*

[5] *Zhang, XS., Wong, H., Leo, CJ., Bui, TA., Wang, JX., Sun, WH., Huang, ZQ.,, "A thermodynamics-based model on the internal erosion of earth structures", Geotech. Geol. Eng.* **31(2)***, page 479–492 (2012).*

[6] *Nova, R., ""Sinfonietta Classica" : an exercice on classical soil modelling" in Saada AS, Bianchini GF (eds) Constitutive equations for granular non-cohesive soils, Balkema, Rotterdam, page 510–519 (1988).*

A finite–deformation elastoplastic model with breakage and damage for cemented granular materials

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Keywords: Granular materials, Breakage, Finite deformations

Weakly cemented granular materials (CGMs) with crushable grains are a class of geomaterials which has recently attracted some interest in various fields of geotechnical engineering, such as, for examplem, deep and offshore foundation design, CO_2 sequestration and stability of underground excavations.

The objective of the work is to develop a thermodynamically–based constitutive model for a particular class of CGMs – i.e., the Apulian calcarenites – whose mechanical behavior can be significantly affected by mechanical and chemical degradation processes like grain fracture and crushing, mechanical and chemical debonding, grain dissolution.

These phenomena can be quantified at the microscale, and studied experimentally by means of modern field measurement techniques such as X–ray Computed Tomography. Recently, Tengattini et al. [1, 2] have advocated the use of microscopically–based state variables [3] – defined in terms of particle size and bond diameter distributions – to quantify the effects of the change in microstructure on the macroscopic material response. The work of Tengattini et al. is developed within the framework of linearized kinematics. However, the large volumetric and shear deformations which are typically associated to mechanical and chemical degradation processes, particularly when grain dissolution effects become significant, may require a fully non–linear kinematic description of the behavior of such materials in practical applications.

In this work, limited to purely mechanical degradation processes, we follow the approach of Tengattini et al., extending it to the finite deformation regime by adopting a multiplicative split of the deformation gradient into an elastic and a plastic deformation gradient. Due to the scalar nature of the degradation–related internal variables, an implicit integration strategy based on a product formula approximation of the flow rule can be adopted, in which the elastic predictor stage is solved exactly, while the plastic corrector stage employs a Backward–Euler approximation in the space of logarithmic elastic principal strains, as in [4].

A series of representative numerical simulations have been carried out to show the model capabilities and the good performance of the proposed integration algorithm, both at the element level and in the simulation of engineering problems of practical interest. In particular, the isoerror maps derived for general rectilinear deformation processes demonstrate the high accuracy of the implicit algorithm, even for relatively large step sizes. The extension of the present work to the case of chemical degradation process requires the introduction of a third component (the chemical deformation gradient) in the multiplicative decomposition and is currently under way.

References

[1] *Tengattini, A., Das, A., Nguyen, G. D., Viggiani, G., Hall, S. A., Einav, I., "A thermomechanical constitutive model for cemented granular materials with quantifiable internal variables. Part I – Theory", Journal of the Mechanics and Physics of Solids, 70, 281–296 (2014)*

[2] *Das, A., Tengattini, A., Nguyen, G. D., Viggiani, G., Hall, S. A., Einav, I., "A thermomechanical constitutive model for cemented granular materials with quantifiable internal variables". Part II – validation and localization analysis. Journal of the Mechanics and Physics of Solids, 70, 382–405 (2014).*

[3] *Einav, I., "Breakage mechanics–part I: theory". Journal of the Mechanics and Physics of Solids, 55(6), 1274-1297 (2007).*

[4] *Borja, R. I., Tamagnini, C., "Cam-Clay plasticity Part III: Extension of the infinitesimal model to include finite strains". Computer Methods in Applied Mechanics and Engineering, 155(1-2), 73-95 (1998).*

3D experimental micromechanics at the grain scale: what for?

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Keywords: X–ray micro tomography, digital image analysis, Level Set–DEM, shear localization

With X–ray micro tomography it is now possible to acquire 3D full–field measurements of granular materials at suitable resolutions. In the first applications of x–ray tomography to soil mechanics, the distribution of porosity was investigated with the aim of analyzing the development of localization phenomena in a soil specimen. More recently, Digital Image Correlation (DIC) has been used to determine the distribution of strain in a specimen – in a continuum framework – and/or individual grain kinematics, i.e., displacements and rotations of individual grains. These works have provided a deep insight into the micro-mechanics of the processes governing the overall behavior of granular materials.

The first part of the work presents recent advances in experimental micro (geo)mechanics achieved thanks to x–ray tomography and digital image analysis. In particular, the attention is focused on some recent experimental measurements of a 3D fabric tensor and its evolution during shearing of granular materials. Triaxial compression experiments on natural sands are chosen to investigate the evolution of fabric. Two different subsets of the specimen are chosen for the contact fabric analysis: one inside and another one outside a shear band. Individual contact orientations are measured using advanced image analysis approaches within these subsets. Fabric is then statistically captured using a second order tensor and the evolution of its anisotropy is related to the macroscopic behaviour. Some recent results obtained on fabric evolution from triaxial compression of lentils (i.e., very anisotropic grains) are also discussed.

The second part focuses on recent discrete element method (DEM) simulations with experimental comparisons at multiple length scales, underscoring the crucial role of particle shape. The simulations build on technological advances in the DEM furnished by level sets (LS-DEM), which enable the mathematical representation of the surface of arbitrarily-shaped particles such as grains of sand. We show that this ability to model shape enables unprecedented capture of the mechanics of granular materials across scales ranging from macroscopic behavior to local behavior to particle behavior. Specifically, the model is able to predict the onset and evolution of shear banding in sands, replicating the most advanced high–fidelity experiments in triaxial compression equipped with sequential X–ray tomography imaging.

More generally, the work is an attempt to convey the following two messages: 1) to stress that X–ray imaging is a measurement tool, not only a way to provide fancy images, and 2) to discuss what sort of modeling applications these rather exotic data can help to inform or inspire.

Developing and testing multiphase MPM approaches for the stability of dams and river embankments

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Keywords: MPM, embankment stability, infiltration.

The safety of earth dams and river embankments is an important issue in many areas worldwide. The failure of these structures can be caused by several mechanisms, e.g. macro-instability, overtopping, erosion (internal and external) which are governed by complex multiphase interactions and non-linear soil behaviour. Numerical methods are valuable tools to study the problem; some of them, such as FEM, are mainly focused to identifying the conditions which lead to the onset of failure and are limited to small deformations. However, the study of the evolution of the failure process from the beginning, where the displacements are small, to the very end after large displacements is important for risk assessment. To this end, a numerical method suitable for large deformation problems is necessary. Several methods have been proposed in the last decades to overcome the difficulties arising with FEM, e.g. SPH, MPM, ALE etc. This paper illustrates the potentiality of the Material Point Method (MPM) for the study of dams and river embankments stability.

In MPM the media is discretized into a set of Lagrangian material points (MPs), which move attached to the material and carry all the updated information such as velocities, strain, stresses, and history variables. Large deformations are simulated by MPs moving through a computational nodal grid that covers the full problem domain. The main governing equations are solved incrementally at the nodes of this grid that typically remains fixed throughout the calculation.

Within the recent years, several hydromecanically coupled MPM formulations were presented in the literature to model saturated [1], [2] and unsaturated soils [3], [4]. In this paper two of these formulations are presented showing their applicability to study embankment stability problems:

- The two-phase double-point formulation, which simulates saturated soil with 2 sets of MP, one for the liquid phase and one for the solid phase. It is well suited for seepage problems and can capture fluidization/sedimentation processes [2]
- The two-phase single-point formulation with suction, which simulates saturated and unsaturated soils with a single set of MP carrying the information of both phases. It is well suited for infiltration problems.

References

[1] I. Jassim, C. Coetzee, and P. A. Vermeer, “A dynamic material point method for geomechanics,” in *Installation Effects in Geotechnical Engineering*, 2013, pp. 15–23.

[2] M. Martinelli and A. Rohe, “Modelling fluidisation and sedimentation using material point method,” in *Proc. 1st Pan-American Congress on Computational Mechanics (PANACM 2015), Buenos Aires, Argentinia*, 2015.

[3] A. Yerro, E. E. Alonso, and N. M. Pinyol, “The material point method for unsaturated soils,” *Geotechnique*, vol. 65, no. 3, pp. 201–217, 2015.

[4] B. Wang, P. J. Vardon, and M. A. Hicks, “Rainfall-induced slope collapse with coupled material point method,” *Eng. Geol.*, vol. 239, no. February, pp. 1–12, 2018.

A DEM investigation of the micromechanics of non-active clays

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Keywords: Clays; Compressibility; Particle-scale behaviour

The micromechanical behaviour of clays cannot be investigated experimentally in a direct fashion due to the small size of clay particles. An insight into clay mechanical behaviour at the particle scale can be gained via virtual experiments based on the Discrete Element Method (DEM) [1]. So far, very few DEM models for clays have been designed, mainly on the basis of theoretical formulations of inter-particle interactions with limited experimental evidence.

This work presents a numerical investigation of the mechanical behaviour of non-active clays. The underlying microscale mechanisms were inferred by indirect experimental evidence [2] and used in this study to design the constitutive contact laws of a simple two-dimensional DEM framework. Clay platelets were modelled as rod-shaped particles made of spherical elementary units, designed to behave as single elements. New contact laws including attractive and repulsive long-range interaction were designed in order to simulate the positive/negative charge characterising the clay particle surface.

The contact laws were tested against the ability of the DEM framework to reproduce qualitatively some aspects of the one-dimensional compression and shear behaviour of clay observed experimentally. Specifically, these include the effect of pH and dielectric permittivity of the pore-fluid on the virgin loading and unloading-reloading lines, the dependency of the slope of the unloading-reloading lines on the pre-consolidation stress, contractive/dilative and monotonic/non-monotonic behaviour under shear. Despite the extreme simplicity of the proposed model [3], distinct microscale mechanisms could be effectively linked with clay response at the macroscale.

References

[1] *Cundall, P.A. and Strack, O.D.L., "A discrete numerical model for granular assemblies", Géotechnique,* ***29****(1), page 47–65 (1979).*

[2] *Pedrotti, M. and Tarantino, A., An experimental investigation into the micromechanics of non-active clays. Géotechnique, 68(8), page 666-683 (2017).*

[3] *Pagano, A.G., Magnanimo, V. Weinhart, T. Tarantino, A., Exploring the micromechanics of non-active clays via virtual DEM experiments, Géotechnique, doi.org/10.1680/jgeot.18.p.060 (2019).*

Modelling the shear wave splitting in fully saturated porous media

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Keywords: Porous media, Shear wave splitting, Finite element method.

The shear-wave splitting occurs when a shear wave propagates into an anisotropic medium and split into polarized waves of distinctive wave speeds. In geology and geosciences, the detecting shear-wave splitting allows one to identify material properties of the anisotropic soil and infer the distributions and orientations of cracks or crystals in the medium. Following the multi-field formulations for the solution of governing equations of porous media dynamics shown in [1], and considering suitable strategies for capturing sharp pore pressure gradient [2]; an improvement of a coupled three-dimensional finite element code, GeoMatFem [3], for the solution of solid-displacements/fluid-diffusion problems of fully saturated porous material is here presented.
The aim of this numerical model is to simulate the shear-wave splitting in anisotropic soils and rocks. In particular, we want to investigate the behavior of these body waves in materials that exhibit coupling effects between the elastic volumetric and deviatoric strain, and the influence of considering a non-coaxial permeability tensor. Finally, a comparison between the so-called *u-p formulation* and the *u-v-p formulation* has done in order to underline the features of the two methods.

References:

[1] *Markert, B., Heider, Y. and Ehlers, W., "Comparison of monolithic and splitting solution schemes for dynamic porous media problems." International Journal for Numerical Methods in Engineering,* ***Vol****.82(11) page1341-1383 (2010).*
[2] *Sun, W., Ostien, J.T., and Salinger, A.G., "A stabilized assumed deformation gradient finite element formulation for strongly coupled poromechanical simulation at finite strain." International Journal for Numerical and Analytical Methods in Geomechanics,* ***Vol****.37(16) page2755-2788 (2013).*
[3] *De Marchi, N., Salomoni, V., and Spiezia, N. "effects of finite strains in fully coupled 3d geomechanical simulations." International Journal of Geomechanics,* ***Vol****.19(4) pages04019008 (2019).*

A multiscale brittle-damage constitutive model to simulate hydro-mechanical processes in rocks

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Keywords: geomaterials, brittle damage, hydraulic fracture

Several concurrent issues, among which the marked anisotropic response - related to the onset and evolution of microcracks- and the strong hydro-mechanical coupling, make very complex the prediction of rock behaviour in engineering applications. In this context, we propose a coupled hydro-mechanical multiscale model of brittle damage [2-3], characterized by nested cohesive/frictional faults, according to hierarchical structures [1], and based on the definition of a reduced number of material constants. The model turns out to be a very effective tool in capturing several important features of the observed mechanical behaviour of rocks [2-3], including the reduction of the overall stiffness as the material deterioration increases, brittle to ductile transition, strain localization and shear-induced irreversible volumetric deformation. The model satisfactorily reproduces both the behaviour of the rocks at the material point scale and at the laboratory scale as a boundary value problem. A key aspect of the model is the capability to directly linking damage evolution to rock permeability increase, providing a further hydro-mechanical coupling term. This feature makes the model particularly suitable to simulate boundary value problems where rock failure is induced by hydraulic solicitations [4].

References

[1] *Pandolfi A., Conti S., Ortiz M. "A recursive-faulting model of distributed damage in confined brittle materials". Journal of the Mechanics and Physics of Solids, Vol. 54, 1972-2003 (2006).*
[2] *De Bellis ML, Della Vecchia G., Ortiz M., and Pandolfi A. "A linearized porous brittle damage material model with distributed frictional-cohesive faults". Engineering Geology, Vol. 215, 10-24 (2016).*
[3] *De Bellis ML, Della Vecchia G, Ortiz M, Pandolfi A. "A multiscale model of distributed fracture and permeability in solids in all-round compression", Journal of the Mechanics and Physics of Solids, Vol. 104, 21-31 (2017).*
[4] *Caramiello G., Montanino A., Della Vecchia G., Pandolfi A. "An approach to hydraulic fracture through a porous brittle damage material model", Advanced Modelling and Simulation in Engineering Science, Vol. 5 (23) (2018).*

A nonlinear anisotropic hyperelastic formulation for soils

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Keywords: hyperelasticity, anisotropy, small strain stiffness.

In the present study a nonlinear hyperelastic anisotropic model is proposed to reproduce the reversible response of soils. The dependence of the small strain stiffness on the current stress and the directional character of soils often play a non-negligible role in many geotechnical applications, such as the prediction of settlements induced by tunnelling and deep excavations. The anisotropic behaviour of soils is a macroscopic manifestation of an oriented internal microstructure, such as grains and particles orientation often combined with the presence of voids and, in some cases, of fissures or cracks. From a modelling point of view, the strategy adopted here is to link these microstructural features to the macroscopic behaviour introducing a symmetric second order fabric tensor that can condense all scalar and directional information pertaining to the anisotropy of the material. The use of a second order tensor restricts the investigated material symmetry to orthotropy. Consistently with the representation theorems for scalar valued isotropic functions, a free energy potential that depends on a series of mixed invariants of the strain and fabric tensors is presented. The proposed model represents a generalisation of some existing elastic laws for soils, while its formulation, based on the definition of a free energy potential, ensures thermodynamic consistency. The model can satisfactorily be employed to reproduce the anisotropic character of the small strain stiffness and its nonlinear dependence on the current stress, as experimentally observed in soils. Its predictive capability is illustrated by comparison with accurate laboratory experimental observations, carried out on both clay and sand specimens, based on accurate reversible stiffness measurements performed propagating shear waves polarised along different planes.

Thermodynamic-based anisotropic elastoplastic coupling of soils

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Keywords: anisotropy, elastoplastic coupling, hyperplasticity.

In the present study a thermodynamic-based constitutive model is proposed to reproduce both the reversible and irreversible anisotropic behaviour of clays. From an experimental perspective, both elastic and plastic anisotropy exhibit an evolving character when irreversible strains occur in the material. This suggests that both reversible and irreversible anisotropic response at the macroscopic level can be described by a unique second order fabric tensor that condenses all directional information pertaining to the soil internal microstructure.

The contribution proposed in this work is developed within the framework of thermodynamics with internal variables, according to the hyper-elastoplasticity theory for rate independent materials [1]. Two specific existing models are considered in the development: a hyperelastic formulation for the elastic anisotropic behaviour and a single surface plasticity model [2], originally developed within the classical elastoplasticity theory, for the plastic anisotropic hardening one. This latter, characterised by isotropic and rotational hardening laws, is first reformulated in a thermodynamically consistent way under triaxial (i.e. axisymmetric) conditions. Then an experimentally-based [3] relationship is proposed between the tensorial internal variable controlling the anisotropic hardening of the material and the fabric tensor accounting for its elastic anisotropy. In such a way, the fabric tensor is no longer constant but evolves by virtue of the rotational hardening law of the model, leading to a form of elastoplastic coupling, driven by tensorial entities, characterised by a mutual influence between the elastic and plastic behaviour. This brings in two remarkable consequences: 1) the resulting thermodynamic-based formulation is characterised by a yield surface in the stress space that displays different shapes as compared to those of the original elastoplastic model, depending on the degree of anisotropic coupling, including non-convex ones; 2) the resulting model has to be non-associated to satisfy the thermodynamics constraints. The implications of the elastoplastic coupling on the overall response of the model are analysed with reference to a series of numerical simulations. Furthermore, the derived formulation is finally used to back-predict the evolution of the elastic anisotropy as observed in laboratory tests carried out on a reconstituted clay [3].

References

[1] *Houlsby, G.T., Puzrin, A.M. Principles of Hyperplasticity: An Approach to Plasticity Theory Based on Thermodynamic Principles. Springer-Verlag, London, (2006).*

[2] *Dafalias, Y. F., & Taiebat, M. Anatomy of rotational hardening in clay plasticity. Géotechnique, 63(16), 1406, (2013).*

[3] *Mitaritonna, G., Amorosi, A., & Cotecchia, F. Experimental investigation of the evolution of elastic stiffness anisotropy in a clayey soil. Géotechnique, 64(6), 463-475, (2014).*

Numerical modelling of seismic wave propagation in liquefiable sand deposits

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Keywords: liquefaction, dynamic fully-coupled formulation, SANISAND.

Positive excess pore water pressures can develop in saturated fine sands under cyclic loading, leading to a progressive reduction of the stiffness and strength of the soil or, in extreme cases, to liquefaction. Seismic recordings during past earthquakes have shown either amplification or attenuation of surface accelerations, depending on the contractant/dilatant response of the underlying saturated sand deposits. Moreover, field observations have shown that geotechnical structures, such as quay walls, may experience severe damages due to the generation of excessive pore water pressures within the adjacent soil.

A reliable numerical prediction of seismically induced excess pore water pressures requires the development of a dynamic fully-coupled formulation capable of reproducing the solid-fluid interaction, together with the adoption of an advanced constitutive model for the soil.

In this work, an original fully coupled dynamic *u-p* formulation was implemented in the finite element code FEAP 8.4 [1] together with the advanced constitutive model SANISAND [2], which was adopted to describe the response of the solid skeleton. The field equations are formulated in a fully saturated condition.

The paper presents the main results of a finite element numerical study on the effects of liquefaction induced phenomena on the dynamic response of a saturated sand deposit. The most relevant physical factors affecting the dynamic response of the liquefied layer are identified. Moreover, key aspects in the constitutive modelling of the mechanical behaviour of sands under cyclic loading are highlighted.

References

[1] *Taylor, R. L., "Feap - - A Finite Element Analysis Program – v.8.4 User Manual". Technical report, University of California at Berkeley, Berkeley, California (2013).*

[2] *Dafalias, Y. F. and Manzari M. T., "Simple plasticity sand model accounting for fabric change effects". Journal of Engineering Mechanics **130**(6), 622–634 (2004).*

Back analysis of the effects of the internal length on the response of fibrous soils in triaxial tests

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Keywords: fibrous soils, internal length, numerical modelling

Constitutive models for soils are traditionally validated against experimental tests assuming these represent single (infinitesimal) element tests. However, the boundary conditions imposed to the sample with standard laboratory equipment induce non negligible stresses and strains non-uniformities. As a result, the observed sample behaviour differs from the true material response. As an interesting example of the misconceptions introduced by end restraint effects on the observed soil behaviour, a series of undrained triaxial compression tests on reconstituted peat samples is presented in this work.

The experimental results indicate dramatic end restraint effects in the apparent shear strength of the tested samples. Moreover, the diffuse fibrous networks present in the peat matrix seem to magnify the severity of the end restraint effects, as compared to previous studies on traditional inorganic soils, by introducing a characteristic length in the response of the material. Starting from the experimental evidence, the triaxial tests have been simulated with a coupled hydro-mechanical FE-IGA formulation, incorporating an advanced model for the soil, enriched with a second-gradient formulation capable of providing an internal length scale to the material [1].

The numerical results show the capability of the model to capture the end restraint effects on the deviatoric stress-strain response and the development of excess pore water pressures within the specimen. The introduction of a second gradient formulation allows reproducing correctly the length scale effects observed for samples with different height to diameter ratio. More importantly, the results suggest the possibility to link the magnitude of the second gradient stiffness coefficient to the characteristic length of the fibrous network in the peat fabric.

References

[1] Plúa, C., “Développement d'une stratégie d'implémentation numérique pour milieu continu poreux de 2nd gradient basée sur les éléments finis isogéométriques, application à un milieu partiellement saturé”. PhD Thesis, Communauté Université Grenoble Alpes and the Consortium of the Universities of Firenze, Pisa and Perugia (2018).

Experimenting with metamaterials and seismic waves at a reduced scale.

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The study of the interaction between waves propagating in a medium and its structure continues to be one of the most active research areas of wave physics. After the introduction of a new class of artificially engineered media called "metamaterials" in electromagnetism and acoustics, the idea that full control on wave propagation can be achieved through an appropriate design of the medium's microstructure is now widely accepted. In elasticity for instance, several laboratory experiments have shown how waves can be stopped, converted or amplified using resonant inclusions or periodic arrangement of heterogeneities.
Also in the field of civil engineering, metamaterials concepts and ideas are progressively gaining relevance with the first experiments addressing wave control capacities and feasibility [1,2]. Major challenges remain in the upscaling of metamaterial designs and physics to both the long wavelength and complexity (P, S, surface waves and other surface layering guided modes) characterizing the propagation of seismic waves in the ground. Here we present the latest numerical and experimental results on wavefield attenuation by arrays of resonators embedded in the soil (using micrometric glass-beads for the experiment) that can be thought as a seismic barrier or resonant foundations. This unique study considers both the attenuation of Rayleigh waves and that of horizontally polarised shear waves with lateral and vertical incidence direction.

References

[1] P. Roux, D. Bindi, T. Boxberger, A. Colombi, F. Cotton, I. Douste-Bacque, S. Garambois, P. Gueguen, G. Hillers, D. Hollis, T. Lecocq, and I. Pondaven. Toward seismic metamaterials: The metaforet project. Seismological Research Letters, 89(2A): 582, 2018.

[2] A. Palermo, S. Krödel, A. Marzani and C. Daraio. Engineered metabarrier as shield from seismic surface waves. *Scientific Reports* volume 6, 39356 (2016)

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