

**12<sup>th</sup> INTERNATIONAL CONFERENCE  
ON STRUCTURAL ANALYSIS  
OF HISTORICAL CONSTRUCTIONS**

**SAHC 2021**

**Online event, 29 Sep - 1 Oct, 2021**

**P. Roca, L. Pelà and C. Molins (Eds.)**





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## **TABLE OF CONTENTS**

Preface .....	7
Supporting Organizations.....	9
Organizers and Committees .....	11
Sponsors .....	15
Summary .....	17
Contents .....	19
Presented Sessions.....	45
Authors Index.....	3661





# PREFACE

The International Conference on Structural Analysis of Historical Constructions (SAHC) was first celebrated in Barcelona in 1995, followed by a second edition also in Barcelona in 1998. Since then, nine subsequent editions have been organized in different countries of Europe, America and Asia. The SAHC conference series is intended to offer a forum allowing engineers, architects and all experts to share and disseminate state-of-art knowledge and novel contributions on principles, methods and technologies for the study and conservation of heritage structures. Through all its successful past editions, the SAHC conference has become one of the topmost periodical opportunities for scientific exchange, dissemination and networking in the field.

During the last decades the study and conservation of historical structures has attained high technological and scientific standards. Today's practice involves the combination of innovative non-destructive inspection technologies, sophisticated monitoring systems and advanced numerical models for structural analysis. More than ever, it is understood that the studies must be performed by interdisciplinary teams integrating wide expertise (engineering, architecture, history, archeology, geophysics, chemistry...). Moreover, the holistic nature of the studies, and the need to encompass and combine the different scales of the problem –the materials, the structures, the building aggregates, and the territory – are now increasingly acknowledged. Due to all this, the study of historical structures is still facing very strong challenges that can only be addressed through sound international scientific cooperation.

Taking these ideas in mind, the 12<sup>th</sup> edition of the SAHC conference aimed at creating a new opportunity for the exchange and discussion of novel concepts, technologies and practical experiences on the study, conservation and management of historical constructions.

The present proceedings include the papers presented to the conference, which was finally celebrated on September 29-30 and October 1, 2021, in an on-line mode due to the world sanitary emergency situation created by the Covid-19 pandemic.

The conference included the following topics: history of construction and building technology; inspection methods, non-destructive techniques and laboratory testing; numerical modeling and structural analysis; structural health monitoring; repair and strengthening strategies and techniques; conservation of 20<sup>th</sup> c. architectural heritage; seismic analysis and retrofit; vulnerability and risk analysis and interdisciplinary projects and case studies.

The SAHC 2021 conference has been possible thanks to the large contribution of the scientific committee and reviewer panel who took care of selecting and review the papers submitted. The contribution of the different sponsors and supporting organizations is also acknowledged. Above all, the conference has been possible thanks to all the authors who have contributed with very valuable papers despite the difficulties caused by the world pandemic. New editions of the conference are already planned in normal face-to-face formats which, in the upcoming years, will provide new opportunities for sharing valuable knowledge and experience on structural conservation, as well as for keeping alive and fulfilling the purpose and aims of the SAHC conference series.

The Organizing Committee





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**ICOMOS**  
international council on monuments and sites

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**Iscarsah**  
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### CODES OF PRACTICE

Eurocode 8, Italian codes.

### MATERIALS

Unreinforced and reinforced masonry, reinforced concrete and generic linear materials.

### LOCAL FAILURE MECHANISMS

Automatic geometry interfacing with PRO\_CineM for kinematic linear and non-linear analyses.

### LINEAR ANALYSIS

Automatic generation of plate and shell linear model from the equivalent frame.

### FREE

PRO\_SAM is free for students, scholars or scientific research.



Asdea Software S.r.l. is part of the burgeoning ASDEA brand, which includes ASDEA S.r.l. and ASDEA Hardware. We are a software development company staffed with engineers, researchers, and software developers. Our goal is to provide innovative software solutions customized for clients and of original in-house design for numerical simulation and data visualization. We are the company behind the revolutionary software STKO (Scientific ToolKit for OpenSees). More than just a simple GUI, STKO features a Python scripting interface, meaning that users can customize and program the already powerful pre and postprocessors as needed, harnessing the full power of OpenSees.



CALSENS develops state-of-the-art fiber-optic sensors and designs, deploys and operates structural health monitoring (SHM) solutions to monitor bridges, buildings and vehicles (ships, airplanes, UAV), among other structures. Our services are based on constant research and innovation, creating products and services at the frontier of knowledge.

CALSENS services cover the full process of monitoring. Starting from the modelling of structural behavior and choice of control parameters, continuing with the election, design, fabrication and installation of the sensors and sensing system, until the processing, interpretation and evaluation of the data.

CALSENS has a multidisciplinary team with a high degree of expertise in the fields of civil engineering, photonic technologies, signal processing, materials engineering or computing.







Kerakoll is the international leader in the GreenBuilding sector, providing solutions that safeguard the health of both the environment and the people.

The company mission is embrace and promote GreenBuilding as the new low environmental impact approach to building and promote higher quality homes around the world through the use of eco-friendly building materials and innovative solutions.

Since 1968 – when the Group was founded in Sassuolo– Kerakoll has been pursuing a clear course of development in Italian and international markets for building materials, that has taken the company to the forefront of the GreenBuilding industry and to a level of technological supremacy famous around the globe.



S.T.A. DATA, founded in 1982 by Adriano Castagnone, civil and structural engineer since 1978, and pioneer of scientific software for structural engineering, is composed of more than 20 people, all highly qualified professionals. Our aim is to offer software for structural calculation that allow designers to face everyday work with simplicity and effectiveness.

S.T.A. DATA offers 3Muri Project, developed specifically for masonry.

In fact, it is not a generic Finite Element software adapted for masonry structures; 3Muri Project was born from the specific research for these structures and captures all the characteristics to obtain a safe and reliable calculation of historical, existing and new buildings.



IRS is a smart Engineering, Research and Development company founded by a group of engineers in 1993. IRS Structural Health Monitoring division designs, develops and integrates automated systems for mechanical and structural monitoring. Thanks to technological innovation, advanced modeling and design as well as professional production and after sales service provide a complete suite of structural health monitoring solutions. Monitoring version are both portable version for laboratory tests and one shot structural assessments and long term and in situ applications like historical sites, buildings, bridges, dams and tunnels. IRS is part of a group of companies including Measureit, with whom provides consultancy and sales of precision sensor and data acquisition systems.

# SUMMARY

## PRESENTED SESSIONS

Conservation of 20th c. architectural heritage .....	47
History of construction and building technology.....	200
Inspection methods, non-destructive techniques and laboratory testing.....	481
Interdisciplinary projects and case studies .....	873
Management of heritage structures and conservation strategies .....	1514
Numerical modeling and structural analysis.....	1675
Repair and strengthening strategies and techniques.....	2439
Resilience of historic areas to climate change and hazard events .....	2746
Seismic analysis and retrofit .....	2846
Structural health monitoring.....	3206
Vulnerability and risk analysis .....	3390



# CONTENTS

## PRESENTED SESSIONS

### Conservation of 20th c. architectural heritage

- An Innovative Shell Structure in Codogno (Italy). Evaluation of Structural and Seismic Performance** ..... 47  
*P. Brugnera, M.G. Costa and G. Mirabella Roberti*
- Anchorage of Reinforcement Bars in Hennebique R.C. Structures** ..... 59  
*A. Brencich and M. Nebiacolombo*
- Challenges in the Reuse and Upgrade of Pier Luigi Nervi's Structures** ..... 71  
*R. Ceravolo, G. De Lucia, E. Lenticchia, G. Miraglia, A. Quattrone, F. Tondolo, E. Matta, G. Sammartano, A. Spano and C. Chiorino*
- Conservation of 20th Century Concrete Heritage Structures in Cyprus: Research and Practice** ..... 82  
*A.V. Georgiou, M.M. Hadjimichael and I. Ioannou*
- Conservation of Historical Reinforced Concrete Structures** ..... 94  
*I. Bucur-Horváth and J. Virág*
- Decay Patterns and Damage Processes of Historic Concrete: A Survey in the Netherlands** ..... 105  
*G. Pardo Redondo, S. Naldini and B. Lubelli*
- Early Concrete Structures and Post-Patented Systems: Lessons to Preserve Early 20th Historical Heritage** ..... 117  
*I. Marcos, L. Garmendia, I. Piñero, Z. Egiluz, E. Briz and A. Gandini*
- Historical Buildings Made of Reinforced Concrete in Timisoara in the Beginning of the 20th Century** ..... 127  
*R. Oprita*
- Reconstruction of a Masonry Windmill Tower with a Multi-Blade Wind Turbine, Steel Reservoir and Water Supply System** ..... 137  
*P.W. Sielicki*
- Reinforced Concrete Floors in Historic Buildings from the Beginning and the Middle of the 20th Century - Examples of Structural Strengthening in the Process of Revitalization** ..... 144  
*G. Dmochowski, P. Berkowski, J. Szolomicki and M. Minch*
- Senate Building of Canada Case Study: Seismic Rehabilitation** ..... 156  
*L.M. Nicol*
- Structural Evaluation and Maintenance of Brooks Aqueduct Historic Site** ..... 168  
*A. Rouhi and N. Shrive*

<b>Structural Evaluation of the Greenhill Mine Tipple Structure Historic Site</b> .....	180
<i>A. Rouhi and N.G. Shrive</i>	
<b>The Safety Level of Concrete Pile Foundations under Industrial Monuments</b> .....	192
<i>S. Pasterkamp</i>	
<b>History of construction and building technology</b>	
<b>“Iron Cages.” Technical Discussions after the 1906 Valparaíso Earthquake and Reconstruction with New Techniques and Materials</b> .....	200
<i>S. Maino, K. Cabezas and M. Koch</i>	
<b>A study of the Historical Construction Technology of Bell Towers in Cyprus</b> .....	212
<i>M.L. Petrou and D.C. Charmpis</i>	
<b>A User-Friendly Digital Tool for the Structural Assessment of Historic Domes: The Case Study of Saint Peter in Rome</b> .....	223
<i>M.F. Funari, D.V. Oliveira, L.C. Silva and P.B. Lourenço</i>	
<b>Amazonas Theater Architectural Construction and Restorations History</b> .....	233
<i>M.S. Sampaio</i>	
<b>An Example of Fit-for Purpose Use of Materials in Roman Architecture: P Temple, Side, Antalya/Turkey</b> .....	245
<i>G. Kaymak Heinz</i>	
<b>First Reinforced Concrete Building in Rijeka Port - Ferenc Pfaff’s Warehouse No.17</b> .....	257
<i>P. Šculac, D. Grandic and N. Palinic</i>	
<b>Foundation Development from 1890-1942 for Long Span and High Rise Buildings at Mexico City</b> .....	269
<i>P. Santa Ana, L. Santa Ana and J. Baez</i>	
<b>From Art to Science of Construction: the Permanence of Proportional Rules in the “Strange Case” of the 19th Century Ponte Taro Bridge (Parma, Italy)</b> .....	279
<i>F. Ottoni, V. Braglia, E. Coisson and L. Ferrari</i>	
<b>Gaudí, a New Architectural Concept of Maximum Structural Efficiency: Catenary Vaults, Complex Ruled Surfaces, Branched Pillars and an Endless Innovative Strategies</b> .....	291
<i>C. Salas, C. Bedoya and J.M. Adell</i>	
<b>Geotechnical Structures in the Ancient World. The Case of the Ziggurat of Ur in Mesopotamia</b> .....	303
<i>E. Kapogianni</i>	

<b>Historical and Typological Characterization of Churches in the Historical Centre of Cusco, Peru</b> .....	314
<i>K. Sovero, N. Tarque, E. Spacone, C. Mazzanti, G. Brando and C. Alfaro</i>	
<b>Iron and Steel Construction Workshops in 19th and early 20th century Belgium: Retrieving their Oeuvre via Trade Catalogues</b> .....	325
<i>I. Wouters and R. Wibaut</i>	
<b>New Lightweight Structures and Historical Heavyweight Structures in Conservation</b> .....	337
<i>A. Mosseri</i>	
<b>Opus Signinum - Roman Concrete without Pulvis Puteolanis: Example of the Substructures of Diocletian's Palace</b> .....	349
<i>M.I. Šimunić Buršić</i>	
<b>Patio as a Structural Invariant. Buildings with Patio Facing Adaptive Reuse in Barcelona</b> .....	361
<i>P. Fuertes, R. Sauquet and N. Salvadó</i>	
<b>Reconstructed Overhanging Battlements. Executive Techniques and their Vulnerability in the Stronghold of Arquata del Tronto (Italy)</b> .....	373
<i>E. Facchi, A. Grimoldi, A. G. Landi and E. Zamperini</i>	
<b>Reinforced Concrete + Masonry: the 'Mixed' Structure of the Novocomum by Giuseppe Terragni</b> .....	385
<i>A. Greppi and C. Di Biase</i>	
<b>Safety Assessment of Existing Post-War Reinforced Concrete Bridges. The Case Study of 'Gerber Girders' Bridges in Italy</b> .....	397
<i>I. Giannetti, S. Mornati, S. Coccia, F. Di Carlo and Z. Rinaldi</i>	
<b>Structural Analysis as a Supporting Method for the Research of Medieval Brick Architecture</b> .....	409
<i>P. Samol, P. Iwicki and J. Przewlocki</i>	
<b>The "Pieve di Santa Maria" in Arezzo (Italy). From the Laser Scanner Survey to the Knowledge of the Architectural Structure</b> .....	421
<i>P. Matracchi, C. Biagini, A. Sadocchi and M. Valieri</i>	
<b>The Dome of the Temple of Diana in Baiae: Geometry, Mechanics and Architecture</b> .....	433
<i>A. Sinopoli and D. Aita</i>	
<b>The Spiral Staircase in the Fortified Tower of Nisida</b> .....	445
<i>C. Cennamo, C. Cusano and M. Angelillo</i>	
<b>The Structural Function of the Dutch Buttressing of the East Curtain Wall of Elmina Castle, Elmina, Ghana</b> .....	457
<i>J. Sun, S. Tezcan and R. Perucchio</i>	
<b>Timber Reinforcements: Local Construction Techniques in Italian Historical Buildings</b> .....	469
<i>S. Della Torre and L. Cantini</i>	

## **Inspection methods, non-destructive techniques and laboratory testing**

<b>Application of Digital Close-Range Photogrammetry to Monitor Local Deformations of Architectural Monuments: A Case Study of el Mirador de Inkaraqay (Machu Picchu)</b> .....	481
<i>J. Kosciuk and M. Pakowska</i>	
<b>Axial Compression Tests on Rubble Stone Masonry Reproducing Opus Incertum of Ancient Pompeii</b> .....	492
<i>F. Autiero, G. De Martino, M. Di Ludovico and A. Prota</i>	
<b>Characterization of Cracks in Historical Buildings Using Image Processing Techniques</b> .....	504
<i>P. Porcel, B. Castañeda and R. Aguilar</i>	
<b>Characterization of Historic Mortars for Compatible Restoration: Case study of South Africa</b> .....	515
<i>M. E. Loke, K. Pallav and R. Haldenwang</i>	
<b>Comparison Between Investigation Techniques for the Evaluation of the Compressive Properties of Brick Masonry Structures</b> .....	525
<i>F. Ferretti, A. Incerti and C. Mazzotti</i>	
<b>Compressive Behaviour of Bonded Brickwork Wallettes with Various Thicknesses: Experimental and Numerical Verification</b> .....	537
<i>J. Thamboo, M. Asad and T. Zahra</i>	
<b>Data Acquisition, Management and Evaluation for Stone Conservation Projects with Digital Mapping</b> .....	547
<i>S. Vetter, G. Siedler and J. Kaminsky</i>	
<b>Dynamic Identification of Damage in Brick Masonry Walls</b> .....	559
<i>S. Ivorra, D. Bru, I. Gisbert, F.J. Baeza, B. Torres and D. Camassa</i>	
<b>Effect of Geometrical Imperfections on the Response of Dry-Joint Masonry Arches to Support Settlements</b> .....	569
<i>C. Ferrero, M. Rossi, P. Roca and C. Calderini</i>	
<b>Evaluation of the Behaviour of Lime and Cement Based Mortars Exposed at Elevated Temperatures</b> .....	581
<i>V. Pachta and M. Stefanidou</i>	
<b>Experimental Campaign on the Use of the Flat Jack Test in Cob Walls</b> .....	593
<i>A. Jiménez Ríos, M. Grimes and D. O'Dwyer</i>	
<b>Experimental Investigation of Scarf Joint of 'Lightning Sign' in Bending</b> .....	602
<i>A. Karolak and C. Jasieńko</i>	
<b>Experimental Investigation on the Torsion-Shear Behaviour at the Interfaces of Interlocking Masonry Block Assemblages</b> .....	614
<i>C. Casapulla, E. Mousavian, L.U. Argiento and C. Ceraldi</i>	



<b>Fatigue Assessment of Old Riveted Railway Bridges: Laboratory Testing of a Real Bridge</b> .....	626
<i>J.M. Adam, P.A. Calderón, M. Buitrago, E. Bertolesi, J.J. Moragues, S. Ivorra and B. Torres</i>	
<b>Influence of Moisture Content on the Application of ND and MD Tests to Various Species of Timber Elements</b> .....	639
<i>M.R. Valluzzi, F. Casarin, L. Scancelli, M. Drdácky, M. Kloiber and J. Hrivnák</i>	
<b>Investigation of Rubble-Masonry Wall Construction Practice in Latium, Central Italy</b> .....	651
<i>O. Al Shawa, G. De Canio, G. De Felice, S. De Santis, S. Forliti, D. Liberatore, D. Mirabile Gattia, S. Perobelli, F. Persia and L. Sorrentino</i>	
<b>Laboratory and In-Situ Characterisation of Masonry Materials in a Large Historical Industrial Building in Barcelona</b> .....	662
<i>A. Cabané, L. Pelà and P. Roca</i>	
<b>Mechanical Characterization of Traditional Masonry in an Homogeneous Territory: Valtellina</b> .....	674
<i>M. Sala, D. Foppoli and S. Della Torre</i>	
<b>Methodologic Evolution Assessment of Large Deformations on Romanesque Masonry in Val d'Aran (XII-XIII centuries), Spain</b> .....	685
<i>J. Lluís i Ginovart, M. Lopez-Piquer and C. Lluís-Teruel</i>	
<b>Modal and Structural Identification of a Multi-Span Masonry Arch Bridge</b> .....	697
<i>P. Borlenghi, A. Saisi and C. Gentile</i>	
<b>Monitoring Deformations of a Wooden Church Tower by Laser Scanning</b> .....	709
<i>L. Truong-Hong, R. Lindenbergh, P. Woudenberg, W. Gard and J.-W. Van de Kuilen</i>	
<b>Non-Destructive Assessment of the Adhesion at the Interface Between FRCM Reinforcements and Masonry Substrates by Non-Linear Ultrasonic Technique</b> .....	722
<i>A. Castellano, A. Fraddosio, T. Kundu and M.D. Piccioni</i>	
<b>Non-Destructive Documentation Methods for Future Seismic and Damage Analysis of Modern Heritage Buildings using Contemporary Tools</b> .....	734
<i>S. Rajabzadeh, M. Esponda and L. Cordero Espinosa</i>	
<b>Non-Destructive Techniques for Characterising Earthen Structures</b> .....	746
<i>E. Bernat-Maso, E. Teneva, L. Mercedes and L. Gil</i>	
<b>Pathological and Structural Health Assessment of a Residential Building in Lota, Chile</b> .....	757
<i>M. Chávez, F. Macaya, E. Nuñez and C. Oyarzo</i>	
<b>Point-Load Test Assessment as Study of Adobe Buildings Damaged after the 2017 Puebla Earthquake</b> .....	769
<i>A. Sánchez, E. M. Alonso and J. A. Bedolla</i>	

<b>Quality and Strength Assessment of Butt Welds in Poland's Oldest Welded Railway Bridges .....</b>	<b>781</b>
<i>B. Wichtowski and J. Holowaty</i>	
<b>Salt Contamination of Wooden Materials: the Case of Trondheim (Norway) Warehouses .....</b>	<b>791</b>
<i>C. Bertolin, M. Strojceki, L. De Ferri, G. Grottesi and A. M Siani</i>	
<b>Stiffness Changes due to Static Loading of a Brick Arch .....</b>	<b>802</b>
<i>J. Bayer, S. Urushadze and J. Witzany</i>	
<b>Structural Performance and Durability Issues of Vernacular Schist Masonry .....</b>	<b>809</b>
<i>C.E. Barroso, D.V. Oliveira and L.F. Ramos</i>	
<b>Testing Calibration Issues in Resistance Drilling Applied to Timber Elements.....</b>	<b>821</b>
<i>F. Casarin, L. Scancelli, M.R. Valluzzi and E. Bozza</i>	
<b>The NDT Investigations Carry out at the Arudj Cathedral, Armenia.....</b>	<b>830</b>
<i>S. Tonna, M. Cucchi and C. Tedeschi</i>	
<b>The State and Condition of Historical Buildings Located on Partisan Hill in Wroclaw .....</b>	<b>842</b>
<i>A. Hola, J. Hola, L. Sadowski and J. Szymanowski</i>	
<b>Towards a Methodology for Use of Sonic and Ultrasonic Tests in Earthen Materials .....</b>	<b>852</b>
<i>R. Martini, J.D. Rodriguez-Mariscal, J. Carvalho, M. Solís and H. Varum</i>	
<b>Using the Ultrasonic Tomography Method to Study the Condition of Wooden Beams from Historical Building .....</b>	<b>863</b>
<i>M. Zielińska and M. Rucka</i>	
<b>Interdisciplinary projects and case studies</b>	
<b>A Preliminary Structural Survey of Heritage Timber Log Houses in Tonsberg, Norway .....</b>	<b>873</b>
<i>A. Shabani, H. Hosamo, V. Plevris and M. Kioumarsi</i>	
<b>A Protected Landmark Monument: Reinforcement, Rehabilitation, and Restoration of the Cathedral Basilica of Manizales .....</b>	<b>885</b>
<i>O. D. Cardona and S. D. Prieto</i>	
<b>Adaptation of a Mid-Nineteenth Century Representative University Building to Office Functions .....</b>	<b>897</b>
<i>J. Szolomicki, M. Minch, G. Dmochowski and P. Berkowski</i>	
<b>An Interdisciplinary Approach for the Experimental Assessments of the Seismic Safety of Artworks .....</b>	<b>909</b>
<i>A. Di Martino, G. Cocuzza Avellino, E. Paterno, F. Cannizzaro, I. Calìò, G. Gianfriddo, R. Valenti and N. Impollonia</i>	

<b>Application of Geophysical Prospecting Methods for Soil Structure Characterization of the Cathedral of Santo Domingo, Dominican Republic</b> .....	921
<i>J. Pérez-Cuevas, V. Flores-Sasso, E. Prieto-Vicioso, L. Ruiz-Valero and S. Sandoval</i>	
<b>Assessment of Tunneling Induced Damage on Historical Constructions Through a Fully Coupled Structural and Geotechnical Approach</b> .....	933
<i>A. Amorosi, M. Sangirardi, G. De Felice and S. Rampello</i>	
<b>Automated Model Updating of a Masonry Historical Church Based on Operational Modal Analysis: the Case Study of San Giovanni in Macerata</b> .....	943
<i>S. Santini, C. Baggio, E. Da Gai, V. Sabbatini and C. Sebastiani</i>	
<b>Betang, a Traditional House of the Dayak Ngaju in Borneo Its Space Related to Structure</b> .....	954
<i>M. Guntur and K. R. Kurniawan</i>	
<b>Claudius Aqueduct in Rome - Kinematic Analyses and Empirical Experiences for the Definition of Structural Restoration Interventions</b> .....	966
<i>F. De Cesaris</i>	
<b>Comparison on Methodologies and Intervention for two Masonry Churches Affected after the 2017 Earthquake in Mexico</b> .....	978
<i>M. Esponda and J. Cooke</i>	
<b>Conservation Beyond Consolidation for Prehistoric Monuments: Finding Narratives from Archaeology to Architecture for Scottish Brochs</b> .....	990
<i>C. Liu and D. Theodossopoulos</i>	
<b>Constructive Analysis and Modelling of a Single Nave Church: a Proposal for S. Sebastiano (EN, Italy)</b> .....	1002
<i>A. Lo Faro, V. Cusmano, B. Pantò and F. Cannizzaro</i>	
<b>Cultural Heritage Exposed to Natural Hazards: the Case Study of the Convent of San Domenico in Maiori</b> .....	1014
<i>R. Landolfo, C. Tarantino, F. Portioli and L. Cascini</i>	
<b>Design of Protective Structures for Active Archeological Sites</b> .....	1026
<i>M. Petrović, I.D. Ilić, N.M. Džombić and N.D. Šekularac</i>	
<b>Determining Qualities of Photogrammetric Models for the Use of Monitoring Movements in Stone Candis in Central Java</b> .....	1038
<i>D. Grandits, L. Stampfer, E. Kodzoman, A. Setyastuti and U. Herbig</i>	
<b>Diagnosis of an Unusual Structural Instability: the Case Study of the Cathedral of San Lorenzo in Viterbo</b> .....	1050
<i>M. Candela, M. Eichberg and C. Tarantino</i>	
<b>Documentation and Structural Appraisal of the Medieval Manor of Potamia, Cyprus: an Interdisciplinary Approach</b> .....	1062
<i>R. Illampas, D. Myrianthefs, D. Nicolaou, V. Lysandrou, M. Philokyprou, G. Papasavvas and I. Ioannou</i>	

<b>Effect of Slow-Moving Landslides on Churches in the Liguria Region: a Geotechnical Approach</b> .....	1074
<i>L. Cambiaggi, C. Ferrero, R. Berardi, C. Calderini and R. Vecchiattini</i>	
<b>From Reality to Point Clouds. Survey and Analysis of Sant Miquel Church of Batea (Spain)</b> .....	1086
<i>A. Costa-Jover, D. Moreno Garcia, S. Coll Pla and J. Lluís i Ginovart</i>	
<b>Historical Analysis and In-Situ Inspections of a Cultural Heritage Masonry Building</b> .....	1097
<i>A. De Angelis, F. Santamato, G. Maddaloni, L. De Filippis and M.R. Pecce</i>	
<b>Identification and Assessment of the Seismic Behaviour of Giotto's Bell Tower in Florence (Italy)</b> .....	1109
<i>P. Spinelli and M. Betti</i>	
<b>Interdisciplinary Assessment, Analysis and Diagnosis of a Historic Timber Roof Structure From the 20th Century</b> .....	1122
<i>B. Isopescu, A. Keller, V. Stoian and M. Mosoarca</i>	
<b>Non-Destructive Techniques in the Consolidation Works of the Church of S.M. of Itria in Piazza Armerina (Italy)</b> .....	1133
<i>T. Basirico, S. Campione and A. Cottone</i>	
<b>Nonlinear Structural Analysis of the Elliptical Dome of the Church in the Universidad Laboral, Gijon, Spain</b> .....	1145
<i>J.J. Coz-Diaz, A. Lozano Martinez-Luengas, M. Alonso-Martinez, M.P. Garcia-Cuetos and F.P. Alvarez-Rabanal</i>	
<b>Parameter Evaluation in Historical Construction: From Sensitivity Analysis to the Test Planning</b> .....	1158
<i>A. Cali, P. Dias De Moraes and A. Do Valle</i>	
<b>Preliminary Structural Analysis of the Western Curtain Wall of Elmina Castle, Elmina, Ghana</b> .....	1170
<i>M.N. Dos Santos, S.A. Abelezele, K.A. Korslund, R.T. Cecil, S. Tezcan and R. Perucchio</i>	
<b>Preserving Historic Bearing Structures by Prudent Integration in New Structures</b> .....	1183
<i>M. Mosoarca, V. Stoian, M. Florea, M. Niculescu and M. Palade</i>	
<b>Reconstructing the Indoor Climate of Historic Buildings</b> .....	1194
<i>W. Stumpf</i>	
<b>Renovation of 16th Century Salt House Roof (Lubań, Lower Silesia, Poland) - Case Study</b> .....	1206
<i>K. Alykow and M. Napiórkowska-Alykow</i>	
<b>Research on Architectural Form and Structural Performance of the Brick-Vault Hall Heritage in China. A case study of Yongzuo Temple</b> .....	1214
<i>Q. Chun, Y. Lin and C. Zhang</i>	
<b>Restoration Authenticity or Reality - A Case Study</b> .....	1222
<i>D. Biggs</i>	

<b>Restoration of the Queen Victoria Market Sheds E-F and J-M, Melbourne, Australia .....</b>	<b>1232</b>
<i>J. Hettinga</i>	
<b>Seismic Vulnerability Assessment of a 17th Century Colonial Adobe Church in the Central Valley of Chile .....</b>	<b>1244</b>
<i>N.C. Palazzi, G. Misseri, L. Rovero and J.C. De La Llera</i>	
<b>Slow-Moving Landslide Damage Assessment of Historic Masonry Churches: some Case-Studies in Italy .....</b>	<b>1256</b>
<i>C. Ferrero, L. Cambiaggi, A. Fenialdi, P. Roca, R. Vecchiattini and C. Calderini</i>	
<b>Soil Settlement and Uplift Damage to Architectural Heritage Structures in Belgium: Country-Scale Results from an InSAR-Based Analysis .....</b>	<b>1268</b>
<i>A. Drougkas, E. Verstryngge, K. Van Balen, M. Shimoni, T. Croonenborghs, R. Hayen, P. Y. Declercq and J. Walstra</i>	
<b>Standard Gravity and Wind Load Analysis on 103-years old Unreinforced Masonry Building .....</b>	<b>1279</b>
<i>A. Kumar and K. Pallav</i>	
<b>Static Analysis of a Masonry Arched and Buttressed Retaining Wall .....</b>	<b>1291</b>
<i>D.. Dogu, C. Molins and N. Makoond</i>	
<b>Static and Dynamic Load Test of Libeň Bridge Over Vltava River in Prague and Concept of Repair .....</b>	<b>1303</b>
<i>P. Tej, J. Mourek and M. Blank</i>	
<b>Structural Assessment of Cultural Heritage Buildings Using HBIM and Vibration-Based System Identification .....</b>	<b>1315</b>
<i>A. Cali, A. Saisi and C. Gentile</i>	
<b>Study on Causative Agents of Damage in the Costa Rican Caribbean Architecture from a Multidisciplinary Perspective .....</b>	<b>1326</b>
<i>K. García-Baltodano, D. Porrás-Alfaro and I. Hernández-Salazar</i>	
<b>Studying a Masonry Sail Vault by Antonio da Sangallo the Elder in the Fortezza Vecchia in Livorno .....</b>	<b>1338</b>
<i>F. Barsi, D. Aita, R. Barsotti, D. Ulivieri and S. Bennati</i>	
<b>The Bridge Over the Adda River in Brivio: History, Full-Scale Testing and FE Modelling .....</b>	<b>1346</b>
<i>G. Zonno and C. Gentile</i>	
<b>The Column-Less Stair at Loretto Chapel in Santa Fe, New Mexico: Strength Analysis .....</b>	<b>1358</b>
<i>A. Sumali</i>	
<b>The Dar al Consul Complex in Jerusalem: Improving the Living Conditions and the Structural Capacity .....</b>	<b>1369</b>
<i>F. Casarin, L. Di Marco, M. Mocellini, R. Sidawi, P. Dahabreh and A.K. Taweel</i>	

<b>The Evangelical Church of Peace in Swidnica, Poland. Several Comments on its Wooden Construction and Building Technology in the Middle of the 17th Century</b> .....	1381
<i>U. Schaaf</i>	
<b>The Influence of Civil Works on Heritage Architecture, El Vergel, Cuenca - Ecuador</b> .....	1393
<i>G. Barsallo, F. Cardoso, E. Sinchi, T. Rodas and M.C Achig</i>	
<b>The Modern Impossibility of Making Art like That of the Past. Intervention Proposal for the Temple of San Juan Bautista, Tochimilico, Puebla, Mexico</b> .....	1402
<i>E. Vera</i>	
<b>The Plaster Ceilings of Buckingham Palace and Windsor Castle: Their Construction, Condition and Conservation</b> .....	1409
<i>S. Brookes, K. Clark, R. Frostick, R. Ireland and L. Randall</i>	
<b>The Restoration Interventions of “Forte Marghera” in Venice</b> .....	1421
<i>F. Casarin, R. Cianchetti, T. Dalla Via, M. Meggiato and M. Mocellini</i>	
<b>The Restoration of the Medieval Walls of San Ginesio: a Dedicated Study for the Conservation, Repair and Enhancement of an Important Military Fortification</b> .....	1433
<i>M. Saracco, F. Mariano, A.A. Giuliano, L. Petetta and F. Piccinini</i>	
<b>The Reuse of Housing Buildings in Barcelona. The Versatility of Old Constructive Structures</b> .....	1445
<i>M. M`aria and X. Monteys</i>	
<b>The Use of a Building Information Model to Support Seismic Analysis: Application to the National Palace of Sintra, Portuga</b> .....	1457
<i>M. Ponte, R. Bento, R. Machete , M. Godinho, A. B. Gonalves and A. P. Falco</i>	
<b>Thermal Behavior Assessment of Two Types of Roofs of the Dominican Vernacular Housing</b> .....	1470
<i>E. Prieto-Vicioso, L. Ruiz-Valero and V. Flores-Sasso</i>	
<b>To Reach the Light: The Monumental Byzantine Stairs of Caesarea, a Conservation and Restoration Project</b> .....	1478
<i>N. Maklada, S. Hadid, D. Abuhatsira, P. Gendelman, Y. Oz and D. Siboni</i>	
<b>Typological Characterization of Ancient Town Walls for Disaster Prevention and Mitigation. The MO.M.U. Project</b> .....	1490
<i>A. De Falco, F. Giuliani, D. Ladiana, L. Rjolli, D. Bordo, F. Gaglio and M. Di Sivo</i>	
<b>Vulnerability Assessment of Italian Rationalist Architecture: Two Case Studies</b> .....	1502
<i>P. Bernardi, R. Cerioni, E. Coisson and E. Michelini</i>	

## Management of heritage structures and conservation strategies

<b>British Colonial Era's Religious Built Heritage in Yorubaland, Nigeria: Key Conservation Problematics and the State of Know-How</b> .....	1514
<i>R. Sabri and O.A. Olagoke</i>	
<b>Conservation of Architectural Complex of Manguinhos, in Rio de Janeiro, Brazil</b> .....	1523
<i>B. Oliveira</i>	
<b>Dacian Fortresses in Orastie Mountains: Management of Heritage Structures</b> .....	1535
<i>G. Paşcu, A. Keller and C. Bocan</i>	
<b>Design Criteria and Procedures for Archaeological Shelters: Towards Flexibility Thanks to Algorithmic Modelling</b> .....	1547
<i>L. Sbrogiò, A. Basso, P. Borin, M.R. Valluzzi and A. Giordano</i>	
<b>Digitization of Cultural Heritage Buildings for Preventive Conservation Purposes</b> .....	1559
<i>M.G. Masciotta, L.J. Sánchez-Aparicio, S. Bishara, D.V. Oliveira, D. González-Aguilera and J. García-Alvarez</i>	
<b>Fill-in-Glass Restoration: Exploring Issues of Compatibility for the Case of Schaesberg Castle</b> .....	1571
<i>L. Barou, F. Oikonomopoulou, T. Bristogianni, F.A. Veer and R. Nijssse</i>	
<b>Integrated Conservation Strategies in the Netherlands</b> .....	1583
<i>S. Naldini, R. Van Hees and E. Van der Grijp</i>	
<b>Modern Consolidation Methods for Catholic Church in Baroque Style from Arad Fortress, Romania</b> .....	1594
<i>A.C. Ion and M. Mosoarca</i>	
<b>Preventive Conservation for Built Heritage. Analysis of Different Models Around Europe</b> .....	1606
<i>D. Stabrauskaite</i>	
<b>Structural Typification of Heritage Buildings Using Modern Technologies for Digital Management and Visualization: Preliminary Applications in Southern Peru</b> .....	1618
<i>S. Huaranga, P. Pórcel, C. Yaya, B. Castañeda and R. Aguilar</i>	
<b>The Iscarsah Guidelines on the Analysis, Conservation and Structural Restoration of Architectural Heritage</b> .....	1629
<i>P. Roca</i>	
<b>Towards a Digital Architectural Heritage Knowledge Management Platform: Producing the HBIM Model of Bait al Naboodah in Sharjah, UAE</b> .....	1641
<i>R. Sabri, S.B. Abdalla and M. Rashid</i>	



<b>Unreinforced Masonry Structures' Seismic Improvement with F.R.C.M.: the Experience of the Vanvitellian Palazzo Murena of Perugia .....</b>	<b>1651</b>
<i>R. Liberotti, F. Cluni and V. Gusella</i>	
<b>Using Information Technologies for Bridge Management in Mexico's Royal Roads Built Between XVI and XVIII Century .....</b>	<b>1663</b>
<i>A. Torres-Acosta, J. Bustamanta-Altamirano and A. Esparza-Carrillo</i>	
<b>Numerical modeling and structural analysis</b>	
<b>3D FE Modeling of Multi-Span Stone Masonry Arch Bridges for the Assessment of Load Carrying Capacity: the Case of Justinian's Bridge....</b>	<b>1675</b>
<i>V. G. Mentese and O. C. Celik</i>	
<b>A Comparison Between Traditional and Modern Approaches for the Structural Modelling of Brick Masonry Barrel Vaults .....</b>	<b>1687</b>
<i>E. Coisson, D. Ferretti and F. Pagliari</i>	
<b>A Constitutive Model for Rubble Masonry Allowing for Spread Micro-Cracks and Localized Macro-Cracks.....</b>	<b>1699</b>
<i>M. Scamardo, A. Franchi and P.G. Crespi</i>	
<b>A Machine Learning Model for the Determination of Macro-Scale Masonry Properties based on a Virtual Laboratory at Micro-Scale.....</b>	<b>1712</b>
<i>P. Kalkbrenner, L. Pelà and R. Rossi</i>	
<b>A Macroscale Modelling Approach for Nonlinear Analysis of Masonry Arch Bridges.....</b>	<b>1724</b>
<i>B. Pantò, C. Chisari, L. Macorini and B.A. Izzuddin</i>	
<b>A Method for the Structural Analysis and Design of Arched Reinforced Masonry and/or Concrete Structures .....</b>	<b>1736</b>
<i>D. López López, P. Roca, A. Liew, T. Van Mele and P. Block</i>	
<b>A Novel Non-Linear Discrete Homogenization Approach for the Analysis of Double Curvature Masonry Structures .....</b>	<b>1746</b>
<i>J. Scacco, G. Milani and P.B. Lourenço</i>	
<b>A Simple and Effective Rigid Beam Model for Studying the Dynamic Behaviour of Freestanding Columns.....</b>	<b>1755</b>
<i>D. Baraldi, G. Milani and V. Sarhosis</i>	
<b>A Simplified Modelling Approach for the Practical Engineering Assessment of Unreinforced Masonry Structures Using Layered Shell Elements.....</b>	<b>1766</b>
<i>A. Hassanieh, M. Gharib and M. King</i>	
<b>Adaptative Pushover Analyses of a Heritage Structure: Application to a Multi-Tiered Pagoda Temple .....</b>	<b>1778</b>
<i>Y. Endo, Y. Kondo and G. Iwanami</i>	
<b>Advanced Tools for Fast Micro-Modelling of Masonry Structures.....</b>	<b>1789</b>
<i>M. Petracca, C. Marano, G. Camata, E. Spacone and L. Pelà</i>	

<b>Analysis and Assessment of Swedish Vaulted Masonry Structures Using Funicular Methods .....</b>	<b>1799</b>
<i>C. Thelin and F. Höst</i>	
<b>Applicability of FEM and Pushover Analysis to Simulate the Shaking-Table Response of a Masonry Building Model with Timber Diaphragms .....</b>	<b>1811</b>
<i>M.P. Ciocchi, R. Marques and P.B. Lourenço</i>	
<b>Assemblability Constraints in the Limit Analysis of 3D Masonry Interlocking Blocks.....</b>	<b>1822</b>
<i>E. Mousavian and C. Casapulla</i>	
<b>Assessment of Structural Damage and Evolution in Time in Historical Constructions Using Numerical Models: the Case of the Church of Saint Bassiano in Pizzighettone, Cremona .....</b>	<b>1834</b>
<i>G. Angjeliu, G. Cardani and D. Coronelli</i>	
<b>Calibration of a FEM Model with Complex Geometry: the Case Study of Santa Maria Maddalena Church in Ischia, Italy .....</b>	<b>1846</b>
<i>B. Di Napoli, M.P. Ciocchi, T. Celano, P.B. Lourenço and C. Casapulla</i>	
<b>Collaborative Use of DEM and FEM for Brick Joint Splitting in Strong Earthquake Ground Motion .....</b>	<b>1859</b>
<i>T. Maeda, H. Tanaka, M. Shirahashi and B. Higashizawa</i>	
<b>Combined Shear-Flexural Verification of in Plane Loaded Reinforced and Unreinforced Masonry Walls.....</b>	<b>1871</b>
<i>A. Benedetti, M. Tarozzi and L. Benedetti</i>	
<b>COMPAS Masonry: A Computational Framework for Practical Assessment of Unreinforced Masonry Structures .....</b>	<b>1882</b>
<i>A. Iannuzzo, A. Dell'Endice, R. Maia Avelino, G.T.C. Kao, T. Van Mele and P. Block</i>	
<b>Correlation Studies for the In-Plane Analysis of Masonry Walls Based on Macroscopic FE Models with Damage.....</b>	<b>1893</b>
<i>M. Nocera, L.C. Silva, D. Addessi and P.B. Lourenço</i>	
<b>Development of a Neural Network Embedding for Quantifying Crack Pattern Similarity in Masonry Structures.....</b>	<b>1905</b>
<i>A. Rózsás, A. Slobbe, W. Huizinga, M. Kruithof and G. Giardina</i>	
<b>Discrete Element Modelling of Single-Nave Churches Damaged after the 2009 Earthquake in l'Aquila, Italy .....</b>	<b>1917</b>
<i>F. Gobbin, R. Fugger and G. De Felice</i>	
<b>Equivalent Frame Method Combining Flexural and Shear Responses of Masonry Buildings .....</b>	<b>1928</b>
<i>C. Marano, M. Petracca, G. Camata and E. Spacone</i>	
<b>Estimation of the Clamping Force of Riveted Assemblies Through a Thermomechanical Modelling. Influence of Clearance and Thickness of the Connection .....</b>	<b>1940</b>
<i>P.-J. Tisserand, S. Sire and M. Ragueneau</i>	

<b>Excess Capacity in Historic American Reinforced Concrete Floors</b> .....	1947
<i>D. Friedman</i>	
<b>Experimental Data for the Calibration of a Non-Linear Numerical Model for Describing the Response of Masonry Constructions under Cyclic Loading</b> .....	1959
<i>A. Castellano, A. Fraddosio, M.D. Piccioni, E. Ricci and E. Sacco</i>	
<b>Fast Seismic Vulnerability Evaluation of Historical Masonry Aggregates through Local Analyses: an Adaptive NURBS-based Limit Analysis Approach</b> .....	1971
<i>N. Grillanda, M. Valente, G. Milani, F. Formigoni, A. Chiozzi and A. Tralli</i>	
<b>General Thrust Surface of the Masonry Domes</b> .....	1984
<i>I. Sajtós, O. Gáspár and A. Sipos</i>	
<b>Geometric and Structural Information for the Analysis of Historical Domes: The Case of the SS. Trinità Church in Torino</b> .....	1996
<i>G. De Lucia and R. Ceravolo</i>	
<b>In-plane Behaviour of an Iron-Framed Masonry Façade: Comparison between Different Modelling Strategies</b> .....	2007
<i>T. Celano, L. Argiento, B. Pantò, F. Ceroni, C. Casapulla, I. Calì and P.B. Lourenço</i>	
<b>Influence of Settlements and Geometrical Imperfections on the Internal Stress State of Masonry Structures</b> .....	2019
<i>A. Dell'Endice, A. Iannuzzo, T. Van Mele and P. Block</i>	
<b>Influence of Temperature on the Structural Behaviour of Masonry Buildings</b> .....	2031
<i>M. Girardi, C. Padovani and D. Pellegrini</i>	
<b>Influence of the Spatial Variability of Joints Characteristics on the Elastic Properties of Masonry</b> .....	2043
<i>M.L. De Bellis, V. Sepe and M. Vasta</i>	
<b>Inspection, Diagnosis and Modelling of Azurara Church in the North of Portugal</b> .....	2054
<i>E.A. Chaves Moreno, E.T. Key, A. Uplekar, O. Pino, G. Vasconcelos, J. Ortega and E. Poletti</i>	
<b>Investigation of the Response of a Masonry Arch Railway Bridge using Membrane Equilibrium Analysis</b> .....	2066
<i>C. Olivieri, S.H. Cocking, M. Angelillo and M.J. DeJong</i>	
<b>Investigation on the Seismic Response of a Large Monumental Complex</b> .....	2076
<i>S. Caprili, I. Puncello and P. Roca</i>	
<b>Lower-Bound Limit Analysis of Masonry Arches with Multiple Failure Sections</b> .....	2088
<i>N.A. Nodargi and P. Bisegna</i>	

<b>Minimum Thickness and Collapse Conditions of the Irregular Masonry Arch Subject to its Own Weight .....</b>	<b>2100</b>
<i>N. Cavalagli, V. Gusella and R. Liberotti</i>	
<b>Neomudejar Architecture and Analysis of Local Stresses of Masonry Structures: The Escuelas Aguirre Case Study .....</b>	<b>2112</b>
<i>J. García-Muñoz, D. Mencías-Carrizosa and F. Magdalena-Layos</i>	
<b>New Strategies to Assess the Safety of Unreinforced Masonry Structures Using Thrust Network Analysis .....</b>	<b>2124</b>
<i>R. Maia Avelino, A. Iannuzzo, T. Van Mele and P. Block</i>	
<b>Nonlinear Behaviour of Two-Whyte Stone Walls .....</b>	<b>2136</b>
<i>B. Dinç-Şengönül, Y.M. Hothot, B. Doran, N. Yüzer, S. Ulukaya and D. Oktay</i>	
<b>Novel Constitutive Modelling Approach for Shape Memory Alloys Vibration Control Devices .....</b>	<b>2146</b>
<i>K. Wasilewski and A. Zbiciak</i>	
<b>Numerical Analysis of Historical Reinforced Concrete Shell.....</b>	<b>2156</b>
<i>P. Kněž, P. Tej and J. Kolísko</i>	
<b>Numerical Development of a Strengthened Wall-to-Diaphragm Seismic Connection: Calibration and Application on a Building Prototype .....</b>	<b>2168</b>
<i>F. Solarino, D.V. Oliveira and L. Giresini</i>	
<b>Numerical Modelling of the Seismic Performance of Romanian Traditional Timber-Framed Buildings.....</b>	<b>2181</b>
<i>F. Parisse, E. Poletti, A. Dutu and H. Rodrigues</i>	
<b>Numerical Simulation of Traditional Timber-Masonry Buildings Subjected to Lateral Loads .....</b>	<b>2194</b>
<i>B. Jimenez and L. Pelà</i>	
<b>Numerical Study of Out-of-Plane Behaviour of Timber Retrofitted Masonry Prisms .....</b>	<b>2206</b>
<i>J. A. Dauda, L.C. Silva, P.B. Lourenço and O. Iuorio</i>	
<b>Numerical Study of Pier-Wall Connections in Typical Dutch URM Buildings .....</b>	<b>2217</b>
<i>D. Fusco, F. Messali, J.G. Rots, D. Addessi and S. Pampanin</i>	
<b>Safe Estimation of Minimum Thickness of Circular Masonry Arches Considering Stereotomy and Different Rotational Failure Modes.....</b>	<b>2229</b>
<i>O. Gáspár, I. Sajtos and A. A. Sipos</i>	
<b>Safety Assessment of Historic Masonry Structures by Limit Analysis and Deterministic Partial Safety Factors .....</b>	<b>2240</b>
<i>F. Magdalena, A. Aznar, J. Antuna and J.I. Hernando</i>	
<b>Seismic Assessment of Masonry Towers: The Case of Castellum Aquae System in Pompeii .....</b>	<b>2251</b>
<i>M. Salvalaggio, V. Sabbatini, F. Lorenzoni, M.R. Valluzzi and H. Wenliuhan</i>	

<b>Seismic Behaviour Analysis of Diaphragm Arches: Case Studies from Catalan Gothic Churches</b> .....	2262
<i>D. Cacace, V. Corlito, M. Zizi, G. De Matteis and P. Roca</i>	
<b>Sensitivity Analysis in the Rehabilitation of Historic Timber Structures on the Examples of Greek Catholic Churches in Polish Subcarpathia</b> .....	2274
<i>K. Szepietowska and I. Lubowiecka</i>	
<b>Simplex Algorithm for 3D Limit Analysis of Roman Groin Vaults</b> .....	2282
<i>C. Baggio and S. Santini</i>	
<b>Simulation of the Out-of-Plane Behaviour of URM Walls by Means of Discrete Macro-Element Method</b> .....	2294
<i>C. Chácaras, B. Pantò, F. Cannizzaro, D. Rapicavoli, I. Calìo and P.B. Lourenço</i>	
<b>Stochastic Micro-Modelling of Historic Masonry</b> .....	2306
<i>J. Adamek and P. Kabele</i>	
<b>Structural Analysis of Historical Constructions by Graphic Methodologies based on Funicular and Projective Geometry</b> .....	2318
<i>J. Suárez, T. Boothby and J. A. González</i>	
<b>Structural Assessment of the Seismic Behavior of the Dome of the Taj Mahal</b> .....	2330
<i>S. Rihal, B. Koh, A. Mehrotra and J. Edmisten</i>	
<b>Structural Evaluation of Typical Historical Masonry Vaults of Cagliari: Sensitivity to Bricks Arrangements</b> .....	2342
<i>A. Cazzani, N. Grillanda, G. Milani, V. Pintus and E. Reccia</i>	
<b>Structural Modelling and Numerical Analysis of the Palace of Sports of Mexico City</b> .....	2354
<i>H. Badillo-Almaraz, A. Orduña, S.G. De La Rosa, G.A. González and G.M. Roeder</i>	
<b>Structural Performance Evaluation of Column-Nuki Connection in Traditional Japanese Wooden Buildings</b> .....	2366
<i>S. Murai and M. Miyamoto</i>	
<b>Study on Rigid Homogenization Method and Model of Masonry under Different Bricklaying Methods Based on Regular Tessellation Theory</b> .....	2378
<i>Y. Chunxia, C. Shu, L. Chenyi and Z. Nan</i>	
<b>Study on Seismic Performance Evaluation of Modern Wooden School Buildings in Japan</b> .....	2390
<i>M. Miyamoto</i>	
<b>The Influence of the Passive Earth Pressure and other Factors on the Stability of the Underground Masonry Vaults of the Paris Metro</b> .....	2400
<i>O. Moreno Regan, E. Bourgeois, J. F. Douroux and A. Desbordes</i>	

<b>The Safety of Masonry Arches Subject to Vertical and Horizontal Forces. A Numerical Method Based on the Thrust Line Closest to the Geometrical Axis .....</b>	<b>2413</b>
<i>S. Galassi and G. Tempesta</i>	
<b>The Unbuilt Musmeci Parabolic Cross Vault Reinvented as a Dry-Masonry Structure .....</b>	<b>2425</b>
<i>C. Intrigila, N.A. Nodargi and P. Bisegna</i>	
<b>Repair and strengthening strategies and techniques</b>	
<b>A New Method for Assessing Compatibility of Consolidation Procedures with Conservation Principles: Intervention Quality Index (IQI).....</b>	<b>2439</b>
<i>N.C. Palazzi, G. Misseri, C. Sandoval, U. Tonietti, J.C. De La Llera and L. Rovero</i>	
<b>Characterization of FRCM- and FRP-Masonry Bond Behavior .....</b>	<b>2451</b>
<i>C. Gentilini, C. Carloni, R. Santoro and E. Franzoni</i>	
<b>Cost-Effective Implementation of Nitinol to Improve the Seismic Performance of an Unreinforced Masonry Building .....</b>	<b>2458</b>
<i>T.F. Paret and J.M. Rautenberg</i>	
<b>Cyclic Tests on Masonry Vaults Strengthened Through Composite Reinforced Mortar.....</b>	<b>2470</b>
<i>N. Gattesco and I. Boem</i>	
<b>Evaluation of Performance of Matured Hydraulic Grouts: Strength Development, Microstructural Characteristics and Durability Issues.....</b>	<b>2480</b>
<i>A. Miltiadou-Fezans, M Delagrammatikas, A. Kalagri and P. Vassiliou</i>	
<b>Experimental and Numerical Analyses on Sandstone Elements Obtained by 3D Printing .....</b>	<b>2492</b>
<i>C. Scuro, S. Tiberti, S. Porzio, R.S. Olivito and G. Milani</i>	
<b>Experimental and Numerical Analysis of a FRCM Reinforced Parabolic Tuff Barrel Vault.....</b>	<b>2504</b>
<i>A. Castellano, J. Scacco, A. Fraddosio, G. Milani and M.D. Piccioni</i>	
<b>Experimental Assessment of Cyclic Shear Response of Brick Masonry Walls Retrofitted with TRM .....</b>	<b>2516</b>
<i>L. Garcia-Ramonda, L. Pelà, P. Roca and G. Camata</i>	
<b>Experimental Investigation of the Bond between Glass Textile Reinforced Mortar (GTRM) and Masonry Substrate: the Effect of Textile Impregnation .....</b>	<b>2528</b>
<i>P.D. Askouni and C.G. Papanicolaou</i>	
<b>Experimental Study on the Shear Behavior of FRCM Strengthened Masonry Panels .....</b>	<b>2540</b>
<i>F. Ferretti, A. Incerti and C. Mazzotti</i>	
<b>Experimental Tests on FRCM and FE Modelling for the Heritage Structure's Reuse .....</b>	<b>2552</b>
<i>R. Liberotti, N. Cavalagli and V. Gusella</i>	

<b>Fibre Reinforced Geopolymers as Inorganic Strengthening Composites for Masonry Structures .....</b>	<b>2564</b>
<i>E. Garbin, M. Panizza, S. Tamburini, M. Natali and G. Artioli</i>	
<b>Flexural Resistance of Masonry Wall Retrofitted with Timber Panels under Out-Of-Plane Loading .....</b>	<b>2576</b>
<i>O. Iuorio, J. A. Dauda and P.B. Lourenço</i>	
<b>From the Cure of the Simple Structural Analysis to the Control of the Final Technological Quality - The Conservation of "Santa Maria Degli Angeli Orphanage" in Castelgrande (Potenza, Italy) .....</b>	<b>2586</b>
<i>F.P.R. Marino, G. Auletta, F. Baldantoni, F.C. Ponzo and F. Lembo</i>	
<b>Historical Timber Structures in Adana-Tepebag Settlement and Consolidation Approach with Modern Timber Prefabricated Systems .....</b>	<b>2600</b>
<i>K. Apak</i>	
<b>Numerical Modelling of Masonry Arches Strengthened with SFRM .....</b>	<b>2612</b>
<i>S. Caddemi, I. Calì, F. Cannizzaro, D. Rapicavoli, N. Simoncello, P. Zampieri, J. Gonzalez-Libreros and C. Pellegrino</i>	
<b>Out-of-Plane Behaviour of Tuff and Brick Masonry Walls Strengthened with FRCM Composite Materials .....</b>	<b>2620</b>
<i>A. Bellini, A. Incerti, A. Nanni and C. Mazzotti</i>	
<b>Overview of the Mechanical Properties of Steel Reinforced Grout Systems for Structural Retrofitting .....</b>	<b>2632</b>
<i>F. Roscini, S. De Santis, P. Meriggi and G. De Felice</i>	
<b>Performance Assessment of Basalt FRCM for the Confinement of Clay Brick Masonry Cylinders .....</b>	<b>2642</b>
<i>J. D'Anna, G. Amato, J.F. Chen, G. Minafò and L. La Mendola</i>	
<b>Performance of Unreinforced Masonry Strengthened with Bed Joint Reinforced Repointing .....</b>	<b>2652</b>
<i>L. Licciardello, J.G. Rots and R. Esposito</i>	
<b>Reinforcement and Consolidation of Masonry Structures. Successful Cases Implemented: From the Study to the Execution Phase .....</b>	<b>2664</b>
<i>J. Dobon and M.A. Soria</i>	
<b>Repair Connection with Wooden Wedged Dowels: Preliminary Experimental Laboratory Tests and FEM Model for the Description of the Mechanical Behavior .....</b>	<b>2673</b>
<i>E. Perria, S. Siegert, X. Li and M. Sieder</i>	
<b>Stabilization and Consolidation of Historical Multi-Leaf Masonry .....</b>	<b>2687</b>
<i>J. Witzany, J. Brožovský, T. Čejka, J. Kubát and R. Zigler</i>	
<b>Static Test on Full Scale Rammed Earth Building with Mesh-Wrap Retrofitting Strategy .....</b>	<b>2696</b>
<i>K.C. Shrestha, T. Aoki, M. Miyamoto, N. Takahashi, J. Zhang, P. Wangmo, N. Yuasa, S. Shin, P. Pema and K. Tenzin</i>	



<b>Structural Restoration and Re-Use of the Historic Coal Mine Tower .....</b>	<b>2708</b>
<i>D. Andic, M. Horvat and J. Pojatina</i>	
<b>The CLT Panels in Structural Restoration: Characteristics and Technical Regulations .....</b>	<b>2718</b>
<i>G. Frunzio, L. Di Gennaro , L. Massaro and F. D'Angelo</i>	
<b>Treatment for Rising Damp and Natural Hydrodynamic Equilibrium in Masonry Walls .....</b>	<b>2729</b>
<i>J. Dobon and M.A. Soria</i>	
<b>TRM-Strengthened Timbrel Cross Vaults Subjected to Vertical Settlements .....</b>	<b>2737</b>
<i>P.A. Calderón, E. Bertolesi, M. Buitrago, J.J. Moragues and J.M. Adam</i>	
<b>Resilience of historic areas to climate change and hazard events</b>	
<b>A Framework for the Detailed Flood Vulnerability Modelling of Built Cultural Heritage .....</b>	<b>2746</b>
<i>R. Figueiredo, X. Romão and E. Paupério</i>	
<b>Assessing the Impact of Seismic Risk Mitigation at the Urban Scale on Community Resilience and Housing Recovery .....</b>	<b>2757</b>
<i>A. Basaglia, A. Aprile, E. Spacone and L. Pelà</i>	
<b>Fire Prevention in Ottoman and Habsburg Building Codes for Bosnia and their Application in Travnik .....</b>	<b>2768</b>
<i>C. Jaeger-Klein, A. Bajramovic and L. Stampfer</i>	
<b>Landslide Hazard Affecting Historical Buildings: Santa Scolastica Monastery in Subiaco .....</b>	<b>2780</b>
<i>M. Sangirardi, A. Amorosi, M. Malena and G. De Felice</i>	
<b>Post-Earthquake Reconstruction of the Historic City Center of l'Aquila: A Proposal Concerning the Rubble Transportation Problem .....</b>	<b>2790</b>
<i>S. Di Marco and M.A. Bragadin</i>	
<b>Post-Quake Small Italian Historical Centres: Urban Resilience between Rhetorics and Reality. The Case Study of Nocera Umbra after the 1997 Umbria-Marche Earthquakes.....</b>	<b>2802</b>
<i>E. Cianci, C. Fontana, G. Occhipinti and G. Romagnoli</i>	
<b>Preliminary Approach for a Prototype of Sustainable Antiseismic Dwelling in Nepal Based on the Historic Vernacular Tradition.....</b>	<b>2814</b>
<i>F. Vegas López-Manzanares, C. Mileto, W. Pisarra and F. Trizio</i>	
<b>Resilience and Vulnerability of Historical Centres: the Case of the District of Camerino in the Marche Region .....</b>	<b>2824</b>
<i>E. Petrucci, L. Barchetta and D. Lapucci</i>	
<b>Resilience of Historic Residential Areas Subjected to Natural Disasters.....</b>	<b>2836</b>
<i>M. Drdác'ky, R. Cacciotti and T. Drdác'ky</i>	

## Seismic analysis and retrofit

- An Integrated Modeling Approach that Combines Elastic Amplification and Rocking Analysis for Seismic Assessment of a Masonry Tower** ..... 2846  
*A. Mehrotra, A. Liew, P. Block and M.J. DeJong*
- Assessment of the Seismic Retrofitting of a Historical Masonry Mosque by means of Nonlinear Dynamic Analysis**..... 2858  
*A. Aşıkoğlu, L.C. Silva, O. Avşar and P.B. Lourenço*
- Comparison of Two Different Approaches for the Seismic Evaluation of the Bonet Building of the National Palace of Sintra, Portugal**..... 2870  
*M. Ponte, M. Malcata and R. Bento*
- Damages Patterns in Historical Temples of Puebla, Morelos and Oaxaca after September 2017 Mexico Earthquakes**..... 2882  
*M. Chávez, F. Peña, N. García and D. Durán*
- Design of Shake Table Tests of Multi-Leaf Masonry Walls Before and After Retrofitting** ..... 2894  
*S. De Santis, O. Al Shawa, G. De Canio, S. Forliti, D. Liberatore, P. Meriggi, I. Roselli, L. Sorrentino and G. De Felice*
- Effect of Historic Timber Roof Structures on the Structural Behaviour of Masonry Buildings during Seismic Events**..... 2902  
*A.I. Keller and M. Mosoarca*
- Evolution of Lateral Design in the United States** ..... 2914  
*N.A. Hicks and E.P. Meade*
- Extrados Strengthening of Single-Leaf Vaults Against Seismic Actions** ..... 2926  
*S. Cominelli, C. Passoni, A. Marini, A. Belleri and E. Giuriani*
- Inadequate Cases of Intervention in Architectural Heritage Buildings in Mexico after the September 2017 Earthquakes**..... 2938  
*F. Peña and M. Chávez*
- Macroelement Numerical Simulation of the Seismic Response of a Timber-Retrofitted Masonry Pier**..... 2946  
*M. Miglietta, N. Damiani, S. Bracchi, G. Guerrini, F. Graziotti and A. Penna*
- Mechanical Characterization of Energy Dissipation Devices in Retrofit Solution of Reinforced Concrete Frames Coupled with Solid Wood Panels** ..... 2958  
*C. Tardo, F. Boggian, M. Hatletveit, E. Marino, G. Margani and R. Tomasi*
- Numerical Investigation of the Retrofitting Interventions of the San Benedetto Church Complex in Ferrara (Italy) from a Seismic Vulnerability Perspective** ..... 2970  
*R. Shehu*

<b>Numerical Investigations for Assessing the Seismic Performance of Multi-Tiered Nepalese Temples</b> .....	2981
<i>M. Pejatovic, V. Sarhosis and G. Milani</i>	
<b>Numerical Simulation on Seismic Performance of Retrofitted Masonry Wall in Historical Buildings Damaged in Earthquake</b> .....	2993
<i>B. Wu, J. Dai and W. Bai</i>	
<b>Repair and Retrofit of a Roman Bridge in Turkey</b> .....	3005
<i>H. Sesigur and M. Alaboz</i>	
<b>Seismic Assessment and Strengthening Interventions of Atop Single-Block Rocking Elements in Monumental Buildings: the Case Study of the San Felice sul Panaro Fortress</b> .....	3016
<i>S. Degli Abbatì, S. Cattari, S. Lagomarsino and D. Ottonelli</i>	
<b>Seismic Assessment of Dutch URM Buildings According to NPR9998:2018 Code with an Equivalent-Frame Approach</b> .....	3028
<i>S. Bracchi, F. Graziotti, F. Messali and A. Penna</i>	
<b>Seismic Assessment of Heritage Buildings in Bulgaria</b> .....	3040
<i>M.D. Traykova and A.V. Traykov</i>	
<b>Seismic Behaviour of La Merced Temple in Morelia, Mexico</b> .....	3052
<i>L. Mejia, G. Martinez, B. Olmos and J.M. Jara</i>	
<b>Seismic Damage Mechanisms for Churches and Damage Sequence: Considerations from a Case Study</b> .....	3065
<i>M.A. Parisi, Y. Anzilotti, G.I. Fuentes Rivera, G. Sferrazza Papa and S. Barbo</i>	
<b>Seismic Fragility Analyses of the Cabinet Stored Artefacts with and without Damping Method</b> .....	3077
<i>W. Bai, J. Dai and Y. Yang</i>	
<b>Seismic Performance Evaluation of Box-Shaped Wall Structures Built with Thick Earthen Walls</b> .....	3087
<i>H. Yokouchi and Y. Ohashi</i>	
<b>Seismic Performance of Masonry Cross Vaults through Shaking Table Testing on a Scaled Model</b> .....	3098
<i>N. Bianchini, N. Mendes, P. Candeias, M. Rossi, C. Calderini, P.B. Lourenço and A. Campos Costa</i>	
<b>Seismic Response of Hagia Sophia Church in Thessaloniki Including Soil-Foundation-Structure Interaction</b> .....	3109
<i>A. Chounta, C. Malakoudi, C. Petridis and D. Pitilakis</i>	
<b>Seismic Retrofitting of Historical Masonry Heritage Structures: A Case Study of an Adobe Masonry Building in Lima, Peru</b> .....	3121
<i>T. Martins, J. García, A. Ferrández, N. Tarque and J. Fernández</i>	
<b>Seismic Stability Analysis of Inca Earthen Walls</b> .....	3133
<i>A. Torres, M. Blondet and S. Santa Cruz</i>	

<b>Simplified Method for the Lateral Strengthening of Earthen Churches .....</b>	<b>3145</b>
<i>R. Enciso, M. Noel and R. Aguilar</i>	
<b>Structural Analysis of a Restored Byzantine Monastery: Effectiveness of the Interventions .....</b>	<b>3156</b>
<i>P. Condoleo and A. Taliercio</i>	
<b>Structural Assessment of the 13th Century Great Mosque and Hospital of Divrigi: A World Heritage Listed Structure.....</b>	<b>3169</b>
<i>C. Demir, O.F. Halici, A.N. Sanver, M. Comert, F. Kuran, N. Berlucchi, A. Hurata and A. Ilki</i>	
<b>The Floor Stiffness Effect on Vulnerability Assessments and Intervention Designs of Historic Buildings: the Case Study of the "Procuratie Vecchie" in Venice, Italy .....</b>	<b>3181</b>
<i>I. Rocca, L. Berto, S. Bellin, B.F. Dongmo, A. Saetta and R. Vitaliani</i>	
<b>Understanding Traditional Anti-Seismic Strategies Beyond Their Disappearance and Distortions: Yazd Qajar Architecture Case Study .....</b>	<b>3193</b>
<i>E. Cr��t��, S. Yadav, N. Farahza, L. Arleo, M. Hajmirbaba, Y. Sieffert and P. Garnier</i>	
<b>Structural health monitoring</b>	
<b>Assessment and Monitoring of Historical Timber Construction: Available Tools to Support Decision-Making Processes .....</b>	<b>3206</b>
<i>M. Riggio</i>	
<b>Continuous Structural Monitoring of Adobe Buildings: Summary of a Three Years Experience in Peru.....</b>	<b>3218</b>
<i>G. Zonno, R. Aguilar, R. Boroschek and P.B. Louren��o</i>	
<b>Data Analysis Using ARX Models Applied to Static Structural Health Monitoring of the Monastery of Sant Cugat.....</b>	<b>3228</b>
<i>N. Makoond, L. Pel��, C. Molins and P. Roca</i>	
<b>Development of a Wireless Acceleration Measurement System.....</b>	<b>3240</b>
<i>T. Yamasaki, K. Ota, M. Miyamoto, Y. Amano, M. Okada and T. Kido</i>	
<b>Dynamic Identification of the So-Called Temple of Minerva Medica: Comparison of Different Instrumentations and Methods for Mutual Validation of the Results .....</b>	<b>3252</b>
<i>C. Baggio, V. Sabbatini, S. Santini, C. Sebastiani, V. Fioriti, I. Roselli, A. Colucci, F. Saitta and S. Forliti</i>	
<b>Health Monitoring Tests of Heritage Structures: Application of MEMS Accelerometers to Two Multi Tier Pagodas .....</b>	<b>3264</b>
<i>Y. Endo and Y. Niitsu</i>	
<b>Long-Term Structural Health Monitoring of the Fortezza Fortress: Application of Damage Detection Techniques on Existing Cracks .....</b>	<b>3272</b>
<i>M. Drygiannakis, G. Vlachakis and A. Tzigounaki</i>	

<b>Monitoring of Indoor Environmental Conditions of the Kvernes (Norway) Stave Church</b> .....	3284
<i>C. Bertolin, L. De Ferri and T.M. Olstad</i>	
<b>Multi-Modal Analysis of Vibration and Meteorological Data for Structures on the World Heritage Site " Battleship Island"</b> .....	3296
<i>N. Kurata, K. Takai, A. Tomioka, T. Daigo, S. Saruwatari and T. Hamamoto</i>	
<b>One-year Static Monitoring of the Milan Cathedral</b> .....	3305
<i>A. Saisi, A. Ruccolo and C. Gentile</i>	
<b>Proposal for a Time-Dependent Dynamic Identification Algorithm for Structural Health Monitoring</b> .....	3317
<i>M.F. Hormazábal, M.G. Masciotta and D.V. Oliveira</i>	
<b>Quantification of the Structural Response of Historical Constructions: Investigation of the Strain Variation at the Acropolis Circuit Wall</b> .....	3329
<i>E. Kapogianni, P. Psarropoulos and M. Sakellariou</i>	
<b>Real-Time Structural Monitoring of Bibi-Khanum in Samarkand (Uzbekistan) Combined with Subsequent Laser Scans</b> .....	3339
<i>S.M. Takhirov, I. Aripov and D. Matrasulov</i>	
<b>Structural Health Monitoring of a Historic Church: Theory and Practice of Diagnostic Approaches Used to Control Risks and Costs</b> .....	3349
<i>T. Morrison and S. Burrill</i>	
<b>Structural Health Monitoring of the Juma Mosque in Itchan Kala in Khiva (Uzbekistan): Laser Scanning Combined with Numerical Modelling</b> .....	3361
<i>S. Takhirov and B. Rakhmanov</i>	
<b>Structural Monitoring in the "Santa Maria de la Asunción" Cathedral of Chilpancingo, Guerrero, Mexico; through Topogeodesic-Photogrammetric Surveying and Ambient Vibration. A Methodological Proposal</b> .....	3371
<i>S. Sánchez Tizapa, R. Aurelio Felicito, R. Vázquez Jiménez, J. L. Carranza Bello and R. Arroyo Matus</i>	
<b>The Influence of External Climate on Church Internal Microclimate</b> .....	3381
<i>L. Balik, L. Kudrnacova and K. Nedvedova</i>	
<b>Vulnerability and risk analysis</b>	
<b>A Comparison Between Empirical Procedures for the Definition of Vulnerability Classes of Masonry Buildings: Application to Five Historical Centres Struck by 2016 Central Italy Earthquake</b> .....	3390
<i>Y. Saretta, L. Sbrogiò and M.R. Valluzzi</i>	
<b>A QGIS Plugin for the Seismic Vulnerability Assessment of Urban Centers: Application to the City of Popoli in Abruzzo (Italy)</b> .....	3402
<i>A. Gonzalez, A. Basaglia, E. Spacone and G. Brando</i>	

<b>Assessment of Seismic Fragility of Historical Buildings at the Urban Scale by Typological-Mechanical Approaches: the Case Study of Foggia</b> .....	3414
<i>V. Leggieri, S. Ruggieri and G. Uva</i>	
<b>Criteria for the Vulnerability Analysis of Structural Aggregates in Historical Centers</b> .....	3426
<i>S. Tonna, M. Boriani, M.C. Giambruno and C. Chesi</i>	
<b>Development of a Fire Damage Index for Immovable Cultural Heritage</b> .....	3438
<i>L.G. Salazar, E. Paupério and X. Romão</i>	
<b>Evaluation of Invasive Retrofitting Interventions on an Unreinforced Masonry Heritage Building</b> .....	3450
<i>A. Scupin, R. Vacareanu and F. Pavel</i>	
<b>Kinematic Approach for Seismic Vulnerability Assessment of Masonry Churches</b> .....	3462
<i>V. Corlito, G. De Matteis and P. Roca</i>	
<b>Managing Natural Disasters in Historic Areas: a Novel Holistic Seismic Risk Assessment Method Applied to a Relevant Case Study</b> .....	3474
<i>E. Quagliarini, G. Bernardini and M. Lucesoli</i>	
<b>Risk Assessment Methodologies to Safeguard Historic Urban Areas from the Effects of Climate Change</b> .....	3486
<i>L. Quesada-Ganuza, L. Garmendia, E. Rojí, I. Álvarez, E. Briz and M. Olazabal</i>	
<b>Risk Management and Built Heritage: Towards a Systematic Approach</b> .....	3498
<i>A. Konsta and S. Della Torre</i>	
<b>Seismic Damage Scenarios Induced by Site Effects of Masonry Clustered Buildings: a South Italy Case Study</b> .....	3510
<i>A. Formisano and N. Chieffo</i>	
<b>Seismic Vulnerability Assessment Method for Vernacular Architecture Considering Uncertainty</b> .....	3522
<i>J. Ortega, S. Saloustros and P. Roca</i>	
<b>Seismic Vulnerability Assessment Methodology for Historical Buildings with Cultural Value</b> .....	3534
<i>E. Onescu, I. Onescu and M. Mosoarca</i>	
<b>Seismic Vulnerability Assessment of a Historic Brick Masonry Building by Fragility Functions</b> .....	3546
<i>K. Demirlioglu and S. Soyoz</i>	
<b>Seismic Vulnerability Assessment of Representative Building Typologies from Barcelona's Eixample District</b> .....	3557
<i>S. Dimovska, S. Saloustros, L. Pelà and P. Roca</i>	

<b>Seismic Vulnerability Assessment of Romanian Historical Building under Near-Source Earthquake .....</b>	<b>3569</b>
<i>N. Chieffo, M. Mosoarca, A. Formisano and P.B. Lourenço</i>	
<b>Seismic Vulnerability of Heritage Churches in Québec: the Néo-Roman Typology .....</b>	<b>3581</b>
<i>G. Sferrazza Papa, M-J. Nollet and M.A. Parisi</i>	
<b>Simplified Seismic Vulnerability Assessment of Medieval Masonry Churches .....</b>	<b>3593</b>
<i>V. Corlito, M. Zizi and G. De Matteis</i>	
<b>The Assessment and Reduction of Seismic Risk: Towards a System of Knowledge for Archaeological Pre-Existences .....</b>	<b>3605</b>
<i>E. Montenegro</i>	
<b>The Damage Survey of Cultural Built heritage Between Simplified Procedures and Needs for Implementation: the Case Study of Emilia-Romagna Cemeteries .....</b>	<b>3617</b>
<i>V. Vona and M. Zuppioli</i>	
<b>Typological Classification and Observed Damage Patterns of Masonry Churches After the 2016 Central Italy Earthquake .....</b>	<b>3629</b>
<i>G. Cianchino, C. De Matteis and G. Brando</i>	
<b>Vulnerability Assessment of Dwellings in the Historic Center of Cusco (Peru) .....</b>	<b>3640</b>
<i>G. Brando, G. Cocco, C. Mazzanti, M. Peruch, E. Spacone, C. Alfaro, K. Sovero and N. Tarque</i>	
<b>Vulnerability Assessment of Italian Unreinforced Masonry Churches Using Multi-Linear Regression Models .....</b>	<b>3649</b>
<i>A. Marotta, D. Liberatore and L. Sorrentino</i>	

## FIBRE REINFORCED GEOPOLYMERS AS INORGANIC STRENGTHENING COMPOSITES FOR MASONRY STRUCTURES

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**Abstract.** *The study presents an assessment of externally bonded Fibre-Reinforced GeoPolymers (FRGPs) as strengthening material for masonry structures. Thanks to their tailored chemical and mechanical characteristics, geopolymer matrices can fulfil the restoration criteria for Built Heritage (BH) with the benefit of heat-resistant performances better than those of organic and inorganic matrices used in Externally Bonded Fibre-Reinforced Polymers (EB-FRP) and Fabric-Reinforced Cementitious Matrix (FRCM) materials, respectively. This work is built on the outcomes of a previous investigation that proved the suitability of the developed geopolymer matrix for applications on clay bricks, revealing a good adhesion to masonry substrates and to embedded reinforcements. The behaviour of three FRGPs, including either a bi-directional basalt mesh, a bi-directional carbon mesh or a unidirectional Ultra High Strength Steel (UHSS) fabric, was explored by means of local tests on masonry sub-assemblages made of soft-mud clay bricks and hydraulic lime mortar. In overall, 9 single-lap shear tests on single bricks with a bonded length of 200 mm and 9 three-point bending tests on 2-brick slices, connected by a mortar joint and reinforced at the bottom face, were carried out. Lastly, the behaviour in alkaline environments of each reinforcement was investigated through tensile tests on coupons immersed for 28 days in alkaline solutions simulating the conditions of the geopolimetric matrices. Results confirmed the interesting potential of FRGPs for strengthening masonry elements, highlighting a good performance of steel and carbon reinforcements. On the other hand, precautions should be taken with basalt meshes that, as expected, were more sensitive to alkaline environments.*

### 1 INTRODUCTION

Existing masonry buildings and Built Heritage (BH) require a permanent maintenance



process to withstand the effects of hazardous natural events and mitigate their effects. This can be accomplished by devoted activities of restoration and structural repair adopting traditional and innovative materials and intervention techniques [1–3]. In the last three decades, the use of Externally Bonded Fibre Reinforced Polymers (EB-FRPs) has grown to be one of the reference interventions for existing buildings and for BH [4–6]. The main advantages of EB-FRPs that fostered their widespread application on existing structures, including also those belonging to the BH, are for instance: their ease and flexibility of application, their fast curing and the related ability in carrying tensile stresses in few hours or days, low weight in comparison to many traditional materials (e.g. steel rods/plates), the high tensile strength and stiffness-to-weight ratio, enhanced fatigue and endurance in aggressive environments [3,5,7]. Nevertheless, FRPs have some compatibility and removability issues with existing and BH masonry structures, mainly due to the adoption of organic matrices [3,8]. In the last decade, research has investigated the replacement of organic (e.g. epoxy) with inorganic matrices made of cement or lime-based mortars [9–13]. The combination of fibres, usually in the form of meshes, with inorganic matrices is currently often labelled with the acronym of Fibre Reinforced Cementitious Matrix (FRCM) [14,15], acronym that also covers for cement-free matrices, while in several former publications the acronym Textile Reinforced Mortars (TRM) was used [3,11,13]. Advantages of FRCMs over FRPs include: better compatibility with masonry substrates and traditional craftsmanship, reversibility, better behaviour under high temperatures and lack of toxic vapours in case of fire, resistance to Ultra-Violet (UV) radiation, water-vapour permeability, applicability over moist substrates, greater deformability and potential lower cost [3,6,8,12,13]. Moreover, inorganic matrices appear particularly suitable for applications to masonry structures, where the bond strength of epoxy matrices can hardly be entirely used due to the inherent mechanical characteristics of the substrate, and for a better compliance with restoration criteria, especially when cement-free matrices are adopted [3,6,12,13]. Nevertheless, traditional lime-based inorganic mortars compatible with BH often show low adhesion to masonry substrates and between the FRCM layers [3,6,13]. To overcome this issue, geopolymers were studied as possible efficient and compatible inorganic matrices for existing masonry substrates and BH [16]. Indeed, geopolymer can meet the dedicated restoration requirements of BH, thanks to their typical chemical composition and porosity which are similar to that of clay bricks [16], while delivering physico-mechanical performances exceeding those of the best inorganic matrices used in FRCMs [16,17].

Geopolymers are relatively recent and emerging inorganic cement-free binders that present a combination of the best characteristics of ceramic and cement-based materials [16,17]. Moreover, they have a clear advantage over EB-FRPs and FRCMs as non-inflammable and heat-resistant matrices for inorganic composites designed to reach temperatures of 1000°C [16,18]. Geopolymers are inorganic quasi-fragile materials produced from aluminosilicates typically activated with alkali hydroxide and/or alkali silicate solutions [16,17]. Several aluminosilicate or calcium-aluminosilicate raw materials can be used, such as dehydroxylated aluminosilicate clay mineral (e.g. metakaolin) and industrial by-products resulting from high temperature processes such as fly ash or ground blast furnace slag, among others [17]. They are also materials suitable for a greener economy, since they can be derived from by-products or from the recycling of industrial waste materials, and they can be produced with up to ten times lower CO<sub>2</sub> emission than Portland cement [17,19]. Geopolymer grouts and mortars can be obtained by charging the geopolymer binder with sand or fine

aggregates [16,17].

Fibre Reinforced GeoPolymer (FRGP) is the combination of a geopolymer grout with fibre meshes or fabrics, similarly to Fibre Reinforced Cementitious Matrix (FRCM) [16]. Several studies were done on geopolymer fibre composites as final product made with both short fibres [20–22] and multiple laminated layers of fabrics [18,23,24], fewer investigations exist on FRGPs for retrofitting structural elements, and most investigations focused on strengthening Reinforced Concrete (RC) beams [25–28]. Whereas, very little contributions on the use of FRGPs as strengthening materials for existing masonry structures are present [16,29]. The mechanical models and the design procedures available for FRCMs [14,15,30,31] can be adopted owing to the inherent quasi-fragile behaviour of the geopolymeric matrix. Lastly, for a successful application of FRPs, their durability should be evaluated. Geopolymers have already shown good resistance towards acid and alkaline environments [16,17]. Therefore, the main durability issue is connected to the endurance of the fibres when embedded in a geopolymeric matrix, which provide an alkaline environment that might result corrosive for certain reinforcements as glass or basalt fibres [32,33]. Indeed, this is a common issue for the glass fibre laths embedded in lime or cement plasters and for any fibre mesh embedded in the cementitious matrices of FRCMs [34].

In this framework, the behaviour of three FRGPs was explored by means of local tests on masonry sub-assemblages made of soft-mud clay bricks and hydraulic lime mortar. The three FRGPs embedded a bi-directional basalt mesh, a bi-directional carbon mesh and a unidirectional Ultra High Strength Steel (UHSS) fabric, respectively. In total, 9 single-lap shear tests on single bricks with a bonded length of 200 mm and 9 three-point bending tests on 2-brick slices, connected by a mortar joint and reinforced at the bottom face, were carried out to evaluate the bond behaviour and the flexural strengthening performances of the three FRGPs. Lastly, the behaviour in alkaline environments of each reinforcement was studied through tensile tests on coupons immersed for 28 days in alkaline solutions, tentatively simulating the pore solution of the geopolymeric matrices.

In this paper, the experimental results about the materials, the durability, the bond behaviour and the flexural behaviour of the strengthened masonry sub-assemblages are presented and discussed. Results confirmed the untapped and interesting potential of FRGPs as strengthening materials, highlighting a good performance of steel and carbon reinforcements. On the other hand, precautions should be taken with un-sized basalt meshes that, as expected, were more sensitive to alkaline environments.

## 2 MATERIALS AND METHODS

Low-strength  $250 \times 120 \times 55 \text{ mm}^3$  soft mud clay bricks, intended to simulate a typical historical masonry unit, were adopted. Their average performance (coefficient of variation – CoV – in brackets) was  $17.7 \text{ N/mm}^2$  (6.2%) in compression and  $4.43 \text{ N/mm}^2$  (10.3%) in bending [35], whereas their apparent density was  $1.63 \cdot 10^3 \text{ kg/m}^3$  (1.0%).

The mortar forming the joint of the 2-brick slice bending specimens was a commercially available pre-mixed cement-free pozzolana lime mortar with siliceous sand aggregates, category M15 according to Eurocode 6 [36], with a 28-day average strength of  $14.7 \text{ N/mm}^2$  (2.5%) measured according to standard EN 1015-11 [37].

The geopolymer matrix, extensively described in [16], was prepared with metakaolin and

ground granulated furnace slag as solid precursors, and sodium silicate with molar ratio  $\text{SiO}_2/\text{Na}_2\text{O}$  of 1.5 and concentration of 41.3% as liquid activator. The binder embedded fine siliceous sand and wollastonite as inorganic aggregates, resulting in a grout with density of  $2.0 \cdot 10^3 \text{ kg/m}^3$  (1.0%), after hardening. The cylinder compressive strength was  $44.6 \text{ N/mm}^2$  (3.0%) and the splitting resistance was  $4.4 \text{ N/mm}^2$  (7.1%) in average, measured on cylindrical specimens with diameter of 35 mm and aspect ratio of 2.

The geopolymer matrix was coupled with 3 types of fibre reinforcements, either a unidirectional steel fabric or two balanced bidirectional fibre meshes, i.e. carbon or basalt, thus generating three Fibre-Reinforced GeoPolymers (FRGP).

The unidirectional steel fabric (STL) was composed by Ultra High Strength Steel (UHSS) strands, mounted on a mesh support, approximately 6 mm spaced apart. The datasheet reports a characteristic tensile strength of  $3070 \text{ N/mm}^2$ , an average elastic modulus of  $190 \cdot 10^3 \text{ N/mm}^2$  and an equivalent thickness of 0.075 mm.

The carbon reinforcement (CAR) was a bidirectional balanced mesh made of uncoated yarns, having a centre-to-centre spacing of about 9 mm, with a surface density of  $200 \text{ g/m}^2$ . It has a characteristic tensile strength of  $2500 \text{ N/mm}^2$ , an average elastic modulus of  $230 \cdot 10^3 \text{ N/mm}^2$  and an equivalent thickness of 0.048 mm, according to its technical datasheet.

The basalt reinforcement (BAS) was a bidirectional balanced mesh made of un-sized yarns, having a centre-to-centre spacing of about 8 mm, with a surface density of  $300 \text{ g/m}^2$ . It has a characteristic tensile strength of  $1735 \text{ N/mm}^2$ , an average elastic modulus of  $90 \cdot 10^3 \text{ N/mm}^2$  and an equivalent thickness of 0.053 mm, according to its technical datasheet.

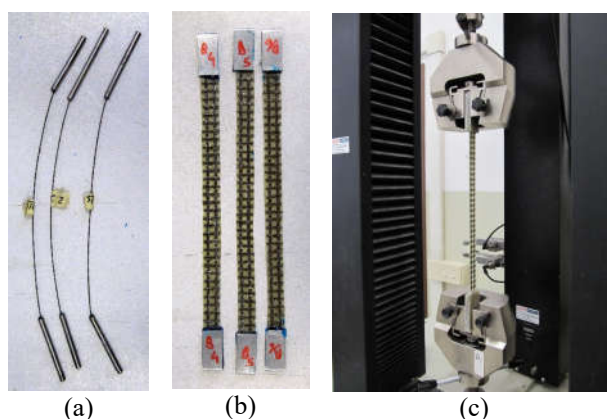
The experimental program herein presented envisaged 3 types of tests, specifically: (i) direct tensile tests carried out on coupons of fibres, either in pristine state or subjected to a 28-day conditioning in 3 different alkaline solutions; (ii) single-lap shear tests performed on FRGPs longitudinally applied to single bricks; and (iii) 3-point bending tests executed on specimens made of 2-brick slices bonded by a mortar joint, either unreinforced or with the FRGP applied to the bottom surface.

## 2.1 Tensile tests on fabric coupons

Either single strand, in the case of steel, or 2-yarns coupons, in the case of carbon and basalt, were tested in tension in a 25 kN electro-mechanic universal machine. Specimens were 380 mm long to allow a free length of about 280 mm after the application at each end of 2 aluminium tabs (or sleeves in the case of steel) 50 mm long, glued with epoxy resin, which were clamped by the test machine. Carbon and basalt yarns were impregnated with a small amount of epoxy resin to load uniformly the yarns and obtaining the full resistance of the mesh, thus preventing or limiting possible uneven distribution of stresses inside the reinforcement.

Tests were carried out either on pristine samples of reinforcements (C0 condition) or on fibres immersed for 28 days in 3 alkaline solutions to investigate their possible degradation in environments simulating the possible pore solution of the geopolymer matrix. C1 consisted in a 5% aqueous solution of NaOH (corresponding to 1.25M), as provided by the standard ASTM E2098/E2098M [38]. Aqueous solutions of either sodium (the same used as binder activator) or potassium silicate were adopted for C2 and C3. The formulation of the potassium silicate had a molar ratio  $\text{SiO}_2/\text{K}_2\text{O} \sim 1.5$ , equal to the silica/sodium one, with a solid matter concentration of 46.0%. Silicates were dissolved in water to achieve the same concentration of

Na (or K) atoms of the C1 solution. At least 4 samples for each type of reinforcement and conditioning solution were tested. After the immersion, fibres were rinsed and dried to measure the weight loss by means of an analytical balance.



**Figure 1:** Samples of steel (a) and basalt (b) reinforcement for tensile tests, and a coupon ready for testing (c)

## 2.2 Single-lap shear tests

Specimens consisted in a single brick with the FRGP applied longitudinally onto the wider surface (Fig. 2a) with a bonded area 200 mm long and 60 mm wide, delimited by masking tape during casting. A protruding portion extending for about 220 mm beyond the edge of the brick was used for the connection to the test machine. The reinforcement was embedded inside the geopolymer matrix for the whole length, except in the case of steel strands that were kept bare beyond the edge of the brick. The area of the reinforcement varied according to the type, since the FRGP included either 8 steel strands, 5 carbon or 7 basalt yarns to achieve the desired width.

The test setup (Fig. 2b), designed for a universal electro-mechanic machine, was the same already adopted in several former researches [6,39]. It consisted in two steel plates 50 mm thick connected by 4 threaded bars, two of which fastened to the bottom head of the test machine. The specimen was inserted between those plates, taking care to alignments and contacts, and the protruding reinforcement was glued with quick setting resin to a steel part connected to the upper head of the test machine by means of a ball joint. Four potentiometers were used to monitor displacements, two positioned at the beginning of the bonded length, one in the middle and one at the unloaded end of the FRGP. Tests were carried out in displacement control, with a rate of the movable loading beam progressively incremented from 0.3 mm/min to 1.2 mm/min in the last stages of the tests. Load and displacement values were recorded by an external acquisition system at 10 Hz.

Three specimens per type of reinforcement were tested, for overall of 9 samples.

## 2.3 Bending tests on 2-brick specimens

Three-point bending tests were carried out on specimens made of 2 slices, about 32 mm thick, cut from single bricks. Those slices were longitudinally aligned and connected by a 10 mm mortar joint, thus obtaining samples approximately 510 mm long (Fig. 3a). Subsequently, the FRGP was centrally applied to the bottom side, extending for about 330 mm. The reinforcement comprised 3 strands or yarns for each type of fibre. The geometry of the

specimens was a trade-off between representativeness and materials availability.

A 50 kN electro-mechanic universal machine equipped with a commercial setup for bending (Fig. 3) was used. The span between the bottom supports was 380 mm, slightly greater than the length of the FRGP. Contacts between sample and steel supports were improved by small rubber inserts. Tests were carried out in displacement control, with a rate of the movable loading beam of 0.5 mm/min. Load and displacements were recorded by the embedded data acquisition of the universal machine.

Three specimens per type of reinforcement were tested, for overall 9 samples. In addition, 3 unreinforced specimens were tested twice at 0.1 mm/min with a 2.5 kN load cell, repairing the failed joint with epoxy resin and testing again the same specimen to measure also the resistance of the strongest mortar-to-brick interface.

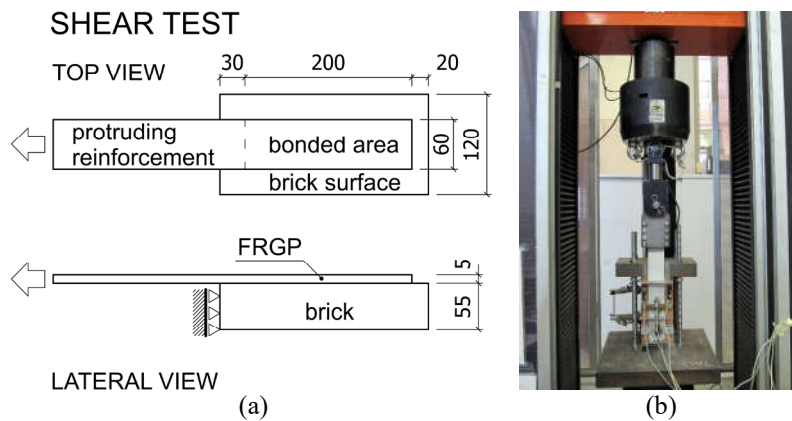


Figure 2: Sketch of a shear test specimen with dimensions in mm (a) and sample ready for testing (b)

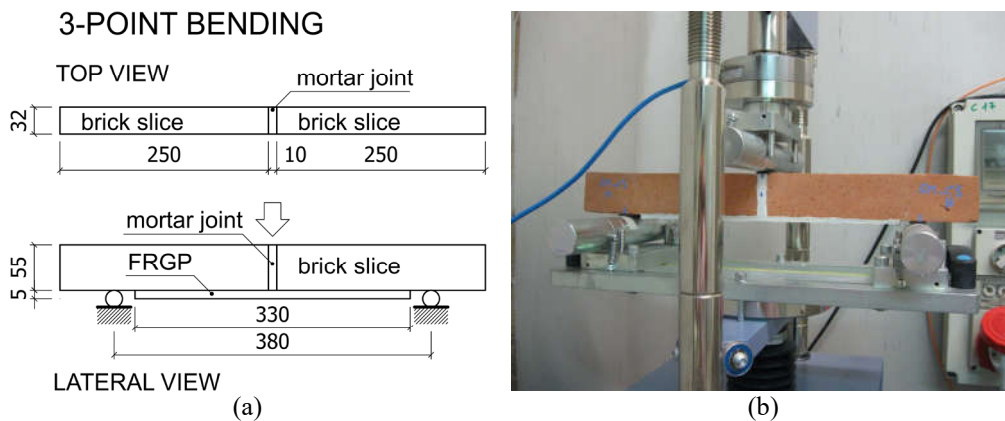


Figure 3: Sketch of a 3-point bending specimen, with dimensions in mm (a) and sample ready for testing (b)

### 3 RESULTS AND DISCUSSION

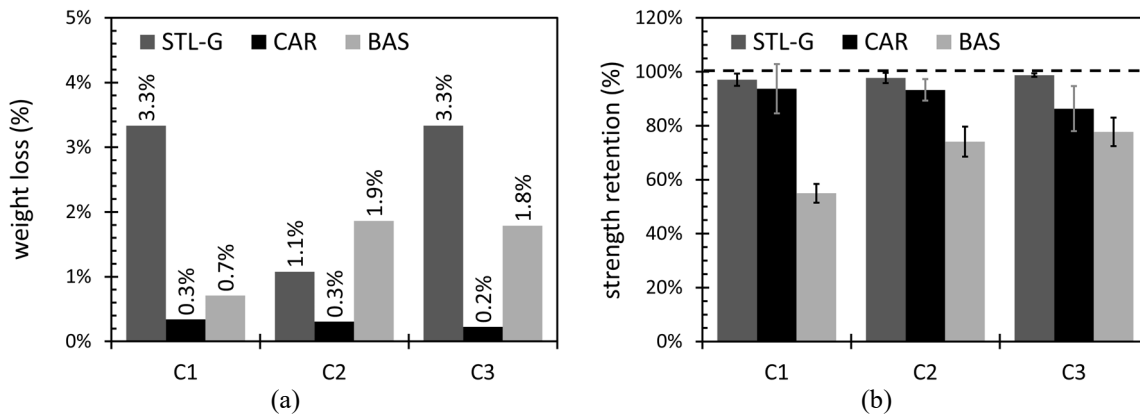
#### 3.1 Tensile tests on fabric coupons

Failure was generally as expected, with a fibre tensile rupture localised inside the free length between the anchoring, in some cases close to the tabs. Although few specimens showed an

irregular failure, due to slippage problems at the connection with the test machine or to an imperfect alignment, at least 4 suitable results were included in calculations.

The average tensile strengths  $f_{t,avg}$ , grouped by fibre and conditioning type, are listed in Table 1 together with their coefficient of variation (CoV). Measured values of weight loss are shown in Figure 4a, whereas tensile strength retentions are shown in Figure 4b.

Steel strands were substantially not affected by the alkaline environment, with a strength loss always lower than 3% that can be considered within a common experimental variability, despite a weight loss that exceeded 3% in two cases, probably due to the loss of the protecting coating without impairing the resisting cross-section. Carbon fibres presented a strength retention of about 93% in sodium hydroxide and sodium silicate solutions and were slightly more sensitive to potassium silicate solutions as proved by a lower strength retention of about 86%. Conversely, they showed the lowest values of weight loss of about 0.2–0.3%. Finally, as expected, the un-sized basal fibres showed the worst degradation, with a strength loss of about 25% in silicate solutions and 45% in sodium hydroxide solution, with a weight loss comprised between 0.7–1.9% (the lowest was measured in NaOH). Strength conversion coefficients for aggressive environments proposed by the Italian guidelines CNR DT200R1 [40] (0.85 for carbon and 0.50 for glass fibres) and CNR DT215 [15] (0.70 regardless of the fibres type), compared to the present experimental results, appear reasonably close where applicable. As observed in [32], there is no apparent correlation between weight loss and strength retention.



**Figure 4:** Weight loss (a) and tensile strength retention (b) measured on conditioned fibres

**Table 1:** average tensile strength in pristine condition (C0) and after treatment in alkalis, with CoV in brackets

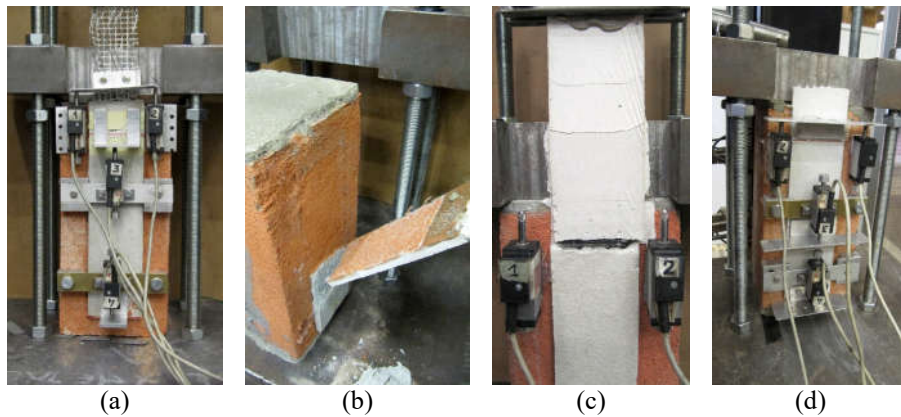
Specimen	C0 – $f_{t,avg}$ N/mm <sup>2</sup>	C1 – $f_{t,avg}$ N/mm <sup>2</sup>	C2 – $f_{t,avg}$ N/mm <sup>2</sup>	C3 – $f_{t,avg}$ N/mm <sup>2</sup>
STL	3125 (0.5%)	3033 (2.4%)	3053 (1.9%)	3086 (0.7%)
CAR	2854 (7.9%)	2675 (9.7%)	2663 (4.3%)	2464 (9.7%)
BAS	1845 (3.2%)	1013 (6.3%)	1367 (7.5%)	1434 (6.8%)

### 3.2 Single-lap shear tests

Failures were substantially different for each type of FRGP. Steel strands failed in tension in 2 specimens (Fig. 5a), while in one case a partial debonding, about 2/3 of the bonded length, occurred (Fig. 5b). Carbon yarns generally slipped inside the matrix (Fig. 5c), with minor signs

of tensile failure in the most external fibrils and several cracks in the protruding FRGP, about 25-30 mm spaced apart. On the other hand, basalt yarns showed a rather clear tensile rupture with no remarkable sign of slippage (Fig. 5d).

Results, in terms of failure mode, maximum load  $P_{max}$  and maximum stress  $\sigma_{max}$ , are given in Table 2, together with the exploitation coefficient  $\eta_{ST}$  calculated as the ratio of  $\sigma_{max}$  and the fibre tensile strength  $f_{t,avg}$  measured in pristine conditions (C0). As expected, the effectiveness of the FRGP was in all cases lower than 1, confirming that shear tests, although excluding bond failures, cannot achieve the reference strength of the fibre reinforcements when embedded in inorganic matrices. Nonetheless, in the case of steel, the exploitation was not lower than 0.8, thus suggesting that steel strands are less sensitive to this type of test. Carbon fibres slipped at values comprised between 0.41 and 0.47, while basalt failed at 0.23 and 0.32, cracked specimen excluded. Similar exploitation coefficient  $\eta_{ST}$  are currently obtained for optimal FRCM systems [6,12,13,34].



**Figure 5:** Failure modes of shear tests: (a) tensile failure and (b) partial debonding of steel FRGP; (c) slippage of carbon fibres and diffuse cracking of the matrix; and (d) tensile failure of basalt mesh

**Table 2:** results of single-lap shear tests

Specimen	Main failure	$P_{max}$ N	$\sigma_{max}$ N/mm <sup>2</sup>	$\eta_{ST}$
ST-STL-1	tensile break	12764	2966	0.95
ST-STL-2	debonding	9214	2141	0.69
ST-STL-3	tensile break	10678	2481	0.79
ST-CAR-1	tensile break/slippage	3271	1140	0.44
ST-CAR-2	tensile break/slippage	3480	1213	0.47
ST-CAR-3	tensile break/slippage	3030	1057	0.41
ST-BAS-1	tensile break (*)	804	271	0.15
ST-BAS-2	tensile break	1285	433	0.23
ST-BAS-3	tensile break	1737	585	0.32

\* specimen cracked during handling before the test

### 3.3 Bending tests on 2-brick specimens

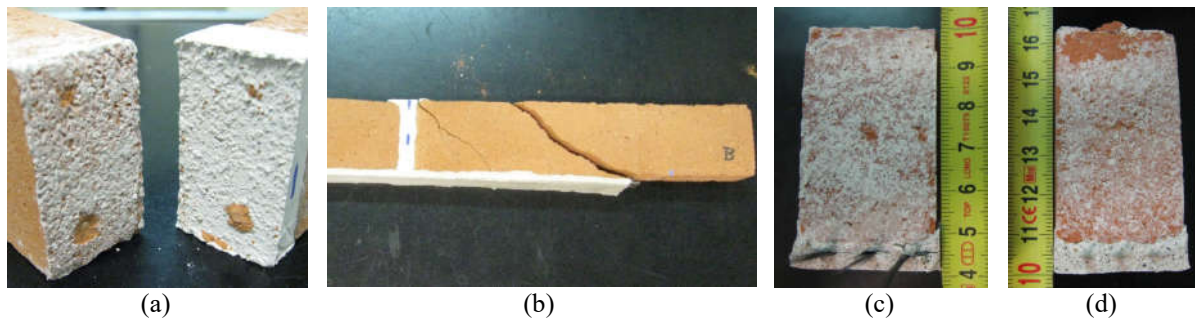
The failure of the 3 unreinforced specimens was always located at the mortar-brick interface (Fig 5a). They were tested twice, the second time after repair of the failed joint, and showed a



remarkably variable resistance comprised between 37 and 129 N, corresponding to a bond strength, calculated as the ratio of maximum bending moment and section modulus, comprised between 0.22 and 0.81 N/mm<sup>2</sup>. The average strength of the weakest joint of each specimen was 0.41 N/mm<sup>2</sup>, while the average of the strongest ones was 0.62 N/mm<sup>2</sup>.

In the case of steel FRGP, failure was due to a shear crack of the brick that started close to the end of the reinforcement (Fig 5b), after a wedge-like cracking of the portion beneath the applied load. Carbon FRGP failed due to slippage of the fibres (Fig 5c), whereas basalt FRGP broke in tension (Fig 5d), in all cases in correspondence of the main crack that opened at the mortar-brick interface.

Results are listed in Table 3 in terms of failure mode, maximum load  $P_{max}$  and maximum stress  $\sigma_{max, sb}$ , the latter calculated through a section analysis based on the assumption of a stress-block  $0.8 \cdot x$  high, being  $x$  the neutral axis depth. The exploitation coefficient  $\eta_{BT}$  was calculated similarly to the case of  $\eta_{ST}$ . Steel-reinforced specimens could not attain a fibre effectiveness close to shear test samples, due to the earlier shear failure of the brick. In the case of carbon FRGP, which also showed one shear failure mode, the exploitation  $\eta_{BT}$  of 0.41–0.44 was comparable to  $\eta_{ST}$ . Conversely, basalt FRGP reached relatively high values of  $\eta_{BT}$  (0.60 and 0.71), more than twice the  $\eta_{ST}$  of ST-BAS-2 and ST-BAS-3, probably thanks to the reduced number of yarns and to the bending specimen that allowed an even stress distribution. Similar exploitation coefficient  $\eta_{BT}$  are currently obtained for optimal FRCM systems [6,10,13,34].



**Figure 5:** Failure modes of bending tests: (a) joint failure of unreinforced specimens; (b) brick shear failure in case of steel FRGP; (c) slippage and partial rupture of carbon fibres; and (d) tensile failure of basalt mesh

**Table 3:** Results of 3-point bending tests

Specimen	Failure	$P_{max}$ N	$\sigma_{max, sb}$ N/mm <sup>2</sup>	$\eta_{BT}$
BT-STL-1	brick shear	1289	1591	0.49
BT-STL-2	brick shear	1425	1799	0.56
BT-STL-3	brick shear	1515	1919	0.59
BT-CAR-1	slippage	1218	1257	0.44
BT-CAR-2	slippage	1119	1170	0.41
BT-CAR-3	slippage / brick shear	1199	1258	0.44
BT-BAS-1	tensile break (*)	321	434	0.24
BT-BAS-2	tensile break	798	1114	0.60
BT-BAS-3	tensile break	927	1302	0.71

\* mortar joint cracked before the test, probably due to drying shrinkage of the FRGP



## 4 CONCLUSIONS

The paper presented an assessment of the adhesion and durability properties of FRGPs as strengthening material for masonry buildings. The FRGPs were made of an eco-efficient and heat-resistant geopolymeric matrix that has a chemical composition and porosity similar to that of soft-mud clay bricks simulating a typical historical masonry unit. Therefore, the matrix is an interesting inorganic bonding agent for the implementation of removable and compatible composites suitable, not only for existing masonry buildings, but also for BH. The three FRGPs studied were reinforced either with a bi-directional balanced basalt mesh, a bi-directional balanced carbon mesh or a unidirectional UHSS fabric.

The adhesion and mechanical performances of the three FRGPs were investigated by means of local 9 single-lap shear tests on single bricks with a bonded length of 200 mm and 9 three-point bending tests on two brick slices, connected by a mortar joint and reinforced at the bottom face. The exploitation coefficients derived from the shear and the bending tests are in accordance with the best performances currently obtained by the FRCMs. Nonetheless, FRGPs are provided with an undoubtedly more innovative inorganic matrix.

On the other hand, further studies are necessary to investigate the durability of the FRGPs. In fact, the behaviour in alkaline environments simulating the pore solution of the geopolymeric matrices highlighted the possibility of undesired corrosive outcomes on the fibres, especially when they are un-sized (or they lost part of the sizing) as the basalt mesh used in this paper.

The results confirmed the untapped and interesting potential of FRGPs. In particular, The FRGPs reinforced with the carbon mesh and the UHSS fabric shown interesting result as potential inorganic composites suitable for strengthening existing masonry buildings and BH.

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