EURODYN 2020
XI International Conference on Structural Dynamics
M. Papadrakakis, M. Fragiadakis, C. Papadimitriou (eds.)
Athens, Greece, 23–26 November 2020

A MULTIDISCIPLINARY APPROACH INTEGRATING GEOMATICS, DYNAMIC FIELD TESTING AND FINITE ELEMENT MODELLING TO EVALUATE THE CONSERVATION STATE OF THE GUIMARÃES CASTLE'S TOWER KEEP

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Keywords: Architectural heritage, geomatics, ambient vibration test, dynamic identification, model updating, numerical simulation

Abstract. *The development of realistic numerical models able to replicate as closely as possible the actual structural behaviour of heritage buildings is crucial for a thorough assessment of their structural performance against exceptional scenarios. In this regard, higher accuracy can be achieved by leveraging a multidisciplinary approach that integrates multiple contributions from different fields, such as geomatics, dynamics and computational modelling. In the present paper, this strategy is applied to the tower keep of the Guimarães castle, in Portugal, a masonry fortified structure dating back to the X century. Starting from an accurate laser scanner survey, a detailed numerical model has been created resorting to efficient algorithms able to represent complex situations. Furthermore, by exploiting the dynamic* *properties extracted from the processing of vibration data collected during field dynamic testing, the mechanical characteristics of the constituent materials of the tower have been estimated by means of a model updating technique embedded in a trust-region scheme implemented in the NOSA-ITACA code. The results obtained so far allowed to establish valuable baseline information that will be of pivotal importance to catch possible changes in the tower's response and to perform more in-depth structural analyses.*

1 INTRODUCTION

Heritage structures represent a significant part of our built environment. Besides their cultural and social importance, historical buildings and sites are touristic attractions that positively impact the economy of the cities and countries in which they are located. Thus, the preservation of the built heritage is of primary concern at the local and global scale and goes beyond cultural requirements.

Since ancient constructions have been exposed to aging and deterioration phenomena for centuries, they are particularly vulnerable to new threats and damages. Material aging, pollution impact, long-term effects of ground subsidence, environmental vibrations and extreme events are just some of the main causes of damage in historical structures. If not detected in due time, damage can irreversibly impair the structural performance over time. However, the structural assessment of built heritage does conceal many challenges owing to the geometrical complexity characterizing age-old constructions, the heterogeneity of materials and building techniques adopted as well as the limited knowledge about past events and interventions that might have affected their actual conservation state [1].

In this context, preventive strategies based on regular condition surveys and periodic or continuous structural monitoring are fundamental to obtain a global insight into the behaviour of such non-conventional systems and promptly identify anomalies in order to plan in advance adequate corrective measures and ensure the good conservation of our built heritage [2], [3], [4]. At the same time, the complexity of old constructions requires the use of advanced tools for their accurate documentation and assessment, trying to improve the level of knowledge about the structure and to obtain reference information for post-event analysis in case of unexpected scenarios. A multidisciplinary approach integrating high-resolution surveys, field dynamic testing and finite element modelling is therefore necessary to achieve a full comprehension of historical buildings [5].

In the present work, this strategy is applied to an ancient masonry tower keep located in the hearth of the medieval castle of Guimarães, in Portugal. First, an accurate survey is performed using a terrestrial laser scanner in order to map the existing damages and develop an accurate 3D numerical model. Then, ambient vibration tests are carried out to extract meaningful information about the most significant dynamic parameters of the keep, namely frequencies, mode shapes and damping ratios. Finally, the experimental results are used to calibrate, through a model updating procedure based on a trust-region scheme [6], two refined FE models of the tower in order to estimate the mechanical characteristics of its constituent materials. Research is still in progress to achieve a very accurate simulation of the dynamic behaviour of the keep; however, the obtained results allowed to set baseline information that will be crucial to identify future deviations in the tower's response and to perform more advanced structural analyses.

2 FROM REALITY TO “AS-BUILT” CAD MODELLING

2.1 Guimaraes castle´s tower keep

Located in the historical center of the homonymous city (District of Braga, Portugal), the medieval castle of Guimarães is a five-sided polygonal military fortification erected during the X century (late Romanesque-early Gothic period) on a small hill formed from granite. The castle was primarily built to defend the Monastery of the city and its population from the attacks of Vikings and Moors, becoming nowadays a symbol of the Portuguese national identity. The construction is delineated by thick perimetral walls which give rise to a shape similar to a shield. Eight flanking towers (turrets) can be found along the walls, with height varying from 12 to 20 m. Turrets and walls surround and protect the inner military square together with the most prominent tower therein located: the central tower keep (Figure 1a). This free-standing structure, 25.86 m high and composed of four squared levels with an estimated area of 76 m^2 each, features massive bearing walls made of three-leaf regular granite masonry varying in thickness from about 1.98 m at the 1st floor, to 1.54 m at the 4th one, and is topped by battlements. Centrally, the construction has a squared granite pillar which tapers upwards from about 1.90 x 1.90 m^2 (base) to 1.20 x 1.20 m^2 (top). The pillar and the walls support the double-warped wooden floor of the different levels as well as the wooden trusses and rafters of the tiled four-pitched roof (Figure 1b).

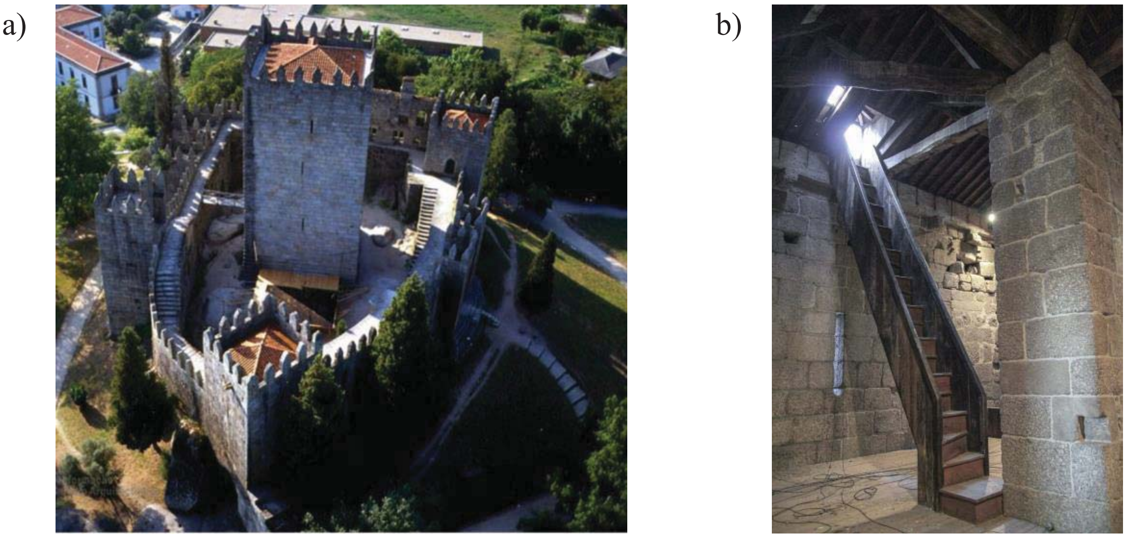


Figure 1: Guimaraes castle: a) outdoor view; and b) detailed view of the central pillar and roof trusses. (First photo source: http://www.monumentos.gov.pt/).

Concerning the state of conservation, the tower keep exhibits typical damages and deterioration processes: moist areas along the walls due to water infiltration and deficiencies in the drainage system; spread biological colonies, especially in the form of lichens, with high concentration on the most exposed parts; longitudinal cracks induced by the out-of-plane deformation of the main façade, likely due to the horizontal thrust of the timber roof structure.

2.2 3D digitalization via TLS technology

The geometrical configuration of the tower, with narrow spaces and unfavorable lighting conditions, made the Terrestrial Laser Scanner (TLS) device the best solution to digitalize the building. The light-weight TLS Faro Focus x330 ® was used for this purpose (Figure 2). Its most relevant features are summarized in Table 1.

Thirty-two scans were needed to capture the whole tower keep (Figure 2): i) eight scan stations to digitalize the façades; ii) sixteen stations to capture the indoor spaces; and iii) eight scans for the roof of the tower. It is worth noting that this large number of scans was due to the necessity of having a good overlap between scan stations in order to carry out a proper cloud-to-cloud alignment.

Specification	Value
Physical principle	Phase shift
Wavelength (nm)	1550
Measurement range (m)	0.60 to 330
Field of view (degrees)	300 V x 360 H
Nominal accuracy value at 25 m (mm)	± 2mm
Capture rage (pts/sec)	122,000 to 976,000
Spatial resolution at 10 m (mm)	6

Table 1: Technical specifications of the TLS Faro Focus.

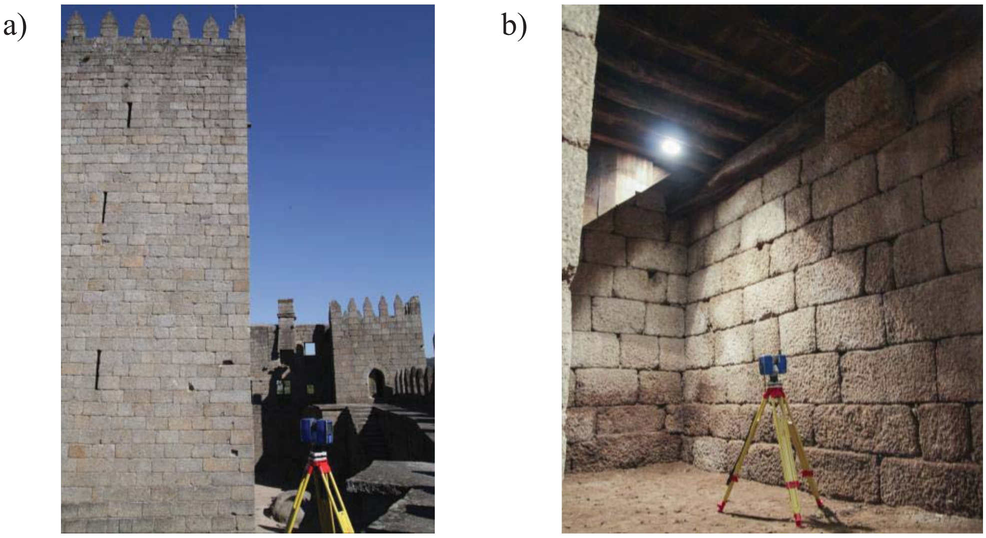


Figure 2: 3D digitization of the tower keep through TLS: a) outdoor; and b) indoor.

2.3 Point cloud processing

All the stations were aligned in a single coordinate system by means of the coarse-to-fine registration proposed in [7]. The approach begins with a pair-wise registration through the ICP (Iterative Closets Point) algorithm [8], followed by the Generalized Procrustes Analysis (GPA) [9], with the aim of minimizing the error accumulation among the different scans. As a result, a complete 3D point cloud of the tower was obtained, with an error of 0.003±0.002 m. The huge amount of captured data, counting about 410,982,656 points, demanded the application of a decimation filter for their manipulation; thus, a curvature-based filter with a threshold of 0.02 m was employed. This filter allows to decimate flat areas while maintaining all the details in curved areas (e.g. edges or timber elements). At the end of the decimation process, the final point cloud contained 32,449,888 points – barely 8% of the original one (Figure 3).

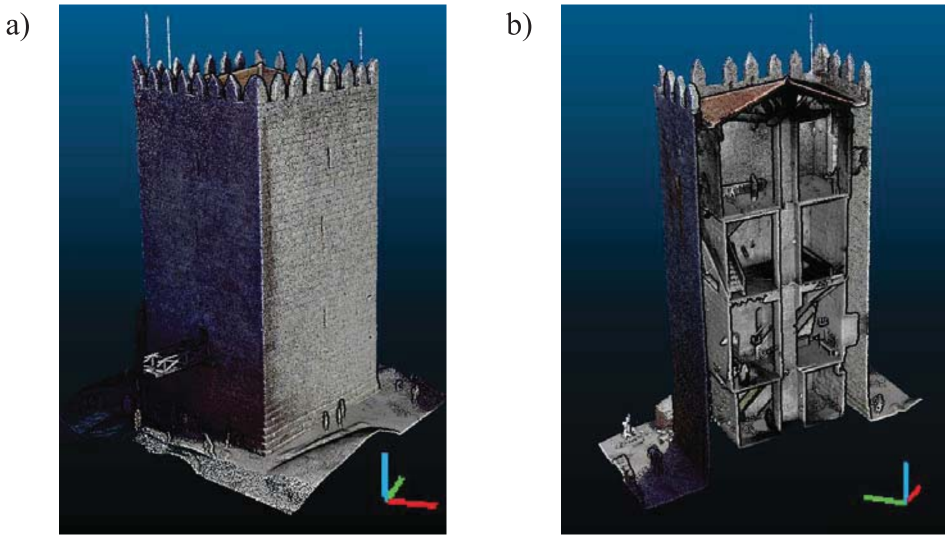


Figure 3: 3D point cloud of the tower keep: a) exterior view; and b) section crossing the center of the tower.

2.4 As-built modelling

As mentioned in Sub-Section 2.1, the main façade of the tower keep suffers visible out-of-plane deformations. With the aim of considering this outward displacement in the numerical analysis of the structure, an as-built CAD modelling stage was carried out, using the reverse engineering workflow proposed by [10]. The approach consists of the following steps: i) 3D Delaunay triangulation; ii) horizontal sections along the z-axis each 2.0 m; iii) b-spline vectorization of each section; iv) creation of surface between b-splines by means of Lofted surfaces; and v) refinement of the model through the use of Boolean operators (Figure 4).

In order to further simplify the subsequent numerical simulation, the timber structure of floors and roof was modelled by means of b-spline curves. To this end, several transversal sections along the different timber elements were extracted; then, a b-spline approximation was computed using as nodes the centroid of each section. This allowed to obtain an accurate as-built CAD model of the tower to be later used as geometrical base for defining the numerical mesh (see Sub-Section 4.2).

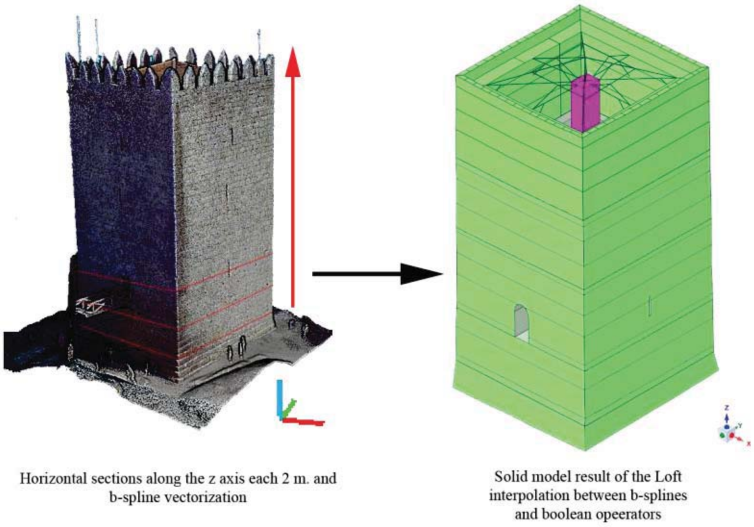


Figure 4: From the point cloud to the CAD model: graphical workflow.

3 OPERATIONAL MODAL ANALYSIS

3.1 Dynamic testing procedure

Dynamic testing can be considered as a global nondestructive tool since it allows to obtain real-time punctual checkups of the structural fitness just by deploying an array of sensors in the structure and recording the corresponding vibration response to random ambient excitations, without resorting to any invasive technique [11]. This aspect represents one of the major strengths of dynamic testing, making it play a leading role in the context of structural health monitoring of historical constructions. From the analysis of vibration signals, it is possible to estimate the dynamic properties of a structural system (frequencies, mode shapes and damping ratios) and use this information for different purposes, including the identification of anomalies and damage mechanisms, the assessment of strengthening needs or the calibration of realistic numerical models for in-depth structural analyses.

As for the Guimarães castle, the dynamic characterization of the tower keep was performed by Operational Modal Analysis (OMA), namely using output-only data acquired from the structure in operating conditions through classical contact vibration sensors. Eleven uniaxial piezoelectric accelerometers (model PCB 393B12, 10 V/g sensitivity, ±0.5 g dynamic range, 8 μg resolution) were distributed across the tower in order to measure its vibration response at strategic locations both in the bearing walls and the central pillar. The testing procedure consisted of two setups, each one recording 600 s acceleration time series sampled at 200 Hz from eleven measurement points; two accelerometers were kept on the top level as reference points for the analysis. In total, records from twenty DOFs (degrees of freedom) were acquired. The complete sensor layout is displayed in Figure 5.

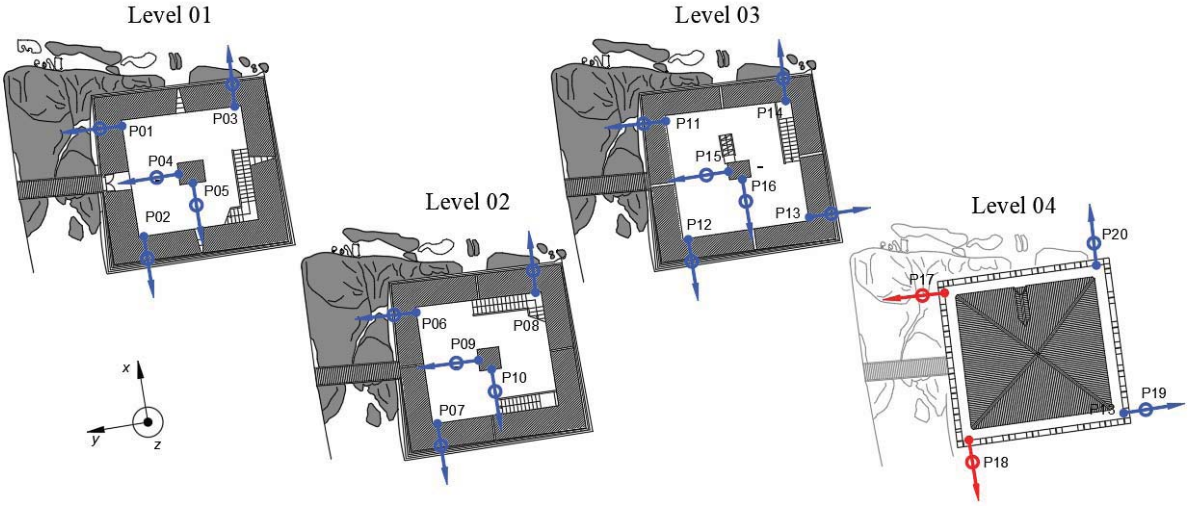


Figure 5: Sensor layout for the dynamic testing (reference sensors are indicated in red).

3.2 Data processing and results

The dynamic properties of the tower keep were estimated using two output-only dynamic identification techniques available in the commercial software ARTeMIS [12], i.e. the Enhanced Frequency Domain Decomposition (EFDD) and the Stochastic Subspace Identification with Extended Unweighted Principal Component (SSI-UPCX). Before elaboration, data were preliminary analyzed to remove trends, down-sample the signals and reduce leakage errors. Indeed, since the power spectral densities of the raw time histories displayed a significant frequency content in the range 2–15 Hz, all data were pre-processed with a decimation of order 5, passing from 102,400 to 20,480 of spectral resolution. Afterwards, both the aforementioned modal estimators were applied, allowing to cross-validate the results of eight out of eleven vibration modes in the frequency and time domains.

The estimated natural frequencies and damping ratios are summarized in Table 2 together with the MAC values indicating the degree of similarity between corresponding mode shapes. Overall, eleven vibration modes were identified for the tower keep: two translation modes at 2.68 Hz (f_1) and 2.74 Hz (f_2) featuring in-phase modal components; one translation mode at 3.88 Hz (f_3) with out-of-phase modal components; one torsion mode at 4.81 Hz (f_4); two bending modes at 5.75 Hz (f_5) and 6.04 Hz (f_6); and five additional higher-order dominant bending modes at 7.22 (f_7), 7.98 (f_8), 9.23 (f_9), 10.22 (f_{10}) and 13.86 Hz (f_{11}).

	f_{EFDD} [Hz]	f_{SSI} [Hz]	$\lvert\Delta f\rvert$ [%]	ξ_{EFDD} [%]	ξ_{SSI} [%]	MAC
φ_1	2.67	2.68	0.37	0.66	1.13	0.98
φ_2	2.74	2.74	0.00	0.71	1.15	0.91
φ_3	3.88	3.88	0.00	1.22	1.41	1.00
φ_4	4.82	4.81	0.21	0.63	0.68	0.94
φ_5	5.38	5.75	6.43	0.78	1.99	0.57
φ_6	6.03	6.04	0.17	1.60	2.16	0.99
φ_7	7.16	7.22	0.83	0.51	1.97	0.48
φ_8	7.90	7.98	1.00	1.27	2.10	0.99
φ_9	9.21	9.23	0.22	0.65	2.22	0.98
φ_{10}	10.47	10.22	2.45	0.18	1.75	0.29
φ_{11}	13.91	13.86	0.36	0.38	1.53	0.92

Table 2: Experimental frequencies, damping ratios and MAC values (highlighted in grey the modal vectors featuring a low correlation).

Very low percentage errors in terms of frequency values are found comparing the two modal estimators, and consistent results are obtained as far as the damping ratios are concerned. It is also highlighted that, despite the inherent difficulties associated with the presence of closely spaced frequencies, a high correlation (MAC > 0.90) is found between all comparable vibration modes, except for modes 5, 7 and 10. Figures 6 and 7 show, respectively, the singular value decomposition (SVD) of the spectral density matrices and the first four estimated mode shapes.

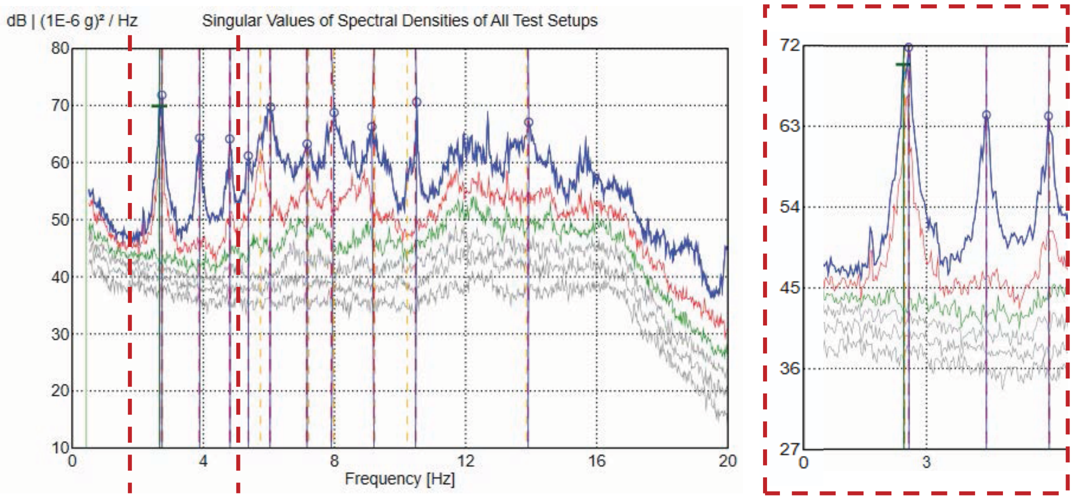
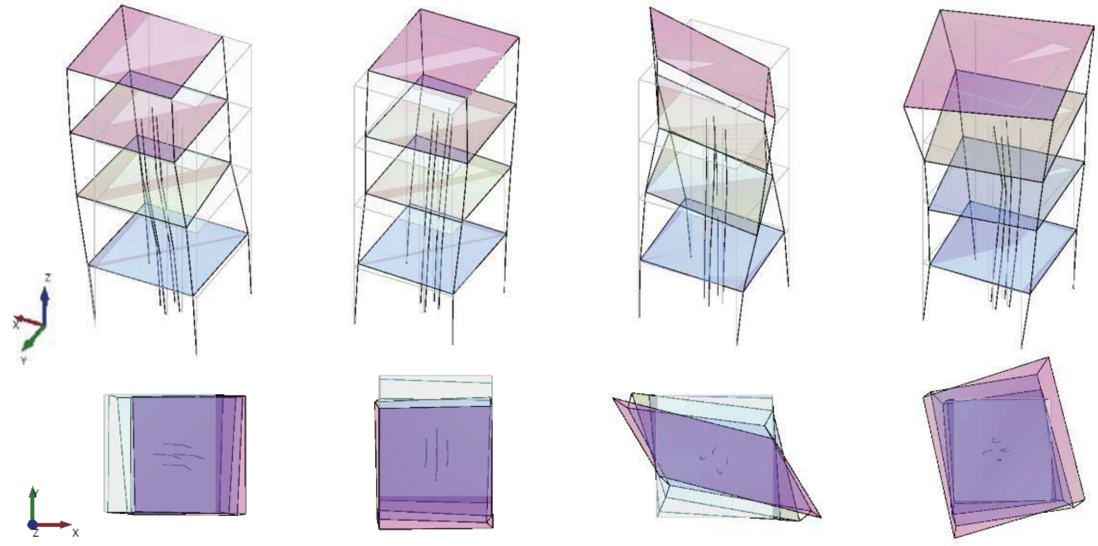


Figure 6: Singular value decomposition: peak picking of dominant frequencies.



φ_1 (f_1 = 2.68 Hz) φ_2 (f_2 = 2.74 Hz) φ_3 (f_3 = 3.88 Hz) φ_4 (f_4 = 4.81 Hz)

Figure 7: Experimental mode shapes of the tower keep (undeformed shape in light grey).

4 MODAL-BASED FINITE ELEMENT MODEL UPDATING

4.1 Model Updating

Model updating is a procedure aimed at calibrating an FE model in order to match the experimental and numerical dynamic properties (frequencies and mode shapes) of a structure [13]. It is an inverse problem based on modal analysis, which in turn relies on the solution of the generalized eigenvalue problem:

$$\mathbf{Ku} = \omega^2 \mathbf{Mu} \tag{1}$$

where **K** and $\mathbf{M} \in \mathrm{R}^{nxn}$ are the stiffness and the mass matrices of the structure discretized into finite elements; $\mathbf{u} \in \mathrm{R}^{n}$ is the vector of the degrees of freedom, with n being the total number of DOFs. The eigenvalue ω_i^2 is linked to the structure's frequency f_i by the relation $f_i = \omega_i/2\pi$ and the eigenvector $\mathbf{u}^{(i)}$ represents the corresponding mode shape.

The model updating problem can be reformulated as an optimization problem by assuming that the stiffness and mass matrices, **K** and **M**, are functions of a parameter vector x varying in a p-dimensional box Ω. The goal is to determine the optimal value of x that minimizes, within the box Ω, the objective function $\phi(\mathrm{x})$ defined by:

$$\phi(\mathrm{x}) = \sum_{i=1}^{q} w_i^2[\overline{f_i} - f_i(\mathrm{x})]^2 + w_{i+q}^2[1-\gamma_i(\mathrm{x})]^2 \tag{2}$$

where $\overline{f_i}$ and $f_i(\mathrm{x})$ are the q experimental and numerical frequencies to match, scalars γ_i are the square root of the modal assurance criterion (MAC) indicators [14] and measure the correlation between the i-th experimental mode shape and the corresponding numerical one, while scalars w_i encode the weight that should be given to each frequency and mode shape in the optimization scheme. Usually, to obtain relative accuracy on the frequencies, w_i is chosen equal to the inverse of the experimental frequency. As for the eigenmodes, weights are typically fixed to 0.1; this value respects the accuracy of the information retrieved from the identification phase, where, in general, eigenvectors are obtained with one magnitude lower accuracy than the corresponding frequencies.

The numerical procedure for model updating herein used to obtain the optimal values of the parameter vector x, and described in detail in [15], [6], is implemented in the NOSA-ITACA code [16], a finite element software developed in house by ISTI-CNR (www.nosaitaca.it). The algorithm is based on the construction of local parametric reduced-order models embedded in a trust region scheme for solving the constrained minimum problem. In particular, it exploits the structure of the stiffness and mass matrices and the fact that only a few of the smallest eigenvalues have to be calculated in order to solve the problem. This procedure reduces both the overall computation time of the numerical process and the user's effort.

4.2 FE Model Calibration

With the aim of understanding the dynamic behavior of the tower and the mutual interaction between wooden elements and masonry structure, two detailed FE models, hereinafter referred to as Model A and Model B, were created via the NOSA-ITACA code and calibrated using the experimental results presented in Section 3. The mesh of each model was obtained from the as-built CAD model described in Sub-Section 2.4. Aiming at exploiting all the defined geometrical features, a tetrahedral mesh algorithm with high-order elements was applied, making sure that the thickness of the walls was defined by at least two elements in order to be able to capture stress gradients correctly in future non-linear analyses.

Model A (Figure 8a) counted 220,854 DOFs and was composed of: 45,296 10-node isoparametric tetrahedral elements (element 27 of the NOSA-ITACA library) – used to model the walls and the central pillar of the tower; 1,457 3-node thick shell elements (element 26 of the NOSA-ITACA library) – employed to simulate the wooden slabs; and 1,542 beam elements (element 9 of the NOSA-ITACA library) – used to model the wooden beams of floors and roof. Model B (Figure 8b) was obtained from Model A by removing all shell and beam elements, and replacing them with equivalent masses (m_1, m_2, m_3, m_4).

The masonry was modeled as a homogeneous isotropic material with a Poisson's ratio $\nu=0.2$ and a mass density ρ_m = 2600 kg/m^3 [17], [18]; whereas a Poisson's ratio $\nu=0.3$ and a mass density ρ_w = 1000 kg/m^3 were adopted for the wood. The structure was assumed to be clamped at the base.

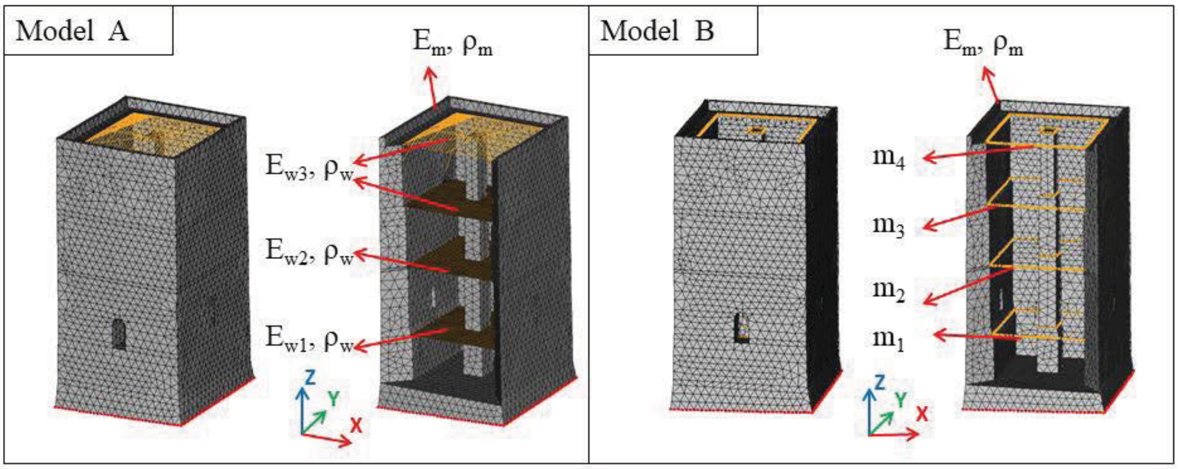


Figure 8: FE modelling of the tower keep: Model A and Model B.

As regards Model A, the numerical procedure recalled in Sub-Section 4.1 was employed to estimate the optimal values for the Young's moduli of masonry E_m, wooden slab and beams E_{w1}, E_{w2}, E_{w3}, assuming for the box Ω the following parameters bounds:

$$1000 \text{ MPa} \leq E_m \leq 8000 \text{ MPa}$$

$$100 \text{ MPa} \leq E_{w1}, E_{w2}, E_{w3} \leq 9000 \text{ MPa}$$

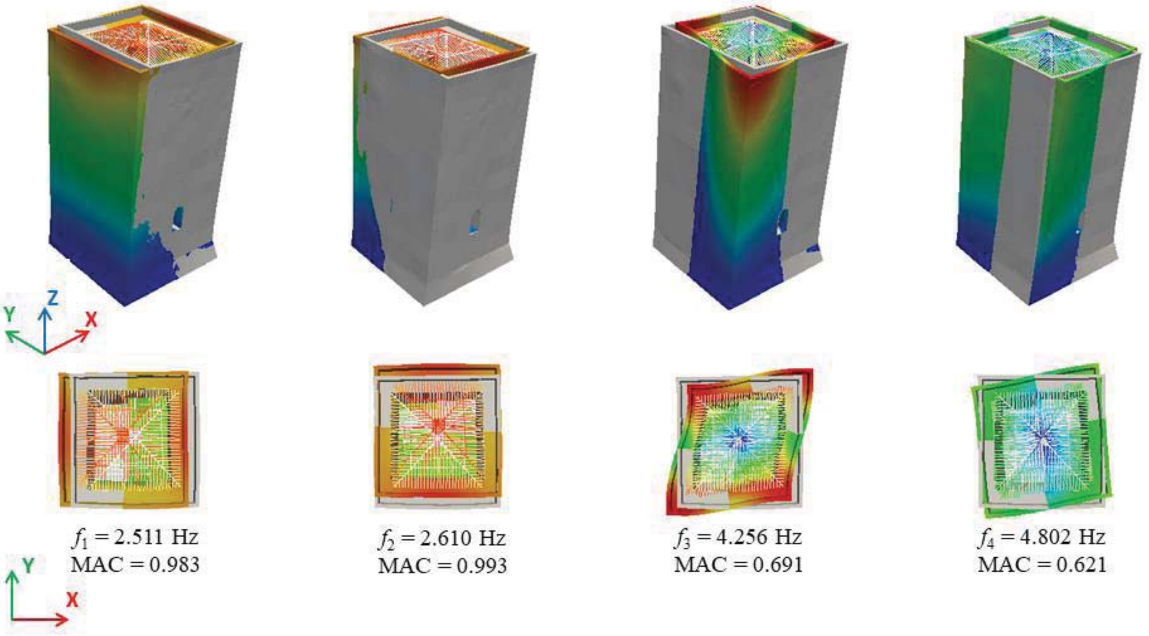
and trying to match the first four experimental frequencies and mode shapes of the tower. The parameter range for the wood material was chosen sufficiently large in order to take into account not only the uncertainties related to the knowledge of the mechanical characteristics of the material itself, but also the possible constraints between the wood elements and the masonry structure. The optimal mechanical parameters obtained through the model updating process are listed below:

$$E_m = 1686.5 \text{ MPa};\; E_{w1} = 290.66 \text{ MPa};\; E_{w2} = 454.76 \text{ MPa};\; E_{w3} = 890.92 \text{ MPa}$$

Table 3 summarizes the results of the optimization algorithm in terms of frequencies, absolute value of relative errors with respect to the experimental frequencies, and MAC values. The numerical mode shapes corresponding to the optimal values of the parameters are shown in Figure 9.

	Exp. [Hz]	Num. [Hz]	$\lvert\Delta\rvert$ [%]	MAC
f_1	2.68	2.51	6.34	0.98
f_2	2.74	2.61	4.74	0.99
f_3	3.88	4.26	9.79	0.69
f_4	4.81	4.80	0.21	0.62

Table 3: Model A – experimental frequencies, numerical frequencies, relative percentage errors, MAC values.



$f_1 = 2.511$ Hz
MAC = 0.983

$f_2 = 2.610$ Hz
MAC = 0.993

$f_3 = 4.256$ Hz
MAC = 0.691

$f_4 = 4.802$ Hz
MAC = 0.621

Figure 9: Model A – numerical mode shapes after the updating process (undeformed shape in grey).

In the attempt to improve the tuning with the experimental results, the same procedure was applied to Model B. In this case, the goal was to estimate the optimal values for the Young's modulus E_m and the mass density ρ_m of the masonry, assuming the following box Ω bounds for the parameters:

$$1000 \text{ MPa} \leq E_m \leq 8000 \text{ MPa}$$

$$2000 \text{ kg/m}^3 \leq \rho_m \leq 3000 \text{ kg/m}^3$$

The following parameter values were obtained through the optimization process:

$$E_m = 1955.8 \text{ MPa}; \quad \rho_m = 2877.14 \text{ kg/m}^3$$

It is interesting to note that the updated Young's modulus and mass density obtained are consistent with the values reported in literature [17], [18].

The overall results in terms of frequencies, absolute value of relative errors between experimental and numerical frequencies, and MAC values are presented in Table 4, while the numerical mode shapes corresponding to the optimal values of the parameters are displayed in Figure 10.

	Exp. [Hz]	Num. [Hz]	|Δ| [%]	MAC
f_1	2.68	2.61	2.61	0.98
f_2	2.74	2.70	1.46	0.99
f_3	3.88	3.83	1.29	0.69
f_4	4.81	5.08	5.61	0.64

Table 4: Model B – experimental frequencies, numerical frequencies, relative percentage errors, MAC values.

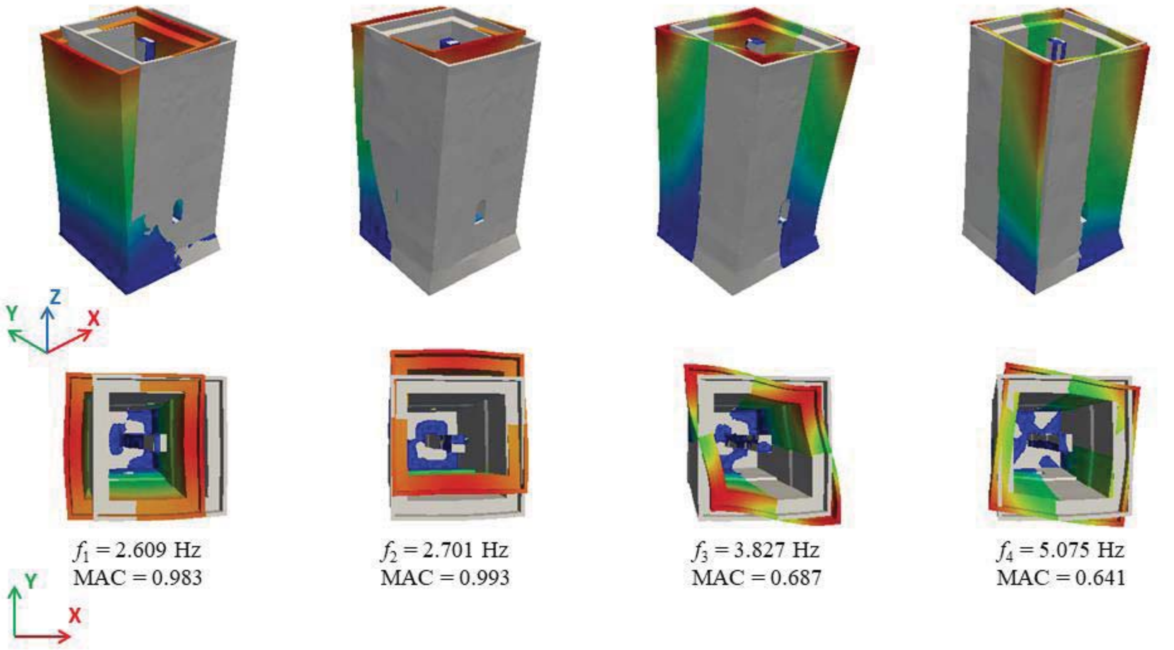


Figure 10: Model B – numerical mode shapes after the updating process (undeformed shape in grey).

Despite the similarities between numerical and experimental mode configurations, a high frequency percentage error is recorded for Model A. The comparison of the results with Model B shows that, if the wooden elements are not considered, the Young modulus of the masonry increases of about 15% and the mass density of nearly 10%; furthermore, the maximum relative error related to the two first frequencies decreases from 6.32% (Model A) to 2.65% (Model B). Regarding the MAC values, a good match between the two first experimental and numerical mode shapes is obtained for both models, while the third and fourth modal vectors are not very well approximated. Using an orthotropic material as done in [19] does not improve the numerical model, since the MAC value related to the third and fourth mode shapes remain unchanged.

5 CONCLUSIONS

The present paper aims to show the capabilities of an integrated and multidisciplinary approach to the complex problem of safeguarding heritage structures. The approach proposed here, encompassing digitalization, monitoring, numerical modelling and simulation, and relying on techniques and tools – either commercial or developed in house – at the disposal of the authors, is tested on the iconic tower keep of the Guimarães castle. The "laser acquisition – 3D digitalization – point cloud processing – CAD modelling – dynamic identification – finite element model updating" chain is described in all its steps, the ultimate goal being an accurate, fine-tuned numerical model of the tower. Such a digital counterpart of the real tower is of fundamental importance, since it constitutes the basis of any eventual finite element simulation aimed to predict the structural behavior of the tower under changing operational and environmental conditions.

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