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Abstract

The assessment of Cultural Heritage buildings is a challenging multi-disciplinary activity, involving different tasks. The paper exemplifies the application of the methodology involving historic and architectural research complemented by a dynamic survey in the structural modelling of the *Galleria degli*

Antichi, a monumental building built in the 16th century in the historic town of Sabbioneta (Italy), which is included in the UNESCO World Heritage list since 2008.
After a concise historic background on the investigated building, the paper focuses on the results obtained from operational modal testing and the subsequent finite element (FE) model correlation analysis.
The good knowledge of the structural geometry and the large number of identified vibration modes, combined with a classic system identification technique, allowed to establish a linear elastic FE model, accurately fitting the modal parameters of the monument in its present condition.

Keywords Architectural research - Cultural Heritage - Non-destructive testing - Operational modal analysis - System identification

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Vibration Testing and System Identification of a Monumental Building in Sabbioneta, Italy

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1 Introduction

The structural assessment of Cultural Heritage (CH) structures is a challenging multi-disciplinary process, whose importance is underlined by the ISCARSAH – ICOMOS Committee in a general document concerning the analysis and the structural restoration of Architectural Heritage [1]. It is generally agreed [2] that the structural assessment process starts with historic and documentary research and accurate on-site inspections and concludes with Finite Element (FE) modelling and numerical analysis: in principle, the collected knowledge of global and local geometry, the characteristics of masonry texture, the construction details and the mechanical characterization of the materials should be synthesized in the FE model of the structure. In the practice, the structural model of a historic structure, even when all the collected information is accurately represented, still involves remarkable uncertainties, e.g. in the material properties as well as in the boundary conditions. Only in recent years, the validation of the global performance of the model (at least in the elastic range) has drawn increasing attention

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as inaccurate assessment of a historic building can lead to overshooting of the structural interventions.

A possible practice to validate models is to employ ambient vibration testing (AVT) and operational modal analysis (OMA) in the diagnostic program. AVT and continuous dynamic monitoring are well-known non-destructive methodologies, generally aimed at identifying the dynamic characteristics of a structure—i.e., natural frequencies, mode shapes and modal damping ratios—from output-only records using OMA techniques, see e.g. [3]. It should be noticed that: (a) AVT is performed by just measuring the structural response to operational loads so that its fully non-destructive (ND) nature makes this test especially suitable to CH structures; (b) the identified modal parameters, describing the global behaviour of the structure in terms of characteristics of the key vibration modes, could be used to validate models [4, 5] and also as features sensitive to the structural condition [5].

The paper exemplifies the application of a fully ND methodology, involving architectural research complemented by AVT, to develop and validate the structural model of a monumental building in the historic town of Sabbioneta (Italy); the building, erected in the 16th century, is known as *Galleria degli Antichi* [6, 7].

A Historic-Building Information Model (H-BIM) is firstly created resuming all the information acquired in the previous investigation [8, 9]. Subsequently, a linear Finite Element (FE) model is established to allow an overall understanding of the structural behaviour [10] and AVT was conducted on the monumental building. A large number of normal modes were identified in the frequency range 0–9 Hz using the classic Frequency Domain Decomposition technique [11]. Therefore, the main assumptions adopted in the FE model were assessed through the comparison of measured and predicted modal behaviour and updating structural parameters of the model were selected and identified by minimizing the difference between theoretical and experimental natural frequencies, through a well-known system identification technique [12].

2 Description of the Monumental Building

The investigated CH building is the *Galleria degli Antichi* in the historic town of Sabbioneta (Italy). The *Galleria degli Antichi* (Fig. 1) was probably designed by Giuseppe Dattaro and built between 1583 and 1584 to host the art collection of the Duke Vespasiano Gonzaga. The town of Sabbioneta, included in the UNESCO World Heritage list in 2008, was built by in the 16th century by the Duke to establish the capital of his duchy. In about 35 years, the traces of the ancient settlements were transformed into a fortified Ideal City, recognized as one of the higher examples of the Renaissance principles in urban planning.

The *Galleria degli Antichi* is characterized by a long open arcade at the ground floor with 27 couple of massive squared columns made by brick masonry (Fig. 1b) supporting cross-vaults. The structure of the gallery is made of brick masonry (Fig. 1c). On the first floor, the building has a long gallery with 26 windows on each side. The gallery walls were frescoed and stuccoed in a very refined way by famous painters and craftsmen of the time [6, 7]. The gallery is covered by the wooden lacunar ceiling with richly decorated panels (Fig. 1c).

(a)
(b)
(c)


Fig. 1. Historic view of *Galleria degli Antichi* (a), masonry columns and crossed vaults (b), and first-floor level of the construction with the lacunar ceiling (c).

The construction is currently used as a museum, but the evidence of several changes of function has been found in the archives [6, 7]. For example, in 1927 troops billeted in the palaces as previously happened with the Napoleon Army (1806). In 1928, the building hosted the offices and the meeting rooms of the fascist party. In 1947 some halls on the ground floor of neighbouring *Palazzo Giardino* were used as food shop with a kitchen and in 1948 an organization - involved in social, cultural and free-time activities for the workers - rent some rooms. In 1975 and 1990 *Palazzo Giardino* and *Galleria degli Antichi* hosted the antique market.

The analysis of several historic documents was the first step of the building investigation. Documentary research was carried out in several archives, collecting documents aimed at pointing out the evolution of the buildings in the 20th century as well as the sequence of interventions and changes of use [6, 7].

The archive research also provides evidence of several repair interventions, which systematically followed each misuse of the building. The restorations mainly concerned the surfaces, the frescoes and the stuccos [6, 7]. Similarly, other interventions were carried out in 1935, 1953, 1966, 1989 and 2001 to repair the effect of the water leakage due to the roof damage. Metal ties restraining the crossing vaults were probably inserted during the works carried out in 1950.

The descriptions of damages and interventions in the archive records are in general very accurate, documenting the presence of cracks, as well. This last information is very useful, for example, to define the real entity of the damage caused by the 2012 earthquake [6, 7]. Furthermore, the available historical pictures (Fig. 1a) are of utmost importance to identify damages, as well as the transformations, occurred to the buildings.

After the 2012 earthquake, both *Galleria degli Antichi* and *Palazzo Giardino* underwent structural interventions. In this intervention: (a) steel ties were inserted at the level of the first floor and roof levels and anchored to the masonry walls (Fig. 2a); (b) at the extrados of the lacunar wooden ceiling, steel beams were anchored to the masonry pillars (Fig. 2b and c) and (c) steel beams were connected by a system of diagonal and transversal steel ties. Besides, timber tie beams were introduced in such an anchoring system, probably to distribute the axial compressive stresses (Fig. 2b).

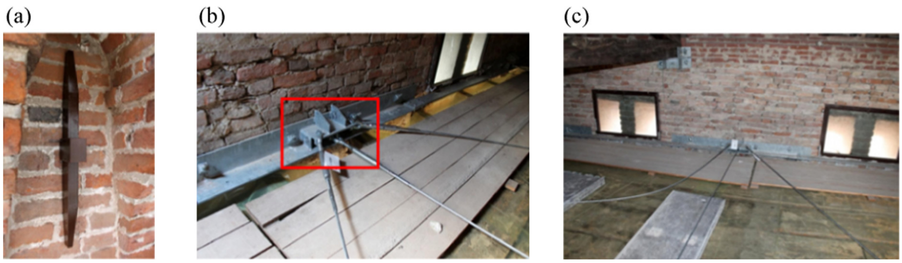

Fig. 2. Intervention after the 2012 earthquake: steel ties anchored to the masonry walls (a), steel beams at the extrados of the lacunar ceiling (b, c).

3 AVT, FE Modeling and Model Tuning

3.1 AVT and OMA

AVTs were conducted in February 2019 to identify the modal parameters of the historic building. Due to its easy accessibility, only the first-floor level was extensively instrumented and two set-ups were performed to cover 23 measurement points (Fig. 3a); 15 accelerometers were used in each set-up and 7 sensors were held stationary as reference transducers (Figs. 3b and 3c).

During the tests, the following devices were used: (a) one acquisition laptop Panasonic Toughbook CF-F9; (b) a multi-channel acquisition system with NI 9234 modules (24-bit resolution, 102 dB dynamic range and anti-aliasing filters); (c) 15 WR 731A piezoelectric accelerometers (10 V/g sensitivity and ±0.50 g of peak acceleration, Figs. 3b and 3c); (d) 15 WR P31 power unit amplifiers (Fig. 3b).

The sampling frequency was set equal to 200 Hz, which is more than enough for the investigated building, whose expected dominant frequencies are below 10 Hz (Fig. 4a). Therefore, low pass filtering and decimation were applied to down-sample the data to 40 Hz.

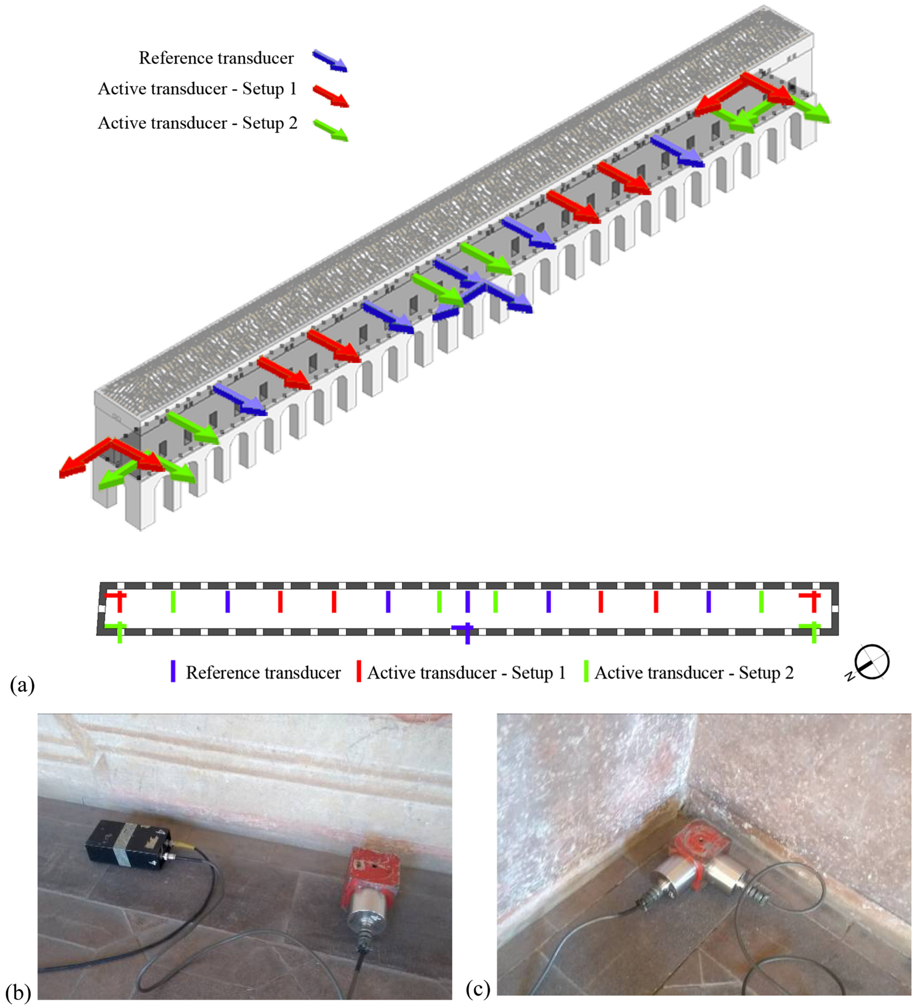

Fig. 3. Accelerometers layout and set-ups adopted in ambient vibration tests (a); Piezoelectric accelerometers in uni-axial (b) or bi-axial configuration (c).

The modal identification was performed considering time windows of 2700 s. The application of the Frequency Domain Decomposition (FDD) technique [11] implemented in the commercial software ARTeMIS [13] to the collected time series led to the identification of 12 transverse vibration modes in the frequency range of 0–9 Hz.

The results of OMA in terms of natural frequencies can be summarized through the plot of Fig. 4a, showing the first singular value lines (SV) of the spectral matrix. The inspection of Fig. 4a highlights that the FDD technique provides a clear indication of the building modes through well-defined local maxima in the first SV.

The corresponding mode shapes, referring to the extrados of the crossed vaults of the first floor, are shown in Fig. 4b: as it has to be expected, the vibration modes involving

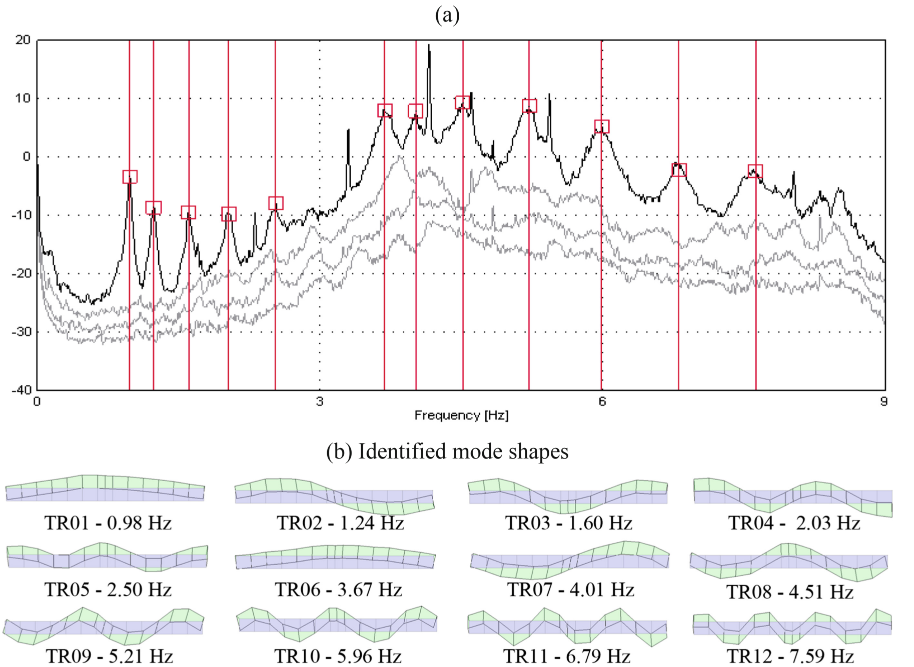

Fig. 4. First singular value lines and identification of natural frequencies (FDD) (a) and experimental mode shapes measured at the extrados of masonry vaults (b).

bending of the building in the transverse direction exhibit a sequence which is similar to the one of a beam supported by springs (Fig. 4b).

3.2 Finite Element Model and Modal Analysis

An H-BIM model was created in Revit® and subsequently exported in Robot Structural Analysis® to obtain a FE model [8, 9]. In such a model, the wall middle planes are represented by thick-shell elements, which are defined as 4-node quadrilateral elements (Q4). Regarding the behaviour of Q4 shell elements in connection with beam elements, perpendicular to the plane of finite elements, pinned connections are generated. The beams are modelled as linear elements, with 6 degrees of freedom at each node. In the lacunar wooden ceilings, the absence of rigid connections between wall-beam and beam-beam elements allows assuming that supports are pinned. The wooden and steel tie beams introduced during the 2012 interventions were modelled as truss elements according to their geometry and position. The selected mesh type is Delaunay, with a 0.2 m element size (Fig. 5a). Such a meshing process led the FE model to have 69179 nodes, with 67169 plane elements and 2676 bar elements; the total number of degrees of freedom is 412482.

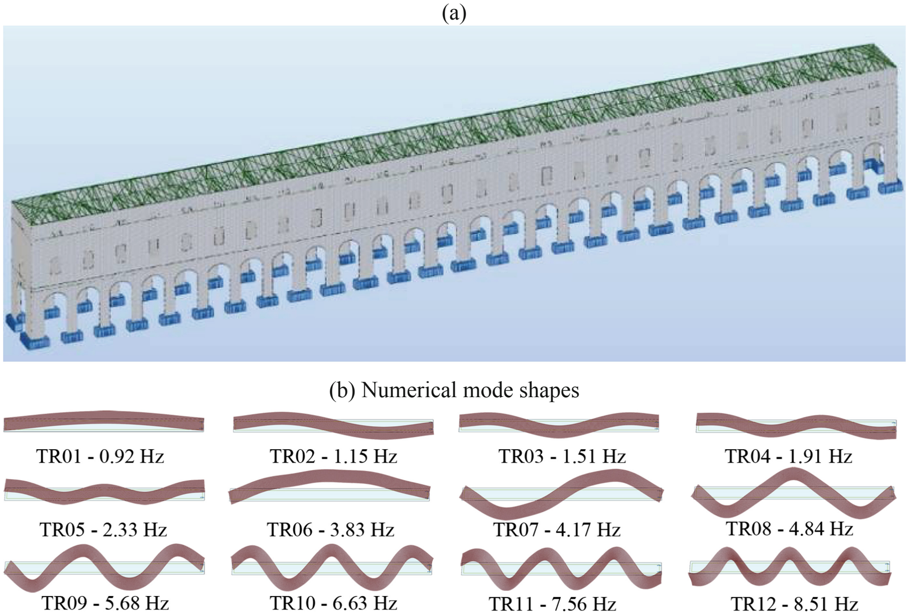

Fig. 5. FE model (a) and numerical mode shapes plotted at the extrados of masonry vaults (b).

The following initial assumptions were assumed for the masonry material in the numerical model: (a) homogeneous distribution of the masonry elastic properties; (b) the weight per unit volume and the Poisson's ratio of the masonry were assumed as 18.0 kN/m^3 and 0.20, respectively; (c) the average Young Modulus E was set equal to 1.8 GPa. Furthermore, the building foundations were supposed as fixed.

The geometric characteristics of the load-bearing walls and pillars were modelled according to the results of the geometric survey and direct inspections: (a) at ground level, the masonry pillars have a thickness of 1.275 m; (b) at first floor, the masonry walls have a thickness of 0.85 m; (c) at the upper level, even if walls are characterized by masonry arches on the façade, a constant equivalent thickness of 1.20 m was assumed (Fig. 5a).

Once the FE model was established, a preliminary modal analysis was performed to check the similarity between experimental and numerical modal parameters. The modal analysis was carried out in the same frequency range (0–10 Hz) of the observed vibration modes.

As usual, the dynamic characteristics of the base model and the experimental results are compared in terms of frequency discrepancy and using the Modal Assurance Criterion (MAC) [14] (Table 2) to establish the correct correspondence between experimental (Fig. 4b) and numerical (Fig. 5b) mode shapes. As shown in Figs. 4b and 5b, the correspondence between experimental and numerical results, notwithstanding remarkable differences in terms of natural frequencies, seems to provide sufficient verification of the model main assumptions, being a one-to-one correspondence between the mode shapes, with a worst MAC value of about 0.77.

3.3 FE Model Tuning

The numerical modes obtained in the previous modal analysis confirms that the simplifying assumptions adopted in the FE model correspond to an appropriate knowledge of the CH building. However, the numerical modal parameters differ from the experimental observations in terms of frequencies and modal shapes. A further refinement of the model consists in the selection of uncertain parameters of the model and in the estimation of those parameters by minimizing the difference between numerical and experimental natural frequencies.

In more details, the optimal values of updating structural parameters were calculated through the procedure proposed by Douglas and Reid (1982) [12]. According to [12], the updating parameters X_k (k = 1, 2, …, n) are iteratively estimated in a pre-selected range of values ($X_K^L \le X_\mathrm{k} \le X_K^U$) in order to minimize the following:

$$J(\boldsymbol{X}) = \sum_{i=1}^{M} w_i \left[f_i^{AVT} - f_i^{*}(\boldsymbol{X}) \right]^2 \tag{1}$$

where w_i is a weighting constant, f_i^{AVT} is the i-th experimentally identified natural frequency and $f_i^{*}(\boldsymbol{X})$ is the polynomial approximation [12] of the i-th natural frequencies of the model, expressed as functions of the $\boldsymbol{X}$ updating parameters.

After a sensitivity analysis, the set of updating parameters includes the following:

- The Young's Modulus (E_m) of the masonry columns and walls (ground floor and first floor levels), whereas the weight per unit volume (ρ_m) of the same structural elements was considered as known and equal to 18.0 kN/m^3 (Table 1);

Table 1. Lower and upper bound (LB, UB), base and optimal values (BV, OV) of the updating parameters of the numerical model.

	E_m (GPa)	E_c (GPa)	E_v (GPa)	ρ_c (kN/m^3)	ρ_v (kN/m^3)	t_v (m)	t_c (m)
LB	1.20	1.20	0.50	15.00	15.00	0.50	0.70
BV	1.80	1.80	1.00	18.00	18.00	0.60	1.20
UB	2.50	2.50	1.50	23.00	23.00	0.80	1.60
OV	1.74	1.97	0.59	15.10	21.61	0.71	1.08

- The Young Modulus, weight per unit volume and thickness both of cornice walls of the upper level (E_c, ρ_c, t_c) and masonry vaults (E_v, ρ_c, t_v) of the first floor (Table 1). It is worth mentioning that the above parameters also account for the simplifications involved by the modelling of vaults and cornice walls through shell-type finite elements.

The results of the model updating procedure are summarized in Tables 1 and 2. As shown in Table 2, the maximum relative error (DF) between natural frequencies, which was before updating 12.11%, became less than 7.0%.; furthermore, also the correspondence in terms of mode shape correlation is improved in the optimal model, with most of the MAC values exceeding 0.9. Hence, the updated FE model represents much better the observed dynamic characteristics of the *Galleria degli Antichi*, in terms both of resonant frequencies and mode shapes.

Table 2. Correlation between the experimental dynamic characteristics and the ones of base and updated model.

Mode	f^{AVT} (Hz)	Base model			Updated model		
		f^{FEM} (Hz)	MAC	DF (%)	f^{FEM} (Hz)	MAC	DF (%)
TR_{01}	0.98	0.92	1.00	−6.17	0.94	1.00	−3.97
TR_{02}	1.24	1.15	0.99	−7.61	1.16	0.99	−6.39
TR_{03}	1.60	1.51	0.98	−5.49	1.52	0.98	−4.95
TR_{04}	2.03	1.91	0.98	−6.08	1.91	0.97	−5.85
TR_{05}	2.50	2.33	0.81	−6.92	2.33	0.81	−6.81
TR_{06}	3.67	3.83	0.99	4.27	3.65	0.98	−0.53
TR_{07}	4.01	4.17	0.93	3.95	3.95	0.93	−1.50
TR_{08}	4.51	4.84	0.91	7.27	4.53	0.94	0.33
TR_{09}	5.21	5.68	0.91	9.16	5.26	0.93	1.02
TR_{10}	5.96	6.63	0.91	11.29	6.11	0.96	2.53
TR_{11}	6.79	7.56	0.77	11.32	7.01	0.91	3.33
TR_{12}	7.59	8.51	0.81	12.11	7.97	0.93	4.97
Average			0.92	7.31		0.94	3.51

4 Conclusions

The present paper shows as historic research, geometric survey and direct inspection - summarized in an H-BIM model - complemented by Ambient Vibration Tests allow understanding the structural modal behaviour of a Cultural Heritage Structure. The insight collected in the research permits drawing some conclusions:

a) merging the information collected by historical and architectural research, H-BIM and experimental tests should allow reducing the main uncertainties of the numerical models and to assess the structural behaviour of the building, in a fully non-destructive way;
b) the experimental results show that the assumptions made in the FE model - aimed at the global understanding of the structural behaviour - were consistent, i.e. all the experimental modes have the corresponding numerical modes;

c) aiming at the increase of the level of knowledge, a further step of model refinement is carried out and main parameters affecting the structural global behaviour were updated by a simple system identification method. As a result, a significant improvement of the correspondence between experimental and numerical modal parameters was obtained, in terms of frequencies and modal shapes.

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Chapter 23

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