THE ROLE OF OPERATIONAL MODAL ANALYSIS IN THE NON-DESTRUCTIVE ASSESSMENT OF AN ITALIAN MONUMENT

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ABSTRACT

The reliability of analyses of historical structures is affected by the large uncertainties in the characterization of construction and material properties as well as structural systems. Thus, non-destructive investigations play a fundamental role in the assessment of historical structures minimizing, at the same time, the invasiveness of interventions. Among non-destructive testing techniques, Operational Modal Analysis (OMA) is very popular and has wide applicative perspectives. The present paper discusses its role with reference to the assessment of an Italian heritage site, the Carthusian Monastery of Trisulti. Attention has been first focused on the use of OMA for the identification of the fundamental periods of the historical bell tower of the Saint Bartolomeo’s church. The fundamental period, in fact, plays a primary role in the definition of the expected earthquake loading on the structure. The second case study, instead, concerns the tests carried out on a number of tie-rods in the central cloister in order to indirectly estimate the tensile load in these members. An innovative system for in-situ non-destructive estimation of the tensile load in tie-rods is described. It takes advantage of an original algorithm for automated OMA and of a high performance measurement chain. This is able to resolve the low amplitude vibrations of the tie-rods in operational conditions without modifying their dynamic response. This result is obtained through the installation of high-performance, low-weight and high sensitivity accelerometers. The algorithm for automated OMA is described in its most relevant aspects and the obtained results are presented, pointing out the stability of the estimates.

Keywords: Operational Modal Analysis, bell tower, tensile load, tie-rods

1. INTRODUCTION

The preservation of historical structures is a challenging technical problem that requires a multidisciplinary approach and advanced diagnostics tools. Non-destructive tests and monitoring can mitigate the uncertainties about the structural behavior in operational conditions and under extreme events. The effects of recent earthquakes (L’Aquila, 2009; Emilia, 2012) on the Italian architectural
heritage stressed the need for a modern approach to assess and upgrade the performance of historical structures. Specific codes and recommendations have been developed, because historical structures share common characters with existing structures but they also show some peculiarities [1, 2]. Based on the most important results of the research in the field, the Italian Guidelines (Direttiva) for interventions on historical structures [3, 4] recommend dedicated investigation and analysis procedures. The Direttiva confirms the relevant role of Non Destructive Testing (NDT) to enhance the knowledge about the behavior of historical structures. In particular, potentialities of ambient vibration modal identification techniques for the estimation of the dynamic properties of structures and components in view of seismic performance assessment are recognized. The extensive literature about Operational Modal Analysis (OMA) confirms the wide applicative perspectives of these techniques. Typical applications are the calibration of Finite Element (FE) models, and vibration based Structural Health Monitoring (SHM). In the first case, the experimentally identified modal properties of the investigated structure are used to validate and refine the numerical model; as a result, an indirect, non-destructive estimation of selected – geometric or mechanical – parameters can be achieved [5]. OMA also plays a key role in damage detection and the development of effective SHM systems. The continuous monitoring of the modal parameters of the structure over time [6, 7, 8] and the analysis of their variations can provide useful information about the presence and eventually the location of damage at an early stage [9]. On the analogy, the analysis of the variations of the experimental estimates of the modal properties can give information about the effectiveness of certain types of strengthening interventions [10].

Attention is herein focused first on the analysis of the dynamic behavior of historical masonry towers by OMA techniques and the opportunities they provide for seismic assessment. In principle, they are characterized by a simple structural scheme, but the accurate prediction of their structural response can be affected by a number of uncertainties concerning, for instance, material properties, dynamic interaction effects and characteristics of foundations and subsoil. In what follows, the application of OMA to the analysis of the dynamic response of a historical masonry bell tower and to the indirect estimation of tensile loads in tie-rods is illustrated. The historical bell tower of the Saint Bartolomeo’s church in the Carthusian Monastery of Trisulti in Collepardo (Italy) represents an interesting and explanatory case study where OMA has provided a quick and reliable insight in the dynamic behavior of a structure characterized by complex construction layout. A short discussion about the use of the experimental estimates of the modal properties in the context of seismic vulnerability analysis of the bell tower is reported. The second case study, instead, concerns the output-only modal identification tests carried out on a number of tie-rods in the central cloister in order to indirectly estimate the tensile load in these members. The knowledge of the tensile load in the tie-rods of ancient masonry vaults is of primary importance to assess the stability of the macro-element and the capability to stand with the horizontal thrusts due to dead as well as earthquake loads. An innovative system for in-situ non-destructive estimation of the tensile load in tie-rods is described. It takes advantage of an original algorithm for automated output-only modal identification and of a high performance measurement chain. This is able to resolve the low amplitude vibrations of the tie-rods in operational conditions without affecting the dynamic response of the members. This result, in particular, is obtained through the installation of innovative, low-weight and high sensitivity accelerometers. The algorithm for automated OMA is described in its most relevant aspects. Then, the obtained results are presented and discussed, pointing out the stability of the estimates.

2. OMA OF MACRO-ELEMENTS AND COMPONENTS OF AN ITALIAN ARCHITECTURAL COMPLEX

2.1. The historical bell tower of the Saint Bartolomeo’s church at the Carthusian Monastery of Trisulti in Collepardo

The dynamic response to ambient vibrations of the San Bartolomeo’s church bell tower in the Carthusian Monastery of Trisulti in Collepardo has been analyzed to identify its fundamental modal properties. The analysis of documents collected in historical archives provided a sound basis for the understanding of the construction features of the tower and guided the definition of the experimental
layout. This was specifically designed to identify the fundamental bending modes of the structure and the related distribution of the modal displacements along the height in view of multi-level seismic analyses. However, due to the limited number of sensors and time constraints, this resulted in a less accurate definition of the shape of torsional modes.

The Carthusian monastery of Trisulti lies on the Ernici mountains in the Apennines of Lazio (Central Italy). The erection of the monastery was completed in 1211; thereafter, it was further enlarged and remodelled in the Baroque Age and in the Eighteenth Century. The church of San Bartolomeo is located at the center of the monastery. A single nave covered by a pointed vault characterizes the interior. The bell tower (Figure 1) is made by limestone with a well-defined and marked cornice for the first half; the remaining half was made by brick masonry to reduce the total weight of the structure. The tower underwent a number of restoration interventions over the centuries. In particular, 2010 the bell tower underwent a major restoration because of the widespread presence of alterations and degradation as well as of micro cracks and fractures. Large cracks were present in the brick masonry near the metallic elements (bells anchoring, railings and reinforcements). Another relevant crack pattern was found in the middle column made by bricks on the outside wall that overlooks the square of the church; this crack was attributed to the stress induced by the swinging bells. Consequently, the whole bell complex, consisting of a central large bell and four smaller bells, was anchored to a new steel frame aiming at reducing the stresses induced on the walls of the tower. The irregularities of shape (Figure 2) and material along the height of the bell tower and the uncertainties in reconstructing the restoration interventions carried out over the centuries made the accurate prediction of the dynamic and seismic behaviour of the structure quite complex.

The interaction with the surrounding structure of the church and the level of restraint that it offers to the lower part of the tower required specific attention in view of the vulnerability assessment of the tower. In order to reduce the uncertainties and get a reference set of accurate modal parameter estimates, experimental investigations have been carried out. OMA tests have been therefore carried out to accurately identify the modal properties of the bell tower in view of multi-level seismic analyses. The dynamic response of the structure was measured at five different levels by seven couples of accelerometers, some of which were placed at opposite corners of the tower to observe bending as well as torsion modes (Figure 2). Force balance accelerometers characterized by 200 Hz
bandwidth (starting from DC), 140 dB dynamic range, 0.5 g full-scale range and 20 V/g sensitivity were installed. The structural response to ambient vibrations was measured for 3600 sec at a sampling frequency of 100 Hz. After the preliminary validation of the recorded time series and offset and spurious trends removal [11], data have been low-pass filtered and decimated (by a factor of four) to focus the attention on the fundamental bending modes that are those of interest in simplified seismic analyses. The corresponding natural frequencies were expected to be well within the range [0, 10] Hz. The focus on the fundamental bending modes of the tower is also witnessed by the adopted sensor layout (Figure 2). In fact, it was set in order to have estimates of the modal displacements of the fundamental bending modes along the whole height of the tower. Due to the limited number of available sensors and time constraints, the discrimination of torsional modes from bending modes was ensured by only four couples of accelerometers installed at the upper levels of the structure. This obviously resulted in a less accurate definition of the shape of torsional modes. However, this was not critical for the objectives of the study. The modal parameters were extracted by applying both parametric and non-parametric OMA procedures, working in time domain as well as frequency domain. In the frequency domain Hanning window and 66% overlap were applied in spectrum computation. The use of different OMA techniques ensured the reliability of the obtained results thanks to the possibility of carrying out cross-validation checks. The accuracy of modal parameter estimates was also ensured by the application of appropriate data processing techniques [12, 13]. Powerful and robust OMA techniques [14], such as the Frequency Domain Decomposition (FDD), the Covariance Driven Stochastic Subspace Identification (Cov-SSI) and the Second Order Blind Identification (SOBI), were adopted.

The results are summarized in Table 1 while the identified mode shapes are shown in Figure 3. The graphical representation of the mode shapes is limited to the upper levels where the adopted sensor layout was adequate to observe also the torsional motion. However, the modal displacements have been estimated also at the lower levels. In fact, the subsequent vulnerability analyses required the knowledge of the distribution of the modal displacements along the whole height of the structure for the fundamental bending modes. Even if not reported, the estimated modal displacements at the lower levels of the tower showed negligible displacements in the X direction for bending as well as torsional modes, while larger displacements were observed in the Y direction, confirming that the nearby church offers different degrees of restraint in the two directions. All the identified modes are normal.

The reliability of the obtained results was confirmed by cross-checks in terms of natural frequencies as well as mode shape estimates. Consistent results, characterized by negligible scatter in terms of natural frequency estimates and good correlation in terms of mode shape estimates, as pointed out by the MAC values close to 1 in Table 1, were obtained from the different methods, thus confirming the
success of the identification process.

Table 1. Output-only modal identification results.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Type</th>
<th>FDD</th>
<th>Cov-SSI</th>
<th>SOBI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>f (Hz)</td>
<td>ξ (%)</td>
<td>MAC_fDD-SSI</td>
</tr>
<tr>
<td>I</td>
<td>Transl. y</td>
<td>4.10</td>
<td>0.4</td>
<td>0.999</td>
</tr>
<tr>
<td>II</td>
<td>Transl. x</td>
<td>4.72</td>
<td>0.5</td>
<td>0.996</td>
</tr>
<tr>
<td>III</td>
<td>Transl. y &amp;</td>
<td>8.16</td>
<td>1.0</td>
<td>0.985</td>
</tr>
<tr>
<td></td>
<td>Torsion</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>Torsional</td>
<td>9.14</td>
<td>0.5</td>
<td>0.979</td>
</tr>
</tbody>
</table>

Figure 3. Plots of the identified mode shapes: mode I to IV from left to right.

2.2. Vibration-based estimation of tensile load in the tie-rods of the Cloister

An attractive application of automated OMA procedures concerns the indirect estimation of tensile loads in cables and tie-rods from vibration measurements. It provides interesting opportunities for cheap and fast quality checks in the construction phase, as well as safety evaluations and structural maintenance over the structure lifespan. An extensive literature review [8] reveals that several vibration-based tensile load estimation methods take advantage of the known input applied by an impact hammer and eventually of the results of a numerical model. The application of a known input is usually more relevant in the case of tie-rods. In fact, when OMA is applied, it requires a trade-off between the needs of resolving low amplitude vibrations and, at the same time, of minimizing the dimensions of the sensors so that they do not alter the dynamic response of the member. Nevertheless, the increasing availability of miniaturized, high performance accelerometers and of automated OMA algorithms is fostering the development of ambient vibration-based systems for tensile load estimation.

The development and application of an innovative system for in-situ vibration-based estimation of the tensile load in tie-rods is herein described. It takes advantage of an original algorithm for automated OMA and of a high performance measurement chain. The automated output-only modal identification algorithm is based on the combination of different OMA techniques in order to simplify the analysis and interpretation of the stabilization diagram. The preliminary, approximate separation of the modal contributions operated by SOBI simplifies the analysis of the data and the interpretation of the stabilization diagram provided by the Covariance Driven SSI method, because the modal information is extracted from individual approximate correlation function, which theoretically include information about one mode at the time. Spurious and physical poles are then discriminated by means of clustering techniques and mode validation criteria [8]. The final estimates of natural frequencies and damping
ratios are obtained by sensitivity analyses with respect to the number of block rows $i$ in SSI, for a fixed value of the maximum model order in the stabilization diagram. The cluster characterized by the minimum variance of the estimates when varying $i$ is selected as the one providing the best estimate of the modal parameters for a given structural mode [8]. Mode shape estimates are finally obtained from Singular Value Decomposition (SVD) of the output Power Spectral Density (PSD) matrix at the previously estimated frequency of the mode [8].

The effectiveness of tensile load estimation depends on the accuracy of modal parameter estimates. Most of the available automated OMA algorithms suffer common drawbacks [6] that affect their accuracy. They are due to the adoption of statically set thresholds and parameters that have to be tuned at startup [6]. The key feature of the proposed algorithm is the absence of any analysis parameter to be tuned [8]. The performance of the proposed algorithm in terms of accuracy and reliability of estimates has been investigated through extensive tests based on simulated data and real measurements [8]. The analysis of the obtained results has pointed out that the algorithm carries out automated output-only modal identification in a very robust way, providing accurate even at low signal-to-noise ratios [8]. The tensile load is obtained from the estimated modal parameters by solving an inverse problem. In the most general case of uncertain boundary conditions, the experimental estimate of the mode shape of the member in at least five positions is needed. In fact, taking into account the equation governing the dynamic behavior of a beam with uniform section subjected to a constant axial tensile force:

$$EI \frac{\partial^4 v(x,t)}{\partial x^4} + N \frac{\partial^2 v(x,t)}{\partial x^2} + \rho \frac{\partial^2 v(x,t)}{\partial t^2} = 0$$

(1)

where $EI$ represents the bending stiffness, $\rho$ is the mass per unit length, $v$ is the transversal displacement and $N$ the tensile force, the shapes of the vibrating beam are given by:

$$\varphi(x) = C_1 \sin(\alpha x) + C_2 \cos(\alpha x) + C_3 \sinh(\beta x) + C_4 \cosh(\beta x)$$

(2)

where:

$$\alpha^2 = \frac{N}{2EI} \left( \sqrt{1 + \frac{4\omega^2 \rho EI}{N^2}} - 1 \right), \quad \beta^2 = \frac{N}{2EI} \left( \sqrt{1 + \frac{4\omega^2 \rho EI}{N^2}} + 1 \right).$$

(3)

The coefficients $C_1$, $C_2$, $C_3$ and $C_4$ are determined from the known modal displacements in four points of the beam, while the last modal displacement is used, together with the estimate of the natural frequency of the mode, to compute the tensile load $N$. More details can be found elsewhere [15].

**Figure 4.** Vibration-based testing of tie-rods: measurement system (a), installed sensor (b).

Starting from the above described algorithms, an innovative system for tensile load estimation has been developed by S2X s.r.l., a spin off company of the University of Molise. It is a compact system able to acquire and automatically process the ambient vibration response of tie-rods, providing estimates of the fundamental modal properties and the tensile load in operational conditions [8]. The portable system (Figure 4a) consists of two boards working in parallel. The first board is dedicated to
data acquisition and storage, while the second carries out the automated modal parameter identification and the estimation of the tensile load. The system can acquire data from a maximum of eight IEPE accelerometers by means of the integrated NI PCI 4472b board. The system is complemented by a set of seismic, miniature (50 gm) IEPE accelerometers (Figure 4b). The characteristics of the sensors are: 10 V/g sensitivity, 0.7-450 Hz bandwidth, 0.5 g pk full-scale range. The data acquisition system is characterized by 24-bit Sigma-Delta ADCs for simultaneous sampling of the eight channels, analog antialiasing filters, 110 dB dynamic range, 102.4 kHz maximum sampling rate. This measurement chain is able to resolve the low amplitude vibrations of the tie-rods in operational conditions without modifying their dynamic response. Non-destructive vibration-based tests have been therefore carried out to estimate the tensile load in four tie-rods of the cloister of the Carthusian Monastery (Figure 5) and assess their role in the present equilibrium condition of the structure.

Reference values of 210 GPa and 7800 kg/m³ have been adopted for the Young’s modulus and the density of the steel, respectively. Stable estimates of the tensile loads have been obtained, as reported in Table 2. Even if the analysis of documents collected in the Public Archive in Frosinone highlighted that, after the restoration interventions carried out in 1936, the tie-rods in the cloister of the Monastery were not tensioned, the obtained results point out that the investigated tie-rods are subjected to tensile loads in operational conditions.

<table>
<thead>
<tr>
<th>Rod #</th>
<th>Base (mm)</th>
<th>Height (mm)</th>
<th>Net span (m)</th>
<th>Number of estimates</th>
<th>f̃ (Hz)</th>
<th>Ñ (kN)</th>
<th>σ (kN)</th>
<th>γ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28.8</td>
<td>29.3</td>
<td>3.21</td>
<td>31</td>
<td>13.58</td>
<td>30.3</td>
<td>0.9</td>
<td>3.0</td>
</tr>
<tr>
<td>2</td>
<td>29.4</td>
<td>29.0</td>
<td>3.24</td>
<td>12</td>
<td>15.72</td>
<td>43.0</td>
<td>0.6</td>
<td>1.4</td>
</tr>
<tr>
<td>3</td>
<td>29.3</td>
<td>29.7</td>
<td>3.17</td>
<td>35</td>
<td>14.46</td>
<td>38.5</td>
<td>0.6</td>
<td>1.6</td>
</tr>
<tr>
<td>4</td>
<td>29.5</td>
<td>29.4</td>
<td>3.17</td>
<td>12</td>
<td>16.17</td>
<td>39.4</td>
<td>0.2</td>
<td>0.5</td>
</tr>
</tbody>
</table>

3. CONCLUSIONS

The applicative perspectives of OMA in the context of multi-level seismic vulnerability analyses of historical structures have been discussed with reference to an explanatory case, the Carthusian Monastery of Trisulti in Collepardo. In agreement with the Italian Guidelines for interventions on historical structures, the paper has remarked how modal parameter estimates obtained from ambient vibration tests can be used to enhance the knowledge of construction and structural detailing and so doing the reliability of seismic vulnerability analyses. Moreover, OMA can be applied as NDT to get additional information for the structural assessment, such as the tensile load in tie-rods. An innovative system for tensile load estimation based on an original automated OMA algorithm has been described, obtaining very stable results.
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