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VULNERABILITY ASSESSMENT OF A CIVIC TOWER USING AMBIENT VIBRATION TESTS

GIAN PAOLO CIMELLARO, MARCO DOMANESCHI, ALI ZAMANI NOORI, and VALENTINA VILLA

Dept of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Turin, Italy

This paper focuses on the vulnerability assessment of a civic tower built in 1512, which is now considered a national monument. It is the original bell tower of S. Ambrogio church that was destroyed in 1809. Experimental investigations have been carried out on this historical tower. First, detailed investigations have been carried out to identify the geometry of the tower as well as the mechanical features of the constituting materials. Then, ambient vibration tests have been applied using five Micro Electro-Mechanical Systems (MEMS) sensors to detect of the main dynamic features, e.g., modal parameters and damping. Two output-only identification methods, including Frequency Domain Decomposition and Random Decrement Techniques, have been used. The outcomes of the modal identification have been employed to inform the FE model. The numerical analysis can be used for vulnerability assessment, providing a valuable picture of possible damage evolution, tower collapse mechanism, and subsequently, useful hints for the execution of structural retrofitting strategies.

Keywords: Structural health monitoring, Output-only method, Damage evolution, Numerical model, Modal shape, Historical monument.

1 INTRODUCTION

A strong earthquake may have disastrous consequences where structures have been designed without appropriate seismic codes. This is even more critical when it comes to national heritage structures such as historical buildings and civic towers. Vulnerability assessment for a historical masonry tower is often a complex task. Historical masonry towers are usually brittle structures due to the limited ductility of the masonry combined with the large scale of the tower. Furthermore, they can be described as coupled modes. Therefore, it is crucial to identify the structural collapse mechanism by evaluating the stable damage patterns and damage evolution.

The seismic vulnerability of a historical heritage depends on several key parameters and it can be described as its susceptibility to damage by ground shaking of a given intensity. The aim is to obtain the probability of a given damage level due to an earthquake scenario. As design data, it requires information such as the quality of the constituting materials, the building age, the level of maintenance, etc., which can be collected through inspections and surveys. Subsequently, it is required to assess the maximum bearing capacity of the structure by the creation of a digital model built on investigational tests. To calibrate the first analytical model, the system identification can be used. The system identification can also be used in a general SHM (structural health monitoring) approach to identify existence, place, and degradation conditions in the structural elements.

Different studies have been performed to assess the vulnerability of historical monuments, including both empirical and analytical methods. Asteris *et al.* (2014) presented a methodology for vulnerability assessment of masonry structural systems. They tested the entire process using case studies from historical masonry structures in Greece, Portugal, and Cyprus. Later on, the seismic vulnerability assessment of a historic masonry building in Central Italy after the 2012 seismic events (May 20th and 29th) are reported by Formisano and Marzo (2017) using a simplified approach given by Italian Guidelines on Cultural Heritage. Di Lorenzo *et al.* (2019) investigated the seismic behavior of a masonry church through a two-steps approach. It consisted of a preliminary experimental campaign based on Ambient Vibration Tests (AVT) to evaluate the modal characteristics of the structure.

This paper proposes a methodology that combines specific processes to identify the vibrational signature, such as modal parameters, applied to a civic tower located in northern Italy. The main goal is to examine the global dynamic behavior of the tower and explain the analysis performed to characterize its dynamic response. The methodology starts with the acquisition of geometry and deviation from verticality by performing a series of experimental field investigations. Then, AVTs are employed to identify its dynamic signature. In order to update the finite element model for further vulnerability assessment, the results of modal identification were used.

2 FIELD INVESTIGATION

A sixteenth-century masonry tower located in Melzo (Italy) has been used as a case study. No information was found for geometry or mechanical characteristics of the tower. Therefore, a detailed geometrical survey and a series of nondestructive evaluation techniques have been adopted to assess the present situation of the tower without perturbations. The tower is a typical bell tower with a square plan of 6.85×6.85 m and a height of about 22.80 m.

Figure **1** shows an external view of the tower. It consists of the three typical bodies of bell towers built on this period: (i) square-basement prism, (ii) central body, and (iii) bell segment.

(a) (b) (c) (d)

Figure 1. Tower 3D view (a), inner cylindrical shell (b), bell (c) and schematic view (d).

The basement is made of stone blocks (Ceppo dell'Adda material), while the central body is made of mortar and bricks. It is composed of an outer square shell and an inner cylindrical ring

(Figure 1b). The inner ring is connected to the outer shell through spiral stairs along with the total height of the tower, making it a rigid column. The outer shell is confined with a 50 cm stone ring beam located at 11.00 m from the ground, and 8 total tie rods inserted in both two principal directions of tower at the two different levels. In addition, the outer shell is flanked at the corners by four pillars made of stone blocks with an average dimension of 0.50×0.75 m. The bell segment is made of perimeter masonry walls consists of four openings at each side. It houses 3 bells supported on a portal steel frame located at an elevation of 2.45 m from the floor slab (Figure 1c). The bell's mass distribution is asymmetric in the plan due to the arrangement of the bells. The tower roof is made of wooden beam elements simply supported on the perimeter walls that do not perform any structural function. A schematic view of the tower is presented in Figure 1d.

Visual inspection of the surface of the exterior finish revealed small cracks. The position analysis showed the presence of microcracks positioned on the inner ring. During the investigation, cracks were detected at the bottom, both on the north and east faces of the tower. The finishing layer consists of plaster about 1 cm thick.

3 DYNAMIC CHARACTERIZATION

The vulnerability assessment is based on the identification algorithm to obtain structural dynamic characteristics. The classical input-output identification algorithms are not applicable to historic buildings. These methods are based on the application of an external perturbation (e.g., hammer test or vibrodyne) to the structure with the collection of the structural response; while considering the historical heritage, avoiding any damage remains the mandatory requirement. This leads to consider output-only techniques using ambient vibrations (Domaneschi *et al.* 2017).

In this paper, dynamic characteristics have been identified using the Ambient Vibration Test (AVT) and the results subsequently have been used to calibrate the FE model. The output-only methods have been used to analyze the experimental data. Output-only methods compared with other methods (e.g., input-output methods) are fast and economical since no equipment is required to excite the structure. Furthermore, the tests can be performed during normal operating conditions. Two different output-only methods, including Frequency Domain Decomposition (FDD) and Random Decrement Technique (RDT), have been implemented to identify the tower dynamic characteristics. Further information about these methods can be found in Cimellaro *et al.* (2012).

4 MODAL PARAMETERS IDENTIFICATION

A wireless sensor network was used to collect accelerations at different heights of the tower during AVTs. The network consisted of five sensing units equipped with five Force Balance (FB) tri-axial accelerometers (numbered from #50 to #54). The sensors are characterized by a low signal-to-noise-ratio (2.5 μg/√Hz) accelerometer with a dynamic range of 160 dB. The units also implemented GPS receivers allowing creating a local network of synchronized instruments using absolute time, in which one sensor assumes to be the '*Master*' and the others are '*Slaves*'. The Master unit was implemented to communicate with the other ones, collecting data from the Slaves units, and coordinate the connection with a remote server. The network can be connected to a PC to manage the data recording, downloading, and processing in real-time through the remote connection.

The sensor configuration was designed in such a way as to record torsional modes of the tower. Thus, two sensors (#53 and #54) were applied diagonally at the top platform of the tower to measure the torsional behavior while the other ones (#51 and #52) were placed at different heights to record the flexural behavior. Furthermore, a sensor was placed at the ground to register the input ambient vibration signals. Due to external conditions and background noise from nearby activities, several tests were repeated at different times to record the least disturbed data possible. Finally, less disturbed signals were considered for dynamic identification. Each test had a duration of about 15 minutes, with a sampling frequency fixed at 200 Hz. Figure 2 shows the positioning of FB accelerometers on the tower schematically. With this arrangement, the E–W and N–S vibrations of the tower can be measured.

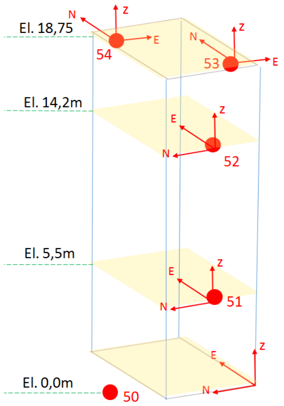
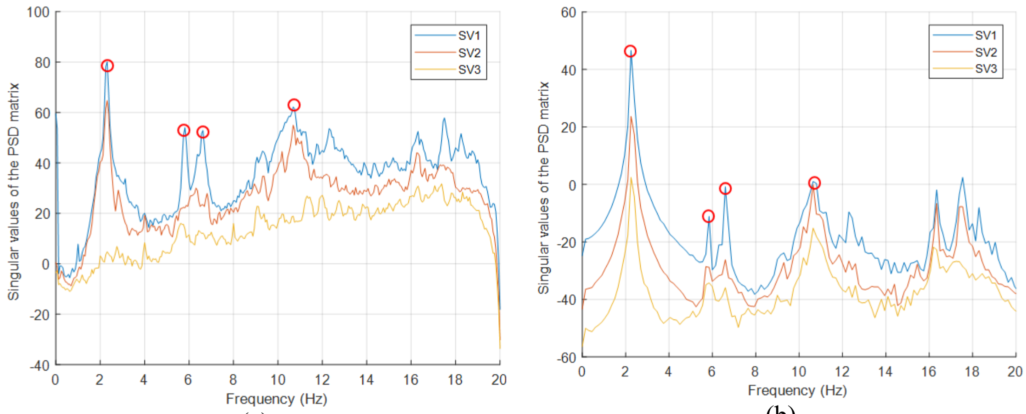


Figure 2. Force balance sensors configuration.

4.1 Data Processing

A low-pass filter was used, setting the cut-off frequency at the value of 20 Hz and the resulting signals were processed through FDD and RDT techniques. Figure 3a and Figure 3b show the identified modal frequencies obtained in the East direction through FDD and RDT techniques, respectively. It shows that the peaks are clearly visible at the same frequency values for both methods.



(a) (b)

Figure 3. Singular values of PSD at East direction; FDD (a) and RDT (b) techniques.

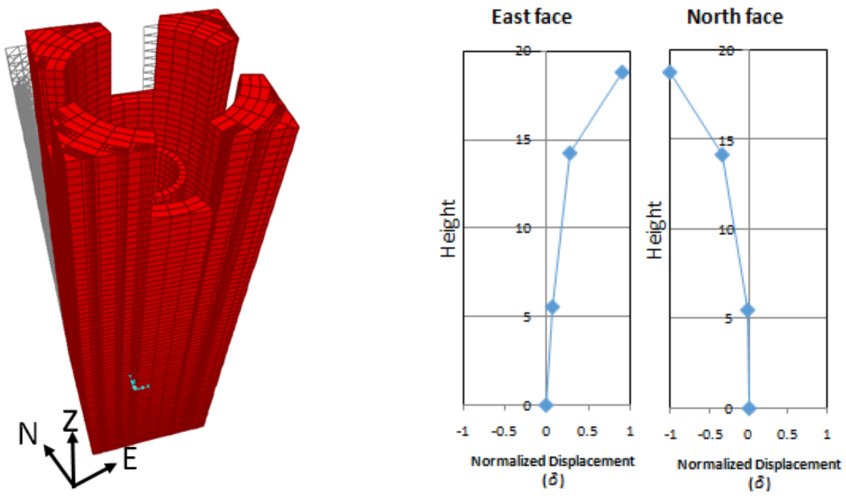
Table 1 presents the tower natural frequencies identified through FDD and RDT techniques. Results indicate equivalent values in both N-S and E-W directions that can be associated with torsional modes or flexural modes along the diagonal direction. In particular, frequencies from both algorithms are comparable, with a main diagonal flexural shape in the direction of N-E, the second flexural diagonal mode in the direction of S-E, and the third as a torsional mode. The results show that the translational and torsional frequencies are coupled due to a high level of structural complexity and rigidity.

Table 1. Identified natural frequencies.

Frequency	**E-W direction**		**N-E direction**	
	FDD [Hz]	**RDT** [Hz]	FDD [Hz]	**RDT** [Hz]
1	2.33	2.28	2.31	2.25
2	5.78	5.88	5.81	5.85
3	6.62	6.62	6.81	6.90
4	10.73	10.66	10.69	10.64

5 NUMERICAL MODELING

A FE model has been created and calibrated with respect to natural frequencies and modal shapes from on-site investigations. The longitudinal elastic modulus proposed within the Italian law has been reduced by about 20% to take into account the presence of cracks detected on the walls of the tower.



(a)

(b)

Figure 4. First modal shape obtained through FE model (a) and experimental tests (b).

The model is based on 8-node solid elements with a uniform mass distribution along with the tower height. It consists of 3259 solid elements and 15605 degrees of freedom. They allow considering shear deformation effects. The inner cylindrical shell is connected to the outer surface by defining rigid link elements to take into account the staircase. Furthermore, 8 tie-rods have been modeled in both x and y directions inserting at two different levels by use of the post-tensioning bar element. The element's internal forces have been varied to calibrate the model with respect to experimental results. Figure 4a shows a qualitative comparison between the first mode shapes of tower computed using the FE model and the one obtained by experimental results (Figure 4b) in the north direction. Furthermore, the results show a good agreement between the natural frequencies for the first three modes calculated by the FE model and output-only methods.

6 CONCLUSIONS

The modal characteristics of a masonry civic tower were determined using ambient vibration tests. Output-only modal identification techniques were used to analyze the registered signals. Measurements were made along with the height of the tower using a wireless sensor network consisting. Mode shapes and frequencies were computed that mainly consist of two flexural modes in the N-W and N-E directions and a torsional mode within the frequency range 0-10.7Hz. Results show that the main frequencies are coupled due to a high level of structural complexity and rigidity. Subsequently, the dynamic parameters were employed in a model updating procedure by modifying the elastic modulus of the material and the post-tensioning force of the tie rods. The results from the numerical analysis, combined with monitoring of the structure, provide valuable hints for assessing the vulnerability of the structure. Further, they can also be useful to evaluate different retrofits and restorations.

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