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NUMERICAL AND OPERATIONAL MODAL ANALYSES OF A MASONRY BELL-TOWER INSERTED IN A BUILDING AGGREGATE

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Abstract

Historical structures are a key asset of the cultural heritage for the fundamental role they play in preserving social identity. Therefore, any conservation techniques should respect their historical and cultural values. In this respect, structural health monitoring through in situ dynamic tests are becoming very popular to define the maintenance condition of a structure and to give insight into its overall behavior. Especially for historical structures, Operational Modal Analysis (OMA) is a powerful approach since it avoids to shake the structure artificially. This paper discusses the assessment of the dynamic behavior of the Sant'Agostino bell-tower in Benevento (Italy). The selected case study represents a typical example of a masonry tower inserted into a building aggregate. Based on experimental results obtained through an ambient vibration test, the frequency domain decomposition (FDD) and Stochastic Subspace Identification (SSI) techniques are employed to evaluate frequencies and mode shapes. These modal parameters are subsequently used to calibrate a 3D finite element (FE) model of the bell-tower by changing material properties and boundary conditions through the application of a systematic manual tuning.

A very good match is reached between analytical and experimental modal parameters and some important structural parameters are identified by the model updating. The results confirms that the OMA technique is able to detect effective information on the dynamic behavior of historical structures that can be useful to update a reliable numerical model for structural analysis.

Keywords: Masonry bell-tower; Ambient vibration test; Dynamic parameters; Operational Modal Analysis; Finite element method; Model updating

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1 INTRODUCTION

The dynamic identification of structures is one of the most important non-destructive techniques to know the seismic behavior of civil engineering building systems. It has been shown that dynamic tests represent a potentially very effective investigation methodology, capable of obtaining multiple information regarding both the entire structure and the local damage [1-2]. The application of these methodologies to the building stock and, more generally, to the historical buildings, is a theme that has been considered and developed only in recent decades and it is still in full evolution [3-5].

In general, the experimental study of the structural vulnerability of a historical structure through the identification of its dynamic characteristics, allows the development and updating of complex finite element models (FEM) [6-7].

It is also possible, through the use of dynamic monitoring systems, to determine both global and local behavior of a structure. This knowledge leads to the best choice of the most appropriate intervention, if necessary, and allows the analysis of the effectiveness of the reinforcement techniques on the considered structures. However, it should be stressed that the application of modal identification to historical buildings is a difficult issue, due to the great variability of the mechanical properties of masonry, unlike other more homogeneous materials, such as r.c. or steel [8-11].

In the paper, the dynamic behavior of masonry tower inserted into a building aggregate, the S. Agostino complex, in Benevento, Italy, is investigated by ambient vibration test and operational modal analysis. The extraction of the modal parameters (frequencies and modal shapes) from ambient vibration data has been carried out both in the frequency and time domain. Two different well-known identification techniques, i.e., the Frequency Domain De-composition (FDD) and the Stochastic Subspace Identification (SSI) were applied yielding to very similar results for all identified modes.

The investigation was completed developing a 3D finite element model of the bell-tower and the correlation between measured and predicted modal parameter is presented and discussed showing the importance of modelling the interaction of the bell-tower with the surrounding masonry complex.

2 THE CASE STUDY

The Sant' Agostino complex (Fig.1) is a historical masonry building located in the city centre of Benevento, Italy. The structure, built most likely in the XIII century, was used for several functions over the years. It was a monastery until 1900 when it was converted into a Carabinieri barrack. Nowadays, it hosts part of the Engineering Department of the University of Sannio. It consists of the ancient monastery (currently a lecture building) with an adjoining bell tower and the Augustinian church (now an auditorium) that includes its oratory.

(a) (b)

Figure 1: (a) View of the Sant'Agostino complex; (b) detail of the bell-tower.

This paper focuses on the bell-tower for which the dynamic identification and the assessment of the degree of constraint with the entire structural complex is performed.

The bell tower that dominates the entire structural complex with its 25 m of height is the oldest structural unit along with the auditorium. Over the years it has experienced countless earthquakes that have characterized the seismic history of the Samnite territory suffering collapses and as well as many reconstructions, the last of which dates back to 1716.

The tower is incorporated into the structural complex. In fact, it is linked to the vertical development of the auditorium, at the South direction, and to the monastery complex at the other directions. The plan dimensions are 7.5 m x 6.45 m. The walls have a thickness that ranges from 2.1 m at the ground floor to 1 m at the top.

The first floor (4.5 m above ground) is a vault with a pointed arch (Fig. 2a) and has the same height as the first floor of the monastery complex. The other two floors (9.2 m and 15.7 m above ground, respectively), consist of cross vaults and can be accessed using two spiral stone staircases with monolithic steps (Fig. 2b). The roof is wooden and supports ancient tiles (Fig. 2c).

(a) (b) (c)

Figure 2: (a) Vault with a pointed arch; (b) spiral stone staircase; (c) wooden roof with ancient tiles.

3 OUTPUT-ONLY IDENTIFICATION OF THE BELL-TOWER

Output-only Modal Analysis (OMA) is an identification process performed to obtain modal properties from structural response to natural excitations (e.g. traffic, wind, human activities) [12]. The overall procedure consists in: (i) building the FEM of the structure; (ii) planning the experimental test on the analytic outcomes; (iii) measuring the structural response (accelerations or displacements); (iv) processing data through algorithms; (v) validating data.

3.1 Preliminary FE model

The experimental investigation was preceded by the development of a 3D finite element model (Fig. 3), through the software MIDAS FEA NX [13], based on the geometric survey. The tower was modelled using 8-node brick elements. A relatively large number of finite elements have been used in the model, in order to obtain a regular distribution of masses. The model results in a total of 44076 nodes, 207778 solid elements with 133332 active degrees of freedom. Regarding the boundary conditions, the tower footing was considered as fixed. Instead, at this preliminary step, the connection between the southern wall of the bell-tower and the vertical left wall of the Auditorium as well as the interaction between the tower and the monastery complex were not accounted for.

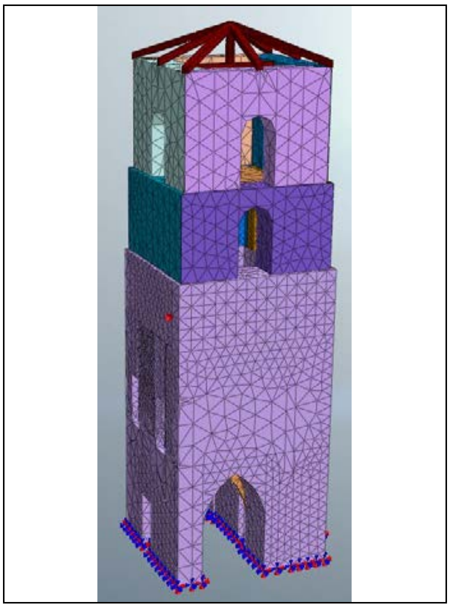


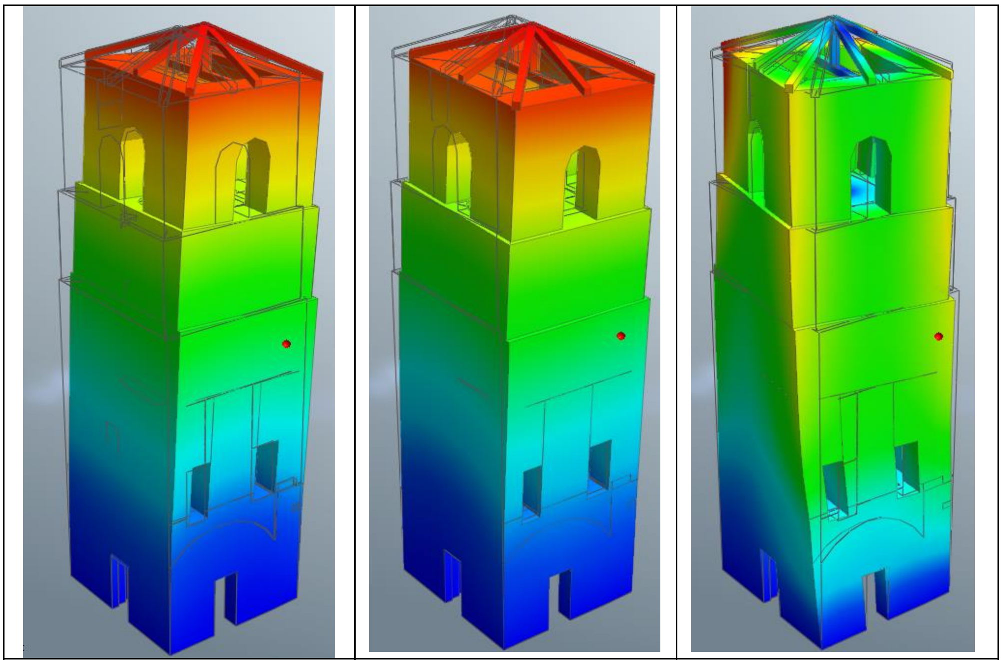
Figure 3: Finite element model of the bell-tower.

A survey by visual inspection to identify the masonry texture of walls and vaults was carried out. Since no information regarding the materials was available from in situ tests, in formulating the model, the mean value of elastic modulus (E) and the weight (w) suggested by the Italian Code [14] were adopted for the identified type of masonry before the model updating. Table 1 reports the properties of the material associated to each structural element.

Structural element	Material type	E [MPa]	G [MPa]	w [kN/m^3]
Masonry	Roughly cut stone with good texture	1740	669	21
Vaults	Solid brick and lime mortar stone	1500	577	18
Spiral staircases	Stone square blocks	2850	1096	22

Table 1: Material properties adopted in the numerical model.

In order to obtain the modal parameters and design the layout of the experimental tests, a modal analysis was carried out. Fig. 4 shows the natural frequencies and corresponding mode shapes obtained. It can be clearly seen from the vibration modes of the tower that the first one is a bending mode in Y direction (f=1.88 Hz), the second is a bending mode in X direction (f=2.18 Hz), and the third one is a torsional mode (f=4.94 Hz), respectively.



First bending Y-direction (1.88 Hz)	First bending X-direction (2.18 Hz)	First Torsional (4.94 Hz)

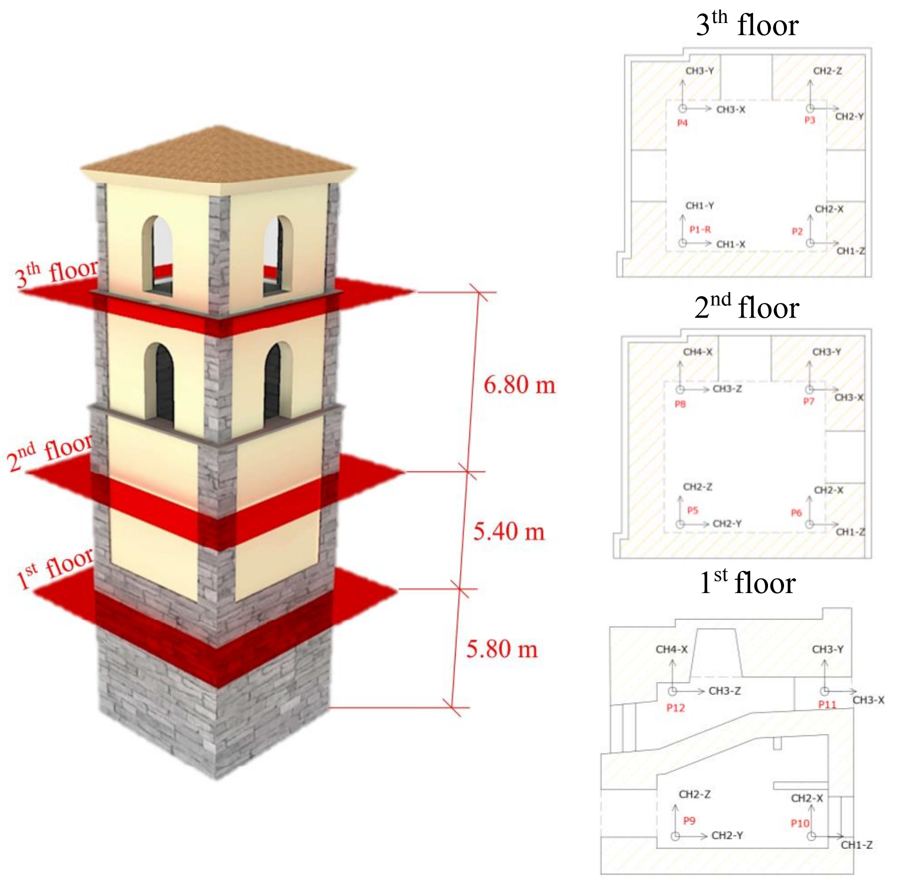
Figure 4: The numerical natural frequencies and corresponding mode shapes.

3.2 The Ambient vibration test: layout definition and acquisition

The modal characteristics of the bell tower were identified by means of an ambient vibration test (AVT). The chain of acquisition is composed of: (i) 10 PCB model 393B12 piezoelectric accelerometers with the following characteristics: 10 V/g sensitivity, ± 0.5 g measurement range and frequency range from 0.05 to 4000 Hz; (ii) a 12-channels Siemens LMS SCADAS XS Data AcQuisition (DAQ) device; (iii) a workstation running the software Siemens Testlab; (iv) Co-axial cables with low impedance and with a length variable from 5.0 m to 50.0 m; and (v) supports.

The response of the tower was measured in 24 selected points, belonging to 3 different cross-sections identified along the height of the building. Having only 12 accelerometers available, three setups were defined to cover all the recording points. The different setups have been defined with a quadrangular grid at each level, allocating the measuring points near the four corners. The sensors' layout adopted for the AVTs is reported in Figure 5, whereas Figure 6 shows the mounting of accelerometers for the instrumented level at 18.0 m.

According to the numerical results previously described, the two reference sensors were placed in X and Y directions on the third floor of the bell-tower since the top level of the tower is characterized by the maximum response.

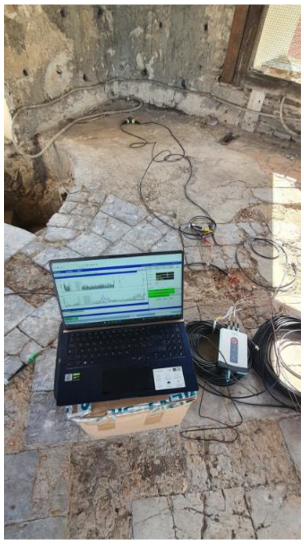


(a) (b)

Figure 5: a) View of the tower; b) Sensors' layout adopted in the dynamic tests.

A time windows of 900s have been adopted in the test to acquire the acceleration time-histories induced by ambient excitation. This choice also allowed to comply the recommendation for OMA techniques of a time windows' duration ranging between 1000 and 2000 times the fundamental period of the structure [15].

Moreover, to avoid loss of information due to the aliasing, a sampling frequency twice the highest contained in the signal should be used [16]. Therefore a sampling frequency of 200 Hz, which means a sampling time step of 0.005 s, was used.

(a) (b)

Figure 6: a) Mounting of the accelerometers at test point P1-R and b) acquisition of the first setup

3.3 Data processing by OMA and validation

The data recorded from sensors were preprocessed in MATLAB [17]; as the significant frequency content of signals is below 10 Hz, low pass filtering and decimation have been applied to the recorded data before using the identification tools. This allowed to reduce the sampling frequency from 200 Hz to 50 Hz.

The extraction of the modal parameters from the recorded ambient vibration data were carried out by using the methods in frequency and time domain available in the commercial software ARTeMIS [18].

Among the OMA algorithms Frequency Domain Decomposition (FDD), Enhanced Frequency Domain Decomposition (EFDD) and Stochastic Subspace Identification (SSI) are the most widespread. It is proven that these methods can be successfully applied when the structure is weakly damped and the modes are well-separated.

In the FDD method the spectral density matrix is decomposed by Singular Value Decomposition (SVD) to obtain frequency values and mode shapes [19]. EFDD improves FDD procedure giving more reliable results and even damping ratios [20]. The SSI method [21] directly works on row data extracting a stochastic state-space model; the mathematical treatment is reported in [22].

The modal analysis performed by applying both frequency and time domain techniques to all of the collected data sets allowed to identify 3 vibration modes within the frequency range 0-10 Hz.

The natural frequencies and the modal shapes identified via FDD method are summarized in Figure 7. As expected from the structural scheme of the investigated structure, the detected modes can be classified as bending and torsion: the first two identified modes are dominant bending whereas the remaining mode can be classified as torsion.

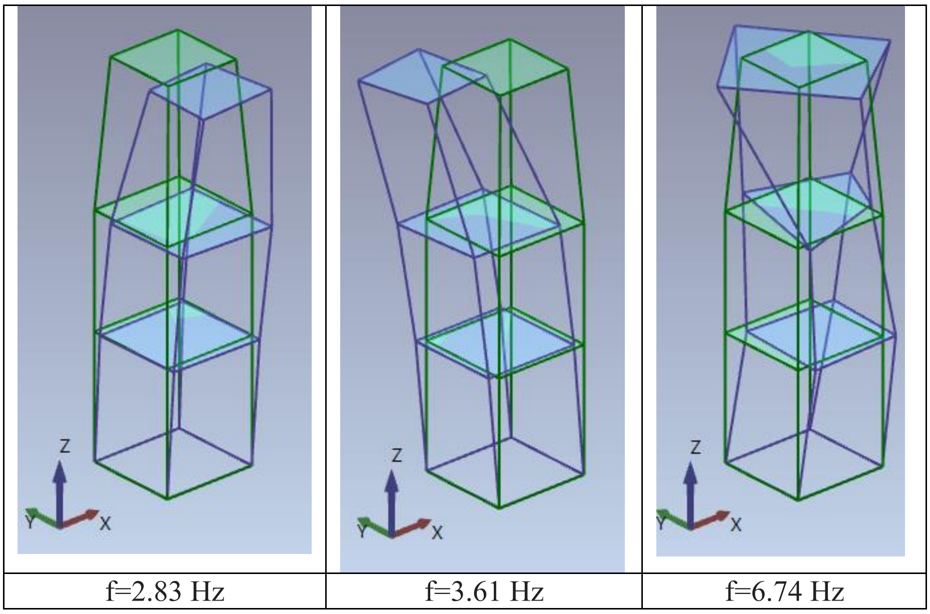


Figure 7: Vibration modes identified with FDD method

The experimental results obtained by the two methods were compared through the frequency discrepancy using equation (1) and the Modal Assurance Criterion (MAC) was applied to validate them by comparing mode shapes. MAC value [22] can be calculated using equation (2).

$$D_f = (f_{FDD} - f_{SSI})/f_{SSI} \tag{1}$$

$$MAC = \frac{\left(\{\varphi_{FDD}^T\}\cdot\{\varphi_{SSI}\}\right)^2}{\left(\{\varphi_{FDD}^T\}\cdot\{\varphi_{SSI}\}\right)\cdot\left(\{\varphi_{FDD}^T\}\cdot\{\varphi_{SSI}\}\right)} \tag{2}$$

The results in Table 2 demonstrate the consistency of the two methods in terms of natural frequencies with the Df being generally less than 2%. A good agreement is also found for all mode shapes, with the MAC ranging between 0.92 and 0.99.

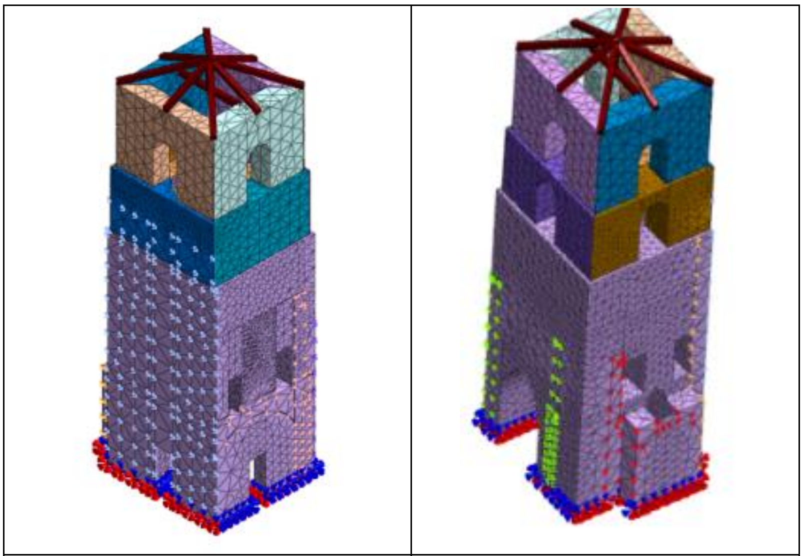
Mode	Mode Type	f_{FDD} [Hz]	f_{SSI} [Hz]	Df [%]	MAC
1	Bending Y	2.83	2.82	-0.35	0.99
2	Bending X	3.61	3.62	0.28	0.99
3	Torsion	6.74	6.66	-1.19	0.92

Table 2: Experimental modes identified from ambient vibration measurements.

4 FE MODEL UPDATING

The modal analysis results indicated that the initial theoretical frequencies are lower than the experimental frequencies, while mode shapes have a good agreement. Taking into account the uncertainty related to some parameters with major influence in the dynamic behavior of the tower, such as the Young's modulus and shear modulus of the walls, it was decided to update the finite element model by trial-and-error, until a suitable coincidence with the experimental test for the first three natural frequencies was registered.

At this stage, the tower interaction con with the Lecture Building and the Auditorium was reproduced using elastic spring (see Figure 8) whose stiffness should be calibrated. These constraints were distinguished according to the interacting structural units and in relation to the spatial orientation with respect to the tower itself.



(a) (b)

Figure 8: Reproduction of the connection with the Auditorium (a) and the Lecture Building (b)

The calibrated elastic properties for both material and boundary condition were defined minimizing the total frequency discrepancy in percentage between experimental (f_{exp}) and numerical (f_{FEM}) frequencies according to eq. (3)

$$D_f = (f_{FEM} - f_{exp})/f_{exp} \tag{3}$$

The manual tuning provided the optimal values reported in Table 3.

Structural element	**E [MPa]**	**G [MPa]**	**w [kN/m^3]**
Masonry	1500	500	21
Vaults	1200	400	18
Spiral staircases	2400	780	22
Interaction with (Direction)	**K_x [kN/m]**	**K_y [kN/m]**	**K_z [kN/m]**
Auditorium (Sud)	8000	2500	7000
Auditorium (Ovest)	10000	4000	10000
Lecture Building (Ovest)	30000	11000	10000
Lecture Building (Est)	50000	1000	7000
Lecture Building (Nord)	10000	5000	500

Table 3: Optimized properties.

The comparison between the natural frequencies from dynamic identification (estimates obtained from FDD method) and those numerically obtained is reported in table 4. A good correlation was obtained for all modes being D_f less than 5% and the MAC values greater than 0.90. Therefore, the correlation analysis provide a sufficient verification of the model assumptions, being a one-to-one correspondence between the mode shapes.

Mode	Mode Type	f_{exp} [Hz]	f_{FEM}[Hz]	Df [%]	MAC
1	Bending Y	2.83	2.81	-0.60	0.95
2	Bending X	3.61	3.48	-3.63	0.95
3	Torsion	6.74	6.63	-1.63	0.92

Table 4: Correlation between experimental and numerical modes.

5 CONCLUSIONS

In this paper the investigations carried out to assess the model of the Sant'Agostino bell-tower, in Benevento, Italy, are described. In particular the calibration of the model using the ambient vibration testing by the OMA procedure was developed, extracting the modal parameters (frequencies and modal shapes) both in the frequency and time domain. The following conclusions can be drawn from this study:

- The fundamental vibration mode of the tower, with a natural frequency of about 2.83 Hz, involves bending in Y direction. The coupled motion (3.61 Hz) is referred to X direction.
- A very good agreement, with a frequency discrepancy less than 2%, was found for the modal estimates obtained from the two classical OMA methods, FDD and SSI.
- The correct reproduction in the model of the interaction with con the Lecture Building and the Auditorium played an important role in the updating of the model; a good correlation between measured and calculated frequencies was obtained for all modes being the frequency discrepancy less than 5% and the MAC values greater than 90%.

The results confirms that the OMA technique is able to detect effective information on the dynamic behavior of historical structures that can be useful to update a reliable numerical model for structural analysis.

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