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DYNAMIC IDENTIFICATION AND FINITE MODEL UPDATING OF TRANI CATHEDRAL'S BELL TOWER

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ABSTRACT

The aim of the paper is to present the dynamical identification of the bell tower of the Cathedral of Trani (Bari, Italy). The tower, built in 1200, is about 60 meters high and has a square plan with a side of about 7.50 meters; moreover it is connected to the church through a step supported by a pointed arch. The tower vibrations due to ambient actions have been recorded and analyzed with different modern algorithms in such a way as to estimate the modal parameters of the tower. The identified modal parameters were utilized to evaluate the dynamic interaction between the tower and the church and some mechanical properties of the structural elements.

Keywords: non-destructive tests, operational modal analysis, model updating, dynamic analysis, FEM analysis.

INTRODUCTION

As it is well known, Italy is a country with a wide, ancient and important building patrimony, and an high seismic risk; as a consequence, during the last decades a great attention has been devoted to the necessity of protecting this patrimony. Nevertheless, the evaluation of the vulnerability of these buildings and the design of possible interventions require a deep knowledge of the examined structures that allows the definition of a detailed model which may be utilized by decision makers.

On the other side, due to the historical character of the examined buildings, all the necessary information for the definition of the aforementioned models are usually unavailable, and the possibility of conducting classical tests is limited to the ones that are not destructive. In this sense, the dynamical tests have acquired a great importance. In detail, these tests are based on the consideration that the modal parameters of a structure are strictly dependent on its geometrical and mechanical characteristics, as a consequence, the analysis of the vibrations of a structure allows the evaluation of these parameters which can be utilized for the update of a detailed FE (Finite Element) model (Ivorra et al. 2006, Diaferio et al. 2007, Lepidi et al. 2009, Foti et al. 2011 and 2012, Trombetti et al. 2011).

In this context, the researchers have proposed different techniques to analyze the experimental data; a preliminary classification of these methods is based on the domain in which these operate (frequency or time domain). Moreover, another important aspect that differentiates the techniques is the request, as an input data, of the time histories of the forces acting on the investigated structures. The methods that do not necessity of the knowledge of these time-histories, the so-called "output-only methods", are widely diffused in the field of monitoring of historical structures, as they may be applied to vibrations induced by ambient actions that have the advantage of being compatible with the ordinary service of the structure, and of reducing the costs connected with the test setup, as the installation of shakers or actuators is not request (Ranieri et al. 2010).

The present paper deals with the identification of a building of the historical Italian heritage through output-only methods. In particular, the paper presents the study of the historical bell tower of the Cathedral of Trani (Apulia, Italy). The tower was built in the 1200 and, during the years, has undergone a series of interventions, that, in many cases, are not documented by adequate structural design drawings or other kinds of information. In this sense, some structural parameters were uncertain and a complete definition of a detailed three-dimensional FE model was not possible.

In order to identify these parameters, a wide dynamical experimental analysis has been performed; in detail, the structural vibrations induced by the ambient actions and, in some cases, by the bells swinging, have been recorded and analyzed to estimate the modal parameters of the tower; two different output-only procedures have been applied: the former, based on the Complex Mode Identification Function (Artemis, Peeters, B., 2001), exploits a frequency representation of the response; the second, based on the Stochastic Subspace Identification (Artemis, Van Overschee, 1996), works in the time domain.

The identified modal parameters have been utilized to evaluate the uncertain parameters of a three dimensional FE model of the bell tower. The estimated parameters and the comparison between the identified modal parameters and the ones evaluated for the updated three-dimensional FE model are discussed.

THE HISTORICAL BELL TOWER OF THE CATHEDRAL OF TRANI

The Cathedral of Trani is one of the most important historical building in Apulian Romanesque style (Italy) (figure 1); its construction began at the end of the 11th century and ended in the 1143. In the 1240, besides the Cathedral, the building of a tall bell tower began and ended in the second part of the 14th century. The original bell tower was realized in rubble masonry where the outer surfaces of the wall were realized by tufa masonry (Stone of Trani). The bell tower has a square plane with a side of about 7.5 m, the masonry thickness is about 1.40 m and it is 57 m tall, and it is connected to the church through a step supported by a pointed arch.

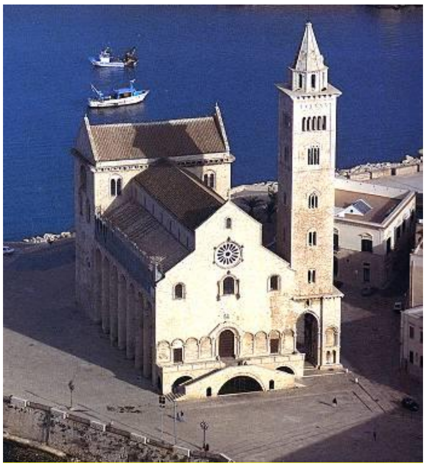


Fig. 1. Cathedral of Trani

The bell tower is supported by strong quadruple arcade, and has a unique rigid floor up to the arcades. At this level about 14.30 m ,the opening, that allows the communication between the church and the tower, is placed. Up to this level, the tower is not connected to the church.
The square section does not change in elevation up to the aforementioned floor till the height of about 47.60 m, up to which the tower section becomes octagonal with a side of about 2.30 m. The octagonal section remains constant till the height of about 51 m from which the dome emerges.
All the four façades of the tower are characterized by the same openings, even if their shape and dimensions vary along the height of the tower. At the fourth level four bells are installed.
During the years, the tower has been undergone to some interventions with the aim of increasing its stability: in the XVIII century some openings were walled and in the XIX century ties have been installed. Nevertheless, the most important intervention was dated 1950 when the tower was completely disassembled and reassembled (Figure 2). The stone blocks were numbered in order to facilitate the installation in the same position, moreover, to improve its strength, the rubble masonry fill was substituted with a reinforced concrete wall.
The available structural drawings and design reports are not sufficiently detailed. The principal uncertainties are: the degree of the restraints between the church and the tower, the masonry and concrete Young's moduli and densities.

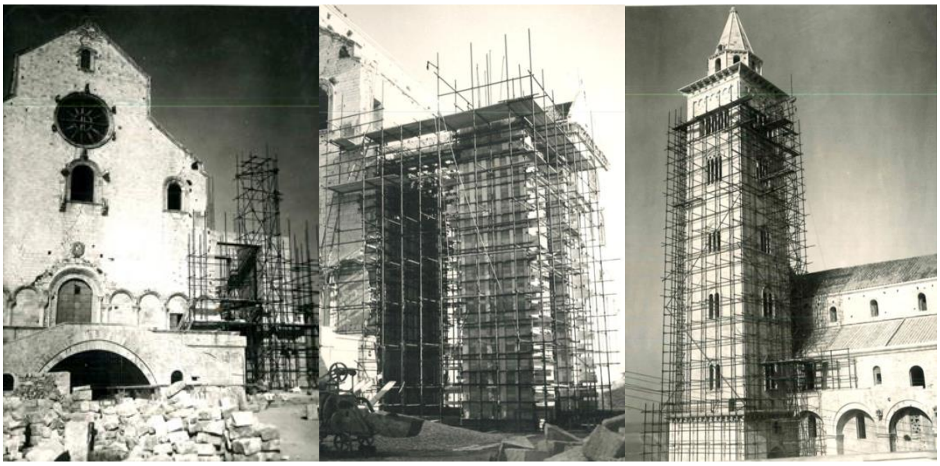


Fig. 2. Three phases of the disassemblage and assemblage of the bell tower of the Cathedral of Trani (1950)

SYSTEM MONITORING

The system monitoring consists of 28 PCB uniaxial piezoelectric accelerometers (PCB Model 393B31) (Figure 3) connected to 4 DAQ. These latter are linked to a switch which is related to a laptop by an ethernet cable.

Fig. 3. Piezoelectric accelerometers (PCB Model 393B31).

The accelerometers were placed on the four different levels shown in figure 4; in figures 5-8 the identification number of the nodes of the model utilized for the identification procedure and the arrows corresponding to the acquisition direction of the sensors are indicated. In detail, 6 accelerometers are placed at the level 22.55 m (Figure 5), 6 at the level 35.57 m (Figure 6), 8 at the level 42.07 m (Figure 7) and the last 8 at the level 49.26 m (Figure 8). Only 1 of the 28 accelerometers had not worked properly.

Fig. 4. Levels of accelerometers installation.

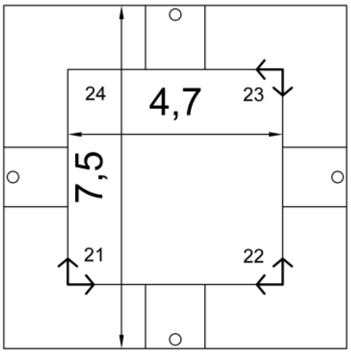


Fig. 5. Plan view at the height 22.55 m. Sensors location and signal acquisition direction..

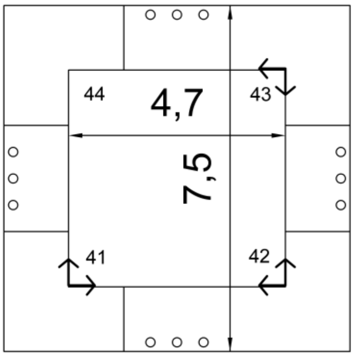


Fig. 6. Plan view at the height=35.57 m.. Sensors location and signal acquisition direction.

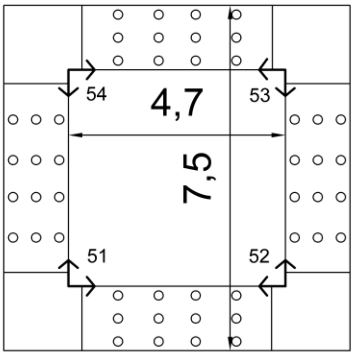


Fig. 7. Plan view at the height=42.07 m. Sensors location and signal acquisition direction.

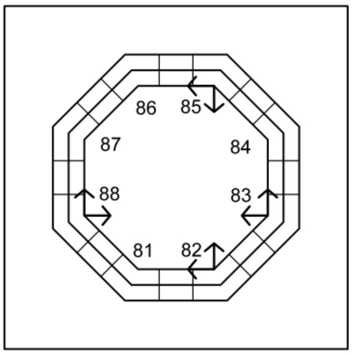


Fig.8. Plan view at the height=49.26 m.. Sensors location and signal acquisition direction.

Eleven tests were conducted on the tower considering the effect of the sound bell and ambient vibrations, as summarized in Table 1. The data acquisition was carried out by recordings of 10 minutes with a frequency of 1024 Hz, which has been subsequently decimated by a factor equal to 4 to have a frequency of 256 Hz.

Table 1. Tests description.

Test	**Time**	**Actions**
1	12.43	bells swinging and ambient actions
2	12.55	bells swinging and ambient actions
3	13.14	ambient actions
4	13.29	ambient actions
5	13.40	bells swinging and ambient actions
6	13.52	bells swinging and ambient actions
7	16.28	ambient actions
8	16.43	ambient actions
9	16.54	bells swinging and ambient actions
10	17.13	ambient actions
11	17.29	ambient action

Figure 9a shows the acceleration time history of the node 82 in figure 8 for the test 1 (cf. Table 1), induced by the bells swinging and the ambient actions. It is possible to observe that, about 80 seconds after the beginning of the acquisition, the bells swinging began and, in detail, 15 bells chimes have been recorded (see fig. 9b), corresponding to the 12.45 o'clock p.m.. In this condition, the induced accelerations are of one order of magnitude greater than the ordinary ones (see fig. 9a).

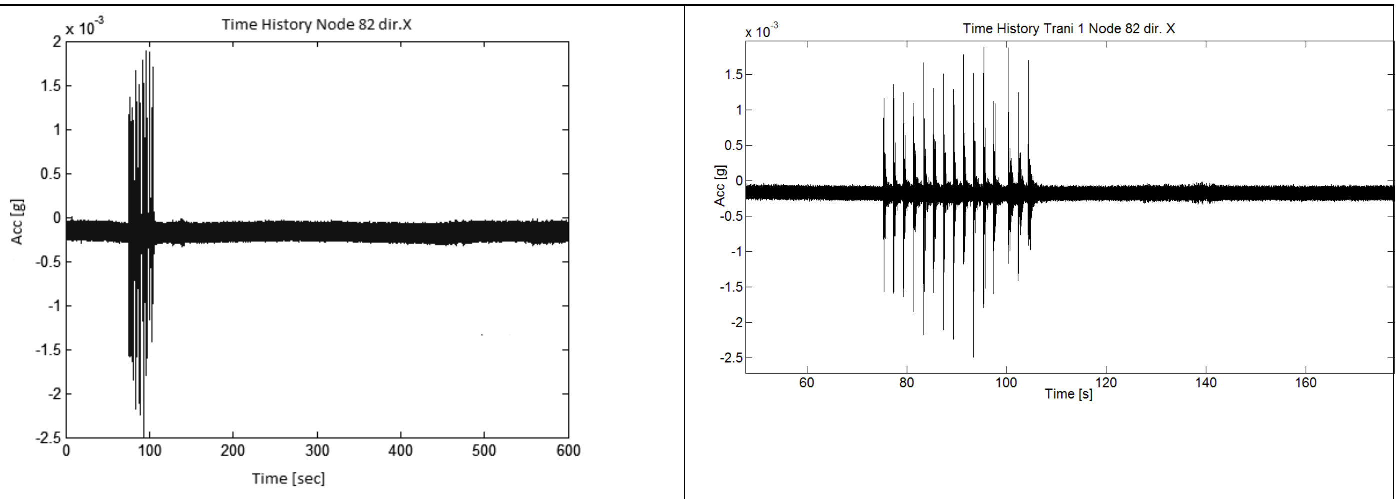


Fig. 9. acceleration time history of node 82 in test 1 (bells swinging and ambient actions) a) time history in the range 0-600 s; b) zoom of the time history during the bells swinging.

OPERATIONAL MODAL ANALYSIS

The structural identification of the bell tower of the Cathedral of Trani has been carried out by means of the techniques of the OMA (Operational Modal Analysis). The OMA methods, based on output-only measured data, here used are: the EFDD (*Enhanced Frequency Domain Decomposition*) that operates in the frequency domain, and the SSI (*Stochastic Subspace Identification*) technique that operates in the time domain. In the examined case, the extraction of the modal parameters from ambient vibration data was carried out using Artemis Extractor software (Artemis).

All the eleven tests have been analyzed by means of the two aforementioned procedures; however, it has been noticed that in all the tests with the bells swinging, the accuracy of the identification was lower than in the other cases, due to the significant influence of the external action.

In the examined tests, the identification of the frequency values has been successfully completed. In fact, the identified frequency values are almost the same for the two adopted procedures and for all the examined tests.

In detail, the results obtained by means of the EFDD and SSI techniques are shown in figure 10 and figure 11 respectively for the case of test n.3. The frequency values estimated by means of these techniques are summarized in Table 2, were the average values and the standard deviation evaluated for the all the examined tests for each procedure; figure 12 shows the corresponding mode shapes for the test n.3. It can be easily observed that the first two modes correspond to the first flexural mode along the z and x axis, respectively; the third mode corresponds to the second flexural mode along the x axis, while the fourth mode is the torsional mode and the fifth is the second flexural model along the z axis.

It is possible to note (Table 2) that the first two frequency values are quite close due to the symmetry of the tower section. The presence of a frequency peak at 6 Hz (see fig. 10 and 11), that has been judged probably due to external actions or noise as the corresponding damping value is close to zero, has made difficult the identification in the frequency range around this value.

Table 2. Mean values and standard deviation of the identified mode shapes for the examined tests and the two adopted procedures.

	EFDD		SSI	
Mode	**f [Hz]**	**σ**	**f [Hz]**	**σ**
1	2.04	0.004	2.03	0.002
2	2.26	0.012	2.28	0.013
3	7.03	0.020	7.07	0.112
4	7.60	0.024	7.68	0.088
5	9.16	0.173	8.94	0.064

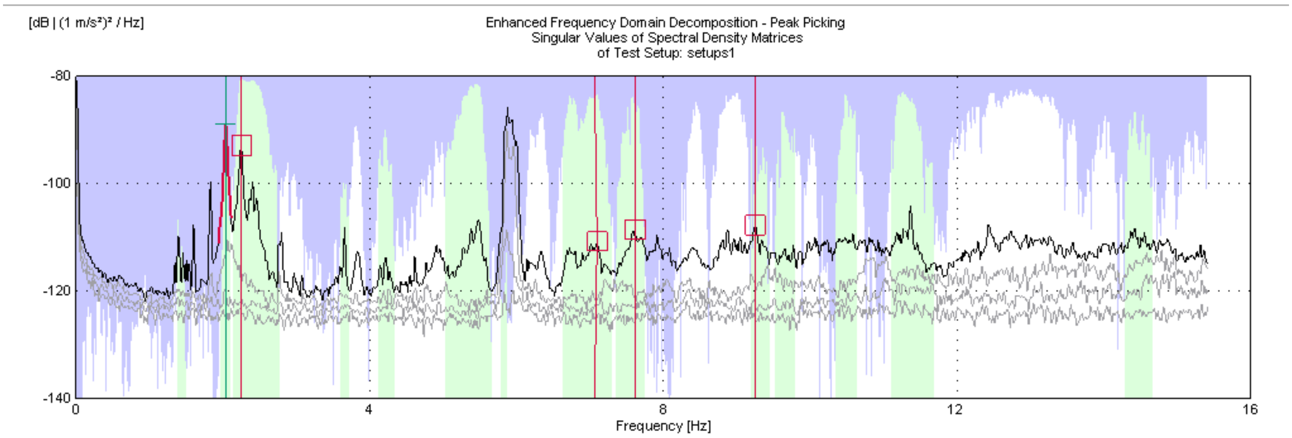


Fig.10 . Results of EFDD technique. (test: 3)

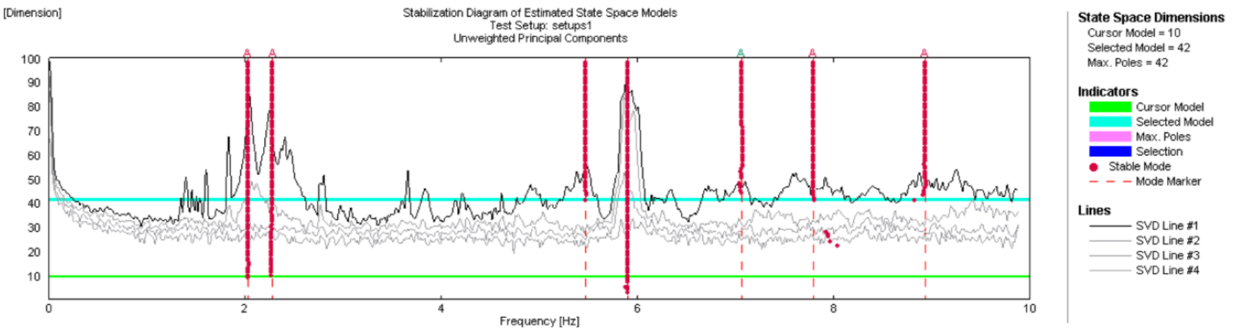
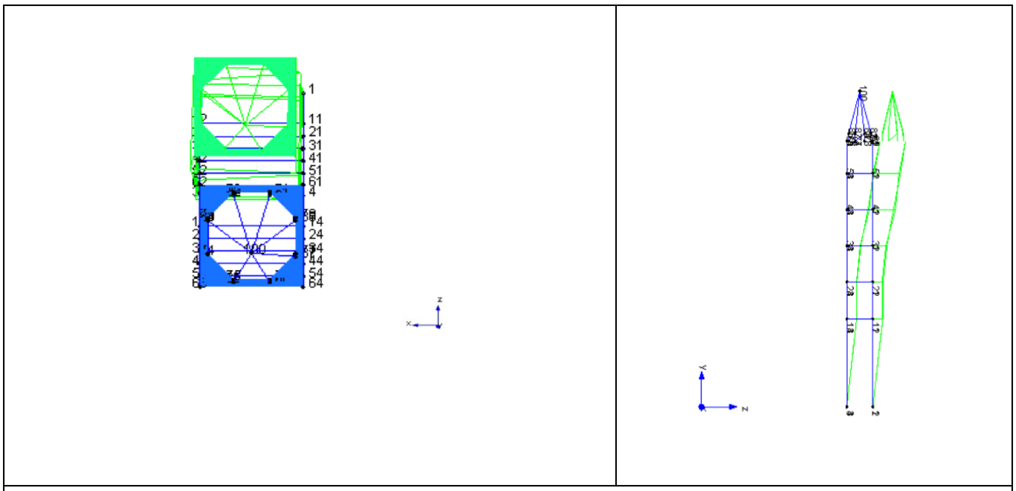
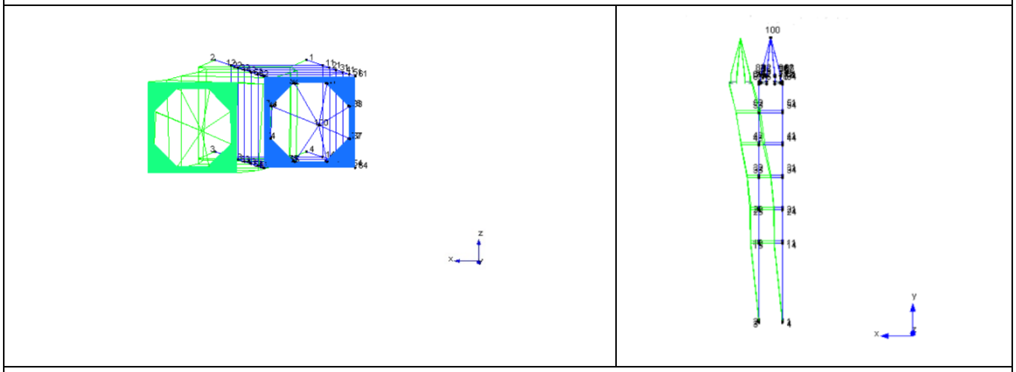


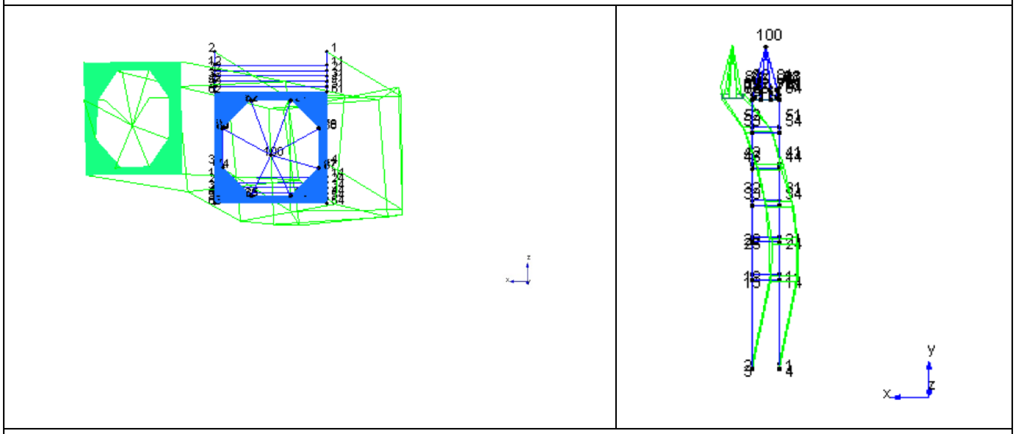
Fig. 11. Results of SSI technique (test: 3).



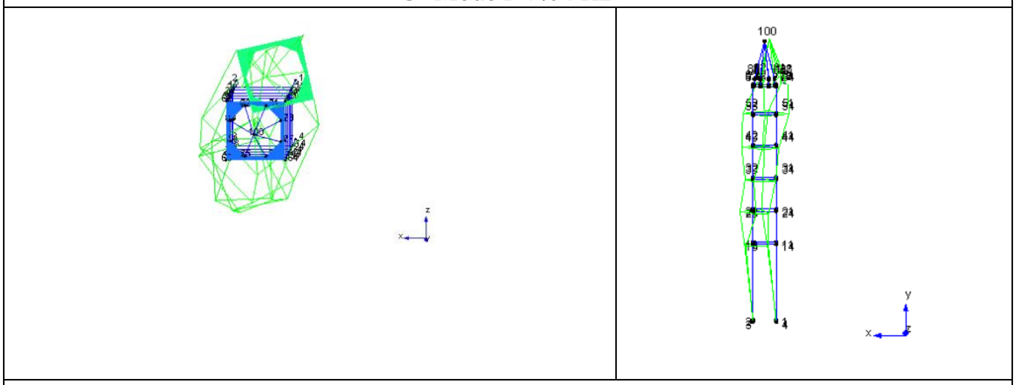
1° Mode f=2.04 Hz



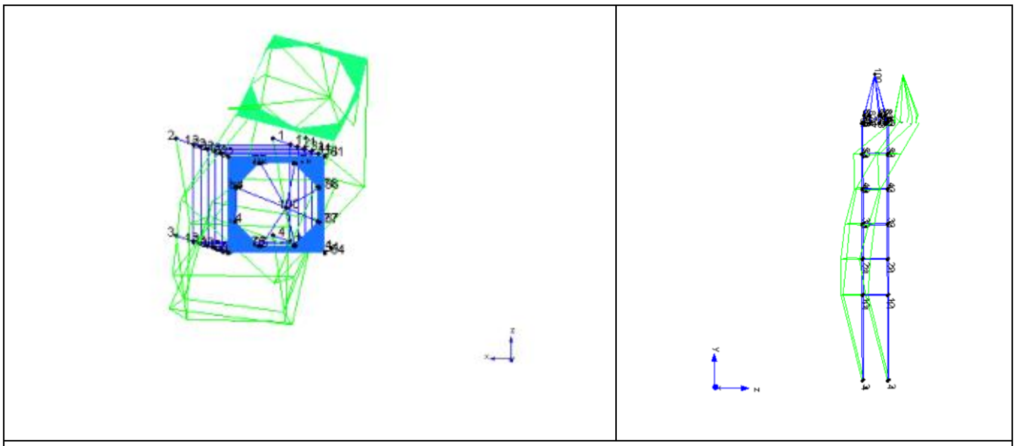
2° Mode f=2.26 Hz



3° Mode f=7.04 Hz



4° Mode f=7.6 Hz

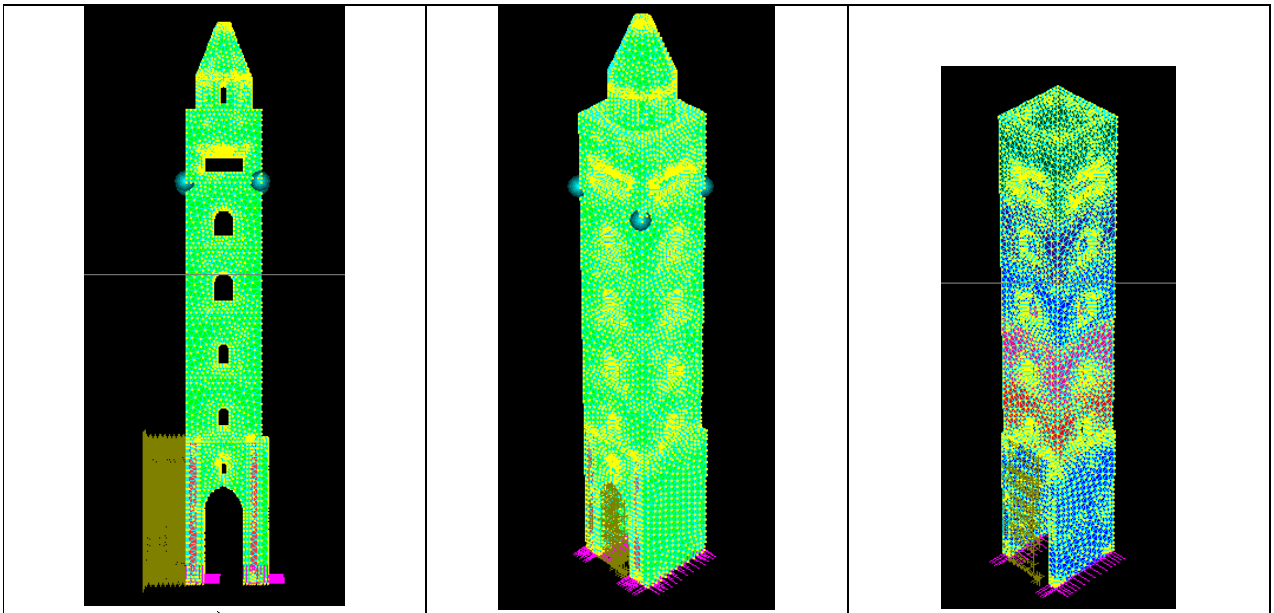


5° Mode f=9.2 Hz

Fig. 12. Identified Mode shapes for the test 3.

FINITE ELEMENT MODEL

The experimental investigation was supported by the development of a 3D finite element model on the basis of historical and geometric information obtained as a result of specific investigations. In particular, the architectural drawings of the aforementioned intervention of the 50’s and the documentation of a subsequent intervention for the building of an internal wooden stair have been utilized for the definition of the FE model of the tower.
The tower was modeled using 197073 brick elements that represent the outer surfaces of the wall and its reinforced concrete core, assuming a perfect adherence between these materials. Moreover, 350 spring elements, acting along the x axis, were added to take into account the interaction between the tower and the church. In addition to the mass of the brick elements, four lamped masses (of 4000 kg each) were considered at the corners of the 4^{th} belfry that are representative of the bells mass.
Due to the lack of information in the available documentation, previously described, the following elements have been assumed as updating parameters: the spring stiffness, the masonry and concrete Young’s moduli and densities. In detail, the tower total height has been divided into six different regions, each one characterized by constant concrete Young’s modulus and density.
In figure 13 the front view, the 3D view corresponding to the external surface of the tower and the 3D view corresponding to the concrete core of the tower divided into aforementioned 6 regions are shown.



a) b) c)

Fig. 13 Tower Finite Element Model:a) front view; b) 3D view of the mansory brick elements; c) 3D view of the concrete brick elements (the core of the mansory).

MODEL UPDATING

The parameters selected for the updating procedure are the concrete Young's modulus E_i and the densities ρ_i in the 6 zones previously indicated, the Young's modulus E and the density of the external masonry layers and the stiffness value of the uniformly distributed springs.
So totally 15 parameters were considered for the model updating, excluding from the considered parameters the added lumped masses that did not significantly influence the final results.
The method used for the normal modes evaluation in the 3D finite element model is the Lanczos subspace method (DDS,2012), while the parameters estimation was carried out minimizing the differences between theoretical and experimental natural frequencies.
The strategy used for updating the 15 parameters previously indicated is the well-known Inverse Eigen-Sensitivity (Friswell,1995) In detail:

$$\mathbf{R}_e = \mathbf{R}_a + \mathbf{S} \cdot (\mathbf{P}_u - \mathbf{P}_0) \tag{1}$$

or in a short form:

$$\Delta\mathbf{R} = \mathbf{S} \cdot \Delta\mathbf{P} \tag{2}$$

where in (1):
$\mathbf{R}_e$ is the vector of the reference system responses (experimental data);
$\mathbf{R}_a$ is the vector of the predicted system responses for a given state $\mathbf{P}_0$ of the parameter values;
$\mathbf{P}_u$ is the vector of the updated parameter values;
$\mathbf{S}$ is the sensitivity matrix;
$\Delta\mathbf{R} = \mathbf{R}_e - \mathbf{R}_a$

$\Delta\mathbf{P} = \mathbf{P}_u - \mathbf{P}_0$.

Equation (1) is usually underdetermined and can be solved using a pseudo-inverse (least squares) method. In this case a weighted least squares or Bayesian technique has been used. The applied least squares solution (DDS,2012) will minimize iteratively the residue defined as:

$$residue = \mathbf{S} \cdot \left[\Delta\mathbf{P}_{n+1} - \Delta\mathbf{R}\right] \tag{3}$$

with $\Delta\mathbf{P}_{n+1}$ calculated as follows:

$$\Delta\mathbf{P}_{n+1} = [\mathbf{S}^T \cdot (\mathbf{S}^T \cdot \mathbf{S})^{-1}] \cdot \Delta\mathbf{R} \tag{4}$$

The previous procedure was applied to achieve the fixed convergence in a limited number of iterations, limiting the variation range of all the 15 parameters considered.
The parameters values calculated after the updating are shown in Table 3; the element classification 1 indicates the external masonry, while 2-7 indicate the six different regions starting from the lower part of the building (cf. fig. 13c). The value of the springs stiffness has been calculated equal to 5.3 10^6 N/m.

Table 3 Parameters calculated after the updating procedure

Element classification	**ρ [kg/m^3]**	**E[MPa]**
1	192.9	6000
2	1186.4	62597
3	4084.9	21396
4	6143.3	14768
5	2558	14179
6	454.2	15872
7	414.2	25048

The comparison of the experimental data with the updated FE model is shown in Table 4 in which the first five estimated experimental frequencies, the first five frequencies of the updated model, the percentage error and the MAC coefficients are shown. It is possible to note that the model natural frequencies are very close to the experimental ones and the correlation (MAC) between mode shapes shows very good agreement for the bending mode shapes (excellent agreement for the first two modes). Moreover, in Figure 15 the comparison between the first five experimental and theoretical mode shapes are shown: the overlapping is evident and the correlation is demonstrated for all the bending modes, besides. Observing the torsional modes (fourth mode) and the second flexional along x axis (third mode), it is evident that the experimental and the theoretical ones are similar, nevertheless the low value of MAC index.

Table 4 Comparison between theoretical and experimental frequencies after the updating.

Frequency number	Theoretical frequency [Hz]]	Experimental frequency [Hz]	Percentage error [%]	MAC[%]
1	2.0355	2.0365	0.06	97.6
2	2.2452	2.2458	0.02	95.8
3	7.0555	7.0589	0.04	10.6
4	7.6155	7.6184	0.03	14.8
5	9.2460	9.2466	0.006	34.0

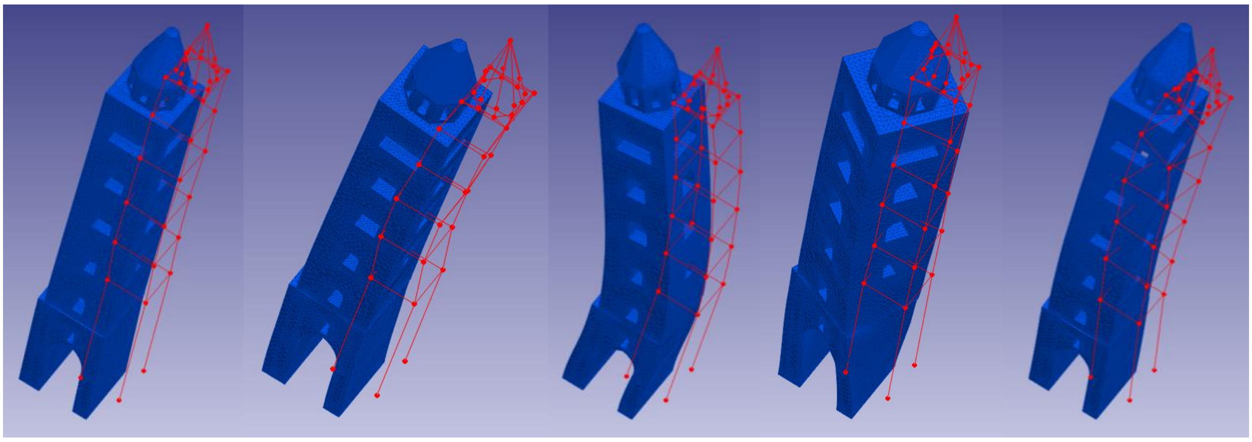


Fig. 14 Comparison between the first five theoretical (blue) and experimental (red) mode shapes

Analyzing Table 3 it is possible to note that some of the obtained values (in particular the ones connected to the higher levels of the tower) are quite different from the expected ones, related to analogous structures in literature. In the authors' opinion this circumstance may be due to the hypothesis that the thicknesses of the structural materials have been assumed constant along the height and equal to the ones deduced, with some uncertainties, from the historical documentation. At this proposal, the aim of a future research will be the experimental evaluation of the distribution of the thicknesses of the materials by means of non-destructive techniques.

CONCLUSIONS

The present paper describes all the phases of the study of a slender important historical bell tower located in Trani (Apulia, Italy). The main aim of the study is the definition of an accurate three- dimensional FE model that is able to evaluate the real dynamical behavior of the structure. The aim has been achieved despite the impossibility of conducting some preliminary classical experimental tests (destructive) for evaluating the structural material properties and the real degree of connection between the tower and the adjacent cathedral. Due to this circumstance, the model validation has been performed by comparing of the first five frequency values estimated by means of operational modal analysis related to the experimental data obtained recording the structural vibrations due to environmental actions (non- destructive technique).
The main problems connected to this structure are the perfect symmetry of the plan that induces the nearness of the frequency values making very difficult the identification. The accuracy of the identification has been guaranteed by considering several experimental data referred to consecutive acquisitions. In this sense, a statistical approach has been performed.

Anyway future researches will consider other non-destructive techniques (GPR system, etc.) for confirming the evaluated parameters.

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