UNCECOMP 2015
1st ECCOMAS Thematic Conference on
Uncertainty Quantification in Computational Sciences and Engineering
M. Papadrakakis, V. Papadopoulos, G. Stefanou (eds.)
Crete Island, Greece, 25–27 May 2015

SENSING HARDWARE OPTIMIZATION AND AUTOMATED CONDITION ASSESSMENT OF A MONUMENTAL MASONRY BELL-TOWER

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Keywords: Structural Health Monitoring, Cultural Heritage Preservation, Masonry Bell-Tower, Monumental Buildings.

Abstract. *Vibration-based structural health monitoring systems have the potential of enabling automated condition assessment of slender structures with a limited number of sensors, leading to a cost-effective optimization of maintenance activities. Nevertheless, the development of SHM systems able to early alert about the occurrence of a structural damage is still quite a challenge due to the weak correlation that typically exists between global dynamic behavior and structural conditions. Methods of multivariate statistical analysis, such as principal components analysis and novelty detection, can be a solution to this issue, but documented validations of their effectiveness at damage detection in full-scale structures are not yet available. This work presents the design and implementation of a vibration-based SHM system, recently installed by the authors on a monumental masonry bell-tower: the bell-tower of the Basilica of San Pietro in Perugia, Italy. The tower, about 61.50 m high, is considered one the symbols of the city of Perugia and was recently restored after a strong earthquake. The monumental tower and its historical background are presented, at first. Then, the results of experimental and analytical dynamic investigations are discussed, including: (i) ambient vibration tests and output-only modal identification using various types of sensors, deployed with different layouts, (ii) remote automated frequency tracking, (iii) numerical modeling, (iv) damage sensitivity analysis and (v) algorithmic strategy for health assessment. The results presented in the paper aim to demonstrate the potential of vibration-based SHM systems for applications to cultural heritage structures, owing to their fully non-destructive and non-invasive character.*

1 INTRODUCTION

Ambient Vibration Testing (AVT) and Operational Modal Analysis (OMA) can be considered as widespread and reliable methods of modal testing in civil engineering. While commonly carried out with reference to flexible structures, such as bridges and cables [1]-[4], in recent years a particular attention has been also devoted to their application to monumental buildings as tools for their conservation [5]-[11] . Within this context, permanent structural health monitoring (SHM) could represent a further step in knowledge and an important challenge to be addressed. Equipping historical and monumental constructions with permanent SHM systems may lead to an optimal employment of the economic resources available for maintenance and rehabilitation activities, especially after seismic events. In fact, permanent SHM systems present all the advantages of both AVT and OMA, being, for instance, fully non-destructive and minimizing the interferences with the normal use of the structure but also allowing a continuous tracking of the actual condition of the structure, typically using a limited number of sensors.

The authors have recently started a research project for monitoring of two relevant historical constructions in Italy: the bell-tower of the Basilica of San Pietro in Perugia and the dome of the Basilica of Santa Maria degli Angeli in Assisi [12]-[13]. This paper reports the first results concerning the former application. In particular, various ambient vibration tests tests have been carried out to characterize the dynamic parameters of the San Pietro bell-tower. These investigations have allowed to attain an optimal hardware sensing layout for the installation of a permanent vibration-based SHM system on the bell-tower. The results of the first months of monitoring are also shown. Moreover, a finite element model of the bell-tower has been realized by tuning the first modal frequencies on the experimental observations. Then, a damage sensitivity analysis on the first modal frequencies has been carried out by introducing damage parameters in some critical parts of the structures. The presented results will constitute a basis for future automated condition assessment of the structure by means of the installed SHM system.

2 SAN PIETRO BELL-TOWER

The Basilica of San Pietro in Perugia belongs to an historical monumental Benedictine abbey located in the southern part of the city. The abbey was erected in 996 while the first erection of the bell-tower dates back to the 13th century. Throughout the centuries the bell-tower has been subjected to several structural and architectural interventions, both for consolidation and for changing its intended use. The actual configuration is dated back to the 15th century and the design is attributed to the architect Bernardo Rossellino. Various structural interventions were necessary to repair damages caused by lightning shocks that several times threatened the stability of the structure. In the last years, the restoration and consolidation measures for the damages occurred after the strong Umbria-Marche earthquake of 1997 have been concluded.

The Benedictine abbey consists of several architectural volumes, including the basilica, the convent and today other local institutions, arranged around three main cloisters (Figure 1(a)). In this context, the bell tower stands out between the basilica and other branches of the abbey, with a total height of about 61.45 m. In the first 17 m the structure is restrained by the bordering buildings, so that the tower is free to move only in the last 45 m (Figure 1(b)).

The bell tower is constituted by a dodecagonal shaft in the first 26 m, a belfry with hexagonal cross section reaching an height of about 41 m and a cusp at the top. The constituent material is not homogeneous. The shaft is made by stone masonry, with large external portions realized in brick masonry as structural rehabilitation measures due to the occurrence of several damages.

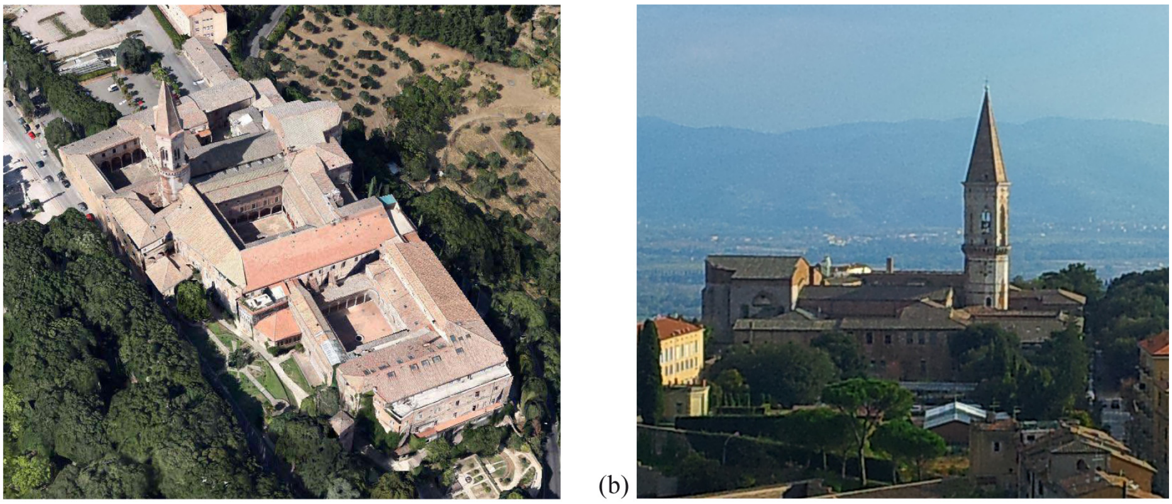


Figure 1: (a) Aerial photograph of the Benedictine abbey of San Pietro in Perugia (Map data ©2015 Google Earth). (b) The bell-tower of the Basilica of San Pietro.

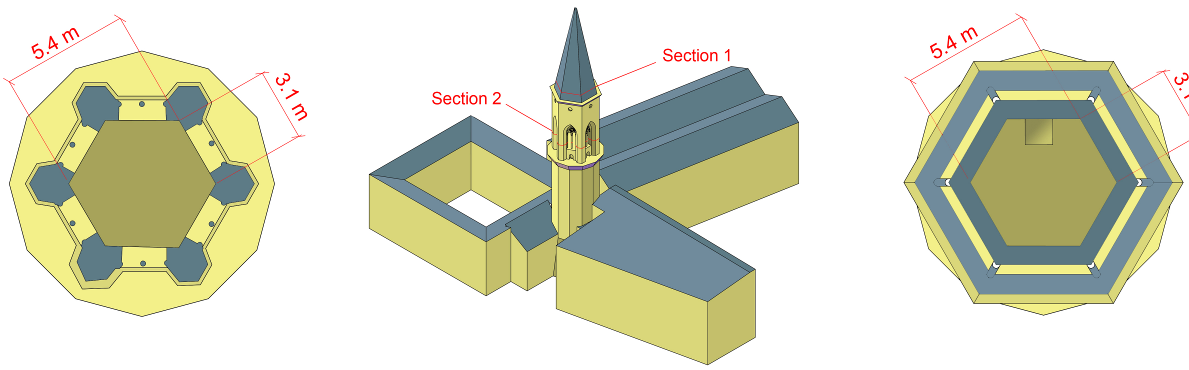


Figure 2: Geometrical survey of the bell-tower: tri-dimensional CAD model of the bell-tower, the surrounding buildings of the Basilica and the Abbey, with details of the plans at a level of 29.1m (left) and 40.8m (right) high.

The belfry and the cusp are made of brick masonry, but the former is characterized by an external curtain of stones. Moreover the belfry presents high mullioned windows in each of the six sides, thus resulting in a significant slenderness degree in the upper part of the structure.

3 PRELIMINARY DYNAMIC INVESTIGATIONS

AVTs and OMA of the bell-tower have been performed in two different periods from December 2013 to February 2015. The main purpose was both to identify the dynamic characteristics and the first natural frequencies of the structure, and to define the most appropriate hardware setup for the SHM system to be installed.

The AVTs have been carried out by using different types of accelerometers located in one or two sections of the bell-tower, as shown in Figure 2. Section 1 is at the base of the cusp (40.8 m), while Section 2 at the base of the belfry (29.1 m).

The following three AVTs have been carried out.

- AVT 1, carried out in December 2013 using three uni-axial MEMS accelerometers model PCB 3711B112G (1 V/g sensitivity) installed at the base of the cusp with the layout of

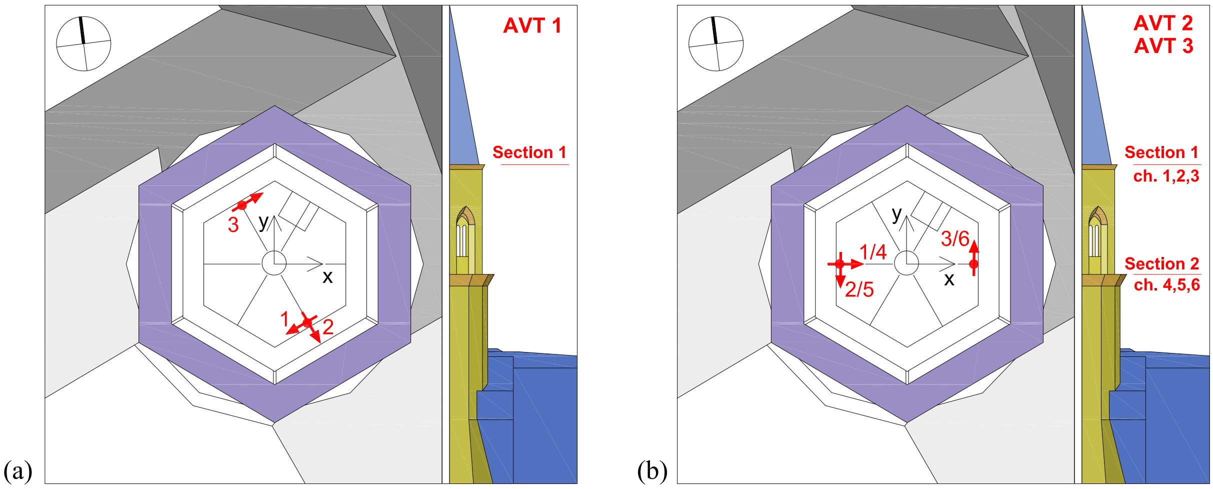


Figure 3: (a) Instrumentations layout used in the AVTs of December 2013 (AVT 1). (b) Instrumentations layout used in the AVTs of September 2014 (AVT 2) and January 2015 (AVT 3).

Figure 3(a).

- AVT 2, carried out on September 23rd 2014, using six piezoelectric uni-axial accelerometers model PCB 393C (1 V/g sensitivity), among which three located at the base of the cusp and three at the base of the belfry with the layout of Figure 3(b).

- AVT 3, carried out on February 16th 2015 using six high sensitivity piezoelectric uni-axial accelerometers model PCB 393B12 (10 V/g sensitivity), among which three located at the base of the cusp and three at the base of the belfry (Fig. 3(b)). Figure 4 is a photo-evidence of the sensors installed on site.

All ambient vibration tests data have been recorded by using a 24-channel system, carrier model cDAQ-9188 with NI 9234 data acquisition modules (24-bit resolution, 102 dB dynamic range and anti-aliasing filters). The data have been stored in separate files of 30 recording minutes and down-sampled at 100 Hz. During AVT 1 (December 2013) a small earthquake occurred [14]. In the following, AVT 1a is used to denote the recorded data of December 26th in operational conditions, while AVT 1b is related to the seismic event of December 22th.

Modal parameters of the bell-tower have been extracted from AVTs data by using a fully automated Stochastic Subspace Identification (SSI) technique [4]. In order to fairly compare the results obtained in the different conditions, both in terms of sensors' layout and type of sensing harware, data sets with similar Root Mean Square (RMS) values have been selected. For appropriate reference, RMS amplitudes for AVT 1, AVT 2 and AVT 3 are summarized in Tab. 1.

Tables 2 and 3 summarize the values of identified natural frequencies and corresponding modal damping ratios, respectively, where mode types are referred to the reference axes depicted in Figure 3. It can be noted that the first two modes are consistently identified in all data sets (small differences in frequencies are conceivably associated with differences in ambient temperature), while higher order modes could be identified only by using high-sensitivity accelerometers. Mode shapes identified in AVT 3 are shown in Figure 5.

Figure 4: Images of the six piezoelectric uni-axial accelerometers (10 V/g sensitivity) used in the AVT 3.

AVT 1a Dec 2013 (MEMS 1V/g)	AVT 1b Dec 2013 (MEMS 1V/g)	AVT 2 Sep 2014 (Piezo 1V/g)	AVT 3 Feb 2015 (Piezo 10V/g)
3.01e-04g	2.67e-04g	4.72e-04g	3.67e-04g

Table 1: RMS amplitudes of the recorded data analysed.

Mode number	Frequency [Hz]				Mode Type
	AVT 1a Dec 2013 (MEMS 1V/g)	AVT 1b Dec 2013 (MEMS 1V/g)	AVT 2 Sep 2014 (Piezo 1V/g)	AVT 3 Feb 2015 (Piezo 10V/g)	
1	1.443	1.411	1.436	1.449	Fx1
2	1.519	1.495	1.510	1.518	Fy1
3	-	-	-	4.345	T1
4	-	-	-	4.586	Fx2
5	-	-	-	4.861	Fy2

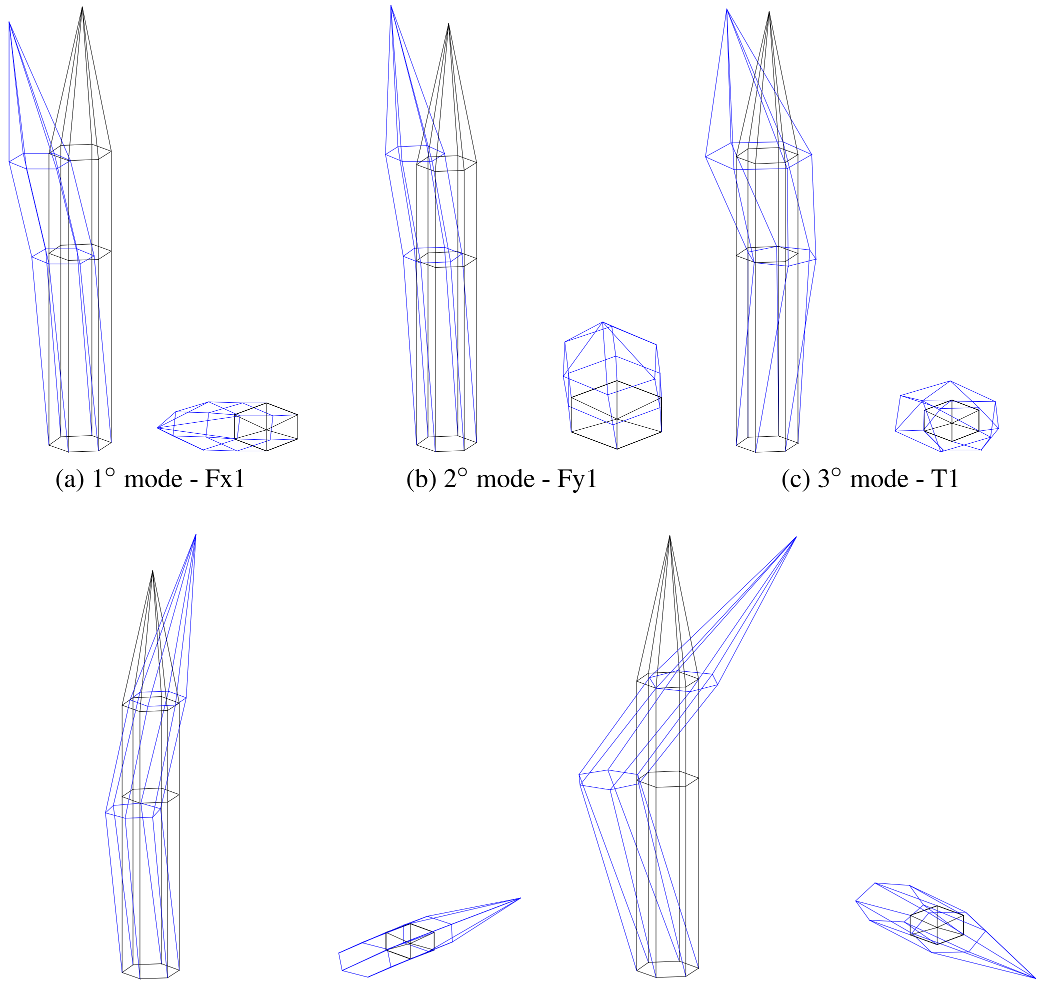
Table 2: Identified natural frequencies of the bell-tower.

4 REMOTE AUTOMATED FREQUENCY TRACKING

Since October 2014 a continuous dynamic monitoring system has been installed onto the bell-tower with the purpose of investigating the evolution of the natural frequencies of the bell-tower and to use such information for early damage detection. The monitoring system comprises three high-sensitivity accelerometers, of the same type of those used in AVT 3, fixed at the base of the cusp, as described in Figure 2(b), Section 1, ch. 1, 2, 3. Monitoring data can

Mode number	Damping [%]				Mode Type
	AVT 1a Dec 2013 (MEMS 1V/g)	AVT 1b Dec 2013 (MEMS 1V/g)	AVT 2 Sep 2014 (Piezo 1V/g)	AVT 3 Feb 2015 (Piezo 10V/g)	
1	1.0	1.6	1.1	1.0	Fx1
2	0.9	1.0	0.9	1.0	Fy1
3	-	-	-	1.5	T1
4	-	-	-	1.7	Fx2
5	-	-	-	3.2	Fy2

Table 3: Damping values of the identified natural frequencies of the bell-tower.



(a) 1° mode - Fx1
(b) 2° mode - Fy1
(c) 3° mode - T1
(d) 4° mode - Fx2
(e) 5° mode - Fy2

Figure 5: Representation of the first identified modal shapes.

be accessed at any time via the internet, Fig. 6, and are transmitted to the server of the Laboratory of Structural Dynamics of University of Perugia were they are automatically processed to extract modal parameters and other synthetic information.

Figure 7 shows the time evolution of the first natural frequencies, where daily fluctuations due to changes in ambient conditions are especially noteworthy. The presented results show that the first two modes are almost steadily identified, while higher order modes are sometimes

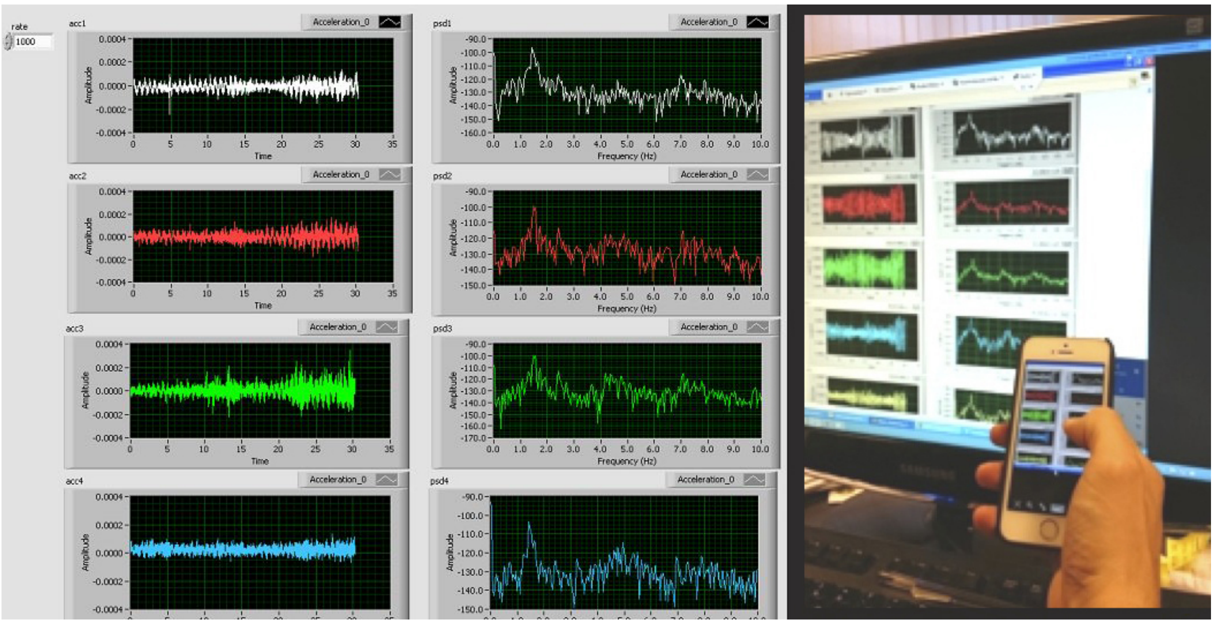


Figure 6: Remote access to monitoring data using PC and smartphone.

not identified due to insufficient levels of vibration.

5 NUMERICAL MODELING

The numerical model has been built by means of a Finite Element commercial code. It comprises both hexahedral and tetrahedral elements, necessary to reproduce the irregular geometry of some structural parts. In particular, a structured mesh has been used in the shaft and the basement regions, and a free mesh in the belfry and the cusp. Specific attention has been focused on a consistent modeling of the bordering constructions, due to the strongly dependence of the modal shapes on the lateral stiffness provided by them. Different values of mechanical properties have been assigned to the volume partitions to take into account the presence of specific inner structural elements. It should be noted that the right stiffness ratio assigned to the partitions allows to obtain the change in direction of the higher flexional modes in comparison to the lower order ones. This is related to the architectural and structural differences between the upper and the lower part of the bell-tower, which give to the structure a quite complex dynamic behaviour. A sketch of the numerical model is shown in Figure 8

The model of the bell-tower has been partitioned in three sub-volumes: the shaft, the belfry and the cusp. The choice of these regions is related to the tuning operations for the correlation between the experimental and numerical modal characteristics. Homogeneous orthotropic materiala have been used in all the parts of the model. In a first step, the elastic parameters have been taken in accordance with the range proposed by the Italian code for each constituent material: the squared stone masonry for the shaft, a brick masonry with squared stone masonry for the cell and the brick masonry for the cusp. In addition, the corrective coefficients suggested in the case of good conditions of mortar have been considered in the case of the elastic moduli of the shaft and the belfry (γ_{1s} = 1.2 and γ_{1b} = 1.5 respectively), while the case of thickness of mortar joints less than 1cm (γ_{2s} = 1.2) only for the shaft. By varying the mechanical parameters of the materials, a modal sensitivity analysis has been carried out to perform a model updating. By a few steps of manual tuning, a consistent numerical model has been obtained.

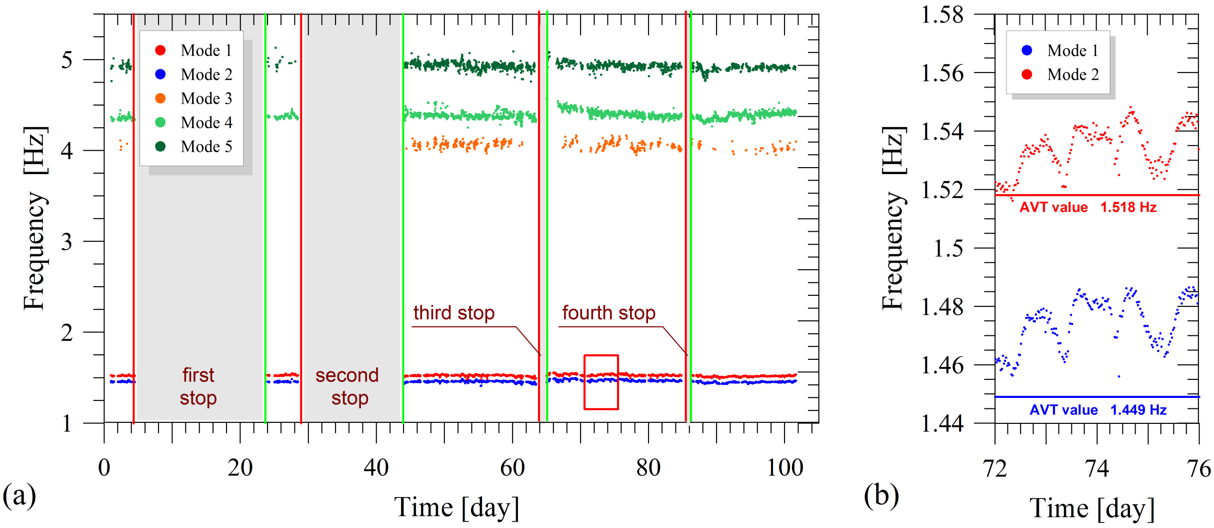


Figure 7: Timeline of the identified natural frequencies of the bell-tower.

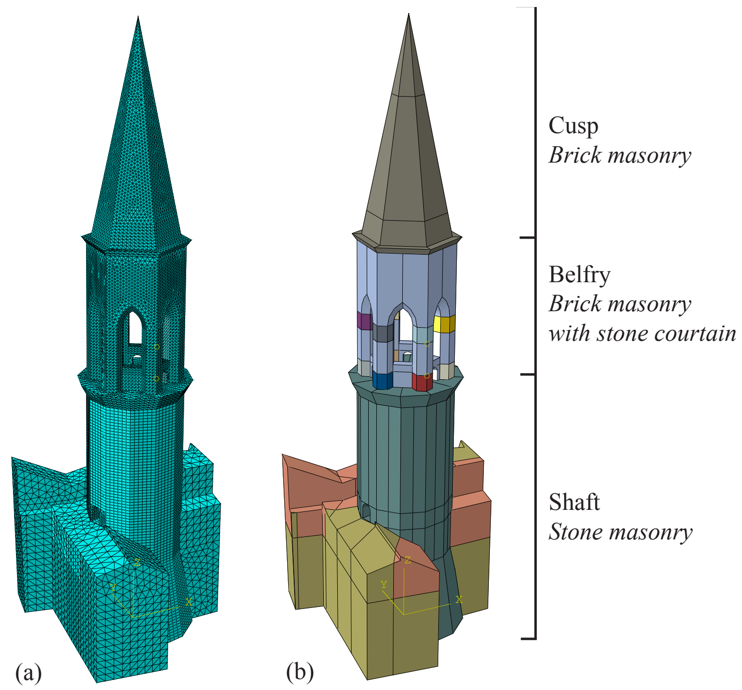


Figure 8: Numerical FE model. (a) Sketch of the mesh. (b) Structural elements and materials used.

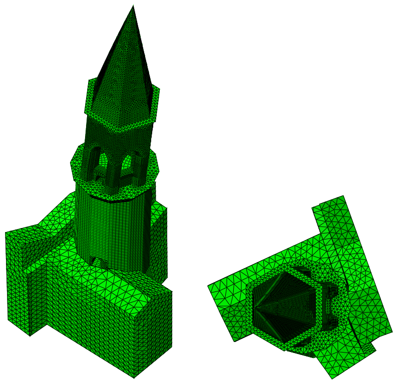
The mechanical characteristics, before and after the model updating process, are summarized in Table 4, and the modal shapes with the related values of frequencies are shown in Figure 9.

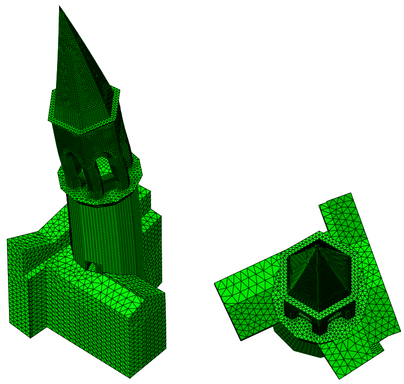
6 STRUCTURAL HEALTH ASSESSMENT: FIRST RESULTS

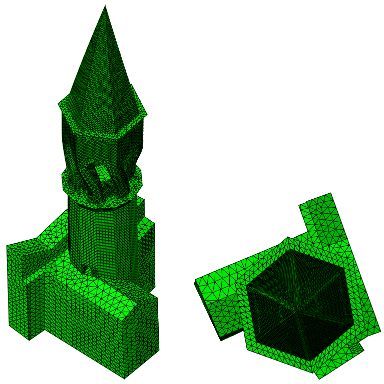
A consistent FE model allows to perform predictive analyses of the structural response due to the possible occurrence of damage conditions. In the following the results of a first investigation about the influence of a structural damage parameter on the natural frequencies of the bell-tower are shown.

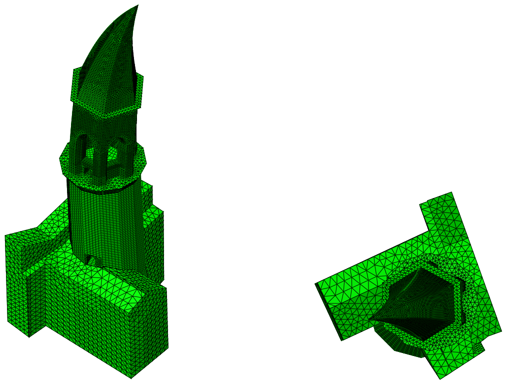
Structural part	Young's modulus [MPa]		Shear modulus [MPa]		Poisson's ratio
	before tuning	after tuning	before tuning	after tuning	
Shaft	4032	5450	1238	1238	0.25
Belfry	2250	2950	750	1920	0.25
Cusp	1500	1500	500	500	0.25

Table 4: Elastic parameters of the orthotropic constitutive model.


(a) Fx1 - 1.448 Hz


(b) Fy1 - 1.518 Hz


(c) T1 - 4.356 Hz


(d) Fx2 - 4.577 Hz

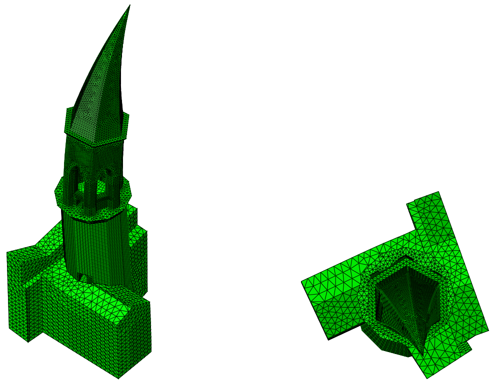

(e) Fy2 - 4.692 Hz

Figure 9: Flexional (F) and torsional (T) modal shape obtained by the FE model.

The study has been focused on the pillars of the belfry. The architectural configuration of the belfry allows to assume that the base and the top of the pillars constitute one of the most critical parts of the structure. In fact, during the recent strengthening measures, carried out on the bell-tower after the Umbria-Marche earthquake of 1997, the masonry of the pillars was reinforced by means of grout injections, owing to an advanced state of decay.

In the analysis, a damage parameter d as been assigned to both the base and the top of each pillar, representing a reduction in elastic stiffness. The analysis considers a leading pillar pillars are characterized by smaller damages depending on the distance from the leading one. The damage parameter linearly reduces the elastic moduli of the material up to 70% of the initial value. The south pillar has been considered as leading one. In Figure 10 the decay of the natural frequencies with the increasing damage parameter is shown, f_u and f_d denoting undamaged and damaged frequencies, respectively.

The results highlight a major sensitivity of the third mode to damage, whose frequency is

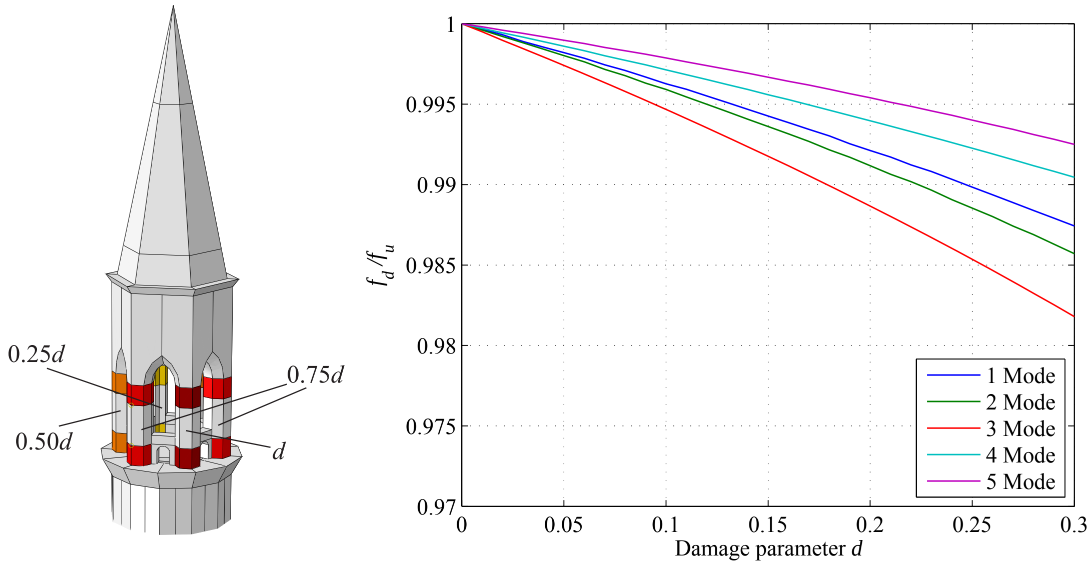


Figure 10: Decay of the natural frequencies in function of the damage parameter.

reduced up to about 1.8% when $d = 0.3$, while lower order modes undergo frequency variations up to 1.3% and 1.4%, respectively. Considering that multivariate statistical analysis tools such as Principal Component Analysis and novelty detection can allow to clearly detect variations in frequencies of the order of 0.1%, it is concluded that the minimum level of detectable damage roughly corresponds to $d = 0.015$, that is, a 1.5% reduction in stiffness in the critical regions of one pillar.

7 CONCLUSIONS

The paper has presented dynamic investigations, first months of permanent monitoring, numerical modeling and damage sensitivity analysis of a monumental masonry bell-tower located in Perugia, Italy. Optimal choice of sensing hardware and sensors' layout have been addressed, at first. Then, a baseline modal identification of the tower has been carried out and a procedure for automated frequency tracking has been developed and implemented. Results of first months of monitoring outline a steady identification of the frequencies of the lowest vibration modes of the structure, which will allow continuous structural health assessment of the tower in the future. Numerical modeling of the tower has demonstrated a good agreement with experimental results. Finally, results of a numerical damage sensitivity analysis have provided information on the minimum level of damage detectable with the developed SHM system.

Overall, the results presented in this paper contribute to demonstrating the potential of permanent vibration-based monitoring systems for automated condition assessment and preservation of cultural heritage structures.

ACKNOWLEDGEMENTS

The Authors gratefully acknowledge the financial support of the "Cassa di Risparmio di Perugia" Foundation that funded this study through the project "Structural Monitoring for the protection of the Cultural Heritage: the bell-tower of the Basilica of San Pietro in Perugia and the dome of the Basilica of Santa Maria degli Angeli in Assisi" (Project Code 2014.0266.021).

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