Materials Research Proceedings **26** (2023) 575-580 https://doi.org/10.21741/9781644902431-93

Post-earthquake continuous dynamic monitoring of the twin belfries of the Cathedral of Santa Maria Annunziata of Camerino, Italy

Gianluca Standoli[1,a], Francesco Clementi[1,b *], Carmelo Gentile[2,c], Stefano Lenci[1,d]

[1] Department of Civil and Building Engineering, and Architecture, Polytechnic University of Marche, Ancona, Italy

[2] Department of Architecture, Built Environment and Construction Engineering, Technical University of Milan, Milan, Italy

[a]g.standoli@univpm.it, [b] francesco.clementi@univpm.it, [c]carmelo.gentile@polimi.it, [d]s.lenci@univpm.it

Keywords: Masonry Towers, Structural Health Monitoring, MEMS, Weather Conditions

Abstract. In this paper the results of over two years of continuous monitoring of the twin bell towers of the Cathedral of Camerino (Italy) are presented. The monitoring activity target is the evaluation of the dynamic behavior of the twin belfries after the damages occurred during the seismic events of 2016 and the application of fast securing. The experimental data are acquired in continuous using four triaxial MEMS accelerometers, two for each structure, on two opposite corners of the bell cells. Data processing is managed with an automatic system which elaborates the signals and executes Operational Modal Analysis to track the modal characteristics of the structures and their evolution in time. Correlation with environmental factors allows to discern the effect of climatic conditions on the variations of dynamics.

Introduction

The preservation of masonry Cultural Heritage (CH) buildings has become one of the main goals for civil engineering [1-3]. Over the last decades, due to their vulnerability to natural hazards, i.e. earthquakes, different methodologies have been developed to assess their health status and consequently design intervention plans. Among the various Non-Destructive Tests (NDT) methods available, one of the techniques that mostly attracts the interest of researchers is the Ambient Vibration Testing (AVT) [4], which consists in monitoring the environmental and anthropogenic vibrations induced on the structure in its operating conditions [5-7], and finally extracting the main dynamic parameters (frequencies, modal shapes, and damping factors) [8, 9], after filtering of the non-structural effects [1,10-12].

A particular application of this technique is the system, composed of four MEMS accelerometers, installed on the 4th February 2020 in the bell towers of the Cathedral of Santissima Maria Annunziata of Camerino. This monument suffered severe damage during the seismic sequence of 2016 that stroked Central Italy, leading to reinforcement interventions that made the church an iconic case study for the development of a continuous monitoring system. In the paper, the first results of the modal parameters tracking are presented, automatically executed [13] with a self-made Matlab© script, on the vibrations data acquired for the twin bell towers during over a year of monitoring activity.

The Case Study: Camerino Cathedral Bell Towers

The city of Camerino (Fig. 1a) arises on a hill (661 m a.m.s.l.) of the Macerata Province, in the Marche region (Italy). In the main square is locate the Cathedral (Fig. 1b), nowadays known as Santissima Annunziata of Camerino, originally built during the V century d.C. as a Roman basilica dedicated to San Giuseppe. Starting from XIII century, according to the historical documentation, the structure is subject to great alterations because of the Swabian devastations and the evolution

Materials Research Proceedings **26** (2023) 575-580 https://doi.org/10.21741/9781644902431-93

of the economy and demography of the city. The renovation culminated with the restoration works following the complete collapse of the bell tower caused by an earthquake in 1279. New restyling operations started between 1748-1749, when the XIII century façade was completely rebuilt with baroque canons.

Figure 1. Localization of the city of Camerino (a) and a view of Santissima Maria Annunziata Cathedral (b)

Due to the 1799 seismic events, the building was destroyed, thus re-building works started under the direction of Andrea Vici. This project contemplated the complete reconstruction of the church with a Latin-cross planimetry and the expansion of the square in the front.

After a stop, due to the French occupation in 1807, the restoration works were resumed 10-20 years later and the Cathedral assumed the shape we observe nowadays, with the two robust symmetrical belfries and the front gallery. The works finished in 1832, when the church was consecrated to Santissima Annunziata.

Other earthquakes occurred in the following years (i.e., 1873, 1897, 1979) and only after the seismic events of 1997 steel curbs were installed in the roof.

The geometrical and material surveys of the Church were operated through laser scanning technology, which allowed to extract the planimetry, the lateral views and the sections of the building. From the right aisle, it is possible to access the relative tower, otherwise the left tower (Fig. 1) is accessible through a door from the outside. The towers are symmetrical, with a peak height of 40.8 meters above the countryside level, with an irregular octagonal cross-section and a planimetric footprint of around 7.40 x 6.92 m^2. The belfries floors stand at around 25 m of altitude and present four vast arch opening on the sides (Fig. 1b).

Several types of masonry texture [14], the presence of opening and different heights of the foundations constitutes vulnerability elements which contributed to reach the observed level of damage.

Ambient Vibration Testing

The continuous monitoring system is composed of four triaxial MEMS accelerometers, installed in pairs on two opposite corners of the towers, at a height of around 4 meters above the bell cell floors (Fig. 2). All the sensors are connected in chain, assuring the synchronization of the measures. Data are acquired for 20 minutes every hour, with a sampling frequency of 200 Hz. When the continuous acquisition process stops, acquisition on trigger activates and, in case of events, registrations start with sampling frequency of 1000 Hz and duration of 90 seconds of pre- and post-triggering.

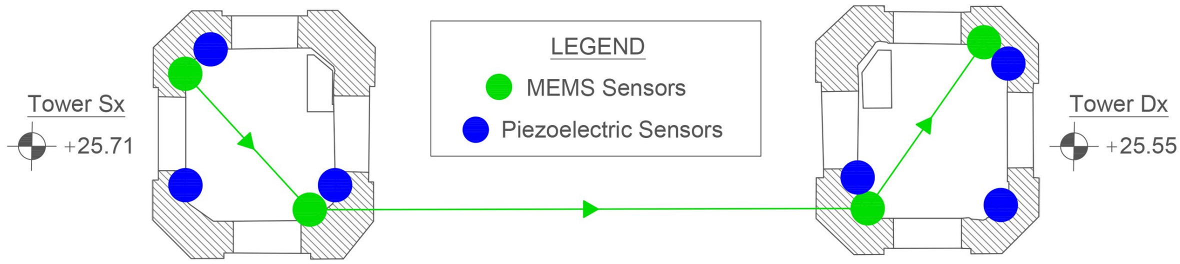

Figure 2. Sensors' layouts: respectively the continuous monitoring system (in green) and the short-time monitoring system (in blue).

Environmental data, concerning external temperature, external humidity, and wind speed, are collected through a weather station positioned in the proximity of the structure, available for consultation on the site http://app.protezionecivile.marche.it/sol/info.sol?lang=it.

In order to assess the initial conditions of the towers at the start of the long-time monitoring process, a short-time acquisition has been made, using 18 monoaxial piezoelectric accelerometers (Fig. 2), with a sensitivity of 10 V/g, fixed in groups of three sensors in six corners of the bell cell (in proximity of the MEMS sensors). This acquisition lasted 40 minutes with a sampling frequency of 1000 Hz.

Modal identification

Data are elaborated automatically through a self-made script developed in Matlab© environment. The towers data are analyzed separately, to highlight the difference in dynamic behavior including the influence of temporary (safety provisions) reinforcement interventions.

The script firstly pre-processes the short-time acquisition, applying de-trending, low-pass filtering and then decimating data in the range of 0-12.5 Hz, which is the one of interest for this type of structure. Then modal parameters identification is operated through automatic Enhanced Frequency Domain Decomposition (EFDD) [15] and Stochastic Subspace Identification - Covariance Based (SSI-Cov) methodology [16] for both towers, and the resulting modal frequencies and mode shapes (Fig. 3) become the targets for modal tracking over the continuous monitoring data.

From the identification operated over the first dataset (Table 1), it is observable that the two towers, have similar in terms of modal frequencies values. In Fig. 3 is reported the modal shapes of only the right tower for brevity reasons.

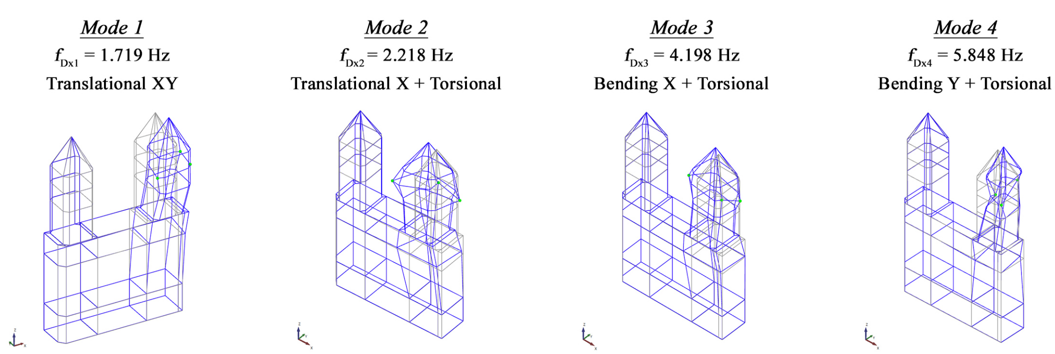

Figure 3. Target frequencies and mode shapes obtained from short-time monitoring data analysis for the right tower

Acceleration files stored through MEMS sensors are initially pre-processed, repeating the operations described for the short-time data. The parameters extraction process is instead operated recurring to two clustering levels: in the first step, hard validation, and minimization of a two terms objective function in Eq. 1 [17] which considers both frequencies variation and MAC values [18]

Materials Research Proceedings **26** (2023) 575-580 https://doi.org/10.21741/9781644902431-93

between consecutives model orders; the second step starts from grouping the parameters corresponding to the same modes and then comparing these ones to the target ones, selecting the values with the best fitting.

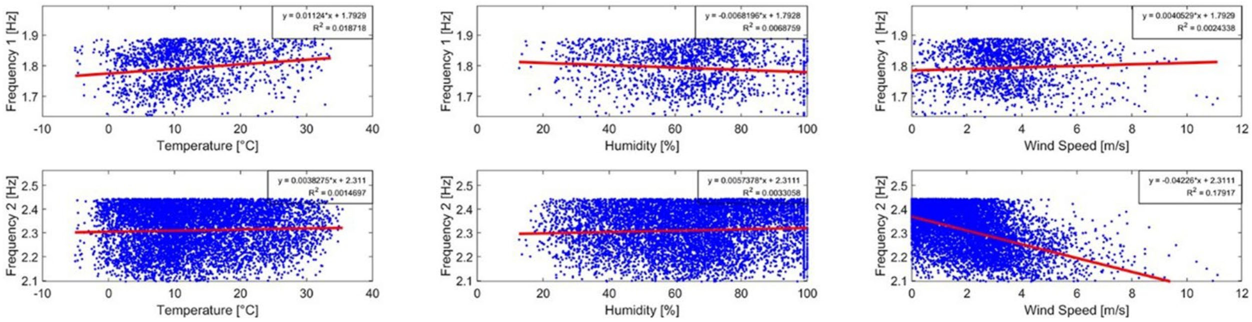

Figure 4. Example of interpolation of environmental data (Temperature, Humidity, Wind Speed) with the first two frequencies of the right tower

Automatically identified parameters are reported and their mean values are compared with the target ones in Table 1.

Table 1. Comparison between target and median automatically identified parameters

Mode	Left Tower			Right Tower			
	f_{Target} [Hz]	f_{Mean} [Hz]	$\Delta f_{Target-Tracked}$ [%]	f_{Target} [Hz]	f_{Mean} [Hz]	$\Delta f_{Target-Tracked}$ [%]	Δf_{L-R} [%]
1	1.805	1.904	5.20	1.719	1.815	5.29	4.90
2	2.318	2.310	0.35	2.218	2.331	4.85	0.90
3	4.218	4.287	1.61	4.198	4.103	2.32	4.48
4	5.906	5.913	0.12	5.848	5.872	0.41	0.70

$$\frac{|f_i - f_{Target}|}{f_{Target}} + (1 - MAC_{i-Target}) \leq 0.05 \quad (1)$$

By overlapping the data before and after environmental effect removal, an interesting phenomenon is highlighted in the fourth modes of both towers: the occurrence of a freezing condition on 15th of February 2021 (day when the minima temperatures of the year were registered), due to the freezing of the water particles contained in masonry micropores, testified by a sudden increment in towers rigidity [5]. In Figure 5, for brevity issues, the results of only the right tower are reported.

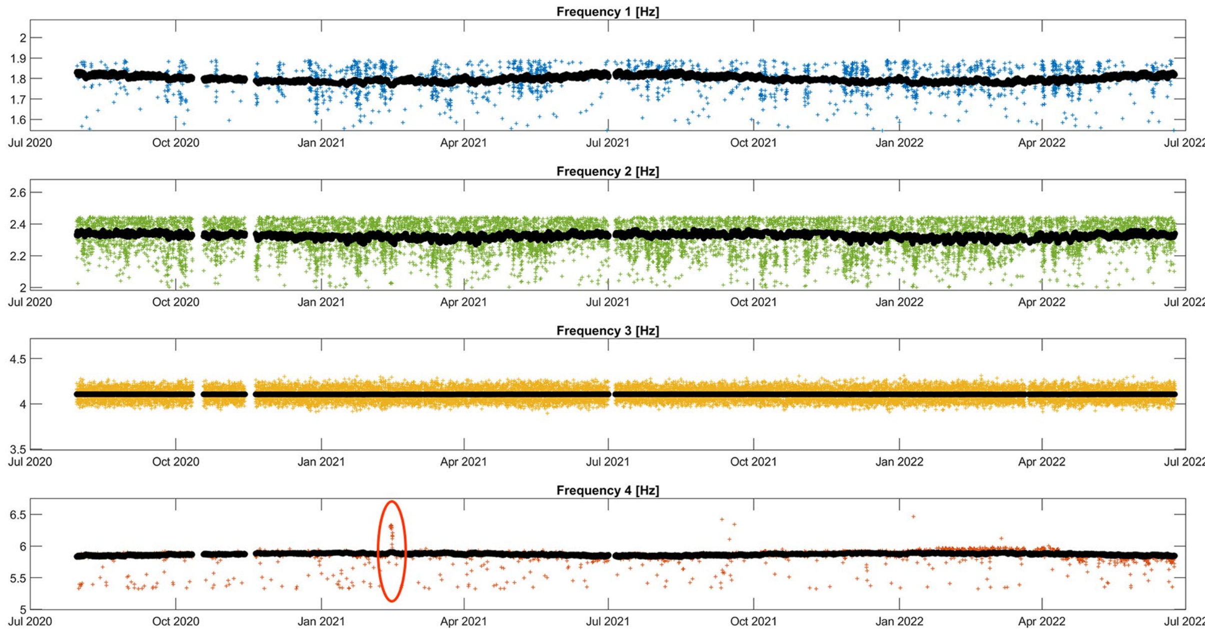

Figure 5. Two years of modal frequencies tracking after removal of environmental effects. The red circle highlights the freezing condition.

Summary

The paper shows an application of continuous structural monitoring by a particular type of accelerometric sensors, i.e. MEMS. Through a Matlab© script it was possible to identify the dynamic characteristics associated to the first four modes of the two twin towers of Santissima Maria Annunziata Cathedral in Camerino, a historical building strongly damaged by the seismic events of 2016-‘17, and then subdued to temporary reinforcement interventions.

The procedure produced interesting results, allowing to understand the differences in the dynamic behavior of the two towers, despite their symmetry. Moreover, it was possible to prove the efficiency of MEMS sensors for continuous monitoring activity.

References

[1] M.G. Masciotta, J. C. A. Roque, L. F. Ramos, and P. B. Lourenço, A multidisciplinary approach to assess the health state of heritage structures: The case study of the Church of Monastery of Jerónimos in Lisbon, Constr. Build. Mater. 116, 169–187 (2016). https://doi.org/10.1016/j.conbuildmat.2016.04.146

[2] F. Magalhães, A. Cunha, and E. Caetano, Vibration based structural health monitoring of an arch bridge: From automated OMA to damage detection, Mech. Syst. Signal Process. 28, 212–228 (2012). https://doi.org/10.1016/j.ymssp.2011.06.011

[3] F. Clementi, A. Ferrante, E. Giordano, F. Dubois and S. Lenci, Damage assessment of ancient masonry churches stroked by the Central Italy earthquakes of 2016 by the non-smooth contact dynamics method, Bull Earthquake Eng. 18, 455–486 (2020). https://doi.org/10.1007/s10518-019-00613-4

[4] A. Pierdicca, F. Clementi, A. Fortunati, S. Lenci, Tracking modal parameters evolution of a school building during retrofitting works, Bull Earthquake Eng. 17(2), 1029-1052 (2019). https://doi.org/10.1007/s10518-018-0483-9

[5] F. Ubertini, G. Comanducci, N. Cavalagli, A. Laura Pisello, A. Luigi Materazzi, and F. Cotana, Environmental effects on natural frequencies of the San Pietro bell tower in Perugia, Italy, and

their removal for structural performance assessment, Mech. Syst. Signal Process. 82, 307–322 (2017). https://doi.org/10.1016/j.ymssp.2016.05.025

[6] A. Deraemaeker, E. Reynders, G. De Roeck, J. Kullaa, Vibration-based structural health monitoring using output-only measurements under changing environment, Mech. Syst. Signal Process. 22, 34–56 (2008). https://doi.org/10.1016/j.ymssp.2007.07.004

[7] A. Saisi, C. Gentile, M. Guidobaldi, Post-earthquake continuous dynamic monitoring of the Gabbia Tower in Mantua, Italy, Constr. Build. Mater. 81, 101-112 (2015). https://doi.org/10.1016/j.conbuildmat.2015.02.010

[8] W. Torres, J. L. Almazán, C. Sandoval, and R. Boroschek, Operational modal analysis and FE model updating of the Metropolitan Cathedral of Santiago, Chile, Eng. Struct.143, 169–188 (2017). https://doi.org/10.1016/j.engstruct.2017.04.008

[9] L. F. Ramos, G. De Roeck, P. B. Lourenço, and A. Campos-Costa, Damage identification on arched masonry structures using ambient and random impact vibrations, Eng. Struct. 32, 146–162 (2010). https://doi.org/10.1016/j.engstruct.2009.09.002

[10] C. Gentile, M. Guidobaldi, and A. Saisi, One-year dynamic monitoring of a historic tower: damage detection under changing environment, Meccanica 51, 2873–2889 (2016). https://doi.org/10.1007/s11012-016-0482-3

[11] P. F. Giordano, F. Ubertini, N. Cavalagli, A. Kita, and M. G. Masciotta, Four years of structural health monitoring of the San Pietro bell tower in Perugia, Italy: two years before the earthquake versus two years after, Int. J. Mason. Res. Innov. 5, 445–467 (2020). https://doi.org/10.1504/IJMRI.2020.111797

[12] R. Ceravolo, G. Coletta, G. Miraglia, and F. Palma, Statistical correlation between environmental time series and data from long-term monitoring of buildings Statistical correlation between environmental time series and data from long-term monitoring of buildings, Mech. Syst. Signal Process. 152 (2021). https://doi.org/10.1016/j.ymssp.2020.107460

[13] E. García-Macías and F. Ubertini, MOVA/MOSS: Two integrated software solutions for comprehensive Structural Health Monitoring of structures, Mech. Syst. Signal Process. 143 (2020). https://doi.org/10.1016/j.ymssp.2020.106830

[14] G.P. Salachoris, E. Magagnini, F. Clementi, Mechanical characterization of "Scaglia Rossa" stone masonry through experimental and numerical analyses," Constr. Build. Mater., 303 (2021). https://doi.org/10.1016/j.conbuildmat.2021.124572

[15] N. J. Jacobsen, P. Andersen, and R. Brinker, Using Enhanced Frequency Domain Decomposition as a Robust Technique to Harmonic Excitation in Operational Modal Analysism, in ISMA2006: International Conference on Noise and Vibration Engineering, Katholieke Universiteit, (2006).

[16] B. Peeters and G. De Roeck, Reference-Based Stochastic Subspace Identification for Output-Only Modal Analysis, Mech. Syst. Signal Process. 13, 855–878 (1999). https://doi.org/10.1006/mssp.1999.1249

[17] G. Standoli, G.P. Salachoris, M.G, Masciotta, F. Clementi, Modal-based FE model updating via genetic algorithms: Exploiting artificial intelligence to build realistic numerical models of historical structures, Constr. Build. Mater., 303 (2021). https://doi.org/10.1016/j.conbuildmat.2021.124393

[18] M. Pastor, M. Binda, and T. Harčarik, Modal Assurance Criterion, Procedia Eng. 48, 543–548, (2012). https://doi.org/10.1016/j.proeng.2012.09.551