The Fourteenth International Conference on
Computational Structures Technology
23–25 August, 2022 | Montpellier, France

Proceedings of the Fourteenth International Conference on
Computational Structures Technology
Edited by B.H.V. Topping and J. Kruis
Civil-Comp Conferences, Volume 3, Paper 8.4
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.3.8.4

Dynamic Identification and Numerical Calibration of a Masonry Tower

F. Bianconi[1], G. Standoli[1], E. Giordano[1], A. Ferrante[2] and F. Clementi[1]

[1]Dept. of Civil and Building Engineering, and Architecture, Polytechnic University of Marche, Ancona, Italy
[2]ILaboratoire de Mécanique et Génie Civil (LMGC), CNRS, University of Montpellier, France

Abstract

Masonry towers are quite widespread in Europe and represent an important portion of the built heritage that must be preserved, especially in high-seismicity regions. Very often, such masonry towers exhibit unique peculiar morphologic and typological characteristics, which might affect their different structural behaviours under horizontal loads. For this reason, accurate knowledge of their dynamical parameters is useful for seismic assessment and the design of risk mitigation interventions. In this work, the opportunities provided by dynamic identification techniques for the non-destructive evaluation of heritage structures are discussed with a focus on the Civic Tower and its annexes, located in Matelica, a village of Marche region (Italy). They were stricken by a long seismic sequence (Center Italy earthquakes between August and October 2016) and are investigated in detail in order to have an insight into their dynamic behaviour. Furthermore, the experimental investigations and the operational modal analysis results are presented, they are useful for defining the Finite Element (FE) model of the complex with a continuum approach. The monitoring system consists of several elements adequately connected. Many operative problems have conditioned the positioning of the instrumentation due to the limited accessibility of the structure, not only to the primary access but also to reach the top. However, it has been possible to identify with certain confidence the first five frequencies and their corresponding mode shapes. The results carried out after the updating procedure may be considered very good. The material data values estimated in this way will constitute an important reference for the evaluation of the state of the building.

Keywords: structural health monitoring, operational modal analysis, finite element model, masonry tower, historical building.

1 Introduction

Europe preserves a large part of the Earth's historical and artistic heritage, Italy is one of the European countries that owns the majority of historical buildings, especially palaces and churches. Because of its particular position, the nation is crossed by African and Euro-Asiatic tectonic plates, the seismic risk is very high and continuously endangers the historical structures [1]–[12]. One of the last examples is the recently Central Italy Earthquakes that hit the areas between Marche, Abruzzo and Umbria Regions causing widespread damages especially at the construction part of the cultural heritage, highlighting, once again, the necessity to find methodologies to take under control their health, in order to intervene before irreparable damages occur. Currently, the most appropriate technique to achieve this purpose is the Structural Health Monitoring (SHM) using the variation of structures dynamic characteristics as frequencies, damping and mode shapes. To obtain these data, accelerometric sensors are placed on specific points of the structure, in order to record accelerometric time histories only from ambient noise. The data acquired are filtered and processed by appropriate techniques able to extract the dynamic information. These data can be used for two different purposes, depending on the acquisition duration: if there are acquired for a short period (Short-term monitoring) they can be used to identify the current building state and to calibrate a numerical model [9], [13]–[17], whereas if there are acquired for a long period (Long-term monitoring), such as more than one year, they can be used to the damage identification [18]–[22], since, the variation of the dynamic characteristics are linked to stiffness or mass variations [23]. In this last case, particular attention must be paid to the ambient conditions because, as many studies showed, they can provoke variation in frequencies, some authors are looking for algorithms to delete them from the signals [24], [25].

In this paper, the monitoring and the Finite Element Model (FEM) calibration are presented taking as a case study a complex composed by a Civic Tower, a Palace and an arcade in Matelica, a village in the hinterland of Marche region (Figure *1*). This study wants to be an example of applicability the dynamic monitoring for protection of the heritage masonry constructions.

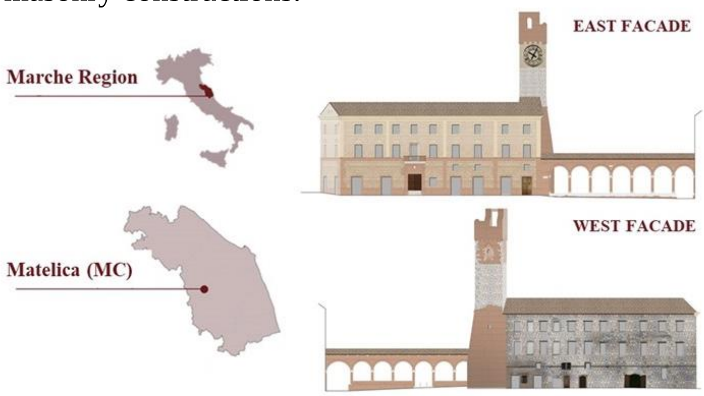

Figure 1: Geographical localization and East and West facades.

2 Methods

First of all, the complex was monitored with Short-Term methodology, performed using four triaxial accelerometers with a sensitivity of 1000 mV/g, a measurement range of ± 8g and A/D converter with a resolution of 24 bit. To obtain as much information as possible with only four sensors six different acquisitions were carried out keeping two sensors on the top fixed as references (Figure 2). Data have been collected with a sample rate of 1024 Hz for periods which vary between 40 and 60 minutes, in order to satisfy Rodriguez condition [26].

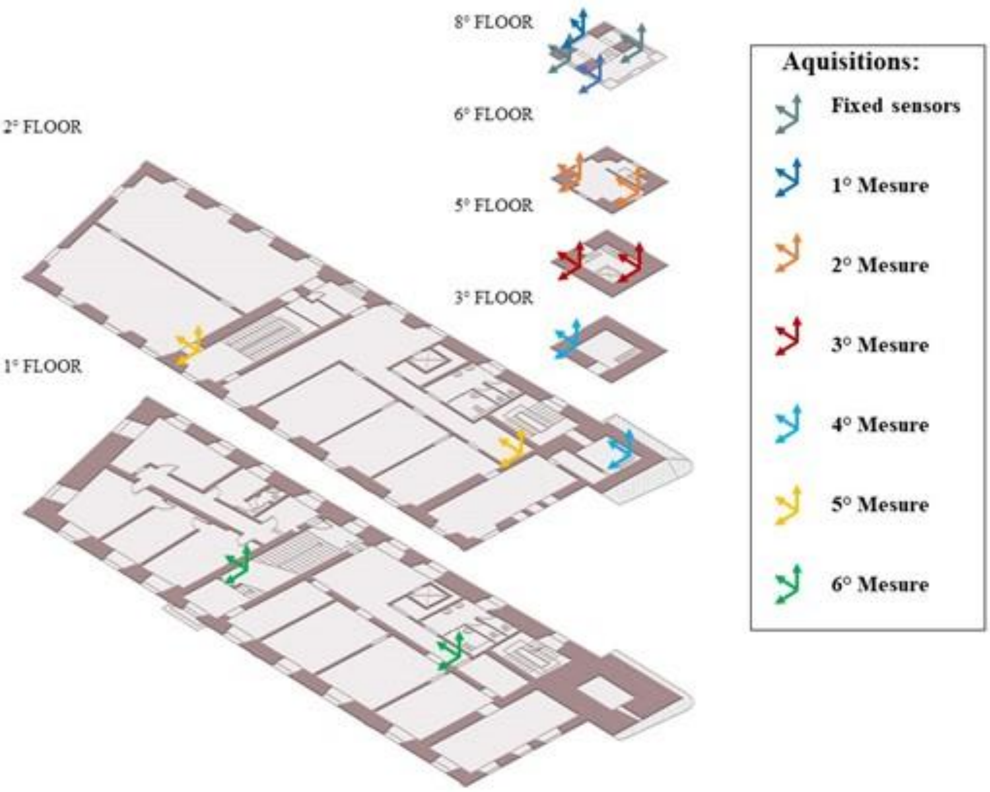

Figure 2: Sensor layouts.

The acquired data, after a filtering process, have been analysed through the Stochastic Subspace Identification (SSI) method [27], a time domain-technique. This elaboration has permitted to extract the natural frequencies and the modal shapes of the case study.

Subsequently, a Finite Element Model (FEM) of the complex was realized (Figure *3*), by assigning the material parameters to the model according to the Italian Code [28], [29]. The model has been subjected to dynamic linear analysis to extract its dynamic characteristics, the difference between them and the experimental ones have been reduced acting on the uncertain parameters like Young Elastic Modulus and density of materials.

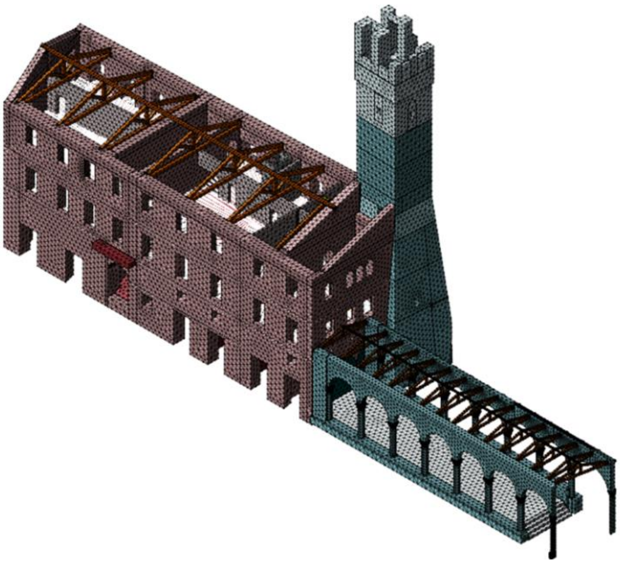

Figure 3: Finite Element Model of the complex.

3 Results

The frequencies and the modal shapes obtain by the dynamic monitoring are reported in Table *1*.

Mode	Frequency [Hz]	Damping [%]	Modal shape
1	1.923	0.679	Y-Translation
2	2.007	0.873	X-Translation
3	5.058	2.931	Y-Flexional
4	6.531	1.569	Distortion
5	7.629	2.705	X-Flexional

Table 1: Modal parameters of Experimental Model.

In order to fit the Numerical Model (NM) with the experiment data, the following steps have been taken. First step of parameter update has been operated only on the elastic modulus of the materials attributed to the tower elements. The criterion was to increase the stiffness of the element subjected to intervention in 2007 and decrease the density of some other elements, whose characteristics are inferior in respect of the previsions. The result of this operation comported a decrement of the frequencies values difference under the 5%, except for the second mode.

In the second step, also the elastic modulus of elements which were not subdued to interventions has been increased, assuming that their deterioration was not as serious as thought at first. The result also comported a decrement of the difference in the values of frequency for the second mode under 5%.

In the last step it has been decided to intervene on the parameters associated to the building, dividing the perimetric walls in three sections, whose stiffness has been increased for the portion nearer the tower, and decreased for the other two parts, Table

2 and Figure 4. The reliability of the results was also proven by the MAC values between experimental and numerical modal vectors indeed, they were quite close to the unit (Table *3*).

Mode	Frequency EM [Hz]	Frequency NM [Hz]	Δf [%]
1	1.93	1.88	2.59
2	2.01	1.92	4.48
3	5.06	5.31	4.94
4	6.53	6.77	3.68
5	7.63	7.82	2.49

Table 2: Comparison of modal frequencies of EM and calibrated NM.

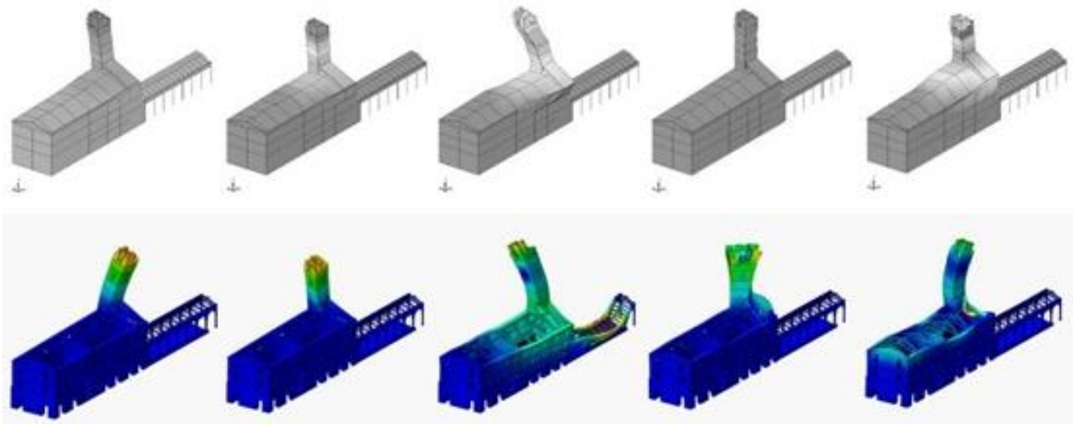

Figure 4: Calibrated numerical model.

		Experimental Model [EM]				
		Mode1	Mode2	Mode3	Mode4	Mode5
Numerical Model [NM]	Mode1	0.89	0.003	0.00	0.00	0.01
	Mode2	0.00	0.98	0.01	0.04	0.02
	Mode3	0.19	0.02	0.70	0.05	0.30
	Mode4	0.00	0.02	0.00	0.81	0.16
	Mode5	0.00	0.09	0.11	0.10	0.78

Table 3: MAC values between experimental and numerical modal vectors.

4 Conclusions and Contributions

The paper analysed the Civic Tower and its annexes, Governor's palace and open gallery, located in Matelica, a village that suffered serious damages from the last Central Italy Earthquake. The complex was subject to dynamic identification that allowed to extract the dynamic characteristics of five modal shapes of the Tower. The finite element model updating process, operated for the tower and the rest of the Governor Palace structure, produced good results in terms of correspondence with the modal parameters and mode shapes extracted from experimental model. The results obtained highlight the low level of interaction between the tower and the palace, whose dynamic behaviours do not influence each other so much, probably due to the different manufacturing and absence of linking elements. In particular, the disorganic movement of the tower, shown for the higher modes, and especially the distorting behaviour of the fourth mode, can be linked to the sectional changes and to the variation of material properties. As concerns the damage propagation, the most damages zones are the ones with low values of Young Elastic Modulus. Once again, dynamic monitoring and modal identification techniques, confirmed their effectiveness in the evaluation of dynamic behaviour and consequently on the health status of historical structures, being the method non-invasive and allowing to produce accurate numerical models, which can be used to implement rapid, localized and economically sustainable interventions.

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