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Prediction of the fundamental frequencies and modal shapes of historic masonry towers by empirical equations based on experimental data

Mariella Diaferio[a], Dora Foti[a,*], Francesco Potenza[b]

[a] Department of Sciences in Civil Engineering and Architecture, Polytechnic of Bari, Via E. Orabona 4, 70125 Bari, Italy
[b] Department of Civil Architectural and Environmental Engineering, University of L'Aquila, Nucleo Industriale di Pile, 67100 L'Aquila, Italy

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ABSTRACT

The adequate knowledge of the modal characteristics (natural frequency, modal shapes and damping) constitutes an important start point to carry out a reliable dynamic structural analysis. In the case of historic masonry towers, in particular, due to their geometric and structural characteristics they can be considered as typical and repetitive structures and predictive empirical laws can be generated. In this paper the performances of some formulas proposed in literature (even only for generic masonry towers) have been assessed on a group of case studies through the Mean Squared Error (MSE). Different results have been found for both bounded and isolated towers. Moreover, to improve to robustness and reliability of the prediction, new optimized functions, obtained minimizing the MSE of the linear regression of a model of exponential law, have been developed. The results, compared using the determination coefficient "*r*", have shown a good capability of the new proposed laws to predict the fundamental frequency for the historic masonry towers. Finally, some correlation regarding the estimation of the higher modes have been highlighted.

1. Introduction

As it is well known, Italy is a country with a wide, ancient and important building heritage and, unfortunately, a high seismic risk [1]. As a consequence, during the last decades a great attention has been devoted to the necessity of protecting this patrimony. A correct seismic assessment and design of risk mitigation interventions, however, need a careful study of the structure.

On the other side, due to the historical character of these buildings, all the necessary information for the definition of a deep knowledge of them are usually unavailable, and the possibility of conducting classical tests is limited to the ones that are non-destructive. In the case of architectural heritage, in fact, destructive tests are hardly carried out; therefore, structural monitoring techniques based on dynamic monitoring of the structures and output-only modal identification techniques become very useful to get the modal parameters of the structure in operational conditions. To this aim, Operational Modal Analysis (OMA) is an efficient method to be utilized in these cases; it allows to know the modal parameters of a structure in a non-invasive way, and can be applied not only to historic and cultural buildings but also to modern ones [2]. Through a process, which is simple and accurate, it is possible then to acquire the ambient vibrations in situ, in order to later estimate the modal shapes of vibration, the natural frequencies and the modal damping ratios based on the processing of the acquired data [3]. Thus, the dynamic identification through operational input is also a solution to evaluate the characteristics of the materials and the boundary conditions of the structure, in order to establish reliable numerical models, through procedures of model updating. Apart from the dynamic identification via finite element 3D modeling, some analysis have been also carried out on a linear simplified model of the tower constituted in a vertical cantilever beam [4].

The techniques, developed for a model updating process and also utilized in some recent studies [5–20], estimate the unknown mechanical properties of the materials and/or the boundary constraints by comparing the identified and the numerical modal parameters and minimizing specific objective functions.

In this context, the so-called "*output-only methods*", are widely spread in the field of monitoring of historical structures, as they may be applied to operationally-induced vibrations 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 requested.

OMA methodology is particularly suited to slender structures such as towers, campaniles, antennas, chimneys, mosques. Indeed, thanks to their geometrical shape, the noise-to-signal ratio becomes very low especially at the top and so this allows to extract important structural

* Corresponding author.
E-mail address: d.foti@poliba.it (D. Foti).

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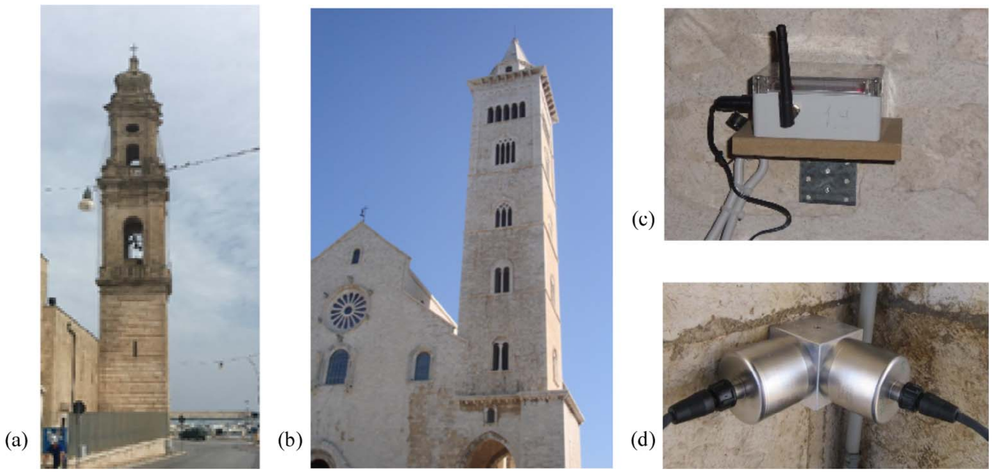

Fig. 1. Two example of typical masonry towers: (a) "Santa Maria di Loreto tower, Mola (Italy); (b) Trani's Cathedral, Trani (Italy); two types of accelerometers: (c) wireless and (d) wired.

information from the acquired accelerations. This type of construction is generally distinguishable according to its prevalent vertical development and constitutes a relevant part of the Italian cultural and artistic heritage. It is also specified in the Italian guidelines "*Evaluation and reduction of seismic risk of the cultural heritage with reference to the technical standards for construction in DM 14/01/2008*" (DPCM 09/02/2011) that the towers, if subjected to vibrations, even of low intensity, generally produce very sharp signals, easily recordable.

These structures are widespread in Central Europe and therefore, for their conservation, it was necessary refined techniques of reinforcement for restoring their performance. In the past, these problems were neglected because the presence of any crack was regarded as part of a normal stage in which the structure is poured. In recent years, however, the sudden collapse of some masonry buildings has prompted researchers to study the response of these structures to the seismic effects and heavy loads. For this reason, a deep knowledge of the dynamic properties is crucial to assess the effective seismic vulnerability of historic towers. Moreover, due to their repetitive and proportional structural features, during the years different Authors have analyzed and proposed models of empirical formulas able to predict the fundamental frequency. Very useful formulas are reported in the standards for construction of Italy [21] and Spain [22]. They have been applied, in particular, to carry out simplified structural analysis able to perform a fast and reliable evaluation of the seismic demand through an empirical determination of such fundamental frequency/period. In the formula of the Italian code the only requested parameter is the total height of the building, while in the Spanish one also the minor side length of the base plan has to be inserted in the formula. It is worth to notice that in both cases only the evaluation of geometrical features are needed, so that these laws are very easy to manage. However, they have been developed for generic masonry structures that, of course, should include also the historic masonry towers. In general, the empirical predictive functions proposed in literature have a marked exponential behavior that decreases the frequency as the total height increases. For example, in Shakya et al. [4] the exponent and amplitude of an exponential model are defined on the basis of the specific masonry structure like towers or minarets. Other formulations have been defined for structures located in specific regions, as in the case of the ones proposed by Ranieri et al. [23] and Faccio et al. [24].

The present paper seeks to face and improve the issue of a rapid evaluation of the modal characteristics for masonry historic towers. Indeed, in some situations, the knowledge of these properties leads to a reduction of cost and time that constitutes one of the priorities for the responsibles of the cultural heritage's management. After the introduction (Section 1), in the second paragraph a wide review of the most important case-studies regarding the analysis of the dynamic behavior for historic masonry towers has been carried out. It has been faced especially through dynamic experimental tests or structural monitoring but also developing and updating 3D finite element modeling. In general, the instrumental setup is composed by an accelerometer wired network and the measured data have been processed using the well-known and consolidated procedures working in both time and frequency domains. The data collected in Section 2 have been analyzed and compared with the numerical results provided by the empirical laws introduced above. In particular, these exponential laws, have been compared using the Mean Squared Error (MSE) between the experimental and predictive fundamental frequencies. Moreover, the latter has been applied to two different sets of towers: bounded and isolated. For the first group it has been estimated the percentage of height constrained only taking into account the information found in the literature. The results appeared good enough even though they are not specific laws for historic masonry towers. For this reason, in Section 4 some new empirical laws more suited for masonry towers have been proposed. They are based on minimizing the MSE of their linear regression. Some considerations are also given about the modal characteristics of the higher modes and their modal shapes and dampings. Finally, in the conclusions some possible suggestions to improve the actual results are highlighted.

2. Experimental applications

The towers are among of the most important cultural heritage to be preserved for their historical relevance in the actual society. During the medieval period this type of structure had especially a territory's defensive and control purpose. For these reasons the height is the principal dimension and, moreover, they show a massive structure with very few and small openings. In Fig. 1a and b two examples of typical masonry towers are reported, while in Table 1 a list of the main cases investigated in recent years by many researches is reported. A lot of structures belong to the Medieval Period (476–1492 A.C.) and other architectures are referred to the Modern Period (1492–1948 A.C.). Notwithstanding this long period (more than 1000 years) the construction technology and the type of material is more or less the same. It seems correct to summarize and organize the common features, in particular from geometrical and mechanical points of view.

The analysis of the scientific publications and researches highlights a common procedure to assess the structural behavior of historic towers:

1. *Construction's identification*: location (focusing the attention to the zone's risks), geometric relief of the building, visual identification of elements and materials (particular attention to the construction details and interconnections), historical overview.
2. *Experimental tests*: they can be divided into static or dynamic tests; to