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Original article

An approach for the mechanical characterisation of the Asinelli Tower (Bologna) in presence of insufficient experimental data

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ABSTRACT

The Asinelli Tower, built at the end of the 12th century, is one of the main symbol of the town of Bologna and a valuable historical heritage of the Medieval age of the entire Italy. For its structural configuration, the tower appears prone to seismic damages and, therefore, an assessment of its dynamic properties is of primary importance to predict its seismic response. In the present paper, based on the results of limited material tests, the mechanical and dynamic properties of the tower are analysed through the development of models of increasing complexity. First, models for the evaluation of the main materials mechanical properties are compared to validate the experimental results. Then, different structural models of the tower (from simple continuum analytical models to more complex finite element models) are developed. The analytical and numerical results obtained from the different models are finally compared to some recent experimental measurements of the free vibration response of the tower conducted by the Italian National Institute of Geophysics and Volcanology (the INGV). The preliminary results indicate that the experimental frequencies are in good agreement with the values obtained from the models. However, additional studies are necessary to better understand the torsional response of the tower.

1. Introduction

The Italian historical-monumental heritage is worldwide recognized as one of the richest and various due to the millenary history of the country affected by the influence of different cultures from the ancient Greeks and Romans to the Muslims. Among the various symbols of the Italian monumental heritage, the two medieval towers of Bologna, the Garisenda tower and the Asinelli Tower, located in the hearth of the town, are among the most known and attractive ones [1].

The Asinelli Tower, the tallest of the two towers with its 97 m height, was built between the XII and XIII century, a historical period characterized by strong political debates, especially between the Church and the Empire. During its almost millenary life, the tower was subjected to various accidents such as fires (the most destructive is dated 1398 and damaged most of the internal wood structures and the selenitic basement), lightings (in 1754 a lighting caused damages to all the upper part of the tower, for about 30 m of lengths) and earthquakes. The 1399 Modena earthquake caused the failure of the upper part of the tower (the little bell tower) which was reconstructed. It fell down again during the 1505 Appennino Modenese earthquake. Beside the above mentioned natural events, in 1943, during the Second World War, the tower was damaged by a bomb explosion.

It clearly appears that, as a consequence of its long history and continuous interventions after the mentioned catastrophic events, the tower is characterized by large dishomogeneities, part due to the construction technique (leading to the so-called “a sacco” masonry, details will be provided in the next section) and part due to different interventions, the tower has been subjected during its history. In these cases, from a structural point of view, it is of fundamental importance to evaluate the mechanical and dynamic properties of such monuments, especially in the case of historical towers which, due to their geometrical configuration, are particularly prone to seismic damages.

During the 1990s, the seismicity of Bologna has been analysed within a research program of the Italian National Institute of Geophysics and Volcanology (INGV) and a first assessment of the Asinelli Tower seismic vulnerability has been carried out (Riva et al., in 1998 [2]). In that study, the authors assumed typical values for the material mechanical properties and concluded that the tower stability seems to be not compromised by seismic events of limited intensity. However, they suggest in situ and laboratory tests in order to characterize the mechanical properties of the tower.

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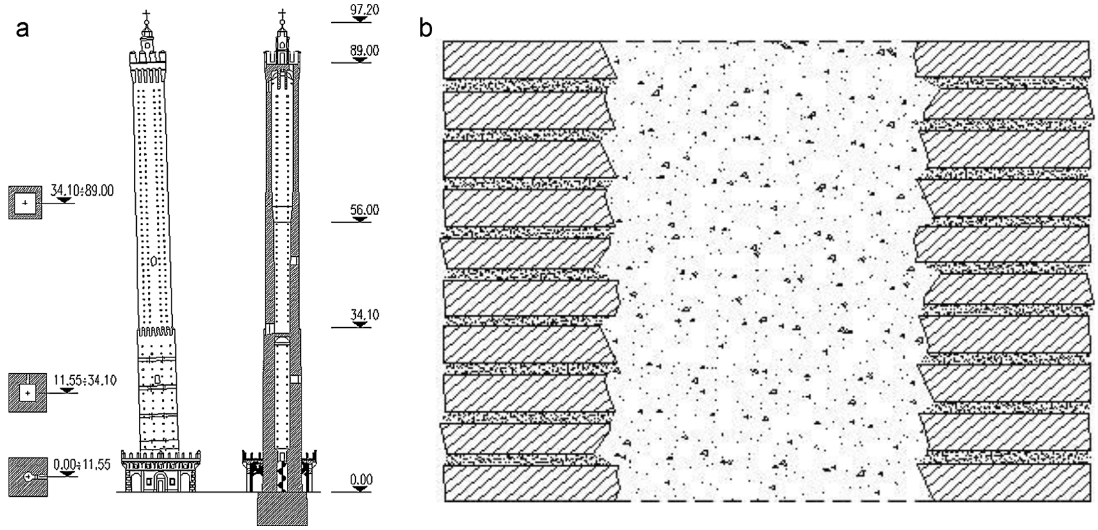

Fig. 1. a: The tower elevation with the indication of the main discontinuities; b: A schematic view (vertical cross-section) of the "a sacco" masonry.

In more recent years (end of 1990s), the tower has been subjected to strengthening interventions as a joint project between the Municipality and the University of Bologna. Before the strengthening, in situ and laboratory tests were performed to characterize the mechanical properties of the masonry. After the strengthening, a monitoring system has been installed in order to control the time evolution of the main cracks, the masonry deformation and the tower inclination. Recently, after the 2012 Emilia earthquake, dynamic tests aimed at identifying the main dynamic properties of the tower have been carried out by the INGV. A report of these experiments is available online [3].

The objective of the present paper is to assess the dynamic behaviour of the tower through the development of several models which are based on the mechanical properties of the materials as obtained from few experimental tests. First, analytical models are developed for the materials to integrate the information as obtained from the few experimental tests. Then, structural models of the towers of increasing complexity (from continuum analytical models to 1-D and 2-D finite element models) are developed to evaluate its fundamental period of vibration and damping ratio. The aim is to evaluate the influence of specific aspects (mass and inertia distribution, soil-structure interaction, P-Δ effects and masonry orthotropy) on the dynamic properties of the tower. Finally, the numerical results are compared with the recent experimental measurements by the INGV.

2. The Asinelli Tower

2.1. The geometry of the tower

The Asinelli Tower is a 97 m-high masonry tower with an inclination of 1.7° (corresponding to a overhanging of 2.5 m) in the West direction (Fig. 1). Its cross-section is approximately square for the whole height with a gradual decrease (almost linear) of the side width from 8.5 m at the base to 6.0 m at the top, excepting a sudden discontinuity at a height of 34 m. The external walls were built using the so-called "a sacco" technique (Fig. 1): two skins of brick masonry with an internal rubble and mortar fill. The fill is composed of irregular materials including brick fragments and irregular stones bound by aerial mortar. Common solid bricks are used for the outer skins, while the basement is realized with selenitic bricks. The total thickness of the masonry (the two skins plus the internal fill) decreases almost linearly from 3.15 m at the base to 0.45 m at the top. Three main discontinuities are present at 11.5 m, 34.0 m and 56.0 m. The masonry assemblies are not regular, with variations in both the width of the bricks and the thickness of the mortar (from 1.0 cm to 3.0 cm). Table 1 provides the main geometrical characteristics along the height of the tower at specific sections.

2.2. The material properties as obtained from experimental tests

In situ and laboratory tests were performed in order to characterize the material properties of the tower. In situ tests included flat jack deformability tests (one compression test and two shear test) according to ASTM 1197 C [4], standard and pointing hardness tests (six tests: one on the internal wall and five on the external walls) with the hammer pendulum (RILEM TC127MS D.2, [5]).

The flat jack tests were performed on the South side of the tower at a height of approximately 7 m. The compression tests allow to evaluate the masonry Young's modulus (E) and the compression strength (f), while the shear tests allow to estimate the masonry shear strength (f_v). During the pointing hardness tests, the penetration of the drill penetration is measured and used for correlations with the previous mechanical properties. The mean values of the Young's modulus (E_m), the compression strength (f_m) and the shear strength ($f_{v,m}$) of the masonry assemblies and mortar as obtained from the in situ tests are collected in Table 2.

Laboratory tests performed on masonry cores included compression tests and measurements of density. One external brick and five cores taken from the internal layer were analysed. The brick showed a compression strength around 10 MPa and a Young's modulus of approximately 8000 MPa. On average, the results of the analyses of the cores reveal that the internal portion of the masonry ("sacco") is characterized by a compression strength of 4 MPa and a Young's modulus of 2500 MPa. It has to be noted that the basement seems to have higher mechanical properties (a compressive strength of 6 MPa and a Young's modulus of 4000 MPa). Density measurements provided the following values: 22–24 kN/m^3 for the selenitic bricks at the base; 17–18 kN/m^3 for the masonry bricks and 16–18 kN/m^3 for the internal fill.

No measurements of tensile strengths and Poisson's coefficients are available. Moreover, no experimental data are available for the selenitic basement at all. Values obtained from other experimental tests (unpublished results of tests commissioned by the University of Bologna) on the selenitic basement of the near Garisenda tower