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Seismic assessment of a historical masonry tower with nonlinear static and dynamic analyses tuned on ambient vibration tests

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ABSTRACT

The paper deals with the dynamic characterization and the evaluation of the seismic performances of historical masonry towers and bell-towers that are particularly vulnerable with respect to seismic actions. The main purpose of the study is to investigate how the seismic assessment of such historical constructions is influenced by the level of refinement of the adopted models and by the type of the performed analyses. The effectiveness of some provisions contained in the Italian guidelines for the seismic risk assessment and mitigation of cultural heritage for this kind of structures is also evaluated. The study is performed with reference to the medieval civic tower of Soncino (Cremona, Italy), that is representative of the considered class of masonry constructions. The dynamic characteristics and the mechanical properties of the masonry tower are evaluated through a dynamic identification with ambient vibration tests. Analytical models of the tower characterized by different refinement levels are calibrated on the results of the performed dynamic identification and used to carry out nonlinear static and dynamic analyses. The performed analyses evidence the very conventional nature of the behaviour factor q for this kind of structure. Moreover from the analyses it results that the q values suggested by the Italian codes overestimate the actual q values. The results obtained with the nonlinear dynamic analysis are in a good agreement with those obtained with the nonlinear static analysis. However the nonlinear dynamic analysis provides levels of displacement capacity lower than those resulting from the nonlinear static analysis and allows to consider the significant effect of the higher frequencies on some of the response parameters, as the base shear. The vulnerability of the tower is also assessed according to the Italian guidelines for the seismic risk assessment and mitigation of cultural heritage using the results of the performed nonlinear static analysis.

1. Introduction

The protection of historical constructions against seismic actions is of strategic importance in Italy considering the richness of its architectural heritage. Most historical constructions are masonry structures that were not conceived to resist lateral forces, indeed the old design concepts mostly focused on the effects of gravity loads and did not provide for adequate lateral resistance and ductility.

Among the constructions characterizing the Italian architectural heritage, masonry structures with a predominant vertical dimension, such as towers and bell-towers, are very common. The limited ductility of the masonry combined with the slenderness of these towers, that behave as a vertical cantilever fixed at the base, generally provides a rather brittle structural behaviour [1]. Therefore these constructions are particularly vulnerable with respect to seismic actions. An effective seismic assessment of such structures can be achieved only through nonlinear static and dynamic analyses once defined suitable finite element models.

Historical structures cannot be investigated through invasive tests due to their preservation needs, in these cases the dynamic identification represents a valid alternative tool to define accurate numerical models. Moreover slender structures are particularly suitable for this type of analysis due to their sensitivity to dynamic vibrations, that produces more clear signals. For these reasons in recent years many masonry towers, such as the San Nicola bell tower in Valencia [2], the bell tower of the Monza cathedral [3], the Hagia Sofia bell tower [4] and the Saint Andrea bell tower in Venice [5] have been investigated through dynamic identification. The results from the in situ campaigns allow to define reliable finite element models [6–9] that constitute an essential tool for the definition of possible strengthening interventions, combining both seismic retrofitting and preservation.

The main purpose of the present paper is to investigate how the seismic assessment of historical masonry towers is influenced by

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the level of refinement of the adopted models and by the type of the performed analyses. The effectiveness of some provisions contained in the Italian guidelines for the seismic risk assessment and mitigation of cultural heritage [10] for this kind of structures is also evaluated. The study is performed with reference to the medieval civic tower of Soncino (Cremona, Italy), that is representative of the considered class of masonry constructions.

The actual constraint conditions of the tower and the mechanical properties of its constituting materials are defined using the results of a dynamic identification based on the records from previously performed ambient vibration tests. The nonlinear static and dynamic analyses are performed on a simplified numerical model, made up of beam elements with plastic hinges at the end, and on a more refined 3D nonlinear model. The obtained results allow to predict the seismic behaviour of the tower and to define suitable strategies for the seismic performance enhancement of the tower according to the provisions of the current Italian guidelines for the seismic risk mitigation of cultural heritage [10].

2. The medieval civic tower of Soncino

2.1. Geometrical survey and historical overview

The medieval civic tower of Soncino (Cremona, Italy) is a historical masonry construction that characterizes the landscape of the small town located in the northern Italy. The tower was erected in the 12th century even if some historical sources date the first phase of its construction at the end of 10th century [11]. Initially the tower was 31.5 m high but in 1575 it was heightened up to 41.8 m, adding a bell chamber on its top. After the 1802 earthquake the tower has undergone several interventions that gave it the present shape (Fig. 1).

The tower has a square plant with a 6 m side; its brick masonry walls have a thickness varying from 1.55 at the base to 0.98 m at the top. This variation creates five thickness discontinuities along the height in correspondence of the wooden floors. At the height of 6.7 m there is a barrel masonry vault, while at the height of 35 m there is a reinforced concrete slab. The tower is adjacent to relevant public constructions, including the town hall, up to the height of 11 m. These constructions are constituted by masonry walls in the east–west direction (*X* direction) and by frames with masonry columns and concrete beams in the north–south direction (*Y* direction), on the southern side only (Fig. 2). The adjacent constructions affect the level of constraint of the tower and can not be neglected in its structural analysis.

Fig. 1. North–west view of the medieval civic tower of Soncino (Cremona, Italy).

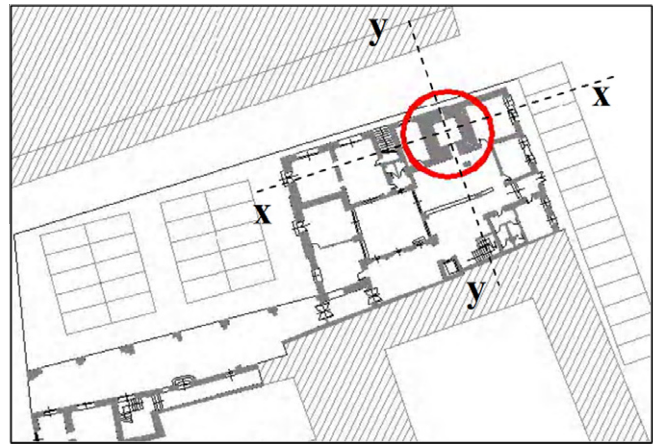

Fig. 2. Plan view of the tower.

The tower shows good preservation conditions, although it presents some superficial cracks and damages due to the aging, the atmospheric exposition and the past earthquakes (Fig. 3). The masonry used to heighten the tower in 1575 shows a higher degradation with respect to the masonry of the original construction. Although the tower does not have serious structural damages, its preservation against potential future earthquakes is of primary importance.

2.2. Seismic hazard

The area of Soncino is a seismic prone zone. Historical catalogues list a $M = 5.7$ earthquake occurred in the area on May 12th 1802: all historical sources indicate Soncino as the most damaged locality, with an assigned MCS intensity of VIII. In the occasion of this earthquake also the tower was damaged. According to the current Italian code [12] the site is characterized by the hazard curve reported in Fig. 4 in terms of PGA at the bedrock a_g versus the return period T_R. The PGA at the bedrock with a 475 years return period is $a_g = 0.119\ g$. For the site effect an amplification factor $S = 1.8$ corresponding to a soft subsoil condition can be assumed.

2.3. Experimental campaign and dynamic identification

The civic tower of Soncino has been the object of an experimental campaign performed by the Milano IDPA-CNR Institute based on ambient vibrations tests [13,14]. The tests were performed using four recording stations: one, TS0, placed at the base of the tower and three, TS1, TS2 and TS3 placed along the tower at the height of 16.5, 26.8 and 35.2 m, respectively (Fig. 5).

The aim of the performed structural identification was the evaluation of the Young modulus *E* of the masonry and of the constraint effect given by the adjacent constructions to the tower. This evaluation is performed, as a first approximation, modeling the tower with a cantilever beam having the same geometrical characteristics of the tower and a constant Young modulus. Two different hypotheses of restraint are considered: (1) the tower is fixed at the base and completely free along the height, without any interaction with the adjacent constructions; (2) the tower is fully restrained up to the top of the adjacent constructions. The matching of the obtained analytical modal shapes with the experimental responses at the recording stations is controlled (Fig. 6). As evidenced by the results reported in Fig. 6, the best fitting between the analytical modal shape and the experimental evidence is