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Seismic vulnerability enhancement of medieval and masonry bell towers externally prestressed with unbonded smart tendons

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A B S T R A C T

Medieval and masonry bell towers are highly vulnerable to suffer strong earthquake damage due to the mechanical and physical characteristics of masonry and other important factors. An approach for the seismic vulnerability reduction of masonry towers with external prestressing is proposed. The devices are vertically and externally located in order to be removable when needed. The characteristic flexural failure mode of medieval towers and the shear mechanism of bell towers are simulated. Both failure modes are in agreement with earthquake damage in similar towers. Medium prestressing level enhances force capacity of towers failing by bending without reducing ductility. High prestressing level slightly reduces the displacement capability of towers failing ductile. In case of belfry failure, both prestressing levels permit to increase displacement but lower force than towers failing by bending. The proposed medium prestressing level is the optimal for masonry towers and other slender structures failing by bending and shear.

1. Introduction

Unreinforced masonry (URM) structures are highly vulnerable under earthquake (EQ) conditions and may present a total collapse. This is due to the anisotropy, heterogeneity and poor tensile strength of masonry and other important factors affecting the structural vulnerability such as geometry, structural configuration, EQ source, etc. Seismic risk management of existing buildings located in EQ prone areas is integrated by two huge stages, the vulnerability assessment and its reduction. There is an enormous number of methods to assess the seismic vulnerability of buildings [14], but not completely clear within the scientific community regarding the procedure to follow for assessing the vulnerability and the measures for its reduction. Recent studies in EQ engineering are oriented to the development, validation and application of techniques to assess the seismic vulnerability of existing buildings [13,4,37,50]. Assessing the seismic vulnerability of a historical building is a complex task if compared to other existing building as explained by Carpinteri and Lacidogna [12], Barbieri et al. [6], Foraboschi [23], Preciado and Orduña [45], Preciado et al. [44], Preciado et al. [46], Preciado et al. [47], Preciado et al. [48]. There is a large variety of techniques and materials available for the protection of historical masonry constructions. Among them, two main techniques are distinguished: rehabilitation and retrofitting. On the one hand, in the rehabilitation process is taken into account materials of similar characteristics to the original ones and the same construction technique to locally correct the damaged structural elements to preserve the building in original conditions. On the other hand, retrofitting uses advanced techniques and materials to improve the seismic performance (energy dissipation) of the building in terms of ultimate lateral load and displacement capacity. Compatibility, durability and reversibility are the fundamental aspects recommended in literature to be taken into account when retrofitting is used for the seismic protection of cultural heritage.

The main objective of this research is the achievement of the seismic vulnerability enhancement of historical masonry towers by the implementation of reversible prestressing devices. The approach is integrated by three main stages: initial analyses of the proposed virtual towers; simulation of typical EQ damage and behavior, as well as the seismic enhancement by externally

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prestressed smart tendons. The devices are vertically and externally located at key locations inside the towers in order to give to the retrofitting the characteristic of reversibility (not invasive), without affecting the architectonic and historic value of the structure. The devices intend to improve the seismic performance by reducing damage with the application of a uniform overall distribution of compressive stresses. This precompression state completely changes the poor response of unreinforced masonry against lateral loading by reducing the tensile stresses at key zones and transforming them into compressive ones. The quasi-brittle behavior of masonry may be changed by means of prestressing in order to obtain a high energy dissipation system by providing more lateral strength and displacement capacity. These improvements at the retrofitted masonry structure in terms of seismic behavior are also represented by more ductile failure mechanisms, which may be interpreted as seismic energy dissipation.

2. Seismic vulnerability of historical masonry towers

Historical masonry towers were built either isolated or commonly included in different manners into the urban context, such as built as part of churches, castles, municipal buildings and city walls. Bell and clock masonry towers (see Fig. 1), also named civic towers, were built quite tall and with large belfries for informing people about time and extraordinary events such as civil defence, fire alarm and social meetings. Another reason that led to the construction of tall civic towers in the medieval cities of Italy was that they were seen as a symbol of richness and power of the great families. On the other hand, medieval towers were built quite high but with almost no openings mainly for warlike purposes. Strong damage or complete loss suffered by the cultural patrimony due to EQs has occurred through the history of humanity. The occurrence of these unexpected and unavoidable events has demonstrated that towers are one of the most vulnerable structural types to suffer strong damage as shown in Fig. 2. Their protection is a topic of great concern among the scientific community. Although recent progress in technology, seismology and EQ engineering, the preservation of these quasi-brittle and massive monuments stills represents a major challenge. Masonry towers in all their uses are highly vulnerable to suffer strong EQ damage, even when subjected to seismic events of low to moderate intensity.

Towers are slender by nature, the slenderness (H/L) is the single most decisive factor affecting their seismic performance, characterized by a ductile behavior where bending and low tensile strength of masonry determine the overall performance. This slenderness may be measured by ambient vibration tests aimed at obtaining the natural frequencies of the tower and the vibration modes may be analyzed by commercial software. These linear elastic evaluations of finite element models (FEM) are relatively fast due to the progress of recent decades on computational tools and in combination with the results from the in-situ campaigns permit to define reliable models as explained by D'Ambrisi et al. [18]. Júlio et al. [35] successfully evaluated the structural integrity of a masonry tower by modal identification and concluded that this is a fast and reliable in-situ technique to establish the structural assessment of towers and other buildings. Bachmann et al. [5], Meli [40], Casolo [15], Preciado [43] describe in their works that the natural frequencies of slender masonry towers are measured between 0.9 and 2 Hz (periods between 0.5 and 1.11 s). As a reference, the reader may find in Table 1 the natural frequencies of 10 historical masonry towers with variations in height and geometrical characteristics.

Also the position of a tower into the urban context is another important aspect that influences vulnerability [54]. These boundary conditions could strongly modify the seismic behavior and failure modes. Non-isolated towers were commonly built as part of churches or next to another building. In addition, the seismic vulnerability of towers is increased by certain important aspects as soil conditions, large openings at belfries, high vertical loading and progressive damage. Towers were built as most of the historical buildings, to mainly withstand their vertically induced self-weight. During construction, wall thicknesses used to be determined by following empirical rules by trial and error, mainly based on the structure's height and previously observed EQ damage. These empirical rules led to the construction of walls with enormous thicknesses, in some cases higher than 2 m. Masonry towers are slender structures under high vertical loading due to the height, wall thickness, tall roof system, high density of masonry and large bells. This loads lead to a concentration of high compressive stresses, mainly at the base. All these issues and moreover taking into account the deterioration of masonry through the centuries make towers extremely vulnerable to suffer a sudden collapse by exceeding the intrinsic compressive strength. These sudden collapses have been occurring since centuries ago in this type of structures as explained in the works of Binda et al. [9], Macchi [39], GES [30], Binda [10].

2.1. Earthquake behavior and typical failure modes of masonry towers

Seismic behavior and failure modes identification of masonry towers subjected to lateral and vertical simultaneous loads

(a) (b)

Fig. 1. Typical historical masonry towers in Italy; (a) medieval tower and (b) bell tower.