

Fundamental aspects on the seismic vulnerability of ancient masonry towers and retrofitting techniques

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Abstract. Ancient masonry towers constitute a relevant part of the cultural heritage of humanity. Their earthquake protection is a topic of great concern among researchers due to the strong damage suffered by these brittle and massive structures through the history. The identification of the seismic behavior and failure of towers under seismic loading is complex. This strongly depends on many factors such as soil characteristics, geometry, mechanical properties of masonry and heavy mass, as well as the earthquake frequency content. A deep understanding of these aspects is the key for the correct seismic vulnerability evaluation of towers and to design the most suitable retrofitting measure. Recent tendencies on the seismic retrofitting of historical structures by means of prestressing are related to the use of smart materials. The most famous cases of application of prestressing in towers were discussed. Compared to horizontal prestressing, vertical post-tensioning is aimed at improving the seismic behavior of towers by reducing damage with the application of an overall distribution of compressive stresses at key locations.

Keywords: towers; old masonry; earthquakes; vulnerability; behavior; failure modes; retrofitting

1. Introduction

Existing ancient masonry towers (AMT) with different characteristics and functions are distributed all over the world and constitute a relevant part of the architectural and cultural heritage of humanity. These vertical structures 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 towers (see Fig. 1), also named civic towers, were built quite tall for informing people visually and with sounds about time and extraordinary events such as civil defence or fire alarm, and to call the community to 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

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(a) Italian bell towers

(b) Clock tower

Fig. 1 Historical masonry civic towers

of richness and power of the great families.

Strong damage or complete loss suffered by the cultural patrimony due to earthquake (EQ) has been occurring through the history of humanity as illustrated in Fig. 2, which shows the effects of the historical EQ occurred in Naples, Italy in 1805. Risk management of existing buildings located in EQ prone zones is integrated by two huge stages, the risk assessment and its reduction (Preciado 2011). Nowadays there is an enormous variety of methods to assess the seismic risk of buildings (Carreño *et al.* 2012) and exists different opinions within the scientific community regarding which is the best procedure to follow for assessing this risk and the reduction measures. Recent studies in EQ engineering are oriented to the development, validation and application of techniques to assess the seismic vulnerability of existing buildings (Carreño *et al.* 2007, Barbat *et al.* 2008, Lantada *et al.* 2009, Pujades 2012, Preciado and Orduña 2014, Preciado *et al.* 2014, 2015).



Fig. 2 Earthquake of Naples, Italy on July 26th, 1805 (Kozak and Thompson 1991)



Fig. 3 San Bernardino church in original conditions and observed damage after the 6.3 magnitude earthquake of L'Aquila, Italy on April 6th 2009

2. Seismic vulnerability aspects on ancient masonry towers

The occurrence of unexpected and unavoidable events such as EQs has demonstrated that AMT are one of the most vulnerable structural types to suffer strong damage or collapse as depicted in Fig. 3. Their protection is a topic of great concern among the scientific community. This concern mainly arises from the observed damages after every considerable EQ and the need and interest to preserve these structures. Although the recent progress in technology, seismology and EQ engineering, the preservation of these brittle and massive monuments stills represents a major challenge. These vertical structures are slender by nature, where bending plays an important role in the seismic performance. Moreover, the seismic vulnerability of masonry towers is increased by certain important aspects such as soil characteristics, adjacent buildings, large openings at belfries, nonlinear behavior of masonry due to its poor tensile strength, lack of good connection between structural elements, high vertical loading and progressive degradation.

2.1 Slenderness

Probably the single most decisive factor affecting the seismic behavior of a wall is its slenderness, commonly expressed in terms of aspect ratio (H/L). High slenderness walls ($H/L \geq 2$) are characterized by a ductile behavior, failing in a predominant bending mechanism similar to the presented by cantilever beams. In low slenderness structures or compact walls ($H/L \leq 1$), the determining factor of the seismic performance is shear (Penelis and Kappos 1997). NTCDF (2004) and Bazan and Meli (2003) affirm that the seismic behavior of walls importantly differs depending of their slenderness. Compact masonry walls ($H/L \leq 2$) are mainly dominated by shear behavior, presenting a brittle failure. On the other hand, slender walls ($H/L \geq 2$) are mainly governed by bending behavior and a ductile failure. If $H/L > 4$, the structure could be considered as excessively slender, being the case of most of AMT as depicted in Fig. 6. This could cause the failure by bending, shear, overturning by instability and transmission of elevated vertical loads to the foundation and soil (Fig. 4).

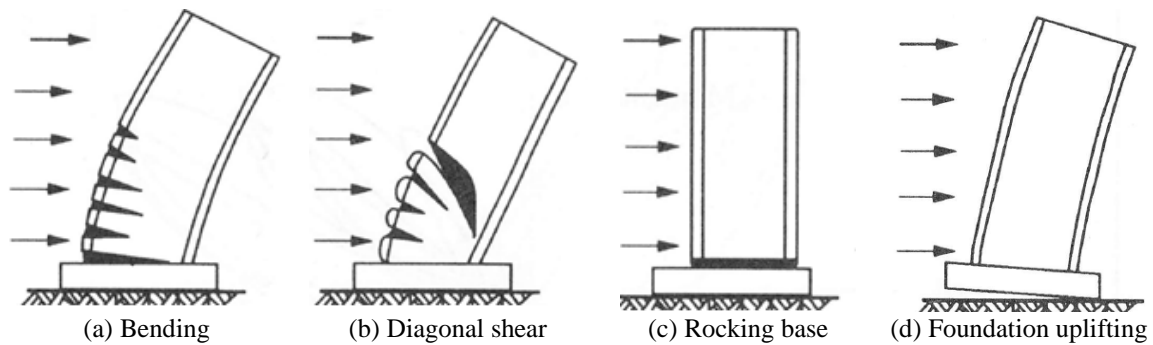


Fig. 4 Failure modes of slender masonry structures (Bazan and Meli 2003)

2.2 Boundary conditions

The position of a masonry tower in the urban context is a very important aspect that influences the vulnerability of the structure (Sepe *et al.* 2008). These boundary conditions (see Fig. 5) could strongly modify its seismic behavior and have enormous impact in the generation of different failure mechanisms. Non-isolated towers were commonly built as part of churches or next to another building. The presence of adjacent walls or façades with different heights than the tower and the lack of connection between elements induce during an EQ a detachment of the different bodies, vibrating in an independent way and hitting each other, leading to serious damages. Curti *et al.* (2008) assessed the damage presented in 31 Italian bell towers (16 isolated and 15 with one or two shared sides with the church) due to the 1976 Friuli EQs (May M6.4 and September M6.1). The authors concluded that the presence of walls and façades adjacent to any tower at different heights are horizontal constraints increasing the seismic vulnerability by limiting the slenderness (short column effect). Moreover, induce localized stiffening zones that could cause the concentration of important stresses.

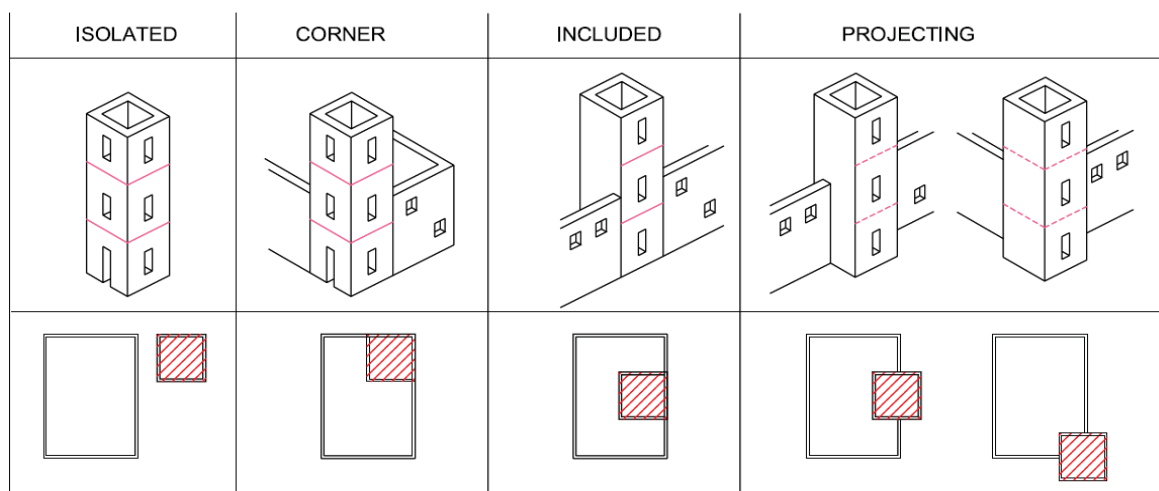


Fig. 5 Position of the tower in the urban context (Sepe *et al.* 2008)

2.3 Long-term heavy loads

AMT were built as most of the cultural patrimony to mainly withstand the vertical loading generated by their self weight. The wall thickness of towers used to be determined by means of empirical rules transmitted from generation to generation by trial and error mainly based on the height (in some cases taller than 60 m) and observed damages after EQs. This led to the construction of walls with enormous thicknesses higher than 2 m. The roof system of masonry towers was usually made of the same material of walls. Even when reduced thicknesses were considered, the elevated mass of masonry generated problems of instability that could lead to its collapse during the construction works. Due to this, is quite frequent to especially find in Italy masonry towers with a plane or leaned roof system integrated by timber beams and fired-clay bricks. In Germany the masonry towers usually have a triangular timber roof externally covered by thin copper plates. On the other hand, fired-clay bricks were frequently used in Mexico and in some cases volcanic stones of low density or artisanal clay vessels to make lighter the roof system. Towers are slender structures under high vertical loading due to the height, wall thickness, presence of a roof system, high density of masonry and heavy bells, leading to the concentration of high compressive stresses at the base. All these issues and the deterioration of masonry through the centuries (progressive damage) make AMT extremely vulnerable to suffer a sudden collapse by an exceeding of their compressive strength or foundation failure. These sudden collapses have been occurring since centuries ago in this type of structures. The most famous cases are reported e.g., in Binda *et al.* (1992), Macchi (1993), GES (1993), Binda (2008). They correspond to the sudden collapses of the bell tower of “Piazza San Marco”, Venice in 1902 (a replica was built as depicted in Fig. 6), the civic tower of Pavia in 1989 (see Fig. 7) and the bell tower of the church of “St. Maria Magdalena” in Goch, Germany in 1992.



Fig. 6 Replica of the collapsed bell tower of “Piazza San Marco” in Venice, Italy



Fig. 7 The collapse of the historical civic tower of Pavia in 1989 (Binda 2008)



Fig. 8 General view of the leaning tower of Pisa, Italy

2.4 Local site effects and soil-structure interaction

Seismic hazard characteristics and soil conditions of the site are important aspects that determine the vulnerability of AMT. Seismic hazard of a certain site is the probability of occurrence of a destructive EQ. This depends on the proximity to a seismic source with events of enough magnitude to generate significant intensities at the site under study. The EQ source is mainly due to the released energy generated by the abrupt movements of the tectonic plates of the earth's crust. The stresses are presented at the contact zone between plates or in geological faults inside of a plate. Ground motion strongly depends on the geology and topography conditions of the site as well as the inherent EQ characteristics.

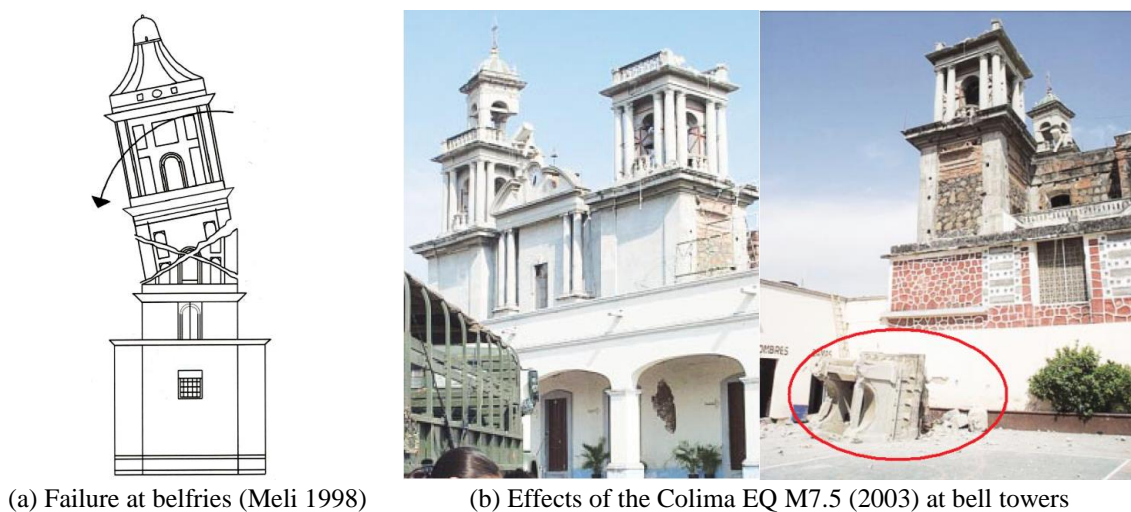
The city of Tenochtitlan (now the historical center of Mexico City) was built by the Aztecs upon raised islets in the Texcoco Lake. Due to this, the soil presents bad conditions, is very soft,

and this modifies the basic characteristics of the seismic source by amplifying the ground motion, represented by low frequencies and high periods. This was the case of the M8.1 EQ of 1985 in the Pacific coast of Michoacan, Mexico, causing thousands of deaths and strong damage to the built environment, mainly in Mexico City, which is located more than 350 km away from the epicenter. These low frequencies, mainly affect slender structures like masonry towers because their fundamental vibrations are in the range of the predominant frequency of the ground motion (resonance phenomena). The high mass of the tower and its natural bending behavior generate that the structure presents during an EQ important top displacements. On the other hand, high frequencies and low periods mainly affect compact structures like most of the historical buildings. Liquefaction due to ground motion and instability conditions by soil settlements are geotechnical issues that depend on the site. The latter issue has been observed at the Metropolitan Cathedral of Mexico City since decades due to soft soil conditions. The most famous case presented in AMT is the leaning tower of Pisa, Italy. Since its construction in the XII century, it started to lean due to irregularities in the soil conditions, being as a result quite vulnerable to overturning (see Fig. 8).

2.5 Seismic behavior and failure mechanisms

Compared to other compact structures, masonry towers fail ductile in a predominant bending behavior due to the excessive slenderness ($H/L > 4$). Due to the slenderness and heavy mass, the lateral vibration at the top of the tower during an EQ is considerably more amplified than the base, inducing important displacements and inertia forces transmitted in-plane and out-of-plane. This behavior could cause as aforementioned different failure mechanisms (Fig. 4). Meli (1998) describes that during an EQ masonry towers present important horizontal top displacements. Bending generates horizontal cracks but rarely the overturning of the structure. This is due to the direction alternation of the movement that causes an opening and closing effect of these cracks, dissipating with the impact an important part of the induced EQ energy.

On the other hand, at bell towers, the presence of large openings at belfry could increase the vulnerability of the structure, being more frequent the failure by shear at this failure points. The



(a) Failure at belfries (Meli 1998)

(b) Effects of the Colima EQ M7.5 (2003) at bell towers

Fig. 9 Typical failure modes of bell towers

belfry could collapse by instability due to the strong damage, endangering the adjacent buildings and people who could be inside or in the surroundings (see Fig. 9). The last almost happened due to the M7.5 Colima EQ in 2003, where one belfry collapsed by overturning on the basketball court of a neighbor building (see Fig. 9(b)). The remaining damaged belfry was removed during the rehabilitation and retrofitting works, and in the end, it was decided to leave the church without belfries for security reasons. The state of Colima is located in the Mexican Littoral in the Pacific Ocean. At national level, the seismic hazard of Mexico is divided in four main zones ranging from A to D, where A represents low hazard and D very high. In the seismological context, Colima is distinguished by its important exposure (seismic zone D), being considered as one of the Mexican states under most significant hazard.

Curti *et al.* (2008), observed in 31 Italian bell towers damaged by the 1976 Friuli EQs that the belfry is the most vulnerable part of the tower due to the presence of large openings, natural bending behavior and low tensile strength of masonry. This amplifies the seismic motion causing critical effects in the higher part of the tower. Based on observed damage after considerable EQs occurred in Italy, Lagomarsino *et al.* (2002) propose the damage mechanisms commonly presented by AMT (see Fig. 10). The body damage of Fig. 10(a) corresponds to horizontal cracking out-of-plane due to bending behavior and diagonal cracking by shear stresses in-plane by contact with the church façade, leading to overturning over the nave. The type of damage of Fig. 10(b) consists of vertical cracking in both planes due to horizontal tension, resulting in the detachment of walls and collapse by instability. On the other hand, the damage mode of Fig. 10(c) is represented by alternated diagonal cracking in-plane due to shear, which could be repaired. The damages at belfries are mainly characterized by horizontal and diagonal cracking due to the presence of large openings, leading to the collapse by overturning (Figs. 10(d)-10(f)).

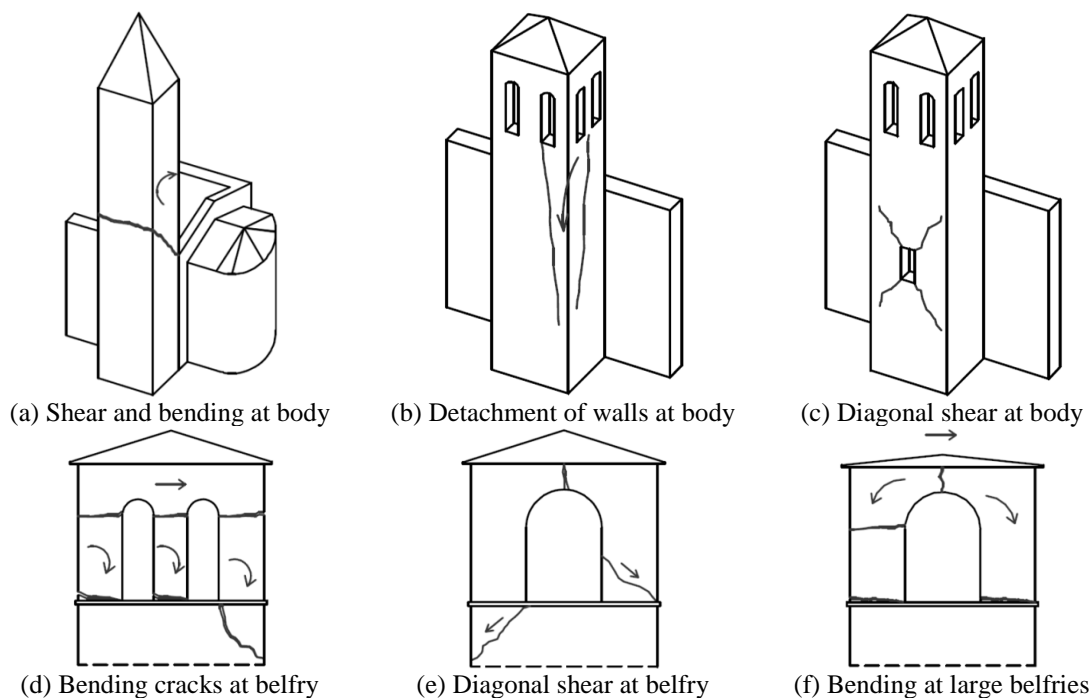


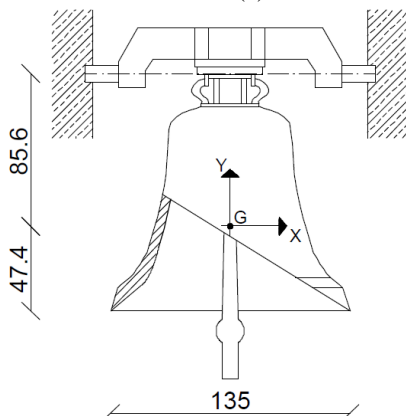
Fig. 10 Damage mechanisms at body and belfries of masonry bell towers (Lagomarsino *et al.* 2002)

2.6 Dynamic actions by bells swinging

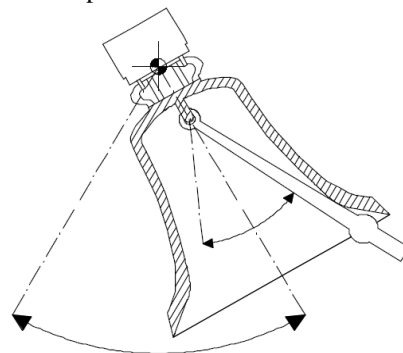
In masonry bell towers, is quite common the presence of large and heavy bells hanging from their supports and anchored in different places at belfry. The swinging of these heavy bells induces dynamic actions that could cause damage to the tower. This motion generates at the bell's support elevated vertical and horizontal inertia forces that are transmitted to the structure. In the work of Ivorra and Cervera (2001), the authors propose a good approximation for determining the magnitude of vertical and horizontal forces induced by bells swinging. Here, bell ringing action is considered to behave as a simple pendulum. Due to the fact that most of the historical towers were mainly built to withstand vertical loading, it is more critical the action of the induced horizontal forces, which generate cracking or detachment of structural elements (Fig. 11(a)). Moreover, the induced excitation by the swinging of bells (Figs. 11(b)-11(c)) could be very close to one of the natural frequencies of the tower, leading to a high dynamic amplification of the structural response by resonance. For more detailed information about the dynamic actions by bells swinging, the reader is referred to the research works of Beconcini *et al.* (2001), Bennati *et al.* (2002), Ivorra and Pallares (2006).



(a) Location of bells at belfry and crack pattern



(b) Bell dimensions (in cm)



(c) Bell swinging

Fig. 11 The bell tower of Matilde in Pisa, Italy (Beconcini *et al.* 2001)

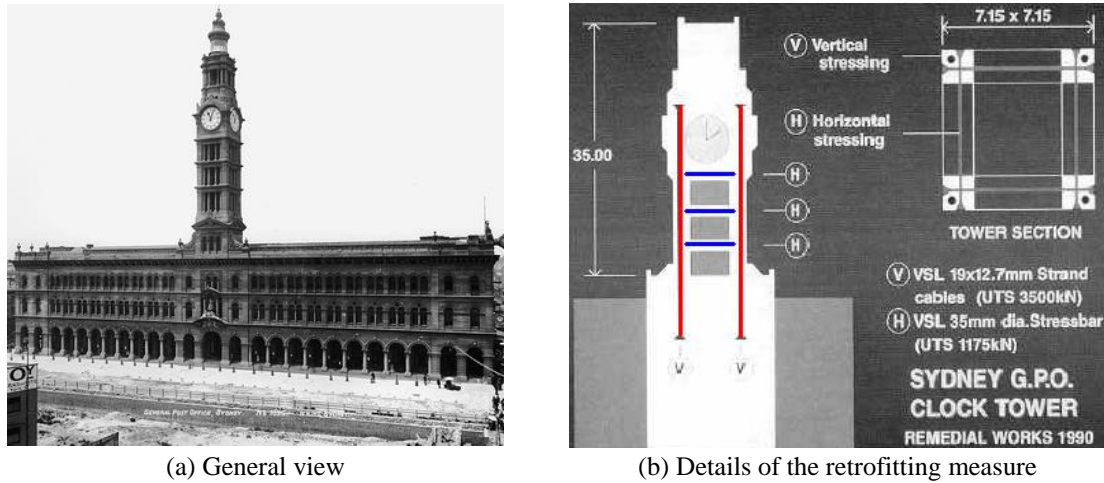


Fig. 12 The General Post Office clock tower in Sydney, Australia (Ganz 1990)

3. Seismic retrofitting techniques on ancient masonry towers

The retrofitting technique by means of prestressing has been successfully used to improve the seismic behavior of concrete structures since the beginning of the XX century. The adaptation of this technique to the seismic retrofitting of cultural heritage has gained in recent decades especial interest for many researchers. Post-tensioning of masonry has shown to improve ductility and strength successfully (Ganz 1990, 2002). However, very few applications of this technique can be found in AMT. One of the few cases reported in literature are related to the strengthening of the General Post Office clock-tower in Sydney, Australia (see Fig. 12). The retrofitting intervention was finished in 1990 with the aiming of increasing its global seismic performance by means of vertical and horizontal steel tendons in drilled holes with prestressing forces of 1771 kN (Ganz 2002).

Another famous real application of prestressing of towers was applied at the bell tower of the church of San Giorgio in Trignano, Italy (see Fig. 13). The bell-tower was strongly damaged by the 1996 M4.8 EQ. A combination of devices such as steel tendons and shape memory alloys (SMA) were vertically installed and without drilling at the four internal corners of the tower aimed to increase its bending and shear resistance. The combined devices were anchored at the top and foundation of the tower and post-tensioned with a prestressing force of 20 kN (80 kN total force). The retrofitting was verified by the occurrence of a similar EQ in 2000 with no damage of any type as explained in the works of Indirli *et al.* (2001), Castellano (2001). However, in both real applications the retrofitting was validated in qualitative terms with no numerical simulations. Moreover, the way of determining the post-tensioning force is not mentioned and the use of a combination of a high resistance material such as steel with an extremely poor material such as masonry is doubtful in terms of compatibility of deformations and stresses concentration.

From an extensive parametric study on different configurations of old masonry towers, Preciado (2011) proposes an optimal prestressing force and post-tensioning FRP device that may be used in any slender or compact masonry structure ranging from light houses, medieval (no openings), civic and bell-towers with large openings. The post-tensioning devices are vertically

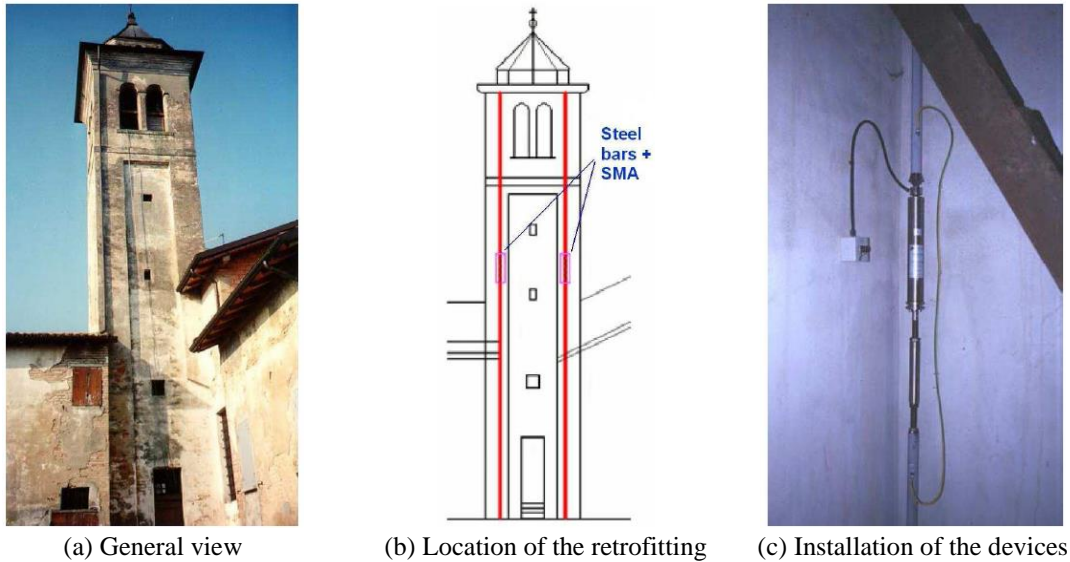


Fig. 13 The bell tower of the church of San Giorgio in Trignano (Indirli *et al.* 2001)

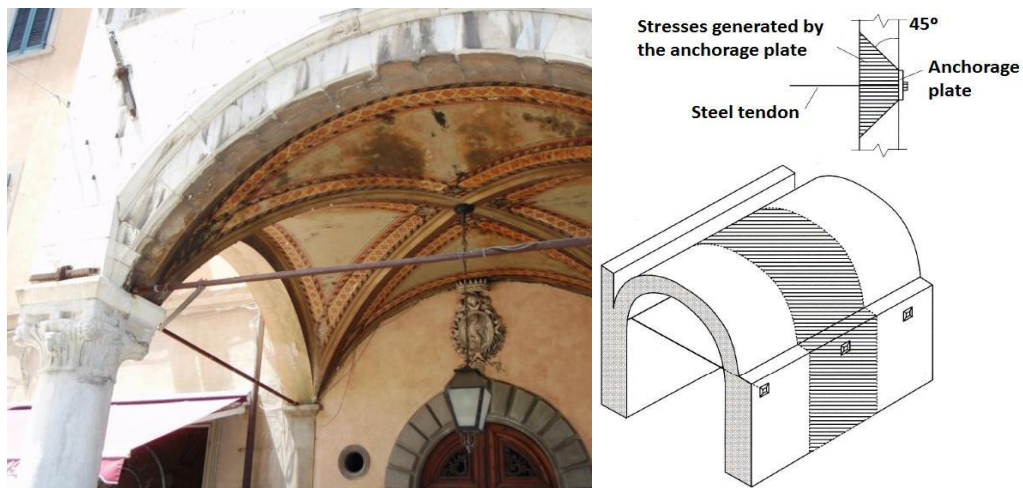


Fig. 14 Presence of horizontal prestressing steel bars in masonry vaulted structures

and externally located at key locations inside the towers in order to give to the retrofitting the characteristic of reversibility, respecting in all senses the architectonic and historical value of the structure. Compatibility, durability and reversibility are fundamental aspects recommended in literature to be taken into account for the seismic retrofitting of cultural heritage. Reversibility is definitely the most important aspect, because if the applied technique shows deficiencies in terms of compatibility and durability that increase the seismic vulnerability of the structure or there is a new material/technique that allows a better seismic performance, this retrofitting could be substituted.

Horizontal external prestressing (see Fig. 14) has been mainly used in the cultural heritage to provide stability out-of-plane at walls or to reduce the tensile stresses generated by supports

opening of vaults, arches and domes (Preciado 2011). By the other hand, vertical external prestressing has proved to be more suitable to increase the in-plane lateral strength and ductility of masonry walls by providing tensile strength at key locations. The level of improvement strongly depends on the level of the prestressing force, so, the higher the prestressing force the higher the lateral strength and ductility. Especial careful may be taken into account in order to use this technique in AMT. Firstly, an optimal prestressing level may be designed, due to high prestressing levels could lead to local damage at the top anchorage zone, or a sudden collapse even in static conditions by an exceedance of compressive stresses at the bottom. Moreover, in seismic conditions, the compressed in-plane and out-of-plane toes could fail by crushing, and leading with this, to a brittle failure. If prestressing is used carefully and with an optimal post-tensioning force, this technique may be quite helpful for the EQ protection of cultural heritage, by increasing strength and ductility, transforming the unreinforced masonry element to an energy dissipative structure.

4. Conclusions

Masonry towers in all their uses (bell, clock and medieval towers) are highly vulnerable to suffer strong damage or collapse in seismic conditions, even when subjected to seismic events of low to moderate intensity. These vertical structures are slender by nature, the slenderness (H/L) of towers is the single most decisive factor affecting their seismic performance, characterized by a ductile behavior where bending and low tensile strength of masonry determinate the overall performance. In addition, the seismic vulnerability of towers is increased by certain important aspects such as soil conditions, adjacent buildings, large openings at belfries, nonlinear behavior of masonry, lack of good connection between structural elements, high vertical loading and progressive damage. These fundamental aspects determine the seismic vulnerability of towers in terms of behavior and failure mechanisms that differentiate them from most of compact historical constructions. The identification of the seismic behavior and failure mechanisms of AMT under in-plane and out-of-plane loading is a complicated task. This identification strongly depends on many factors such as soil and boundary conditions, geometrical characteristics and mechanical properties of masonry, level of vertical loading and the EQ characteristics. All these factors play an important role in the determination of the seismic behavior and failure mechanisms of AMT. There is a huge variety of available materials for the development of prestressing devices for the seismic retrofitting of AMT. The selection of the appropriate technique and materials depend on every case study and the purpose of the intervention. The use of steel is not recommended as retrofitting of brittle old masonry structures due to the great difference regarding compatibility of deformations and susceptibility of corrosion. The recent tendencies on the seismic retrofitting of historical structures by means of prestressing are related to the use of smart materials of low elasticity modulus and high resistances (NiTi and FRPs). It is strongly needed a compatibility of deformations between the retrofitting material and masonry. The most famous cases related to the application of prestressing in bell and civic towers were discussed. Vertical prestressing is aimed at improving the seismic behavior of AMT by reducing the expected damage with the application of a uniform overall distribution of compressive stresses at key locations identified at the seismic analyses, enhancing strength and ductility. This enhancement allows to the unreinforced masonry element to be transformed into a high energy dissipative structure. This could be achieved by taking especial care when designing the prestressing device and the application of an optimal

prestressing force that accurately improves strength and ductility without endangering the structure to fail under of an exceedance of its compressive strength.

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