2011-02

Seismic Behavior and Failure Mechanisms Identification of Ancient Masonry Towers

Preciado, Adolfo; Budelmann, Harald; Sperbeck, Silvio T.; Bartoli, Gianni

Preciado, A. et al. (2011). Seismic Behavior and Failure Mechanisms Identification of Ancient Masonry Towers. 1st. Interquadrennial ICF Conference in Middle East and Africa

1ST INTERQUADRENNIAL ICF CONFERENCE
IN MIDDLE EAST AND AFRICA

ESLIA
Egyptian Society for Laser Industrial Applications

Processing, Performance and Failure Analysis of Engineering Materials

February 14–17, 2011, Luxor, EGYPT

SEISMIC BEHAVIOR AND FAILURE MECHANISMS IDENTIFICATION OF ANCIENT MASONRY TOWERS

Adolfo PRECIADO-QUIROZ*, Harald BUDELMANN*, Silvio T. SPERBECK, and Gianni BARTOLI*****

* Technical University of Braunschweig, Faculty of Architecture, Civil Engineering and Environmental Sciences, iBMB Institute, Braunschweig, Germany
** Society for the Safety of Reactors and Nuclear Power Plants (GRS) mbh, Germany
*** University of Florence, Faculty of Engineering, Dept. of Civil Eng., Florence, Italy

ABSTRACT

Strong damage or complete loss suffered by the cultural patrimony when subjected to considerable earthquake ground shaking has been occurring through the history of humanity. The occurrence of these unexpected and unavoidable events has demonstrated that ancient masonry towers are one of the most vulnerable structural types to suffer strong damage or collapse. There are certain relevant aspects determining the seismic vulnerability of towers in terms of behavior and failure mechanisms that differentiate these vertical structures from most of compact historical constructions. This is the first stage of an international scientific research between the University of Braunschweig and the University of Florence, aimed to develop a methodology to mitigate the seismic risk of ancient masonry towers located in seismic zones with the use of prestressing devices of smart materials. Therefore results quite important a deep understanding and identification of all the most important aspects that determine the seismic vulnerability of ancient masonry towers in terms of behavior and failure mechanisms. For achieving this, it is considered the relevant literature, observed damage after real earthquakes and mainly engineering experience.

Keywords: Old masonry towers, seismic vulnerability, behavior, failure mechanisms, prestressing devices.

INTRODUCTION

Existing ancient masonry towers 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 important vertical structures were built either isolated or commonly included in different manners in the urban context, such as built as part of churches, castles, municipal buildings and city walls. Bell and clock towers, also named civic towers, were built quite tall with the important purpose of informing people visually and with sounds by ringing bells and striking clocks about time and extraordinary events such as civil defence or fire alarm, and moreover to call the community to social meetings (see Figure 1).

Figure 1 San Bernardino church undamaged and observed damage after the 6.3 magnitude L'Aquila, Italy earthquake on April 6th, 2009 [Bazrafshan, 2009]

Another important reason that led to the construction of tall civic towers, especially in the medieval cities of Italy, was that they were seen as a symbol, representing by the height and architecture sophistication the richness and power of the great families.

SEISMIC VULNERABILITY OF ANCIENT MASONRY TOWERS

Strong damage or complete loss suffered by the cultural patrimony when subjected to considerable earthquakes has been occurring through the history of humanity. The occurrence of these unexpected and unavoidable events has demonstrated that ancient masonry towers are one of the most vulnerable structural types to suffer strong damage or collapse as depicted in Figure 1. There are certain relevant aspects determining the seismic vulnerability of towers in terms of behavior and failure mechanisms that differentiate them from most of compact historical constructions. These relevant aspects correspond to its slenderness, the presence of adjacent walls or façades with different height than the tower, the lack of good connection between structural elements due to the poor tensile strength of masonry, the presence of large openings and belfries, long-term heavy loads and deterioration of masonry through the centuries (progressive damage) that could lead to a sudden collapse by an exceeding of its compressive strength, local site effects and soil structure interaction, dynamic actions generated by bells swinging, and definitively the most important aspect, the in-plane and out-of-plane behavior of the tower during earthquake ground shaking. This is the first stage of an international scientific research between the University of Braunschweig and the University of Florence, aimed to develop a methodology to mitigate the seismic risk of ancient masonry towers located in seismic zones with the use of prestressing devices of smart materials. Therefore results quite important a deep understanding and identification of all the most important aspects that determine the seismic vulnerability of old masonry towers in terms of behavior and failure mechanisms. For achieving this, it is considered the relevant literature, observed damage after real earthquakes and mainly engineering experience.

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 flexural mode similar to that of beams. Different to this, in low slenderness or compact walls ($H/L \leq 1$) the factor dominating the seismic performance is shear [Penelis and Kappos, 1997].

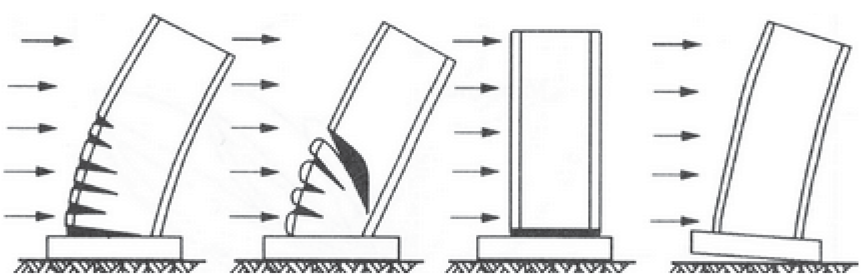

Figure 2 Failure modes of slender masonry structures: flexion; shear; rocking by base uplifting and rocking by foundation uplifting [Bazan and Meli, 2003]

NTCDF [2004] and Bazan and Meli [2003], affirm that the seismic behavior of walls differs importantly depending of their slenderness. Compact walls ($H/L \leq 2$) are dominated mainly by shear effects. By the other hand, slender walls ($H/L \geq 2$) behave mainly as cantilever beams with generally low vertical loading, dominating mainly the effect of flexion. If $H/L > 4$, the structure could be considered as excessively slender, being this the case of most of the historical masonry towers (Figure 4). This could cause its failure by flexion, shear, overturning by instability and transmission of elevated vertical loads to the foundation and soil as depicted in Figure 2.

Boundary conditions

The position of a historical 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 Figure 3) could strongly modify its seismic behavior and to have big impact in the generation of different failure modes. Non-isolated towers were commonly built as a part of a church or next to another building. The presence of adjacent walls or façades with different height than the tower and the lack of connection between elements due to the poor tensile strength of masonry could generate during an earthquake a detachment of the different bodies, vibrating independently and hitting between them generating serious damages.

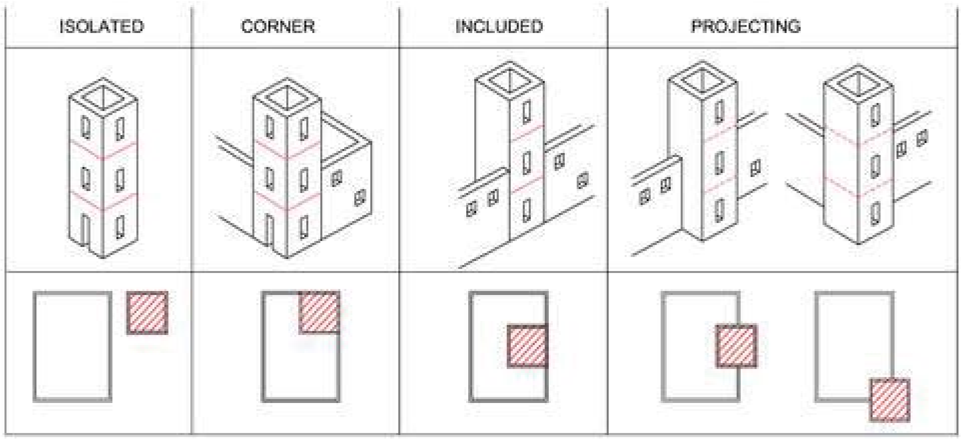

Figure 3 Position of the tower in the urban context [Sepe et al., 2008]

Curti et al. [2008] observed in 31 Italian bell towers (16 isolated and 15 with one or two sides shared with the church) damaged by the 1976 Friuli earthquakes (May M6.4 and September M6.1), that the presence of walls and façades adjacent to any tower at different heights are horizontal constraints that increase the seismic vulnerability of the tower by limiting its slenderness and by creating localised stiffening zones that could cause the concentration of important stresses.

Long term heavy loads

Historical masonry towers were built as most of the historical buildings to withstand mainly the vertical loading generated by their self weight. The walls thicknesses used to be determined following empirical rules transmitted from generation to generation by trial and error depending mainly of its height (in some cases taller than 60 m) and observed damages after earthquakes. This led to the construction of walls with enormous thicknesses, in some cases bigger than 2.0 m. The roof system of historical masonry towers was made commonly of the same material of the walls, even when reduced thicknesses were considered, the elevated mass of masonry generated problems of instability that could lead to its collapse even during the construction works. Due to this, and by architectonic aspects is very frequent to find especially in Italy masonry towers with a plane roof system integrated by wooden beams and fired-clay bricks. In Germany the masonry towers have commonly a triangular timber roof covered externally by thin plates made of metal (copper). By the other hand, in Mexico it was utilized frequently fired-clay bricks and in some cases to make lighter the roof system it was built with volcanic stones of low density and placed in some cases into the structural element a great number of artisanal clay vessels.

Figure 4 Replica of the collapsed bell tower of "Piazza San Marco" in Venice, Italy

Historical masonry towers are slender structures under high vertical loading. This is due to its height, wall thickness, the presence of a roof system, the high density of masonry and heavy bells, leading to a concentration of high compressive stresses at their base. All these issues and moreover taking into account the deterioration of masonry through the centuries (progressive damage), make the historical masonry towers extremely vulnerable to suffer a sudden collapse by an exceeding of its compressive strength, or in some cases the failure of the foundation or the soil. 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] and 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 Figure 4), the civic tower of Pavia in 1989 and the bell tower of the church of "St. Maria Magdalena" in Goch, Germany, in 1992.

Local site effects and soil-structure interaction

Seismic hazard characteristics and soil conditions of the site are important aspects that determine the vulnerability of historical masonry towers. Seismic hazard of a certain site is the probability of occurrence of an earthquake. This depends on its proximity to a seismic source with events of enough magnitude to generate significant seismic intensities at the site under study. The source of the earthquakes is due mainly to the released energy generated by the abrupt movements of the tectonic plates of the earth´s crust, presented in the zone of contact between plates or in geological faults inside of a plate. Earthquake shaking depends strongly of the geotechnical conditions of the site in terms of geology, topography and soil. The city of Tenochtitlan (now the historical center of Mexico City) was built by the Aztec empire upon raised islets in Lake Texcoco. Due to this, the soil presents bad conditions, is very soft, and this modifies the basic characteristics of the seismic source by amplification of the ground motion (higher seismic intensity), represented by low frequencies and high periods. This was the case of the earthquake occurred in 1985 (magnitude 8.1) at the Pacific coast of Michoacan, Mexico, it caused thousands of deaths and strong damages to the built environment, mainly in Mexico City that is located more than 350 km away from the epicenter. This low frequencies affect mainly slender structures like in the case of historical masonry towers that their fundamental vibration frequency is into the range of the earthquake frequency. The high vertical loading of the tower and its flexibility due to its slenderness generate that the structure presents during an earthquake important top displacements. By the other hand, high frequencies and low periods like those presented by an earthquake in hard soil, affect mainly compact buildings.

Figure 5 General view of the leaning tower of Pisa, Italy

Another geotechnical issue that depends on the local site effects and the seismic action corresponds to liquefaction and instability conditions by soil settlements. This is the case of the Metropolitan Cathedral of Mexico City that has been presenting since decades important settlements due to the soft soil conditions. The most famous case presented in historical masonry towers corresponds to the leaning tower of Pisa, Italy, as shown in Figure 2.14. It started to incline since its construction in the XII century due to the irregularities in the soil conditions, being with this quite vulnerable to overturning.

Seismic behavior and failure mechanisms

The excessive slenderness of historical masonry towers (H/L > 4) is characterized by a ductile behavior, failing in a predominant flexural mode similar to that of cantilever beams. Due to all these factors and its heavy mass, the lateral vibration at the top of the tower is considerably more amplified than the one of the base, generating with this important horizontal top displacements and inertia forces transmitted in-plane and out-of-plane as a consequence of the earthquake ground shaking. This behavior could cause as previously mentioned different failure mechanisms generated by flexion, shear, base and foundation uplifting due to the transmission of elevated vertical loads or poor soil conditions (see Figure 2). Moreover these poor conditions could generate an amplification of the ground shaking and an excitation very close to the natural frequency of the tower, leading to its failure by the resonance effect. Meli [1998] describes that during an earthquake historical masonry towers present important horizontal top displacements. The flexion generates horizontal cracks but rarely the overturning of the structure. This is due to the alternation of the direction of the movement that causes an opening and closing effect of these cracks, dissipating with this impact an important part of the energy induced by the earthquake. By the other hand, in bell towers, the presence of large openings at the belfry could increase the vulnerability of the structure, being more frequent its failure by shear.

Figure 6 Typical failure mechanisms of bell towers: (Left) [Meli, 1998]; (Right) Effects of the 7.6 magnitude Colima, Mexico earthquake on January 21st, 2003

Due to the strong damage, the belfry could collapse by instability, endangering the adjacent buildings and mainly the people who could be inside or in the surroundings (see Figure 6). Curti et al. [2008] observed in 31 Italian bell towers damaged by the 1976 Friuli earthquakes that the belfry is the most vulnerable part of the tower due to the presence of large openings, leading the pillars to be slender and by the top masses. This amplifies the seismic motion causing critical effects in the higher parts of the tower.

Dynamic actions by bells swinging

In masonry bell towers results quite common the presence of large and heavy bells hanging from their respective support and anchored in different places at the belfry.

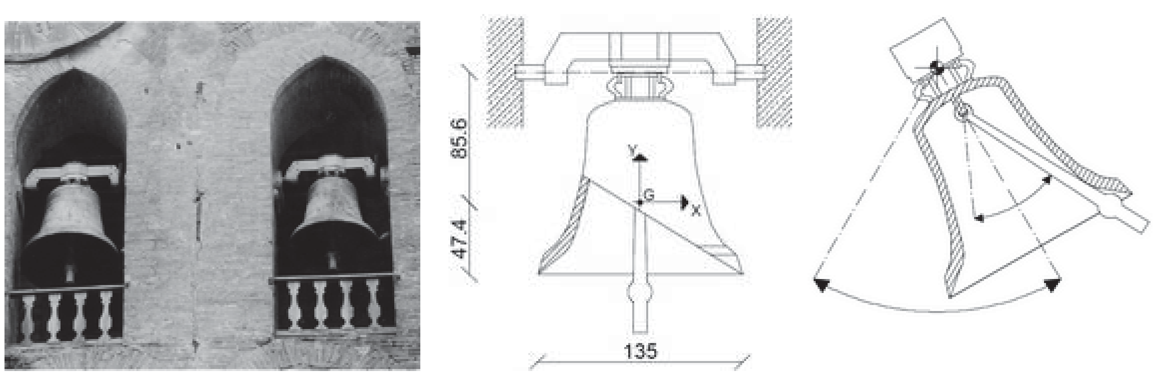

Figure 7 The bell tower of “Matilde” in Pisa, Italy: location of bells at belfry and crack pattern; bell dimensions (in cm) and bell swinging [Beconcini et al., 2001]

The swinging of the heavy bells induces dynamic actions that could cause damage to the tower. By the one hand, this motion generates at the bell´s support elevated vertical and horizontal inertia forces that are transmitted to the structure. Considering that most of the towers were built mainly to withstand their vertical loading, results more critical the action of the induced horizontal forces that could generate cracking or the separation of structural elements due to the low tensile strength of masonry (Figure 7). By the other hand, the excitation induced by the swinging of bells could be very close to one of the natural frequencies of the tower, leading to a high dynamic amplification of the structural response by the resonance effect. For more detailed information about the dynamic actions by bells swinging the reader is referred to Beconcini et al. [2001], Bennati et al. [2002] and Ivorra and Pallares [2006].

DISCUSSION

This paper presented a brief description of all the most important aspects that determine the seismic vulnerability of ancient masonry towers in terms of behavior and failure mechanisms. For achieving this, it was taken into account the relevant literature, observed damage after real earthquakes and mainly engineering experience. A deep understanding of all these aspects will allow us to develop a suitable methodology to mitigate the seismic risk of ancient masonry towers located in seismic zones with the use of prestressing devices of smart materials. This research corresponds to an international participation between the University of Braunschweig and the University of Florence. Afterwards, as a second stage, the methodology will be applied on theoretical and real ancient masonry towers by means of intensive numerical simulation to assess their seismic vulnerability in static and dynamic conditions. Moreover, the towers will be retrofitted with different prestressing devices of smart materials such as Fiber Reinforced Polymers (FRPs) and Shape Memory Alloys (SMAs) in order to assess quantitatively which of the prestressing devices improves in a better way the seismic performance of this type of structures.

REFERENCES

1. E. Bazrafshan, "Investigation of non-strengthened and post-tensioned masonry towers in case of earthquake loading by means of numerical simulations", Master thesis, Technical University of Braunschweig, Germany, 2009.
2. G. G. Penelis, A. J. Kappos, "Earthquake-resistant concrete structures", Published by E and FN Spon, an imprint of Chapman and Hall, London SE1 8HN, UK, 1997.
3. NTCDF, "Complementary Technical Norms of the Mexican Construction Code (in Spanish)", Mexico, 2004.
4. E. Bazan, R. Meli, "Seismic design of buildings (in Spanish)", Limusa, Mexico, 2003.
5. V. Sepe, E. Speranza, A. Viskovic, "A method for large-scale vulnerability assessment of historic towers", Structural control and health monitoring, 15:389-415, 2008.
6. E. Curti, S. Parodi, S. Podesta, "Simplified models for seismic vulnerability analysis of bell towers", Proceedings of the 6th International Conference on Structural Analysis of Historical Constructions (SAHC), July 2-4, Bath, UK, 2008.
7. L. Binda, G. Gatti, G. Mangano, C. Poggi, G. Sacchi-Landriani, "The collapse of the civic tower of Pavia: A survey of the materials and structure", Masonry International 11-20, 1992.

8. G. Macchi, "Monitoring medieval structures in Pavia", Structural Engineering International, I/93, 1993.
9. GES, "Technical opinion about the collapse of the bell tower of St. Maria Magdalena in Goch, Germany", Gantert Engineering Studio, 1993.
10. L. Binda, "Learning from failure: Long-term behaviour of heavy masonry structures", Politecnico di Milano, Italy. Published by WIT press, GB, 2008.
11. R. Meli, "Structural engineering of the historical buildings (in Spanish)", Civil Engineers Association (ICA) Foundation, A. C., Mexico, 1998.
12. M. L. Beconcini, S. Bennati, W. Salvatore, "Structural characterization of a medieval bell tower: First historical, experimental and numerical investigations", Proceedings of the 3rd International Seminar on Structural Analysis of Historical Constructions (SAHC), Guimaraes, Portugal, 2001.
13. S. Bennati, W. Salvatore, L. Nardini, M. Della Maggiora, "Bell´s dynamic action on a historical masonry tower", Proceedings of the 4th International Conference on Structural Dynamics (EURODYN), Munich, Germany, 2002.
14. S. Ivorra, F. J. Pallares "Dynamic investigations on a masonry bell tower", Engineering structures, 28: 660-667, 2006.