SEISMIC VULNERABILITY OF HISTORICAL MASONRY STRUCTURES IN CHILE: A STATE-OF-THE-ART REVIEW

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ABSTRACT

Historical constructions represent an important legacy for all the cultures. It is obvious that an adequate structural analysis is required for effective retrofitting purposes, in which non-destructive techniques are always desired for an accurate structural assessment. Recent earthquake events have shown the important vulnerability of such structures, and especially for those made of masonry. For that reason, seismic vulnerability studies are mandatory for historical buildings constructed in seismic areas. In this sense, Chile represents an interesting case of a very high seismicity country, with an important historical patrimony to protect. The present work is an up-to-date state-of-the-art review regarding the seismic vulnerability of historical constructions made of masonry, in which the case of the Chilean heritage is exposed. The discussion of the analysis results of some important buildings located in the world heritage city of Valparaíso is shown, as well as the analysis case of two masonry churches damaged by the severe Mw = 8.8 off-shore Chilean earthquake occurred on February 27, 2010. Results of this investigation suggest the urgent need of accurate seismic vulnerability studies for historical structures in Chile, in order to prevent undesirable failures or collapses.

Keywords: Seismic Vulnerability, Heritage Structures, Historical Structures, Masonry Structures

1. INTRODUCTION

Historical heritage structures are constructions that can be seen in almost all countries and cities, surviving in the midst of urban and modern buildings. For that reason, they can be considered as great touristic attraction for visitors and a new focus for the economy. Depending on their location, they are conceived according to the structural typology and materials. This makes them unique and the reason why it is necessary accurate and detailed analyses to study them, being the structural analysis much more complex than the case of ordinary structures. During the last decade in Europe, important efforts have been concentrated with the aim of improve the existing numerical techniques and the development of new numerical tools for the analysis of the mechanical behavior of such systems. As a special point, the interest has been focused on the ultimate load analysis in terms of heterogeneity of materials and the evaluation
of specific properties. The mechanical behaviour of the masonry, shows that the non-linear phase is dominant, mainly characterized by cracking at the connections between structural elements. This phenomenon has a fragile dissipation response and is currently investigated [1]. In Ferrara, Italy, the seismic behaviour of an important Renaissance palace called Palazzo Renata di Francia was studied. A 3D nonlinear analysis showed that the building collapses due to out-of-plane actions, and low seismic coefficients. The main facade was especially analyzed using three different 2D models: applying an equivalent seismic model, using a homogenized kinematic plane model and an inelastic plane model. The numerical analyses were compared in order to obtain an accurate evaluation of the seismic vulnerability on the facade. While the limit analysis can be capable of provide a very close ultimate load to the inelastic 2D model, the equivalent analysis provides lower displacements and lower collapse loads. Disparities obtained between the 2D model and the equivalent model can be explained in terms of the incorporation of additional stiffness at the column – wall links, as the limit load and collapse displacement provided by an equivalent approach, may vary considerably if different behaviours are prescribed for the horizontal elements. As a consequence, underestimation or overestimation of the bending moments can be experienced. Another key that influences the ultimate load and the post-peak behaviour is the ductile limit of the elements, considered as a fixed percentage of its height. As a result of the use of the models, it is important to say that restoration interventions focused on the improving of the stiffness of slabs and slab-wall connections are necessary to prevent partial out-of-plane collapse for individual elements.

The cultural importance of monumental buildings usually limits the possibility to update the structural behavior from a seismic point of view; mainly due to the apprehensions regarding the use of intervention techniques that could be negative for their cultural value. Consequently, considerable interest has been focused on the development of sustainable methods using Reversible Mixed Technologies (RMT), for the seismic protection for historical buildings. The RMT are designed to maximize the characteristics of innovative materials and special devices that can be easily removed when necessary. Mazzolani [2] carried out experimental tests and numerical analyses for five different levels: full-scale models, scale models, subsystems, devices, materials and elements. Important results were obtained that could motivate the use of these techniques for the seismic protection of heritage buildings.

Goded et al., [3], conducted a study to re-evaluate the seismic damage to historical monuments, produced by earthquakes in Malaga, Spain, one of the seismic areas in that country. A preliminary study of the damage levels to monuments based on the vulnerability indices, which were compared with the real observed damage, was conducted. Thanks to the detailed information collected, an accurate analysis was performed, and the structural behavior, condition of the materials as well as repairs performed, could be assessed. Comparing the analyses, it was found that in the case of churches, the observed damage compared with the calculated damage was very similar, but in castles and monasteries, the differences were greater. Currently, a detailed micro-zonation of the city center is carried out, in order to improve the results and the estimations of the damage probabilities for each historical building, showing damage scenarios in the city.

Martinez et al. [4] studied the Cathedral de Mallorca, in Spain, with the main purpose of presenting a methodology for dynamic characterization of large historical buildings, starting from a structural model calibrated using the results obtained from ambient vibration measurements in different points of the structure. This method proved to be productive, allowing a simple strategy to calibrate a complex analytical model, obtaining mechanical properties for different materials as a starting point for nonlinear structural analysis, considering the most appropriate seismic action for the site. This technique using ambient vibration measurements is economic and does not require the artificial excitation of the structure, an important aspect to take into account, because sometimes could be impossible in a large building. However, the main disadvantage is the impossibility to obtain adequate information in order to evaluate the dynamic properties of the structure in the presence of high levels of deformation (such as those induced by strong motions). Despite this condition, it is considered that this information is really useful to characterize in global terms the structural properties, and of course, it can be considered as the starting point of vulnerability and seismic risk studies of
the cathedral [5]. In this sense, a push-over analysis was performed using the finite element model combined with partial constitutive models. Results showed a fragile behavior of the materials, with minimum tension strength and limited resistance to compression. Also, it was possible to obtain important results in terms of the seismic behavior, in which important damage was obtained for the seismic demand. For that reason, a second stage of this study was carried out, including now an accurate assessment of the seismic hazard in terms of accelerations, considering site-effects and applying both probabilistic and deterministic strategies to consider the demand.

When a research is conducted for conservation purposes of structures, a lot of information can be obtained that usually is not managed by the owners or authorities involved in the process. The consequence is that valuable information is lost or forgotten during the complex process of making a decision. In this sense, a study was carried out for structures with extensive damage and also significant conservation work, which, besides being the main objective the preservation of the structure, efficient management and adequate strategies for the use of the generated information was considered. This is the case of the Monastery of Santa Maria de Salved, Spain [6]. Conservation works in the cloister included an investigation and characterization of the damage and in situ and laboratory tests that identified the need for intervention. After numerical analyses, it was concluded that immediate intervention was necessary because of the low security standard reached. For that reason, the repairing intervention was designed to stop the degradation of materials and to avoid possible collapse. In addition to the proposed remedial strategy, a database for the entire intervention process was generated. This database becomes a management tool, providing simple technical information and easy access to all documentation coming from the experts related with past, present and future actions in the monastery. This information is available on internet, for professionals and the general community in different levels of course.

As a contribution to the safety assessment of historical buildings using simplified methods, Lourenço and Roque, [7] conducted a study with a large sample of 58 churches located in seismic areas of Portugal. The applied methodology is simpler, faster and cheaper, and is based on a simplified geometric approach for immediate detection when a large number of buildings at risk are necessary to evaluate. The aim is to discover unsafe historical buildings for further and advanced studies with more detailed experimental and numerical simulations. The indices are based mainly on the dimensions of the buildings. This assessment applying simplified methods indicates that the average area of resistant walls in plant, and the average height are independent on the seismicity. Similar studied were performed, using the same methodology, for 44 churches in Portugal, Spain and Italy [8].

In Iran, in the city of Tabriz, a large masonry structure, the Rage Tabriz, which was built in the XIV century, was studied by Miyajima et al [9]. They proposed a methodology for evaluating the seismic vulnerability of historical masonry buildings. In this investigation, they took into account the importance of the actual resistance of the building, as the magnitude of potential ground motion, which is crucial in this case, since an important fault is located in the north of Tabriz. This fault is about 200km long and the area closest to the building is about 2km far. The last strong earthquake occurred in 1706, in which the Rage Tabriz was severely damaged. Using micro tremor measurements, amplification factors were obtained, as well as the dynamic characteristics of the building, including the predominant frequency and damping ratio. The expected motions resulted greater than those measured during the Bam Earthquake, in 2007, concluding that the structure is at serious risk. A more accurate seismic diagnostic of the structure is scheduled to be performed in the future.

2. THE CHILEAN EXPERIENCE

Chilean Heritage with Masonry

Chile exposes a wide variety of historical buildings made of different materials and architectural typologies. Some of them were built since the arrival of the Spanish, during the conquest period, starting from the 17th century onwards. This heritage is structured by churches, cathedrals,
palaces, forts and towers. One of the main sources of damage in those structures are the earthquakes, frequent and very strong in more than 3000km long in Chile. Some of such structures have been totally or partially destroyed during severe events, although those in "good condition" are still at high seismic risk, because of the poor regulations related and the lack of qualified technical experts in this matters.

Since 1645, important Spanish fortress began to build that now are part of the Chilean heritage (Fig. 1). The main ones were located in Mancera Island, and the towns of Niebla and Corral, whose structures and design does not differ much from those built in Europe for the same purpose, between the sixteenth and eighteenth centuries. These structures were designed by Spanish military engineers and used stone and brick masonry. Also, it is possible to observe similar constructions in Osorno and Chiloe Island, in the south.

In central Chile, it is possible to observe important churches that are part of the historical monuments. This is the case of San Francisco Church (Fig. 2), declared a National Monument. This is one of the oldest monuments in Santiago and Chile, since it was built between 1586 and 1628, with adobe walls, being rebuilt several times. Another example is the Santiago’s Metropolitan Cathedral (Fig. 3), whose construction began in 1748. It has also been rebuilt several times by the damage caused by earthquakes.

Despite the large and varied range of structures that are part of the heritage and history of the country, Chile has no specialists in seismic vulnerability of historical constructions. Research and work in this issue, have been focused on risk mitigation in essential structures, specifically hospitals, and the seismic vulnerability analysis of urban areas in the north part of the country (Arica, Antofagasta, Copiapo).

**Analysis of Historical Buildings in Valparaiso**

The first investigations regarding the structural conservation of heritage structures considering specific vulnerability studies began in 2008 with a thesis on the vulnerability of historical
buildings in Valparaíso [10]. The main objectives of this research were: to generate a methodology for the study of the seismic vulnerability of masonry buildings in the historical area of Valparaíso, and to compare the results with those carried out in other countries with similar seismic conditions.

The seismic demand in this area is controlled by off-shore thrust type earthquakes, whose hypocenters are located in the Nazca plate subducted under the continental plate or also called South American Plate. This area is characterized by concentrating some of the strongest and harmful earthquakes in the history of Chile. Major earthquakes with off-shore epicenters in this area have occurred in the years 1647 (M = 8.5), 1730 (M = 8.75), 1822 (M = 8.5), 1906 (M = 8.2) and 1985 (M = 7.8) [10], all catalogued as thrust type. The observed damage after the last two earthquakes was a direct consequence of the poor quality of the masonry and the lack of integrity of the structural links and reinforcements between the structural elements. Also, it was observed that the main damage was experienced for those structures founded on fill soils.

In the seismic vulnerability analysis of historical buildings, two important palaces were studied in Valparaíso: Luis Cousiño Palace (National Monument), and Subercaseaux Palace (Fig. 4). Luis Cousiño Palace consists of a four-story building plus a basement. The structural system consists of masonry walls in two axes distributing the lateral stiffness in the longitudinal direction and six resistant lines in the transverse direction. The walls of the basement are made of stone. The rest of the masonry is made of clay bricks and mortar of lime and sand.

Subercaseaux Palace was built between 1881 and 1889. It includes two floors in one facade, and a three-story facade plus a basement in the other. Walls were made of brick masonry and mortar of lime and sand, but the basement was built with stone masonry.

For the seismic vulnerability analysis of the selected buildings, Meli indices [11], and Lourenço and Roque [12], Gallegos [13] and GNDT (Gruppo Nazionale per la Difesa Terremoti, Italy) methodologies were used. These methods quantify the different structural characteristics giving an index value that identifies the vulnerability of the whole system.

From the analysis of the seismic behaviour of these structures, it can be concluded that, in the case of Luis Cousiño Palace, a better performance than other structures is expected, mainly due to its high wall density and the adequate foundation soil. In the case of Subercaseaux Palace, its performance is lower, because of the lower wall density in one direction and the inadequate stiffness distribution. Probably, the main reason why this structure is in a good structural condition is because is founded on rock. In relation with the GNDT index for housing, the values obtained for these buildings are below the risk limit, which means that they are not vulnerable.

3. PRELIMINARY OBSERVATIONS FROM THE Mw=8.8 CHILEAN EARTHQUAKE OCURRED ON FEBRUARY 27, 2010

The Chilean Seismic Sequence of Maule-Concepción, 2010.

Chile is the most seismically active country in the world with a frequency of seismic events 3 times higher than Japan, which follows. These earthquakes are caused primarily by a subductive process, in which the Nazca plate subduces below the South American plate, penetrating...
approximately 7cm/year. The subduction fault is 3000km long parallel to the Chilean coast and also generates an intense volcanism and mountain building in the country.

On February 27, 2010, a strong Mw=8.8 earthquake occurred, whose epicenter was located off-shore in front of Cobquecura, a little town in the Maule area. With more than 450km of fault length, and a focal depth of 30km (Fig. 5), this event is actually considered the fifth strongest earthquake ever recorded in the world. The duration of the event was two minutes and 45 seconds. As a result of the earthquake, a powerful tsunami struck the coast of Chile, destroying the towns in a length of more than 500 km. About 80% of Chile's population was affected, leaving more than 500 deaths and thousands of people homeless.

**Observed Vulnerability**

As part of the observations made during a reconnaissance trip to the epicentral area [14], here are exposed some preliminary cases of old historical masonry buildings severely damaged by the earthquake.

The first case is the parish "Holy Name of Jesus" and the second case is the Church of San Alfonso. The Holy Name of Jesus parish is located in Quirihue, Bio-Bio region. This church was rebuilt after the 1939 earthquake, and after the last event, it was so damaged that demolition is planned by the authorities because of the insecurity condition of the structure. Observations indicate important post-earthquake damage presented in the facade, where part of the non-structural masonry wall collapsed. Also, important damage in the front wall and deep cracks due to excessive shear forces, are present on the walls too (Fig. 6.).

San Alfonso church is located in the city of Cauquenes, in the region of Maule. It was built in 1850 and it was one of the few buildings that remained standing after the strong 1939 earthquake that affected this area. As a consequence of the 2010 earthquake, the greatest damage was observed in the towers, which at that time the current height was twice the original one. In the first evaluations of the post-earthquake condition, fortunately in opinion of experts, San Alfonso Church is a candidate to be rehabilitated. The damage suffered after the 2010 earthquake, was mainly focused on the towers due to sudden change of the lateral stiffness, resulting in a bending failure. In the front, important shear failure is observed, due to the short-beam effect in the area between the entrance and the round window. Similarly, important non-structural elements were damaged, and specifically facade elements, which today are still in a serious instability condition (Fig. 7). There was also severe damage to the buttresses of the walls, in which some of them were almost completely destroyed.
In Santiago, the Basilica del Salvador (Fig. 8), which is a National Monument, was built in 1870, with three parallel bays of the same height, a single and unique typology in Chile. Although the restoring works as a consequence of the damage caused by the 1985 Mw=7.8 earthquake were not finished, the building resisted the 2010 earthquake. Detachment in the front wall of the chapel as well as in a lancet arch was observed. In the same way, Las Animas Chapel, located in Santiago, and built around the beginning of the twentieth century (Fig. 9), was damaged, exposing mainly nonstructural problems.

Another historical masonry building damaged during the Maule earthquake, is the Alhambra Palace, constructed in 1873, which was inspired in the original architectural forms of the structure placed in Granada, Spain. The observed damage was concentrated in the towers, arcs, ceilings and similar ornamental elements (Fig. 10). Also, the building built in 1910 to celebrate the centenary of the Republic and today converted in the Museum of Fine Arts, was damaged by cracking in the front facade. The arch of the building was seriously damaged, with important
broken glasses in the dome (Fig. 11). Another museum that was damaged is the Military History Museum. This building was built in 1887 as school for officers. It consists of a two-story building with a mansard roof on the main facade. The damage was detachment of layers on the facade and main span, cornices, and balustrades as well as cracking on the beam of the main span.

4. CONCLUSIONS

1. The post-earthquake damage caused by the strong Mw=8.8 Chilean earthquake, observed in the analyzed masonry heritage churches, occurred mainly in facades and walls, with collapse or important risk of detachment originated by shear failure in front-wall elements and buttresses, as well as bending failure in towers and slender elements.

2. Important damage was observed in ornamental and nonstructural elements, which increases notably the seismic vulnerability. The current research efforts have been focused on the study of the seismic vulnerability of structural elements, with detailed and advanced numerical and experimental techniques. However, it is important to insist in the need of the study of nonstructural elements of historical masonry buildings, because this is an important source of human losses, increasing the seismic risk, and considering the important amount of such elements found in historical constructions.

3. There is a notable lack of specialists in earthquake vulnerability and risk mitigation for historical heritage structures in Chile. This is one of the most seismic countries in the world, with an important productivity in terms of destructive events. Because of the frequent earthquakes recorded, the Chilean heritage is at constant risk that needs to be calculated and studied to implement rehabilitation strategies. This is even more urgent after the last earthquake on February 27, 2010, which demonstrated the vulnerability status of these systems.

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5. REFERENCES

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