Seismic Vulnerability Assessment of Unreinforced Masonry Churches in Central Chile

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Abstract. In the central region of Chile, the unreinforced masonry (URM) churches underwent extensive structural damage during the 2010 Maule earthquake (Mw 8.8), highlighting the importance of implementing seismic risk reduction plans. These religious buildings are characterized by profound typological and constructive peculiarities, originated by the combination of the local build culture with European architectural revivalisms(i.e., *Neo-Baroque*, *Neo-Classic*, *Neo-Renaissance* and *Neo-Gothic*)during the Spanish domination (1536–1818). The uniqueness of this heritage and the seismic risk of the Chilean territory lead to the need to define a systematic method to assess the seismic vulnerability of the Chilean URM churches. In this paper, some results of an in-depth investigation on a representative stock of churches are reported. The investigation was based on a database implementation with geometrical, constructive, and structural characteristics of 40 URM churches in the Metropolitan Region of Chile. A preliminary qualitative assessment of the seismic capacity of these churches is provided using a survey of geometric indices. Than specific damages observed after the 2010 earthquake have been related to the recurrent failure mechanisms of masonry structures, taking into account 21 local mechanisms involving the macro-elements of the churches. The average level of damage suffered by each church was calculated through the global damage index and a histogram of damage levels frequencies has been arranged. These results are preliminar suitable probabilistic tools to support seismic risk reduction plans.

Keywords: Chilean architectural heritage · Unreinforced masonry churches Seismic vulnerability assessment · Geometrical index · Damage level

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1 Introduction

After 2010 Maule earthquake (Mw 8.8), surveying activities of post-earthquake scenarios have highlighted that extensive structural damages afflicted the Chilean Built Heritage, and in particular the Unreinforced Masonry (URM) churches. Safeguard and safety strategies of this Heritage need not only studies on the single monument (e.g., [1–4]), but also studies at urban and territorial level that allow preventive action plan for risk mitigation. The Chilean territory is characterized by an Architectural Heritage with unique constructive and typological features, but, despite the high seismic hazard, the seismic vulnerability assessment of monumental building at territorial level has not yet been investigated.

This paper reports some results of an investigation carried out on a representative stock of 40 churches in the Metropolitan Region of Chile. In particular, a data-base has been created, including geometrical, constructive, and structural characteristics of the churches and damage levels, recorded after the Maule 2010 earthquake.

A preliminary qualitative assessment of the seismic capacity of the masonry churches has carried out by the survey of some geometrical indices. This procedure is based on a simplified approach that permits an immediate screening of a large number of buildings. The vulnerability is highlighted comparing the geometrical data and taking into account local seismic hazard (PGA). The analyzed indices are recurrent in the literature [5–8] and are codified in some international Codes as: the European Standards of Design of masonry structures (Eurocode 6 [9]) and Design of structures for earthquake resistance (Eurocode 8 [10]) the Chilean Standard for the Structural Intervention of Earthen Historical Buildings (INN, 2013, [11]), and the American Building Code Requirements for Masonry Structures (ACI-530-99/ASCE 5-99, [12]).

From the surveying activities of damage produced by 2010 Maule earthquake on the 40 analyzed churches, the global damage index was calculated for each church applying the second level of the macro-seismic method proposed in [13]. In agreement with [14] a preliminary probabilistic analysis of the seismic vulnerability of the analyzed churches was carried out, using the empirical approach for a future computation of Damage Probability Matrixes (DPMs) for global behaviors [15, 16].

2 The Religious Architectural Heritage in the Central Region of Chile

2.1 The European Influences

The Chilean Architectural Heritage exhibits profound architectural particularities, due to the introduction of European Architecture characters in the Chilean constructive cultures during the Spanish domination (1536–1818). The result is a very interesting architecture with uniqueness features. The local Chilean constructive culture before Spanish period was awareness of seismic risk, and many structural solutions derived from Inca domination (1470–1530); on the contrary, the Spanish constructive cultures were not aware of the seismic risk and were characterized by the European architectural revivalisms (i.e., Neo-Baroque, Neo-Classic, Neo-Renaissance and Neo-Gothic).

Consequently, this architectural Heritage comprises a considerable variety of buildings with different characteristics, as well as buildings where different materials and construction techniques coexist. In particular, the use of adobe masonry (earthen blocks) derive from Incas culture and the use of cyclopes stone masonry, the *cob* technique (mix of earth, straw and water) and the *quincha* technique (timber structure with earth and straw) derive from indigenous architecture [17].

2.2 Geometrical, Constructive, and Structural Features

Geometrical, constructive, and structural features of the representative stock of 40 churches of the Metropolitan Region (RM) were collected according to the GEM Guidelines for empirical vulnerability assessment [18], which provides the basic characteristics of a quality empirical database. The following parameters (and the related categories) are considered, to analyze the buildings: Masonry type (categories: Stone [S], Brick [B], and Adobe [A]);Architectural layout (categories: Basilica (three naves) [Bs], Latin-cross [L-c], and Single-nave [S-n]); Architectural style (categories: Colonial Style [CL], Neo-Classic Style and Variants [Nc&V], and Neo-Gothic [NG]); and Foot-print area (categories: 90 m^2 < A1 $\leq$ 500 m^2; 500 m^2 < A2 $\leq$ 900 m^2; and A3 > 900 m^2).

The frequency distribution of selected parameters in the studied buildings is shown in the diagrams of Fig. 1. From these diagrams it is possible to observe that half of the whole stock is made of brick and adobe masonry; in fact, only five churches, mainly concentrated in the Santiago City, are made of stone masonry. The three naves Basilica (28% with transept) and the single nave layouts represent the most common plan arrangements, unlike the Latin-cross layout which corresponds only to 10% of the sample. The foot-print area is about evenly distributed in the studied churches. Reciprocal correlations of the selected parameters (masonries type, architectural style, architectural layout and foot-print area) are shown in Fig. 1(e) by histograms.

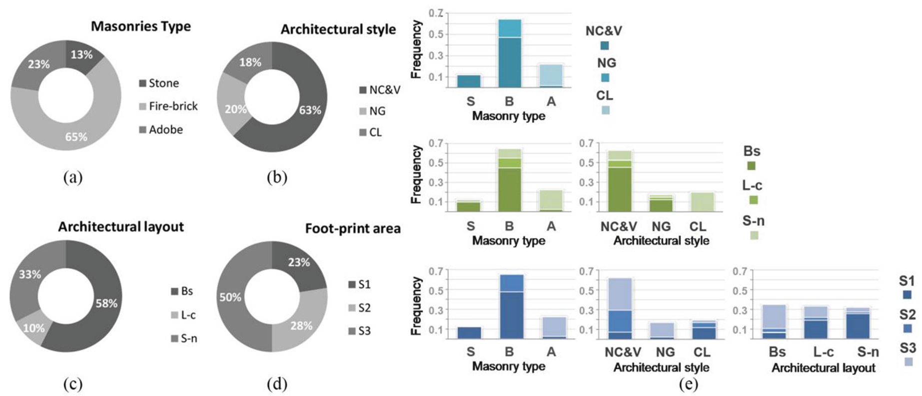


Fig. 1. Frequency distribution (a), (b), (c), and (d), and reciprocal correlation (e) of selected parameters for the population of studied buildings.

The histograms of Fig. 1(e) allowed detecting a close correlation and interdependence between the construction, architectural and typological features of the building. It can be observed, for example, that Colonial churches have predominantly a Single-nave layout and are made in adobe, and that the Neo-classics churches have Basilica layout and are made of bricks. Regarding the foot-print area, the Colonial churches have a low area, while the Neo-classical has a higher area. In particular, by architectural styles, it is possible to divide the analyzed churches in three groups with homogeneous typological, geometrical, and material features: Colonial churches (CL), churches with Neo-classic style & Variants (NC&V); and Neo-gothic churches (NG).

In the analyzed area, eight CL churches have been identified. These buildings represent a constructive variant of the original Colonial typology, i.e. the Northern Andean typology, determinate by the different climatic conditions. The Colonial churches of Chilean Central Valley are characterized by a simple and austere design: a single nave with elongated layout, sloping timber roof, with a par and *nudillo* traditional trusses (tijeral), a plan ceiling, in some case buttresses, and an adobe or wooden bell-tower (Fig. 2).

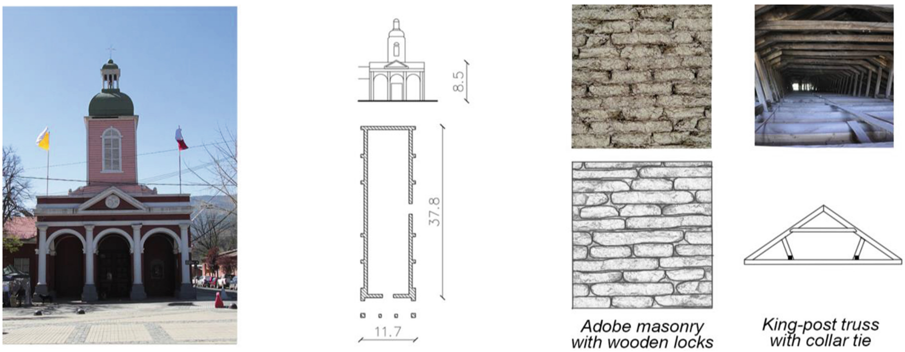


Fig. 2. Colonial church (CL), San José de Maipo church in Maipo village

As concern the NC&V style, twenty-six churches have been identified. The majority of these monuments are localized in Santiago City (75%) and, compared to CL churches, are designed with greater freedom and resourcefulness. In fact, the Basilica layout (rarely Latin-cross, 10% of the total sample), more complex morphology than single nave, was introduced. This new structural system consists of: a central nave higher than the lateral ones, two side aisles, in some case crossed by a transept, an apse, two bell towers, a sloping roof, and false vaults (Fig. 3).

Finally, fifteen Neo-Gothic (NG) churches of brick masonries have been identified in the studied area. These huge buildings represent the transposition of the *Backsteingotik* (German Brick-Gothic) in highly seismic framework. The complexity of the

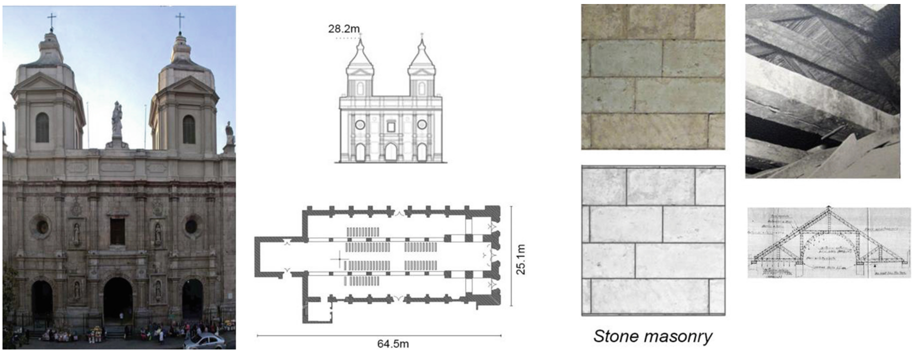


Fig. 3. Church with Neo-classic style &Variants (NC&V), Santo Domingo church in Santiago center

layout is due to the presence of the following macro-elements: a façade bell-tower setting on the gable, a narthex, and a three naves Basilica layout where the lateral aisles are lower than the central nave, generally crossed by a transept, a semicircular apse, an ambulatory, and false rib vaults. The absence of effective anti-seismic devices able to guaranteeing a box-behavior to the structure, the high conventional slenderness of the walls, and the lack of roof rigid diaphragm are the main weaknesses that characterize these structures (Fig. 4).

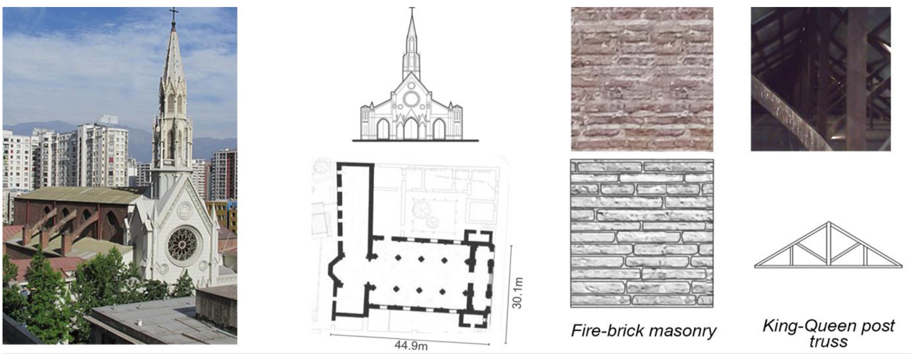
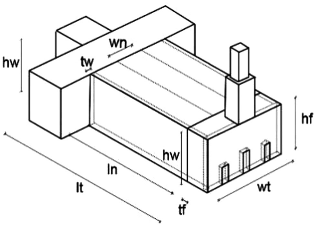


Fig. 4. Neo-gothic church (NG), Dulce Nombre de Maria church in Santiago center

3 Geometrical Indexes

A preliminary qualitative assessment of the seismic capacity of the churches has been provided through the survey and analysis of some geometric indices, involved in the local mechanisms induced by seismic actions or connected with the global seismic response of the buildings. The selected indices, summarized in Table 1, are: the width-to-length [wt/lt] of the church, the nave length-to-total length [ln/lt], the nave width-to-total width [wn/wt], the façade clear height-to-width [hf/wt], the façade thickness-to-height [tf/hf], and lateral walls thickness-to-height [tw/hw].

Table 1. Analyzed geometric ratios. (σ*, coefficient of variation is between brackets) for the three classes: Colonial churches (CL), Churches with Neo-classic style and Variant (NC&V), Neo-gothic churches (NG). *(Cruz, 1995; Elnashai and Di Sarno 2008); ** (Eurocode 8); *** (Eurocode 6; Eurocode 8; and ACI-530-99/ASCE 5-99);**** (INN, 2013)



ID	wt/lt	ln/lt	wn/wt	hf/wt	tf/hf	tw/hw
CL (σ*)	0.34 (24.1)	1.0 (0)	1.0 (0)	0.95 (28.9)	0.12 (26.1)	0.123 (27.6)
NC&V (σ*)	0.44 (23.0)	0.67 (19.3)	0.5 (50.0)	0.64 (30.3)	0.111 (23.4)	0.12 (26.1)
NG (σ*)	0.38 (24.0)	0.71 (31.7)	0.68 (35.0)	1.7 (31.7)	0.08 (17.0)	0.07 (35.1)
Thresholds	0.5*	–	–	2**	0.111*** or 0.145***	0.111*** or 0.145***

Furthermore, the in-plane (γ1, i, γ2, i, and γ3, i) and out-of-plane (t_w/h_w) indices in the longitudinal (L) and transverse (T) directions are calculated: (i) γ1, i ratio between the area of the earthquake resistant walls (A_{wi}) and the total plan area of the buildings (S), γ1, i = A_{wi}/S; (ii) γ2, i ratio between the A_{wi} and the total weight of the building (G), γ2, i = A_{wi}/G [m^2/N]; γ3, i ratio between the shear strength of the structure ($F_{RD,I}$), calculated as $F_{RD,I} = \Sigma A_{wi} f_{vk}$ according to Eurocode6 (fvk = fvk0 + σd) and the total base shear for the seismic loading (F_E), i.e. γ3, i = $F_{RD,i}/F_E$; and t_w/h_w ratio between the thickness (t_w) and the height (h_w) of the perimeter walls. These results are compared with the same indices of 44 Portuguese, Spanish and Italian churches investigated in [7], see Fig. 5.

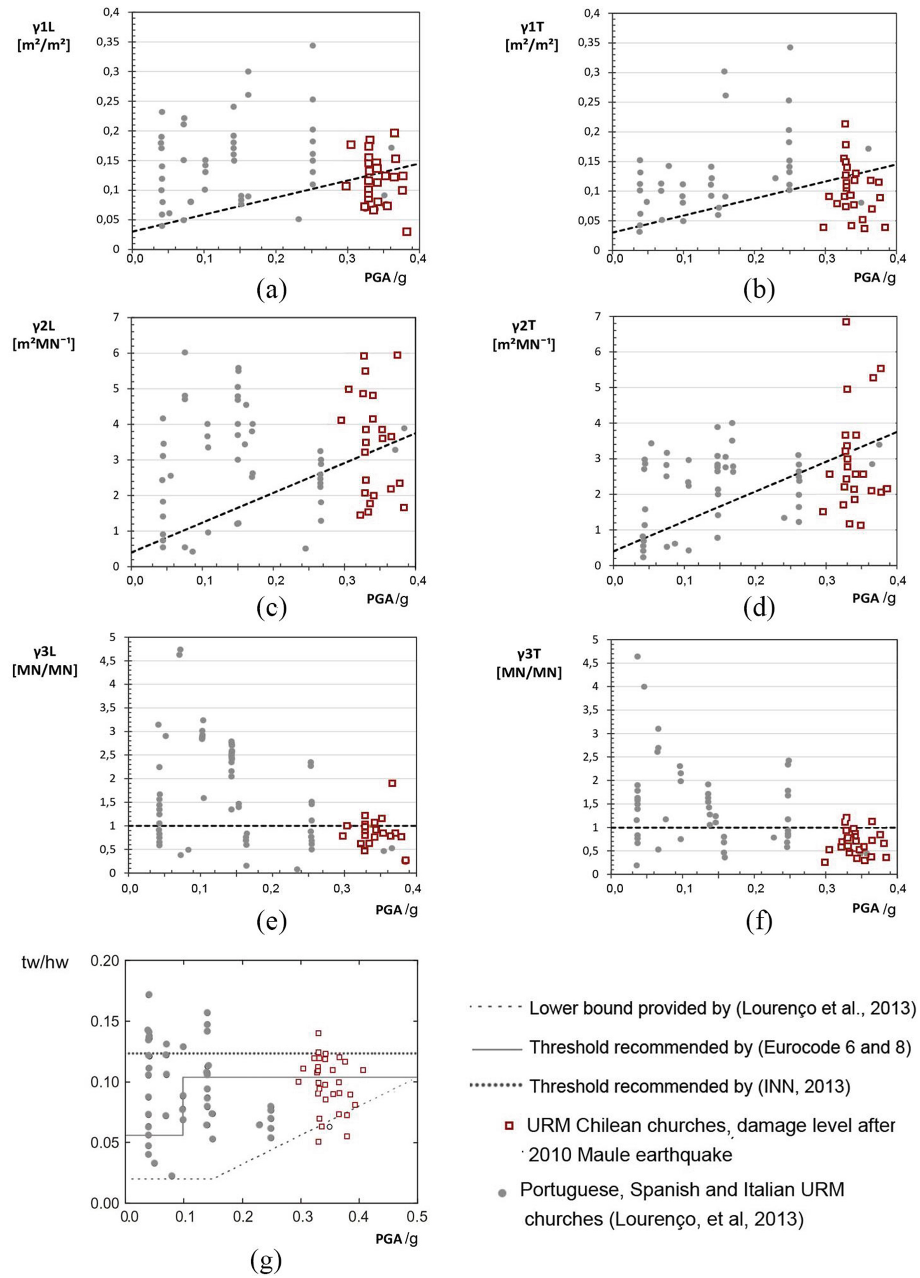


Fig. 5. The in-plane indices: (a), γ1L, in-plane area ratio in the longitudinal direction; (b), γ1T, in-plane area ratio in the transverse direction; (c), γ2L, area to weight ratio in the longitudinal direction; (d), γ2T, area to weight ratio in the transverse direction; (e), γ3L, base to shear ratio in the longitudinal direction; (f), γ3T, base to shear ratio in the transverse direction; and (g) the out-of-plane index of lateral walls, thickness-to-height [tw/hw], of 40 URM Chilean churches compared with the same indexes of 44 Portuguese, Spanish and Italian churches investigated in (Lourenço et al., 2013)

4 Probabilistic Analysis of the Seismic Vulnerability

The post-seismic scenarios of 2010 Maule earthquake for the studied churches have been analyzed according to the dominant behavior of macro-elements of church architectural typology (i.e. façade, narthex, bell-tower, lateral walls, transversal walls, colonnade, transept, apse, and chapels), using the catalogue of mechanisms developed in [19]. The global damage index was calculated for each church applying the second-level of the macro-seismic method proposed by [13]. Due to the specific features of the Chilean churches, the 28 analyzed collapses mechanisms, assessed in [13] post-earthquake survey form, are reduced to 21 mechanisms. Since the values of the global damage index are real numbers, a transformation of the indices into a discrete variable was carried out to obtain a measurable level of damage comparable with the European Macro-Seismic Scale (EMS-98). Thus, each damage index was correlated to a damage level, ranging between 0 and 5. In particular, as suggested in [13] and [14], the damage classification is graduated in five levels according to EMS-1998 scale. In Fig. 6, the damage levels frequencies for the churches divided in Architectural Styles (Colonial, CL, Neo-Classic, NC&V, and Neo-Gothic, NG), normalized with respect to the total number, for the PGA of 2010 Maule earthquake are shown. The Architectural Style is reflexed by the reciprocal frequency distributions between the damage levels resulting from the 2010 Maule earthquake, and the construction, architectural, and typological features of the building.

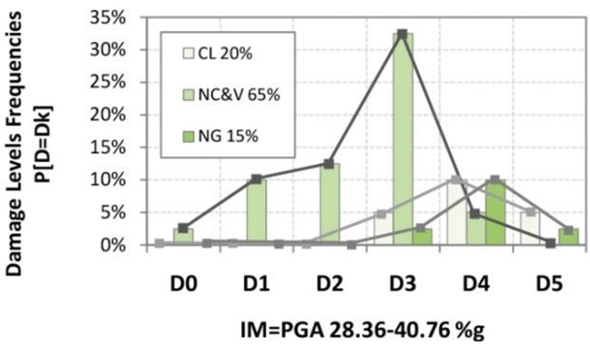


Fig. 6. Damage levels frequencies for the churches divided according to the Architectural styles, normalized with respect to the total number, for the PGA suffered during 2010 Maule earthquake. For each style, the percentage number of churches is reported.

5 Conclusions

In order to support risk reduction plans, some preliminary results are reported:

– The analysis of the damage caused by the 2010 Maule earthquake showed that the CL churches were the most affected (5 level damage in 5% of cases and 4 level damage in 10% of cases), severe damages were also recorded for NG churches

(5 level damage in 3% of cases and 4 level damage in 10% of cases), while the NC&V churches underwent an intermediate level of damage (3 level damage in 33% of cases, 4 level damage in 5% of cases).

– The slenderness of the facades of Colonial churches (mostly built in adobe) does not meet the requirements of the Chilean Code for Intervention of Historic Adobe Structures.
– As regards the out-plane behavior, of both, the facade and lateral walls, the Neo-classical churches satisfy the threshold imposed by Eurocode8 for high seismicity, while the Neo-gothic churches do not verify the threshold.
– The longitudinal behavior, both in terms of area of the earthquake resistant walls on total plan area and area of the earthquake resistant walls on total weight, it is more critical than the transversal one.

These preliminary results could provide general indications regarding the strategies for the choice of earthquake improvement interventions on analyzed churches and a priority program.

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