SAHC2014 – 9th International Conference on
Structural Analysis of Historical Constructions
F. Peña & M. Chávez (eds.)
Mexico City, Mexico, 14–17 October 2014

REDISCOVERING EARTHQUAKE-RESISTANT KNOWLEDGE IN CHILEAN UNREINFORCED MASONRY HERITAGE

Natalia Jorquera S.[1]

[1] Architecture Department, Universidad de Chile
Avenida Portugal 84, Santiago de Chile
e-mail: nataliajorquera@uchilefau.cl

Keywords: Earthquake-resistant, Traditional Knowledge, Unreinforced masonry, Chilean architectural heritage.

Abstract. *This article aims to show the first phase of research project FONDECYT Initiation [1] nº 11130628 "Rediscovering Vernacular Earthquake-resistant Knowledge: Identification and analysis of built best practice in Chilean masonry architectural heritage". The objective of this research is to recover vernacular knowledge which is the basis of good structural performance of some historic buildings and which would explain why they have survived in one of the world's most earthquake affected regions, Chile.*
The case study is the historic centre of Santiago within its colonial boundaries. This research has 3 main phases: the first to identify historical buildings built in unreinforced masonry in the established area; the second to classify the identified buildings according to architectural and technological typologies, to identify those "knowledge and technical practices" that have allowed their survival; in the last phase those examples considered the most effective in terms of earthquake-resistant performance will be analysed in depth according to their architectural and constructive characteristics.
Here the development of the first and part of the second phase will be presented: a cadastre of the historic buildings examples of good structural performance in Santiago followed by a comparative typological analysis that will allow the drawing of preliminary conclusions about their earthquake-resistant strategies.

INTRODUCTION: CHILE, A LABORATORY OF EARTHQUAKE RESISTANT CONSTRUCTION.

Chile is one of the most seismic countries in the world. Earthquakes that exceed magnitude 7º occur at regular intervals, around every 10 years, and according to the historical record of the National Seismological Centre of the Universidad de Chile [2] there have been more than 100 earthquakes above magnitude 7° since the year 1570.

Despite this most of the historic buildings of northern and central Chile, from Spanish Colonial and Republican period, were built mostly in unreinforced masonry (adobe, fired brick or stone masonry). They consist of buildings which are both important “Monuments” and “minor” heritage representing 200 years old or more of construction. Following numerical modern approaches unreinforced masonry would not have the capability to withstand dynamic forces and thus these Chilean buildings should have collapsed or have been substantially damaged during their first exposure to earthquake activity. In practice however there are still many buildings that have perfectly withstood the seismic action. How can this survival being explained? According to the research hypothesis "surviving unreinforced masonry historic buildings have a technical and empirical knowledge which is un-coded and has accumulated over time, this is what explains their survival" [3].

In a seismic zone like Chile earthquakes have become real laboratories of constructive experimentation where the historic buildings that still exist are the best examples of accumulated local knowledge and learning through experience. This knowledge or “local seismic culture” [4] with the advent of modern materials and techniques has been lost. Sadly moreover, in Chile after every earthquake, damaged buildings are immediately demolished without any diagnosis, and surviving buildings are not studied. However if they were there would be much to learn from them. Instead the rediscovery of this knowledge would allow an understanding of the strengths and vulnerabilities of historic buildings, to promote their correct maintenance, adequate structural interventions and preventive measures to preserve the architectural heritage. In the medium term recovered knowledge could become the basis for the correct development of technical standards for historic buildings.

This research intends to enhance Chilean architectural heritage from a technical and scientific perspective, as the identified buildings will be examples of international significance for earthquake-resistance studies. Besides these factors the socio-cultural and environmental dimension will be also enhanced with a “rescue” of "local-vernacular know-how" to put in evidence the relationship between traditional earthquake-resistance strategies and the local resources taken directly from environment and transformed by local communities.

1 UNREINFORCED MASONRY BULDINGS OF THE HISTORIC CITY CENTER OF SANTIAGO DE CHILE

The historic centre of Santiago within its colonial boundaries (Fig. 1) has been taken as the case study as in that area there is a significant concentration of historic unreinforced masonry buildings. Also Santiago, as the capital of Chile, is home to many of the oldest and important buildings of the country are there which means that they are the buildings that have survived to a mayor number of earthquakes.

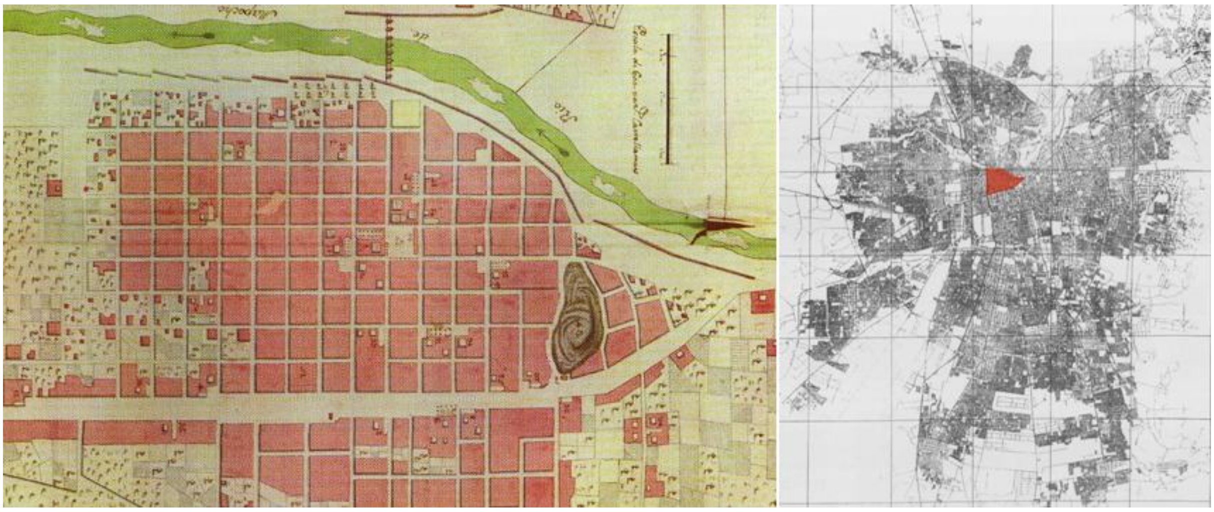

Figure 1: Left: a map of Santiago at the end of the Colonial period [5]. Right: the Colonial area in red colour inside nowadays Santiago's surface.

Since the founding of Santiago in 1541 until the arrival in 1780 of the most important architect of the Colonial period, the Italian Joaquín Toesca, there were 200 years of experimentation and improvement of traditional construction technologies. This was driven by the two largest earthquakes of the Colonial period: the earthquake of 1647 and in 1753, after which there were no surviving buildings in Santiago besides the church of San Francisco (Fig. 2), which is the oldest building of Santiago [6]. This building because of its importance has been included in the tentative list of the UNESCO World Heritage List Nominations since 1998 [7].

Figure 2: San Francisco church, Santiago.

The subsequent reconstruction processes must have improved the construction techniques based only on the use of unreinforced masonry (adobe, brick or stone), as there were no other known techniques because the wood was abandoned after several fires in Santiago and the modern techniques were not been invented yet.

From the late eighteenth century to the early twentieth century (that is, until the advent of modern materials) the civic and religious unreinforced masonry buildings of Santiago would have reached their highest technological development as they collected and applied the accumulated knowledge of the preceding centuries. This knowledge would explain the good structural behavior of many buildings and therefore their survival until today.

Despite the importance of this unreinforced masonry architectural heritage there is neither a cadaster and nor a scientific literature that permits its identification and thus its enhancement.

2 PHASES AND METHODOLOGYCAL APPROACH

In order to recover earthquake-resistant vernacular knowledge through the analysis of certain buildings that have demonstrated good structural behavior the first step is to identify them, in order to subsequently classify and analyze them. Thus the research is divided into three phases during a three year period.

In the first phase the unreinforced masonry cases of good earthquake-resistance behaviour in the case study area are identified. For this purpose indirect analysis by collecting historical background records and direct field analysis are integrated.

In the second phase the identified cases are classified and the general rules of good structural behavior are described. The classification is based on the identification of architectural and technological typologies that allows the recognition of common patterns between the cases such as geometry, architectural configuration, slenderness, constructive materials and building systems, age of construction, etc.

In the third and last phase those examples considered the most effective in terms of earthquake-resistant performance will be analyzed in depth according to their architectural and constructive characteristics. This will be carried out by; direct observation and diagnosis, qualitative a quantitative analysis of the main components of the building using tests such as thermographic analysis to identify the inner composition of the walls, analysis of the superficial compression strength, the characterization of materials (bricks, stones, mortars, etc.) through archeometric laboratory tests, etc. Finally in this phase the tools of “Knowledge Management” theory [8] will be applied to transform the identified empirical knowledge into one which is systematized, encoded and transferable.

At the moment the first phase of the research is completed and the second one is in progress. These phases will be now presented in depth.

3 FIRST PHASE: IDENTIFICATION OF STUDY CASES

Besides defining the territorial limits into which the individual case studies were identified, a time frame limit was established: the period from 1753 to 1860. This includes the period from the second big historical earthquake, which nothing survived besides the San Francisco church, and the date of arrival of the first constructive elements made of iron which could be used as reinforcements for walls. Thus it is supposed that all buildings constructed before 1860 in Santiago correspond to examples of unreinforced masonry. Of course this identifies the San Francisco church is one of the first case studies. To identify the rest of the cases methodologies of indirect and direct analysis were integrated.

3.1 Indirect analysis by collecting historical background records

To identify the historical buildings through the analysis of historical documentation three main inquiries were realized:

- Analysis of historical maps of Santiago of the period between 1541 (the data of the foundation of the city) and 1860 with the aim of analyzing the evolution of the city identifying the buildings that have remained and those that have disappeared.
- Literature review (books, magazines, papers) related to the history of the city of Santiago and its architecture, to collect information about the historical buildings.
- Analysis of historical chronicles and other official documents (decrees, press articles) written after the largest earthquakes that have affected Santiago and their subsequent reconstruction processes.

3.2 Direct field analysis

The direct field analysis was conducted by walking block by block in the chosen area of Santiago in order to visually identify visually the case studies built before 1860. The parameters taken for this identification were:

- An architectural morphology and style corresponding with the architecture of the eighteen and nineteen century in Chile.
- The predominance of some unreinforced masonry building system such as adobe, brick or stone masonry.
- Where materials were hidden under the plaster, some architecture features that respond to unreinforced masonry technology, such as wall thickness, slenderness, fenestrations dimensions, etc. were taken into consideration.
- Additional information on the buildings façades, such as signage or plaques with the year of construction and history of the building, or any other evidence to find out other indirect sources of information.

All the identified buildings were located on a map and were photographed.

From this first visual identification the main issue was that a large number of the cases appeared to have been built before 1860 in unreinforced masonry. However there was some doubt as to the actual construction process as in actual fact they could have be built afterwards using industrialized technologies and imitate historical architecture or they could have suffered strong retrofitting interventions which questions their value as case studies. Thus, from this first approach, a map with three categories of buildings were made: a) Certain or definite cases (red color); b) Cases whose building system and construction date have to be further investigated (pink color); c) Cases in which retrofitting interventions need to be discarded (orange color) (Fig. 3). “B” and “C” categories required further investigation which was conducted both through the collection of historical information and a second deeper field analysis. With this first range of case studies more maps were elaborated including; map of building uses, map of architectural typologies, and a map of building systems.

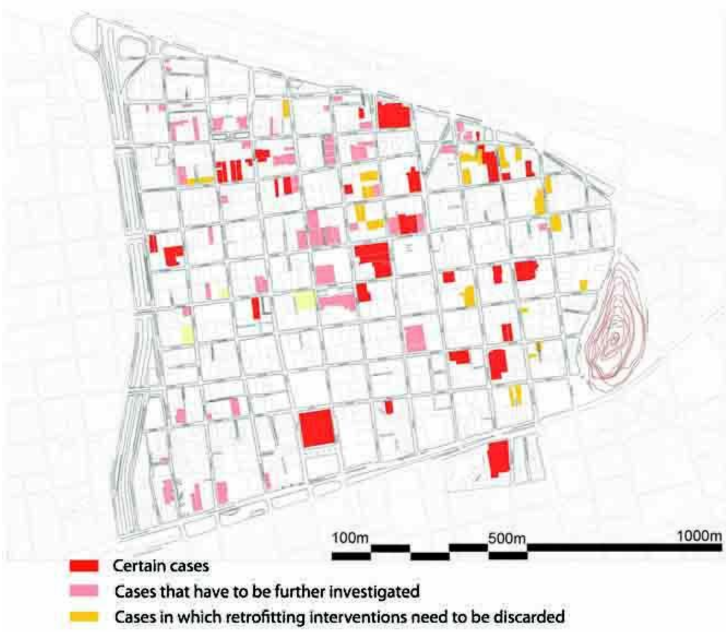

Figure 3: A map with the study cases.

Around 25 "pure" unreinforced masonry historical buildings were found through this integration of field analysis and historical information, among which the most important are: the Cathedral of Santiago, The Moneda Government Palace, the previously mentioned San Francisco church, and several other churches and colonial houses (Fig. 4).

Figure 4: Some of the most important Santiago's unreinforced masonry buildings.

Some smaller houses that were probably built before 1860 in unreinforced masonry were not taken into consideration, as they do not represent much architectural value and additionally they are too small to be examples of construction techniques in earthquake-resistant behaviour.

4 SECOND PHASE: COMPARATIVE ANALYSIS AND PRELIMINARY CONCLUSIONS ABOUT EARTHQUAKE-RESISTANT STRATEGIES

4.1 First classification of the cases

At the moment the comparative analysis is based on these first 25 cases. The analysis started with a classification of the buildings according to their use, date of construction and predominant building system (Fig. 5). From this classification, the preliminary results are: according to use, 8 churches and 1 religious building, 9 Colonial and Republican houses, 1 theater, 2 museums, 2 civil buildings, 1 market place and 1restaurant. According to the date of constructions, there is 1 from the beginning of the XVII century, 2 from the second half of the XVII century, 5 from the first half of the XVIII century, 3 from the second half of the XVIII century, 5 from the first half of the XIX century and the rest from around 1860. According to the building systems there are 3 buildings built in adobe, 15 in fired brick, 1 in stone masonry and the rest in a mixed of 2 or 3 of these mentioned systems.

FICHA CLASIFICACIÓN CASOS DE ESTUDIOS

n°	Nombre	Ubicación y manzana de referencia	Fotografía	Año de construcción apróx.	Uso	Sistema constructivo predominante	Protección legal	Observaciones
1	Iglesia de San Francisco	Alameda frente a San Antonio 0		1595-1613 1857 (la torre)	Religioso	- Mampostería de piedra - Adobe - Albañilería de ladrillo	MH 1951	
2	Iglesia de La Merced	Mac Iver esquina Merced 15		1760 - 1795-99 (modificaciones de Toesca) 1859 y 1885 (las torres)	Religioso	- Albañilería de ladrillo	MH	
3	Casa de Velasco	Santo Domingo 689. (Mac Iver esquina Santo Domingo) 18		+ 1730	Residencial	- Adobe	MH 1981	
4	Casa Manuel Montt	Merced 738-748 23		1830 - 1840	Residencial	- Albañilería de ladrillo	MH 1966	

Figure 5. Classification sheet.

4.2 Preliminary conclusions about comparative analysis

After this preliminary classification, some first conclusions can be made:

- The smaller buildings are houses of just one or two floors and most of them are built in adobe. This means that the weakest building technology is properly used for an architectural model that does not present great challenges from the earthquake resistant point of view.
- Churches are the oldest and most numerous surviving buildings, which means that they have an efficient earthquake resistant model.
- Churches present the most audacious structural model because of their dimensions, height and because they do not have intermediate walls to buttress longitudinal walls. Thus, the higher they reach the walls are thicker to keep a slow slenderness. One interesting point about churches is that besides some architectural similarities the building

technologies are very different, these include: a church built completely in stone, one built half in stone half in fired brick, one built half in stone and half in adobe, and four built completely in brick masonry but each with very different brickwork, dimensions of the parts, mortars and specific constructive solutions.
- Slender elements such as church towers have often been built with more flexible technologies such as wooden frames. Additionally most of the towers are newer than the original building.
- Buildings of the late XVIII century and of subsequent dates are built completely in fired brick, which means that adobe and stone masonry technics were abandoned. This could be explained by the fact that fired brick allows a more standard element than pre-industrial technology and thus faster processes of construction.
- All the identified buildings are symmetric and well proportioned. They also have slow slenderness, simple geometries a prevalence of thick walls with few fenestrations, etc.
- The structural design of the buildings follows static principles: lighter loads while increasing height, thicker walls and fewer openings on the first floors and external walls. Materials with higher strength are in the first floors and in the base of walls.
- All material used are local and correspond with the nearby available resources of the time period: adobe and fired brick were made with the local raw earth and clay; stone which came from the two hills in the city: “Santa Lucia” and “Cerro Blanco”; mortars were made of mud (for adobe masonry), clay or lime (for fired brick) and lime for stone. Additionally at the end of the XVIII century a mix of lime and eggs was used as mortar for the main civil buildings; this mortar is known locally as “*cal y canto*”.
- Wooden reinforcements have not been found. This could be because wood was a very scarce resource in central Chile in the preceding centuries due to the very dry climate.

In synthesis it can be preliminarily established that earthquake-resistant strategies are based on proper morphology of buildings combined with the right strength of local materials. Deeper analysis of the local strategies will be performed in the next months.

5 CONCLUSIONS

The Chilean Law for Monuments safeguards most of the first identified buildings because of their historical and aesthetic value but their technical aspects are not recognized. However the technical dimension is an important part of the architectural heritage, it is a testimony of how our ancestors built and managed the available resources to transform them into building materials. Restoration that maintains the architectural appearance but distorts structural and material integrity of the historical buildings undermines the authenticity of this heritage.

In Chile, due to its highly seismic condition, interventions in architectural heritage have always been very invasive with the excuse that historical buildings are built of 'fragile' technologies and thus they need to be "strengthened" to be preserved. Practice has proved the opposite: those buildings that have been strongly reinforced with concrete have been seriously damaged during the recent earthquakes (Fig. 6). Instead those who have maintained their original structural and construction design have survived for centuries despite the earthquakes and despite their “weak” technologies. The cadaster made in the first phase of this research aims to highlight that there are many examples of historic buildings that have survived without the help of modern reinforcement because they have a good structural and earthquake resistant design which therefore should be recognised for its value.

To understand earthquake-resistant strategies of every important historical building will help to generate guidelines to promote correct and sensitive interventions and promote preventive measures to contribute to the conservation of this rich heritage.

REFERENCES

[1] FONDECYT Initiation. *Fondo Nacional de Desarrollo Científico y Tecnológico* ("National Fund for Scientific and Technological Development") is the principal Chilean fund for promoting the development of basic scientific and technological research. The "Initiation" funding is aimed at young researchers who have obtained a PhD in the last five years.

[2] Centro Sismólogico Nacional de la Universidad de Chile. http://www.sismologia.cl/ [28/06/2013].

[3] N. Jorquera, *Rediscovering Vernacular Earthquake-resistant Knowledge: Identification and analysis of built best practice in Chilean masonry architectural* heritage. In submission to FONDECYT Initiation into Research 2013, Santiago of Chile.

[4] P. Pierotti, D. Ulivieri, *Culture sismiche locali*. Edizioni Plus, Pisa, Italy, 2001.

[5] *Plano de la ciudad de Santiago del Reino de Chile, 1809*. In http://www.memoriachilena.cl/602/w3-article-80842.html

[6] C. Valenzuela, *La construcción en Chile. Cuatro siglos de Historia.* Ed. Cámara Chilena de la Construcción, Santiago de Chile, 1991.

[7] whc.**unesco**.org/en/**tentativelists**/chile.

[8] N. IKUJIRO, *A Dynamic Theory of Organizational Knowledge Creation*. In Organization Science, Vol. 5 n°1, 14-37, 1994.