The Chilean adobe as a seismic vernacular technology, the study of the "Norte Chico" area

A. Rivera Vidal
Escuela de Construcción en Tierra ECoT, Santiago, Chile

ABSTRACT: Chile is one of the most seismic countries in the world where large earthquakes have occurred in the past and surely great earthquakes will occur in the future. The "Norte Chico" is an area of transition from arid to vegetation. It is located between the big Atacama Desert and the Chile's capital Santiago. There is a large influence of colonial constructions, making adobe block widely used in the vernacular architecture. It is possible to identify a particular culture of adobe construction with seismic technologies which had been proved on the 8.3 Mw earthquake that took place in September 2015.

1 INTRODUCTION

1.1 *Chilean seismic cultures*

The Chilean territory exists because of the confrontation of two tectonics plate: The Nazca plate and the American plate. The permanent glide of one under the other generates subduction that gives origin to the principal characteristic of the territory: The Andes mountain range.
The ancestral cultures that inhabited this territory knew this well and adapted to it, creating seismic structures that could resist the high intensity earth movements. In the arid north they built with stone and earth, and earthquake resistant strategies based on the geometry of the buildings. In the centre and south of the country wooden reinforcements are the most common seismic resistant solutions (Jorquera & Pereira 2015). About 40% of the official heritage declared sites are built on earthen techniques predominating the raw earth masonry and the mixed techniques of wood and earth (Contreras & al. 2011).

1.2 *The territory of the "Norte Chico"*

Limited to the north by the arid Atacama Desert and to the south by the Aconcagua river. Located between aridness and fertility. It is a territory with over 700 km of the Copiapó river (27°19′00″S 70°56′00″W) and the Aconcagua river 32°54′54″S 71°30′30″W).

This territory has been inhabited since 10,000BCE and around 2,000BCE the first sedentary people settled in this area. Until the arrival of the Spanish conquerors, and since around 95BCE, the territory was inhabited by people grouped into the *Diaguita* culture (name given by the *Quechuas*), who were dominated by the Inca empire.
During the Spanish conquest it was a transitional area, from the capital of the Peruvian Viceroyalty and the south. For this reason, the second city of Chile was founded here: the port of La Serena in 1544.
The "Norte Chico" is composed by a diversity of small cities and villages, distributed between the two mountains range: The Andes and The Coast.
Around the second half of the 18th century, because of the improvement of mining and farming activities, the territory became more populated, with about 200 years of the Spanish presence in Chile and two centuries of earthquake activity.

Figure 1. Continuous façade at the urban area of Combarbalá after the 2015 earthquake. (Credits: Amanda Rivera, 2016)

Figure 2. *Quincha* of the “Norte Chico” with medium size branches as structure. (Credits: Amanda Rivera, 2016)

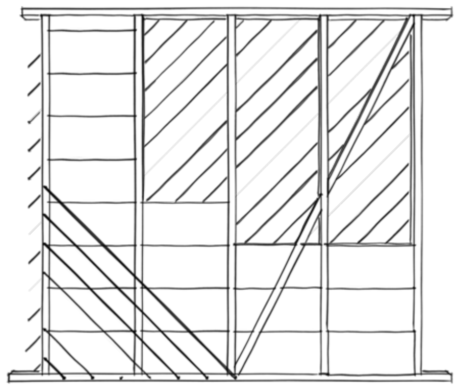

Figure 3. Scheme of the “adobe en pandereta” system (Credits: Amanda Rivera, 2012)

2 CONSTRUCTIVE TYPOLOGIES

2.1 *Building typologies*

The traditional architecture of the territory is characterized by its simple aesthetics with neither a clear style nor fine decorations. Its simple definition is supported in context with the environment and available resources (Ferrada & Segovia 2007).

Three principal types of building may be distinguished by its purpose: the agricultural, the religious and the dwelling, the latter. two used predominantly nowadays.

The religious buildings are located mostly in urban areas but with isolated construction typologies. While the houses are also located in urban as well as rural areas, the urban dwellings are composed of several units attached one to another, making one constructive unit (Fig.1). There are also different typologies in rural settlement. First the *casonas patronales* are the landowners houses that are isolated and built around an interior courtyard. It acts as an independent structural unit. There are also smaller houses much more compact and related to farming activities that also had their own independent structural unit.

2.2 *Earthen constructive typologies*

The territory features mixed wooden-earthen construction as well raw earth masonry.

The *quincha* or wattle-and-daub construction is a technique built with a main structure of medium-sized branches with thinner branches from local bushes which were filled in with a mix of mud and straw. It is the main native constructive typology, used by the *diaguitas* (Fig.2).
The colonial constructions, both in cities and in the countryside, have a raw earth masonry as main structure and a secondary structure of wood and earth called *pandereta* (Fig.3)*,* where the earthen block is used edgeways. In this area it is possible to identify a culture of adobe constructions with an anti-seismic technology of horizontal timber embedded as horizontal ladders and with large wall thicknesses of at least 60 cm. Structures of two floors made of load-bearing earthen masonry are not uncommon.

3 THE RAW EARTH MASONRY AND THE SEISMIC STRATEGIES

3.1 *The mass*

The mass strategy gives the main importance to the thickness of the walls, making it the centre of the structural system together with the geometry of the

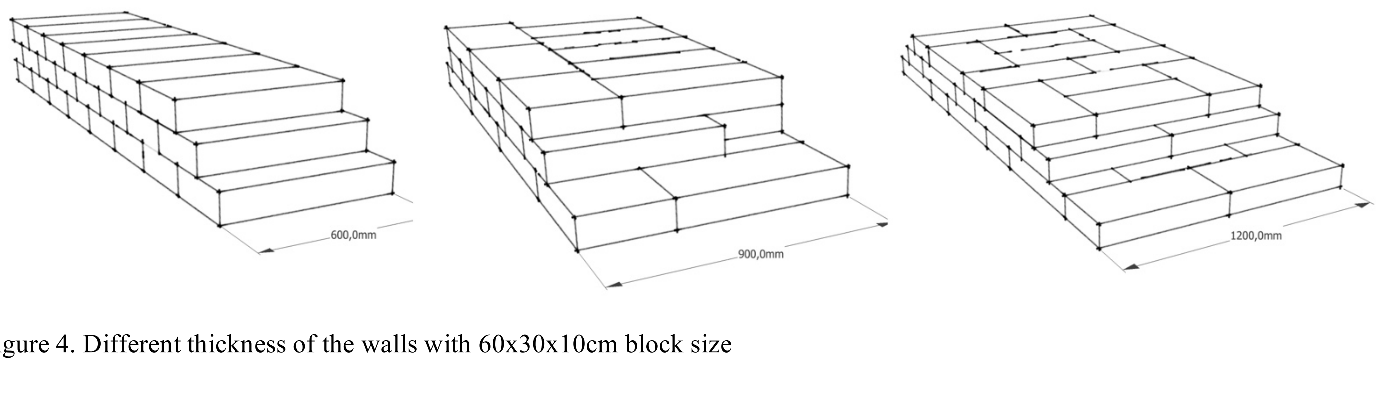

Figure 4. Different thickness of the walls with 60x30x10cm block size

building. It is the first basic strategy for seismic areas. The adobe construction found have a minimum slenderness ratio of 1:8, with the most used being 1:7. For this reason, to maintain this relationship and increase the height of the buildings there are thick walls, being 50cm the minimum found in traditional architecture, to reach the height of 3.5 meters. In spite of that, walls of more than 60cm of thickness are much more frequent, to reach thus at least four meters' height, where the most common earthen block size is 60 x 30 x 10cm. At greater heights, the walls increase to 90, 120 and up to 150 cm thick, measures that arise from the modulation of block (Fig.4). The adobes, in the traditional construction, are always disposed of blight, where the length of the block becomes the thickness of the wall (Muñoz & Rivera 2012). The continuity of the walls, reducing the door and window spans are of great importance for this strategy, as they decrease the wall volume. Also the structure has to guarantee a box-like behaviour that can be achieved through firm connections in the corners between perpendicular walls (Dipasquale & al. 2014).

3.2 *The stability*

The counterforts were the first elements of reinforcements that can be observed in the traditional construction to counteract the effort of the earthquakes, supporting the walls in the dynamic moments, and avoiding their overturning to the outside. These stability devices have been used in great length walls which lack interior support elements. This feature is found mainly in the central nave of churches (Fig.5).

The counterforts are the continuity of the wall to the exterior in their perpendicular direction. It must be united to the rest of the wall as in two perpendicular walls: in each one of its threads. It generally has, an angle that generates a push towards the wall. This lowers the centre of gravity of the wall, reducing its fragility.

3.3 *The reinforcements*

Reinforcement systems are built with complementary materials to earth, in traditional architecture are made of wood, because of its great elastic properties. Its characteristics of flexibility, lightness and deformability without reaching the breaking point, offers good resistance capacity against horizontal loads, and enables the dissipation of substantial amounts of energy (Dipasquale & Mecca 2015). This is the reason why most of the reinforcement strategies are based on wood as a seismic solution.

Roof system are always present but not always thought of as part of the structural strategy of adobe construction. In the traditional architecture of the area they contribute to the horizontal stiffening, to the bracing and to the distribution of the loads.

Las trabas are specific wooden elements (Fig. 6) used to support the joining of other wooden elements of the construction, such as mezzanines and roof structures, with the outer adobe walls. Within the reinforcements are the most precarious devices and made with the smaller woods, which means less access to reinforcement resources. They can be found perpendicular to the wall, where the element crosses the wall and on the inside is attached to the structure of wood or mezzanine. Or when it is the same roofed wood or between the floor that crosses the wall and it is hooked with a piece of wood of a smaller section to avoid its displacement These *trabas* have also been observed in diagonal positions, where an element independent of the wooden structure is arranged as a square and is hooked in the same way by a wood of smaller section in both outer points. This system is of great vulnerability, especially when the pieces of wood are exposed, they are in permanent exposure to water and xylophages, which generates their frequent rotting and finally, added to the absence of maintenance, its disappearance in the reinforcement system.

Figure 5. One of the few buildings with counterforts in the area. San Antonio del Mar church of Barraza built in 1795 (Credits: Amanda Rivera 2016)

Figure 6. Trabas: Wooden pieces to join perpendicular walls in the town of Cogotí 18 (Credits: Amanda Rivera, 2016)

The punctual reinforcements in the join of the walls are frequently founded, either in T or in L. They are wooden elements of different dimensions that are inserted between the layers of adobe in the most critical points of the construction, due to their material they give flexibility to the system which works primarily by its weight. There is a great presence of these elements, mainly with woods of reduced section that are arranged in the outer and inner part of the wall, being united by perpendicular elements of wood like a horizontal ladder. They are sometimes reinforced with a diagonal element that ties two perpendicular walls going from outside of both wall and passing trough the interior of the enclosure (Fig. 7).

The horizontal chains join elements of roof systems with raw masonry walls. They are not always present, and the importance has been verified, mainly by the contribution of the distribution of loads and the ceiling bracings, besides contributing to the unification of the system in the point of greater risk in vertical terms. The chains can be executed in different ways, the most recurrent being woods of smaller sections placed in parallel and joined by third elements in the form of a ladder laid on the top of the wall.

3.4 *Horizontal ladder culture*

The *escalerillas* are horizontal ladders that are composed of woods of different sections, which generally comprise two parallel woods of small section joined by thirds as a ladder, thus its name. These devices have also been found with woods of larger section that come to represent the height of a block. They are introduced in the points where they can generate continuity in the construction, in mezzanines, line of lintels, and in window supports. If the wood is of sufficient length it is used to replace the lintels of doors and windows. In masonry with horizontal inserts of wood, its massive and rigid character assumes a primary importance (mass and rigidity). However, the inserts give them a certain flexibility to the walls thanks to the elasticity of the wood and its resistance to the tensile forces (flexibility). In these structures the dissipation of a part of the seismic energy is due to the level of friction between the insertions and the units of masonry as well as between them, which contributes an increase to their capacity of deformation (ductility). The friction that allows the dissipation of seismic energy can be favoured by the absence of mechanical links between the wood parts and freemasonry, thus allowing a displacement in the interface planes (Hofmann 2015).

This system represents the greatest technology present in the adobe construction of the area and even after many great earthquakes has verified its efficiency in the dynamic moment. It is hard to find earthen masonry in the area without the horizontal ladders, and even in modest dwellings these horizontal ladders are present. Even when many of the others seismic strategies are not present. The most common finding is the mass and the reinforcement strategies together, but the counterforts as a stability strategy, are only present in some larger structures such as churches. Most of them are based on the horizontal ladder strategy (Fig.8-9).

4 THE "NORTE CHICO" EARTHQUAKE OF 2015

Since 1570 until the present there have been over 40 earthquakes of large magnitude, seven of which have surpassed 8Mw. The first were recorded in 1604 and 1634 both in La Serena, of unknown magnitude but with terrible and devastating consequences. Papudo earthquakes that happened in1703 had a magnitude of 8.7Mw, Valparaíso in 1822 of 8.5Mw, Vallenar in 1922 of 8.7Mw, and the last in Canela in 2015 of 8.4Mw.

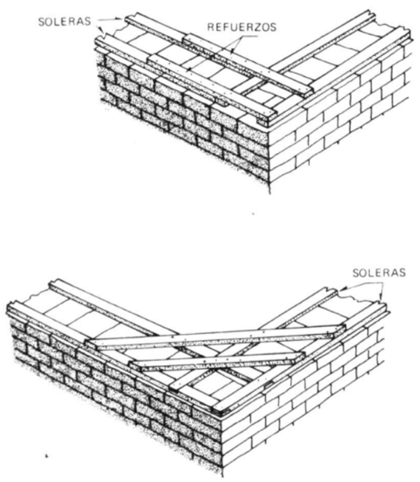

Figure 7. Wooden reinforcements in L with parallel and diagonal elements (Credits: Euclides Guzman)

Figure 8. Corazón de María church in Ovalle. Case with mass, counterforts and horizontal ladders. State after the earthquake of 2015 (Credits: Amanda Rivera, 2015)

The last big event occurred on 16th September 2015 at 22:54 UTC, which had a magnitude of 8.4Mw and a depth of 22.4km. Paradoxically it produced small damage, both to material and lives. Although the magnitude of the event is not synonymous of destructive power, it is a fact that the strength of the local construction culture is precisely one of the main factors to reduce seismic risk. The territory is expressed in its splendour and especially in the internal reinforcements that represent the horizontal wooden elements in the constructions.

The most common damages seen in the territory, during our visits ten days, one month and four months after the latest earthquake in 2015 were:

- Problems of humidity and water from the interior to the exterior of the buildings, generally in bathrooms and kitchens. This erodes the structure of the masonry walls of earth, even reaching to rot and to undo the structures of the wooden reinforcement inside the walls.
- Changes to the original configuration, great opening and in inadequate locations that weaken the structural system.
- Separation of perpendicular walls, caused by the inefficiency of the anchoring system and reinforcement of the corners, mainly due to the presence of xylophages and the rotting of wooden elements because of their Exposition.
- Absence of maintenance that provokes quickly deterioration process, the most typical the presence of excessive humidity (Fig. 10).

Other damages frequently encountered were vertical cracks at the junction of the wooden frame and the earthen mortar fill; this represents just the discontinuity between both materials, but neither a structural nor life-threatening problem. (Jorquera & Baglioni 2011)

5 CONCLUSIONS AND PERSPECTIVES

The earthquake had its epicentre on the shores of the Canela commune, Coquimbo Region. The locality of the same name was closest to the epicentre, which is why most of the post-earthquake activities have been carried out in this locality: volunteerism, seminars, earthen murals, children's workshops, the Adobe Festival, and other activities. All of these activities have helped to reinforce the culture around the construction, to relearn the constructive techniques and to promote new reinforcement methods.

The traditional constructions have survived at least four major earthquakes greater than 8Mw, but the lack of information and discontinuity of the constructive tradition have been the main threats to the preservation of the built heritage. Public policies reacting to catastrophe led to the demolition of structures by authorities without fully evaluating their state of damage, resulting in a number of families losing both their homes and their heritage.

In el "Norte Chico", due to the learning through experience of great earthquakes prior to 2015 in Chile (2005, 2007 and 2010) and to the strength of citizens' movements, protection and subsidy strategies have been implemented to repair damage built heritage in the area. Including achieving the protection of the epicentre town, Canela, as a *zona típica* by the Chilean Monuments Law, in addition to processing the same protection for at least two more important cities in the area.

The earthen construction culture of the area may not presently appear threatened, but it is of main importance to reinforce the culture and preserve the information to ensure the permanence of the built heritage of the territory, which has so much to teach the world about anti-seismic strategies.

Figure 9. Rural two-floor house in Monte Patria. Case with mass and horizontal ladders. State after the earthquake of 2015 (Credits: Amanda Rivera, 2016)

Figure 10. Rural abandoned church in Río Hurtado. Case with mass and horizontal ladders. State after the earthquake of 2015 (Credits: Amanda Rivera, 2016)

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