

SIMPLE AND EFFECTIVE SEISMIC-RETROFIT TECHNIQUES FOR EARTHEN-MASONRY BUILDINGS

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Theme 1: Latin-American Earthen Architecture at Risk: Earthquakes, Rain and Flood Damage

Keywords: Earthen masonry, stability-based retrofits, earthquake damage

Abstract

This paper describes how field studies of the seismic behavior and performance of adobe buildings following earthquakes in California, Central and South America, and shake-table tests performed in different countries have contributed to the development of appropriate and minimally intrusive stability-based retrofit measures for culturally and historically significant adobe structures, and for low-strength masonry, in general. It concludes that understanding how these buildings perform during and after earthquakes is the key to directing minimal, stability-based intervention efforts, aimed at the specific needs and structural behaviors of unreinforced-adobe buildings without compromising their historical and cultural integrity.

1. INTRODUCTION

Although earthquakes over historic time have destroyed uncountable numbers of earthen buildings and dwellings, killing and injuring hundreds of thousands people, it has only been in the last three decades that engineers and architects have systematically investigated the types of damage that occur to them, and to develop simple cost-effective techniques of reinforcement in order to mitigate the risks that millions of people who currently live in them face. It is generally assumed that adobe structures are quite vulnerable to earthquake shaking (Mehrain and Naeim, 2004; Torrealva, Vargas-Neumann, and Blondet, 2009; Webster, 2009). However, it has been observed that specific types of damage can be expected to occur, and that these can be addressed by simple, yet effective retrofit measures in order to mitigate collapse and to enhance life safety.

Field studies of seismic performance of adobe buildings have now been carried out in several countries, including: Peru, Mexico and other Latin-American countries, the US, and Iran. In addition, shake-table tests of adobe structures have been conducted in Peru, Australia, the US, and Iran, and have duplicated several of the types of damage observed in the field. Shake-table testing has also been used to study the efficacy of different reinforcing measures, generally known as stability-based retrofit techniques (GCI, 1991; 1993; Tolles, Kimbro, Webster, and Ginell, 2000; Torrealva, Vargas-Neumann, and Blondet, 2009). The principle goals of stability-based retrofit systems are to:

- 1.Ensure structural continuity of the walls by installing bond beam, tie rods, diaphragm, or some other types of continuity elements at the tops of the walls;
- 2.Prevent out-of-plane overturning of walls with either horizontal or vertical straps, or surface mesh interconnected with the top-of-wall continuity elements;
- 3.Limit relative displacement across cracks or potential cracks in the walls by through-wall ties interconnected to the horizontal and vertical straps, or the surface mesh, basically containing the earthen material.

Stability-based retrofit techniques promise to provide simple and effective life-safety measures for mitigating the vast number of deaths and injuries related to damage and collapse of earthen buildings and dwellings in seismic zones.

2. DAMAGE TYPOLOGIES

Designing effective stability-based retrofits for adobe dwellings requires knowledge of the types of structures that are typical in a specific region or country, as well as the types of damage that frequently recur to these typical structures during earthquake events and are life-safety hazards. For example, based on field reconnaissance surveys in California (Tolles, Webster, Crosby, & Kimbro, 1996), the types of damage observed that influence the seismic performance of a typical unreinforced adobe building in the United States are shown in Fig.1.

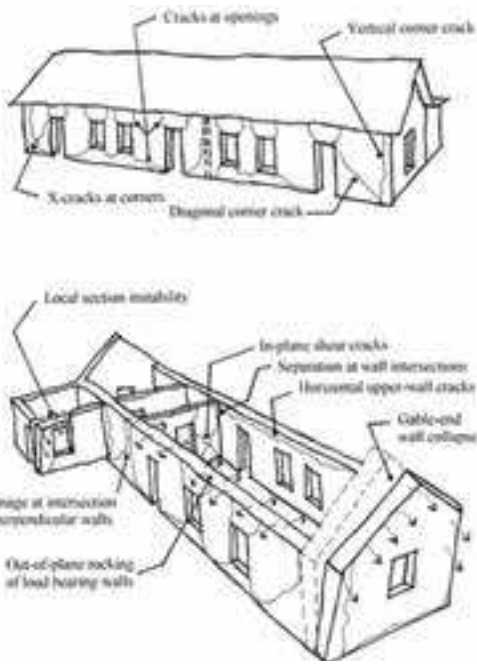


Fig.1 Typical damage observed in unreinforced adobes in the US. Illustration from Survey of Damage to Historic Adobe Buildings after the January 1994 Northridge Earthquake (credits: 1996, The J. Paul Getty Trust. All rights reserved)

2.1 Out-of-plane flexural damage

Out-of-plane damage is initiated as vertical cracks that form at the intersection of perpendicular walls. These cracks extend downward or diagonally to the base and run horizontally along the base between transverse walls. A wall can rock out-of-plane, rotating about a horizontal crack that forms at the base [Fig.2 (a) and (b)]. As a consequence, longitudinal walls pull away from the transverse walls. In many cases there is no physical connection at the intersection of longitudinal and transverse walls, having been constructed by simply abutting one wall against another.

Gable walls are taller than longitudinal walls, and usually not well supported laterally. Unless anchored to the roof diaphragm, they can slip out from underneath roof framing.

Slippage [Fig.2 (e)] of the top plate and/or displacement of the top courses of adobe blocks are another result of the out-of-plane movement of longitudinal walls. Very limited friction is generated by the dead weight of the roof bearing on the wall, and due to the friable nature of the top of the walls, slippage may occur.

Finally, vertical cracks on two perpendicular wall faces at a building corner [Fig.2 (f)] due to rocking of one or both walls results in a freestanding column at this location that is quite vulnerable to overturning and collapse.

2.2 In-plane shear cracking

X-shaped diagonal-crack damage [Fig.2 (g)] and simple diagonal cracks result from shear forces in the plane of the wall.

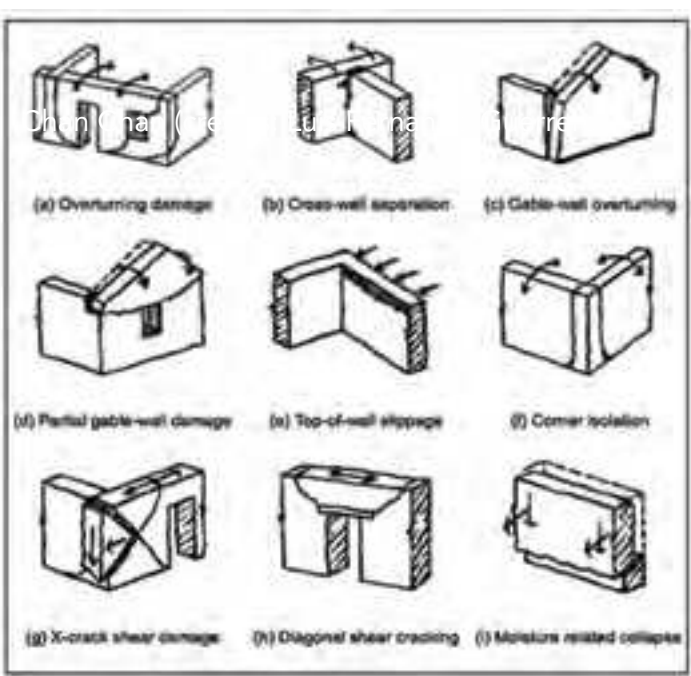


Fig.2 Typical out-of-plane and in-plane wall damage (credits: Fred Webster, 2012)

These cracks are generally not a serious threat to life safety unless the relative displacement across them is large. These cracks represent a lessening of in-plane lateral stiffness, but unless a segment of wall on one side of the crack is in danger of losing its purchase on the adjacent segment, such as at or near a corner, the gravity-load path remains intact. Diagonal cracks also occur at the corners of doorways and windows and result from peak ground acceleration (PGA) levels as low as 0.1g to 0.2g [Fig.2 (h)].

2.3 Moisture-related wall collapse

Although not the result of earthquake ground shaking, moisture in adobe walls does affect the seismic performance. This includes excessive spalling of plaster and adobe, as the wall rocks out-of-plane; instability caused by basal erosion that removes material at the base of the wall; and reduced wall strength from repeated wet-dry cycles or rising damp. If the base of the wall is wet during ground shaking, a through-wall slip plane may develop along which the upper portion of the wall can slip and collapse [Fig.2 (i)].

3. STABILITY-BASED RETROFITS

Stability-based measures in general do not stiffen the structure. In fact, they typically do not come into play until the structure has developed cracks and has moved enough to engage the seismic-upgrade elements. These measures,

however, provide reduction in the response of the building by increased damping in the structure due to sliding friction across the cracks and lowering the response frequency once cracks have formed.

The principle goals of a stability-based retrofit system are to:

- 1) Provide structural continuity;
- 2) Prevent out-of-plane overturning of walls; and
- 3) Contain the wall material.

Table 1 lists some of the more basic types of stability-based measures that have been used recently in some historic and older adobes in California, to meet these goals.

Stability-Based System Goal	Possible Retrofit Elements
Structural continuity of walls:	• Bond beam^{1,2} • Tie rods² • Continuity hardware^{3,4}
Out-of-plane overturning stability:	• Vertical straps or cables^{4,5} • Surface mesh^{4,5} • Top-of-wall pins^{1,5} • Vertical center core reinforcing^{1,5}
Containment of wall material:	• Horizontal straps or cables⁴ • Vertical straps or cables^{4,5} • Surface mesh^{4,5} • Vertical center cores^{1,5}

1. Fastened to roof structure

2. Anchored to walls

3. Straps, cables

4. Thru-wall ties

5. Connected to structural continuity

Table 1. Stability-based measures recently utilized in some California adobe buildings

3.1 Structural continuity

Probably the most significant improvement in the seismic behavior of any unreinforced-adobe building is the inclusion of structural continuity of the wall system. In the design of an effective retrofit system, providing continuity throughout the structure is the most important aspect. Adobe masonry has substantial capacity to carry compressive forces, but little or no capacity to transfer tension forces from one structural element to another.

During an earthquake, the tendency of walls that are perpendicular to the direction of shaking is to separate or tear from those walls that are parallel to the motion. This occurs at the corners of the building starting at the top, where the tearing or tension stresses are the greatest. This mode of failure has been seen time and time again in both shake-table testing and in damage surveys following earthquakes (Scawthorn and Becker, 1986; Tolles et al., 1996; Dowling, Samali, and Li, 2005).

Providing structural-continuity elements, such as horizontal straps, tie rods, or a bond beam that is anchored to the wall [see Fig.3: (a), (b) and (c)], very effectively resists these wall-separation forces and keeps them from overturning, and thereby stabilizes

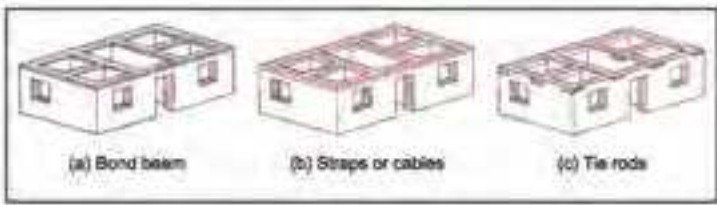


Fig.3 Structural-continuity elements (credits: Fred Webster, 2012)

the structure. It should be noted that for any of these elements to work properly, they must be fastened to the roof structure, and because of the friable nature of the masonry at the top of the wall, anchored down into the wall with rods or pins that engage more of the wall than just the top few courses. Note also that for the strapping or cable-continuity hardware to work, the straps on the inner and outer surface of the wall must be interconnected with through-wall ties.

3.2 Overturning stability

When discussing overturning stability of earthen-masonry walls, it is important to recognize the influence of the thickness of the walls and their inherent stability, or lack thereof. The dynamic out-of-plane motion of thin walls is significantly different from that observed in moderate and thick walls. At tests on the shake table at Stanford University (Tolles et al., 2000), thin walls (height-to-thickness ratio of 11) easily rocked about their base, the principal lateral support being provided by the bond beam. This behavior was not observed in walls of moderate thickness (height-to-thickness ratios of 7.5 and 5) with the same bond beam; the thickness of the wall did not permit easy rocking about the base, which significantly affected the dynamic motion of the walls. The out-of-plane motion at the tops of the walls was not amplified as it was in thinner walls.

Providing resistance to out-of-plane overturning cannot be separated from the structural continuity of the walls that are addressed in Section 3.1. However, to enhance the stability and survivability of the structure, a system of vertical straps or a surface mesh can be applied to the adobe walls [see Fig4: (a) and (b)].

Vertical straps of nylon or some other flexible durable material, when combined with through-wall ties and structural continuity, even though not providing any stiffening of the wall, are simple to install and work to enhance the stability of thin adobe walls. Center-core rods [Fig.4 (c)], on the other hand, are difficult and relatively expensive to install. Where they are most useful is in the application to historic adobe structures where the wall surfaces may be rendered with artwork that needs to be preserved. Center-core rods, when set in an epoxy grout, stiffen the wall significantly, as well as provide limitation on the relative displacement across cracks that form during the shaking. Surface mesh of chicken wire, welded-wire fabric, or some synthetic material such

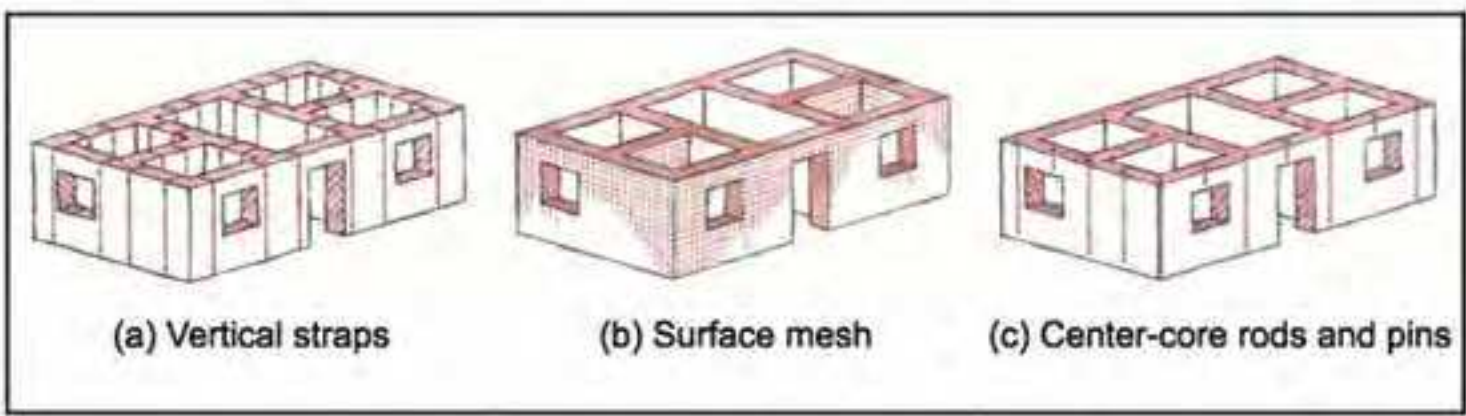


Fig.4 Overturning stabilization (credits: Fred Webster, 2012)

as polypropylene (geo-grid), when through-wall tied and attached to the structural continuity elements, act in similar fashion as the vertical straps against overturning.

3.3 Containment

Containment of the wall material is probably the second most important feature of seismic retrofit of earthen masonry. If the wall material can be contained so that it does not fall from the plane of the wall during a seismic event, it will continue its function of holding up the roof. Even in a severely cracked condition that may occur, adobe is still capable of transferring compressive forces as long as it is contained [see Fig.4 (b) and Fig.5].

Testing of an adobe structure on the shake table at University of California at Berkeley in the 1980s retrofitted with a wire mesh showed the efficacy of such a simple containment system (Scawthorn and Becker, 1986). The idea was then expanded by researchers at the Catholic University of Peru and tested in many different configurations, focusing recently on geo-grid meshes of polypropylene (Blondet, Vargas, Velasquez, & Tarque, 2006). These efforts have also been developed into engineering-design guidelines for new adobe structures (Torrealva, 2009).

During the 1990s, the Getty Conservation Institute sponsored shake-table testing of adobe structures at Stanford University in California (Tolles et al., 2000) and at the Institute of Earthquake Engineering and Engineering Seismology in Macedonia (Gavrilovic, Sendova, Taskov, Krstevska, Tolles, and Ginell, 1996). One of the focuses of these tests was containment with minimal intervention such as vertical and horizontal straps and center-core rods, whereas the mesh solution is more invasive, but does a better job of containment. As a practical matter, therefore, the straps and center-core rod elements are more appropriate for use with historically significant and/or culturally sensitive structures, whereas, the mesh solution to retrofitting and new construction of adobe masonry may be the simplest and most effective overall.

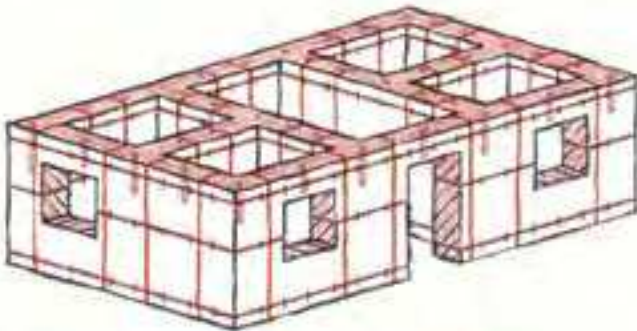


Fig.5 Containment with horizontal and vertical straps and top-of-wall pins (credits: Fred Webster, 2012)

4. CONCLUSIONS

The information obtained during field study of the seismic behavior and performance of historic and older adobes following earthquake events is invaluable to the development of appropriate and minimally intrusive stability-based retrofit measures. Categorization of the types of damage allows an evaluation of the causes and hazards of such damages and has been the basis for development and implementation of effective retrofit measures for earthen masonry in California and elsewhere. Indeed, this information, in conjunction with the shake-table test results, has been the basis for design of appropriate seismic-retrofit measures that ensure life safety, while protecting historic fabric and cultural value.

The challenge of improving the structural performance and mitigating life-safety hazards of adobe buildings, both old and new, for future earthquakes is great. The key is to understand how these buildings perform, and to direct stability-based minimal interventions toward specific needs of known structural behavior. We can, in fact, improve the performance of earthen-masonry buildings without significantly compromising the existing architectural heritage embodied in these resources, and do so both simply and effectively.

References

Blondet, M., Vargas, J., Velasquez, J., & Tarque, N. (2006). Experimental study of synthetic mesh reinforcement of historical adobe buildings. In: *Proceedings of the 5th International Conference, Structural Analysis of Historical Constructions*. New Delhi, 6-8 November 2006. New Delhi, India: Macmillan India Ltd., pp. 709-716.

Dowling, D., Samali, B., & Li, J. (2005). An improved means of reinforcing adobe walls – external vertical reinforcement. In: M. Blondet (ed) *SismoAdobe 2005: Architecture, Construction and Conservation of Earthen Buildings in Seismic Areas*. 16-19 May 2005, Lima, Peru: Pontificia Universidad Católica del Peru. [CD]. Available at: <http://www.pucp.edu.pe/eventos/SismoAdobe2005>.

Gavrilovic, P., Sendova, V., Taskov, L., Krstevska, L., Tolles, E.L., & Ginell, W. (1996). Shaking table tests of adobe structures. *Report IZlIS 96-36*. Skopje, Republic of Macedonia: Institute of Earthquake Engineering and Engineering Seismology. Los Angeles, USA: Getty Conservation Institute.

Getty Conservation Institute (1991). *GSAP - Getty Conservation Institute Guidelines for the Seismic Retrofitting of Adobe Project: Report of First Year Activities*. Marina del Rey, USA: The Getty Conservation Institute.

Getty Conservation Institute (1993). *GSAP - Getty Conservation Institute Guidelines for the Seismic Retrofitting of Adobe Project: Report of Second Year Activities*. Marina del Rey, USA: The Getty Conservation Institute.

Mehrain, M. & Naeim, F. (2004). Housing Report - Adobe House. *Report No. 104, World Housing Encyclopedia*. Berkeley, USA: Earthquake Engineering Research Institute. Available at: <http://www.world-housing.net>.

Scawthorn, C. & Becker, A. (1986). Relative benefits of alternative strengthening methods for low strength masonry buildings. In: *Proceedings of the 3rd U.S. National Conference on Earthquake Engineering*. Charleston, South Carolina 24–28 August 1986. Oakland, USA: Earthquake Engineering Research Institute, pp. 2023-34.

Tolles, E.L., Webster, F.A., Crosby, A., & Kimbro, E.E. (1996). Survey of damage to historic adobe buildings after the January 1994 Northridge earthquake. *GCI Scientific Program Reports*. Los Angeles, USA: Getty Conservation Institute. Available at: http://www.getty.edu/conservation/publications/pdf_publications/adobe_northridge.pdf.

Tolles, E.L., Kimbro, E.E., Webster, F.A., & Ginell, W.S. (2000). Seismic stabilization of historic adobe structures: final report of the Getty Seismic Adobe Project. *GCI Scientific Program Reports*. Los Angeles, USA: Getty Conservation Institute. http://www.getty.edu/conservation/publications/pdf_publications/seismicstabilization.pdf.

Torrealva, D., Vargas-Neumann., J., & Blondet, M. (2009). Earthquake resistant design criteria and testing of adobe buildings at Pontificia Universidad Católica del Perú. In: *Proceedings of the Getty Seismic Adobe Project 2006 Colloquium*. Los Angeles, California 11-13 April 2006. Los Angeles, USA: Getty Conservation Institute, pp. 3-10. Available at: http://www.getty.edu/conservation/publications/pdf_publications/gsap_part1a.pdf.

Torrealva, D. (2009). Diseño sísmico de muros de adobe reforzados con geomallas. Lima, Perú: Departamento de Ingeniería, Pontificia Universidad Católica del Perú.

Vargas-Neumann, J., Bariola-Bernales, J.J., Blondet, M., & Mehta, P. K. (1984). *Resistencia de la mampostería de adobe*. No. DI-84-01. Lima, Peru: Departamento de Ingeniería, Pontificia Universidad Católica del Perú.

Webster, F.A. (2009). Application of stability-based retrofit measures on some historic and older adobe buildings in California. In: *Proceedings of the Getty Seismic Adobe Project 2006 Colloquium*. Getty Center, Los Angeles, California 11-13 April 2006. Los Angeles, USA: Getty Conservation Institute, pp. 147-158. Available at: http://www.getty.edu/conservation/publications/pdf_publications/gsap_part4a.pdf.

EARTHEN-BUILDING CULTURES AND SEISMIC HAZARD: CHILEAN TRADITIONAL ARCHITECTURE

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Theme 1: Latin-American Architecture at Risk: Earthquakes, Rain and Flood Damage
Keywords: Building culture, earthen-architecture, seismic hazard

Abstract

This article will disclose the partial results of a doctoral thesis developed between 2009-2012 within the Department of Technology of the Faculty of Architecture of the University of Florence. The final results, were presented during TERRA 2012 conference. The core aim of the thesis is the seismic-risk assessment of different building cultures in Chilean territory that use earth as the predominant building material, in order to propose retrofitting techniques to reduce the threat. The research is inserted within the context of recent major earthquakes that have affected Chile, which have been particularly destructive to earthen buildings, raising the need to develop preventive actions to preserve this relevant heritage.

1. PRESENTATION OF THE RESEARCH

1.1 Introduction

Two thirds of the Chilean territory have abundant earthen architectural buildings, both in rural and urban areas, from the north (lat. 18, 11’S) until the beginning of the Bio-Bio Region (lat. 36 8’S), down to the south, i.e. between latitudes, where arid-dry and Mediterranean temperate climates prevail. This long building tradition dates back to pre-Columbian times, when earth was used as molded earth in highland regions of northern Chile (1), and with the *quincha* technique by indigenous people of the central region. The use of adobe, introduced with the Inca conquest of the Northern Territory in the late 15th century, was greatly expanded during the period of the Spanish colonization (16th-19th centuries), when the technique became virtually the only building system used for founding cities. Mixed systems, meanwhile, were developed from the 19th century onwards, incorporating wood, aimed at gaining height, slimness, formal expression and better seismic-resistant behavior, relegating adobe to in-filling of walls. The long tradition of using earthen construction materials experienced a decline in post 1940s, following the earthquakes of Talca in 1928 and Chillan in 1939 in the southern central region of Chile. Historic adobe buildings were blamed for the numerous deaths. As a result of both disasters, the first General Regulation for Urban Planning and Construction (1929) and seismic-resistant regulations (1940) were created, respectively. Both regulations abolished the use of earth as building material,

leading to the massive use of industrial constituents, and to the consolidation of modern architecture. Since then, earthen construction has diminished but not disappeared altogether. Nowadays in Chile, there is still an important presence of earthen monuments (churches, factories), and a large number of houses, mostly inhabited, that constitute settlements of architectural and environmental significance. According to the analysis made by Karmelić (2009) based in the Inventory of Cultural Heritage Property (2001) prepared by the Ministry for Public Works, it is estimated that 40% of the Chilean architectural heritage is built of earth, mainly adobe (Karmelić, 2009, p. 212). This number is significant when taking into consideration the high seismic activity that characterizes the Chilean territory, which has propelled the development of seismic-resistant techniques throughout history.

1.2 State of the art

Despite being a rather anonymous architectural heritage, little researched and the focus of ever greater criticism after each earthquake, in present-day and subsequent the earthquake of February 2010, there has been an interesting process of appraisal of the traditional architecture built of earth, recognizing that this is an important part of the Chilean identity (Ministry of Public Works (2010). This process has contributed the following factors: