Earthen Construction: Structural Vulnerabilities and Retrofit Solutions for Seismic Actions

Oliveira, C. F.
Universidade de Aveiro, Aveiro, Portugal

Varum, H.
Universidade de Aveiro, Aveiro, Portugal

Vargas, J.
Pontificia Universidad Católica del Perú, Lima, Peru

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ABSTRACT:
Earthen structures present very appealing characteristics regarding a more sustainable practice with the preservation of our natural resources. However, when subjected to earthquake ground motions, this type of construction may present a deficient performance, which may cause significant human losses and important structural damage. The seismic response of earthen structures is typically characterized by fragile failures. There are several examples of recent earthquakes that affected earthen buildings in a severe way, evidencing the vulnerability of this type of construction, like the El Salvador earthquake, in 2001, the Bam, Iran earthquake, in 2003, the Pisco, Peru earthquake, in 2007 and the Maule, Chile earthquake, in 2010.
The construction of earth structures on earthquake-prone areas must be carefully studied and should include seismic reinforcement solutions in order to improve their seismic performance.
In this paper, the performance of earthen structures in recent earthquakes will be examined, analyzing failure modes inherent to these particular construction materials and associated construction techniques. Also, seismic reinforcement approaches and techniques will be presented in a comprehensive manner. Examples of tests conducted for the assessment of retrofitting solutions efficiency will be presented, and the results obtained will be discussed.

Keywords: earth construction, adobe, rammed earth, seismic vulnerability, seismic strengthening

1. INTRODUCTION

Earth has been used in construction since ancient times due to cultural, climatic and economic reasons. In fact, this kind of materials presents qualities such as low cost, thermal and acoustic insulation, local availability and recyclability, which allow a more sustainable construction practice, with the preservation of our natural resources. In addition, this type of construction is associated to quite simple construction methods that require small quantities of energy. Currently, one third of the world population lives in earthen houses [Minke, G.; 2003], as a result of cultural, climatic and economic reasons. Large percentage of these buildings is currently associated to rural populations with low economic resources. There is a vast architectural heritage stock, mainly in developing countries, which needs to be preserved. From the places and monuments classified as World Heritage, 10% are entirely or partially built in earth, and 16% of the ones that are in the list of heritage at risk are also built in earth [ICOMOS, 2003].

However, this type of material presents low tensile strength and fragile behaviour, and can thus cause a deficient response to horizontal actions. Particularly when subjected to earthquake ground motions, earth constructions can suffer severe structural damage and eventually total collapse, with significant human losses. The seismic behaviour of earthen structures is typically characterized by fragile failures [Tolles, E.; Krawinkler, H; 1990]. There are several examples of recent earthquakes that affected earthen buildings in a severe way, evidencing the vulnerability of this type of construction, like the El Salvador earthquake, in 2001, the Bam, Iran earthquake, in 2003, the Pisco, Peru earthquake, in 2007 and the Maule, Chile earthquake, in 2010.

Being related to traditional construction, the existing knowledge concerning earthen construction is still mainly empirical. Few countries have codes for the rehabilitation and building with earth, and the existent codes are frequently incomplete [Delgado, M., Guerrero, I.; 2007]. On the other hand, the study of earthen structures has been mainly oriented towards the architectural and historical aspects, while the material and structural characterization has been systematically relegated to a second plan. In addition, buildings are generally constructed and rehabilitated by non-specialized staff and normally do not consider appropriate behaviour improvement solutions.

Earth construction continues to be used in places with high seismicity which shows the urgent need to develop means of improving the seismic behaviour of these structures [De Sensi, 2003].

In order to provide an adequate stability and resistance to earth structures, it is necessary to complement the utilization of the traditional construction materials and techniques with innovative and inexpensive tools for repair, strengthening and retrofit which may allow reducing the seismic vulnerability of this type of constructions. It is necessary to conduct research on retrofit and performance enhancement solutions.

Nevertheless, important research work has been conducted on the characterization of earth buildings behaviour under horizontal actions and on the development of seismic reinforcement design. The Civil Engineering Department of Aveiro University, in Portugal, has been developing several scientific studies on the behaviour of adobe structures since 2005, concerning structural properties of adobe and its constituting materials, such as composition, resistance and stiffness, ductility, energy dissipation capacity and collapse mechanisms ([Arêde et al.; 2007], [Silveira et al.; 2007], [Varum et al.; 2008], [Varum et al.; 2005]).

A research group from Catholic University of Peru (PUCP) has been performing an important role on the knowledge acquisition on earthen constructions behaviour and on the development of reinforcement solutions against earthquakes. Part of the significant work developed by this research group in the last 35 years is reported in detail in [Vargas et al.; 2005]. Collapse modes of adobe blocks have been characterized through experimental tests [Corazao and Blondet, 1973]. In addition, several reinforcement solutions have been studied with real-scale shaking table tests. Geosynthetic, plastic or metallic meshes were evaluated for seismic retrofit of existing adobe constructions [Blondet et al.; 2004]. The use of vertical canes, horizontal ropes and enveloping plastic meshes was compared and assessed [Torrealva, D.; Acero, J.; 2005]. The performance of adobe vaults with and without reinforcement was also investigated [Torrealva et al.; 2006].

Other works have also been providing important information on the theme [Dowling et al.; 2005], [Noguez, R.; Navarro, S.; 2005], [Rodriguez et al.; 2003], [Zavala, C.; Igarashi, L.; 2006].

2. PERFORMANCE OF EARTHEN STRUCTURES UNDER SEISMIC ACTIONS

Earthen structures, if not properly reinforced, can present a deficient response to seismic actions, due to inherent material properties such as high mass, limited tensile strength, fragile behaviour, and softening and loss of strength upon saturation. When under seismic actions, these structures can suffer severe and cumulative structural damage and collapse, causing innumerable human and material losses. The statistics on losses caused by recent earthquakes, in regions where constructions are mainly made of earth, clearly attest the deficient behaviour of these structures.

In 2001, two earthquakes occurred in El Salvador (January, 13 and February, 13), with momentum magnitudes (Mw) of 7.7 and 6.6, causing severe damage, or even collapse, on 200.000 adobe houses, and the loss of 1100 lives [Blondet, M. et al.; 2003]. In the same year, Peruvian regions of Arequipa, Moquegua and Tacna were affected by an earthquake with a momentum magnitude of 8.4 causing the destruction of 36.000 houses, 25.000 of which were made of adobe, and the death of 81 people [Blondet, M. et al.; 2003]. In 2003, Bam earthquake with a momentum magnitude of 6.6, caused damage or collapse in 70% of the houses in Bam, destroying the earthen citadel of Arg-e-Bam, an important ancient historical monument [Blondet, M; Aguillar, R.; 2007].

In 2007, another earthquake was felt in the coast of Peru, 169 km southeast of the capital, Lima. Its magnitude reached 8 degrees on Richter scale, causing the partial or total destruction of approximately 38.000 dwellings, the majority of which made of adobe, and causing 500 casualties.

At the present time, a large part of the existing earth constructions is located in regions where seismic hazard cannot be disregarded, namely in Southern Europe, Western North and South America, Central America, some regions of Africa, Southern Asia, and Australia [De Sensi; 2003]. Seismic reinforcement techniques are required to improve structural performance and consequent reduction of damages and casualties.

The failure of non-reinforced adobe structures due to seismic actions is a brittle failure. The small tensile resistance of the masonry causes the failure of the connection of the walls in the corners, starting in the upper part. This isolates the walls from each other and conducts to a loss of lateral stability, causing the collapse of the wall out of the plane. If the corners failure is controlled, than the walls can support horizontal seismic forces in its plane. The second type of failure that occurs is due to shearing force. In this case, the typical inclined cracks of diagonal traction appear.

Figure 1 shows adobe and rammed earth models with no seismic reinforcement tested in PUCP facilities, on the shaking table. In the adobe model, it is possible to see vertical out-of-plane cracks in the corners, which correspond to the failure of the connections between walls, and in-plane diagonal cracks, relative to shear failure. The rammed earth model presents different crack patterns more concentrated next to the model corners.

a) **b)**

Figure 1 – Experimental tests of unreinforced earthen models: a) adobe house, b) rammed earth house (credits: [Zegarra, L. et al.; 1997])

3. SEISMIC REINFORCEMENT SOLUTIONS (performance based design criterion)

Walls are the fundamental structural elements in earthen buildings. Earthquakes cause the sudden formation of cracks in the earthen walls at the beginning of any ground motion. Adequate seismic reinforcement solutions are needed to assure the safety of earthen construction by controlling the displacements of fissured walls. Furthermore, due to the fact that the large majority of earthen dwellings are located in developing countries, the implementation of low-cost seismic strengthening solutions using widely available materials is crucial.

Several studies to achieve this goal have been conducted, especially for adobe structures (e.g. [Blondet, M. et al.; 2005], [Memari, A., Kauffman, A.; 2005]). The main objectives of the developed strengthening or reinforcement schemes are to assure a proper connection between construction elements and how to reach global stability behaviour.

Before presenting seismic reinforcement solutions (performance based design criterion), it is important to mention one simple and effective method for structural rehabilitation in general, also valuable for seismic retrofit: injection of grouts in earthen constructions (strength based design criterion).

Grout injection is one of the most common consolidation and strengthening techniques applied to masonry walls [Silva, R. et al.; 2009], and can also be an interesting solution for earthen constructions. Other traditional techniques used to repair cracks in earthen constructions are very disturbing and intrusive when compared to grout injection. This could be, however, a non-reversible technique, which can originate durability and compatibility problems if non-suitable materials are chosen to compose the grout [Silva, R. et al.; 2009], particularly for earthen structures [GCI; 2008]. Earthen grouts could be good enough to get a restitution of the low tensile strength of earthen construction.

The improvement of the mechanical behaviour requires a fluid grout with very good penetrability and bonding properties, while durability requires the development of a microstructure as close as possible to the microstructure of the existing materials. Currently, a design methodology for grout injection of earthen constructions is trying to be developed [Blondet, M. et al.; 2007], which could represents an important step forward in the repair of these structures. However, mechanical injection techniques are not totally yet developed.

On the other hand, strength based design criterion is usually only a complementary support of a performance based design criterion. Injection is good, but not good enough. Earthquake engineering needs ductility to dissipate seismic energy and this requires reinforcement.

3.1 Cane or timber internal reinforcements

This type of reinforcement consists of placing an internal grid, with vertical and horizontal elements, able to bond efficiently with the structure, improving its seismic performance (see example in Figure 2). The vertical elements should be conveniently anchored to the foundation and to a collar beam on top of the walls. The spacing of the vertical or horizontal elements should be such to provide an efficient connection to the structure. [Blondet, M.; Aguillar, R.; 2007] provides design rules for these reinforcements. Bamboo canes or eucalypt dry timber is recommended for these reinforcements [SENCICO; 2000]. It should be noted that this type of reinforcement can only be done in new constructions.

Figure 2 - Internal cane mesh reinforcement (credits: [Vargas et al.; 2005])

However, the placement of the horizontal layers should be carefully carried out, as these can become weak points, which, under seismic forces, can cause horizontal cracks. In the case of rammed earth, it is difficult do compact the earth near the reinforcement, while for adobe structures, in order to provide an effective bonding, mortar thickness between two rows of adobe blocks, with reinforcement in between, can become larger than desirable [Minke, G.; 2001]. Laboratory tests proved that high thickness mortars correspond to less wall masonry strength.

Full-scale shaking table tests were conducted with adobe houses using this kind of reinforcement, demonstrating a good response to save lives [Blondet et al.; 1988]. The model reinforced with an internal cane mesh suffered significant damage, but did not collapse. A major restraint in using this strengthening solution is the fact that cane or adequate timber is not available in all seismic regions [Blondet, M.; Aguillar, R.; 2007].

3.2 Cane external reinforcement

For repair or seismic retrofit of existing structures, an external reinforcement using a grid of canes and ropes can be a good solution. Canes are placed vertically and externally to the wall, on both sides, inside and outside. Ropes are then positioned horizontally tying the vertical canes along the walls and involving the structure. Different rows of horizontal ropes are placed along the height of the wall with a spacing of 30~40cm. In order to connect the two grids, outside and inside grids, and thus confine the earthen structure, small extension lines are placed connecting the two grids, crossing the wall from one side to another through holes, made at each 30~40cm. This reinforcement grid can then be covered with plaster for adequate finishing, providing at the same time more confinement to the earth structure.

Figure 3 shows an example of this type of reinforcement applied to a real-scale model tested in PUCP, where only part of the structure was covered with plaster.

The main limitation of this type of reinforcement is the fact a great quantity of cane is required. As cane is not available in all regions, industrial material must be studied and tested.

Figure 3 - External cane-rope mesh reinforcement (credits: [Torrealva y Acero et al.; 2005])

3.3 Reinforced concrete as internal reinforcements

This technique consists of building first the adobe walls with gaps in the corners, or connections with other walls to be filled by concrete. Steel bars are then placed and the concrete is poured in order to form a confined system with columns and collar beam. This solution is rather expensive, conducting to a high stiffness system with low ductility [Minke, G; 2001]. Furthermore, important collapses in earthen construction with reinforced concrete elements were reported, implying that this can be an inadequate reinforcement solution, though more studies on the subject are required. Figure 4 shows examples of collapses after reinforcement using concrete: Tarapaca Cathedral, Iquique earthquake, 2005, Chile and San Luis de Cañete Church, Pisco earthquake, 2007, Peru. In Tarapaca Cathedral, the bending of the reinforced concrete beam destroyed completely the main adobe wall with 1.30m of thickness. In San Luis de Cañete Church, the frames of reinforced concrete changed the behaviour of the structure and unfilled adobe walls were overturned.

a)

b)

Figure 4 – Examples with collapses after reinforcement using concrete: a) Tarapaca Cathedral, Chile, 2005 [Chesta, J; 2005] b) San Luis de Cañete Church, Peru, 2007 (credits: [Vargas, J. et al.; 2007])

3.4 Synthetic mesh strengthening systems

Reinforcement solutions with synthetic meshes (geogrids) involving the walls have been studied and tested, proving its applicability, simplicity and efficiency. Figure 5 show examples of application. In [Oliveira, C. et al.; 2010], real-scale tests of adobe walls with and without reinforcement were tested and compared. The solution for filling the wall cracks (injection of hydraulic lime grout) combined with the strengthening solution (synthetic mesh incorporated in the plaster) proved to be very effective. Figure 6 shows the comparison between walls. The tests on the retrofitted wall demonstrated that the lateral strength increased slightly, and the ductility and the energy dissipation capacity improved significantly. The wall was able to recover its initial stiffness.

a) b)

Figure 5 – Synthetic meshes in adobe structures: a) [Oliveira. C. et al.; 2010]; and, b) [Blondet, M.; Aguillar, R.; 2007]

In [Blondet, M. et al.; 2006], several similar full-scale adobe housing models with different amounts and types of synthetic mesh were tested in a shaking table. The results showed that the damage decreased as the amount of synthetic mesh placed involving the walls increased. In [Vargas, J. et al.; 2007], the use of geogrid in adobe constructions is extensively explained, with comprehensible details on how to cut and place the grid with the objective of improving seismic performance.

The use of synthetic mesh bands involving the adobe walls and covering them with cement mortar is also possible. The mesh is placed in horizontal and vertical strips, following a layout similar to that of beams and columns. This solution is able to provide additional strength to the structure, though the failure mode observed was brittle and dangerous [Blondet, M.; Aguillar, R.; 2007]. The use of cement also makes this an expensive solution.

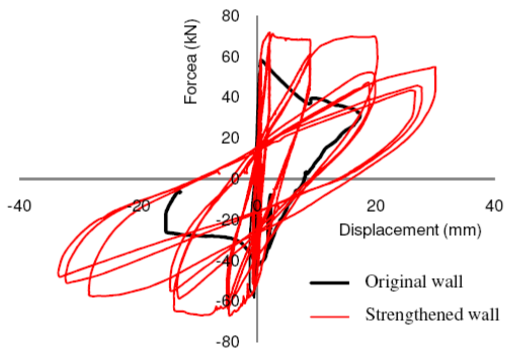

Figure 6 – Adobe wall tests: Horizontal force versus displacement - original and strengthened wall ([Oliveira, C. et al.; 2010])

3.5 Base Isolation

Earthen constructions are ideal candidates to be seismically protected with base isolation. This is an innovative strategy that has been adopted for monumental masonry buildings, since it does not involve great interventions on the upper structure [Guerreiro, L.; 2006]. It decouples the horizontal movement of the building from the horizontal ground motion. This causes a decrease in the fundamental frequency of the structure, consequently reducing the seismic force demand. The adaptation of this system for earthen construction will be of great value. However, the application of this technique for repair and seismic retrofit may be complex as the stability of the structure must be assured while the connection to the foundation is removed and substituted by base isolation bearings.

4. CONCLUDING REMARKS

Earth construction is one of the oldest and most widespread construction materials in use, due to its unique properties and accessibility. In spite of its appealing characteristics, earth construction present important structural fragilities. These structures have brittle failure with low tensile resistance, showing a deficient behaviour under seismic actions. Currently, in many of the high seismicity places zones in the world, earth is the only affordable type of construction material. It is well known the lack of official dissemination or educational programmes to change the rural population costumes to build without reinforcements. Furthermore, it is hard to change construction habits from generations that have gained cultural roots in the population. It is urgent to develop, disseminate and apply low-cost and effective reinforcement techniques.

Presently, there are several reinforcement solutions possible to apply in order to improve their structural performance and to prevent their collapse during earthquakes. However, these techniques are still not established in worldwide standards and regulations. It is urgent to conduct an effective dissemination of available successful seismic reinforcement solutions, with information spread to the populations through education and standards, as well as the description of the behaviour of earthen structures under seismic actions.

In this paper, an overall view of the behaviour of earthen structures under seismic actions is presented along with seismic reinforcement solutions techniques already developed and tested.

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