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SEISMIC BEHAVIOR AND REHABILITATION ALTERNATIVES FOR ADOBE AND RAMMED EARTH BUILDINGS

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SUMMARY

Approximately one fifth of the world's population and some 35 million people in South America inhabit adobe and rammed earth constructions. These buildings have demonstrated poor seismic behavior in earthquakes occurred over the last 50 years all around the world generating thousands of casualties. In addition a large number of historic and cultural earth built constructions are located on high seismicity zones. The current lack of knowledge of the behavior and characteristics of this type of constructions has led to a poor development of innovative seismic retrofit alternatives. Therefore, the development of technical, economical, aesthetical and functional retrofit alternatives for the preservation of this heritage is urgently required.

This paper summarizes the main results of a research project carried out to determine the main characteristics and mechanical properties of the structural elements that conform the earth made constructions, and to propose seismic rehabilitation alternatives according to the seismic hazard and characteristics of this kind of structures in Colombia. The proposed seismic rehabilitation alternatives consist of reinforcement with wire mesh covered with lime based mortar, and confining reinforcement with wooden elements. These alternatives were subjected to a series of tests on small specimens, full scale walls loaded on both directions, shaking table tests on 1:5 scale models and cyclic horizontal loading on 1:1.5 house models. The results of the research allow to establish advantages and disadvantages for the rehabilitation alternatives studied. Its found that, in spite of the high seismic vulnerability of these construction systems, the confining reinforcement with wooden elements was found to be a promising alternative for the seismic retrofit for this type of constructions.

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INTRODUCTION

Most of the buildings in the Spanish colonial period were built in adobe and/or rammed earth masonry. The materials for the construction of churches and houses at that time were limited to those available in the region and were usually worked by local workmanship. As a result of the age, design and functions, the adobe and earth wall buildings are structures of historic type and represent an important cultural legacy within the communities. The high seismic vulnerability of this architectural heritage has been clearly identified, as much as many of these structures have been repaired or rebuilt several times in the same place where the preceding structure was destroyed by an earthquake. With the occurrence of earthquakes in the world, structures built with these materials have shown to have a poor behavior, most of them collapsing even with moderate magnitude earthquakes, resulting most of the time in loss of human lives and large economic, cultural and patrimonial losses.

The reduction of seismic vulnerability in historical and cultural buildings involves further considerations to rehabilitation process of conventional buildings, such as the need to preserve as much as possible, the historical and cultural features of the same.

EXPERIMENTAL PHASE

A general characterization was carried out of the mechanical properties of the materials used in earth constructions concerning weight and strength according to the different stress solicitations. In the first stage of the experimental phase characterization tests were developed (compression, diagonal tension, flexure, etc.) to determine the properties relating the mechanical behavior of adobe and rammed earth walls. In addition, reduced scale tests were made to verify that corresponding properties were similar to those resulting from real scale tests. Figure 1 shows photographs diagonal tension tests on real scale and reduced scale (1:5) wallettes.

Figure 1.
Diagonal tension test on real scale (left), and reduced scale wallettes (right).

Table 1 summarizes typical mechanical properties obtained.

Table 1.
Mechanical properties obtained

Parameter	Units	Real scale		1:5 Scale	
		Adobe	Rammed Earth	Adobe	Rammed Earth
Density	Ton/m³	1.80	1.92	1.87	1.82
Elasticity modulus	kgf/cm²	1170	800*	1305	602
Rigidity modulus	kgf /cm²	302	315	179	109
Compression strength	kgf /cm²	12.2	3.3	15.8	7.12
Shear strength	kgf /cm²	0.31	0.37	0.8	0.6
Flexural strength	kgf /cm²	-----	0.15	0.23	0.28

From the results obtained in the characterization tests it was observed that the main mechanical properties of the materials do not change considerably with the scale of test, except for the cases where self weight of the sample affects the results. It is clear that in these cases the strengths measured in reduced scale models shall give larger values compared with the corresponding real scale parameters.

In addition to material characterization tests developed on wallettes, real scale adobe and rammed earth walls (2.5m long, 2.0m high and 0.5m wide) were constructed to determine the behavior of main structural elements (bearing walls) in buildings constructed with traditional techniques.

In-plane tests were developed on full scale walls applying cyclic loading on the upper part of the specimen (Figure 2). These tests allow estimating the in-plane properties of the walls under cyclic loading, such as initial rigidity and degradation of the rigidity with horizontal deformation, maximum horizontal capacity for different levels of vertical loading, ductility, residual shearing strength after first failure and an estimate of energy dissipation and damping capacities. A total of six (6) cyclical in-plane loading tests were performed on adobe and rammed earth walls with different levels of vertical loading. The vertical loads applied correspond to typical load acting on bearing walls for one and two story buildings.

Figure 2.
In-plane cyclic loading Test

Most of the failures related to adobe and rammed earth buildings have been caused by a combination of shearing stresses in the wall plane and bending stresses perpendicular to the wall under seismic action. To determine the out-of-plane flexural capacity of real scale wall, overturning tests were developed. In those tests an increasing load perpendicular to the wall is applied by a progressive inclination of the sample maintaining a constant vertical load over the wall. To simulate the effect generated by the walls in the orthogonal direction of the tested wall, reduced walls of the same materials were constructed on each side of the tested wall. Figure 3 shows a photograph of general setup of out-of-plane loading test.

Figure 3.
Loading test perpendicular to the plane

In order to study the simultaneous effect of in-plane and out-of-plane cyclic action, two adobe reduced scale modules were constructed (1:5 and 1:1.5 scales). The 1:5 scale model (Figure 4) was subjected to a shaking table test by using a seismic record characteristic of an earthquake corresponding to Colombia's central region. During the test the maximum acceleration was gradually increased until failure. In addition, the 1:1.5 scale model was tested by means of an applied cyclic load at roof level simulating inertial effects generated over the bearing walls.

Figure 4.
1:5 scale models tested on shaking table and 1:1.5 scale models tested with applied cyclical loading

From the results obtained in the wallettes, reduced scale and full scale wall tests it can be concluded that buildings constructed with traditional techniques present low capacity to resist stresses and deformation imposed by seismic events, and therefore these constructions are classified in general as highly vulnerable.

SEISMIC REHABILITATION ALTERNATIVES

Considering that adobe and rammed earth buildings in Colombia are subjected to high seismic hazard and are vulnerable to this type of events, it's necessary to develop strengthening or rehabilitation alternatives which consider no only the technical aspects related to the materials behavior but the socioeconomic conditions and the historical and cultural character of these buildings. It is intended, therefore, to preserve at the most the original architecture, by using as much as possible, similar or compatible materials with the original ones. The main objective of the strengthening alternatives proposed is to reduce the seismic risk to which these buildings are subjected. It is intended to avoid the collapse of the building during the earthquake in order to preserve the occupant's life. In addition, it is intended to minimize the economic losses associated in general with low income population. The proposed measures are addressed mainly to rehabilitation of existing buildings rather than construction of new earthquake-resistant construction houses.

Two rehabilitation alternatives were selected according to the following criteria: economic materials and construction and installation easiness. The first alternative consists of wall strenghthening by means of wire mesh and lime mortar in selected zones of the structure and is based on wide research developments performed in countries like Perú (Zegarra [1]). The second alternative consists in the strengthening with boundary wooden elements, which is based on research works carried out in CITEC- Centro de Investigación y Desarrollo Tecnológico, (Redriguez [2]).

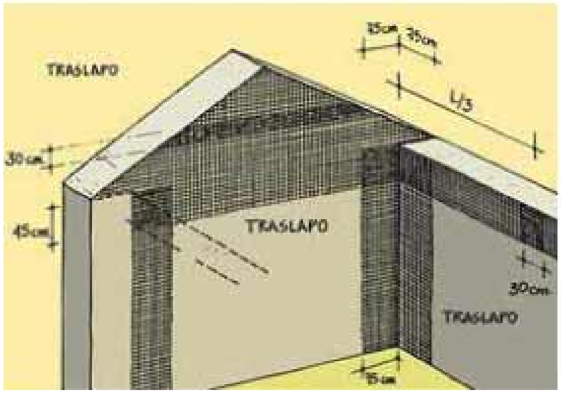
Strengthening with wire mesh and lime mortar

This technique consists in placing wire mesh in horizontal and vertical strips (simulating confinement beams and columns, respectively) in the critical zone of the construction. The mesh is attached to the wall by nails and soda caps each 30 cm and is installed in the outside as well as the inside part of the wall. In addition, anchors or connectors running through the wall are provided with 50 cm spacing in both ways. These connectors are made of 8 mm wire and placed in previously drilled holes which are filled with lime and sand mortar in proportion 1:2. Later on, the wire mesh is covered with lime and sand mortar. It is expected that this rehabilitation technique prevents lateral instability that appears suddenly in nonreinforced constructions which are heavily damaged during earthquakes.

This strengthening alternative has been widely studied in Perú, Mexico and other countries. The technique is based mainly on the results of the Project "Stabilization of existing adobe constructions in the Andean countries" developed by the Centro Regional de Sismología para América del Sur (CERESIS) and the Pontificia Universidad del Perú. This type of rehabilitation which that has been tested during recent seismic events is described in detail in the consulted bibliography (Zegarra [1] and Rodriguez [2]).

Figure 5 presents schemes and photographs of the strengthening technique with wire mesh and lime mortar.

Figure 5.
Strengthening with wire mesh and mortar



Strengthening with boundary wooden elements

This alternative consists in installing wooden elements in the wall plane, on both faces simultaneously. The elements are interconnected to each other by through bolts whose previously drilled hole is filled with cement mortar. The location and dimensions of the wooden elements will be variable, depending upon the specific design of the wall. Nevertheless, some tentative minimum specifications are described below.

The boundary wooden elements for one and two story houses shall have a minimum dimension of 15cm x 2cm and shall be installed both in the horizontal and vertical directions. For installation purposes, it is recommended to form trenches on the adobe and/or rammed earth walls with the dimensions of the wood and a thickness slightly larger in order to "plaster" later the wooden element and keep the original appearance of the wall.

In the horizontal direction elements shall be placed near the wall base and near the upper floor slab at vertical distances not greater than 2.0m. In the vertical direction boundary elements shall be placed near the joints or intersections with other perpendicular walls, around the openings for doors and windows at horizontal distances not greater than 3.0 m. The vertical and horizontal elements shall be interconnected to each other by 1/4 inch through bolts placed at the intersection center point. Besides, the horizontal elements for orthogonal walls shall be connected each other by ¼ inch steel plates matching the corner shape.

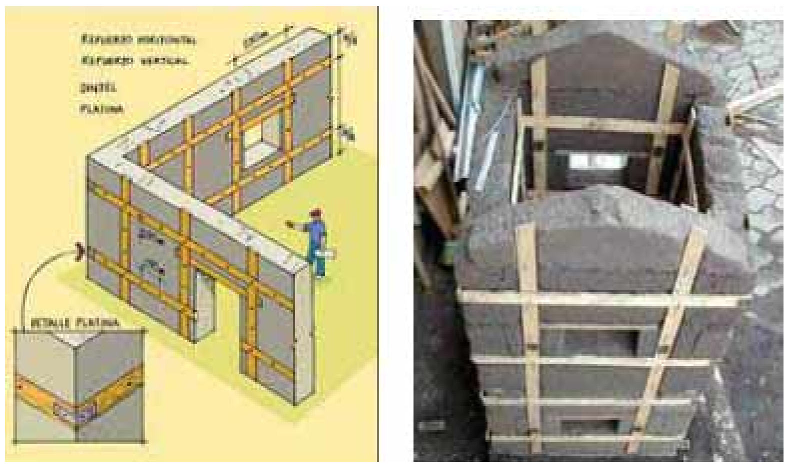
The connection shall be done in the inside face as well as the outside face. The connecting plate shall be anchored to the wall and the wooden elements by ¼ inch through bolts. All boundary wooden elements shall be firmly anchored to the wall by ¼ inch through bolts every 50 cm. The drilled hole shall be filled with cement mortar.

Besides, all wood used for strengthening earth walls shall be nailed every 15 cm to produce a rough contact surface with the walls, in order to guarantee the deformation compatibility between the two materials.

Whenever doors or window openings are present in the wall, boundary wooden elements shall be placed in the vertical direction side by side of the opening. These elements shall be extended, if possible, up to the slabs of the upper and lower mezzanine on the floor to be strengthened or up to the closest horizontal wooden elements

After this rehabilitation alternative is applied on rammed earth walls the holes left by the construction forms shall be filled with lime and sand mortar. Wooden wedges shall be nailed over the mortar to guarantee appropriate bond. This type of reinforcement was applied in two models, one on earth walls and the other on adobe walls. Figure 6 shows a rehabilitation scheme using boundary wooden elements.

Figure 6.
Strengthening with boundary wooden elements

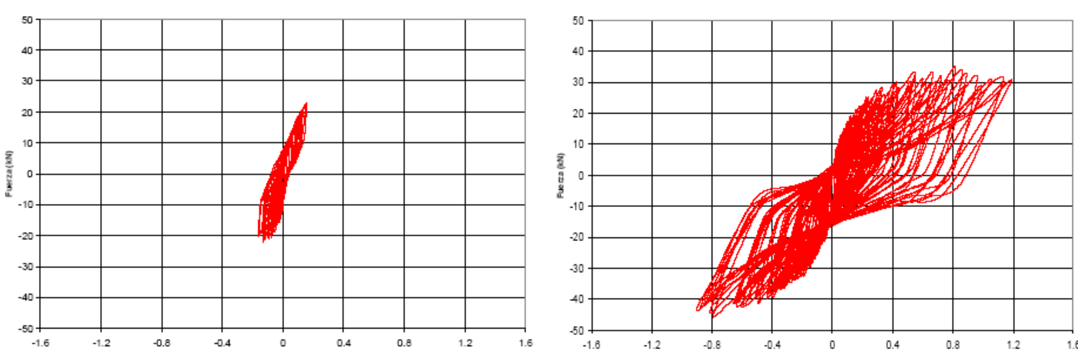


REINFORCED ELEMENTS TESTING

In order to study the behavior of the two proposed alternatives a testing program was developed including real scale walls and reduced scale modules. Ten (10) test were carried out on full scales walls (6 in-plane cyclic loading test and 4 out of plane monotonic out of plane tests), three (3) shaking table test on 1:5 scales models and two (2) test on 1:1.5 scales modules tested with applied cyclic loading.

The hysteretic behavior for reinforced in-plane cyclic test indicate greater resistance, a higher deformation capacity and a much better energy dissipation characteristics in comparison with non reinforced equivalent walls. Figure 7 presents a comparison wit of the hysteretic behavior for unreinforced and reinforced in-plane cyclic test on walls with the same level of vertical load.

Figure 7.
Hysteresis cycles unreinforced wall (left) and reinforced wall (right)



For the out of plane overturning tests, an increase of near 100% in the bending strength was observed for walls reinforced with boundary wooden elements. None of the out of plane tests on walls reinforced with woods, reached a failure for an inclination of 90°(horizontal wall) and an uniformly distributed overload approximately equal to its own weight.

In order to study the dynamic behavior of the rehabilitation alternatives proposed, three (3) reduced scale (1:5) models were built and retrofitted to be tested in the shaking table. The first one correspond to a one story adobe model reinforced with wire mesh, the second model was built like the fist one but reinforced with boundary wooden elements and the last one correspond to a two story rammed earth model reinforced with rammed earth model reinforced with boundary wooden elements. Figure 8 shows photographs of the three 1:5 scale models tested on shaking table.

Figure 8.
Reinforced models tested on vibratory table

For the model reinforced with wire mesh and lime mortar, although it exhibited a more ductile behavior as compared with the equivalent unreinforced model, a separation between the reinforcement elements and the original the original wall was clearly observed, generating general cracking of the walls and affecting the general stability of the structure.

On the other hand, the one and two story models reinforced with boundary wooden elements exhibited a more ductile behavior and a better resistance to the earthquake input. Although failure was attained at certain acceleration level, a much higher number of cycles of greater intensity were needed to produce collapse.

Figure 9 shows photographs of the collapse suffered by the three reinforced 1:5 scale models. In general, a better behavior of the boundary wooden elements rehabilitation alternative was observed in the scale models.

Figure 9.
Failure- mechanism for 1:5 scale models tested on

CONCLUSIONS AND RECOMMENDATIONS

Adobe and rammed earth housing classifies as a high seismic vulnerability construction type mainly because of poor tensile strength of the materials, poor quality of the constructions and the absence of basic considerations such as confinement, continuity, tying, rigid diaphragms and others

The proposed rehabilitation alternatives improved the seismic behavior of this construction type although they didn't prevent the collapse of the tested models. These alternatives provide a limited structural continuity and generate certain level of confinement that reduce the probability of anticipated failure and delay the occurrence of collapse, reducing the probability of casualties. These alternatives have a little impact on the architectural appearance of the construction and are based on economic aspects, ease of use and availability of materials in remote zones.

The reinforcement based on boundary wooden elements has a better seismic behavior and present some advantages with respect to the other alternative studied. Full scale shaking table test shall be developed in order to confirm the obtained results.

In addition roof structures shall be studied in detail in order to prevent total or partial collapse of roof elements. Reinforcement strategies for typical roof structures should be developed and implemented.

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