

EARTHQUAKE RESISTANT EARTHEN BUILDINGS?

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SUMMARY

Every significant earthquake that occurs in regions where earthen buildings are prevalent causes tragic death and destruction. This paper explores the reasons for the endurance of some historical mud structures and the failure patterns of modern earthen buildings under seismic events. It also presents relevant results of experimental research at the Catholic University of Peru on the seismic behavior of adobe structures, considers these results from the viewpoint of their application to massive construction programs, and discusses the new challenges associated with the problem of earthquake resistance of earthen structures.

INTRODUCTION

Many civilizations have used soil as building material, during their early stages. Adobe, rammed earth and other construction techniques with soil are still used in many developing countries because of their low cost and self-construction possibilities. Many countries with a long tradition in the use of soil as a building material are located in areas of high seismic hazard (Fig. 1). Unfortunately, the seismic performance of traditional unreinforced earthen buildings is extremely poor, as has been clearly demonstrated during the recent Bam and Morocco earthquakes.



Figure 1. Earthen construction and high seismic risk areas in the world (from De Sensi [1])

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This article discusses the seismic performance of ancient and modern earthen buildings, presents the results of experimental research at the Catholic University of Peru on the seismic response of adobe houses, and discusses the challenges associated with the implementation of large-scale earthen construction programs.

SEISMIC BEHAVIOR OF EARTHEN BUILDINGS

As a construction material, soil is heavy, weak and brittle. During seismic motion heavy walls develop large inertia forces, which they are unable to resist, and thus they suddenly fracture and many times collapse, preventing evacuation and causing death and material loss (Fig. 2).



Figure 2. Destruction of adobe buildings during earthquakes

In Peru, several historical earthen constructions have been able to withstand severe earthquakes because of their massiveness and regular configuration. For example, the Chan-Chan archeological site (1200 - 1400 A.D.), located on the coast of Peru, and occupying 20 km², is considered to be the world's largest mud citadel, and has survived many severe earthquakes during the past 600 years. Decorated boundary earthen walls (Fig. 3, left) up to 9 m tall and 3 m wide at the base can be found in the citadel. Many long walls without buttresses and with slenderness ratios smaller than 3 are still standing. On the other hand, the latest earthquake in Iran (December 2003, M_w 6.6), has destroyed not only thousands of poorly made adobe houses but also important ancient historical monuments such as the earthen citadel of Bam (Fig. 3, right). This seriously questions the argument of massiveness as a guarantee for earthquake endurance. The architectural design of the Bam citadel and surroundings includes upper thin walls standing over thick base walls, irregular plan configurations, and high wall densification. It seems that slender walls have collapsed, impacting adjacent walls and constructions, causing total destruction of the site, in spite of its massiveness.



Figure 3. Ancient earthen citadels of Chan-Chan and Bam (from Moallemian [2])

"Modern" earthen dwellings in many countries are built to imitate the architectural features of clay brick masonry houses. Thus earthen houses are built without any structural reinforcement, with several stories, thin walls, large window and door openings and irregular plan and elevation configurations (Fig. 4). These buildings are extremely vulnerable to earthquakes. When an earthquake occurs, the out-of-plane seismic forces produce large vertical cracks at the corners, and in-plane shear forces produce diagonal cracks in the walls. The walls are thus broken in large independent pieces, which fall down, causing in turn the collapse of the roof.



Figure 4. "Modern" adobe houses in Peru

RESEARCH AT THE CATHOLIC UNIVERSITY OF PERU

The M_w 7.8 Huaraz earthquake of 1970 caused the death of around 70 000 people, about half of them buried under their adobe houses. This tragedy raised the consciousness in Peru about the need to investigate the problem of seismic strength of adobe buildings. Initially, research at the Catholic University of Peru (PUCP) was oriented towards the experimental study of several different alternatives of structural reinforcement using rural materials. This was done with a 4x4 meter reinforced concrete tilting platform used to test full-scale adobe modules (Fig. 5). The seismic force was represented by the lateral component of the weight of the modules. The main conclusion was that an interior reinforcement made of vertical cane, combined with an arrangement of horizontal crushed cane every fourth layer of adobe blocks substantially increased the seismic strength of the adobe modules (Corazao and Blondet [3]).



Figure 5. Full-scale adobe modules over tilting platform

The influence of the properties of the soil and the use of natural additives on the shear strength of adobe masonry was then studied, with the support of US AID. The main conclusions were that clay is the most important component of soil, since it provides the dry strength of the blocks. However, excessive clay content increases drying shrinkage, and thus microcracking of the mortar and blocks. Microcracking due to drying shrinkage can be controlled with the addition of straw or coarse sand to the mortar. The traditional process of "sleeping" or soaking the mud 24 hours previous to use, in order to activate the bonding properties of the clay, was found to be beneficial (Vargas et al. [4]).

An important research project was started in 1992, with the financial support of the International Development Research Center of Canada (IDRC). The seismic simulator of the Structures Laboratory of the PUCP was used to perform dynamic testing of full-scale adobe modules. Figure 6 shows the test setup. The modules had variations in the constructive technique, in the cane reinforcement system and in the configuration of wall openings. The command signal of the simulator was derived from the longitudinal displacement component registered in Lima during the May 31st, 1970 earthquake. This signal is typical of Lima's stiff soil conditions. All the modules were subjected to the same sequence of tests, with increasing intensity until collapse or significant damage was produced. The main conclusions of this project were that improvement in the construction technique (quality of materials and labor) by itself increased the strength and stiffness of uncracked walls, but had negligible influence after significant cracking occurs. During severe shaking, only the presence of the horizontal and vertical cane reinforcement shown in Figure 7, combined with a solid collar beam, were able to prevent the separation of the walls in the corners, thus maintaining the integrity of the structure. In consequence, this reinforcement is effective in preventing or delaying the collapse of the building (Ottazzi *et al.* [5]).





Figure 7. Vertical and horizontal cane reinforcement

After more than twenty years of adobe research in the PUCP dedicated to the improvement of the seismic behavior of new adobe dwellings, an experimental project was funded in 1996 by the Deutsche Gesalischft für Technische Zusammenarbeit (GTZ) to develop simple techniques to reinforce existing adobe buildings. "U" shaped walls were tested on the seismic simulator with different reinforcement materials like wooden boards, rope, chicken wire mesh and welded mesh. The best results were obtained with welded mesh (1mm wires spaced at 20 mm), nailed with metallic bottle caps against the adobe and covered with cement-sand mortar. The mesh was placed in horizontal and vertical strips, as shown in Figure 8, simulating beams and columns. After successful testing of four full-scale modules on the seismic simulator, this solution was applied to the reinforcement of existing adobe houses located in different regions of Peru (Fig. 9, Zegarra *et al.* [6]). In 2001, a strong earthquake (magnitude 8.4)

occurred in Southern Peru and destroyed most adobe houses in the affected region. However the houses located in the region that were reinforced with welded mesh suffered no damage at all and were used as shelters (Zegarra *et al.* [7]).





Figure 8. Welded wire mesh (from [8])

Figure 9. Reinforced house (from [8])

ADEQUATE REINFORCEMENT TECHNIQUES

The two reinforcement systems developed at PUCP: interior cane mesh and exterior welded mesh covered with cement mortar have proved to be adequate for the seismic protection of earthen houses, which might suggest that the problem of constructing earthquake resistant earthen buildings has been technically solved. Indeed, the major issue of safe evacuation during a strong earthquake is solved with both reinforcement technologies, because they help to effectively control or delay total collapse of the dwellings.

A technical solution, however, does not mean that the real problem has been solved. On one hand, people who have traditionally used adobe are reticent to changes, especially if the changes imply the need for higher skills and require different reinforcement materials. The adobe users admire masonry brick houses as a status symbol of progress. Thus, they consider an adobe dwelling only as a temporary housing solution, not worthy of any special construction effort, and they do not care to provide adequate reinforcement, even though it will increase the safety of the house where they will probably live for the rest of their lives.

On the other hand, the reinforcement systems have their limitations. The main limitation of cane is the fact that it is not available in all regions. Moreover, even in areas where cane is produced, it is practically impossible to obtain the required quantity for a massive construction or reconstruction program. External reinforcement with welded mesh costs around US \$200 for a typical one floor, two room adobe house. This amount exceeds the economic capacity of the Peruvian adobe user, whose monthly income most likely is the legal minimum, less than US \$150.

Therefore, the proposed reinforcement systems, technically efficient for earthquake endurance, are still far from being real alternatives to improve the seismic behavior of adobe houses. It seems imperative to continue research to develop reinforcement systems that use industrially produced materials, acceptable to adobe users because of their low cost and simplicity of application.

RECENT AND ONGOING RESEARCH

During 2003 a first attempt towards the application of Fiber Reinforced Polymer (FRP) rods as replacement for cane reinforcement was carried out during an academic earthen construction workshop at the PUCP (Fig. 10). Five small size adobe modules $(0.95 \times 0.95 \times 1.15m)$ with the same geometrical characteristics but with different reinforcement configurations were tested on the seismic simulator. For comparative purposes, the command signal was the same one used in previous research with full-scale modules.



Figure 10. Seismic testing of small-scale adobe modules with FRP reinforcement

A traditional unreinforced module and another one with interior cane mesh were tested as baselines. The other three had different FRP reinforcement patterns. The results confirmed that the traditional adobe module collapsed and the cane reinforced adobe module was able to withstand the strongest tests with only a low level of cracking. Although the FRP reinforced modules did not collapse, they were severely damaged. FRP rods are stiffer than cane and during shaking they push the adobes out of place. Besides, the bond between FRP rods and mud is lesser than the bond developed between cane and mud (Villa García *et al.* [9]) These results as well as the cost associated with FRP rods in developing countries suggest that FRP reinforcement is not an adequate replacement for cane.

A preliminary research project is currently being developed (March 2004) with the objective of studying the technical and economical feasibility of using locally available industrial products such as wire, plastics and geosynthetics in the seismic reinforcement of adobe houses. Six "I" shaped full-scale adobe walls (Fig. 11), with and without reinforcement, are being constructed at the Structures Laboratory and will be tested under horizontal cyclic loading. The geometric configuration, including a small central window, and the overall dimensions are similar for all the walls. Three baseline walls include one traditional unreinforced, one with interior cane reinforcement and one with welded mesh placed externally simulating beams and columns. The reinforcement proposals include:

- 1. Adding ¹/₂" diameter PVC water pipes as inner vertical reinforcement, combined with a low-cost ¹/₂" plastic mesh embedded horizontally in the mortar every fourth layer. Both reinforcement elements are tied together with plastic string. The PVC pipes are anchored in the foundation beam and in the upper tie beam, both made of concrete.
- 2. Placing vertical ¹/₂" diameter corrugated steel bars inside the walls at the corners, with no horizontal reinforcement.
- 3. Fixing a geosynthetic mesh externally to the walls, simulating columns and beams. The covering is made of mud mixed with straw.

To select the products to be used as reinforcement materials for the walls, several locally available plastic and geosynthetic meshes have been tested for their bond with the mud mortar as well as for their tensile behavior (Fig. 12). Adequate bond will guarantee integration of adobe masonry. Unit elongation of the mesh has to be small because it is expected to keep together the adobe units after cracking occurs.



Figure 11. Geometric configuration of walls



Figure 12. Plastic mesh

The cost associated with the proposed reinforcement alternatives will also be evaluated, because its effect on the total cost of the house will determine its acceptance by potential users. This project is only a preliminary study, because the efficiency of any technology associated with the seismic behavior of an earthen building can only be demonstrated under realistic seismic testing.

CONCLUSIONS

Experimental research has shown that it is possible to mitigate the effects of strong earthquakes on earthen buildings, delaying or even preventing their collapse. However, the scope of the problem is much bigger, because it involves acceptance by users, availability of adequate materials and further economical aspects. The challenge is to continue exploring new alternatives until a technically good solution is found that will contribute to solving the housing deficit in the most impoverished third world countries and at the same time guarantee survival during strong earthquakes.

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