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AVAILABLE LOW-COST TECHNOLOGIES TO IMPROVE THE SEISMIC PERFORMANCE OF EARTHEN HOUSES IN DEVELOPING COUNTRIES

M. Blondet[1], J. Vargas[2] and N. Tarque[3]

[1] *Professor of Civil Engineering, Dept. of Engineering , Catholic University of Peru (PUCP), Lima Peru*
[2] *Professor of Civil Engineering, Dept. of Engineering, Catholic University of Peru (PUCP), Lima Peru*
[3] *PhD student, ROSE School, Institute for Advanced Study of Pavia, Pavia, Italy.*

Email: mblondet@pucp.edu.pe jhvargas@pucp.edu.pe sntarque@pucp.edu.pe

ABSTRACT:

A recent earthquake (August 15th 2007) in Pisco (Peru) has destroyed almost all the adobe houses and historical monuments in Pisco and neighboring cities, towns and villages, killed more than 500 persons, and left thousands of people with injuries and homeless. This catastrophe was neither unexpected nor surprising, because every single earthquake that occurs in developing countries where construction with earth is common leaves a similar sequel of destruction, economic loss, injuries and deaths. Earthen buildings are particularly vulnerable to earthquakes because of the low strength and fragile behavior of their walls. Inhabitants of earthen houses in the seismic areas of the world, most of them poor, therefore live under unacceptable risk.

This paper first describes the observed response of traditional, unreinforced earthen buildings during earthquakes. Several low-cost reinforcement techniques developed at the Catholic University of Peru over more than 35 years of research, in order to improve the seismic safety of earthen buildings, are then presented and compared. Finally, the challenges involved in the dissemination of economical and safe construction techniques to the actual builders and dwellers of earthen houses are briefly discussed.

KEYWORDS: Earthen, construction, adobe, earthquake, reinforcement.

1. SEISMIC RESPONSE OF EARTHEN BUILDINGS

Men have used soil to build their homes and monuments since the beginning of civilization. In many developing countries soil is still a widely used construction material because it is readily available at little or no cost. Most underprivileged people in these countries, therefore, have no alternative but to build with soil, because the cost of manufactured or industrial materials such as wood, fired clay bricks, cement, or reinforcing steel is completely beyond their economic possibilities. Many construction techniques using earth as the main material are employed throughout the world. The most common are adobe and rammed earth. Because building with earth is relatively simple, it is usually performed by the residents themselves, without technical assistance or quality control. Reasonably well built earthen houses are, however, very comfortable because the walls have excellent thermal and acoustic characteristics.

The high seismic vulnerability of earthen buildings is due to a perverse combination of the mechanical properties of their walls: earthen walls are dense and heavy, have extremely low tensile strength and they fail in a brittle fashion, without any warning. As a consequence, every significant earthquake that has occurred in regions where earthen construction is common has produced tragic loss of life and considerable material damage (Fig. 1).

(Photo: D. Dowling)

Figure 1 Destruction of adobe houses in El Salvador (2001) and Pisco (2007)

During earthquakes the ground shakes in all directions and generates inertia forces that the construction material should be able to withstand. Since the tensile strength of adobe masonry is very low (and much lower than its compressive strength), significant cracking starts in the regions subjected to tension. Seismic forces perpendicular to the walls produce out-of-plane bending, and vertical cracking starts at the lateral corners of the walls, where the tensile stresses are higher. Large vertical cracks that separate the walls from one another are thus produced (Fig. 2, left). Front walls are usually the first to collapse in an earthquake, overturning onto the adjacent street. Lateral seismic forces acting within the plane of the walls generate shear forces that produce diagonal cracks, which usually follow stepped patterns along the mortar joints. The diagonal cracks often start at the corners of doors and windows, due to the stress concentration at these locations (Fig. 2, right). If the seismic movement continues after the adobe walls have cracked, the wall breaks in separate pieces, which may collapse independently.

Vertical crack at corner of front wall

Diagonal cracks

Figure 2 Seismic cracks in adobe houses (Pisco earthquake 2007)

In Peru, many 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 CE), located on the coast of Peru, is considered to be one of the world's largest mud citadels, and has survived many severe earthquakes during the past 600 years. Decorated boundary earthen walls, some of them up to 9 m tall and 3 m wide at the base, can be found in the citadel. Many long and slender walls without buttresses are still standing (Fig. 3, left). On the other hand, the 2003 Bam earthquake in Iran has destroyed not only several thousands of poorly made adobe houses, but also important ancient historical monuments such as the earthen citadel of Arg-e Bam (500 BCE; Fig. 3, right). This seriously undermines 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 densities. It seems that slender walls have collapsed, impacting adjacent walls and constructions, causing total destruction of the site, in spite of its massiveness.

(Photo at right: Cultural Heritage News.)
Figure 3 Ancient earthen citadels of Chan-Chan and Arg-e Bam

Most vernacular earthen houses are built without any professional intervention, and thus with poor construction quality. Furthermore, they tend to imitate the architectural features of clay masonry houses.. Therefore, most present-day 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 and suffer significant damage or collapse during earthquakes.

Figure 4 Contemporary adobe houses in Cusco, Peru

2. REINFORCEMENT TECHNIQUES FOR EARTHEN BUILDINGS

During the last three decades, researchers at the Catholic University of Peru (PUCP) have attempted to find solutions for improving the seismic performance of earthen buildings (Vargas et al. 2005). Several related publications can be found in http://www.pucp.edu.pe/secc/civil/publicaciones.php. The principal alternatives of seismic reinforcement for these vulnerable buildings are described below.

2.1. Internal cane mesh reinforcement

The reinforcement consists of vertical cane rods anchored to a concrete foundation and placed inside the adobe walls. The adobe block layout defines the distance between the vertical cane rods at 1,5 times the thickness of the wall. Horizontal layers of crushed canes are placed every few adobe rows and tied to the vertical cane reinforcement (Fig. 5, left). Finally, this internal cane mesh reinforcement is tied to a wooden crown beam (Fig. 5, right).

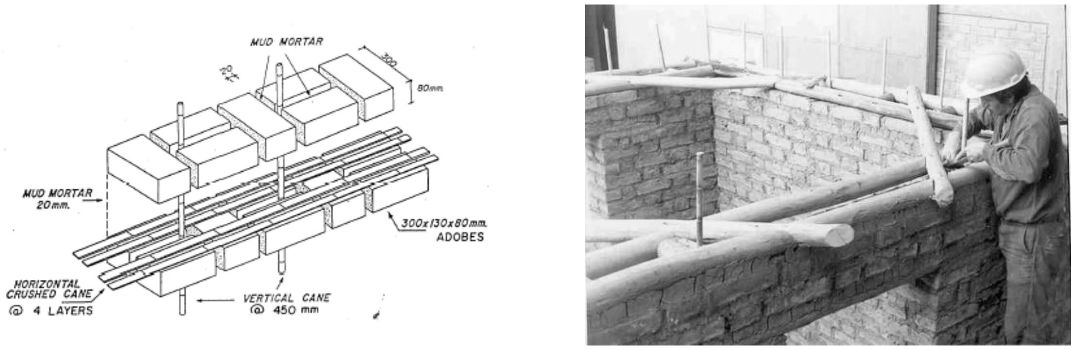


Figure 5 Internal cane mesh reinforcement

This reinforcement system has demonstrated excellent response in full-scale shaking table tests (Blondet et al. 1988). Figure 6 shows the collapse of a full scale adobe house model subjected to simulated seismic motion (left). During a similar test, the model reinforced with an internal cane mesh suffered significant damage, but did not collapse.


Figure 6 Adobe models after seismic tests. L: Unreinforced. R: Reinforced with cane

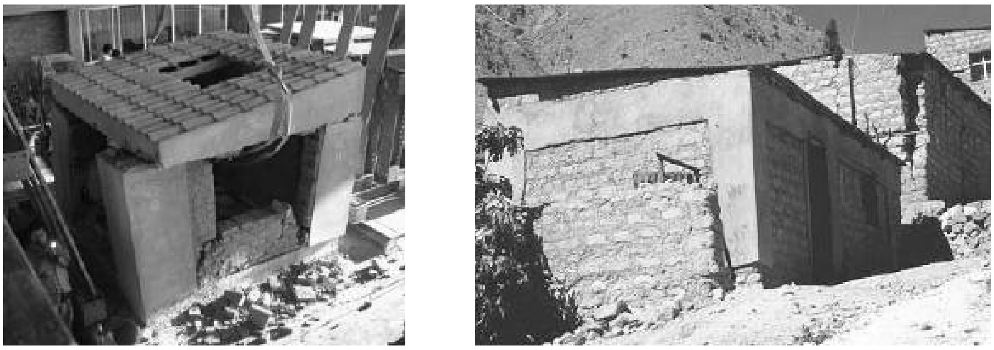
The main limitation of this reinforcement system is the fact that cane is not available in all seismic regions. Moreover, even in areas where cane is produced, it is practically impossible to obtain the required quantity for a massive construction or reconstruction program.

2.2. External wire mesh reinforcement

This technique consists of nailing wire mesh bands against the adobe walls and then covering them with cement mortar. The mesh is placed in horizontal and vertical strips, following a layout similar to that of beams and columns (Fig. 7).

Placing the mesh on the wall. Reinforced house (Pisco earthquake 2007)
Figure 7 External wire mesh reinforcement

This reinforcement system provided significant additional strength to adobe models under earthquake simulation tests. The performance of the model was adequate during moderate and severe shaking. However, the mode of failure was brittle during a strong event (Fig. 8, left). During a moderate earthquake in Peru, while surrounding houses were severely damaged or destroyed, houses reinforced with this system did not suffer any damage and were used as shelters (Zegarra et al.1997 and 2001) as shown in Fig. 7 and 8, right.



Reinforced model after seismic test   Reinforced house (Arequipa earthquake 2001)

Figure 8 Adobe buildings with external wire mesh reinforcement

Wire mesh and cement are prohibitively expensive for the inhabitants of earthen houses in developing countries. External reinforcement with welded mesh could cost up to US $200 for a typical one floor, two-room adobe house, which exceeds the economic capacity of most Peruvian adobe users.

2.3. External polymer mesh reinforcement

A recent study has been performed at PUCP to evaluate the possibility of using polymer mesh to reinforce earthen buildings (Blondet et al. 2006). Several similar full-scale adobe housing models with different amounts and types of polymer mesh were tested on the unidirectional PUCP shaking table. The reinforcement provided consisted of bands of polymer mesh tied to both sides of the walls with plastic string threaded through the walls (Fig. 9).

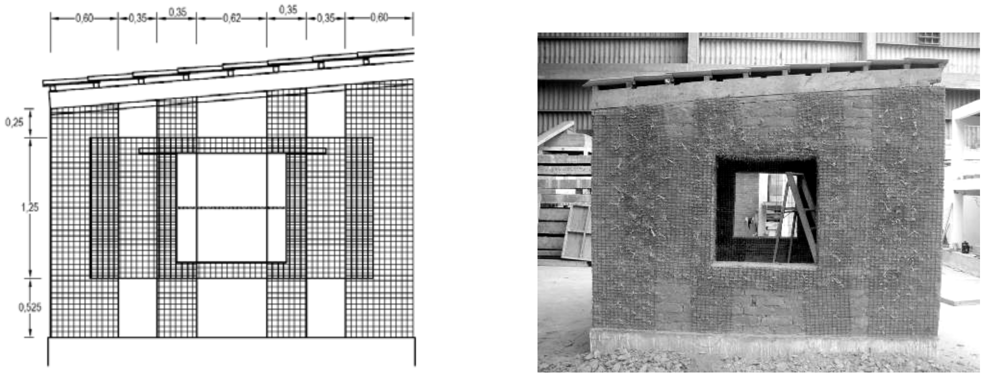


Figure 9 External geogrid mesh reinforcement (75% of walls covered)

The first models were reinforced with different amounts of geomesh and they showed good dynamic response during the earthquake simulation tests: although the adobe walls suffered some damage, collapse was avoided even under very strong shaking. As expected, however, the amount and spread of damage on the adobe walls increased as the quantity of polymer mesh reinforcement decreased.

Since geogrid polymer mesh is quite expensive in Peru, it was decided to study the use of a cheaper plastic mesh, usually employed as a soft safety fence in construction sites. The adobe model shown in Fig. 10 was reinforced with bands of plastic mesh located in the regions where most damage was expected on the adobe walls. The plastic mesh bands were tied to the walls with plastic string placed across the walls during construction. After a strong shaking test, the adobe walls were broken into several large pieces, which were held together by the plastic mesh. The mesh was deformed and broken in several places, indicating that the amount provided was barely adequate. It is clear, however, that although the building suffered significant damage, collapse was averted.

Figure 10 Adobe model reinforced with plastic mesh

Moderate amounts of strategically placed polymer mesh reinforcement can therefore be used to prevent the collapse of adobe buildings, even during severe earthquakes. However, further research is needed to determine the optimal amount and placement of the mesh, and to develop simple reinforcement design procedures and construction recommendations, in order to provide the professional community with tools to design and build economical and safe earthen houses in seismic areas.

3. MAIN CHALLENGES (AND POSSIBLE SOLUTIONS)

The reinforcement systems studied at PUCP have proved to be adequate for the seismic protection of earthen houses. This might suggest that the problem of constructing earthquake resistant earthen buildings has been solved. Indeed, the application of these technical solutions would provide a sufficient degree of safety to these buildings to prevent their collapse and therefore to avoid personal injuries and loss of life.

After the Pisco earthquake, the PUCP, in collaboration with CARE Peru, published a manual for the construction of hygienic and earthquake-resistant adobe houses reinforced with geomesh (Vargas et al. 2007). A massive training program led by PUCP and CARE Peru was also carried out for the reconstruction of adobe houses reinforced with geomesh. This project was designed and implemented with the cooperation of many private and public institutions, as well as local and central government agencies. The first step involved training of personnel from NGOs and municipalities, engineers and architects. About 100 persons were trained. A reinforced adobe house demonstration model was built in the campus of the university, and a construction manual and a video were also released and widely distributed among the population affected by the earthquake. The second stage was developed in the field, where the PUCP and CARE Peru team built nine reinforced adobe houses. Homeowners, neighbours and local community members participated in this “learn by doing” process. These reinforced adobe houses were built in different districts of the areas affected by the earthquake. The Peruvian Ministry of Housing has validated the reinforcement technique and will distribute a free materials kit of materials to victims in the damaged areas. Several NGOs are also participating in the reconstruction process by building adobe houses reinforced with geomesh.

The availability of technical solutions, unfortunately, is not sufficient to solve the real problem of the unacceptable seismic risk for the millions of earthen house dwellers. This problem has important social dimensions that need to be addressed, because in many cases significant cultural transformations are required to change the way people build their dwellings.

Many people who have traditionally used soil as a construction material are reticent to change the way they build. In many cases it is because the communities have an adverse reaction to interference in their traditional way of life from persons extraneous to the community. Another very important reason for the rejection of new construction techniques is certainly economical, because these techniques necessarily imply a higher cost, either in money to buy extra reinforcing materials, or in time because training is required or the new building process is more elaborate. Another problem is the short seismic memory of the population. Awareness of seismic hazard is only high after an earthquake, and fades away in a matter of a few years. If earthquakes are not perceived as an immediate danger, there does not seem to be a need to spend for seismic prevention scarce resources which are required for daily subsistence.

Furthermore, in many places there is a social stigma attached to earthen houses. In Peru, for instance, masonry brick houses are regarded as a status symbol of progress, especially in urban areas. Thus, urban dwellers consider adobe houses only as temporary solutions, not worthy of any special additional construction effort.

Mitigation of seismic risk will therefore be possible only when the users themselves adopt improved earthen construction systems as part of their own culture. A possible set of actions to achieve this transformation is suggested below. Several of them can be performed simultaneously.

Development of adequate reinforcement methods. Although technical solutions to improve the seismic safety of earthen buildings are available, they are still expensive and require relatively high technical skills. It is necessary to find cheaper and simpler reinforcement techniques.

Development and implementation of national seismic design codes. Design codes are official documents with technical specifications for structural design and construction of buildings. The seismic design philosophy of earthen buildings should recognize that the material is heavy, weak and brittle. It must be accepted, therefore, that significant cracking may occur even during moderate earthquakes. Brittle collapse should always be avoided in order to prevent loss of life. Several countries, such as Peru, have already developed design codes for earthen buildings (MTC 2000). Several published documents could also serve as guidelines for the development of new codes (CYTED 1985, IAEE 1986). It is important to take into account, however, that code provisions are addressed to professionals (who rarely live in earthen houses) and that most of the people that build (and live) in earthen houses will not use the design codes.

Development and dissemination of educational materials for safe construction with earth. The knowledge required for guaranteeing safe and economical earthen construction must be disseminated at all levels: engineers, architects, masons, construction workers, government officials, dwellers. Each group requires the information in a different technical level and format. An important dissemination tool is the internet. There is a wealth of material already published there, such as the EERI/IAEE World Housing Encyclopedia (www.world-housing.net), which contains a tutorial on adobe building in Spanish and English available for download (Blondet et al. 2003).

Development and implementation of seismic risk awareness campaigns. It is indispensable to find ways to reach the communities who build with earth in regions with high seismic hazard in order to persuade them that earthquakes will happen again and again, to remind them that their earthen houses are vulnerable and will collapse or suffer devastating damage, and to convince them that with simple technical improvements their houses will be safer. This communication effort is complex and multidimensional. It cannot (and should not) be performed by the academic community alone. It must involve the contribution of the government, at central, regional, and local levels; of NGOs involved with urban and rural development; of the professional communities of engineers, architects, social scientists, and communicators; the educational system starting in elementary school; and the media in all its forms.

Development and implementation of community training programs. Educational campaigns should be designed and implemented through popular organizations and local governments to train the community builders and the inhabitants on the basic concepts of earthquake-resistant construction with earth. This effort should be guided by social scientists and communicators. The professional community has the responsibility of disseminating the technical knowledge required to mitigate the risk of earthen houses in seismic areas, which today has reached unacceptable levels.

Development and implementation of massive programs for construction of new earthen houses and retrofit of existing houses. Ideally, all existing vulnerable earthen houses should be retrofitted and every new earthen house should incorporate adequate seismic reinforcement. This can be achieved only through massive construction and retrofit programs, which could be sponsored by the central government and partially financed by private investors.

4. CONCLUSIONS

Vernacular earthen houses located in seismic areas are at risk because of their inherent structural vulnerability. However, and due to economic reasons, earth is the only available building material for many communities in developing countries. It is urgent therefore to take action in order to mitigate this unacceptable risk.

It is possible to provide reinforcement to earthen buildings in order to improve their structural performance and to prevent their collapse during earthquakes. These techniques for safe and economical earthen construction should be transmitted to builders in developing countries located in seismic areas.

The challenges to be undertaken would involve educational campaigns to reach awareness of the seismic risk, cultural transformations to adopt better construction techniques with earth, and massive construction programs. These steps will contribute to solve way the housing deficit in the most impoverished countries of the world.

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