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Building Codes for Earthen Buildings in Seismic Areas: The Peruvian Experience

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ABSTRACT

Every time a strong earthquake occurs in areas where earthen building is common, there is widespread damage, economic losses and death caused by the collapse of the earthen houses. In some cases, as in Peru, the academic and professional communities have reacted against this dreadful situation by conducting research to find adequate seismic reinforcement alternatives for earthen buildings, and the resulting solutions have been implemented in a building code.

This paper starts by presenting the effects of earthquakes on earthen dwellings and the technical solutions for seismic reinforcement developed at the Catholic University of Peru (PUCP). The Peruvian Adobe Code is then briefly described, with critical comments on some design considerations. Finally, the authors share some thoughts and reflections on the usefulness of building codes for earthen building in developing countries.

Keywords: adobe, earthen houses, seismic, design codes.

1 INTRODUCTION: Earthen houses in seismic developing countries

In many developing countries, earthen dwellings are a traditional housing solution, because soil is abundant and cheap. Unfortunately, because earthen houses are built informally, every time an earthquake occurs many of these buildings collapse, causing considerable economic losses and regrettable casualties. The earthquakes that occurred in Huaraz (Peru, 1970) and in Bam (Iran, 2003) caused the tragic deaths of thousands of people, crushed under their own earthen houses.

The academic and professional communities have not remained passive against this critical situation. For example, in Peru, research on earthen construction in seismic zones has been performed for more than thirty years. Simple techniques have been developed to reinforce earthen buildings, which have shown their effectiveness in full-scale laboratory tests of adobe houses and in the field during moderate earthquakes. The main results of the research performed have been incorporated in the Peruvian Adobe Design Code.

This paper describes the effects of earthquakes on earthen buildings and the technical solutions developed at the Catholic University of Peru (PUCP). It then critically discusses important issues of the seismic design requirements provided in the current Peruvian Adobe Code and finally gives some reflections on the usefulness of earthquake-resistant code provisions to build safe adobe houses to the most impoverished peoples of the world.

2 EFFECTS OF EARTHQUAKES ON EARTHEN BUILDINGS

Earthen houses are warm during the winter and are fresh during the summer because dry soil has excellent thermal properties. However, the adobe walls have adverse seismic properties because they are heavy, weak and brittle. Colonial earthen houses that still survive have a large density of thick walls with small openings. Currently, the land for house construction is scarce in urban areas. Adobe houses are therefore built with slender walls, imitating architectural configurations from the "modern" masonry houses. In Peru most adobe houses are very vulnerable because they are built imitating architectural features of clay brick masonry houses with large openings, long and slender walls and very heavy roofs (Fig 1).

Figure 1. Seismically vulnerable adobe houses in Peru.

During earthquakes the ground shakes in all directions and generates inertia forces that the material should be able to withstand. Since the compression strength of adobe is much higher than its tensile strength, significant cracking starts in the regions subjected to tension. Seismic forces perpendicular to the walls produce out-of-plane bending. 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. 2a). 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. 2b). If the seismic movement continues after the adobe walls have cracked, the wall breaks in separate pieces, which may collapse independently.

a) Vertical crack at corner of front wall   b) Diagonal shear cracks

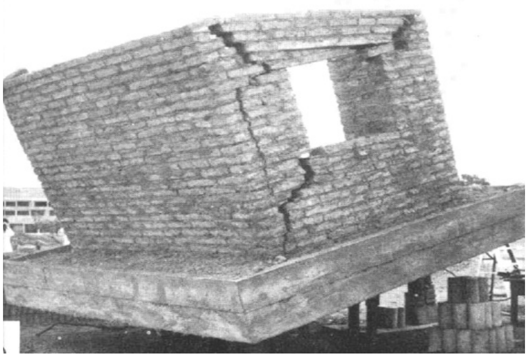
Figure 2. Seismic cracks of adobe houses

In most cases, the adobe walls can sustain the seismic stresses due to vertical shaking. During superficial earthquakes, however, the strong vertical seismic forces may weaken walls and roofs and hasten the structural collapse. If the walls are wet the strength of adobe masonry decays drastically and, of course, the seismic vulnerability of the house increases accordingly.

Traditional adobe houses are extremely vulnerable to earthquakes. Because adobe is brittle, failure is always sudden, and the dwellers do not have enough time to leave their house. It is indispensable therefore to provide additional reinforcement to prevent sudden collapse during earthquakes.

3 SEISMIC REINFORCEMENT SYSTEMS: PUCP Contribution

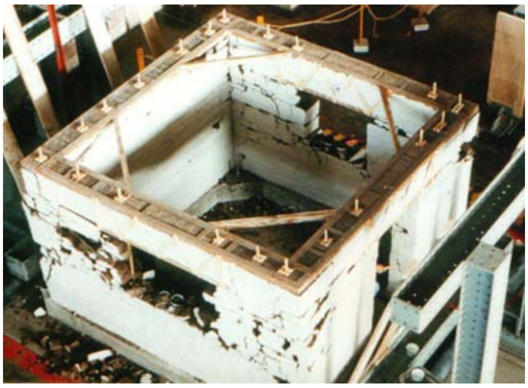
Initial research at the Catholic University of Peru (PUCP) was oriented towards the experimental study of different reinforcement alternatives using rural materials. A reinforced concrete tilting platform was used to test full-scale adobe modules, where the seismic force was represented by the lateral component of the weight of the modules (Ref. 1, Fig. 3a). The failure mode was very similar to what was observed after an earthquake had occurred. An internal reinforcing system consisting of vertical cane rods anchored to the foundation, combined with horizontal crushed cane strips placed within the mortar every four layers, was quite effective in providing additional strength and deformation capacity to the adobe houses (Ref. 2, Fig. 3b).



a) Without reinforcement b) With horizontal cane reinforcement

Figure 3. Full-scale adobe modules over tilting platform

To test the effectiveness of the interior cane mesh, full-scale seismic simulation tests of adobe dwellings were performed. The interior reinforcement, combined with a wooden crown beam at the top of the walls was very effective because cane and adobe masonry are two compatible materials. During the most severe seismic movements, the internal mesh prevented the separation of the walls in the corners, thus maintaining the integrity of the structure (Ref. 3, Fig. 4).



a) Tying the horizontal crushed cane strips b) Module after seismic simulation test

Figure 4. Adobe housing modules with internal cane mesh reinforcement

Unfortunately, the use of interior cane mesh has the following shortcomings: 1) To build adobe walls with internal reinforcement requires significantly more labor than to build traditional adobe walls without reinforcement. 2) Cane is not available in all regions. Even in areas where cane is available, it is practically impossible to obtain the required quantity for a massive construction or reconstruction program. 3) It cannot be used in existing houses.

In 1996 the PUCP began an experimental project to develop reinforcement techniques for existing adobe buildings. U-shaped walls were tested on the seismic simulator with different reinforcement materials, such as wooden boards, rope, chicken wire mesh and welded mesh. The best results were obtained with welded wire mesh nailed with metallic bottle caps against the adobe walls and covered with cement-sand mortar (Fig. 5a). The mesh was placed in horizontal and vertical strips, 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 (Ref. 4). In 2001, an earthquake occurred in Arequipa, in southern of Peru, and destroyed most adobe houses in the affected region. The reinforced houses, however, suffered no damage and were used as shelters (Ref. 5, Fig 5b). The external wire mesh reinforcement thus proved to be successful for moderate earthquakes.

a) Nailing the welded wire mesh b) Reinforced house after the 2001 earthquake

Figure 5. Adobe houses with external wire mesh reinforcement

External reinforcement with welded wire mesh, however, also has some disadvantages: 1) It costs around US $200 for a typical one-floor, two-room adobe house. This amount exceeds the economic capacity of most Peruvian adobe users. 2) Due to economical reasons, the reinforcement is only placed on wall edges, which means that it does not cover the whole wall surface. 3) The post-elastic behavior of these walls shows stiffness and strength degradation, which could lead to sudden and brittle failure during a severe earthquake.

A research project is being developed at the PUCP, to study the feasibility of using industrial materials for the seismic reinforcement of adobe houses. Encouraging results have been obtained with cyclic tests of adobe walls, with and without reinforcement (Ref. 6). Currently, several shaking table tests have been performed and the data is being processed.

Even though effective technical solutions have been developed to reduce the seismic vulnerability of adobe houses, the real problem is far from being solved, mainly because the adobe builders do not accept these new construction techniques as their own. The persons who build traditional, unreinforced adobe houses are reticent to change, especially if change implies higher skills, more labor, and higher cost. It is then urgent to explore ways to raise consciousness of the seismic risk among the adobe dwellers, to develop effective training techniques, and to implement construction programs of safe earthen buildings, in order to develop a national culture of disaster prevention.

4 THE PERUVIAN ADOBE SEISMIC DESIGN CODE

A seismic design code is an official document which contains technical specifications for the structural design and construction of buildings in seismic areas. Conventional earthquake-resistant design philosophy states that buildings must not suffer any damage during frequent, small earthquakes, could have repairable damage during moderate earthquakes, and should not collapse during severe earthquakes.

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. However, brittle collapse during moderate and severe earthquakes should always be avoided by placing the necessary reinforcement, in order to prevent the loss of life.

The first Peruvian the Adobe Code was approved in 1985 as an integral part of the National Building Code (Ref. 7). This code has been used to develop general guidelines to generate seismic codes (Refs. 8 and 9), and as a crucial reference for the development of seismic codes in other countries, such as India and Nepal.

The current version of the Peruvian Code (Ref. 10) has a rather typical format. First, it presents a declaration of scope, general requirements and definitions of structural elements and components. Then, it describes the seismic behavior of adobe buildings, gives the expression for the calculation of the seismic design force, and provides specifications for the dimensioning of the structural systems. Finally, it defines allowable stresses for the masonry and gives specifications for the design of adobe walls. Adobe buildings should be dimensioned by rational methods based on principles of mechanics and with elastic behavior criteria. However, it also recommends placing reinforcement in slender walls to improve their behavior during the inelastic phase.

The seismic action is represented by a lateral force H = SUCP, where C is the percentage of weight that must be applied laterally as seismic load. C depends on the zone where the building is located. In the highest seismicity zones, C is equal to 0,20. The soil factor S is 1,00 if the soil is good (rock or very dense soil) and 1,20 when the soil is soft or intermediate. The use factor U is 1,00 for houses and 1,20 for buildings such as schools or medical facilities. The weight P must include 50% of live load. Therefore, an adobe building house located at a place of high seismicity with intermediate soil conditions, must be designed to elastically withstand a lateral force H =SUCP = 1,20 x 1,00 x 0,20 x P = 0,24 P, or almost one fourth of its total weight.

Past earthquakes have shown that adobe buildings suffer much more damage when located on soft soils rather than on stiff soils. Hence, it would seem adequate to increase the soil coefficient S for adobe buildings on intermediate soil and forbid earthen buildings on soft soils.

In the zone of highest seismicity 2-story adobe houses are not allowed. They are only allowed in zones of lower seismic hazard, as long as the second story is built with a lightweight material such as *quincha* (wooden frames filled with crushed cane and plastered with mud).

Some general recommendations for good seismic behavior are that adobe houses must have sufficient wall density in both principal directions, with a floor plan as symmetric as possible, wall openings should be small and centered, and reinforcement should be provided to tie the walls together. Foundation and plinth should be built with cyclopean concrete or stone masonry.

The adobe walls must be designed to elastically withstand seismic forces and to transmit them to the foundation. The allowable stresses are: 1) Compressive strength of adobe blocks, f_o = average strength of 6 cubes, or f_o =12 kg/cm^2. 2) Compressive strength of adobe masonry, f_m = 0,25 f'_m, where f'_m is the compressive strength of adobe masonry piles, or f_m = 2 kg/cm^2. 3) Crushing strength of adobe masonry = 1,25 f_m. 4) Shear strength of adobe masonry, V_m = 0,40 f'_t , where f'_t is the ultimate strength of small walls in tested under diagonal compression, or V_m = 0,25 kg/cm^2.

All adobe walls must be adequately braced by transverse walls, buttresses or reinforced concrete columns. Horizontal braces can be provided by wooden or concrete crown beams. The Code provides geometric specifications to guarantee reasonable seismic behavior. The maximum length of the wall between braces must be 12 times the thickness of the wall, and the openings must be centered and short (Fig. 6).

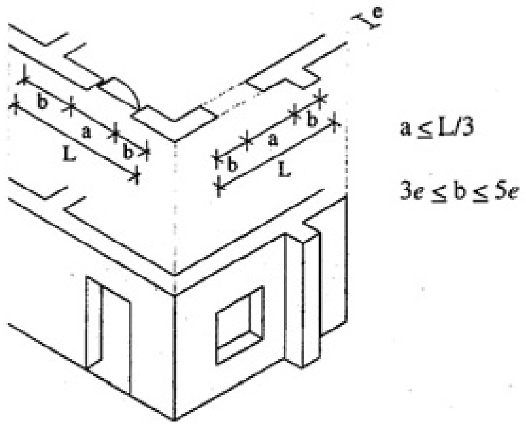


Figure 6. Code specifications for wall openings

The presence and amount of reinforcement requirements depend on the slenderness of the walls, as shown in table 1. The reinforcement of adobe walls can be made out of cane, welded mesh or concrete.

Table 1. Reinforcement specifications for adobe walls. Slenderness λ is the heigth/thickness ratio

Slenderness	*Mandatory Reinforcement*	*Minimum wall thickness (m)*	*Maximum wall height (m)*
$\lambda \leq 6$	Crown beam	0,4 – 0,5	2,4 - 3,0
$6 \leq \lambda \leq 8$	Crown beam + horizontal and vertical reinforcement elements at wall joints	0,3 – 0,5	2,4 – 4,0
$8 \leq \lambda \leq 9$	Crown beam + horizontal and vertical reinforcement elements along wall length	0,3 – 0,5	2,7 – 4,5

The Code requires the use of crown beams on the top of all adobe walls. This requirement is reasonable, because it is consistent with experimental evidence that shows that the crown beam integrates the walls and helps to delay collapse of the walls after they have developed vertical cracks at the corners. Additionally, crown beams contribute to a more effective distribution of the weight of the roof over the walls and to include the roof in the overturning control of exterior walls.

Table 1 shows that walls with slenderness λ smaller or equal to 6 can be built without reinforcement. This specification contradicts field and laboratory observations that walls without reinforcement have a brittle failure after they have cracked due to the seismic action. For walls with slenderness between 6 and 8, the Code only requires horizontal and vertical reinforcement elements at the joints. However, the collapse of heavily cracked adobe walls, which have separated into independent pieces, can only be avoided with a continuous reinforcement configuration along the entire wall. The Code also allows the construction of slim walls, with slenderness between 8 and 9 (and up to 12 with technical validation) that must be integrally reinforced. It would seem too risky to build such slender walls in zone of high seismic hazard. It seems, therefore, that these Code specifications are not conservative and are unsafe. Continuous reinforcement should be mandatory for all adobe walls, independently of their slenderness, at least for zones of high seismicity, and where collapse of adobe houses has been reported, and the maximum slenderness requirements should depend of the seismicity of the building site.

5 FINAL THOUGHTS AND RECOMMENDATIONS

The aim of any building code for earthquake-resistant design of adobe buildings should be to disseminate the construction knowledge that will guarantee the safety and economy of the users.

The earthquake-resistant code provisions for adobe are addressed to professionals involved in the design and construction of adobe buildings. In most countries, only certified professionals are legally allowed to sign projects, and these professionals belong to the formal system, where very few people live in earthen houses designed in accordance with the code. On the other hand, most of the people that build and live in adobe houses belong to the informal system and do not know or use the Code. Therefore, most Adobe Codes for seismic areas do not fulfill their aim, because they do not reach the users whom it should benefit.

In order to take care of the needs of the majority of people that belong to the informal system, it is necessary to use tools complementary to the Code, such as construction manuals and booklets and educational campaigns through popular organizations, local governments, and the media. This will help disseminate the basic concepts earthquake-resistant construction with adobe.

The code provisions should faithfully collect the acquired knowledge from research programs and from observation of the effects of past earthquakes. This knowledge must be translated into simple and direct recommendations that could be implemented by the dwellers, with limited technical support. The acquired knowledge should not be distorted with less demanding requirements, with the idea of reaching a greater number of users. This would be a serious blunder, similar to lowering the quality of medicine in order to make it more affordable to more patients.

The contents of the Code are the result of considerable research efforts to reduce the consequences of earthquakes, especially in highly populated areas. A well conceived code is an indispensable tool to guide the professional community in the design and construction of affordable and safe earthen buildings.

It is clear that, in order to succeed, any massive dissemination and implementation program on safe earthen construction must have political support from the government. The professional community, however, has the responsibility of disseminating the knowledge among the adobe builders, to mitigate the risk of earthen houses in seismic areas, which today has reached unacceptable levels.

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