Earthquake Resistant Design Criteria and Testing of Adobe Buildings at Pontificia Universidad Católica del Perú

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Abstract: *Research work on the seismic resistance of earthen buildings started in Peru at the beginning of the 1970s with the occurrence of the devastating May 31, 1970, Huaraz earthquake. The Pontificia Universidad Católica del Perú (PUCP), or Catholic University of Peru, among other institutions, began a program to investigate the seismic behavior of earthen buildings using a tilt-up table where full-scale models 4 × 4 m (about 13 × 13 ft.) in plan could be built and tested. The main outcome of these initial tests was identifying the need for using continuous, compatible reinforcement inside the adobe walls, such as that provided by the choice of round and split bamboo cane as an appropriate reinforcing material. In the 1980s a shake table was installed at the PUCP Structures Laboratory for testing similar models using seismic unidirectional simulation. These dynamic tests corroborated the results obtained using the tilt-up table. In the 1990s the research program focused on reducing the vulnerability of existing buildings through the use of reinforcement techniques that could be applied externally on the wall surface—mainly welded steel mesh covered with a sand-cement stucco. Since 2003 dynamic testing on full-scale adobe models has focused on the use of polymer mesh as a reinforcement material. This appears to be compatible with earthen buildings up to high levels of seismic acceleration. Continuing work on the seismic resistance of earthen buildings carried out by the Catholic University over the last thirty-five years has provided valuable input to the seismic design criteria stated in the various Peruvian adobe building codes. In all versions of the code (1977, 1985, and 2000), the elastic criterion has been used to design for initial strength, and the limit state design concept is present in the reinforcing systems required to avoid collapse.*

Introduction

Peru is located in the Pacific Ocean Ring of Fire, where most of the world's earthquakes occur. Seismic activity has been frequent and intense in the coastal areas of Peru throughout its history. Peru is also a repository of a long tradition of earthen building construction, from pre-Inca times through the colonial period and up to the present. Many examples of monumental and vernacular earthen architecture have survived that show the degree of technical expertise of the ancient builders. At present, earthen building construction is mostly used in the rural areas, with a diminishing quality of construction either because of the workmanship or because of changes in the architectural layout, such as the imitation of modern brick masonry architecture, which has negative consequences for the building's seismic resistance. The occurrence of a number of strong earthquakes between the years 1940 and 1978 sparked a systematic research project in several Peruvian universities, among them the Catholic University, which began studies on the seismic resistance of earthen buildings in 1972. The results obtained during this continuous research period have provided invaluable input to the three versions of the Peruvian Adobe Building Code. This paper summarizes the contribution to the knowledge regarding earthen buildings obtained from the experimental research projects carried out at the PUCP.

Beginning of Research at PUCP: 1972–80

It is widely recognized that analysis of the response of earthen buildings is particularly complex when they are subjected to static testing. Because of their large mass, weakness in tension, and brittleness, it is difficult to apply concentrated loads to earthen models. The first tests carried out at the Catholic University were performed with a tilt-up table that simulated the inertial earthquake forces with the inclined component of its own weight. With this testing technique, several reinforcement procedures using wood, bamboo cane, and steel wire were tested on full-scale models (Corazao and Blondet 1973). Nevertheless, static tests were also performed on full-scale walls subjected to horizontal shear and flexure, in order to study the mechanical characteristics of adobe masonry (Blondet and Vargas 1978). The most efficient reinforcement procedure at this stage was found to be placement of whole bamboo canes in the interior of the walls at a spacing of one and a half times the wall thickness. The canes were cross tied with horizontal split canes placed every four layers. Initial monotonic tests of this reinforcement showed that this technique provided an important increase in the deformation capacity of adobe walls.

Initial Dynamic Testing: 1980–90

In 1984 the first seismic simulation tests using the unidirectional shake table of the Structures Laboratory at PUCP were performed within the framework of a cooperative project with the financial support of the United States Agency for International Development (USAID) (Vargas et al. 1984). Full-scale adobe building models without roofs, and with and without internal cane reinforcement, were tested by subjecting them to several seismic motions of increasing amplitude. The main conclusion was that in the event of a severe earthquake, the internal cane reinforcement together with a wooden ring beam located in the upper part of the wall prevents wall separation and consequent out-of-plane collapse. In a subsequent research project, models with a roof and several alternative methods of cane reinforcement, including one model reinforced with only vertical canes, were subjected to similar seismic simulation tests. It was concluded that in order to maintain the integrity of the adobe walls, both horizontal and vertical reinforcements are necessary. These tests were performed using a displacement command signal derived from the longitudinal component of the May 31, 1970, Huaraz earthquake. The signal was then filtered for low and high frequencies in order to meet the table capabilities.

Focus on the Vulnerability of Existing Houses: 1990–2000

In accordance with the International Decade for the Reduction of Natural Hazards, a joint research project between the Centro Regional de Sismología para América del Sur (CERESIS), the German Agency for International Development (GTZ), and PUCP focused experimental work on existing houses, with the objective of reducing the seismic vulnerability of earthen buildings. Natural fiber ropes, wood, chicken wire, and welded steel wire mesh placed at critical points were tried as reinforcement materials (Zegarra et al. 1997). The best solution found was the use of welded steel mesh applied on both faces of the wall, vertically at the corners and horizontally at the top of the walls, simulating columns and beams. The tests were performed on U-shaped walls to increase the number of directional effects obtained in each seismic simulation. As a practical complement to the experimental research program, rural houses in several parts of Peru were reinforced using this technique (Zegarra et al. 1999).

Dynamic Testing on Retrofitting Techniques: 2003

In 2003 a strong earthquake hit the southern part of Peru, causing extensive damage in all types of buildings. Among them, thousands of earthen houses in the coastal and Andean areas were affected. The houses retrofitted with steel mesh and sand-cement plaster in 1999 withstood the effects of this earthquake without damage, becoming a model for a reconstruction project of several hundred houses in the area (Zegarra et al. 2001). In order to corroborate the effectiveness of this reinforcement, three model houses with a geometrical layout similar to the one built in the reconstruction project were tested dynamically (Zegarra et al. 2002).

The first model (URM-01) was built without any reinforcement in order to serve as a baseline for the reinforced models. The second model was reinforced on both sides of the wall with horizontal and vertical bands of welded wire mesh protected with a cement mortar (RM-SM). Vertical bands were placed at all corners, and the horizontal band was placed at the top of the walls, simulating a ring beam. The third model (RM-RC) was similar to the previous one, but a reinforced concrete ring beam was added that was anchored to the walls with shear connectors at all corners. All models were subjected to several seismic motions of increasing intensity. The seismic performance of the unreinforced model was used to establish a relationship between the table displacement and the Modified Mercalli intensity scale (MMI).

The results showed that for strong motions, equivalent to intensity MMI = X, partial collapse and global instability are not avoided with this reinforcement technique. The reinforced mortar bands are much stiffer than the adobe walls and tend to absorb most of the seismic forces until the elastic resistance is reached and a fragile rupture occurs.

Introduction of Polymer Mesh as a Compatible Reinforcing Material: 2003–6

Since 2003 polymeric materials were used in the experimental work as an alternative for reinforcement in earthen buildings. The advantage of this material lies in the compatibility with the earthen wall deformation and its ability to provide an adequate transmission of tensile strength to the walls up to the final state. In the first experimental program (Blondet et al. 2005), I-shaped adobe walls with several reinforcing techniques were subjected to cyclic static tests. Among them, internal and external polymer mesh was used as wall reinforcement (see fig. 1).

The results showed that external polymer mesh confines the adobe wall up to high levels of horizontal displacement, allowing a great amount of energy dissipation in comparison with the unreinforced wall and with the wall reinforced with stiff steel mesh and sand-cement plaster.

In 2004 a joint project between the PUCP and the Getty Conservation Institute (GCI) aimed to corroborate dynamically the effectiveness of external compatible reinforcement using natural and industrial meshes. Two model houses with geometrical characteristics similar to the CERESIS-GTZ-PUCP project were tested with external reinforcement. One of them (RM-NM) was reinforced with natural materials using whole bamboo cane as vertical reinforcement and ropes as horizontal reinforcement (see fig. 2). The reinforcement was placed at both sides of the wall and connected with a small cabuya thread through a hole previously drilled in the wall. The second model (RM-PM100) was reinforced with a polymer mesh (geogrid) completely covering the walls on both sides. The mesh was connected with plastic thread through holes previously drilled in the walls spaced 40 cm (15.6 in.) in two orthogonal directions. In both models, mud stucco was applied to half of the structure in

FIGURE 1 Cyclic static test results.

FIGURE 2 Natural materials (RM-NM).

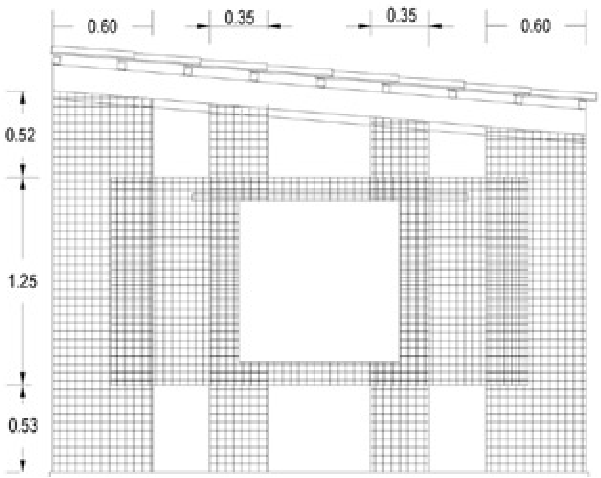

FIGURE 3 Reinforcement distribution for RM-PM75 (dimensions are given in meters).

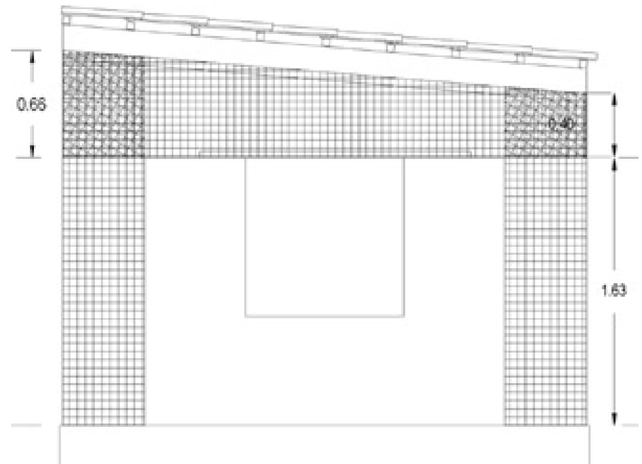

FIGURE 4 Reinforcement distribution for RM-PM50 (dimensions are given in meters).

order to study the effect of stucco on the effectiveness of reinforcement (Torrealva and Acero 2005).

The results showed that placing an external natural or industrial mesh on both sides and connecting through the thickness of the adobe wall is an effective way to avoid partial or total collapse of adobe buildings, even in severe earthquakes. If the mesh is not covered with mud stucco, the initial strength is the same as the plain, unreinforced wall, and the mesh becomes effective after the wall is cracked. After the cracking, the mesh confines the different sections into which the wall is broken, thus preventing partial or total collapse. In both cases, the mud plaster over the mesh greatly increases the initial shear strength and the stiffness of the wall, controlling the lateral displacements and preventing the cracking of the wall to a great extent. This is particularly notable in the case of the polymer mesh.

Based on these results, the polymer mesh reinforcement placed over the entire wall can be considered the upper limit of the amount of external reinforcement. The natural alternative, on the contrary, can be considered as near the lower limit of the external reinforcement, because of the bigger spacing between horizontal and vertical elements.

After the GCI-PUCP project, additional dynamic testing was performed on models with the same geometric characteristics, but with varying amounts and quality of polymer mesh, in an attempt to reduce the overall cost of the mesh technique. Three additional models were tested using the same geometric characteristics and seismic motions as in the two previous projects. Model RM-PM75 was reinforced by covering 75% of the wall surface with polymer mesh (see fig. 3), model RM-PM50 covered 50% of the wall surface (see fig. 4), and model RM-LCM was reinforced at 100% on one longitudinal wall and at 70% on the parallel wall but with a low-cost polymer mesh (see fig. 5).

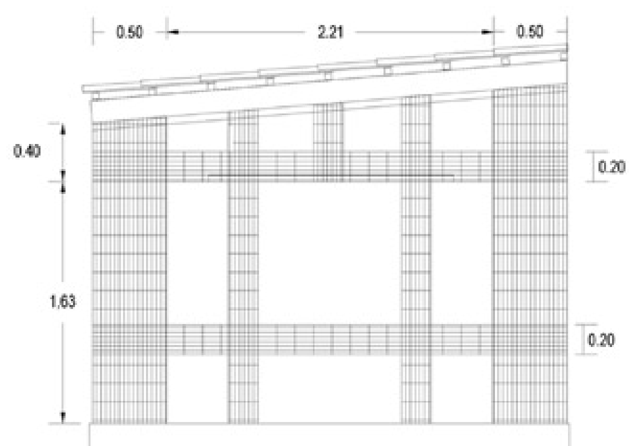

FIGURE 5 Reinforcement distribution for RM-LCM (dimensions are given in meters).

The results of this last group of dynamic tests showed that the amount of mesh placed on the walls is more important than the resistance of the mesh. The wall, fully plastered and reinforced with low-cost mesh, had a better seismic performance than the models reinforced with stronger mesh at 75%. In all cases, the testing also confirmed the beneficial effect of having the plaster cover the mesh.

Application of Polymer Mesh Reinforcement to Vaulted Models

Between December 2005 and February 2006, two vaulted models were subjected to seismic simulation tests using the same earthquake signal, for the sake of comparison with the models with traditional occidental architecture. The models were designed by the Program for the Enhancement of the Modernization of the Health Sector in Rural Areas (AMARES), a nongovernmental organization (NGO) working on implementation of health infrastructure in the Andean areas of Peru, with the technical advice of architects from the University of Kassel in Germany.

Model URV was unreinforced, and model RV-PM100 was fully reinforced with polymer mesh on both sides of the wall. The results showed that the unreinforced adobe vault was very vulnerable and collapsed at lesser motion intensity than did the unreinforced traditional houses (see fig. 6a). The fully reinforced vault, on the contrary, performed well even in the final phases of testing at the maximum acceleration intensities of table shaking (see fig. 6b).

Seismic Performance of Models

Almost all seismic simulation testing performed in the Structures Laboratory at PUCP has been done using a table command signal derived from the longitudinal component of the May 31, 1970, Peruvian earthquake. In addition to this, the last three experimental projects have tested identical models while varying the amount and type of reinforcement. This fact makes it possible to compare the seismic performances of the different models tested through the years. Table 1 shows a list of all models tested in the last four years along with their reinforcing characteristics: unreinforced models, models reinforced with welded wire mesh, and models reinforced with polymer mesh placed in several configurations.

For the purpose of comparison, a range of table-induced damage was established: ND means no damage; LD means light damage, with small cracks; HD stands for heavy damage, with large cracks and some structural instability; and C signifies total or partial collapse. The seismic performance of all these models is depicted in table 2.

(a) (b)

FIGURES 6A AND 6B Test results showing the collapse of unreinforced model URV (a); the fully reinforced vault RV-PM100 (b) fared better.

Table 1 Reinforcement description for models

Model	Reinforcement description
URM-01	Nonreinforced—traditional
RM-SM	Welded wire mesh with cement plaster, vertically at corners and horizontally at top on both sides of wall
RM-RC	Welded wire mesh as RM-SM, plus reinforced concrete ring beam with shear anchors to the wall at corners
RM-NM	Natural mesh with vertical whole cane and horizontal fiber rope placed externally on both sides of wall
RM-PM100	Polymer mesh covering the wall at 100% on both sides
URM-02	Nonreinforced—traditional
RM-PM75	Polymer mesh covering the walls at 75% on both sides
RM-PM50	Polymer mesh covering the walls at 50% on both sides
RM-LCM	Low-cost polymer mesh covering half of the model at 100% and the other half at 70%
URV	Nonreinforced vaulted model
RV-PM100	Vaulted model with polymer mesh covering the model completely on both sides

Table 2 Seismic performance of models (2003–6) (ND = no damage; LD = light damage with fine cracks; HD = heavy damage with wide cracks; C = total or partial collapse with instability)

Maximum table displacement D_0 (mm)	Associated intensity (MMI)	CERESIS-GTZ-PUCP (2003)			GCI-PUCP (2005)			PUCP (2005-2006)			AMARES vaults (2006)	
		URM-01	RM-SM	RM-RC	RM-NM	RM-PM100	URM-02	RM-PM75	RM-PM50	RM-LCM	URV	RV-PM100
≤ 30	< VI	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
$30 < D_0 \leq 70$	VII	LD	ND	ND	LD	LD	—	—	—	—	LD	LD
$70 < D_0 \leq 90$	VIII	HD	LD	LD	HD	LD	HD	HD	HD	LD	C	HD
$90 < D_0 \leq 110$	IX	C	HD	HD	HD	HD	—	—	—	—	—	HD
$110 < D_0 \leq 135$	X	—	C	C	HD	HD	C	HD	C	HD	—	HD

Table 2 shows that the general conclusion is that continuous external reinforcement is necessary to avoid collapse, and this reinforcement has to be compatible with the deformations of earthen building. In this sense, stiffer bands, such as welded wire mesh with sand-cement stucco, prevent cracking at higher levels of seismic intensity but do not work jointly with an adobe wall for severe seismic motions, and they show brittle final behavior. On the contrary, polymer and natural flexible meshes embedded in a mud mortar work together with adobe walls up to high levels of seismic intensity without collapse. In addition, it can be said that the polymer mesh is also appropriate for any type of architectural configuration.

Evolution of Adobe Building Codes and Design Criterion

From the beginning of the research program in 1972 until now, the focus of the design has been placed on avoiding the collapse of the earthen structures (ultimate state criterion) in addition to providing adequate elastic resistance. The first Adobe Building Code, in

1977 (Oficina de Investigación y Normalización 1977), established the basic architectural configurations that should be used in order to obtain an adequate seismic behavior. Such considerations have been improved in the subsequent versions of the code. The use of natural cane as reinforcement is also indicated in a general way as a means of preventing failure. The 1987 version of the code (Instituto Nacional de Investigación y Normalización de la Vivienda 1987), based on the experimental work at PUCP, established a specific procedure for using cane as internal reinforcement. The elastic criterion and the ultimate state criterion are maintained in this version. The 2000 code (Ministerio de Transportes, Comunicaciones, Vivienda y Construcción 2000), influenced by the work performed in the Getty Seismic Adobe Project (GSAP), introduced the concept of stability based on the slenderness of the wall (Tolles, Kimbro, and Ginell 2002). Another important inclusion was the shift in the target structures from new to existing buildings, with alternative design criteria influenced by the use of stronger and stiffer reinforcing materials. Even though the use of external reinforcement is mandatory for existing buildings, it has been quickly demonstrated that flexible and compatible materials perform much better than stiffer and stronger materials in large earthquakes. On the other hand, the present version of the code maintains the architectural layout recommendations regarding wall thickness, plan dimensions, and location of openings that were present in all previous versions of the Peruvian code.

Therefore, it can be said that the general criterion that governs the design of earthen buildings is based on the seismic performance for small, medium, and strong earthquakes. For small earthquakes the aim is to minimize the wall cracking by following certain architectural configurations and by a simple calculation of shear forces in the elastic range. For medium and strong earthquakes, the target performance is to avoid both partial and total collapse by the use of continuous, flexible, and compatible external or internal reinforcement. In the case of external reinforcement, it is recommended that it be embedded in a mud plaster.

Conclusion

The work performed over the last thirty-five years at PUCP has confirmed the basic engineering principles that can be applied in developing reinforced earthen buildings to resist earthquakes. The next step is to determine the technical specifications necessary to design earthquake resistant earthen buildings.

Adobe walls must work jointly with the compatible reinforcements embedded in the walls. This is obtained by the application of mesh-type reinforcement either internally or externally. In the case of external reinforcement, it has to be applied on both sides of the wall and connected by natural or industrial threads in holes through the wall. The plaster mortar has to have a minimum thickness to assure the integrity of the reinforcement with the wall and to provide protection from the environment. Mud mortar mixed with fibers should be used as plaster to allow moisture transfer between the wall and the environment.

Polymer mesh has proven to be an adequate material for reinforcing earthen buildings because of its compatibility with the earth material, because of its resistance to biological and chemical agents, and because its tensile strength can be transferred to the wall where it is applied.

The solution found so far for traditional, occidental architectural configurations can also be applied to other architectural typologies around the world where earthen construction is used.

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