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SEISMIC REINFORCEMENT OF ADOBE HOUSES USING EXTERNAL POLYMER MESH

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SUMMARY

Earthquakes occurring in developing countries demonstrate again and again that adobe houses are highly vulnerable and that millions of people who live in these houses are at great risk. This underscores the urgency to find simple and economic solutions to reinforce these buildings. This paper summarizes a research project developed to explore the use of plastic meshes as reinforcement for adobe structures. Five full-scale adobe house models were tested on the shaking table of the Catholic University of Peru. The first model was unreinforced and represented a typical adobe dwelling. Its behavior under strong shaking was quite poor, with brittle failure of the walls. The second model was overreinforced by completely wrapping all walls with a geogrid. During the dynamic tests the model moved practically as a rigid body, with little damage on the adobe walls and a sliding failure of the walls on their concrete foundation. The third and fourth models had a more sparse reinforcement consisting of bands of a lighter geogrid, placed at selected locations. Their seismic behavior was adequate. Although the walls were damaged, the reinforcement bands were able to hold the pieces together and collapse was averted. The fifth model was reinforced with a cheaper plastic mesh used as protection in construction sites. Its seismic response was also adequate. These tests show that it is possible to use plastic mesh as a convenient seismic reinforcement of adobe houses.

1. INTRODUCTION

Sun dried mud blocks, or adobes, are one the oldest and more widely used building materials in the world. Adobe is still used in many developing countries because soil is easily available and self-construction with this material is relatively simple. Furthermore, adobe dwellings have excellent thermal and acoustic characteristics. The seismic performance of vernacular adobe dwellings, however, is extremely poor. Every significant earthquake that has occurred in regions where adobe construction is common has produced tragic loss of life and considerable material damage (Fig. 1).

Figure1. Destruction of adobe houses in El Salvador (2001) and in Iran (2003).

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The high seismic vulnerability of adobe masonry is due to a perverse combination of its mechanical properties: relatively high density, extremely low tensile strength, and brittle failure mode. The problem is made worse because most “modern” vernacular adobe houses are built without technical assistance, and thus with poor construction quality, and they tend to imitate the architectural features of clay masonry buildings: several stories, thin walls, large openings, and irregular configurations (Fig. 2).

Figure 2. “Modern” adobe houses in Cusco, Peru.

During the last three decades, researchers at the Catholic University of Peru (PUCP) have attempted to find solutions to improving the seismic performance of earthen buildings. They have developed reinforcement systems using natural materials such as wood and cane (Blondet et al. 1988), or industrial materials such as wire mesh covered with cement mortar (Zegarra et al.1997).

Although a bamboo cane mesh was found to be an effective and economical seismic reinforcement for adobe houses, it is not possible to use this technology in massive construction programs, because in most places cane is not available in the quantity required. Wire mesh covered with cement mortar, on the other hand, can be used as an external reinforcement for new and existing houses. However, wire mesh and cement are prohibitively expensive for the inhabitants of earthen houses in developing countries. An important challenge is therefore to develop an adequate reinforcement technique using cheap, industrially manufactured materials.

This paper describes the results of an experimental program developed at PUCP whose main objective was to find ways to use small amounts of polymer mesh reinforcement as seismic reinforcement of earthen buildings.

2. PROJECT DESCRIPTION

The project described in this paper consisted of the seismic testing of five full-scale adobe housing models using the unidirectional PUCP shaking table. The adobe models had the configuration and overall dimensions shown in Fig. 3 below.

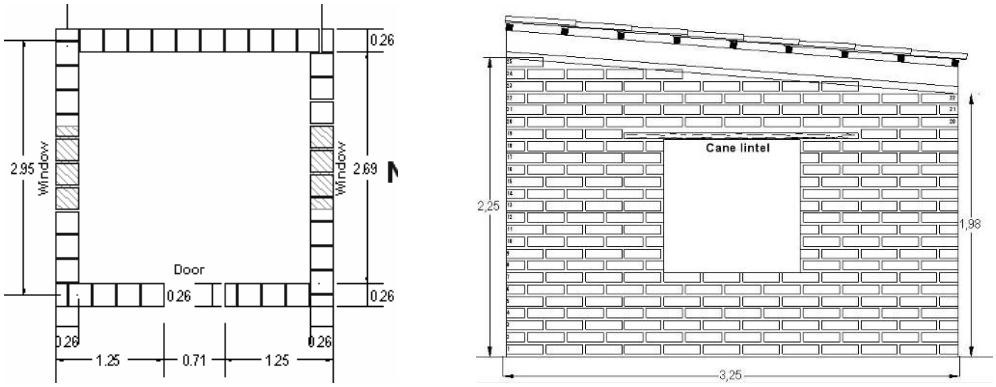


Figure 3. Plan view and elevation of adobe models (Dimensions in m)

The adobe models consisted of four walls 3.21 m long, variable height, and 0.26 m thickness. The longitudinal walls (parallel to the direction of shaking) included a central window opening. The front transverse wall had a door opening and the taller back wall did not have any openings. They were reinforced with different amounts

and types of polymer mesh, designed according to the stability based criterion used in the Getty Seismic Adobe Project (GSAP, Tolles et al. 2000), which attempts to predict the crack patterns of the adobe walls and then provides the minimum amount of reinforcement required to control these cracks and therefore to avoid significant damage.

Two types of polymer mesh were used: an industrial geogrid and a more economical plastic mesh commonly used as a "soft" fence in construction sites. Table 1 identifies the adobe models tested and provides some information on the polymer mesh used in each case. Tensile strength values are shown as force per unit width at 2% elongation and correspond to the strongest mesh direction. Reinforcement cost estimates are given in US dollars per square meter of model's plan area (10.3 m^2) and include only the cost of the materials employed (mesh, plastic string, nails).

Table 1. Adobe housing models tested and mesh reinforcement characteristics

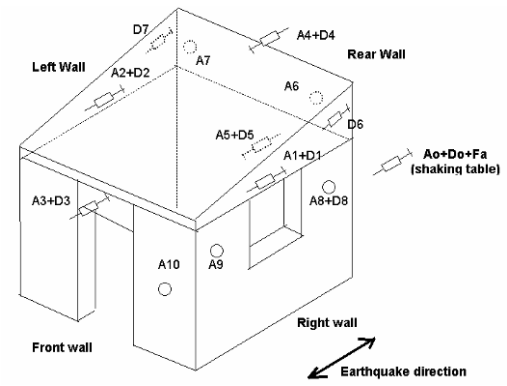
Model ID	Reinforcement amount	Mesh type	Mesh Strength kN/m	Mesh cost US$/$m^2$	Reinforcement cost US$/$m^2$
M000	None	-	-	0.00	0.00
M100-T12	Full (100%)	Tensar BX1200	9.0	2.00	19.00
M075-T11	Partial (75%)	Tensar BX1100	6.6	1.50	9.00
M050-T11	Partial (50%)	Tensar BX1100	6.6	1.50	6.00
M080-E	Partial (80%)	Soft plastic fence	1.4	0.50	4.00

All models were built using traditional techniques, representative of seismically vulnerable adobe construction in Peru. The adobe blocks were fabricated with soil, coarse sand and straw in proportion 5:1:1. They measured 65x250x250 mm and were joined with mud mortar made with soil, coarse sand and straw in proportions 3:1:1. Each specimen was built over a reinforced concrete foundation ring beam, which also served to anchor the specimen to the shaking table and as support during transportation from the construction yard to the laboratory. A wooden crown beam was placed on top of all specimens, except model M000, to integrate all walls and to transmit the roof weight to the longitudinal walls.

The roof consisted of wooden joists covered with cement tiles. Each specimen weighed around 140 kN. Both windows had flexible lintels made of cane rods, except model M100-T12, which had wooden lintels. The flexible lintels were used as an attempt to avoid local failure, observed in previous tests, caused by the impact of the stiff wooden lintel against the earthen walls. Masons with experience in building adobe houses were hired to fabricate the adobe blocks and to build the housing models. The reinforcement provided consisted of bands of polymer mesh tied to both sides of the walls with plastic string threaded through the walls. Figure 4 shows two models under construction. Observe the plastic strings that have been left across the walls of one of the models.

Figure 4. Construction of adobe models

Instrumentation consisted of accelerometers and displacement transducers (LVDTs). Actuator pressure differential (proportional to force), and table acceleration and displacement were also recorded. See Fig. 5 below.



a) Instrumentation schematics

b) Instruments on M000's left wall

Figure 5. Model instrumentation

The 4x4 m unidirectional shaking table at PUCP is displacement controlled. The 30 second displacement control signal used in this project was generated from an acceleration record obtained during the 1970 Huaraz earthquake. Each model was subjected to a sequence of table motions with increasing amplitude. Except for M100-T12, they were subjected to three successive motions ("test phases"), defined by their peak command displacements D = 30, 80 and 130 mm. These motions represented earthquakes of low, medium and severe intensity, respectively. Model M100-T12, tested during a previous project, was subjected to motions with D = 15, 30, 60, 80, and 100 mm, followed by two strong 120 mm shakings. The displacement transducers were removed before the final severe test phases, to prevent damage due to the collapse of the model.

3. TEST RESULTS

3.1 Model M000

This unreinforced model represented a typical vernacular adobe building. During test phase 1 (30mm) diagonal cracks appeared on both longitudinal walls, and the wooden beams supporting the roof detached from the walls. In phase 2 (80mm) important vertical cracks appeared at the corners of the transverse walls, which collapsed during phase 3 (Fig. 6, right). This type of failure is representative of that of vernacular earthen structures: a few large cracks divide the walls in several pieces, which afterwards fail independently.

Figure 6. Unreinforced model M000

3.2 Model M100-T12

Model M100-T12 was completely covered by geogrid on both sides of the walls (Fig. 7). During the first test phases the model moved almost as a rigid block. It remained in the elastic range until phase 3 (60 mm). In phase 4 (80 mm), small cracks appeared in the walls. The cracks were more visible in the mud-plastered right side. In phase 5 (100 mm) the right wall slid from its base almost as a rigid body, without any significant damage. The left wall showed large displacements and significant cracking. Phases 6 and 7 (both 120 mm), caused significant torsional response, sliding at the base, and additional cracking in the non-plastered walls. After the test the mud plaster was removed, revealing the plastered walls suffered very minor damage. This indicates that the mud plaster has an important contribution to the strength and stiffness of the adobe walls.

Figure 7. Reinforced model M100-T12.

3.3 Model M075-T11

This model was partially reinforced with geogrid, which covered around 75% of the total wall surface (Fig. 8).

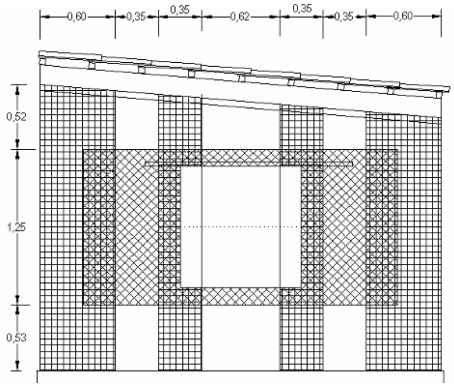


Figure 8. Model M075-T11

The first cracks appeared during phase 2 (80mm), indicating the start of significant nonlinear response, as shown in the force-displacement curves (Fig.9, left). The cracking pattern was typical: vertical cracks at the corners and diagonal cracks at the longitudinal walls (Fig. 9, right).

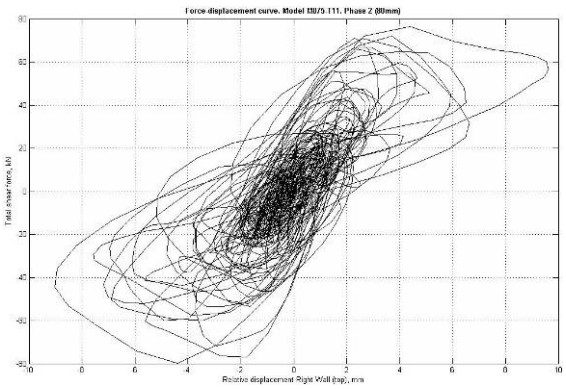


Figure 9. Seismic behavior of model M075-T11

Wall cracking continued in phase 3 (130 mm), but the building kept its integrity because the mesh reinforcement was able to provide displacement control and a more uniform distribution of cracking of the walls. When the mesh was removed after testing, it could be verified that it was deformed or broken in critical locations, such as where it was nailed to the crown beam. Figure 10 (left) clearly shows that the response of the mud-plastered right wall had a higher frequency than that of the unplastered left wall, which confirms that the mud plaster over the external reinforcement substantially increased the stiffness and the strength of the adobe walls.

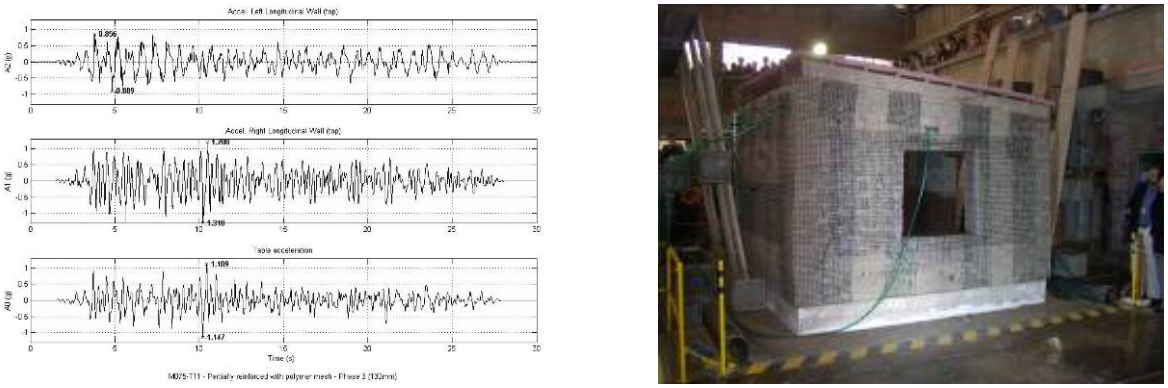


Figure 10. Seismic behavior of model M075-T11 until phase 3

3.4 Model M050-T11

In order to reduce the amount of polymer mesh employed, geogrid reinforcement was placed only in the most critical regions of model M050-T11. As shown in Fig. 11, vertical bands were placed at wall corners and horizontal bands at the top and bottom of the window openings. The reinforcement covered around 50% of the total wall surface.

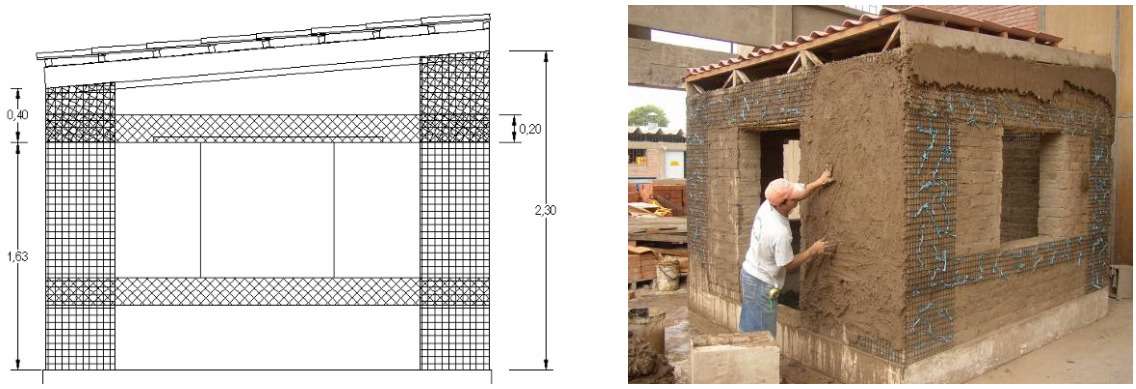


Figure 11. Reinforcement arrangement and construction of model M050-T11.

As for the previous model, the first cracks appeared in phase 2 (80mm). Figure 12 shows that, due to the lesser amount of reinforcement provided, cracks were much larger and consequently, nonlinear response was more pronounced.

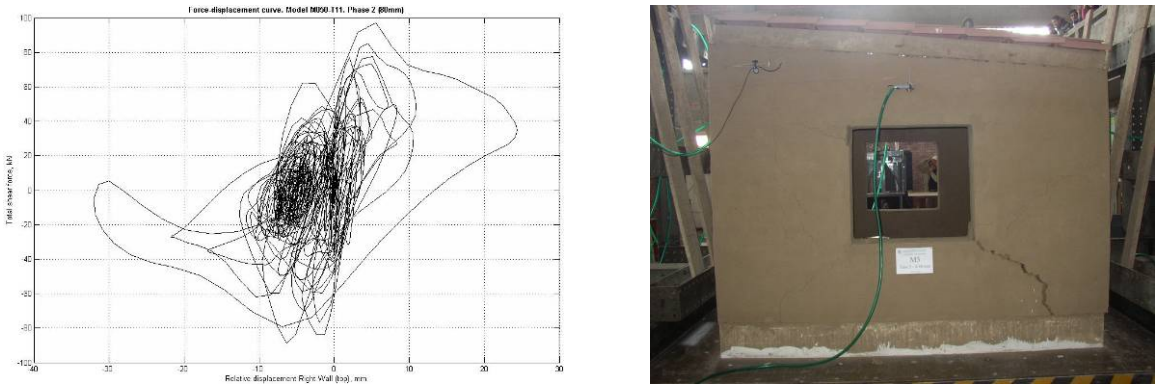


Figure 12. Seismic behavior of model M050-T11

During the strong shaking of phase 3 (D = 130 mm) the model suffered significant damage. Although collapse was averted, the brittle failure of the longitudinal walls showed that the amount of reinforcement provided in those walls was insufficient (Fig. 13).

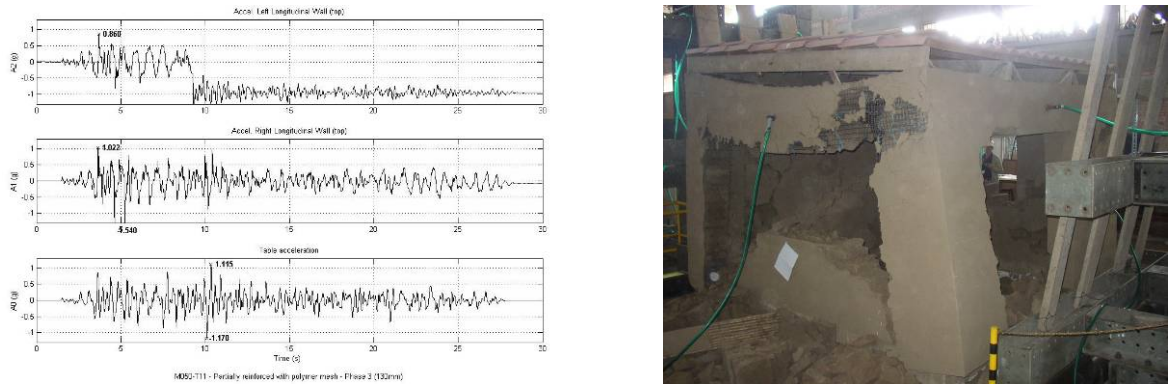


Figure 13. Seismic behavior of model M050-T11 until phase 3

3.5 Model M080-E

Since geogrid 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 left wall was completely covered and the right wall was partially covered, as shown in Fig. 14. Around 80% of the wall surface was thus reinforced.

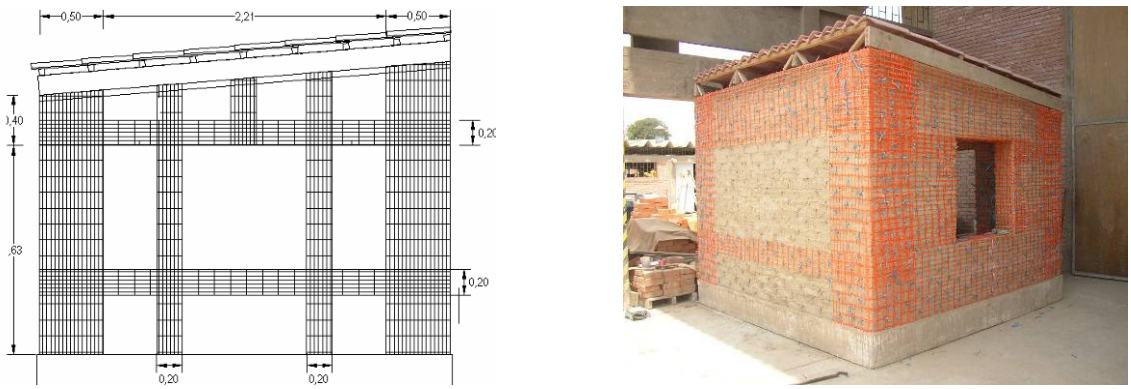


Figure 14. Reinforcement arrangement and finished model M080-E.

During phase 1 (30mm) the model showed an elastic behavior and remained practically uncracked. Some sliding was noticed at the base of the walls. In phase 2 (80mm) diagonal cracking started from the corner of the windows of both longitudinal walls (Fig. 15). Also, some mud plaster fell apart. The transverse wall also showed significant cracking, but did not collapse.

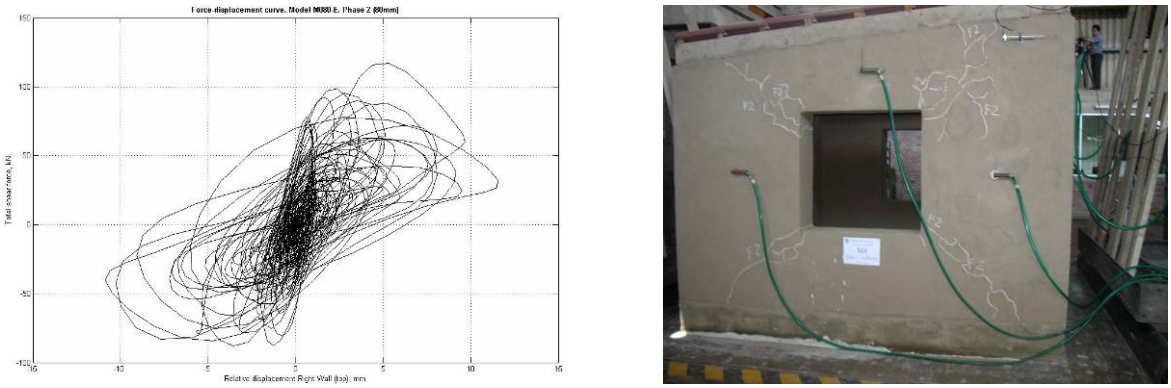


Figure 15. Seismic behavior of model M080-E until phase 2

In phase 3 the model suffered significant damage. The left wall (totally reinforced) had many uniformly distributed cracks. The right wall (partially reinforced) had fewer, larger cracks and was practically broken into several pieces, held together by the plastic mesh (Fig. 16). The mesh was deformed and broken in several places, indicating that the amount provided was barely adequate.

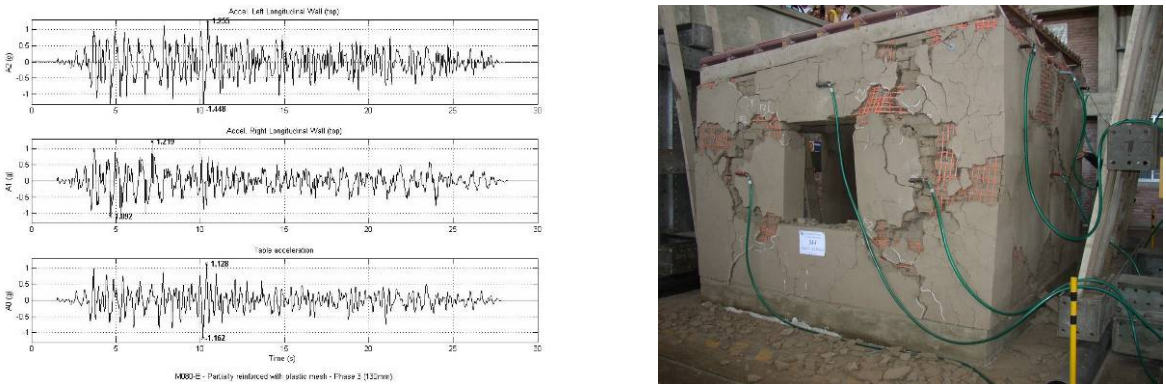


Figure 16. Seismic behavior of model M080-E until phase 3

4. CONCLUSIONS

- Moderate amounts of strategically placed polymer mesh reinforcement can be used to prevent partial or total collapse of adobe buildings, even during severe earthquakes. The mesh should be placed on both sides of the walls, and tightly connected through the walls.
- The polymer meshes used in this project were compatible with the adobe walls. They worked well together even for high levels of seismic intensity.
- It is convenient to cover the reinforcement mesh with mud stucco. The mud plaster increases the initial shear strength and the stiffness of the walls. The mesh starts working after the walls have cracked. Stucco will also protect the polymer mesh from ultraviolet radiation.
- It is not necessary to completely cover the walls with the polymer mesh. Although the optimal amount and placement of polymer mesh should be investigated, it has been found that placing the mesh in critical locations could be sufficient to avoid collapse.

5. REFERENCES

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