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Experimental Study of Synthetic Mesh Reinforcement of Historical Adobe Buildings

Marcial Blondet, Julio Vargas, Jose Velasquez and Nicola Tarque
Catholic University of Peru, Department of Engineering, Lima, Peru

ABSTRACT: This paper describes the results of an experimental program developed at the Catholic University of Peru (PUCP) to provide seismic reinforcement to adobe buildings using small amounts of polymer mesh. The objectives were to avoid the brittle collapse of adobe dwellings and to provide seismic retrofit to historical earthen monuments. Five full-scale adobe housing models with similar dimensions and different amounts of plastic mesh reinforcement were tested on the PUCP shaking table. The unreinforced model suffered brittle failure, revealing the high seismic vulnerability of traditional earthen construction. All the reinforced models had an adequate seismic response and thus showed that it is possible to retrofit earthen structures using moderate amounts of strategically placed plastic mesh.

1 INTRODUCTION

Earthen monuments and buildings are highly vulnerable in earthquakes, as is painfully evident each time a strong earthquake strikes in areas where earthen building is common: there is widespread damage of earthen historical monuments and housing and tragic loss of life due to the collapse of these constructions.

The seismic vulnerability of earthen buildings is due to a perverse combination of mechanical properties of dry earth: 1) earthen structures are massive and thus attract large inertia forces, 2) they are weak and cannot resist these forces, and 3) they are brittle and break without warning. Retrofit of earthen monuments has the objective of providing life safety and structural integrity with minimal impact reversible intervention.

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 mortar reinforced steel mesh (Zegarra et al. 1997) and polymer mesh (Blondet et al. 2005, Torrealva and Acero 2005, Blondet et al. 2006).

Reinforcement solutions that require materials such as wire mesh and cement are too expensive to be used in vernacular housing. They are also inadequate because the stiffness of cement plaster is incompatible with that of earthen walls. Furthermore, in buildings of cultural value cement-based stuccos are inconvenient because they change the plastic appearance of the adobe walls.

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 in order to provide seismic safety to earthen dwellings and historical monuments.

2 PROJECT DESCRIPTION

The project described in this paper consists of the seismic testing of five full-scale adobe housing models using the unidirectional PUCP shaking table. To date (April 2006) the first five models have been tested and are be the subject of this paper.

2.1 Model characteristics

The five models tested had the configuration and overall dimensions shown in Fig. 1. They were reinforced with different amounts and types of polymer mesh. The design of the test specimens followed 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.

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.

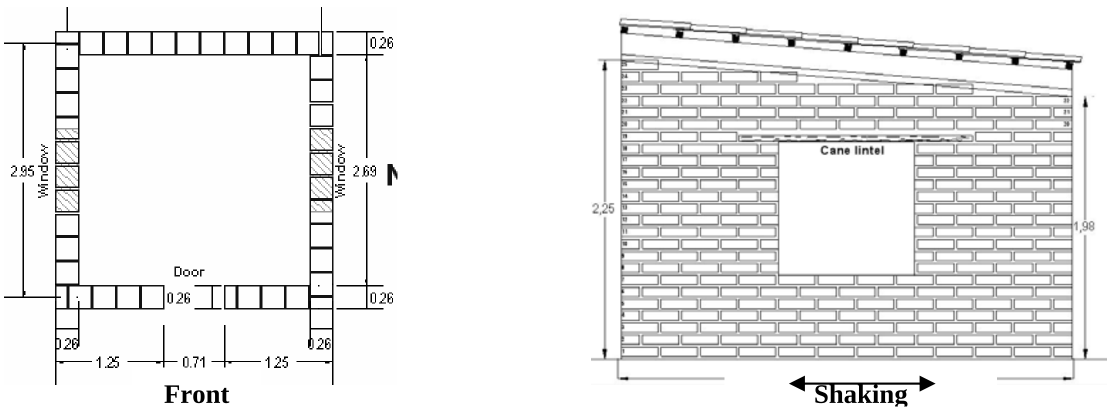


Figure 1 : Plan view and elevation of adobe models (Dimensions in m).

Reinforcement consisted of bands of polymer mesh tied to both sides of the wall with plastic string threaded through the wall. 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 in chronological test date. Tensile strength values are shown as force per unit width at 2% elongation and correspond to the strongest mesh direction.

Table 1 : Adobe models tested and mesh characteristics

Model ID	Reinforcement	Mesh type	Strength kN/m	Approx. cost US$/m^2	Test date
M100-T12	Full (100%)	Tensar BX1200	9.0	2.00	Jan 20, 2005
M000	None	-	-	0.00	May 16, 2005
M075-T11	Partial (75%)	Tensar BX1100	6.6	1.50	May 18, 2005
M050-T11	Partial (50%)	Tensar BX1100	6.6	1.50	Oct 25, 2005
M080-E	Partial (80%)	Safety fence	1.4	0.25	March 23, 2006

2.2 Model construction

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 65x260x260 mm and were joined with mud mortar (3:1:1 of soil:sand:straw). 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.

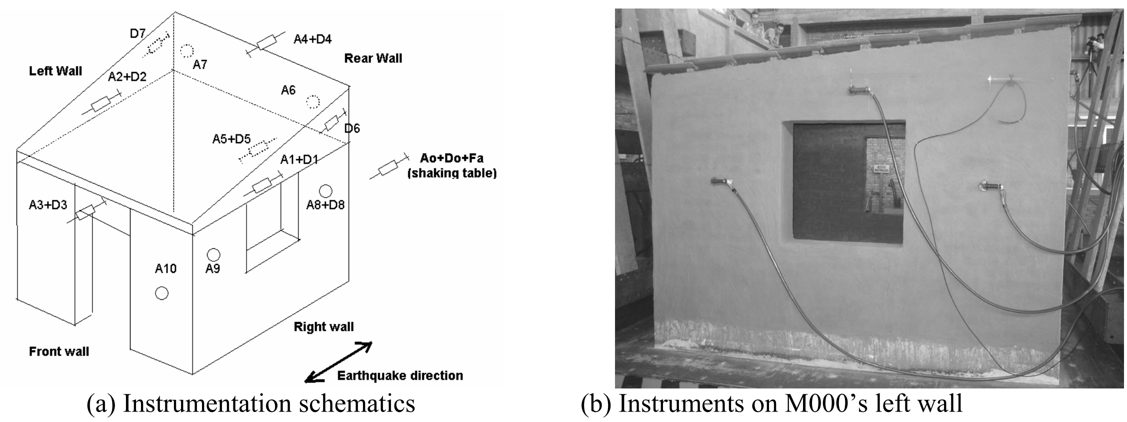
Both windows had flexible lintels made of cane rods, except model M100-T12, which had wooden lintels. The flexible lintels were used as an attempt to avoid local failure, observed in previous tests, caused by the impact of the stiff wooden lintel against the earthen walls. Bricklayers with experience in building adobe houses were hired to fabricate the adobe blocks and to build the housing models. Figure 2 shows two models under construction. Observe the plastic strings that have been left across the walls of M075-11.

(a) Model M000 (b) Model M075-T11

Figure 2 : Construction of adobe models.

2.3 Instrumentation and testing

All models were instrumented with accelerometers and displacement transducers (LVDTs). Actuator pressure differential (proportional to force), and table acceleration and displacement were also recorded. See Fig. 3 below.



(a) Instrumentation schematics (b) Instruments on M000's left wall

Figure 3 : 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 the longitudinal component of the accelerogram registered in Lima during he 1970 Huaraz earthquake (Ms = 7.6). The acceleration record was processed numerically through double integration, bandpass filtering (0.15 – 15 Hz) and smoothing at both ends. Each model was subjected to a sequence of table motions with increasing amplitude. Except for M100-T12, they were subjected to three successive 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 EXPERIMENTAL RESULTS

3.1 Model M100-T12

Model M100-T12 was completely covered by geogrid on both sides of the walls (Fig. 4). 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 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. This effect was corroborated during the tests of model M075-T11 (see Fig. 8).

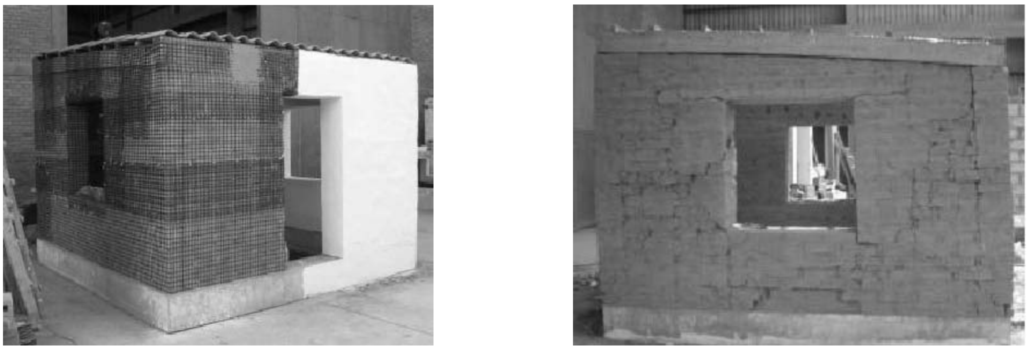


Figure 4 : Reinforced model M100-T12. Geogrid reinforcement and left wall after mesh removal.

3.2 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. 5). 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 5 : Unreinforced Model M000 before the test (left) and after the test (right)

3.3 Model M075-T11

This model was partially reinforced with geogrid, which covered around 75% of the total wall surface (Fig. 6).

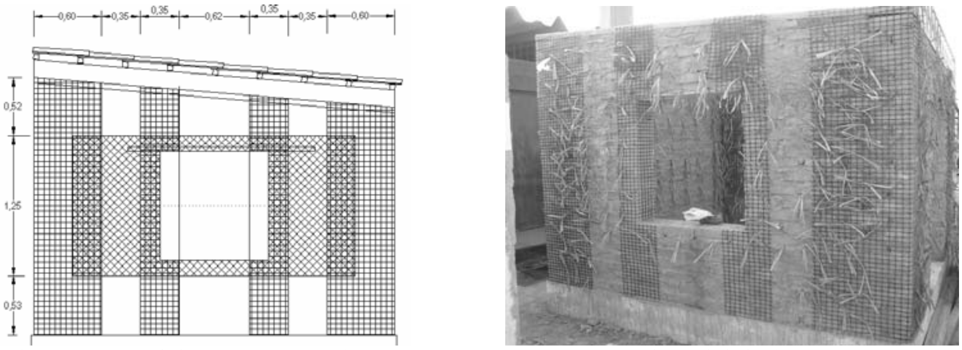


Figure 6 : Model M075-T11: reinforcement arrangement and model during construction.

The first cracks appeared during phase 2 (80mm), indicating the start of significant nonlinear response, as shown in the force-displacement curves (Fig.7, left). The cracking pattern was typical: vertical cracks at the corners and diagonal cracks at the longitudinal walls (Fig. 7, right).

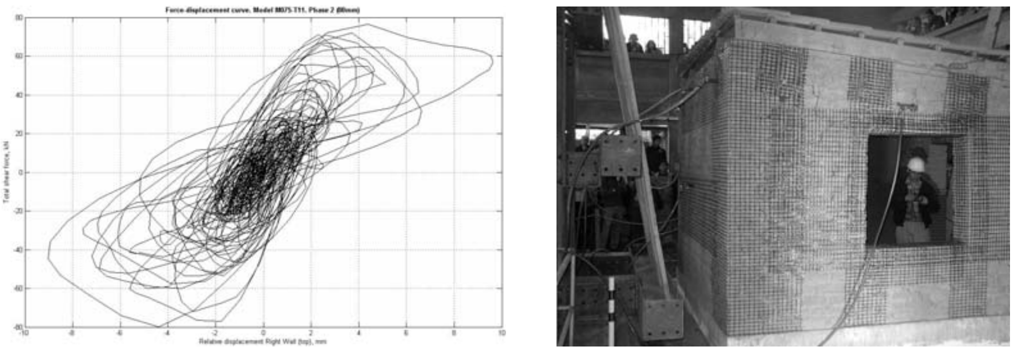


Figure 7 : Seismic behavior of model M075-T11 until phase 2
Hysteretic cycles and model view after testing

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.

The acceleration records presented in Figure 8 (left) clearly show that the response of the mud-plastered right wall (middle plot) had a higher amplitude and frequency than that of the unplastered left wall (top plot). This confirms that the mud plaster over the external reinforcement substantially increased the stiffness and the strength of the adobe walls.

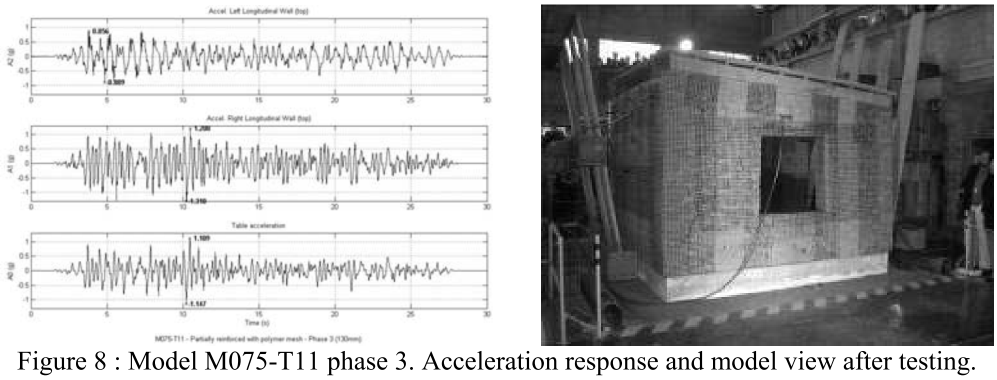


Figure 8 : Model M075-T11 phase 3. Acceleration response and model view after testing.

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. 9, 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.

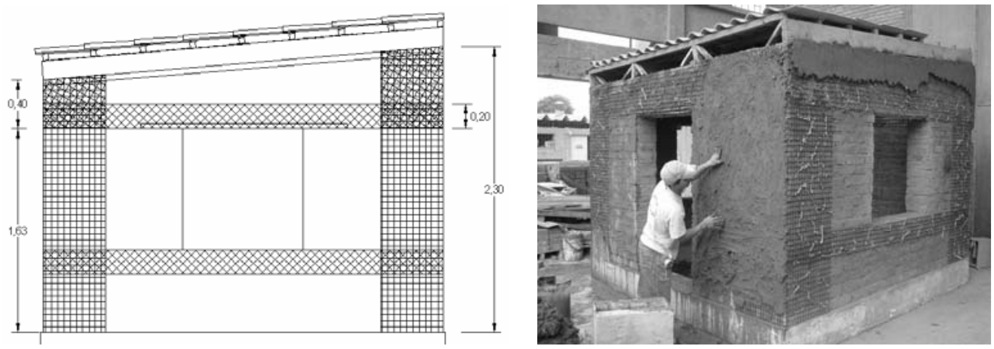


Figure 9 : Reinforcement arrangement and construction of model M050-T11.

As for the previous model, the first cracks appeared in phase 2 (80mm). Figure 10 shows that, due to the lesser amount of reinforcement provided, cracks were much larger and consequently, nonlinear response was more pronounced.

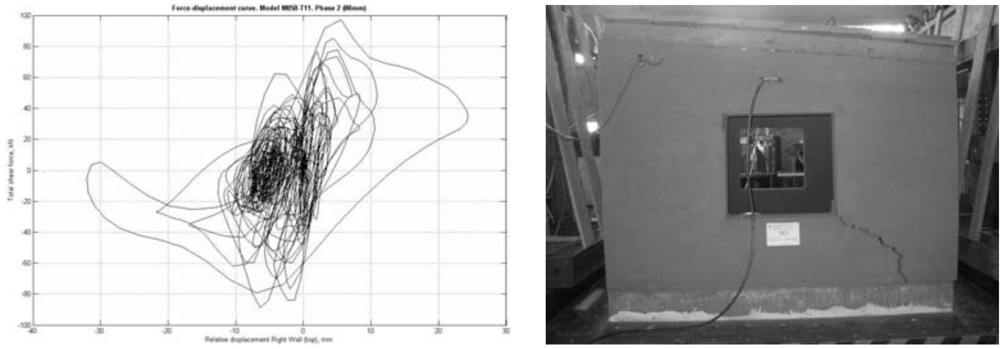


Figure 10 : Seismic behavior of model M050-T11 until phase 2.
Hysteretic cycles and model view after testing.

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. 11).

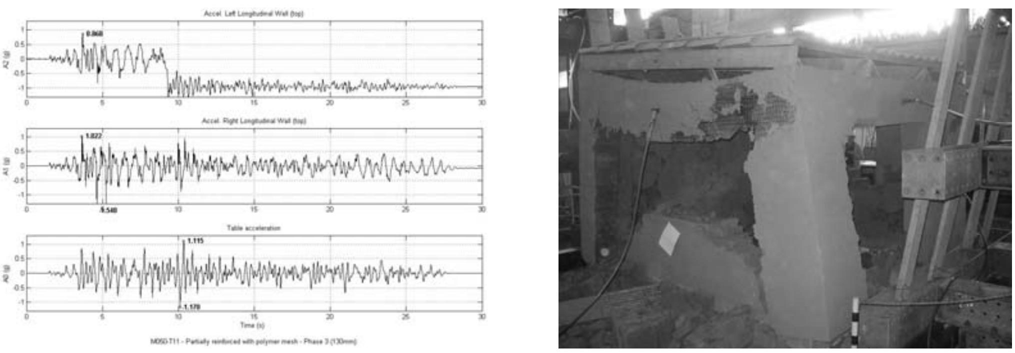


Figure 11 : M050-T11 phase 3. Acceleration response and model view after testing.

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. 12. Around 80% of the wall surface was thus reinforced.

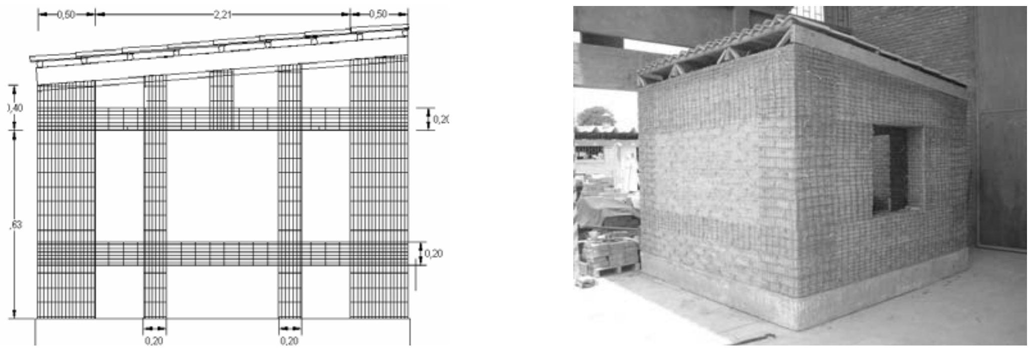


Figure 12 : Reinforcement arrangement and finished model M080-E.

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. 13). Also, some mud plaster fell apart. The transverse wall also showed significant cracking, but did not collapse.

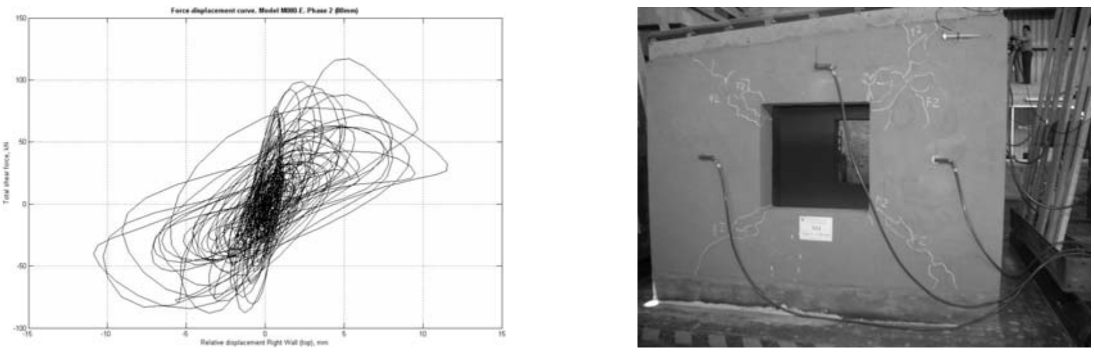


Figure 13 : Seismic behavior of model M080-E until phase 2.
Hysteretic cycles and model view after testing.

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. 14). The mesh was deformed and broken in several places, indicating that the amount provided was barely adequate.

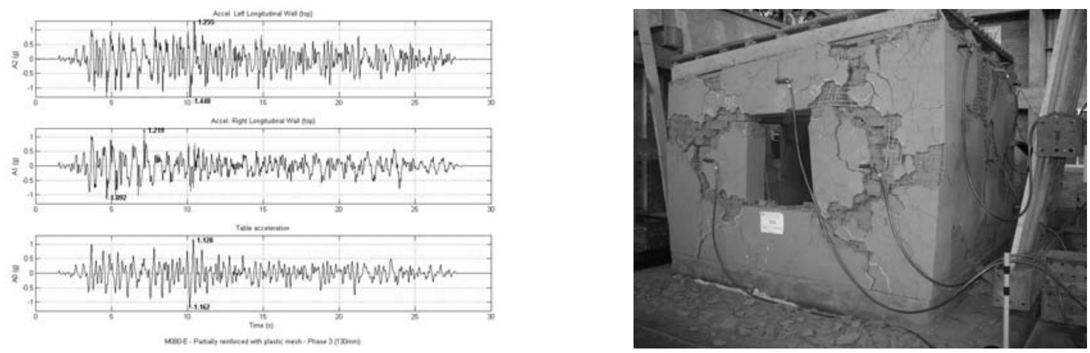


Figure 14 : Model M080-E phase 3. Acceleration response and model view after testing.

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.

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