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USING MUD INJECTION AND AN EXTERNAL ROPE MESH TO REINFORCE HISTORICAL EARTHEN BUILDINGS LOCATED IN SEISMIC AREAS

M. Blondet[1], J. Vargas[2], C. Sosa[2] and J. Soto[2]

[1]Pontificia Universidad Católica del Perú (PUCP)
Avenida Universitaria 1801, Lima 32, Perú
e-mail: mblondet@pucp.pe

[2] Pontificia Universidad Católica del Perú (PUCP)
Avenida Universitaria 1801, Lima 32, Perú
{jhvargas, carlos.sosa, jonathan.soto}@pucp.pe

Abstract. This paper presents preliminary test results from an ongoing research project conducted at the Catholic University of Peru (PUCP), whose aim is to develop reliable techniques for the repair and retrofit of historical earthen constructions damaged by earthquakes. Initial test results showed that liquid mud injections were effective in restoring most of the strength of small adobe walls which had been previously cracked under to diagonal compression, and of full-scale adobe walls subjected to lateral cyclic loads. This repair procedure, however, was not adequate in recovering the original structural properties of a full-scale adobe model tested under simulated seismic loads on the PUCP´s shaking table. Mud injection, therefore, must be complemented with other techniques which use minimal and reversible reinforcements made of materials compatible with adobe.

A second full-scale adobe model was built, tested at the shaking table to induce seismic damage, and repaired via mud injection combined with an external mesh made of nylon ropes tightened with metal turnbuckles. The adobe model and the shaking sequence were identical to those used in the previous test. This time, the mesh reinforcement worked to maintain structural integrity and stability, and prevented the partial collapse of wall portions that had separated during the shaking. Further research is required on the use of simpler and cheaper procedures to install and tighten the nylon ropes (turnbuckles are relatively expensive), and the development of analytical tools to design the most adequate seismic reinforcement configuration. It is hoped that these promising results will be useful towards the development of adequate reinforcement systems for earthen constructions located in seismic areas of the world.

Keywords: adobe, seismic reinforcement, mud injection, external cable mesh.

1. INTRODUCTION

Earthquakes cause extensive damage to earthen dwellings and historical monuments worldwide. Damaged earthen houses usually need to be rebuilt. Monuments, however, are unique cultural heritage and they must be repaired and strengthened to ensure their stability during future earthquakes. This is a difficult task because it is required by the International Letters of Conservation (ICOMOS, 1964) to preserve as much as possible of the original fabric.

A research team at the Catholic University of Peru (PUCP) is studying a retrofitting procedure for adobe walls, devised according to the conservation principles of minimum intervention, compatible reinforcement and reversible solutions. At first, a repair procedure involving injection of liquid mud on seismic cracks was investigated (Blondet M. *et al.,* 2007). The aim was to recover as much as possible the strength and stiffness of the original structure. Although monotonic and cyclic static tests on masonry elements performed at PUCP showed that mud grout injection could be effective in restoring the original strength of damaged adobe masonry walls, a full-scale seismic simulation test on an adobe house model repaired with this technique was not successful (Groenenberg R., 2010; Blondet M. *et al.,* 2012). It became clear, therefore, that the injection procedure should be complemented with an additional reinforcement technique. For this project, a second full-scale adobe model, identical to the one tested previously, was built and tested at the PUCP's shaking table to induce seismic damage. Next, the walls were repaired via mud grout injection. The model was then reinforced with an external mesh made with nylon ropes (halyard) covering all the walls. (In sailing, a halyard is a rope that is used to hoist a sail, a flag or a yard).

The retrofitted model was tested again on the shaking table to evaluate the efficacy of this dual seismic protection technique. Its seismic performance was satisfactory because the provided reinforcement prevented partial collapse and preserved the structural integrity of the model (Blondet M. *et al.,* 2013).

This paper summarizes the experimental results obtained and outlines the current work being performed by the PUCP adobe research team to improve the proposed retrofit technique.

2. MODEL CONSTRUCTION

A full-scale adobe house model, shown in Figure 1, was built at the PUCP´s Structures Laboratory to be tested on the shaking table. It was similar to the model repaired only with mud injection, which did not have a satisfactory dynamic response during a previous project (Groenenberg R., 2010; Blondet M. *et al.,* 2012). The purpose of this test was to evaluate the efficacy of a reinforcement system complementary to the mud injection repair procedure.

The adobe masonry house consisted of four walls (3.00 m long and 0.25 m wide, with different heights). Adobe blocks measured 250 x 250 x 90 mm (full size and half-size blocks were used). They were made using soil, straw and coarse sand (5:1:1 in volume). The adobe blocks (approximately 20 mm thick) were joined with mud mortar also made with soil, straw and coarse sand (3:1:1 in volume). The left and right walls were identical and had a central window opening. The door was located on the front wall. The back wall had no openings and was higher than the front wall in order to have a sloped roof. The roof was made of a wooden framework covered with light tiles. It was attached to the four walls with a wooden crown beam. It was expected that the crown beam would contribute towards an integrated structural response during shaking and would transfer the weight of the roof to the walls. The door and the windows had lintels made with cane rods tied up with wire. These lintels are lighter and more flexible than those made with wood pieces to avoid pounding on the adobe walls during earthquakes. The model was built on a reinforced concrete square ring, which provided a rigid foundation and was used to attach the model to the shaking table and to serve as a support during transportation from the building area to the test site (Blondet M. *et al.,* 2013).

Compression tests of adobe masonry piles yielded an average value of the tangent elastic modulus of 400 MPa. The density of the adobe blocks was 1700 kg/m^3.

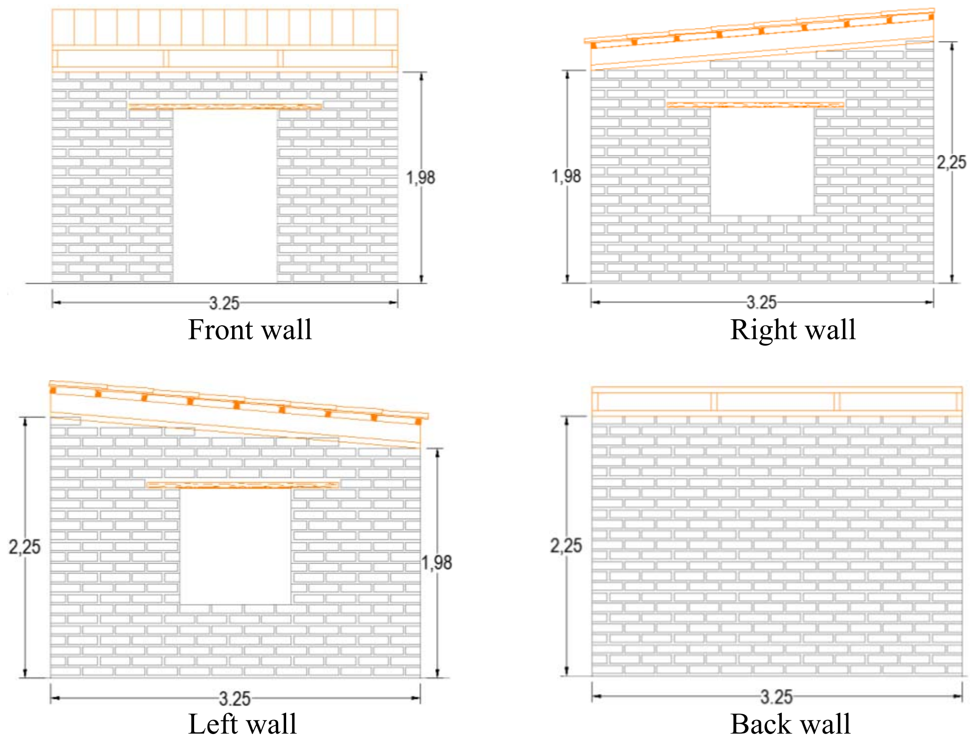


Figure 1. Sketch of the full-scale adobe model. Dimensions are in meters.

3. TEST PROTOCOL AND INSTRUMENTATION

The shaking table displacement command signal used in the tests was derived from the longitudinal component registered on the May 31, 1970 earthquake in Lima, Peru. Figure 2 shows the table acceleration recorded during a simulation test corresponding to a peak command displacement D = 130 mm. The peak table acceleration A_0 was 1.53g.

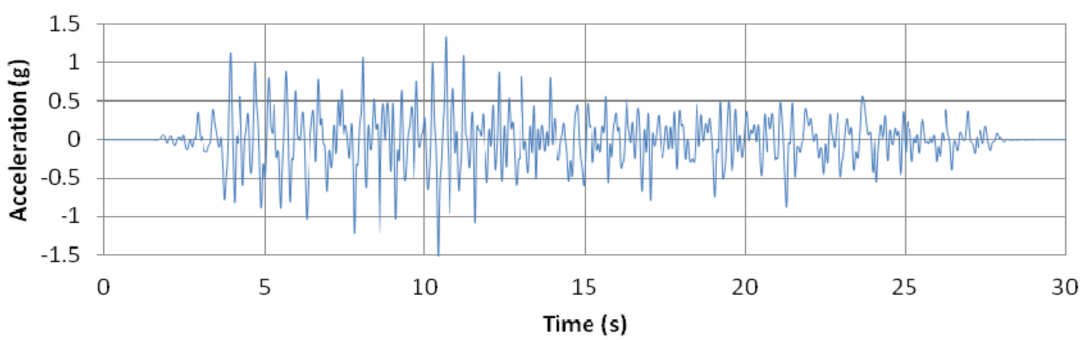
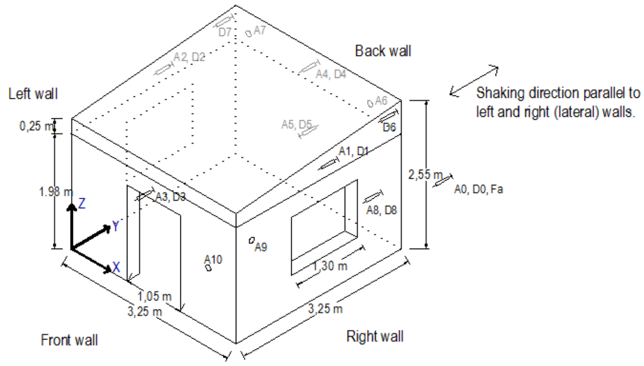


Figure 2. Shaking table acceleration recorded in a test with D = 130 mm peak command displacement.

The instrumentation included accelerometers to measure absolute accelerations and linear variable differential transducers (LVDTs) to measure absolute displacements. The acceleration and the displacement of the shaking table as well as the force delivered by the hydraulic actuator were also measured. The sampling rate for all instruments was 200 Hz (time interval of 0.005 s).

Model on the shaking table



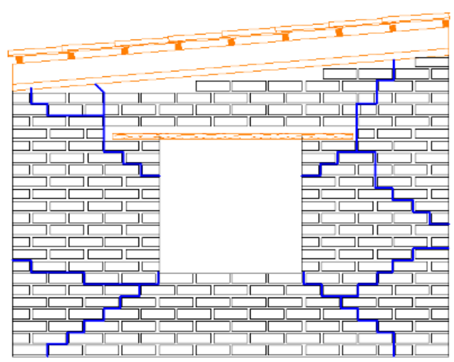
Location of instrumentation

Figure 3. Full scale adobe house model and instrumentation scheme.

4. DYNAMIC TESTS TO INDUCE SEISMIC DAMAGE

The original, undamaged model was subjected to a sequence of three phases of shaking table tests to induce wall cracking representative of seismic damage as observed in adobe masonry constructions. The first phase, with a peak command displacement D = 30 mm (peak table displacement D_{0max}= 28.90 mm and peak acceleration A_{0max}= 0.31g), did not cause any visible damage in the model. During the second phase with D = 60 mm (D_{0max} = 58.50 mm and A_{0max}= 0.64g) the model suffered extensive cracking. Large diagonal shear cracks were visible in the lateral (left and right) walls, starting in the corners of the window and propagating outwards. Since the cracks were quite thin (3 mm or less), it was decided to carry out a third shaking phase D = 60 mm (D_{0max}= 58.50 mm and A_{0max}= 0.64g) to induce further damage, with wider cracks. This last shaking phase was stopped after 15 seconds to avoid irreparable damage (as occurred in the previous project). Figure 4 shows the cracking patterns on the adobe walls, representative of seismic damage on adobe wall structures.

Right wall



Cracking scheme of right wall

Figure 4. Damage in the original adobe model after second (D = 60 mm) testing phase.

5. DYNAMIC TESTING OF RETROFITTED MODEL

5.1. Repair procedure

The damaged model was retrofitted (repaired and strengthened) in the laboratory yard. Repair with grout injection required that the cracks be opened to allow for full penetration of the grout (which may be in conflict with the conservation principle of minimum intervention). In the cases of historical monuments, it is advisable to proceed step by step with the sequence of crack opening and grout injection. In this case, because of time constraints, it was decided to open all the cracks in the adobe walls simultaneously. All cracks wider than 1 mm were opened to about 8 mm wide using a drill and an electric knife, as shown in Figures 5 a) and b). Then, all the cracks were sealed with a layer of silicon on both wall faces, leaving small openings separated approximately 100 mm from each other. Afterwards, liquid mud grout was injected on the openings. The grout consisted of a mixture of one part of soil sieved through #10 mesh (2 mm opening), 50% in volume of finely cut dried grass (10 mm average length), and 35% in weight of water. This mixture was injected inside the cracks until they were completely full with, as shown in Figure 5 c).

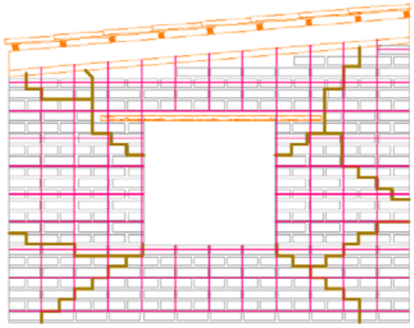
a) Using electric drill b) Using electric knife c) Injecting mud grout

Figure 5. Opening seismic cracks and injecting mud grout.

After all cracks were repaired with liquid mud, the model was left to rest for two months to allow for an adequate drying of the sealed cracks.

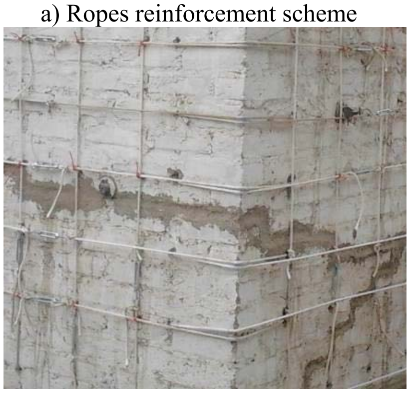
5.2. Strengthening procedure

After the injected grout had completely dried, all the walls of the repaired model were reinforced with an external mesh made of nylon ropes (known as halyard) with ¼" nominal diameter. Tension tests performed at the laboratory on pieces of the halyard used for the repair yielded an ultimate strength of 2 kN (nominal ultimate stress of 63 MPa) and a reference modulus of elasticity of 100 MPa. Figure 6 a) schematically shows the provided mesh configuration. The vertical ropes were placed at 250 mm intervals (the length of one adobe block) in two parts. The lower part of the rope, measuring about 1.20 m, was inserted across the wall through the first (bottom) course of mud mortar. The top part of the rope was placed over the walls, nailed to the wooden crown beam and joined to the bottom ropes on each side of the wall, using metal turnbuckles. The horizontal ropes were also placed at 250 mm intervals (two and a half courses of adobe masonry) in two parts joined by turnbuckles. All the ropes were manually tensed by means of the turnbuckles (Figure 6 b). The tensile force provided by the turnbuckles is estimated at 200 N. At each vertical corner, the ropes were placed inside a small plastic tube in order to protect the adobe walls, especially when the mesh coincided with a mortar joint. The meshes on both faces of each wall were joined together by 1/8" halyard ropes (crossties), which crossed the walls through the mortar joints at selected places. Figure 6 c) shows a detail of the reinforcement elements, and Figure 6 d) presents the retrofitted model ready to be tested again on the shaking table.

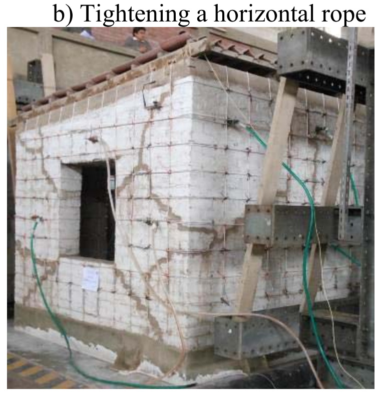


a) Ropes reinforcement scheme

b) Tightening a horizontal rope



c) Reinforcement detail



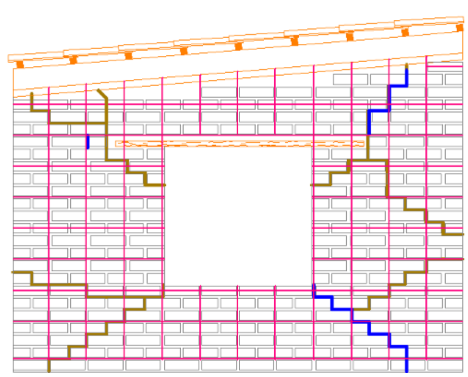
d) Repaired and strengthened model

Figure 6. Strengthening of the repaired model with halyard mesh.

6. EVALUATION OF THE RETROFIT TECHNIQUE

The retrofitted (repaired and reinforced) adobe model was tested again on the shaking table following the same protocol as the virgin, undamaged model. During the first shaking phase (D = 30 mm; D_{0max}= 29.40 mm; A_{0max}= 0.30 g), there was no visible damage to the structure. Figure 7 b) shows the cracking pattern corresponding to the second testing phase (D = 60 mm; D_{0max}= 58.40 mm; A_{0max}= 0.71g). Previously repaired cracks are emphasized: brown lines show cracks that remained closed; blue lines show those which open due to shaking.

a) Damage inspection



b) Cracking scheme (in blue)

Figure 7. Retrofitted model after second testing phase (D = 60 mm).

The third testing phase (D = 90 mm; D_{0max}= 89.30 mm; A_{0max}= 1.08g) proved the effectiveness of the external mesh reinforcement. If the model had been repaired only with mud injection, it would have collapsed due to this ground shaking. The nylon rope mesh was able to maintain together the large pieces in which the walls had been broken. It was decided to subject the model to two additional intense shaking phases (D = 130 mm; $D_{0\,max}$= 128 mm; A_{0max}= 1.53g), which produced a significant amount of damage: all the repaired cracks opened and new cracks appeared in all the walls (Figure 8, left). Even though the crown beam got detached due to the damage at the top of the back wall, the reinforcement mesh and the wooden crown beam worked well together in keeping the integrity of the structure, (Figure 8, right). It was noticed that the horizontal halyard ropes, located in the mortar close to the base of the window, started to cut into the mud mortar.

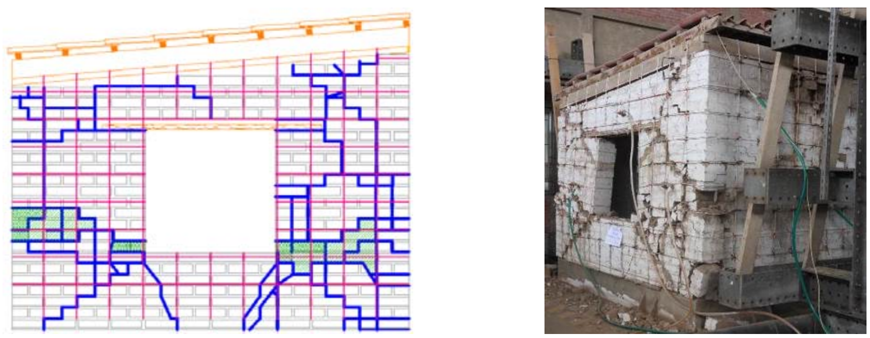
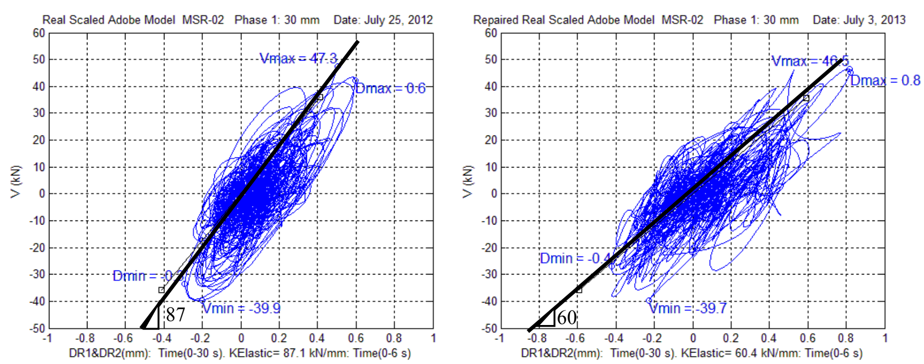


Figure 8. Sketch of damage pattern and general view of the model after all shaking phases.

The base shear versus global displacement curves corresponding to the first low level shaking phases (D = 30 mm) for the model in its original and retrofitted conditions are shown in Figure 9. The retrofit procedure of mud injection plus external nylon mesh reinforcement was quite effective in recovering the mechanical characteristics of the undamaged model. In both cases, the maximum base shear sustained by the model was close to 47 kN, and the retrofitted model had almost 70% of the lateral stiffness of the original model (60 kN/mm versus 87 kN/mm).

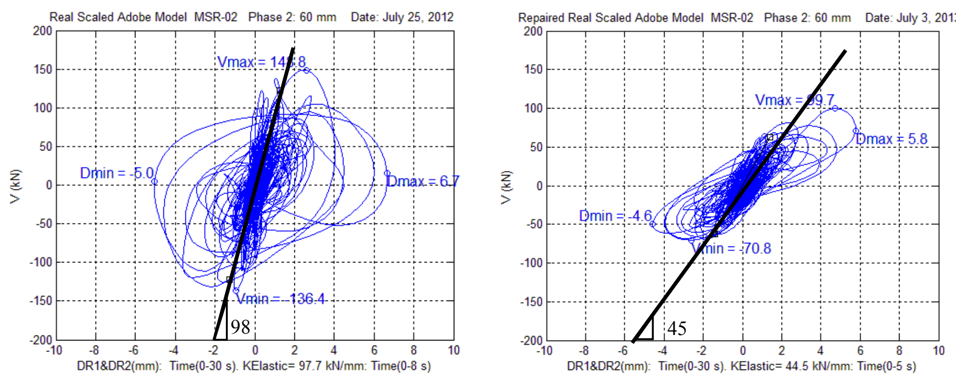


a) Original model b) Repaired and strengthened model

Figure 9. Base shear vs. top displacement curves for first testing phase (D = 30 mm)

For a higher level of shaking, corresponding to a command displacement D = 60 mm, there was significant nonlinear response in the original and retrofitted conditions. The original model was severely cracked and was close to collapse, but the reinforcement was successful in keeping the structural integrity. The lateral force versus displacement graphs presented in

Figure 10 show that the retrofit scheme was effective in preserving a stable dynamic response, even when the structure suffered some structural damage, manifested by a reduction in lateral strength of about 33% (from 149 kN to 100 kN) and a stiffness degradation of about 54% (from 98 kN/mm to 45 kN/mm).



a) Original model b) Repaired and strengthened model

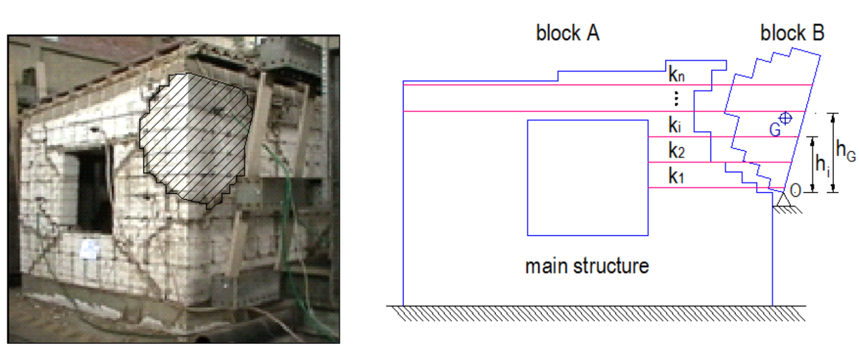
Figure 10. Base shear vs. top displacement curves for second testing phase (D = 60 mm)

The seismic response for the strongest shaking imposed on the retrofitted model (D = 130 mm; D_{0max}= 128 mm; A_{0max}=1.53g) was excellent because the provided mesh reinforcement maintained the structural connection between roof and walls, controlled excessive displacements and avoided partial collapses, thus preserving the integrity of the structure.

7. PRELIMINARY ANALYSIS PROCEDURE

During most strong shaking table tests performed on adobe structures at the PUCP, it was observed that the adobe walls break in large pieces, which then detach and collapse by overturning. In this project, a portion of the back wall (shown hatched in Figure 11 a) was detached from the rest of the structure during the strong shaking tests performed with the retrofitted adobe model.

A simplified structural model was generated by considering that the main structure and the detached wall portion are rigid blocks, as shown in Figure 11 b). Block A represents the main structure (assumed undamaged) and block B is the detached portion of wall. The nylon ropes prevent the overturning of block B. This situation can be represented schematically by a simple dynamic model in which the two blocks are connected by a set of N horizontal elastic ropes.



a) Damaged full scale model b) Simplified model

Figure 11. Simplified model for adobe block interaction.

This simple model was then used to try to estimate the forces in the elastic ropes caused by the dynamic ground motions. Figure 12 shows the free body diagram of block B, including the inertia forces caused by translational and rotational accelerations. Absolute displacements of any point *P* with respect to an inertial reference system are denoted by x_P. Rigid block A is fixed to the ground, with absolute displacement x_O. Rigid block B, with mass m_B and mass central moment of inertia I_G, pivots around ground point O. Relative displacement (with respect to O) of any point *i* located on block B at height h_i is noted as u_i. A viscous damper (not shown) with damping factor ζ_B is attached at the center of mass G. (Free vibration tests performed on the adobe model between shaking phases yielded equivalent viscous damping factors between 9% and 12%). Rope *i* has elastic stiffness k_i and is attached to blocks A and B at a height h_i

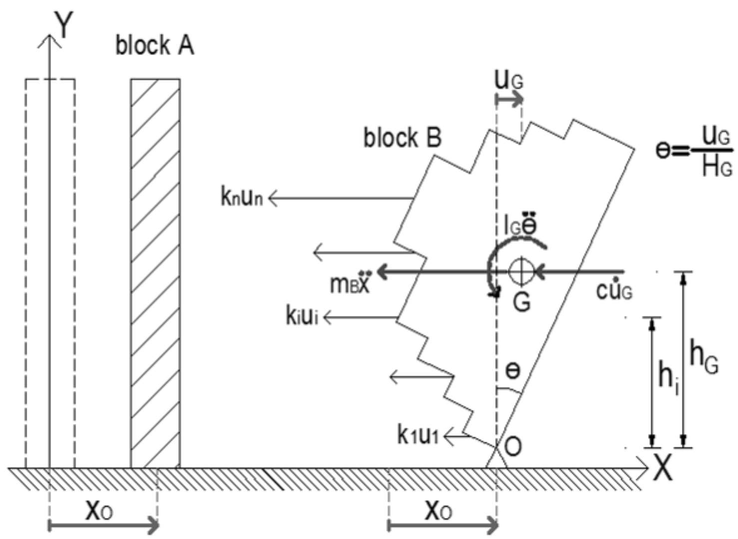


Figure 12. Free body diagram of block B

The resulting equation of motion of the model, obtained through dynamic equilibrium, is:

$$\mathrm{M}_e \ddot{u}_G + C_e \dot{u}_G + \mathrm{K}_e u_G = -\mathrm{m}_B \ddot{x}_O \quad (1)$$

Where the equivalent coefficients for mass (M_e), stiffness (K_e) and damping (C_e) coefficients are, respectively:

$$\mathrm{M}_e = \frac{1}{h_G^{\,2}}\left(I_G + m_B h_G^{\,2}\right) \quad (2)$$

$$\mathrm{K}_e = \frac{\sum k_i h_i^{\,2}}{h_G^{\,2}} \quad (3)$$

$$C_e = 2\zeta_B \sqrt{K_e M_e} \quad (4)$$

The natural vibration period of the system is

$$T_B = 2\pi \sqrt{M_e / K_e} \quad (5)$$

Therefore, if the displacement response spectrum of the ground motion, $S_d(T, \zeta)$, is known, the peak seismic displacement of the center of mass G of block B is $S_d(T_B, \zeta_B)$, and the force in cable *i* is found to be:

$$F_i = \frac{h_i}{h_G} k_i S_d(T_B, \zeta_B) \tag{6}$$

This simple analysis procedure is currently being refined and calibrated, and it is hoped that it will serve as a basis for a design procedure for rope reinforcement system for adobe structures in seismic areas.

8. CONCLUSIONS

The main conclusion obtained from this experimental project is that the damaged full scale adobe model, tested under severe dynamic excitations, was adequately protected by a retrofit technique consisting on the combination of sealing the seismic cracks via mud grout injection and providing an external reinforcement made of a nylon rope mesh covering all the walls.

This combined retrofit technique maintained structural integrity, prevented excessive stiffness degradation and strength loss, and provided displacement control to the cracked structure during intense dynamic shaking, thus avoiding potential loss of life. The authors are therefore confident that this protection system could be effectively used to protect earthen historical monuments located in seismic areas.

Furthermore, the rope mesh reinforcement studied here has great potential to be used as seismic reinforcement for low-cost earthen dwellings. The rope used here (halyard) is relatively cheap, easy to use, and available in warehouses.

Further research is required to optimize the reinforcement system, to reduce its cost (the turnbuckles are relatively expensive), and to develop reliable analysis and design procedures.

There is hope that the results presented here could contribute to protect earthen monuments and to build safer dwellings in seismic countries where earthen construction is the main housing solution for most families.

9. REFERENCES

[1] Blondet M., Vargas J., Morales K., and Iwaki C. *Preliminary study on the usage of mud mortars to repair structural cracks in historical adobe buildings*. In Spanish. Adobe USA 2007. El Rito, New Mexico, USA, 2007.

[2] Blondet M., Vargas J., and Groenenberg R. *Evaluation of the efficacy of mud injection to repair seismic cracks on adobe structures via full-scale shaking table tests*. 15th World Conference on Earthquake Engineering, 15WCEE. Lisbon, Portugal, 2012.

[3] Blondet M., Vargas J., Sosa C. A., and Soto, E. J. *Seismic simulation tests to validate a dual technique for repairing adobe historical buildings damaged by earthquakes*. New Generation Earthen Architecture: Learning from Heritage. (pp. 269-276) ESTAMBUL: Istanbul Aydin University, 2013.

[4] Groenenberg R. *The reparation of adobe constructions damaged by earthquake loading and development of an ATENA-GiD model to simulate shaking table tests for these structures*. MSc. Thesis, PUCP, Lima, Peru, 2010.

[5] ICOMOS (International Council of Monuments and Sites). *International letter related to Conservation and Restoration of Historical Monuments.* Venice, Italy, 1964.