Evaluation of the Efficacy of Mud Injection to Repair Seismic Cracks on Adobe Structures via Full-Scale Shaking Table Tests

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SUMMARY:
A testing program was developed at the Catholic University of Peru (PUCP) to evaluate the possibility of repairing adobe buildings damaged by earthquakes by injecting the seismic cracks with mud-based grouts. A full scale adobe housing model was tested at the shaking table to induce cracking representative of seismic damage. The model was then repaired by injecting the cracks with a mud grout, and tested again under the same dynamic motions. The data obtained were used to estimate the model's global force-displacement response, as well as stiffness and strength before and after each test. The main conclusion is that although repair via mud injection is useful to partially recover the original stiffness and strength of the structure, this method must be combined with other reinforcing technologies to ensure that the repaired structure is stable against further seismic shaking.

Keywords: Adobe masonry, repair, mud grout, injection, shaking table

1. INTRODUCTION

Earthquakes in Peru have caused extensive damage to adobe structures. Many adobe houses and earthen historical monuments have been affected by earthquakes. Repair of damaged earthen monuments is particularly challenging because it requires minimal intervention to preserve as much as possible the original fabric.

A research team at the Catholic University of Peru (PUCP) has been working in the recent past at developing technologies to repair adobe structures with injection of mud-based grouts after they have been damaged by earthquake loading (Blondet *et al.*, 2007, Dandona *et al.*, 2008, Vargas, Blondet and Iwaki, 2009). The objective of the repair is to recover at least partially the strength and stiffness of the original structure, in order to allow it to sustain future earthquakes. Several static tests performed at PUCP have demonstrated that the mud-based grout injection repair method is effective in restoring the original strength of damaged adobe masonry.

A test program was developed to evaluate efficacy of mud injection to repair cracked adobe walls through shaking table tests of a full-scale adobe house. The idea was to induce damage with a realistic simulated seismic shaking, to repair the model by sealing the cracks with mud-based grout, and to test the structure again. The strength and stiffness of the model would be estimated before and after each shaking to evaluate the efficacy of the repair process in recovering the mechanical properties of the structure.

2. MODEL CONSTRUCTION

The full-scale adobe housing model, shown schematically in Fig. 1, was identical to models built and tested at the PUCP's Structures Laboratory during previous research projects in order to be able to compare the results obtained (Blondet, Vargas and Tarque, 2008; Bossio, Blondet and Rihal, 2011).

The model consists of four adobe masonry walls measuring 3,25 m long, 0,25 m wide, with variable height. Adobe blocks measured 500 mm x 250 mm x 70 mm (full size and half-size adobes were used). They were made using soil, straw and coarse sand (5:1:1 in volume). The adobe blocks were joined with mud mortar also made with soil, straw and coarse sand (3:1:1 in volume), approximately 20 mm wide. 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; thus the roof had a slope, as can be seen in the schematic diagrams presented in Fig. 1.

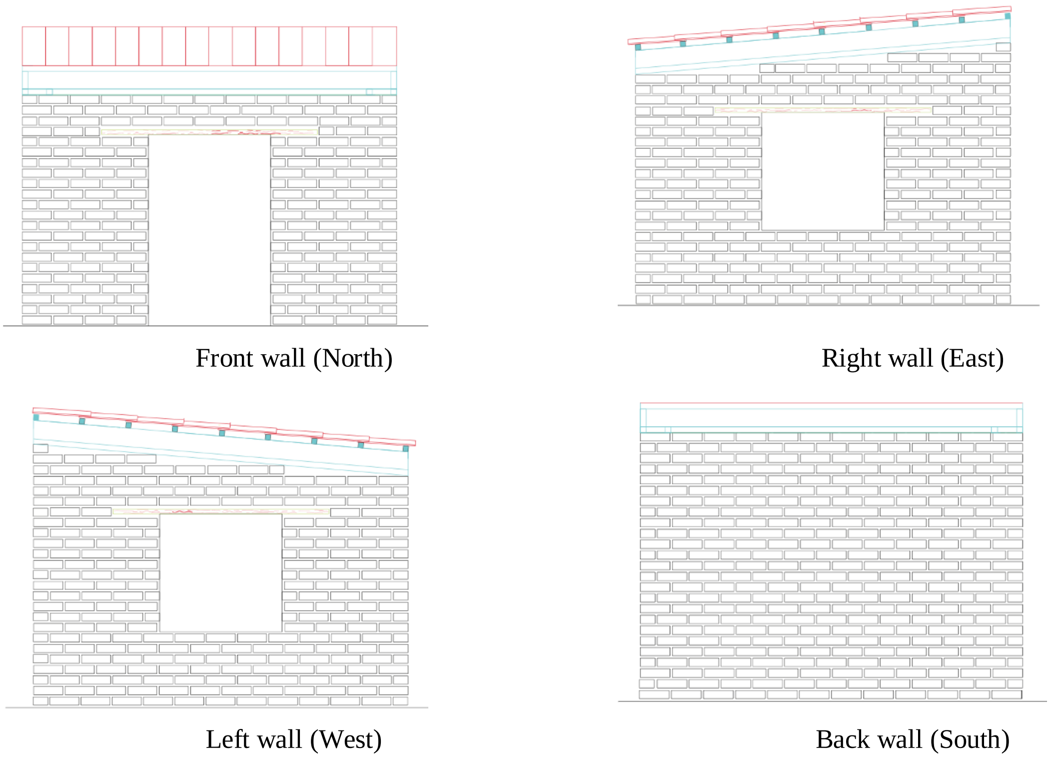


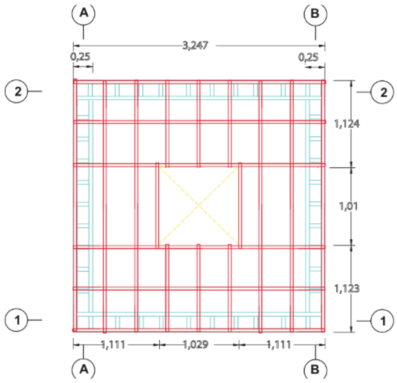
Figure. 1 Sketch of the full-scale adobe model

The model was built on a reinforced concrete square ring 3,25 m long each side and with 0,30 m x 0,30 m section that provided a rigid foundation and was used to attach the model to the shaking table and as a support during transportation from the building area to the test site.

The door and the windows had flexible lintels made with cane rods placed in three layers and tied up with #16 wires. The flexible lintels were intended to avoid the cracks usually caused due to pounding during earthquakes when rigid wooden lintels are supplied (Fig. 2, left). A wooden crown beam was placed on top of the model to contribute towards an integrated structural response during shaking and to transfer the weight of the roof to the walls (Fig. 2, right).

The roof was placed on the wooden crown beam that ties all walls. It consisted of 2” x 6” wooden joists placed in the N-S direction (front wall-back wall) and strips of wood measuring 1½” x 2” placed on top of the joists. Corrugated cement fiber sheets were then directly placed upon the strips of wood fitted on the walls to simulate the typical construction of unreinforced adobe houses in the highlands of Peru.

Flexible cane roof lintel and
cover fiber-cement sheets



Wooden roof configuration
(Crown beam shown in blue)

Figure 2. Flexible roof lintel and support configuration

3. TEST PROTOCOL AND INSTRUMENTATION

The shaking table displacement command signal used in the tests was derived from the longitudinal component registered on May 31st 1970 earthquake in Lima, Peru. Figure 3 shows the displacement pattern, normalized to a peak displacement of 1 mm. This signal is electronically amplified to obtain the desired shaking table peak displacement.

It was decided to test the model in two phases: the first phase with a peak displacement of 30 mm to induce minor cracking, followed with a second phase with a peak displacement of 60 mm, capable of producing large cracks in the adobe walls. Before and after each phase the model was subjected to small ground pulses to measure its free vibration response.

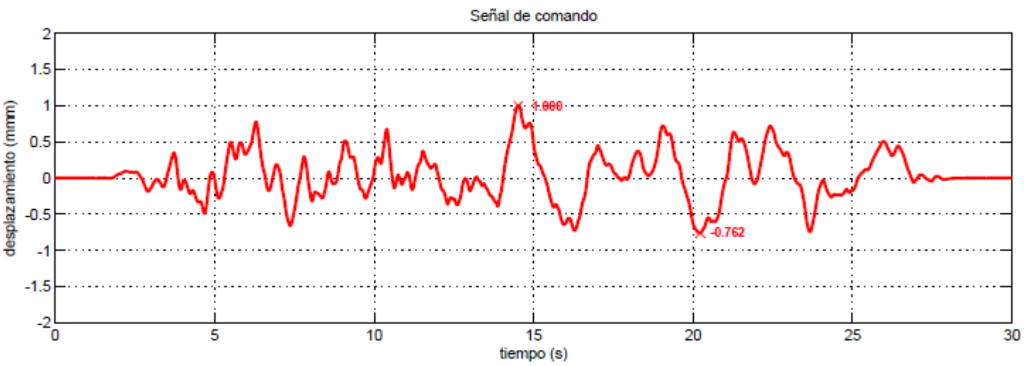


Figure 3. Shaking table command displacement (normalized to 1 mm).

The instrumentation placed to measure the dynamic building response included ten accelerometers to record absolute accelerations and eight linear variable differential transducers (LVDTs) to record absolute displacements. Additionally, table motion was recorded with one LVDT and one accelerometer, and the force in the servohydraulic actuator was measured with a load cell. Figure 4 shows the location of the instrumentation.

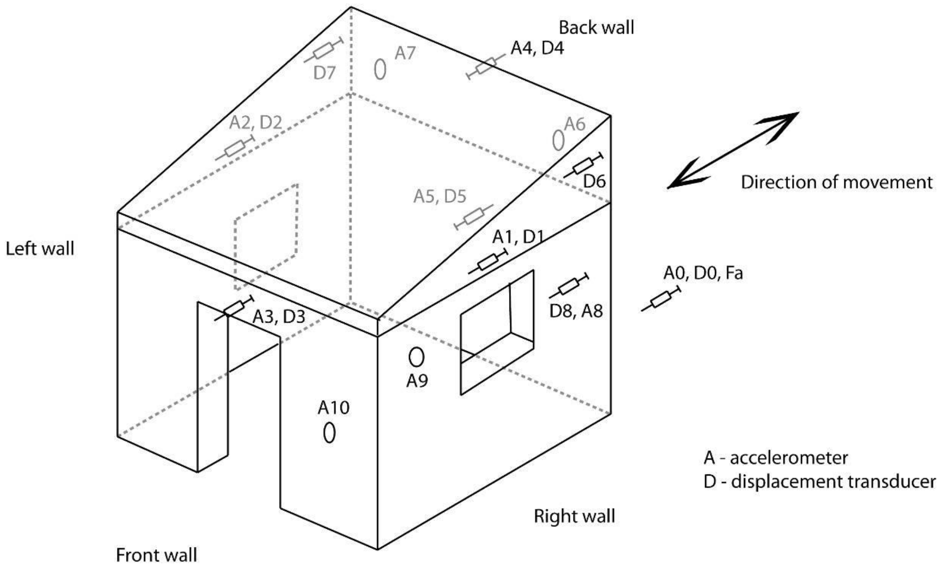


Figure 4. Instrumentation location

A photograph of the model ready to be tested on the shaking table is presented in Fig. 5. The reinforced concrete foundation, the angled roof and the wooden crown beam can be clearly seen. The garden hoses are used to protect the accelerometer cables.

Figure 5. Full-scale model on shaking table

4. DYNAMIC TESTS TO INDUCE WALL CRACKING

The undamaged model was subjected to a sequence of two phases of shaking table tests in order to induce wall cracking representative of seismic damage in adobe masonry construction.

After the first phase (Dmax = 30 mm) there was no damage visible in the model. The free vibration frequency measured on top of the back wall was reduced from 19,95 Hz to 12,88 Hz. This suggests that the global stiffness after shaking, estimated as the square of the frequency ratio, is about 40% of the original stiffness.

During the second phase (Dmax = 60 mm), the model suffered extensive damage, as shown schematically in Fig. 6. Large diagonal shear cracks were visible in the right wall, starting in the corners of the window and propagating outwards. The left wall, suffered less damage, as diagonal cracking occurred only at the bottom part of the wall.

Important vertical cracking occurred at the corners of the walls with windows and the back wall. The free vibration frequency measured at the top of the back wall dropped from 12,88 Hz to 9,02 Hz, indicating a further loss of stiffness of about 50% with respect to the stiffness at the beginning of the test, and 80% of stiffness loss with respect to that in the undamaged state.

The level of cracking produced in the adobe walls was considered to be representative of extensive but repairable seismic damage and therefore it was decided to proceed to the repair of the structure by injecting mud-based grouts in the seismic cracks.

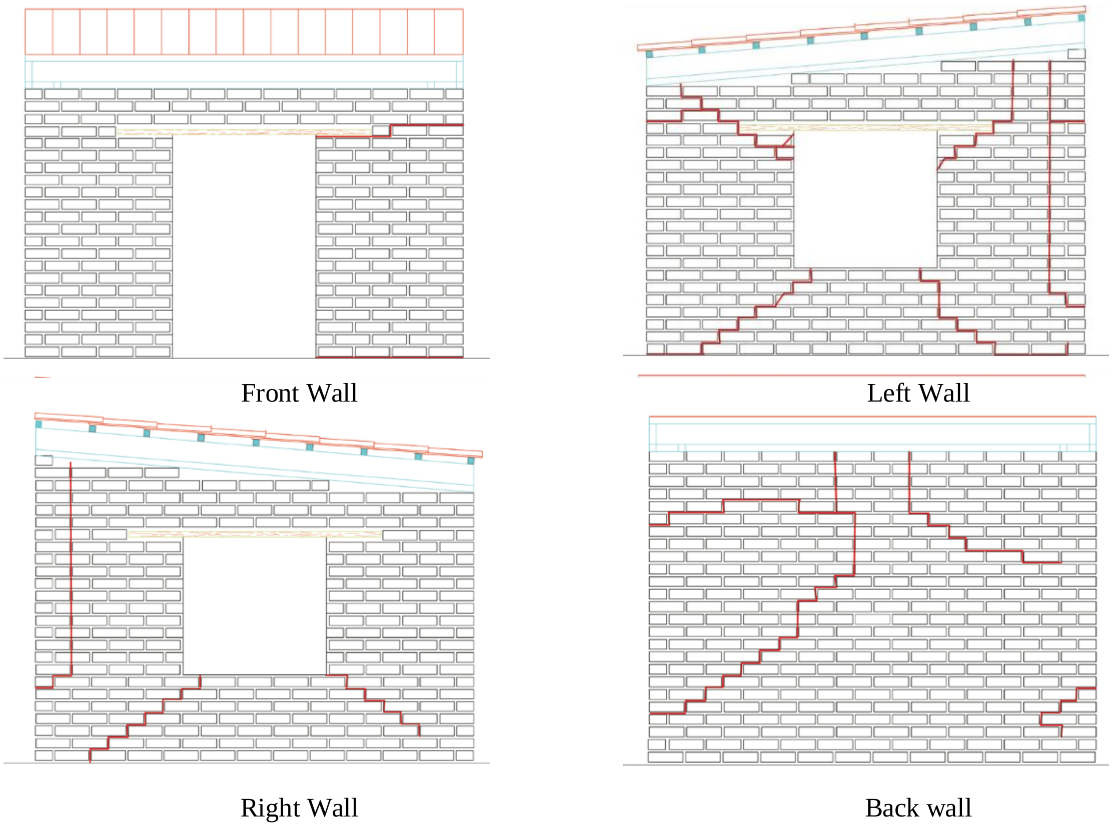


Figure 6. Cracking pattern after phase 2 (D = 60 mm)

Figure 7 presents total base shear versus global displacement curves calculated for both testing phases. Base shear was computed subtracting the table inertia force from the actuator force. The global displacement is the displacement of the top of the back wall with respect to the table. During phase 1 the model remained essentially elastic, with a peak base shear of 75 kN (Fig. 7, left) and a lateral stiffness of about 60 kN/mm. During the second phase the model showed significant nonlinear response, consistent with the damage observed. The lateral strength of the module was estimated at 92 kN (Fig. 7, right).

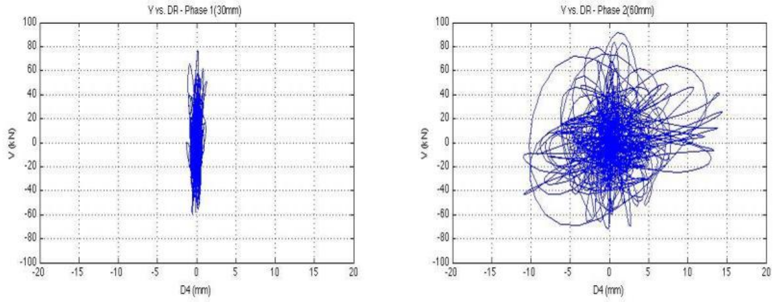
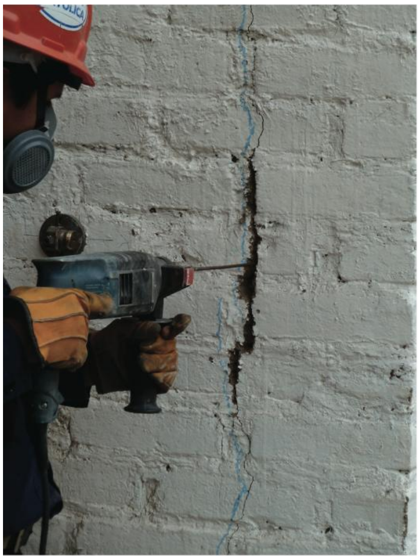


Figure 7. Base shear vs relative displacement response of the original structure

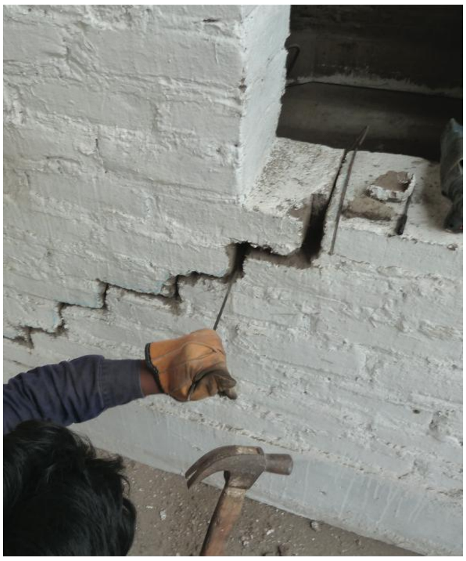
5. REPAIR BY INJECTION OF MUD-BASED GROUT

The model was transported to the laboratory yard to be repaired. Grout injection requires that the cracks be opened to allow for full penetration of the grout. This, in some cases may in contradiction with the conservation principle of minimum intervention. Also, in the cases of historical monuments it seems 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 structure at once.

All major seismic cracks (wider than 1 mm) were opened using a drill and a hammer and pin as shown in Fig. 8, in order to facilitate mud penetration during the repair. The thicker cracks (more than 20mm after opening) were filled manually with mud (Fig. 9, left). Then the thinner cracks were prepared for injection by sealing them with a layer of silicon over them and leaving small openings at 50 mm distance approximately. The mud-based grout was then injected through these openings until the cracks were fully filled (Fig. 9, right).



Using a drill



Using pin and hammer

Figure 8. Opening the seismic cracks


Filling thicker cracks manually


Injecting mud-based grout

Figure 9. Repairing the cracks with mud

Figure 10 shows the repaired structure. After 28 days of drying the model was tested again on the shaking table.

Figure 10. Adobe model with all major seismic cracks repaired

6. SHAKING TABLE TEST TO EVALUATE EFFICACY OF REPAIR

The second shaking table test was carried out the same way as the first shaking table test.

The free-vibration frequency measured at the top of the back wall increased from 9,02 Hz before repair to 10,86 Hz after repairing and drying, indicating an increase of global stiffness of the order of

45%. The frequency of the undamaged structure was, however 19,95 Hz. Therefore the repair procedure was not able to recover global structural stiffness, since it was only about 30% of that of the undamaged structure.

During the first phase (30 mm peak table displacement), there was no visible damage to the structure. After watching the video recordings, however, it was clear that the roof had detached from the walls. The crown beam, therefore lost its capacity to hold the walls together. Because of this, the part of the back wall collapsed during the second phase (60 mm). Figure 11 schematically presents the damage after this test. New cracks are shown in blue. Figure 12 presents a photograph of the model after the test where the partial collapse of the back and side walls can be observed. Notice also the separation of the roof and the side wall.

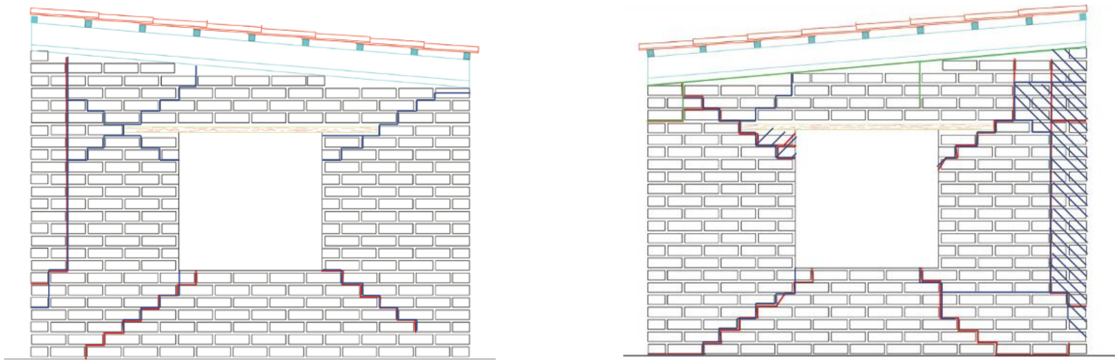


Figure 11. Damage after the second test

Figure 12. View on collapsed wall of module after test

The base shear versus global displacement curves for both testing phases on the repaired model are shown in Fig. 13. These curves show that even during the low level phase 1 (D = 30 mm) the global response was nonlinear. The peak base shear was 38.4 kN, a much lower value than that of the original model (75 kN). During the second phase there was significant nonlinear response, consistent with the damage observed. The lateral strength of the module was estimated at 50 kN. This is about 54% of the strength shown by the original, undamaged structure.

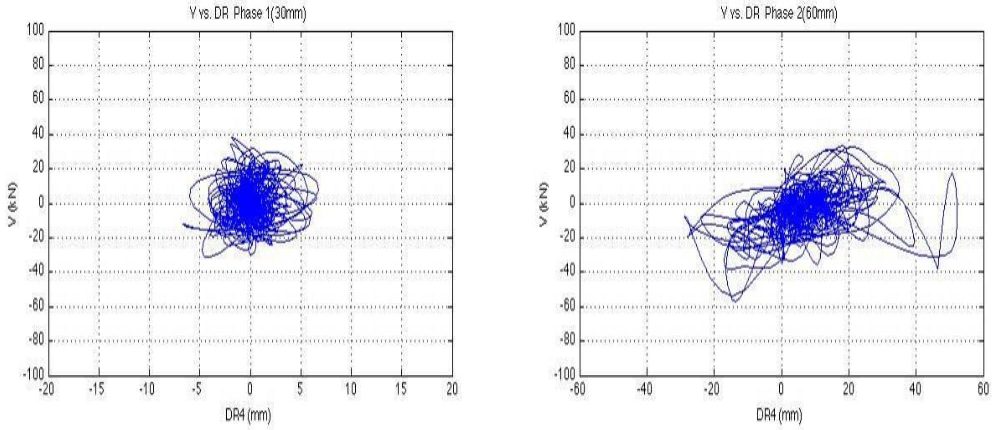


Figure 13. Base shear vs relative displacement response of the repaired structure

These results show that the repair technique was not adequate to achieve a significant recovery of the initial stiffness and strength of the original structure. This could be due to the combination of several effects:

- The early detachment of the roof in the low level shaking (D = 30 mm) probably caused the partial collapse of the back wall during the stronger shaking (D = 60 mm).

- It seems possible that the interface between the material used to fill the cracks (mud or grout) and the existing adobe masonry was not sufficiently strong. Whereas during construction, the blocks are pressed on the mud mortar, when putting the filler material in the cracks, it is difficult to apply pressure. Thus, the bond between new and old material is not as strong as in the original masonry. Cracking due to drying shrinkage of the grout could also have occurred, preventing the development of good bond in the repaired areas.

7. CONCLUSIONS & RECOMMENDATIONS

Test results indicate that the technique applied to repair the seismic damage on the adobe masonry house was not adequate: after the repair lateral strength was only 54% of the original strength and lateral stiffness was only about 30% of the original stiffness. This is not sufficient to protect adobe masonry structures from further seismic damage.

Detachment of the crown beam during low intensity shaking prevented the walls from working together and precipitated the partial collapse of the back wall. This could have been prevented by adding extra reinforcements.

The main conclusion is therefore that, although repair via mud injection is useful to recover partially the original stiffness and strength of the structure, this method must be combined with other reinforcing technologies to ensure that the repaired structure is stable against further seismic shaking.

Additional analytical and experimental work is recommended to explore the possible combinations of repairing techniques to achieve better protection of adobe masonry structures located in seismic areas.

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