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SEISMIC REINFORCEMENT OF EARTHEN CONSTRUCTIONS

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Abstract

It is known that unreinforced earthen buildings are highly vulnerable to seismic activity and thus millions of people living in earthen dwellings are at risk. This article presents preliminary results from an ongoing project undertaken at the Pontifical Catholic University of Peru (PUCP), whose main objective is the development of reinforcement techniques for earthen constructions located in seismic areas.

Two techniques have been investigated: the repair of seismic damage by liquid mud (grout) injection in adobe cracked walls, and the reinforcement of earthen constructions by covering all the walls with an orthogonal mesh made of nylon ropes.

The repair of adobe walls via mud injection was studied by performing cyclic tests of adobe masonry specimens and with shaking table tests of full-scale adobe models. It was found that sealing the cracks with mud is not sufficient to recover the original strength and stiffness of the adobe walls. As a result, mud injection should be combined with an additional reinforcement system. Another full-scale adobe model was built and subjected to strong seismic-like shaking. The damaged model was then repaired with liquid mud grout injection and reinforced with a nylon rope mesh which covered all the walls. Each rope was tensioned with metal turnbuckles. The repaired and reinforced model was tested again on the shaking table. In spite of the significant damage on the adobe walls, the provided reinforcement was capable of maintaining the structural integrity and stability of the adobe model.

Currently, analytical and numerical studies are being conducted to develop simple analysis procedures and design guidelines for the reinforcement of earthen buildings with orthogonal meshes made with ropes. Once these studies are completed a new full-scale adobe model will be tested on the shaking table to validate the design guidelines and the proposed construction procedures for seismically safe earthen buildings.

It is hoped that the results obtained will contribute to the protection of vernacular and historical earthen buildings located in seismic areas.

Keywords: earthen construction, adobe, seismic reinforcement, mud injection, nylon mesh

1. Introduction

In many developing countries, earthen dwellings are a traditional housing solution, because soil is abundant and cheap. However, earthen structures are highly vulnerable to seismic activity because their walls are not strong enough to withstand the inertia forces caused by ground shaking. As a result, earthquakes around the world have caused tragic losses in human lives and property damage and the destruction of invaluable historical monuments. Examples of this situation have occurred in Iran (2003, 6.6 M_w), Peru (1970 and 2007, both 7.9 M_w), Pakistan (2005, 7.6 M_w), China (2008, 7.9 M_w), Afghanistan (2015, 7.5 M_w).

Collapse of earthen constructions is triggered by the progressive formation of cracks in the walls. The most common types of cracks are x-shaped cracks due to shear, and vertical cracks at the corners. Vertical cracking at the corners may be followed by overturning of exterior walls (Fig.1), which may in turn pull the roof with them if they support the roof joists. On the other hand, if the joists are supported by walls perpendicular to the façade, the roof may not collapse. The high seismic damage on adobe buildings is mainly due to the lack of appropriate structural reinforcement of their walls.

Fig. 1 - Damage of adobe houses during the Pisco (Peru) earthquake of 2007

The conservation of historical structures located in seismic areas is particularly challenging. Monuments are unique cultural heritage and they must be repaired and strengthened to ensure their stability during future earthquakes. This is complicated because of the conflicting requirements of providing additional strength and stability to the structure while at the same time preserving as much as possible of the original fabric, as stated by the conservation charters and doctrinal texts [1]. ICOMOS-Peru adopted the Principles for the Conservation of Earthen Heritage located in Seismic Areas: “Interdisciplinary analysis and structural assessment of heritage buildings must include the use of traditional materials and technologies, if they are adequate. Considerations should be given to the deep understanding of the historical buildings and their seismic behavior through analytical or physical modeling, non-destructive tests and other modern tools and to document it. Performance-based criterion complemented with strength based criterion should be considered”.

It is the duty of the world engineering community to find ways of protecting earthen constructions built in seismic areas. This paper summarizes the preliminary results obtained during an ongoing PUCP research project regarding the seismic reinforcement of earthen monuments and vernacular dwellings.

2. Proposed retrofit technique for earthen structures

A group of researchers are currently working at the PUCP on a retrofit method consisting of a procedure to *repair* seismic damage on adobe walls by injecting mud grout in the larger cracks, combined with a technique to *reinforce* the earthen buildings by wrapping all the walls with a mesh made of nylon ropes. The repair procedure was devised to be applied mainly on historical monuments, and is intended to recover as much as possible of the original strength and stiffness of the undamaged walls [2]. It basically consists in repairing existing cracks by injecting liquid mud prepared with sieved soil and chopped up grass. The purpose of the nylon mesh reinforcement is to maintain the integrity of the earthen walls after they have been severely cracked by an earthquake, by preventing broken wall portions from falling off. Initially, mesh spacing was selected according to the masonry configuration. Rope crossties placed in the mortar at regular intervals were provided to join the exterior and interior meshes, and all ropes were tensioned using metal turnbuckles to provide confinement to the adobe walls. These techniques were devised according to the conservation principles of minimum intervention, compatible reinforcement and reversible solutions.

2.1 Validation of the proposed reinforcement technique

A full-scale adobe house model was built at the PUCP´s Structures Laboratory to be tested on the unidirectional shaking table [3]. The purpose of the test was to evaluate the efficacy of the mesh reinforcement retrofit system, which would complement the mud injection repair procedure. The model consisted of four adobe walls (3.00 m long and 0.25 m wide, with different heights). Adobe blocks measuring 250 x 250 x 90 mm were made using soil, straw and coarse sand (5:1:1 in volume). The adobe blocks were joined with 20 mm thick mud mortar also made with soil, straw and coarse sand (3:1:1 in volume).

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. The test protocol consisted of several shaking phases with increasing shaking intensity of peak table accelerations of 0.30 g, 0.60 g, 0.90 g and 1.30 g. The original, undamaged model (Fig.2), was subjected to one Phase 1 and two consecutive Phase 2 table motions, in order to induce representative seismic damage (Fig.3).

Fig. 2 - Adobe model on the shaking table, prior to testing

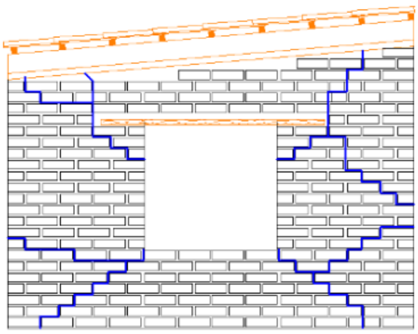


Fig. 3 - Cracking patter induced on the full scale adobe masonry model (right wall)

After the test, the damaged model was retrofitted 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). All cracks wider than 1 mm were opened to about 8 mm wide, by carefully using a drill and an electric knife. 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 into 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. After all cracks were repaired, the model was left to rest for two months to allow for an adequate drying. Then, all the walls were reinforced with an external mesh made of nylon ropes (halyard) with ¼” nominal diameter (Fig.4). The vertical ropes were placed at 250 mm intervals (the length of one adobe block) and 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, with an average force of 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 crossties, which crossed the walls through the mortar joints at selected places.

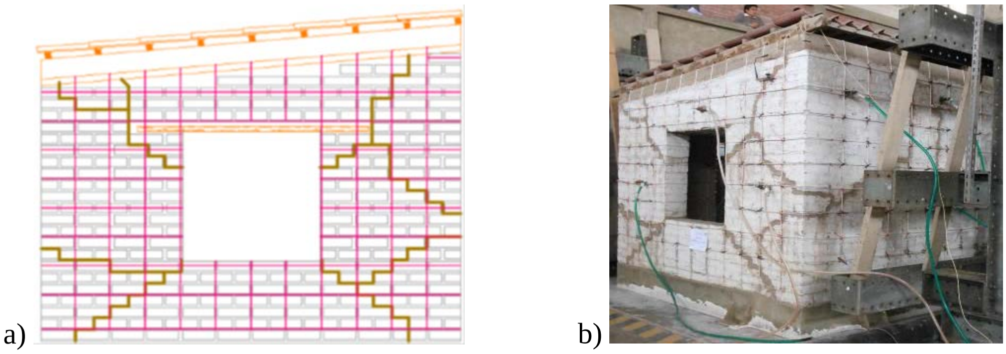


Fig. 4 – Retrofitted adobe model before the test.
(a) Scheme of the reinforcement, (b) photo of the model

The retrofitted adobe model was tested again on the shaking table. This time the model was subjected to successive testing phases with 0.30 g, 0.71 g, 1.08 g and 1.53g horizontal acceleration. During the first phases all the repaired cracks opened and new cracks appeared in all the walls (Fig.5a). In the last phase the mesh was able to keep together the large pieces in which the walls had been broken (Fig.5b). Even though the crown beam got detached due to the damage at the top of the back wall, the reinforcement mesh and the crown beam worked well together in keeping the integrity of the structure. It was noticed that the horizontal ropes placed near the base of the window started to cut into the mud mortar.

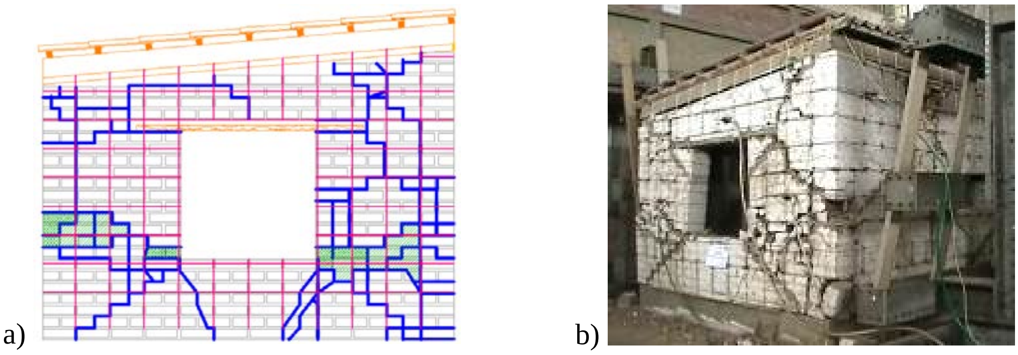


Fig. 5 - Retrofitted adobe model after the test.
(a) Cracking pattern of the right wall. (b) Snapshot of the adobe model during the test

The seismic response of the retrofitted model during the strongest shaking was considered to be excellent because the reinforcement maintained the structural connection between roof and walls, controlled excessive displacements and avoided partial collapses, thus preserving the integrity of the structure.

3. Simplified block analysis

Although Tolles *et al*. [4] have developed general guidelines for the reinforcement of earthen historical monuments and dwellings located in seismic areas, a simple design procedure of the rope mesh reinforcement, aimed at practitioners, does not exist. Furthermore, analysis of retrofitted adobe constructions using elastic finite element methods (FE) would be inaccurate because their seismic response is highly nonlinear. The dynamic interaction between the different broken wall portions joined by the nylon ropes is particularly difficult to model using commercial software. It seems important, therefore, to find relatively simple methods to estimate the amount and distribution of mesh reinforcement to protect earthen constructions subjected to earthquakes.

A first attempt to estimate the forces on the nylon strings is described below.

3.1 Dynamic block analysis

The photo in Fig.6a shows the full-scale adobe model tested on the shaking table. The shaded area highlights a detached portion of wall due to out-of-plane actions. Fig.6b shows a simplified rigid block model of the interaction between the main structure (Block *A*) and the detached wall portion (Block *B*). Both blocks are joined by a set of n horizontal elastic springs, which prevent the overturning of block B. Fig.6c shows the free body diagram of block B, including inertia forces. Block A is fixed to the ground, which moves with absolute displacement x_O. Block B has mass m_B, central moment of inertia I_G, and 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 joins block A and the center of mass G of block B. Spring i has elastic stiffness k_i and is attached to blocks A and B at a height h_i.

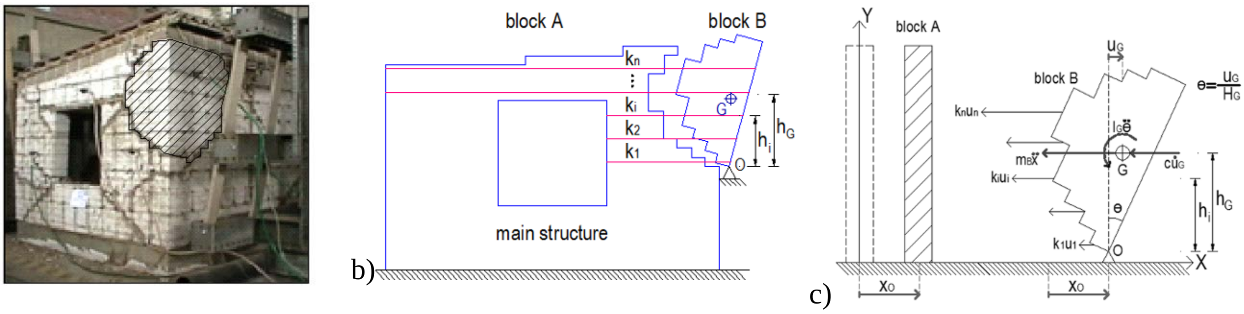


Fig. 6 - Interaction between adobe blocks and reinforcement due to seismic motion.
a) Damaged full scale model; b) simplified block model; c) free body diagram of block B

The resulting equation of motion of block B, obtained through dynamic equilibrium, is

$$\mathrm{M_e}\ddot{u}_G + C_e\dot{u}_G + \mathrm{K_e}u_G = -m_B\ddot{x}_O \tag{1}$$

where the equivalent coefficients for mass (M_e), stiffness (K_e) and damping (C_e) are

$$\mathrm{M_e} = \left(I_G + m_B h_G^{\,2}\right)/\,h_G^{\,2} \tag{2}$$

$$\mathrm{K_e} = \left(\sum k_i h_i^{\,2}\right)/\,h_G^{\,2} \tag{3}$$

$$C_e = 2\zeta_B\sqrt{K_e M_e} \tag{4}$$

The natural vibration period of the system is

$$T_n = 2\pi\sqrt{M_e / K_e} \tag{5}$$

Therefore, if the pseudo-acceleration response spectrum of the ground motion is $S_a(T, \zeta)$, the peak horizontal acceleration of the center of mass G of block B would be $S_a(T_n, \zeta)$, and the force in cable i is

$$F_i = \frac{h_i}{h_G} k_i S_a(T_n,\zeta)\left(\frac{2\pi}{T_n}\right)^2 \tag{6}$$

This block analysis procedure was applied to estimate the forces on the reinforcement provided to three similar full-scale adobe models tested in different projects on the PUCP's shaking table. The table motion pseudo-acceleration spectrum computed for a damping ratio of 10% (Groenenberg [6]) is presented in Fig.7. It corresponds to a shaking motion with peak acceleration of 1.53 g, for which an unreinforced adobe model would have collapsed.

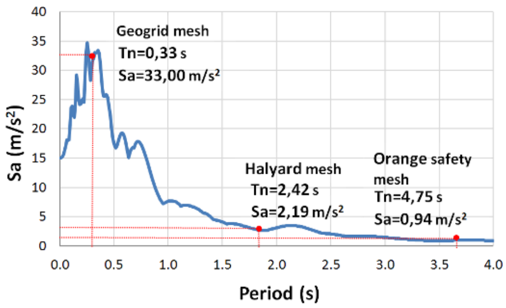


Fig. 7 – Pseudo-acceleration spectrum for examples

Fig.8 shows the values of the peak load on the most stressed string and the corresponding working load ($f_w = f_u/2$, where f_u is the ultimate load of a single string) calculated for three types of reinforcement mesh: 1) nylon rope mesh; 2) biaxial geogrid mesh; and 3) plastic safety mesh. These calculations predicted correctly the observations in the laboratory: the forces in the nylon string mesh and the geogrid mesh reinforcement were below their working limit ($f_{max} < f_w$), and the safety mesh failed locally ($f_{max} > f_w$).

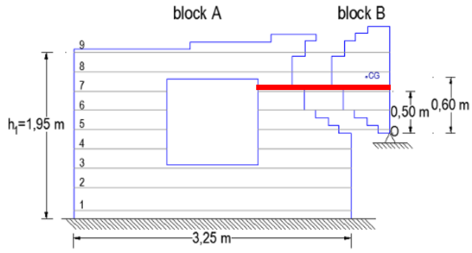
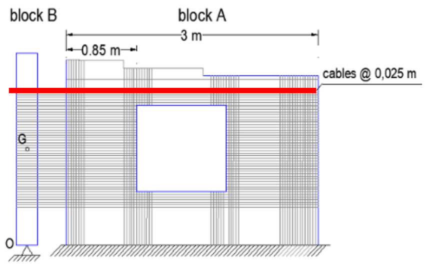
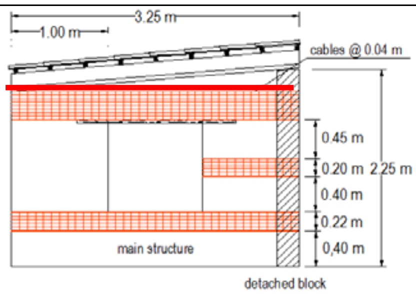
1			a) I_o=320 kg-m^2 b) k_i =3,00 kN/m c) T_n= 2,42 s. d) f_{max}= 0,83 kN. e) $f_{max} < f_w$ = 1,0 kN.
2			a) I_o=2590 kg-m^2 b) k_i =1,80 kN/m. c) T_n= 0,33 s. d) f_{max}= 0,44 kN. e) $f_{max} < f_w$ = 6,0 kN.
3			a) I_o=2590 kg-m^2 b) k_i =0,12 kN/m. c) T_n= 4,75 s. d) f_{max}= 0,10 kN. e) $f_{max} > f_w$ = 0.035 kN

Fig. 8 – Evaluation of maximum forces according to design procedure

These examples are encouraging since their results are consistent with the observed response of different reinforcing meshes. However, it seems that this analysis procedure may be not accurate because it does not consider the observed pounding between the adobe wall blocks.

4. Numerical modelling of block pounding

A 3D numerical finite element model was created in SAP2000 [5] using shell elements, in order to analyze the elastic seismic response of the adobe house model (Fig.9). The base excitation input was the acceleration record measured on the first phase 1 of shaking. Linear, elastic and isotropic behavior was assumed for the adobe masonry since no cracks were visible in the adobe walls during Phase 1. An elastic modulus E= 250 MPa was selected to match the experimental natural frequency of the adobe model of 12.3 Hz. Fig.10 shows in light gray the areas where highest tensile stresses occur. They match the locations where diagonal cracking initiated in the experimental model during subsequent Phases 2 and 3. Although this linear model was reasonable to predict shear cracking, it could not predict overturning of the back wall.

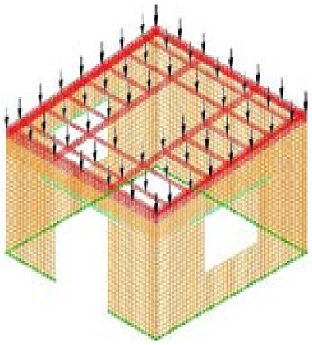
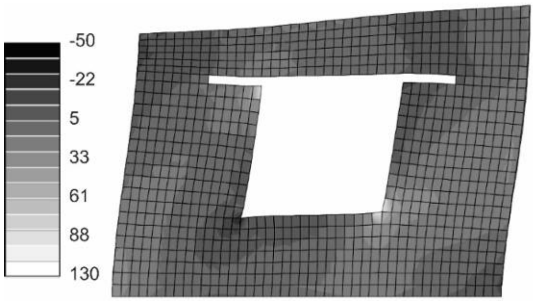


Fig. 9 - Finite element model



Right wall deformation x 400
Fig. 10 - Principal stresses (kPa) at 11.97 s

During the shaking table tests the reinforced adobe walls broke into big pieces which collided with each other. Commercial linear elastic FE analysis software cannot capture this behavior because the shell elements simply intersect each other. Fig.11 shows a linear elastic FE model where the back wall is separated from the main structure. The nylon ropes are represented by bar elements. During the dynamic simulation the back wall overlaps the main structure and the ropes are in compression, something that clearly does not happen in the real world.

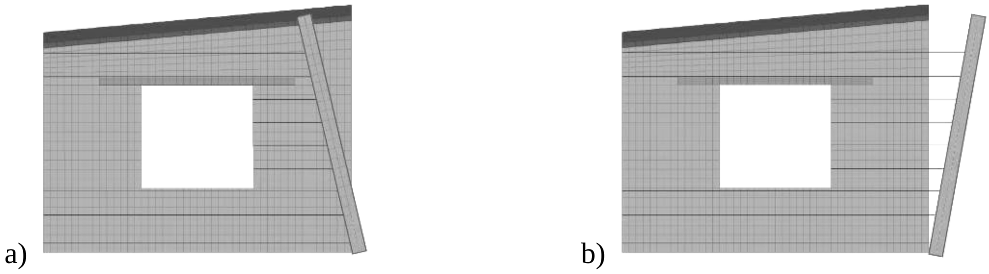
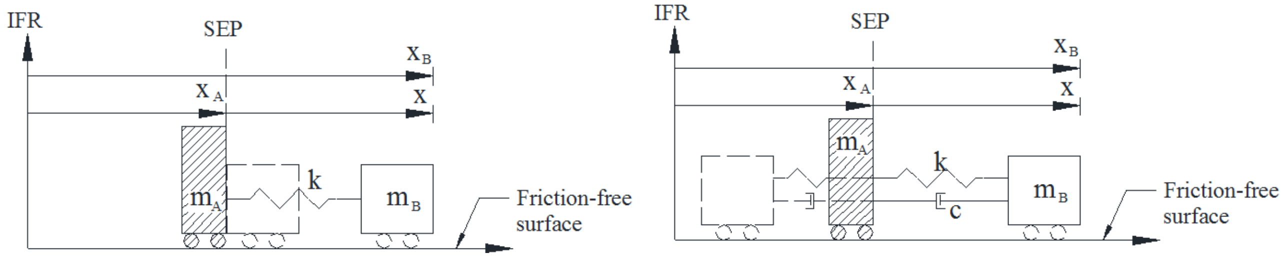


Fig. 11 – Wall overturning sequence in analysis using commercial linear FE software

Modelling the observed impact between wall portions is thus not possible with commercial structural analysis software. It was then decided to explore the possibility of estimating the energy lost during the inelastic collisions between the wall blocks through the incorporation of additional viscous damping to the elastic block model.

Fig.12a shows a block *B* attached to a massive rigid block *A* by a spring of stiffness *k*. Block A motion represents the input excitation for block B. During shaking, blocks *A* and *B* may collide inelastically, with coefficient of restitution *e*. Fig.12b shows the same blocks, but arranged in a way that they can move independently without colliding. In this case a viscous damper with damping coefficient *c* is added between the blocks. The idea is to select a damping coefficient *c* such that the damper dissipates the same amount of energy than that lost during the inelastic collisions.



a) Colliding SDF system   b) Underdamped SDF system

Fig. 12 - SDOF systems

The simplest analysis case for both *sdof* systems is when block *A* is attached to a static ground, block *B* is separated a certain distance from block *A*, and then released with zero initial velocity. It is easy to show that the equivalent damping ratio required to have the same peak displacement on both systems is:

$$\zeta_{eq} = \frac{-\ln(e)}{\pi} \tag{7}$$

A simple test was developed to estimate the coefficient of restitution between a dry low plasticity clay ball and an adobe block. The ball was released from a height of 200 mm, collided with an adobe block and rebounded to a height of 20 mm. The corresponding coefficient of restitution is $e = 0.3$ and the equivalent damping ratio obtained from equation (7) is ζ_{eq}= 0.38.

Fig.13 shows the computed displacement response of block *B* when it is separated from static block A, a distance of 100 mm and then released. The natural frequency of block B when block A is fixed is f_n = 1 Hz. For comparison purposes, the absolute value of the response is plotted for the equivalent damped system. The peak response displacement is similar in both cases, showing that for the case of free vibrations of block B, the equivalent damped system would dissipate approximately the same amount of energy than the colliding system.

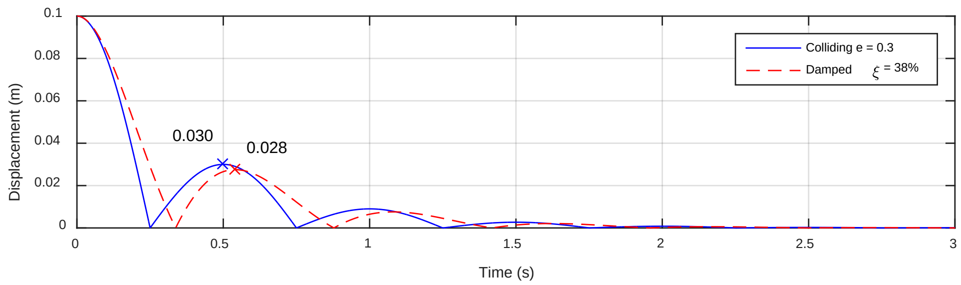


Fig. 13 – Block B displacement response for colliding and equivalent damped systems

Fig. 14 corresponds to the envelopes of relative displacement (in absolute value) of block B with respect to block A, computed for the case when block A moves harmonically with frequency f_A. The damped system ratio is ζ_{eq}= 0.38, obtained for fixed block A. It is clear that the damped response with this equivalent damping underestimates the relative response when the blocks collide, for all range of frequency ratios f_A/fn.

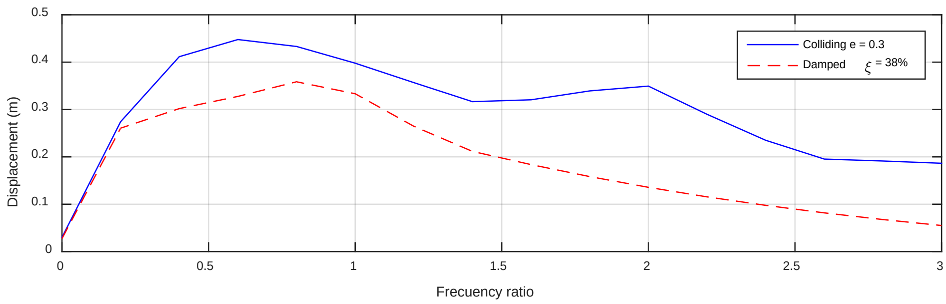


Fig. 14 – Relative displacement response envelopes for harmonic input

The equivalent damping ratio to be used for seismic analysis and design should be selected conservatively, i.e, it must provide design forces larger than those calculated for the case where the blocks collide. Therefore, the equivalent damping ratio obtained from Eq. 7 is too large and cannot be used for design of adobe structures. Fig. 15 shows the results of a time history analysis of the relative response of block B for a smaller equivalent damping ratio of 10%, selected empirically. The input motion is the recorded shaking table acceleration during an adobe house test. In this example, the displacement response of the equivalent damped system is larger than that of the colliding system, and thus it leads to larger elastic forces than the colliding system.

This problem is still being studied, and it is hoped that a solution based on rational principles will be obtained soon.

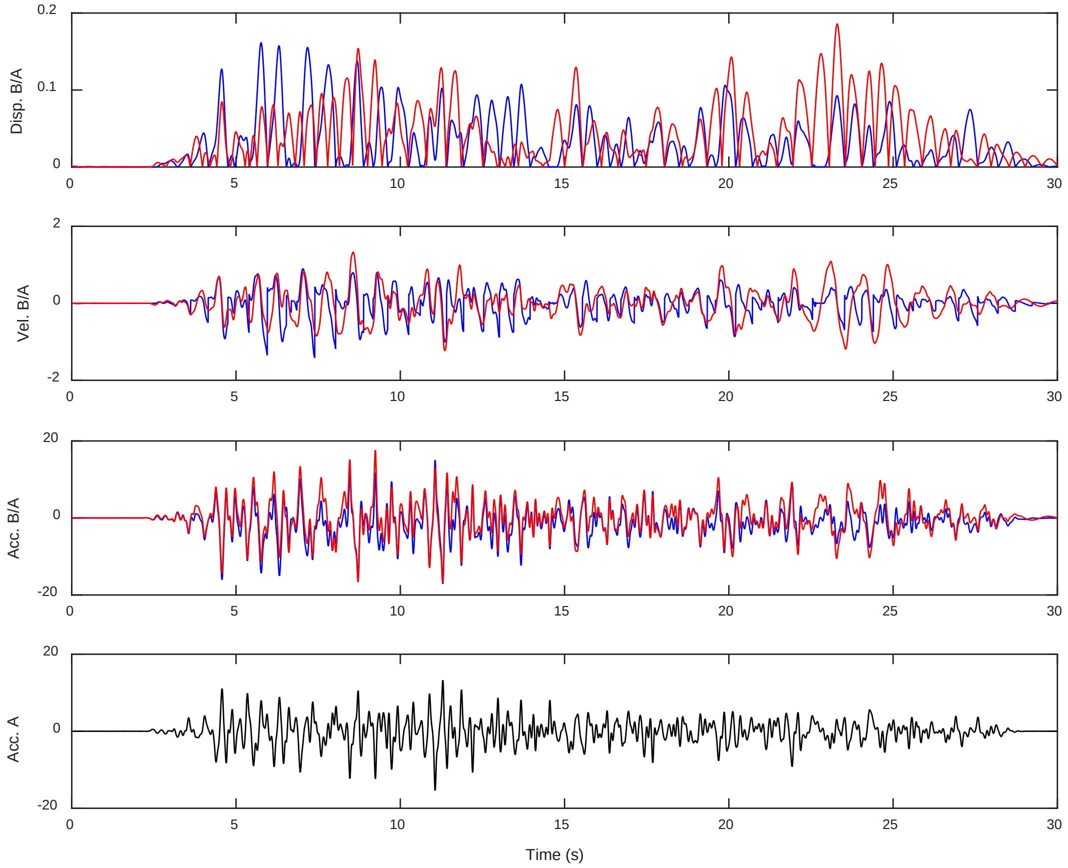


Fig. 15 – Relative response for colliding system (e = 0.3, blue lines) and equivalent damped system (ζ_{eq}= 10%, red lines) for shaking table acceleration input (black line, bottom graph). SI units (m, s)

5. From the academy to the field: technology transfer initiative

The reinforcement mesh used at the laboratory consisted of nylon ropes joined by metal turnbuckles costing around US$ 1.20 each. Eight turnbuckles are needed for each m^2 of wall. This is too expensive for rural dwellers in developing countries, and furthermore, the turnbuckles are not easy to find in rural areas. Therefore it was decided to discard their use and to join the ropes using knots. A short experimental program was developed to select a simple and adequate knot, able to keep the tension for a long time. Several knot combinations were tested, based on their ease to be made and their ability to keep the original tension. Finally, a combination of an "eight" knot and a "half-hitch" knot, shown in Fig.16, was selected. Constant load tests showed that 5/32" halyard ropes joined with the selected knot combination were able to hold about 60% of its initial tension after a week, as can be seen in Fig.17.

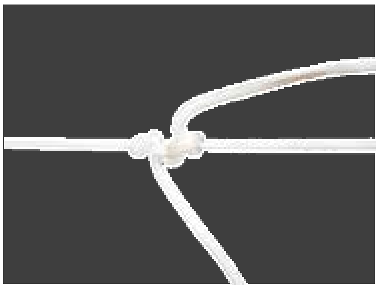


Fig. 16 - Selected knot to join the nylon ropes

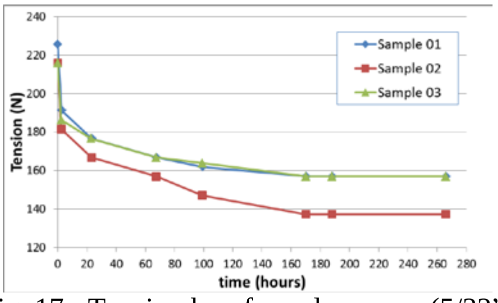


Fig. 17 - Tension loss for nylon ropes (5/32")

The nylon rope mesh reinforcement technique was tried in a pilot project in Pullo, an Andean rural community in Peru, where over 80% of the houses are made of traditional adobe and built without technical assistance or seismic reinforcement criteria [7] [8]. Two communication and educational tools were used to disseminate the nylon rope mesh seismic reinforcement among rural dwellers: a portable shaking table and an illustrated construction manual. The portable shaking table was used to perform dynamic tests on reduced-scale adobe models (Fig.18). Its main goal is to educate community members about the high seismic vulnerability of their dwellings, and to show the value of building earthquake-resistant adobe houses. The illustrated construction manual is a technical document that fully describes how to reinforce an adobe house with nylon ropes using simple language and easy-to-follow drawings (Fig.19).

Fig. 18 - Demonstration on the portable shaking table

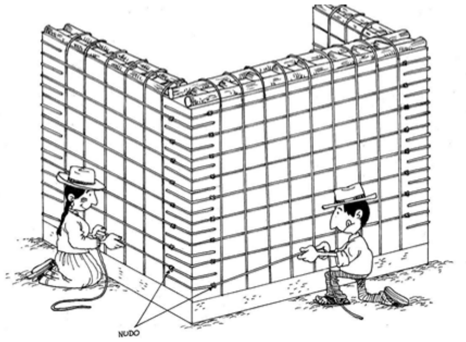


Fig. 19 - Booklet to build safety adobe houses (in Spanish)

6. Conclusions

The proposed retrofit technique developed at the PUCP to protect earthen buildings in seismic areas has shown to be efficient in full scale unidirectional shaking table tests. The technique is reversible and not very intrusive, and therefore it seems suitable for the seismic protection of earthen monuments. It is also relatively simple and cheap, and therefore seems convenient for the construction of safe adobe rural dwellings. There is a need, however, to develop reliable analysis and design procedures aimed at engineers and architects, to give them tools to specify the amount and distribution of reinforcement for a given structure. The simple procedures presented in this paper seem to be a reasonable step in that direction, but they still need to be refined and tested in the laboratory and the field.

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