SEISMIC REINFORCEMENT OF TWO-STORY EARTHEN BUILDINGS USING A ROPE MESH: PRELIMINARY TABLE TEST RESULTS

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Abstract

Millions of low-income families living in earthen dwellings in seismic areas around the world are at significant risk because most of these structures are built informally and without any seismic reinforcement. Every single earthquake occurring in these areas has caused an unacceptable loss of life, injuries, and property damage. Earthquakes are recurring and construction damage is cumulative. It is urgent, therefore, to devise low-cost and easy to implement seismic reinforcement systems and to make them available to the actual dwellers. The researchers at the Pontifical Catholic University of Peru (PUCP) have been working towards that goal for almost half a century and have recently proposed design guidelines and a construction methodology for a seismic reinforcement system consisting of a mesh of nylon ropes confining all earthen walls, in order to control displacements and to prevent the overturning of wall portions that have separated due to seismic shaking. The effectiveness of this system has been validated for single-story adobe structures via shaking table tests of (almost) full-scale one-story adobe housings models.

In the Andean regions, however, many families build multistory earthen houses, and it is not known whether the proposed rope reinforcing system would be effective in protecting these structures. Therefore, the PUCP researchers decided to start an experimental and analytical project devoted to the study of the seismic response of multistory earthen buildings. The main objective of the project is to assess whether the proposed rope mesh reinforcement would also be effective in providing seismic safety to multistory earthen constructions.

This paper presents some preliminary results obtained during the experimental campaign, where four half-scale two-story adobe housing models were tested at the PUCP's unidirectional shaking table under simulated strong seismic motions. The same command signal, derived from a Peruvian acceleration record, was used at different amplitudes for each shaking table test. As expected, both unreinforced models, which simulated local vernacular constructions, suffered rapid and total collapse. All the walls fractured in a few large pieces, which were not held together by the provided wooden crown beams and thus fell to the ground. The next two models were reinforced using an external nylon rope mesh, basically with the same configuration as that successfully used in the one-story models. Again, as expected, all the adobe walls fractured in large pieces, but this time the provided mesh reinforcement was able to hold the pieces together, thus maintaining structural integrity and preventing collapse.

These results are encouraging, and thus the project is being continued with an analytic study of the dynamic response of big blocks of adobe masonry wall joined by elastic ropes and subjected to earthquake ground motions. The aim of this stage of the project is to attempt to explain the dynamic response of broken adobe walls, as observed during the experimental stage.

The authors hope that this project will help to understand the complex response of earthen structures and that its results will lead to construction procedures for the protection of vernacular and historical earthen buildings located in seismic areas.

Keywords: earthen construction, seismic protection, rope mesh reinforcement

1. Introduction

Earthen buildings around the world have shown to be extremely vulnerable to earthquakes. This is due to the poor structural properties of their walls: earthen walls are dense and heavy, have extremely low tensile strength and fail in a brittle fashion and without any warning during earthquakes. As a consequence, every significant earthquake that has occurred in regions where earthen construction is common has produced tragic loss of life and considerable material damage.

The collapse of earthen constructions is usually triggered by the progressive formation of cracks in the walls. First, a combination of in-plane diagonal cracks and vertical corner cracks occurs due to the low tensile strength of the adobe masonry. Then, exterior walls may overturn out-of-plane, sometimes dragging the roof with them [1]. Fig. 1 shows the partial collapse of adobe dwellings during the Pisco, 2007 earthquake in Peru. It is quite revealing to notice that the confined masonry house shown in the photo at the left did not suffer any damage, whereas the neighboring adobe houses lost their façade walls and most probably had to be demolished. Unfortunately, adobe is the only construction material available for a large portion of the population in Peru and many developing countries in seismic areas of the world.

Fig. 1 – Adobe buildings heavily damaged by the Pisco, 2007 earthquake in Peru.

A team of researchers from the Pontifical Catholic University of Peru (PUCP) has been working since the 1970s towards finding simple and economical ways to provide seismic safety to earthen buildings. Recently, they have developed an innovative reinforcement system conceived to prevent the overturning of wall portions during earthquakes. The reinforcement system, consisting of enveloping all the walls with a mesh made of synthetic ropes that completely envelopes all the walls, was successfully validated at the PUCP´s Structures Laboratory, as reported in [2].

Two one-story adobe models were built, reinforced with nylon string meshes and tested at the shaking unidirectional table [2]. The first one-story model was first shaken in order to induce representative seismic damage. Then, the larger cracks were repaired via mud grout injection, and after the repaired cracks were suitably dry, the model was reinforced with a mesh made of 1/2” nylon ropes and tested again on the shaking table with a sequence of movements of increasing intensity (0.30 g, 0.71 g, 1.08 g and 1.53 g horizontal base acceleration). The model’s seismic response was considered to be excellent because even during the strongest shaking the mesh reinforcement maintained the structural connection between roof and walls, controlled the excessive displacements of the walls and avoided partial collapses thus preserving the integrity of the structure Figure 2a shows the model after the whole testing campaign.

Based on the experimental results obtained, a design procedure was devised in order to be able to specify the rope mesh reinforcement required to provide seismic safety against collapse of any one-story earthen building. A second one-story model, was then built and reinforced with thinner 5/32” nylon ropes [3], which were tied by hand, thus avoiding the use of turnbuckles. This new reinforced model was subjected to a single strong base motion with 1.4 g peak acceleration, and its dynamic response was also considered to be excellent, as the rope mesh was capable of preventing the overturning of the large wall portions which were cracked due to the strong shaking, as shown in Fig. 2b.

a) 1/2” nylon mesh reinforcement b) 5/32” nylon mesh reinforcement

Fig. 2 – Cracking patterns on reinforced full-scale one-story adobe models after strong shaking table tests.

This dynamic testing campaign on full-scale adobe masonry models reinforced with nylon ropes has revealed that this system is adequate to prevent the collapse of one-story earthen buildings subjected to strong seismic shaking. The next challenge is to determine whether this mesh reinforcement would be suitable to protect buildings with more than one story, which are very common in Peru, as in many other countries.

2. Seismic retrofitting of two-story adobe buildings using a nylon mesh

Dynamic testing of large-scale models of two-story earthen buildings is not possible on the PUCP’s shaking table because the weight of test specimens would exceed 150 kN maximum capacity of the equipment. The only possibility to perform shaking table tests on two-story adobe models was therefore to work on reduced-scale specimens. Consequently, it was decided to build four half-scale two-story models, in order to study the seismic response of typical two-story adobe housing models, with and without mesh reinforcement. The four adobe models were tested at the shaking table, under simulated seismic motions of several amplitude levels.

2.1 Scaling process

The four identical reduced-scale adobe specimens were designed by establishing similitude ratios λ between physical property parameters of a full-scale *prototype* and a half-scale *model* [4]. The selected length scaling ratio (Prototype/Model) was therefore $\lambda_L = LP/LM = 2$. Correspondingly, the scaling ratios for area and volume were, respectively, $\lambda A = 4$ and $\lambda V = 8$. Since the test models were to be made with the same soil as the real buildings, the scaling ratios used for density, modulus of elasticity and mechanical strength were set equal to 1. Therefore, the mass ratio was $\lambda_M = \lambda_V = 8$, and assuming that the applied stress ratio was equal to the material strength ratio (i.e. ignoring gravity stresses) the force ratio is equal to the area ratio ($\lambda_F = \lambda_A = 4$). Finally, Newton’s 2nd law (F = ma) implies that an acceleration ratio $\lambda_a = ½$ and therefore, to have $\lambda_L = 2$, the time ratio must be $\lambda_T = TP/TM = 2$.

The shaking table displacement command signal used to test the half-scale two-story adobe models was therefore obtained by halving the amplitude of the prototype displacement command signal ($LM/LP = 1/\lambda_L = ½$), and by compressing the time scale by a factor of two ($TM/TP = 1/\lambda_T = ½$). It is important to remark that this scaling process is valid only in the elastic phase, but the adobe material breaks promptly during shaking and ceases to be in the elastic range.

Figure 3 shows the final dimensions of the half-scale adobe models. The rope reinforcement pattern selected is also shown. The total weight (including the reinforced concrete foundation) for each model was around 115 kN, which is below the maximum bearing capacity of the PUCP's shaking table.

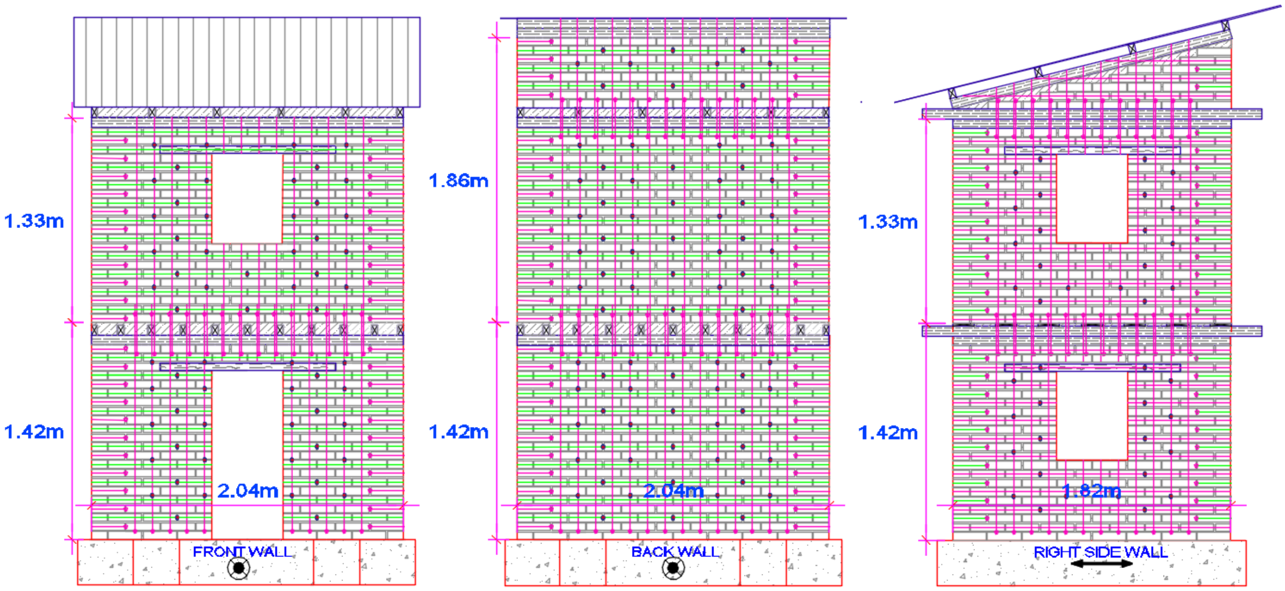

Fig. 3 – Mesh-reinforced half-scale adobe model schematics.

2.2 Construction of test specimens

The same soil was used for the fabrication of both the adobe bricks and the mud mortar, in order to avoid variability in the materials. The material proportions in volume were 5:1:1 (soil:coarse sand:straw) for the adobe bricks and 1:1 (soil:coarse sand) for the mud mortar. All blocks were 221x221x50 mm and were sun-dried for at least 28 days. The four models were identical. Each model was built over a concrete beam that was used as foundation and as transporting base from the yard to the shaking table. The mortar thickness was around 10 mm. The lintels of doors and windows were made of cane rods tied with wire. The roofs were built using wooden boards supported on 2”x3” wooden beams. A wooden crown beam was placed at the top of each floor of the reinforced models to guarantee a boxlike behavior. A mud stucco was applied at the exterior of the walls of the models, except for one of the reinforced model, which was left without stucco for easier observation of the seismic cracks.

The rope reinforcement consisted of 1/8” vertical and horizontal nylon strings placed on both faces of all walls. The horizontal strings were doubled. The reinforcement spacing was specified to be consistent with the masonry layout: every two rows horizontally and every block vertically. Holes were drilled on the mortar to allow passing the ropes through the walls. These perforations were carried out mainly in the vertical joints close to the wall corners for the placement of the horizontal ropes. Also, the horizontal joints located in lower areas were drilled for the placement of the vertical ropes. Additional holes were drilled in order to connect the internal and external meshes with pass-through ropes. The first story vertical ropes were placed first, passed over the wooden floor beams and tied to the second story ropes. Then, the horizontal ropes (which were doubled) were placed. The inner and outer meshes were joined with pass-through ropes. Figure 4 shows two stages of the construction of one reinforced adobe model.

Fig. 4 – Construction of a half-scale reinforced adobe model.

2.2 Test set up

The PUCP shaking table is displacement controlled. The same unit displacement command signal, shown in Fig. 5, was used for all tests, multiplying its amplitude by the desired peak table displacement.

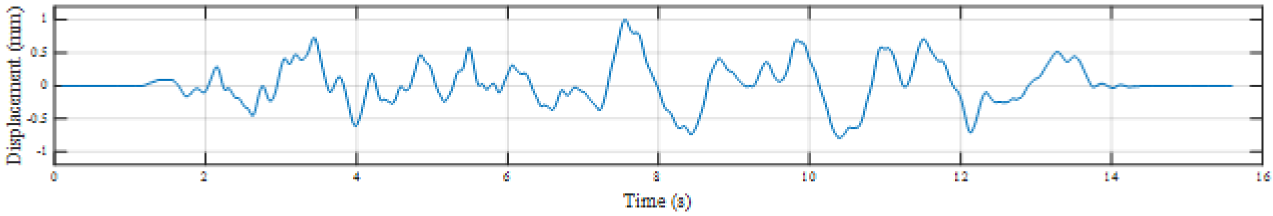

Fig. 5 – Unit displacement command signal.

The following nomenclature was used to identify the test specimens: URM-N for Unreinforced Model N, and SRM-N for String Reinforced Model N. Table 2 summarizes the command peak displacement $D0_{max}$ and the expected peak table acceleration $A0_{max}$ for this testing campaign. It was considered that a peak table displacement smaller than 15 mm would represent a slight earthquake; that between 30 and 45 mm, a moderate earthquake; and that greater than 60 mm, a strong earthquake.

Table 2 – Summary of maximum motion intensities for each half-scaled adobe model.

Table motion intensity	**$D0_{max}$**	**$A0_{max}$**	**URM-1**	**URM-2**	**SRM-1**	**SRM-2**
Slight	15 mm	0.5 g	✓		✓	
Moderate	30 mm	1.0 g	✓		✓	
	37.5 mm	1.12 g	✓			
	45 mm	1.27 g		✓		
Strong	60 mm	1.75 g		✓	✓✓	✓✓
	90 mm	2.20 g		✓		

Figure 6 summarizes the instrumentation used to record the response of the models. It consisted of 11 displacement sensors (LVDTs), 10 accelerometers and 02 load cells placed within selected horizontal ropes. Each model was placed on the shaking table in such a way that the walls with windows were parallel to the base movement. Additionally, the force applied by the actuator (F0) and the table displacement and acceleration (D0, A0, respectively) were also recorded.

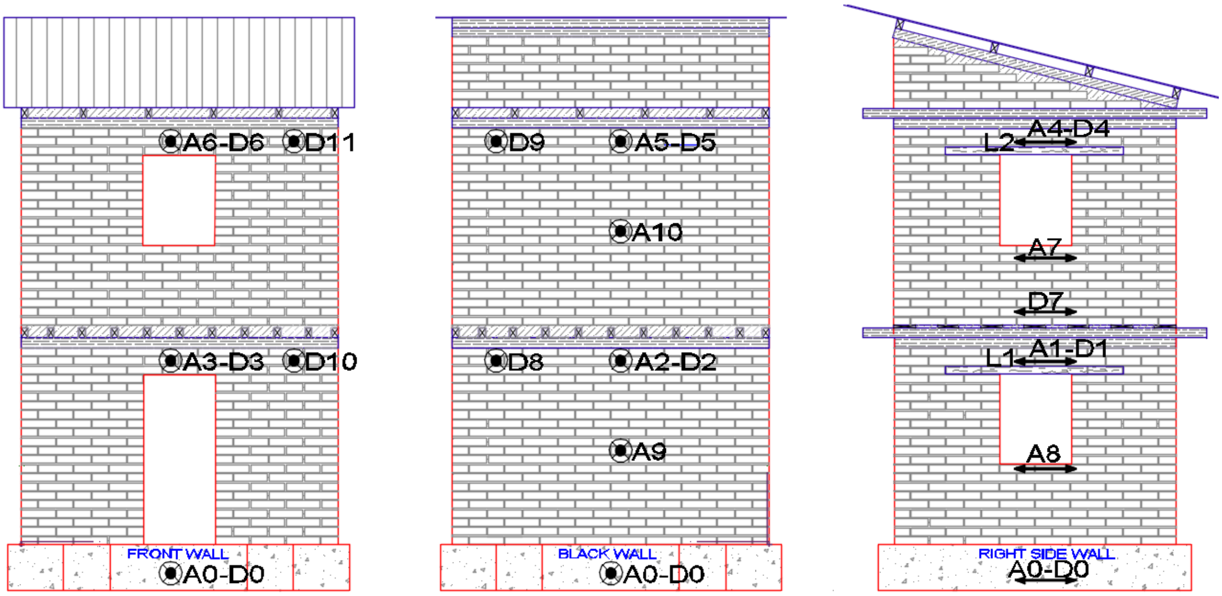

Fig. 6 – Distribution of LVDTs and accelerometers in the half-scale adobe model.

2.4 Seismic performance and test results

The URM-1 and SRM-1 were first subjected to an input signal with $D0_{max}$ =15 mm. The corresponding table acceleration was 0.5g. Although none of the models showed external cracking, their lateral force versus first-floor displacement (at D1) diagrams shown in Fig. 7 indicate that, whereas the response of the unreinforced model was nonlinear, which means that cracking in the walls had occurred, the force-displacement loops of the SRM are narrow and suggest a global linear response.

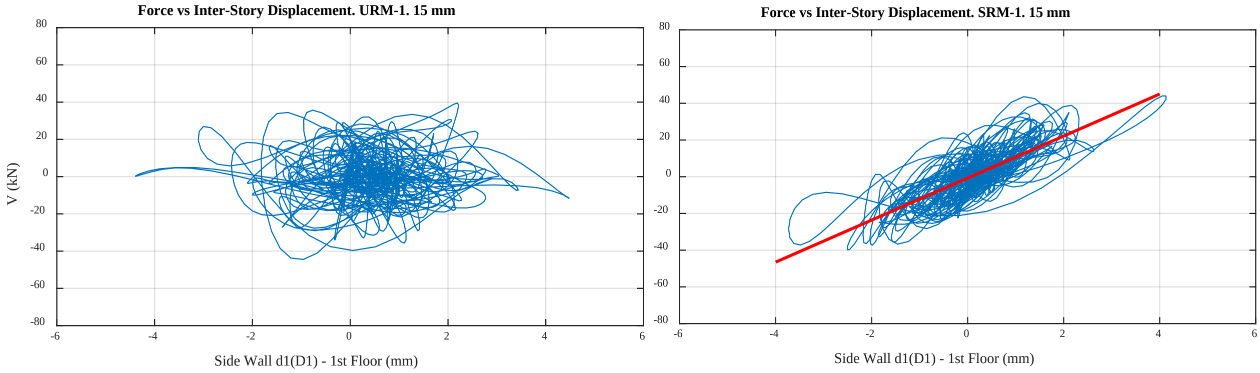

Fig. 7 – Lateral force vs first floor displacement for URM-1 and SRM-1 at 15 mm table displacement

Testing of URM-2 started with a moderate table motion with $D0_{max}$ = 45 mm and $A0_{max}$ =1.27g. During the shaking, this unreinforced model suffered significant damage: many portions of stucco fell down, and diagonal and vertical cracks appeared in the lateral walls, which were therefore broken into separate wall pieces (see orange lines in Fig. 8a). This level of damage is consistent with the observation in the field that actual 2-story adobe buildings collapse or are inhabitable after moderate earthquakes. During the following strong motion with $D0_{max}$ = 60 mm and $A0_{max}$ =1.64 g, the model was close to collapse: the front first story wall got separate from the floor beams, and thick diagonal cracks were formed on the second story back wall, across the full wall thickness (see orange and red lines in Fig. 8a). Also, there was a clear separation between the walls and the sloped roof. Fig. 8a shows the URM-2 after this test.

The first reinforced model was subjected to four shaking table motions. During the two firsts tests, with $D0_{max}$ of 15 and 30 mm, some small horizontal cracks appeared at mid-height of the first floor front and back walls (see green lines in Fig. 8b). Then, two similar strong motions with $D0_{max}$ = 60 mm and $A0_{max}$ = 1.67 g were applied successively. During the first 60 mm shaking, diagonal cracks appeared near the openings of both levels, dividing the wall into several blocks (see green and red lines in Fig. 8b). In the second 60 mm tests all these fissures opened a little more and a slight relative movement between the different wall blocks was detected. The rope mesh reinforcement, however, was able to keep together all these wall portions. The reinforcement provided, therefore, allowed the structure to keep together in a stable manner, even though some walls were significantly damaged. None of the nylon strings failed during these tests. Fig. 8b shows the condition of the reinforced model after the second strong 60 mm, 1.67 g shaking.

a) URM-2 b) SRM-1.

Fig. 8 – Damage of two models after strong shaking ($D0_{max}$ =60 mm, $A0_{max}$= 1.67g).

Measured peak values of some response parameters for one unreinforced model and reinforced for typical light, moderate and strong simulated seismic shaking are summarized in Table 3 below. Both models could be considered mechanically comparable, as their main vibration periods before testing started were quite similar (0.11 s). Clearly, the URM suffered considerably more damage than the SRM, especially on the second story, where the relative displacement was 50% larger than that of the first story during the 15 mm test and more than 400% larger on the last, strong 60 mm test. Since the ropes were able to restrain the relative displacements in the SRM and to keep together the adobe wall blocks, the SRM lateral strength was larger than that of URM. This is observed for the strong shake, were the peak base shear for the SRM was 17% larger than that of the URM, and with the possibility to resist more lateral load since the SRM was still stable. At this point, the maximum registered force at the rope was 0.57 kN at the first level, while its ultimate strength is 1.4 kN. Therefore, the ropes did not reach their maximum capacity.

Table 3 – Summary of measured peak values.

Model ID	**Secant Period Tn (s)**	**Shaking intensity**	**Table**		**Base shear V (kN)**	**Relative displacement (mm)**		**Rope force F (kN)**
			displacement D0 (mm)	**acceleration A0 (g)**		**1st level**	**2nd level**	
URM-2 SRM-1	0.14 0.15	Light	15 mm	0.5 g	44.5 44.0	6.3 5.3	8.7 5.8	- 0.13
URM-2 SRM-1	0.35 0.25	Moderate	30 mm	1.0 g	66.7 58.9	79.6 14.5	90.3 21.5	- 0.30
URM-2 SRM-1	0.50 0.30	Strong	60 mm	1.75 g	68.9 83.6	61.6 42.2	256.4 48.4	- 0.57

Figure 9 shows the time history graphs of relative displacements of the back wall of the URM-2 and SRM-1, together with the base acceleration for a strong shaking with $D0_{max}$ = 60 mm and $A0_{max}$ = 1.68 g. Damage of the URM is evidenced by the permanent residual deformations of the URM, while the SRM returns almost to its original position.

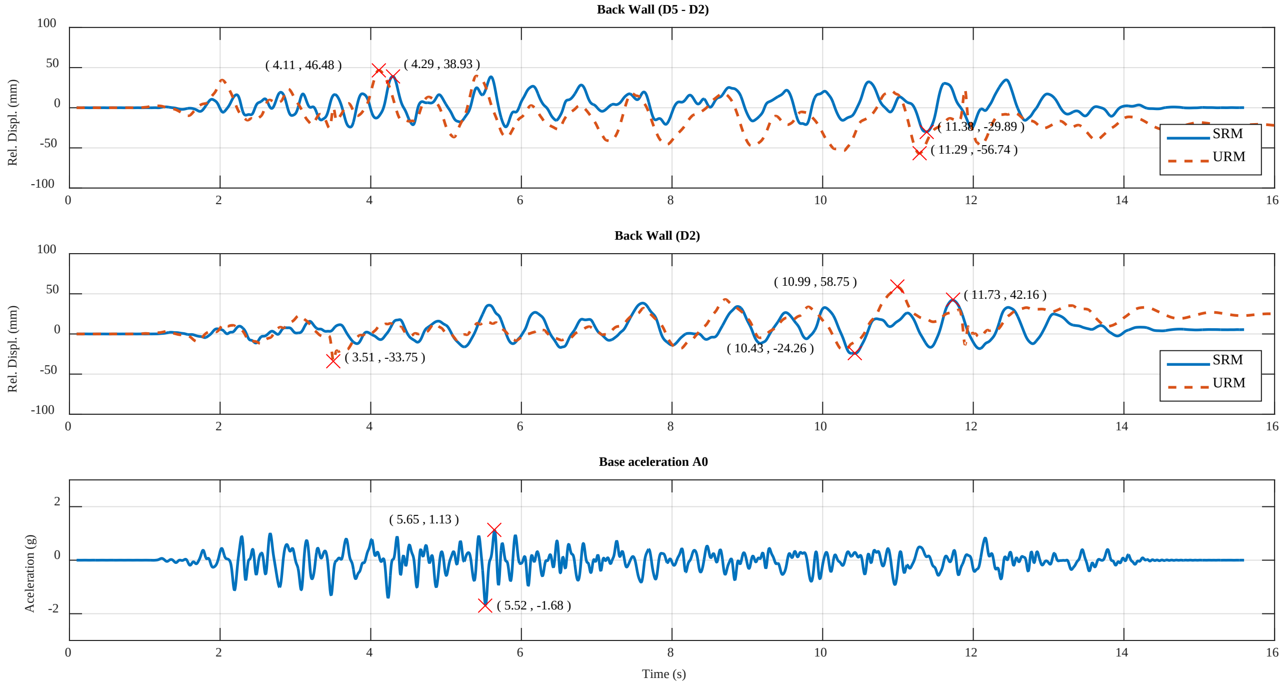

Fig. 9 – Back wall inter-story displacements of URM-2 and SRM-1 for strong $D0_{max}$ = 60 mm, $A0_{max}$= 1.68g shaking.

For visual comparison between the relative wall displacements for a strong shake ($D0_{max}$ =60 mm), Fig. 11 shows a profile of the movement of the back wall of the URM-2 and SRM-1 remarking some displacements at specific times. It is observed that the back wall of the SRM responds with its first vibration mode (e.g. shear wall deformation); while the URM, with the second vibration mode because and inverse of the deformations is seen along the wall height. Again, it is demonstrated that the reinforcement not only control the relative displacements, also the way the structure response. Although the back wall of the SRM seems to reach, at the second level and for the 10-15 s interval, similar relative displacement as the URM, it returns to its original position, while residual displacements appear in the URM wall.

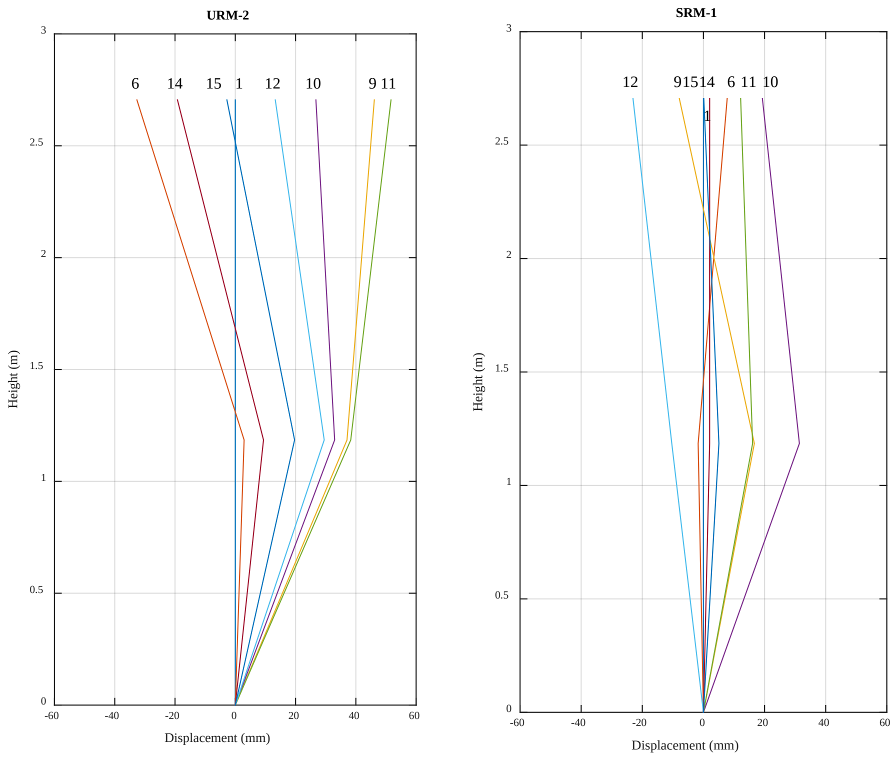

Fig. 10 – Profiles of back wall displacement at selected instants D_{0max} =60 mm and $A0_{max}$= 1.67g.

4. Conclusions

The shaking table tests showed that the URMs suffered significant damage and became unstable during moderate shakes, and became close to collapse after strong motions. This did not occur for the SRMs, which were able to resist stronger motions and higher lateral forces. Therefore, the SRMs showed a good seismic behavior for strong motions. The adobe walls broke in big portions, but the ropes kept them together, thus preserving structural integrity.

Another advantage of the rope reinforcement is their capacity to restrain the residual deformations. While the URMs presented significant residual deformations, the reinforcement mesh returned the SRM adobe walls to their original position, without exceeding their tensile strength. It is clear, however, that a proper design procedure is required in order to optimize the amount of reinforcement required.

The extensive research effort developed at the PUCP and other institutions has shown that the construction of earthquake-resistant buildings is therefore feasible. A reinforcing system consisting of a rope mesh that envelopes all walls and connects them with the foundation and the roof, combined with a continuous crown beam at the roof level has demonstrated to be effective in preventing the collapse of one- and two-story adobe models during different levels of unidirectional shaking.

This technical solution, unfortunately, is not enough to solve the real problem of the unacceptable seismic risk for the millions of earthen house inhabitants. Mitigation of seismic risk will be possible only when the users themselves adopt improved earthen construction systems as part of their own culture.

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5. Copyrights

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