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NUMERICAL MODELING OF THE SEISMIC RESPONSE OF ADOBE HOUSES PROTECTED WITH USED CAR TYRE STRAPS

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Abstract. *Earth is one of the most ancient building materials, and has been used by many to build their own houses by themselves for centuries, because is readily available at little or no cost. Such people, however, often live in high seismic hazard zones, and earth is a fragile material, with almost no tensile strength. Consequently, Adobe houses can suffer severe damage or collapse due to earthquakes, leading to considerable economic loss, injuries and deaths. The purpose of this paper is to support adoption of car tyre straps as a means to ameliorate deficiencies of Adobe buildings. The use of this reinforcing technique satisfies at the same time two interesting requirements: on the one hand, low-income people in developing countries need almost-no-cost reinforcement techniques to succeed in improving the safety of their houses, and spent car tyre can represent one of such low-cost techniques. On the other hand, by using spent car tyre, the huge environmental issue of waste disposal is exploited as a resource, and no more as a burden. Some initial experimentation with used car tyre straps has already been done, and the results were very encouraging. On this base, in the present work numerical modeling of full Adobe buildings is carried out to assess the effectiveness of used car tyre straps as an efficient reinforcement for Adobe houses.*

1 INTRODUCTION

At present, a large part of the world population lives in earthen (Adobe) houses. Moreover, they often happen to live in high seismic hazard zones, since there is a detrimental correlation [1] between developing countries and the seismically most active areas of the world. Earth is a fragile material, with almost no tensile strength. Low-income people use this technique because it is easy and low-cost. It follows that every earthquake that occurs in developing countries can produce considerable damage or collapse, with consequential large economic loss, personal injuries and deaths. Trying to exploit intellectual and practical sources to find a smart solution to help those who have no choice, an accurate analysis of the state of art of different reinforcing systems, and of their behavior, has been carried out. It seems that a new technology is attractive: the use of waste material to be transformed in ropes or straps having a reasonable tension strength, namely car tyre straps. Low-income people in developing countries need almost-no-cost reinforcement techniques for Adobe houses to succeed on their own. External mesh made of polypropylene or traditional steel reinforcement and concrete can be expensive, while natural reinforcement like bamboo, or cane, are in general not always available. Furthermore, the huge environmental issue of waste disposal is exploited as a resource, and no more as a burden. Some initial experimentation has already been done, and the results were very encouraging. On this base, in this work numerical modeling of full Adobe buildings is carried out to assess the thesis that used car tyre straps can be an efficient reinforcement for Adobe houses. If it is proven, one more time, that this kind of reinforcement is reliable and useful for earth dwellings against earthquakes, a step forward will be made for a smart solution of a real and important problem that concerns several millions people.

2 SEISMIC RESPONSE OF ADOBE BUILDINGS AND IMPROVEMENT OF THEIR PERFORMANCE

The behavior of Adobe structures loaded by seismic actions is the same (e.g. [2]) as that of a common masonry structure: the resisting part of the building are the walls loaded in their own plane (see Fig. 1), while out-of-plane walls represent just an added source of mass and earthquake forces. Since compression strength of Adobe is much higher than tensile strength, this last factor is the weak point of the material. Significant cracking starts in the regions subjected to tension, then propagate and usually create independent portions of the wall that may collapse, compromising the global equilibrium of the structure.

The ground shaking generates inertia forces all over the building. Seismic forces perpendicular to the walls produce out-of-plane bending that the material isn't able to withstand. Similarly to poorly engineered masonry constructions, cracking starts at the lateral corners of the walls, where the tensile stresses are higher, causing large vertical cracks that separate the walls and lead to the overturning of the same, possibly onto adjacent streets or courtyards. This one is, actually, the first collapse that usually occurs, and if the roof stands on the wall that overturns the collapse will be total. Lateral seismic forces act within the plane of the walls generating shear forces that produce diagonal cracks. Often they start at the corners of the openings and follow the mortar joints.

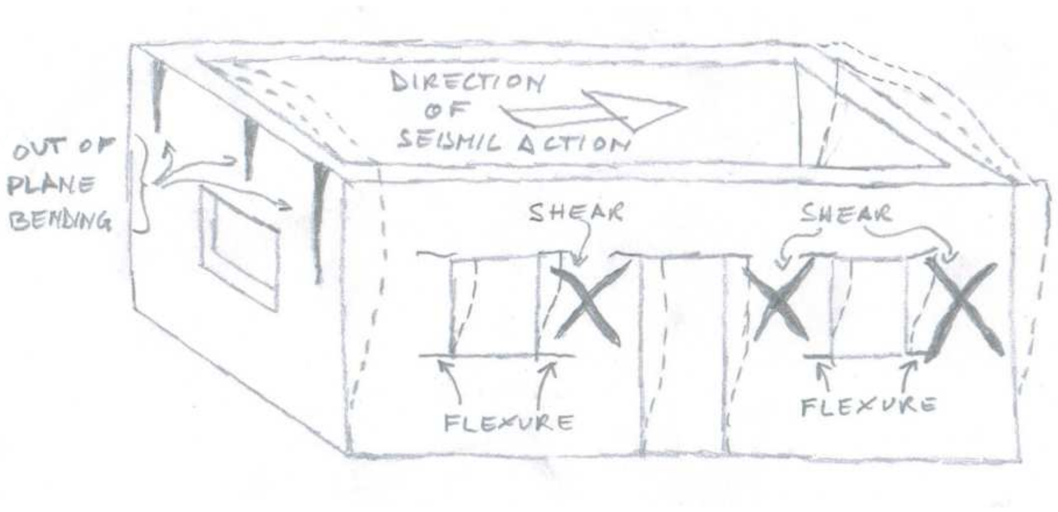

Figure 1: Typical behavior of historic Adobe buildings.

To improve the behavior of Adobe dwellings during seismic events, various reinforcements techniques have been devised and designed. For new constructions, some are: fiber reinforced bricks and mortar, wood or concrete crown beam, internal cane reinforcement, external cane reinforcement, external mesh made of polypropylene, steel wire mesh, plastic mesh, used car tyre straps mesh. For existing structures: steel wire mesh covered by cement mortar, concrete columns and beams and used car tyre straps mesh.

Since people that live in Adobe houses do this because they have no alternative, the reinforcement should be almost at no cost, as well as is the structure itself. So, besides simple recommendations about a proper thickness of the walls, an efficient connection between different building elements, the regularity of the house plan, the homogenous distribution of stiffness and strength along the whole structure, the symmetry of the openings and their appropriate dimensions, it’s a clever choice to focus on the reinforcement consistent with the concept just exposed: Adobe and mortar reinforced with straw fiber, external cane mesh and used car tyre straps mesh. All the three of them share a simple constructive technique and, possibly, large availability. In this respect, they are a smart solution for people having very limited resources.

2.1 External cane mesh

With this technique (Torrealva [4]) the reinforcement consists of vertical cane rods, that can be anchored or not at the foundation; this last is often absent in rural houses, and fixed, on the top, at the crown beam (again if existing). On the other hand, the horizontal reinforcement can be cane rods as well, or just ropes. In fact this kind of reinforcement works mainly in tension, so there isn’t much difference. The mesh of cane (or ropes) covers the internal and external side of each wall, framing the openings.

The external cane frame is fixed and connected to the internal one through plastic laces that were placed before along the mortar beds. If the construction is already existing they may pass through some holes expressly made in the walls. Usually the behavior of this kind of reinforcement improves if it’s covered with mud plaster.

The role of this type of reinforcement is to provide, side by side of the Adobe walls, a light resisting frame of canes, that stiffens the structure and prevents the single collapse of the independent portions of the cracked walls.

2.2 Used car tyre straps

The idea is (see [3]) to circumferentially cut straps from the treads of used steel belted radial car tyres. Although the steel wires in the two belts are not continuous, they are actually the elements that give the straps sufficient strength and stiffness, to balance the Adobe weakness. Each strap is connected to the other using a special yet simple nailed joint, constituted of 4 nails, 3.15 mm in diameter and 70 mm long.

To allow straps to pass through the walls, some holes are drilled in these. For this reason, and since this kind of reinforcement doesn’t need a crown beam, used car tyre straps are an especially clever choice for existing structures, besides being suitable also in the case of new construction. The tyre straps are then wrapped horizontally around walls, with maximum vertical spacing of 600 mm. Vertical straps, spaced horizontally at approximately 1.2 m center to center, pass underneath or through the bottom of the wall, then rise up on both sides of the walls, wrap over the wall top and finally connect to roof timbers (Fig. 2-3).

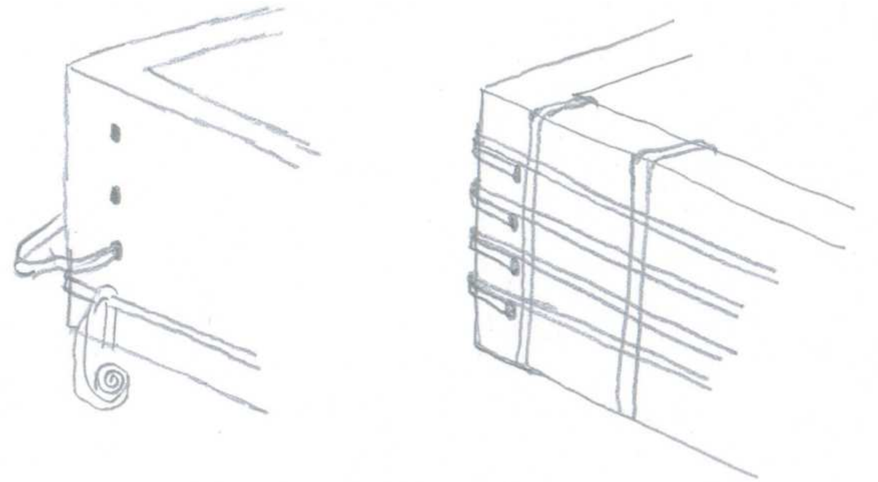

Figure 2: Steps in the process of reinforcing (form Charleson [3], redrawn).

Figure 3: Module tested on a shaking table (from Charleson [3]).

2.3 Experimental research

The effectiveness of the above two types of reinforcement was proven through an extended experimental work. Tests on reinforced and unreinforced Adobe models in various scales were carried on, and the aim of validation of a bamboo mesh and of a used car tyre straps mesh has been achieved. In the following, two examples are reported.

In 2004 a joint project between PUCP (Pontificia Universidad Catolica del Perù) and GCI (Getty Conservation Institute) aimed to test dynamically the effectiveness of external reinforcement using natural and industrial meshes [4]. The results showed that both of them succeed in avoiding partial or total collapse of Adobe buildings in severe earthquakes. The tests were carried out using a shaking table, the signal was derived from a component of the May 31, 1970, Peruvian earthquake. The experimental model reinforced with bamboo cane resisted to an earthquake of intensity X of the Mercalli scale, corresponding to a Peak Ground Acceleration of 1.2 *g* and a maximum table displacement of 135 mm, without collapsing.

Some years later, a similar model, having the same geometry and acceleration input, but reinforced with used car tyre straps was tested [3]. Again the model did not collapse, even if it’s important to say that also this model was heavily damaged in the testing final phase. The scope of the reinforcement, in fact, is not to prevent damage, but just to save lives by avoiding total collapse. Figure 4 shows the crack pattern after the test. In this work, the numerical simulation of these latter tests has been developed.

Figure 4: The cracking pattern after the test on the module (from Charleson [3]).

3 NUMERICAL MODELING AND ASSESSMENT OF REINFORCED ADOBE BUILDINGS

Numerical modeling is nowadays a smart alternative to experimentation, since is much less expensive and is a very flexible means of studying several different solutions. However, it is totally effective when used as complementary to testing for both interpreting and understanding experimental results. In developing the numerical model of the test structure, a macro-modeling approach has been adopted, in line with the need of referring to continuum mechanics rather than to micro-modeling which relates more to fracture mechanics.

That choice is based on simple considerations: in Adobe masonry both the mortar and the bricks are made of mud (occasionally reinforced with straw fibers); so, even if the weakest part is mortar, it is not a significant limitation to consider it as a continuum, where the mechanical characteristics are homogeneously assigned all over the masonry. Moreover, recent studies confirm the effectiveness of this method, which can evaluate satisfactorily the global behavior of the Adobe buildings [5].

The construction material under study may present extremely variable properties, as well as the buildings themselves. The quality of the walls, of their connection, of the mortar and so of the whole construction depend strictly not only on the quality of the earth used, but also on the level of workmanship. This consideration corroborates the hypothesis that an excessive precision in modeling can be not worthy, since it may hardly correspond to a better representation of reality. We have, in fact, to deal with a non-standardized material, likely to be cracked because of previous earthquakes and characterized by a constructive technique which is far from being accurate.

So the general aim was to achieve a good modeling of the global behavior of Adobe buildings and of their reinforcement, considering also the non linearity of the materials, within a widely available computer code. The employed computer program is SAP2000 [6].

A pushover analysis has been performed for: a) an almost full-scale model of I-shaped Adobe walls, 2 meters tall, 30 cm thick, and 3 meters long, and b) for an unreinforced model of a small Adobe house of one room, 3 x 3 meters, both previously tested on the shaking table.

Inside SAP2000 the Adobe material was defined as homogeneous, isotropic, and continuum; the employed constitutive law comes from studies by Lourenço [7], that identified the compressive part of the uniaxial stress-strain relationship as parabolic, and the tensile branch as exponential. Results obtained by Tarque [5], who calibrated a larger set of mechanical parameters, have been used for a best reproduction of the experimental results. The values adopted in the numerical analyses for the material parameters are listed in Table 1.

Table 1: Adobe characteristics.

Mechanical	Characteristics
f_c	0,3 MPa
f_t	0,04 MPa
E	200 Mpa

Such values are used to define a “concrete-like” constitutive law (see Figure 5), which describes the behavior of the material along the three principal directions in the numerical model; a shear-stress-strain constitutive relationship is then derived by the computer code, based on the tensorial rotation of stresses and strains.

In all the models, the Adobe walls were discretized by four node shell elements, with two Gauss integration points along the thickness, since both the membrane and the flexural behavior are considered in this kind of elements.

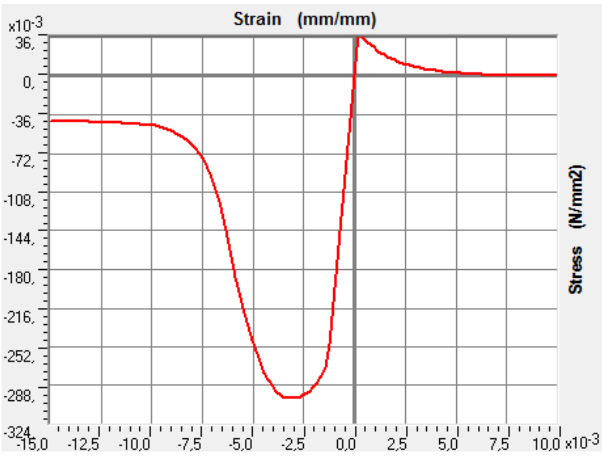

Figure 5: The constitutive law of Adobe.

3.1 Static non linear analysis (pushover) of I shaped Adobe walls

This type of analysis is a simple yet meaningful alternative to the dynamic analysis, since it allows a global evaluation of the seismic performance of a structure.

The reference experimental model was tested at PUCP in 2005 by Blondet [4, 5]. The specimens (Fig. 6) are I-shaped Adobe walls, 2 meters high, with a thickness of 30 cm, and approximately 3 meters long, with a crown beam in concrete to simulate the roof weight. The purpose was the evaluation of the seismic in-plane behavior of the Adobe wall with an opening (40 x 60 cm), subject to increasing displacements.

The pushover curve (Fig. 7), shows to match well both the elastic part and the post peak non linear range. Furthermore, crack propagation and the stress distribution over the wall are consistent with the experimental findings: cracks start at the corners of the opening (see Fig. 8) and then spread over the wall. As the imposed displacement reached the value of 10 mm, crack opening in the experimental model was 10 mm.

In the numerical model, self-weight was applied through a linear step before starting the pushover analysis.

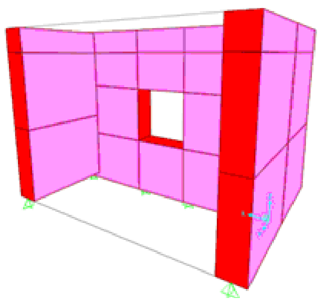

Figure 6: Geometric model for the numerical tests.

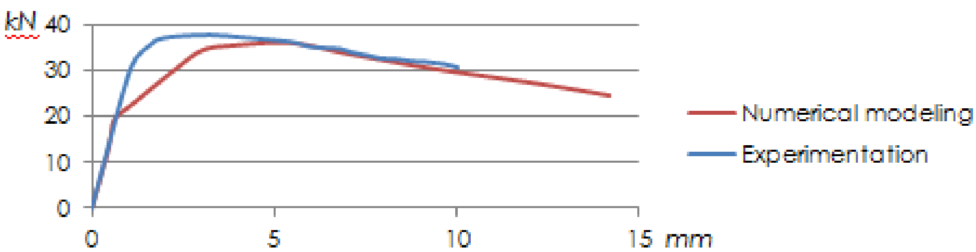

Figure 7: Pushover curves.

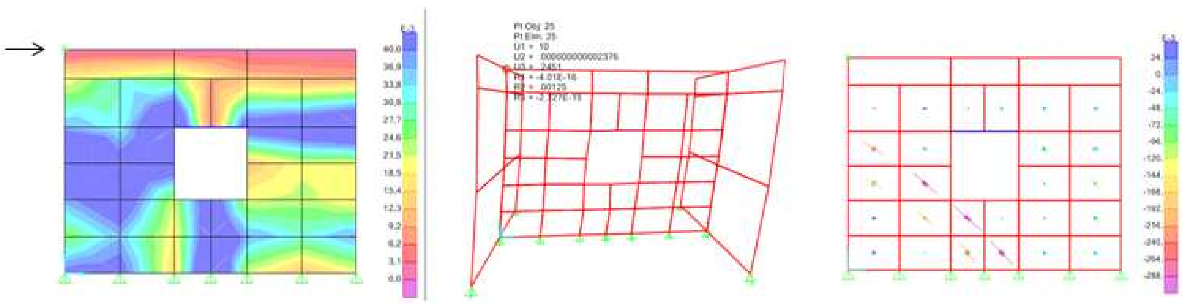

Figure 8: Principal tensile stresses [Mpa].

If the specimen is reinforced with used car tyre straps the response in the non-linear field undergoes a substantial improvement, as the resistance decay is very limited (Fig. 9). Improving is localized in the non linear range since it is known that this type of reinforcement doesn’t act in the elastic field, but reacts only after that Adobe has cracked. In the SAP2000 numerical model the straps were modeled with cable elements having a light pretension (307 N), as the constructive technique mandates, exploiting the facility that allows to model pretension imposing a length of the cable element shorter (here only 1 cm) than the real length. During the numerical test they remain safely and abundantly under their limit of resistance: 1.1 kN of maximum tension against 12.3 kN of resistance of the straps and 11.8 kN of resistance of the connections.

As a comparison, Figure 9 shows also the capacity curve for Adobe reinforced with bamboo frames, modeled as frame elements having appropriate cross-section and material properties. The reinforcement with tyre straps behaves even better than the bamboo frame reinforcement, even if the curves are very similar. Also the cane reinforcement was modeled in line with the previously exposed construction technique.

Refining the mesh of the wing walls in the I-shape layout by using four time the elements in Fig. 8, lead to unchanged results in terms of the model pushover curve.

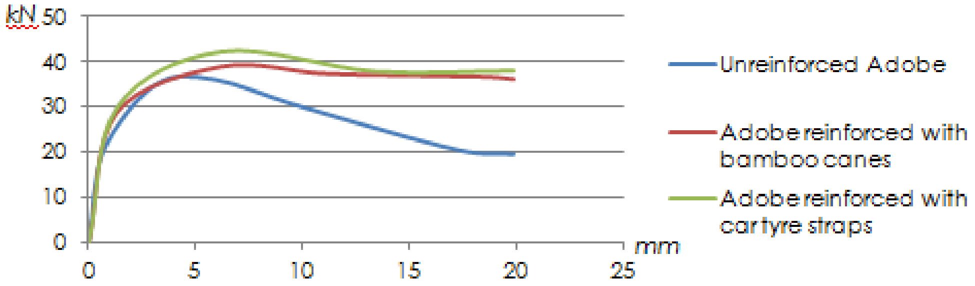

Figure 9: Pushover curves.

3.2 Cyclic non linear analysis of I shaped adobe walls

A second set of numerical analyses had the purpose of reproducing the cyclic non linear response of “I” shaped adobe walls characterized by a hysteretic behavior. The geometry of the models was not changed, but a cyclic history of displacements (Fig. 10) was imposed at the wall top.

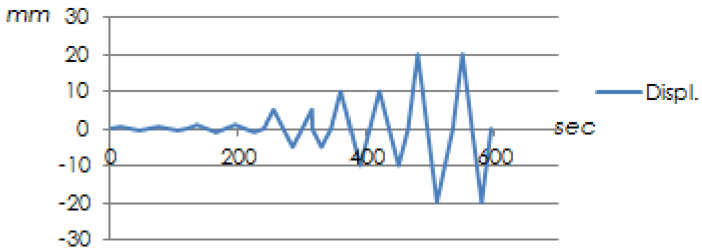

Figure 10: Displacement history of the cyclic test.

Figure 11: Hysteresis cycles.

The numerical response (Fig. 11) did not catch satisfactorily the pinching phenomenon, which is typical of the shear behavior. It is worth noting that, to the purpose of analyzing the cyclic behavior, the skeleton curve in Fig. 5 was complemented with a Takeda type hysteretic law, suitable for brittle materials like Adobe. Nevertheless, energy dissipation looks to be too high in the model.

Reducing the resistance in traction, the shape of the hysteresis loops changes drastically, resulting in a more shear-like response but still far from the observed experimental behavior.

This numerical analysis points out as further studies on the constitutive law are necessary, since a small change of the material parameters can lead to huge consequences in terms of structural response. In addition to this, a more precise definition of the hysteresis parameters is required.

3.3 Elastic dynamic analysis

Elastic dynamic analyses have been performed in order to verify if the SAP2000 model can reproduce crack opening and propagation. Referring to the available experimental data, the results of shaking table tests on an unreinforced model of Adobe are compared to those coming form the numerical investigation. The specimen (Fig. 12) is represented by a little house of one room, 3 x 3 m in plan, subject to ground motion in the direction parallel to the wall with windows, while the wall with the door and the back wall is loaded out of plane. The imposed base acceleration is a simple sine function, scaled to different Peak Ground Accelerations. The damage sequence is as follows:

From the experimental work (initial period of the first mode $T_1 = 0.17$ s):

- 0.3g: few and thin cracks at walls intersections and at the corners of the openings.
- 0.8g: remarkable openings of cracks and complete vertical cracks.
- 1.2g: collapse of the out-of-plane walls.

From the numerical analyses (initial period of the first mode $T_1 = 0.16$ s):

- 0.2g: the tensile resistance (0.04 MPa) is never exceeded.
- 0.3g: tensile stresses of 0.04 MPa are reached at the corners of the openings.
- 0.4g: vertical cracking starts and stresses in shear walls increase.
- 0.8g: wide expansion of the regions where the tensile resistance limit is exceeded.

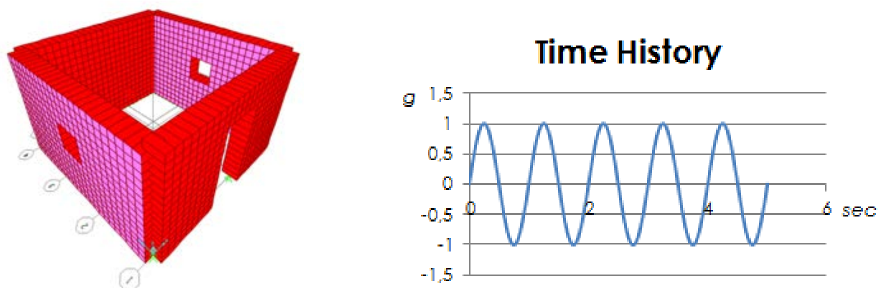

Figure 12: Model for dynamic analyses and input acceleration time history.

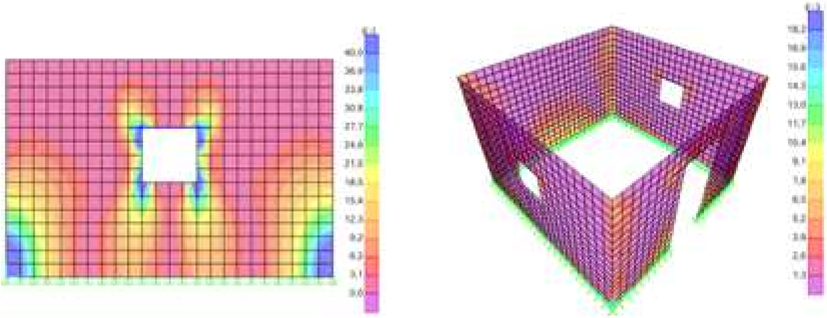

Figure 13: Principal tensile stresses on the left and s_{23} on the right [MPa] for 0,4g of PGA.

The numerical model can therefore provide a good representation of the initial behavior of Adobe walls: cracking starts at the right places and, with a very good level of approximation, at the correct PGA (see Figure 13). This hopefully hints that this model can be useful to determine whether and where the first cracks will generate in a seismic event, even for more complex geometries. However, since this is an elastic analysis, the concept is valid till the first crack is created. After this point a non linear analysis is necessary.

Introducing the reinforcement in this model, doesn't change the results in a significantly way in terms of stresses, displacements and base shear. This is consistent with the way the tyre straps reinforcement acts in reality because, as we have seen, it acts in the post peak (post linearity) range.

3.4 Non linear dynamic analysis

For this type of analysis the same model and the same time acceleration time history where used as in the previous section. The material model was the same as in the pushover analysis.

Reaching convergence with this kind of input motion is not easy (a sine function, with maximum acceleration = 1 g) Analyses are still in progress and preliminary results only are available.

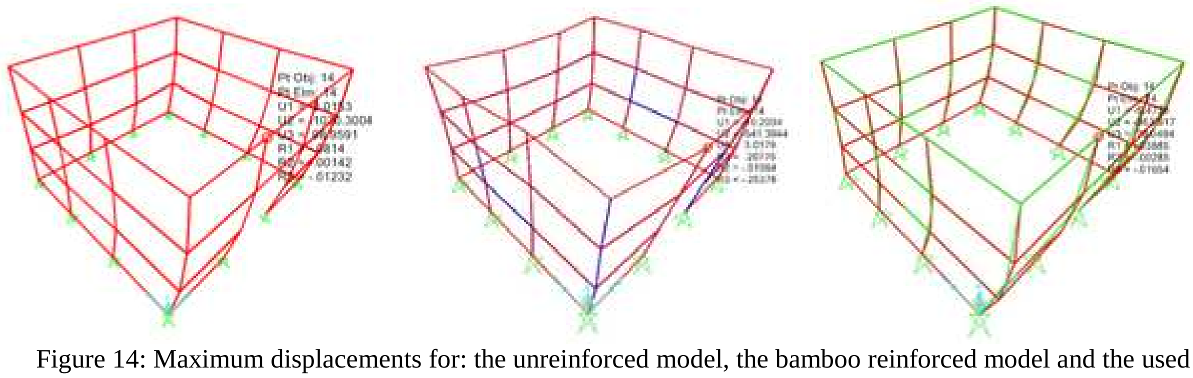

Figure 14: Maximum displacements for: the unreinforced model, the bamboo reinforced model and the used car tyre straps mesh reinforced model.

In Perù, a PGA of 1 g corresponds to a strong seismic event, with an estimated return period of 475 years. Reaching the collapse in the numerical analysis is therefore consistent to both experimentation and reality. The same model, but reinforced with bamboo cane, provides a 50 % reduction of the displacements (Fig. 14). The function of the bamboo frame is fully realized in this case: it stiffens the model absorbing a large part of the stresses and unloading the Adobe walls. On the other hand, the car tyre strap mesh reduces the displacement by 10% only, consistently with the flexibility of this kind of solution. In the numerical analysis second order effects had to be considered, because of the large displacement allowed by the reinforcing tyre mesh.

4 CONCLUSIONS

The purpose of this paper was to support a new technology for seismic strengthening, based on the re-use of car tyres; this might be environmentally sustainable and, at the same time, seismically efficient. This is only one of the many reuses of car tyres, but it may become of interest for its applications in terms of saving human lives.

From experimental testing, it comes out that the main function of used car tyre straps is to provide connection among the independent blocks of wall which form by crack propagation. Several numerical analyses have been performed; the best results come from the pushover analysis, which can provide useful indications on how, and how much, the reinforcement acts.

The numerical results, however, point out as necessary further studies on the Adobe constitutive law, since a minimum variation of its characteristics can lead to large consequences in terms of structural response.

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