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SEISMIC BEHAVIOUR OF RAMMED EARTH DWELLINGS REINFORCED WITH WOOD ELEMENTS AND A UPPER CONCRETE BEAM

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Abstract

Earth constructions have a wide presence all over the world represented in housing architecture and architectural heritage. A large number of these constructions are located in seismic regions and have a significant seismic vulnerability because of their structural features. Reinforcement alternatives have been proposed to improve their behavior and to prevent collapse. As a contribution to this purpose, this paper proposes an integrated strategy consisting in external reinforcement with wood elements on both sides of the walls of rammed earth construction and a rigid diaphragm by means of an upper concrete beam. This beam is proposed to be built with a smooth transition between the earth and the concrete to enhance compatibility. The results of shake table tests on a 1:6 scaled model and its unreinforced counterpart show a significant improvement in the global behavior of the construction, achieving the main goal of preventing collapse.

Keywords: Rammed earth buildings; reinforcement solutions; seismic reinforcement; wood reinforcement

1. Introduction

In Colombia, as well as in other developing countries, the housing problem for lower income groups has not been yet solved. Complete solutions for these groups are still required. Besides, earth construction is an important part of the cultural heritage of the country and for some people it may be the only feasible choice for having an acceptable dwelling place. Earth housing has several advantages: i) it is sustainable in the long term since it consumes a low quantity of natural resources with low greenhouse gas emissions, ii) it has good thermal and acoustic insulation properties and iii) it allows the families to work together in the construction of their houses which is an efficient way of creating social bonds. However, earth construction is not included as a structural system in the Colombian Seismic Resistant Building Code, NSR-10, because adobe and rammed earth walls have low strength and low displacement ductility capacity when submitted to earthquake loads. In fact, several rammed earth buildings failed during the March 10th 2015 Los Santos earthquake (Mw = 6.4), in Colombia, due to cracking, separation and collapse of the walls [1, 2].

Several solutions have been proposed to improve the seismic behaviour of earth buildings: i) stabilisation of the earth material with additions such as cement, ash, vegetal fibres, etc. to improve the mechanical properties of the material, ii) wall reinforcement with cane or bamboo bars, iii) external reinforcement of walls with wood frames, steel grids, steel bars, plastic grids, etc. to preserve the integrity of the wall during a seismic event and prevent collapse and iv) an effective diaphragm made of wood or concrete beams and a floor system, to improve the structural behaviour of the whole construction. Among these strategies, reinforcement with wood elements has proved to be an efficient way of improving the seismic behaviour of earth walls and preventing collapse. Also the existence of a diaphragm has shown to be essential. However, the compatibility between the diaphragm and the walls is still an issue due to the difference between the mechanical properties of earth material and wood or concrete.

Accordingly, this work proposes an integrated strategy: external reinforcement with wood frames on a construction with rammed earth walls with an upper concrete beam implemented by means of a smooth transition between the earth and the concrete material. This scheme was tested on a 1:6 scaled rammed earth construction, representative of a residential house and the results were compared with those of an identical unreinforced earth rammed building. The results show a significant reduction in the lateral displacements and an increase in the load capacity. The reinforcement solution achieves the main goal of preventing collapse while the integrity of the walls remains good, suggesting a better performance with less damage and the possibility of minor repair works before occupancy is authorized.

2. Seismic performance and reinforcement solutions

2.1 Seismic performance of earth constructions

Numerous studies on earth construction and the experience of seismic events in several regions have shown a high seismic vulnerability of these constructions. This vulnerability is mainly due to the intrinsic properties of the earth material, the configuration of these constructions and environmental factors. There exists a consensus on the following main causes of the poor behaviour of these structural systems when facing seismic events: i) the lack of in-plane and out-of-plane tensile strength of the walls, ii) the absence of soundness in the corners, iii) the absence of a proper rigid diaphragm at the roof level and iv) the deficient connections between the walls and also between the walls and the roof ([3, 4, 5, 6]). As a consequence, during strong seismic events, the walls tend to separate from the corners, to crack and disintegrate and finally to collapse due to a loss of the vertical load bearing capacity.

2.2 Reinforcement solutions for earth construction

Usually reinforcement strategies focus on providing the structure with the required strength, stiffness and ductility to deal with a seismic event. In the case of earth structures, it is difficult to reach the expected behaviour of traditional new construction hence the reinforcement strategies are aimed mainly at preventing collapse in order to save lives.

Some strategies are oriented to improve the mechanical and cohesive properties of the earth material by means of stabilization techniques such as the addition of cement, gypsum, lime or even natural fibres [7, 8]. However, these strategies by themselves are not enough to tackle all the mentioned drawbacks. Other strategies based on external elements of reinforcement are oriented to provide properties the earth walls system do not have: confinement, ductility, shear strength and bending strength. Examples of these initiatives are: i) reinforced plaster layers on both sides of the walls, ii) wood frames put on one or both sides of the walls, iii) the implementation of concrete frames attached to the walls, iv) steel straps installed horizontally or vertically to confine the walls, v) tyre straps around the walls and vi) beams or plates made of concrete or wood to provide a rigid diaphragm.

The plaster layer may be composed of earth or lime mortars and may be reinforced with steel or plastic mesh. This plaster is applied on the whole wall area but the grids may be on the whole area or only on critical regions such as the corners, the boundaries and around the openings. This solution has been applied on real scale walls and also on reduced scale buildings and it has proven to be effective in increasing the global strength, reducing the lateral displacements and delaying the collapse which permits the evacuation of the building. However, it is also observed that due to the cyclic nature of seismic loadings the mentioned advantages disappear when the plaster detaches from the wall. After that, the wall behaves as an unreinforced wall [3, 4, 9, 10].

As stated before, the tension strength of earth walls is not enough to deal successfully with the tension stresses produced by seismic forces. Lopez et al. [11] proposed a confinement system based on steel tensioned bars, put horizontally and vertically on both sides of the wall, so that the whole wall is subjected to compression stresses (some kind of pre-compression). The results show that this method achieves the objective of preventing the total collapse with some local failures at the corners. Also, the shear strength increases by 17% and the deformation capacity by 85%. The whole behaviour in improved and there was no loss of strength during the whole test. The main issue to be fixed within this solution is how to maintain the required tension on the steel bars in the long term.

Also with the aim of providing confinement to the walls Charleson and Blondet [12] proposed a system, similar to that of steel bars but with tyre straps. The results of shake table tests conducted on a reduced scale model show that this method manages to avoid the global collapse but with significant damage which means higher reconstruction works and costs.

As for external reinforcement with wood elements, this solution has proven to be very effective according to several research works and the experiences of real reinforced structures during moderate seismic events. That was the case of the "*Centro cultural del oriente*" in Bucaramanga, Colombia, which was partially reinforced with this system in 2012. This building withstood with no visible damage the Los Santos Earthquake mentioned before, a ground motion whose epicentre was 35 km from Bucaramanga and which had a magnitude and depth of Mw=6.4 and 160 Km respectively. This solution as well as the implementation of a rigid diaphragm is explained in more detail hereafter.

2.3 Wood frame reinforcement

This method proposed by Yamín et al. [13] consists in providing some confinement to the walls by means of wood elements interconnected on both sides of a wall. Usually the wood elements are placed in both horizontal and vertical directions and connected to one another. Also they are connected by bolts piercing the wall and in order to improve the bond with it, each element is attached to the wall with steel nails placed lengthways. Finally, the wall intersection is reinforced by means of steel angles.

There are some additional directions about how to install the elements on the walls, as illustrated in Fig. 1. For instance: i) there must be a horizontal element near the foundation and near the , ii) the distance between horizontal elements should not exceed 2.0 m, iii) near the intersections between walls and around windows or door openings there should be vertical elements, iv) vertical elements should not be separated by more than 1.5 m [14].

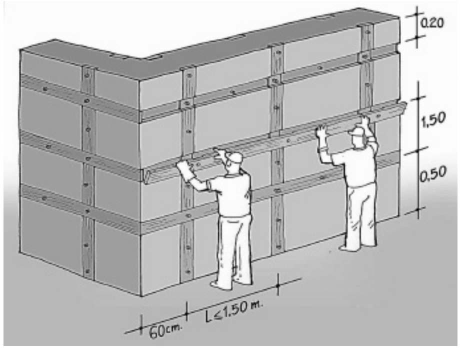


Fig. 1 – Configuration and installation of confinement wood elements (reprinted from Yamín *et al*.[3], with permission)

This strategy has been tested on real scale walls, reduced scale models and reduced scale 16th and 17th century churches [3, 4, 15, 16]. The results show a significant improvement of the global behavior: less cracking, less damage, reduced displacements and no collapse. In fact, the increase in the in-plane shear capacity was up to 400% and up to 100% for the deformation capacity, according to Yamin *et al*. [3].

2.4 Implementation of a rigid diaphragm

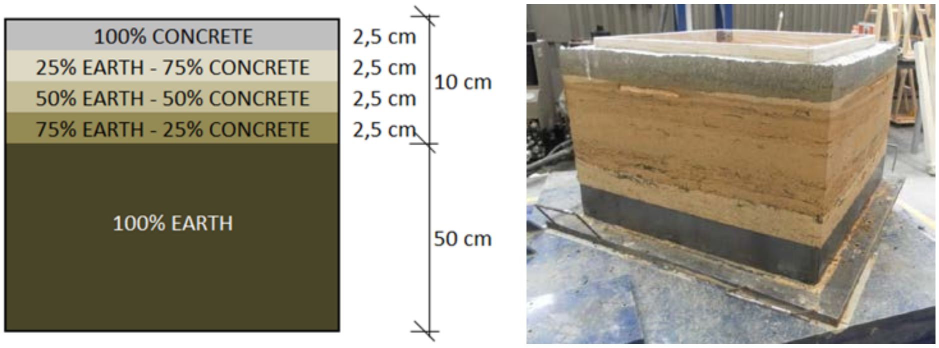
One of the main causes of the earth construction vulnerability during a seismic events is the absence of a rigid diaphragm causing the walls to act as individual elements weakening the corners and finally failing themselves. The implementation of a rigid diaphragm is therefore necessary to guarantee that the building behave as a whole during a seismic event and to reduce the probability of failure at the corners. Several proposals for reinforcement of earth structures used diaphragm systems and beams made of wood or concrete. These alternatives have resulted in improvements of the global performance. However the major concern about this system is the compatibility between both materials (concrete-earth or wood-earth) at the beam – wall connection since their mechanical properties and hence their stiffness are quite different. It may cause a predetermined failure surface and both elements (beam and wall) tend to separate, as it was observed by Lopez et al. [11] during a lateral pseudo-static tests on real scale walls with wood upper beams.

3. Proposal of an integrated strategy for the reinforcement of rammed earth construction

Taking into account that reinforcement with wood elements has proved to be an efficient way of improving the seismic behaviour of earth walls and the mentioned drawback of wood or concrete upper beams, this work proposes an integrated strategy: external reinforcement with wood elements with rammed earth walls with an upper concrete beam implemented by means of a smooth transition between the earth and the concrete.

The wood reinforcement is in accordance with to the recommendations of the rehabilitation manual for adobe and rammed earth constructions [14]. Concerning the connection between the foundation and the reinforcement elements, most of the existing proposals try to embed the elements into the base foundation. However for existing buildings this practice is difficult to achieve. Therefore, it was decided here not to fix the wood elements to the foundation in order to analyze the effect of this lack of connection on the global behavior.

In order to assure the compatibility between walls and concrete beams, a transition made of four layers is proposed. The layers are composed of concrete and earth in different proportions of the pure earth wall and the concrete beam: 75% – 25 %, 50%-50%, 25%-75% and 0%-100% respectively for earth and concrete, see Fig. 2a and 2b. This transition occurs at the upper section of the wall, corresponding to 20% of the wall height. For instance, a wall of 3 m height would have 60 cm of transition and each layer would be of 15 cm.



a) b)

Fig. 2 – a) Scheme of the smooth transition between the walls and the upper concrete beam and b) Scaled building model with the transition to the concrete upper beam at the top of the wall confinement wood elements

4. Tests and results

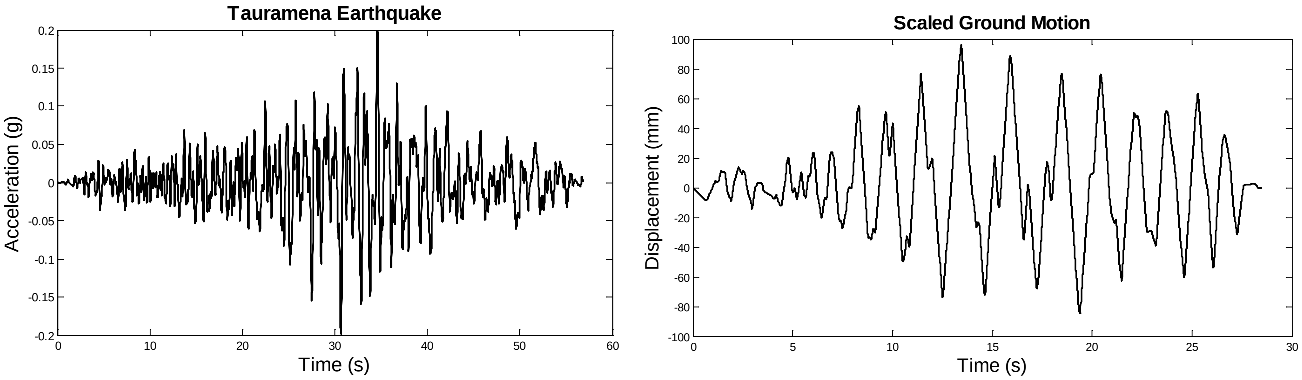
In order to test the proposed strategy, two reduced scale models were built: one without reinforcement or upper beam, and the other with the mentioned transition to the upper beam and wood reinforcement. Both were on a 1:6 scale from a representative dwelling house of one story and 36 m^2 plan area, which is the minimum plan size for a low income housing in Colombia. The plan dimensions of each model were 1m x 1m and the height was of 57 cm. The model had 4 walls with a thickness of 8 cm: one complete and the other three with openings for windows and a door. In order to analyze the effect of the location of openings, one wall had its window at the center and the other on the edge section of the wall, near the corner. Finally, the left wall had a central door. The roof was designed as a truss wooden roof where several metal pieces were attached to simulate the mass of the roof. The foundation was built over a metal framework with a mix of stone, sand and clay, with the same thickness of the walls, see Fig. 3a.

The wood reinforcement was composed of vertical and horizontal elements of 35 mm wide and 5 mm thick, separated 250 mm in both directions, according to the recommendations of the AIS manual [14]. They were connected to one another by 6.35 mm rods that also pierce the wall to connect the system on both sides of the wall. At the corners the elements were connected by bolted steel angles. The transition between the wall and the upper beam was of 10 cm wide with 4 layers of 2.5 cm each, see Fig. 2 b) and Fig. 3b.

a) b)

Fig. 3 – Reduced scale models: a) unreinforced model and b) reinforced model

These models were tested on a unidirectional shaking table (1.5 m x 1.5 m) controlled by a 100-kN load capacity MTS dynamic actuator with a 250-mm total stroke, which can generate accelerations up to 5.0 g while supporting structural models weighing up to 15 kN. The models were subjected to a real strong motion record representative of the seismic hazard of Bogotá (19 January Tauramena Earthquake), see Fig. 4a. This record was scaled and the time axis scale was modified to adjust to the size of the models tested. The acceleration levels were increased based on the recommendations by Harris and Sabnis [17]. The resultant displacement versus time signal is shown in Fig. 4b).



a) b)

Fig. 4 – a) Tauramena earthquake record and b) Scaled ground motion used in the shake table tests

In order to have seismic excitation in their two principal directions, the models were rotated 45 degrees in plan. The instrumentation consisted of three accelerometers, four Load Variable Displacement Transducers (LVDTs) and a set of orthoptic cameras placed in such a manner as to register displacements and accelerations on each main axis of the model, on each wall and on each axis of the shaking table, see Fig. 5.

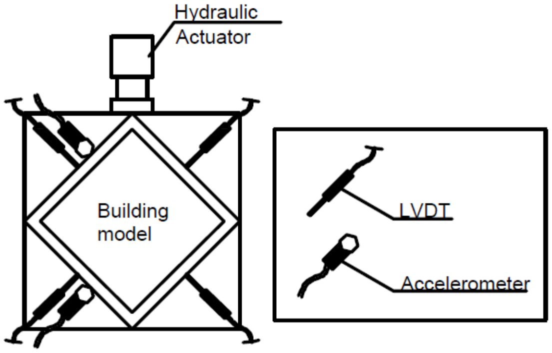
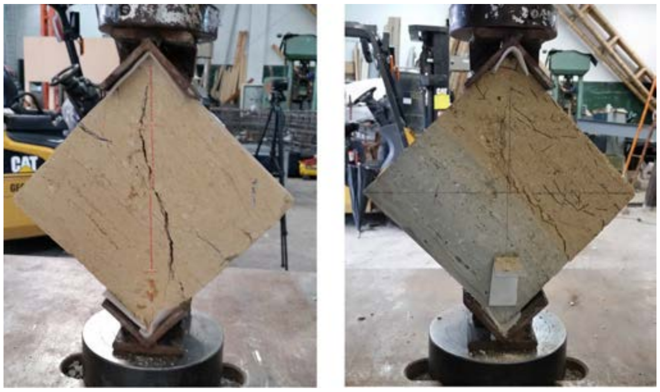


Fig. 5 – Instrumentation of the model

4.1 Global results

With the aim of analysing the effectiveness of the transition between the wall and the upper beam, two masonry assemblages were built, one made just with rammed earth and the other with transition but without wood reinforcement. The dimensions of these specimens were 20 x 20 cm and the same thickness of the model walls, 8 cm. Diagonal tension tests were performed on these specimens according to the ASTM E519 standard [18]. The results indicate a good bond between the wall and the transition, as shown in Fig. 6b, since the failure spread vertically until reaching the more resistant material. Then it followed a path which was parallel to the joining surface but it did not occur right along this surface. According to this result, the transition fulfilled its purpose of improving the compatibility between the wall and the beam.



a) b)

Fig. 6 – Failure mechanisms under a diagonal tension test for: a) rammed earth masonry assemblage and b) rammed earth with smooth transition and upper beam assemblage

Regarding the building models, the global behaviour of both structures was quite different as expected. The unreinforced model did not resist the whole signal since at 16 seconds all walls presented local failures and partial collapse and at approximately 20 seconds the whole structure collapsed, see Fig. 7a. The reinforced model on the contrary withstood the complete ground motion with only a few cracks in the lower regions, near the corners and the foundation, and also near the first horizontal element, see Fig. 7b and Fig. 8.

a) b)

Fig. 7 – Global behaviour of: a) unreinforced model after the test, and b) reinforced model after the test

Fig. 8 – Complete wall view of the reinforced model after the test

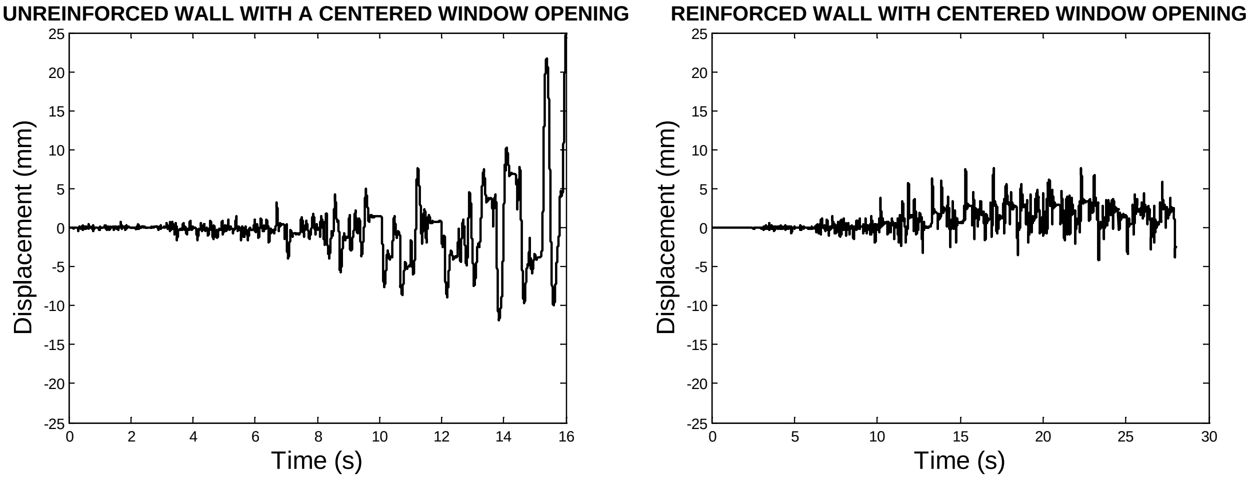
4.2 Displacements

It was observed from the overall results that the lateral displacements are reduced between 65% and 80% when those of the reinforced model are compared with thon the unreinforced model. Table 1 shows the reduction of displacement for each wall.

Table 1 – Comparison of the maximum out of plane displacements of each wall of the building

Wall	**Out of plane maximum displacements (mm)**		
	Unreinforced model	**Reinforced model**	**Reduction (%)**
Complete Wall	19.4	5.64	70.6
Wall with centred window opening	24.6	7.67	68.8
Wall with eccentric window opening	24.0	7.53	68.6
Wall with a door opening	26.4	5.68	78.5

As an example, Fig. 9 shows the case of the wall with a central window opening. A stiffness increasing represented by a reduction in the maximum out of plane displacement (from 24.6 mm to 7.67 mm) and a reduction of the response period from 0.42 to 0.14 seconds. Finally, there was no permanent displacement after the application of the whole strong motion signal. The other three walls behaved equally well.

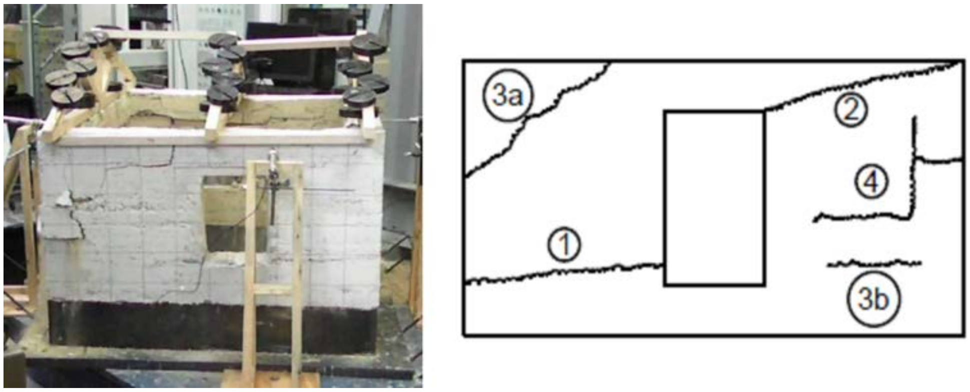


a) b)

Fig. 9 – History of displacements of the wall with centered opening for: a) the unreinforced model and b) the reinforced model

4.3 Cracking pattern and failure mechanism

As every model was tested on its two principal directions, every wall was subjected to in-plane and out-of-plane bending and shear. Fig. 10 shows the cracking pattern and appearance sequence for the wall with a centred window opening (the same wall which was analysed for displacements in the previous section of this document). Fig. 11 shows the cracking patterns for the complete wall and that with an eccentric window opening. From these results it can be said that the failure mechanism for the unreinforced model is a combination of in-plane and out-of-plane failures of the walls initiated by bending and shear cracks spreading from the openings to the exterior region of each wall. Also, as it was expected, the lack of soundness at the corners was also a triggering cause of failures.



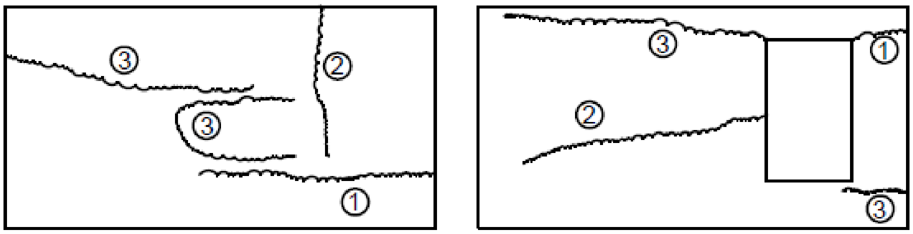
1: Flexural crack appearing at 10 seconds, going from the base window to the corner

2: Shear crack appearing at 11 seconds causing the corner failure 3 seconds later

3a and **3b:** Shear and flexural cracks appearing at 12 seconds

4: Last crack appearing 2 seconds before global collapse at 16 seconds, caused by the wall separation at the corner.

Fig. 10 – Sequence of cracking pattern of the wall with a central window opening



a) b)

Fig. 11 – Sequence of cracking pattern of the: a) complete wall and b) wall with eccentric window opening

Concerning the reinforced model, there was no collapse after it was subjected to the same strong motion. The most fragile region seems to be the one between the foundation and the first line of horizontal reinforcement. Horizontal cracks were observed right above the foundation and right below the first line of horizontal reinforcement. As a consequence the bottom section of one corner, wedge shaped, splits away from the model, see Fig. 8. Despite of these localised cracks, the soundness of the model was well preserved.

5. Conclusions

A mixed reinforcement solution for rammed earth construction was proposed here. Its primary objective was to reduce the vulnerability of this construction type by the implementation of a rigid diaphragm and the reinforcement of the walls by means of wood elements attached to both sides, providing in this way confinement and stiffness.

Promising results were found after tests on a shaking table of a 1:6 reduced scale unreinforced model and its reinforced counterpart under a real seismic ground motion. The results showed a significant improvement in the load capacity and in the global stiffness of the reinforced model represented in a reduction of its displacements and the fact that the ground motion produced only light damage. The main purpose of a reinforcement strategy on earth construction was successfully reached since on one hand there was no collapse and on the other, the integrity of the structure remained practically intact. This might suggest that in a real house only a few restoring works are required before the construction become again habitable after a damaging earthquake.

6. Acknowledgements

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