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A Review on the Large-Scale Modeling for Seismic Strengthening of Adobe-Mud Brick Structures

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Abstract

To know the mechanical behaviour of adobe-mud brick structures in individual and collective units, there are some laboratory tests on scaled specimens: small-scaled specimens with compressive strength (σr, Ey, ν) and bending strength tests; and medium and large-scaled specimens with compression / shear / bending tests, combined compression and shear tests, tests on walls construction and earthquake shaking table tests. The aim of these laboratory tests is to enable the restorers, through enough study about the mechanical characterization of adobe-mud bricks in small-scaled and the typical mechanism of their damages in medium and large-scaled adobe models, to propose adequate repair and/or strengthening solutions. These knowledge even have reference values for the design and construction of new adobe structures. Generally, in this paper to better know the mechanical behavior of reinforced and non-reinforced adobe structures and to valorize the possibility of the application of new proposed intervention methods on historic adobe-mud brick structures, a review has been conducted on internationally adapted and tested technical retrofitting proposals for seismic upgrading of adobe structures through small, medium and especially large-scale adobe specimens and modeling tests.

Key words: Adobe-Mud Bricks, Scaled Modeling, Seismic Strengthening

1. Introduction

In recent decades, the field of earthen architecture conservation has grown significantly. This progression is reflected in a series of still continuing and very active international conferences devoted to the study and preservation of earthen architectural heritage, the 1st held in Yazd, Iran - November 25-30, 1972 - Conseil International des Monuments et des Sites et ICOMOS-Iran, and the latest as the Terra 2016 - July 11-14, 2016 held in Lyon, France. From the beginning of these conferences up to date, the number of participants in each of them has increased along with their geographic and professional diversity. In these conferences, different issues related to earthen structures such as chemistry, soil science, seismology, hydrology, structural engineering, archaeology, sociology, and sustainability are discussed by scholars united by their interest in earthen architecture and conservation; academics, scientists, architects and conservation practitioners.

As the result of researches conducted for seismic retrofitting of adobe building, the options available for their reinforcement recently have been developed. Nowadays, the new construction techniques are intended to product stronger adobe buildings in the future, including: (i) internal and external reinforcement (e.g. synthetic wire meshes and rods, tying, anchorage etc.); (ii) structural design (e.g. buttresses and pilasters, robust layout, solid foundation, tapered wall (wide at base and thin at top), ring beam, etc.); (iii) stabilization of adobe mixture and mortar using chemical stabilizer and natural fibers; and (iv) diagnostic investigation (e.g. realization of hidden cracks, weaknesses, declines, etc.). Contrary to the modern adobe buildings, dealing with historical and cultural adobe architectural heritage encounters some restrictions on the level of the interventions, through which the authenticity of the monument should not be disrupted. Due to the dependence of the restoration on the preservation of the aesthetic and historical values of adobe monuments, techniques, materials and design procedures in use for their structural reinforcement encounter many limitations, which is a real challenge for the engineers and architects.

However, seismic retrofitting measures in historic adobe structures should be based on a series of criteria conducted to manifest the efficiency of the interventions together with their compliance with recommended restoration criteria, the criteria that are imposed in international documents such as the Venice Charter (1964), and in a more specific way, in the ICOMOS/ISCARSAH (2003). Although the criteria proposed in these documents cannot be known as absolute requirements, but those basic principles developed will assist in conceiving and designing both efficient and respectful interventions. Fundamentally, the seismic retrofitting in historic structures absorbs some basic principles, which regardless of the location of the monuments and sites, and their constituent materials, they can guide the design of interventions contemplated for structures with high historical value. Therefore, the main principles that must be under consideration for seismic strengthening of historic adobe structures are: comprehensive study; respect to original materials and authentic documents; minimal intervention; compatibility and durability; reversibility; non-invasivity; distinguishability.

As an important point, the seismic resistance of adobe building is not convenient enough; the interventions in residential adobe houses just can give time to evacuate, while in historic ones, they can only reduce the possibility of severe destruction. Nevertheless, in order to reduce the seismic risk at these vulnerable types of structures and to have better justification about their seismic behaviour, it is important to promote an adequate methodology to survey the efficiency of possible reinforcement measures. Therefore, the examination of dynamic performance of cracked adobe structures is completely imperative. In this issue, as mentioned by AAVV (2005), “the lack of expertise and research in the area has gained the attention of people who deal with heritage and the university researchers who share the same interest" [1]. Although the experiences of these researches have been based on different philosophies and approaches, they could enrich our knowledge about the various aspects of seismic intervention in culturally/architecturally important adobe-mud brick structures at risk of earthquake losses. Occasionally, although there are different views towards seismic upgrading of adobe architectural heritage both in selection of ideal materials and techniques, and also in the rate of authorized intervention, their contributions are nonetheless appreciated.

Through the world, there are some universities and laboratories, which have conducted projects to evaluate seismic behaviour of reinforced and non-reinforced adobe structures such as those performed in the Pontifical Catholic University of Peru, The Getty Conservation Institute in USA, Stanford University in USA, IZIIS-Ss. Cyril and Methodius University in Republic of Macedonia, Saitama University in Japan, University of Aveiro in Portugal and University of Sydney (UTS) in Australia among others. In this paper, to better known the efficiency of different possible anti-seismic measures, and to consider the ideal one, based on some necessary requirements, during seismic strengthening of new and old adobe structures, a review is made on the internationally performed on the large-scale modeling for seismic strengthening of adobe-mud brick structures.

2. Experimental Studies at the Pontifical Catholic University of Peru (PUCP)

In 1972, several large-scale modeling tests have been conducted at the Pontifical Catholic University of Peru (PUCP) on different adobe structures reinforced with locally available materials. In this model, a reinforced-concrete tilting platform was used to test full-scale adobe models, where the seismic force was represented by the lateral component of the weight of the models. As the result of laboratory tests implemented on the non-reinforced adobe structure and reinforced adobe structure (consisting of vertical cane rods anchored to the foundation and horizontal crushed cane placed between mortar joints at every fourth courses), the deformation capacity and strength of the adobe structure was notably increased. As can be seen in Figure 1, the internal alternatives with prevention of the occurrence of cracks at the corners and connections could hold the integrity of the adobe walls. However, since 1992, once again at the PUCP some other large-scaled adobe models have been tested on the shake table test. In each of these models, some new intervention plans have been proposed for seismic reinforcement of adobe structures, as following:

1-2- Adobe Reinforcement with Cane Rods, Cane Meshes and Solid Ring Beam

This type of reinforcement consists of placing an internal grid, with vertical and horizontal elements, able to bond efficiently with the structure, improving its seismic performance [2]. In this model, it was pointed out that the cane reinforcement elements should be properly tied together and conveniently anchored to the adjoining structural elements. As the result of test shown, this reinforcement technique can prevent the separation of walls at corners, even during high cyclical lateral loads. The reinforcement proved to be very effective in preventing building collapse [3]. Although the reinforced model suffered significant damages, it did not collapse. In addition to a ring beam and cane reinforcement, the use of truss-like timber ties between the lintel and ring beam proved to be effective [4]. The results of the seismic behaviour of non-reinforced and reinforced adobe models are shown in Figure 1. Meanwhile, it should be noted that the use of interior cane rod and mesh has the following shortcomings: unless to post-earthquake reconstruction, this technique is inefficient for existing historic adobe structures; its application is hard and a high accuracy and time needed for placement of cane rods and meshes; availability of materials in any region.

Figure 1: (a) Placement of wooden ring beam, vertical and horizontal cane reinforcement on adobe model (Source: Blondet et al., 2002), and (b) non-reinforced and reinforced adobe models after shake table tests [4].

2-2- Adobe Reinforcement with External Cane-Rope Mesh

In this test, the adobe model was externally wrapped with vertical and horizontal canes fixed through holes made in adobe walls in every 30-40 cm. As can be seen in Figure 2, except of some cracks, the model was not suffered any collapse.

Figure 2: An adobe-building model with external vertical cane and horizontal rope reinforcement (Source: (Left) [3]; and (Right) [5]).

3-2- Adobe Reinforcement with Welded Wire Mesh

In this model, the welded meshes consisting of 1 mm diameter wires at 20 mm spacing were positioned horizontally and vertically, across the walls. Then all were nailed with metal bottle caps to the adobe walls, at the end, and the walls were covered with a 20 mm thick cement and sand mortar.

As the result of shake table test implemented on the two U-shape walls, while the non-reinforced model has almost collapsed, the reinforced model just faced some cracks in its body, Figure 3(a). The researchers found that it is possible for the walls to disintegrate into large blocks during severe ground shaking; however, the mesh prevents the walls from falling apart, and collapse can be avoided [6]. This seismic reinforcement scheme proved to be effective during the 2001 Arequipa, Peru earthquake (Mw = 8.4) and the 2007 Pisco, Peru earthquake (Mw = 8.0). Several adobe houses built with welded wire mesh had faced less damage than other non-reinforced adobe structures.

4-2- Adobe Reinforcement with Polymer Mesh (Geomesh)

Like previous model, the polymer meshes were positioned horizontally and vertically, across the walls, and they were tied together through plastic or nylon strings placed during construction. As Blondet et al. (2011) Stated, "This reinforcing scheme demonstrated excellent seismic response during high intensity shake table tests (roughly equivalent to MM 7) on a full-scale adobe building model. The geomesh reinforcement increased the stiffness, strength and deformation capacity of the adobe walls. Total building collapse was prevented due to the confinement provided by the mesh." [3], Figure 3(b).

(a) (b)

Figure 3: (a) Shake table testing of non-reinforced and reinforced U-shaped adobe walls (Source: Blondet et al., 2011); (b) Geomesh attached to adobe walls, Reinforced adobe house with geomesh during a shake table test at the PUCP (Source: (Left) [3]; and (Right) [7]).

5-2- Adobe Reinforcement with Car Tire Straps

In this system to improve the seismic resistance of adobe wall, the circumferentially cut straps from the treads of car tires was used as tension reinforcement element. As schematically shown in Figure 5.8, to wrap adobe model with car tire straps, vertical straps (every 1.2 m) under or through foundation together with horizontal straps (every 6 cm max) passed from holes made on the walls. The purpose of the tests was to verify that the reinforcement system could meet the performance objective of preventing building collapse in moderate to severe earthquakes, and to obtain data to pre-engineer these strap-reinforced structures [8]. Regularly spaced horizontal and vertical tensile elements have the potential to create a rational strut-and-tie bending force resisting mechanism, however, horizontal and vertical straps work together to improve in–plane shear strength [9]. As shown in Figure 4, results showed that the tire strap reinforcement system prevented building collapse, even during simulated ground shaking of high intensity [10].

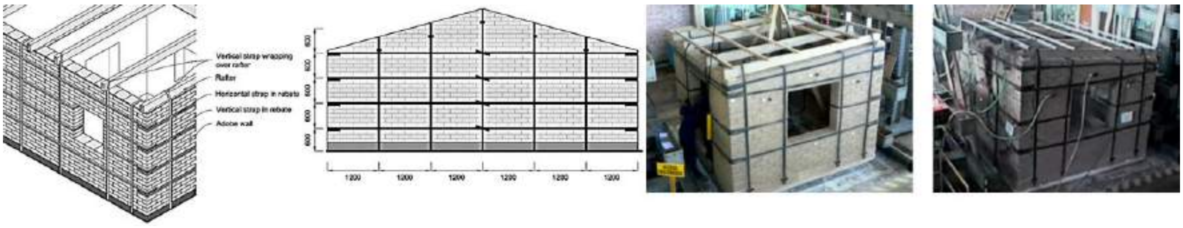

Figure 4: (left) Schematic view of the installation of vertical and horizontal straps; and (right) adobe model reinforced with Car tire straps, before and after shake table test [8].

6-2- Adobe Reinforcement with Integral masonry system (IM)

In the form of a joint project between UPM and PUCP, the seismic viability of the Integral Masonry System (IM) through a two-storey adobe model (3m×3m×3m) has been tested under the dynamic stresses imposed by the shake table test. As Adell et al. (2009) explained about this test, “The truss-reinforcement system consists of interlaced truss-reinforcement which crosses over each other in a three-dimensional manner. The voids are subsequently filled with brick, block, adobe, mud or recycled material in order to form the walls and boarding may be set on the trusses to form the floors.” […] “A polyethylene geomesh with 0.15 m openings was tied to the wall by the raffia strips on just two sides of the prototype. This was made with the aim of verifying the differences between the rendered and unrendered faces after testing on the displacement table.” [11]. As the test results showed, although under the largest displacement (130 mm), there cracks were seen at different parts of the model, especially along the lines of the reinforcement, they did not incur any damage that might affect the stability of the structure. Meanwhile, it was provoked that the polymeric mesh and rendering do not have any special effect on the seismic behaviour of the walls.

Figure 5: (a) The process of adobe model’s construction by ISM system; and (b) damages on adobe model reinforced with IM system after shake table test [11].

7-2- Evaluation of the Efficacy of Mud Injection to Repair Seismic Cracks on Adobe Structures

In 2012, to evaluate the possibility of mud injection to repair seismic cracks on adobe structures, a large-scaled adobe model in two phases was tested at PUCP. During the first phase of this laboratory test, to induce wall cracking representative of seismic damage, the undamaged model was subjected to a realistic simulated seismic shaking. After that, as explained by Blondet et al. (2012) “All major seismic cracks (wider than 1 mm) were opened using a drill and a hammer and pin as shown in Figure 6, in order to facilitate mud penetration during the repair. The thicker cracks (more than 20mm after opening) were filled manually with mud. Then the thinner cracks were prepared for injection by sealing them with a layer of silicon over them and leaving small openings at 50 mm distance approximately. The mud-based grout was then injected through these openings until the cracks were fully filled.” [12]. Then once again, the repaired model was subjected to the simulated seismic shakes. As the result of the test, the intervention carried out to repair the seismic damage could just retain 54% of the original lateral strength and 30% of the original lateral stiffness of the adobe model. Therefore, the main conclusion of this test was that although repair via mud injection is useful to recover the original stiffness and strength of the structure partially, this method must be combined with other reinforcing technologies to ensure that the repaired structure is stable against further seismic shaking [12].

Figure 6: The adobe model before phase 1 (grouting of cracks after finishing of the first phase), and after phase 1 and 2 [12].

3- Experimental Studies at the University of Tokyo

PP-Band Retrofitting Technique is one of the appropriate retrofitting techniques and different aspects of this method have already been studied in Meguro Laboratory, the Institute of Industrial Science (IIS), and The University of Tokyo [13]. As the advantage of PP-band reinforcement, this system is inexpensive, worldwide available, tolerates large deformations, durable, easy workmanship and has no need to special technology and knowledge. Furthermore, this material has no corrosion or insect failure effect and possesses excellent resistance to organic solvents and degreasing agent as well as electrolytic attack [14]. Because of tests implemented, it was conducted that PP-band may potentially be used to prevent/delay brittle collapse of non-engineered structures under seismic loading [15]. Figure 9(a) shows bending and diagonal shear tests on reinforced and non-reinforced models, and Figure 9(b) shows a full-scale adobe model reinforced with PP-bands before and after shake table test.

4- Experimental Studies at the University of Aveiro

Since 2005, concerning the mechanical properties and structural characterization of adobe structures and their constituting materials several scientific studies have been conducted at the Civil Engineering Department of Aveiro University of Portugal (e.g. Varum et al., 2005; Arêde et al., 2007; Silveira et al., 2007; Varum et al., 2008; Figueiredo et al., 2012). Thorough evaluation of the performance of non-reinforced and reinforced adobe structures, the aim of these studies have to establish a basis of knowledge essential for the safety analysis of adobe structures. Given that the structural behaviour of adobe structures are deficient under horizontal loads, especially those loads are induced by the seismic motions, the Department of Civil Engineering of Aveiro University has recently been conducting several experimental tests on the seismic behavior of adobe structures located in the Aveiro district. In one of these tests, a Double-T adobe wall (height = 3.07 m, length =3.5 m and thickness = 0.29 m) was tested by applying of the uniform vertical loads at the top of the wall (20KN) and cyclic horizontal forces of increasing amplitude, the model was built by using of adobe bricks from a demolition site in the Aveiro region. The adobe blocks used had mean dimensions of 29×45×12 cm , a specific weight of approximately 16 KN/m , a mean compression resistance of 0.46 MPa and a mean tensile resistance of 0.15 MPa [16].

However, the model was imposed with two series of tests. During the first series of the test, the non-reinforced model was subjected to cyclic and dynamic tests, as the result, wall was faced with cracks in its façade, which these cracks have significantly reduced its strength and stiffness. Then during second series of the test, the damages have been repaired by the grouting injection of lime gum into the cracks, after that the wall was reinforced with synthetic mesh-band. As explained by Figueiredo et al. (2012), "The mesh was fixed to the wall with angle beads and angle profiles in PVC using highly resistant nylon threads on all of the wall's concave vertices. Plastic fixing plugs with a depth of 70 cm and cylindrical base of 4 cm in diameter were used, forming a 0.5 m square mesh. The wall was then plastered with lime mortar, similar to the original wall." [16]. Then after repairing and retrofitting of the cracked adobe wall, the same test that was utilized for the non-reinforced model was also implemented on reinforced model. As the result showed, the grouting injection of cracks along with mesh-band wall reinforcement significantly improved the seismic resistance of the adobe wall, Figure 10.

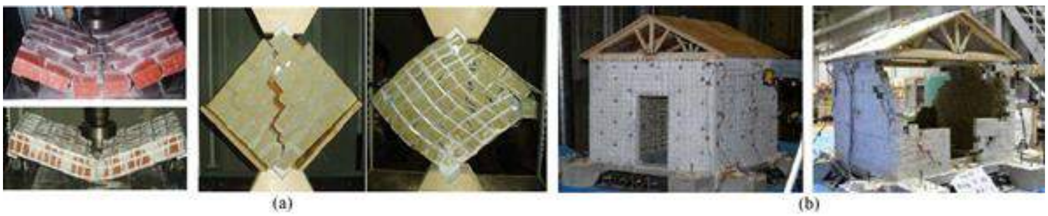

Figure 9: (a) Failure patterns of brick masonry wallettes with and without retrofitting by PP-band mesh under bending and diagonal shear tests; (b) The result of shake table test on reinforced and non-reinforced adobe models [15].

Figure 10- Respectively from right to left U-shape model after first simulated cracking, after grouting, after reinforcing with mesh-band and final damage state [16].

5- Experimental Studies at the University of Sydney (UTS)

In 2006, Dowling as a part of its Doctoral dissertation "Seismic strengthening of Adobe-Mud brick Houses" has studied the seismic behaviour of U-shaped adobe wall units, under a modified version of the EI Salvador design spectrum. The dynamic simulation was undertaken on the state-of-art MTS uni-axial shake table located at the University of Technology, Sydney (UTS) [7]. The main aim of the project was to find cost-efficient retrofitting methods for adobe structures in developing countries. In this project, different reinforcement solutions have been tested included: the use of pilasters/buttresses at wall corners, internal wire mesh reinforcement, internal/external bamboo rods, chicken wire, string and ring beam, details of models tested can be seen in Table 1. The models had been built with adobe blocks (150 mm ×150 mm ×50 mm) and 12-13 mm thick mortar joints. In these tests, the U-shape walls were considered as non-load bearing walls, the weight of adobe roof is not applied. In addition to those experimental tests carried out shake table, a model house was reinforced in a similar manner to 3f U-shaped adobe wall, (Figure 11), the testing sequence of this test is exposed in Table 2.

Figure 11: Specimen 4A after simulation of S8 [7].

Table 1: The specifications of U-shape adobe walls tested in UTS [7].

Model	Horizontal reinforcement	Vertical reinforcement	Ring Beam
3A	None	None	None
3B	None	Corner Pilasters	None
3C	Chicken wire mesh (internal)	None	None
3D	Chicken wire mesh (external wrapping)	Chicken wire mesh (external wrapping)	Timber
3E	Chicken wire mesh (internal)	Bamboo(external)*	Timber
3G	Chicken wire mesh (internal)	Bamboo(internal)*	Timber
3I	Chicken wire mesh (internal) Bamboo (external)	Bamboo(external)*	Timber
3H	Chicken wire mesh (internal)	Bamboo(external)	Timber**
3F	Fencing wire (external)	Bamboo(external)	Timber**
3J	Chicken wire mesh (internal) Fencing wire (external)	Bamboo(external)	Timber**

3K	Chicken wire mesh (internal)	Timber poles (internal)*	Timber**
Notes: *Vertical reinforcement connected to concrete foundation of test frame - ** Timber Ring Beam Connected to Wall Restraint			

Table 2: Testing sequence and resultant of damage grades for all U-shape adobe units [7].

	Simulation	Intensity Displacement	3 A	3 B	3 C	3 D	3 E	3 G	3 I	3 H	3F	3 J	3K
Unscaled	S1	40%	0	0	0	0	0	0	0	0	0	0	-
	S2	100%	0	0	0	0	0	0	0	0	0	0	-
	S3	150-200%	0	0	0	0	0	2	0	0	0	0	-
Scaled	S4	20%	0	-	0	0	0	-	0	0	0	0	0
	S5	50%	0	0	0	0	0	-	0	0	0	0	0
	S6	75%	4	-	1	1	0	-	0	0	0	0	0
	S7	100%	-	4	4	3	1-2	-	0-1	1	1	0-1	1
	S8	125%	-	-	-	-	3-4	-	1-2	1-2	1	1	2
	S9-S10	75%(×2)	-	-	-	-	-	-	2-3	2-3	2	2	2-3
	S11-S12	100%(×2)	-	-	-	-	-	-	3	3	3	2-3	3-4

The successful testing of eleven U-shaped adobe wall units revealed the following general outcomes [7]:

- Major improvements in the seismic capacity of adobe-mud brick structures can be achieved using low-cost and low-tech means. Such improvements are viable and effective for both new-build constructions and for the retrofitted-strengthening of existing dwellings.
- U-shaped adobe wall panels (with appropriate 'wing' wall restraint) exhibit classic failure patterns when subjected to shake table testing using a suitable input time history. Damages were consistent with real structures subjected to real earthquakes.
- Test results confirm the importance of appropriate time scaling of input time history to induce damaging near-resonance conditions in a structure. Time scaling is also necessary to ensure dynamic similitude between specimens, such that accurate comparisons may between the performance of different specimens.
- Test results challenge the assumption that corner pilaster/buttresses will adequately restrain the out-of-plan overturning moment induced in a wall, which create vertical corner cracking due to tearing failure in the orthogonal wall.
- Test results indicate that there is some uncertainty relating to the structural performance of internal vertical reinforcement, with significant cracking occurring at a lower intensity than expected. It would appear that the presence of internal vertical reinforcement introduces significant discontinues in the structure. This aspect, coupled with the complexity of construction, raises questions about the viability of using this from of reinforcement.
- Test results indicate that significant improvement in the earthquake resistance of adobe mud brick structures can be obtained by using external vertical and-or horizontal bamboo reinforcement, external horizontal wire and/or internal horizontal chicken wire mesh

reinforcement and a ring beam. These additions, when securely tied together, create ad integrated matrix which restrains movement and enhances the overall strength of the structure. The reinforcement system acted to delay the onset of initial cracking, and reduce the severity of cracking during repeated high intensity shaking. Most importantly, collapse of reinforced structures was prevented.

Table 3: Testing sequence and observation for model of 4A [7].

Simulation	Intensity	Damage grade	Observation
S1	10%	0	No damage observed
S2	25	0	No damage observed
S3	50	0	No damage observed
S4	75	1	Rocking of E shear wall. Separation at base. Minor cracking from lintel above door (E wall).
S5	100	2-3	Major rocking of E shear wall. Major cracking in E shear wall. Minor cracking in all other wall panels.
S6	125	3	Sever rocking of E shear wall. Sever cracking in E shear wall. Moderate cracking in all other wall panels.
S7	100	3	Progressive additional damage in all wall panels. Severely damaged. Collapse prevented.
S8	Shakedown	4	Progressive additional damage in all wall panels. Severely damaged. Collapse prevented.

6- Experimental Studies of Getty Conservation Institute (GCI)

In the last decade 20th century, the Getty Conservation Institute within the Getty Seismic Adobe Project (GSAP) carried out a vast investigation into different methods that could be employed for seismic reinforcement of historically or culturally important adobe structures. The research that was carried out during the GSAP was designed to provide knowledge about of the existing historic adobe structures, adobe's seismic damage typologies both through field observations following the Northridge earthquake and the results from an extended dynamic research program, and to develop theory, tools and techniques for seismic upgrading of historic adobe structures. As part of the GSAP sponsored by the Getty Conservation Institute, with emphasis on minimal intervention to the original fabric of historic adobes, nine small-scale (1:5) and two large-scale (1:2) model buildings with different reinforcement system were respectively tested on the shake table at Earthquake Center at Stanford University and at the Institute of Earthquake Engineering and Engineering Seismology (IZIIS), the result of tested adobe models can be seen in Table 4 and Figure 12. The primary purposes for using large-scale models were to gather numerical data on the buildings' dynamic behavior and to compare the performance of the large-scale models with that of the small-scale models, in particular, to evaluate the influence of gravity loading on failure modes [17]. During the GSAP, the results of the research program clearly demonstrated that the basic theory of stability-based design can efficiently fulfills the demands for seismic retrofitting of historic adobe structures. Based on these laboratory tests implemented, the GSAP (2002) has developed an effective retrofit system “global design issues”. The basic elements of global design are [18]:

- Upper-wall horizontal elements (mandatory): Three possible types of upper-wall elements are (1) partial plywood diaphragm, (2) concrete or wood bond beam, (3) external nylon or steel straps or cables combined with existing, flexible roof or floor framing. Upper-wall horizontal elements are most effective in providing anchorage to the roof or floor, providing out-of-plane strength and stiffness and establishing in-plane continuity.
- Vertical wall elements (optional except for thin-walled structures): This design is consisted of center-core rods anchored with an epoxy grout, which is exemplified by nylon straps, steel straps, or steel cables, should be attached to both interior and exterior wall surfaces. The use of vertical elements can greatly increase the “ductility” of the walls, as shown in combination with upper and lower wall elements.
- Lower-wall horizontal elements (optional): These elements can consist of straps or cable elements or even buttresses. Lower-wall horizontal elements can be used to improve the performance of adobe walls by preventing cracked wall sections from “kicking out” in plane, along the length of the wall.

Table 4: The GSAP’s Model Adobe House Testing: Specification and Results [17].

Model No.	**Scale and SL**	**Walls**	**Type of retrofit**	**Collapse level**
1	1.5 (7.5)	NE	Upper horizontal strap	X
		SW	Upper and lower horizontal straps	No collapse
2	1.5 (7.5)	NE	Bond beam and center-core rods	No collapse
		SW	Bond beam, lower internal horizontal straps, and vertical straps	
3	1.5 (7.5)	ALL	Bond beam, lower internal horizontal straps, and vertical center-core rods	No collapse
4	1.5 (5)	NE	Upper horizontal strap	No collapse
		SW	Upper and lower horizontal straps	
5	1.5 (11)	ALL	None (control model)	VII
6	1.5 (11)	NE	Bond beam, lower horizontal straps, and vertical straps	VII
		SW	Bond beam, lower horizontal straps, and local ties at piers between the door and windows.	VII&IX
7	1.5 (5)	NE	Partial wood diaphragm—upper strap at attic-floor level, lower straps, and vertical straps.	No collapse
		SW	Partial wood diaphragm—upper strap at attic-floor level, lower straps, and vertical straps.	X
8	1.5 (7.5)	NE	Partial wood diaphragm—upper strap at attic-floor level, lower straps, and vertical straps.	No collapse
		SW	Partial wood diaphragm—upper strap at attic-floor level, lower straps, and vertical center-core rods; no lower strap on west wall	
9	1.5 (7.5)	ALL	None (control model)	VI
10	1.2 (7.5)	ALL	None (control model)	VIII
11	1.2(7.5)	NE	Partial wood diaphragm—upper strap at attic-floor level, lower straps, and vertical straps.	No collapse
		SW	Partial wood diaphragm—upper strap at attic-floor level, lower straps, and vertical center-core rods; no lower strap on west wall	

Figure 12: East wall in Model 10 test VIII (left), and Model 11 test VIII (right) [17].

Conclusion

As a general overview have been cast on the techniques that have shown their effectiveness in shake table tests, and based on limitation existed in application of each of these techniques, it well indicates that making decision for the selection of an appropriate seismic upgrading measure is not a simple task. To construct new adobe structures, each of these techniques can be followed as a method of operation. While during seismic retrofitting of historic adobe-mudbrick structures, both before and after an earthquake, depending on the physical condition of structure, if the materials in retrofitting projects are durable, readily available, and compatible with the original fabric of the structure, and also if the interventions are minimally invasive and reversible, it can be under consideration. Therefore, in this special case, the efforts must be made to standardize the realization and utilization of these terms across disciplines.

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