Low-Cost and Low-Tech Reinforcement Systems for Improved Earthquake Resistance of Mud Brick Buildings

Dominic M. Dowling and Bijan Samali

Abstract: *Traditional, unreinforced adobe mud brick structures are highly susceptible to damage and destruction during seismic events. This vulnerability is evident in historic adobe structures around the world, as well as in traditional adobe homes in developing countries where severe earthquakes repeatedly cause drastic losses of life and livelihood. Adobe research at the University of Technology, Sydney (UTS), Australia, is focused on the development of low-cost, low-tech reinforcement systems for adobe structures. To date, ten U-shaped adobe wall panels and one full model house (1:2 scale) with different reinforcing systems have been subjected to transient dynamic loading using a shake table to evaluate the response to seismic forces. Time-scaled input spectra have been used to ensure dynamic similitude and impart sufficient energy to each structure to induce damaging conditions. The force-displacement characteristics and failure mechanisms of each structure have been studied to determine the resistance capacity of each system. Results indicate that a major improvement in structural performance can be achieved by using stiff external vertical reinforcement (e.g., bamboo), external horizontal reinforcement (e.g., bamboo or wire), and a timber ring/crown beam. This integrated matrix acts to restrain movement and enhance the overall strength of the structure. Tests have shown this system to effectively delay the onset of initial cracking and prevent collapse, even during severe shaking. The proposed system is effective, simple, affordable, and widely adaptable to a variety of materials and local conditions. It can be used for the retrofit-strengthening of existing structures, as well as in new construction. It shows tremendous promise for application in developing countries and for the protection and preservation of historic adobe structures around the world.*

Introduction

Traditional adobe mud brick structures are highly vulnerable to the effects of earthquakes, a problem that is particularly acute in rural housing in developing countries and in historic adobe buildings worldwide. Influencing factors include the inherently brittle nature of the material itself, its widespread use, its generally poor construction quality, limited awareness of concepts of aseismic design and construction, and limited resources to address the issue.

Adobe research at UTS is focused on developing and assessing methods to reduce the vulnerability of adobe housing to extreme dynamic loading such as caused by earthquakes (Dowling 2006). This research combines traditional building techniques, inexpensive reinforcement systems, and state-of-the-art facilities, including the UTS shake table, to investigate low-cost, low-tech solutions for application in developing countries.

Earlier Studies

The most notable shake table testing of adobe structures has been undertaken in Peru (Bariola et al. 1989; Zegarra et al. 1999; Quiun et al. 2005), Mexico (Hernández et al. 1981; Flores et al. 2001), the United States (Tolles and Krawinkler 1990; Tolles et al. 2000), and Colombia (Yamin et al. 2004).

U-shaped wall panels and model houses ranging in size from 1:6 scale to 3:4 scale have been subjected to uniaxial shake table testing. A number of reinforcement systems for adobe houses have been proposed and tested. These include external reinforcement (e.g., corner pilasters, timber boards, rope, wire, wire mesh, welded mesh, nylon straps, Geogrid mesh) and internal reinforcement (e.g., bamboo, chicken wire mesh, wire). Past research has made a significant contribution to the understanding of the behavior of adobe structures when subjected to earthquake forces. Furthermore, it has yielded a number of effective reinforcement systems to delay and/or prevent serious damage and collapse of adobe structures, even during high-intensity ground motion. The results have been used to develop a number of design and construction manuals and guidelines (e.g., International Association for Earthquake Engineering 1986; Blondet, Garcia, and Brzev 2003). Large-scale implementation of the solutions, however, has not occurred. While a wide range of factors contribute to this lack of local implementation (e.g., cultural attitudes, resistance to change, lack of resources available for training, supervision, materials and tools, etc.), it seems that the development of a practical solution that is within the resource and skill levels of the rural poor is a critical initial step in the challenge of generating sustainable change.

In addition to the practical limitations of previously proposed systems, research to date has tended to focus on qualitative performance (observations) rather than on the collection and analysis of quantitative response (displacement, acceleration, dynamic amplification, etc.). Quantitative data provide important objective information about the behavior of specimens at a microscale, as well as increase the accuracy of comparative studies among different specimens and different tests. The collection of detailed quantitative data is also an important step toward developing a reliable finite element model for adobe structures.

Research at UTS endeavors to advance both academic studies (vis-à-vis the collection and study of qualitative and quantitative data) and the development of practical solutions for field application.

Testing Methodology

Description of Specimens

Research at UTS has included static and dynamic testing of adobe prisms and structures. This paper focuses on the dynamic testing of adobe structures. To date, ten U-shaped adobe wall panels and one full model house (1:2 scale) have been subjected to transient dynamic loading using a shake table to evaluate the response to seismic forces.

U-Shaped Wall Panels

It is widely known that the predominant failure modes of common adobe houses subjected to earthquake loads are vertical corner cracking at the intersection of orthogonal walls, and horizontal, vertical, and diagonal cracking due to out-of-plane flexure (Tolles and Krawinkler 1990; Flores et al. 2001). This often leads to overturning of walls and collapse of the roof. Improvement systems or techniques that are designed to reduce damage and destruction of adobe structures should primarily address these main failure modes. In order to assess the capacity of different improvement systems to reduce such failure, a series of shake table tests of 1:2 scale U-shaped adobe wall units was undertaken at UTS (fig. 1). A variety of reinforcement systems and configurations were tested separately and/or collectively, as shown in table 1.

For each specimen, a downward restraining force was applied to the tops of the short wing walls (acting as in-plane shear walls) to simulate the restraint provided by a continuous wall and to reduce sliding, rocking, and overturning of the complete unit (fig. 1). This restraint acts to effectively transfer the bulk of the seismic loading to

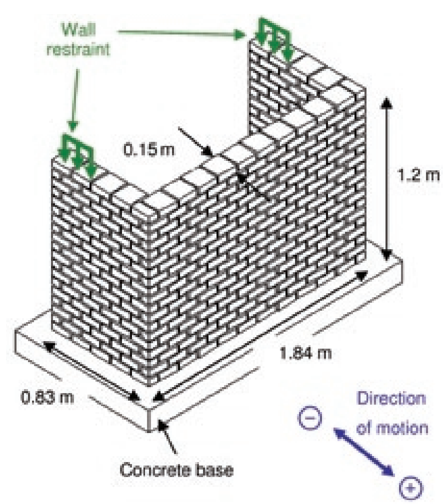


FIGURE 1 Specimen configuration and dimensions. Wall width = 0.15 m (5.9 in.), except for specimen 3H (= 0.10 m, or 3.9 in.); mortar joints, 12–13 mm (0.5 in.).

Table 1 Specifications of U-shaped adobe wall panels

Specimen	Reinforcement	1st natural frequency, f_1 (Hz)	Time scaling factor
3A	Unreinforced, common	29.6	2.0
3B	Corner pilasters/buttresses	34.1	2.3
3C	*Horizontal:* chicken wire mesh (internal)	33.0	2.2
3D	Chicken wire mesh (external wrapping) + timber ring beam	32.8	2.2
3E	*Horizontal:* chicken wire mesh (internal) + timber ring beam; *vertical:* bamboo (external)	30.8	2.1
3I	*Horizontal:* chicken wire mesh (internal) + bamboo (external) + timber ring beam; *vertical:* bamboo (external)	31.6	2.1
3H	*Horizontal:* chicken wire mesh (internal) + timber ring beam; *vertical:* bamboo (external). Thin wall (= 0.10 m)	33.0	2.2
3F	Retrofit. *Horizontal:* fencing wire (external) + timber ring beam; *vertical:* bamboo (external)	33.7	2.2
3J	Optimized. *Horizontal:* chicken wire mesh (internal) + fencing wire (external) + timber ring beam; *vertical:* bamboo (external)	33.0	2.2
3K	*Horizontal:* chicken wire mesh (internal) + timber ring beam; *vertical:* timber poles (internal)	27.0	1.8

the areas of main interest: the critical corner connections and the vulnerable out-of-plane long wall. The use of this applied restraining force constitutes a significant difference between this research and other dynamic tests of U-shaped adobe wall panels, which do not include any shear wing wall restraint and thus neglect the additional stiffness and restraint contributed by the shear walls (Zegarra et al. 1999; Quiun et al. 2005).

Model House

A model house (1:2 scale) was constructed, retrofitted, and tested on the UTS shake table (fig. 2). Its dimensions were 3.53 × 1.84 m (11.6 × 6.0 ft.), with a wall thickness of 0.15 m (5.9 in.) and a height of 1.2 m (3.9 ft.). The model house featured two doors and one window; the direction of shaking was north–south, perpendicular to the long walls.

The sequence of construction and retrofitting of the model house was: (1) construct unreinforced house and allow to dry; (2) mark and drill holes in rows at top, middle, and bottom of each wall; (3) insert polypropylene string loops through holes; (4) fill holes with mud, allow to dry; (5) place timber ring/crown beam on top of wall and connect with bamboo dowels and wire; (6) place external vertical bamboo (inside and outside house), tied with through-wall polypropylene string ties; (7) place and tension galvanized fencing wire horizontally between bamboo poles (top, middle, and bottom); and (8) connect bamboo poles and ring beam with wire loops.

FIGURE 2 Model house 4A prior to testing; south and east walls are visible.

If desired, the bamboo, string, and wire could be easily covered with a mud or lime render to provide an attractive finish, as well as afford protection from weathering.

Description of Equipment and Input Time History

The dynamic testing was undertaken on the 10 tonne capacity, 3 × 3 m (9.8 × 9.8 ft.) MTS Systems uniaxial shake table at UTS. A series of accelerometers and dynamic LVDT displacement transducers was used to record the dynamic response at key locations on each specimen and the shake table during the series of simulations. Of main interest was the response of the mid-span-top of the out-of-plane long wall in relation to the ground motion (shake table displacement).

In this study the input time history from the January 13, 2001, El Salvador earthquake (M_w 7.7) was used (station, Hospital Santa Teresa, Zacatecoluca, La Paz; site geology, soil; epicentral distance, 51.2 km, or 31.7 miles [COSMOS 2006]). This earthquake, in combination with an M_w 6.6 earthquake on February 13, 2001, in the same area, caused the destruction of over 110,000 adobe houses (Dowling 2004).

In order to subject each specimen to similar test conditions (to allow reliable comparisons between the structural response and overall performance of each specimen), the following objectives were set for the shake table testing:

- Ensure dynamic similitude between all U-shaped adobe wall units, such that the frequency ratio, defined as the ratio of dominant input excitation frequencies to structural frequencies (first natural frequency of each specimen; see table 1), was identical for each specimen prior to testing.
- Ensure damaging near-resonance conditions, which are achieved when the pretest natural frequency of each specimen (U-panels and model house) is matched with the dominant frequency range of the input spectrum.

Given the variation in first natural frequencies of each specimen prior to testing, the input spectra were uniquely time-scaled for each individual specimen, using the time scaling factor (table 1). This was done to meet the above objectives and to ensure that consistent and sufficient energy was imparted to each structure to induce damaging conditions and allow comparative studies among specimens.

In addition to the time scaling of the input spectra, scaling of the intensity was undertaken. This was achieved by scaling the displacement component of the displacement time history. Intensity scaling was necessary in order to subject each specimen to a series of earthquake simulations of increasing magnitude, to gauge the response prior to cracking (elastic behavior), as well as for severe damaging conditions (postelastic behavior).

Results

U-Shaped Wall Panels

Each specimen was first subjected to three simulations using the raw, unscaled (with respect to time) input spectra, ranging in intensity from 40% to 200% of the displacement time history. In each case, no damage was observed, even for the unreinforced specimen 3A. Each specimen was then subjected to a series of time-scaled shake table tests of increasing intensities (20%, 50%, 75%, 100%, 125%, 75%, 75%, 100%, 100% of the displacement time history). The results from the time-scaled tests confirmed the destructive nature of ground motions containing sufficient energy and possessing dominant frequencies in the region of the natural frequencies of the wall units. This outcome clearly demonstrates the importance of appropriately time scaling the input motion during laboratory tests to ensure that sufficient energy is imparted to structures to induce damaging conditions, thus allowing a detailed study of the response and performance of different reinforcement systems.

In this paper, the behaviors of specimens 3A, 3F, and 3K are presented in detail, considering both qualitative results (observations, photographs) and quantitative results (displacement–time graphs)

Specimen 3A

Specimen 3A represented a common, unreinforced adobe structure. Sudden, brittle failure occurred during the moderate, 75% intensity simulation, S6 (figs. 3a and 3b). The primary failure modes for the unreinforced

(a)

(b)

FIGURES 3A AND 3B Specimen 3A after simulation S6 (75%). The in-plane wall and corner connection (a) and the out-of-plane wall (b) are shown.

specimen 3A (and lightly reinforced specimens 3B, 3C, and 3D) were: (1) vertical corner cracking at the intersection of orthogonal walls; (2) midspan vertical cracking in the out-of-plane long wall; and (3) horizontal and diagonal cracking in the out-of-plane long wall, with a propensity for overturning of the affected panel. These damage patterns are consistent with common damage to real houses subjected to real earthquakes. This feature confirms that the selected specimen configuration, boundary conditions, and input spectra are an acceptable means of assessing the seismic capacity of different reinforcement systems for adobe structures.

Specimen 3F

Specimen 3F was built as a common, unreinforced structure (as was specimen 3A); it was then retrofit-strengthened with external vertical bamboo poles, external horizontal fencing wire, and a timber ring beam (using the same procedure as described above for the model house). Specimen 3F performed extremely well. The reinforcement system was observed to delay the onset of initial cracking and reduce the severity of cracking, even during the series of high-intensity simulations (figs. 4a and 4b).

Specimen 3K

Specimen 3K included internal vertical reinforcement (25 mm [1 in.] diameter timber broom poles), plus internal horizontal chicken wire mesh reinforcement. This method and derivations thereof have been widely promoted as an effective earthquake strengthening

(a)

(b)

FIGURES 4A AND 4B Specimen 3F after simulation S12 (100% repeated). The out-of-plane wall (a) and the in-plane wall and corner connection (b) are shown.

(a)

(b)

FIGURES 5A AND 5B Specimen 3K after simulation S12 (100% repeated). The in-plane wall and corner connection (a) and the out-of-plane wall (b) are shown.

technique for new adobe houses (e.g., International Association for Earthquake Engineering 1986; Blondet, Garcia, and Brzev 2003). This system, however, has a number of deficiencies, which have limited its widespread acceptance and use. The main problem is that the method is complex and time-consuming and requires continuous involvement by skilled masons. Concerns also exist about the durability of the natural materials commonly used as internal vertical reinforcement (e.g., bamboo, reeds, timber), which cannot be checked or replaced when encased in the structure. Despite these practical limitations, specimen 3K performed well during testing (figs. 5a and 5b). The reinforcement acted to reduce the severity of cracking, although it was observed that the internal vertical poles introduced discontinuities to the structure, evidenced by vertical cracking concentrated around the location of the vertical poles. This feature may be attributed to a difference in dynamic response between the stiff adobe wall and the flexible timber poles, as well as the reduced cross-sectional area of the wall around the poles.

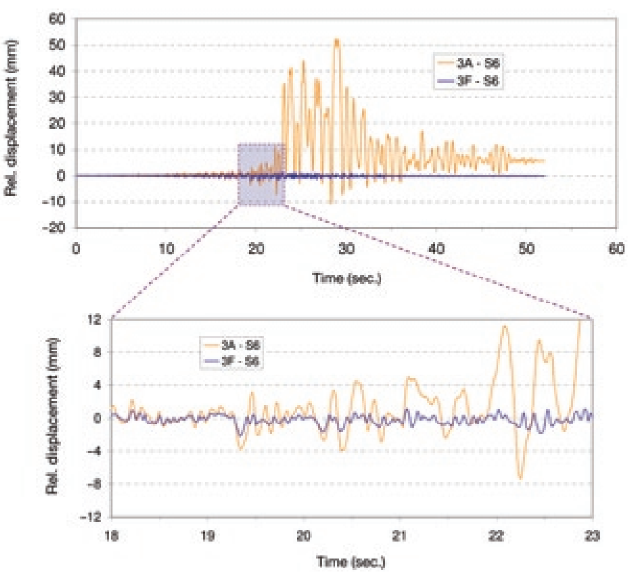


FIGURE 6 Specimens 3A and 3F: displacement (relative to shake table) at midspan-top of wall for simulation S6 (75%).

Relative Displacement

Figure 6 shows the displacement of the midspan-top of the "long" wall relative to the shake table displacement for specimens 3A and 3F during simulation S6 (75%). The major difference in relative displacement between the unreinforced specimen 3A and the reinforced specimen 3F is evident. Initial cracking of specimen 3A appears to have occurred around t = 19.3 sec., with significant cracking occurring around t = 22 sec. The peak relative displacement of specimen 3A (52.34 mm, or 2.0 in.) was 24 times that of specimen 3F (2.16 mm, or 0.1 in.) for simulation S6 (75%).

Figure 7 shows the relative displacements of the midspan-top of the long wall for specimens 3F and 3K for simulation S7 (100%). For specimen 3K the amplification of the response was much larger than for specimen 3F, even in the initial stages of the simulation when there was relatively little ground motion. This confirms the progressive damage and loss of stiffness of specimen 3K, even from the low-intensity simulations (most probably due to discontinuities and cracking around the internal vertical reinforcement). The peak relative displacement of specimen 3K (10.81 mm, or 0.4 in.) was 1.6 times that of specimen 3F (6.81 mm, or 0.3 in.) for simulation S7 (100%).

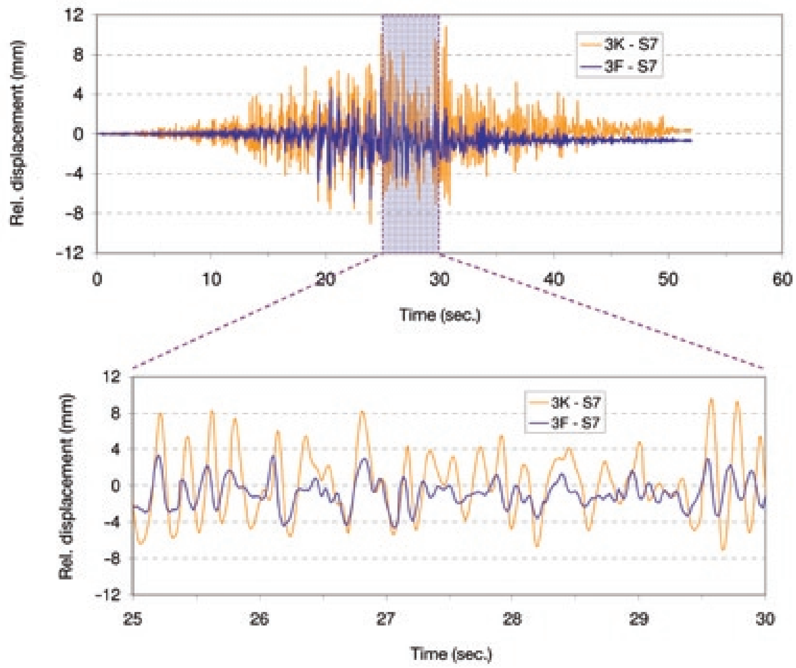
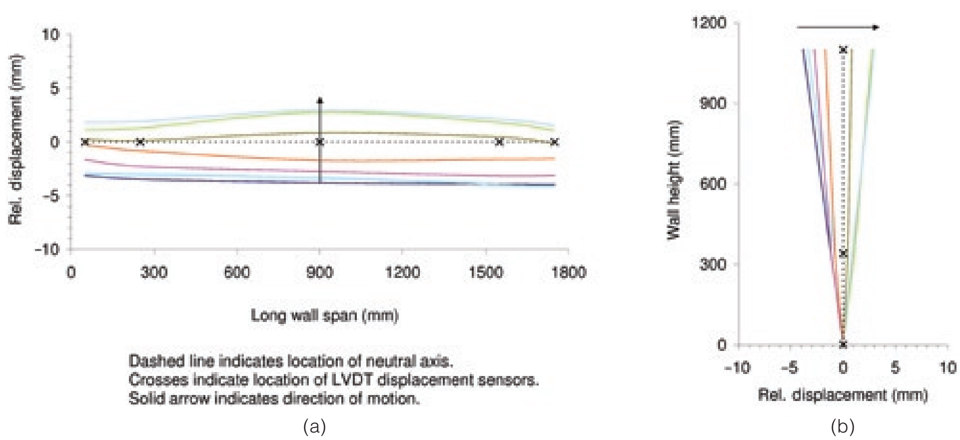


FIGURE 7 Specimens 3K and 3F: displacement (relative to shake table) at midspan-top of wall for simulation S7 (100%).

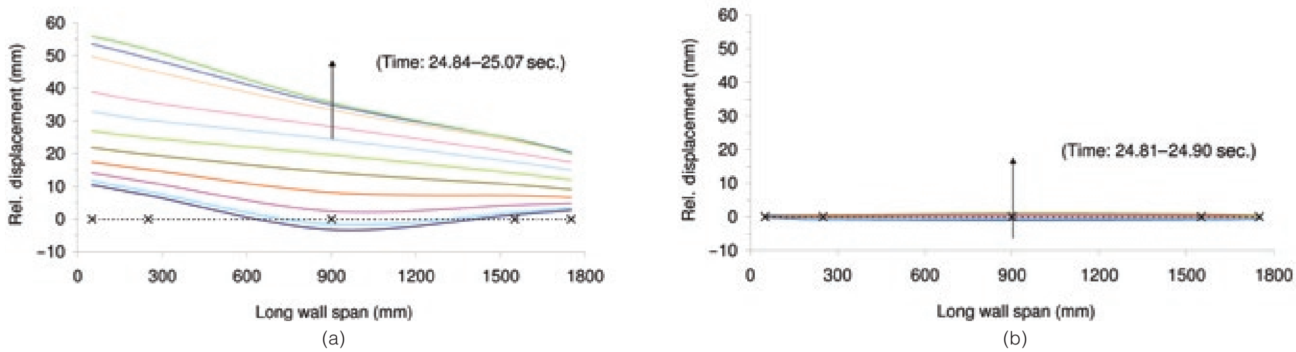
Flexural Response

Snapshots of the flexural response of specimens 3A, 3F, and 3K during simulation S6 (75%) and simulation S8 (125%) are shown in figures 8–10. The precracked behavior of specimen 3A is shown in figures 8a and 8b, which reveal a moderate flexural response. This response is significantly different from the post-cracked snapshot (fig. 9a), which shows the large flexure of the wall, in particular on the left-hand side, where the main vertical corner cracking occurred (fig. 3). By comparison, the flexural response of reinforced specimen 3F (fig. 9b) at the same approximate time (~24.9 sec.) shows the contribution of the reinforcement system in reducing the flexure of the wall, thus delaying the onset of initial cracking.

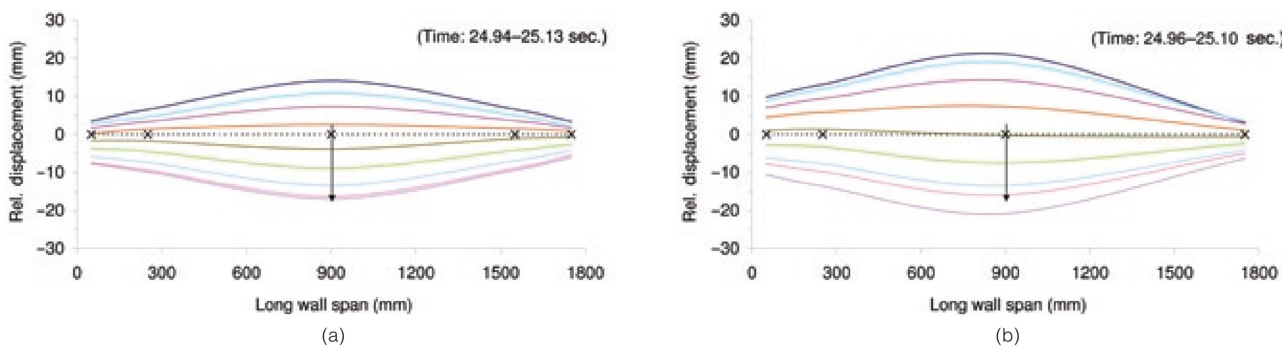
Figures 10a and 10b show the horizontal flexure of specimens 3F and 3K during simulation S8 (125%). The graphs show the larger flexural response of specimen 3K, which, when matched with the results presented in figure 7, confirm the effectiveness of the external reinforcement matrix (specimen 3F) at reducing movement, even during high-intensity simulations.



FIGURES 8A AND 8B Specimen 3A during simulation S6 (75%): horizontal flexure of top of "long" wall (a), and vertical flexure at midspan of long wall (b) (time: 19.35–19.47 sec.).



FIGURES 9A AND 9B Specimens 3A and 3F during simulation S6 (75%): horizontal flexure of top of long wall for specimen 3A (a) and specimen 3F (b).



FIGURES 10A AND 10B Specimens 3F and 3K during simulation S8 (125%): horizontal flexure of top of long wall for specimen 3F (a) and specimen 3K (b).

Failure Mechanisms

The observed damage patterns can be attributed to the following factors:

a. Flexure induced in the out-of-plane long wall, causing a splitting-crushing cycle at the midspan of the wall and the intersection with the orthogonal shear wing walls (see figs. 8–10).
b. Large relative displacement between the "flexible" out-of-plane long wall and the stiff in-plane shear wing wall, leading to tearing failure of both the mortar-brick interface and the individual brick units at the corner intersection (vertical corner cracking).
c. Vertical flexure and overturning of the out-of-plane long wall leading to horizontal cracking, and contributing to diagonal cracking, in combination with the horizontal flexure.

Model House 4A

Model house 4A was subjected to a series of time-scaled shake table tests of increasing intensities (10%, 25%, 50%, 75%, 100%, 125%, 100% of the displacement time history); this procedure was followed by a "shakedown," which involved subjecting the specimen to approximately ten minutes of sinusoidal shake table motions, covering a range of frequencies (1–20 Hz) and displacements (1–30 mm, or 0.04–1.17 in.), in an effort to identify the resonant frequencies of the damaged house and shake the house to pieces.

Observations

Initial, minor cracking occurred during simulation S4 (75% intensity), with hairline cracking evident above the lintel in the east shear wall. (Recall that the unreinforced U-shaped wall panel 3A was severely damaged during a 75% intensity simulation—see fig. 3.) Damage of model


(a)


(b)

FIGURES 11A AND 11B Model house 4A: damage after simulation S8 (shakedown). The south wall (a) and the east wall (b) are shown.

house 4A increased during subsequent simulations. Figures 11a and 11b show the condition of the house after simulation S8 (shakedown). Despite being severely damaged, the structure resisted collapse, even after the series of severe earthquake tests.

The reinforcement system acted as a netting to contain the structure, even after significant damage. Cracking was distributed around the structure, with major damage occurring around the window and door openings. Vertical cracking at the corner intersections was largely prevented. This represents a major positive outcome, as one of the main failure modes of adobe houses is vertical corner cracking, which often results in the overturning of the walls and the collapse of the roof (as discussed above). There was no evidence of failure or breaking of the bamboo, string, or wire during testing.

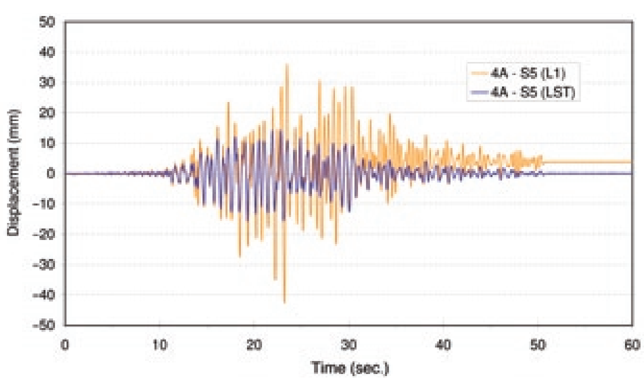


FIGURE 12 Model house 4A: absolute displacement of top NE corner (L1) and ST (shake table) for simulation S5 (100%) (peak displacements: L1, 58.79 mm, or 2.29 in.; ST, 19.12 mm, or 0.75 in.).

Displacement

Figure 12 shows the response at the top northeast corner (L1) of the model house, plus the movement of the shake table (LST) during simulation S5 (100% intensity). The graph clearly shows the amplification of the response at L1, due largely to the presence of the door in the east shear wall.

Flexural Response

Figure 13 shows a snapshot of the relative horizontal and vertical flexure of the north wall. The snapshot corresponds with the peak response at L1 (top, northeast corner) and clearly shows the significant movement at the east end of the wall and the stability at the west end. This large difference is due to the influence of the door opening in the east shear wall, which was significantly less stiff than the opposite west shear wall (without penetration). This difference in response had a significant effect on the entire structure, with the introduction of severe warping (combination of horizontal and vertical flexure) in the house.

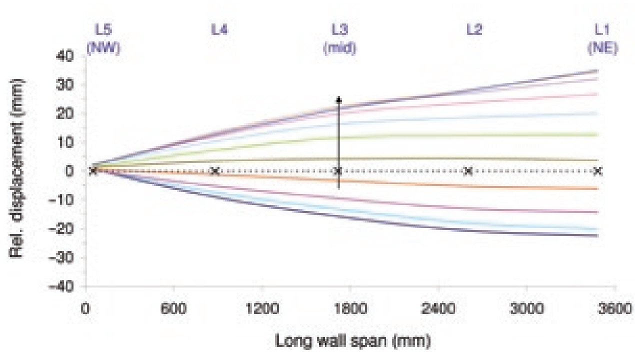


FIGURE 13 Model house 4A during simulation S5 (100%): horizontal flexure of top of north wall (time: 26.72–26.95 sec.).

Conclusion

The successful testing and analysis of ten U-shaped adobe wall units revealed the following general outcomes:

a. 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.
b. Test results confirm the importance of appropriate time scaling of input time history to induce damaging conditions in a structure. Time scaling is also necessary to ensure dynamic similitude among specimens, such that accurate comparisons may be made among the performances of different specimens.
c. The dynamic testing and assessment proved both reinforcement systems (3F and 3K) to be effective at improving the seismic capacity of adobe mud brick U-panels. Although significantly damaged after the rigorous testing program, both wall units resisted collapse. Overall, specimen 3F performed significantly better, maintaining dynamic stiffness at lower-intensity simulations and exhibiting less relative wall movement and more even distribution of cracking. By contrast, the loss of stiffness of specimen 3K at the lower-intensity simulations, plus the major failure in the wing wall, indicate a generally weaker and more vulnerable structure. In addition to the superior dynamic performance of specimen 3F, a major advantage of the system is the relative simplicity of construction, which makes it a more appealing reinforcement alternative.

The dynamic testing of model house 4A confirmed the efficacy of the reinforcement system used in U-shaped wall panel 3F. Results indicate that a major improvement in the earthquake resistance of adobe mud brick structures can be obtained by using external vertical bamboo reinforcement, external horizontal wire reinforcement, and a timber ring beam. These additions, when securely tied together, create an integrated matrix that restrains movement and enhances the overall strength of the structure. The model house performed extremely well, even during repeated high-intensity shake table simulations, with catastrophic failure and collapse prevented in all cases. The proposed system is effective, simple, affordable, and widely adaptable to a variety of materials and local conditions. It can be used for the retrofit-strengthening of existing structures, as well as for new-build construction.

The proposed reinforcement system was recently incorporated in an existing adobe dwelling in rural El Salvador. The retrofit-strengthening procedure was undertaken by two people in one week, with material costs of fifty U.S. dollars and equipment costs also totaling fifty U.S. dollars. This represents a substantial improvement on previously proposed reinforcement systems and paves the way for wide-scale implementation.

Acknowledgments

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