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SEISMIC TESTING ON SMALL SCALE MODELS OF ADOBE HOUSES

E. Leroy Tolles[1] and Helmut Krawinkler[2]

[1] PhD. Candidate, Deptartment of Civil Engineering,
Stanford University, Calif., USA

[2] Professor, Department of Civil Engineering,
Stanford University, Calif., USA

SUMMARY

This paper presents a summary of results from shaking table tests of 1:5 scale models of adobe houses at Stanford University. The purpose of these tests is to study the dynamic behavior of Low Strength Masonry (LSM) buildings and to evaluate the relative benefits of simple Structural Improvement Techniques (SIT's) designed to prevent collapse during strong ground motion. The program included materials testing and shaking table tests on six scale models. Both bond beams and anchored roof beams significantly improve the dynamic stability of these buildings by preventing wall overturning which was the mode of failure in most of the models.

INTRODUCTION

The failure of LSM buildings is responsible for the majority of lives lost during earthquakes. LSM is also the world's most common building material and is frequently used in many areas of high seismicity. Adobe, or mud brick, construction is probably the most common type of LSM material. Despite its poor performance during seismic events, houses throughout the world will continue to exist and to be built with LSM for a number of socio-economic reasons. The primary purpose of this study is to analyze the behavior of LSM buildings subjected to earthquake motions and to assess the relative effectiveness of inexpensive improvements techniques. The specific objectives of the study are (a) to explore the possibilities and limitations of reduced scale mode testing, (b) to evaluate the problems of dynamic similitude and material simulation in small-scale models, (c) to study the dynamic response of simple adobe house configurations and (d) to assess the relative effectiveness of several simple SIT's in the seismic behavior of adobe houses.

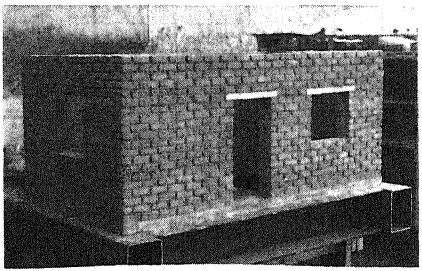


Figure 1: Photograph of Model Structure

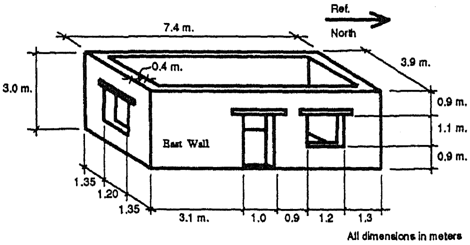


Figure 2: Prototype Structure

To fulfill these objectives, a series of six 1:5 scale model buildings were constructed and tested on the shaking table at Stanford University. The investigation included a materials testing program designed to assess the use of adobe in reduced-scale models and to find a model adobe material that would simulate 'average' adobe.

MATERIALS TESTS

The adobe material used in the study was fabricated by mixing a well-graded sand with a commercially available clay using a 5:1 ratio of sand to clay. The prototype material properties were based upon an average adobe material as determined by a study conducted at the National University of Mexico(ref. 1). These properties are based upon the strength of brick-mortar assemblies tested in compression, diagonal tension and flexure about both the horizontal and vertical axes of the walls. The comparison of the material strengths between the prototype and the model assemblies, Table 1, shows adequate correlation between the model and prototype material strength properties although the model material behaved more monolithically than the prototype.

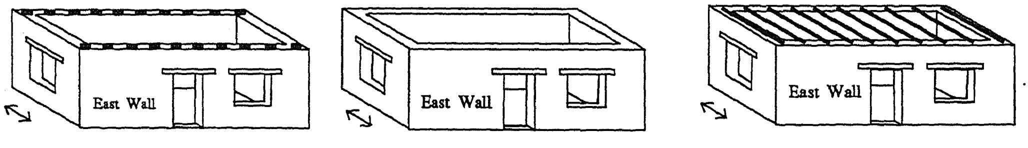
Table 1: Comparisons of Prototype and Model Assembly Strength Properties

Type of Test		Stress (psi)	(kg/cm2)
Compression	Prototype	192	13.5
	Model	135	9.8
Flexure #1 (vertical axis)	Prototype	37.0	2.6
	Model	39.2	2.8
Flexure #2 (horizontal axis)	Prototype	N.A.	N..A.
	Model	20.8	1.5
Diagonal Tension	Prototype	19.0	1.3
	Model	24.4	1.7

(N.A. = data not available)

DYNAMIC TESTS ON SCALE MODELS

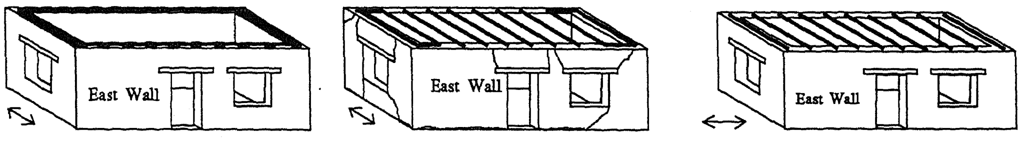
Introduction The six model buildings used in the testing program are shown in Figure 3. The prototype structure was again based upon the previous study on adobe houses conducted in Mexico(ref. 1). Structure #1 was designed to simulate an adobe house with a six inch earthen roof. Lead weights were anchored to the top of the wall to simulate the roof weight. Structure #1 was used as the base building for the study to which improvements were made.



a) Structure #1
Roof Weights

b) Structure #2
No Roof Weights

c) Structure #3
Anchored Roof Beams



d) Structure #4
Bond Beam

e) Structure #5
Repaired Building

f) Structure #6 (same as #3 but tested parallel to long axis)

Figure 3: Six Model Adobe Structures

Structure #2 was built to simulate a building in which the heavy earthen roof had been replaced by a lightweight roof. The roof weights were removed. Structure #3 had the same roof weight as the first building but roof beams were added which were securely anchored to the tops of the walls. Structure #4 is identical to #1 except a wood bond beam was added at the roof level. Structure #5, a previously damaged building, was repaired by filling large cracks with adobe mortar and adding anchored roof beams and ties to stabilize the end walls. Each of these building was tested with the shaking table motion perpendicular to the long axis of the building. Structure #6 was the only building in which the table motion was parallel to the long axis of the structure. This building was identical to Structure #3 in all other respects.

Model Similitude The buildings in this study were designed to satisfy the requirements of dynamic testing for models which neglect the simulation of gravity forces (ref 2). This type of model was used because the buildings have a uniformly distributed mass, which is difficult to simulate in scale models, and are single story which reduces the effects of gravity loads(ref 3).

Modal Analysis The modal shapes and frequencies for the first four model buildings are shown in Figure 4. The modal frequencies were determined experimentally. A grid of points was placed on the building and an impact hammer was used to excite the structure at different points on the grid. An accelerometer was mounted at one of the grid points. The set of transfer functions between the impact load and the accelerometer was then used to determine the frequencies and mode shapes.

A Finite Element (FE) modal analysis was also performed. There was very good agreement between the experimental and FE mode shapes and frequencies. The modal shapes shown in Figure 4 were generated from the FE simulation.

Shaking Table Test Procedure Each of the six model buildings was tested on the shaking table at Stanford University which can

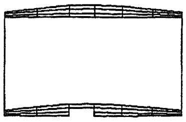
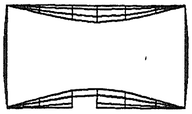
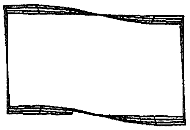
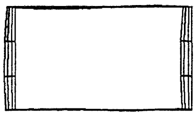
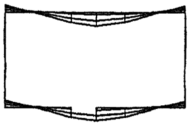
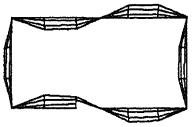
Mode	Struc.	Frequency	Mode Shape (Plan view)
1	#1:	6.3 Hz.	
	#2:	7.2 Hz.	
	#3:	6.2 Hz.	
	#4:	6.4 Hz.	
2	#1:	8.8 Hz.	
	#2:	10.4 Hz.	
	#3:	N.E.	
	#4:	8.4 Hz.	
3	#1:	10.4 Hz.	
	#2:	11.4 Hz.	
	#3:	9.8 Hz.	
	#4:	10.2 Hz.	
4	#1:	N.A.	
	#2:	N.A.	
	#3:	11.2 Hz.	
	#4:	N.A.	
5	#1:	13.0 Hz.	
	#2:	14.0 Hz.	
	#3:	12.4 Hz.	
	#4:	11.8 Hz.	
6	#1:	18.6 Hz.	
	#2:	20.8 Hz.	
	#3:	N.E.	
	#4:	18.8 Hz.	

Figure 4: Mode Shapes

N.A. = mode not observed; N.E. = mode does not exist

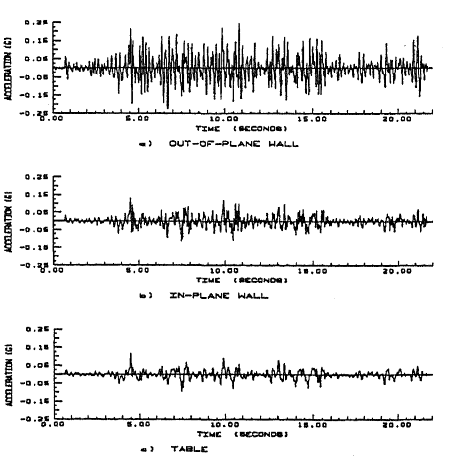


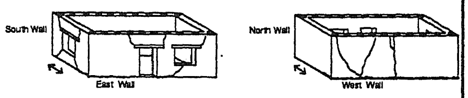
Figure 5: Typical Wall and Table Accelerations

reproduce only uniaxial horizontal motion. The input motion was the N21E component of the Taft Earthquake recorded on July 21, 1952 in Kern County, California.

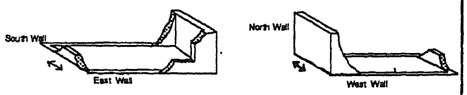
The models were first tested at low levels to study their elastic, dynamic behavior. Next, each structure was subjected to a series of increasing table motions with each succeeding test approximately 30 percent larger than the previous test. Comparisons of the severity of the shaking table motions are based upon an "Effective" Peak Ground Acceleration, EPGA (ref. 3). The models were instrumented to record the accelerations and relative displacements at the top center of each of the four walls in the direction of the table motion.

Results of Shaking Table Tests Figure 5 shows typical acceleration records for low-level tests. The in-plane walls, parallel to the table motion, followed the table motion very closely having a Dynamic Amplification Factor (DAF) between 1.2 and 1.4. The out-of-plane walls showed significant amplification; the response was dominated by excitation of the first and/or second modes having DAF's between 2 and 3. The long wall with the openings had higher accelerations and larger displacements than the long solid wall in each of the first five structures.

A brief pictorial summary of the damage from subsequent shaking table tests are shown in Figures 6 to 11. In each figure, the upper drawing shows the damage after tests of intermediate severity. The EPGA of the test that caused the damage is shown in the caption below each drawing. The lower part of each figure shows the damage after Test #7 which was the test during which the models either collapsed or were very severely damaged.

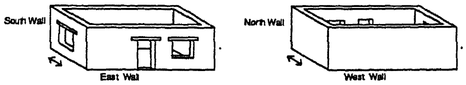


a) Damage after Test #5 (0.26 g)

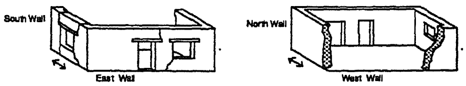


b) Damage after Test #7 (0.42 g)

Figure 6: Damage to Structure #1

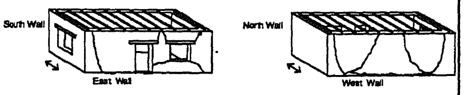


a) No Damage after Test #6 (0.32 g)

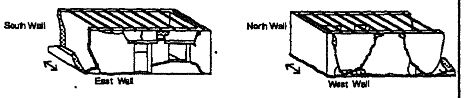


b) Damage after Test #7 (0.42 g)

Figure 7: Damage to Structure #2



a) Damage after Test #4 (0.23 g)



b) Damage after Test #7 (0.42 g)

Figure 8: Damage to Structure #3

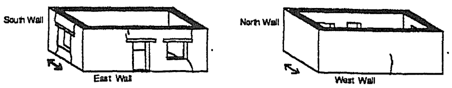
The damage to structure #1 began on Test #4 (0.23 g) with a very small crack over the doorway. The damage after Test #5 (0.26 g) is shown in Figure 6(a). During test #7 (0.42g) three of the four walls collapsed. The collapse of Structure #2 also occurred on Test #7 (0.42 g) although no previous damage had been observed. The west wall overturned and the east wall nearly collapsed.

Structure #3 developed substantial damage after Test #4 (0.23 g) as shown in Figure 8(a). The damage was only slightly worse after the following two tests. After test #7 (0.42 g) , the two long walls were still standing but the south wall collapsed perpendicular to the table motion. Structure #4, with the bond beam, developed cracking after Test #5(0.26 g). Because of the bond beam, relatively small cracks occurred in the long walls. The load was forced into the end walls causing greater cracking in the short wall with openings. The building was first to survive Test #7 (0.42 g) and continued standing through Test #8 (0.49 g). Test #9 (0.54 g) caused complete collapse.

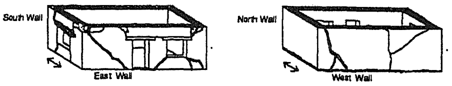
The repairs to Structure #5 proved very effective. Cracking developed early along the same lines as the pre-existing damage. This was the second model to withstand Test #7 (0.42 g) and continued until collapse in Test #9 (0.54 g) . The anchored roof beams provided surprisingly good resistance to overturning of the long walls and the ties across the corners provided sufficient continuity to prevent collapse of the short transverse walls, as observed in Structure #3. Although Structure #6 was tested in the longitudinal direction, this model nearly collapsed after Test #7 (0.42 g). It did collapse at the beginning of the following test.

The drawings in Figure 12 and 13 summarize some of the results of the test. Figure 12 has plots of the EPGA versus the peak displacement. The lines with arrows indicated which walls have collapsed. The plots show the failure of three of the four walls in Structure #1 while only the south wall failed in Structure #3 during the test of the same severity. The plots show that both Structure #4 and #5 were able to withstand larger displacements without collapsing during more severe tests. The improvements to the latter buildings provided them with some amount of 'ductility.'

Figure 13 is a plot of the EPGA versus a subjectively evaluated Damage Index. The plot shows that Structures #1 and #3 cracked earlier but collapsed during the same test as Structure #2. Both Structure #4 and #5 were able to withstand larger ground motions without failure.

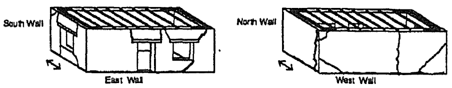


a) Damage after Test #5 (0.26 g)

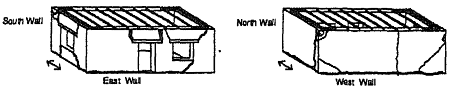


b) Damage after Test #7 (0.42 g)

Figure 9: Damage to Structure #4

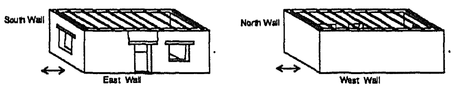


a) Damage after Test #5 (0.26 g)

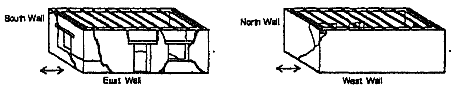


b) Damage after Test #7 (0.42 g)

Figure 10: Damage to Structure #5



a) Damage after Test #5 (0.28 g)



b) Damage after Test #7 (0.42 g)

Figure 11: Damage to Structure #6

CONCLUSIONS

The principal conclusions of this study are:

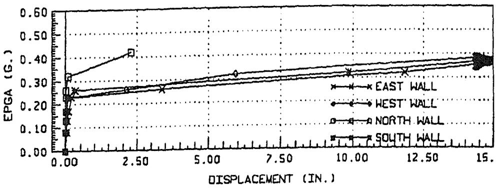
1. To fully understand the behavior of LSM buildings during large seismic events, it is necessary to test these buildings to collapse.
2. The severity of ground motion which causes first damage cannot be correlated to the severity of motion which will cause collapse.
3. The most important aspect of the improvements used on the buildings in this study was the prevention of wall overturning.
4. Both bond beams and anchored roof beams significantly improve the dynamic stability of adobe houses. Each of these improvements help prevent wall overturning. Bond beams also strengthen the walls after cracking has occurred.
5. If a building is repaired such that overturning of the walls is prevented, pre-existing structural cracks do not necessarily reduce the severity of ground motion at which collapse occurs.

BIBLIOGRAPHY

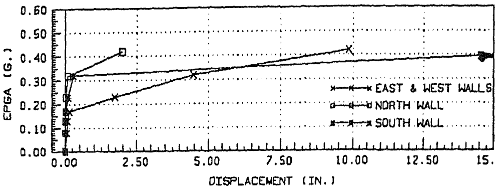
1. Hernandez, O., Meli, R., and Padilla, M.,(1980), " Strengthening of Adobe Houses for Seismic Actions," Proceedings of the Seventh World Conference on Earthquake Engineering, pg. 465-472.

2. Moncarz, P.D. and Krawinkler, H., Theory and Application of Experimental Model Analysis in Earthquake Engineering, (John A. Blume Earthquake Engineering Center, Department of Civil Engineering, Stanford, Calif., June 1981), Report No. 50

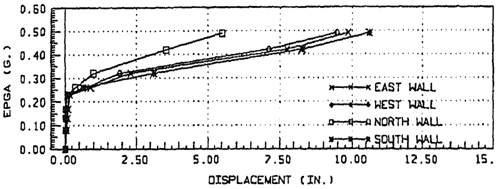
3. Tolles, E.L. and Krawinkler, H. "Performance Evaluation of Adobe Houses through Small-Scale Model Tests on a Shake Table," Proceedings of Middle East and Mediterranean Regional Conference on Earthen and Low-Strength Masonry Buildings in Seismic Areas (Middle East Technical University, Ankara, Turkey, Sept. 1986).



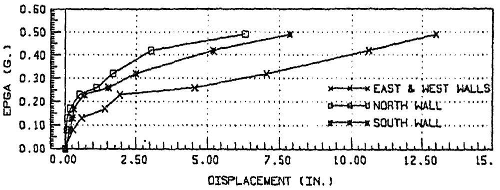
a) STRUCTURE #1



b) STRUCTURE #3



c) STRUCTURE #4



d) STRUCTURE #5

Figure 12: EPGA vs. Maximum Displacement (Arrows indicate a collapsed wall)

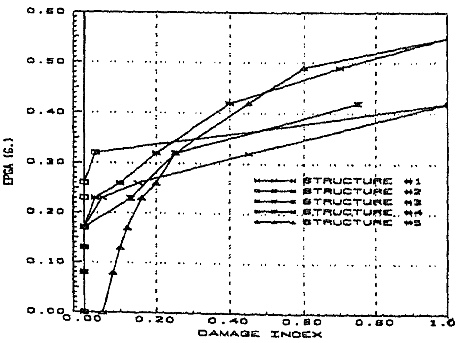


Figure 13: EPGA vs. Damage Index