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SHAKING TABLE TESTS OF IMPROVED ADOBE MASONRY HOUSES

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SUMMARY

The main results of an experimental research project in adobe earthen buildings are presented in this paper. The objective was to determine the influence of improved construction techniques and reinforcement on the seismic behavior of adobe buildings. To fulfill these objectives, eight full-scale adobe housing modules representing one story rural dwellings, were tested on the shaking table at the Structures Laboratory of the Catholic University of Peru (PUCP), under simulated seismic base motions derived from the acceleration record registered in Lima-Peru during the May 1970 earthquake.

INTRODUCTION

Adobe is used for shelter by a large percentage of the developing countries population. In Peru (Ref. 1), 65% of the rural population and 37% of the urban population are estimated to live in earth constructions. The advantages of adobe dwellings are: low cost, easy availability, good thermal and heat insulation and the possibility of its production by unskilled owners (self-construction). However, adobe and others earth constructions often exhibit poor construction techniques and lack of reinforcement; for this reason, much of the death, injury and material looses caused by earthquakes occur because the collapse of earth buildings.

The first step towards improvement of the seismic safety of adobe and other earthen buildings is to understand the structural behavior of these constructions during seismic excitations. It is recognized (Ref. 2) that one of the most adequate way to study the seismic performance of adobe buildings is through full-scale dynamic tests. For these reasons, this research project consisted mainly on dynamic tests of adobe modules, in order to determine experimentally the influence of materials, reinforcing, roofing and improved construction techniques on seismic performance of adobe houses.

FULL SCALE MODULES

Eight full-scale adobe house modules named M1 through M8 were designed and constructed for dynamic testing on the shaking table. Traditional and improved construction technologies were used. All the modules had the same dimensions (3.25 x 3.25 x 2.40 m) and the location and size of openings were a window in the

longitudinal (parallel to table motion) walls and a door in one of the transverse walls; the only exception were modules M6 and M7 that had no windows. Symmetry was sought in all the modules to avoid torsional effects during shaking. Each module was built over a reinforced concrete foundation beam, designed to transport and connect the module to the shaking table.

Adobe bricks and mortar were made with soil from the PUCP campus, which is a low plasticity clay.

The main characteristics of the modules are summarized in Table 1. The improved construction technology differs from traditional by the use of stronger adobe units and the addition of straw and coarse sand to the mud mortar in order to reduce cracking due to drying shrinkage. Reinforcement technique consisted of an interior cane mesh plus a crowning tie beam on top of the walls, made of eucalyptus trunks. Fig. 1 shows the cane mesh.

Module M8 had not horizontal cane reinforcement, in an attempt to simplify the construction process, since the placement of this reinforcement is cumbersome.

The eight modules had the same type of roof, made of eucalyptus beams, cane and mud. Fixing of the roof to the walls varied, since modules M1 and M2 did not use a crowning tie beam; in these modules, roof beams rested directly over the walls. In the other modules, roof beams were fixed to the crowning tie beam. An overall view of a typical module is shown in Fig. 2.

It must be noted that modules M1 and M3 -built with traditional construction technology- showed heavy cracking in the mortar due to drying shrinkage. The same phenomenon was almost imperceptible in the other modules.

Immediately after the construction of each module, a series of small specimens was prepared using the same materials and technique as its corresponding module. These specimens were used in static tests to determine characteristic properties of the materials used in the modules and to correlate them with previous research.

TEST PROGRAM

The PUCP 4.4 x 4.4 m. shaking table is designed to move in one horizontal direction only. Specifications for maximum displacement, velocity and acceleration are $\pm$ 150 mm, $\pm$ 500 mm/sec and 1 g, respectively. Maximum specimen weight is about 160 kN.

The table displacement command signal was derived from the strong motion record of the longitudinal component of May 31, 1970 earthquake, registered in Lima at the Geophysics Institute of Peru (Ref. 3). This is a typical record of earthquakes registered on the stiff soil conditions of Lima. The strongest part of this record was filtered and scaled according to performance specifications of the seismic simulator.

Each module was subjected to a series of shaking table motion (Runs) with increasing amplitude. The sequence of motions was basically the same for all the modules, beginning with a very mild movement, and increasing the intensity of shaking until failure of specimen was evident due to partial or total collapse. The sequences of table movements are listed in Table 2. Before each table movement, a free vibration test was performed, using a low amplitude square wave as the table command signal. Accelerations and displacements were registered with transducers placed on the modules and on the table as shown in Fig. 2.

Intensity of each table Run is shown in Table 2, and can be compared with those of some well known earthquakes (Ref. 4). As an example, for the El Centro 1940 earthquake, the total destructiveness potential factor (DP) is 84 mm.sec and the total Arias Intensity is 3367 mm/sec, both lower than those corresponding to table Runs 4, 5 and 6.

Fig. 3 shows typical displacement and acceleration time histories from the shaking table; these correspond to a movement with a maximum amplitude of 80 mm. Records from different table Runs differ only in displacement amplitude and maximum acceleration, without noticeable distorsion of the waveform. Acceleration response spectrum, normalized to the maximum table acceleration, is shown in Fig. 4.

OBSERVATIONS AND INTERPRETATION OF DATA

Unreinforced modules were subjected to Runs 1 to 4a; they showed the typical behaviour of traditional adobe houses subjected to severe ground shaking. Vertical cracks developed at the corners, isolating the walls, and the structures collapsed. Damages were already important in Run 4. Photo 1 shows the unreinforced module M1 after the test.

The reinforced modules showed a completely different behavior; even though they were subjected to stronger shaking (Run 5), integrity of the structure was maintained by the reinforcement and collapse was avoided. Photo 2 shows the reinforced module M4 after Run 5. The crowning tie beam and cane mesh maintained the walls together. Most of the damage was concentrated on the lateral walls (parallel to table movement), and the cracks began at the corners of the window openings. Module M3, although exhibited a poor masonry work, had a much better behavior after cracking than the unreinforced modules. In contrast, module M8, without horizontal reinforcement, collapsed in Run 5.

Pattern of cracks differed greatly between traditional and improved masonry. In modules with traditional technology, the cracks follow the weak zones between adobes, caused by the already existing cracks due to shrinkage of the mortar. In the modules with improved technology, cracking occurred suddenly and it followed a diagonal pattern typical of shear failures.

Peak values of seismic coefficient on the modules, shown on Fig. 5, are significantly different between modules, even though shaking table movement was very similar. Up to Run 3, reinforcement had no influence on the level of maximum seismic coefficient. On Run 4, differences between modules with improved and traditional technology are very important, regardless of the reinforcement; however, reinforcement is fundamental for the structure to withstand more severe shakings. This is noticeably in module M3 with traditional technology but reinforced, which could be subjected to Run 5.

Fig. 6 shows natural frequencies of the modules for each free vibration test. Natural frequencies did not change significantly during Runs 1 and 2. Run 4 causes an important reduction in natural frequency, indicating the presence of serious damage. It is clear that improved technology provides for higher stiffness.

Representative lateral displacement time histories for Run 4 are shown in Fig. 7. The effect of the reinforcement to control excessive displacements and permanent offset is noticeably.

Fig. 8 shows typical force-displacement relationships during Run 3. It can be seen that modules with traditional technology exhibit already large inelastic

deformation cycles, indicating the occurrence of damage and overall loss of stiffness; in contrast, modules with improved technology show higher lateral stiffness and lower energy dissipation. This indicates that improved technology provides for greater strength and stiffness than traditional technology, before cracking occurs. Up to Run 3, reinforcement has not significant influence on the stiffness and strength. However, the effect of reinforcement is noticeable after cracking; Fig. 9 shows force-displacement relationships during Run 4, and it can be seen that reinforcement helps to control excessive displacements, reducing damage and avoiding collapse caused by instability of loose adobe walls.

CONCLUSIONS

The difference in behavior between unreinforced and reinforced modules provides an excellent evidence that the interior cane mesh reinforcement, combines with a crowning tie beam at the roof level, greatly improve the seismic performance of adobe constructions. The need of placing horizontal reinforcement is confirmed by results from module M8, which completely collapsed in Run 5, while the other similar modules with horizontal and vertical reinforcement withstood this Run.

Improvement in the quality of materials and workmanship is effective to increase wall strength and stiffness, but it must be complemented by additional structural reinforcement, in order to prevent fragile collapse of the adobe buildings.

ACKNOWLEDGEMENTS

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Table 1. Main Characteristics of Modules
(x indicates presence of the corresponding characteristic)

Characteristic	M1	M2	M3	M4	M5	M6	M7	M8
Traditional technology	x	-	x	-	-	-	-	-
Improved technology	-	x	-	x	x	x	x	x
Horizontal reinforcement	-	-	x	x	x	x	-	-
Vertical reinforcement	-	-	x	x	x	x	-	x
Crowning tie beam	-	-	x	x	x	x	-	x
Windows	x	x	x	x	x	-	-	x

Table 2. Sequence of Shaking Table Movements

Run	Max. Table Disp., mm	Max. Table Accel., g	AI[1] mm/sec	DP[2] mm.sec	VO[3] 1/sec
1	10	0.10	193	2	9.8
2	20	0.21	791	9	9.4
3	40	0.46	3131	34	9.7
4	80	0.88	12294	156	8.9
4a	100	1.09	19068	251	8.7
5	120	1.36	26870	341	8.9
6	140	1.71	34815	482	8.5

1: Arias Intensity (Ref. 5).
2: Destructiveness Potential Factor (Ref. 4).
3: Intensity of zero crossings of the signal.

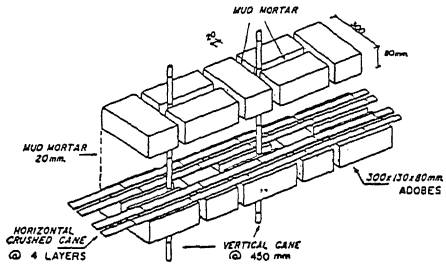

Fig. 1 Cane Reinforcement

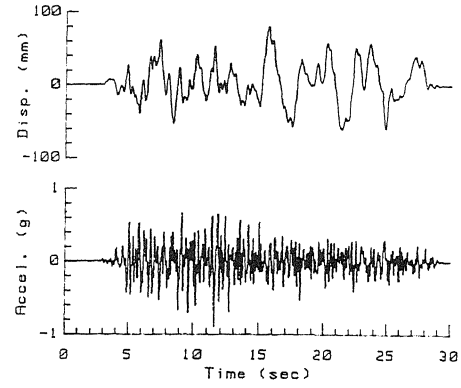

Fig. 3 Run 4. Table Movement

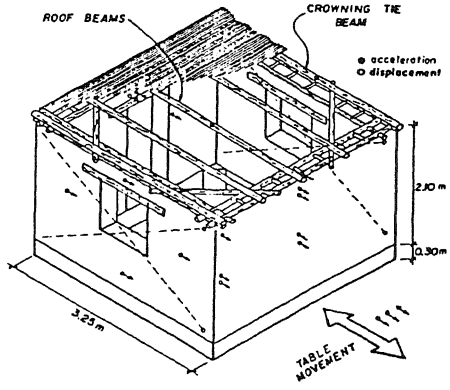

Fig. 2 Reinforced Module

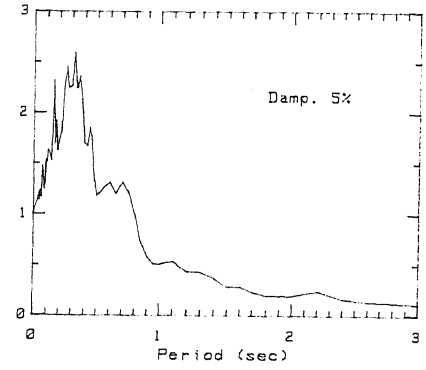

Fig. 4 Acceleration Response Spectrum

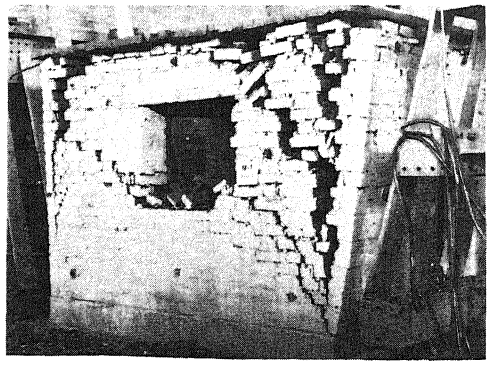

Photo 1 Module M1 After Run 4a

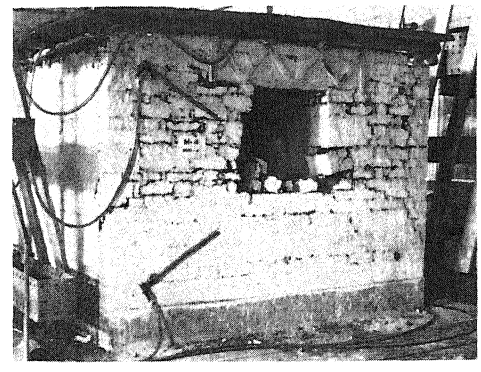

Photo 2 Module M4 After Run 5

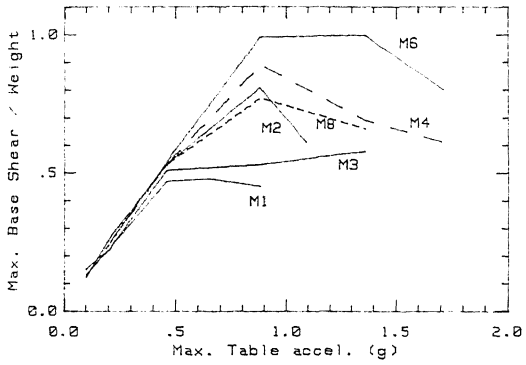

Fig. 5 Seismic Coefficient

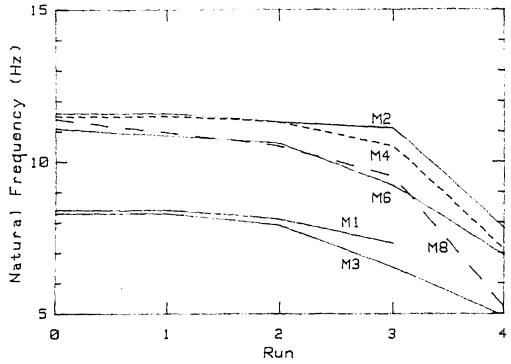

Fig. 6 Natural Frequencies

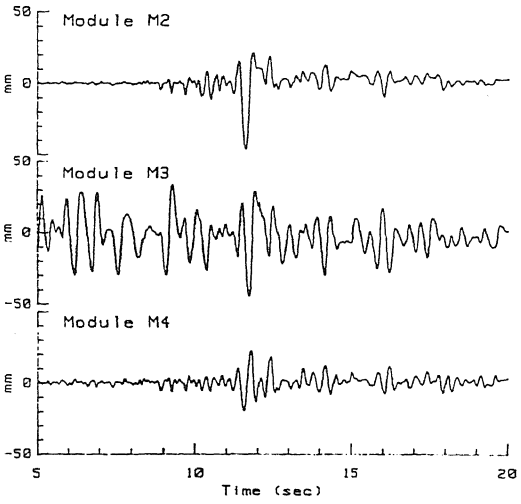

Fig. 7 Run 4. Lateral Displacement Shear Walls

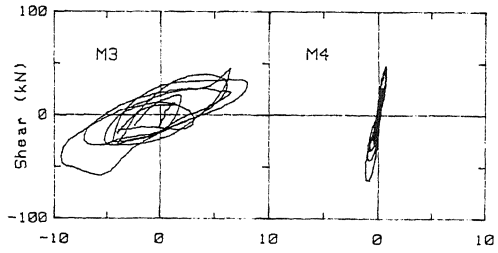

Fig. 8 Run 3

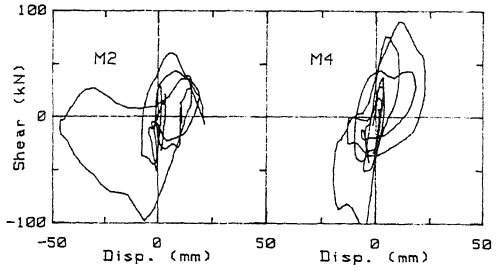

Fig. 9 Run 4. Base Shear - Lateral Displacement

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