Seismic Response of Fiber-Reinforced and Stabilized Adobe Structures

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Abstract: *Most losses of life and wealth in developing countries during earthquakes are due to the collapse of adobe houses. In spite of this, after considering different socioeconomic reasons and the availability of other alternate solutions, it is expected that these types of structures will continue to be built for the decades to come, especially in developing countries. Seismic deficiencies of adobe structures are caused by their inelastic and brittle behavior and by weakness of the mortar. Reinforcement for adobe structures should be inexpensive, locally available, and easy to construct. In this context, hemp, jute, and straw have been selected to improve the seismic resistance of adobe block. Cement has been selected to improve the strength characteristics of the mortar. Uniaxial test results showed that jute and straw effectively incorporate ductility in the adobe, but hemp is not effective to incorporate ductility in adobe. However, the strength of straw-reinforced adobe is significantly lower than that of jute-reinforced adobe. It means that jute is the best option among these fibers to improve the seismic performance. Adobe reinforced with 2% jute is the most effective to improve the seismic performance of adobe block. Jute length should be 1–2 cm (0.4–0.8 in.) for the best seismic performance. With the use of jute or jute and cement together, the strength of the mortar can be increased. Jute fiber is also effective to reduce cracking in the mortar. Shake table test results also showed that jute-fiber-reinforced adobe structures have the maximum seismic resistance.*

Introduction

Historically the use of adobe construction has many advantages, including low cost, easy availability, easy construction, low energy requirements, environmental friendliness, and comfort. It is estimated that about 50% of the population in developing countries lives in earthen houses (Houben and Guillaud 1994). This type of structure is common in developing countries such as Afghanistan, Bangladesh, Guatemala, India, Iran, Pakistan, Peru, and Turkey. Under favorable weather conditions (in climates of extreme dryness), these earth structures can be extremely durable. Unfortunately, they are very vulnerable to earthquakes. The February 22, 2005, Zarand earthquake and the December 26, 2003, Bam earthquake, both in Iran, bear ample testimony to this fact. While adobe structures cause most losses of human lives, relatively few published technical papers deal with this type of building. It is evident that technical solutions have to be developed to improve the seismic resistance of adobe structures.

Seismic behavior of adobe buildings is commonly characterized by a sudden and dramatic failure. From historical earthquake events it is estimated that the collapse of adobe structures is mainly due to the following three reasons: (1) adobe is a brittle material and has practically no tensile strength; (2) poor construction practices often decrease the bond between adobe and mortar, so that mortar partly or totally disintegrates under a few cycles of a moderate earthquake; (3) they are massive and heavy and thus they are subject to high levels of seismic force. Additionally, architectural concepts of the past have changed, and at present the typical thickness of adobe walls has been greatly reduced to make them externally similar to brick masonry. These factors, together with lack of maintenance, contribute greatly to increased adobe vulnerability.

Possibilities of using concrete beams, wooden beams, anchored roof beams, horizontal steel rods, welded wire mesh, steel mesh with cement mortar, and tensile steel bars to improve the seismic resistance of adobe structures have been investigated by various researchers (e.g., Torrealva Davila 1987; Scawthorn and Becker 1986; Tolles and Krawinkler 1990; Tolles et al. 2000). These methods were found to be effective to improve the seismic resistance of adobe structures; however, they can be expensive and they require skilled design and construction. In this context, natural fibers, such as straw, jute, and hemp, were selected as reinforcing materials to improve the seismic resistance of adobe block. Cement has been selected to improve the strength characteristics of the mortar. This paper describes the effectiveness of the proposed reinforcing materials to improve the seismic resistance of adobe structures. The seismic response of fiber-reinforced and cement-stabilized adobe structures is also presented.

Selection of Soils

Adobe can be made with many types of soil. Old adobe from Iran and Bangladesh was collected and the grain size distributions of the samples determined, in order to try to match the grain size distribution. The adobe from Iran was provided by the Iran Cultural Heritage Organization. The sample was taken from the ziggurat at Al-Untash-Napirasha, which was the capital city of the Elamite king Untash-Naprisha (ca. 1260–35 BC). The adobe from Bangladesh was collected from a fifty-year-old adobe building situated in the Comilla district of Bangladesh. Locally available Japanese soils were selected to prepare the adobe in the present research. Acadama clay, Toyura sand, and bentonite have been mixed with a ratio of 2.5:1.0:0.6 by weight. This mixture is called "soil-sand mixture" in this study. Grain size distribution of the soil-sand mixture along with those collected from Iran and Bangladesh are presented in figure 1. It is seen that the grain size distributions of the soil-sand mixture are similar to those of old adobe from Iran and Bangladesh. More details about the soil selection are available in Islam (2002).

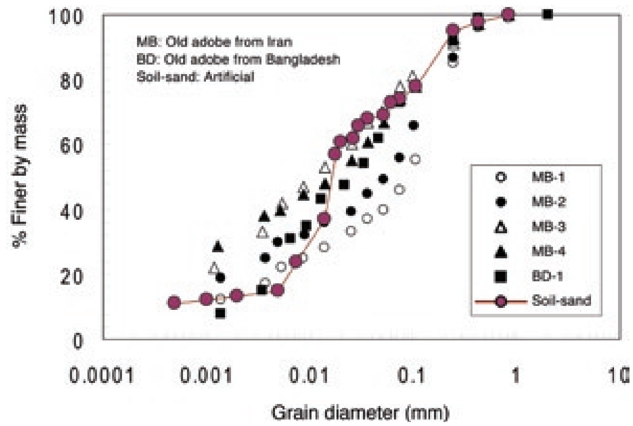


FIGURE 1 Grain size distribution of the soil-sand mixture.

Uniaxial Test

Uniaxial tests were conducted on several groups of cylindrical block and cylindrical sandwich specimens to investigate the effectiveness of the proposed reinforcing material on adobe block and mortar respectively. For each group, three specimens were tested to check the repeatability of the test results. Specimen preparation, characteristics of fiber-reinforced adobe, and the effect of fiber content and fiber length on adobe are presented in the following sections.

Preparation of Specimens

Specimens were prepared from soil-sand mixture, fiber, and cement. At first, water and soils were mixed vigorously so that a homogeneous mix was formed. The mix was then poured into a steel mold 5 cm (2.0 in.) in diameter and 10 cm (3.9 in.) in height in three layers. Each layer was compacted to remove the entrapped air. After that, the mold with the sample was kept in an oven at 60°C for three days. Finally, specimens were taken out from the mold and returned to the oven at the same temperature for three more days. Figures 2a–c show the details of specimen preparation using an oven.

Characteristics of Fiber-Reinforced Adobe

The effect of three different fibers—hemp, jute, and straw—on the seismic resistance of adobe material was investigated. In all cases, specimens were prepared by mixing the soil-sand mixture with 1.0% fiber (by weight) of 1.0 cm (0.4 in.) in length. Final water content and dry

(a) (b) (c)

FIGURES 2A–C Preparation of adobe specimens: soil-sand slurry (a); steel mold for specimen preparation (b); and oven used for drying specimens (c).

Table 1 Characteristics of unreinforced and reinforced adobe

Reinforcement	Final water content (%)	Dry density (g/cm^3)	Comp. strength (kPa)	Toughness (kPa)
Unreinforced	4.3–5.2	1.16–1.17	1177.8	10.09
Straw	5.3–5.6	1.05–1.11	585.6	8.26
Hemp	3.5–4.5	1.09–1.14	1058.3	8.48
Jute	5.3–5.8	1.14–1.15	996.3	15.93

density of the specimens are presented in table 1. From the table, it is seen that final water content and dry density of the specimens varied from 3.5% to 5.8% and from 1.05 to 1.17 g/cm^3 (65.5 to 73.0 lb./ft.^{3}), respectively. Figure 3 presents typical stress-strain relationships of reinforced and unreinforced adobe. It is observed that failure of unreinforced and hemp-reinforced adobe is brittle. But the failure of jute- and straw-reinforced adobe shows ductile behavior. However, straw-reinforced adobe has significantly lower strength than jute-reinforced adobe. More details about straw reinforcement for adobe are available in Islam and Watanabe (2001).

Toughness is a measure of the total energy that can be absorbed by a material before failure. To compare, toughness has been calculated using the area under the stress-strain curve under uniaxial test up to failure. Failure point was defined corresponding to the 2/3 q_u (where q_u is the compressive strength). Average compressive strength and toughness of the reinforced and unreinforced adobe are also presented in table 1. It is seen that jute-reinforced adobe has the maximum toughness. Thus, jute fiber is the best option among these three fibers for improving the seismic resistance of adobe material. Figures 4a and 4b show unreinforced and jute-reinforced specimens at failure, respectively.

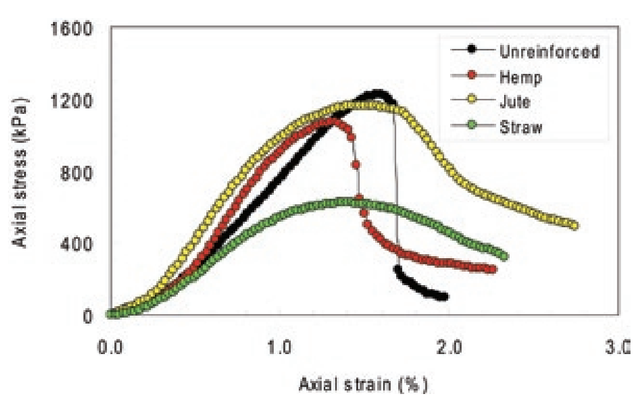


FIGURE 3 Stress-strain relationships of adobe.

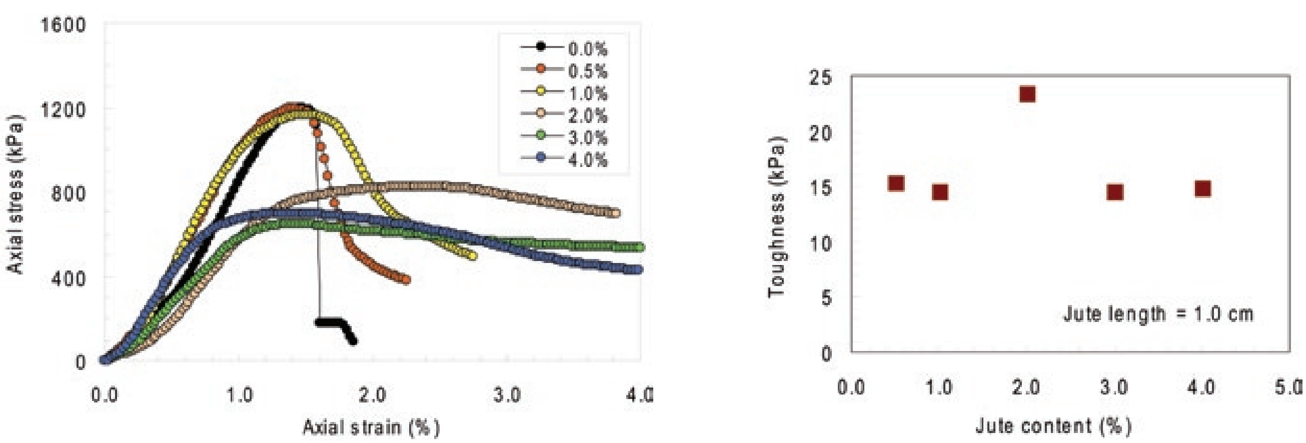
(a) (b) (c)

FIGURES 4A–C Failure pattern of reinforced and unreinforced adobe: failure of unreinforced adobe (a); failure of jute-reinforced adobe (b); detail of failure plane of jute-reinforced adobe (c).

Figure 4c is a detail of the failure plane of the jute-reinforced specimens. In this photograph, the action of the fiber can be seen clearly. It is clear that fiber resists the brittle failure of the adobe material.

Effect of Fiber Content

To investigate the effect of fiber content on adobe, specimens were prepared using 1.0 cm (0.4 in.) long jute by varying the jute content from 0.5% to 4.0% by weight. Final water content and the dry density of the specimens varied between 3.2% to 4.6% and 0.93 to 1.15 g/cm^3 (58.1 to 71.8 lb./ft.^{3}), respectively. Typical stress-strain relationships of jute-reinforced adobe have been presented in figure 5a. It is seen that the compressive strength of the specimens containing 2% to 4% jute is significantly lower than that of specimens containing 0% to 1% jute. But while the failure of the specimens containing jute up to 1% is brittle, the failure pattern of adobe reinforced with jute from 2% to 4% shows ductile behavior. Variation of toughness with jute content has been presented in figure 5b. It is observed that adobe reinforced with 2% jute fiber has the maximum toughness. Results indicate that 2% fiber is optimal for improving the seismic resistance of adobe material.



(a) (b)

FIGURES 5A AND 5B Typical stress-strain relationships of jute-reinforced adobe (a), and variation of toughness with jute content (b).

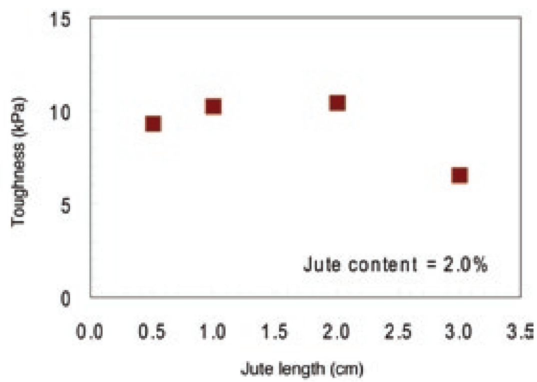


FIGURE 6 Variation of toughness with jute length.

Effect of Fiber Length

To investigate the effect of jute length on adobe, specimens were prepared using 2% jute and varying the jute length from 0.5 to 3.0 cm (0.2 to 1.2 in.). The variation of toughness with jute length is presented in figure 6. In this case, the toughness has been calculated using the area under the stress-strain curve until peak. It is observed that toughness of the material is almost the same in all cases, except in the case of 3.0 cm (1.2 in.) long fiber. Toughness of the specimens reinforced with 3.0 cm long fiber is significantly lower than that of other cases. From figure 6, it is also evident that jute length should be 1–2 cm (0.4–0.8 in.) to obtain the best seismic performance.

Mortar Strength

Past earthquakes showed that mortar is the weakest part of adobe structures. Cylindrical sandwich specimens were prepared to investigate the effectiveness of selected reinforcing material in improving mortar characteristics. Sandwich specimens were prepared cutting cylindrical specimens into two pieces at 60° to horizontal, since failure of specimens under uniaxial compression showed that specimens failed at 60°–70° to horizontal. Mortar of about 0.5 cm (0.2 in.) thickness was inserted between the two parts. The sandwich specimens were then kept in an oven at 60°C for three to four days for drying. Figures 7a–c show the details of the sandwich specimen preparation.

Composition of the sandwich specimens is presented in table 2. It is seen that in groups C-2 through C-4, the jute content was 1%, while the specimens of the C-5 group contain 2% jute in both the block and the mortar part. Table 2 also presents the mean compressive strength (q_u) and failure strain (ε_f) of the sandwich specimens. It is observed that the strength of the adobe material with mortar is significantly lower than that of the specimen without mortar (see tables 1 and 2). It is seen that mortar strength can be increased from 33.2 to 129.7 kPa (4.8 to 18.8 psi) using 1% jute in both the block and mortar. By using 1% jute in the block and 1% jute and 9% cement together in the mortar, the strength of the mortar can be increased from 33.2 to 196.1 kPa (4.8 to 28.4 psi). But in all of these cases, the strength is

(a) (b) (c)

FIGURES 7A–C Making of sandwich specimens: cutting of cylindrical specimens at 60° to horizontal (a); two parts of specimen after cutting (b); and a sandwich specimen (c).

Table 2 Characteristics of sandwich specimensw

Specimen designation	Reinforcement		Jute content (%)	Comp. strength q_u (kPa)	Failure strain ε_f (%)
	Block	Mortar			
C-1	—			33.2	1.10
C-2	Jute		1.0	68.1	2.13
C-3	Jute	Jute	1.0	129.7	2.71
C-4	Jute	Jute and cement	1.0	196.1	2.47
C-5	Jute	Jute	2.0	527.0	0.50

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significantly lower than that of the adobe block. From the test results of the group C-5, it is observed that by using 2% jute both in the block and the mortar, the strength can be significantly increased, up to 527.0 kPa (76.4 psi).

Figures 8a–e show the failure patterns of the mortar specimens. It is seen that in all cases, separation has occurred between the two parts during failure. However, in unreinforced cases, the mortar also failed. It is also seen that unreinforced mortar has many cracks. But mortar reinforced with cement and fiber does not have any cracks. These results indicate that jute, or jute and cement together, are effective in preventing cracks in mortar. Cracks in the mortar might be the reason for the low strength of the unreinforced sandwich specimens.

Shake Table Test

In the preceding sections, uniaxial compression test results have been presented to describe the effectiveness of the selected reinforcing material in improving the seismic resistance of adobe block and mortar. Shake table tests were also conducted to investigate the seismic performance of the fiber-reinforced and stabilized adobe structures. Shake table test results are provided below.

Construction of Models

Preparation of Adobe Block

For constructing models, adobe blocks were made first. Materials were mixed in dry condition, then water was added and the mixture was mixed vigorously by hand. The mix was poured into a steel mold 20 cm (7.8 in.) in length, 9 cm (3.5 in.) in width, and 10 cm (3.9 in.) in height. Blocks were kept in the steel mold to reduce the water content, so that blocks can stand without any support. After that, blocks were taken out of the mold and kept in the natural weather condition for approximately seven to ten days. Once the blocks were strong enough to handle, they were placed in an oven at 40°C for two

(a) (b) (c) (d) (e)

FIGURES 8A–E Sandwich specimens after failure; samples C-1 (a), C-2 (b), C-3 (c), C-4 (d), and C-5 (e) are shown.

(a) (b)

FIGURES 9A AND 9B Procedure for adobe model making. Models are placed in the oven (a), resulting in a finished adobe model (b).

days. Finally, the temperature of the oven was raised to 60°C until the blocks were dry.

Construction of Model

Each model was constructed using four blocks. At first, mortar of about 1–2 cm (0.4–0.8 in.) thickness was inserted between blocks. After that, the model was kept in an oven at 40°C for two days. Then the models were kept in the oven for two more days at 60°C. Details of adobe model making have been presented in figures 9a and 9b.

Description of Models

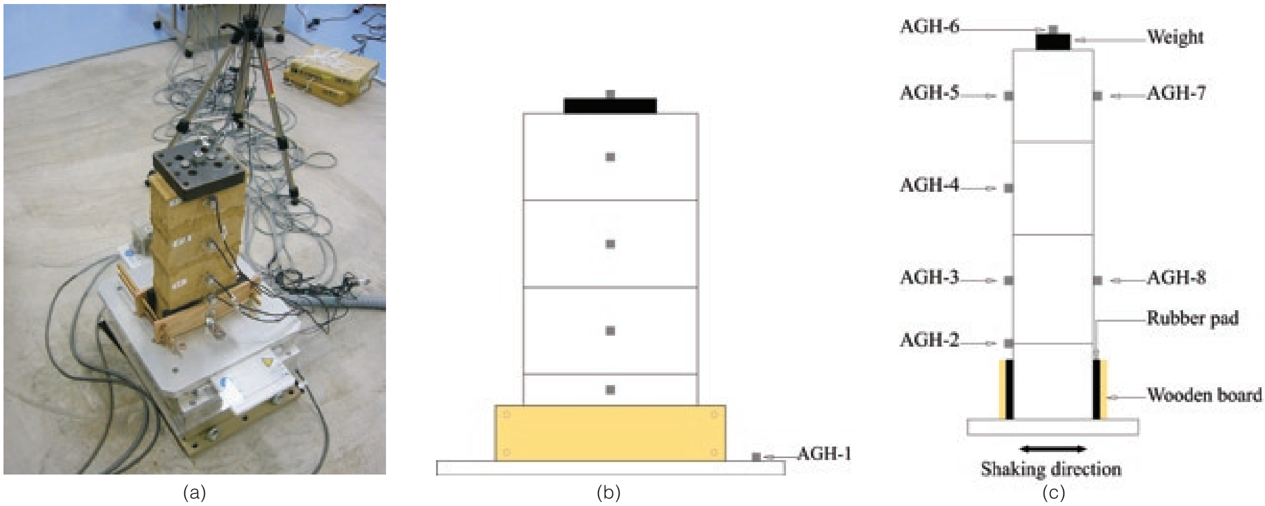
Five models were tested to check the effectiveness of the fiber and cement on the mortar characteristics. Dimensions of each model were about 20 cm (7.8 in.) in length, 9 cm (3.5 in.) in width, and 40 cm (15.6 in.) in height. Composition of the blocks and mortar of the models is presented in table 3. Soil composition of the blocks was soil-sand mixture (i.e., Acadama clay, Toyura sand, and bentonite mixed at the ratio of 2.5:1.0:0.6 by weight). From table 3, it is seen that all of the blocks of the models M-1, M-2, M-3, and M-4 were reinforced with jute. Blocks of all four models M1 to M4 contained 2% jute of 3.0 cm (1.2 in.) length; the blocks of the model M-5 did not have any fiber. Mortars of models M-1 and M-5 are unreinforced. Mortar of models M-2 and M-3 were reinforced with 2% jute and 9% cement, respectively, while the mortar of model M-4 was reinforced with 2% jute and 9% cement together.

Table 3 Composition of block and mortar of test models

Model	Block	Mortar
M-1	Jute	Unreinforced
M-2	Jute	Jute
M-3	Jute	Cement
M-4	Jute	Jute and cement
M-5	Unreinforced	Unreinforced

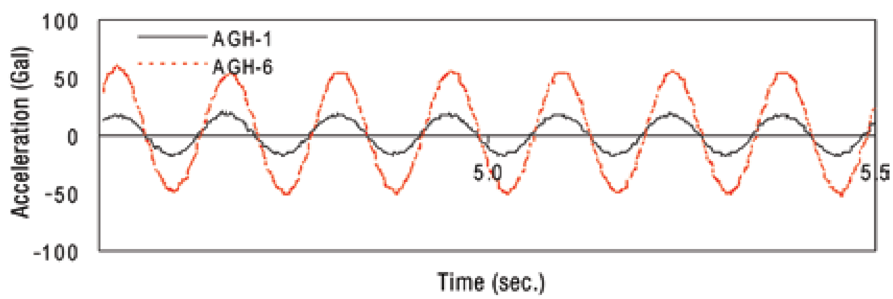
Instrumentation

The shake table available at the Vibration Engineering Laboratory of Saitama University, near Tokyo, Japan, was used to shake the models. The shake table has the capacity to give acceleration up to 1170 Gal (1.193 g). The maximum weight that can be shaken by this table is 20 kg (44 lb.). The frequency range of the table is 0.5–20 Hz. The maximum force that can be applied by the table is 294 N (30 kgf). Figures 10a–c show the instrument setup for the shake table test. Eight accelerometers of piezoelectric type were used to record the acceleration of the shaking models. Positions of the accelerometers (named AGH-1 to AGH-8) on the models are presented in figures 10b and 10c. AGH-1 was used to record the base acceleration. AGH-6 was put on the top of the model to record the acceleration at the top. An external weight of 4.0 kg (8.8 lb.) was fixed on the top of the model to represent the load on the wall. The base of the model was fixed to the table using a rubber pad, bolts, and wooden board, as shown in figures 10a and 10c. Models were shaken parallel to the shorter dimension. Figure 11 presents a typical recording of acceleration at the base and its response at the top of the model. Models were shaken using a sinusoidal wave of 7.0 Hz for 10.0 sec., with variance of the input base acceleration until failure, as shown in figure 11.



FIGURES 10A–C Instrument setup for shake table test: model with instruments (a); schematic diagram of front (b); and schematic diagram of side (c).

FIGURE 11 Typical input base acceleration and its response at the top.



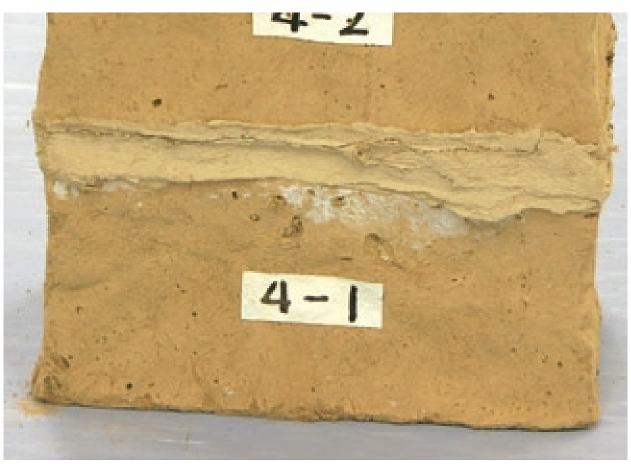


FIGURE 12 Model M-4 after failure.

Test Results

Description of Failure

All the models failed at the same level, at the top of the first mortar layer and the bottom of the second block. A photograph of the model M-4 after failure is presented in figure 12; the crack line can be seen clearly. Base accelerations that were observed at failure for each model have been presented in table 4. Description of failure and photographs of the failure surface are also presented in the table.

From table 4, it is seen that model M-1 failed at the base acceleration of 55.0 Gal (0.056 g). Separation occurred between the top of the first mortar layer and the bottom of the second block. Some parts of the mortar also failed. In the photograph, it is seen that there are many cracks in the mortar. However, there was no crack or damage to the blocks.

Table 4 Comparison among model performances

Model	Reinforcement: Block	Reinforcement: Mortar	Accel. (Gal)	Description of failure	View of failed surface
M-1	Jute	Unreinforced	55	Many cracks in the mortar; first mortar layer failed; no damage to the block; poor bonding between block and mortar in comparison to model M-5	
M-2	Jute	Jute	630	Separation between block and mortar; failure initiated from the second block; no significant damage to the block and mortar; strong bonding between block and mortar; failure plane is curved	
M-3	Jute	Cement	120	Cracks in the mortar; separation occurred; first mortar layer failed; no damage to the block; moderate bonding between the block and mortar	
M-4	Jute	Jute and cement	305	Separation between block and mortar; failure initiated from the second block; no significant damage to the block and mortar; good bonding between block and mortar	
M-5	Unreinforced	Unreinforced	180	Many cracks in the mortar; separation between block and mortar; bonding between block and mortar is moderate	

Model M-2 failed when the input base acceleration achieved 630.0 Gal (0.642 g). Failure initiated from the second block, as seen from the photograph in table 4, and failure was at the top of the first mortar layer. However, there was no damage to the block or mortar. There was no crack in the mortar of this model. This result indicates that jute fiber is effective in preventing cracking in the mortar.

Model M-3 failed at the top of the first mortar layer when the input base acceleration reached 120.0 Gal (0.122 g). Some parts of the mortar also failed, and there were many cracks in the mortar. However, cracks were fewer than in models M-1 and M-5.

Model M-4 failed at the top of the first mortar layer, as did the other models. This model failed at a base acceleration of 305.0 Gal (0.311 g). In this case, failure was also initiated from the second block. There were no cracks in the mortar. This indicates that jute and cement together are also effective in preventing cracks in mortar.

Model M-5 failed at the top of the first mortar layer when the base acceleration reached 180.0 Gal (0.184 g).

The failure occurred at the top of the first mortar layer and at the bottom of the second block. Separation between block and mortar occurred, and some parts of the mortar also failed. There were many cracks in the mortar.

Comparison Between Model Performances

From table 4, it is seen that the base acceleration at failure for model M-1 was 55 Gal (0.056 g), while for model M-5 it was 180 Gal (0.184 g). The difference between these two models is in the composition of the block only. The block of model M-1 contains jute, while the block of model M-5 is unreinforced. The shrinkage in the mortar and in the block was not the same, since the block had fiber but the mortar did not have any fiber. For this reason, there might be some gap between the block and mortar. Bonding between the block and mortar was poor. That is why the cohesion between the block and mortar of model M-1 is not as high as that of model M-5.

Model M-2 is the strongest among all the models. It contains fiber in both the block and the mortar. The bonding between the block and the mortar is very good. In the case of the sandwich specimens, it was observed that both the mortar and the block reinforced with 2% fiber were the strongest.

Model M-3 has cement in its mortar. It is stronger than model M-1 but weaker than the unreinforced one. In this case the bonding is not as good as in the case of model M-2. However, as the model was dried using an oven, the time might not be enough for the hydration of cement. This might be one reason for the lower strength of the model M-3.

Model M-4 failed at the base acceleration of 305 Gal (0.311 g). It is stronger than models M-1, M-3, and M-5. This means that the bonding between the block and mortar is better than that of these three cases. It is weaker than model M-2. It indicates that the use of jute alone is better than mixing jute and cement together. Also in this case, lack of hydration of cement might be one reason for lower strength.

The statistical uncertainty of using one sample of each type of model should be considered. Significant statistical uncertainty is inherent in any test when only one specimen is used, especially for soil materials. Another factor is that all the models were prepared using an oven, which constitutes a variation from the natural condition.

Estimation of Design Strength

Strength obtained from the uniaxial compression and shake table tests cannot be used directly for design purposes, because real structures are different in several ways—an example being openings in the wall construction. It is necessary to estimate the strength of the adobe material that can be used for design purposes.

Using the Mohr-Coulomb failure criterion, cohesion of an adobe model can be determined (assuming angle of internal friction, $\varphi = 0$) as stated in equation 1.

$$c = \tau = \frac{\sigma}{2} \tag{1}$$

where c is cohesion, τ is shear strength, and σ is axial stress, which can be determined as follows.

$$\sigma = \frac{F}{A}$$

where F is force, and A is the cross-sectional area of the failure surface. Force can be determined from equation 2.

$$F = mk \tag{2}$$

where $k = \frac{\alpha_f}{g}$ and m is the mass of the model above the failure line (see fig. 13).

Here, α_f is the base acceleration of the model at failure; g is acceleration due to gravity.

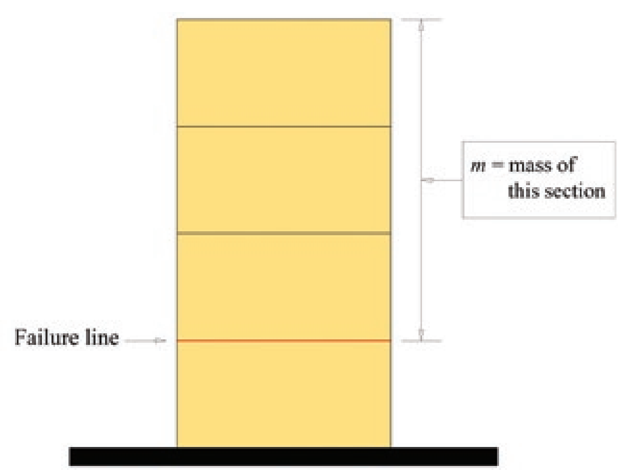


FIGURE 13 Description of mass used for calculating cohesion.

Table 5 Estimated design earthquake intensity of adobe walls

Model	Estimated base acceleration (Gal)	Earthquake intensity (JMA scale)	Earthquake intensity (MMI scale)
M-1	14.0	3	IV
M-2	161.0	5 Low–5 High	VII–VIII
M-3	30.5	4	IV–V
M-4	78.0	4–5 Low	VI–VII
M-5	44.7	4	V

Assuming failure of an adobe wall at the same level as indicated in figure 13, the design base acceleration (α_i) for the wall can be estimated from equation 3, using the cohesion value calculated from equation 1.

$$\alpha_i = \frac{2gcA}{m_i} \qquad (3)$$

where c is cohesion, m is mass of the wall above the failure line, and A is the cross-sectional area of the wall.

Estimated base accelerations of a 2.4 m (7.9 ft.) high wall for five cases are presented in table 5. From the table, it is seen that an unreinforced adobe wall can survive an earthquake of the intensity of 4 according to the Japanese Meteorological Agency (JMA) scale, and an intensity of V according to the Modified Mercalli intensity (MMI) scale. Adobe walls reinforced with jute fiber, in both the block and the mortar, can survive an earthquake of 5 Low to 5 High on the JMA scale, or VII to VIII on the MMI scale.

Cost of Reinforcement

The reinforcement cost for a two-room, typical adobe house (6.1 × 9.15 × 2.90 m, or 20 × 30 × 9.5 ft.), as described by Coburn and colleagues (1995), has been estimated. If an adobe house of this dimension is reinforced with 2% jute fiber in both block and mortar, the total cost of the reinforcement will be about thirty U.S. dollars. The unit price of jute was taken from the local market price in Bangladesh, where adobe houses are being used on a large scale and jute is also locally available.

Conclusion

Natural fibers and cement were selected as reinforcing material for improving the seismic resistance of adobe structures. From the uniaxial and shake table test results, the following conclusions can be drawn:

- Jute is effective for improving the ductility and toughness of adobe material. However, there is an optimal jute content (i.e., 2%) for the best performance. Jute length should be in the range of 1.0 to 2.0 cm (0.4 to 0.8 in.) for the best seismic performance of adobe material.
- The strength of adobe with mortar is very low. By adding 1% jute, the strength of the mortar can be increased from 33.2 to 129.7 kPa (4.8 to 18.8 psi). Again, using 1% jute and 9% cement together, the strength of the mortar can be increased from 33.2 to 196.1 kPa (4.8 to 28.4 psi). But by using 2% jute in both the block and mortar, the strength can be increased significantly, from 33.2 to 527.0 kPa (4.8 to 76.4 psi). Many cracks were observed in the unreinforced mortar. This might be the reason for the low-strength, unreinforced sandwich specimens.
- All the shaking models failed at the same level, at the top of the first mortar layer and the bottom of the second block. Shake table test results also showed that jute is the most effective among the selected reinforcing materials for improving the seismic resistance of adobe structures. A strong bond between the mortar and block in the case of the jute-reinforced sample is the reason for its best seismic performance. Adobe walls reinforced with 2% jute in both block and mortar can survive an earthquake up to VII–VIII on the MMI scale. In unreinforced cases, there are many cracks, and bonding between the block and mortar is poor. This might be the reason for poor seismic performance of unreinforced adobe walls.

Finally, it can be concluded that 2% jute is effective to improve the seismic resistance of adobe structures. The cost of jute reinforcement is about thirty U.S. dollars for a standard, two-room adobe house. Gross national income (GNI) data indicate that this cost of reinforcement can be afforded by the dweller of developing countries such as Afghanistan, Bangladesh, India, and Pakistan. However, in the current research, the adobe specimens, blocks, and models were dried in an oven—a factor that varies from natural conditions. This fact must be considered in the design strength.

Acknowledgments

The authors express their deep gratitude to K. Honda, former postgraduate student, and to M. Kin and Y. Kamata, former undergraduate students of the Vibration Engineering Laboratory of Saitama University, for their help in conducting laboratory and shake table tests.

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