EXPERIMENTAL STUDY OF THE BEHAVIOR OF PP-BAND MESH RETROFITTED MASONRY HOUSES USING MINIATURE MODELS

Takumi FUJIEDA[1], Paola MAYORCA[2],
Navaratnaraj SAKTHIPARAN[1] and Kimiro MEGURO[3]

ABSTRACT: Adobe/masonry houses are the most seismic vulnerable structures. It is indispensable to retrofit them economically and efficiently to prevent future human casualties. PP-band mesh retrofitting has been proposed for this purpose. In this paper, the seismic behavior of PP-band mesh retrofitted houses is investigated with miniature models made with acryl blocks as masonry units and lime mortar as paste. The main advantage of this approach is that it is possible to reuse the blocks and carry out many tests without significant additional investment for each test. In this way, various conditions can be readily evaluated [1]. Although not discussed in this paper, this type of tests can also be used as in-situ demonstrations to increase the public's awareness of the vulnerability of adobe/masonry structures and the urgency to retrofit them.

Key Words: PP-band, unreinforced masonry, adobe, shaking table test, miniature model

INTRODUCTION

Past earthquakes have shown that the collapse of seismically weak adobe/masonry structures is responsible for most of the fatalities in developing countries. It is, thus, urgent to improve their seismic performance in order to reduce future fatalities and to protect the existing housing stock. To encourage seismic retrofitting, inexpensive and easy to implement technical solutions are desirable. Retrofitting by polypropylene band (PP-band) meshes satisfies these requirements. These bands commonly used for packing are resistant, inexpensive, durable and worldwide available.

In order to assess the seismic performance of retrofitted structures, full scale shaking table tests are very useful. However, these are expensive and resource consuming thus limiting the number of tests that can be carried out. On the other hand, small-scale models are more accessible requiring smaller testing facilities as well as smaller specimens. This type of tests can be even more cost efficient if the materials used to build the model are reusable.

Considering the above-mentioned situation for the testing of adobe/masonry houses, the use of acryl blocks for adobe brick units and lime mortar for paste is proposed. With these materials several 1:12 small scale specimens with two types of architectural configurations were tested to assess the seismic performance of retrofitted structures. It was verified that under certain conditions it is possible to replicate the seismic behavior of non-retrofitted and retrofitted adobe/masonry structures with these materials in spite of their differences with the materials found at the site. Furthermore, failure mechanisms were clarified and meaningful comparisons between non-retrofitted and retrofitted houses

[1] Graduate student, Institute of Industrial Science, The University of Tokyo
[2] Project Research Associate, International Center for Urban Safety Engineering, The University of Tokyo
[3] Director/ Professor, International Center for Urban Safety Engineering, The University of Tokyo

were carried out.

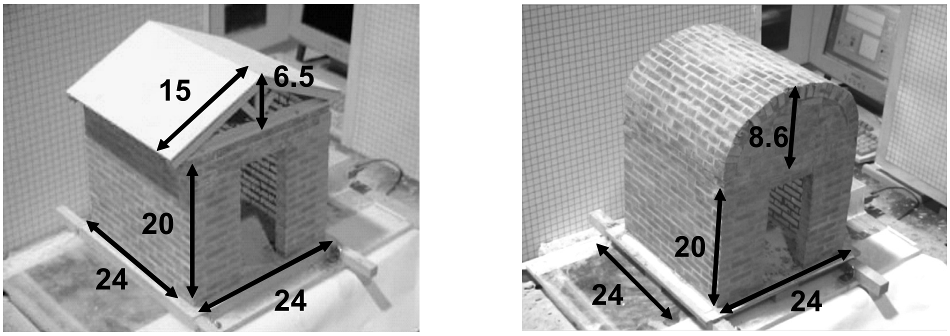
The potential of miniature model testing is not only limited to research. Because performing numerous tests does not require significant additional investment they can also be used as educational tools to increase the public's awareness of the vulnerability of adobe/masonry houses as well as the need to retrofit them. Similar demonstrations have been carried out and have had a great impact on the general public, politicians, practitioners, mass media people, etc. However, these still use relatively large models which are expensive and require a great deal of preparations. With miniature models as the one presented in this paper it may be possible to expand the scope of these demonstrations making them more affordable.

EXPERIMENTAL SETUP

Specimen characteristics

Two types of structures, which are representative of those widely used in the world, were investigated in this study. The first one consisted of a single square room structure with wooden roof whereas the second was also a single square room but with a vault roof as shown in Figure 1.

For each of these two structures, several cases were tested as shown in Table 1. The wooden roof series (W-series) consisted of several non-retrofitted and retrofitted models with added masses, consisting of steel plates attached to the roof. The wooden roof was attached to the four walls with adhesive tape. The vault roof series (V-series) included specimens with and without PP-band mesh and with and without tie-bar. Tie-bars are commonly used in the field to increase the structure stability by taking the trust forces created by the vault roof. In these series, masses were also added in the roof. Because of the roof shape, steel nuts pasted with adhesive tape as shown in Figure 3 were used.



(a) Wooden truss roof (b) Vault roof

Figure 1. Specimen characteristics (measurements in cm)

Table 1. Cases considered in this study

Roof condition	Case Name	Conditions
No roof	**N**	Non-retrofitted
Wooden roof	**WU-0000**	Non-retrofitted, no additional mass
	WU-0500	Non-retrofitted, 500g additional mass
	WU-1000	Non-retrofitted, 1000g additional mass
	WU-2000	Non-retrofitted, 2000g additional mass
	WU-4000	Non-retrofitted, 4000g additional mass
	WR-0000	Retrofitted, no additional mass
Vault roof	**VU-0000-X**	Non-retrofitted, without tie bar
	VU-0000-T	Non-retrofitted, with tie bar
	VR-0000-T	Retrofitted, with tie bar
	VR-2000-T	Retrofitted, with tie bar, 2000g additional mass

Figure 2. Vault model with tie bar

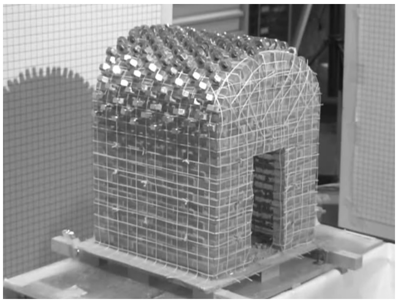


Figure 3. Additional mass on vault roof model

Materials used for model construction

As mentioned earlier, one of the purposes of this experimental program was to develop a system by which experiments could be carried out several times without significant additional investment cost. Considering this, acryl blocks were chosen for units and lime-sand-water mix was used for mortar paste. The advantage of using these materials is that after each experiment, blocks can be washed and reused. Although mortar cannot be reused, its cost is negligible compared to the overall cost of carrying out the experiments. Two sizes of acryl blocks were prepared: (1) 40mm x 20mm x 10mm (Figure 4) and (2) 20mm x 20mm x 10mm. To model the tie-bars for the vault roof models a steel rod was used (Figure 5).

In order to choose the appropriate material for the paste, strength, mix workability, and ability to replicate the behavior of the real structures were taken into account. Several options were considered including hair wax, hair gel, and lime mortar. Material tests, i.e. bond and direct shear, that were carried out suggested that any of them would be suitable for the miniature models. However, failure patterns obtained with specimens made of wax and gel did not reflect the behavior of real structures, whereas lime mortar did. The mix was finally made of 20 parts of sand, 5 parts of lime, and 6 parts of water in weight. The mix was prepared in small quantities of 200gr of sand each.

A reduced scale PP-band mesh was prepared for the retrofitted structures (Figure 6.) The mesh was made of 0.75mm-width and 0.03mm-thick bands spaced at 20mm. The mesh pitch was chosen so that each brick would be crossed by at least two bands thus preventing blocks from falling outside of the mesh. The bands were cut from commercially available PP-bands to the minimum possible size and pasted at the intersections with a plastic welder. Perforated steel plates were used at the connectors which were made of strings.

Miniature shaking table test, instrumentation and loading conditions

The shaking table consisted of a 550mm x 320mm acryl platform mounted on a rotating motor whose rotating movement was transformed into horizontal movement through a connecting rod. The generated input motion was a 1-direction sinusoidal wave with constant maximum displacement amplitude and frequency varying from 2 to 6Hz. Two maximum displacement amplitudes, 5 and 15mm, set at the beginning of each test, could not be changed during the experiment. Frequency was controlled manually through a dial and was measured throughout the test. The input wave consisted of

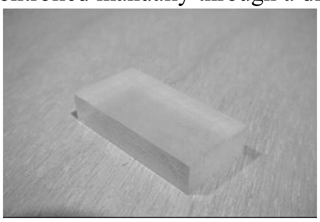


Figure 4. Acryl block

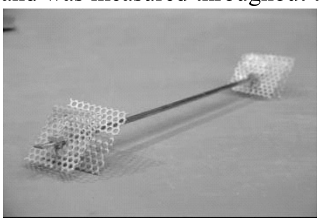


Figure 5. Tie bar

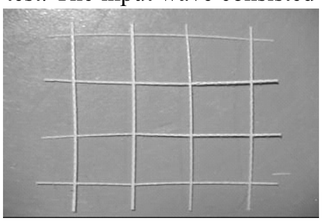


Figure 6. PP-band mesh

(a) t=30s (b) t=50s

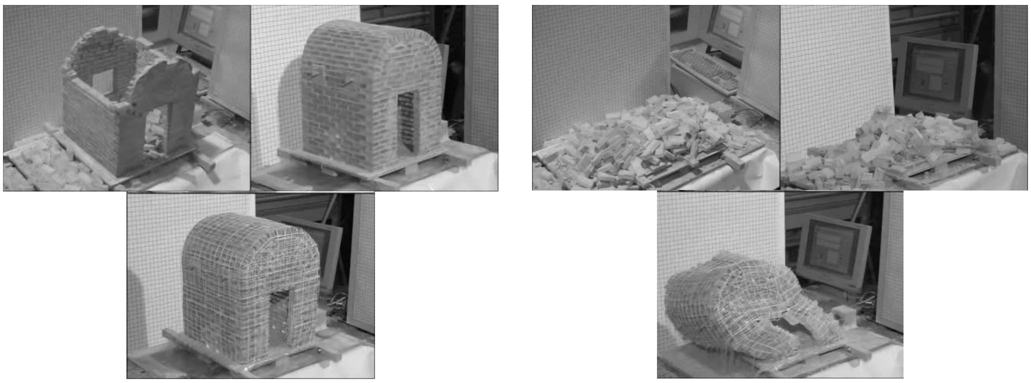
Figure 7. W-series (N, WU-0500, WR-0000, WU-1000, from the top left in clockwise direction)

a series of 10-sec long sinusoidal waves with frequencies varying from 2 to 6 Hz at a 1Hz step. A 10-sec transition was used to increase between frequencies. This loading condition implied a steady increment in the velocity and acceleration of the base motion. Accelerations were monitored throughout the test with a 2g sensor.

DISCUSSION

Figure 7 shows W-series specimens at different stages of the experiment. Crack patterns and sequence of appearance were similar to those observed in full scale tests and in the field. First, diagonal shear cracks appeared in the walls parallel to the shaking motion followed by cracks in the walls subjected to out-of-plane inertial forces. When failure occurred, out-of-plane walls, perpendicular to the motion, collapsed first followed by in-plane walls, parallel to the motion. The specimens without PP-band meshes failed at some point during the test whereas the one with the mesh remained standing after the shake.

In the case of the V-series, cracks appeared at first in the vault roof. VU-0000-X roof collapsed soon after whereas VU-0000-T resisted a slightly severer shake before collapsing. In both cases, after the roof felt, the walls failed. VR-0000-T was stronger than the specimens without PP-band mesh but suffered extensive damage as shown in Figure 8. Figure 9 and Figure 10 show the specimens after the experiment.



(a) t=10s (b) t=90s

Figure 8. V-series (VU-0000-X, VU-0000-T, VR-0000-T,
from top left in clockwise direction)

Figure 9. WR-0000 after test

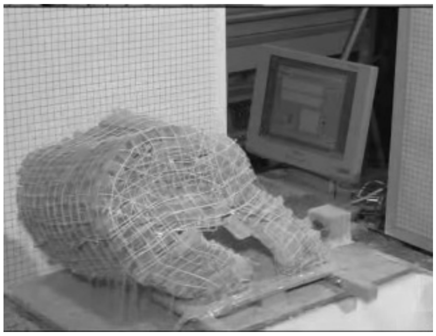


Figure 10. VR-0000-T after the test

In order to analyze the test results, the Japan Meteorological Agency intensity (JMAI) and the Arias intensity of the input motion as a function of time were calculated. In this way, based on the time at which each specimen collapsed, it was possible to estimate the maximum sustained intensity. Figure 11 and Figure 12 show the comparison of performances of W-series, and V-series specimens, respectively. The hidden and continuous lines correspond to the JMA and Arias Intensity, respectively.

WU-0000, WU-0500, and WU-1000 specimens collapsed almost at the same time which corresponded to a JMAI 5-. Model WU-2000 was able to resist a JMAI 5+ suggesting that the additional mass increased the model strength. This is because the additional mass has two effects on the seismic behavior of the structure. On one hand, it increases the inertial forces acting on the structure, a negative effect. On the other, it increases the masonry shear strength because the contribution of friction increases. Up to some point the positive effect is larger than the increased inertial forces. However, beyond it the negative effect is dominant and therefore the failure occurs earlier. This explains why WU-4000 collapsed earlier than all the other non-retrofitted models. The only model that did not collapse was WR-0000, which had the PP-band mesh.

Figure 12 shows the results of different V-series. The specimens without PP-band mesh collapsed soon after the experiment started. Although VR-0000-T and VR-2000-T suffered severe damage beyond repair, the seismic behavior was considerably improved. Total disintegration of the structure was prevented and therefore it can be concluded that lives could have been spared would it have been a real structure.

There are several factors that affect the results of the small scale shaking table tests. For instance, the relation between blocks and mesh properties (weight, stiffness, etc.) is different in the small model compared to the real size structure. As a result, the inertial and truss forces may have been comparatively smaller. Similarly, the PP-mesh relative contribution to the structural behavior is larger in the small model and also, the quality of installation is better. Furthermore, mesh splicing is not as necessary in the small model as it is in the full scale structure. How all these factors affect the observed structural response is currently under consideration.

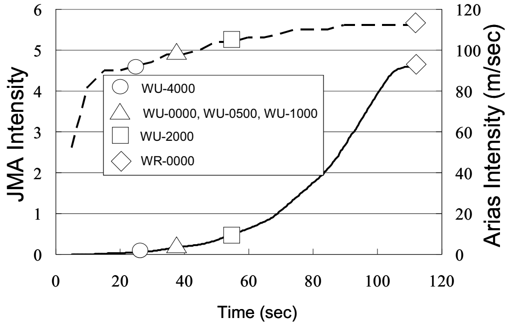


Figure 11. Comparison of W-series specimens

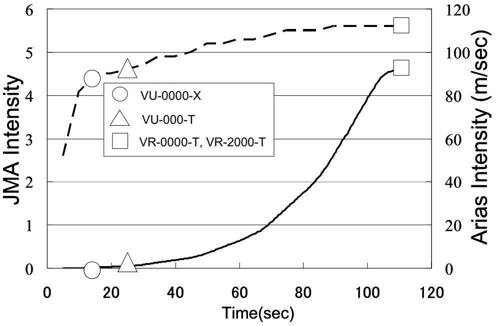


Figure 12. Comparison of V-series specimens

CONCLUDING REMARKS

In this paper, the seismic behavior of PP-band mesh retrofitted houses is investigated using miniature masonry models. These were made of acryl blocks, which can be reused, and lime mortar. The main advantage of this type of tests is that several tests can be carried out without a significant additional investment. Models with wooden truss roofs and vault roofs, with and without PP-mesh retrofitting, were tested. In all the cases, specimens retrofitted with PP-band meshes outperformed the non-retrofitted specimens and did not collapse during the experiment. Due to the limitations inherent to small scale testing model, the presented preliminary observation needs to be further investigated.

Although it is not discussed in this paper, miniature models have also a potential as educational tools used to increase the public's awareness of the vulnerability of adobe/masonry houses as well as the urgency to retrofit them.

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