## 1. INTRODUCTION

One of the vital tasks for engineers is to minimise life loss, injury and property damage under extreme dynamic loading. Devastating earthquakes in Asia, The Middle East, Africa and Latin America have served as recent reminders of the vulnerability of non-engineered, low-cost dwellings to seismic forces. The loss of life and livelihood is often drastic, with millions of people in the poorest communities most severely affected. Adobe (mudbrick) housing is particularly vulnerable because of its inherently brittle nature, wide-spread use, generally poor construction quality and the limited awareness of concepts of aseismic design and construction. Despite this limitation, there is little doubt that adobe will continue to be the choice construction material for the majority of the rural poor who simply cannot afford any alternative.

The most widely publicised method of improving the seismic resistance of new mudbrick houses incorporates bamboo or cane reinforcement placed vertically within the walls, with chicken wire, bamboo or wire running horizontally in the mortar joints (IAEE, 2004; RESESCO, 1997; Equipo Maíz; 2001; Pérez, 2001). A variety of static and dynamic tests have shown this system to be effective at significantly delaying structural collapse (e.g. Zegarra, *et al.,* 1997; Blondet, *et al.,* 2003), however, the system has a number of deficiencies which have limited their widespread acceptance and use. The main problem is that the method is complex and time-consuming and requires continuous involvement by skilled and trained masons (who also find the system overly complicated). The use of internal vertical reinforcement introduces complications in each stage of wall construction, including:

- Preparation of the foundation and initial alignment of reinforcement;
- Special preparation of bricks with notches (which also introduce weaknesses in the bricks);
- Adjusting and trimming the bricks to fit the reinforcement (natural products such as bamboo are seldom consistent in dimensions and straightness);
- Placement and adequate connection of the ring beam;
- Difficult and time-consuming process to satisfactorily protect the walls in wet-weather during construction;

Concerns have also been raised about the durability of the natural materials commonly used as internal vertical reinforcement (e.g. bamboo, reeds, timber). There is little doubt that when the internal reinforcement is completely encased it is afforded some protection from attack by insects, air and moisture, however, it is extremely difficult to adequately assess the condition of the reinforcement over time, and it is impossible to change the reinforcement if deterioration does occur.

In response to these deficiencies, researchers at the University of Technology, Sydney (UTS) have been developing a low-cost reinforcing system which is simple to construct and performs effectively under extreme dynamic loading. The most promising system incorporates:

- vertical reinforcement (e.g. bamboo or cane) attached to the outside of the walls (external);

- horizontal reinforcement (e.g. wire and/or wire mesh) running within the mortar joints (internal) and/or between the external vertical reinforcement (external);
- timber ring beam / wall plate.

## 2. DESCRIPTION OF SPECIMENS

In order to assess the behaviour and capacity of different reinforcement systems a series of shake table tests of 1:2 scale u-shaped adobe mudbrick wall units have been undertaken at UTS (Figure 1). This paper focuses on the preparation and testing of specimens 3J and 3K, whose specifications are summarised in Table 1 and discussed below.

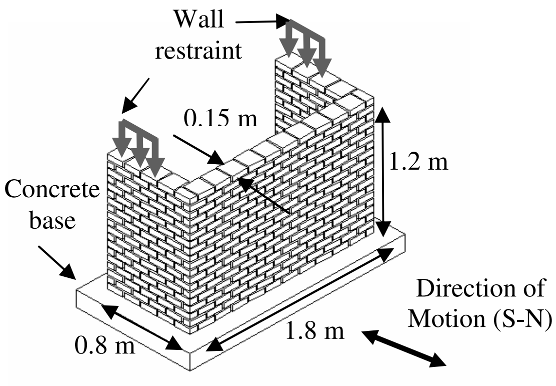


Figure 1. Specimen configuration and dimensions

Table 1. Specimen specifications

| | |
|---|---|
| 3J | External vertical poles (bamboo)<br>Internal horizontal wire mesh<br>External horizontal wire<br>Timber ring beam |
| 3K | Internal vertical poles (timber)<br>Internal horizontal wire mesh<br>Timber ring beam |

### 2.1. Specimen 3J

Specimen 3J was reinforced with external vertical bamboo reinforcement, internal horizontal chicken wire mesh, external horizontal wire and a timber ring beam (Figure 2a). The horizontal chicken wire mesh reinforcement was laid horizontally in the mortar joints every three courses during construction. Prior to laying the mesh polypropylene strings were woven through the mesh (perpendicular to the wall). After construction and curing of the wall the vertical bamboo was tied to the wall (via the polypropylene string). 2 mm-gauge wire was tied horizontally between the bamboo poles at the base, middle and top of the wall, and tensioned using pliers. The timber ring beam was connected to the wall via dowels (resisting shear forces), plus staples and 2 mm-gauge wire securely attached to the external bamboo (Figure 2b).

(In practice, an attractive finish could be easily achieved by covering the wall and reinforcement with an appropriate render (e.g. lime, sand and/or mud). Periodically, the render could be removed at certain locations and the condition of the reinforcement assessed. Deteriorated reinforcement could be easily removed and replaced, and a new render applied. Cracking and spalling of the render is expected during significant seismic events.)


Figure 2a. Specimen 3J prior to testing.

Figure 2b. 3J: Connection between bamboo + ring beam.

### 2.2. Specimen 3K

Specimen 3K was reinforced with internal vertical poles (timber ‘broom sticks’), internal horizontal chicken wire mesh (every three courses), and a timber ring beam. (Timber ‘broom stick’ poles were used in this specimen for ease of construction and to create an ‘idealised’ system.) The poles were securely attached to the foundation prior to construction, and half bricks and full bricks with notches were configured to encase the poles at alternate courses (Figure 3). Holes were drilled in the timber ring beam to snugly fit the vertical poles and provide a connection between the wall and the ring beam.

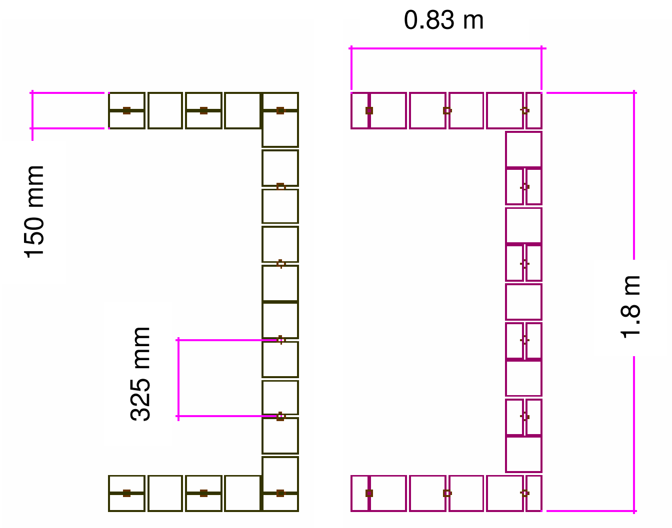


Figure 3a. Plan layout for Specimen 3K

Figure 3b. Layout of bricks and poles (3K)

## 3. DESCRIPTION OF DYNAMIC TESTING

The dynamic testing was undertaken on the 10-tonne capacity, 3m x 3m MTS uni-axial shake table at the University of Technology, Sydney. The shake table is capable of high fidelity seismic simulations. In this study, the input time history from the $M_w$ 7.7 January 13, 2001 El Salvador earthquake was used (Figure 4). (This earthquake, in combination with a $M_w$ 6.6 earthquake on February 13, 2001 in the same area, caused the destruction of over 110,000 adobe houses (DIGESTYC, 2001; Dowling, 2004b)). The approach taken to choose, modify and apply the input time history has been described in detail in Samali, *et al.* (2004) and Dowling, *et al.* (2005).

Modal analysis and Frequency Response Function (FRF) calculations were used to identify the first resonant frequency (natural frequency) of each specimen. The input spectra time scaling factor (Table 2) was then calculated for each specimen to ensure a similar frequency ratio (defined as the ratio of the dominant frequency of the input excitation to the dominant first natural frequency of the structure) in order to maintain dynamic similitude and induce damaging near-resonance conditions.

In order to study the behaviour and performance of the structures at different load levels a series of simulations was undertaken with varying displacement intensities, ranging from 20% - 125% for the time-scaled input.

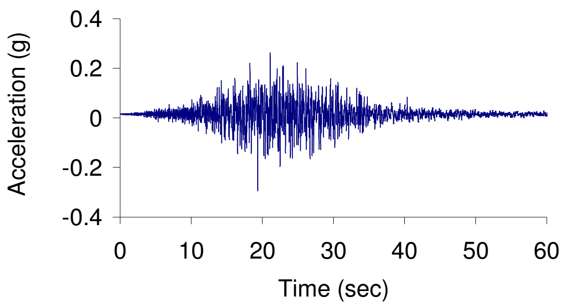


Figure 4. Unscaled input time history, El Salvador earthquake (January 13, 2001) (UCA Station, Zacatecoluca).

| Specimen | 1st Natural Frequency (Hz) | Time Scaling Factor |
|---|---|---|
| 3J | 33.8 | 2.2 |
| 3K | 27.0 | 1.8 |

Table 2. Specimen frequency and time scaling.

## 4. RESULTS

Both specimens 3J and 3K performed extremely well, withstanding the forces of a series of simulations of varying intensity: S4 (20%), S5 (50%), S6 (75%), S7 (100%), S8 (125%), S9 (75%), S10 (75%), S11 (100%), S12 (100%). [By contrast, an unreinforced specimen (3A) was severely damaged (collapse imminent) after S6 (75%) (Dowling *et al.*, 2004).] Initial hairline cracking appeared in specimens 3J and 3K during simulation S7 (100%) with progressive additional damage during subsequent simulations. Figures 5 and 6 show the state of each specimen after the full testing sequence.


Figure 5a & b. Specimen 3J after simulation S12 (100%)


Figure 6a & b. Specimen 3K after simulation S12 (100%)

For both specimens collapse of the structure was prevented by the combined contributions of the vertical poles, wire mesh, wire and ring beam. This integrated matrix acted to restrain movement, and absorb, dissipate and redistribute energy within the structure. The main factors contributing to damage were:

- Flexure in the out-of-plane ‘long’ wall generating vertical and diagonal cracking.
- Tearing failure at the corners due to the relative movement between the ‘flexible’ out-of-plane ‘long’ wall and the stiff in-plane shear ‘wing’ wall causing vertical cracking in the shear wall at or near the corner.

Of special interest was the failure pattern in specimen 3K, with vertical cracking concentrated around the location of the vertical poles. This phenomenon may be attributed to a difference in dynamic response between the stiff mudbrick wall and the flexible timber poles which caused a pounding effect in the out-of-plane ‘long’ wall. In the shear 'wing' wall, the vertical poles introduced a discontinuity in the wall, which also reduced the effective cross-sectional area, making tearing failure more likely (Figure 6b). Weaknesses in the bricks may have also been introduced during the process of 'notching' the bricks (moulded during brick fabrication, or notched with a trowel, machete or masonry drill after curing).

Figure 7 shows the displacement (relative to the shake table) of the top/mid-span of the 'long' wall during simulation S7 (100%) for both specimen 3J and 3K. The graph clearly shows the effective containment provided by the external reinforcement (3J) which experiences a smaller relative displacement than specimen 3K. Larger displacements for specimen 3K are expected, given its lower stiffness, confirmed by the lower first natural frequency (Table 2).

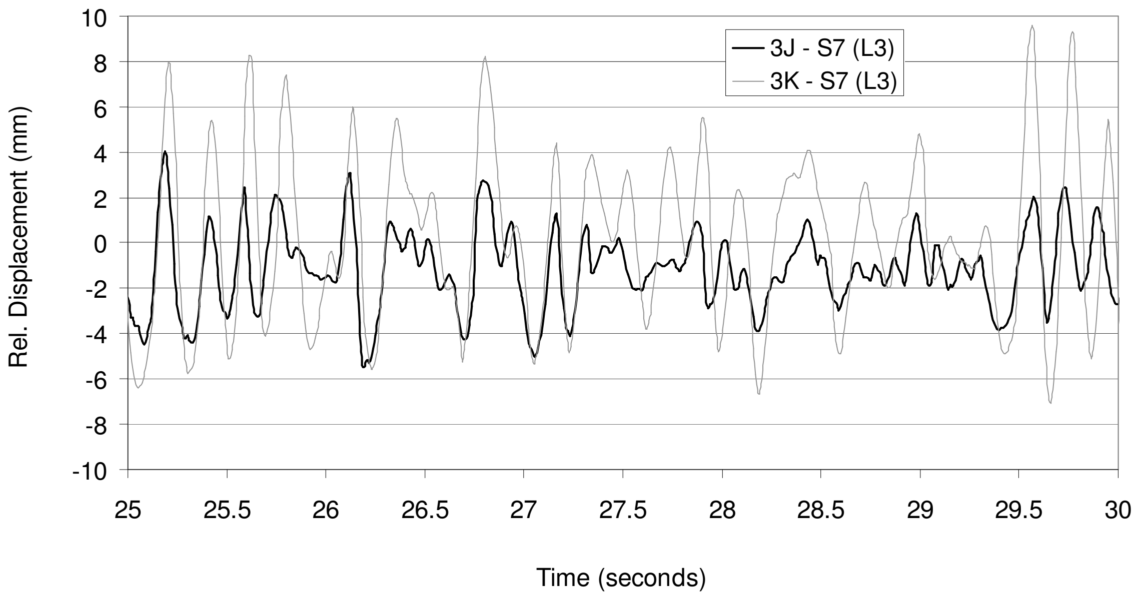


Figure 7. Displacement of the top/mid-span (L3) of the 'long' wall relative to shake table displacement for specimen 3J (dark line) and specimen 3K (light line) during the period of intense shaking during time-scaled simulation S7 (100% intensity).

## 5. CONCLUSIONS

The shake table testing proved both systems (3J and 3K) to be an extremely effective means of improving the seismic capacity of adobe-mudbrick u-panels. Although significantly damaged after the rigorous testing program, both wall units resisted collapse. Overall, specimen 3J performed marginally better, exhibiting less relative wall movement and more even distribution of cracking, with no single crack of major concern. By contrast, the large failure in the shear wall in specimen 3K (Figure 6b) presents a major problem in terms of structural stability.

In addition to the superior dynamic performance of specimen 3J, a major advantage of the system is the relative simplicity of construction, which makes it a more appealing reinforcement alternative. The system (without the internal wire mesh reinforcement) can also be used for the retrofit-strengthening of existing dwellings, which represent a significant risk in many parts of the world.

Further research at the University of Technology, Sydney will include the shake table testing of a scale-model house (complete with window and door openings) incorporating a slightly amended version of the system used in specimen 3J.

## 6. REFERENCES


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