1. INTRODUCTION

Recent major earthquakes around the world confirm their potentially devastating consequences: injuries, loss of life and damage to property. Such disasters often most severely impact the poorest communities of the world where millions of people live in vulnerable, non-engineered, low-cost dwellings. Traditional adobe-mudbrick constructions, which are primarily used in these regions, are particularly susceptible because of their inherently brittle nature, generally poor construction quality and the limited awareness of concepts of aseismic design and construction. The use of adobe as a construction material will, however, persist for the majority of the rural poor since they simply cannot afford any alternative.

Adobe-mudbrick research undertaken at the University of Technology, Sydney focuses on the development and assessment of strengthening systems which improve the earthquake resistance of adobe houses. In order to investigate the seismic behaviour of such structures, scaled (1:2) u-shaped adobe wall panels with different structural reinforcement systems have been built and subjected to dynamic excitation using a state-of-the-art shake table.

In conjunction with the extensive shake table testing, Experimental Modal Analysis (EMA) plays an important role in this research project. EMA is used to determine the unique dynamic features of each specimen, including individual fundamental natural frequencies. This information is used to appropriately scale (with respect to time) the input excitation (ground motion) to ensure dynamic similitude (detailed in Samali *et al.,* 2004). This process means that strength improvement can be assessed through comparative study. In addition, EMA reveals the vibrational mode shapes contributing to the dynamic responses of the specimen which provide an understanding of the failure mechanisms of the structure.

Eleven u-shaped adobe-mudbrick wall units with different structural reinforcement systems were tested in total. To reduce material and specimen variability, all bricks and specimens were fabricated using consistent raw materials, curing conditions and construction practices. This paper describes the Experimental Modal Testing and Analysis of the final two specimens, 3J and 3K. The outcomes of the Experimental Modal Analysis for the impact excitation of the fully reinforced structures are presented and discussed. (Other results are presented in Samali *et al.*, 2005 and Dowling *et al.*, 2005.)

2. DESCRIPTION OF SPECIMENS

The specimens tested were u-shaped adobe units which represent a wall section of an average traditional adobe house in a scale of 1:2. An additional downward restraining force was applied to the in-plane shear walls to simulate the restraint provided by a continuous wall and to prevent over-turning of the complete unit. The dimensions and configuration of the units meet the design criteria recommended in relevant guidelines (e.g. IAEE 2004) and can be seen in Figure 1. Table 1 shows the specifications of each specimen.

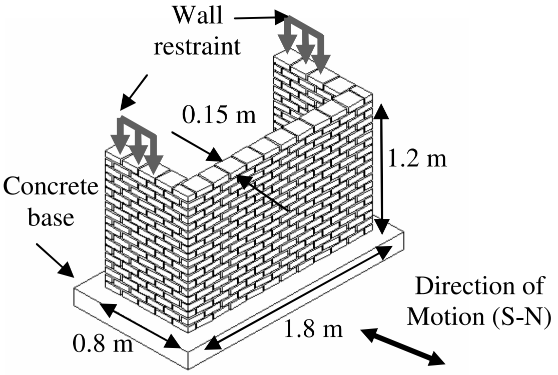


Figure 1. Specimen configuration and dimensions

3J	External vertical bamboo Internal horizontal chicken wire mesh External horizontal wire Timber ring beam
3K	Internal vertical poles Internal horizontal chicken wire mesh Timber ring beam

Table 1. Specimen specifications

3. EXPERIMENTAL MODAL TESTING AND ANALYSIS

Experimental Modal Testing and Analysis (EMTA) is the process of characterising the dynamic properties of a test structure by exciting the structure artificially and identifying its modes of vibration (Ramsey, 1982). Each of these vibration modes is defined by a specific natural frequency, modal damping and a mode shape, and can be identified from practically any point on the structure (Ramsey, 1982). The modes of vibration of a structure reveal the frequencies at which the structure can be excited into resonant motion, and the predominant wave-like motions it will assume at these resonant frequencies (Richardson, 1978).

3.1. Modal Testing

In this study, each specimen was first excited by an impact hammer to identify its fundamental frequency and then tested on a shake table with the excitation of an earthquake spectrum with its dominant frequency shifted to the vicinity of the specimen's fundamental frequency to investigate near-resonance behaviour (Samali *et al*,. 2004). In addition to the final hammer test on the fully reinforced structure, hammer tests were carried out at different stages of reinforcing to investigate the influence of each alteration. This paper focuses on the Experimental Modal Testing and Analysis from the hammer tests. A detailed paper on the EMTA undertaken for the shake table testing will be published at a later date.

Test Procedure and Instrumentation

A large 12 lb Modally Tuned ICP Sledge Hammer was used to excite the specimen (Figure 2). (The impact point was located at the top of the centreline of the out-of-plane wall.)The vibration response of the structure was measured by piezoelectric-type accelerometers (PCB 356A08 and PCB 337A26) which were attached to the outside face of the out-of-plane wall. The signal of the hammer (impact force) and the accelerometers (acceleration) were first amplified by signal conditioners and then recorded by a data acquisition system. The acquired frequency range was set from 0 Hz to 512 Hz with 8192 data points sampled.

Data Acquisition

The main data acquisition system consisted of a Hewlett Packard state-of-the-art Vxi system equipped with leading software from LMS (LMS CADA-X).

The system comprised of two HP Vxi 16 channel 51.2 kHz digitizers with anti-aliasing filter and DSP (digital signal processing) on board in a C-size frame. The frame was equipped with a controller and high speed Mxi bus, connecting it to the HP workstation. The digitizer had an implemented DSP and a 4-32MB FIFO (file input, file output) digital anti-aliasing filter. UTS LMS CADA-X software contains three main parts (modules): data acquisition; modal analysis; and structural modifications (Samali *et al.*, 2002).

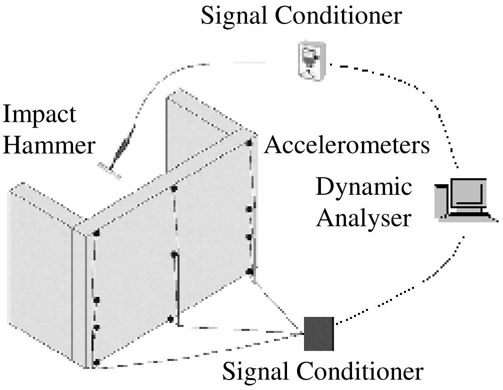


Figure 2. Hammer Test

3.2. Modal Analysis

Experimental Modal Analysis is an established and reliable vibration analysis tool, providing information on the characteristics of the structure and the excitation. It represents the dynamics of the structure as well as the performance criteria through modal testing procedures (Samali *et al.*, 2002). The process is outlined in Figure 3.

The analysis of the data was executed using the Modal Analysis Module of the software LMS CADA-X. The time signals (amplitude versus time) sampled during the test were first converted (transformed) into frequency spectra (amplitude versus frequency) using the Fourier Transform. The Fourier Transform signals of the accelerometers (output) were then divided by the Fourier Transform signal of the hammer impact (input), resulting in the Frequency Response Function (FRF). The FRF determines how much acceleration response a structure has per unit of force excitation. The relation between the FRF's and the modal parameters is given in Equation 1 (Samali *et al.*, 2002).

$$h_{ij}(\omega) = \sum_{k=1}^{N} \left(\frac{r_{ijk}}{(\omega-\lambda_k)} + \frac{r^*_{ijk}}{(\omega-\lambda^*_k)}\right) \qquad (1)$$

where:

N = number of modes of vibration that contribute to the structure's dynamic response within the frequency range under consideration

r_{ijk} = residue value for mode k

λ_k = pole value for mode k.

h = unit impulse response function

ω = frequency in rad/sec

* designates complex conjugate

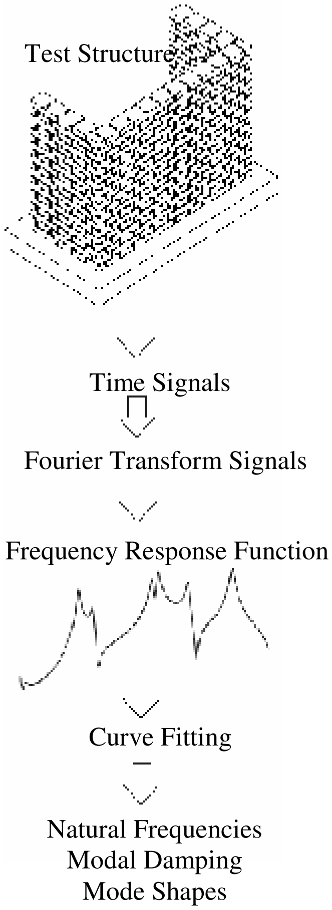


Figure 3. Phases of the modal analysis

To identify the modal parameters, further computations using curve fitting algorithms were performed. The LMS CADA-X software comprises different parameter estimation techniques. In this project the Least Square Complex Exponential method combined with the Least Square Frequency Domain was used. This method first calculates the system poles in the time domain. The response can be expressed in terms of modal parameters in the time domain in the form of the least squares complex exponential, using Equation 2 (Kelley *et al.*, 1996). Once the system poles were identified, the modal parameters were then estimated in the frequency domain.

$$H(t) = \sum_{k=1}^{m} \frac{1}{m_k \omega_{dk}} e^{-\lambda kt} \sin \omega_{dk} t \tag{2}$$

where:

ω_{dk} = Damped Natural Frequency of mode k

m_k = Modal mass of *k*th mode

Validations

When a modal model is established it is essential to validate the model. Validation of a modal model is usually accomplished by several mode identification tools which aid locating the number of modes in a given frequency band (Kelley *et al.*, 1996). Among the most common of these techniques are the FRF Summation, the Mode Indicator Function and the Stabilization Diagram (which were utilised in this project).

Mode Indicator Function

The Mode Identification Function (MIF) is a tool available in many commercial software packages to aid in the identification of modes in measured data. The MIF is formulated to take advantage of the real component of the response vector being a minimum at resonance (Kelley *et al.*, 1996).

Stabilisation Diagram

The stabilisation diagram is a tool used during the least square complex exponential pole estimation process. The diagram identifies the stability of a pole as the order of the model is increased. Stability is defined for different modal parameters (frequency, damping and shape) as having less than some defined amount of change between successive order models (Kelley *et al.*, 1996).

Modal Assurance Criteria (MAC)

The Modal Assurance Criteria is a commonly used method for assessing the degree of correlation between any two vectors and is formulated in Equation 3 (Kelley *et al.*, 1996).

$$\{\mathrm{x}_\mathrm{n}\} = \begin{Bmatrix} \mathrm{x}_\mathrm{a} \\ \mathrm{x}_\mathrm{d} \end{Bmatrix} = [\mathrm{T}]\{\mathrm{x}_\mathrm{a}\} \tag{3}$$

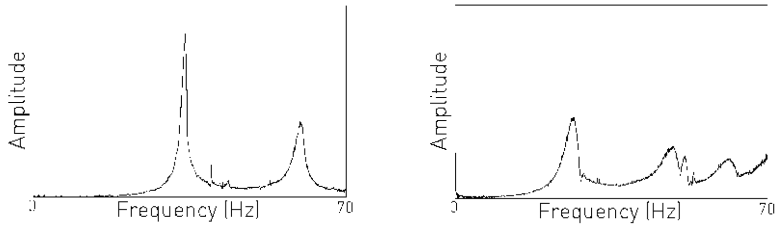
where:

x_a and x_d are the vectors being compared

Other validation tools are Modal Scale Factors and corresponding correlation factors, Mode Participation Reciprocity between inputs and outputs, Mode complexity, Modal Phase Colinearity and Mean Phase Deviation indices, visual comparison of mode shapes in the animated display and Synthesis of FRF's (Samali *et al.*, 2002).

4. RESULTS AND DISCUSSION

The modal testing (the Frequency Response Functions (FRFs) and subsequent modal analysis) produce the natural frequencies, modal damping and mode shapes. Figure 4 shows the sum of FRF's of the two specimens, 3J and 3K, from 0 to 70 Hz. The first peaks of the FRF's are clear which indicate that the first vibrational modes of the specimens are dominant modes under the given input excitation.



3J

3K

Figure 4. Summed FRF's of the fully reinforced specimens 3J and 3K

The first frequencies of the two specimens obtained from the modal analysis were critical since they were used to scale the earthquake excitation for subsequent shake table testing (Samali *et al.*, 2004). The second modes are not clearly seen in the FRFs. This indicates that under the given excitation the second vibrational mode contributes very little to the vibration response of the structures.

The natural frequencies (f_i) and the modal damping (ζ_i) of the first three modes are listed in Table 2. The frequencies of specimen 3K (internal vertical reinforcement) are lower than those of specimen 3J (external vertical reinforcement). This feature can be attributed to the discontinuity of the panel caused by the internal reinforcement, which reduces the cross-sectional area of the mudbrick masonry, resulting in an overall reduction in stiffness of the structure.

Table 2. Modal frequencies (f_i) and damping (ζ_i) of the first three modes of both specimens

	1st Mode		**2nd Mode**		**3rd Mode**	
	f_1	ζ_1	f_2	ζ_2	f_3	ζ_3
3J	33.82	1.08	42.19	0.44	59.98	1.40
3K	26.96	1.61	35.48	0.13	48.85	2.12

Figure 5 shows the typical mode shapes for the first three frequencies. The first mode shape predominantly demonstrates vertical and horizontal bending (flexure). The second mode shape introduces torsion to the structure. The third mode shape indicates a return to flexural response. The failure modes evident in the specimens subjected to the shake table testing confirm the predominance of vertical, horizontal and diagonal bending (flexure) in the structure, matching the first mode shapes. This is most apparent in the lightly reinforced specimen 3C, shown in Figure 6 (Dowling et al., 2004). (The failure patterns are less clear in specimens 3J and 3K because of the improved performance of the structures and the presence of reinforcement, which obscures the cracking patterns, thus indicative images from 3C are shown.)

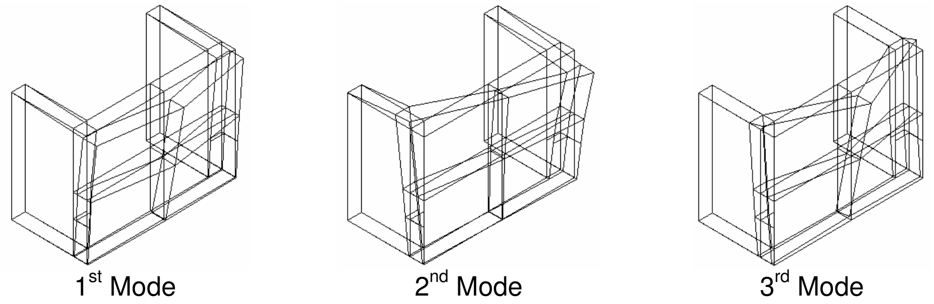


Figure 5. First three modes of a typical U-panel specimen

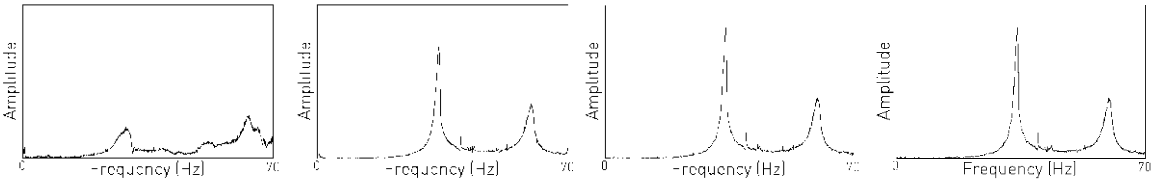
Figure 6a&b. Vertical corner cracking and mid-span vertical cracking of Specimen 3C (with horizontal mesh reinforcement) after shake table testing (Dowling, *et* al., 2004)

Effects of reinforcement

For specimen 3J, modal testing and analysis was undertaken at each stage of reinforcing to assess the influence on overall stiffness and mode shapes. The mode shapes were generally unaffected. The modal frequencies, however, did change, especially with the addition of the restraint applied to the wing walls (Table 3 and Figure 7).

Table 3. Natural frequencies of first three modes of specimen 3J during reinforcement

Configuration	**Natural Frequencies [Hz]**		
	f_1	f_2	f_3
3J – a: mesh	28.99	54.84	63.41
3J – b: mesh + restraint	33.60	42.70	59.50
3J – c: mesh + restraint + ring beam	33.62	42.40	59.67
3J – d: mesh + restraint + ring beam + bamboo + wire	33.82	42.19	59.98



3J - a 3J - b 3J - c 3J – d

Figure 7. Summed FRFs of the different stages of reinforcing specimen 3J

The results of modal analysis show that the application of the restraint to the wing walls significantly increased the stiffness of the structure. Thereafter, there was little change in the frequencies (modes 1 to 3), which indicates that the stiffness of the structure is uninfluenced by the addition of external strengthening measures. The subsequent shake table test results, however, show a major increase in earthquake resistance due to the reinforcing.

5. CONCLUSION

Experimental modal testing and modal analysis have been successfully used to study the dynamic features of u-shaped mudbrick wall structures. It provides knowledge of natural frequencies of the specimens in order to correctly scale the input time history for shake table testing to maintain dynamic similitude. Furthermore, the experimental modal analysis provides insight into the dynamic behaviour of the structure under given excitation which offers tools for understanding and improving the earthquake resistance of the mudbrick structures.

6. REFERENCES

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