Forced Vibration Response of Small Scale URM House with Flexible Timber Diaphragm

A. R. Abdul Karim[1,3]✉, C. Oyarzo-Vera[1,2], N. M.Sa'don[1,3], and J. M. Ingham[4]

1. Corresponding Author: PhD Student, Department of Civil & Environmental Engineering, The University of Auckland, Private Bag 92019, Auckland 1142, New Zealand. Email: aabd079@aucklanduni.ac.nz

2. Lecturer, Departamento de Ingeniería Civil, Universidad Católica de la Santísima Concepción, Chile. Email: coyarzov@ucsc.cl

3. Senior Lecturer, Civil Engineering Department, Faculty of Engineering, Universiti Malaysia Sarawak (UNIMAS), 94300 Kota Samarahan, Sarawak, Malaysia. Email: msazzlin@feng.unimas.my

4. Associate Professor, Department of Civil & Environmental Engineering, The University of Auckland, Private Bag 92019, Auckland 1142, New Zealand. Email: j.ingham@auckland.ac.nz

Abstract

The results of non-destructive forced vibration tests on a small scale URM house with a flexible timber diaphragm are presented. The primary purpose of this research programme was to investigate the system level response of URM buildings and to identify potential research areas that require further attention. The 4 m × 4 m URM house consisting of a flexible timber diaphragm was constructed and tested to determine the possible mode shapes of the structure. The frequencies of the diaphragm and walls were determined and the damping ratios were calculated from the frequency response function (FRF) curves. A finite element (FE) model of the structure was initially prepared in order to predict the frequency range of interest that needed to be applied during actual modal testing. A reasonably good match of frequency modes was found between the FE model and experimental data, specifically for NS excitation. However, the frequency mode in the EW direction estimated by the FE model was significantly greater than the experimental value. This may be due to the assumptions used in the FE model regarding material properties. It is proposed that, in future studies, FE model updating will be established as this enables better estimation of the mechanical properties of the structural elements and improves the modelling of boundary conditions (especially the joist-walls connections) in the initial FE model.

Keywords: non-destructive test, forced vibration test, modal testing, unreinforced masonry structure, finite element model

1. INTRODUCTION

Unreinforced masonry (URM) buildings have long been recognised to perform poorly in an earthquake. This deficient performance was clearly demonstrated in several major earthquake episodes such as the 1931 Hawke's Bay (Dowrick 1998), 1989 Loma Prieta (Bruneau 1994), and 1989 Newcastle (Griffith 1991) earthquakes. In accordance with their poor performance in earthquakes, an understanding of the dynamic behaviour of URM buildings when subjected to seismic excitation is of major interest in many seismically active countries such as the United States, New Zealand, Italy, Portugal and Chile. Therefore, it is essential to determine dynamic parameters such as natural frequencies, damping factors and mode shapes, which are typically obtained using modal identification techniques by conducting ambient or forced vibration tests (De Sortis et al. 2005). The results of such tests are normally expressed in terms of the frequency-dependent ratio between the response (output) and the excitation (input), known as a frequency response function (FRF).

Ambient vibration can be from sources such as wind, waves, pedestrian or vehicles, with the vibration not controlled but instead considered as a stationary random process. Thus, the response data from the structure alone is used to estimate the dynamic parameters (Shabbir 2008). But, because of the lack of information on the actual forcing, ambient identification procedures may lead to inaccurate or wrong identification of results. In contrast, forced vibration testing provides a known input force over the frequency bands of interest, which can be achieved by proper design of the excitation systems, typically being either sinusoidal or sweep input motions. Thus, the dynamic characteristics of structures can be explicitly recognized. De Sortis et al. (2005) concluded that the sinusoidal input motion is more reliable for use in the dynamic identification of URM buildings when compared to sweep input motion. This is because some nonlinearity is likely to occur in URM buildings even at low levels of vibration, and in the presence of close natural modes.

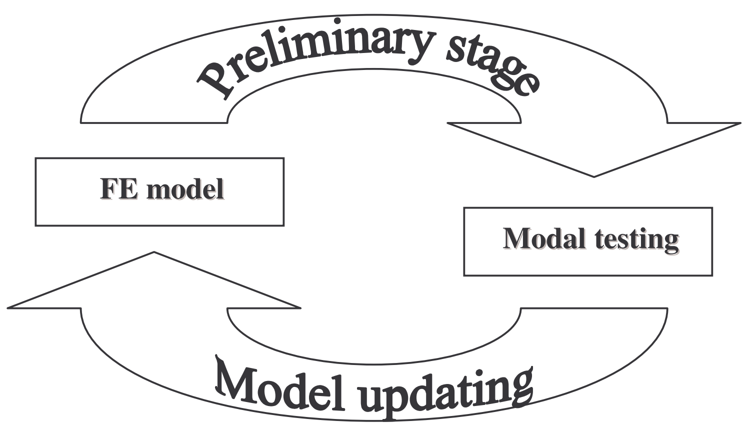


Figure 1: Cycle between FE model and modal testing

Preparing a Finite Element (FE) model to estimate the natural frequencies and to investigate the possible modes of the structures is a wise preliminary stage to be performed before conducting actual modal testing (**Figure 1**). This is because the targeted frequency range of interest could be approximately identified using the FE model, which may then save a lot of time by avoiding a trial and error process for selecting the frequency range during testing. The dynamic parameters obtained from the modal testing provide information that is important to update the FE model. Model updating is an essential process because the number of assumptions made in preparing the initial FE model requires supplementary techniques to calibrate the models, by verifying their output against actual measured data. The philosophy behind this model correlation is that the modal model derived from measurement, though incomplete due to lack of sufficient numbers of vibration modes and measured locations, truly represents the structure's dynamic behaviour. Thus, it can be used to 'correct' the numerical model (He and Fu 2001).

2. DESCRIPTION OF THE URM SPECIMEN

The URM house having a 4 m × 4 m plan was constructed and tested as shown in **Figure 2**. The north wall was a single leaf 110 mm thick solid brick wall with a 1.91 m height, whereas the south, west and east walls were double leaf 230 mm thick brick walls with opening(s) and a 2.2 m height. For the double leaf thick walls the header course was at every fourth course. The timber diaphragm was comprised of six 45 mm × 140 mm joists at a 704.5 mm centre to centre spacing and 45 mm × 140 mm blockings at 1149 mm centre to centre spacing. The joists were supported by the interior leaf of the east and west brick walls and covered with 32 mm × 140 mm timber flooring.

Figure 2: North Western Elevation of small scale URM house

As mentioned previously, before conducting the modal testing, it is advisable to prepare a FE model for estimating the natural frequencies, and investigating the possible modes of the structures. Therefore, the following section provides details of the initial FE model of the small scale URM house that was developed.

3. FINITE ELEMENT MODELLING

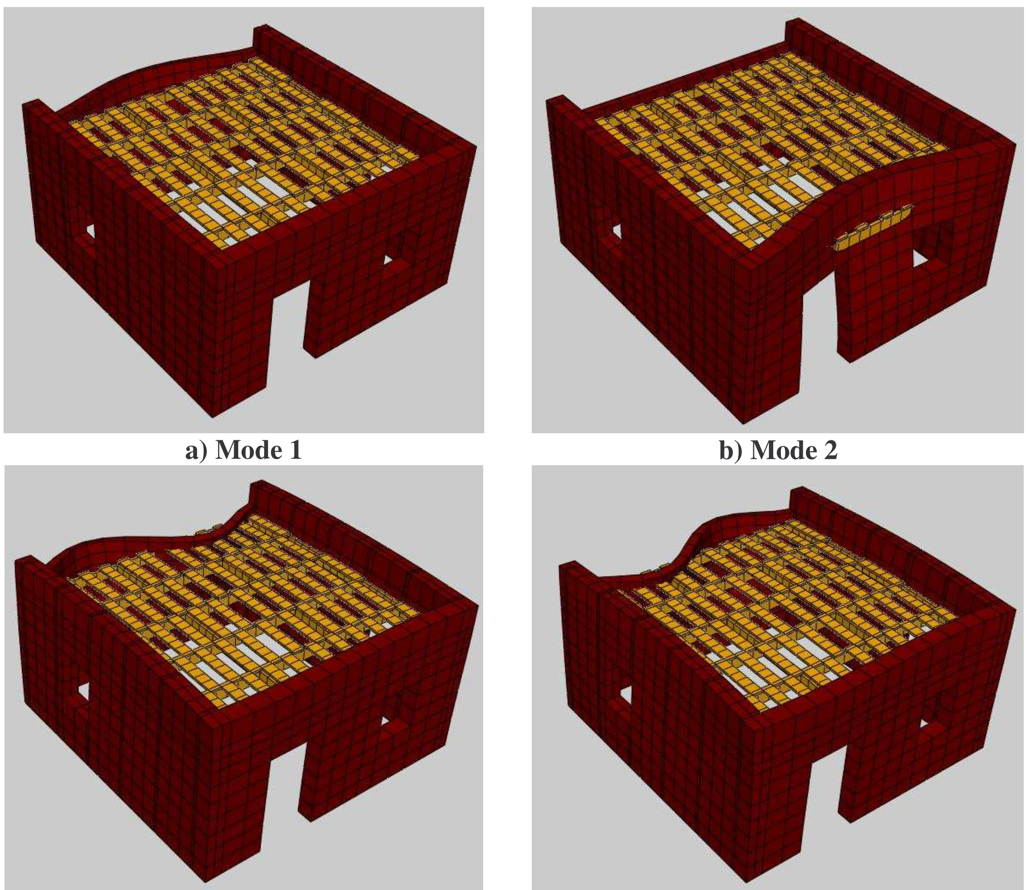
A finite element model of the structure was prepared using the software Abaqus/CAE (DS Simulia 2007), considering every component of this building. The unreinforced masonry walls were modelled using solid 8-nodes linear hexahedral elements (C3D8I), commonly known as “bricks elements” with mechanical properties compatible with the average properties of the masonry (E_m= 0.71 GPa). These properties were obtained from compression tests applied to a set of three-bricks prisms constructed with the same materials used to build the structure under study. These tests were performed in the material’s laboratory of the University of Auckland and the results are presented in **Table 1**. The timber joists, blockings and floor boards were modelled using the same brick element as for masonry (C3D8I), but in this case mechanical properties compatible with radiata pine timber were considered (E_m= 12.0 GPa), according to the technical specification provided by the supplier. In addition, other properties (density and Poisson’s ratio) were considered using standard values available in the literature. A summary of the mechanical properties used in the model is presented in **Table 2**. The structure was considered fully connected to the ground at its base (encastred) and the connections between elements were modelled as tie connections, which is appropriate for the joist-floor and joist-blocking nailed connections, but is conservative for joist-walls connections, that depend mainly on contact and friction conditions. Results from the modal analysis of this structure identified four modes, which are presented in **Table 3** and **Figure 3**.

Table 1: Masonry prisms compression test. Young's modulus

Sample	Prism 1	Prism 2	Prism 3	Average
E (GPa)	1.29	0.21	0.61	0.71

Table 2: Mechanical properties considered in the finite element model

Sample	Density (kg/m^3)	E (GPa)	Poisson's ratio
Masonry	1400	0.71	0.2
Timber	545	12.00	0.2



a) Mode 1 **b) Mode 2**

c) Mode 3 **d) Mode 4**

Figure 3: Modal response of the structure

Table 3: Modal response of the structure

Mode	Natural Frequency (Hz)	Mass-participation	
		NS direction	EW direction
1	8.48	6.1%	–
2	13.12	13.8%	–
3	18.55	–	26.3%
4	19.72	–	21.0%

From the above results, the second mode was more associated with overall excitation of the structure in the NS direction, when compared to the first mode. This is identified by the significant mass-participation of the structure in this direction. The third and fourth modes were more related to an overall EW vibration and it was deemed that separate detection of these last two modes would be difficult because their natural frequencies were very close and because their modal shapes were very similar. Thus, from the results of the FE model, the frequency range from 10 Hz to 20 Hz was chosen for conducting the forced vibration tests in both the NS and EW directions. The frequency range chosen was not started below than 10 Hz because of the first mode was more associated with individual response of the north wall as shown by the low mass-participation of the structure and the modal shape obtained. Therefore, mode with higher percentage of mass-participation was selected to investigate the system level response of the URM house as a whole.

4. FORCED VIBRATION TESTING, RESULTS AND DISCUSSION

Forced sinusoidal vibration tests were conducted using an APS Dynamics Model 400 electrodynamic mass shaker. The shaker was placed on the top of the timber diaphragm and operated in the horizontal mode with 0.8 g forcing amplitude to produce lateral vibration of the timber diaphragm. Six Jewell Instruments Model LCA-100 accelerometers were used to measure the structural response of the diaphragm and walls (output). The excitation of the shaker (input) was recorded using a small Crossbow accelerometer sensor attached to the arm of the shaker. All accelerometers used were only capable to measure a single direction of acceleration. MATLAB computer software (The MathWorks Inc. 2007) was used to control the shaker and data acquisition operations.

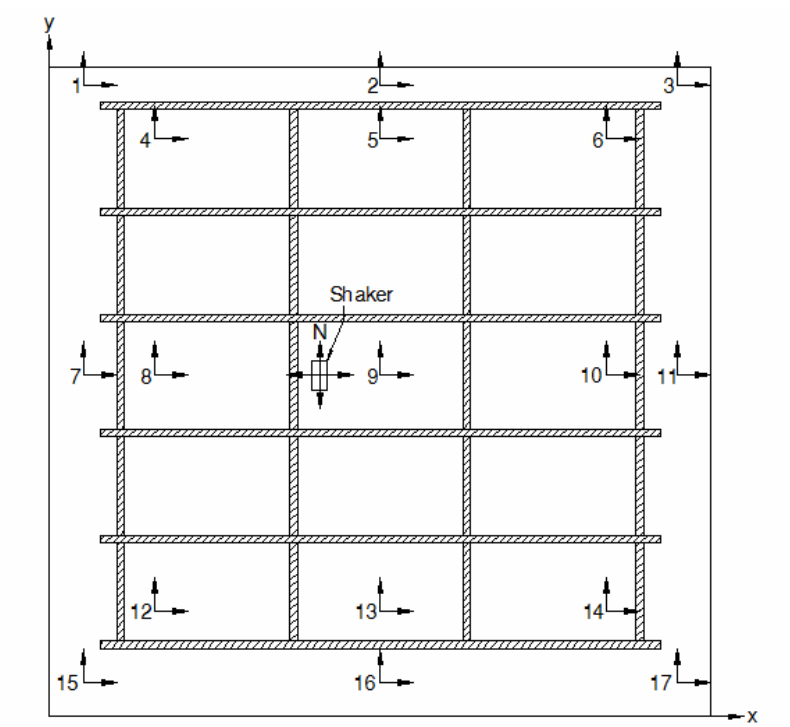


Figure 4: Location and direction of accelerometers and shaker

In order to obtain sufficiently accurate vibration properties of the diaphragm and walls, a total of seventeen test points were established to measure the diaphragm and wall accelerations as shown in **Figure 4**. Due to the limitation of number of instrumentation channels available, six stages of modal testing were performed for each direction of shaker excitation (north-south and east-west directions). Each test was conducted by issuing a stepped sine input motion command to the shaker, which the frequency was gradually increased from 10 Hz to 20 Hz with a step increment of 1 Hz. Zero amplitude phase or time delay of 30 seconds was included before each increment of the frequency to permit the vibration of the structure to become stationary. The zero amplitude phases were also included to allow any structural response that was related to a particular frequency to dissipate before the new frequency was applied (Wilson et al. 2008). During each test, both excitation and response signals were simultaneously recorded with sample rate of 500 data per second. Details of the tests are summarised in **Table 4**.

Table 4: Summary of modal testing details

Shaker excitation	Number of test	Test points measured		Freq. range (Hz)	Freq. step (Hz)	Excitation (s)	Delay (s)
		x direction	y direction				
NS	1	1 to 6	–	10-20	1	60	30
	2	7 to 11	–				
	3	12 to 17	–				
	4	–	1 to 6				
	5	–	7 to 11				
	6	–	12 to 17				
EW	1	1 to 6	–	10-20	1	60	30
	2	7 to 11	–				
	3	12 to 17	–				
	4	–	1 to 6				
	5	–	7 to 11				
	6	–	12 to 17				

The forced vibration test results, which have been published elsewhere (Ingham et al. 2008), show that two modes were identified in the NS direction (12 Hz and 15 Hz) and one mode identified in the EW direction (13 Hz). The result obtained from the EW direction show a significant difference from the FE model, as tabulated in **Table 5**. This was expected as some of the mechanical properties of the materials (density and Poisson's ratio of both the masonry and timber) applied to the FE model were extracted from the literature without conducting proper material testing as stated previously.

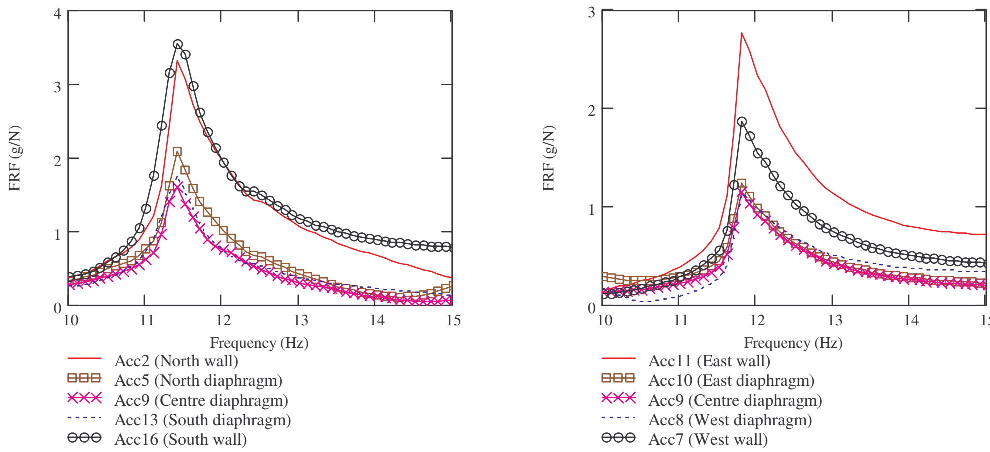
Table 5: Comparison between FE model and experimental results

Mode	Frequency (Hz)	
	FE model	Experimental
NS	13.12	12
EW	18.55	13

Table 6: Summary of frequencies and damping ratios

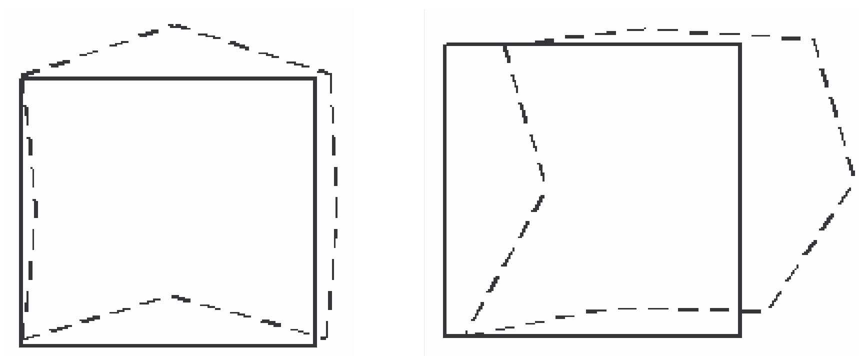
	Frequency (Hz)		Damping ratio (%)	
	NS	EW	NS	EW
Diaphragm	11.41	11.81	1.8	1.9
North wall	11.41	11.81	2.1	2.0
South wall	11.41	11.81	2.3	1.9
East wall	11.41	11.81	1.7	2.1
West wall	11.41	11.81	1.8	2.0

To improve accuracy, the forced vibration tests were next repeated from 10 Hz to 15 Hz with a step increment of 0.1 Hz. The wall and diaphragm responses are plotted in **Figure 5** for NS and EW excitations. From **Figure 5b**, east (Acc10) and west (Acc8) diaphragm responses show a slight increase in amplitude from 10.5 Hz to 10 Hz. This increment was suspected to be associated with individual response of the diaphragm, thus, not related to an overall response of the structure. This is because other fifteen test points recorded were not indicating this increment. Results of the frequencies and damping ratios are summarised in **Table 6**. **Figure 6** illustrates that the identified translational mode shapes corresponded to 11.41 Hz and 11.81 Hz for the NS and EW excitations respectively.



a) NS excitation **b) EW excitation**

Figure 5: Wall and diaphragm responses



a) NS excitation **b) EW excitation**

Figure 6: Mode shapes

5. CONCLUSIONS

Non-destructive forced vibration test results from a small scale URM house are presented. The frequency of 11.41 Hz for the NS mode that was obtained from modal testing was reasonably matched with the FE model of 13.12 Hz. In the case of EW excitation, the frequency mode of 11.81 Hz (from modal testing) showed greater disparity compared to 18.55 Hz (from FE model). In order to achieve a better estimation of the mechanical properties of the structural elements, the information gathered from the modal testing will be used to update the FE model. The joist-wall connections (boundary condition) of the structure in the FE model, which were conservatively modelled at the preliminary stage, may also be improved by performing a model updating procedure. Therefore, FE model updating procedures, which are not presented in this paper, will be established in future studies.

6. ACKNOWLEDGEMENTS

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