DYNAMIC TESTING OF A TIMBER FLOOR DIAPHRAGM IN AN UNREINFORCED MASONRY BUILDING

A.W. Wilson[1], A.R. Abdul Karim[1], C. Oyarzo-Vera[1], P. Omenzetter[1] and J.M. Ingham[1]

[1] *Dept. of Civil and Environmental Engineering , University of Auckland, Auckland, New Zealand*
Tel.: +64 9 3737599 Ext. 84521; fax: +64 9 3737462; Email: awil222@aucklanduni.ac.nz

ABSTRACT :

The flexibility of timber diaphragms in unreinforced masonry buildings has been reported to have a significant effect on the seismic performance of the complete structure. In New Zealand, there currently exists a need to improve the knowledge and expertise associated with the performance of timber diaphragms to assist the seismic assessment of unreinforced masonry buildings and design of seismic retrofit solutions. To address this issue, a series of modal tests were conducted on the third floor timber diaphragm of the Nathan Building located in Auckland's Britomart Precinct, which is a building typical of New Zealand historic unreinforced masonry construction. Preliminary analysis indicates that the fundamental horizontal natural frequency occurs at 20.5 Hz which reasonably matched the finite element model, which predicted a frequency of 18.49 Hz. Further testing, system identification and finite element updating is required to determine accurate dynamic diaphragm properties. An investigation of typical New Zealand diaphragm details was also conducted to aid future testing and finite element modelling.

KEYWORDS: Dynamic testing, forced vibration, diaphragm, unreinforced masonry building, New Zealand

1. INTRODUCTION

Unreinforced masonry (URM) buildings have proven to perform poorly in earthquakes due to their brittle nature and inability to dissipate hysteretic energy. In New Zealand, the introduction of by-laws (DBH 2004) mandating the seismic upgrade of these earthquake-risk buildings, combined with the potential loss of human life and destruction of its heritage structures, has necessitated research focussed on mitigating these adversities. To address a comparative absence of a national platform of knowledge and expertise associated with seismic retrofit or rehabilitation of New Zealand's earthquake-risk buildings, a collaborative research programme named Seismic Retrofit Solutions was initiated in 2005 (Retrofit Solutions (n.d.)).

Typical multi-storey URM construction in New Zealand consists of solid URM walls and timber floor diaphragms. It is widely recognised that the behaviour of these light timber diaphragms is crucial to the seismic response of the complete structure (Abrams 1995; Bruneau 1994). A problem currently exists that researchers and practitioners must predict building response and formulate retrofit solutions based on limited laboratory data and inadequately validated modelling techniques. Practitioners have communicated the need for better data on the dynamic characteristics of heritage timber diaphragms in order to improve the accuracy of their seismic assessments with particular emphasis on data associated with diaphragm stiffness and level of damping.

This article has two purposes. The first is to present typical New Zealand timber diaphragm details collected from case studies of actual URM buildings, that will aid future test planning and ensure representative finite element (FE) modelling. The results from a series of modal tests conducted on the third floor timber diaphragm in the Nathan Building, one of New Zealand's heritage URM structures, is then presented with comparison to a FE model. This form of testing is conducted in the linear-elastic range and is used to establish modal properties such as natural frequencies, mode shapes and modal damping. These results can later be used to refine the initial FE model using sensitivity-based updating techniques that are well established in the mechanical and aerospace industries (Friswell and Mottershead 1995).

2. PREVIOUS RESEARCH

Bruneau (1994) reported that most URM building earthquake-induced failures in the last 20 years were related to the performance of timber diaphragms. This likely motivated the many research studies that aimed to determine the influence of flexible timber diaphragms on the seismic performance of URM buildings (Abrams 1997; Paquette and Bruneau 2003; Tena-Colunga and Abrams 1996). The lack of in-plane shear connection to the URM walls and lively in-plane shear rotation of flexible timber diaphragms has caused significant damage to building corners during past earthquakes (Bruneau 1994). Insufficient positive connections between the URM walls and diaphragm was also observed. This causes the out-of-plane walls to behave as cantilevers and increases the likelihood of out-of-plane failure.

Hunt et al. (2007) explored system level assessment techniques for in-place timber floor systems in historic URM buildings. The fundamental concept of this study was to determine whether timber deterioration due to decay could be identified using forced vibration and static loading to ascertain natural frequency and stiffness respectively. While this method proved successful, it was performed in the vertical direction which can not be emulated in the horizontal direction to determine lateral stiffness. The flexible nature of timber diaphragms was highlighted by the ABK joint venture (1981) who pseudo-statically and dynamically tested fourteen different full-scale diaphragm arrangements. Peralta et al. (2004) further investigated the seismic performance of wood diaphragms typical of pre-1950's URM buildings and found that they could deform beyond the 2% drift limit without significant yielding.

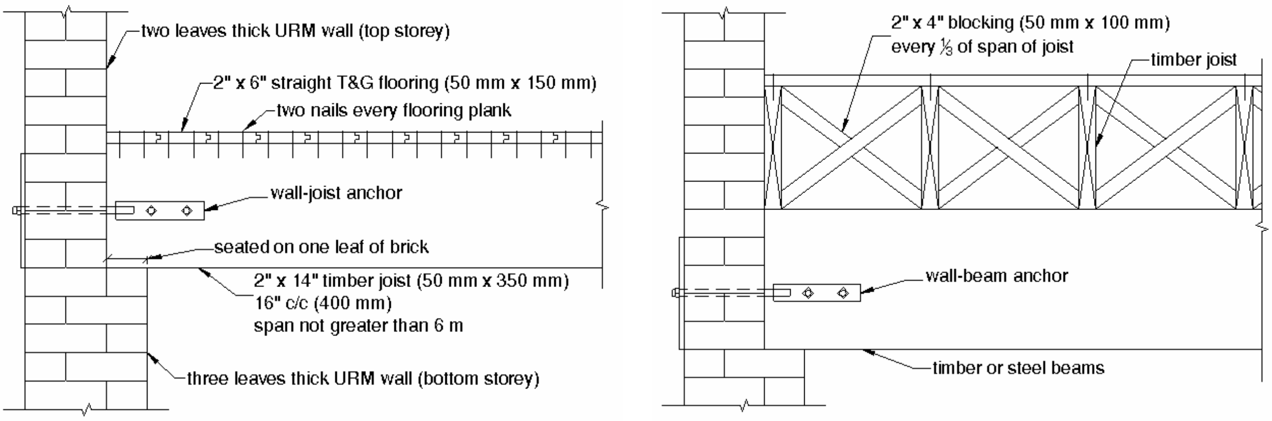
From review of published literature, only Pavic et al. (2007) have reported forced vibration, modal identification and sensitivity-based FE model updating of a floor system. Though the test structure was an open-plan concrete slab diaphragm and the study concentrated on vertical modal properties, the procedure can be entirely emulated to determine lateral modal properties. These lateral modal properties can be used to determine physical dynamic properties such as stiffness and damping that will assist in seismic assessment of URM buildings.

3. TYPICAL DIAPHRAGM DETAILING IN NEW ZEALAND

To ensure that realistic diaphragm construction details are reproduced in laboratory test specimens and that representative FE models are developed, an investigation of typical New Zealand diaphragm details is necessary. To address this, a series of case study URM buildings in Auckland were used in conjunction with consultation with experienced structural engineering practitioners to determine typical details for diaphragm framing arrangements, seating methods and floor-to-wall connections.

3.1. Diaphragm framing

Typical diaphragm framing was constructed by nailing floor planks to joist bearers that were intermediately bridged to prevent lateral buckling and were seated on either timber or steel transverse beams (Figure 1). It was found that lumber used in the construction was native New Zealand hardwoods, such as Kauri, Rimu or Matai, and the nails were punched from sheet iron. It was identified that tongue and groove floor planks measuring 50 mm x 150 mm most commonly occur, except in URM buildings constructed for warehouse purposes, where straight timber planks were used because eliminating floor gaps was not critical. Joists were typically 50 mm x 350 mm spaced at 450 mm centres and not spanning lengths greater than 6 m. Intermediate joist bridging was provided by nailing 50 mm x 100 mm timber boards diagonally to form an X pattern. The typical framing details are illustrated in Figure 1.



(a) Perpendicular to URM wall (b) Parallel to URM wall

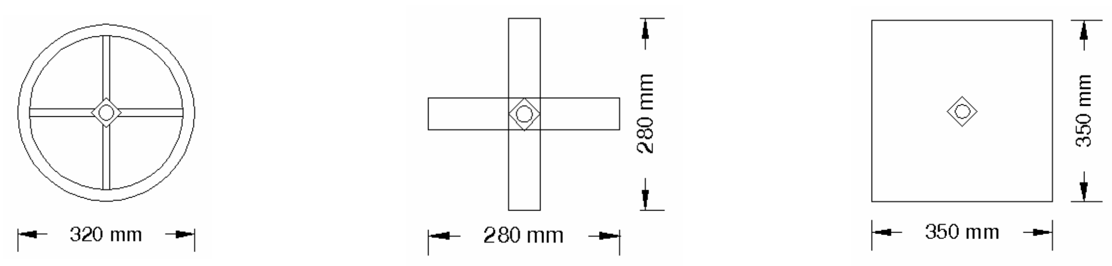
Figure 1: Typical diaphragm details

3.2. Seating method

The URM wall thickness configuration over the height of the building determined the diaphragm seating method. The most common construction practice was to reduce the wall thickness by one leaf at each storey height and subsequently, the most common diaphragm seating method was to bear the joists and transverse beams on a single brick width without embedment. This arrangement is illustrated in Figure 1.

3.3. Floor-to-wall connection

Like most URM buildings worldwide, the degree of floor-to-wall connection was found to be insufficient, ranging from no connection to connections every 3rd joist. Typical New Zealand wall anchors were made up of a steel rod that passed through the URM wall and was attached to the joists using a rectangular connection plate. Exterior connection to the URM wall was provided by either a rosette plate, spike plate or square plate. These common wall anchor bearing plates are illustrated in Figure 2 with typical dimensions.



(a) Rosette plate (b) Spike plate (c) Square plate

Figure 2: Wall anchor bearing plates

4. NATHAN BUILDING

Nathan Building is a five storey URM structure located at 42 Customs Street East in Auckland's Britomart Precinct. It is rectangular in shape and shares its western wall with the adjacent Australis House. All walls are of clay brick URM construction and vary in thickness from three leaves at the top floor to six leaves at the ground floor. Constructed in 1903, the history of Nathan Building extends more than 100 years, beginning with Arthur Hyam Nathan, who commissioned its construction on the newly reclaimed land fronting Customs Street to accommodate his expanding merchant business, A H Nathan & Co. His company continued to operate out of Nathan Building for 67 years before relocating and has since been inhabited by offices, restaurants and retail stores (Bluewater Management Company 2002). A historic and modern picture of Nathan Building are provided in Figure 3.

(a) Circa 1910 (b) Present day

Figure 3: Nathan Building

5. FLOOR DESCRIPTION

Although an outline of typical diaphragm details has been given, a brief report of the specific floor structure is provided with illustrations. The data reported herein is specifically associated with the third floor diaphragm of Nathan Building. It has approximate plan dimensions of 29.2 x 17.7 m, in the X and Y direction respectively. Based on visual inspection and information provided, the timber used in the floor construction is native New Zealand Kauri. The floor structure comprises straight timber planks running in the Y direction that form the floor surface. The planks are nailed to 50 mm x 350 mm timber joists spaced at 400 mm centres running in the X direction. Typical 'X' pattern joist bridging is used (see Figure 4). The joists are embedded into the URM walls and are seated on steel 'I' beams that run in the Y direction, which are seated on the intermediate steel columns (see Figure 4). The floor was vacant at the time of testing. Figure 5 shows the floor plan details, including three large openings that existed at the time of testing.

(a) Cross bracing

(b) Member details

Figure 4: Floor structure detail

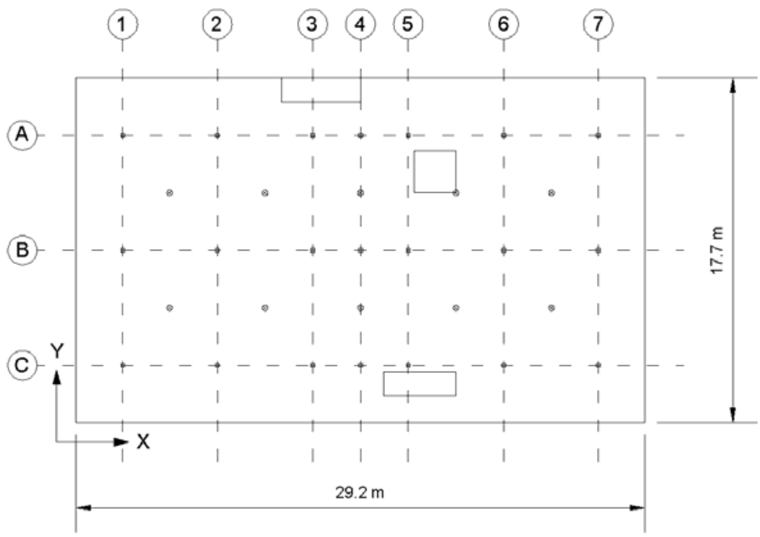
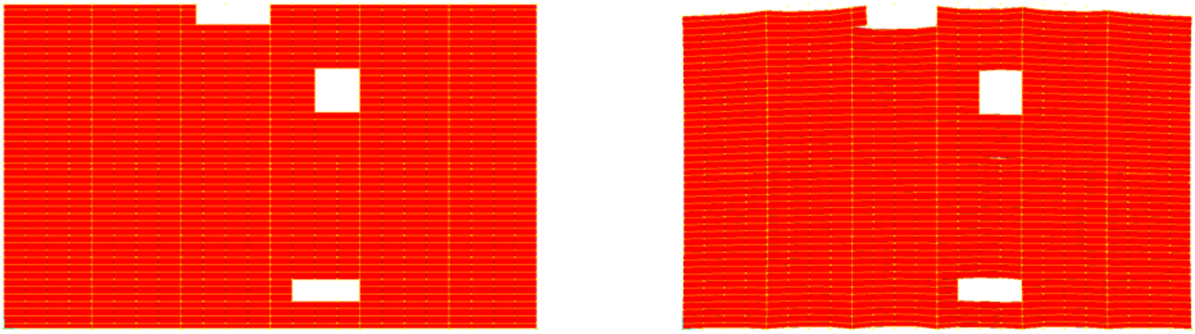


Figure 5: Plan details of the third floor diaphragm

6. FINITE ELEMENT MODELLING

A FE model was developed in SAP2000 v10.0.4 (Computers & Structures Inc 2007) using best engineering judgement. Modelling decisions were based on available information, such as measured dimensions and details from architectural drawings (Salmond Architects 2000), published values for material properties (MSJC 2002; NZSEE 2006; Tomazevic 1999) and idealised floor-wall connections. Joists and sheathing elements were assigned isotropic material properties with a density of 576 kg/m^3, modulus of elasticity of 13 GPa and a Poisson's ratio of 0.49 (Reid 1961). Density was set as 1400 kg/m^3, elastic modulus 3.3 GPa and Poisson's ratio 0.2. The transverse 'I' beams and columns were assigned the SAP2000 default STEEL material property.

The FE model was used to calculate the first one hundred modal properties of the floor diaphragm with frequencies between 12 and 34 Hz. The occurrence of closely spaced modes is common in floor structures due to repetitive geometries and overall symmetry of the construction (Pavic et al. 2007). Of the first one hundred modes only six were displacing predominantly in the horizontal plane, which was the plane of interest. Only horizontal Mode Y1 was initially investigated because it was the most excitable. This mode was predicted to occur at approximately 18.49 Hz. A plan view of the un-displaced and displaced Mode Y1 of the floor are shown in Figure 6.



(a) Undeformed mesh (b) Mode shape of horizontal Mode Y1

Figure 6: Plan view of FE floor mesh

7. MODAL TESTING

7.1. Equipment

Modal tests were conducted using an APS Dynamics Model 400 electrodynamic mass shaker that was operated in horizontal mode to provide a single point of transverse excitation (see Figure 7). A small Crossbow acceleration sensor was attached to the shaker arm for the purpose of recording the input excitation history. Structural response of the diaphragm was measured by seven Jewell Instruments Model LCA-100 accelerometers that were mounted to steel base plates that could be levelled to ensure proper alignment. Data acquisition was performed using an interface between eight straight-through cards in which the accelerometers were connected to and a laptop containing a traditional 6036E National Instruments 16-bit DAQ card. MATLAB was used to issue shaker operation and data acquisition commands, and to also calculate Fast Fourier Transforms (FFT) of the data so that the quality of the measurements could be assessed as the testing progressed. The data acquisition equipment was set up in the adjacent Australis House to avoid any additional local mass affecting floor vibration (see Figure 7). Connection leads were run between the shaker and accelerometers to the data acquisition equipment through an opening in the buildings' shared URM wall.

(a) APS Dynamics Model 400 shaker and Jewell Instruments LCA-100 accelerometers (b) Data acquisition operation centre in the adjacent Australis House

Figure 7: Nathan Building testing

7.1. Test procedure

The procedure adopted for these tests was based upon the work of Pavic et al. (2007). Notable differences include lateral excitation and measurement, and fixing the point of excitation while moving the accelerometer locations. This alternate procedure has no effect on the computation of FFT's and Frequency Response Functions (FRF's). In order to establish sufficiently accurate vibration properties of the diaphragm, including natural frequencies and mode shapes, it is necessary to develop a grid of test points at which FRF measurements are made (Pavic et al. 2007). A larger grid results in a more refined model but is dependant upon the number of channels of instrumentation and time available.

The test was performed in three stages, recording seven accelerometer response signals during each. The grid consisted of 21 test points, divided into three rows in the X direction, labelled A to C, and seven rows in the Y direction, labelled 1 to 7 (see Figure 5). The shaker was located at grid point A4 for all tests, as this was the location of maximum displacement for horizontal Mode Y1 (see Figure 6). Testing commenced with two five minute ambient vibration tests to establish whether any local vibrations or spurious noise signals were to be recorded that were not related to the forced vibration response of the diaphragm. Modal testing of Row A then commenced by applying a stepped sine signal through the shaker and simultaneously recording both the excitation and response signals. The stepped sine signal consisted of a series of sine wave excitation and zero amplitude phases that increased in frequency by a discrete quantity for every next phase. The zero amplitude phase was included to allow any structural response that was related to a particular frequency to dissipate before the new frequency was applied. The test procedure was then repeated for Rows B and C. Details of the tests are outlined in Table 1.

Table 1. Sine step testing summary

Row	Test Number	Frequency Range (Hz)	Step Size (Hz)	Excitation (s)	Zero pad (s)	Total time (s)
A*	1	10-12.5	0.5	30	10	240
	2	13-15.5	0.5	30	10	240
	3	16-18.5	0.5	30	10	240
	4	19-30	0.5	30	10	920
B	5	10-30	0.5	20	5	1025
C	6	10-30	0.5	20	5	1025

*Row A was split into four tests due to shaker operation problems

8. RESULTS

Results presented here utilise FFT operations to establish possible natural frequencies of the diaphragm. FFT's transform the response data from time-domain to frequency-domain, so that the frequency content of the response signal can be interpreted.

8.1. Ambient vibration testing

Ambient vibration tests with and without the accelerometers connected yielded almost identical FFT output plots (see Figure 8). It can be seen that spikes occur at the approximate frequencies 5.5, 8.5, 10.0 and 12.5 Hz. The observed spikes were not caused by structural response but by some spurious electromagnetic signals that were interfering with the data acquisition. This theory is plausible as the large Britomart extraction fans and a construction site with heavy machinery were nearby during the testing.

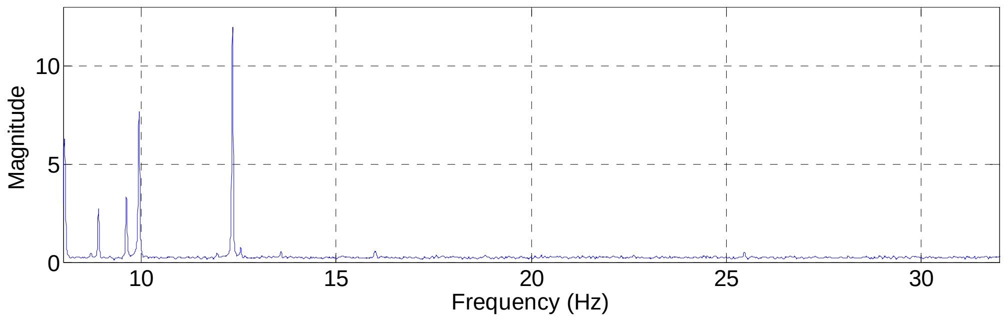


Figure 8: Typical FFT output of ambient test response data

8.2. Stepped sine testing

Results from the three rows of testing were very similar, so only Row A is reported. Frequencies below 13 Hz were ignored due to the spurious signals identified from the ambient vibration tests. It can be seen in Figure 9 that spikes occur at 0.5 Hz intervals, which is expected as the shaker forced excitation at these frequencies. However the magnitude of the spikes increase and decrease around a frequency of 20.5 Hz, indicating that the diaphragm responded most significantly at this frequency. Therefore Mode Y1 was excited at a frequency of approximately 20.5 Hz.

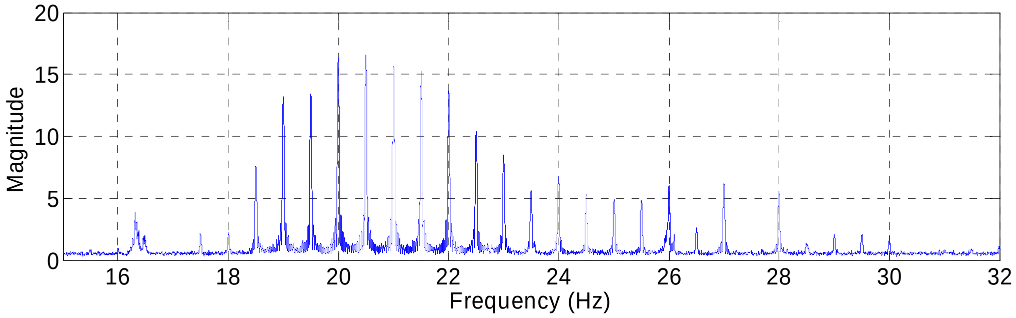


Figure 9: Typical FFT output of stepped sine response data

These preliminary results of the vibration testing are promising when compared to the initial FE model. The measured natural frequency of approximately 20.5 Hz reasonably matches the FE model which predicted a natural frequency for Mode Y1 of 18.49 Hz. Until formal system identification is performed, it can not be confirmed that measured response of 20.5 Hz is accurate and related to Mode Y1.

8. CONCLUSIONS

Practitioners have communicated the need for better data related to the dynamic properties of timber diaphragms in New Zealand URM buildings in order to improve the design of retrofit solutions. To ensure that realistic specimens are constructed for laboratory testing and representative finite element models are developed, typical New Zealand diaphragm details are presented. Dynamic diaphragm properties were determined from in-field vibration tests conducted on Nathan Building, one of New Zealand's heritage URM structures. Preliminary analysis of the vibration data is presented. These results indicate that the natural frequency of Mode Y1 is approximately 20.5 Hz which matches reasonably well with the FE model which predicted a frequency of 18.49 Hz. Further testing, formal system identification and FE model updating is required to establish accurate dynamic properties of the diaphragm.

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