Dynamic performance of timber diaphragms in the 1903 Nathan Building

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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. The current absence of New Zealand specific data has resulted in practitioners adopting assessment guides developed overseas to assist in seismic assessment and the design of seismic retrofit solutions. To address this issue a series of modal tests were conducted on the third floor timber diaphragm in 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 matches the finite element model, which predicted a frequency of 18.49 Hz. Further testing, system identification and finite element updating is intended to be conducted to refine these preliminary results.

1 INTRODUCTION

The retrofit of New Zealand’s earthquake risk multi-storey buildings has become an important issue for practitioners and research groups due to laws set in place by the Building Act 2004. This document mandates that any modification to an earthquake risk building must be met with an increase in seismic performance to at least 33% of current standards. Damage observations from the recent 2007 Gisborne earthquake and larger earthquakes of the past, such as the 1931 Hawke’s Bay earthquake (Dowrick 1998) and 1987 Edgecumbe earthquake (Dowrick 1991; Dowrick and Rhoades 1993) have illustrated the necessity for such regulations and for effective retrofitting of the nation’s earthquake risk building stock.

To address the comparative absence of a national platform of knowledge and expertise associated with seismic retrofit or rehabilitation of the nation’s earthquake risk multi-storey buildings a collaborative research programme named ‘Seismic Retrofit Solutions’ was initiated in 2005 (Retrofit Solutions (n.d.)). This six year research programme is evenly shared between the Universities of Auckland and Canterbury, and is focussed on developing cost effective retrofit solutions. The University of Auckland (UoA) is responsible for the component of the research agenda that considers unreinforced masonry (URM) buildings, which are potentially New Zealand’s most earthquake risk structures due to their brittle nature and inability to dissipate hysteretic energy. URM buildings today represent the predominant architectural heritage in New Zealand and form a significant percentage of its building stock (Russell and Ingham 2008). For these reasons, should a large earthquake strike, New Zealand is at risk of incurring death and injury to human life, losing many of its heritage buildings, and suffering considerable damage and reconstruction costs.

Typical multi-storey URM construction in New Zealand consists of solid URM walls and timber floor

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diaphragms. It is widely recognised that the behaviour of these light timber diaphragms is crucial to the response of the structure as a whole (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, in particular their stiffness, level of damping and floor to wall force transfer capability.

The aim of this article is to present and compare results from finite element (FE) modelling and modal testing of the third floor timber diaphragm in the Nathan Building, located in Auckland’s Britomart Precinct. 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. The desired outcome of this exercise is to refine the initial FE model using sensitivity-based updating techniques that are well established in the mechanical and aerospace engineering disciplines (Friswell and Mottershead 1995). This updating process uses experimental data from in-field testing and aims to produce a FE model that more confidently represents the real-life structure and thus more realistic physical properties are obtained. Due to time constraints, the scope of this paper will be limited to comparison of the initial FE model and experimental modal property results, while sensitivity-based updating will be reported later.

2 PREVIOUS RESEARCH

Bruneau (1994) reported in that most of the 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 approach 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 Peralta et al. (2004) who investigated the Seismic performance of wood diaphragms in pre-1950’s URM buildings. Three timber diaphragms typical of a mid-America ‘firehouse’ were constructed and tested in the laboratory, and it was found that the diaphragms could deform beyond the 2% drift limit without significant yielding (Peralta et al. 2004).

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.

It has been communicated that New Zealand’s current state-of-the-art assessment guide for URM buildings is difficult to follow for the purpose of diaphragm retrofit design. For this reason, and because of the absence of research data on New Zealand URM building timber diaphragm properties, designers are choosing to use assessment guides developed overseas (ABK 1984; ASCE 2007). Dynamic properties of timber diaphragms determined from in-field testing will provide the necessary data to develop a retrofit assessment guide that is relevant for historic New Zealand URM construction.
3 NATHAN BUILDING

3.1 Building description

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. The building comprises open plan timber floor diaphragms with steel encased timber columns providing intermediate structural support. A modern picture of Nathan Building is given in Figure 1.

3.2 History

Arthur Hyam Nathan arrived in Auckland in 1869 to work for his uncle’s merchant firm L.D. Nathan & Co. He continued to work there for a decade until 1880 when, after some acrimony, he left the company to start his own firm. This firm, known as A H Nathan & Co carried on the business as wholesale merchants, selling a range of goods from groceries to Kauri gum. A H Nathan & Co proved very successful and to accommodate the expanding enterprise, Arthur commissioned the construction of a building on the newly reclaimed land fronting Customs Street which he secured a 50 year lease for at auction. Originally named Launceston Building, after Arthur’s birthplace, it was completed in 1903. A H Nathan & Co continued to operate out of Nathan Building for 67 years until 1970 when they sold their Customs Street building and moved to a new warehouse in Ellerslie. Since the vacation of A H Nathan & Co the Nathan Building has been inhabited by many different businesses and organisations using the above ground floors as office space. An Italian restaurant operated out of the ground floor until it was converted into a retail store in recent years (Bluewater Management Company 2002). A picture of Nathan Building circa 1910 is given in Figure 2.

4 FLOOR DESCRIPTION

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 likely to be New Zealand Kauri. The floor structure comprises straight timber board sheathing running in the Y direction that forms the floor surface. The sheathing is nailed to timber joists spaced at 400 mm centres running in the X direction. Cross bracing consists of short wood boards which are nailed diagonally between the joists to form an “X” pattern perpendicular to the joists (see Figure 3). The joists are embedded into the URM walls and are seated on steel ‘I’ beams that run in the Y direction, which are

Figure 1 – Nathan Building present day (on right)  
Figure 2 – Nathan Building ca. 1910 (on right)
seated on the intermediate 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.

![Figure 3 – Timber cross bracing](image3)

![Figure 4 – Under floor detail](image4)

![Figure 5 – Plan details of the third floor diaphragm](image5)

5 **FINITE ELEMENT MODELLING**

A FE model was developed in SAP2000 v10.0.4 (Computers & Structures Inc 2007) using best engineering judgement (see Figure 6). 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). No definitive material properties have yet been documented for New Zealand URM, so values were selected from suggestions in a variety of publications including MSJC (2002), NZSEE (2006) and Tomazevic (1999). 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. 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 Figures 7 and 8 respectively.

6 MODAL TESTING

6.1 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 9). 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 10). Connection leads were run between the shaker and accelerometers to the data acquisition equipment through an opening in the buildings’ shared URM wall.
6.2 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 8). 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>
<thead>
<tr>
<th>Row</th>
<th>Test Number</th>
<th>Frequency Range (Hz)</th>
<th>Step Size (Hz)</th>
<th>Excitation (s)</th>
<th>Zero pad (s)</th>
<th>Total time (s)</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>10-12.5</td>
<td>0.5</td>
<td>30</td>
<td>10</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>13-15.5</td>
<td>0.5</td>
<td>30</td>
<td>10</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>16-18.5</td>
<td>0.5</td>
<td>30</td>
<td>10</td>
<td>240</td>
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<td>19-30</td>
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<td>30</td>
<td>10</td>
<td>920</td>
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<td>6</td>
<td>10-30</td>
<td>0.5</td>
<td>20</td>
<td>5</td>
<td>1025</td>
</tr>
</tbody>
</table>

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

Results presented here are provisional and utilise only basic 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 ‘energy’ at any given frequency can be interpreted. It is intended to undertake formal system identification to confidently determine natural frequencies and mode shapes.

7.1 Ambient vibration testing

Ambient vibration tests with and without the accelerometers connected yielded almost identical FFT output plots (see Figure 12). 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 11 – Typical FFT output of ambient test response data](image)

7.2 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 12 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. Further testing will involve using a stepped sine signal with a smaller discrete frequency increase in order to refine this value.

![Figure 12 – Typical FFT output of stepped sine response data](image)

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.
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. Nathan Building represents typical historic New Zealand URM construction and provides a unique opportunity to address this issue by establishing dynamic properties gathered from in-field testing. Preliminary analysis of 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 will be performed to establish accurate dynamic properties of the diaphragm.

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