Ambient and Forced Vibration Testing and Finite Element Model Updating of a Full-scale Post-Tensioned Laminated Veneer Lumber Building

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M.L. Worth, P. Omenzetter & H. Morris

The University of Auckland, Auckland, New Zealand

ABSTRACT: The Nelson Marlborough Institute of Technology Arts and Media building was completed in 2011 and consists of three seismically separate complexes. This research focussed on the Arts building as it showcases the use of coupled post-tensioned timber shear walls. These are part of the innovative Expan system. Full-scale, in-situ dynamic testing of the novel building was combined with finite element modelling and updating to obtain an understanding of the structural dynamic performance within the linear range. Ambient testing was performed at three stages during construction and was combined with forced vibration testing for the final stage. This forms part of a larger instrumentation program developed to investigate the wind and seismic response and long term deformations of the building. A finite element model of the building was formulated and updated using experimental modal characteristics. It was shown that the addition of non-structural elements, such as cladding and the staircase, increased the natural frequency of the first mode and the second mode by 19% and 24%, respectively. The addition of the concrete floor topping as a structural diaphragm significantly increased the natural frequency of the first mode but not the second mode, with an increase of 123% and 18%, respectively. The elastic damping of the NMIT building at low-level vibrations was identified as being between 1.6% and 2.4%.

1 INTRODUCTION

The Nelson Marlborough Institute of Technology (NMIT) Arts and Media building complex was completed in 2011 and showcases the use of the post-tensioned wall system developed by the University of Canterbury and the Structural Timber Innovation Company, and now branded as Expan. Funding towards the construction of this government owned building was provided by a Ministry of Agriculture and Forestry (MAF) contestable fund.

1.1 *Monitoring of the NMIT Arts and Media building*

A long term instrumentation system has been developed for the NMIT Arts and Media building with additional MAF funding. The system has been designed to monitor the long term static performance of the Arts and Media buildings, the dynamic performance of the Arts building floors, and the dynamic performance of the Arts building in an earthquake or major wind event. GNS Science has collaborated with the University of Auckland and installed high quality dynamic instrumentation for measuring the seismic and wind response and deformation of the energy dissipating devices (Morris et al 2011). This research fitted into the instrumentation program by providing initial information about the Arts building’s dynamic performance and a comprehensive finite element model of the building.

1.2 *Structure and novel technology*

The Arts building contains staff offices and small classrooms and is constructed out of non-moment resisting laminated veneer lumber (LVL) frames for vertical loads. The key innovation is the use of coupled LVL post-tensioned shear walls in both directions. These are one component of the Expan technology. Expan is a form of timber construction based on PRESSS technology developed for precast concrete buildings. The Expan system uses LVL or glued laminated timber and post-tensioning tendons to create a re-centering wall action in a seismic event; energy dissipating devices may also be used. The Expan shear walls are connected to the foundations via post-tensioned Macalloy bars, which allow the walls to rock from side to side in a major earthquake; there are also U-shaped flexural plates used as energy dissipaters between the two panels of each shear wall couple (Morris et al 2011).

1.3 *Aims of the dynamic study*

The dynamic properties of the NMIT building were evaluated during different stages of construction using ambient vibrations. Changes in the building properties during the progress of building construction were analysed to assess the influence of the structural and non-structural components. Stiffness was not directly measured; however, changes in stiffness were inferred from changes in natural frequencies. Forced vibration testing (FVT) was also performed toward the end of construction. FVT results were then used to update a finite element model of the building using a sensitivity based iterative method. This provided a comprehensive finite element model of the Arts building for the NMIT instrumentation program.

2 **RESEARCH ON THE POST-TENSION TIMBER SYSTEM**

2.1 *Scale testing*

The post tensioned moment resisting frames and vertically post tensioned shear walls were evaluated for ultimate seismic performance at the University of Canterbury using quasi-static cyclic testing on a two-third scale two storey building (Newcombe et al 2010). The quasi-static cyclic testing was performed at two stages of construction and deformations were systematically increased well into the non-linear range. The walls showed a linear elastic response for up to 2% drift. The experimental capacity was shown to be 35% higher than the combined design base moment capacity of the walls and columns. Overall the building showed excellent seismic performance, with no significant damage at 2% drift.

Pino et al (2010) conducted uniaxial shake table tests on two one-quarter scale post-tensioned frames to determine the real time response and damping. The frames were three storeys and five storeys high; both of the frames consisted of two adjacent post-tensioned frames that were connected in the short direction by secondary beams and bracing elements. The testing showed that the elastic damping was dependent on the drift level applied to the structure. The sinusoidal testing at the serviceability drift levels gave a minimum damping value of 3% and the ultimate level state drift levels gave a minimum value of 5%. Results from the earthquake records gave a minimum equivalent viscous damping value of 5%, with the rest of the values ranging to 15%. It was also shown that the mass of the frames and the number of connections did not appear to influence the elastic damping values.

2.2 *Displacement based design procedure*

Newcombe (2010) proposed a direct displacement design procedure for the design of the coupled post-tensioned LVL shear wall system. This development was based on the procedure proposed by Priestley et al (2007). It assumed a linear displacement profile and adopted a single degree of freedom idealisation. The equivalent viscous damping, ζ_{eq}, used in the procedure was calculated from the equation:

$$\zeta_{eq} = \kappa\zeta_{el} + \zeta_{hyst} \tag{1}$$

where ζ_{el} is the elastic damping contribution, ζ_{hyst} is the hysteretic damping, and κ a correction factor. The elastic damping contribution was assumed to be 2% for light-frame wood buildings (Filiatrault & Folz 2002). Priestley et al (2007) used the correction factor κ in order to use in the design the equivalent secant stiffness; however for this purpose it was set to one as the 2% elastic damping contribution was arguably already a conservative value. The calculation of the hysteretic damping contribution was more complex and an estimate of the yield displacement was necessary. This meant the design was an iterative procedure for which a calculation was given to assume the yield displacement of the shear walls; this was checked at the end of the procedure and the design iterated if the assumed value was not within a suitable range of the calculated yield displacement (Newcombe 2010).

2.3 *Full scale testing of timber buildings*

A number of full scale or near full scale tests on timber buildings have been reported in the international literature. This work indicated the amplitude and frequency dependence of light timber frame structures, the significance of non-structural elements, the value of instrumentation of real buildings, and finite element (FE) analysis. Some representative investigations are reviewed below.

Sutoyo (2009) used earthquake records from two instrumented light-frame timber buildings and compared these with two- and three-storey shake table records. A representative finite element model was used as a validation tool to assess the accuracy of extracting the building's hysteretic loops from earthquake records. It was concluded that a substantial amount of information about the hysteretic behaviour of timber frame buildings could be extracted from earthquake records such as hysteretic curves, structural deformations and amount of energy dissipated. The seismic record database would substantially benefit from multi-axial sensors placed strategically. The integration of model updating into the investigations was seen as highly useful.

Filiatrault et al (2010) tested a full-scale, two-story, light-frame town house building on two tri-axial shake tables operating in unison. The influence of internal gypsum wallboards and external stucco was investigated. These were shown to improve the seismic response substantially, reducing the first floor drift by 66%. Looking at hysteretic response of the centre of the roof indicated that the wall finishes not only reduced its displacement, but also changed its overall hysteretic characteristics. The timber-only building showed a moderate non-linear response, whereas the other configurations showed an almost linear response. It was concluded that the development of a performance based seismic design method taking into account the effect of wall finishing materials was urgently needed.

Ellis and Bougard (2001) dynamically tested a six-story medium-frame timber building at different stages during construction. The purpose of this was to quantify the difference between the stiffness of the bare timber frame of the building, which was used in the dynamic design, and the stiffness of the complete building. Ambient and forced vibration testing were used to measure the characteristics of all the fundamental modes at three key stages of construction. Results from the experiments showed that the stiffness was increased five-fold for torsion due to the addition of the masonry cladding. The plasterboard and the stairway also had a large effect on the translational stiffness of the building. Results also showed that with increasing seismic amplitudes, modal frequencies decreased and the damping ratios increased. The authors concluded that an important method for the understanding of the building behaviour is using numerical modelling combined with experimental measurements at various stages of construction.

3 **TESTING METHODOLOGY**

Dynamic testing was carried out at six stages of construction on the NMIT Arts building in order to observe the changes of dynamic characteristics of the building due to structural and non-structural components. Ambient testing was performed for all six stages and FVT was also performed for the last stage. However, only three stages, as shown in Table 1, provided reliable data. FVT was performed in order to acquire more reliable dynamic characteristics and to gauge the accuracy of the ambient testing. The information from FVT will be used for FE model updating.

Honeywell Q-Flex QA-750 accelerometers were used to measure the output accelerations for both the ambient vibration testing and FVT. Two APS Dynamics Model 400 ELECTRO-SEIS® long stroke shakers were used to excite the building during FVT. Each shaker is capable of a peak 445N lateral load in the range of frequencies from 1Hz to 12Hz.

For all constructions stages, the accelerometer placements were based on the modal results of an initial finite element model and prior experimental results. The shakers were positioned in several setups in the locations which had relatively large displacements for most of the mode shapes. It was chosen to put the shakers at the third level diaphragm as this would ensure the force excited a number of modes. Testing was performed to determine if full force transferral was occurring between the shear walls and diaphragm in the north-south direction for the short side shear walls, and east-west direction for long side shear walls.

During FVT a sine sweep was run from a frequency of 1Hz to 8Hz over a duration of ten minutes and another from 8Hz to 15Hz; both were sampled at 500Hz. This was deemed a long enough time for the building to reach steady state at the buildings natural frequencies. During ambient testing, sampling was done at a rate of 100Hz for one hour. The records were then analysed and the natural frequencies, mode shapes and damping ratios identified.

Table 1: Stage of construction for dynamic test discussed

Construction stage/test type	Construction progress
Stage 1/ambient testing	Frame, partial concrete floor on level two (no diaphragm action)
Stage 2/ambient testing	Frame, concrete floor, roofing, elevator shaft, shear walls post-tensioned and some external cladding
Stage 3/ambient and FVT	Frame, concrete floor, roofing, elevator shaft, shear walls post-tensioned, external cladding, internal cladding almost finished and staircase installed

4 SYSTEM IDENTIFICATION METHODOLOGY

An in-house system identification toolbox was used to perform system identification (Beskhyroun 2011). The peak picking (Bendat and Piersol 1993), enhanced frequency domain decomposition (Brincker et al 2000) and data driven stochastic subspace identification (SSI) (Van Overschee and Moor 1996) methods were used. Stability diagrams were also produced for the SSI method.

To analyse the ambient data each of the hour-long recordings were broken up into six ten minute sections. The results from these three techniques were compared for similar identified frequencies. The mode shapes of the frequency identified from each method were compared for similarity using the modal assurance criterion (MAC) (Friswell and Mottershed 1995):

$$MAC(\phi_1, \phi_2) = \frac{|\phi_1^T \phi_2|^2}{(\phi_1^T \phi_1)(\phi_2^T \phi_2)} \times 100\% \qquad (2)$$

where $\phi_1$and ϕ_2 are the mode shapes to be compared, and superscript T denotes vector transpose. If the MAC value between each of the three techniques was above 80%, indicating similar mode shapes, then the frequency was considered to be a possible natural frequency. If the possible natural frequency was found in more than one ten minute recording with a simular and reasonable mode shape then it was considered likely that this was a real mode.

FVT provided more reliable results than the ambient testing as there was an improved noise to signal ratio. The peak picking and SSI methods were used to analyse the records. Initially, each sweep record was processed using the peak picking method and the natural frequencies were identified and judged according to the sensibility of the corresponding mode shapes. The data was then processed using SSI, and the identified mode shapes compared to those found from peak picking using MAC in order to gauge their validity. Stability diagrams were used for SSI results in order to gauge the accuracy of the frequency, mode shape and damping values. The peak picking method is an output only method whereas the SSI method is an input-output method; because of this the SSI method was expected to give better quality results, however, peak picking was still useful as a form of comparison.

5 DYNAMIC TESTING RESULTS

The natural frequency, damping ratios and mode shapes of the Mode 1 (the 1st translationally dominant mode) and Mode 2 (the 1st torsionally dominant mode) were found for the three construction stages discussed via ambient and FVT (Table 2). Considering the ambient testing results, the natural frequency of Mode 1 more than doubles between construction Stage 1 and Stage 2 with an increase of 1.6Hz or 123%. This is likely due to the addition of the concrete diaphragm on level two and level three and the post tensioning of the shear walls. The natural frequency does not change as significantly between construction Stage 2 and Stage 3, with an increase of 0.55Hz or 19%. However, the amount of torsion apparent in the mode shape significantly decreases which can be attributed to the addition of the external cladding.

The change in natural frequency for Mode 2 is not as significant between construction Stage 1 and Stage 2 as it was for Mode 1, with an increase of just 0.5Hz or 18%, but is still marked. The change in frequency between construction Stage 2 and Stage 3 was 0.8Hz or 24%, showing that the addition of non-structural elements such as the staircase and cladding contributes significantly to the buildings overall stiffness.

FVT had identified the natural frequency, mode shape and damping ratio for the first four modes with acceptable accuracy. Damping ratios of between 1.6% and 2.4% is consistent in all of the modes, except mode 3 for which damping results were unreliable.

Table 2: Summary of dynamic test results (natural frequencies and damping ratios)

Stage	Frequency	Damping
Stage 1	Mode 1: ambient 1.3Hz Mode 2: ambient 2.8Hz	Mode 1: - Mode 2: -
Stage 2	Mode 1: ambient 2.9Hz Mode 2: ambient 3.3Hz	Mode 1: - Mode 2: -
Stage 3	Mode 1: ambient 3.45Hz, FVT 3.52Hz Mode 2: ambient 4.1Hz, FVT 4.07Hz Mode 3: FVT 6.96Hz Mode 4: FVT 7.42Hz	Mode 1: FVT 1.6% Mode 2: FVT 2.4% Mode 3: - Mode 4: FVT 1.8%

6 MODEL UPDATING

The finite element model was constructed to plan the forced vibration testing and later used for finite element model updating. The updated model would also assist in interpreting results from the instrumentation program. (For preliminary results from the on-going seismic monitoring see Gaul et al (2012).)

Model updating was conducted using the software FEMtools. The FE model used a mixture of frame, spring and shell elements, with member dimensions and sizes taken from building construction plans. FEMtools uses the sensitivity based iterative updating method, formulated from the matrix equation:

$$\partial R = S\ \partial P \tag{3}$$

where ∂P is the change in the model parameters (such as stiffness or mass), ∂R is the error between the current modal properties and the experimental modal properties, and S is the sensitivity matrix (Friswell and Mottershed 1995). The procedure is iterative: changes to parameters are applied until the modal properties of the FE model agree with the experimental ones within acceptable tolerance.

The response values used for updating were picked by evaluating the correlation between the experimental modes and the original FE model modes. When comparing the values, a MAC of 80% was considered a good match. Only Mode 1 and Mode 3 correlated well and their frequency and MACs were used as the response values during updating. The total updating error was assumed to be the sum of the relative absolute value errors between experimental and FEM frequencies and MACs.

The parameters chosen for updating were the stiffness of the LVL, concrete and cladding elements. To choose suitable updating parameters, a sensitivity analysis was performed using the elastic modulus of various materials in the model. Due to the small number of response values only a small number of parameters could be chosen for updating. The elastic modulus was used as member stiffness is proportional to it. However, any increase/decrease in the elastic modulus of the materials indicated in updating could well be due to an error in the material properties, or section properties, or boundary and connectivity condition modelling.

Table 3 shows a comparison between the frequencies and mode shapes (MACs) identified by FVT and those identified by the FE model. The mean relative difference between the four frequencies dropped from 7.4% to 3.0% as the result of updating. It is interesting that while only two frequencies (of Mode 1 and Mode 3) were considered as responses during updating improvement in all fours frequencies can be observed. Also, the overall agreement in MAC values improved markedly form 52% to 71% before and after updating, respectively. The final updated mode shapes are shown in Figure 1.

After updating, the elastic modulus of the LVL increased by 9% indicating that the LVL members were stiffer than anticipated. The concrete stiffness increased by 39%, which is a large increase but could be due to a combination of the concrete being stronger than its 28 day strength and the concrete floors being poured thicker than what the drawings indicated. The stiffness of the cladding dropped by 81% indicating that the assumption of the cladding being fixed to the building elements was incorrect; the large drop could also be due to holes in the cladding (e.g. for windows).

Table 3: Comparison between experimental modes and FE modes

Mode	Experimental frequency (Hz)	Initial FE frequency (Hz)	Frequency difference (%)	Initial MAC (%)	Final FE frequency (Hz)	Frequency difference (%)	Final MAC (%)
Mode 1	3.52	3.71	5.4	78	3.68	4.6	78
Mode 2	4.07	4.43	9.1	25	4.14	1.8	54
Mode 3	6.96	6.48	-6.9	72	6.67	-4.2	71
Mode 4	7.42	6.80	-8.3	32	7.51	1.3	79
Mean absolute value			7.4	52		3.0	71

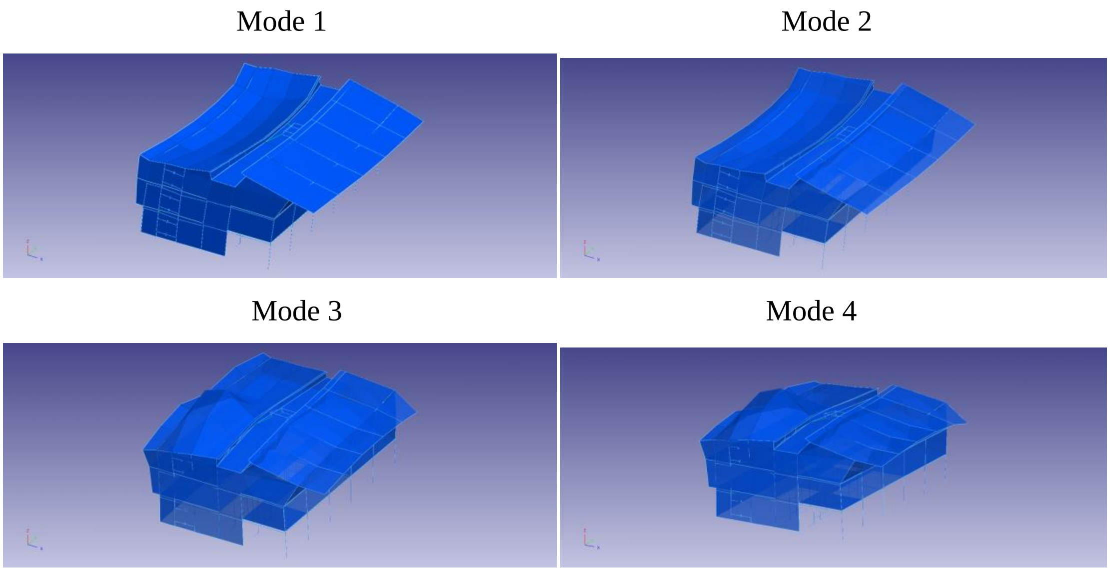

Figure 1. Final updated mode shapes

In order to verify the accuracy of the updated parameters the updating was repeated using starting values perturbed around the final parameter values. The values were each modified by +/-10% and 26 different combinations were used. The results are plotted in Figure 2, where four clusters of final updated values can be seen to be forming. The largest cluster corresponds to the value of mean absolute frequency error of 3.0 and corresponds to the final updating parameters reported above. This confirms that this cluster is the correct updating minimum, and at the same time emphasizes the need to safeguard against updating being trapped in local, suboptimal and/or wrong, minima.

In Figure 2, the updated value for the LVL seems to be relatively stable, however, the updated values for the cladding and concrete vary significantly. The updated parameter value coefficient of variance for LVL is 1%, for concrete 8% and for cladding 9%. The large variance of the concrete and the cladding can be attributed to their relatively low influence on Mode 1 and Mode 3.

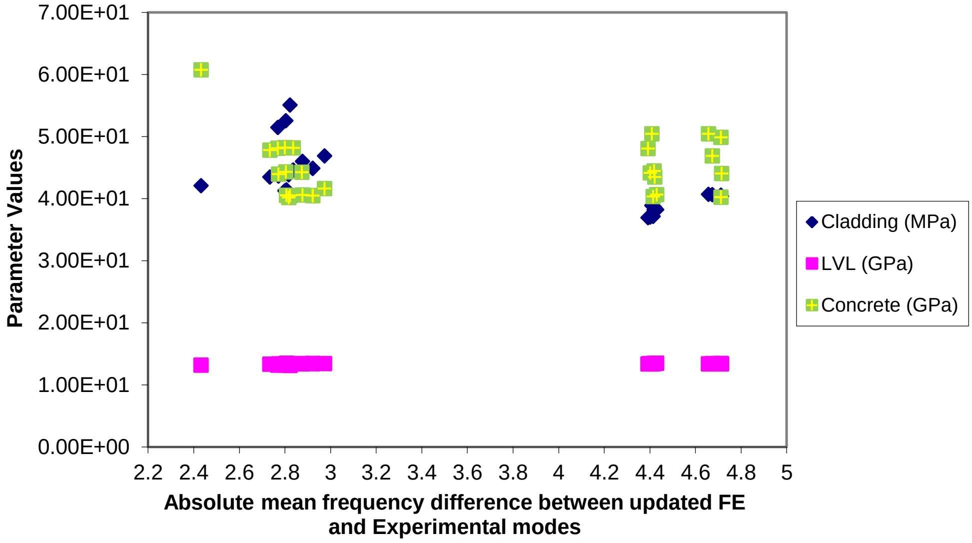

Figure 2. Scatter of updating parameters against relative absolute mean frequency difference

7 CONCLUSIONS

The following observations and conclusions can be drawn from this research:

1. The research has shown the addition of non-structural elements contributes significantly to the global stiffness of the building. The addition of cladding and the staircase increased the stiffness of the building within the linear range. This was shown in the increase of natural frequency for Mode 1 and Mode 2 by 19% and 24%, respectively, between Stage 2 and Stage 3.

2. The influence of non-structural components is consistent with research on light-frame timber buildings, and confirms that the direct displacement design procedure for the shear walls would be improved by accounting for the effect on non-structural elements within the serviceability limit state. Further work would quantify this.

3. The addition of the concrete floor topping as a structural diaphragm significantly increased the stiffness of the Mode 1, but not Mode 2. This was shown by the increase of natural frequency for Mode 1 and Mode 2 by 123% and 18%, respectively, between construction Stage 1 and Stage 2.

4. The damping ratio of the NMIT building at low-level vibrations was between 1.6-2.4%. The elastic damping contribution of 2% was used for the direct displacement design of the post-tensioned LVL shear walls of this building and is appropriate.

5. Forced vibration testing at low level vibrations provided much better data compared to ambient testing. Such tests at different stages of construction are more appropriate than ambient testing for identifying dynamic properties of a real building given the time constraints and vibrational noise of on-site activities.

6. Model updating has helped to give insight into the performance of the building and the level of accuracy of the FE model. Model updating indicates that stiffness of LVL elements had to be increased by 9%, concrete stiffness by 39%, and cladding stiffness decreased by 81%, respectively, compared to the initial assumptions.

7. The complexity of the structure and amount of variability inherent in timber construction made creating a representative model of the building as well as the selection of updating parameters challenging. By combining experimental testing and FE updating a fuller picture of how the building was preforming could be formed which gave a good basis for interpreting results from the long-term instrumentation program.

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