Monitoring the Seismic Performance of a Post-Tensioned LVL Building During the 2011 Canterbury Earthquake Sequence

Rocco DITOMMASO*, Felice Carlo PONZO
DiSGG – University of Basilicata,
Viale dell'Ateneo Lucano 10, 85100 Potenza, Italy
r.ditommaso@unibas.it, felice.ponzo@unibas.it

Tobias SMITH, David CARRADINE, Stefano PAMPANIN
Department of Civil and Natural Resources Engineering, University of Canterbury
20 Kirkwood Ave, Christchurch 8041, New Zealand
tobias.smith@live.com, stefano.pampanin@canterbury.ac.nz, david.carradine@canterbury.ac.nz

ABSTRACT

The following paper presents the seismic performance of a two storey post-tensioned Laminated Veneer Lumber (LVL) building during the aftershock sequence following the 6.3 MW 22nd February 2011 Canterbury earthquake. Composed of walls in one direction and frames in the other, the structure under analysis was originally tested quasi-statically in the structural laboratories of the University of Canterbury (UoC), Christchurch, New Zealand. Following testing the building was demounted and reassembled at the offices of the STIC research consortium on the campus of UoC with several significant changes being made to convert the building from its initial use as a test specimen into a functioning office structure. Close to the beginning of construction the 7.1 MW 2011 Darfield earthquake occurred in the Canterbury area however construction went ahead as planned with the building being almost complete when the more devastating 2011 February event occurred. An array of 3 dimensional acceleration sensors was installed on the building follow completion. Using time-frequency analyses, in this paper we present a general overview of the dynamic buildings performance during these seismic events.

Keywords: *S-Transform, Structural Health Monitoring, Dynamic Identification, Nonlinear Dynamics, Post-Tensioned LVL Building.*

1 INTRODUCTION

Post-tensioned timber construction is an innovative new technology which is currently used in New Zealand in the construction of multi-storey seismic resistant timber structures and is being adopted worldwide. Dynamic structural analysis is an ever-growing research field with innovative methods and technologies continuously being developed.

1.1 The System

Recent developments in the field of seismic design have led to the development of damage control design philosophies and innovative seismic resistant systems. In particular, jointed ductile connections for precast concrete structures have been implemented and successfully validated. One

* Corresponding author

jointed ductile connection, originally developed for precast concrete during the U.S.-PRESSS program (PREcast Seismic Structural System), coordinated by the University of California, San Diego, for frame and wall systems has been particularly successful [1]. This system, referred to as the hybrid system, combines the use of unbonded post-tensioned tendons with grouted longitudinal mild steel bars or any other form of dissipation device

The post-tensioned timber concept has been developed and extensively tested at the University of Canterbury using laminated veneer lumber (LVL), in a system known as Pres-Lam. Extensive medium and large scale testing has been performed [2-4] All of these tests have validated the excellent performance of the system. Several buildings have now been completed using this technology such as the Nelson Marlborough Institute of Technology (NMIT) building as described in [5].

1.2 The Structure

The structure which was analysed was initially a two storey test structure built in the structural laboratory of the University of Canterbury. The open-plan building consisted of lateral resisting post-tensioned timber frames in one direction and post-tensioned shear walls in the opposite direction (Figure 1). The floor of the structure, which was of area 41m^2 on two levels (i.e. a total area of 82m^2), was a timber concrete composite flooring system developed at the University of Canterbury [6].

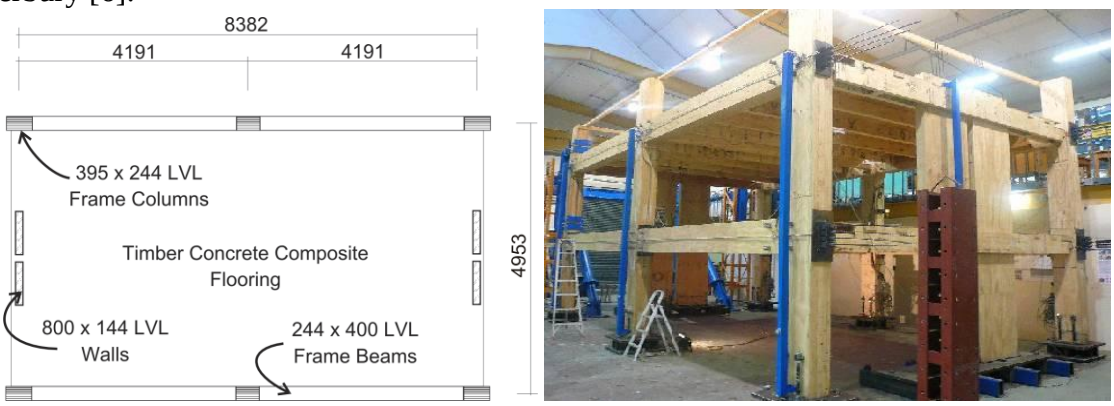

Figure 1 - Pres-Lam Test Building Floor Plan (Left) And Constructed Test Building (Right)

Quasi-static cyclic testing was performed in both the frame and wall directions separately as well as simultaneously. The test building displayed excellent seismic performance with complete recentering and no significant damage up to 2% drift [4]. It was noted that the simultaneous bi-directional loading had no major effect on the in-plane resistance the frames or walls. Once the Pres-Lam test building was completed, a proposal was made to recycle the structural components to form a new office structure for STIC, the Structural Timber Innovation Company (Figure 2).

Figure 2 - The Expan Office Structure For STIC

To transform the experimental building into a new office building, most components of the existing experimental building were fully utilised with over 90% of the structural components being

reused, however due to the original purpose as a 2/3 scale test specimen, some changes had to be made [7]. The building was designed before the September earthquake therefore, the codes in place at the time were used in design (i.e. PGA for Canterbury = 0.22). The building was estimated to have a fundamental period of 0.34 seconds.

2 BUILDING INSTRUMENTATION AND SELECTED RECORDS

The structure was almost fully complete when the February 22nd event occurred however instrumentation had not been yet installed. Instrumentation was installed on the Expan building at the end of March 2011 and consisted of three triaxial accelerometers mounted at the foundation, first floor and second floor. As shown in Figure 3, the first and second floor accelerometers were positioned in the centre of the central beam, while the foundation accelerometer is near the west end of the structure.

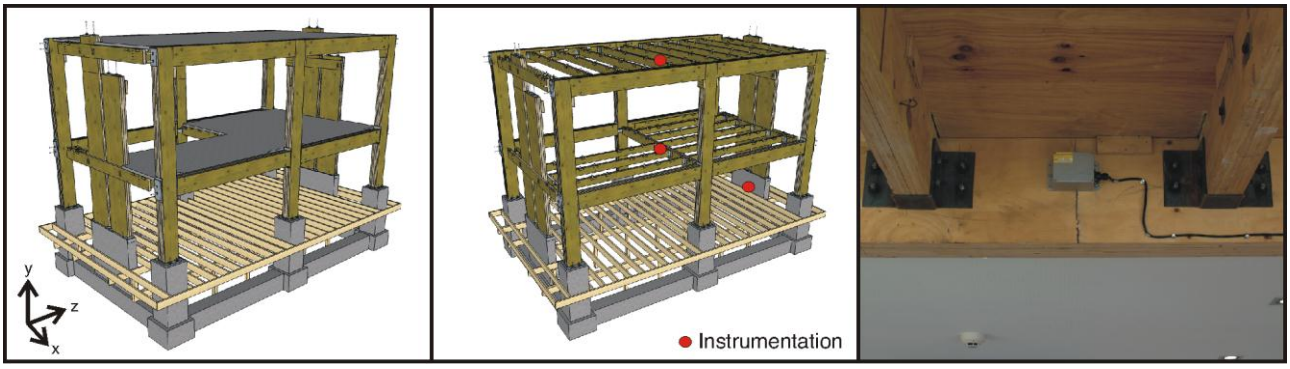

Figure 3 - Instrumentation Layout Placed On The Expan Building, Showing Axes For Recorded Accelerations. Note The Varying Purlin Layout At Each Level, And The Irregular Concrete Diaphragm.

The three instruments represent a full CUSP-3C3 low-noise strong motion unit (24 bit, 200 Hz) with two external sensors. Data is only captured during seismic activity, with a 20 second buffer either side of a threshold-triggering event. Following the installation of the instrumentation trigger thresholds have been surpassed over 1000 times leading to a significant database of records available to the current research. In this paper a selection of 6 records have been chosen based on the largest accelerations measured at the second storey of the building between the installation of the instrumentation and the 1st of October 2011. Information regarding the selected records is presented in Table 1.

Table 1 - Selected Earthquake Used In Study

	Mag.	Depth (km)	Date and Time (CUT)		Date and Time (Local)		Acc. Z (g)
A	6.41	6.92	13/6	2:20 am	13/6	2:20 pm	0.393
B	5.89	8.90	13/6	1:01 am	13/6	1:01 pm	0.437
C	5.54	9.33	5/6	9:09 pm	6/6	9:09 am	0.279
D	5.44	8.67	21/6	10:34 am	21/6	10:34 pm	0.285
E	5.31	8.96	16/4	5:49 am	16/4	5:49 pm	0.173
F	5.24	12.00	9/5	3:04 pm	10/5	3:04 am	0.255

3 STRUCTURAL PERFORMANCE

A series of indicators have been used to monitor building performance during the seismic sequence described. These range from simple visual inspection to advanced techniques including S-transform analysis of acceleration data. Damping has been evaluated using the NonPaDAn [8] method. This section describes and analyses the results of these monitoring data evaluations.

3.1 Visual Inspection

While the Expan building was not constructed during the September 2010 earthquake, it was 95% completed when subject to the February 2011 earthquake. The only building components not installed in February 2011 were the spiral staircase and the railing around the opening of the 2nd floor. Extensive visual inspections verified that the building suffered no damage to the structure, the interior linings or the exterior cladding during the February 2011 event. Additionally, subsequent aftershocks and the earthquakes in June (earthquake A in Table 1) and December 2011 have also not resulted in any damage to any of the building components or the structure.

3.2 Time History Accelerations

The first study made of the data involved the evaluation of the individual time history responses. One of the principle objectives of this was to ensure instrumentation was functioning properly and to study the way in which accelerations were transmitted up the structure. Figure 4 shows the acceleration, displacement and drift recorded during Earthquake A.

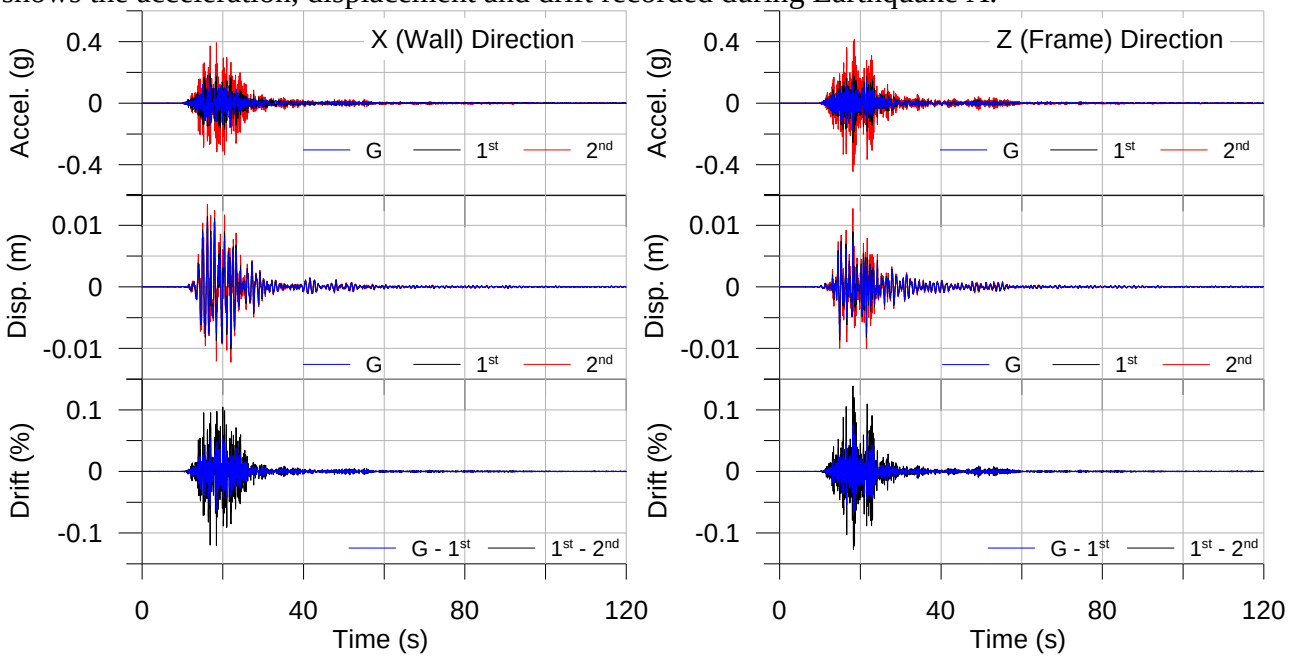

Figure 4 - Time History Response In X (Wall) And Z (Frame) Direction In Terms Of: Acceleration, Displacement And Drift

From the figure showing the acceleration time-history it can be seen that a significant increase in acceleration occured from the base of the structure to the 3rd floor with this effect being larger in the Z (frame) direction. Maximum interstorey drifts recorded were not significant enough to observe the elastic non-linear behaviour which is characteristic of this type of construction system. Interstorey drifts were not constant throughout the structure with larger values occurring at the second level. This is likely due to the large concrete plinths and effectively fixed base connection which were used as shown in Figure 2.

3.3 Spectral Response

The acceleration spectra for the six selected earthquakes are shown in Figure 5. Along with the recorded responses the thick red line shows the design spectrum used as derived from the design parameters stated in Section 1.2.

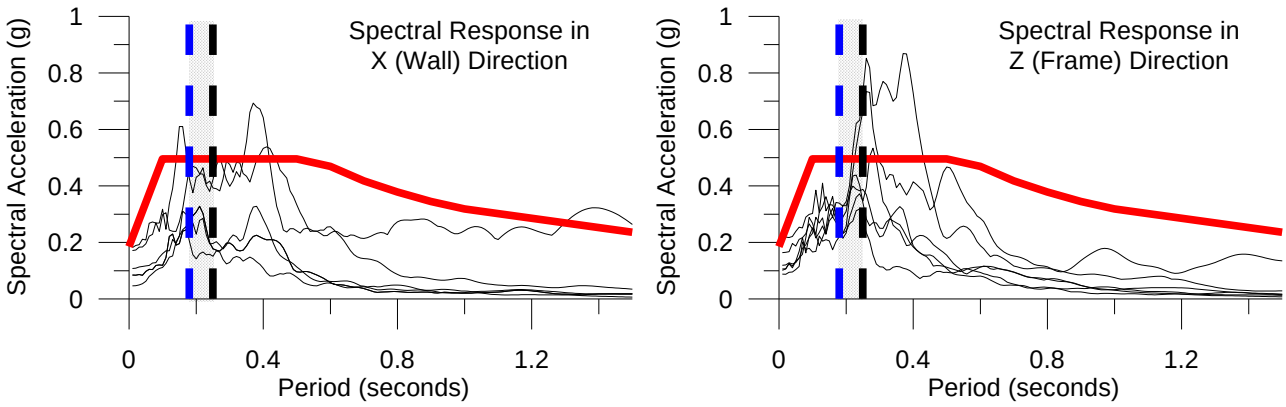

Figure 5 - Acceleration Spectra For Selected Records

Direct comparison between the input spectra and design spectrum shows that on more than one occasion input has been either equal to or above the design value in the range of the building period. This has been calculated to be 0.18 in both directions which has been identified as a possible torsional mode (shown as a blue dashed line in Figure 5). The black dashed line and shaded area indicates the frequency range during forced motion.

3.4 Damping

Damping was evaluated using a method proposed by Mucciarelli and Gallipoli [8] for the simple non-parametric analysis (NonPaDAn) of the damping factor of buildings. This simple method allows the calculation of damping values from a single short input, also under forced conditions, using statistical analysis of decreasing peaks in the displacement, velocity, or acceleration time history response. The damping factor is estimated using the logarithmic decrement method on a minimum of three consecutive decreasing peaks separated by the same period T (within a bracket of ± the tolerance level (ε) as a function of T). Damping values obtained for the structure are shown in Figure 6 which shows the damping in the X (black squares) and Z (red dots) along with the average of the values (red and black continuous lines for X and Z direction respectively). The results of the NonPaDAn method show nominal damping in the system of between 3 and 4%. This is reinforced by the base shear versus displacement plots also displayed in Figure 6. Although the small levels of displacement seen in the structure would indict the absence of non-linearity and thus hysteretic damping in the structure results are congruent with the laboratory testing of Newcombe et. al [4] which displayed only nominal damping up to design drift levels under quasi static loading.

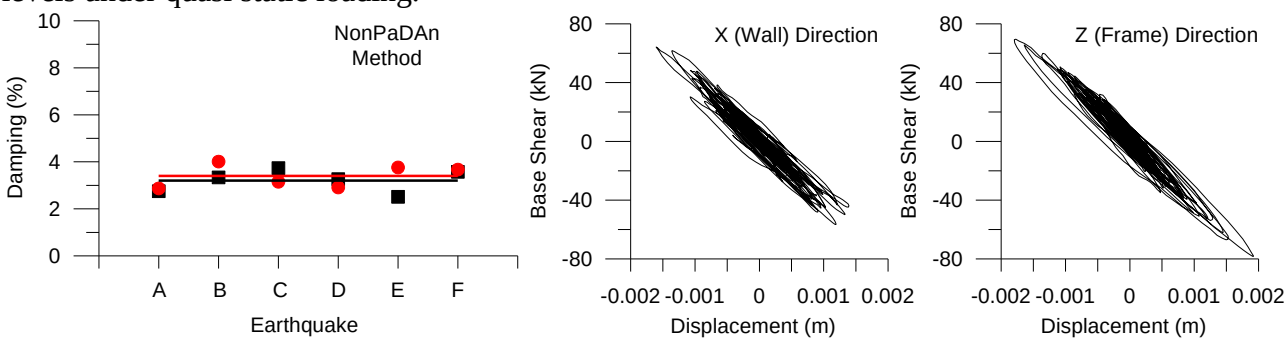

Figure 6 - *Damping of Expan Building under Excitation and Force-Displace plots for Earthquake A*

3.5 Examined Correlations

During the examination of the results obtained from the 5 acceleration records being studied several key parameters which are commonly used in structural dynamic analysis have been

calculated and compared. These parameters were the: Peak Ground Acceleration (PGA), interstorey drift, spectral acceleration at the buildings fundamental period of T = 0.18 seconds and the Housner Intensity. Often used as an indicator for structural damage, the Housner Intensity is evaluated as the area under the velocity spectrum between a given period range [9]. Comparisons between a selection of these parameters are shown in **Errore. L'origine riferimento non è stata trovata.**.

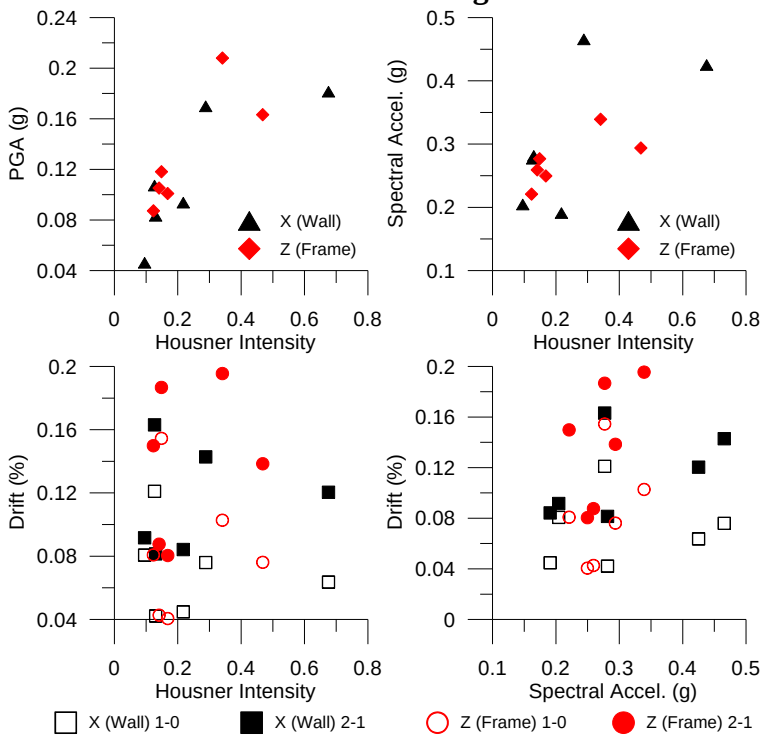

Figure 7 – Comparison Between: PGA, Spectral Acceleration, Drift And Housner Intensity and Drift and Spectral Acceleration

As shown in the figure some correlation was found for the 5 cases studied between the Housner intensity and both PGA and Spectral acceleration. No relation was seen however between the Housner Intensity and interstorey drift. The final comparison made was between the spectral acceleration and interstorey drift which shows a slight correlation.

3.6 S Transform

In recent times several techniques for both signal analysis and structural dynamic identification have been proposed in order to characterise the dynamic behaviour of structures [10]. Most of these techniques are useful in the characterisation of stationary structural behaviour but are not effective when structures display non-stationary and/or non-linear behaviour. One of the most common tools used in the dynamic analysis of systems is the Fourier transform. However, this technique (along with all techniques which are founded on the assumption of stationary system behaviour) is not adequate for the study of a system which changes its characteristics over time.

Although several tools exist for the study of non-stationary signals each come with their own compromise or inherent issue, one method that overcomes most of these limitation is the S Transform [11]. This transform allows the accurate assessment of both the spectral characteristics and their local variations over time. For a signal h(t) the S Transform is described as:

$$S(\tau, f) = \frac{|f|}{2\pi} \int_{-\infty}^{+\infty} h(t) \cdot e^{-\frac{(\tau - t)^2 \cdot f^2}{2}} \cdot e^{-i \cdot 2 \cdot \pi \cdot f \cdot t} dt \qquad (1)$$

Where: t = time, f = frequency and τ = a parameter that controls the position of a Gaussian window along the time axis. This method of analysis has been used on the selected records with the results of the analysis of Earthquake A shown in Figure 8.

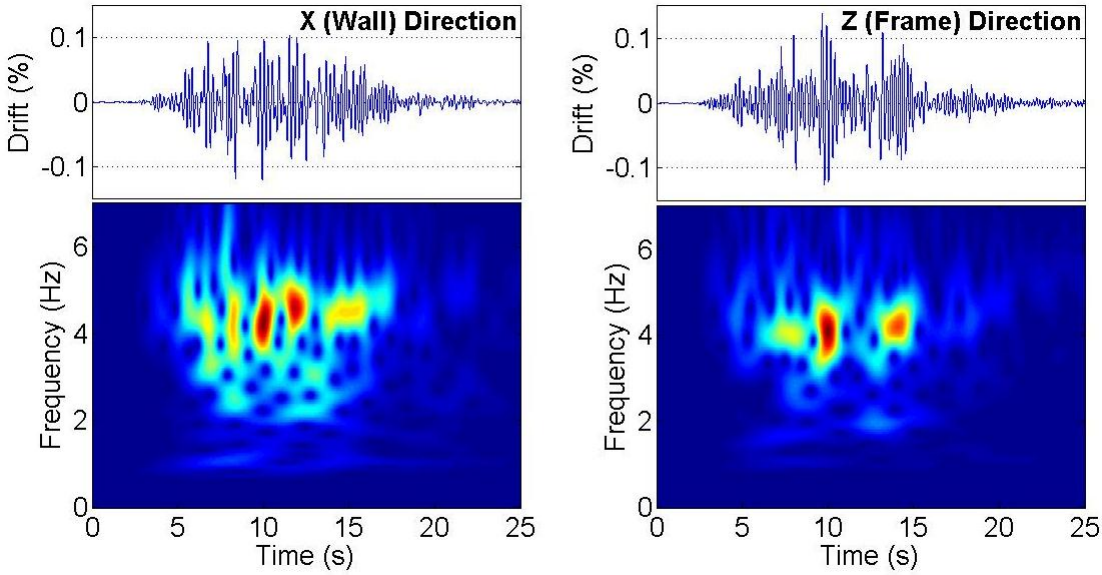

Figure 7 - S Transform of Earthquake A in X and Z direction given Time Frequency Response

The fundamental frequency of the building in both directions is approximately 5.5 Hz which gives a fundamental period of 0.18 seconds. This is lower than the estimated value which was used in design (T = 0.34 s). The closeness of the two values indicates that probably a torsional mode is governing the system response. This is possible and may be arising from the large section of floor which was removed in order to allow for the stairs (Figure 3). From Figure 8 the relationship between the buildings frequency and drift is shown clearly with the buildings frequency drop from its stationary value of 5.5 Hz to a value of approximately 4 during the structures maximum excursions in terms of drift.

4 CONCLUSIONS

The seismic response of a post-tensioned timber building has been studied and the preliminary results have been presented. The structure, which began life as a laboratory test specimen, has been constructed as the offices of the Structural Timber Innovation Company (STIC) on campus at the University of Canterbury and named the Expan Building. The structure was 95% completed when the earthquake of February 2011 struck and has since been subjected to subsequent aftershocks without any damage to building components or the structure.

Three strong-motion sensors were installed on the structure in March 2011 and have registered over 1000 seismic events since activation. The largest six events have been considered for this study and have been shown to be near and in some cases to exceed considered design values (considering that structural design took place before September 2010).The time histories of these records have been studied and show that a significant increase in acceleration is registered from ground input to the second storey with this effect being more severe in the frame direction. All signals were analyzed using both a standard approach, based on the response spectra, and an innovative approach based on the S-Transform. This latter approach allows the analysis of the time-varying behaviour of the building in the time-frequency domain. Study of the time-frequency response of the structure showed that the buildings natural frequency dropped from its stationary value of 5.5 Hz to approximately 4 Hz in correspondence with the building maximum drift. The Housner intensity was calculated and some correlation was found for the 5 cases studied between

the Housner intensity and both PGA and Spectral acceleration. No relation was seen however between the Housner Intensity and interstorey drift. Further analyses are necessary to better understand the non-stationary behaviour of the Expan Building and to better understand the dissipative behaviour of post-tensioned timber buildings during strong motion excitation.

5 ACKNOWLEDGEMENTS

Financial support of STIC is greatly appreciated along with the technical support of Canterbury Seismic Instruments. Thanks also to Ben Carter for assistance in data gathering and instrumentation.

REFERENCES

[1] Priestley, N., Sritharan, S., Conley, J., & Pampanin, S. 1999. Preliminary Results and Conclusions From the PRESSS Five-Story Precast Concrete Test Building. *PCI Journal(November-December 1999)*, 42-67.

[2] Iqbal, A., Pampanin, S., Palermo, A., & Buchanan, A. H. 2010. Seismic Performance of Full-scale Post-tensioned Timber Beam-column Joints. *11th World Conference on Timber Engineering*, Riva del Garda, Trentino, Italy.

[3] Palermo, A., Pampanin, S., Buchanan, A., & Newcombe, M. 2005. Seismic Design of Multi-Storey Buildings using Laminated Veneer Lumber (LVL). *2005 New Zealand Society for Earthquake Engineering Conference*, Wairakei Resort, Taupo, New Zealand.

[4] Newcombe, M. P., Pampanin, S., & Buchanan, A. H. 2010. Global Response of a Two Storey Pres-Lam Timber Building. *2010 New Zealand Society for Earthquake Engineering Conference*, Wellington, New Zealand.

[5] Devereux, C. P., Holden, T. J., Buchanan, A. H., & Pampanin, S. 2011. NMIT Arts & Media Building - Damage Mitigation Using Poat-Tensioned Timber Walls. *9th Pacific Conference on Earthquake Engineering*, Auckland, New Zealand.

[6] Yeoh, D. 2010. Timber-Concrete Composite Floor System, Doctoral Thesis, University of Canterbury, Christchurch, New Zealand.

[7] Smith, T., Wong, R., Newcombe, M., Carradine, D., Pampanin, S., & Buchanan, A. 2011. "The Demountability, Relocation and Re-use of a High Performance Timber Building. *9th Pacific Conference on Earthquake Engineering*, Auckland, New Zealand.

[8] Mucciarelli M. and Gallipoli M. R. 2007. Non-parametric analysis of a single seismometric recording to obtain building dynamic parameters. *Annals of Geophysics*, 50(2), April 2007.

[9] Housner GW. 1952 Intensity of ground motion during strong earthquakes. Second technical report. August 1952, California Institute of Technology, Pasedena, California

[10] Ditommaso R., Mucciarelli M., Ponzo F. C. 2012. Analysis of Non-stationary Structural Systems by Using a Band Variable Filter, *B EARTHQ ENG*. DOI: 10.1007/s10518-012-9338-y.

[11] Stockwell, R. G., L. Mansinha, and R. P. Lowe 1996. Localization of the complex spectrum: the S transform. *IEEE Trans. Signal Process.*, 44. 998–1001.