Seismic performance of core-walls for multi-storey timber buildings

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ABSTRACT: This paper describes the results of experimental tests on two post-tensioned timber core-walls tested under bi-directional quasi-static seismic loading. The half-scale two-storey test specimens included a stair with half-flight landings.

The use of Cross-Laminated Timber (CLT) panels for multi-storey timber buildings is gaining popularity throughout the world, especially for residential construction. Post-tensioned timber core-walls for lift-shafts or stairwells can be used for seismic resistance in open-plan commercial office buildings

Previous experimental testing has been done on the in-plane behaviour of single and coupled timber walls at the University of Canterbury and elsewhere. However, there has been very little research done on the 3D behaviour of timber walls that are orthogonal to each other, and no research to date into post-tensioned CLT walls.

The “high seismic option” consisted of full height post-tensioned CLT walls coupled with energy dissipating U-shaped Flexural Plates (UFPs) attached at the vertical joints between coupled wall panels and between wall panels and the steel corner columns. An alternative “low seismic option” consisted of post-tensioned CLT panels connected by screws, to provide a semi-rigid connection, allowing relative movement between the panels, producing some level of frictional energy dissipation.

1 INTRODUCTION

Multi-storey timber structures are becoming increasingly desirable for architects and building owners due to their aesthetic and environmental benefits. In addition, there is increasing public pressure to have low damage structural systems with minimal business interruption after a moderate to severe seismic event.

Timber has been used extensively for low-rise residential structures in the past, but has been utilised much less for multi-storey structures, traditionally limited to residential type building layouts which use light timber framing and include many walls to form a lateral load resisting system. This is undesirable for multi-storey commercial buildings which need large open spaces providing building owners with versatility in their desired floor plan.

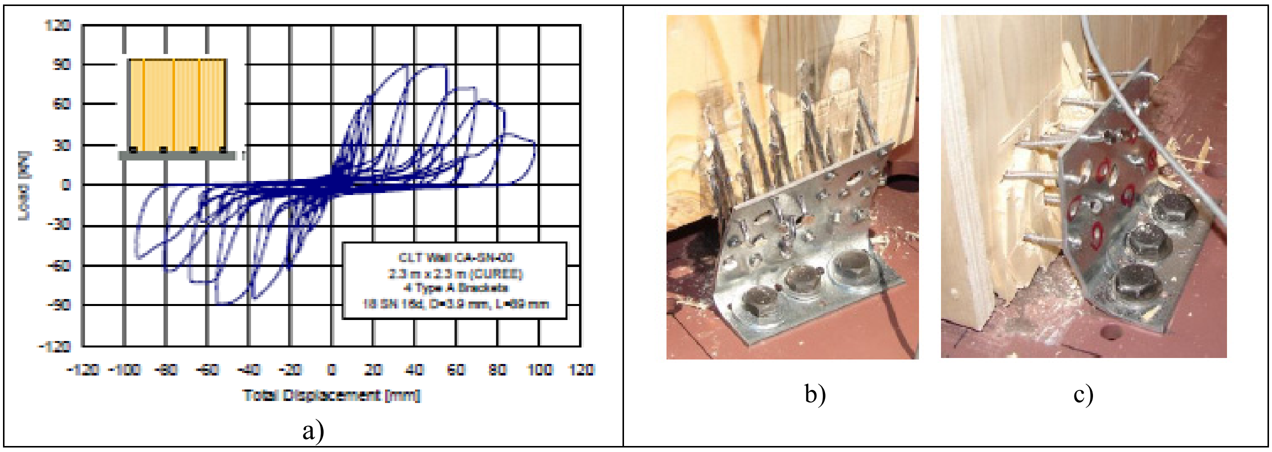
Options are needed for architects and engineers to utilise timber walls around stairwells and lift shafts. To date, little research has been done on lateral load resistance of timber stairwell and lift shaft cores (especially for the Pres-Lam system). There is an urgent need for stairwells to have more seismic resistance, following the potentially disastrous collapse of stairs in a number of buildings in the Christchurch earthquakes.

This paper describes the test results of two post-tensioned timber stairwells solutions tested under bi-directional quasi-static seismic loading and provides recommendations for building designers.

2 MOTIVATION FOR RESEARCH

In research previously conducted (Smith 2006, Palermo et al., 2006, Iqbal et al., 2007, Newcombe *et al.* 2010) and continuing at the University of Canterbury (Sarti *et al.* 2013), the behaviour of post-tensioned timber (LVL) rocking and dissipative single and coupled walls, loaded in plane have been comprehensively investigated . The natural extension was to investigate how the Pres-Lam system could be incorporated into timber walls of different shapes, such as for the purpose of stairwell and lift shaft cores. This research intended to develop technical solutions for Pres-Lam core walls and used the experimental tests to validate the efficiency and practicality of the systems whilst providing practical guidelines for engineers and architects as to use such systems for a number of stairwell layout options.

The use of CLT is steadily growing in Europe (Ceccotti 2008) and Canada (Popovski *et al.* 2011, mgb *et al*. 2012) and is gaining traction in New Zealand since the commissioning of a CLT plant in Nelson by XLam Ltd. To date, the primary construction method for CLT panels is to use screws or similar mechanical fasteners as the connectors. Popovski and Karacabeyli (2011) at FPInnovations in Canada investigated the seismic performance of CLT panels. A variety of panel and fastener layouts were investigated, however, all of the test specimens involved in-plane walls. No L or C shaped configurations were tested. The performance of each specimen was determined and typical results of the test specimens loaded cyclically are shown in Figure 1.



a)

b)

c)

Figure 1. (a) typical hysteretic behaviour of a CLT wall, (Popovski and Karacabeyli 2011); typical damage to angle brackets and fasteners b) during testing, c) following testing (Popovski et al. 2010) (images courtesy of M. Popovski)

It is reported by various authors (Ceccotti 2008,Popovski et al. 2010) that experimental testing on CLT wall configurations showed that CLT structures can have adequate seismic performance when nails or screws are used with steel angle brackets. The definition of adequate seismic performance is in this case debatable. The hysteretic behaviour of the system is influenced heavily by the behaviour of the mechanical fasteners at the base or edges of the wall panels. From Figure 1a, which shows typical hysteretic behaviour of nail type connections, it can be seen that there is a very significant amount of stiffness and strength degradation. For large displacement cycles, large amounts of slip appears to have occurred as the shear fasteners have pulled out from the CLT panels and provide little resistance to further displacement cycles. Typical damage to these types of fasteners is shown in Figure 1b and 1c, where the nails have withdrawn from the timber and yielded. Therefore, following a large earthquake, the structural system would be left with greatly reduced strength and stiffness capacities.

This research was aimed at developing seismic resisting stairwells, which could be either fully independent or detached from a structure, or act as core-walls for the whole or portion of a structure.

3 EXPERIMENTAL TESTING

Two two-storey, ½ scale, stairwell cores were tested under uni and bi-directional quasi-static cyclic loading. The first specimen was referred to as the Low Seismic option consisting of post-tensioned CLT walls screwed together. The second specimen, referred to as the High Seismic option, comprised of post-tensioned CLT walls coupled with UFP devices. Various tests were performed on each specimen, altering the post-tensioned force and connection details. The test setup for both options is shown in Figure 2, 2a shows loading in the X direction and 2b shows loading in the Y direction.

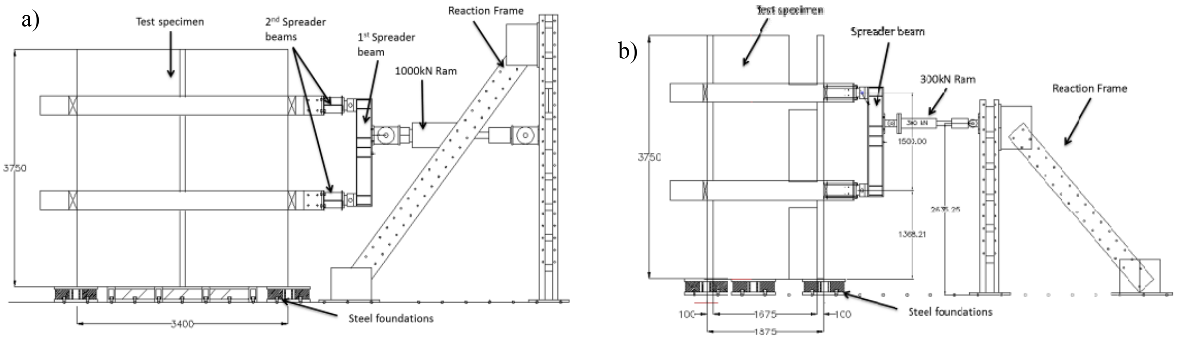


Figure 2. Test setup for a) loading in the 'X' direction, and b) loading in the 'Y' direction

3.1 Low seismicity option

The primary objective of the Low seismic test was to investigate the performance of the rocking system with simple screwed connections. The layout of this specimen consisted of a rectangular tube with two sets of coupled walls in the longitudinal direction and two sets of single walls (one with doorway openings), in the transverse direction as shown in Figure 3a. Horizontal screws connected the coupled and perpendicular panels (Figure 3b). The screws provided a semi-rigid connection, allowing a relative movement between the wall panels. The relative movement caused deformation in the screws which acted as ductile fuses. Seven-wire tendons were used to post-tension the CLT panels as shown in Figure 3c.

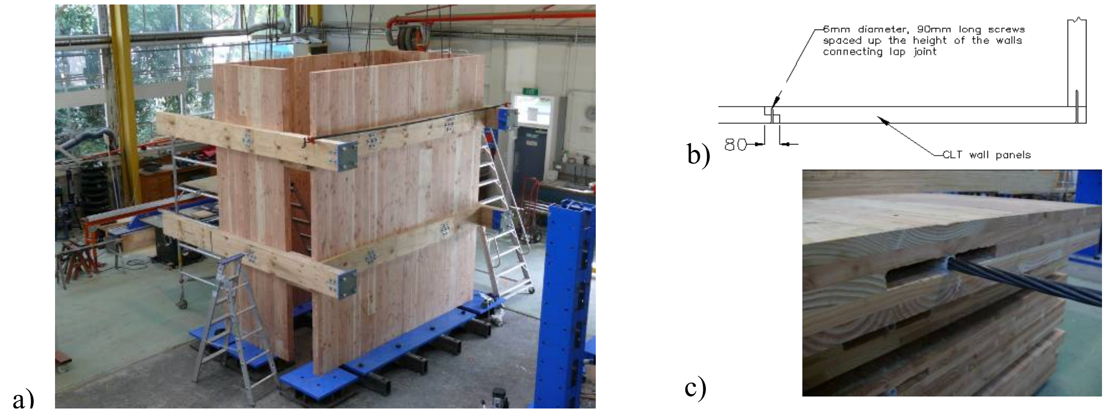


Figure 3. a) Low Seismicity option. Post-tensioned rocking walls with screwed connections acting as ductile fuses, tested at1/2 scale, b) screwed connections between panels, c) post-tensioning tendon

Beams representing the floor slab (Figure 3a) were connected to the walls, such that there were two beams running in the long direction and short direction of the stairwell. The beams represent gravity and drag beams respectively and are part of the floor diaphragm. The loading beams were connected directly to the walls with rings of bolts forming an approximate pinned connection near the centre of each wall (Figure 4b). Due to the direct connection between the beams and the walls, when the walls rock the beams are uplifted as shown in Figure 4a.

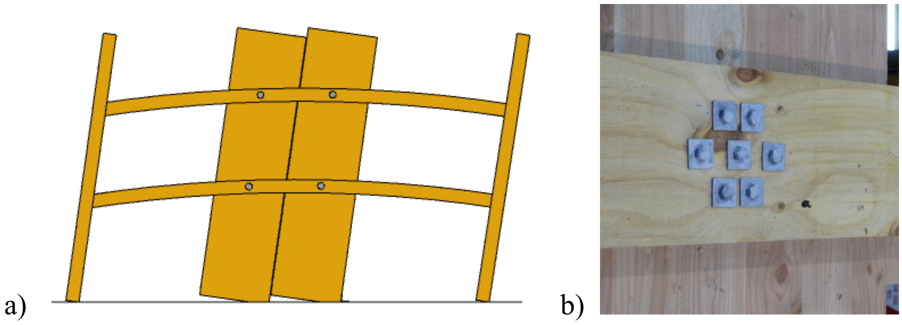


Figure 4. a) Representation of the behaviour of the loading beams for the Low Seismic option, as uplift occurs in the walls, b) pinned connection between loading beams and walls.

3.2 High seismicity option

The lateral load resisting system of the High Seismic specimen was comprised of post-tensioned rocking CLT walls coupled with energy dissipation devices. Energy dissipaters were used in the form of U-shaped Flexural Plates (UFPs) attached between wall panels and the corner columns as shown in Figure 5. The corner columns were steel, square hollow sections. The focus of the testing was not to look at the optimum seismic design; particular attention was instead paid to the construction of the system and its overall seismic behaviour. Reduction of damage to the floors and loading beams was also investigated as part of a larger study into floor and diaphragm behaviour (Moroder 2104).

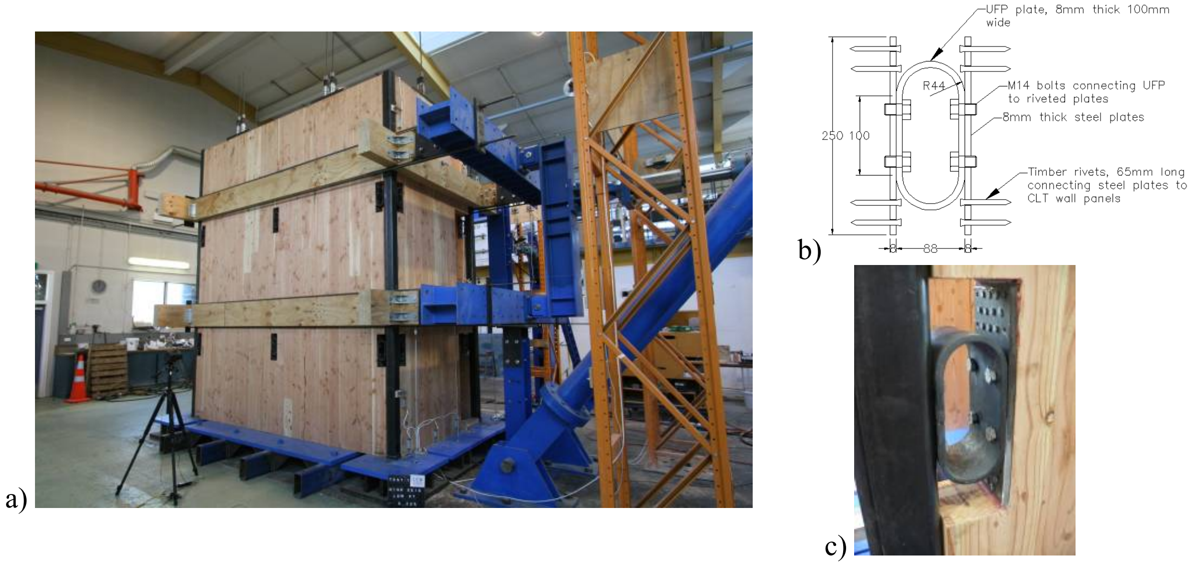


Figure 5. High Seismic option. Post-tensioned CLT walls with UFP devices and steel corner columns, tested at ½ scale, a) General test setup, b) UFP connection details between coupled walls, c) UFP-SHS connection.

Similar loading beams to those used for the Low Seismic specimen were used for the High Seismic specimen; however, the loading beams were connected to SHS corner columns rather than directly into each wall. The post-tensioned wall panels were in contact with the corner columns, such that the load was transferred from the columns to the walls by friction. The objective of applying the load through the columns and then into the walls was to minimise deformations of the flooring system. As the walls rock, one end of the walls will uplift. A representation of the behaviour of the loading beams is shown in Figure 6a. As the walls rock, the loading beams, and hence floor slab, remain level. Figure 6b shows the pinned connection between the SHS columns and the loading beams.

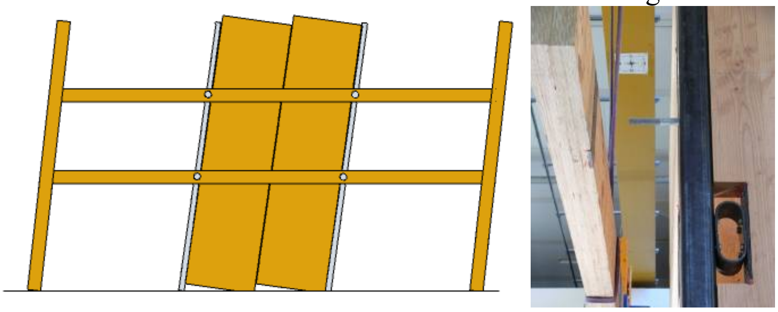


Figure 6. a) Representation of the behaviour of the loading beams for the High Seismic option, as uplift occurs in the walls, b) pin connection between SHS and loading beams, during construction.

4 RESULTS AND DISCUSSION

4.1 Low Seismic option

For the purposes of this experimental investigation, six tests were undertaken. Each test had three primary variables: the post-tensioned force, the number of screws per joint and the type of loading.

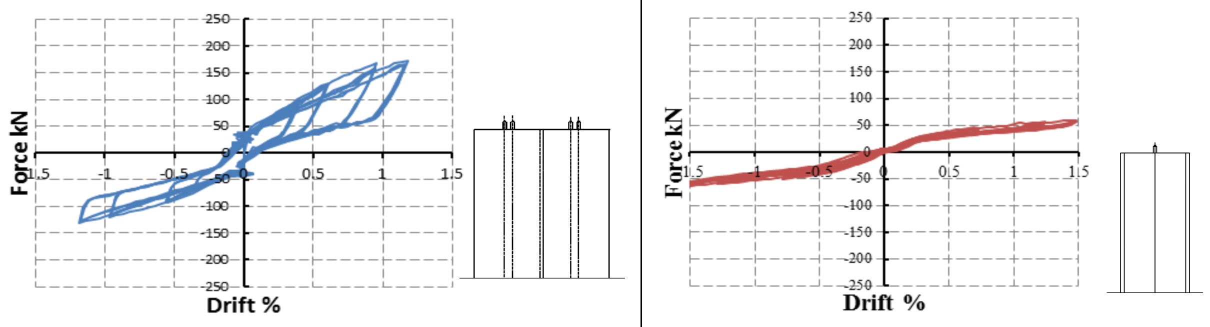
The tests performed are outlined in Table 1. Two seven-wire tendons were in each wall.

Table 1. Summary of the Test schedule for the Low Seismic specimen

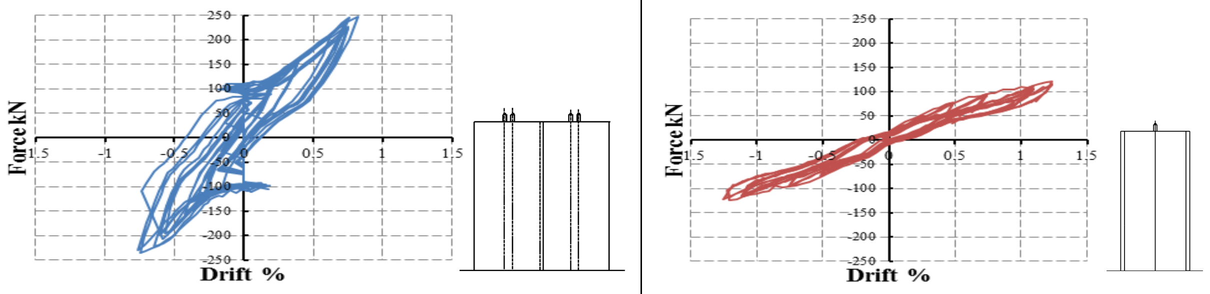
Test	Post-Tensioning	Screws / joint	Loading	Max Drift (%)
1	Low (40kN/tendon)	3	X/Y Separate	1.5
2	Low (40kN/tendon)	20	X/Y Separate	0.5
3	High (100kN/tendon)	3	X/Y Separate	1.5
4	High (100kN/tendon)	3	Clover	1.25
5	High (100kN/tendon)	20	X/Y Separate	1.25
6	High (100kN/tendon)	20	Clover	1.05

Selected test results of the Low Seismic specimen are shown in Figure 7, with full results discussed in Dunbar (2014). Figure 7a and 7b show the results of coupled and single walls respectively for Test 1 with a low post-tensioning force and a low number of screws (3) per joint. Figure 7c and 7d show the results of coupled and single walls respectively for Test 5 with a high post-tensioning force and a high number of screws (20) per joint. The results of the test on the coupled walls have been filtered to remove horizontal slip which occurred in the test rig.

For each test, the coupled walls behaved noticeably different from that of the single walls. The single walls for test configurations with a low number of screws (Figure 7b) displayed the hysteretic behaviour of a wall with only post-tensioning. This behaviour is characterised by a bi-linear elastic response with no energy dissipation. Full re-centring behaviour was observed for these test configurations. For test configurations with a large number of screws (Figure 7d), slightly more energy dissipation was observed in the hysteretic behaviour.



a) Coupled walls-Low PT, Low screws, X direction b) Single wall - Low PT, Low screws, Y dir



c) Coupled Walls–High PT, High screws, X direction d) Single wall – High PT, High screws, Y dir

Figure 7. Selected results from testing of the Low Seismic specimen

For all of the tests, significantly more energy dissipation was observed in the hysteretic behaviour of the pairs of coupled walls than the single walls. Even for the tests with a low number of screws, a large amount of energy dissipation was observed. Whilst some of the energy dissipation was provided by the deformation of screws (Figure 8a), the majority was produced by friction in the vertical joint between the two adjacent wall panels. For the high screws tests (Figure 7c), the effect of having a large number of screws was to restrict the relative movement between the coupled panels. With a low number of screws, the panels were able to ‘rock’ freely, relative to one another. The large number of screws locked the panels together. A greater strength and stiffness was observed for the high screw configurations. However this produced large horizontal forces at the toe of the wall, resulting in inelastic crushing of the timber as shown in Figure 8b.

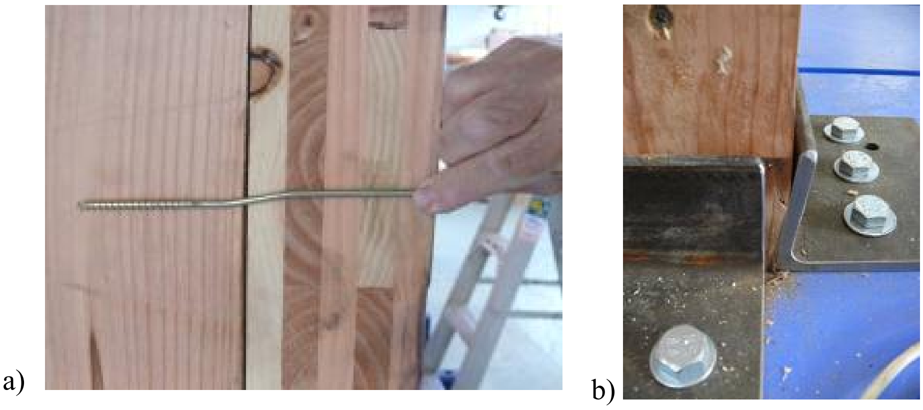


Figure 8. a) deformation of screws connecting perpendicular panels following Test 1 (low screw configuration), b) crushing at the toe of a wall and deformation of the shear key during Test 5 (high screw configuration)

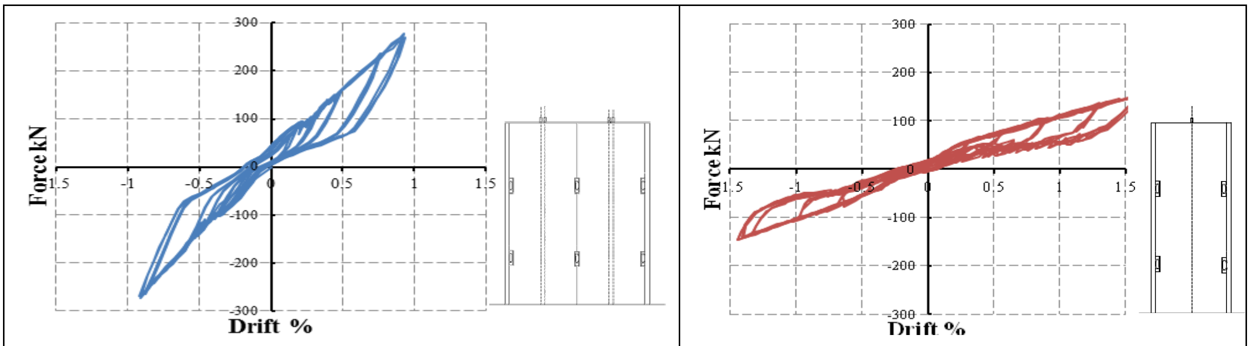
4.2 High Seismic

For the purposes of this investigation, seven tests were undertaken. In a similar fashion to the Low Seismic tests, each test had three primary variables: the post-tensioned force, the number of dissipaters and the type of loading. A summary of the High Seismic test schedule is shown below in Table 2. Two seven-wire tendons were used to post-tension each wall. Each UFP was designed to provide 30kN of shear force.

Table 2. Summary of the Test schedule for the High Seismic specimen

Test	Post-Tensioning	UFPs/ joint	Loading	Max Drift (%)
1	Low (40kN/tendon)	2	X/Y Separate	1.5
2	Low (40kN/tendon)	2	Clover	1.05
3	High (100kN/tendon)	2	X/Y Separate	1.0
4	High (100kN/tendon)	1	X only	1.25
5	High (100kN/tendon)	2	Y only	1.75
6	High (100kN/tendon)	0	Y only	3.5
7	High (100kN/tendon)	0	X only	3

Selected test results of the High Seismic specimen are shown in Figure 9, with full results discussed in Dunbar (2014). Figure 9a and 9b show the results of coupled and single walls respectively for Test 4. Figure 8a and 8b show the results of coupled and single walls for Test 6 and 7 respectively.



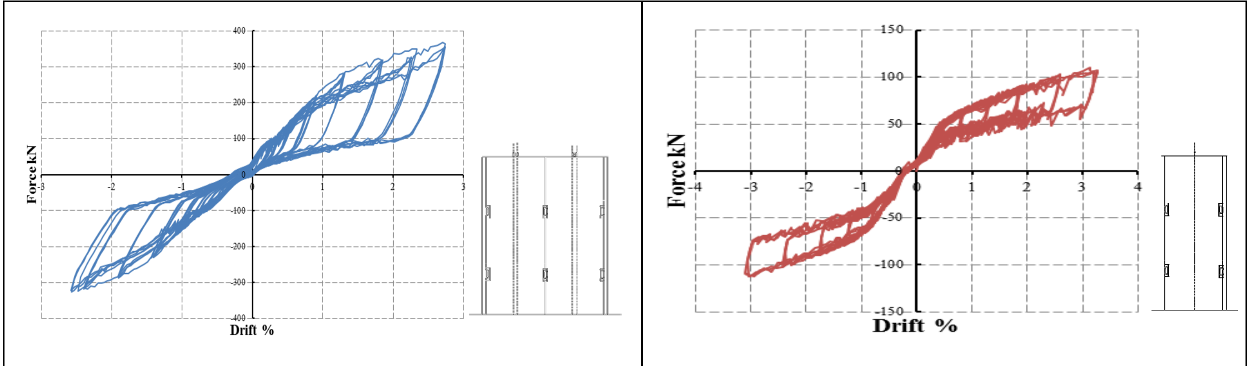
Coupled walls – High PT, 1 UFP per joint

Single wall – High PT, 2 UFPs per joint

Figure 9. Results from testing of the High Seismic specimen for a) Test 4, b) Test 5

For each test, the hysteretic behaviour of the coupled walls was significantly different to that of the single walls (Figure 9). The response of the coupled walls was influenced significantly by friction between adjacent panels. The UFP devices did not have a significant effect on the hysteretic behaviour of the coupled walls as the behaviour was dominated by the friction contribution. From Test 3 to Test 4, one UFP per joint was removed from the coupled walls. It was observed that this had little effect on the strength and stiffness.

Further tests were performed where the UFP devices were removed from the coupled walls (Figure 10a) and the single walls (Figure 10b). A reduction in stiffness and strength was observed. For all walls, especially the coupled walls, a significant amount of energy dissipation was achieved. The single walls displayed the more conventional hybrid hysteretic behaviour, with a bi-linear backbone, energy dissipation and re-centring properties. For the single walls, no stiffness or strength degradation occurred. However, some stiffness degradation was observed in the response of the coupled walls.



a) Coupled walls – High PT, no UFPs

b) Single wall – High PT, no UFPs

Figure 10. Results from testing of the High Seismic specimen for a) Test 6 and, b) Test 7 (note different scales)

5 CONCLUSIONS, AND RECOMMENDATIONS FOR DESIGNERS

5.1 Conclusions

A series of experimental quasi-static cyclic testing under uni- and bi-directional cyclic loading were performed on two ½ scale, two-storey stairwell cores. Key points from the results of the Low Seismic and High Seismic specimens are shown below.

5.1.1 *Low Seismic:*

- The construction of the Low Seismic specimens was simple and rapid, enabled by the prefabrication of the CLT panels and simple screw connections between them. Accurate tolerances were not a concern.
- The Low Seismic specimens were tested with both high and low numbers of screws.

  - The low screw configurations produced the best seismic behaviour, with considerable sliding displacement at the junctions between panels.
  - The high screw configurations gave increased stiffness and strength (150kN to 250kN), but restricted the amount of uplift, causing lateral sliding displacement and some crushing at the base of the walls. These configurations would be better suited to an elastic design procedure.
- For both low and high screw configurations, very little energy dissipation was provided by the deformation of the screws. For all low seismic tests, a large amount of energy dissipation was generated from friction at the vertical joint between the two coupled wall panels in the same plane, and less from the joints between panels at the corners of the stairwell.

5.1.2 *High Seismic:*

- The speed of construction of the High Seismic specimen was limited by the high degree of accuracy required in all connections, especially between the corner columns and the foundation, the panels and columns, the coupled wall connections, and the UFPs.
- Good hysteretic response was observed with excellent energy dissipation and re-centring in all tests. The energy dissipation contribution to the total hysteretic behaviour was significantly influenced by friction between adjacent elements. The friction component of the energy dissipation was greater for the coupled walls than for single walls. For tests where all the UFPs were removed, there was a significant amount of energy dissipation from friction alone.
- The steel corner columns were very effective in isolating the floor system from the uplift of the rocking walls. Minimal vertical displacement of the loading beams was observed during testing. The corner columns were also very effective in acting as shear keys for the panels.

5.2 **Recommendations for Building Designers**

- In simple terms, for buildings in high seismic regions (such as Wellington), the “high seismic” option appears to be more suitable, using post-tensioned walls coupled with UFPs. The influence of friction on the response of the system could be reduced by adding a low friction surface between coupled walls.
- For buildings located in low seismic areas (such as Auckland), the “low seismic” option might result in a more cost-effective design, using post-tensioned walls connected together with screws and designed to be elastic.
- For intermediate seismic areas (such as Christchurch), either a “high seismic” option or a modified “low seismic” option could be considered, using post-tensioned walls connected together with a small number of screws, and some additional dissipation devices such as epoxied steel rods or other dissipaters. See Dunbar, 2014 for further discussion.
- For all seismic zones, particular attention must be paid to preventing horizontal sliding of the panels by providing appropriate shear keys at the foundation.

6 ACKNOWLEDGEMENTS

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