NEW ZEALAND SOCIETY FOR
EARTHQUAKE ENGINEERING

Repair and Reinstatement of Douglas-fir CLT Hold-down Connections using Mixed Angle Self Tapping Screws

T.D.W. Wright, M. Li, M Gedyma, & H. Lim
University of Canterbury, Christchurch.

D. Moroder
PTL | Structural Consultants, Christchurch.

D. Carradine
BRANZ, Wellington

ABSTRACT

The system ductility of timber structures under seismic loads relies on well detailed connection systems. With the increasing popularity of mass timber structures, CLT shear walls provide an efficient seismic load resisting system. In CLT shear walls, hold-downs are often specified as ductile links to provide system ductility. This paper experimentally evaluates cyclic performance of mixed angle screwed hold-downs that are not only easy to implement, but also easy to repair post-earthquake. These connections utilise a mixture of screws installed at an inclined angle and 90 degree to the timber surface. The inclined screws are able to provide high connection strength and stiffness while the 90 degree screws mainly contribute to connection ductility and energy dissipation. Previous research on timber connections using mixed angle self-tapping screws has also indicated that the damage in this connection type is localised around the fastener, with inclined screws pulling out from the timber surface (withdrawal failure), and 90 degree screws causing embedment crushing under the fastener. In this study, a series of cyclic tests were conducted on Douglas-fir CLT hold-downs using mixed angle screw installations. The tested connections were then repaired by first repairing the damaged screw holes with epoxy resin, and then installing new screws with a small offset (half of the original fastener spacing) such that the new screws were installed into undamaged timber. The cyclic performance of the repaired connections was experimentally investigated. The experimental results showed that the repaired connections still had high strength and stiffness, comparable to the undamaged connections.

1 INTRODUCTION

Mass timber buildings continue to grow in popularity as an alternative to traditional steel and concrete construction. As a popular mass timber panel product, Cross Laminated Timber (CLT) has been widely used as wall and/or floor systems in buildings. As with all timber products, CLT panels exhibit brittle ultimate failure in bending and shear. Therefore, if ductility is required for seismic demands, this can not be provided through the timber material itself, and must instead be provided in the connections.

Mixed angle self-tapping screws are one such connection system that can provide ductile connections between CLT panels. Mixed angle screws are a concept first developed in Europe by Tomasi (Tomasi et al., 2006) and further developed in CLT wall systems by other researchers (Brown et al., 2020; Hossain et al., 2018). Screws are installed at two different angles of installation relative to the timber surface. Screws installed at an inclined angle relative to loading e.g. 45 degrees, have high initial stiffness and strength, but lack ductility or displacement capacity. Screws installed at 90 degrees to loading have low initial stiffness, but high ductility and displacement capacity. By combining screws of both installation angles in a joint we can optimise the connection seismic behaviour such that it exhibits high strength, high initial stiffness and high ductility / displacement capacity. Recent research at the University of Canterbury has developed this mixed angle screw hold-down connection solution for the steel to timber hold-down interface at the base of CLT walls (Wright et al., 2021).

From the outset, timber research in New Zealand has been at the forefront of developing low damage design in timber, most notably the Pres-Lam system (Moroder et al., 2018; Smith et al., 2014). A key finding of the Canterbury Earthquakes Royal Commission was the need for low damage design, with new connection systems being developed aiming to satisfy this philosophy (Canterbury Earthquakes Royal Commission, 2012). In conventional timber buildings, damage due to seismic loads is often concentrated in the connections. This, combined with the workability of the timber material, means conventional timber connections (non-post-tensioned) can be an ideal example of low-damage design through reparability. This paper explores one solution for low damage design through the repair and reinstatement of conventional timber connections using mixed angle self-tapping screws.

2 EXPERIMENTAL PROGRAMME

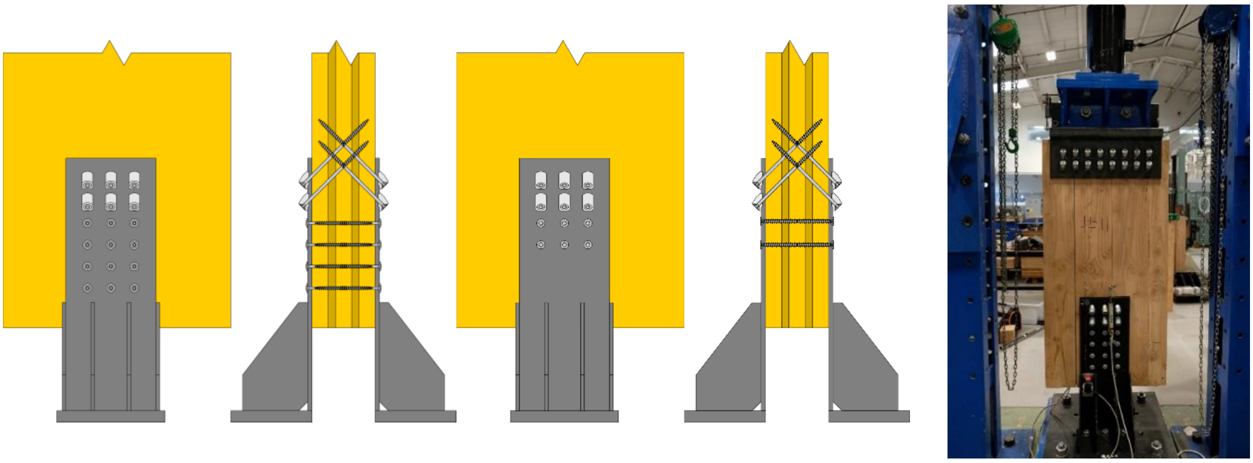
The objective of this study was to determine the suitability of mixed angle screw connections for repair, and evaluate one possible method of repair and reinstatement in CLT wall systems that have experienced inelastic deformation due to earthquake events. Key properties to determine were strength and stiffness, and displacement capacity of both original and repaired connection specimens, so these properties could be used to evaluate the proposed repair methodology.

2.1 Test Programme

Table 1 lists the test matrix including the size and amount of the screws, number of replicates, and loading types (monotonic and cyclic). A total of 16 tests were undertaken with two different mixed angle screw arrangements. All tests utilised mixed angle screw hold-down connections as described by Wright et al. (Wright et al., 2021). Test Set 1 used 12 SPAX ϕ12x260 mm partially threaded (PT) screws installed on a 45 degree inclined angle, and 24 ϕ10x180 mm PT screws installed on a 90 degree angle to the grain. Similarly Test Set 2 used 12 ϕ12 mm by 260 mm inclined screws, but for 90 degree screws used 12 ϕ12 mm by 180 mm screws instead. These screw layouts are shown in Figure 1a and Figure 1b, respectively.

Table 1 – Summary of Test Programme

Test Set	Inclined Screws		90 Degree Screws		Ratio	Original Replicates		Repaired Replicates	
	Qty	*Size*	*Qty*	*Size*		*Monotonic*	*Cyclic*	*Monotonic*	*Cyclic*
1	12	12x260 PT	24	10x180 PT	1:2	1	3	1	3
2	12	12x260 PT	12	12x180 PT	1:1	1	3	1	3



a – Test Set 1 fastener layout *b – Test Set 2 fastener layout* *c – Test Setup*

Figure 1 – Fastener layouts and test setup

Test Setup

Testing was conducted using a 1000 kN hydraulic actuator in conjunction with a steel reaction frame. Steel hold-down brackets were used either side of a 5-ply 175 mm thick Douglas-fir CLT panel with a 45/20/45/20/45 layup, as shown in Figure 1. All screws were supplied by SPAX Pacific and inclined angle washers by Rothoblaas were used for inclined screw installations. A loading rate of approximately 0.2 mm/s was used for both monotonic and cyclic tests. The cyclic loading protocol followed the ISO16670 test standard and was based on the monotonic tests (International Organization for Standardization, 2003)

2.2 Repair Methodology

Properly designed and installed mixed angle screw connections cause very localised damage to the timber panel. This localised damage leaves the integrity of the timber panel itself intact, with the damaged screws able to be withdrawn and removed. It is also recognised that timber connections utilising external steel side plates have a key advantage in that fasteners inserted from the outside can be easily removed post-earthquake. Inclined screws experience local withdrawal failures with shearing of wood fibres around their threads. 90 degree screws experience local crushing or embedment failure around the screw shank. Based on the localised damage observed, a two-step repair and reinstatement process was employed.

2.2.1 Step 1: Repair with epoxy

The first step is to repair the damage to timber caused by the withdrawal of inclined screws, and the lateral deformation of the 90 degree screws. This is shown in Figure 2. First the holes are cleaned of loose timber fibres. For the inclined screw holes, this is done by reaming the hole with a drill bit sized to suit an epoxy injection tube. For the 90 degree screw holes, the loose timber on the edges of the hole is removed by hand with a chisel and pliers, or by using a handheld router to trim the edges of the hole. These holes are then blown out with compressed air to remove any remaining timber fibres or dust. Epoxy is then injected into the holes making sure that the epoxy can penetrate and fill the entire hole. In this study Hilti HIT RE-500 was used, with an extension tube being used to inject epoxy into the base of the hole similar to conventional use in concrete construction. Excess epoxy was cleaned off, and once cured the area sanded to remove any remaining excess epoxy from the timber surface.

2.2.2 Step 2: Shift and reinstate fasteners

The second step is to shift and reinstate the connection with brand new fasteners. Due to the localised damage, the connection can be shifted and fasteners reinstalled at a small offset from the original damaged holes. When repairing with epoxy it is important to install new fasteners at an offset to the repaired holes as this avoids installing fasteners into the much stiffer and stronger epoxy. In this testing, the new fasteners were installed half way between the damaged holes. i.e. half a spacing either side to epoxy. As original fasteners were spaced at 2.5d (30 mm) a shift of 15 mm was used.

A – Damage post original test　*B – Removal of loose fibres with pliers*　*C – Blowing out of dust*

D – Injecting of epoxy　*E – Epoxy post smoothing*　*F – Finished repair ready for new fasteners*

Figure 2 – Repair Process

3 RESULTS

Table 2 provides a summary of experimental testing results, showing the key properties determined for all 16 tests including yield strength, F_y, yield displacement, Δ_y, ultimate strength, F_u, ultimate displacement, Δ_u, stiffness, K, and ductility, μ. These were calculated in accordance with EN12512 (British Standards Institution, 2001). The 30 mm limit on ultimate displacements stipulated in EN12512 was not applied to allow proper evaluation of the highly ductile joints being tested.

Table 2 – Results summary for connection tests

Test	**Repair**	**F_y (kN)**	**F_{max} (kN)**	**F_u (kN)**	**K (kN/mm)**	**Δ_y (mm)**	**Δ_u (mm)**	**μ**
1.1 Monotonic	Original	524	643	515	223	1.97	38.7	19.7
	Repaired	*555*	*653*	*522*	*211*	*2.37*	*37.9*	*16*
1.2 Cyclic	Original	506	622	498	230	1.95	39.8	20.4
	Repaired	*561*	*658*	*527*	*226*	*2.17*	*38.4*	*17.7*
1.3 Cyclic	Original	492	609	487	256	1.67	39.1	23.4
	Repaired	*562*	*621*	*497*	*192*	*2.71*	*36.9*	*13.6*
1.4 Cyclic	Original	537	633	506	249	1.82	39.6	21.7
	Repaired	*579*	*692*	*554*	*253*	*1.96*	*39.5*	*20.1*
2.1 Monotonic	Original	354	466	373	411	0.733	38.9	53.1
	Repaired	*424*	*484*	*387*	*260*	*1.51*	*36.7*	*24.4*
2.2 Cyclic	Original	447	515	412	233	1.74	40.7	23.4
	Repaired	*431*	*521*	*417*	*237*	*1.59*	*40.3*	*25.3*
2.3 Cyclic	Original	403	494	395	301	1.2	38.1	31.7
	Repaired	*410*	*507*	*405*	*330*	*1.13*	*36.7*	*32.4*
2.4 Cyclic	Original	451	512	410	241	1.71	36.9	21.6
	Repaired	*458*	*542*	*433*	*303*	*1.34*	*34.8*	*25.9*

4 DISCUSSION

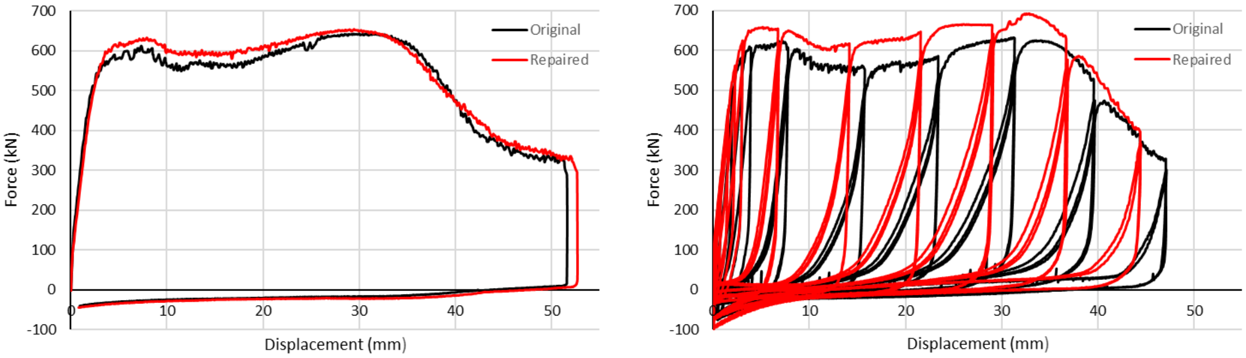
4.1 Performance of mixed angle screws

Previous research has shown the ability of mixed angle screws to provide a strong, stiff, and ductile connection (Brown et al., 2020; Hossain et al., 2018; Tomasi et al., 2006; Wright et al., 2021).

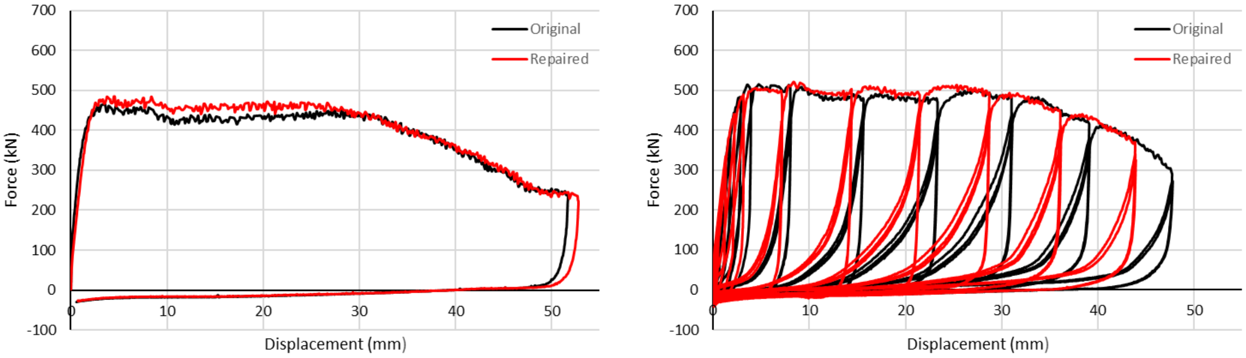
The results presented in Table 2 confirm the high strength and high initial stiffness of mixed angle screw connections. Test Set 1 has an average yield strength of 515 kN and an average initial stiffness of 240 kN/mm. Test Set 2 has an average yield strength of 414 kN and an average initial stiffness of 297 kN/mm.

From Figure 3a and b, it can be seen that Test Set 1 using 12 inclined fasteners and 24 10 mm diameter 90 degree fasteners has greater ultimate and yield strengths than Test Set 2. Test set 1 reaches a clear initial peak at a displacement of approximately 5 mm, where the inclined screws reach their maximum capacity, followed by a drop as the inclined screws withdraw from the timber. The second peak at a displacement of approximately 30 mm corresponds to the 90 degree screws reaching their maximum capacity.

Test Set 2 reaches an initial peak at approximately 5 mm displacement as shown in Figure 3c and d, but in contrast to Test Set 1 has no second peak at approximately 30 mm due to the reduced number of 90 degree screws decreasing the load carrying capacity at high displacements. Covered in more detail by Wright (Wright et al., 2021), this shows how inclined to 90 degree screw ratio can be used to adjust the performance of the overall connection.



a – Test Set 1 Monotonic *b – Test Set 1 Cyclic*



c – Test Set 2 Monotonic *d – Test Set 2 Cyclic*

Figure 3 – Load displacement curves showing original vs repaired connections

4.2 Strength

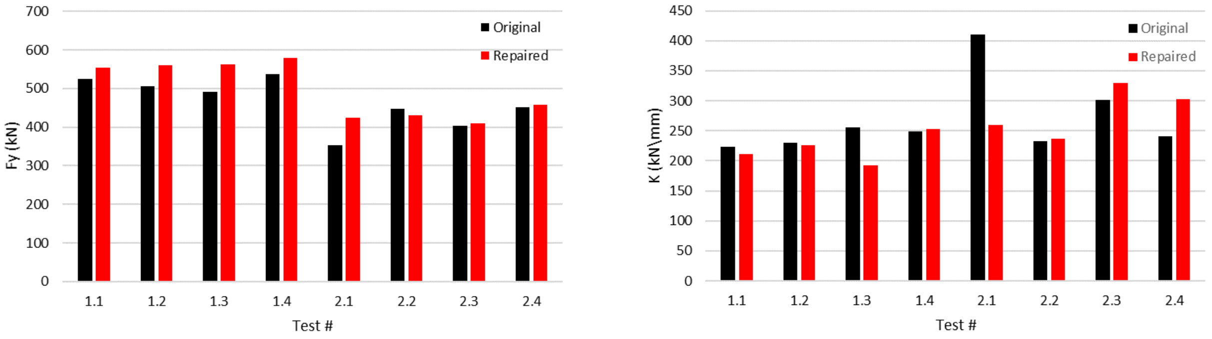
A comparison of yield strength between original and repaired tests is shown in Figure 4a. It can be seen that yield strength has increased slightly among all repaired tests. This is confirmed through a statistical hypothesis t-test where it is found yield strength of the repaired tests is greater than the original test at a 5% level of significance. Therefore, there is a statistically significant increase in yield strength after the repair.

This increase in strength could be due to two factors: 1) some of the inclined fasteners may hit layers of epoxy on installation. This would lead to an increase in withdrawal strength in the inclined fasteners, and be evident on the initial peak seen in Figure 3; and 2) the epoxy may provide a local reinforcement of the timber and increase the bearing strength of the nearby 90 degree fasteners. This would lead to an increase in shear strength of the 90 degree fasteners and would be seen as a slight increase across the full displacement range, partially apparent where the 90 degree screws hit their max capacity at approximately 30 mm displacement.

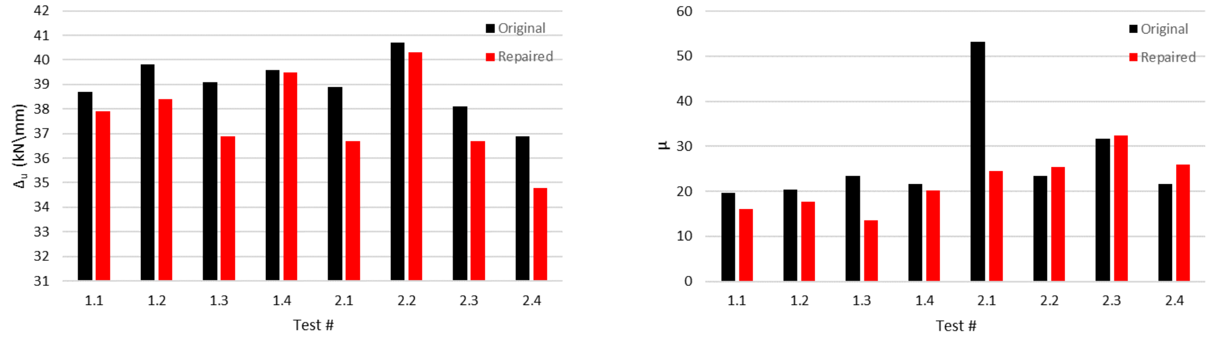
Based on the curves presented in Figure 3, it was most likely that the increase was due to inclined fasteners hitting epoxy as the greatest increase in strength is at the initial peak.

It should be noted that any increase in strength post-repair could have overstrength related implications for capacity design,

although the ability to use probable strengths in assessment may mitigate this issue.



a – Yield Strength *b – Initial Stiffness*



c – Ultimate Displacement *d - Ductility*

Figure 4 – Bar charts comparing original and repaired test results for key properties

4.3 Stiffness

Figure 5b shows the stiffness comparison between the original connections and the repaired connections. It can be seen that there is no clear trend on stiffness between original and repaired tests. This is confirmed by a statistical t-test where there is no statistically significant difference between original and repaired samples at a 5% level of significance.

The inherent natural variability of the timber and the high dependence of stiffness on the initial conditions of the connection lead to some uncertainty in the stiffness values reported. In this case, all screws were torqued to the same setting, but differences were observed in how well the steel hold-downs were sitting against the timber surface, and how the screws are sitting in their holes despite best efforts to be consistent.

Given the increase of yield strength and physical reason proposed above, it is unlikely there is a drop in stiffness in the repaired connections, and would seem likely that there should be a corresponding increase in stiffness. With these confounding variables the sample size is simply too small to draw a conclusion other than there has been no significant decrease in stiffness.

4.4 Displacement Capacity and Ductility

Displacement capacity or ultimate displacement is shown in Figure 4c, and ductility results are shown in Figure 4d. In most tests repaired displacement capacity was still quite high, although slightly lower than the original ones. From Figure 3, it can be seen that the performance of the original or repaired curves is very similar. In this study, ultimate displacement is defined as the displacement where the load drops to 80% of the peak. Due to the slight increase in strength discussed previously, this definition of ultimate displacement is causing the repaired ultimate displacement values reported to be slightly smaller than the original even though the performance of the repaired test was very similar to the original test. Comparing the load displacement curves of all original and repaired tests, there is no significant change in performance at large displacements. Similarly, ductility is highly dependent on the yield point of the connection. In stiff but highly ductile connections such as mixed angle screws, small changes in yield displacement can result in large changes in ductility. When considering the previous discussion about variability in stiffness, the differences in ductility observed should be considered with caution.

4.5 Failure Modes

As previously discussed, mixed angle screw connections may have highly localised damage when detailed correctly. In all the tests presented in this paper, partially threaded screws were used to encourage a ductile withdrawal failure in the timber, rather than a brittle steel tensile failure in the screw. In all original tests, the failure mode observed for the inclined fasteners was screw withdrawal. In Test Set 1 using 10 mm 90 degree screws some screw head failures were observed in the 90 degree screws, but it was found that there was a strong correlation between incidents of over-torquing during installation and head failure on these 10 mm washer head screws. In Test Set 2, all 90 degree screws failed due to bearing in the timber.

No significant changes in the damage to timber were observed between original and repaired tests, as illustrated by the original and repaired Specimen 1.2 in Figure 5. In both original and repaired tests there were instances where cracks formed along a row of fasteners, but this row shear was restrained by the internal CLT cross-layers. There was no evidence to suggest any differences in failure mode due to epoxy repair, although it should be noted that in some cases epoxy was hit when installing the screws. As previously discussed this may result in an increase in withdrawal strength, but due to the partially threaded inclined and 90 degree screws, this increase in screw strength did not result in screw tensile failure.

a - Original *b - Repaired*

Figure 5 – Comparison of timber surface after original test and after repaired test

5 CONCLUSIONS

A total of 16 experimental tests of mixed angle screw hold-down connections in Douglas-fir CLT were undertaken to assess the repair and reinstatement of mixed angle screw hold-down connections in CLT shear wall structures. The key findings are:

- Mixed angle screw hold-down connections can provide a high performance connection with high strength, high initial stiffness, and high ductility for CLT wall systems.
- Mixed angle screw hold-down connections exhibit localised damage that can be repaired and reinstated using epoxy and a small amount of shift of new screw locations.
- The test results showed an increase in strength of the repaired connections using the epoxy+shift method. However, the repair did not significantly affect the connection stiffness.
- After the repair, the repaired connections showed comparable ductile response to the original connections with a significant amount of energy dissipation.
- The experimental study only tested two specific connection details. More work is needed to study the influence of fastener sizes, CLT layups, fastener spacing, and new screw offset on the reparability of the CLT hold-down connections using mixed angle screw installations.

6 REFERENCES

British Standards Institution. (2001). *BS EN 12512:2001: Timber structures. Test methods. Cyclic testing of joints made with mechanical fasteners*. British Standards Institute.

Brown, J. R., Li, M., Tannert, T., & Moroder, D. (2020). Experimental study on orthogonal joints in cross-laminated timber with self-tapping screws installed with mixed angles. *Engineering Structures*, 111560. https://doi.org/10.1016/j.engstruct.2020.111560

Canterbury Earthquakes Royal Commission. (2012). *Volume 3: Low-Damge Building Technologies*.

Hossain, A., Popovski, M., & Tannert, T. (2018). Cross-laminated timber connections assembled with a combination of screws in withdrawal and screws in shear. *Engineering Structures*, *168*, 1–11. https://doi.org/10.1016/j.engstruct.2018.04.052

International Organization for Standardization. (2003). *Timber structures—Joints made with mechanical fasteners—Quasi-static reversed-cyclic test method (ISO 16670:2003)*.

Moroder, D., Smith, T., Dunbar, A., Pampanin, S., & Buchanan, A. (2018). Seismic testing of post-tensioned Pres-Lam core walls using cross laminated timber. *Engineering Structures*, *167*, 639–654. https://doi.org/10.1016/j.engstruct.2018.02.075

Smith, T., Ponzo, F. C., Di Cesare, A., Pampanin, S., Carradine, D., Buchanan, A. H., & Nigro, D. (2014). Post-Tensioned Glulam Beam-Column Joints with Advanced Damping Systems: Testing and Numerical Analysis. *Journal of Earthquake Engineering*, *18*(1), 147–167. https://doi.org/10.1080/13632469.2013.835291

Tomasi, R., Piazza, M., Angeli, A., & Mores, M. (2006). A new ductile approach design of joints assembled with screw connectors. *WCTE 2006*.

Wright, T. D. W., Li, M., Moroder, D., & Carradine, D. (2021). Cyclic behaviour of hold-downs using mixed angle self-tapping screws in Douglas-fir CLT. *Proceedings of the 2021 New Zealand Society for Earthquake Engineering Annual Technical Conference 2021*, 10.