Technical Report

Experimental testing of high capacity screwed connections in Douglas-fir CLT

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Date: 16-01-2021

Report: SWP-T119

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EXECUTIVE SUMMARY

This report presents experimental results of high capacity hold-down connections in Douglas-fir Cross Laminated Timber (CLT) using self-tapping screws installed with mixed angles (inclined and 90° angle to the timber surface).

This report consists of two experimental phases. In phase 1, a total of 28 small scale connection tests (50-100 kN capacity) were performed to identify the optimal threaded length of screws under withdrawal loads, the suitability of 45° washers to the mixed angle screw applications, and the optimal ratio of inclined screws to 90° screws. In phase 2, a total of 27 large scale connection tests (300-700 kN capacity) were performed to evaluate the performance of the mixed angle hold-downs performed in a CLT shear wall system. The tests also investigated the difference between single sided hold-downs and the double sided hold-downs, the optimal ratio between inclined and 90° screws, and the reparability of mixed angle screw connections after severe damage.

It was found that:

- Fully threaded screws can provide higher stiffness and more load carrying capacity per fastener, tensile failure of the screw must be avoided to allow their use in this style of connection.
- The 45-degree washers evaluated are suitable for mixed angle screw connection type if proper detailing allows for the formation of a plastic hinge at the head of the withdrawal screw.
- The ratio of 1:2 (number of withdrawal screws to number of shear screws) was found to be the optimum ratio (compared to 1:1 and 1:1.5).
- Double sided horizontal hold-down tests provided significant displacement capacity performance benefits over a single sided test, as that was not well horizontally constrained.
- Tests prove the suitability of mixed angle screw hold-down connections to repair and both repair methods had broadly similar behaviour to the original connection.

The experimental results confirmed the suitability of Douglas-fir CLT and mixed angle screw installations for high capacity hold-down systems. These connection results will provide valuable technical information for engineers to design mass timber structures utilising Douglas-fir CLT in the lateral load resisting system to resist seismic loads.

INTRODUCTION

Cross Laminated Timber (CLT) is an increasingly popular product used in the construction of large timber structures. Being a panelised timber product CLT is primarily used for the construction of timber wall and floor assemblies in large timber buildings.
In timber buildings that utilise CLT wall systems as their lateral load resisting system, the connection properties play a key role in wall performance. As timber is primarily a brittle material any ductility/yielding and energy dissipation in a timber system comes from the connections between timber elements. It is therefore imperative that the performance of these connections needs to be well understood.

Wall to foundation hold-down systems are critical when determining the lateral resistance of CLT structures under wind or seismic loading. Previous research on CLT hold-down connections has focused on connection systems such as off the shelf steel nail brackets, steel dowels, and proprietary Holz-Stahl-Komposit (HSK) systems. These connection systems have been proven to work well under seismic loading but have some limitations/concerns such as low capacity for off the shelf steel nail brackets, strict installation tolerances for steel dowels, and quality control issues for HSK systems that must be taken into account.

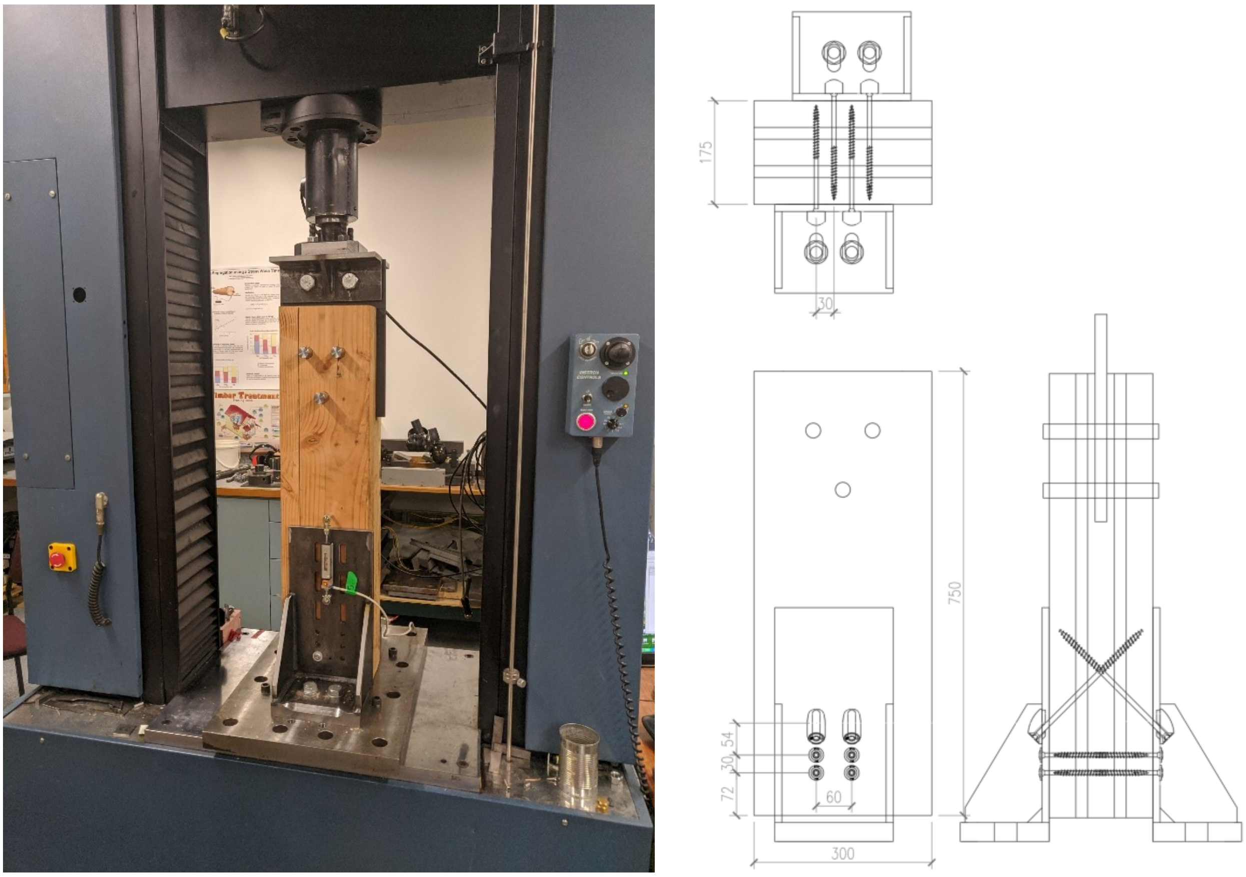
Large self-tapping screws are an increasingly common fastener type used in mass timber construction. Easy to install on site by hand tools, these fasteners have allowed more efficient connections than other dowel-type fasteners by exploiting the withdrawal capacity for increased load carrying capacity (Blaß and Bejtka 2001). By increasing the angle of the screw we can increase the connection stiffness, but with reduced ductility. Previous work (Tomasi et al. 2006) investigated the suitability of mixed angle screw connections. In these connections both screws are installed at both 45 degrees and 90 degrees to the grain, with the 45 degree screws acting primarily in tension or withdrawal, and the 90 degree screws acting in shear. More work has investigated their use in timber to timber in-plane joints between timber shear walls (Hossain, Popovski, and Tannert 2018; Brown et al. 2020). Further work by Brown has investigated the performance of these mixed angle screws as a hold-down system for a CLT core wall.

This study assesses the performance of mixed angle screw connections in steel to timber hold-down joints. The influence of parameters such as screw thread length, washer choice, and ratio of withdrawal to shear fasteners on key properties such as strength, stiffness, and ductility were investigated under both monotonic and cyclic loading. These test results provide a first look into the performance of these mixed angle screw installations in steel to timber connections, and provide a good testing base for future design guidance for this type of connection.

PHASE 1 TESTS: CONNECTIONS WITH 50-100 KN CAPACITY

Phase 1 tests aimed to conduct initial research to assess the performance of mixed angle screw hold-down connections at a small scale. The hold-down specimens consisted of 2~6 fasteners and the design load levels were between 50 and 100 kN. This small scale testing allowed for more tests to study different parameters in a rapid fashion while keeping costs low.

The material used in all tests was Douglas-fir CLT provided by XLam New Zealand. The CLT used a 175 mm thick 5 layer layup (45/20/45/20/45) with characteristic density of 470 kg/m^3. Tests were undertaken on a 250 kN Instron testing machine shown in *Figure 1*a. The test setup uses two steel hold-downs at the base of the specimen in a symmetrical layout, and a dowelled overstrength connection at the top of the connection as shown in *Figure 1*b.



a b

Figure 1 – Phase 1 testing setup (a – Picture of testing setup, b – drawing of testing setup)

All tests were displacement controlled with monotonic tests undertaken in accordance with EN12512 'Timber structures - Test methods - Cyclic testing of joints made with mechanical fasteners' (British Standards Institution 2001). Cyclic tests were undertaken in accordance with ISO 16670 'Timber structures - Joints made with mechanical fasteners - Quasi-static reversed-cyclic test method' (International Organization for Standardization 2003). The rate of loading for monotonic tests was 2 mm per minute, and 30 mm per minute for cyclic tests to meet EN12512 and ISO16670 respectively.

For all tests, the yield point was calculated using the procedure outlined in EN12512, where the yield point is the intersection of a line through 0.1*F_{max} and 0.4*F_{max} and a tangent with 1/6th the gradient. This method is shown graphically in *Figure 2*. Ultimate displacement was calculated as failure or 0.8*F_{max} deviating from EN12512's 30 mm displacement limit. This was done as a 30 mm displacement limit does not make sense when testing highly ductile connection systems that can sustain peak load well past this limit.

The cyclic loading protocol from ISO16770 was used. This protocol is defined as repeated cycles to an increasing percent of ultimate displacement and is shown in *Table 1* and *Figure 3*.

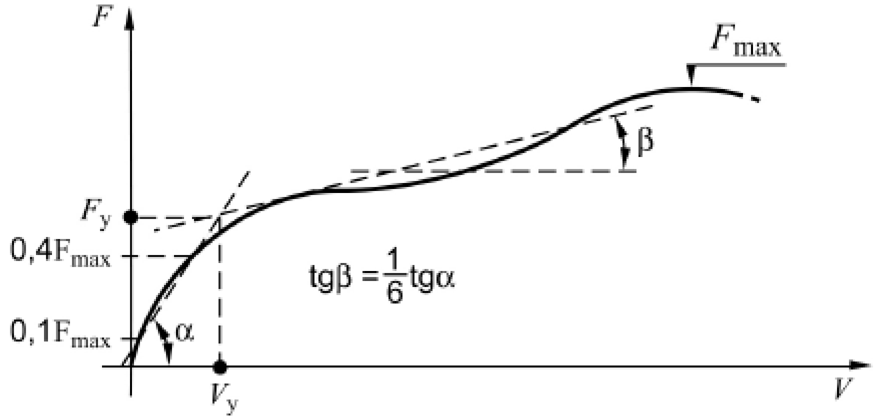


Figure 2 – EN12512 definition of yield point (British Standards Institution 2001)

Table 1 – Cyclic displacement protocol as defined by ISO16670 (International Organization for Standardization 2003)

Step	No. of cycles	Amplitude (% of Δ_u)
1	1	1.25
2	1	2.5
3	1	5
4	1	7.5
5	1	10
6	3	20
7	3	40
8	3	60
9	3	80
10	3	100
11	3	120

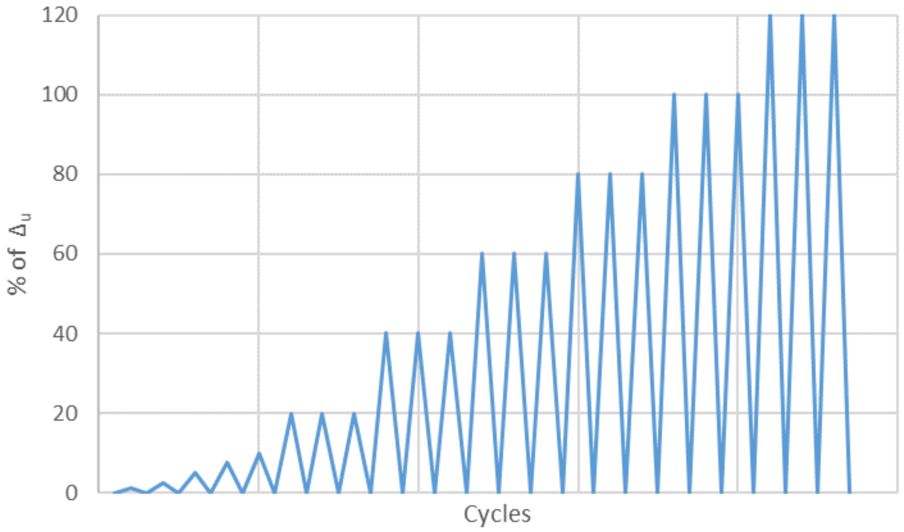


Figure 3 – Cycle displacement protocol as defined by ISO16670 (International Organization for Standardization 2003)

Test Program

A total of 28 tests were undertaken to determine the following:

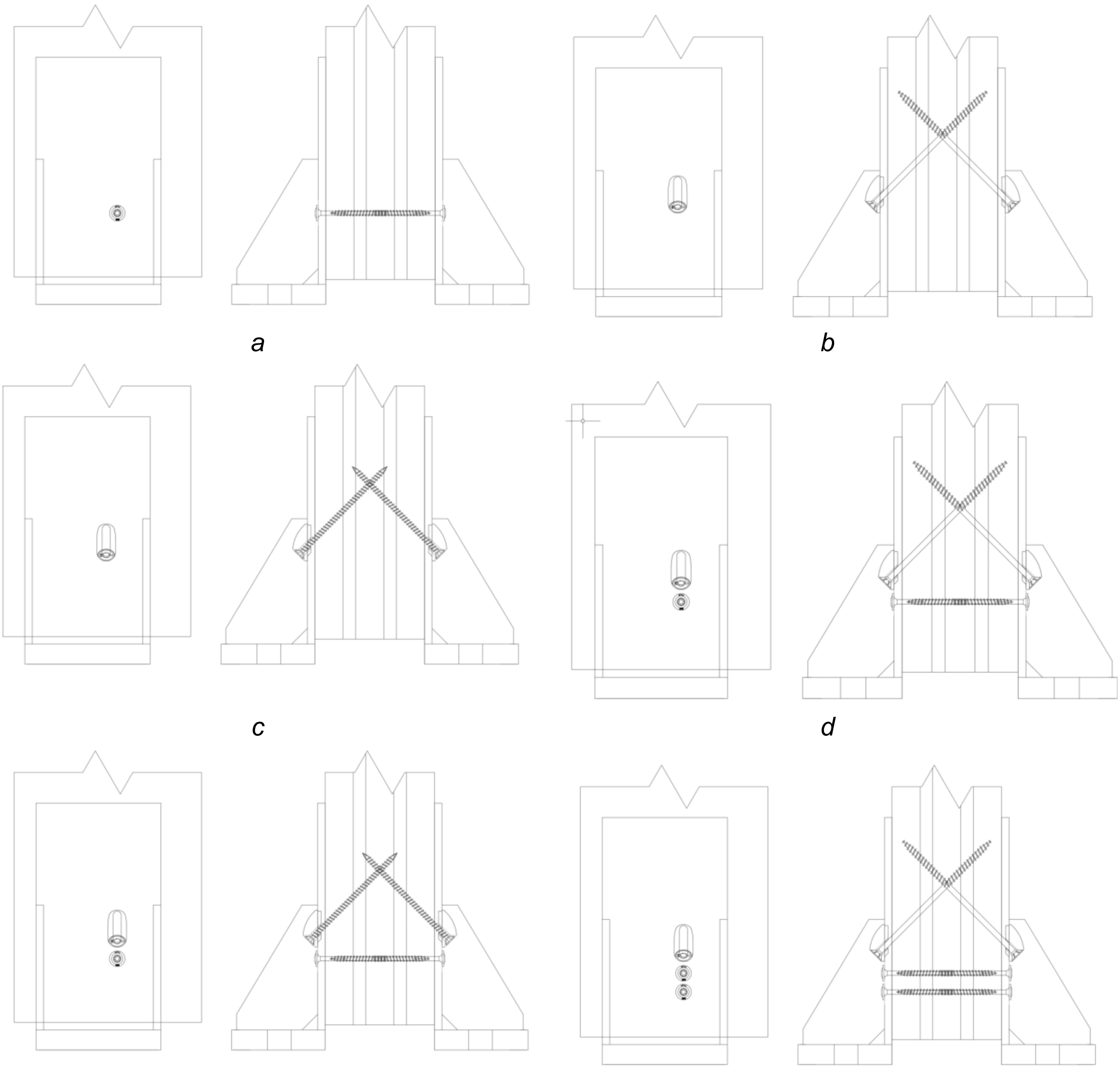
1. Optimal threaded length of screw
2. Suitability of 45 degree washers to this application
3. Optimal ratio of withdrawal to shear fasteners

The test matrix is shown in *Table 2*. The testing program began with tests with fasteners just in withdrawal or just in shear, followed by tests of partially threaded vs fully threaded inclined screws, and finally tests with both screws in withdrawal and screws in shear. Drawings of all the configurations tested are shown in *Figure 4*.

The screws used in testing were all supplied by SPAX Pacific. All tests use 12 mm countersunk screws at 45 degrees and 10 mm washer head screws at 90 degrees. This is because SPAX does not manufacture a washer head screw larger than 10 mm diameter suitable for use in the shear connection.

Table 2 – Test matrix for Phase 1

Test Set	**Description**	**Withdrawal Screws**		**Shear Screws**		**Ratio**	**Replicates**	
		Qty	***Size***	***Qty***	***Size***		***Monotonic***	***Cyclic***
1	2 Shear			2	10x180 PT		2	2
2	2 Withdrawal	2	12x260 PT				3	3
3	2 Withdrawal Fully Threaded	2	12x200 FT	2	10x180 PT		1	1
4	2 Withdrawal 2 Shear	2	12x260 PT	2	10x180 PT	1:1	2	6
5	2 Withdrawal 2 Shear Fully Threaded	2	12x200 FT	2	12x180 PT	1:1	1	3
6	2 Withdrawal 4 Shear	2	12x200 FT	4	12x180 PT	1:2	1	3



a b c d e f

Figure 4 – Phase 1 test configurations. (a – 2 Shear, b – 2 Withdrawal, c – 2 Withdrawal Fully Threaded, d – 2 Withdrawal 2 Shear, e – 2 Withdrawal 2 Shear Fully Threaded, f – 2 Withdrawal 4 Shear)

Results

Testing results for the 28 Phase 1 specimens are shown below in *Table 3*.

Table 3 – Phase 1 test results

		F_y *kN*	F_{max} *kN*	F_u *kN*	K *kN/mm*	Δ_y *mm*	Δ_{Fmax} *mm*	Δ_u *mm*	μ
1	**2 Shear**								
Monotonic	1	20.5	29.2	23.3	3.16	6.2	24.8	37.4	6.04
	2	20.3	31.1	24.9	3.63	4.71	23.7	37.1	7.88
	Mean	**20.4**	**30.1**	**24.1**	**3.39**	**5.46**	**24.3**	**37.3**	**6.96**
Cyclic	1	26.1	35	28	2.95	8.43	26.7	37.5	4.45
	2	23.5	33.3	26.6	3.13	6.42	26.3	36.9	5.75
	Mean	**24.8**	**34.1**	**27.3**	**3.04**	**7.43**	**26.5**	**37.2**	**5.1**
2.1	**2 Withdrawal Un-welded**								
Monotonic	1	33.7	43.6	34.9	37	0.83	3.46	9.14	11
	2	51	53.8	43	9.56	5.25	7.7	12.4	2.36
	Mean	**42.3**	**48.7**	**38.9**	**23.3**	**3.04**	**5.58**	**10.8**	**6.69**
Cyclic	1	57.1	61.6	49.3	21.5	2.5	4.01	8.39	3.36
	2	55.8	61.1	48.9	19.2	3.5	5.64	8.99	2.57
	3	49.4	52	41.6	8.53	5.41	7.54	11.3	2.09
	Mean	**54.1**	**58.2**	**46.6**	**16.4**	**3.8**	**5.73**	**9.55**	**2.67**
2.2	**2 Withdrawal**								
Monotonic	1	56.5	63	50.4	21.4	3.31	5.55	10.9	3.29
3	**2 Withdrawal Fully Threaded**								
Monotonic	1	73.8	77.6	62.1	26.6	3.18	4.32	9.14	2.87
Cyclic	1	70.4	75.1	60.1	23.6	2.99	4.26	8.82	2.95
4.1	**2 Withdrawal 2 Shear Un-welded**								
Monotonic	1	79.3	79.3	63.5	14.4	5.04	5.5	11.5	2.28
Cyclic	1	88.5	96.4	77.1	27.9	3.72	6.71	11.8	3.17
	2	80.3	82	65.6	17.8	4.27	4.88	11.8	2.77
	3	77.2	78	62.4	17	4.5	5.52	11.7	2.6
	Mean	**82**	**85.5**	**68.4**	**20.9**	**4.16**	**5.7**	**11.8**	**2.84**
4.2	**2 Withdrawal 2 Shear**								
Monotonic	1	66.3	73	58.4	24.2	2.47	4.86	13.7	5.52
Cyclic	1	63.3	71.9	57.5	27.1	2.12	4.62	35	16.5
	2	68.6	74	59.2	26.1	2.39	3.74	15	6.27
	3	66.3	75.4	60.3	33	1.8	3.71	10.7	5.95
	Mean	**66.1**	**73.8**	**59**	**28.7**	**2.1**	**4.02**	**20.2**	**9.56**
5	**2 Withdrawal 2 Shear Fully Threaded**								
Monotonic	1	92.4	99	79.2	32.2	2.62	4.27	7.52	2.87
Cyclic	1	97.1	110	87.8	41.3	2.14	4.2	5.43	2.54
	2	102	102	81.4	23.3	4	4.72	7.73	1.93
	3	89.8	98	78.4	35.2	2.24	3.92	10.2	4.57
	Mean	**96.2**	**103**	**82.5**	**33.3**	**2.79**	**4.28**	**7.79**	**3.01**
6	**2 Withdrawal 4 Shear**								
Monotonic	1	59.6	79	63.2	45	1.17	4.44	44	37.5
Cyclic	1	78.1	94.3	75.5	33.8	1.94	29.5	39.9	20.6
	2	78.1	97.2	77.8	43.6	1.6	28.9	35.5	22.2
	3	78.7	99.1	79.2	43.1	1.66	7.5	38.4	23.2
	Mean	**78.3**	**96.9**	**77.5**	**40.1**	**1.73**	**22**	**37.9**	**22**

Discussion

Optimal threaded length of screw

In mixed angle screw connections it is important to size withdrawal screws such that they do not fail prematurely in tension, but rather withdrawal from the timber in a less brittle failure mechanism. As the performance of the joint is a combination of the performance of both the withdrawal screws and the shear screws it is important that the withdrawal screws continue to maintain some load carrying capacity as the shear screws take up the load at higher displacements. Otherwise an abrupt transfer of load may result in a progressive failure mechanism being triggered.

Results from our previous testing showed that in Douglas-fir timber the screw embedment length required to fail the screws in withdrawal is between 12d and 16d, or less. Tests were therefore undertaken with both partially threaded screws (100 mm of threaded length) and fully threaded screws (200 mm is the smallest length available). Accounting for the length of a 45 degree washer and 12 mm plate a 200 mm fully threaded screw has a threaded embedment of 163 mm, which for a 12 mm screw is 13.6d. During the 2 withdrawal test set, the fully threaded screws with 200 mm of threaded length initially worked well with higher strength and stiffness than partially threaded screws, while still maintaining similar displacement capacity as seen in *Figure 8*. However during further testing in the 2 withdrawal 2 shear configuration it was found that the fully threaded screws were prone to tensile failure at the screw to timber interface as shown in Figure 5. Figure 6 shows a plot of the 2 withdrawal 2 shear test with fully threaded screws against the partially threaded screws. Note the large drop in force in the fully threaded test due to the tensile failure of one of the two withdrawal screws.

Figure 5 – Example of fully threaded screw tensile failure at the timber to steel interface.

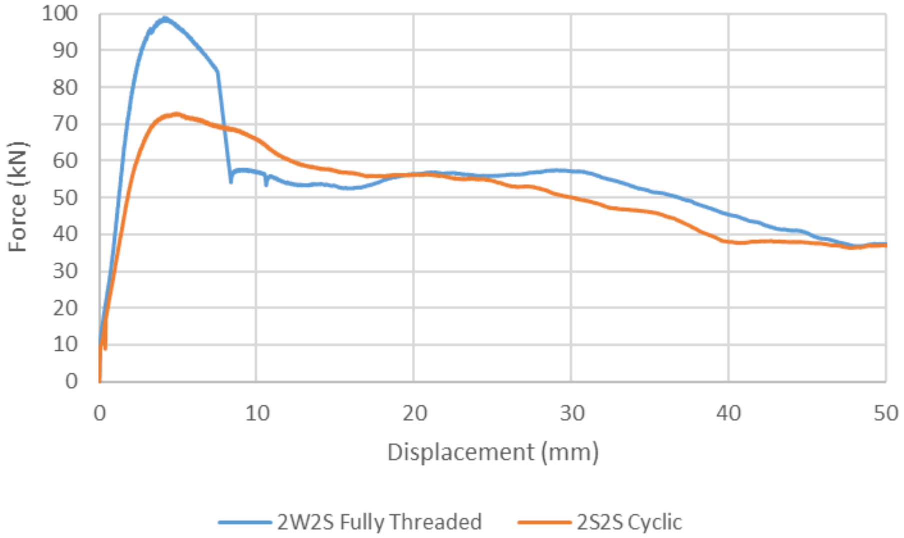


Figure 6 – Plot showing monotonic fully threaded vs partially threaded tests with 2 screws in withdrawal 2 in shear.

Suitability of 45 degree washers to this application

45 degree washers from two manufactures were used and evaluated for this study. In phase 1 washers supplied by Wurth were used, and in phase 2 washers supplied by Rothoblaas were used. These inclined washers are typically used for traditional steel to timber joints where only inclined screws are used. These connections are typically designed to remain elastic or with limited ductility. In the 2 withdrawal tests the yield displacement was determined to be around 3 mm. As a consequence these washers were likely not envisioned to be taken to the high displacements required in a mixed angle screw connection where the 45 degree screws are required to still provide some load carrying capacity up to around 40 mm.

Tests with 2 withdrawal and 2 withdrawal 2 shear fasteners were initially undertaken with 45 degree inclined washers installed as per the manufacturer specifications. During the testing it was found that at large displacements, the bending moment developed in the screw caused an action that pushed the tip of the washer out of its slot, meaning the connection lost its ability to carry load as seen in *Figure 7*a. This bending action in the screw is shown in *Figure 7*c, where it can be seen that a plastic hinge has been developed near the head of the screw as the washer provides some rotational restraints to the head. In cyclic tests there were also issues where the 45 degree screw withdrew significantly from its original position and when unloaded the washer slipped down the screw shank and out of its slotted hole as seen in *Figure 7*b. To address these issues, two tack welds were added to the tip of each washer as seen in *Figure 7*d. These tack welds allowed a small tensile force to be transferred between the tip of the washer and the hold-down while not effecting the bearing of the tip of the washer against the end of the slotted hole. These tack welds allowed the full development of the plastic hinge shown in *Figure 7*c, restraining the washer from being able to slip out of place, thus allowing the screws in withdrawal to continue carry some load well past their ultimate displacement.

In phase 2 the Rothoblaas washers used are designed for much thinner plates than the Wurth washers used in phase 1, and as such, the plastic hinge developed about the edge of the slotted hole rather than bearing into the washer.

Figure 8 shows a comparison for the 2 withdrawal tests between the welded and un-welded washers. It can be seen that the un-welded washers reached failure at under 20 mm when the 45 degree washer slipped from its slot preventing any further load carrying by the screws in withdrawal. In comparison the other two tests shown on *Figure 8*, both with welded washers, show the ability of the welded washers to continue to provide some load carrying capacity right out to 40 mm of displacement.

a b

c d

Figure 7 – Pictures demonstrating 45 degree washers (a – 45 degree washer slipped from hole, b – 45 degree washer unable to re-find hole under cyclic loading, c – withdrawal screws showing two plastic hinges, d – 45 degree washer with two tack welds at the tip)

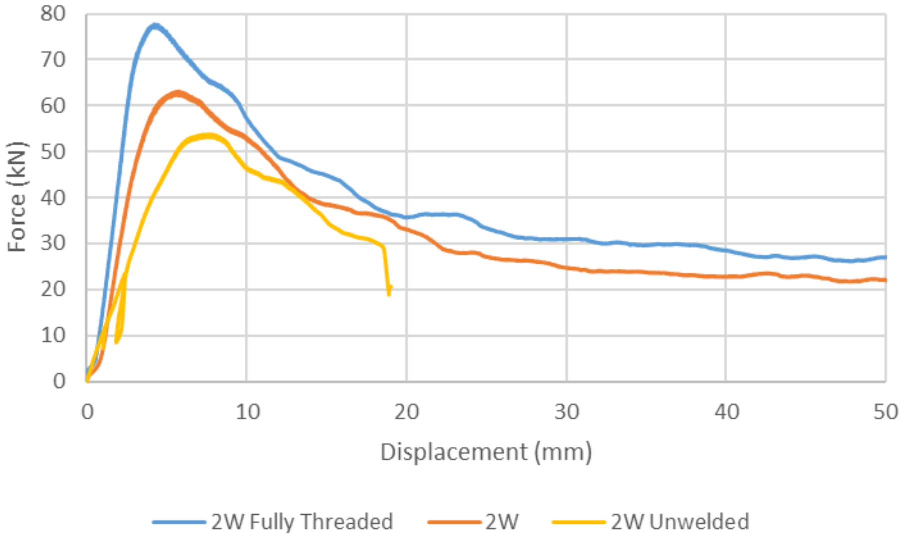


Figure 8 – Plot showing monotonic fully threaded vs partially threaded vs partially threaded un-welded washers tests with 2 screws in withdrawal

Optimal Ratio of withdrawal to shear fasteners

Tests were conducted varying the ratio of withdrawal screws to shear screws between 1:1 and 1:2. Due to constraints in the test setup for phase 1, intermediate ratios such as 1:1.5 could not be investigated, and as such, they will be investigated in phase 2.

Figure 9 shows a plot of monotonic shear and withdrawal only tests against the tests with 1:1 ratio and 1:2 ratio of withdrawal to shear fasteners. It can be seen that withdrawal fasteners have high initial stiffness, but low ductility/displacement capacity, whereas shear fasteners have relatively low initial stiffness and high ductility/displacement capacity. When these two types of fasteners are combined into one connection, the behaviour could be superimposed with improved overall performance , i.e., high initial stiffness and high ductility/displacement capacity.

Due to constraints discussed previously the withdrawal screws used were 12 mm diameter while the shear screws were 10 mm diameters, therefore, any ratios provided are specific to this combination of diameters. From Figure 9, it can be seen that both 2 withdrawal 2 shear and 2 withdrawal 4 shear curves have high initial stiffness, but the 2 withdrawal 2 shear curve drops quickly at higher displacement indicating the need for more shear fasteners to sustain the loads. The 2 withdrawal 4 shear curve with the two additional shear fasteners was able to sustain peak load until a much larger displacement, and thus, leading to significantly higher ductility/displacement capacity.

Cyclic performance of both 2 withdrawal 2 shear and 2 withdrawal 4 shear connections is shown in Figure 10 and Figure 11 respectively. From Figure 10 it can be seen that the cyclic performance of the 2 withdrawal 2 shear connection closely matches the monotonic performance. Similarly in Figure 11 the cyclic performance of the 2 withdrawal 4 shear connection is comparable to the monotonic connection, but is slightly stronger for most displacements, and perhaps, shows some cyclic degradation at high displacements (40 mm +).

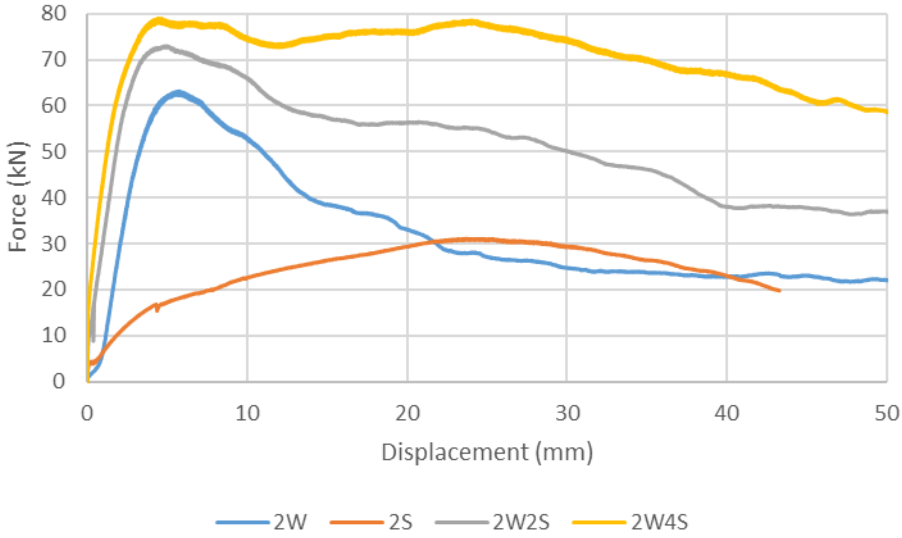


Figure 9 – Plot of monotonic shear and withdrawal only screws against 1:1 ratio and 1:2 ratio tests

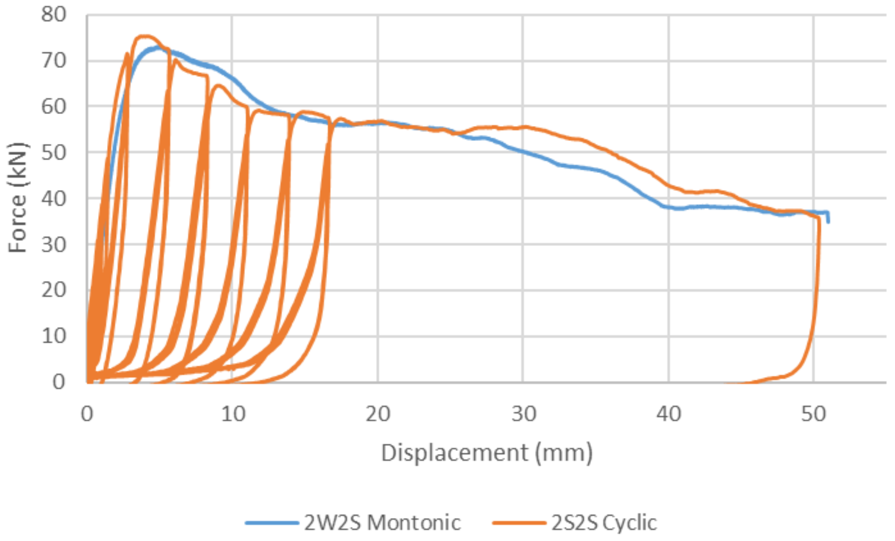


Figure 10 – Plot of 2 withdrawal 2 shear monotonic loading against cyclic loading

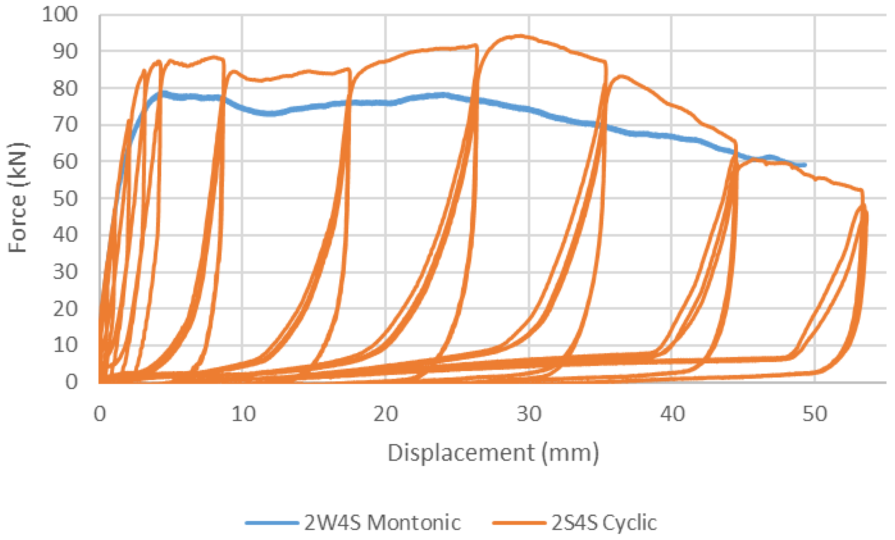


Figure 11 – Plot of 2 withdrawal 4 shear monotonic loading against cyclic loading

PHASE 2 TESTS: CONNECTIONS WITH 300-700 KN CAPACITY

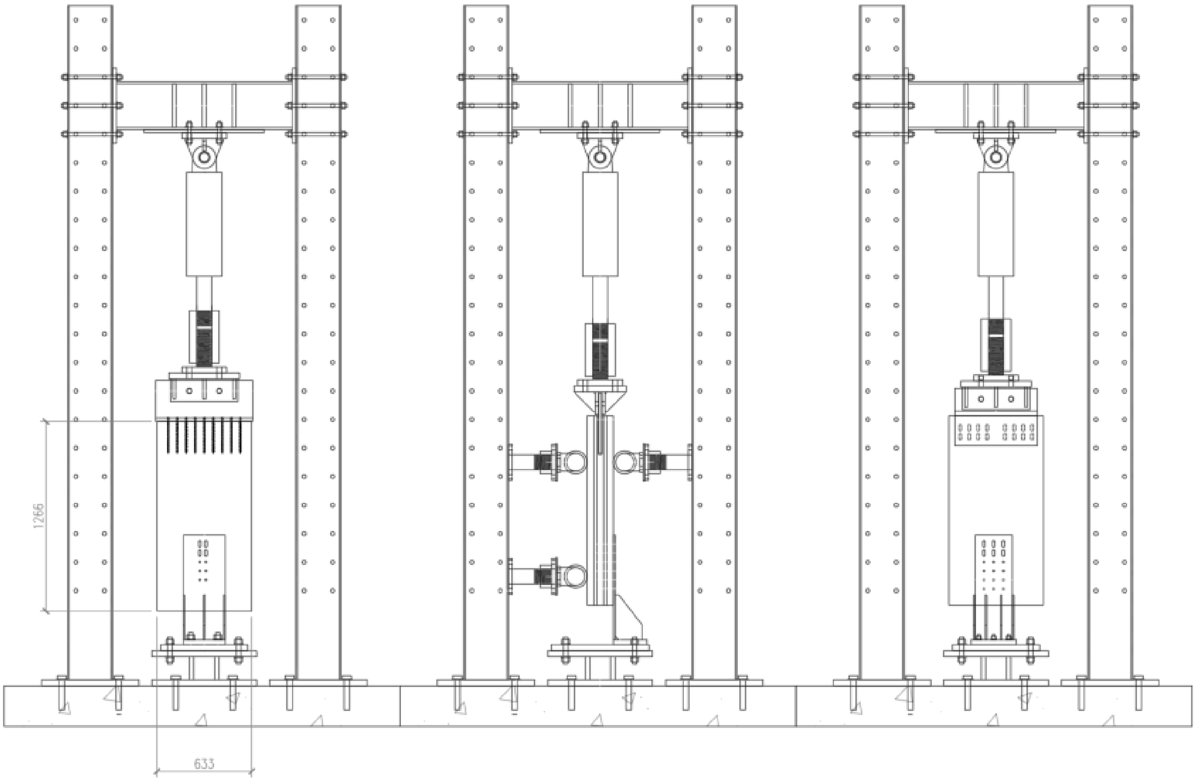
Phase 2 aimed to build upon the findings of phase 1 tests and extend the findings at a larger scale while optimising screw ratios, and testing possible post-earthquake repair solutions.

Tests undertaken in phase 2 evaluated connections with between 18 and 36 fasteners and load levels between 300 and 700 kN. This larger scale tests provided results at a scale similar to what is likely used in a multi-storey CLT building, proving the performance of these connection systems at a more realistic scale.

Tests were undertaken on a steel loading frame using a 1000 kN hydraulic actuator. As shown in *Figure 12* and *Figure 13* the testing setup features a mixed angle screw hold-down connection with the base plate bolted to a steel foundation. Load is then applied to the specimen through a screwed overstrength connection to the hydraulic actuator. Throughout testing the hold-downs and arrangements were varied to provide different test cases.

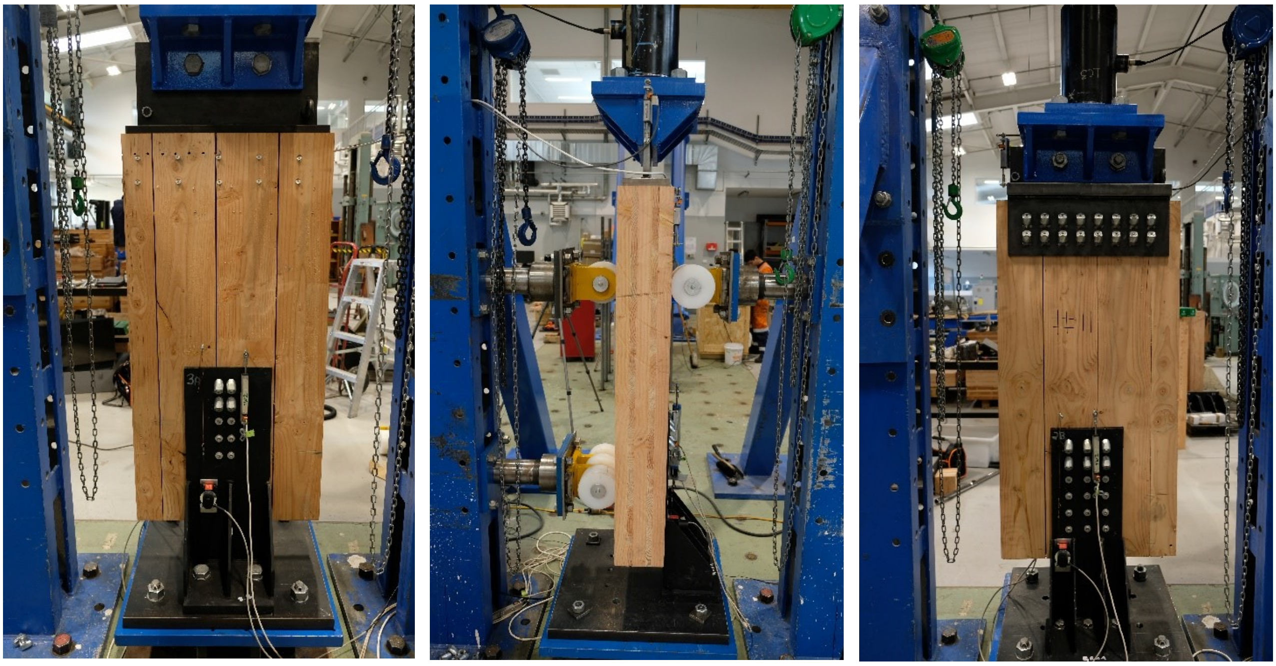
The material used in all tests was Douglas-fir CLT provided by XLam New Zealand. The CLT used a 175 mm thick 5 layer layup (45/20/45/20/45) with characteristic density of 470 kg/m^3. The specimens used in phase 2 had a width of 632.5 mm and height of 1265 mm.

Similar to phase 1, EN12512 test standard was used for monotonic tests, and ISO 16670 test standard for cyclic tests. A target speed of 12 mm/min was chosen as this suited the capabilities of the hydraulic actuators.



a b c

Figure 12 – Drawings of Phase 2 test setups (a – 8 withdrawal 12 shear, b – 6 withdrawal 12 shear singled sided, c – 12 withdrawal 24 shear)



a b c

Figure 13 - Pictures of Phase 2 test setups (a – 8 withdrawal 12 shear, b – 6 withdrawal 12 shear singled sided, c – 12 withdrawal 24 shear)

Test Program

A total of 27 tests were undertaken to determine the following:

- How the hold-downs performed in previous wall testing (SWP-T082).
- How the single sided performance of the hold-down compares to the double sided performance.
- Optimal ratio of withdrawal to shear screws.
- How this connection system can be repaired post-earthquake event such that it regains similar performance to new.

A test matrix of all unrepaired tests is shown in *Table 4*, and a test matrix of all repaired tests is shown in *Table 5*. Drawings of all four testing configurations are shown in *Figure 14*. Repaired tests all utilise a horizontal shift from the original position of half the screw spacing. As the screw spacing used in the 12 withdrawal 24 shear hold-downs was 32.5 mm, the hold-downs were shifted 16.25 mm horizontally then reinstalled. This was achieved by moving the baseplate horizontally in slotted holes while keeping the specimen in the same position.

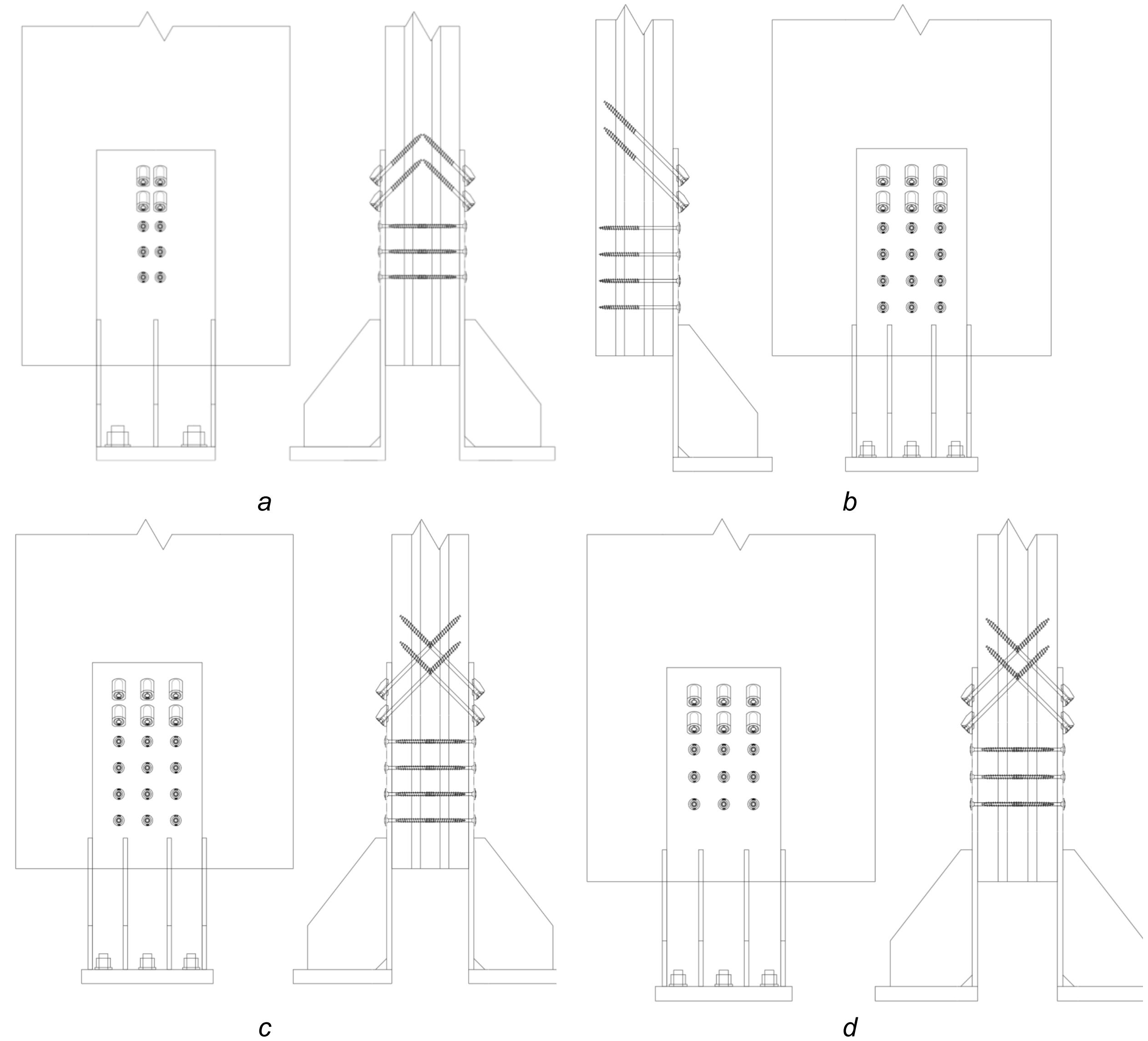
Similar to Phase 1, screws used in testing were all supplied by SPAX Pacific. All tests use 12 mm screws at 45 degrees and 10 mm screws at 90 degrees.

Table 4 – Test matrix for Phase 2 original tests

Test Set	**Description**	**Single Sided**	**Withdrawal Screws**		**Shear Screws**		**Ratio**	**Replicates**	
			Qty	***Size***	***Qty***	***Size***		***Monotonic***	***Cyclic***
1	8 Withdrawal 12 Shear	No	8	12x160 PT	12	10x180 PT	1:1.5	1	3
2	6 Withdrawal 12 Shear Single Sided	Yes	6	12x260 PT	12	10x180 PT	1:2	2	3
3	12 Withdrawal 24 Shear	No	12	12x260 PT	24	10x180 PT	1:2	1	3
6	12 Withdrawal 18 Shear	No	12	12x260 PT	18	10x180 PT	1:1.5	2	3

Table 5 – Test matrix for Phase 2 repaired tests

Test Set	**Description**	**Repair**	**Withdrawal Screws**		**Shear Screws**		**Ratio**	**Replicates**	
			Qty	***Size***	***Qty***	***Size***		***Monotonic***	***Cyclic***
4	12 Withdrawal 24 Shear Repaired	Hilti + Shift	12	12x260 PT	24	10x180 PT	1:2	1	3
5	12 Withdrawal 18 Shear Repaired	Shift	12	12x260 PT	18	10x180 PT	1:1.5	2	3


a

b

c

d

Figure 14 – Phase two test configurations (a – 8 Withdrawal 12 Shear, b – 6 Withdrawal 12 Shear Single Sided, c – 12 Withdrawal 24 Shear, d – 12 Withdrawal 18 Shear)

Results

Testing results for the 27 phase 2 specimens are shown below in *Table 6*.

Table 6 – Phase two test results

		F_y *kN*	F_{max} *kN*	F_u *kN*	K *kN/mm*	Δ_y *mm*	Δ_{Fmax} *mm*	Δ_u *mm*	μ
1	**8 Withdrawal 12 Shear**								
Monotonic	1	250	322	258	114	1.94	27.4	39	20.1
Cyclic	1	295	363	290	107	2.55	30.7	39.6	15.5
	2	359	391	312	116	2.9	4.88	36.1	12.4
	3	290	341	273	134	1.89	4.95	36.8	19.5
	Mean	**315**	**365**	**292**	**119**	**2.45**	**13.5**	**37.5**	**15.8**
2	***6 Withdrawal 12 Shear Single Sided***								
Monotonic	1	331	372	297	149	2.03	5.46	23.8	11.7
	2	251	314	251	135	1.59	18.9	24	15.1
	Mean	291	343	274	142	1.81	12.2	23.9	13.4
Cyclic	1	316	372	298	151	1.85	21.1	26.4	14.3
	2	314	342	274	123	2.32	17.2	22.7	9.8
	3	276	328	262	150	1.67	16.9	23.2	13.9
	Mean	**302**	**347**	**278**	**141**	**1.94**	**18.4**	**24.1**	**12.7**
3	**12 Withdrawal 24 Shear**								
Monotonic	1	522	643	515	216	2.04	30.6	39.5	19.3
Cyclic	1	504	622	498	222	2.01	36	40.6	20.2
	2	498	609	487	238	1.81	31.2	39.6	21.8
	3	544	633	506	223	2.04	31.8	40.3	19.7
	Mean	**515**	**621**	**497**	**228**	**1.96**	**33**	**40.2**	**20.6**
4	**12 Withdrawal 24 Shear Repaired with Hilti Epoxy + Shift**								
Monotonic	1	555	653	522	195	2.56	30.2	38.9	15.2
Cyclic	1	559	658	527	229	2.12	6.05	38.9	18.4
	2	556	621	497	187	2.76	7.5	37.7	13.6
	3	587	692	554	240	2.11	33.1	40.1	19
	Mean	**567**	**657**	**526**	**219**	**2.33**	**15.6**	**38.9**	**17**
5	***12 Withdrawal 18 Shear***								
Monotonic	1	433	546	437	286	1.37	6.25	36.5	26.7
	2	423	535	428	295	1.19	7.06	39.2	32.9
	Mean	**428**	**540**	**432**	**290**	**1.28**	**6.65**	**37.8**	**29.8**
Cyclic	1	521	614	491	294	1.54	4.61	40.5	26.2
	2	487	590	472	271	1.47	5.43	35.9	24.4
	3	447	535	428	270	1.42	4.16	37.6	26.5
	Mean	**485**	**580**	**464**	**278**	**1.48**	**4.73**	**38**	**25.7**
6	***12 Withdrawal 18 Shear Repaired With Shift***								
Monotonic	1	453	509	407	185	1.92	4.54	35.9	18.7
	2	362	489	391	224	1.3	29.2	38.4	29.6
	Mean	**408**	**499**	**399**	**204**	**1.61**	**16.8**	**37.1**	**24.1**
Cyclic	1	407	542	433	294	1.97	31.2	40.6	20.7
	2	426	516	413	223	1.72	32.6	39.1	22.7
	3	355	447	357	265	1.11	3.97	36.3	32.6
	Mean	**396**	**501**	**401**	**261**	**1.6**	**22.6**	**38.7**	**25.3**

Discussion

Hold-down component test for previous wall testing

Previous wall testing (SWP-T082) used mixed angle screw hold-downs on the base of a 2/3rd scale 4-storey CLT core wall. This hold-down test set was an exact replica of the hold-down setup used on the wall tests and provided a calibration for hold-down forces in future modelling work.

For this test hold-downs with reduced spacing (20 mm horizontally) are used with shorter 12x160 mm partially threaded countersunk screws. The same 10x180 mm washer head screws were used in shear.

Figure 15 shows a plot of monotonic vs cyclic behaviour for this connection. It can be seen that in this case the monotonic test was weaker than the cyclic test, although this is likely due to variability in the timber rather than a significant trend. It should be noted that for the 1:1.5 withdrawal to shear ratio in these tests we observed a slightly lower initial peak and slightly higher second peak which was not the case in later tests with 1:1.5 ratio. It was likely that in this case either the length of screw or spacing was contributing to slightly lower withdrawal strength than compared to other similar tests with higher spacing and longer screws. Further work is required to address this cause separately.

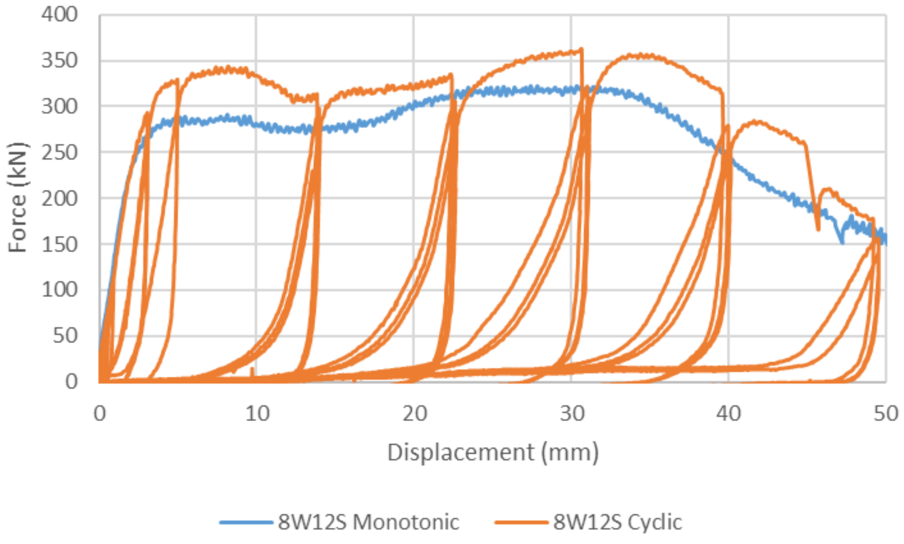


Figure 15 – Plot of 8 withdrawal 12 shear monotonic vs cyclic

Single sided vs double sided

Figure 19 shows a monotonic comparison between the recorded strength of the 6 withdrawal 12 shear single sided hold-down and half the recorded strength of the 12 withdrawal 24 shear double sided hold-down test. Similarly *Figure 20* shows a cyclic comparison between these two test sets.

From *Figure 19* and *Figure 20* it is apparent that the single sided hold-down test had higher strength than the equivalent double sided hold-down test. This difference might be caused by the different frictional effect between the two tests. In a double sided hold-down test the timber specimen fits snugly between the hold-downs, and the base is constrained from sliding inwards. When the fasteners engage and try to pull the hold-downs inwards, stiffeners prevent the base of the hold-down from bending inwards to contact the timber surface, although the top of the hold-down is free to bend in. In the single sided test there is only a connection on one side of the timber so the horizontal component of the fasteners resistance across the steel timber interface is unbalanced as such the hold-down is allowed to sit firm against the single sided hold-down generating more frictional resistance.

It is also apparent from *Figure 19* and *Figure 20* that the single sided hold-down has significantly less ductility/displacement capacity than the double sided hold-down. This was likely due to the horizontal constraint present in the double sided hold-down test. At high displacements the inclined screws in the connection seek to push the hold-down away from the timber specimen as shown in *Figure 18*a. In the double sided hold-down test this action is well constrained by the opposing hold-down. In the single sided test this action is only constrained by a roller support only tightened until snug. In some tests this allowed a small gap to form between the hold-down and the timber surface significantly reducing the load carrying capacity of the joint. An accentuated version of this is seen in *Figure 18*b when the roller support has not been tightened sufficiently and the timber has been allowed to push away from the hold-down.

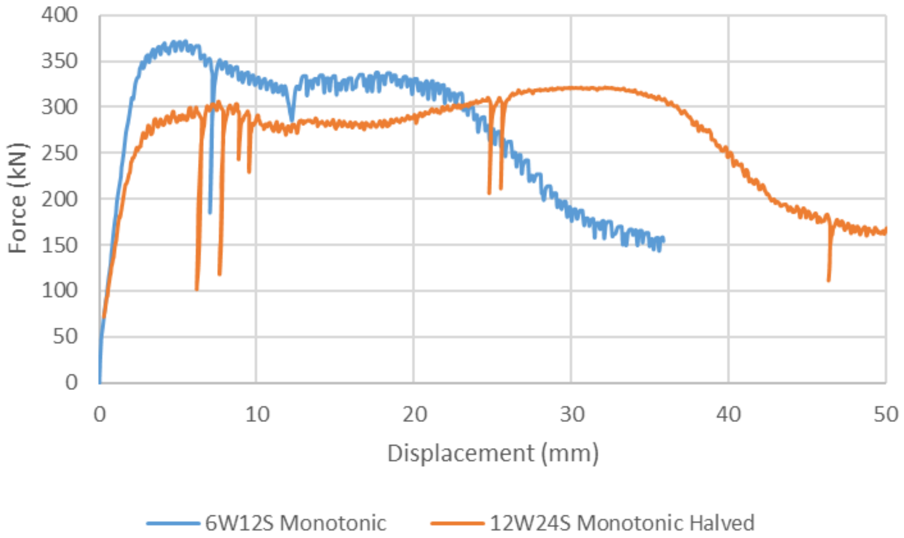


Figure 16 – Plot of 6 withdrawal 12 shear vs 12 withdrawal 24 shear monotonic halved for comparison

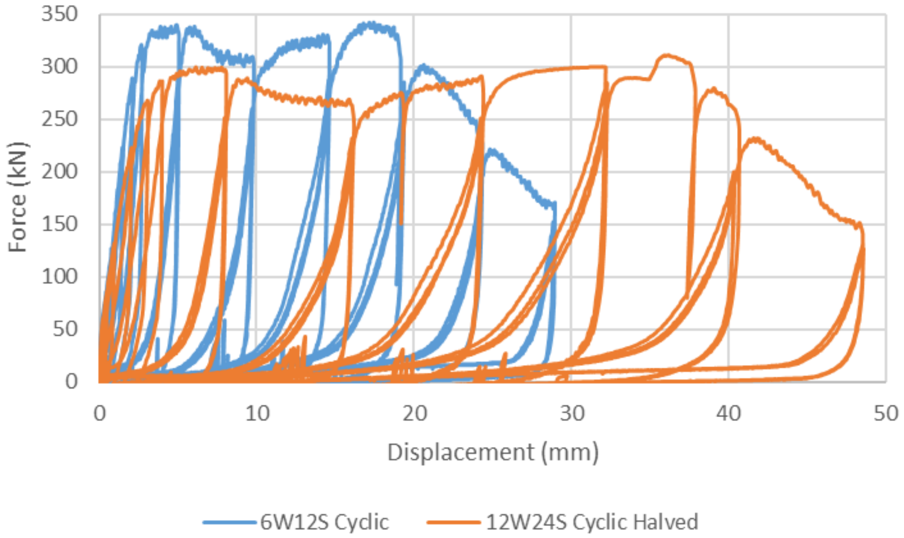


Figure 17 - Plot of 6 withdrawal 12 shear vs 12 withdrawal 24 shear cyclic halved for comparison

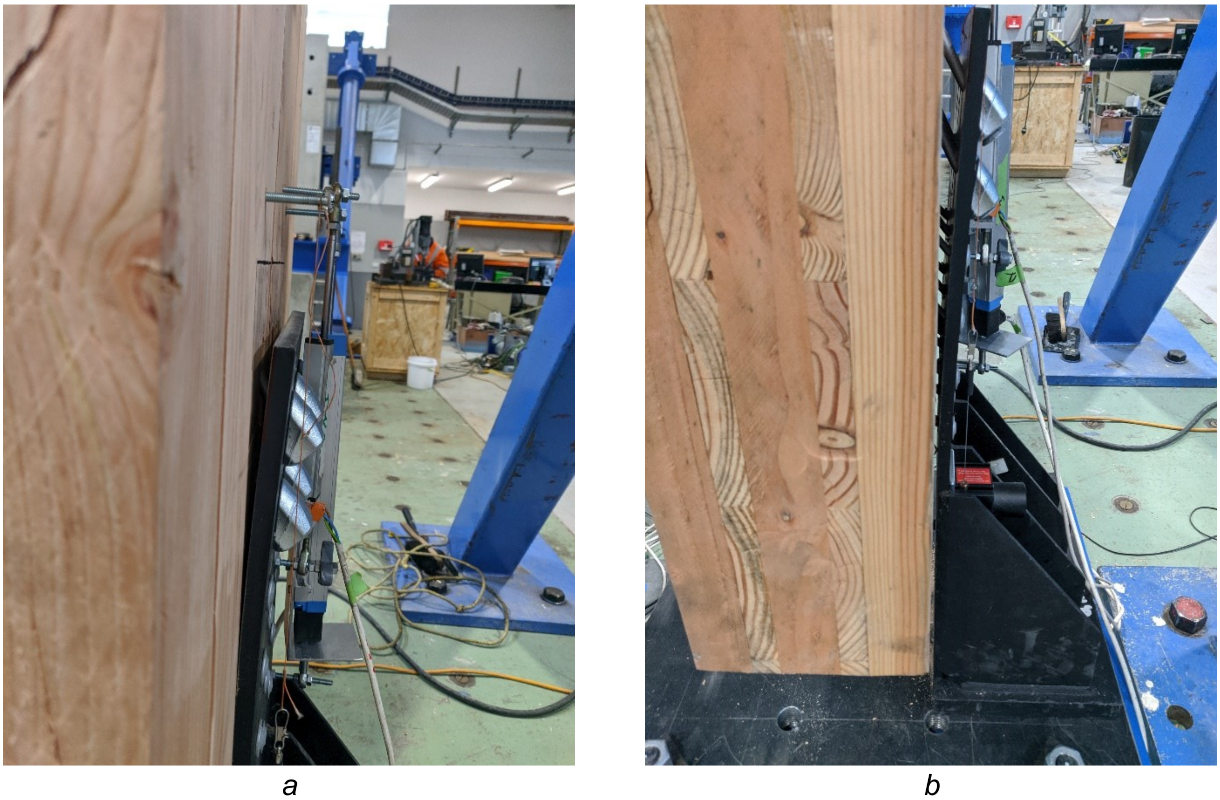

a b

Figure 18 – Photos of the hold-down being forced away from the timber specimen by the inclined screws at high displacements (a – Hold-down being forced away but being held snug against the hold-down by 90 degree screws, b – Hold-down being forced away from the timber specimen)

Optimal ratio of withdrawal to shear screws

From Phase 1 testing it was concluded that a 1:2 ratio of withdrawal to shear screws performed better than a 1:1 ratio. In the larger scale tests of Phase 2 it was possible to test both 1:2 and 1:1.5 ratio to find a more optimal solution. *Figure 19* shows a monotonic comparison between 12 withdrawal 24 shear (1:2 ratio) and 12 withdrawal 18 shear (1:1.5 ratio). Similarly, *Figure 20* shows a cyclic comparison between 12 withdrawal 24 shear and 12 withdrawal 18 shear. In both *Figure 19* and *Figure 20* it can be seen that 1:2 provided slightly higher yield strength and was much stronger at high displacements. This is intuitive as the extra shear screws will provide less capacity at lower displacements and more capacity at higher displacements. Based on the tabulated values in *Table 6* it can be seen that for cyclic tests 1:1.5 ratio achieved a higher ductility ratio (25.7 to 20.6). On further investigation it can be determined that this is actually due to a slightly lower yield strength due to the way it is calculated using EN12512. Discarding this, it can be seen that 1:2 ratio has a higher mean ultimate displacement (40.2 mm vs 38 mm) therefore meaning that the 1:2 ratio has a higher displacement capacity.

Dividing average cyclic max load through by the number of fasteners it can be seen that 1:1.5 has a slightly higher force per fastener than 1:2 (19.33 kN/fastener vs 17.25 kN/fastener).

As the load drops away at high displacement with 1:1.5 ratio it is recommended that 1:2 is used as this has more favourable performance at high displacements.

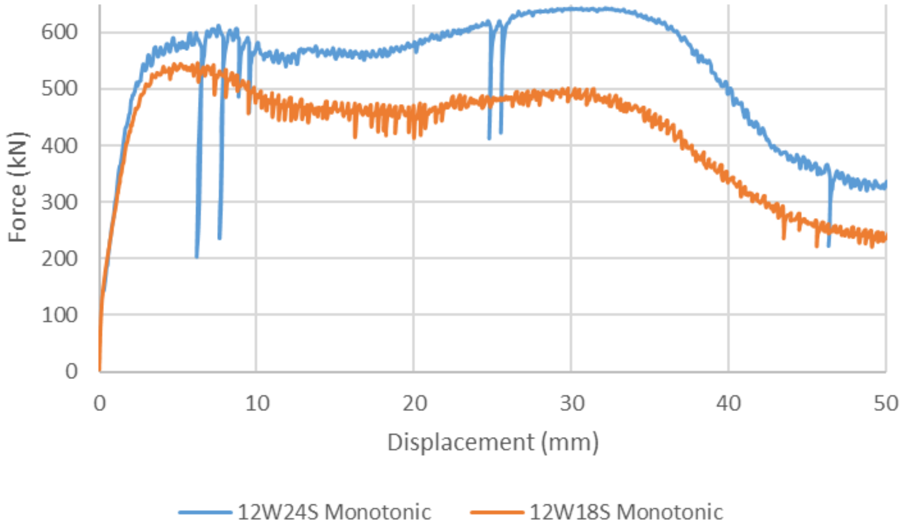


Figure 19 – Plot of 12 withdrawal 24 shear vs 12 withdrawal 18 shear monotonic

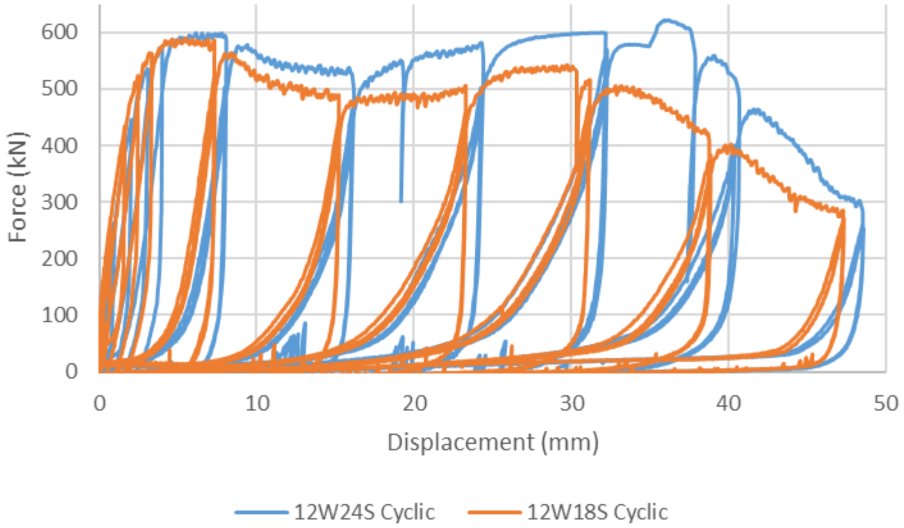


Figure 20 – Plot of 12 withdrawal 24 shear vs 12 withdrawal 18 shear cyclic

Repairs

Large self-tapping screw assemblies have a key advantage compared to other connection systems such as dowels or HSK in that they can be installed into the face of CLT walls when the CLT wall is already in place. Taking this ease of assembly advantage a step further, it is possible to install these connections after the CLT building is completed and in service as a repair for existing connections. Looking at the damage sustained in the previous tests that were taken to ultimate load, it can be seen that the damage was localised and concentrated around the screw hole. It was therefore possible to repair this connection type by shifting the connection horizontally by half spacing and installing new fasteners into the same steel hold-down bracket.

Two repair solutions were investigated. The first used Hilti HIT-RE 500 v3 epoxy injected into damaged holes to repair the damaged timber, then shifting the connection horizontally by half spacing. The second left the damaged holes untouched and simply implement the half spacing shift with no repair to the damaged timber. Pictures of the Hilti + shift and shift only connections are shown in *Figure 25*a and *Figure 25*b respectively.

From *Figure 21* and *Figure 22* it can be seen that under both monotonic and cyclic loading the connection repaired with Hilti epoxy + a horizontal shift has higher peak load, but slightly reduced displacement capacity. This is likely due to the high strength Hilti epoxy filling gaps and voids in the timber, providing extra resistance for screws in withdrawal. The same increase in strength is not seen at large displacements suggesting that the Hilti epoxy only affects the withdrawal resistance and not the shear resistance. This makes sense as at the surface of the timber, the shear fasteners are bearing into fresh undamaged timber with no Hilti epoxy.

From *Figure 23* and *Figure 24* it can be seen that under both monotonic and cyclic loading the connection repaired by just a horizontal shift has consistently lower strength than the original undamaged connection throughout all displacements. It should be noted that although there is a drop in strength, this drop is small compared to the magnitude of the load.
These tests prove the suitability of mixed angle screw hold-down connections to repair and present two viable methods, one achieving greater load than un-repaired, the other slightly lower, but both having broadly similar behaviour to the original connection.

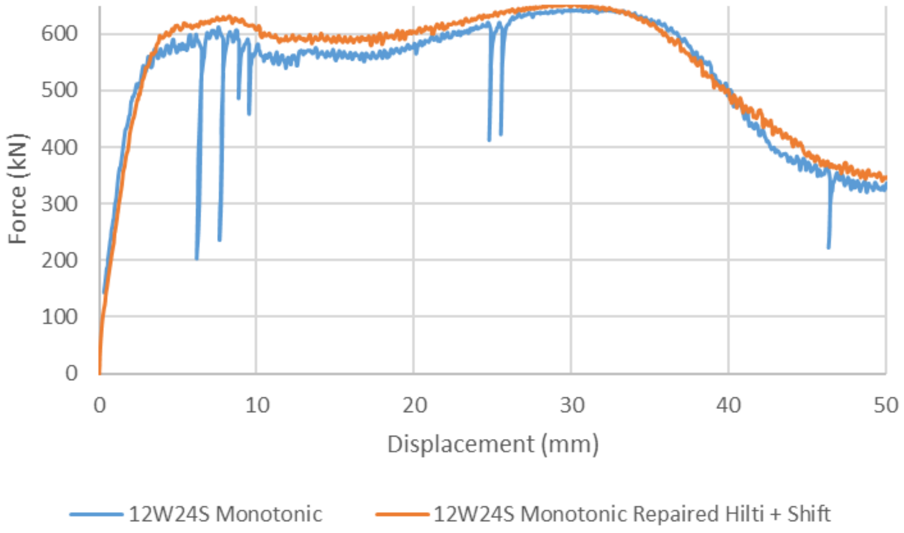


Figure 21 – Plot of monotonic 12 withdrawal 24 shear original vs repaired with Hilti + shift

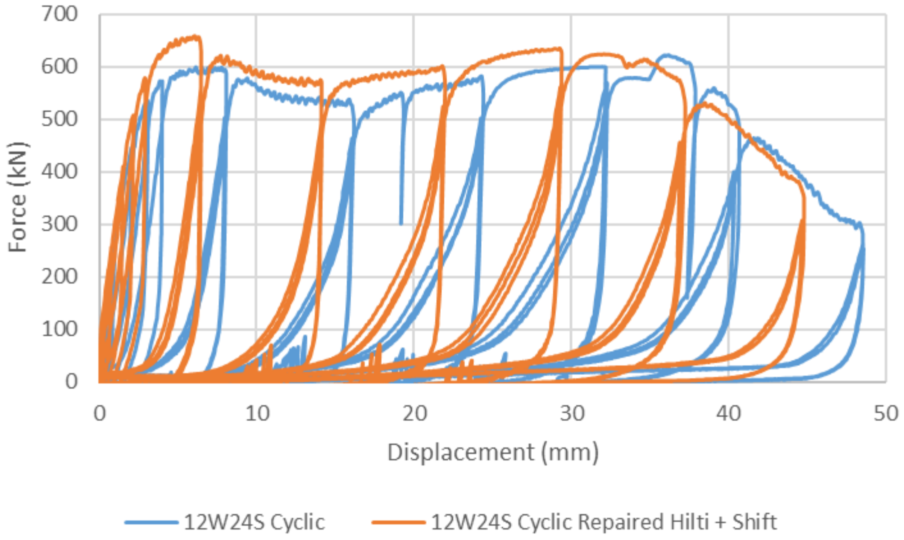


Figure 22 - Plot of cyclic 12 withdrawal 24 shear original vs repaired with Hilti + shift

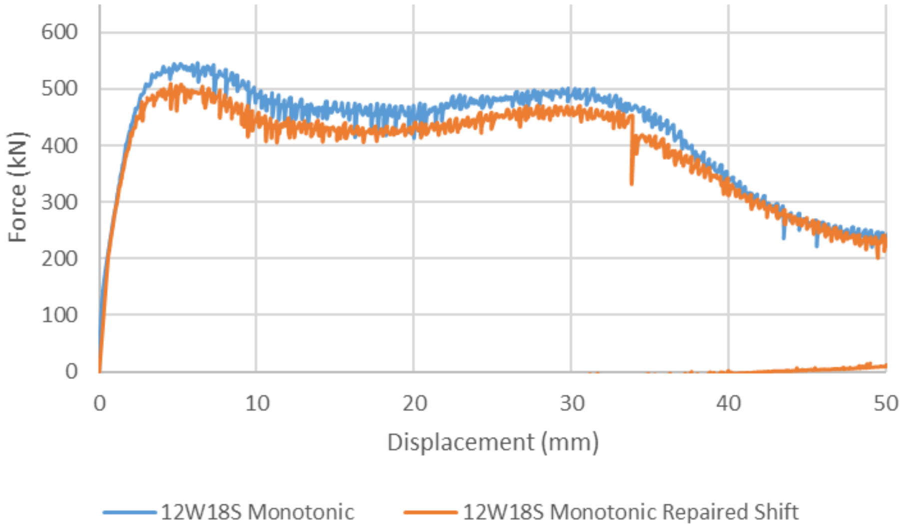


Figure 23 - Plot of monotonic 12 withdrawal 18 shear original vs repaired with shift only

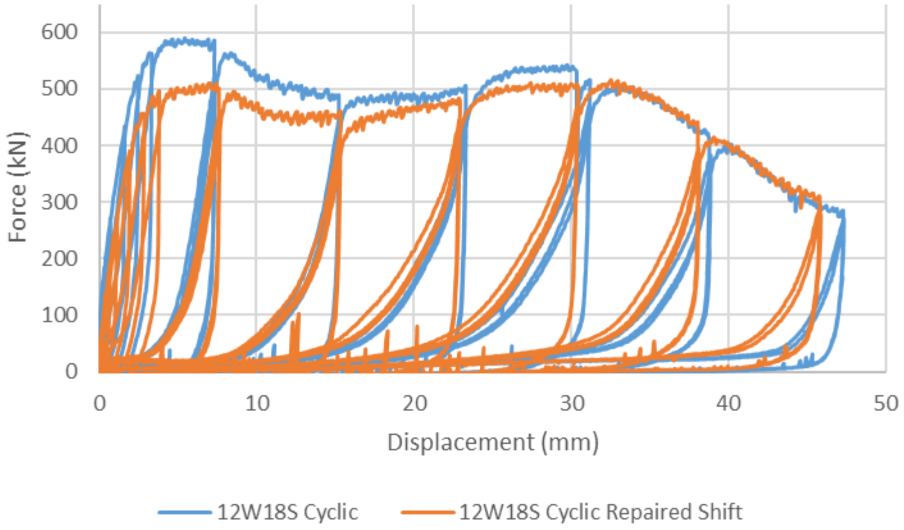


Figure 24 - Plot of cyclic 12 withdrawal 18 shear original vs repaired with shift only

a b

Figure 25 – Photo of repaired connections after being tested twice (a – Hilti + shift, b - shift)

CONCLUSION

The experimental project confirmed the suitability of Douglas-fir CLT and mixed angle screw installations for high capacity hold-down systems. These connection results will provide valuable technical information for engineers to design mass timber structures utilising Douglas-fir CLT in the lateral load resisting system to resist seismic loads.

Main findings from Phase 1 small scale tests are listed as follows:

- *Optimal threaded length of screw*

From these tests it can be seen that although fully threaded screws can provide higher stiffness and more load carrying capacity per fastener, tensile failure of the screw must be avoided to allow their use in this style of connection. Shorter fully threaded screws are available from other suppliers, but by reducing their length to avoid tensile failure, the benefits of fully threaded screws over partially threaded screws may be reduced.

- *Suitability of 45 degree washers to this application*

Both the Wurth and Rothoblaas washers evaluated are suitable for mixed angle screw connection type as long as proper detailing allows for the formation of a plastic hinge at the head of the withdrawal screw. For the Wurth washer used in phase 1 this required the addition of two tack welds at the tip of the washer, but with significantly thicker plate this would not be required. Similarly the Rothoblaas washers tested did not require any tacks welds when used with the 12 mm thick plate but would require tack welds for the 8 mm thick plate or thinner.

- *Optimal Ratio of withdrawal to shear fasteners*

Using a combination of fasteners in withdrawal and fasteners in shear both high initial stiffness and high ductility/displacement capacity can be achieved. With the configuration tested (12 mm screws in withdrawal, 10 mm screws in shear), the ratio of 1:2 was found to perform better than a ratio of 1:1. Further testing in phase 2 will work to investigate the ratio of 1:1.5 as this may be more efficient than 1:2. During testing it was found that this connection type performs well under both monotonic and cyclic loading, with some cyclic degradation being seen at very high displacements. It is worth mentioning though that the cyclic protocol used from ISO 16670 is a very demanding testing protocol compared to what a timber building is likely to experience in an earthquake event.

Main findings from Phase 1 small scale tests are listed as follows:

- *Component test for hold-downs used in previous wall testing*

The hold-downs used in previous wall testing had high initial stiffness and significant ductility/displacement capacity as would be expected for a mixed angle screw hold-down. This data showed that the hold-downs installed in the wall tests performed well, and provided calibration data for future numerical simulations of the wall system.

- *Single sided vs double sided*

Testing showed that the horizontal constraints imposed by a double sided hold-down test provided significant displacement capacity performance benefits over a single sided test that was not well horizontally constrained. The impact of these constraints provided implications for how these hold-downs are used in future CLT structures. Although the wall is likely constrained horizontally out of plane by other connections and fasteners, the significant performance reduction should be noted and further research in this area is required.

- *Optimal ratio of withdrawal to shear screws*

The 1:1.5 ratio of withdrawal to shear screws was found to have higher load carrying capacity per fastener and therefore be more efficient. However, it should be noted that at high displacement the load sustained was less than the peak (although more than 80%) and therefore, it is recommended that the 1:2 ratio be used as this has more favourable performance at high displacements.

- *Repairs*

Of the two repair strategies tested it was found that both performed well under both monotonic and cyclic loads, although displacement capacity was slightly reduced. This proved the suitability of mixed angle screw hold-down connections to repair. Of the two repair methods presented it is recommended to use the Hilti + shift method.

ACKNOWLEDGEMENTS

The authors would like to thank University of Canterbury technicians Mr. Gavin Keats and Mr. Alan Poynter, for their valuable input and support throughout the test programme.
Additional support provided by Spax Pacific Ltd and XLAM Ltd is greatly appreciated for supplying the fasteners and CLT materials.

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