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Cyclic behaviour of hold-downs using mixed angle self-tapping screws in Douglas-fir CLT

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ABSTRACT

Long self-tapping screws are now commonly used in mass timber construction in New Zealand and globally due to their high strength and ease of installation on site. Under axial loads, self-tapping screws are strong and stiff but are not ductile. However they are very ductile under lateral loads similar to other dowel-type fasteners. Previous research has shown the possibility to achieve strong and ductile connections when self-tapping screws are installed with mixed angles so that axially and laterally loaded screws work together to resist the loads. However, previous research was limited to timber-to-timber joints. So far, no experimental testing has been done to investigate the performance of steel-to-timber joints using self-tapping screws with mixed angle installations. These steel to timber joints can be used as hold-down connections in cross laminated timber (CLT) shear walls. In this study, cyclic performance of the mixed angle steel-to-timber connections were experimentally investigated in Douglas-fir CLT. Testing results showed that mixed angle installations can provide high strength and stiffness, as well as high ductility and displacement capacity. The performance of these connections was also compared to similar dowelled hold-down connections with the results showing an increase in initial stiffness as well as the elimination of initial slip due to installation tolerances, confirming the suitability of these connections as a viable alternative for dowelled connections as hold-downs in CLT shear walls.

1 INTRODUCTION

Cross Laminated Timber (CLT) is an increasingly popular product used in the construction of large mass timber structures. Being a panelised timber product CLT is primarily used for the construction of timber wall and floor assemblies. CLT buildings in seismic areas commonly use CLT shear walls as their primary lateral load resisting system, with large hold-down connections being required to resist the overturning moment at the base of the wall. As timber is primarily a brittle material, ductility/yielding and energy dissipation of a timber system comes from the connections between timber elements. It is therefore imperative that performance of these hold-down connections is well understood. Currently hold-down connections in CLT shear walls often utilise off-the-shelf nailed steel brackets or sometimes dowelled connections. Commercially available off-the-shelf nailed hold-down brackets usually have low capacity (less than 100 kN), while dowelled connections can be difficult to install on site with construction tolerances required. Easy to install on site with common hand-tools, self-tapping screws can be installed without the construction tolerances required for dowelled connections, or the rigorous quality control required for glued in rod or HSK connections. However, self-tapping screws installed at an inclined angle, e.g., 45 degrees, to the timber surface provide limited ductility, while self-tapping screws installed at 90 degrees lack initial high stiffness. Therefore, this experimental study investigates the performance of self-tapping screws in CLT hold-down connections, using mixed angle screw arrangements to achieve high strength, high initial stiffness, and high ductility.

1.1 Previous research

Self-tapping screws have allowed more efficient connections than other dowel-type fasteners by exploiting the axial withdrawal capacity for increased load carrying capacity (Blaß & Bejtka, 2001). By decreasing the angle of the screw relative to the grain, we can increase the connection strength and stiffness, but ductility and displacement capacity is reduced. Previous work (Tomasi et al., 2006) investigated the suitability of mixed angle screw connections. In these connections screws are installed at both 45 degrees and 90 degrees to the grain. 45 degree screws (inclined) act primarily in tension or withdrawal and have high stiffness, but low ductility. 90 degree screws act primarily in shear and have low stiffness, but high ductility. By combining the two installation angles together the resulting connection has high stiffness, and high ductility. Further work has investigated their use in timber-to-timber in-plane joints between timber shear walls (Brown et al., 2020; Hossain et al., 2018). This study extends on previous research and assesses the performance of mixed angle screw connections in steel to timber hold-down joints.

2 EXPERIMENTAL PROGRAMME

The key goal of this study was to determine the performance of mixed angle screw arrangements in steel-to-timber hold-down connections, building on previous research findings in timber-to-timber connections. Key parameters such as strength, stiffness, ductility, and displacement capacity were investigated through a total of 24 monotonic and cyclic tests.

2.1 Test programme

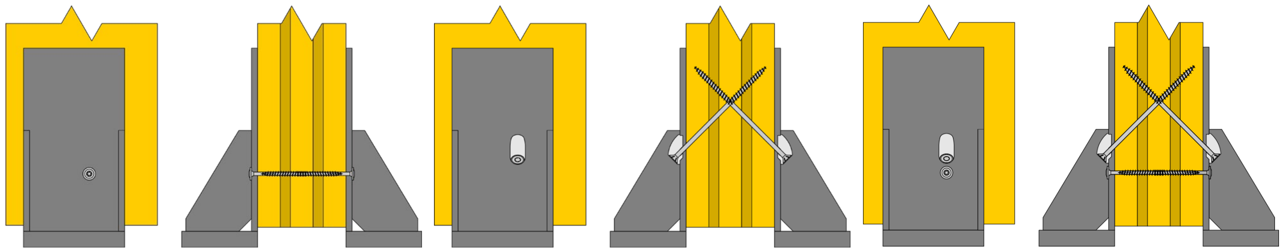
Connection tests were undertaken at both a small and medium scale. Small scale connection specimens consisted of 2 to 6 fasteners with a variety of layouts. Medium scale testing built on the results of small scale testing and the connection specimens consisted of 36 fasteners being used to achieve maximum loads between 600-650 kN.

The test programme is shown below in Table 1 with drawings in Figure 1. Test Sets 1 and 2 investigated the connection performance of 90 degree screws and inclined screws respectively. Test Sets 3 and 4 investigated the performance of two inclined angle screws and two 90 degree screws in a mixed angle connection. Test

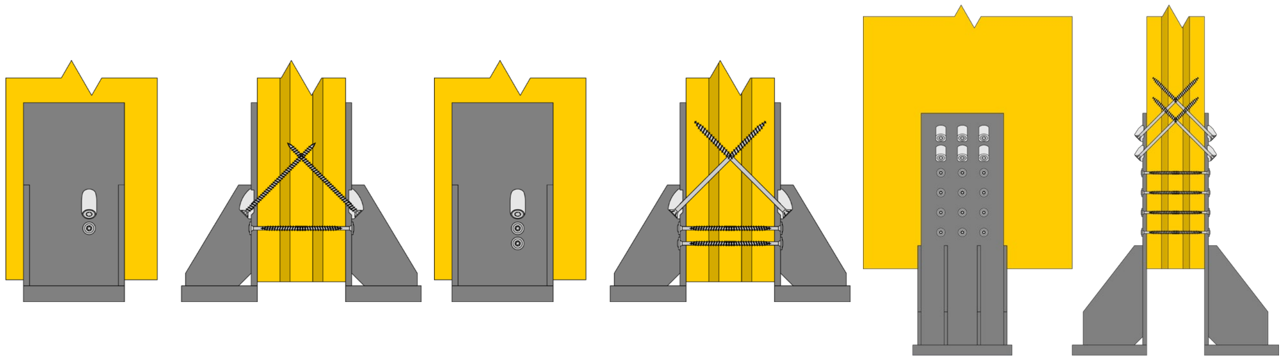
Set 3 uses partially threaded (PT) inclined screws, while Test Set 4 uses fully threaded (FT) inclined screws. Test Sets 5 and 6 investigate the performance of mixed angle screws with a ratio of one inclined angle screw to two 90 degree screws, with Test Set 6 being conducted at a much higher capacity than the previous Test Sets.

Table 1: Test matrix for connection tests

Test Set	**Description of screwed connection**	**Inclined Screws**		**90 Degree Screws**		**Ratio**	**Replicates**	
		Qty	Size	Qty	Size		Mono	Cyclic
1	2 90 degree	-	-	2	10x180 PT	-	2	2
2	2 inclined	2	12x260 PT	-	-	-	1	3
3	2 inclined 2 90 degree partially threaded	2	12x260 PT	2	10x180 PT	1:1	1	3
4	2 inclined 2 90 degree fully threaded	2	12x200 FT	2	10x180 PT	1:1	1	3
5	2 inclined 4 90 degree	2	12x260 PT	4	10x180 PT	1:2	1	3
6	12 inclined 24 90 degree	12	12x260 PT	24	10x180 PT	1:2	1	3



Test Set 1 *Test Set 2* *Test Set 3*



Test Set 4 *Test Set 5* *Test Set 6*

Figure 1: Drawings of each connection setup tested.

2.2 Test setup and material properties

Small scale testing was conducted using a 250 kN Instron universal testing machine as seen in Figure 2. Load was transferred to the 300 x 750 mm CLT specimens through a dowelled connection with inserted steel plate that was overdesigned to remain elastic compared with the testing connection of interest. The connection displacement/slip was measured by using two 100 mm potentiometers placed between the steel side plate and the timber surface (one on each side).

Medium scale testing was conducted using a 1000 kN hydraulic actuator in conjunction with a steel reaction frame as seen in Figure 2. Load was transferred to the 650 x 1275 mm CLT specimen through a screwed overstrength connection. Displacement was measured by 4 potentiometers placed between the steel side plate and the timber surface (two on each side).

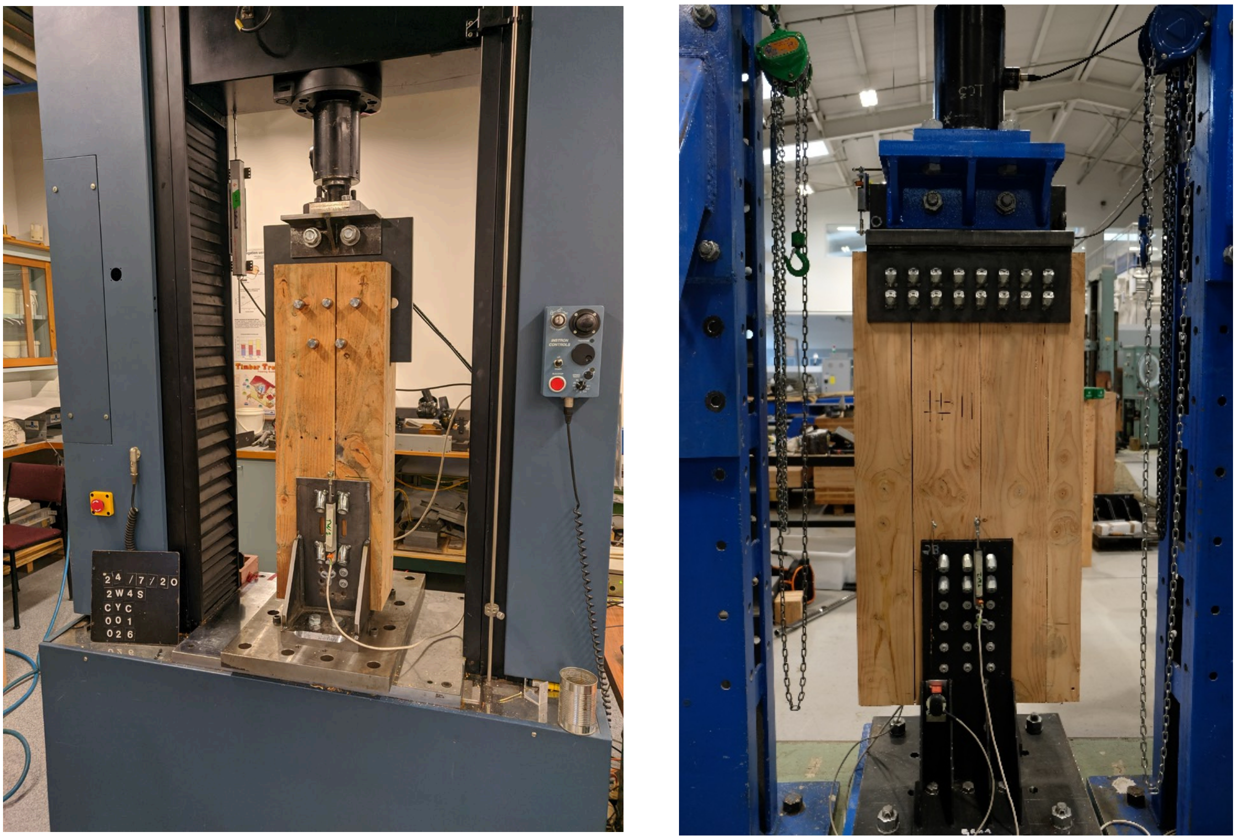


Figure 2: Connection test setups with tested connections at the bottom. Left: Small scale. Right: Medium scale

2.2.1 Material and protocol

CLT specimens were supplied by XLAM Ltd using Douglas-fir lamella. Lamella were graded SG8 as per NZS 3603 (Standards New Zealand, 1993). All specimens were 5-layer and 175mm thick with a 45/20/45/20/45 layup. Moisture content of the specimens at testing was around 10% on average, and mean density was 467 kg/m^3. All screw holes were fully predrilled for ease of installation. Predrill hole diameter was 7 mm for Φ12 mm screws and 6 mm for Φ10 mm screws as per the SPAX European Technical Approval (ETA-12/0114, 2020).

The screws were supplied by SPAX, with Φ12 mm counter-sunk screws being used for inclined angles, and Φ10 mm washer head screws being used for 90 degree installations. For 90 degree screws, Φ10 mm screws were used due to the lack of availability of washer head screws in a Φ12 mm size. To facilitate the use of inclined screws at 45 degrees, 45 degree washers from both Wurth and Rothoblaas were used, removing the need to mill 45 degree countersunk holes in thick steel side plates. These washers fit into slotted holes in the steel, and allow much thinner steel side plates to be used. The use of washers makes the fabrication of steel much less labour intensive as the slotted holes can be cut by laser or high-definition plasma cutter. In contrast holes counter-sunk on a 45 degree angle would first require a 45 degree flat to be milled, followed by drilling and countersinking at 45 degrees. In both small and medium scale tests steel hold-down brackets can be considered nominally fixed at the base, and are able to flex out of plane higher up as stiffeners do not run full height. Slotted holes for 45 degree washers were laser cut as per the manufacturer specification, while holes for 90 degree screws were 2 mm oversize as per NZS3404 (Standards New Zealand, 1997).

Monotonic testing was conducted at a rate of 2 mm/min for small scale and 6 mm/min for medium scale. Cyclic testing was conducted at a rate of 30 mm/min for small scale and 15 mm/min for medium scale. Cyclic testing used a half cyclic loading protocol based on ISO16670 (International Organization for Standardization, 2003).

3 RESULTS

Table 2 provides a summary of the key connection parameters derived for each connection specimen.

Yield strength, F_y, yield displacement, Δ_y, ultimate strength, F_u, ultimate displacement, Δ_u, and ductility, μ, were calculated in accordance with EN12512 (British Standards Institution, 2001). For the calculation of ultimate displacement EN12512 stipulates that ultimate displacement is either failure displacement, displacement when post-peak load reduces to 80% of max load, or 30 mm displacement. Due to the highly ductile nature of the joints being tested, the 30 mm displacement limit was deemed not applicable in this case. Due to the tight fitting of the screws in the connections, initial slip typically observed in dowelled or bolted connections did not occur, thus no correction for initial slip was needed.

4 DISCUSSION

4.1 Performance improvements with mixed angle screw installations

From Figure 3a, it can be seen that the screws installed at 90 degrees to the grain had low initial stiffness but high displacement capacity. From Figure 3b, it can be seen that the screws installed at an inclined angle (45 degrees) to the grain had high initial stiffness, but low displacement capacity only reaching an average ultimate displacement of 10.3 mm compared to 37.2 mm for 90 degree screws. Figure 3c shows a combination of inclined and 90 degree screws, and it can be seen that by combining both in a single mixed angle connection, the connection can achieve both high initial stiffness and high displacement capacity. Under cyclic loading the mixed angle screw connections had similar performance to the connections tested under monotonic loading, but with heavily pinched hysteresis loops.

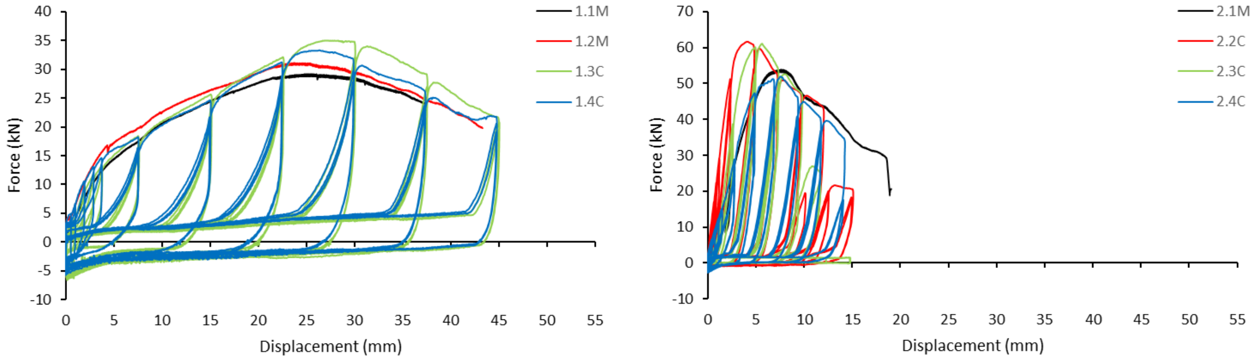
The Φ10 mm 90 degree screws used in these tests had significantly less load carrying capacity than the equivalent number of Φ12 mm inclined angle screws. This means that although the behaviour of inclined and 90 degree screws was superimposed, when installed with a 1:1 ratio between inclined and 90 degree screws, load carrying capacity decreased significantly at high displacements. This is evident in Test Set 3 where the load reached the peak at an average of 4.2 mm and decreased significantly thereafter. To achieve better performance, Test Set 5 and 6 used twice as many 90 degree screws as inclined angle screws with a 1:2 inclined to 90 degree ratio. From Figure 3e and Figure 3f it can be seen that the connections with mixed angle screws had no significant load drop until the onset of failure in 90 degree screws at more than 30 mm displacement. These tests show that mixed angle screws can provide high strength and initial stiffness, while maintaining high ductility and displacement capacity.

Table 2 – Connection testing results summary

Test #*	F_y	F_{max}	F_u	K	Δ_y	Δ_{Fmax}	Δ_u	μ
	kN	kN	kN	kN/mm	mm	mm	mm	
1.1M	20.5	29.2	23.3	3.16	6.2	24.8	37.4	6.04
1.2M	20.3	31.1	24.9	3.63	4.71	23.7	37.1	7.88
1.3C	26.1	35	28	2.95	8.43	26.7	37.5	4.45
1.4C	23.5	33.3	26.6	3.13	6.42	26.3	36.9	5.75
2.1M	51	53.8	43	9.56	5.25	7.7	12.4	2.36
2.2C	57.1	61.6	49.3	21.5	2.5	4.01	8.39	3.36
2.3C	55.8	61.1	48.9	19.2	3.5	5.64	8.99	2.57
2.4C	49.4	52	41.6	8.53	5.41	7.54	11.3	2.09
3.1M	66.3	73	58.4	24.2	2.47	4.86	13.7	5.52
3.2C	63.3	71.9	57.5	27.1	2.12	4.62	35	16.5
3.3C	68.6	74	59.2	26.1	2.39	3.74	15	6.27
3.4C	66.3	75.4	60.3	33	1.8	3.71	10.7	5.95
4.1M	92.4	99	79.2	32.2	2.62	4.27	7.52	2.87
4.2C	97.1	110	87.8	41.3	2.14	4.2	5.43	2.54
4.3C	102	102	81.4	23.3	4	4.72	7.73	1.93
4.4C	89.8	98	78.4	35.2	2.24	3.92	10.2	4.57
5.1M	59.6	79	63.2	45	1.17	4.44	44	37.5
5.2C	78.1	94.3	75.5	33.8	1.94	29.5	39.9	20.6
5.3C	78.1	97.2	77.8	43.6	1.6	28.9	35.5	22.2
5.4C	78.7	99.1	79.2	43.1	1.66	7.5	38.4	23.2
6.1M	522	643	515	216	2.04	30.6	39.5	19.3
6.2C	504	622	498	222	2.01	36	40.6	20.2

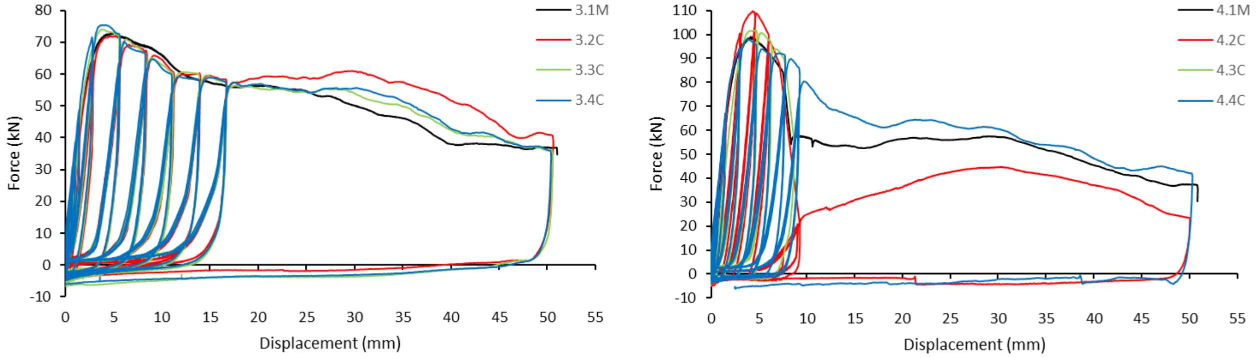
6.3C	498	609	487	238	1.81	31.2	39.6	21.8
6.4C	544	633	506	223	2.04	31.8	40.3	19.7

* M represents a monotonic load protocol, and C a cyclic.



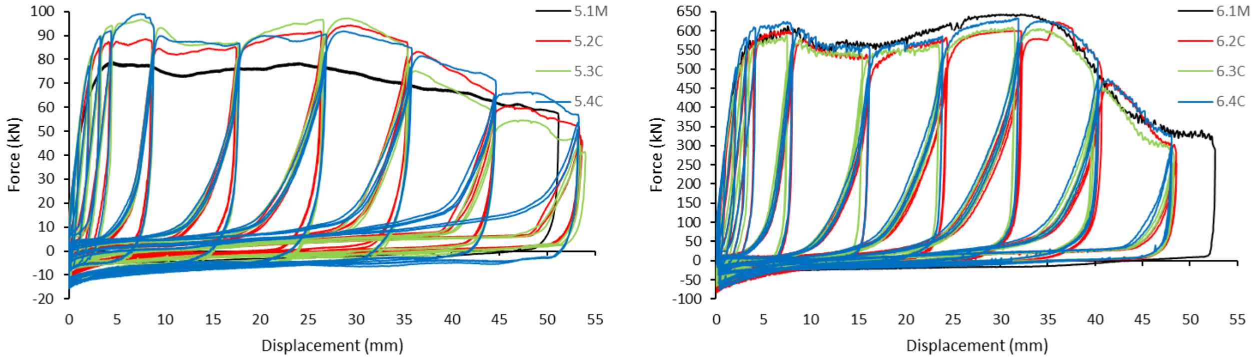
a – Test Set 1

b – Test Set 2



c – Test Set 3

d – Test Set 4



e – Test Set 5

f – Test Set 6

Figure 3 – Plots a to f show Test Sets 1 to 6, respectively.

4.2 Failure modes

For screws installed at 90 degrees, the failure mechanism was timber crushing and fastener yielding, with rope effect being significant at large displacements. Two plastic hinges were formed in the fastener, one at the timber steel interface, the other at a distance into the timber.

For fasteners installed at an inclined angle (45 degrees) the primary failure mechanism was fastener withdrawal. In mixed angle tests, inclined screws were loaded to displacements much larger than their ultimate displacement when tested alone. At these large displacements fastener yielding and limited timber crushing occurred. Similar to 90 degree screws, one hinge was formed at the steel timber interface, and the other at a distance into the timber. At large displacements the inclined screws pushed the top of the steel side plate away from the timber surface. The stiffeners in the hold-downs did not run full length, therefore at larger displacements, the steel side plate was allowed to bend away from the timber surface (Figure 4). Future testing will address the possible implications of this.

For inclined screws, most tests utilised Φ12x260 partially threaded screws with 100 mm threaded length installed at 45 degrees. To achieve more optimal performance using less fasteners, Test Set 4 used Φ12x200 fully threaded screws (200 mm threaded length 163 mm in the timber). For these tests using fully threaded screws, the failure mode of the inclined screws varied between withdrawal and tensile failure of the screw. As highlighted by Brown (Brown et al., 2020), when tensile failure of the screw occurs there is not a smooth transition of load sharing between the inclined and 90 degree screws but rather a sudden drop of the load. This is highlighted in Figure 3d by Test Set 4.2C where there is a sudden drop in load just prior to 10 mm displacement corresponding to the failure of screws in tension. To avoid this sudden drop of load carrying capacity, inclined screws should be designed such that their failure method is screw withdrawal instead of screw tensile failure.

Looking at the overall connection performance, load carrying capacity continued to drop gradually as fasteners started to withdraw. Assuring block shear failure mechanisms are capacity protected, damage to the timber was limited to concentrated areas in the vicinity of the fastener where timber crushing occurred (Figure 4), leaving the timber panel as a whole with minor damage.

4.3 Performance at different capacities

Test Sets 5 and 6 evaluated the performance of mixed angle connections with the same 1:2 ratio of inclined to 90 degree screws, but at a small and a medium scale respectively. The number of screws in Test Set 6 was 6 times of that in Test Set 5. Comparing the maximum load achieved in both test sets it can be seen that on average Test Set 6 has maximum load slightly higher than 6 times the average of Test Set 5 specimens. This indicated that when brittle failure mechanisms were capacity protected, mixed angle screwed hold-downs achieved similar performance in small scale and medium scale. Therefore, it is possible to achieve the same performance in a large-scale connection with a similar screw layout but increased number of screws.

4.4 Comparison with high capacity dowelled CLT hold-down connections

Figure 5 shows a representative force-displacement curve of a medium-scale mixed angle screwed hold-down (6.3C) plotted against a representative force-displacement curve from a dowelled CLT hold-down test undertaken by Ottenhaus (Ottenhaus et al. 2018). The dowelled hold-down specimen used 16 Φ20 mm steel dowels in 205 mm (45/40/35/40/45) Radiata Pine CLT with a 25mm thick inserted steel plate. The dowelled hold-down specimen had standard dowel spacing and reached a maximum load of 871 kN. The medium-scale mixed angle hold-down specimen (6.3C) reached a maximum load of 609 kN. Despite the discrepancy between the sizes of the connections, the mixed angle screw hold-down test shows significantly higher initial stiffness compared to the dowelled hold-down connection, even though the load-carrying capacity was 30% lower.

Figure 4: Left: Hold-down bent away from the timber surface by inclined screws. Right: Damaged zone where hold-down was installed.

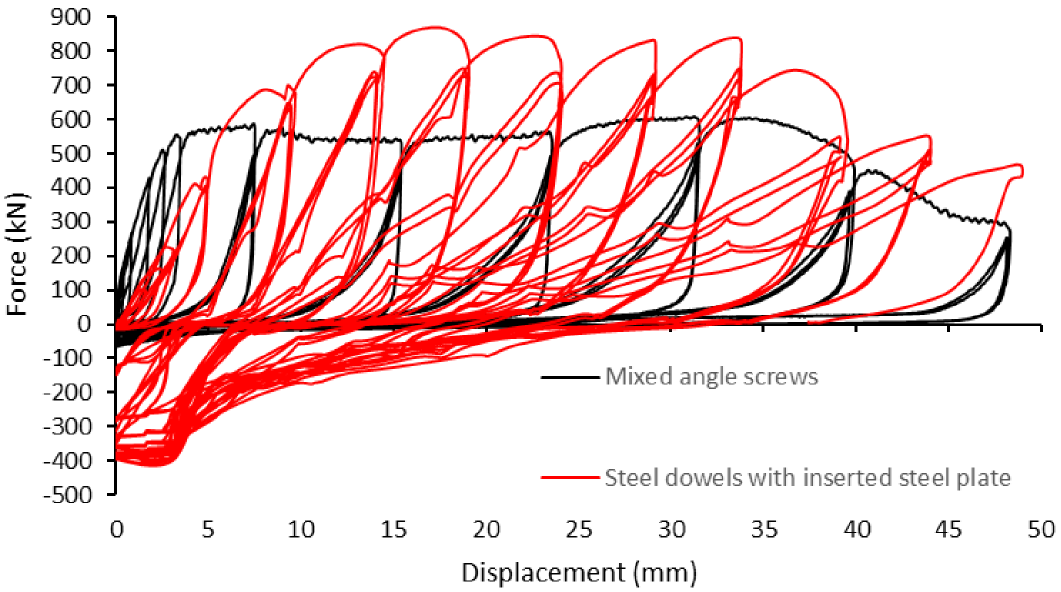


Figure 5: Comparison of dowelled and mixed angle screw connections

Mixed angle screws also achieved similar ultimate displacements to the dowelled connection. However, the average ductility ratio 20.25 of the mixed angle screw hold-downs were significantly higher, with an average of 20.25 compared to that of 4.8 for the dowelled connection. It should be noted that the definition of ductility is highly sensitive to the definition of the yield strength and yield displacement, and does not take into account other factors such as the significant pinching observed in the mixed angle screw hysteresis loops. Therefore, although the mixed angle screw has significantly higher ductility values than those reported by Ottenhaus (Ottenhaus et al. 2018), the energy dissipation for mixed angle screws was much lower. Overall the mixed angle screw connection presents a good option for designers looking for high strength, stiffness, ductility, and displacement capacity.

5 CONCLUSION

A total of 24 experimental tests on mixed angle screw hold-downs were conducted with differing layouts and sizes. The key findings of this study are:

- Overall mixed angle screw connections can provide a strong, stiff, and also ductile hold-down option for CLT shear walls.
- Inclined screws should be designed to avoid tensile failure, allowing a smooth transition of load sharing between the inclined and 90 degree screws.
- In the configurations tested, mixed angle screw connections can be scaled up to 600 kN capacity without significant loss of performance due to size effects.
- Mixed angle screw connections can provide high displacement capacity, while having higher initial stiffness than comparable dowelled connections.

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