Design of Mixed Angle Screw CLT Hold-Down Connections to New Zealand Timber Standards

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ABSTRACT

Mixed angle screws provide a strong, stiff, and ductile hold-down solution for high-capacity Cross Laminated Timber (CLT) shear walls. Timber is an inherently brittle material and most inelastic responses in timber structures are concentrated in connections. Seismic performance of a CLT shear wall system is typically governed by connection behaviour. By combining screws installed at an inclined angle and a 90° angle to the grain, the strength and stiffness of inclined screws and the ductility of 90° screws can be superimposed for strong, stiff, and ductile connection performance. Previous research presented to NZSEE has demonstrated the performance of mixed angle screw hold-down connections under cyclic loading, and their ability to be easily repaired post seismic events. This paper extends on this research topic and presents high-capacity testing results along with a discussion on design methodology. The high-capacity testing results showed that mixed angle screw hold-down connections can achieve yield forces averaging 952 kN in Douglas fir CLT and 1029 kN in radiata pine CLT. Strength predictions from Eurocode 5 and NZS AS 1720.1:2022 are discussed, with NZS AS 1720.1:2022 being more conservative. The conservatism of current approaches is also discussed with analytical predictions underestimating the characteristic 5th percentile yield strength from testing by a factor of 1.3. The observed overstrength factor based on analytical predictions and characteristic 95th percentile values of maximum force averaged 2 with a maximum of 2.4. NZS AS1720.1:2022 introduces a cap on overstrength demand at the maximum action generated due to equivalent elastic seismic demand. Therefore, for structures designed with system ductility of 2 overstrength demands are likely to be governed by the equivalent elastic demands.

1 INTRODUCTION

The mass timber construction sector in New Zealand continues to grow as architects and engineers recognise the social, economic, and environmental benefits of timber construction. Cross Laminated Timber (CLT) shear walls are an efficient lateral load resisting system for mass timber buildings. As timber is an inherently brittle material, inelastic response of timber buildings is typically governed by the connections. As the connections govern the performance of CLT shear wall systems, it is imperative that they be strong, stiff, and ductile under seismic loading.

Connections using mixed angle screws are a growing concept in timber design. It is well known that self-tapping screws installed with inclined angles can transfer loads in the withdrawal mode, and have increased strength and stiffness compared with laterally loaded screws (also referred to as 90° screws) (Bejtka and Blaß 2002; Blaß and Bejtka 2001; Kevarinmaki 2002). However, inclined screws have lower ductility and displacement capacity despite increased strength and stiffness. Therefore, further research has been conducted into the concept of mixed angle screw installations, where some screws are placed at an inclined angle to the grain, and others at a 90° angle to the grain. Experimental testing has found combining screws of mixed installation angles leads to optimized performance of high strength and stiffness but also high displacement capacity/ductility (Tomasi et al. 2006). Further research on this concept has been undertaken in inter-panel joints (Hossain, Popovski, and Tannert 2018), in orthogonal joints (Brown et al. 2021), and most recently as hold-down connections for CLT shear walls (Wright et al. 2021; 2022) As a hold-down connection, mixed angle screws have been found to be not only strong, stiff, and ductile, but also easily and economically repairable (Wright et al. 2022).

The purpose of this paper is to build on the previous research, present high-capacity connection test results from the University of Canterbury, and present guidance and discussion around the design of mixed angle screw hold-down connections in New Zealand.

The key outcomes of this paper include the following:

- Present high-capacity connection test results that push the boundaries of utilizing the CLT panel capacity.
- Introduce and discuss a design method for mixed angle screw connections using both Eurocode and NZS AS 1720.1:2022.
- Use the large number of testing results undertaken from this connection type to determine the overstrength factor and discuss the accuracy of the analytical predictions.

2 EXPERIMENTAL PROGRAM AND METHODS

As part of a wider investigation into mixed angle screw hold-down connections at the University of Canterbury three stages of experimental testing have been undertaken. Tests from Stages 1 and 2 have been presented at NZSEE Conferences from 2021 and 2022 (Wright et al. 2021; 2022). As part of Stage 3, six test results from high-capacity hold-down testing (1000 kN +) are presented in this paper alongside a collation of previous test results for the evaluation of overstrength.

The key objective of the hold-down tests presented from Stage 3 is to validate the performance of mixed angle screw connections at high capacities. The specimen design was chosen to push the limits of the structural engineering lab testing facilities at the University of Canterbury and the limits of what can be reasonably achieved in practical design.

2.1 Test Programme

Table 1 presents a test matrix for Stage 3 summarising the CLT material, size and quantities of screws used in the connection as well as the number of replicates of monotonic and cyclic loading. A total of six tests were undertaken, all with the same connection detail, but three using Douglas fir CLT and three using radiata pine CLT. The connection detail tested used 24 screws installed at a 45° inclined angle to the grain, and 36 screws installed at a 90° angle to the grain. Inclined screws were SPAX ϕ12x260 mm partially threaded (PT) screws, and 90° screws were SPAX ϕ12x180 mm PT screws. All screws used countersunk (CSK) heads. Inclined angles were achieved using 12 mm Rothoblaas VGU inclined washers. The connection layup is shown in Figure 1. Both Douglas fir and radiata pine CLT were made of SG8 lamellas (Standards New Zealand 1993), and had a 205 mm thick 45/35/45/35/45 layup. Mean density was determined in accordance with NZS 1080.3:2000 (Standards New Zealand 2000) and found to be 472 kg/m^3 for Douglas fir and 460 kg/m^3 for radiata pine specimens. Characteristic 5th percentile densities were found to be 429 kg/m^3 for Douglas fir and 417 kg/m^3 for radiata pine specimens.

Table 1 – Summary of Test Programme

Test Set	CLT Material	Inclined Screws		90° Screws		Ratio	Replicates	
		Qty	*Size*	*Qty*	*Size*		*Monotonic*	*Cyclic*
1	Douglas fir	24	12x260 PT	36	12x180 PT	1:1.5	1	2
2	Radiata pine	24	12x260 PT	36	12x180 PT	1:1.5	1	2

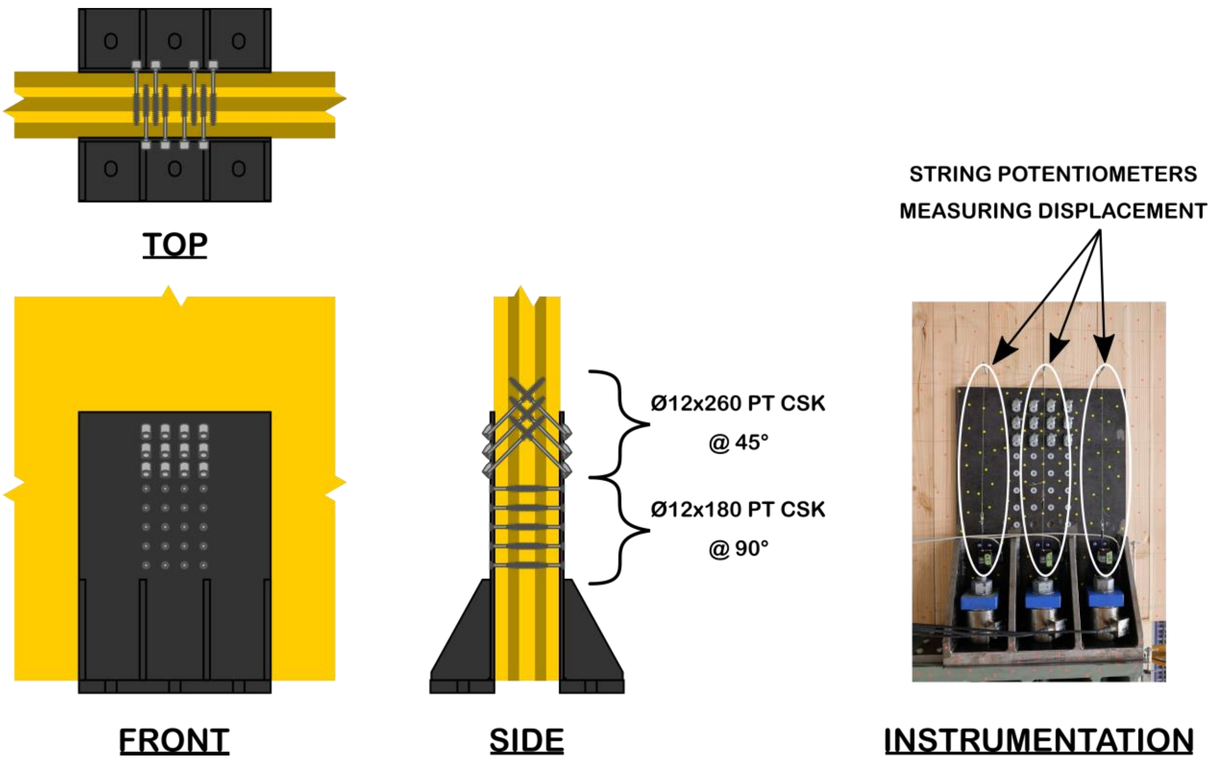


Figure 1 – Diagram showing connection setup for both Douglas fir and radiata pine tests

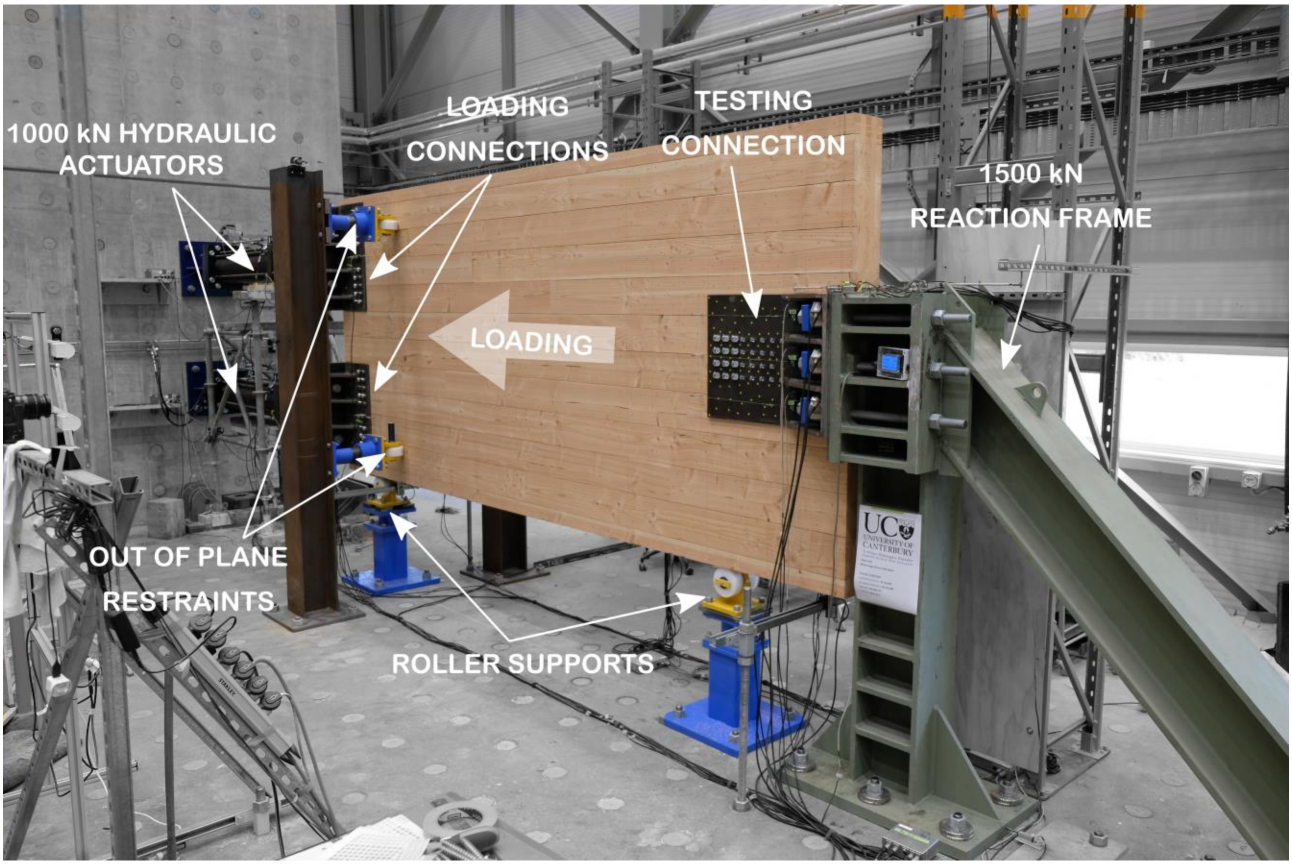


Figure 2 – High-capacity testing setup

2.2 Test Setup

Testing was conducted using two 1000 kN Parker hydraulic actuators in conjunction with a 1500 kN steel reaction frame. Load was transferred into the CLT specimen using inclined screws and steel side plates designed for the overstrength of the testing connection. Custom steel hold-down brackets with 12 mm steel side plates were used either side of the 5-ply 205 mm thick CLT panels as shown in Figure 1 and Figure 2. A loading rate of approximately 12 mm/min was used for both monotonic and cyclic tests. The cyclic loading protocol used was derived from ISO 16670, with displacement steps based on the ultimate displacement measured during monotonic tests (International Organization for Standardization 2003).

3 RESULTS

Table 2 provides a summary of experimental testing results from Stage 3 testing. Key parameters such as strength, stiffness, and ultimate displacements are all presented. For the definition of yield displacement and ductility, the results from two approaches are presented. EN 12512 defines the yield displacement using a gradient of 1/6 of the initial stiffness . EEEP defines an equivalent elastic perfectly plastic curve of equal energy or area under the force displacement curve (British Standards Institution 2001; ASTM 2011). Due to the specific shape of the force displacement curve with high initial stiffness, the EN 12512 method was found to underestimate the yield force. For most cases the EEEP method provided a good definition of the yield point, but for some cases with high post yield strength increase, it was found to overestimate the yield force. To provide a better approximation for comparison with analytical formulae, the term F_{exp} has been presented as in Wright et al. (2023). F_{exp} represents the maximum force up to 5 mm displacement and for this type of connection has been found to be a good approximation of the yield point (Wright et al. 2023). Force displacement plots of all tests are shown in Figure 3.

Table 2 – Results summary for Stage 3 high-capacity connection tests

								EN12512			EEEP		
Material	#	F_{exp}	F_{max}	F_u	Δ_{Fmax}	Δ_u	K	F_y	Δ_y	μ	F_y	Δ_y	μ
		kN	kN	kN	mm	mm	kN/mm	*kN*	*mm*		*kN*		
D. fir	M1	945	1082	865	29.9	42.1	342	828	1.66	25.4	1024	2.99	14.1
	C1	947	1108	886	28.9	39.6	394	808	1.32	29.9	1039	2.64	15.0
	C2	962	1052	842	27.7	39.9	385	833	1.28	31.1	1009	2.62	15.2
	Mean	**952**	**1081**	**864**	**28.8**	**40.5**	**374**	**823**	**1.42**	**28.8**	**1024**	**2.75**	**14.8**
Pine	M1	1001	1175	940	22.0	37.6	457	848	1.26	29.8	1100	2.41	15.6
	C1	1050	1174	939	20.1	37.2	536	849	0.98	38.0	1111	2.07	17.9
	C2	1037	1173	938	18.5	35.8	584	829	0.86	41.6	1105	1.89	18.9
	Mean	**1029**	**1174**	**939**	**20.2**	**36.8**	**526**	**842**	**1.03**	**36.5**	**1105**	**2.12**	**17.5**

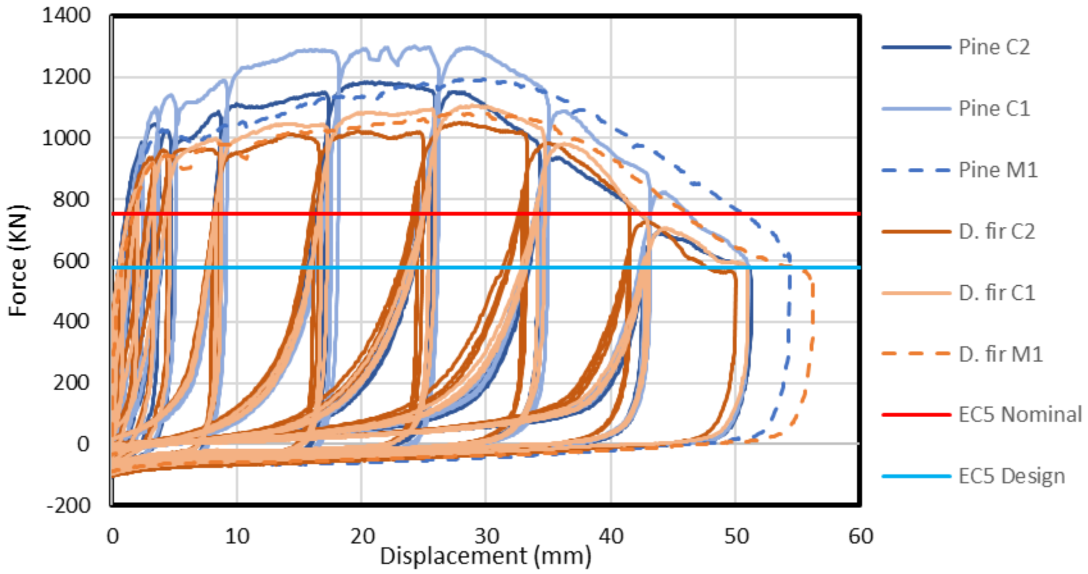


Figure 3 – Monotonic and cyclic force-displacement curves of high-capacity connections, with nominal and design force predictions overlaid

4 DISCUSSION

4.1 Overall Performance

The key purpose of the testing results presented is to evaluate the performance of the large-scale mixed angle screw hold-downs under high loads and compare it with previous tests on smaller scale connections. To that end, high strength, stiffness and ductility were achieved with strength and stiffness results being approximately double previous testing which used half the fasteners (Wright et al. 2022).

F_{exp} averaged 952 kN for the connections in Douglas fir CLT and 1029 kN for the connections in radiata pine CLT. F_{max} averaged 1081 kN and 1174 kN for the Douglas fir specimens and the radiata pine specimens, respectively. Stiffness values were more variable with Douglas fir tests averaging 374 kN/mm and radiata pine tests averaging 526 kN/mm.

Ultimate displacement averaged 40.5 mm for the Douglas fir specimens and 36.8 mm for the radiata pine specimens. Note this is not necessarily indicative of performance difference but rather linked to ultimate displacement being defined as when post-peak load dropped to 80% of F_{max}, and F_{max} being approximately 9% higher for the radiata pine specimens.

Ductility values varied from 14.1 to 18.9 following the EEEP approach and from 25.4 to 41.6 following the EN 12512 approach. This highlighted the significant difference following these two different approaches. In part, this difference was magnified by the very high initial stiffness of these mixed angle screw connections causing very low yield displacements compared to ultimate displacements. This is also attributed to the variability in initial stiffness. All the connections tested exhibited highly ductile behaviour, but due to the variability in ductility values, ultimate displacement (also referred to as displacement capacity) is recommended as a more reliable judge of the connection's seismic performance.

The number of tests in this large-scale experimental campaign is limited due to the high cost and time associated with this scale of testing. Therefore, this testing campaign serves primarily to prove the high capacity performance of this connection type, and results should be read in conjunction with the numerous smaller scale tests presented in (Wright et al. 2021; 2022).

4.2 Design Strength

To design mixed angle screw connections there are two key components. First, design capacities for the inclined and 90° screws must be determined. Second the contributions of inclined and 90° screws must be combined.

4.2.1 Design of inclined screws

Models for determining the design strength of screws installed at an angle to the grain have been proposed by Kevarinmaki, Bejtka and Blaß (Kevarinmaki 2002; Blaß and Bejtka 2001; Bejtka and Blaß 2002). The Kevarinmaki model is a simple truss model that accounts for the withdrawal of the screw and friction between the two members. The Bejtka and Blaß model is similar but also includes a term to account for the bearing or shear resistance from the fastener. Both models are discussed and compared in detail by (Wright et al. 2023) and both models showed conservative predictions for mixed angle screw hold-down connections. In this paper the Kevarinmaki model, as shown in Eq. (1), will be used as it is less complex and better represents a mixed angle screwed hold-down connection where there is a length of screw shank free to bend between the inclined washer and the timber surface.

$$R_{inclined} = R_{ax}(\cos\alpha + \mu_f \cdot \sin\alpha) \tag{1}$$

where R_{ax} = axial capacity of the screw; α = angle of screw inclination relative to direction of loading; and $\mu_f = 0.25$ is the kinetic friction coefficient between members.

The axial capacity of the screw is either the withdrawal strength of the fastener or tensile strength of the fastener. For partially threaded screws as used in mixed angle screw connections, withdrawal strength typically governs. The withdrawal strength of a fastener can be determined using the manufacturer European Technical Approval (ETA) (ETA-Danmark A/S 2020). The New Zealand timber standard NZS AS 1720.1:2022 provides withdrawal calculation for gauge screws, but also allows for the use of ETAs or similar for proprietary fasteners (Standards New Zealand 2022). For the SPAX screws used in this study, these gauge screw equations are not appropriate, and yield more conservative design strength than the manufacturer's ETA. Previous testing from the University of Canterbury has found the ETA predictions for SPAX screws are conservative by a factor of 1.3 (J. Brown et al. 2020) so it would be inappropriate to use a more conservative formula.

4.2.2 Design of 90° screws

The strength of 90° screws can be determined using the European or Johansen Yield Model (EYM) as described in Eurocode 5 or the recently published NZS AS 1720.1:2022 (European Committee for Standardization 2004; Standards New Zealand 2022; Johansen 1949). This requires input values from embedment strength and fastener yield moment. As CLT is outside the scope of both Eurocode 5 and NZS AS 1720.1:2022, the CLT embedment strength specified in the manufacturer ETA should be used. ETA values should also be used for determining fastener yield moment as NZS AS 1720.1:2022 limits the application of formulae for small diameter fasteners to 6.3 mm (gauge screws) and does not provide yield moment formulae for screws exceeding this size. Note that the EYM equations presented in NZS AS 1720.1:2022 differ slightly from those in Eurocode 5. The NZS AS 1720.1:2022 equations drop the "pre-factors" from the Eurocode 5 which account for differing material safety factors between steel and wood in favour of dealing with this directly in the strength reduction factors instead. NZS AS 1720.1:2022 also only provides equations for two embedment members, where Eurocode 5 provides further simplified equations for steel side plates based on the assumption that the embedment strength of steel is much higher than timber. Both these equations lead to the same calculated value, however the simplified formulas reduce the number of terms/complexity of calculation considerably.

Rope effect for the 90° screws can be calculated using the withdrawal strength formulae discussed above.

4.2.3 Combining inclined and 90° screw contributions

To account for the contributions of both inclined and 90° fasteners, previous studies from Brown and Wright have concluded that a direct combination of the two parts is appropriate (Wright et al. 2023; Brown et al. 2021). While it is recognised that this approach may be slightly unconservative as the design strength of inclined and 90° screws do not occur at the exact same displacement, the conservativism in other parts of the prediction balances this out and still leads to a conservative approach overall.

$$R = R_{inclined} + R_{90°} \tag{2}$$

4.2.4 Strength Reduction Factors

NZS 3603:1993 provides a strength reduction factor, ϕ, of 0.7 for connections other than nails. Eurocode 5 provides a γ_m factor of 1.3, which is equivalent to a ϕ factor of 0.77. NZS AS 1720.1:2022 takes a different approach and breaks down the strength reduction factors into components/failure modes. For the design of mixed angle screw connections, the factor for yielding failure of timber, $\phi_y = 0.8$, and the factor for withdrawal of fasteners, $\phi_{ax,w} = 0.6$, are used where appropriate. For steel bending and embedment, the strength reduction factor $\phi = 0.9$ is used from NZS 3404:1997 (Standards New Zealand 1997).

Although mixed angle screw connections are not covered by the clauses of NZS AS 1720.1:2022, clauses for other types of mechanical fasteners suggest that the strength reduction factors from NZS AS 1720.1:2022 should be used where appropriate.

For the testing results presented in Table 2, analytical predictions are presented using both the Eurocode EYM and the NZS AS 1720.1:2022 EYM implementations and associated strength reduction factors. These values are presented in Table 3, with nominal representing the calculated strength before strength reduction factors are applied and design representing the calculated strength after strength reduction factors are applied. From the NZS AS 1720.1:2022 predictions, it can be seen that although the ϕ factor has been split into multiple parts, the overall strength reduction is very similar to $\phi = 0.7$ from NZS 3603:1993.

Table 3 – Analytical predictions in kN for high-capacity testing results

Eurocode 5			NZS 1720.1:2022	
Nominal	Design	Design*	Nominal	Design
753	579	540	703	499

* Using NZS AS 1720.1:2022 strength reduction factors for timber failure modes, but Eurocode 5 EYM equations with the "pre-factors"

Both approaches provide very conservative estimations of the characteristic 5th percentile strength, when compared to the tested F_{exp} values of 923 kN for the Douglas fir connection specimens and 900 kN for the radiata pine connection specimens. This conservatism is plotted in Figure 3, which overlays the nominal and design predictions onto the force displacement plots from testing.

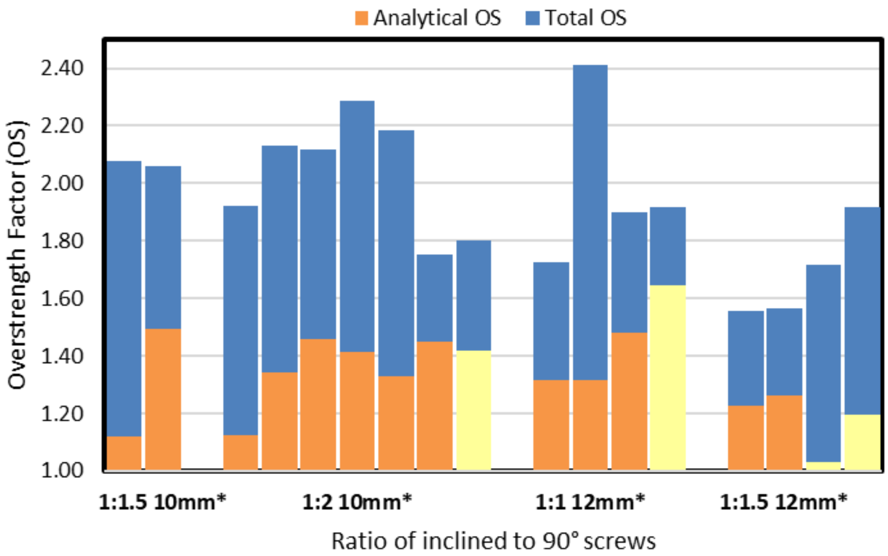
Some of this conservatism comes from underestimation of withdrawal strength. Withdrawal of fasteners is a highly variable failure mode, but currently in design, no account is given for the large number of fasteners and number of boards being penetrated in CLT. Eurocode 5 has a k_{sys} factor which has been proposed for use in similar screwed CLT connections as multiple layers are penetrated, but NZS AS 1720.1:2022 has no system or reliability based adjustment factors. Further research is required into the reliability of these connection types and whether system factors are suitable based on probability. This is also combined with the significant conservatism observed by Brown (2020), and the use of $\phi_{ax,w} = 0.6$ leads to a highly conservative prediction of design strength for screwed connections.

4.3 Overstrength

Overstrength for mixed angle screw connections is complex as it can change depending on the ratio of inclined and 90° screws used. In principle adding more 90° screws will increase the strength of the connection at higher displacements, and thus, if a prediction of the yield strength is being used for design, there will be a higher overstrength than a connection with less 90° screws.

In this paper the total overstrength was calculated as the ratio of the nominal strength based on the Eurocode 5 predictions to the 95th percentile of maximum force (F_{max}) recorded from each test set. Analytical overstrength is calculated as the ratio between experimental characteristic 5th percentile strength and the design strength (Jorissen and Fragiacomo 2011). In this study, the analytical overstrength was calculated as the ratio of the nominal strength to the characteristic 5th percentile F_{exp} for each test set. A bar chart showing total and analytical overstrength for a wide variety of mixed angle screw connections is shown in Figure 4. Testing results are collated from Wright et al. (2023; 2021; 2022). Results showed an average total overstrength factor of 1.95 among the configurations tested, with a maximum of 2.4. Analytical overstrength makes up a significant portion of the total overstrength with the analytical overstrength factor averaging 1.3. This factor of 1.3 corresponds to a 30% underprediction of characteristic 5th percentile values by analytical models. Therefore, the overstrength factor could change or reduce with a different or less conservative analytical model.

Both total and analytical overstrength values were derived from relatively small sample sets. This means the data sets with relatively high variance may overpredict 95th percentile values and underpredict 5th percentile values. To show this visually, total overstrength values for each individual test were calculated and are overlaid in Figure 5 on the bar graph showing total overstrength based on 95th percentile values. The highest total overstrength reached in any single test is 2.2 with only 3 results exceeding 2.0. It is worth noting that all results that exceed 2.0 were from non-standard edge case layouts unlikely to be used in real-world design. Therefore further research into deriving an analytical definition of overstrength similar to that done by Ottenhaus (2018) for dowelled connections may result in a less conservative overstrength value than the values presented in this paper.



**** 10 mm represented 10 mm diameter 90° screws, and 12 mm represents 12 mm diameter 90° screws***

Figure 4 – Bar graph showing total and analytical overstrength values. Douglas fir values in orange, radiata pine values in yellow

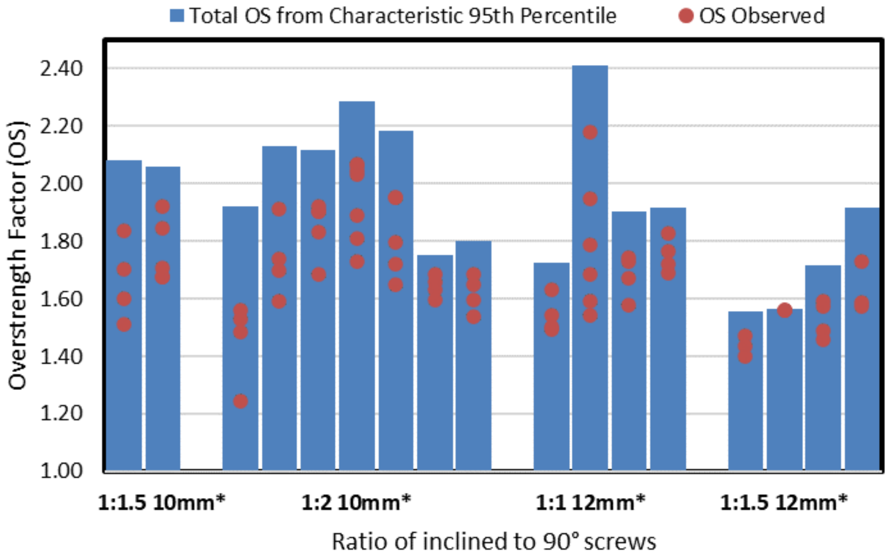


Figure 5 – Bar graph showing total overstrength with the observed overstrength value from each individual test overlaid

For implementation into design NZS AS 1720.1:2022 states that "capacity design actions for CPEs (capacity protected elements) need not exceed the design actions for an equivalent structure with a structural ductility factor of 1.0". For structures designed with a global ductility demand of 2, this means capacity design actions will be governed by the equivalent ductility 1 structure rather than the full overstrength of the mixed angle screw connections. Therefore, before any further study to derive the system ductility of the CLT shear walls using this type of hold-down connections is completed, no definitive overstrength factor is recommended for design.

4.4 Stiffness

Stiffness of timber joints can be difficult to accurately predict and has been found to be quite variable based on initial conditions. For mixed angle screw connections, the ideal way to predict stiffness is to undertake computational modelling of the connection. The simplest model might be the beam on foundation model where the screw is modelled as a steel beam element with distributed non-linear springs representing embedment behaviour. Withdrawal contributions can also be modelled with non-liner springs along the screw axis. In lieu of computational modelling, a simplified method has also been suggested where an upper and lower bound are considered for yield displacement, and upper and lower bound stiffness' are derived from this. From the various test campaigns conducted on mixed angle screw hold-down connections, values for lower and upper bound yield displacements can be considered between 1-2 mm and 3-4 mm, respectively.

5 CONCLUSIONS

A total of six high-capacity mixed angle screw hold-down tests are presented, in conjunction with a discussion on the design of the mixed angle screw connections. The key findings were:

- The mixed angle screws high-capacity hold-down connections provided a strong, stiff, and ductile connection system with the average yield strength of 952 kN for the Douglas fir CLT and 1029 kN for the radiata pine CLT.
- Design strength calculations can follow the screw manufacturer ETAs and either Eurocode 5 or NZS AS 1720.1:2022. The predictions from NZS AS 1720.1:2022 were slightly more conservative for the examples presented.
- Current design methods were found to be conservative with an average analytical overstrength factor of 1.3 for the mixed angle screwed hold-downs. A significant portion of this conservatism was due to conservatism in withdrawal strength predictions and lack of reliability-based system factors.
- Total overstrength factors of the connections tested had an average of 2 with a maximum of 2.4. Therefore, capacity design demand is likely to be capped by the equivalent ductility 1 demand for assumed ductility of 2 structures.
- Stiffness of timber predictions is difficult to predict through analytical or numerical means, therefore a simplified upper and lower bound method is recommended for these connections.

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