

WITHDRAWAL BEHAVIOUR OF SELF-TAPPING SCREWS IN NEW ZEALAND CROSS-LAMINATED TIMBER

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ABSTRACT

Self-tapping Screws (STS) are commonly used in cross-laminated timber (CLT) construction. However, design provisions with STS and CLT are currently not covered by NZS 3603:1993 or AS 1720.1:2010. Manufactured by hardened steel, STS have high withdrawal strength and provide an efficient connection type. Previous research and analytical design equations for STS connections were focused on European softwood species which often have lower densities than New Zealand grown Radiata Pine and Douglas-fir. This paper presents an experimental study to evaluate withdrawal properties of STS in New Zealand made Radiata Pine and Douglas-fir CLT. A total of 202 withdrawal tests were performed with Ø8mm and Ø12mm STS in three-, five- and seven-layer CLT specimens. The experimental results were compared with the analytical design equations in literature. It was found that the design equations are generally applicable to the New Zealand CLT specimens. The penetration length of the threaded portion of STS should be limited to 12d (12 times the screw diameter) to avoid brittle fastener tensile failure. For partially threaded screws, increasing embedment length of the unthreaded portion of STS could prevent timber surface splitting and the average withdrawal strength slightly increased by 10-15%.

1 INTRODUCTION

Self-tapping screws (STS) are the most popular fastener type used in cross-laminated timber (CLT) construction, in part due to their ease of installation and flexibility in design (Brandner et al., 2016). For common wood screws and coach screws, New Zealand Timber Structures Standard NZS 3603 (Standards New Zealand, 1993) and Australian Timber Structures Standard AS 1720.1 (Standards Australia, 2010) provide tabular values for characteristic withdrawal capacity per millimetre of thread penetration for each timber species group. The recently proposed draft standard DZ NZS AS 1720.1/V6 (2018) to supersede NZS 3603 only covers wood screws with Ø6.3mm or less. Design methods for the withdrawal capacity of STS are not covered by any of these standards.

The benefit of utilizing the high withdrawal strength of inclined STS was first presented by Bejtka and Blaß (2002). Since then, Uibel and Blaß (2007) developed a predictive analytical model for the withdrawal capacity of STS in CLT. Numerous subsequent studies in Europe, summarized within Ringhofer et al. (2015), have investigated the influence of gaps between timber boards in laminated timber products, the influence of the number of timber laminations

penetrated, and the influence of the moisture content on the withdrawal capacity of STS in CLT. Figure 1 shows a typical layout of non-edge-glued CLT with some definitions such as small gaps, w_{GAP} between adjacent laminated boards. Most recently, Ringhofer et al. (2015) proposed a universal analytical approach to calculate the withdrawal capacity for STS in solid timber and laminated timber products. European screw suppliers, such as Rothoblaas (2019), SPAX (2017), and Würth (2018) among others, also provide European Technical Approvals (ETA) to guide the design of their proprietary products. Meanwhile, Eurocode 5 (2014) provides analytical design equations based on the previous research on STS.

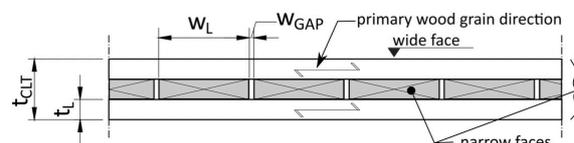


Figure 1: CLT layout with definitions.

In North America, many STS suppliers provide designers with Canadian Construction Materials Centre (CCMC) or International Code Council (ICC) reports which in principal are similar to an ETA in Europe. In contrast to NZS 3603 (1993) or AS 1720.1 (2010), these CCMC and

ICC reports are sufficient to allow designers to use STS within the Canadian Timber Standard (CSA O86, 2019) and American National Design Standard (AWC, 2015). Currently, designers in New Zealand and Australia may use a screw supplier ETA with New Zealand and Australian timber characteristic densities.

In this study, the withdrawal strength of STS in New Zealand Radiata Pine and Douglas-fir CLT was experimentally investigated with SPAX STS. The results were compared to the screw design equations in literature, which have generally been derived from European softwood species which typically have lower density than New Zealand grown Radiata Pine and Douglas-fir. As an extensive recent study comparing 65 ETAs by Ringhofer (2017) has reported meaningful differences in withdrawal strength parameters, the experimental results are compared with the SPAX ETA (2017) only and not ETAs in general. The effect of embedding the threaded portion of the partially threaded screw was also investigated.

2 WITHDRAWAL STRENGTH FORMULAS

Eurocode 5 (2014), SPAX ETA (2017), Uibel and Blaß (2007), and Ringhofer et al. (2015) provide methods for determining the withdrawal capacity of screws in solid and laminated timber products. EN 1382 (2016) specifies the formulation of the withdrawal parameter, f_1 in Eq. (1), to determine the fastener withdrawal capacity, F_{ax} . The key STS parameters to determine F_{ax} are shown in Figure 2. Following recent work by Ringhofer et al. (2018) and Westermayr & van de Kuilen (2019), the results presented herein are for the withdrawal strength, f_{ax} , defined in Eq. (2)

$$f_1 = \frac{F_{ax,max}}{l_{ef}d} \left(\frac{N}{mm^2} \right); \quad (1)$$

$$f_{ax} = \frac{f_1}{\pi} \left(\frac{N}{mm^2} \right); \quad (2)$$

$$l_{ef} = l_{nom} - xd; \quad (3)$$

$x = 1$ (Westermayr et al. 2019)

where d is the screw diameter; l_{nom} is the nominal screw installation length; l_{ef} is the effective thread embedment length excluding the length of the screw tip; and l_{emb} is the embedment length of unthreaded portion for a partially threaded screw.

SPAX ETA (2017) and the method presented by Ringhofer et al. (2015) do not include l_{ef} in the calculation of f_1 whereas Eurocode 5 (2014) and

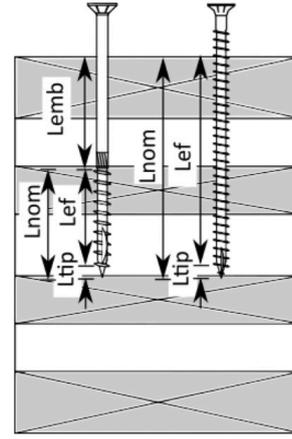


Figure 2: STS key parameters (partially threaded vs. fully threaded)

Uibel and Blaß (2007) include l_{ef} as an influencing parameter. Further, Eurocode 5 (2014), SPAX ETA (2017), and Uibel and Blaß (2007) consider the screw tip length, l_{tip} , within l_{ef} for the calculation of f_1 , whereas the Ringhofer et al. (2015) and the proposed draft DZ NZS AS 1720.1/V6 (2018) specifically state to neglect l_{tip} in the calculation of f_1 or l_{ef} . While the current NZS 3603 (Standards New Zealand, 1993) and AS 1720.1 (Standards Australia, 2010) do not explicitly feature STS withdrawal equations, tables based on the joint group provide the characteristic capacity per millimetre penetration of the threaded portion for wood screws and coach screws. It is not clear if l_{tip} is considered or not. The embedment length of unthreaded portion, l_{emb} shown in Figure 2, is not considered as an influencing parameter in any design equations. The following lists the Eurocode 5 (2014), the SPAX ETA (2017), Uibel and Blaß (2007), Ringhofer et al. (2015), and DZ NZS AS 1720.1/V6 (2018) equations to determine the characteristic withdrawal capacity. For simplicity, the analytical design methods are referred to as EC5, SPAX, U&B and Ringhofer in the following context.

EC5 (2014):

$$F_{ax,\alpha,k} = \frac{f_{1,EC5} d l_{ef} k_d}{1.2 \cos^2 \theta + \sin^2 \theta} (N) \quad (4)$$

$$f_{1,EC5} = 0.52 d^{-0.5} l_{ef}^{-0.1} \rho_k^{(0.8)} \left(\frac{N}{mm^2} \right), k_d = \min \left\{ \frac{d}{8, 1} \right\}$$

SPAX (2017):

$$F_{ax,\alpha,k} = \frac{f_{1,SPAX} d l_{ef} k_d}{1.2 \cos^2 \theta + \sin^2 \theta} \left(\frac{\rho_k}{350} \right)^{0.8} (N) \quad (5)$$

$$f_{1,SPAX} = 12.0 (\text{Ø}8\text{mm}); 11.0 (\text{Ø}12\text{mm}) \left(\frac{N}{mm^2} \right)$$

U&B (Blaß & Uibel, 2007):

$$F_{ax,\alpha,k} = \frac{f_{1,U\&B} d l_{ef}}{1.5 \cos^2 \theta + \sin^2 \theta} \left(\frac{\rho_k}{400} \right)^{0.75} (N) \quad (6)$$

$$f_{1,U\&B} = 0.35 d^{-0.2} l_{ef}^{-0.1} \rho_{ref}^{0.75} \pi \left(\frac{N}{mm^2} \right), \rho_{ref} = 400 \frac{kg}{m^3}$$

Ringhofer (2015):

$$F_{ax,\alpha,k} = d l_{ef} k_{ax,k} k_{sys,k} f_{1,R} \left(\frac{\rho_k}{350} \right)^{k_\rho} (N) \quad (7)$$

$$f_{1,R} = 0.013 d^{-0.33} \rho_{ref}^{1.11} \pi \left(\frac{N}{mm^2} \right), \rho_{ref} = 350 \frac{kg}{m^3},$$

$$k_{ax,k} = \begin{cases} 1.00 & 45^\circ \leq \theta \leq 90^\circ \\ 0.64 k_{gap} + \frac{1 - 0.64 k_{gap}}{45} \theta & 0^\circ \leq \theta \leq 45^\circ \end{cases}$$

$$k_{gap} = \begin{cases} 0.90 & \text{CLT narrow face} \\ 1.00 & \text{other} \end{cases}, k_\rho = \begin{cases} 1.10 & 0^\circ \leq \theta \leq 90^\circ \\ 1.25 - 0.05 d & \theta = 0^\circ \end{cases}$$

$$k_{sys,k} = \begin{cases} 1.00, \text{solid timber} \\ 1.10, \text{CLT, if } N \geq 3 \\ 1.13, \text{Glulam} \end{cases}$$

where in all instances θ is the angle between the screw axis and the timber grain direction. In the Ringhofer et al. (2015) analytical method $k_{ax,k}$ accounts for STS installation angles, k_{gap} accounts for STS installed in the CLT narrow face, k_ρ considers the influence of density, and $k_{sys,k}$ accounts for increased homogeneity when a screw penetrates multiple layers of laminated timber products. Following Eurocode 5 (2014), the design withdrawal capacity of a single screw is then:

$$F_{ax,\alpha,d} = \frac{k_{mod}}{\gamma_m} F_{ax,\alpha,k} \quad (8)$$

Where k_{mod} = load duration factor similar to k_t of NZS 3603 or AS 1720.1 and $\gamma_m = 1.3$ and is the connection partial factor similar to the inverse of the strength reduction factor ϕ of NZS 3603 or AS 1720. Within DZ NZS AS 1720.1/V6.0 (2018), the design withdrawal capacity of wood screws or coach screws is:

$$n_{ax,w} = n_{ax,w} n k_{15} k_{13} (N) \quad (9)$$

$$n_{ax,w} = \phi_{ax,w} d^{0.82} \rho^{1.77} \frac{t_p}{2770}, n = \text{number of screws},$$

k_{15} = in service moisture factor, k_{13} = end grain factor,
 $\phi_{ax,w} = 0.6$, t_p = penetration length less the tip length (mm)

This study will focus on the characteristic withdrawal strength instead of the design withdrawal strength. Thus, k_{mod} , γ_m , ϕ , and k_t are not considered in comparing the test results with the analytical design equations.

3 EXPERIMENTAL TEST PROGRAMME

A total of 202 screw withdrawal tests were performed using Ø8mm and Ø12mm SPAX Delta Seal flat countersunk head screws. The CLT specimens were fabricated by XLAM Ltd. The Radiata Pine (RP) and Douglas-fir (DF) lamellas were graded SG8 with an average Modulus of Elasticity of 8 GPa according to NZS 3603 (Standards New Zealand, 1993). The CLT specimens tested were 3-layer (CLT3) 5-layer (CLT5) and 7-layer (CLT7) as shown in Figure 3. The STS were installed on either the wide face or narrow face of CLT. Figure 4 shows the screw installation angles and possible screw location in the CLT wide or narrow

face. The primary thread-grain angle α is shown as per Figure 4 and the secondary angle β is out-of-plane of the primary wood grain (see Figure 1 and Figure 4b) direction. In this testing programme, screws installed in the CLT narrow face were only installed in position 4 of Figure 4b. The other possible STS positions shown in Figure 4b were not investigated in this study. When a single install angle α was used, $\alpha = \theta$ for design equations. In some instances, a compound $\alpha^\circ + \beta^\circ$ angle was used and then $\cos(\theta) = \cos(\beta) \sin(90^\circ - \alpha)$. The CLT specimens had an average moisture content of 11% and the mean and characteristic densities as per EN 14358 (2016) are provided in Table 1.

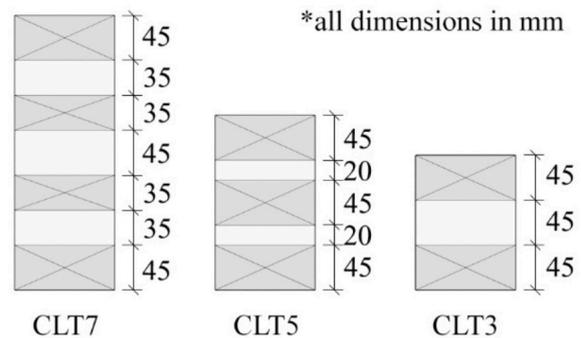


Figure 3: CLT types used in test programme.

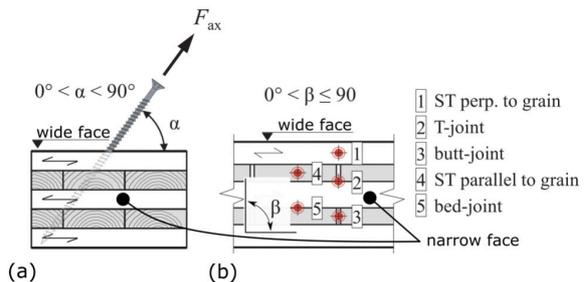


Figure 4: Screw installation angle: (a) relative to outer wood grain and (b) possible positions in CLT narrow face. Adopted from (Ringhofer et al., 2018).

Group 1 test series consisted of 187 withdrawal tests with varied CLT types, CLT installation faces, timber species (Radiata Pine and Douglas-fir), fastener diameters, screw installation angles as per Figure 4 ($\alpha + \beta$), and l_{nom} with a constant $l_{emb} = 0$. Group 2 test series consisted of 15 withdrawal tests with varied l_{emb} and a constant l_{nom} . Generally, five replicates were performed at each of the 8d, 10d, 12d, and 16d nominal installation lengths, l_{nom} . With reference to Figure 2, $l_{nom} = 8d$ resulted in $l_{ef} = 56mm$ (excluding the screw tip of 1d) for a Ø8mm STS. For the l_{emb} test series, partially threaded screws were used to embed the threaded portion with various distances (0, 50mm, 100mm) from the timber surface. The full experimental test programme is outlined in Table 2 and Table 3.

Table 1: CLT specimen and individual layer density (kg/m³)

Species	Radiata Pine (RP)			Douglas-fir (DF)			
CLT	CLT3	CLT3	CLT3	CLT5		CLT7	
Sample	specimen	specimen	specimen	45mm lamella	20mm lamella	specimen	35mm lamella
ρ_m (kg/m ³)	470.5	478.4	463.7	461.8	538.6	457.4	464.5
ρ_k (kg/m ³)	430.2	426.4	421.8	413.3	487.3	416.5	420.5

Table 2: Test matrix for Group 1: Screw withdrawal series

Test ID	CLT Type	CLT Installation Face	Timber Species	Screw Diameter, \emptyset (mm)	Angle to grain ($\alpha^\circ + \beta^\circ$)	Number of tests at each l_{nom}			
						8d	10d	12d	16d
CLT3-8-90-RP	CLT3	Wide	RP	8	90	5	5	5	5
CLT3-8-90				8	90	5	5	5	5
CLT5-8-90	CLT5		8	90	6	5	6	5	
CLT5-8-60			8	60	5	5	5	-	
CLT5-8-60+15		8	60+15	5	5	-	-		
CLT5-8-0	CLT5	Narrow	DF	8	0	5	5	5	1
CLT5-8-30				8	30	8	5	6	-
CLT5-8-30+15		8	30+15	5	5	5	-		
CLT7-12-90	CLT7	Wide	DF	12	90	5	5	5	5
CLT7-12-60				12	30	5	5	-	-
CLT7-12-0		Narrow		12	0	5	5	-	-
CLT7-8-0				8	0	-	-	5	5

Table 3: Test matrix for Group 2: screw withdrawal embedment length, l_{emb} , series

Test ID	CLT Type	Timber	Screw Diameter, \emptyset (mm)	Angle to grain (α°)	Embedment Length l_{emb} (mm)	Number of Tests
CLT7-12-90-0	CLT7	DF	12	90	0	5
CLT7-12-90-50					50	5
CLT7-12-90-100					100	5

All tests were performed in a displacement controlled manner following EN 1382 (2016). The test set-up for the 90° and inclined screw withdrawal tests are shown in Figure 5 and Figure 6.

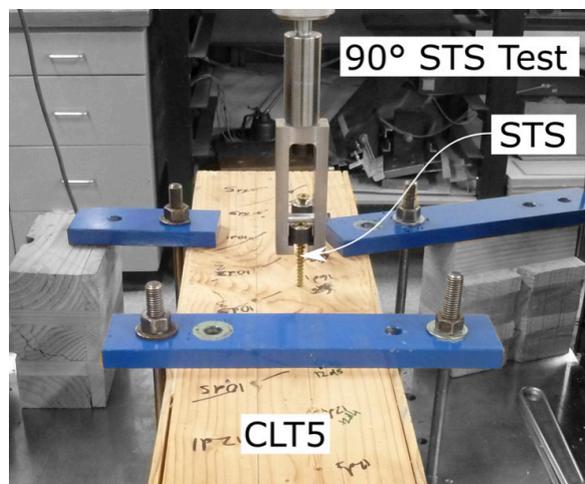


Figure 5: 90 degree screw withdrawal test setup.

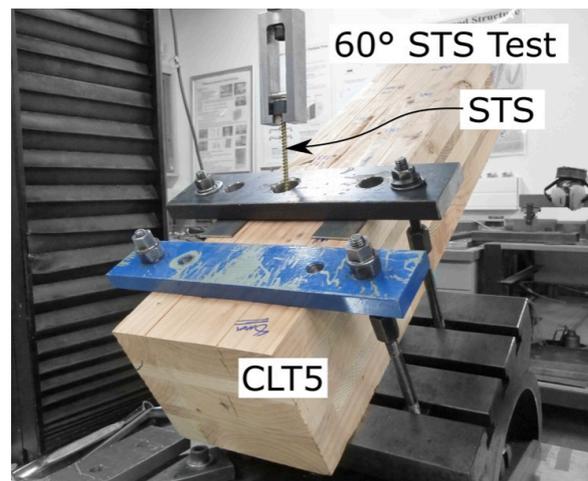


Figure 6: Inclined screw withdrawal test setup.

4 EXPERIMENTAL RESULTS AND DISCUSSION

Figure 7 shows the summary of the withdrawal strength for each test series of Group 1. The experimental results combine the l_{nom} tests of 8d, 10d and 12d assuming l_{ef} is not an influencing parameter on

withdrawal strength as per Ringhofer et al. (2015). As expected, the withdrawal strength was higher for the Ø8mm series compared to the Ø12mm screw series. Further, an increasing strength and homogenization was observed with increasing number of CLT layers penetrated as previously reported by Ringhofer et al. (2015). Withdrawal strengths for the CLT5 test series on the narrow face, which included the installation angles of 0°, 30°, and 30°+15°, had high strength but also high variability. This higher withdrawal strength is in part due to the higher density of the 20mm lamella layer as reported in Table 1. The compound installation angle ($\alpha+\beta$) on the CLT narrow face had a lower coefficient of variation (CV) when compared to the single angle. Therefore, engaging more CLT layers with a compound angle installation increased homogenization. The benefit of lower dispersion was not observed in compound angle withdrawal tests on the CLT wide face.

In all test series, the 16d embedment length reached the steel tensile capacity of the screws. In this instance, the 5th percentile steel tensile results were determined as per EN 14358 (2016). Table 4 provides a comparison of the experimental results to the provided SPAX ETA (2017) characteristic tensile values.

Table 4: Tensile capacity of screw with comparison to ETA

Screw	$F_{tens,SPAX,k}$ (kN)	$F_{tens,exp,0.05}$ (kN)	$F_{tens,exp,mean}$ (kN)	Samples
Ø8mm	17	19.2	21.4	16
Ø12mm	38	41.8	49.0	3

Typical failure modes in the CLT wide face and CLT narrow face testing are shown in Figure 8 and Figure 9.



Figure 8: Timber splitting in CLT wide face 90° screw withdrawal test.



Figure 9: Shear cylinder failure in CLT narrow face 0° screw withdrawal test.

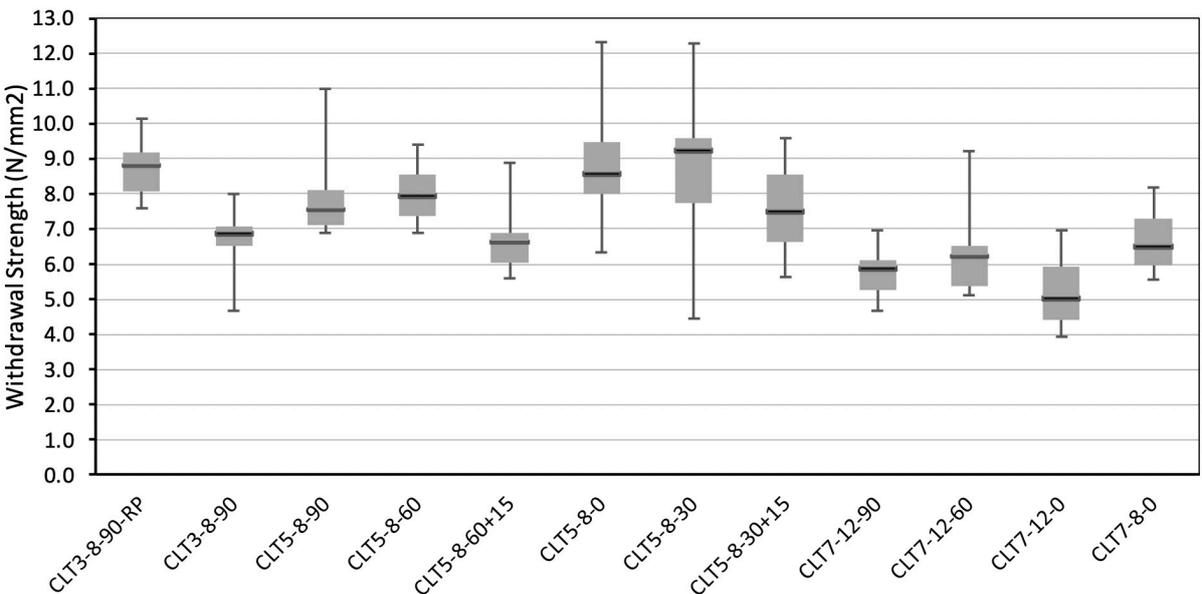


Figure 7: Withdrawal strength of various test series.

4.1 Comparison to Design Standards

Table 5 compares the 5th percentile withdrawal strength determined as per EN 14358 (2016) with the calculations by the SPAX and Ringhofer analytical methods. The SPAX ETA and Ringhofer methods were compared because they do not include l_{ef} as an influencing parameter on f_{ax} . In general, there is good agreement between the analytical methods and the experimental results given the relatively small sample size of each test series. The higher characteristic withdrawal strength predicted by the Ringhofer method when compared to the SPAX ETA is in part due to the higher density correction factor used by Ringhofer. The experimental results of the narrow face 0° installation are significantly higher than the analytical methods. With reference to Figure 4, this result is expected as all experimental tests were installed in location 4 (screws driven in end grain) whereas both SPAX ETA and Ringhofer methods account for all possible installation locations. If a screw was installed in location 3 of Figure 4 the withdrawal strength would be lower. It is important to note that currently Eurocode 5 (2014) requires screw axis-grain angles $\alpha \geq 30^\circ$ while more recent STS ETAs require $\alpha \geq 15^\circ$ (ETA-12/0114, 2017), or allow $\alpha = 0^\circ$ but with significant reduction (ETA-11/0030, 2019; ETA-11/0190, 2018). Allowable withdrawal screw axis-grain angles is an area of current research.

Based on the experimental results presented, the average ratio of $f_{ax,0.05,exp}$ to $f_{ax,k,SPAX}$, defined as γ_{an} , is 1.3 excluding test series with $\alpha = 0^\circ$. This means that the SPAX ETA equation was appropriate as similar analytical model conservatism has been reported for laterally loaded dowelled connections (Jorissen & Fragiaco, 2011). If $\rho_k = 440 \text{ kg/m}^3$ for SG8 New Zealand timber in DZ NZS AS 1720.1/V6 was used in lieu of reported experimental densities in Table 1 with

SPAX ETA analytical equations, the average $\gamma_{an} = 1.3$ excluding test series with $\alpha = 0^\circ$ as well. Therefore, the proposed characteristic density in DZ NZS AS 1720.1/V6 was appropriate in this instance as well.

Figure 10 shows the comparison between the seven analytical design methods, $f_{ax,i}$, described in Section 2 and the characteristic withdrawal strength of test series CLT3-8-90 and CLT7-12-90. Most methods under-predicted the withdrawal strength except for the Ringhofer method. U&B, EC5, and SPAX all provide similar strength predictions with the inclusion of l_{tip} having a larger impact on the Ø12mm screw size for U&B and EC5. It should be pointed out that NZS 3603 and AS 1720.1 tabular values and the proposed design method in DZ NZS AS 1720.1/V6.0 for coach screws were used and they are not representative of STS as expected.

4.2 Embedment Length Test Series Results

The load slip curves of Group 2 test series are shown in Figure 11 and the strength results are given in Table 6. With increased l_{emb} , no significant effect on the displacement capacity was observed. However, the withdrawal strength in this instance increased by 15% and 10% for $l_{emb} = 50\text{mm}$ and 100mm , respectively. A larger parametric study is required to further quantify this behaviour. Once localized shear failure at the timber-thread interface occurred, the withdrawal capacity decreased in a similar manner. Figure 12 shows that increased l_{emb} prevented timber surface splitting which had also been observed by Westermayr & van de Kuilen (2019).

5 CONCLUSIONS

A total of 202 STS withdrawal tests of Ø8mm and Ø12mm screws in three-, five- and seven-layer New Zealand Radiata Pine and Douglas-fir CLT were

Table 5: Comparison of full experimental characteristic withdrawal strength, $f_{ax,k,i}$ (N/mm²)

Test ID	CLT3-8-90-RP	CLT3-8-90	CLT5-8-90	CLT5-8-60	CLT5-8-60+15	CLT5-8-0
$f_{ax,0.05,exp}$	7.3	5.2	5.9	6.6	4.9	5.9
CV _{exp} (%)	8.7	12.2	16.6	9.6	15.2	18.5
$f_{ax,k,SPAX}$	4.5	4.5	4.4	4.2	4.2	4.1
$f_{ax,k,Ringhofer}$	6.0	6.0	5.9	5.9	5.9	3.3
Test ID	CLT5-8-30	CLT5-8-30+15	CLT7-12-90	CLT7-12-60	CLT7-12-0	CLT7-8-0
$f_{ax,0.05,exp}$	5.3	5.5	4.6	4.2	3.4	4.9
CV _{exp} (%)	21.5	15.4	11.2	20.0	19.2	14.2
$f_{ax,k,SPAX}$	4.3	4.3	4.0	3.8	3.4	3.7
$f_{ax,k,Ringhofer}$	5.4	5.4	5.1	5.1	2.5	2.9

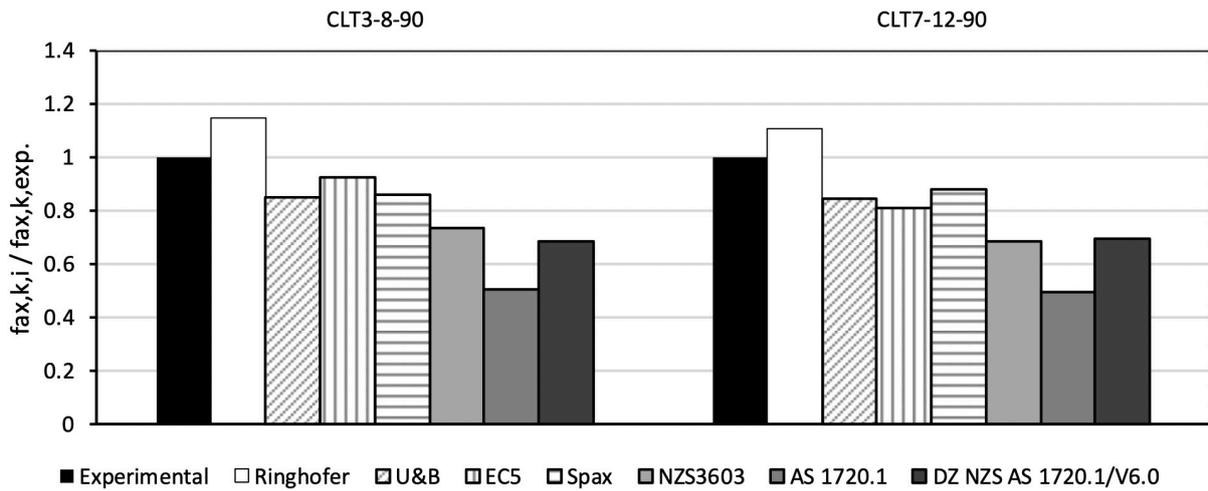


Figure 10: Comparison of characteristic withdrawal strength according to experimental results for Ø8mm and Ø12mm screws at constant 10d length and 90° installation.

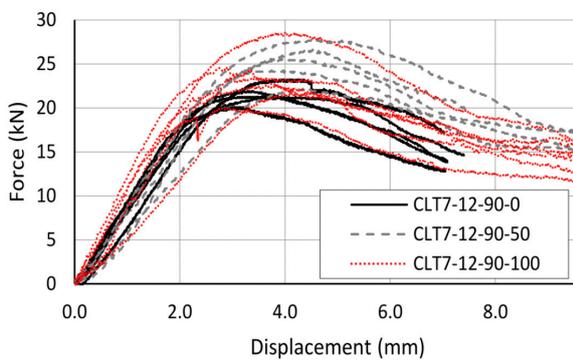


Figure 11: l_{emb} test series load-slip curves.



Figure 12: Comparison of $l_{emb} = 0$ and 100mm.

Table 6: l_{emb} test series experimental results

Test ID	CLT7-12-90-0	CLT7-12-90-50	CLT7-12-90-100
$f_{ax,mean,exp}$ (N/mm ²)	6.5	7.4	7.1
CV (%)	5.3	8.9	12.6

performed. Experimental results were compared with seven analytical design methods in literature. Because the STS from one supplier were used in the study, some of following experimental findings cannot be assumed for all other STS suppliers as meaningful withdrawal strength differences within ETAs have been reported recently by Ringhofer & Schickhofer (2019).

- While the current NZS 3603 (Standards New Zealand, 1993), AS 1720.1 (Standards Australia, 2010) do not specify STS, using their design values for coach screws significantly under-predicted the withdrawal strength of STS. The proposed DZ NZS AS 1720.1/V6 (2018) analytical equation for screws with Ø6.3mm or less and coach screws significantly under-predicted the withdrawal strength.
- The ratio of the average experimental 5th percentile withdrawal strength to the ETA analytical model calculation, γ_{an} , was 1.3 using both experimental

and AS 1720 timber densities. Therefore, the SPAX ETA provided reasonably good predictions for the New Zealand Radiata pine and Douglas-fir CLT.

- To avoid brittle steel tensile failure of STS, embedment length of the threaded portion should not be greater than 12d.
- The experimental withdrawal strength from CLT narrow face installation generally was higher than all predictions. However, this study only considered one screw installation location without considering all possible locations on the narrow face. It should also be noted that current design standards generally do not recommend parallel to grain screw installation.
- Increased embedment length of unthreaded portion of partially threaded screws, l_{emb} , was able to increase the average withdrawal strength by

10%-15% by eliminating timber surface splitting. However, it did not significantly affect the displacement capacity.

6 ACKNOWLEDGEMENTS

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