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PREDICTION OF WITHDRAWAL STIFFNESS OF SELF-TAPPING SCREWS

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ABSTRACT: Self-tapping screw is a new generation of fasteners which is often inserted into the face of timber members at an angle to develop stiff and strong connections. The withdrawal stiffness of self-tapping screws is an important property that influences the performance of the connection. The designs of composite timber hybrids incorporating inclined self-tapping screws, such as timber-concrete and timber-steel, can be governed by the stiffness of their connections, which is in turn influenced by the fastener withdrawal stiffness. This study proposes empirical equations for directly predicting the withdrawal stiffness of the self-tapping screws, based on wood density, fastener diameter, insertion angle and penetration length. These empirical equations were developed based on an analysis of withdrawal test data from several test programs, covering two wood species and two screw diameters. They could be used in conjunction with appropriate models to predict the stiffness of connection containing self-tapping screws inserted at an angle to the wood member surface.

KEYWORDS: Withdrawal stiffness, Non-linear regression, Self-tapping screw, Insertion angle

1 INTRODUCTION

Self-Tapping Screw (STS) is an improved threaded fastener specifically developed for mass timber and is the key factor contributing to the emergence of modern tall mass timber structures. STS mostly features a continuous thread over the whole or partial length leading to a uniform load transfer between the screw and the wood material specifically under withdrawal action while the special self-drilling tip helps to avoid pre-drilling in timber members [1, 2, 3]. Many experimental and theoretical studies of STS connections conducted in timber-to-timber, steel-to-timber and concrete-to-timber have concluded that there is a substantial increase in the strength and stiffness of the STS connection if the screws are installed at an angle (e.g., 45° or 30°) to the surface of the timber member, instead of normal (90°) to the surface [4, 5, 6, 7, 8]. Stiffness of connections is a critical design property that governs the structural performance of timber structures, such as drift of lateral load resisting system, deflection of composite systems under gravity load and dynamic response of structural systems. Despite this, it is a property that is not given much attention in timber design standards compared to strength properties [9, 10, 11]. Withdrawal stiffness is an important input parameter for the evaluation of connection stiffness containing the self-tapping screws, which are measured by conducting tests following standards, such as ASTM D1761-12 [12] and EN 1382 [13]. There is currently limited information in timber design standards on withdrawal stiffness properties to allow designers to utilize any analytical solutions to calculate connection stiffness containing self-tapping screws. Therefore, in this study, withdrawal test data were accumulated from various studies and non-linear regression analyses were performed to derive equations for predicting the withdrawal stiffness of STS, based on wood density, fastener diameter, and angle.

2 WITHDRAWAL TEST

Withdrawal tests of the screws from timber at various angles to the grain were performed according to EN 1382 [4] procedure to evaluate the withdrawal stiffness. With this test setup, the measured withdrawal deformation includes both slips between the wood and screw and the axial elongation of the screw. Fully threaded self-tapping screws with a countersunk head and self-drilling tip were selected. Two screw diameters of 9 and 11 mm from a single manufacturer were tested at five different insertion angles, 0°, 30°, 45°, 60° and 90°. Wood specimens were cut from spruce-pine-fir (SPF) and Douglas fir (DF) Glued Laminated Timber (GLT). Two penetration lengths were studied for each combination of screw diameter and insertion angle. Five replicates were used for each combination of parameters, giving a total of 100 withdrawal tests. The mean density of the SPF and DF woods were 429 kg/m^3 and 533 kg/m^3 respectively. The mean moisture content of SPF and DF woods was 8.3% and 9.2% respectively based on measurements using an electrical resistance moisture meter. Each wood specimen was pre-drilled with a diameter equal to the shank diameter of the screws to avoid any splitting. In each wood specimen, three screws were placed on one side and two on the opposite side at 10d spacing to reduce the amount of wood specimen preparation. The spacing of the fasteners meets the requirement of EN 1382 [13], to avoid any splitting and optimize the wood-effective areas. It should be noted that the wood members were cut to allow the load to be applied which simulates the withdrawal of a screw in a connection when it is inserted at an angle to the wood member surface. A typical withdrawal test setup at a 45° insertion angle is shown in *Figure 1*.

The test specimen was first attached to a 75 mm thick steel plate with a 20 mm hole that was created to accommodate different screw diameters. The steel plate was anchored to

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the laboratory floor. The screw head was then locked to a 50 mm thick steel plate which was attached to the actuator of the test machine. Two Linear Variable Differential Transformers (LVDTs) were attached to the same steel plate which was connected to the test jack to measure the relative displacement between the two steel plates. The tests were conducted at a constant displacement rate of 1.5 mm/min. The load and displacement were recorded during the test and the test was stopped after the withdrawal failure of the screw from the wood. The slope of the load-displacement response at between 10% and 40% of the maximum load was used to calculate the stiffness. The withdrawal stiffness, K_{ax} in N/mm^3, was calculated using equation (1).

$$\boldsymbol{K_{ax}} = \frac{S}{\pi d l_e} \tag{1}$$

where S is the slope of load-displacement response between 10% and 40% of the maximum load (N/mm), d is the nominal thread diameter of the screw (mm) and l_e is the effective penetration length (mm) excluding the length of the tip.

Figure 1: *Withdrawal test of screws at 45 °angle to timber grain*

Table 1: *Withdrawal stiffness of self-tapping screws in timber*

Diameter (mm)	Angle	Penetration Length (mm)	Mean Density (kg/m^3)	Mean Stiffness (N/mm^3)	CoV (%)
11	0°	70	429	4.8	21.2
	30°			4.6	5.5
	45°			4.0	15.8
	60°			4.1	17.5
	90°			3.5	15.1
11	0°	90	429	4.8	11.5
	30°			4.7	11.8
	45°			3.8	11.0
	60°			3.9	11.1
	90°			3.6	14.4
9	0°	80	533	5.7	9.9
	30°			5.4	22.8
	45°			5.0	17.8
	60°			5.0	15.0
	90°			5.2	16.3
9	0°	100	533	6.9	14.7
	30°			6.0	20.0
	45°			6.5	8.2
	60°			5.5	13.5
	90°			5.6	12.6

Withdrawal test results are summarized in *Table 1* for different configurations and the mean wood density for each species. The results are graphically represented in *Figure 2*. Mean withdrawal stiffness per unit area (K_{ax}) are shown with their CoVs in the table, which was calculated using equation (1). It should be noted that the small sample size influences the CoV which is within a range of 5%-22% for stiffness. From the withdrawal test results, it can be seen clearly that the withdrawal stiffness decreased with the increase of insertion angle for both SPF and DF specimens. For each screw diameter, the highest stiffness was found at 0° angle and the lowest was noted at 90° angle. DF specimens showed higher stiffness compared to SPF specimens.

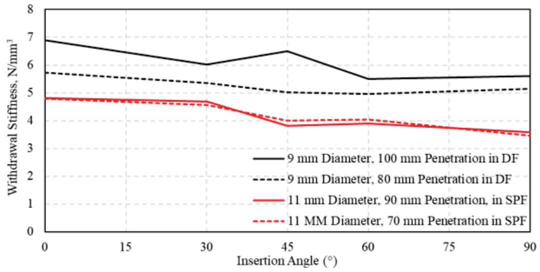

Figure 2: *Withdrawal stiffness of self-tapping screws for different parameters*

The main reason for testing each species/diameter combination with effective different penetration lengths was to explore if the withdrawal stiffness is directly proportional to penetration length, as is commonly assumed in design standards [14] for other dowel-type fasteners such as lag screw, wood screw and nail. To explore this issue, the measured stiffness property at the longer effective penetration length was divided by that at the shorter effective penetration length for each screw diameter/species/angle combination as shown in *Figure 3*. As can be seen in the figure, for the SPF wood with an 11mm screw, the penetration length had practically no impact on withdrawal stiffness, even for a 30% increase in length. For the DF wood with a 9mm screw, the withdrawal stiffness increased with a larger penetration length. However, the property increase does not appear to be directly proportional to the length increase. This issue will require further investigation given that the finding is not in line with the common assumption for other threaded fasteners such as lag screws and wood screws [14].

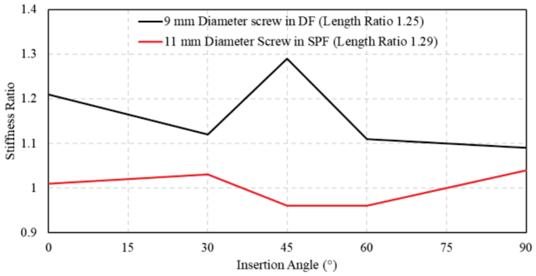

Figure 3: *Influence of the screw penetration length on the withdrawal properties of self-tapping screws*

3. PARAMETRIC ANALYSIS

Parametric analyses were performed by curve-fitting the measured withdrawal stiffness data to develop predictive equations for stiffness. MATLAB programming was used to perform non-linear regression analyses to determine the influence of density, diameter, penetration length and insertion angle on the withdrawal stiffness of the self-tapping screw. Initially, two different regression analyses were performed for SPF and DF data sets to evaluate any potential differences between the two groups. Then, regression analyses were conducted on the combined SPF and DF data to come up with the general stiffness equation.

Non-linear regression analysis was carried out using the SPF and DF data and the following equation was used to determine the relevant coefficients and quantify the results of the test series. The withdrawal stiffness mostly depends on the diameter, penetration length and insertion angle of the screw and density of timber. Therefore, the equation format for the withdrawal stiffness, $K_{ax,\alpha}$ is shown in equation (2).

$$\boldsymbol{K_{ax,\alpha}} = \frac{w_1\, l_e^{\,w_2}\ \rho^{w_3}\ d^{w_4}}{w_5\ cos^2(\alpha) + w_6\ sin^2(\alpha)} \tag{2}$$

where α is the insertion angle to timber grain, d is the nominal diameter of the fastener, l_e is the fastener penetration into wood excluding the tip and ρ is the timber density.

After performing the non-linear regression analysis with the SPF test data, the screw withdrawal stiffness in the SPF timber can be expressed as shown in equation (3).

$$\boldsymbol{K_{ax,\alpha,SPF}} = \frac{0.30 l_e^{\,-0.01}\ \rho^{0.18}\ d^{1.09}}{2.37cos^2(\alpha) + 3.22sin^2(\alpha)} \tag{3}$$

The coefficient values and their related errors and p-values are presented in *Table 2*. Analysis of the coefficient of determination (R^2) has revealed a strong correlation, with a value of 0.9. The root mean square error (RMSE) was found to be 0.152. The p-values associated with the length of Equation (3) for SPF data were found to be high indicating that the influence of length was less significant compared with other parameters based on the SPF test results.

Then, a non-linear regression analysis was carried out with the DF test data and the screw withdrawal stiffness in the DF timber can be expressed as shown in equation (4).

$$\boldsymbol{K_{ax,\alpha,DF}} = \frac{0.44 l_e^{\,0.69}\ \rho^{2.93}\ d^{-7.82}}{5.32cos^2(\alpha) + 6.32sin^2(\alpha)} \tag{4}$$

The coefficient values and their related errors and p-values are presented in *Table 2* where, the analysis of the coefficient of determination (R^2) has revealed a reasonable correlation, with a value of 0.83. The root mean square error (RMSE) was found to be 0.249. The lower p-value associated with the length of equation (4) indicates that the influence of penetration length in withdrawal stiffness is high based on the test results.

Finally, after performing the non-linear regression analysis with all the SPF and DF test values in this study, the screw withdrawal stiffness for both SPF and DF timber can be expressed as shown in equation (5).

$$\boldsymbol{K_{ax,\alpha,G}} = \frac{0.17 l_e^{\,0.41}\ \rho^{0.72}\ d^{-0.51}}{5.09cos^2(\alpha) + 6.35sin^2(\alpha)} \tag{5}$$

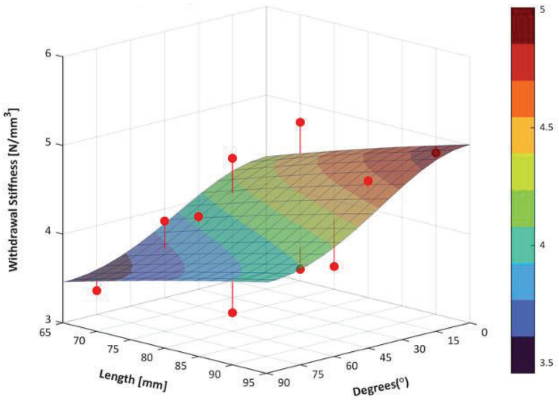

Figure 4: *Surface of withdrawal stiffness vs insertion angle and penetration length for 11 mm diameter SPF data using combined coefficient (ρ=429 kg/m³)*

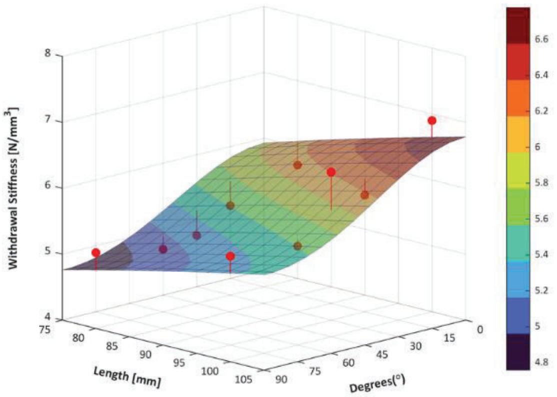

Figure 5*: Surface of withdrawal stiffness vs insertion angle and penetration length for 9 mm diameter DF data using combined coefficient (ρ=533 kg/m³)*

The coefficient values and their related errors and p-values are presented in *Table 2*. Analysis of the coefficient of determination (R^2) and the root mean square error (*RMSE*) has revealed a strong correlation, with a value of 0.885 and 0.315 respectively, which is promising. The standard errors are found within an acceptable range which subsequently yielded a smaller range for a 95% confidence interval for all the coefficients. The surface of the withdrawal stiffness values represented by equation (5) for SPF and DF data associated with their respective diameter are shown in *Figure 4* and *Figure 5* respectively. The surface depicts expected values based on equation (5)

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while individual data points depict the experimental withdrawal stiffness. The mean density of 429 kg/m^3 and 533 kg/m^3 was considered for the SPF and DF wood samples in *Figure 4* and *Figure 5* respectively following the test data.

Table 2: *Coefficient estimation for each data set of withdrawal stiffness after parametric studies*

Equation	Species	Coefficients	Values	p-Value	Standard Error	Lower 95%	R^2	RMSE
3	SPF	w_1	**0.30**	0.495	0.419	-0.661	0.900	0.152
		w_2	**-0.01**	0.930	0.118	-0.283		
		w_3	**0.18**	0.621	0.340	-0.607		
		w_4	**1.09**	0.012	0.306	0.382		
		w_5	**2.37**	3.47E-08	0.067	2.214		
		w_6	**3.22**	1.30E-09	0.053	3.096		
4	DF	w_1	**-0.44**	2.09E-06	0.031	-0.515	0.830	0.249
		w_2	**0.69**	0.002	0.150	0.337		
		w_3	**2.93**	4.79E-09	0.086	2.724		
		w_4	**-7.82**	3.24E-15	0.030	-7.888		
		w_5	**-5.32**	2.57E-09	0.142	-5.652		
		w_6	**-6.32**	2.32E-10	0.120	-6.599		
5	DF + SPF	w_1	**0.17**	0.855	0.929	-7.532	0.851	0.315
		w_2	**0.41**	0.011	0.142	0.101		
		w_3	**0.72**	0.271	0.626	-1.551		
		w_4	**-0.51**	0.473	0.696	-3.054		
		w_5	**5.09**	9.511E-16	0.147	-0.566		
		w_6	**6.35**	1.466E-18	0.118	-0.706		

Based on equations (3)-(5), a comparative study was undertaken for all diameters, insertion angles, penetration length and wood species to compare the effectiveness of the general combined equation which is shown in *Figure 6*. The statistical analysis for SPF and DF data concluded that the combined general equation (5) can be used for both the SPF and DF wood species instead of using individual equations (3) and (4) for SPF and DF separately. Therefore, to predict the withdrawal stiffness of the screws with known insertion angle and penetration lengths within the diameter of 9-11 mm, and wood density of 429-533 kg/m^3, the general equation (5) may be utilized based on the parametric studies conducted in this study. However, further studies are required with a wider range of test data to cover more diameter, penetration length and density. In the case of CLT, as long as the input parameters are within the mentioned range, the average value of withdrawal stiffness of all penetrated screw layers can be considered as the final withdrawal stiffness.

Also, the withdrawal stiffness of all possible screw diameters ranging from 8-12 mm at 0°, 30°, 45°, 60° and 90° insertion angles, penetration length from 50-200 mm in SPF and DF wood with a density of 425 and 525 kg/m^3 is calculated and presented in *Figure 7*. From the figure, it can be seen that the withdrawal stiffness decreases with increasing insertion angle to timber grain and the screw diameter but increases with the increase of wood density and screw penetration length. Therefore, withdrawal stiffness is sensitive to the screw penetration length and wood density.

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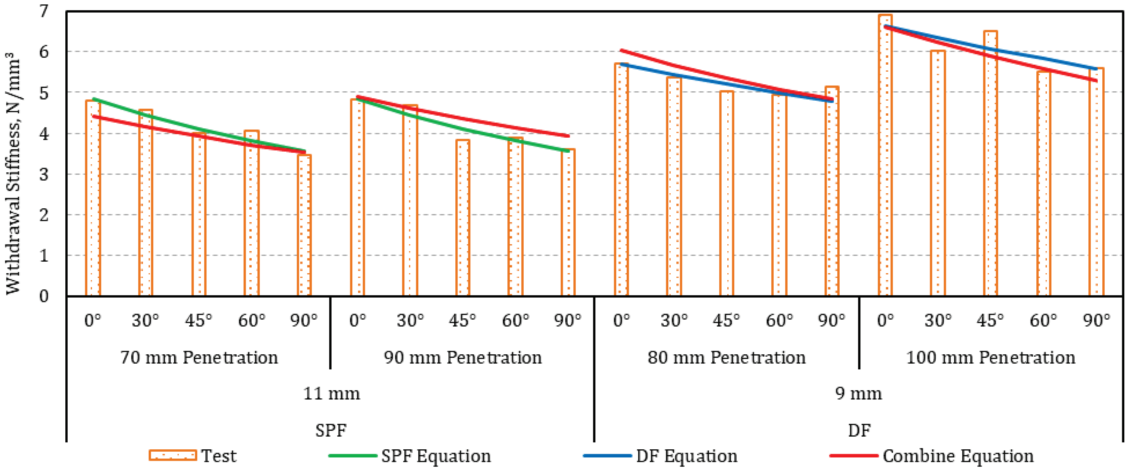

Figure 6: *Withdrawal stiffness comparison*

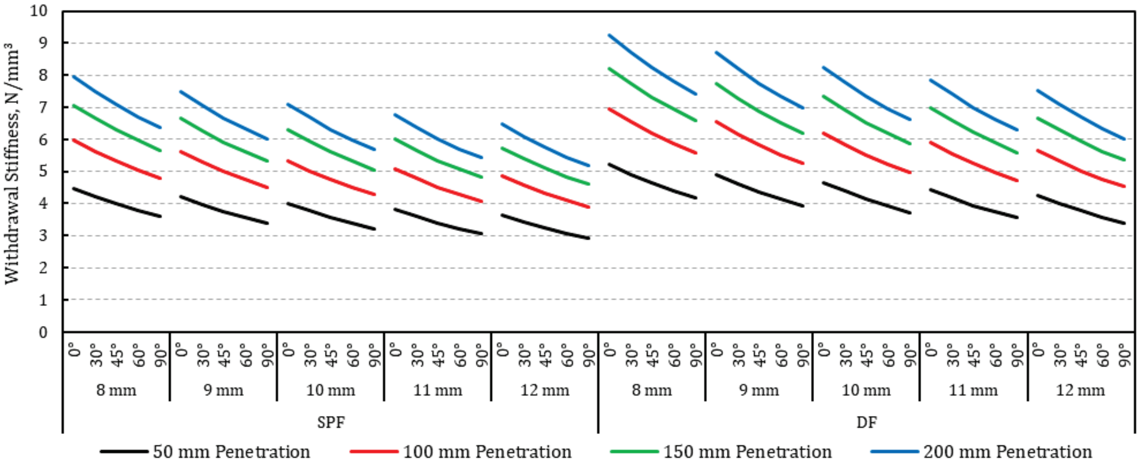

Figure 7: *Predicted withdrawal stiffness of different diameter screws in SPF and DF using general withdrawal stiffness equation for different penetration lengths (ρ_{SPF} = 425 kg/m^3 and ρ_{DF} = kg/m^3)*

4. CONCLUSIONS

Self-tapping screws are often inserted into the face of timber members at an angle to take advantage of their high withdrawal strength and stiffness to resist lateral loads. Because of the inclined arrangement, the calculation of the stiffness of such self-tapping screw connections requires knowledge of withdrawal stiffness at various insertion angles relative to the grain of wood on the timber member surface. From a design calculation perspective, it would be beneficial to express these stiffness properties in terms of wood density and fastener diameter, similar to parallel expressions for withdrawal strength, as well as the insertion angle. The main goal of this study was to provide a preliminary indication if it is feasible to develop empirical equations to express withdrawal stiffnesses in terms of the geometry of the fastener, wood density and insertion angle. Although the databases used in this study were limited in terms of the range of parameters studied, results from non-linear regression analyses performed on the collected data have shown that the withdrawal stiffness of self-tapping screws could be estimated from wood density, screw diameter, insertion angle, and effective penetration length. While the influences of wood density and screw diameter are as expected, it was noted that insertion angle influences withdrawal stiffness directly. Based on this study, withdrawal stiffness decreases with increasing insertion angle.

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