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THE IMPACTS OF SCREW TIP, INCLINATION ANGLES AND NUMBER OF PENETRATION LAYERS ON SCREW WITHDRAWAL CAPACITY IN AUSTRALIAN MACHINE GRADED PINE

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ABSTRACT: Connections play an important role in timber structures as they govern the overall stiffness, load-carrying capacity, and most of the ductility in a timber structure. Due to the high axial load-carrying capacity and ease of installation, self-tapping screws are nowadays one of the most widely used fasteners in timber construction. However, variations in national standards, regulations, or even timber species might lead to incorrect predictions for the screw's load-carrying capacity. The current Australian Timber Standard AS 1720.1-2010 has some fundamental limitations since it was primarily derived from old North American research and supplemented in the 1970s with empirical data on Australian hardwoods and a few softwoods. Modern European fasteners are increasingly employed in the Australian building industry, making it critical to examine their performance consistency in the context of Australian timber products. This research work, therefore, aimed to a) evaluate the interactions of numbers of penetration layers, screw tip, and screw characteristic withdrawal strength, b) evaluate the influence of inclination angles on characteristic withdrawal strength, and c) compare experimental results with existing models and provide recommendations.

KEYWORDS: axially loaded self-tapping screws, withdrawal strength, sawn timber

1 INTRODUCTION

McLain stated that 'a structure is a constructed assembly of joints separated by members' [1] and this is especially accurate to describe timber structures. Connections govern the overall structural performance, such as stiffness, strength, and most of the ductility in a timber structure. Due to their high axial performance, flexible geometry, cost efficiency, and quick installation, self-tapping timber screws are nowadays one of the most popular fasteners in global timber construction.

In recent years, European connectors and fasteners are increasingly employed in the Australian market due to the rapid development of the Australian timber building industry and the lack of local suppliers and experiences. In such a case, a performance solution allows the engineer to use the manufacturer's technical approval. However, an inappropriate capacity estimation can cause overstrength and brittle failure of European fasteners in Australian timber species [2,3]. Since the Australian timber standard (AS 1720.1 [4]) was originally derived from North American research and supplemented by Australian empirical data in the 1970s, it is lacking consistent analytical equations to adapt to various modern screws. It is, therefore, of great importance to carefully assess the suitability and performance consistency of European screws in the context of the Australian market.

Withdrawal strength is one of the most critical parameters that govern the performance of axially and laterally loaded screws (i.e., the rope effect that was introduced in Eurocode 5). The geometry of the screw (e.g., diameter, thread, tip), the number of penetrated layers/studs, and screw thread-to-grain angle affect the withdrawal resistance of screws. These potential influences are rarely considered in most of the existing design codes in Australia.

1.1 SCREW PENETRATED LAYERS

Light timber framing is commonly constructed with double studs in Australia, and fasteners penetrate both timber members (i.e., without glue) in most cases. AS 1720.1 [4] does not specify a minimum/maximum penetration length in the second member for withdrawal, yet it stipulates l_{ef} >17d for laterally loaded connections. Hence, the conservativeness of AS 1720.1 needs to be re-evaluated regarding the minimum effective screw penetration length in one or two non-glued timber layers. Moreover, Ringhofer et al. [5–7] studied the influence of the number of penetration layers on screw withdrawal parameter in cross-laminated and glue-laminated timber. They suggested system factors, k_{sys}, for up to 10-layer laminated timber products. As part of this study, the feasibility of applying k_{sys} to non-glued double-layered Australian sawn timber was evaluated.

1.2 SCREW THREAD-TO-GRAIN ANGLE

As inclined screws provide greater strength under lateral loading than orthogonal screws, they are now widely used in timber construction [8]. Pirnbacher et al. [9] adapted Hankinson's relation and developed a modified model to fit the screw thread-to-grain angles (α) between 0° and 72.5°. In contrast, Ringhofer et al. [6] propose a bilinear model to predict the relationship between screw thread-

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to-grain angle and withdrawal performance. According to their research, the withdrawal performance of the screw did not change for $\alpha > 30°$ [6,10]. This study compared the inclined screw withdrawal performance in Australian sawn timber with previous studies.

1.3 SCREW EFFECTIVE LENGTH

Eurocode 5 [11] states that the effective penetration length of the screw (l_{ef}) is limited to the threaded part. However, it is unclear whether the tip should be considered since modern screws commonly have fully threaded tips. The Canadian standard CSA O86 [12] requires l_{ef} to be the threaded length minus the tip length (typically equal to one nominal thread diameter, d). In contrast, AS 1720.1 [4] does not consider the potential influence of the tip and states that l_{ef} is equal to the entire length of a fastener's penetration, which includes the unthreaded shank and tip. Nevertheless, European scientists conventionally agreed that the screw tip should be deducted from the profiled length [13], and a length correction factor should be applied. From this, several questions arise: (1) Defining the length of the tip - should it be the exact length of the tip or include a certain length of regular thread? (2) While some European literature and experimental tests concluded that the tip length should be equal to $1.11d$ [13] or $1.17d$ [9], it is still uncertain whether this applies to Australian timber species due to their relatively higher density compared to European species.

Consequently, this work examined the interactions of numbers of penetration layers, screw thread-to-grain angle, screw tip, and screw characteristic withdrawal strength; evaluated the influence of inclination angles on characteristic withdrawal strength; compared and verified existing models and provided recommendations.

2 MATERIAL AND METHODS

2.1 SPECIMEN CONFIGURATION

This study was separated into three phases: (1) examine the effects of the penetrated layers (single or double stud); (2) assess the effects of different screw-to-grain angles, and (3) evaluate the contribution of screw tip during withdrawal.

2.1.1 TIMBER SAMPLES

Machine grade pine (MGP) specimens with orthogonal or inclined screws were tested according to the Australian Standard AS 1649 [14]. Clear 170 mm long specimens were cut from 3 m long 45×90 mm MGP10 boards. Timber densities were measured according to the weight and dimensions of each specimen. Timber densities were assumed as normal distributed, and the characteristic timber densities, ρ_k were calculated based on EN 14358:2016 [15]. Knotty specimens were removed to obtain more consistent results [5–7]. It is worth mentioning that AS1720.1 gives a mean density $\rho_m = 500$ kg/m^3 for MGP10, however, the timber density is not directly related to connection strength prediction which is based on joint groups that depend on species. Thus, a regression prediction model established by Pirnbacher et al [5] was also compared and verified in this study for the mean value of the screw withdrawal strength.

2.1.2 SCREW SAMPLES

A total of 330 8×120 mm Schmid Rapid screws (ETA-12/0373 [10]) were tested in single stud, double stud, and different inclination angles. All screws were manually installed in the timber specimens using a cordless handheld drill. To ensure the accuracy of inclination angles, a screw installation guide was used. The edge and end spacing of each test were checked according to the requirements of the ETA-12/0373 [10], Australian Standard AS 1649 [14] and EN 1382 [16].

In this study, the effects of the screw penetrated layers (Phase 1) were tested by inserting screws in both single and double layers of 45×90 mm MGP10 boards. The effects of the screw tip and penetrated layers (Phase 2) were examined by installing screw with the tip inside and outside timber specimens, respectively (Table 1). Axial withdrawal tests for inclined screws were carried out, and three load-to-grain angles were tested (Phase 3). In specimen designations, the first letter relates to layers (S = single, D = double) and the second letter relates to the tip position (W = within, O = outside). L is the nominal thread length that penetrated the timber specimen, and n is the replication of each test. The number (i.e., 90, 75, 60, 45 and 30°) attached to the letters indicates the inclination angle of the screws. A schematic diagram of all test series is shown in Figure 1.

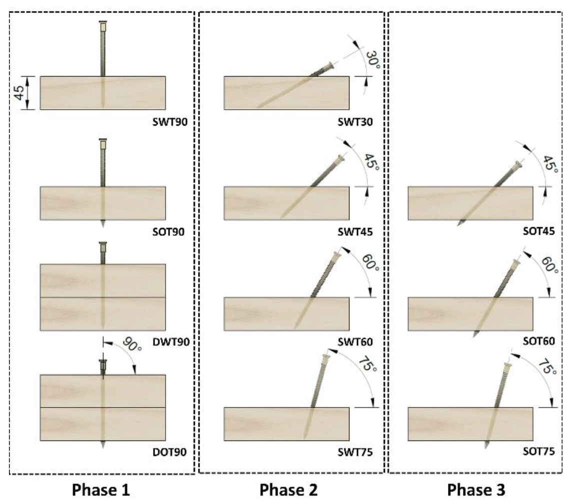

Figure 1. *Illustration of the configurations of all test series*

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__Table 1:__ Test specimen specifications for test assemblies, and number of repetitions.

Test series	Test name	α [°]	L [mm]	n [-]
Phase 1	SWT90	90	45	30
	SOT90	90	45	30
	DWT90	90	90	30
	DOT90	90	90	30
Phase 2	SWT75	75	47	30
	SWT60	60	52	30
	SWT45	45	64	30
	SWT30	30	90	30
Phase 3	SOT75	75	47	30
	SOT60	60	52	30
	SOT45	45	64	30

2.2 WITHDRAWAL TESTS

Withdrawal tests were carried out according to AS 1649 (with the addition of inclined screw tests) using an Instron universal testing machine with a test rig that was specially made for inclined screw withdrawal (Figure 2). The screws were withdrawn at a constant rate of 2.5 mm/min. The moisture content was determined according to AS 1080.1 [17] (oven drying at 103°C) immediately after withdrawal testing as 12.9±1.1%.

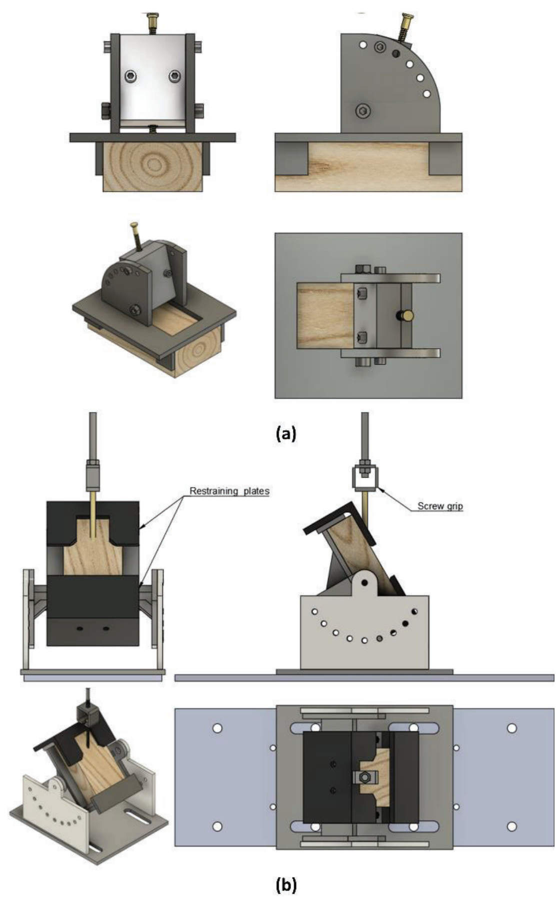

***Figure 2**: (a) Screw installation guide and (b) withdrawal test setup.*

2.3 STATISTICAL DATA ANALYSIS

The statistical analysis of the test data was performed using SPSS. The Shapiro-Wilk test, Levene's test, ANOVA, student's T-test, and post-hoc test were used as statistical analysis methods in this study.

3 THEORY

The experimentally determined screw withdrawal parameter $f_{ax,exp}$ was modified from EN1382:2016 [16] as

$$\boldsymbol{f_{ax,exp}} = \frac{\boldsymbol{F_{ax,exp}}}{\boldsymbol{l_{ef} \cdot d}} \qquad (1)$$

where $F_{ax,exp}$ is the maximum force recorded from the individual screw withdrawal tests, and l_{ef} is the effective penetration length of the screw, where the penetration length is reduced by the tip length, l_{tp}. In ETA-12/0373 [10] l_{tp} is 11.0 mm for 8×120 mm Schmid Rapid screws. The experimentally determined screw withdrawal parameters were assumed as lognormal distributed, and the characteristic withdrawal parameter, $f_{ax,k,exp}$ was calculated according to EN 14358:2016 [15].

The screw's characteristic withdrawal parameter, $f_{ax,k,ETA}$ given in Schmid's ETA-12/0373 [10] is 13.1 N/mm^2. An equation that considers timber density, species, material, and screw installation angle is proposed by ETA-12/0373 [10] and calculated as

$$\boldsymbol{f_{ax,k,pre}} = \cdot\, \boldsymbol{f_{ax,k,ETA}} \cdot \boldsymbol{k_{ax}} \cdot \boldsymbol{k_{sys}} \cdot \left(\frac{\boldsymbol{\rho_k}}{\boldsymbol{\rho_{k,ref}}}\right)^{\boldsymbol{k_\rho}} \qquad (2)$$

where k_{ax} is the angle factor (k_{ax} = 1 for 30°≤ $\alpha \leq 90°$), k_{sys} is the system factor (k_{sys} = 1 for solid timber, however, k_{sys} =1.06 was additionally considered and assumed for DWT and DOT series for this research only), k_ρ is the density factor (k_ρ = 1.1 for softwood and 15°≤ $\alpha \leq 90°$), and $\rho_{k,ref}$ is the reference characteristic density ($\rho_{k,ref}$ = 350 kg/m^3). It is important to note that all factors were determined based on the previous study by Ringhofer et al. [5–7].

Apart from the characteristic value, a regression model established by Pirnbacher et al. [9] for predicting mean orthogonal screw withdrawal parameter, $f_{ax,mean,pre}$ is adapted as:

$$\boldsymbol{f_{ax,mean,pre}} = (\boldsymbol{0.01353 \cdot \rho_m - 0.68679 \cdot d^{0.572} + 2.18888) \cdot \pi} \qquad (3)$$

Eq (3) was first derived by Pirnbacher et al. [9] after conducting a series of screw withdrawal tests for d = 6 to 12 mm and timber density ρ = 300 to 600 kg/m^3. This Equation was then further verified by Ringhofer et al [5] using screw diameters ranging from 6 to 12 mm and timber density ranging from 375 to 475 kg/m^3. The premise of this equation considered the effective length of screw penetration equals to $l_{ef} = L - 1.17d$.

4 RESULTS AND DISCUSSION

Test results are summarised and compared graphically in notched boxplots and in the following tables. All outliers presented in boxplots were removed from the statistical analysis and were considered as extreme values. Table 2 lists the mean density, ρ_m, coefficient of variation (COV), characteristic density, ρ_k and the number of timber

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samples for each test series, n. SWT90 and SOT90 were carried out as the control group since $f_{ax,k,exp}$ were in good agreement with the prediction value $f_{ax,k,ETA}$. All screws failed in screw axial withdrawal and no other failure modes were observed during the tests. It is worth mentioning that after conducting the ANOVA and post-hoc tests, the mean densities of all tested samples presented statistically non-significant differences to each other. Thus, in most instances, the mean withdrawal parameter, $f_{ax,m}$ can be directly compared after applying the student t-test to access the influence parameters.

Table 2: *Sample densities and number of samples*

Test series	Test name	ρ_m	*COV*	ρ_k	*n*
		[kg/m³]	[%]	[kg/m³]	[-]
Phase 1	SWT90	405.1	6.3	357.0	30
	SOT90	423.7	5.3	381.9	30
	DWT90	401.2	4.7	365.8	60
	DOT90	401.3	4.0	371.1	60
Phase 2	SWT75	428.4	8.6	359.4	30
	SWT60	448.9	7.7	384.0	30
	SWT45	446.0	4.8	405.7	30
	SWT30	442.2	7.8	377.7	30
Phase 3	SOT75	424.9	7.9	362.0	30
	SOT60	420.6	9.2	348.7	30
	SOT45	425.7	8.0	361.7	30

4.1 Phase 1 – Screw penetrated layers

The effective penetration length, l_{ef} for Phase 1, was considered as L - l_{tp}. In Figure 3, $f_{ax,mean,pre}$ values were calculated according to ρ_m from Table 2. Considering the sample size, the experimental results agreed well with the predictions by Eq (2) and (3) and were only slightly non-conservative for SOT and DOT series.

After conducting the statistical analysis, the mean withdrawal parameter between SWT90 and DWT90 groups showed a non-significant difference, thus, this finding indicates that the multiple penetration layers did not influence screw withdrawal strength when the full length of the screw tip was deducted. In the DOT series, L in the second timber layer is 4.4*d*, indicating that a penetration length of 4.4*d* can still provide conservative withdrawal strength. The notched boxplot in Figure 3 shows that the difference between the SOT90 and DOT90 median values is about 1. The notch areas for SOT90 and DOT90 do not overlap, and a p-value < 0.05 indicates that the median and mean values differ significantly. The screw withdrawal parameter was thereby reduced by multiple studs when the screw tip stuck out of the timber specimen, and no glue was applied to the middle of the double boards. This finding was contrary to previous results by Ringhofer et al. [5]. In Table 3, the experimental results for SWT and DWT series are slightly higher than the prediction value. It is suggested to quantify the contribution of the screw tip in future studies. As of this section, it is concluded that the screw tip has a slightly positive effect on the withdrawal parameter, and therefore the accuracy of the deduction length should be re-verified.

Table 3: *Result comparisons - Single/double penetration layer with tip inside/outside of the timber specimen*

		With tip		**Without tip**	
		SWT90	DWT90	SOT90	DOT90
$f_{ax,m}$	[N/mm²]	18.1	17.3	17.2	16.3
COV	[%]	15.5	7.7	9.3	6.5
P[1]	[-]	0.31		0.00	
$f_{ax,mean,pre}$	[N/mm²]	17.0	16.8	17.8	16.8
$f_{ax,m,exp}/f_{ax,m,pre}$	[-]	1.06	1.03	0.97	0.97
$f_{ax,k,exp}$	[N/mm²]	13.7	15.0	14.4	14.5
$f_{ax,k,pre}$	[N/mm²]	13.4	14.6	14.4	14.8
$f_{ax,k,exp}/f_{ax,k,pre}$	[-]	1.02	1.03	1.00	0.98
		Single layer		**Double layer**	
		SOT90	SWT90	DOT90	DWT90
P[1]	[-]	0.32		0.00	

[1] ***P-value for ln(f_{ax})***

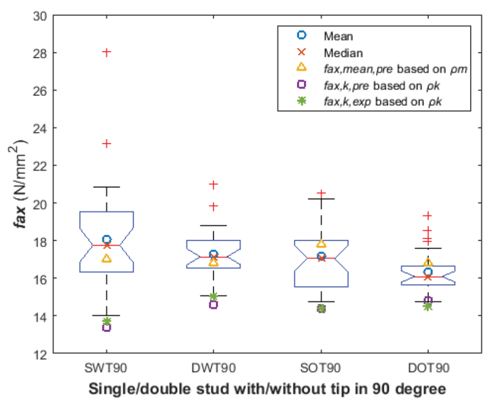

Figure 3: *Single/double penetration layer with tip inside/outside of the timber specimen*

4.2 Phase 2 – Screw inclination angles

SWT and SOT inclined screw withdrawal tests are summarised and compared in Table 4, Figure 4, Table 5, and Figure 5. As previously mentioned in Section 4.1, the effective penetration length for Phase 2 was also calculated as $l_{ef} = L - l_{tp}$.

The results for both SWT and SOT were generally consistent with the previous literature by Ringhofer et al. [6], in which the f_{ax} exhibited a bilinear behaviour (i.e., screw withdrawal strength is constant for $\alpha > 30°$ then a gradual decrease can be observed). Based on statistical analysis, no significant f_{ax} deviations were detected for α = 45, 60 and 75°.

In the SWT series, the screw withdrawal strength gradually increased with decreasing inclination angle (α from 90° to 45°). The boxplots in Figure 4 also suggest that the median values did not show statistical differences for $\alpha > 30°$. However, for $\alpha = 30°$, the ETA prediction equation overpredicted the withdrawal strength, and a dramatic decrease was observed. The strength reduction

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for α = 30° might be explained by the orientation of the screw axis approaching the fibre grain direction.

Due to the limitation of the test rig, SOT30 was not conducted. Thus, only 90° to 45° screw withdrawal tests were achieved and evaluated. Future research should confirm whether the strength reduction observed for SWT30 applies to SOT30. In general, Eq. (2) works conservatively in the SOT series and the screw withdrawal strength increased when α decreased to 75°. Since the notched area for SOT90 and SOT75 were not overlapped, the result indicates that the medians differ significantly.

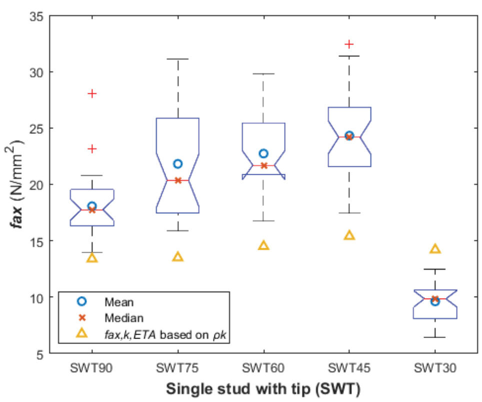

Figure 4: *Different inclination angles in single stud (with tip)*

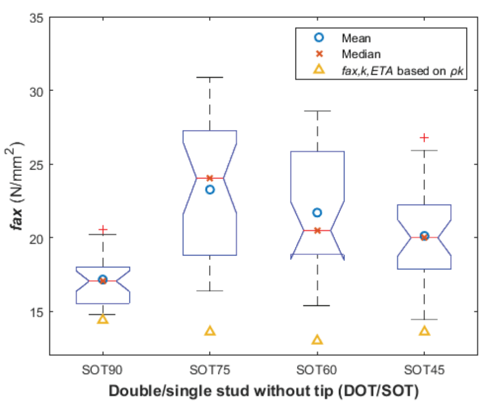

Figure 5: *Different inclination angles in single/double stud (tip outside of the timber specimen)*

Table 4: Result comparisons - Single penetration layer with tip inside of the timber specimen and different inclination angles

		SWT				
		90	75	60	45	30
$f_{ax,m}$	[N/mm^2]	18.1	21.8	22.7	24.3	9.6
COV	[%]	15.5	22.4	14.2	15.8	18.1
$f_{ax,k,exp}$	[N/mm^2]	13.7	14.2	17.3	17.8	6.7
$f_{ax,k,pre}$	[N/mm^2]	13.4	13.5	14.5	15.4	14.2
$f_{ax,k,exp}/f_{ax,k,pre}$	[-]	1.02	1.05	1.19	1.16	0.47

Table 5: *Result comparisons - Single penetration layer with tip outside of the timber specimen and different inclination angles*

		SOT			
		90	75	60	45
$f_{ax,m}$	[N/mm^2]	17.2	23.3	21.7	20.1
COV	[%]	9.3	20.2	18.4	15.8
$f_{ax,k,exp}$	[N/mm^2]	14.4	15.4	15.2	14.7
$f_{ax,k,pre}$	[N/mm^2]	14.4	13.6	13.0	13.6
$f_{ax,k,exp}/f_{ax,k,pre}$	[-]	1.00	1.13	1.17	1.08

4.3 Phase 3 – Screw tip lengths

Figure 6 illustrates the ratio between $f_{ax,k,exp}$ and $f_{ax,k,ETA,}$ and confirms the conservativeness of selected calculation methods for l_{ef} (i.e., (a) $l_{ef} = L$, (b) $l_{ef} = L - 1.11d$, (c) $l_{ef} = L - 1.17d$ and (d) $l_{ef} = L - l_{tp}$). Table 6 lists the results from the student t-tests. Since no differences were observed for timber mean densities after statistical analysis, $f_{ax,m}$ was chosen to be compared directly. The SOT series was considered as the control group in this test campaign. From Table 6, student t-test p-values indicate that the tip length, l_{tp} should not be considered in the full threaded length, except when α = 45° and $L = 8d$. This finding was consistent with the results of a previous study by Pirnbacher et al. [5] in which the tip effect decreased with increasing penetration length.

As stated in Eurocode 5 [11] and ETA-12/0373 [10], l_{ef} must include l_{tp}. As shown in Figure 6, however, the results indicate that $f_{ax,k,pre}$ was overestimated for $l_{ef} = L$. This suggests that the screw tip should not be treated as a fully threaded element, and a length correction parameter should be considered.

Following the statistical analysis, p-values in Table 6 indicate the tip length should be fully subtracted from the penetration length, i.e., $l_{ef} = L - l_{tp}$ when $\alpha \geq 75°$ with $l_{tp} = 1.38d$. However, when $45° > \alpha > 75°$, $l_{tp} = 1.11d$ seems more appropriate for Australian timber species.

Generally, $l_{tp} = 1.17d$ [9] versus $l_{tp} = 1.38d$ only resulted in minor differences in withdrawal strength (i.e., the purple-square, green-cross, and blue-circle lines are positioned closely together) with little feasibility at different inclination angles.

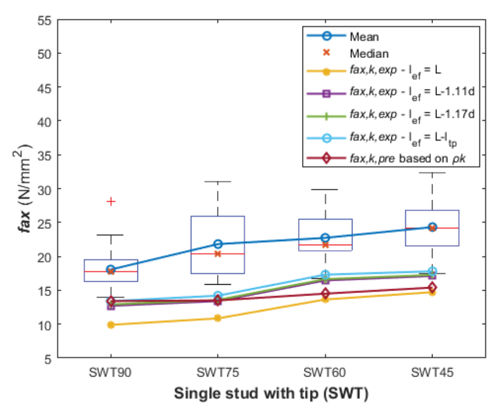

Figure 6: *Comparison of using different lef to calculate withdrawal strength over different inclination angles.*

Table 6: *Sample densities and number of samples.*

Comparison group		***T-test *p-values***			
		$l_{ef} = L$	$l_{ef} = L - 1.11d$	$l_{ef} = L - 1.17d$	$l_{ef} = L - l_{tp}$
SWT90	SOT90	0.00	0.09	0.26	0.31
SWT75	SOT75	0.00	0.03	0.04	0.23
SWT60	SOT60	0.00	0.95	0.74	0.21
SWT45	SOT45	0.60	0.00	0.00	0.00

p-value for ln(f_{ax})

5 CONCLUSION

This paper presented an experimental study on the effects of screw tip, inclination angles, and the number of penetration layers on screw withdrawal capacity of Australian machine graded pine. A total number of 330 Schmid screws according to ETA-12/0373 [10] were tested in double or single layers of Australian MGP10 board with inclination angles of 90, 75, 60, 45 and 30 degrees.

Overall, the key findings are:

- When the screw is installed perpendicular to the grain, prediction models based on previous literature and manufacturers' ETA are appropriate for Australian MGP10 and generally give conservative results. However, the tip length should not be fully considered in the screw effective penetration length, l_{ef}, and the ETA model should be re-evaluated when the thread-to-grain angle, α, is equal to 30°.
- Consistent with previous research, the thread-to-grain angle is negatively correlated with axial withdrawal strength in the range between $90° \geq \alpha > 30°$.
- The inclination angle factor k_{ax} in ETA-12/0373 [10] should be re-evaluated for $\alpha = 30°$ in Australian timber species. A deduction factor/equation should be further studied and applied to k_{ax}. To optimise k_{ax}, a regression model is recommended to consider all configurations.
- The tip length, l_{tp} (1.11d) suggested by Pirnbacher et al. [9] is generally conservative and acceptable except when $\alpha > 75°$. In contrast, l_{tp} (1.38d) is generally more versatile as it can be easily adapted for all inclination angles. However, to further evaluate this finding, more experimental tests should be conducted.
- Further research is suggested to develop a more versatile length correction factor. The length correction factor (length of screw tip, l_{tp}) should be optimised and verified using a regression model.
- Using screws in double timber layers (without adhesive) reduced the screw withdrawal parameter, likely due to insufficient local stiffness on layered timber. If no adhesive is applied between layered timber, the k_{sys} factor could likely be conservatively ignored for sawn timber. More experimental tests are suggested to determine the reduction factor.
- Further regression model analysis should be established to obtain an optimized analytical equation for the interactions of the screw tip, numbers of penetration layers, and screw characteristic withdrawal strength in Australian timber species.

In conclusion, the results of this study provide some insights into the withdrawal capacity of modern European screws in Australian machine graded pine. The study highlights the need for further research in this field, particularly in relation to the development of more accurate predictive models for Australian timber products.

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