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IMPACT OF MOISTURE CYCLING ON SCREW WITHDRAWAL CAPACITY OF TREATED AND UNTREATED RADIATA PINE

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ABSTRACT: The increased use of wood products for construction has intensified the need to understand how moisture affects the mechanical properties of timber connections. The withdrawal capacity of dowel-type fasteners, such as screws, needs to be measured, or estimated, for the design of timber systems having connections with axially loaded dowel-type fasteners. The influence of the moisture content changes on the timber is often examined, but its effect on the mechanical performance of connections is poorly considered, including the design codes. This work examined changes in the screw withdrawal capacity in light organic solvent preservative-treated and untreated Radiata pine with type 17 screws inserted perpendicular and parallel to the grain and subjected to repeated wetting and drying cycles. A comparison of the screw withdrawal capacities with those predicted from Australian and European codes was performed. The results presented here are part of a larger project that includes the study of embedment strength and lateral resistance in combination with different wood treatments and pine species.

KEYWORDS: Screw withdrawal capacity, Preservative treatment, Moisture content, Radiata pine

1 INTRODUCTION

Wood is a hygroscopic material that easily absorbs and desorbs moisture from the environment, producing swelling or shrinking. Dimensional changes induce stresses in the timber elements that can lead to cracks or failures [1]. Induced stress is even more important in timber connections, as the deformations and movement incompatibilities produced by differential moisture responses create even more stress [2]. For example, the screw withdrawal capacity (SWC) in timber can be affected by moisture/drying exposure conditions that eventually reduce fastener capacity and can also induce metallic corrosion [3].

Most timber buildings are designed to exclude moisture, but some elements may be subjected to wetting and must be supplementally protected with preservatives to provide acceptable service life. Many of these preservatives are water-based products that may accelerate fastener corrosion and eventually the loss of mechanical properties of the timber connection [4]. For this reason, most preservative suppliers recommend the use of either stainless steel or hot-dip-galvanized fasteners.

Despite the potential for preservative treatment to affect fastener performance, there is limited research on the impact of moisture content (MC) changes on treated timber connections. The increased use of wood products in construction has intensified the need to understand how moisture affects the mechanical properties of timber connections, as wetting of these elements can occur due to rain penetration, condensation [5], as well as bathroom or pipe leakages.

Design standards can be used to estimate the strength of a timber connection, and ultimately design safe structures. According to Eurocode 5 (EC5) [6], the withdrawal capacity of dowel-type fasteners is necessary for the design of connections with axially loaded dowel-type fasteners. Nevertheless, the influence of the MC on the mechanical performance of these connections is poorly considered. In the EC5, the design value (X_d) of a strength property of a timber connection is calculated by modifying the characteristic value (X_k) according to Equation 1:

$$X_d = X_k \frac{k_{mod}}{\gamma_M} \tag{1}$$

where k_{mod} accounts for the service class (a function of load duration and expected equilibrium moisture content of the material) and γ_M is the partial factor (a function of the type of material, e.g., solid timber, particleboard). The impact of the MC in the design is considered only through k_{mod} with discreet values ranging from 0.2 to 0.6 in 0.1 intervals. Other design standards, such as the Australian standard AS 1720.1-2010 (AS1720) [7] only consider moisture effects on member strength, but not on the connection strength.

Screws are one of the most used timber fasteners. Nevertheless, little research has been conducted on the effect of MC variations on SWC [8]. Apart from MC, the SWC depends on several factors including connection

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geometry (e.g., diameter and penetration depth), tensile screw capacity (which in turn depends on the material and diameter), timber density, and the direction of loading with respect to the grain orientation for larger screws. While this creates an infinite array of possible tests, these can be simplified to several critical factors.

This work examined changes in the SWC in light organic solvent preservative (LOSP) treated and untreated Radiata pine with screws inserted perpendicular and parallel to the grain and subjected to repeated wetting and drying cycles. A comparison of the experimental withdrawal capacity with those predicted from the standards AS1720 [9] and EC5 [6] are presented and discussed. This work is part of a larger project that aims to assess the impact of moisture cycles on the withdrawal capacity, embedment strength and timber joints for a series of Australian timber species and preservative treatments.

2 EXPERIMENTAL

2.1. SPECIMEN CONFIGURATION

Defect-free 272 mm long Radiata pine (*Pinus insignis*) specimens were cut from 5 m long 45 x 90 mm boards with and without LOSP treatment.

LOSP-treated and untreated specimens were conditioned at a temperature of 25 °C and 65 % of relative humidity, using an environmental chamber (Labec F-HWS-250B). The samples were kept inside the chamber until constant mass to ensure moisture equilibrium.

Stainless steel screws with a 4.2 mm outer thread diameter (Table 1) were driven into a lead hole with a 2.94 mm diameter, to a penetration depth of 37.5 mm. Three screws were inserted perpendicular to the grain, and two parallel to the grain (Figure 1). The specimens were designed to meet the minimum requirements according to the testing standards AS 1649 [10] and ASTM D1761 [11]. The screws were weighed before being driven into the wood. After installing the screws, timber samples were checked to ensure that no cracks developed.

Table 1: *Wood and screw specifications for creating the test assemblies, and the number of specimens built for testing.*

Wood type	2	Radiata pine (LOSP treated and untreated)
Screw types	1	Type 17 (8g), SS 304, 4.2 x 50 mm
Screws per specimen	3 + 2 5	Side + end grain TOTAL
Test conditions	5	0, 2, 4, 8 and 12 moisture cycles
Repetitions per condition	15 10	Side grain End grain
TOTAL	**50** **250**	**Wood specimens** **Screws**

The moisture content of the conditioned LOSP-treated and untreated woods was determined using the oven-dry method from 20 smaller samples from the same boards. For the determination of the density, the dimensions (L, W, T) were measured at three different points, using a digital calliper, for each specimen and then averaged (Table 2).

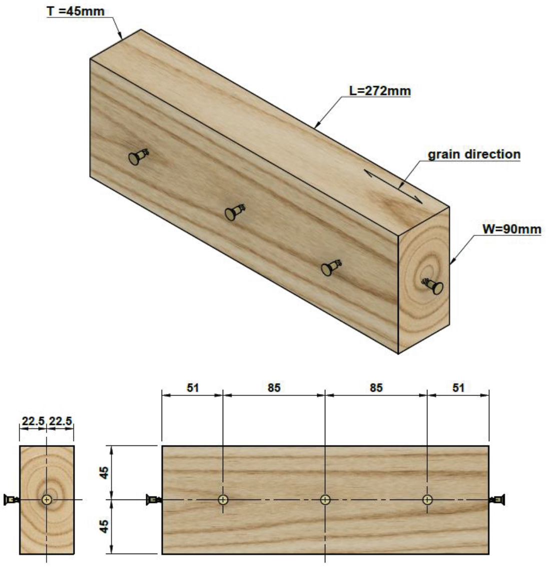

Figure 1: *Specimen dimensions and configuration showing the relative position of the screws and the grain direction. All distances are in mm (L = length, W = width, T = thickness).*

Table 2: *Wood types, mean density, and moisture content of the treated and untreated wood used in the experiments. Values in parenthesis are standard deviations.*

Wood type	*Mean density (kg/m3)*	*MC (%)*
Untreated	485 (49)	11.7 (0.8)
LOSP treated	465 (37)	12.9 (0.9)

2.2. MOISTURE CYCLES

One set of five specimens (controls) was immediately tested, while the remaining specimens were weighed to determine the initial weight and then soaked until their moisture contents had reached 50-60 wt% (between 4 and 6 days). The samples were then dried for 40-50 hours at 50 °C for a slow loss of moisture to a final MC between 10 and 15 wt% before being weighed again. At this point, the specimens were tested or subjected to another wet/dry cycle.

2.3. WITHDRAWAL TESTS

The effects of wetting and drying on withdrawal capacity were assessed after 0 (controls), 4, 8, 12 and 16 moisture cycles. Screw withdrawal tests were carried out according to the standard AS 1649 [10] using an Instron 3400 universal testing machine (Instron, Inc. Norwood, MA, USA). The speciemens were conditioned in the same environmental chamber and conditions mentioned before. The specimens were placed in a specially constructed assembly (Figures 2 and 3) and the screw was withdrawn at a rate of 2.5 mm per minute. The load required to withdraw the screws was recorded as a function of time.

2.4. COMPARISON WITH DESIGN STANDARDS

The comparison of the experimental SWC with the estimated from the current Australian (AS1720 [9]) and European (EC5 [12]) codes was done based on the following ratio (Equation 2):

$$Ratio = \frac{SWCe}{SWCp} \tag{2}$$

where *SWCe* is the fifth percentile of the experimental SWC values from each series, and *SWCp* is the predicted SWC using Equations 3 and 4, corresponding to the AS1720 and EC5, respectively.

$$N_{k,j} = k_{13} l_p n Q_k \tag{3}$$

In Equation 3, $N_{k,j}$ is the *SWCp*, k_{13} is a modification factor (1.0 for screws on the face grain and 0.6 for screws in the end grain), l_p is the depth of the screw penetration (37.5 mm), n is the number of screws (1 screw), and Q_k is the characteristic capacity (56 N/mm).

$$F_{ax,\alpha,Rk} = \frac{n_{ef}\, f_{ax,k}\, d\, l_{ef}}{1.2cos^2\alpha + sin^2\alpha}\left(\frac{\rho_k}{\rho_a}\right)^{0.8} \tag{4}$$

In Equation 4, $F_{ax,\alpha,Rk}$ is the *SWCp*, n_{ef} is the number of effective screws (1 screw), d is the outer thread diameter of the screw (4.2 mm), l_{ef} is the penetration depth of the threaded part (35 mm), ρ_k is the characteristic density of the wood (considered as the fifth percentile of the density of the batch, in kg/m^3), and ρ_a is the associated density (considered as the 5th percentile of the densities of all the specimens, 418 kg/m^3), $f_{ax,k}$ is the characteristic withdrawal parameter, determined with the 5th percentile of the *SWCe* of the controls (specimens at week 0), and α is the load-grain angle, with screws driven into end grain α = 0º and screws driven into side grain α = 90º.

In practice, *SWCp* values are used to design timber structures. A safe prediction is considered when the ratio is above 1.

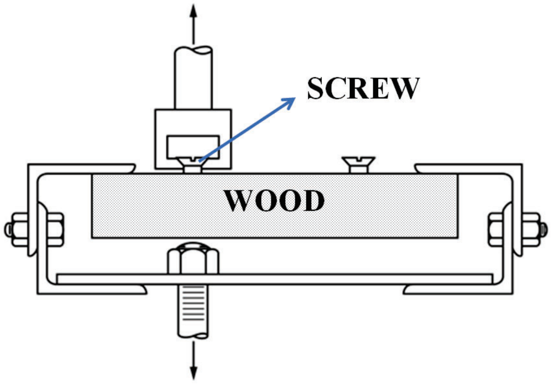

Figure 2: *Diagram of the screw withdrawal test assembly (adapted from* [11]*).*

2.5. STATISTICAL ANALYSIS

The data were subjected to an Analysis of Variance (α = 0.05) to determine the effects of the moisture cycles on the screw withdrawal capacity. Differences between means were examined using T-tests at a confidence interval of 95 %. Normal distribution was verified through Shapiro-Wilk tests.

Figure 3: *Screw withdrawal test setup, showing (a) grip and (b) test rig.*

3 RESULTS AND DISCUSSION

3.1. SCREW WITHDRAWAL TESTS

All withdrawal tests, regardless of load-grain angle, exhibited the same failure mode, as shown in Figure 4. The failure was characterized as a shear failure of the wood spile around the screw's thread.

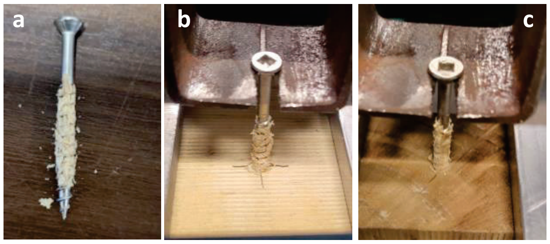

Figure 4: *Failure mode of the specimens, showing the wood spile around the screw's thread (a), the failure on a side-grain test (b) and the failure on an end-grain test (c).*

All load-displacement curves exhibited linear-elastic behaviour up to failure (Figure 5). Screws inserted in the side grain exhibited an initial linear phase, followed by limited 'yielding' (quasi-brittle behaviour) with a significant load drop of about 50 %, after which the load reached an almost constant region, until complete withdrawal from the timber. In contrast, screws inserted in the end grain showed a linear relationship until the maximum load, with a sharp and more significant load drop (about 70-80 %). Furthermore, the curves exhibited half-sine-wave-like shapes during the final withdrawal.

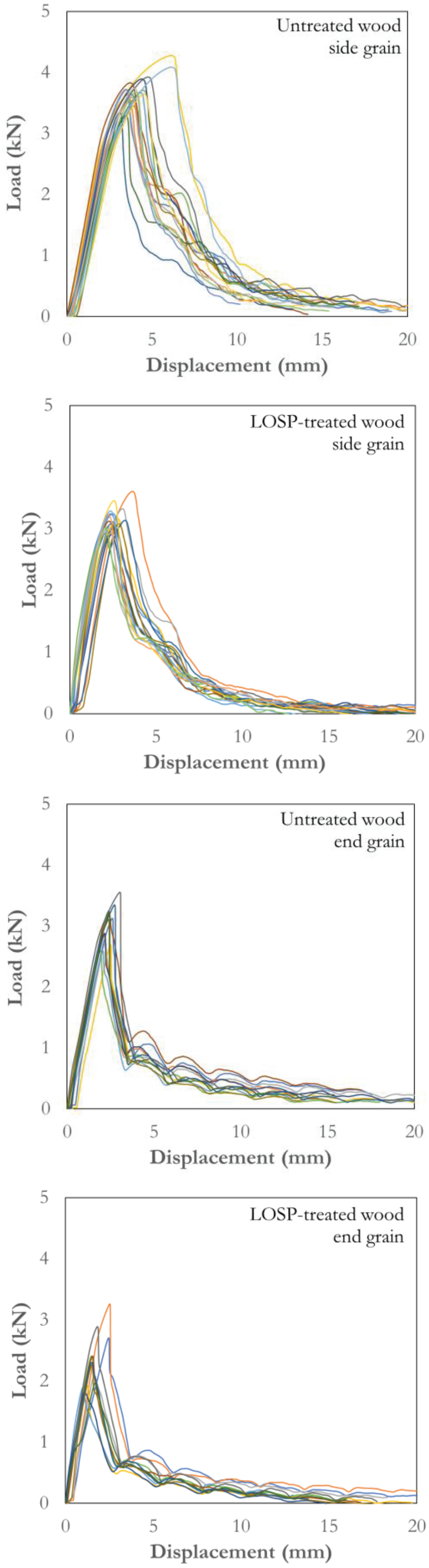

Figure 5: *Examples of load-displacement curves for specimens subjected to 8 moisture cycles***.**

Gutknecht and MacDougall [13] observed similar behaviour for screws inserted in the end grain of Douglas fir and eastern white pine. Although they found two different failure modes, they describe this behaviour as a residual strength in the connection after the withdrawal limit is reached due to changes in the friction of the wood spile as it is pulled out. Interestingly, the authors also found that the distance between the minimums of these half-sinus waves coincides with the thread spacing of the screws. The same relationship was found here.

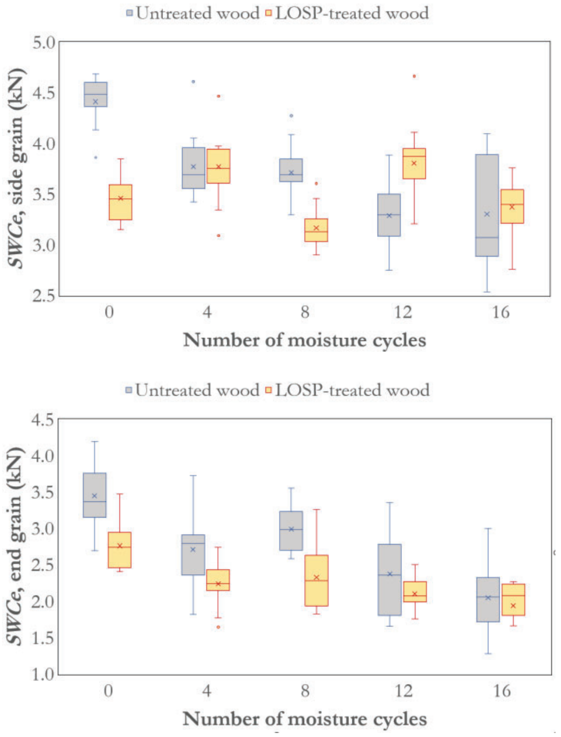

Figure 6: *Experimental withdrawal capacity for screws inserted in the side grain (top) and end grain (bottom) of LOSP-treated and untreated wood. The* X *and line represent the average and median values, respectively. The circles represent the outlier values.*

In terms of maximum withdrawal capacity, results showed that the initial (week 0) *SWCe* in LOSP-treated samples was lower than those in the untreated wood, for both side and end grain. Moreover, the impact of the moisture cycles showed a strong dependence on the timber faces the screws were driven into, only when LOSP-treated wood was tested. To analyse the significance of these differences, independent t-tests for the *SWCe* values in paired moisture cycles were performed (Table 3).

For screws driven in the side grain, the *SWCe* in untreated wood was reduced with increasing moisture cycles (26 % reduction after 16 moisture cycles), whereas the *SWCe* in LOSP-treated wood showed significant fluctuations. Meanwhile, for screws driven in the end grain of untreated

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wood, the *SWCe* showed the same behaviour as the side grain, but with a drop of 42 % in this case. Nevertheless, the *SWCe* in LOPS-treated wood showed a 19 % loss after 4 moisture cycles, remaining statistically unchanged afterwards.

The moisture cycling had less effect on the *SWCe* of screws in LOSP-treated samples, possibly due to the protective effects of the residual solvent. LOSP-treated material typically contains up to 50 litres of residual solvent per m^3 of wood and can limit the initial moisture uptake around the connections, although it would eventually evaporate.

Table 3: *P-values results from the T-test performed (the null hypothesis is the SWCs are not significantly different) and the difference of the SWCe averages (Av. diff.) for paired moisture cycles. P-values below 0.05 reject the null hypothesis. Values in bold correspond to SWCe values that are not statistically different.*

Face	Wood	Moisture Cycles	p-value	Av. diff. (%)
Side	Untreated	0 - 4	< 0.001	-15
		4 - 8	**0.526**	**N/A**
		8 - 12	< 0.001	-11
		12 - 16	**0.919**	**N/A**
	LOSP-treated	0 - 4	0.006	+9
		4 - 8	< 0.001	-16
		8 - 12	< 0.001	+20
		12 - 16	< 0.001	-11
End	Untreated	0 - 4	0.002	-21
		4 - 8	**0.098**	**N/A**
		8 - 12	0.007	-21
		12 - 16	**0.160**	**N/A**
	LOSP-treated	0 - 4	< 0.001	-19
		4 - 8	**0.568**	**N/A**
		8 - 12	**0.127**	**N/A**
		12 - 16	**0.269**	**N/A**

3.2. COMPARISON TO DESIGN STANDARDS

The comparison of the 5th percentile of the *SWCe* values with those calculated from the standards AS1720 and EC5 are represented in Figure 7, as per Equation 2.

The results showed a significant overestimation of the *SWC* using the AS1720, with ratios closer to 2, or even above in some cases. This standard was developed about 15 years ago and lacks variables in the prediction. For example, the prediction from the AS1720 does not consider the actual density of the timber, but instead a characteristic density for groups of timber species.

This results in the same predicted value for that group of timber species which needs to be overestimated to compensate for the natural variability in the timber density. On the other hand, the EC5 showed ratios closer to the unit in every case, although in some cases the ratios were below 1. This highlights the importance of considering more specific system characteristics (e.g. wood density, nail diameter) for these predictions.

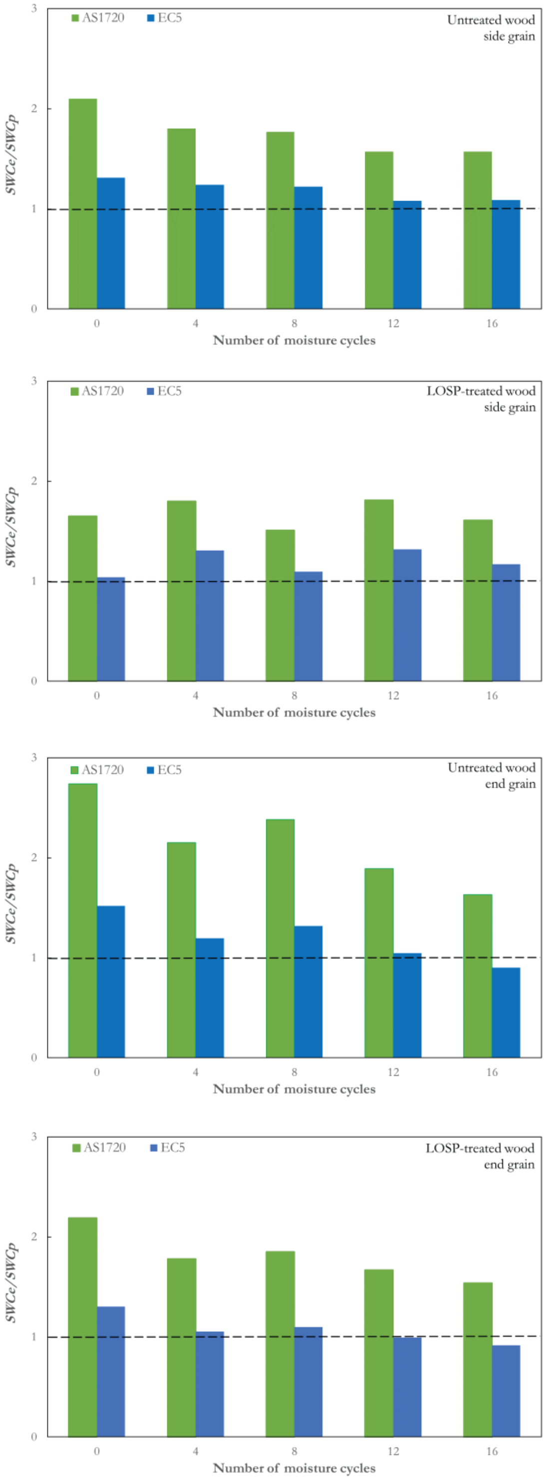

Figure 7: *Ratios of experimental and predicted SWCs for the different series tested (see Equation 2). The dashed line, at ratio =1, marks the limit where the predictions are safe.*

4 CONCLUSION

The main conclusions from this work are as follows:

- The withdrawal capacity for screws driven into the side and end grain of untreated wood after 16 moisture cycles was reduced by 26 and 42 %, respectively.
- The moisture cycling had less effect on the *SWCe* of screws in LOSP-treated samples. For screws driven into the side grain, the *SWCe* fluctuated, having an overall reduction of 2% after 16 moisture cycles. The *SWCe*, in the end, grain showed an initial loss of 19 % after 4 moisture cycles, remaining constant afterwards.
- The Australian standard AS1720 significantly overestimates the SWC value. This would lead to a misuse of resources and also to an over-design and overstrength of the timber connections, which in turn can trigger undesired brittle failures.
- Although in some cases the prediction from EC5 was not safe (ratios below 1), it showed a better prediction than the AS1720. This highlights the importance of considering more system characteristics for these predictions.

5 ACKNOWLEDGEMENT

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