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MOISTURE-INDUCED VARIATIONS IN WITHDRAWAL CAPACITY OF PIN-SHAPED ELECTRODES IN WOOD: EXPERIMENTAL INSIGHTS AND CORRELATIONS

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ABSTRACT: Withdrawal testing is being used for various reasons such as testing hypotheses on durability or developing new connectors using various screw-types or nails. New research questions extend these testing methods to other topics such as rammed-in electrodes for moisture content determination by the electrical resistance method. Three Australian wood species, *Corymbia maculata*, *Eucalyptus nitens*, and *Pinus radiata D. Don.,* are therefore investigated using a fixed load rate. This paper outlines the methodologies employed in withdrawal testing and highlights key findings. Preliminary results indicate that moisture variations affect the fit of any pin-shaped object in wood, impacting their withdrawal load peak values. These findings contribute to understanding the impact of moisture on contact pressure and withdrawal capacity, crucial not only for designing reliable timber connections in construction, but also other applications such as wood moisture determination.

KEYWORDS: *Nail withdrawal testing, withdrawal capacity, moisture content, electrical resistance method, timber species*

1 – INTRODUCTION

Using a universal testing machine (UTM) to pull a certain component apart until failure is a typical mechanical method used in a laboratory to quantify materials' properties, such as tensile and compressive capacity. This method may also be used to quantify the fit of pin-shaped metal fasteners in wood, such as screws, nails, but also stainless-steel electrodes.

2 - BACKGROUND

2.1 BACKGROUND OF WITHDRAWAL TESTING WITH SCREWS AND NAILS

Screws and nails have become widely used metal fasteners in timber construction due to their ease of installation and high withdrawal capacity, particularly for self-tapping screws [1]. Timber screws typically have higher withdrawal capacity than engineered nails because the thread cuts into the timber fibres and tightly embeds into the wood. In contrast, nails do not cut the internal timber fibres but rely on embedment strength and friction with the wood. Predrilling can enhance the overall strength of connections, providing more embedment strength and friction to nails compared to non-predrilled connections. Previous studies have shown that factors such as metal corrosion of fasteners, changes in timber dimensions, and moisture fluctuations significantly affect the withdrawal capacity of nails [2] and screws [3]. Therefore, it is crucial to quantify and establish correlations between moisture fluctuations and the withdrawal capacity of metal fasteners, especially when using electrical resistance measurements to determine the moisture content (MC) of wood.

2.2 BACKGROUND ON CONTACT PRESSURE IN MC MEASUREMENTS

In electrical resistance measurements for determining the *MC* of wood, stainless steel electrodes are often either hammered or screwed into the predrilled material in pairs with a fixed spacing. The measured electrical resistance increases as contact pressure decreases. A significant decrease in contact pressure, for example due to dimensional changes in wood geometry, would therefore results in lower electrical resistance readings. The accuracy of electrical resistance measurements is correlated with the manually checked positioning of electrodes [4]. Pairs of electrodes, in which both have a very tight fit in the wood, provide results that match a known calibration curve best. To further quantify this manual inspection and classification later, mechanical withdrawal tests are conducted to confirm these findings across three Australian wood species.

3 – PROJECT DESCRIPTION

In the context of electrical resistance measurements, stainless steel electrodes are often either rammed or screwed into the material in pairs with a fixed spacing, typically by first pre-drilling two holes with a reduced diameter. In general, the measured electrical resistance increases with decreasing contact pressure. In extreme

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cases, disconnected contact will lead to a total loss of electrical conductivity. A significant decrease in contact pressure, for example due to changes in the geometry of the wood, would therefore lead to higher electrical resistance *R* [Ω]. This should be avoided, as it can lead to significant misinterpretation of the measurement result and underestimation of the actual wood moisture content.

The dissertation [4] on which this conference paper is based examined the following research questions in part: What is the effect of the pre-drilled hole diameter on the electrical resistance between the two electrodes? How does R_T, the electrical contact resistance between electrode and wood, change with varying climate and how big is the overall impact on the equivalent wood moisture content *EMC* [m.-%]?

4 – METHODOLOGY

4.1 METHODS TO INVESTIGATE THE INFLUENCE OF FIT ON ELECTRICAL RESISTANCE MEASUREMENTS FOR ESTIMATING THE WOOD MOISTURE CONTENT

The electrical resistance method (ERM) is used to estimate the equivalent wood moisture content *EMC* in mass percent [m.-%] = [g/g]. It uses physical variables, which are measured in the SI units Ampere [A] and Kelvin [K]. They are given as electrical resistance *R* [Ω] and temperature *T* [°C], which are converted directly from these and used to compute the *EMC* based on wood-species specific calibration curves. As a control measure, the wood moisture content *MC* [m.-%] was determined via gravimetric method. This means oven-drying at 103±2 °C until mass constancy is reached, controlled by a precision balance (KERN KB 360-3N) with a readability and reproducibility of 0.001 g [5]. Before the start of each experiment, the balance was checked and recalibrated using two standard calibration weights with 100 g and 200 g. The electrical resistance *R* [Ω] was measured with monitoring devices with eight connection ports via BNC-plug each and a measuring range of at least $10^4\,\Omega$ - $10^{11}\,\Omega$ (Gigamodul Scanntronik), which were regularly connected to standard resistors for several hours and checked for accuracy. The electrodes have a thickened cylindrical head and insulated shaft (green Teflon lacquer) and were rammed into the material (Figure 1). This type of electrode is documented to be employed in several monitoring projects, for instance in [6], [7].

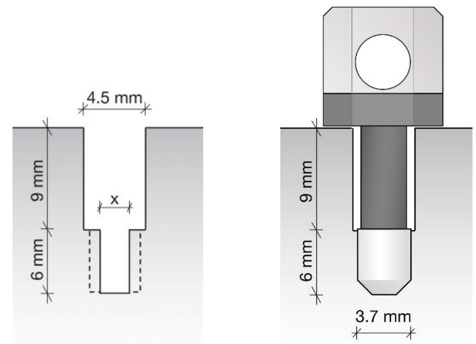

Figure 1: Cross section of predrilled holes and final fit of 15 mm rammed-in electrode

Previous measurement results on Norway spruce (*Picea abies Karst.)* [4] found a correlation between the tightness of fit and the precision of the electrical resistance measurements. The more easily the electrodes could be moved in the Norway spruce specimens, the higher the overall measured electrical resistance *R* [Ω]. Each specimen was equipped with a pair of electrodes (length: 15 mm) for which two holes were drilled with a center-to-center distance of 30 mm (across the fiber). The upper section had a constant diameter of 4 mm, while the lower section had a variable diameter to investigate the contact pressure on the conductive head of the impact electrode as shown in Figure 1. The tightness or looseness of the electrodes in the wood were checked periodically by carefully moving them by hand.

To more accurately quantify the contact pressure behavior of the pin-shaped stainless-steel electrodes in the wood, the withdrawal resistance was then additionally measured similarly to the methods described in [3].

4.2 METHODS TO INVESTIGATE THE WITHDRAWAL CAPACITY OF SCREWS AND NAILS

The withdrawal resistances of fasteners such as screws and nails are commonly assessed through standardised pull-out tests, as described in EN 1382 [8] and AS 1649 [9]. These tests are typically conducted using a UTM at a constant displacement rate until either the peak load or failure occurs. The withdrawal capacity is primarily influenced by factors including the density and fibre orientation of the wood, the geometry and penetration depth of the fastener, and the degree of contact between the fastener and the surrounding timber fibres (i.e., with or without predrilling).

Predrilling plays an essential role, particularly in dense hardwood species. Excessive driving force without predrilling may cause splitting and reduce the quality of embedment. Prior studies have shown that the fit between a fastener and the timber is highly sensitive to changes in moisture content and temperature (T). Under cyclic wetting and drying, moisture-driven dimensional changes can generate internal gaps at the wood-to-metal interface, which can lower the contact pressure. This

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reduction in pressure leads to a noticeable drop in withdrawal resistance and, in some cases, results in loosening of the connector. This phenomenon is particularly evident in high-density hardwoods.

Based on this background, the present study applies standard withdrawal testing methods to investigate whether similar mechanical principles can be used to assess the fit of smooth, non-threaded stainless-steel electrodes. These electrodes are commonly used in resistance-based wood moisture measurements. Although they do not engage the fibres mechanically through threads, their holding strength still depends on surface friction and the contact quality with the timber. Therefore, withdrawal testing serves as a meaningful approach to quantify fit tightness and examine how it relates to moisture variation and timber species.

To carry out the tests, a series of low-force withdrawal experiments were conducted on three Australian timber species: radiata pine (Pinus radiata D. Don), shining gum (Eucalyptus nitens), and spotted gum (Corymbia maculata). These species were selected to represent a range of densities, varying from 412 to 995 kg/m^3. All specimens were cut to equal size and preconditioned at a stable climate of 23 ± 0.5 °C and 57 ± 2% relative humidity, until their mass remained constant. Each specimen was then drilled with two pairs of holes, with a tip diameter of 3.2 mm, to prepare for electrode insertion. The first pair of holes in each specimen was used for the initial test. Electrodes were inserted using a consistent manual method, and Figure 2 and Figure 3 illustrates the test setup and electrode preparation.

4.2 TEST CONFIGURATIONS

The first test series was carried out under stable thermal and humidity conditions. A total of 48 electrodes were tested using an Instron 5584 UTM equipped with a one-kilonewton loadcell. The electrodes were pulled out vertically at a constant rate of three millimetres per minute, and the peak withdrawal force was recorded for each specimen.

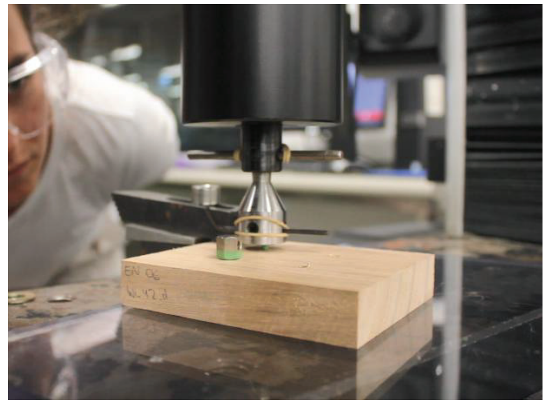

Figure 2: Electrode withdrawal testing with the Instron UTM on a sample from shining gum

The second series of tests was designed to assess the effect of short-term drying on withdrawal capacity. A second set of electrodes was inserted into the unused holes in each specimen, which were again conditioned at 23 ± 0.5 °C and 57 ± 2% relative humidity (RH) for more than 65 days. After that, the specimens were exposed to a warmer and drier environment at 35 ± 1 °C and 36 ± 5% relative humidity for 45 hours. Immediately after this drying period, the withdrawal tests were repeated using the same method. Throughout the conditioning phase, the mass of the specimens was monitored using a precision balance. Figure 4 shows the full sequence of climate conditioning and testing.

This two-stage experimental setup enables direct comparison between withdrawal behaviour under equilibrium moisture content and after drying. It helps reveal how short-term moisture reduction can influence contact quality and withdrawal performance for embedded electrodes.

Figure 3: Selection of four charges of specimens for electrical resistance measurements with pin-type electrodes for wood moisture content determination.

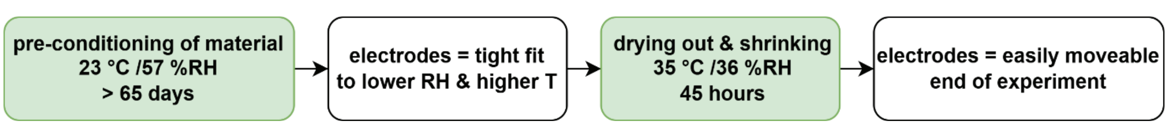

Figure 4: Summary of conditioning and resulting electrodes´ fits in shining gum and radiata pine

5 – RESULTS AND DISCUSSION

5.1 APPLICABILITY OF NAIL WITHDRAWAL PRINCIPLES TO ELECTRODE TESTING

The conventional withdrawal tests were applied to quantify the retention strength of stainless-steel electrodes embedded in timber. Although electrodes lack threads or mechanical interlock, they still rely on friction and surface contact for stability. By adapting the principles used in fastener testing, electrode withdrawal capacity can be evaluated as a quantification method for fit tightness, which is known to affect both mechanical retention and moisture measurement reliability.

The relationship between contact pressure and withdrawal resistance becomes relevant under moisture variation. Shrinkage caused by drying reduces lateral pressure on embedded components, which may lead to measurable loss in withdrawal strength. This mechanism is well documented in past fastener research [10], [11], and the current study explores whether similar behaviour is observed for pin-type electrodes under changing environmental conditions.

The following section presents the results of two-stage withdrawal testing conducted on three Australian wood species. It examines the correlation between withdrawal force, manually perceived fit tightness, and wood type, both under equilibrium moisture conditions and after short-term drying.

5.2 ELECTRODE WITHDRAWAL TESTING

The previous results from experiments with Norway spruce (*Picea abies Karst.)* did not establish a clear correlation between the pre-drilled hole for the electrodes and the accuracy of the electrical resistance measurement. However, they showed a correlation between the manually checked position of the electrode and the accuracy of the measurement. Pairs of electrodes, in which both have a very tight fit in the wood, provide results that match a known calibration curve best. To additionally quantify this manual inspection and classification later, mechanical extraction tests were carried out additionally on three Australian wood species.

Figure 5 and Figure 6 show the independently determined "tightness of fit" according to a similar evaluation. In a subsequent investigation using withdrawal testing with a UTM, this shows a correlation to the electrode maximum withdrawal capacity (*EWC*) at *EWC* = 20 N – 150 N. Above that, at *EWC* > 150 N, electrodes seem to not be hardly moveable by hand and therefore sort as "very tight-fitting" according to the previous manual evaluation. In contrast, the electrodes in the specimens made of shining gum (*Eucalyptus nitens*) and radiata pine (*Pinus radiata D. Don*.) all show a medium to very tight fit. However, the electrodes rammed into the wood species spotted gum (*Corymbia maculata*), sit either exceptionally loose or exceptionally tight in the material; there are no intermediate stages with this wood species in this experiment. It should be noted that the latter is a hardwood species with more than twice the oven-dry density ρ_0 than the other two.

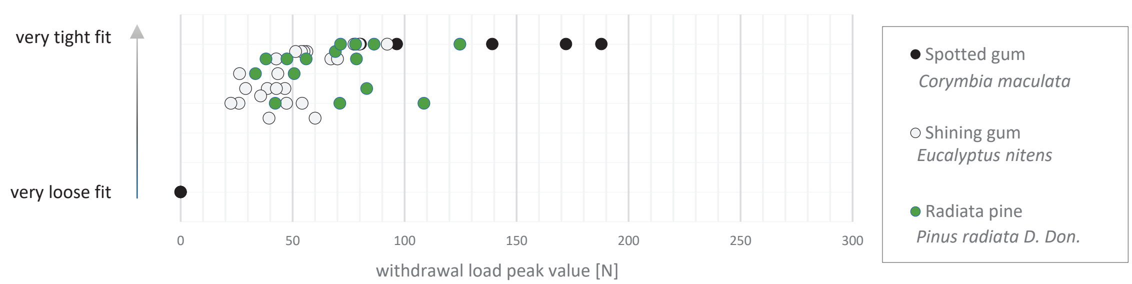

Figure 5: Results of first measurement series showing a correlation between withdrawal peak load capacity [N] and manually estimated movability of electrodes in three different subtropical wood species; measurements at mass constancy, after steady pre-conditioning at 23±0.5 °C / 57±2 %RH for 65 days

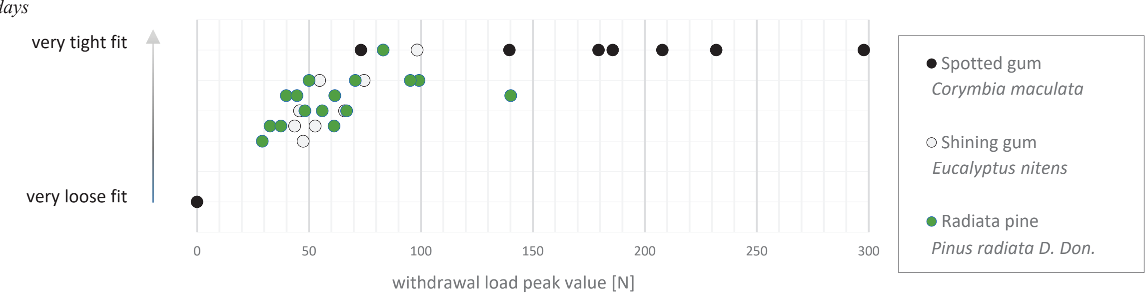

Figure 6: Results of second measurement series showing a correlation between withdrawal peak load capacity [N] and manually estimated movability of electrodes in three different subtropical wood species; measurements after climate step chance to 35±1 °C / 36±5 %RH for 45 hours, possibly with moisture gradients in the specimens

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As shown in Figure 5, both Eucalyptus nitens and Pinus radiata specimens exhibited visibly tighter fits under the initial conditioning phase compared to the post-drying condition. The electrodes became looser following moisture loss, consistent with known shrinkage-induced effects on timber–metal interfaces. Similar findings are supported by observations in past timber connector literature, which report decreased withdrawal strength due to loss of contact pressure during drying [4]. Mainey et al. [12] demonstrated that moisture cycling can reduce nail plate withdrawal strength by up to 60% because of timber shrinkage and reduced frictional engagement.

Withdrawal test data of this research further validated this trend. Under constant climate, the average withdrawal capacity was 52 N (SD = 19 N) for Eucalyptus nitens and 69 N (SD = 29 N) for Pinus radiata. After drying, Pinus radiata showed a slight decrease to 64 N (SD = 26 N), while Eucalyptus nitens unexpectedly increased to 60 N (SD = 19 N). This inconsistency may stem from variability between test locations, as new predrilled holes were used in the second round of testing. The limited sample size and relatively high standard deviations also introduce statistical uncertainty, although emerging trends remain evident.

Figure 7 presents a schematic interpretation of the observed relationship between withdrawal force and perceived fit tightness. This non-linear correlation offers practical guidance for determining optimal installation tightness in timber-based sensing applications.

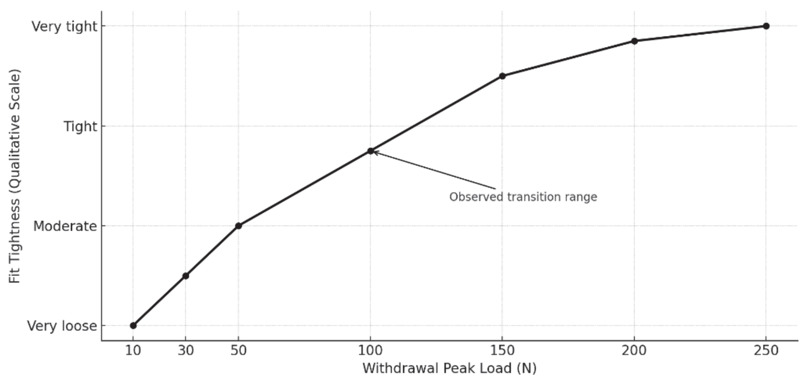

Figure 7. Schematic Relationship Between Withdrawal Load and Electrode Fit

The first series of withdrawal testing, maintaining the constant climate, result in mean electrode withdrawal peak load capacity of $\overline{EWC}$ = 52 N (SD = 19 N) for shining gum and $\overline{EWC}$ = 69 N (SD = 29 N) for radiata pine. After the drying-out phase, the force required to pull out the electrodes from the radiata pine specimens is measured at a lower value of $\overline{EWC}$ = 64 N (SD = 26 N), as expected. In shining gum, on the other hand, this force even has increased to $\overline{EWC}$ = 60 N (SD = 19 N). The reason for this is not yet clear. However, it should also be mentioned that for the second round of measurements, the electrodes were each rammed into new pre-drilled holes; hence there might be significant material differences even within the same test specimen. Furthermore, explicit reference is made to the comparatively high values for *SD*. The number of specimens and tests might simply be too small to allow a statistically reliable statement. Despite this statistical inaccuracy, the measurement results already provide initial indications of trends.

5.3 MC MEASUREMENTS

Figure 8, 9 and 10 show results that were determined on the three types of wood after achieving constant mass at 23±0.5 °C / 57±2 % RH. They may therefore also serve as reference points for future calibration curves. Figure 8 shows the electrical resistance values R [Ω] measured in the test specimens of the three Australian wood species in relation to the wood moisture content MC [m.-%] determined using the gravimetric method. Since the measurement result of the electrical resistance measurement always refers to a pair of electrodes, the looser-fitting electrode of the two is used for evaluation in Figure 9 and Figure 10.

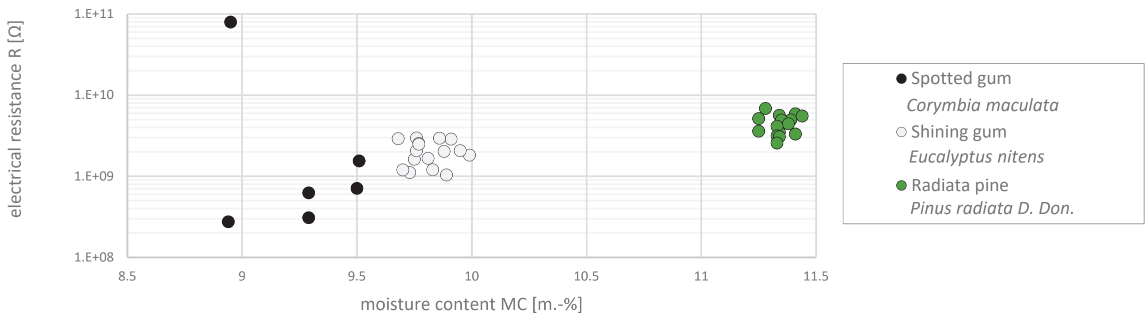

Figure 8: Results of electrical resistance measurements in spotted gum (Corymbia maculata), shining gum (Eucalyptus nitens), and radiata pine (Pinus radiata D. Don.) at 23 °C

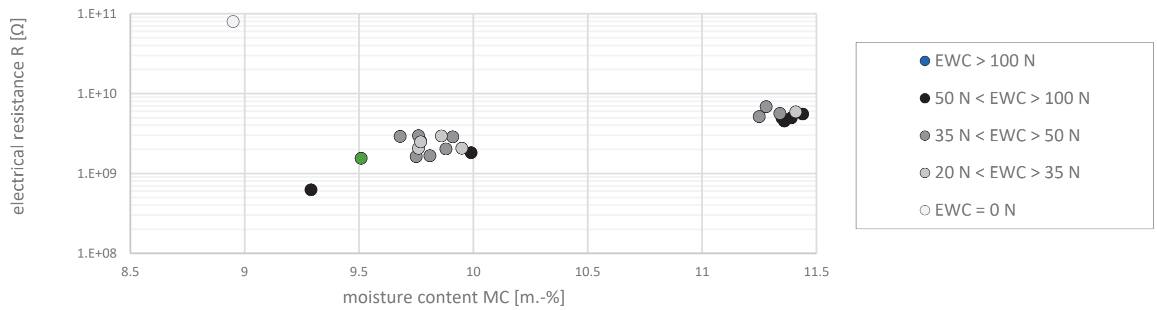

Figure 9: Selection of measurement results shown in Figure, sorted by their electrode withdrawal peak load capacity EWC [N] at 23 °C

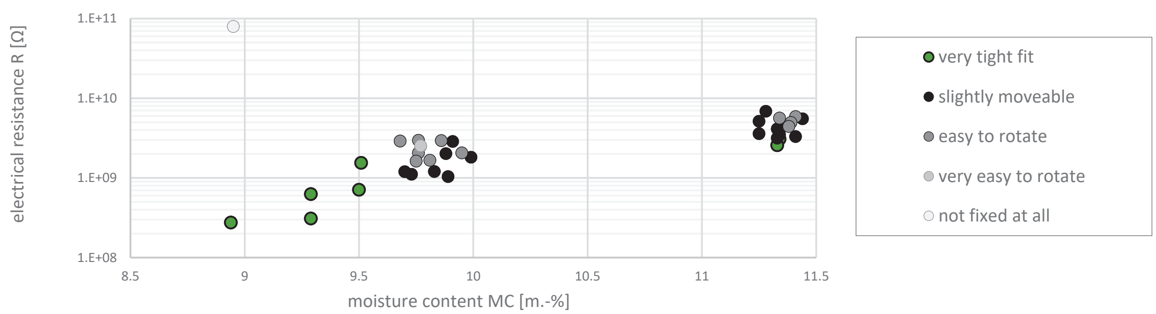

Figure 10: Results, as shown in Figure, sorted by the electrodes´ manually determined tightness of fit at 23 °C

At the time of writing, there was no reliable calibration curve available for measuring the electrical resistance in three types of wood: spotted gum (*Corymbia maculata*), shining gum (*Eucalyptus nitens*), and radiata pine (*Pinus radiata D. Don.*). This indicates that a comparison of the extent to which the position of the electrodes influences the position of the measuring points within a known confidence interval was not possible. Nevertheless, the results on radiata pine are compared with the characteristic curve determined for Scots pine by [13]. Although these are two different wood species, the evaluation in Figure 11 shows results consistent with the previous evaluations of Norway spruce, as detailed in [4].

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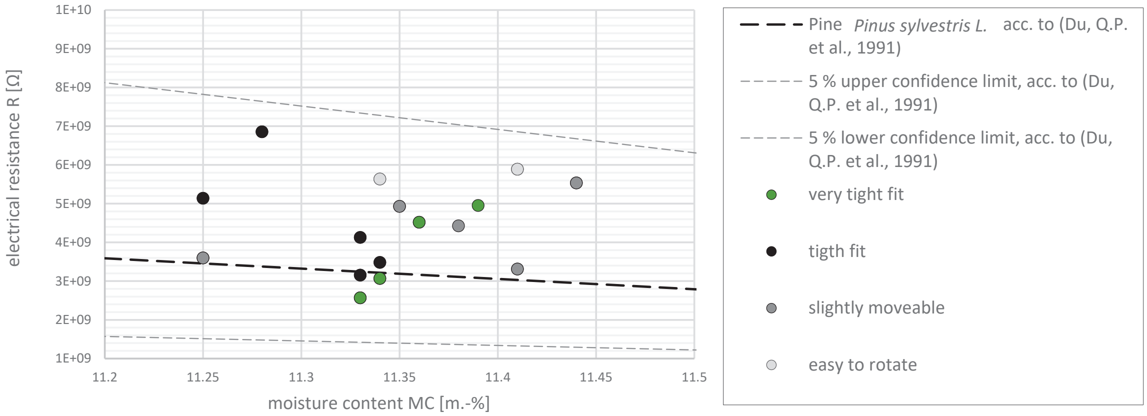

Figure 3: Tightness of fit for electrodes in radiata pine after preconditioning at 23±0.5 °C / 57±2 %RH for >65 days; juxtaposed to the calibration curve for Scots pine by (Du et al., 1991).

6 – CONCLUSIONS AND RECOMMENDATIONS

This study investigated the withdrawal behaviour of pin-shaped stainless-steel electrodes embedded in three Australian timber species under varying moisture conditions. The results confirmed that wood moisture loss leads to a measurable reduction in contact pressure between the electrode and the surrounding timber, which is consistent with previous findings on Norway spruce [4].

Withdrawal testing under isothermal and isohumid conditions demonstrated that electrodes with a very tight fit, identified manually, consistently exhibited withdrawal forces above 150 N. These electrodes were found to correlate closely with known calibration curves for electrical resistance-based moisture measurements. In contrast, looser-fitting electrodes showed substantially lower withdrawal capacity and, by implication, weaker electrical contact.

Following a short-term drying cycle, a moderate decrease in withdrawal resistance was observed in Pinus radiata, while an unexpected increase was noted in Eucalyptus nitens. These variations may be attributed to localised material differences between drilling locations or the limited number of replicates. Despite this, the observed trends reinforce the influence of climate-induced shrinkage on contact conditions at the wood–metal interface.

The results support the use of mechanical withdrawal testing as a reliable proxy for evaluating electrode fit tightness and installation quality in timber. Withdrawal peak loads in the range of 20 to 150 N may be used to classify fit conditions from loose to very tight, with a threshold of 150 N proposed for identifying electrodes unlikely to loosen under standard moisture fluctuations.

Future research should explore the influence of predrill diameter on long-term retention and stability. It is hypothesised that reducing hole diameter may improve withdrawal resistance and electrical resistance after humidity and temperature fluctuations, thereby enhancing the reliability of moisture monitoring systems embedded in timber structures.

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