WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA

Advancing Timber for the Future Built Environment

EFFECT OF WOOD RELAXATION ON NAIL WITHDRAWAL CAPACITY

Yuhao Zhang[1], Lisa-M. Ottenhaus[2], Jeffrey J. Morrell[3], Tripti Singh[4], Luis Yermán[5]

ABSTRACT: Nails are among the most frequently used fasteners in timber construction, with nail withdrawal capacity (NWC) being a critical performance parameter. Although NWC has been extensively investigated under various conditions, the influence of wood relaxation is often overlooked. This omission can lead to substantial errors in structural design and NWC studies. This study examined the effects of wood relaxation on the NWC of smooth-shank nails. Nails were driven into radiata pine samples conditioned at three moisture contents (MC) and stored under constant conditions for up to 28 days before the NWC test. Results show an exponential decline in the NWC. NWC stabilized two days after driving in wood at 9% MC. In contrast, stabilization required 14 days for wood at 12% and 18% MC. NWC decreased by 40% over 28 days in wood at 9% or 12% MC. However, wood at 18% MC exhibited a 10% increase in NWC during the same period.

KEYWORDS: moisture content, radiata pine (Pinus radiata), nail withdrawal capacity, wood relaxation

1 – INTRODUCTION

Connections are often designed as the weakest point of the overall system in timber structures (Australian Standard, 2010; Jockwer et al., 2018). A variety of fasteners and connectors are available to connect wood elements but the most frequently employed fasteners are nails and screws (Task Committee on Fasteners, 1996).

Nail withdrawal capacity (NWC) is an extensively studied parameter of nails. The NWC for smooth-shank nails primarily relies on friction between the shank and the wood. According to Coulomb's Law of Friction, this friction is determined by the stress around the nail shank, the contact area between the nail shank and the wood, and the friction coefficient at the wood-nail interface (Y. Wang & Lee, 2018).

Previous studies have documented notable changes in NWC under varying environmental conditions. Several investigations reported substantial decreases in NWC resulting from wood moisture changes (Perkins, 1971; Que et al., 2015; Yermán et al., 2021). Conversely, other studies noted increased NWC under high humidity attributed to minor nail corrosion (Senft & Suddarth, 1971; S. Wang et al., 2023). The impact of fungal degradation on NWC also received attention (Gao et al., 2021; Yermán et al., 2022). Most studies exposed wood-nail assemblies to a specifically designed environment (fungi or moisture) for a certain duration (typically weeks or months) and evaluated the NWC loss.

The primary causes of NWC loss in moist environments were identified as nail backout, fastener corrosion, wood cracking, and wood relaxation (Dietsch, 2017; Mainey et al., 2019; McLain, 1997; Wahyudianto et al., 2022).

Nail backout is the outward movement of the nail due to wood dimensional change caused by moisture changes (Groom, 1994). Wood species and fibre direction affect the magnitude of dimensional change. Tangential and radial fibre orientations experience larger dimensional changes than the longitudinal direction (Forest Products Laboratory, 2010).

Corrosion is the oxidation process that forms rust on metal surfaces. Metal nails may be corroded if exposed to high-humidity environments after driving (Wahyudianto et al., 2022). Corrosion can temporarily increase NWC by developing a rougher nail surface. However, NWC will

[1] Yuhao Zhang, School of Civil Engineering, The University of Queensland, Brisbane, Australia, yuhao.zhang@uq.edu.au

[2] Lisa-M. Ottenhaus, School of Civil Engineering, The University of Queensland, Brisbane, Australia, l.ottenhaus@uq.edu.au

[3] Jeffrey J. Morrell, Department of Wood Science and Engineering, Oregon State University, Corvallis, USA jeff.morrell@oregonstate.edu

[4] Tripti Singh, National Centre for Timber Durability and Design Life, University of the Sunshine Coast, Sunshine Coast, Australia, tsingh1@usc.edu.au

[5] Luis Yermán, School of Civil Engineering, The University of Queensland, Brisbane, Australia, l.yerman@uq.edu.au

https://doi.org/10.52202/080513-0204

ultimately experience significant loss. (Senft & Suddarth, 1971).

Wood cracks are caused by the internal stress within the wood triggered by uneven dimensional changes due to moisture gradients within the wood (Simpson, 1991). The formation of cracks reduces stress levels within the wood. Cracks developing in the wood surrounding the nail can also reduce the stress level on the nail shank, consequently reducing NWC (Dietsch, 2017; Yermán et al., 2021).

Wood relaxation refers to the gradual stress loss within the wood over time. The nail compresses its surrounding wood and creates localized stress while driving (Task Committee on Fasteners, 1996). Wood relaxation reduces this stress, which can subsequently lead to NWC loss (Saifouni et al., 2016).

McLain (1997) mentioned that wood relaxation can cause up to 70% loss in the NWC of smooth-shank nails. Lhuede (1985) reported 12% NWC loss in radiata pine and 26% NWC loss in mountain ash with 3.15 mm diameter smooth-shank nails, although duration and storage conditions were not specified. Zhao et al. (2010) reported 7% NWC loss over 7 days using 2.82 mm diameter smooth-shank nails driven in the side grain of Chinese fir at 20°C and 65% relative humidity (RH).

The wood moisture content (MC) significantly affects relaxation behaviour (Navi & Stanzl-Tschegg, 2009). Saifouni et al. (2016) observed a higher degree of tension relaxation in wood at higher MC, by testing silver fir under RH ranges between 30% and 70%. Similarly, Pina et al. (2022) reported a 200% higher bending relaxation for radiata pine at 28°C and 81% RH than at 28°C and 45% RH.

Previous studies have demonstrated NWC loss due to wood relaxation, which can lead to a gradual stress loss. However, the extent of NWC loss and the time required for wood relaxation remain unclear. Understanding these dynamics is instrumental in quantifying the impact of wood relaxation on NWC and is essential for accurately assessing the influence of external variables on NWC.

Most existing studies have not completely considered the impact of wood relaxation on NWC, which may lead to errors and misinterpretations. An in-depth investigation addressing this research gap is crucial.

This study assessed the effects of wood relaxation on the NWC of smooth-shank nails, determining NWC loss and required stabilization time. These findings can facilitate more accurate evaluations of NWC in future studies examining NWC loss resulting from external factors.

2 – MATERIALS AND METHODS

2.1 SAMPLE PREPARATION

MGP12 machine-graded radiata pine (*Pinus radiata*) by AS/NZS 1748 (Standards Australia Limited, 2011) boards (90 mm x 45 mm x 2400 mm) with densities between 500 and 650 kg/m^3 were cut into one hundred twenty-six 320 mm long blocks and conditioned at 23 ± 2°C and 65 ± 10% RH.

The blocks were divided into three groups of 42 samples and reconditioned at a 23°C and 65% RH before measuring dimensions and mass. The three groups were subsequently conditioned to three target wood MCs (9%, 12%, and 18%), termed DRY, SERVICE, and WET, using the moisture conditions listed in Table 1. The actual wood MC was determined by oven drying following ASTM Standard D4442-20 (ASTM, 2007).

Table 1. Temperature, relative humidity, wood MC and average density for the radiata pine specimens conditioned at DRY, SERVICE and WET conditions. Bracketed values represent standard deviations.

Conditions	DRY	SERVICE	WET
Temperature (°C)	23	23	32
Relative Humidity (%)	45	65	90
Wood MC (%)	9.0 (0.3)	12.2 (1.5)	17.7 (0.9)
Avg. density after cutting (kg/m^3)	575 (33)	573 (34)	577 (31)
Avg. density after conditioning (kg/m^3)	569 (31)	577 (30)	582 (32)

NWC specimens were assembled following ASTM Standard D1761-12 (ASTM, 2012) using conditioned wood specimens and smooth-shank nails (2.8 × 50 mm, 316 stainless steel). The nails were cleaned with isopropyl alcohol wipes and perpendicularly driven into the side grain of the wood to 36 mm depth using a hammer.

Each wood specimen received five nails spaced to minimise splitting (Figure 1). After nail driving, 18 out of 126 specimens were immediately tested while the rest were returned to their respective environmental conditions and tested on the target date.

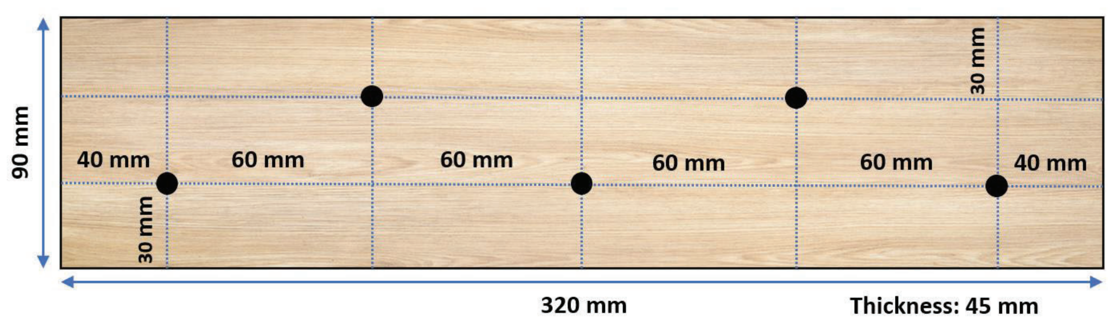

Figure 1. The Layout of nail withdrawal specimens. Black dots represent the nail driving locations.

https://doi.org/10.52202/080513-0204

2.2 NAIL WITHDRAWAL TEST

NWC was tested at 0 (immediately after nail driving), 1, 2, 3, 7, 14, and 28 days after nail driving, with 30 repetitions for each condition (Table 2). The nail head was gripped using a metal rig during withdrawal, which was further attached to a universal testing machine (UTM, Instron 3400) as illustrated in Figure 2a. The wood specimen was fixed to the base of the UTM using steel frames (Figure 2b). Nails were withdrawn following BS EN 1382 (BSI, 2016) at a constant rate of 0.4 mm/min while recording load and displacement. The maximum load from each test was determined as the NWC.

Table 2. Test variables and repetitions for NWC tests.

Variables	Number	Description
Moisture content	3	DRY (9%), SERVICE (12%), WET (18%)
Time steps	7	0, 1, 2, 3, 7, 14, and 28 days
Repetitions	30	6 specimens per condition
Total tests	630	3 x 7 x 30

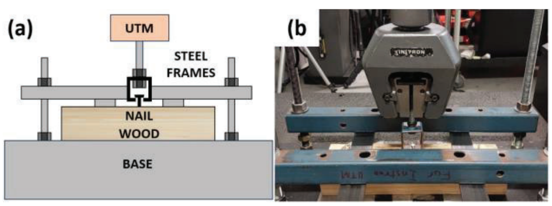

Figure 2. (a) The schematic layout of the NWC test and (b) the actual test layout using metal frames.

2.3 STATISTICAL ANAYLSIS

NWC test results were subjected to Analysis of Variance (ANOVA, α = 0.05). Normality was checked using Q-Q plots and equality of variance was verified using Levene's Test. Standard post hoc tests were employed to detect significant differences in parametric data. Kruskal-Wallis tests and Dunn's post hoc tests were employed to identify significance in non-parametric data.

3 – RESULTS AND DISCUSSION

Load-displacement curves from the NWC tests exhibited inconsistencies, reflecting the heterogeneous nature of wood. Most curves demonstrated a linear behaviour before approaching their maximum load, but other curves experienced slip before establishing the linear behaviour (Figure 3).

Figure 4 shows the changes in average NWC at the three moisture conditions. NWC significantly decreased by 41% under the DRY condition within the first two days after driving, with no further significant changes observed over the subsequent 26 days. A significant NWC loss occurred between 7 and 14 days for the SERVICE condition. NWC did not decline under the WET condition but increased by 10% after 28 days compared to the initial (day 0) NWC.

The initial NWC of the DRY condition was 16% lower than that of the SERVICE and the WET conditions. According to Coulomb's Law of Friction, variations in the NWC system with the same contact area (i.e. nail driving depth) can be attributed to differences in the stress provided by the wood or to varying friction coefficients at different wood MCs.

The wood around the nail shank is compressed as the fastener is driven, generating stress (Task Committee on Fasteners, 1996). Stress intensity is directly related to the compressive strength of the wood. Research has demonstrated that wood compressive strength decreases as MC increases (Al-musawi et al., 2023; Kretschmann, 2010). In addition, wood relaxation is more pronounced under high-humidity conditions (Saifouni et al., 2016). Therefore, wood at higher MC is expected to have lower compressive strength, providing less stress under compression and theoretically resulting in a reduced NWC. However, this hypothesis contradicts our results, where higher wood MC produced higher NWC.

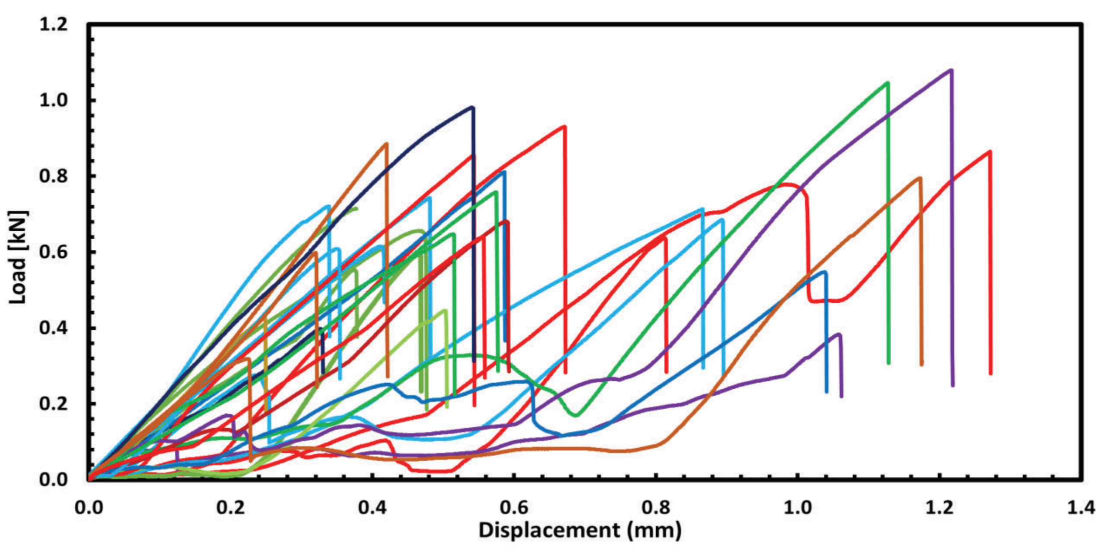

Figure 3. Load-displacement curves of the NWC tests, immediately tested (day 0) under the DRY condition. Most of the nails immediately engaged in linear-elastic-like behaviour (peak on the left side), whereas some nails exhibited significant slip before engagement (peaks on the right side).

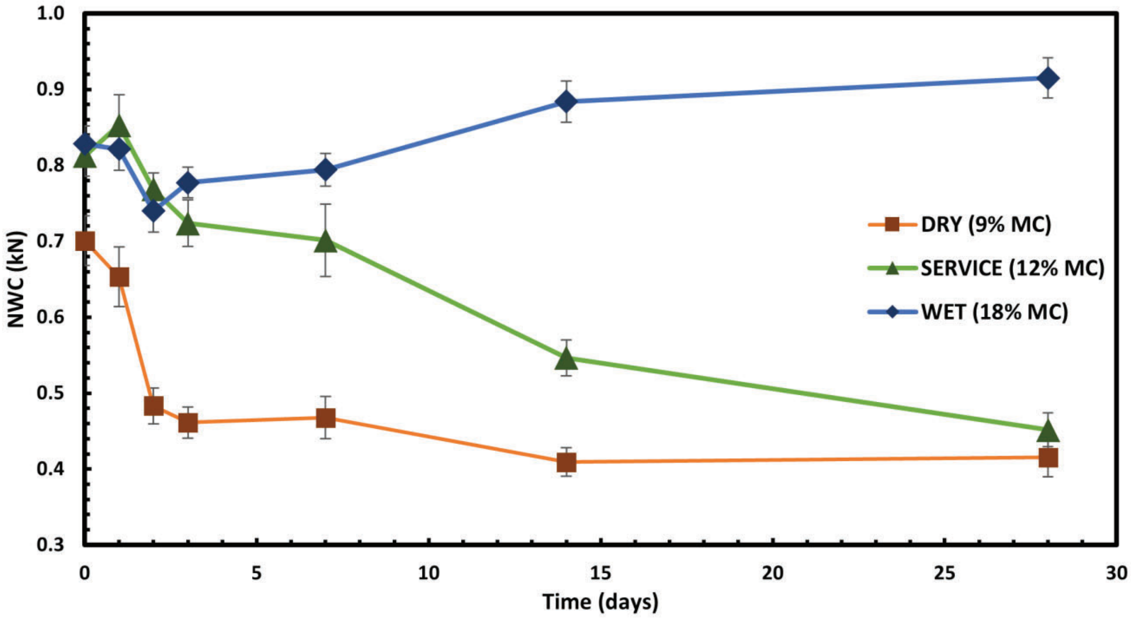

Figure 4. Changes in average NWC on radiata pine conditioned at DRY, SERVICE, and WET conditions over 28 days. Error bars indicate standard error.

The enhancement of NWC at higher wood MC may be attributed to the increased friction coefficient at higher wood MC, as the contact area was the same across all conditions and wood at higher MC has lower compression strength. This is supported by the study of Dorn et al. (2021), where the friction coefficient between metals and wood increases as the wood's MC rises. Specifically, the friction coefficient can more than double when the wood MC reaches the fibre saturation point (~30%) compared to the value at 10% MC (Murase, 1984).

Conducting additional studies on the stress surrounding the nail and friction coefficient at the wood-nail interface is recommended to better understand the impact of wood relaxation and MC on NWC.

4 – CONCLUSION

The key findings from the nail withdrawal tests were as follows:

- Wood relaxation significantly impacted the NWC of smooth-shank nails and caused up to 40% loss depending on wood moisture content.
- The impact of wood relaxation stabilized after 14 days in all tested conditions.

The implications of this study were as follows:

- Existing NWC studies may be inaccurate if wood relaxation is not adequately considered.
- Future research must consider wood relaxation.

5 – ACKNOWLEDGEMENT

The authors gratefully acknowledge Rebecca Cherry and Hyne Timber for supplying the wood used in this project, and Van Thuan Nguyen for his assistance with the experimental setup for the tests.

REFERENCES

Al-musawi, H., Huber, C., Grabner, M., Ungerer, B., Krenke, T., Matz, P., Teischinger, A., & Müller, U. (2023). Compressive strength of beech and birch at different moisture contents and temperatures. *Journal of Materials Science*, *58*(35), 13994–14008. https://doi.org/10.1007/s10853-023-08882-w

ASTM. (2007). Standard test methods for direct moisture content measurement of wood and wood-base materials - D4442-20. *Annual Book of ASTM Standards*, *92*(December), 1–6. https://doi.org/10.1520/D4442-20.These

ASTM. (2012). Standard Test Methods for Mechanical Fasteners in Wood -D1761-12. *ASTM*, *2013*, 42–44. https://doi.org/10.1520/D1761-12

Australian Standard. (2010). *AS 1720.1 - Timber structures Part 1 : Design methods*. Standards AUstralia Limited.

BSI. (2016). Timber Structures — Test methods — Withdrawal capacity of timber fasteners BS EN 1382:2016. *BSI Standards Publication*.

Dietsch, P. (2017). Effect of reinforcement on shrinkage stresses in timber members. *Construction and Building Materials*, *150*, 903–915. https://doi.org/10.1016/j.conbuildmat.2017.06.033

https://doi.org/10.52202/080513-0204

Dorn, M., Habrová, K., Koubek, R., & Serrano, E. (2021). Determination of coefficients of friction for laminated veneer lumber on steel under high pressure loads. *Friction*, *9*(2), 367–379. https://doi.org/10.1007/s40544-020-0377-0

Forest Products Laboratory. (2010). Wood Handbook: Wood as an Engineering Material. In *USDA - General Technical Report*.

Gao, Y., Mei, S., Ma, X., & Meng, X. (2021). Effects of decay on the mechanical properties of nailed joints in light wood frame structure. *Forest Products Journal*, *71*(1), 46–57. https://doi.org/10.13073/FPJ-D-20-00054

Groom, L. H. (1994). Effect of Moisture Cycling On truss-plate joint behaviour. *Forest Products Journal*, *44*(3), 21–29.

Jockwer, R., Fink, G., & Köhler, J. (2018). Assessment of the failure behaviour and reliability of timber connections with multiple dowel-type fasteners. *Engineering Structures*, *172*(December 2017), 76–84. https://doi.org/10.1016/j.engstruct.2018.05.081

Kretschmann, D. E. (2010). Chapter 5 - Mechanical Properties of Wood. *Wood Handbook - Wood as an Engineering Material*, 1–46.

Lhuede, E. P. (1985). *Side and end grain withdrawal loads for single nails in Australian timber species*.

Mainey, A., Gilbert, B. P., Bailleres, H., Gunalan, S., & Smith, M. (2019). Solutions to reduce moisture driven backout and improve withdrawal strength of nailplates: experimental investigations. *European Journal of Wood and Wood Products*, *77*(2), 257–269. https://doi.org/10.1007/s00107-019-01386-y

McLain, T. E. (1997). Design axial withdrawal strength from wood: II. Plain-shank common wire nails. *Forest Products Journal*, *47*(6), 103–109.

Murase, Y. (1984). Friction of Wood Sliding on Various Materials. *Journal of the Faculty of Agriculture, Kyushu University*, *28*(4), 147–160. https://doi.org/10.5109/23785

Navi, P., & Stanzl-Tschegg, S. (2009). Micromechanics of creep and relaxation of wood. A review. COST Action E35 2004-2008: Wood machining - Micromechanics and fracture. *Holzforschung*, *63*(2), 186–195. https://doi.org/10.1515/HF.2009.013

Perkins, R. H. (1971). Nail withdrawal resistance in plantation red pine grown in Indiana. *Forest Products Journal*, *21*(6), 29–32.

Pina, J. C., Guzmán, C. F., Yanez, S. J., García-Herrera, C. M., Herrera Gonzalez, Á. A., Palma Medel, G. A., & Saavedra Flores, E. I. (2022). Experimental study on the short-term stress relaxation response of Chilean radiata pine. *Wood Science and Technology*, *56*(3), 833–850. https://doi.org/10.1007/s00226-022-01380-3

Que, Z., Yang, L., Wang, F., Zhu, X., Wang, Y., & Mori, T. (2015). Effects of salinity on the nail-holding power of dimension lumber used in light-frame wood building. *Journal of Forestry Research*, *26*(3), 765–770. https://doi.org/10.1007/s11676-015-0118-9

Saifouni, O., Destrebecq, J. F., Froidevaux, J., & Navi, P. (2016). Experimental study of the mechanosorptive behaviour of softwood in relaxation. *Wood Science and Technology*, *50*(4), 789–805. https://doi.org/10.1007/s00226-016-0816-2

Senft, J. F., & Suddarth, S. K. (1971). Withdrawal resistance of plain and galvanized-steel nails during changing moisture content conditions. *Forest Products Journal*, *21*(4), 19–24.

Simpson, W. T. (1991). Dry kiln operator's manual. In *Agriculture Handbook No.188*. https://www.fpl.fs.usda.gov/documnts/usda/ah188/ah188.htm

Standards Australia Limited. (2011). *AS/NZS 1748 Timber Stress-graded Product requirements for mechanically stress-graded timber*.

Task Committee on Fasteners. (1996). *Mechanical Connections in Wood Structures* (L. A. Soltis (ed.)). American Society of Civil Engineers.

Wahyudianto, A., Fernandes, A., Erwin, & Wajilan. (2022). Metal corrosion in wood joint products and structures: a review. *International Journal of Corrosion and Scale Inhibition*, *11*(3), 1269–1281. https://doi.org/10.17675/2305-6894-2022-11-3-21

Wang, S., Wang, F., Kong, F., Ma, P., Chen, Z., & Que, Z. (2023). Influence of repeated wetting and drying on withdrawal capacity of wooden nails and metal nails. *Construction and Building Materials*, *409*(November), 133991. https://doi.org/10.1016/j.conbuildmat.2023.133991

Wang, Y., & Lee, S. H. (2018). A theoretical model developed for predicting nail withdrawal load from wood by mechanics. *European Journal of Wood and Wood Products*, *76*(3), 973–978. https://doi.org/10.1007/s00107-017-1227-2

Yermán, L., Ottenhaus, L. M., Montoya, C., & Morrell, J. J. (2021). Effect of repeated wetting and drying on withdrawal capacity and corrosion of nails in treated and untreated timber. *Construction and Building Materials*, *284*, 1–9. https://doi.org/10.1016/j.conbuildmat.2021.122878

Yermán, L., Zhang, Y., He, J., Xiao, M., Ottenhaus, L. M., & Morrell, J. J. (2022). Effect of wetting and fungal degradation on performance of nailed timber connections. *Construction and Building Materials*, *353*(September). https://doi.org/10.1016/j.conbuildmat.2022.129113

Zhao, R. J., Fei, B. H., Chen, E. L., Guo, W., & Zhou, H. Bin. (2010). Nail withdrawal strength of Chinese fir dimension lumbers. *Jianzhu Cailiao Xuebao/Journal of Building Materials*, *13*(4), 463–467. https://doi.org/10.3969/j.issn.1007-9629.2010.04.009

https://doi.org/10.52202/080513-0204