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EFFECT OF FUNGAL DECAY ON WITHDRAWAL CAPACITY OF TIMBER NAIL CONNECTIONS IN RADIATA PINE

Camilo Montoya[1], Lisa-Mareike Ottenhaus[2], Tripti Singh[3], Jeffrey J Morrell[4], Luis Yermán[5]

ABSTRACT: This study investigated the effects of early fungal decay on the mechanical performance of nailed timber connections. Radiata pine (*Pinus radiata*) sapwood blocks with stainless-steel or galvanised nails were exposed to a brown-rot (*Fomitopsis ostreiformis)*. Four stages of early decay up to 10% wood mass loss were assessed. Connection performance was evaluated through withdrawal tests and expressed as normalized nail withdrawal capacity. Fungal decay significantly reduced this capacity for both fastener types. Galvanized nails initially showed a reduction in normalized withdrawal capacity to 0.5, which later increased to 1.68 at 140 days; however, this effect was complicated by simultaneous corrosion. In contrast, stainless-steel connections, which showed no corrosion, experienced a reduction of over 95% in withdrawal capacity over the fungal exposure period.

KEYWORDS: Wood, fungal decay, withdrawal capacity, corrosion.

1 – INTRODUCTION

Timber connections, often points of weakness in structures, are particularly vulnerable to moisture ingress due to the inherent gaps between fasteners and connected wood elements. Exposure to wet conditions can compromise connection integrity by reducing connector capacity and promoting fastener corrosion [1]. Wood moisture contents exceeding 30% also create an environment conducive to fungal growth [2], [3], which can produce significant reductions in fastener withdrawal capacity [4]. While proper design, adhering to established standards and best practices [1], [5], can mitigate some of these risks, inspections of relatively new buildings reveal instances of fungal damage in connections [6]. The presence of decay significantly affects both connector functionality and overall structural integrity.

Wood connections function as complex systems whose performance is determined by interactions between the wood element's properties and the fastener type. In this context, the "system" encompasses the wood element(s) and the connector(s). Nails, the most prevalent fastener type, are subjected to both axial and lateral loads. Nail resistance to axial load, termed withdrawal capacity, arises from the friction between the fastener and the timber. Eurocode 5 [7], Australian Standards [8] and Forest Group Laboratory [9], provide methods to estimate the withdrawal capacity of smooth shank nails driven perpendicular to the grain, based on wood density, penetration depth, and nail diameter. While nail capacity is typically determined for dry wood, in-service wetting can lead to both fastener corrosion and the conditions necessary for fungal decay.

Fungal decay is divided into early or incipient, moderate and late stages [10]. Incipient decay occurs at approximately 3-5% wood mass loss and is visually undetectable. Early decay, characterized by around 10% mass loss, may manifest as subtle colour or texture changes, depending on the wood and fungal species [2]. While these visible changes might appear minor, this stage can already involve substantial reductions in certain wood properties.

Moisture significantly impacts connector performance, and this effect is amplified by fungal decay near the fastener [11]. Decay alters the chemical environment surrounding the connector, potentially accelerating corrosion [12]. Corrosion, in turn, diminishes the effective fastener diameter, weakening the connection [13]. Studies have demonstrated that advanced decay can reduce the mechanical performance of timber connections by up to 60% [4], [10], [14]. However, the

[1] Camilo Montoya, The University of Queensland, Australia, https://orcid.org/0000-0003-3226-736X
[2] Lisa-Mareike Ottenhaus, The University of Queensland, Australia, l.ottenhaus@uq.edu.au
[3] Tripti Singh, University of the Sunshine Coast, Australia, tsingh1@usc.edu.au
[4] Jeffrey J Morrell, University of South Australia, Australia, jeffrey.morrell@unisa.edu.au
[5] Luis Yermán, The University of Queensland, Australia, l.yerman@uq.edu.au

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impact of incipient and early decay on connector performance remains poorly understood [4].

A deeper understanding of how these early stages of fungal decay affect connector performance is crucial for developing mitigation strategies. This is particularly important because connections are often the most vulnerable points in timber structures [15]. This study, part of a larger project investigating the underlying mechanisms affecting connector withdrawal performance during early fungal decay, focuses specifically on the withdrawal performance of connectors exposed to a brown-rot fungus.

2 – EXPERIMENTAL WORK

2.1 SPECIMENS

A simple connector specimen consisting of a smooth shank nail driven perpendicular to the grain of a small wood block was used (Figure 1). Radiata pine sapwood was selected as it is commonly used in construction in Australia. Specimens with a density range of 50 kg/m^3 (i.e., 440 to 490 kg/m^3) were selected to reduce variability.

A total of 180 wood blocks with dimensions of 30 x 35 x 70 mm^3 were cut from kiln-dried radiata pine sapwood boards. Blocks were conditioned to constant weight at 23°C and 65% relative humidity (RH), weighed and their dimensions measured before nail insertion. The moisture content (MC) of the blocks was determined by the oven-dry method (average MC = 12.5%) following the ASTM Standard D4442-20 [16]. To avoid splitting the blocks during nail insertion, 2 mm wide and 15 mm deep lead holes were drilled perpendicular to the grain in the centre of the blocks. This approach complied with Eurocode [7] while specifically limiting pre-drilling to a maximum of 0.8 times the diameter of the fastener. Similar holes were drilled parallel to the grain, for fungal inoculation [17]. These holes were located 15 mm apart from the centre of the nail hole to avoid affecting the connector capacity (Figure 1).

Smooth shank nails (2.5 mm in diameter and 40 mm long) made of stainless-steel (non-corrosive) or hot dip galvanised (corrosive potential) were utilized. The nails were cleaned with alcohol wipes and weighed before being driven perpendicular to the grain in 120 wood blocks (60 galvanized and 60 stainless-steel) to a depth of 30 mm (70% of nail length), as per ASTM Standard D1761-20 [18]. The remaining 60 wood blocks were used as controls without nails. Subsequently, all specimens were immersed in deionized water until they reached 45-65% (oven-dry basis) moisture content, weighed and then stored in polyethylene bags to minimise drying and contamination. Each bag included between 3 to 4 wood specimens that were sterilized by exposure to 3 to 5 Mrads of gamma-ray irradiation.

2.2 FUNGAL INOCULATION AND INCUBATION

A common brown-rot fungus (*Fomitopsis ostreiformis*) was inoculated into petri dishes containing 1% malt extract agar and incubated at room temperature until the fungus covered the agar surface. Sterilized toothpicks (~1.5 cm long) were placed on the agar surface and incubated until the wood was thoroughly colonized (Figure 1). The fungal infested toothpicks were inserted into the predrilled holes parallel to the grain [17]. A total of 180 blocks were inoculated and the blocks were then placed in polyethylene bags with small openings that allowed for some oxygen exchange but minimised the risk of contamination. Decay was assessed 35, 70, 105 and 140 days after inoculation, targeting approximately 10% wood mass loss after 140 days of fungal exposure. An additional 60 wood blocks without nails were similarly inoculated and were used to monitor the degree of decay.

The samples were removed from the bags when the targeted mass losses were reached and any residual mycelium on the specimens was wiped using 70% ethanol. Specimens were then conditioned at 23°C and 65% RH, visually assessed for physical changes, weighed and their dimensions were measured (to determine density), before nail withdrawal capacity testing.

2.3 WITHDRAWAL PERFORMANCE

Galvanized and stainless-steel nails were subjected to withdrawal testing using an Instron 3400 universal testing machine (Instron, Inc. Norwood, MA, USA) at a rate of 2 mm per minute. The nail withdrawal capacity (NWC) was determined as per ASTM Standard D143-22 [19] and the results normalized using Eq (1) from [9].

$$p = 54.12G^{5/2}DL \quad (1)$$

Although Eq 1 is widely used in industry to estimate NWC, this equation neglects the major influence of friction on nail withdrawal performance [20]. Friction

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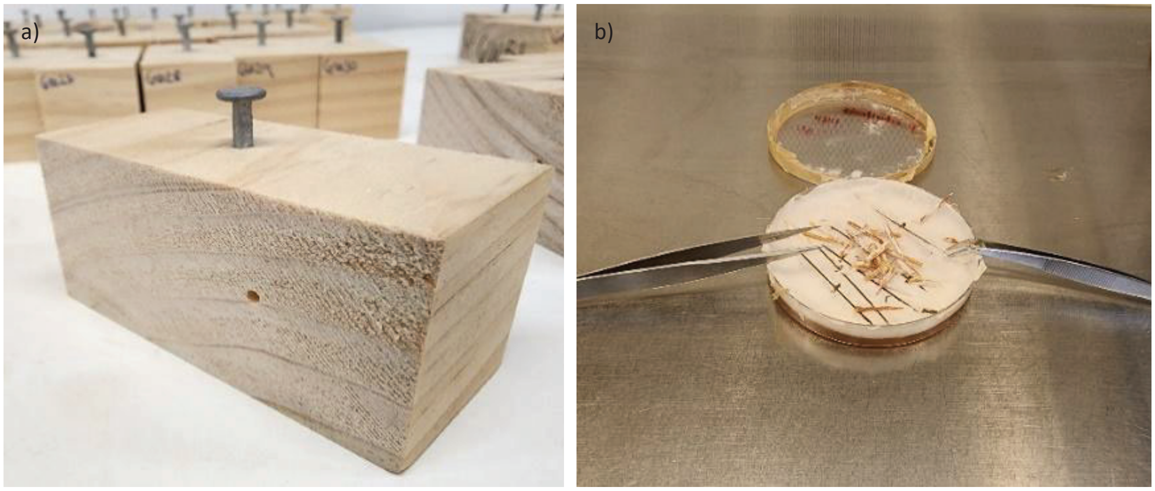

Figure 1. a) Timber specimen with galvanised nail depicting hole for fungal inoculation. b) Brown-rot fungi (F. ostreiformis) in agar discs with toothpicks ready for sample inoculation.

between the fastener and the wood can be affected by moisture fluctuations or moisture cycles due to wood experiencing volumetric changes and sometimes fastener corrosion that led to variable fastener performance and ultimately loss of mechanical capacity [21].

2.4 STATISTICAL ANALYSIS

Wood decay represented as mass loss and nail withdrawal capacity were correlated and subjected to an ANOVA. Significant differences between treatments were testing using Tukey's HSD/Kramer at $\alpha = 0.05$. The normality of results was evaluated by using Shapiro-Wilk tests.

3 – RESULTS AND DISCUSSION

3.1 MASS LOSSES

Mass losses in decayed radiata pine specimens averaged 10.64% ± 0.3 (standard error, SE) after 140 days of exposure (Figure 2). No significant mass losses (0.51% ± 0.12) were observed in the first 35 days, likely due to the time required for the lag phase of fungal colonization. This contrasts with previous findings on screw connectors in radiata pine with a similar density (459 ± 30 kg/m^3) exposed to the same brown-rot fungus (*F. ostreiformis)* [17]. They reported wood mass losses of 17.7% ± 2.4 at 105 days (15 weeks) and 27.6% ± 3.5 at 175 days (25 weeks), suggesting a faster decay rate than was observed in the present study. The variability in mass losses at similar periods could be mainly attributed to differences in experimental setup as decay rates generally do not follow a linear relationship [3].

Another study on nails driven into the face grain of slash pine sapwood with a density of 491 kg/m^3 exposed to the same brown-rot fungus experienced mass losses of 11.1% ± 3.1 at 60 days (8 weeks) and up to 13.7% ± 5.8 at 240 days (34 weeks) [4]. While these decay rates were faster than those observed in the present study, they were lower than those reported for pine with screw fasteners [17]. This shows that decay (represented in timber mass loss) is influenced by factors beyond wood density and fungal species [2]. It can also be affected by the size of the timber specimen and presence of metal fasteners. For instance, Tanakashi *et al.* [4] used small, fastener-free blocks as controls for connector assemblies. After 126 days (18 weeks) of exposure, a 15.5% difference in mass loss was observed between these control blocks and the connector assemblies.

In the current study, mass losses averaged 2.85% ± 0.34 after 70 days indicating that the fungus was actively degrading the wood. The non-linear increase in mass loss, reaching 6.96% ± 0.37 and 10.57% ± 0.3 at 105 and 140 days, respectively, suggests that wood degradation was accelerating over time. This acceleration could be attributed to the exponential growth phase of the fungus [2]. Mass losses were similar among samples exposed for the same time, suggesting consistent decay patterns among the replicates.

Decay studies in wood, especially those involving metal connections, face challenges in consistency and

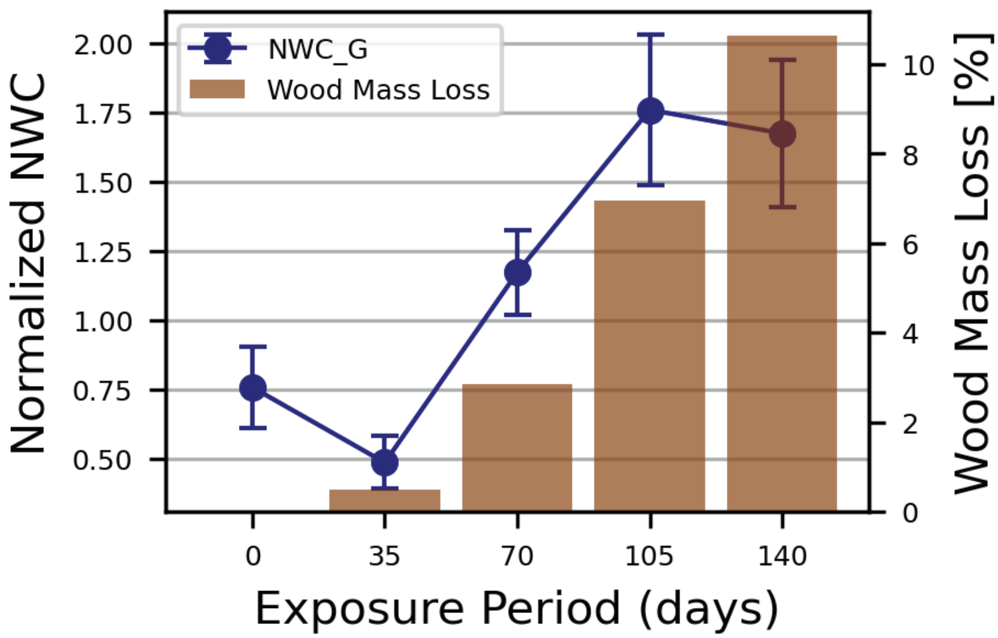

Figure 2 Normalized nail withdrawal capacity of galvanized (G) specimens and wood mass losses in radiata pine sapwood blocks exposed to F. ostreiformis for 0 to 140 days. (Error bars represent one standard error).

comparability. This variability, even in similar wood species, highlights the need for additional analyses such as chemistry and microscopy to more closely characterize the wood at various decay stages, which is a future objective of this project.

3.2 NAIL WITHDRAWAL CAPACITY

Nail withdrawal capacity of radiata pine samples exposed to brown-rot was normalized with the NWC calculated using Eq (1) [9] accounting for reductions in wood density and volumetric changes due to moisture and fungal decay. Specimens with galvanized nails showed a decrease of normalized NWC from 0 days of being exposed to experiment conditions that involved increased MC and gamma irradiation.

Normalized NWC continued to decline, reaching 0.5 ± 0.1 by day 35. Subsequently, it gradually increased to almost 1.17 ± 0.15 by day 70 and 1.76 ± 0.27 at 105 days. At 140 days it stabilized, resulting in a normalized NWC of 1.68 ± 0.27 (Figure 2). This contradicts previous studies where wood mass loss was associated with reduced nail withdrawal capacity [4], [14], [17]. Corrosion was observed in the galvanized nails from 35 days of exposure and may have enhanced the mechanical interlocking or friction between the nail and the wood, as reported in [21]. This might explain the increased NWC after 70 days.

Stainless-steel nails experienced significant NWC losses above 95% after 35 days of fungal exposure despite minimal wood mass loss (data not shown). This suggests that fungal decay was not the primary cause of NWC reduction. Instead, moisture-induced swelling of the wood likely reduced the friction or interlocking between the smooth stainless-steel and the wood, leading to a weaker connection even after the wood was reconditioned to its original MC. As no corrosion was present in the nails, NWC did not recover over time. This highlights the methodological importance of both understanding the distinct role of moisture and specimen assembly influence in research involving wood connections with fungal decay.

4 – CONCLUSIONS

This study demonstrates the significant influence of decay and corrosion on the withdrawal capacity of nails in timber connections. Variability in decay rates highlights the challenge of replicating and comparing studies, emphasizing the need for standardized

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methodologies. Future research should expand on these findings by incorporating a wider range of variables and employing complementary techniques like chemical and microscopic analysis to provide a more holistic understanding of the impact of decay on timber connections.

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