ORIGINAL ARTICLE

Effect of wetting and fungal degradation on the withdrawal capacity of stainless-steel screws in radiata pine

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Abstract
The effects of exposure to two decay fungi on the withdrawal capacity of stainless-steel screws inserted in the face and end grain of radiata pine specimens were assessed. Wetting followed by steam sterilization significantly increased capacity by 55–65%. Exposure to a brown (*Fomitopsis ostreiformis*) or white rot fungus (*Pycnoporus coccineus*) over 25 weeks was associated with 81–83% and 24–42% losses in withdrawal capacity, respectively. Comparison of experimental results with those predicted from design codes (Australia, Europe, US) showed an overestimation of the screw withdrawal capacity for the control specimens and highlighted the risk of strength degradation, especially in those specimens affected by brown rots.

1 Introduction

Wood decay fungi can be highly destructive and a widespread cause of timber structure deterioration, especially in tropical and subtropical areas. Fungal attack is mainly divided into three types based on the appearance of decayed wood, i.e., brown rots, white rots, and soft rots. Although decay fungi grow in wet timber, brown rots are also tolerant of low moisture conditions; therefore, they are commonly found in wood structures above ground. In contrast, white rots are predominantly present at or below the ground line, in wood that is in ground contact. Meanwhile, soft rots typically affect the surface of the wood and therefore its attack is relevant only in relatively thin wood elements (Clausen 2010).

While moisture in timber is necessary for fungal growth, it is also associated with dimensional changes in timber (Yermán et al. 2021b), loss of structural performance below the fibre saturation point (Glass and Zelinka 2010), as well as fastener corrosion (Djarwanto et al. 2019) which eventually reduces the capacity of the connections (Yermán et al. 2021a). Both brown and white rots can impact the strength of the timber connections (Yermán et al. 2021a, 2022). While the effects of corrosion can be minimized using galvanized or stainless-steel fasteners, the effects of wetting and fungal attack are difficult to study separately.

The effects of fungal decay on timber properties have been researched in the past, mostly on timber elements without fasteners (Wilcox 1978; Curling and Winandy 2002; Ibach and Lebow 2014; Maeda et al. 2015; Witomski et al. 2016; Kleindienst et al. 2017; Wang et al. 2020). However, as the integrity of timber structures relies on the performance of their connections, it is important to understand the effects of decay on the performance of the connections, as well as the wood decay process itself. In particular, the early stages of fungal decay are of extreme importance, as they tend to dramatically decrease the mechanical properties while resulting in little mass loss and often going unnoticed during inspections (Wilcox 1978; Yermán et al. 2022). Understanding this performance loss can help fabricators to design more resilient systems and guide builders in constructing more durable structures.

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Despite the importance of the effects of timber decay on the mechanical performance of their connections, this has received little attention in the literature (Kent et al. 2005; Takanashi et al. 2017; Sawata and Sasaki 2018; Ueda et al. 2021; Yermán et al. 2022). While screws are one of the most common types of fasteners used in timber connections, the study of the effects of wood decay on screwed connections is limited to the work of Ueda et al. (2020) who studied the effects of Sakhalin fir (*Abies sachalinensis*) decay produced by brown rots (*Fomitopsis palustris*) after 4 weeks of exposure on the shear performance of screwed joints. The decay level was studied by Pilodyn penetration depth, although there was no correlation with the mechanical properties of the joints (maximum load, yield load, and stiffness). A significant decrease of around 20% in these three mechanical properties was found, however, the mass loss was not reported. This research highlights the importance of studying the impact of fungal decay on screwed timber connections to ensure safe structures.

In this work, the withdrawal capacity of screws driven into the face grain and end grain of untreated radiata pine was evaluated after being exposed to *Fomitopsis ostreiformis* or *Pycnoporus coccineus* for 15, 20, and 25 weeks. The effects of wetting and sterilization (autoclaving) on the mechanical properties were also assessed. Stainless steel screws were used to minimize the effects of corrosion.
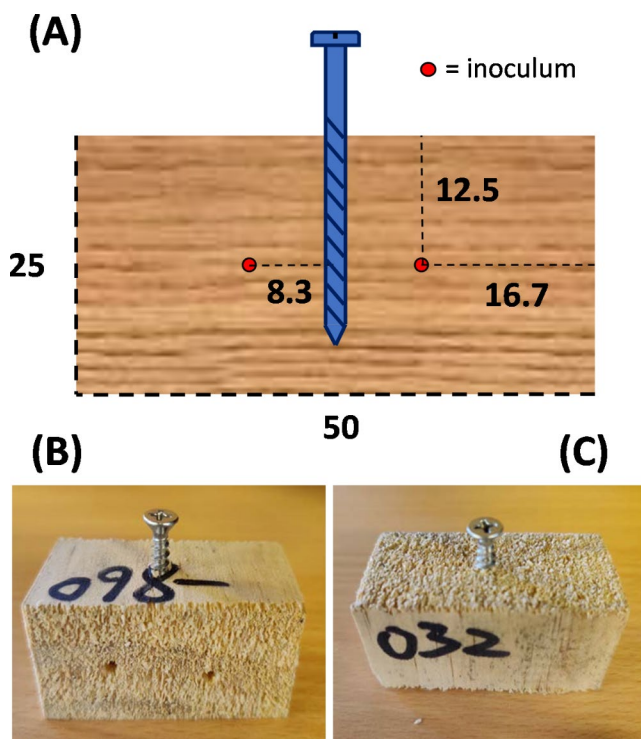
Fig. 1 **A**) Dimensions and relative position of the inoculum/toothpick in the specimen. All distances are in mm; **B**) a specimen with the screw driven into the face grain; **C**) a specimen with the screw driven into the end grain

Design standards can be used to estimate the strength of a timber connection, and ultimately design safe structures. However, structural durability risks such as strength degradation due to early-stage fungal decay have not been quantified. Hence, a comparison of the experimental results with strengths predicted from Australian standard AS 1720.1–2010 (AS1720.1) (Standards Australia 2010), Eurocode 5 (EC5) (CEN 2004), and The Wood Handbook from the United States Department of Agriculture (USDA) (Rammer 2010) are presented and its implications for practice are discussed.

2 Materials and methods

2.1 Specimen configuration and assembly

Kiln-dried radiata pine (*Pinus insignis*) boards $25 \times 50 \times 2400$ mm (H x W x L), were cut into three hundred 25 mm long defect-free blocks. The wood was mostly sapwood, however some transitional heartwood was possibly present. The average wood moisture content of each board was determined from twelve smaller specimens (25 mm cubes) and then averaged, according to ASTM Standard D4442-16 (ASTM International 2016). Dimensions were measured twice on each specimen side using digital callipers to estimate the initial specimen density. The average initial moisture content (standard deviation) and density of the whole batch were 8.9 (0.3) % and 459 (30) kg/m³, respectively.

A stainless-steel 304 7G screw (3.84 mm outer diameter, pitch = 2 mm, and 30 mm long) was driven in each specimen, on the face or end grain face, at a 20-mm depth in a 3-mm deep lead hole (1.9 mm in diameter), according to the AS 1649 (Standards Australia 2001). Two holes (2 mm in diameter by 10 mm deep) were drilled perpendicular to the screw to serve as inoculation points. The holes were approximately equidistant from the screw (Fig. 1).

The specimens were conditioned at 25 °C and 65% relative humidity (RH) and then weighed to determine the initial weight. Twenty-eight specimens of each group (screws on face or end grain) were set aside to serve as untreated controls, while the remaining specimens were immersed in tap water until periodic weighing showed that the moisture contents had risen to 55 ± 5% (oven-dry basis). The specimens were then placed inside heat-resistant plastic bags and steam sterilized for 20 min at 121 °C. Fifty-three specimens were then removed to assess the effects of wetting and sterilization on the withdrawal capacity. The remaining specimens were later inoculated with one of two decay fungi. The number of specimens tested and the average initial density of the conditioned specimens are shown in Table 1.

2.2 Fungal inoculation

Sterile toothpicks (65 mm long x 2 mm in diameter) were placed inside Petri dishes with an actively growing edge of cultures of the brown and white rot decay fungi, *Fomitopsis ostreiformis* or *Pycnoporus coccineus*, respectively. Colonized toothpicks were aseptically cut in four, and one quarter was inserted in each of the 2 mm diameter holes. The sterilization bags were then closed to minimize the risk of contamination and incubated at 22–25 °C and 65–75% RH. A total of two hundred samples were inoculated, one hundred with each fungus. This provided an excess of samples to provide replacements for assemblies due to contamination. Several were contaminated during the incubation period.

2.3 Mechanical tests

After 15, 20 or 25 weeks of incubation, the bags with specimens were opened. The wood samples were covered with fungal mycelium (Fig. 2). This was mechanically removed before samples were conditioned in the environmental chamber at 25 °C and 65% RH, which corresponds to a moisture content of 11.9%.

Screw withdrawal tests were performed following Sect. 5 of the ASTM Standard D1761-12 (ASTM International 2012). The screwed timber element was placed into an assembly as shown in Fig. 3. The screws were withdrawn at a rate of 3 mm per minute using an Instron 3400 universal testing machine (Instron, Inc. Norwood, MA, USA). The withdrawal load was recorded as a function of time and displacement. The load-displacement plots were used to determine the load peak values representing the screw withdrawal capacity (SWC). These values were averaged for each series, and the standard deviation was calculated.

2.4 Comparison with design codes

The experimental SWC was compared with the estimated SWC from design codes for each test group, using the

Table 1 Number of specimens tested (n), and average initial density of the conditioned specimens (ρ_i) under the different experimental conditions. Values between brackets represent the standard deviation

Fungus/Condition	Screw on	Exposure time (weeks)	n	ρ_i (kg/m^3)
Control (no sterilized, no fungus)	Face grain	0	28	456 (35)
	End grain	0	28	463 (35)
Sterilized (no fungus)	Face grain	0	23	524 (34)
		25	10	512 (38)
	End grain	0	10	505 (16)
		25	10	453 (32)
Fomitopsis ostreiformis (brown rot)	Face grain	15	11	451 (48)
		20	12	447 (31)
		25	11	444 (46)
	End grain	15	14	442 (18)
		20	14	468 (38)
		25	20	441 (23)
Pycnoporus coccineus (white rot)	Face grain	15	12	465 (54)
		20	13	451 (41)
		25	13	463 (58)
	End grain	15	16	473 (37)
		20	18	458 (49)
		25	20	464 (40)

Fig. 2 Photographs of decayed samples after 20 weeks of exposure. (**a**) top view, brown rots; (**b**) side view brown rots; (**c**) top view, white rots; (**d**) side view, white rots
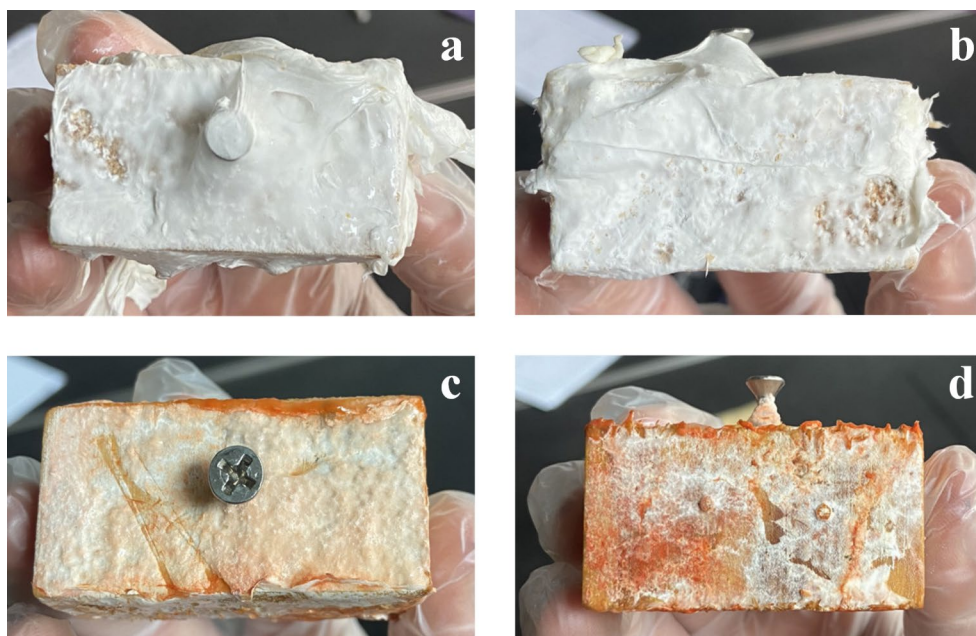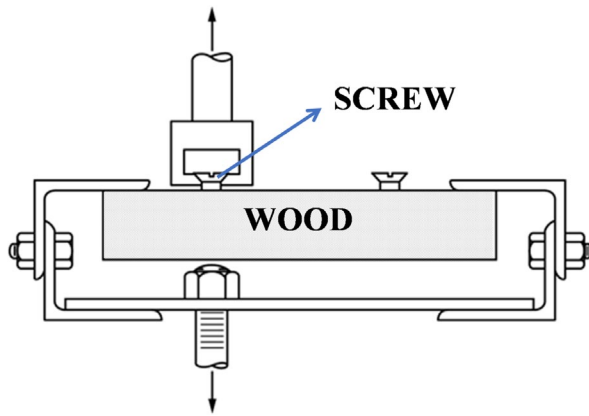
Fig. 3 Diagram of the screw withdrawal test assembly, adapted from (ASTM International 2012)

5th percentile of the experimental SWC values from each group and the predicted SWC determined from the equations shown in the third column of Table 2. The values of the decayed density were used in these equations (except for the AS 1720 Standard which does not consider density). A safe prediction is considered when the ratio is above 1.

2.5 Statistical analysis

The data were subjected to an Analysis of Variance ($\alpha = 0.05$) to determine the effects of wetting and sterilization and fungal exposure on the withdrawal capacity. Differences between means were examined using Tukey's HSD ($\alpha = 0.05$). Normal distribution was verified in every case using Shapiro-Wilk tests and the standard errors were calculated at the same confidence interval.

3 Results and discussion

3.1 Effects of wetting-sterilization on the screw withdrawal capacity

Load-displacement curves of the 283 screw withdrawal tests performed are shown in the Supplementary Information. Control specimens refer to non-sterilized and non-fungal-inoculated specimens, while sterilized specimens refer to non-fungal inoculated. All specimens, including the control group, exhibited typical load-displacement curves. The plots showed an initial linear relationship between load and displacement, followed by a sharp load drop of about 50%, after which the load reached an almost constant region. The maximum load in each of these plots was taken as the SWC. Results of the decayed density before testing (ρ_f), mass loss, and SWC for each batch are presented in Table 3.

3.1.1 Sterilized specimens

The changes in mass and density of the sterilized specimens were minimal. The sterilized specimens showed that after 25 weeks, the SWC in the end grain was approximately 67% of that in the face grain, as expected (Rammer 2010). Nevertheless, the SWC in sterilized specimens at week 0 showed the SWC in the end grain to be higher than the SWC in the face grain. The small differences in the density (502 and 522 kg/m^3) cannot explain this difference. In addition, the wetting and sterilization process increased the SWC. Statistical analysis showed that significant increases were observed between the controls with screws in the end grain and the sterilized samples at week 0 (p-value $= 0.004$), on the same face; but not between the sterilized specimens at 0 and 25 weeks (p-value $= 1.0$). On the contrary, in the case of

Table 2 Formulas used in the calculations of the predicted values for the SWC from the different design standards

Source	Predicted SWC	Formula	
AS 1720.1 (Standards Australia 2010)	$N_{k,j}$	$N_{k,j} = k_{13} l_p n Q_k$ $k_{13} = 1.0$ for face grain; 0.6 for end grain $l_p =$ depth of screw penetration $= 20$ mm $n =$ number of screws $= 1$ $Q_k =$ characteristic capacity $= 51$ N/mm	(Eq. 1)
EC5 (CEN 2004)	$F_{ax,\alpha,Rk}$	$F_{ax,\alpha,Rk} = \dfrac{n_{ef} f_{ax,k} d l_{ef}}{1.2 cos^2 \alpha + sin^2 \alpha} \left(\dfrac{\rho_k}{\rho_a}\right)^{0.8}$ $n_{ef} =$ effective number of screws $= 1$ $f_{ax,k} = 0.52 d^{-0.5} l ef^{-0.1} \rho k^{0.8}$ $d =$ shank diameter $= 3.84$ mm $l_{ef} =$ depth of screw penetration $= 20$ mm $\rho_k =$ characteristic density $= 5$th percentile of the batch $\rho_a =$ associated density $= 419$ kg/m^3 $\alpha =$ angle between the screw axis and grain direction	(Eq. 2)
USDA (Rammer 2010)	P	$P = 108.25 G^2 DL$ $G =$ specific gravity of wood at 12% MC $D =$ screw shank diameter $= 3.84$ mm $L =$ depth of screw penetration $= 20$ mm	(Eq. 3)

Table 3 Decayed wood density means (ρ_f), mass loss means, and SWC means of the specimens exposed to F.ostreiformis (brown rot) and P.coccineus (white rot) for 15, 20, and 25 weeks, controls, and sterilized specimens. Values between brackets represent the standard deviation

Sample	Exposed time (weeks)	Screw on	ρ_f (kg/m^3)	mass loss (wt %)	SWC (kN)
Control	0	Face grain	-	-	1.38 (0.49)
		End grain	-	-	1.07 (0.40)
Sterilized	0	Face grain	522 (35)	0.1 (0.1)	1.49 (0.20)
	25		518 (36)	1.1 (0.2)	2.17 (0.18)
	0	End grain	502 (4)	0.5 (0.1)	1.75 (0.21)
	25		462 (33)	0.6 (0.3)	1.46 (0.33)
Brown rot	15	Face grain	390 (45)	17.7 (2.4)	0.42 (0.12)
	20		367 (25)	22.8 (2.4)	0.42 (0.09)
	25		360 (42)	27.6 (3.5)	0.26 (0.06)
	15	End grain	376 (20)	18.4 (2.5)	0.49 (0.15)
	20		391 (41)	22.4 (2.4)	0.51 (0.11)
	25		351 (26)	29.4 (4.3)	0.33 (0.11)
White rot	15	Face grain	417 (54)	7.9 (1.5)	1.13 (0.34)
	20		390 (42)	11.8 (1.5)	1.16 (0.27)
	25		403 (57)	11.8 (3.0)	1.13 (0.25)
	15	End grain	420 (36)	8.5 (3.0)	1.07 (0.12)
	20		403 (48)	10.0 (1.2)	1.10 (0.21)
	25		412 (38)	10.6 (2.5)	1.02 (0.16)

face grain specimens, the increase of SWC between the control and sterilized at week 0 was not statistically significant (p-value = 0.865), but it was between the sterilized specimens at 0 and 25 weeks (p-value < 0.001). In any case, the small differences observed in the mass or density were not able to explain these increases in the SWC.

There is not much evidence in the literature about the effects of wood sterilization at high temperatures on its properties. A study of the effects of steam sterilization (110 °C for 1 h) on southern pine sapwood showed mass loss levels of the same order as those found here (Curling and Winandy 2008). Nevertheless, that paper showed a contrary effect on the mechanical properties, reporting a loss in the modulus of rupture above 20%. In the case presented here, it is presumed that the swelling and shrinking of the cells around the fastener could produce some tightening of the screw in the wood, increasing the SWC.

The wood fibre relaxation can also affect SWC. Wood relaxation refers to the reduction of stress under constant strain (the screw) over time (Engelund and Svensson 2011), and it has been shown to also affect the withdrawal capacity of fasteners (Rammer et al. 2001). The literature suggests that wood relaxation can produce up to 50% loss in the withdrawal capacity of nails after three months (Rammer and Zelinka 2004). In our case, wood relaxation was observed only in the end grain specimens, with a 17% loss of SWC after 25 weeks. This means that wood relaxation is probably also affecting the loss of SWC of the decayed samples.
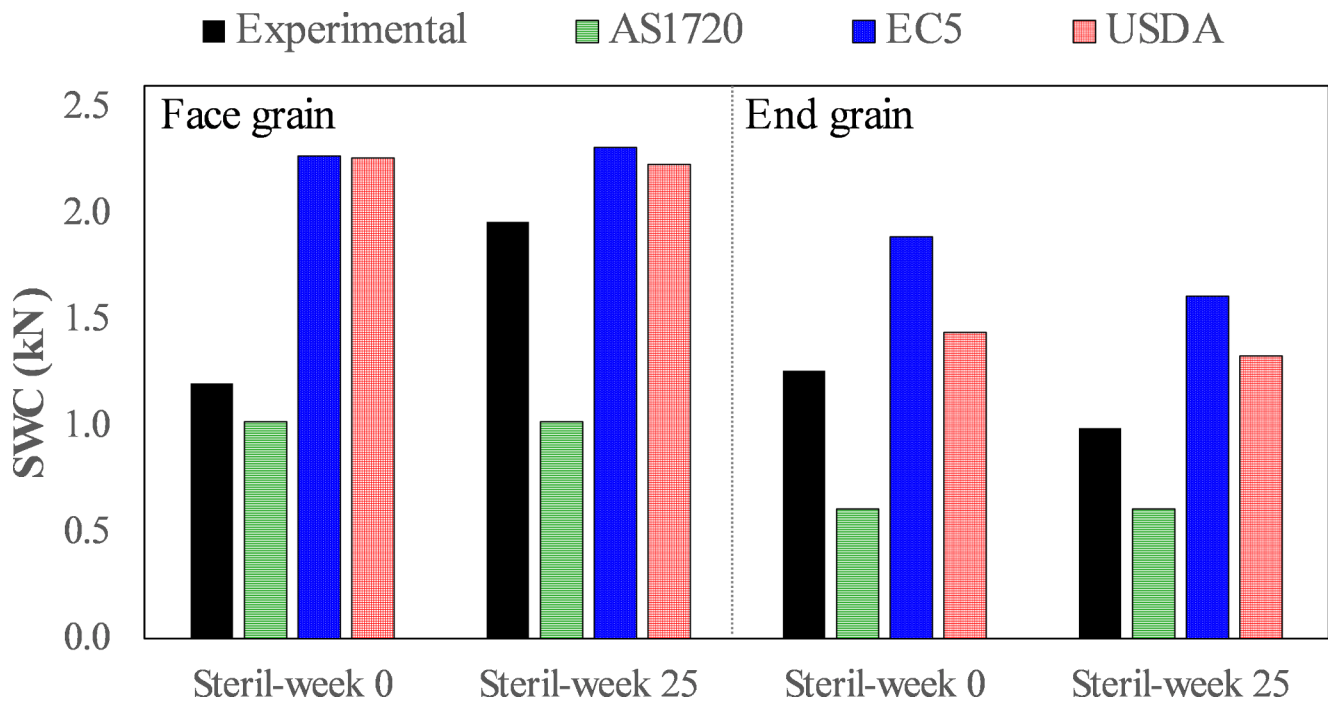
3.1.2 Decayed specimens

The results of the specimens exposed for 15 weeks to brown and white rots showed a dramatic loss of the SWC, especially for brown rots (72–83 for brown rots, and 22–42% for white rots, respectively). From 15 weeks onwards, the withdrawal capacities were not statistically different for specimens exposed to either white or brown rots (p-values = 1.0, 1.0, 1.0, 0.992, 1.0 and 0.531). As expected, the mass losses for specimens exposed to brown rots were higher than those exposed to white rots (Yermán et al. 2022), and this could explain the general differences observed in the SWC. Nevertheless, from 15 to 25 weeks of exposure to brown rots, there was an increase in the mass loss from 20 to 30% (p-value < 0.001) but no significant differences were observed in the SWC. The mass losses in the case of the specimens exposed to white rots showed results that were more consistent with the observed SWC. This observation highlights the fact that the mass or density losses are not a good indicator of the loss of performance of screwed timber connections (Ibach and Lebow 2014).

3.2 Comparison with design codes

Figures 4 and 5 show a comparison of the mean experimental SWCs and the predicted SWC (using Eqs. 1–3) for sterilized and decayed specimens, respectively. Predicted SWCs in Fig. 5 were calculated using the decayed wood densities. Figure 4 shows that the strength predictions for sterilized specimens were safe (experimental SWC > predicted SWC) when using AS 1720.1. The other predictions (EC5 and USDA) produced unsafe predictions in every case but after 25 weeks. These results highlight the importance of using Australian standards with Australian wood species and fasteners or recalibrating parameters such as $f_{ax,k}$ for Australian timbers and fasteners.

Fig. 4 Comparison of the mean experimental and predicted SWCs for the sterilized samples

Regarding the decayed specimens (Fig. 5), the results showed unsafe predictions in every case, except for the AS 1720.1 prediction for the specimens exposed to white rots with the screw driven in the end grain (Fig. 5, bottom left). Importantly, in some critical cases, the experimental values were as low as 10–20% of the predicted SWC.

The design standards considered here do not account for capacity loss due to early-stage fungal decay. Moreover, the Australian standard does not even account for the effects of moisture content increase on connection capacity (only on member strength). Furthermore, routine inspections generally only detect water leaks or insect infestation. Even if the early onset of decay was detected in a routine inspection (which is highly unlikely), and a sample was extracted, using decayed density to predict the integrity of screwed timber connections is not safe. Therefore, it is suggested to investigate the adoption of risk and reliability-based concepts for timber durability issues like those adopted for load and resistance factor design (Smith and Foliente 2002).

4 Conclusion

The effects of exposure to two decay fungi, and autoclave sterilization, on the withdrawal capacity of stainless-steel screws in radiata pine were assessed. The wetting and sterilization process improved the screw withdrawal capacity potentially due to the swelling and shrinking effects of the wood fibres around the fasteners. Wood fibre relaxation had

an impact on the withdrawal capacity of sterilized samples, and this must be considered when assessing the decayed specimens over time. Wood exposed to brown and white rots showed mass losses that cannot account for the loss of mechanical performance of screwed connections, especially when exposed to brown rots. This highlights the importance of looking for other alternatives to measure the impact of decay.

A comparison of the experimental results with theoretical values calculated from AS 1720, EC5, and USDA showed that design codes overestimate the screw withdrawal capacity in most of the cases. This was the case even for the control specimens. For specimens exposed to brown rots after 25 weeks, the experimental values were as low as 10–20% of the predicted SWC. The utilization of the decayed wood density in the formulas of EC5 and USDA did not improve the estimation of the predicted values, showing that the decayed wood density is not appropriate to assess the capacity of decayed timber connections. Therefore, it is suggested to investigate the adoption of risk and reliability-based concepts for timber durability issues to quantify the risk of wetting, probability of decay, and its impact on material and connection properties, similar to concepts adopted in load and resistance factor design.
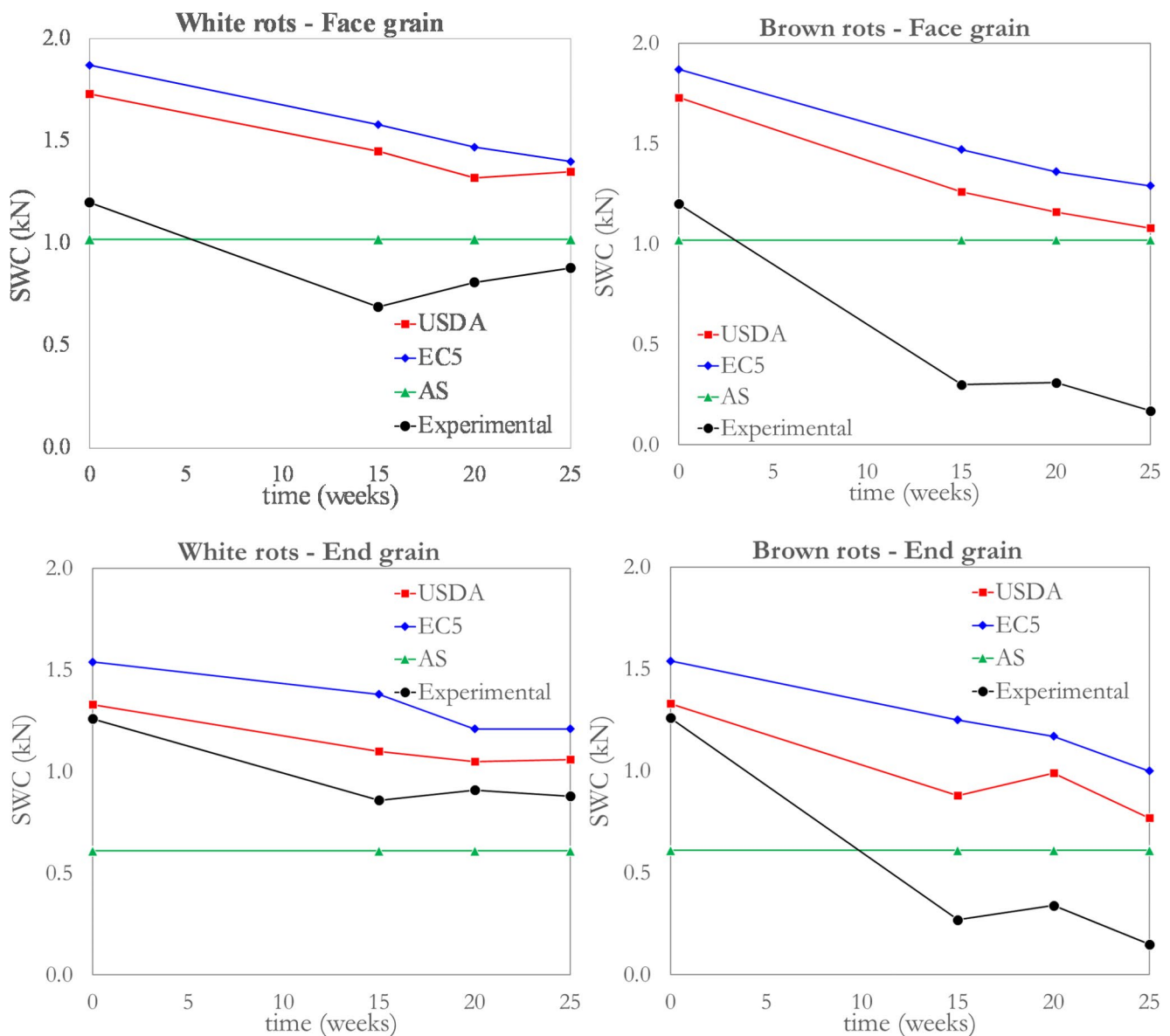
Fig. 5 Experimental and predicted SWC as a function of the exposure time to white and brown rots. The prediction for EC5 and USDA was done using the decayed density. The AS prediction does not account for the wood density

Declarations

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