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NOTE

Withdrawal strength of nailed joints with decay degradation of wood and nail corrosion

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Abstract Nailed timber joints are widely used in timber structures, and their deterioration may cause significant damage. We investigated the withdrawal strength of joints using steel wire nails in specimens exposed to a brown-rot fungus. We also examined the effects of nail corrosion on withdrawal strength, because high humidity conditions accelerate not only wood decay but also the corrosion of nails. We found that nail corrosion increased the withdrawal strength. The ratios of withdrawal strength of nailed joints with rusted nails to that of joints with a minimally rusted nails were 1.47 and 1.56 in joints nailed in radial and tangential directions to annual rings, respectively. Withdrawal strength, excluding the effects of nail corrosion, had a negative correlation with mass loss and Pilodyn-pin-penetration-depth-ratio. We estimated the withdrawal strength of the nailed joint with decayed wood and rusted nails by multiplying the values from the empirical formula (obtained from mass loss and Pilodyn-pin-penetration-depth-ratio) by 1.47 and 1.56 for joints nailed in radial and tangential direction to annual rings, respectively.

Keywords Common nail · Brown-rot fungus · Mass loss · Pilodyn

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Introduction

The strength of timber joints often contributes to the safety and serviceability of timber structures. Wood decay reduces the strength of timber joints, and this reduction in strength may lead to a reduction in the safety and serviceability of the timber structures. Estimating the residual strength of timber joints exposed to wood-decaying fungi would allow appropriate repair, leading to the improved long-term usability of timber structures.

A number of studies have investigated the strength of wood when exposed to wood-decaying fungi [1–4]. Recent studies have examined the effects of decay on the strength of timber joints with respect to the shear performance of nailed joints, dowel-type joints, and screwed joints exposed to decay fungi [5–10]. However, there has been little investigation into the relationship between the withdrawal strength of nails and decay. Nailed joints are often subjected to lateral rather than withdrawal forces [11]. Even when nailed joints are subject to lateral force, the shear strength of the joint is affected not only by the embedding strength of the main and side members, the bending strength of the nail, and the nail-head pull-through strength on the side member, but also by the withdrawal strength on the main member. The withdrawal strength especially affects the shear strength of nailed joints at large deformation. Therefore, it is important to investigate the relationship between decay and nail withdrawal strength.

Wood-decaying fungi grow well under conditions of high moisture content [12], and the exposure of nailed joints to high moisture encourages corrosion [13]. When rust forms on the surface of the nail shank, the volume of the nail shank increases owing to oxidation, and the surface roughness of the shank increases [14]. Therefore, nail corrosion leads to an increase in withdrawal strength

[14, 15], so that high humidity may affect the withdrawal strength of nailed joints by a simultaneous decrease in strength due to decay and an increase in strength due to nail corrosion. Both these factors must, therefore, be considered when investigating the withdrawal strength of nailed joints exposed to wood-decaying fungi.

The aim of this study was, therefore, to investigate the effects of degree of decay and nail corrosion on withdrawal strength.

Materials and methods

Specimens

We conducted withdrawal tests on todomatsu (*Abies sachalinensis*) specimens penetrated by CN65 nails. The CN65 nail is common steel wire nail according to JIS A5508, with a nominal shank diameter and length of 3.33 and 65 mm, respectively. Todomatsu specimens were 90 mm long, 30 mm wide, and 50 mm thick. The orientations of nail penetration into the wood specimen were radial (R type) and tangential (T type) to annual rings. The nails were hand-driven into the specimens, and the length of penetration into wood was 48 mm. Specimens are illustrated in Fig. 1.

We exposed 60 specimens each of R and T type to a wood-decaying fungus. In addition, we used end-matched specimens for each decay-treated specimen as controls. The mean air-dried density of the all clear specimens was 405 kg/m^3, with a standard deviation of 33.6 kg/m^3.

To induce decay in the nailed positions, we drilled 20 mm away from the nailed point in a longitudinal direction, using a drill with a diameter of 2.8 mm (Fig. 1). We expected mycelial growth to begin along the drilled hole and then proceed along the longitudinal grain to finally reach the nailed position.

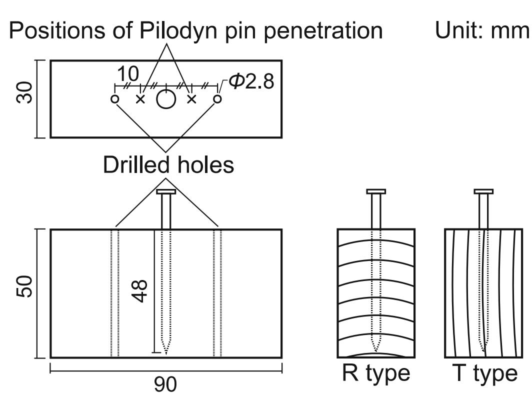


Fig. 1 The outline of the specimen

Decay treatment

To increase moisture content, we immersed control specimens and specimens before decay treatment in a water bath for 2 weeks, after which they were sterilized using an autoclave at 121 °C for 15 min. Then we placed their specimens in polypropylene boxes with nail heads facing down. The boxes contained a liquid culture medium (4.0% D-glucose, 1.5% malt extract, and 0.3% peptone), inoculated with the brown-rot fungus *Fomitopsis palustris*.

We incubated both the inoculated and control specimens in a temperature-controlled room at 26 °C for 30, 60, 90, or 120 days. The mean relative humidity in this room was 83.5%.

Withdrawal tests

Moisture content significantly affects nail withdrawal strength when it is below the fiber saturation point (FSP), with a less potent effect above the FSP [16]. To subject all specimens to a moisture content above their FSP, after the decay treatment we immersed the inoculated and control specimens in a water bath for 2 weeks.

Immediately after the water bath treatment, we conducted withdrawal tests using a hydraulic testing machine (RUE2–10D TOKYO KOKI CO. LTD.). Decay-treated specimens and end-matched control specimens were tested on the same date. We tested the monotonic loading of specimens, with a loading rate ranging between 0.7 and 4.0 mm per min, until the withdrawal load reached the maximum load. We terminated the test when the nails were fully removed from the wood. We calculated the withdrawal strength (P_w) as follows:

$$P_w = \frac{P_{max}}{l}, \quad (1)$$

where P_{max} is the maximum load, l is the penetration length of the nail into the specimen before tests. The mean moisture contents of R type and T type specimens during withdrawal test were 163% (standard deviation 33%) and 166% (standard deviation 36%), respectively.

Measurement of decay degree of wood

Depth of pin penetration

We measured the depth of pin penetration for all specimens using Pilodyn, which is a widely used apparatus to measure degree of decay [4, 6, 8, 10, 17, 18]. Pilodyn that we used has 2.5 mm pin diameter, 40 mm maximum penetration depth, and 6 J penetration energy. Penetration points by Pilodyn were parallel to the nail axis, and were 10 mm away from the nailed point in a longitudinal direction

(Fig. 1). If the pin penetration value was greater than 40 mm, we recorded the depth of pin penetration as 40 mm. We calculated the depth of pin penetration using the mean value of each side of the nail hole.

Measurements of density of wood

We measured the oven-dried weight of the specimens after the withdrawal and pin penetration tests. We calculated the density (ρ) of the specimens as follows:

$$\rho = \frac{m_o}{V_a}, \tag{2}$$

where m_o is the over-dried weight of the specimen, V_a is the dimension of the specimen before decay treatments. We calculated mass loss (Δm) based on the density as follows:

$$\Delta m = \frac{\rho_c - \rho_d}{\rho_c} \times 100(\%), \tag{3}$$

where ρ_c is the density of the end-matched control specimen calculated from Eq. (2), ρ_d is the density of the decayed specimen calculated from Eq. (2).

Measurement of nail corrosion

We evaluated the degree of nail corrosion based on the change in nail shank diameter. We measured nail shank diameters including the rust layer before nailing and after the withdrawal tests, using a micrometer (accurate to 0.001 mm) at three points along the penetrating nail shank: upper, intermediate, and lower (Fig. 2). We obtained the mean nail shank diameter before nailing (D_b) and after the withdrawal test (D_a) of the three measurement points. When nail penetrates in edge grain and flat grain, nail would not receive a uniform pressure on circumference from wood. The pressure perpendicular to the grain would be larger than that parallel to the grain. Hence, the rust on the nail, which received pressure perpendicular to the grain, peeled off through the nail withdrawal and the rust on the nail, which received pressure parallel to the grain, remained. Therefore, we measured nail shank diameter in the direction parallel to the wood grain (Fig. 2). We obtained the change in nail shank diameter (D_c) as follows:

$$D_c = \frac{D_a - D_b}{D_b} \times 100(\%), \tag{4}$$

where D_a is nail shank diameter after the withdrawal test, D_b is nail shank diameter before nailing.

Measurement and treatment procedures mentioned above were illustrated in Fig. 3.

Results and discussion

Effect of stress relaxation

We predicted that the withdrawal strength would decrease because of stress relaxation, as the nailed period was longer, and would then attain a constant value [15, 19]. When rust formed on the nail, we expected to observe both the effects of reduced P_w by stress relaxation, and increased P_w by nail corrosion. We, therefore, examined the relationship between P_w and D_c in the control specimens and in the periods after nailing to investigate the effects of stress relaxation. The means and standard deviation of P_w and D_c of the control specimens for periods after nailing are shown in Fig. 4. The nailed period ranged from 30 to 120 days, and there was no significant difference (5% significance level) in P_w during each period between control specimens, and R and T type specimens. There was also no significant difference (5% significance level) in D_c values between the control and the R and T type specimens. Therefore, stress relaxation after nailing was not considered an important factor in this study, and control specimens were regarded as a single group, regardless of the period after nailing.

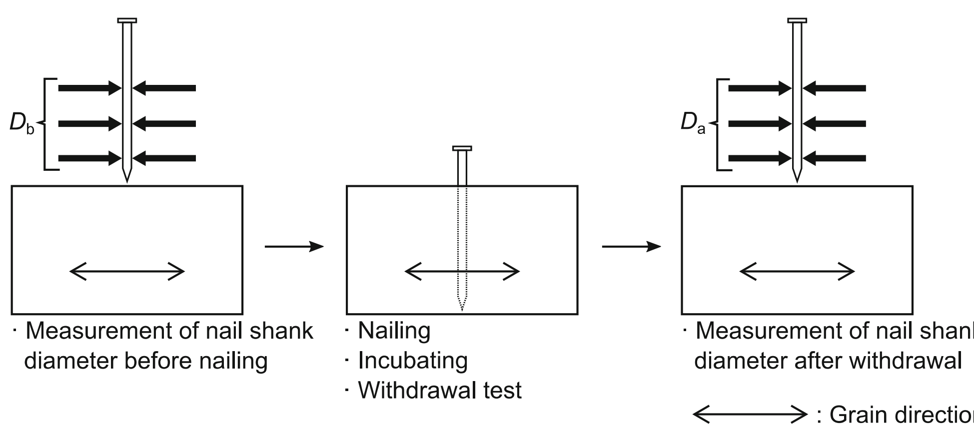


Fig. 2 Measurement of nail shank diameter. D_b: mean nail shank diameter of values at three measured points before nailing. D_a: mean nail shank diameter of values at three measured points after the withdrawal test

Fig. 3 Measurement and treatment procedures

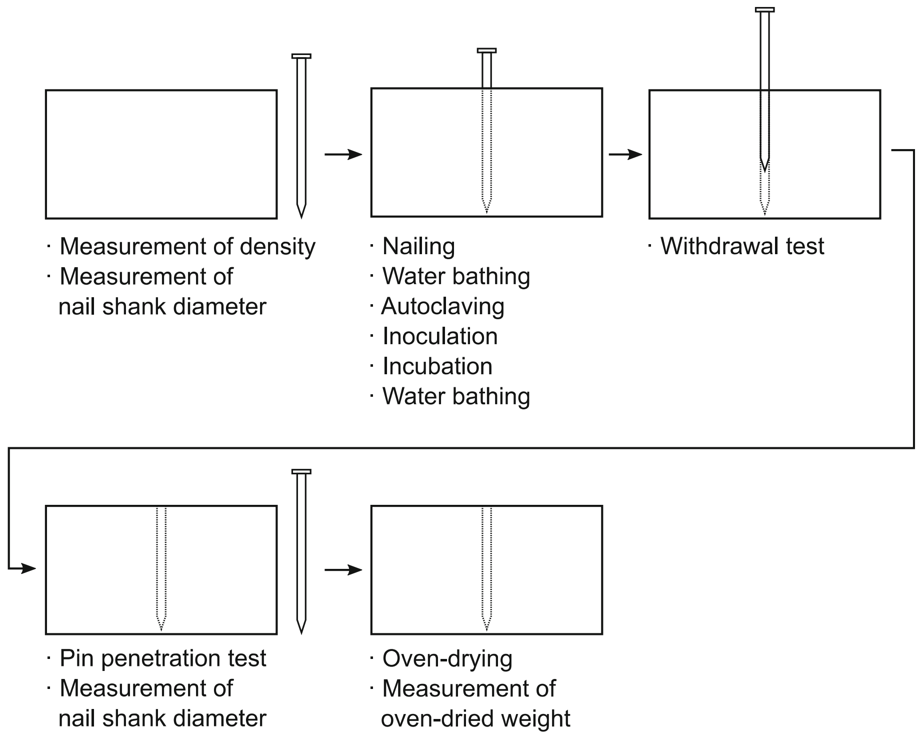
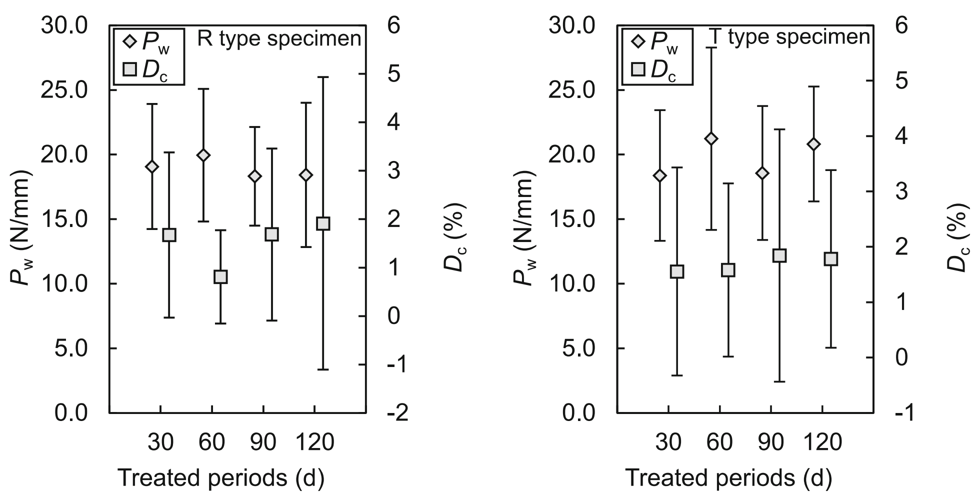


Fig. 4 Withdrawal strength and change in nail shank diameter of the control specimens for each fungus-treated periods. P_w: maximum withdrawal load divided by the penetration length of the nail. D_c: change in nail shank diameter between before nailing and after withdrawal



Effect of nail corrosion on withdrawal strength

We visually observed corrosion on nail surface of all specimens after withdrawal. However, we could not clearly distinguish the degree of nail corrosion by visual observation. The relationship between P_w and D_c in control specimens is illustrated in Fig. 5. When rust forms on the surface of the nail shank, the volume of the nail shank increases owing to oxidation [14], leading to a nail diameter of rust that is larger than that of non-rusted nails. The D_c of control specimens ranged between −0.4 and 10.5%. The positive values of D_c suggest that the diameter of the nail is larger than before nailing. The positive values of D_c were exhibited in several specimens, although some specimens showed the negative values. Hence, a value of 0.4% for D_c suggests that the nail diameter varies by 0.013 mm for the nominal shank diameter of 3.33 mm. The difference in nail diameter at the three measurement points before nailing ranged from 0.000 to 0.018 mm. Therefore, we suggest that the negative values of D_c are measurement errors, and those specimens with D_c values $\leq$0.4% are considered as specimens with minimal rust.

Nail corrosion significantly affected withdrawal strength. Specimens with rust had greater withdrawal

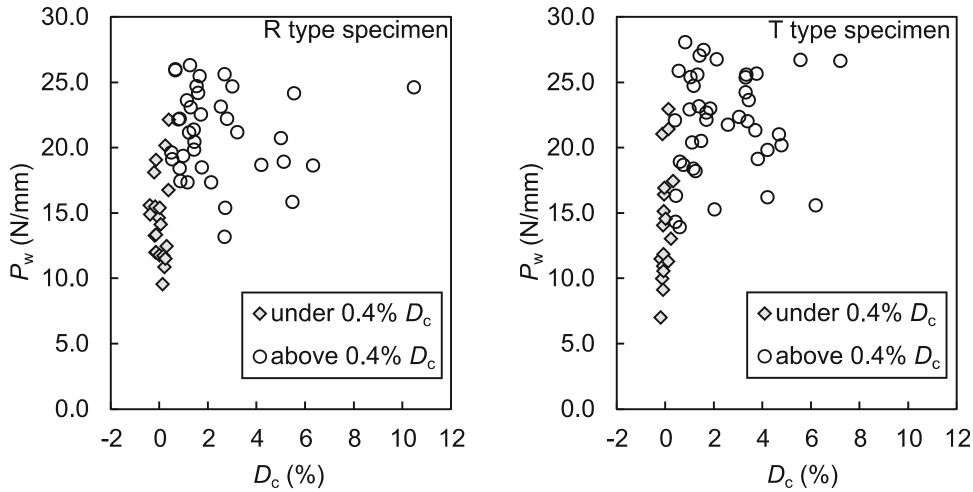


Fig. 5 Relationship between withdrawal strength and the change in nail shank diameter for control specimens. P_w: maximum withdrawal load divided by the penetration length of the nail. D_c: change in nail shank diameter between before nailing and after withdrawal

strength than specimens with minimal rust. However, the withdrawal strength with rust did not greatly increase when the value of D_c was higher than 2% (Fig. 5), a finding supported by the results of previous studies. For example, Ishiyama [14] reported that the degree of corrosion has little effect on the withdrawal strength of a specimen that has advanced corrosion, because the nailed joints under the withdrawal force fail at either the rust layer or the interface between the wood member and the rust layer.

The ratio of mean P_w of specimens with rust, which did not include specimens with minimal rust, to that with minimal rust was 1.47 for R type specimens and 1.56 for T type specimens. The mean P_w of specimens with rust differed significantly (1% significant level) from that of specimens with minimal rust. This finding agrees with those of previous studies, which show the withdrawal strength of wet wood specimens with rust to be 50% higher than that of specimens without rust [15]. Furthermore, in withdrawal tests using steel wire nails and galvanized nails, the withdrawal strength was higher in decayed specimens with rust than in those without rust [20]. To consider the effects of decay and corrosion on withdrawal strength separately, we divided the values of P_w where $D_c \geq 0.4\%$ by 1.47 (for R type specimens) and 1.56 (for T type specimens), and termed this derived value, the modified withdrawal strength ($P_{w,\ m}$) as follows:

$$P_{w,\,m} = \begin{cases} P_w & (D_c \leq 0.4\%) \\ \dfrac{P_w}{1.47} & (\text{R type specimens}, D_c \geq 0.4\%) \\ \dfrac{P_w}{1.56} & (\text{T type specimens}, D_c \geq 0.4\%) \end{cases}, \quad (5)$$

where P_w is the withdrawal strength calculated from Eq. (1), D_c is change in nail shank diameter calculated from Eq. (4).

Effect of decay on modified withdrawal strength

The relationship between $P_{w,\ m}$ and specimen density is shown in Fig. 6. Specimen density ranged from 269 to 416 kg/m^3 in control specimens and from 185 to 410 kg/m^3 in decay-treated specimens. When the density of the specimen was greater than 300 kg/m^3, the value of $P_{w,\ m}$ of decay-treated specimens was similar to that of control specimens. The decay-treated specimens with a density less than 300 kg/m^3 had a significantly reduced $P_{w,\ m}$; this positive correlation between $P_{w,\ m}$ and specimen density is illustrated in Fig. 6. However, it was difficult to estimate the withdrawal strength using density because the variation of withdrawal strength to the density was too great.

The relationship between the value of $P_{w,\ m}$ and mass loss is shown in Fig. 7. Here, the values of $P_{w,\ m}$ decreased linearly as mass loss increased. A number of studies have investigated the relationship between strength of decayed wood and mass loss [2, 3, 6], as well as the relationship between strength of decayed timber joints and mass loss [6, 7, 9]. Toda revealed a relationship between maximum resistances of nailed joints subjected to a lateral force and mass loss, and described that a mass loss of 20% reduced the maximum resistance of joints by approximately 40%, as against that with 0% mass loss [7]. We found that a mass loss from 0 to 20% decreased $P_{w,\ m}$ on average by 35% (R type) and 47% (T type). The decrease in $P_{w,\ m}$ due to mass loss was similar to that of the maximum resistance of nailed joints subjected to a lateral force, and was particularly high in T type specimens.

We calculated the Pilodyn-pin-penetration-depth-ratio of decay-treated specimens to that of control specimens as an indicator of decay. Figure 8 shows the relationship between the value of $P_{w,\ m}$ and the Pilodyn-pin-penetration-depth-ratio. Here, $P_{w,\ m}$ decreased linearly as the Pilodyn-pin-penetration-depth-ratio

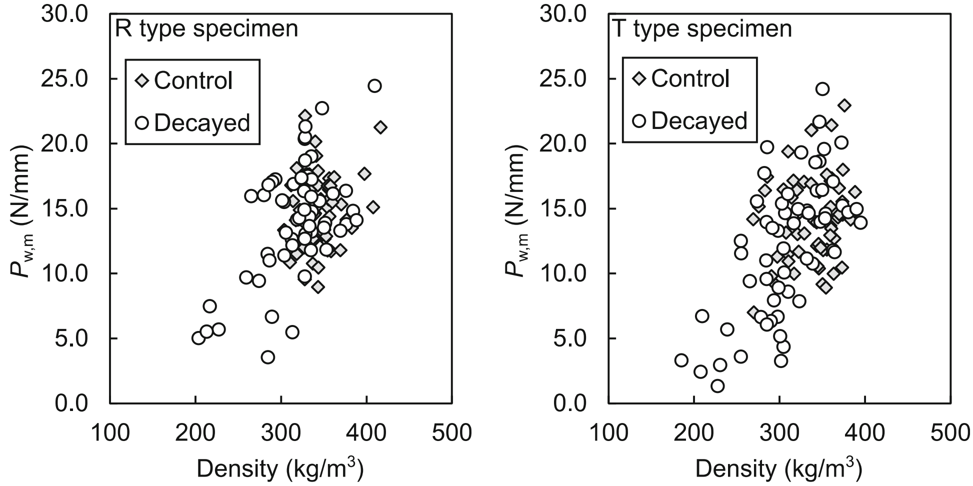


Fig. 6 Relationship between modified withdrawal strength and specimen density. $P_{w,\ m}$: withdrawal strength modified by nail corrosion coefficient

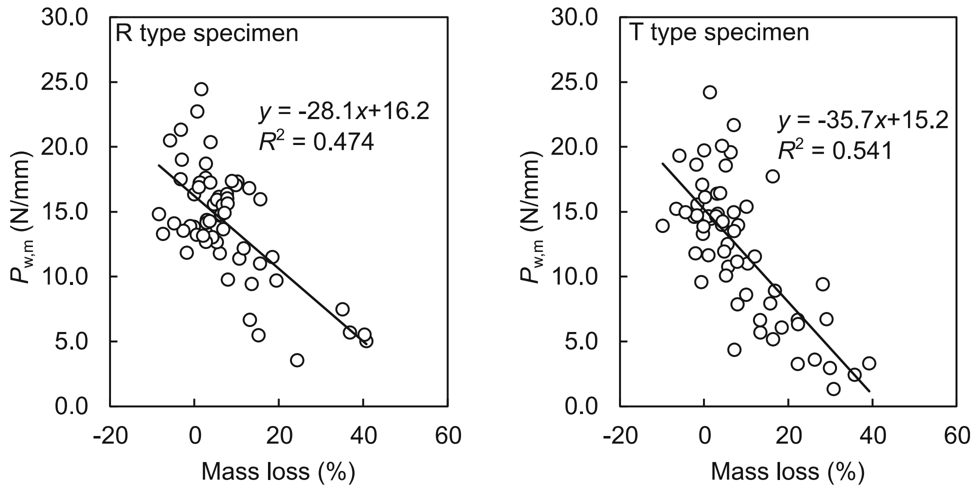


Fig. 7 Relationship between modified withdrawal strength and mass loss. $P_{w,\ m}$: withdrawal strength modified by the nail corrosion coefficient

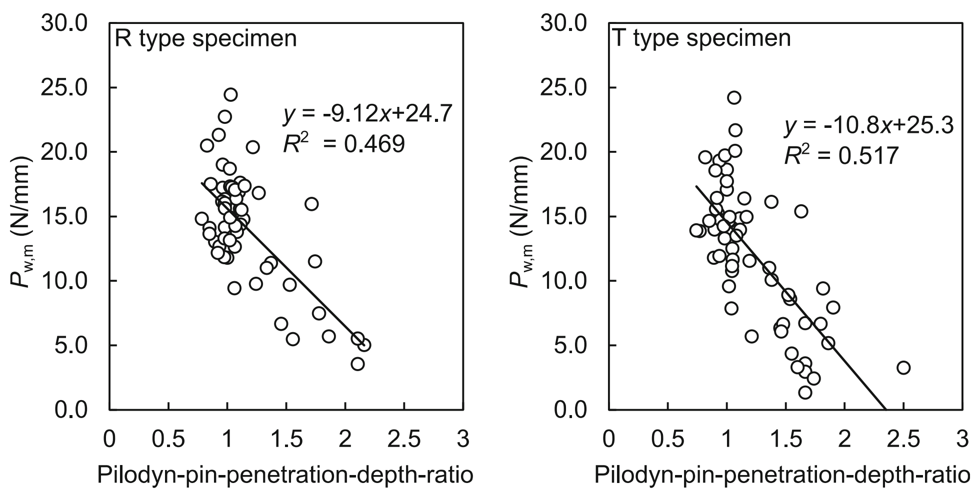


Fig. 8 Relationship between modified withdrawal strength and the Pilodyn-pin-penetration-depth-ratio of the decayed specimen to that of control specimen. $P_{w,\ m}$: withdrawal strength modified by the nail corrosion coefficient

increased, and we estimated $P_{w,\ m}$ using mass loss or Pilodyn pin penetration depth. We can estimate the withdrawal strength of nailed joints when the nailed joints were under decay conditions, and rust formed on the penetrated nail, by multiplying the regression lines shown in Fig. 7 or 8, by the coefficients of increase of withdrawal strength as a result of the rust on the nails. The coefficients for joints nailed in radial and tangential direction to the annual ring were 1.47 and 1.56, respectively.

Conclusions

We conducted withdrawal tests on specimens nailed by CN65 steel wire nails on todomatsu, *Abies sachalinensis*, exposed to the brown-rot fungus, *Fomitopsis palustris*. We summarize the results below:

1. Nail corrosion increased withdrawal strength. However, withdrawal strength was almost constant when the change in nail shank diameter was higher than 2%. The ratios of withdrawal strength of the nailed joint with rusted nails to that with minimal rusted nails were 1.47 in the joints nailed in the radial direction to annual rings, and 1.56 in the joints nailed in the tangential direction.
2. We estimated the withdrawal strength, except the effects of nail corrosion, using mass loss or the decayed wood Pilodyn-pin-penetration-depth-ratio.
3. It is possible to obtain the withdrawal strength of nailed joints with decayed wood and rusted nails by multiplying the empirical formula exhibited in Fig. 7 or 8 by the coefficients of increase of withdrawal strength by the corrosion. The coefficients of joints nailed in the radial and tangential direction to the annual ring were 1.47 and 1.56, respectively.

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