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Author(s)	Takanashi, Ryuya; Sawata, Kei; Sasaki, Yoshihisa; Koizumi, Akio
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Withdrawal strength of nailed joints with decay degradation of wood and nail corrosion

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Authors: Ryuya Takanashi, Kei Sawata, Yoshihisa Sasaki, Akio Koizumi

Ryuya Takanashi, Kei Sawata (corresponding author), Yoshihisa Sasaki, Akio Koizumi
Research Faculty of Agriculture, Hokkaido University, N9 W9, Sapporo, 060-8589,
Japan

E-mail: ksawata@for.agr.hokudai.ac.jp

TEL: +81 11-706-2528, FAX: +81 11-706-3636

Ryuya Takanashi

Forest Products Research Institute, Hokkaido Research Organization, 1-10 Nishikagura,
Asahikawa, 071-0198, Japan

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1 Abstract

2 Nailed timber joints are widely used in timber structures, and their
3 deterioration may cause significant damage. We investigated the withdrawal strength
4 of joints using steel wire nails in specimens exposed to a brown-rot fungus. We also
5 examined the effects of nail corrosion on withdrawal strength, because high humidity
6 conditions accelerate not only wood decay but also the corrosion of nails. We found
7 that nail corrosion increased the withdrawal strength. The ratios of withdrawal strength
8 of nailed joints with rusted nails to that of joints with a minimally rusted nails were
9 1.47 and 1.56 in joints nailed in radial and tangential directions to annual rings,
10 respectively. Withdrawal strength, excluding the effects of nail corrosion, had a
11 negative correlation with mass loss and Pilodyn-pin-penetration-depth-ratio. We
12 estimated the withdrawal strength of the nailed joint with decayed wood and rusted
13 nails by multiplying the values from the empirical formula (obtained from mass loss
14 and Pilodyn-pin-penetration-depth-ratio) by 1.47 and 1.56 for joints nailed in radial
15 and tangential direction to annual rings, respectively.

1 Introduction

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

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

21 Wood decaying fungi grow well under conditions of high moisture content [12],
22 and the exposure of nailed joints to high moisture encourages corrosion [13]. When
23 rust forms on the surface of the nail shank, the volume of the nail shank increases
24 owing to oxidation, and the surface roughness of the shank increases [14]. Therefore,
25 nail corrosion leads to an increase in withdrawal strength [14, 15], so that high
26 humidity may affect the withdrawal strength of nailed joints by a simultaneous
27 decrease in strength due to decay and an increase in strength due to nail corrosion.

1 Both these factors must therefore be considered when investigating the withdrawal
2 strength of nailed joints exposed to wood-decaying fungi.

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

1 Materials and methods

2 Specimens

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

10 We exposed 60 specimens each of R and T type to a wood-decaying fungus. In
11 addition, we used end-matched specimens for each decay treated specimen as controls.
12 The mean air-dried density of the all clear specimens was 405 kg/m³, with a standard
13 deviation of 33.6 kg/m³.

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

18

19 Decay treatment

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

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

1 humidity in this room was 83.5 %.

2

3 Withdrawal tests

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

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

$$15 P_w = \frac{P_{\max}}{l} \quad (1)$$

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

20

21 Measurement of decay degree of wood

22 Depth of pin penetration

23 We measured the depth of pin penetration for all specimens using Pilodyn,
24 which is a widely used apparatus to measure degree of decay [4, 6, 8, 10, 17, 18].
25 Pilodyn that we used has 2.5 mm pin diameter, 40 mm maximum penetration depth, and
26 6 J penetration energy. Penetration points by Pilodyn were parallel to the nail axis, and
27 were 10 mm away from the nailed point in a longitudinal direction (Fig. 1). If the pin

1 penetration value was greater than 40 mm, we recorded the depth of pin penetration as
2 40 mm. We calculated the depth of pin penetration using the mean value of each side of
3 the nail hole.

4

5 Measurements of density of wood

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

$$8 \quad \rho = \frac{m_o}{V_a} \quad (2)$$

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

$$11 \quad \Delta m = \frac{\rho_c - \rho_d}{\rho_c} \times 100 \quad (\%) \quad (3)$$

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

14

15 Measurement of nail corrosion

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

1 follows:

$$2 \quad D_c = \frac{D_a - D_b}{D_b} \times 100 \quad (\%) \quad (4)$$

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

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

6 3.

1 Results and discussion

2 Effect of stress relaxation

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

17

18 Effect of nail corrosion on withdrawal strength

19 We visually observed corrosion on nail surface of all specimens after
20 withdrawal. However, we could not clearly distinguish the degree of nail corrosion by
21 visual observation. The relationship between P_w and D_c in control specimens is
22 illustrated in Fig. 5. When rust forms on the surface of the nail shank, the volume of
23 the nail shank increases owing to oxidation [14], leading to a nail diameter of with rust
24 that is larger than that of non-rusted nails. The D_c of control specimens ranged between
25 -0.4% and 10.5%. The positive values of D_c suggest that the diameter of the nail is
26 larger than before nailing. The positive values of D_c were exhibited in several
27 specimens, although some specimens showed the negative values. Hence, a value of

1 0.4% for D_c suggests that the nail diameter varies by 0.013 mm for the nominal shank
2 diameter of 3.33 mm. The difference in nail diameter at the three measurement points
3 before nailing ranged from 0.000 to 0.018 mm. Therefore, we suggest that the negative
4 values of D_c are measurement errors, and those specimens with D_c values $\leq 0.4\%$ are
5 considered as specimens with minimal rust.

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

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

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

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/m³ in control specimens and from 185 to 410 kg/m³ in decay-treated specimens. When the density of the specimen was greater than 300 kg/m³, 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/m³ 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.

1 We calculated the Pilodyn-pin-penetration-depth-ratio of decay-treated
2 specimens to that of control specimens as an indicator of decay. Fig. 8 shows the
3 relationship between the value of $P_{w,m}$ and the Pilodyn-pin-penetration-depth-ratio.
4 Here, $P_{w,m}$ decreased linearly as the Pilodyn-pin-penetration-depth-ratio increased, and
5 we estimated $P_{w,m}$ using mass loss or Pilodyn pin penetration depth. We can estimated
6 the withdrawal strength of nailed joints when the nailed joints were under decay
7 conditions, and rust formed on the penetrated nail, by multiplying the regression lines
8 shown in Fig. 7 or 8, by the coefficients of increase of withdrawal strength as a result
9 of the rust on the nails. The coefficients for joints nailed in radial and tangential
10 direction to the annual ring were 1.47 and 1.56, respectively.

11

1 Conclusions

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

5 1. Nail corrosion increased withdrawal strength. However, withdrawal strength was
6 almost constant when the change in nail shank diameter was higher than 2%. The ratios
7 of withdrawal strength of the nailed joint with rusted nails to that with minimal rusted
8 nails were 1.47 in the joints nailed in the radial direction to annual rings, and 1.56 in
9 the joints nailed in the tangential direction.

10 2. We estimated the withdrawal strength, except the effects of nail corrosion, using
11 mass loss or the decayed wood Pilodyn-pin-penetration-depth-ratio.

12 3. It is possible to obtain the withdrawal strength of nailed joints with decayed wood
13 and rusted nails by multiplying the empirical formula exhibited in Fig. 7 or 8 by the
14 coefficients of increase of withdrawal strength by the corrosion. The coefficients of
15 joints nailed in the radial and tangential direction to the annual ring were 1.47 and 1.56,
16 respectively.

17

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Figure legends

Fig. 1 The outline of the specimen

Fig. 2 Measurement of nail shank diameter

Note: 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

Note: 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

Fig. 5 Relationship between withdrawal strength and the change in nail shank diameter for control specimens

Note: 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

Fig. 6 Relationship between modified withdrawal strength and specimen density

Note: $P_{w,m}$: withdrawal strength modified by nail corrosion coefficient

Fig. 7 Relationship between modified withdrawal strength and mass loss

Note: $P_{w,m}$: 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

Note: $P_{w,m}$: withdrawal strength modified by the nail corrosion coefficient

Fig. 1

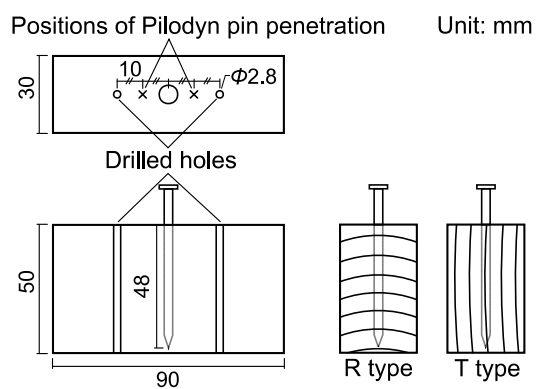


Fig. 2

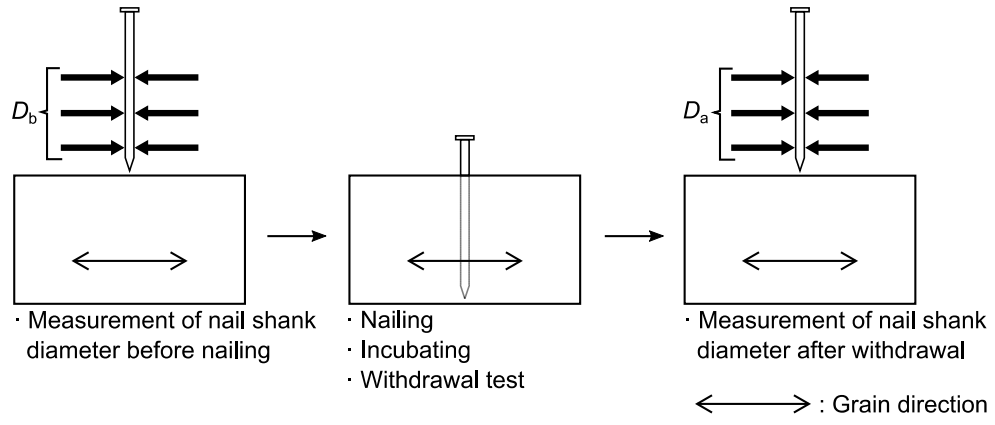


Fig. 3

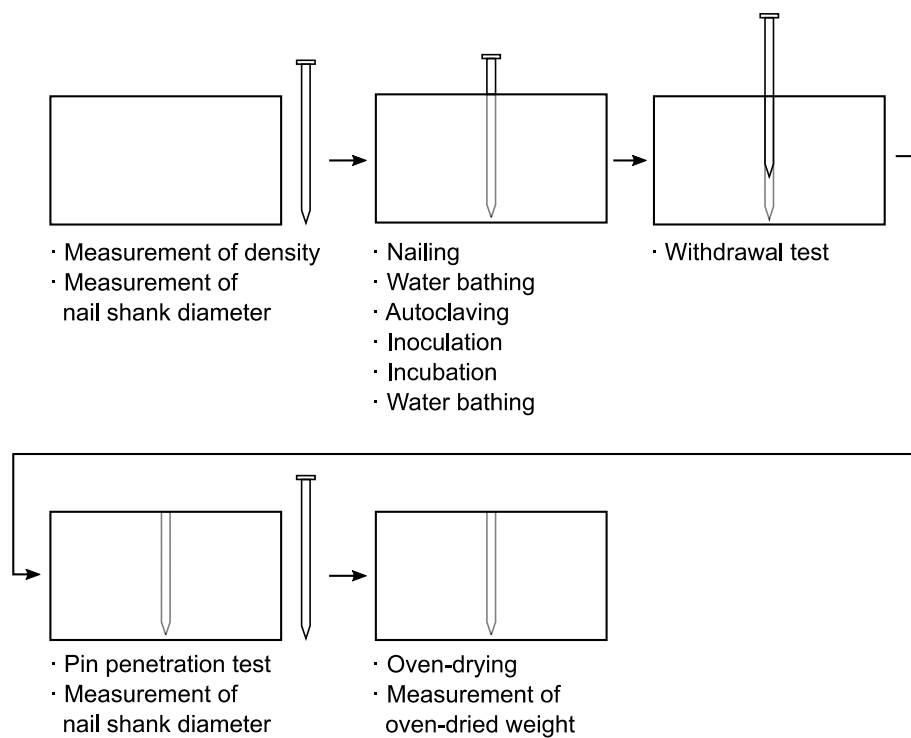


Fig. 4

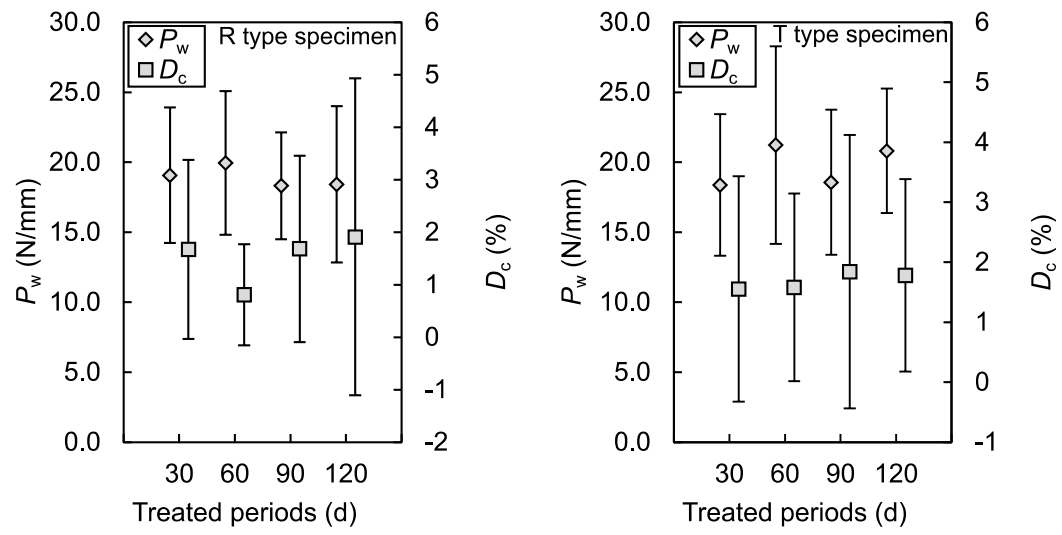


Fig. 5

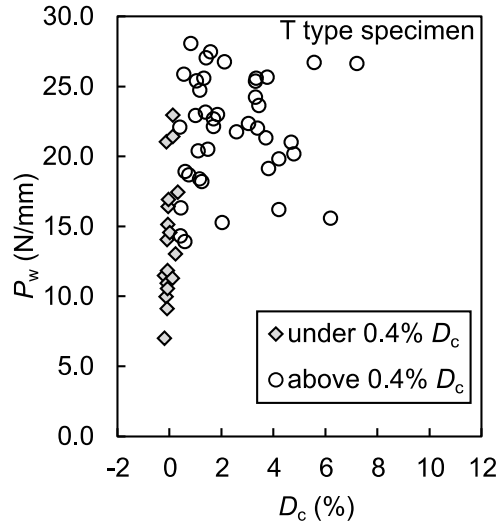
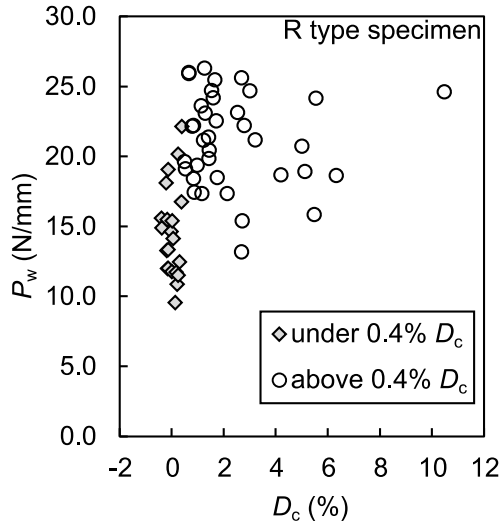


Fig. 6

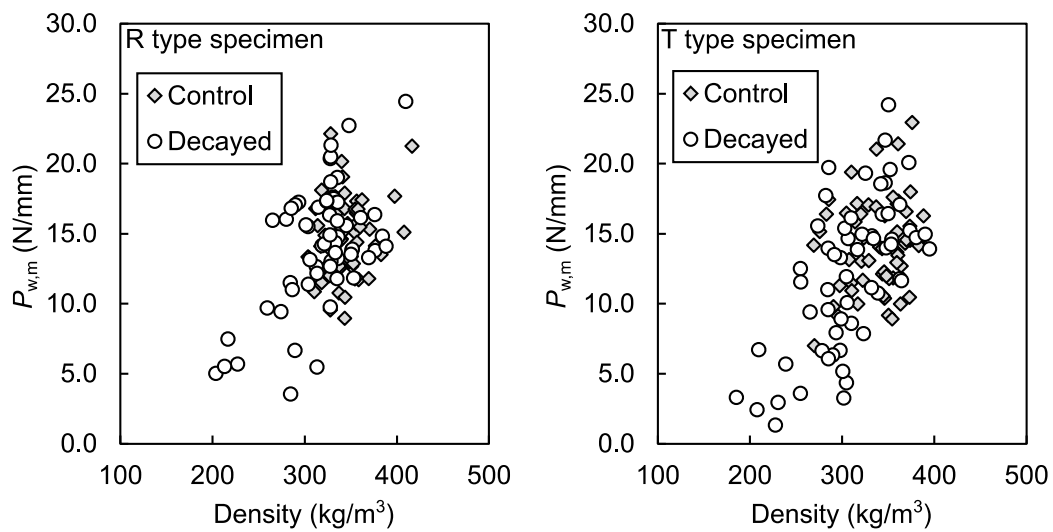


Fig. 7

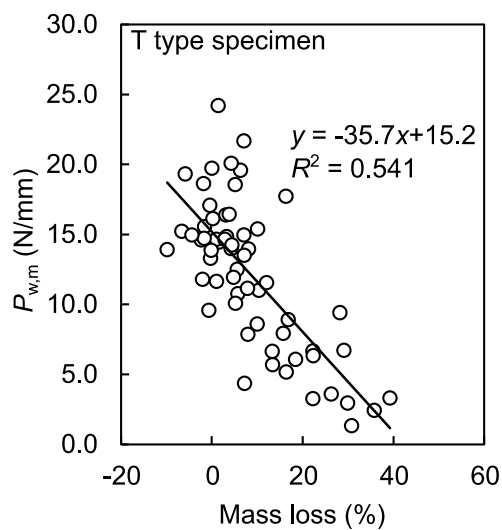
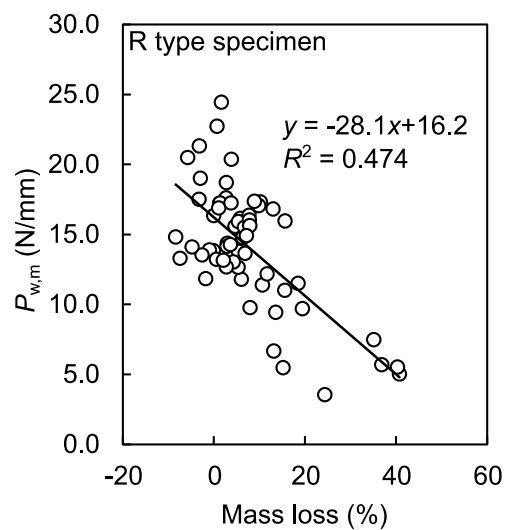


Fig. 8

