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Effects of decay on the shear properties of nailed joints parallel and perpendicular to the grain

Rintaro Ueda¹, Kei Sawata^{2*} , Takanobu Sasaki² and Yoshihisa Sasaki²

Abstract

Information on the properties of nailed joints with decayed member is necessary to evaluate the remaining structural properties of timber constructions. In this study, loading tests were conducted on nailed joints parallel and perpendicular to the grain with decayed members, and the relationship between the decrease in shear properties and the loading direction to the grain was investigated. After the loading tests, the extent of decay of the specimens was evaluated by the penetration depth of Pilodyn and the decay depth, and these were compared with the shear properties of the nailed joints. The nailed joints with decay had a low load at the initial deformation, regardless of the loading direction to the grain. The initial stiffness, yield resistance, and maximum resistance of the nailed joints parallel to the grain were negatively correlated with the Pilodyn penetration depth, and those of the nailed joints perpendicular to the grain showed no significant correlation with the Pilodyn penetration depth at the 5% level. The initial stiffness, yield resistance, and maximum resistance of the nailed joints parallel to the grain tended to decrease with increasing decay depth, and those of the nailed joints perpendicular to the grain did not exhibit this tendency. The shear properties of the nailed joints significantly decreased at small decay depths.

Keywords: Wood decay, Nailed joints, Degradation of wood, Timber construction, Decay treatment

Introduction

In recent years, the lifespans of timber constructions have increased as the use of timber in construction could help us meet the global sustainable development goals (SDGs). The safety of timber constructions must be guaranteed during the service period of the constructions. The materials used in timber construction have factors that degrade the construction's mechanical properties. The integrity of wood can be compromised by wood-rot fungus and termites. These significantly degrade the mechanical properties of wood, and the degradation may result in a decrease in the load-bearing capacity of timber construction [1]. Because the structural properties of

timber construction generally depend on those of timber joints, it is important to assess the remaining properties of timber joints with biologically degraded wood for safety evaluation of timber construction.

Regarding the impact of decay on the shear resistance of timber joints, some studies have been conducted on nailed joints [2–8], screwed joints [9–11], and drift-pinned joints [12]. The effects of decay on the initial stiffness, yield resistance, and maximum resistance of timber joints were clarified in these studies. These were obtained from shear tests of timber joints parallel to the grain; however, few studies have been conducted on timber joints perpendicular to the grain.

When a sound nailed joint was loaded in the direction perpendicular to the grain, the maximum resistance was lower than that in the direction parallel to the grain [13] and the maximum resistance affected the failure mode that was classified into three modes, i.e., nail withdrawal,

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nail-head pull-through, and main member splitting [14]. Since the growth of mycelium is faster in the direction parallel to the grain than in that perpendicular to the grain [15], and the factors that determine the strength of nailed joints differ with loading directions due to the anisotropic nature of wood, effects of decay on the residual strength and failure modes of nailed joints might differ according to the loading direction. The nailed joints frequently have various loading directions, e.g., shear wall under lateral force. Therefore, the knowledge on the degraded shear properties of nailed joints would be important not only on those parallel to grain but also those perpendicular to the grain. Furthermore, understanding the difference between those parallel and perpendicular to the grain would be useful in evaluating the remaining properties of shear walls and floors with wood decay.

Therefore, we conducted shear tests of nailed joints parallel and perpendicular to the grain using decayed wood and investigated the effects of the decay on the deformation behavior, failure modes, and residual shear properties of the nailed joints.

Materials and methods

Materials

The main members were prepared from solid lumbers of Sakhalin fir (*Abies sachalinensis*), whose cross sections were 180 mm in length, 105 mm in width, and 105 mm in thickness. The mean density was 389 kg/m³ (standard deviation 24.3 kg/m³), and the mean moisture content after the shear tests was 7.9% (standard deviation 2.98%). There were 6 control and 12 decayed specimens. Assuming the shear walls, side members were prepared from Larch plywood with dimensions of 200 mm × 70 mm × 12 mm. The mean density was 707 kg/m³ (standard deviation 12.1 kg/m³).

Decay treatment

The fungus *Fomitopsis palustris* is a standard test fungus specified by Japanese Industrial Standards [16], and have been adapted in most of the preceding studies on timber joints with decayed Sakhalin fir member [2, 5, 7–11, 17, 18]. Nutrient agar, floras of *Fomitopsis palustris*, and 17 small pieces of Sakhalin fir were placed in congealed nutrient agar containers. The dimensions of the small piece were 8 mm × 16 mm × 16 mm. The containers were placed in a closed environment with a temperature of 28 °C and a relative humidity of 75% for 4 weeks until the mycelia grew sufficiently.

Thereafter, the containers were attached to the main member specimens using a stretch wrap so that the center of the container coincided with the specimen. The specimens were sealed with polypropylene tape to

avoid mold intrusion, as shown in Fig. 1, and then placed in a closed environment with a temperature and relative humidity of 28 °C and 75%, respectively, for more than 20 weeks. After the decay treatment period, the containers were detached from the specimens. Subsequently, the specimens were air-dried at room temperature and humidity for more than 2 weeks. A container where flora of wood rot fungus is cultured on congealed nutrient agar with small target wood pieces is called a “rot fungus feeder unit” [17]. Decay tests utilizing rot fungus feeder units have been conducted on nailed joints [2], screwed joints [9, 11], and column-sill joints [17, 18]. This method is suitable for decaying only a limited portion of a wood member.

Single shear tests of nailed joints

After the decay treatment, the main and side members were connected with a CN50 nail with a diameter of 2.87 mm and length of 50.0 mm. The predrilled hole for nailing was not located in the main member. It was located in the side member and had a diameter of 2.5 mm. The nails were moderately hammered, leaving a slight gap to avoid initial friction between the main and side members. The main members of the nailed joints parallel and perpendicular to the grain were the same wood piece. Nailing was on the same side of the wood piece; however, the nailing positions were sufficiently apart from each other. The specimen with nailed joints parallel to the grain is shown in Fig. 2, and the setup of the shear test is shown in Fig. 3. The end distances of the main and side members were 80 mm and 26 mm, respectively.

The specimen of nailed joints perpendicular to the grain is shown in Fig. 4, and the setup of the shear test is shown in Fig. 5. The edge distances of the main and side members were 26 mm, which is applied in conventional wooden shear walls in Japan. When plywood is nailed to the lumber of wooden shear walls, the edge distance of the main member is normally a quarter of the lumber width, and the edge distance of 26 mm corresponds to 1/4 of the width of a 105 mm square lumber [14]. The standard of Architectural Institute of Japan [19] specifies

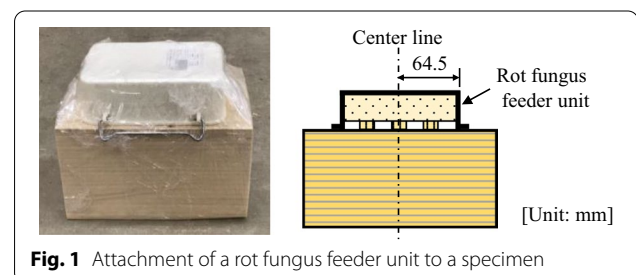
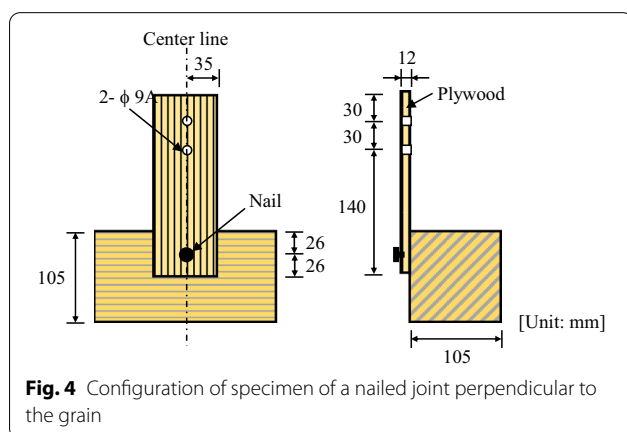
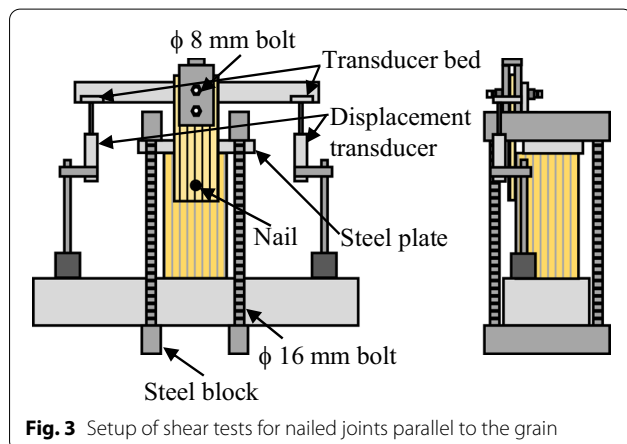
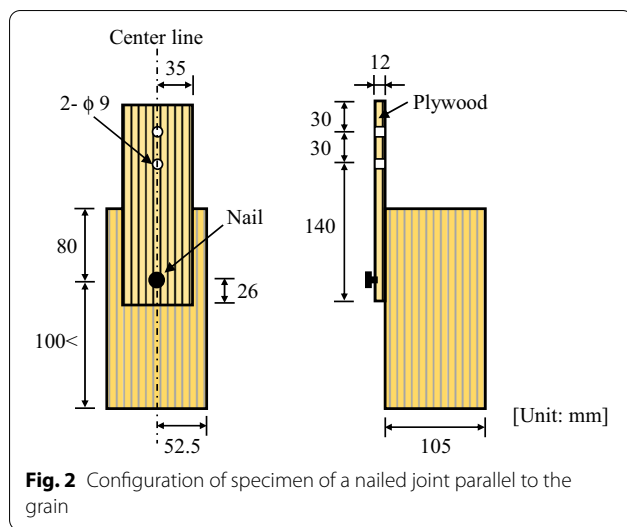
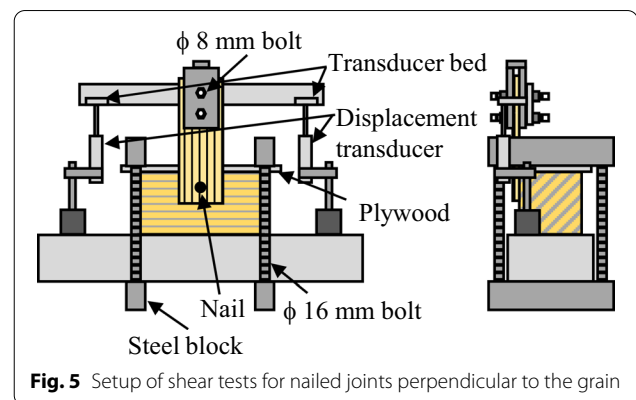


Fig. 1 Attachment of a rot fungus feeder unit to a specimen



that the edge distance of nailed joints perpendicular to the grain should not be less than 8 times the nail diameter. The edge distance in this study was 9.1 times the nail



diameter and met the standard. The surfaces of the CN50 nails were cleaned with acetone before nailing.

The slips are the mean values of two displacement transducers located on the side of the main member. The tests were conducted using a computer-controlled hydraulic actuated testing machine. The load was applied to produce a slip of 0.5 mm, which was subsequently reduced to 0 mm. This loading procedure was repeated to produce slips of 1.0, 2.0, 4.0, and 6.0 mm; subsequently, the load was monotonically applied, and the tests were terminated when the load fell below 50% of the maximum load or the slip reached 30 mm. The slip level was determined from the yield slip obtained from the preliminary monotonic loading test of the nailed joint with an un-decayed main member. The yield slip was approximately 1.0 mm in both nailed joints parallel and perpendicular to the grain. The relative slips of 0.5, 1.0, 2.0, 4.0, and 6.0 mm were equivalent to 1/2, 1, 2, 4, and 6 times the yield slip, respectively.

Evaluation of the extent of decay

After the shear tests, the extent of decay of the main members was evaluated as the Pilodyn penetration depth and decay depth. The Pilodyn® tests have been employed in many studies on nailed and screwed joints with wood decay [2, 4, 5, 7, 9–11, 17] and the correlation between the Pilodyn penetration depth and the residual strength of those joints have been investigated. The Pilodyn penetration depth was measured in this study to compare with the results of those studies. The Pilodyn penetration depth (d_p) was measured with a Pilodyn® 6 J (Proceq, Switzerland) with a pin diameter of 2.5 mm, and the mean of four measurements was obtained for each specimen as shown in Fig. 6. The decay depth (d_d) was obtained nearby the nailing position for nailed joint tests perpendicular to the grain, from the difference between the thickness of the main members and the length of the un-decayed part, as shown in Fig. 6. The length of

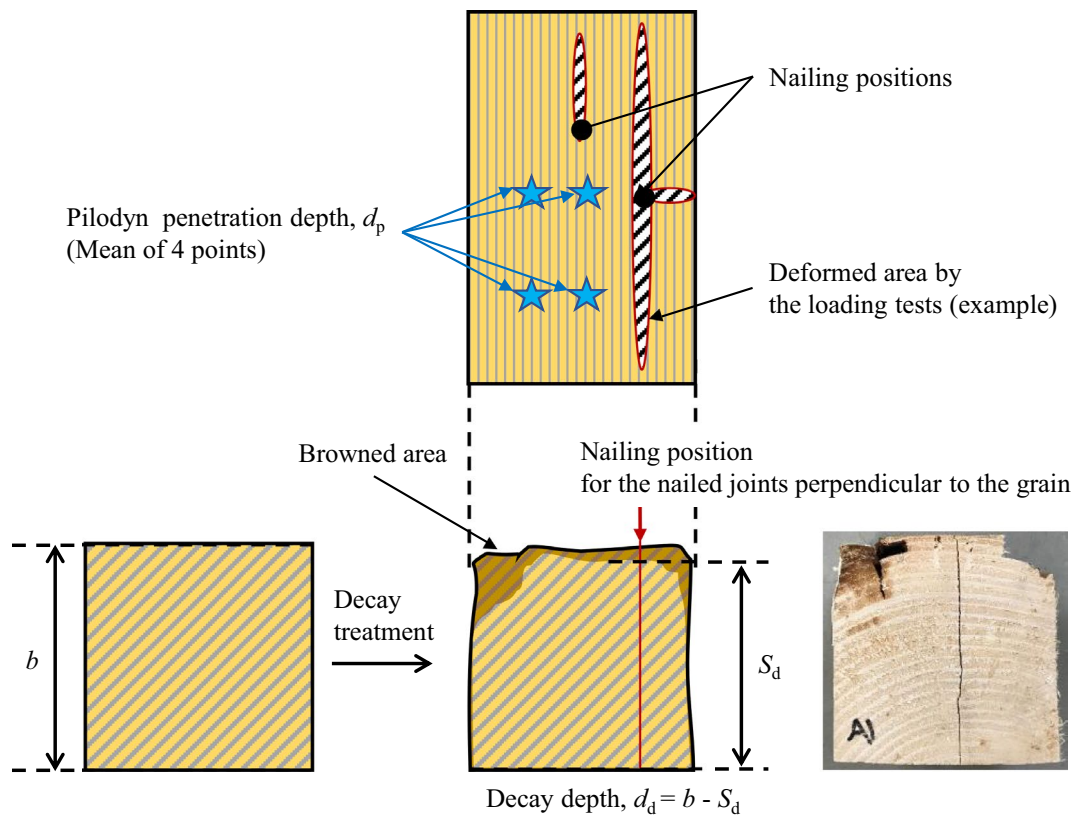


Fig. 6 Method to measure the Pilodyn penetration depth (d_p) and the decay depth (d_d). Note: b , thickness of the main member; S_d , length of un-decayed part at the nailing position

the un-decayed part was obtained as the length of the part without visible changes below the browned area, determined as the decayed part. Since the d_d could be measured visually, that would be easily obtained in the investigation of existing houses with degradation. In a previous study, the d_d showed a better relation with the shear properties of screwed joints with wood decay than the d_p [11]. Therefore, the d_d was adopted in this study to investigate the relation with the shear properties of nailed joints.

Results and discussion

Failure mode

The failure modes of the control and decayed specimens parallel to the grain were all nail withdrawals. An apparent difference in failure mode between the control and decayed specimens was not observed in the main members, as shown in Fig. 7. The deformation of the nails can be classified into two modes, as shown in Fig. 8: the mode that has a plastic hinge in the nail (mode I) and the mode with two plastic hinges (mode II). The all-control specimens parallel to the grain exhibited mode II. Six of the twelve decayed specimens exhibited mode I and six

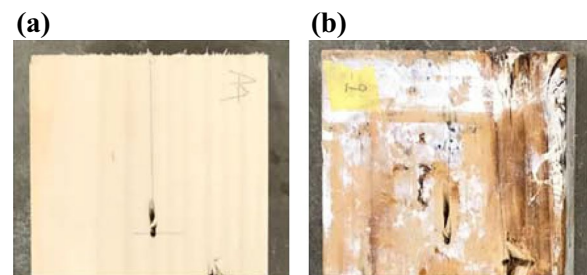


Fig. 7 Control (a) and decayed (b) specimens parallel to the grain after shear tests

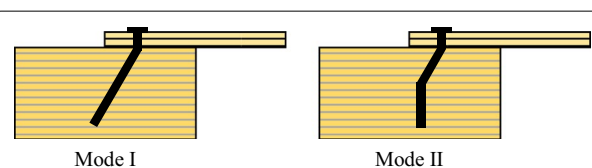


Fig. 8 Deformation modes of the nails

specimens exhibited mode II. Toda et al. [2] reported that the formation of the plastic hinges in the nails was interfered by the decrease of embedding strength caused by wood decay, and a similar tendency was observed in this study.

The failure mode of the nailed joints perpendicular to the grain can be classified into two types: nail withdrawal and main member splitting. No specimen exhibited nail-head pull-through. The failure mode of all the control specimens was nail withdrawal. Five decayed specimens failed by nail withdrawal, and seven exhibited main member splitting, as shown in Fig. 9. It is most likely that the degradation of wood by decay changed the failure mode of nailed joints perpendicular to the grain. Deformation of the nail was by mode II for all the control specimens and 10 decayed specimens. The two decayed specimens deformed by mode I. In the nailed joints perpendicular to the grain, embedding and tensile stress perpendicular to the grain are generated around the

nail holes. Degradation of tensile strength perpendicular to the grain would cause main member splitting, and then the formation of plastic hinges in the nails might be interfered by a large decrease in the embedding strength perpendicular to the grain.

Load–slip curve

Figure 10 shows the envelope load–slip curves of the nailed joints parallel and perpendicular to the grain. The load of the control specimens parallel to the grain increased up to 5–8 mm and then decreased owing to nail withdrawal. The decayed specimens parallel to the grain showed a low load during the initial deformation. The load increased from 5 to 18 mm and then gradually decreased. The decayed specimens perpendicular to the grain also exhibited a lower load at the initial deformation than the control specimen. The slip at the maximum load of the control specimens perpendicular to the grain was 5–8 mm and that of the decayed specimens was

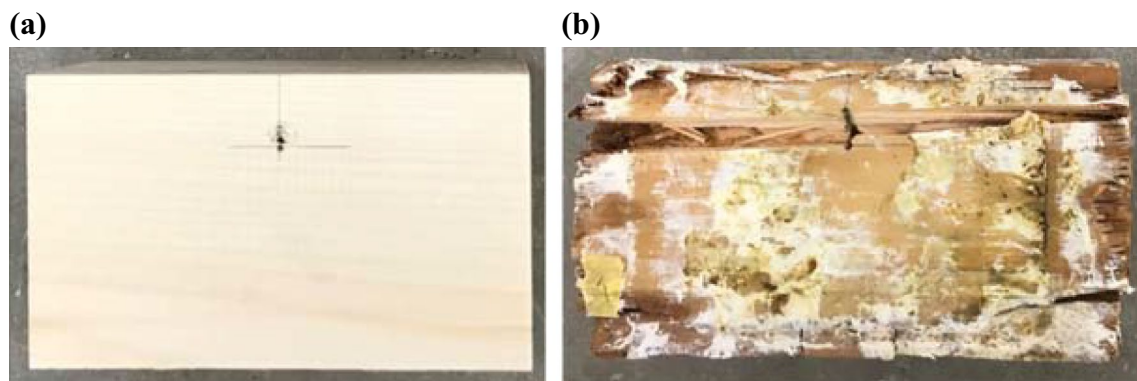


Fig. 9 Control specimen with nail withdrawal (a) and decayed specimen with main member splitting (b) after the shear tests perpendicular to the grain

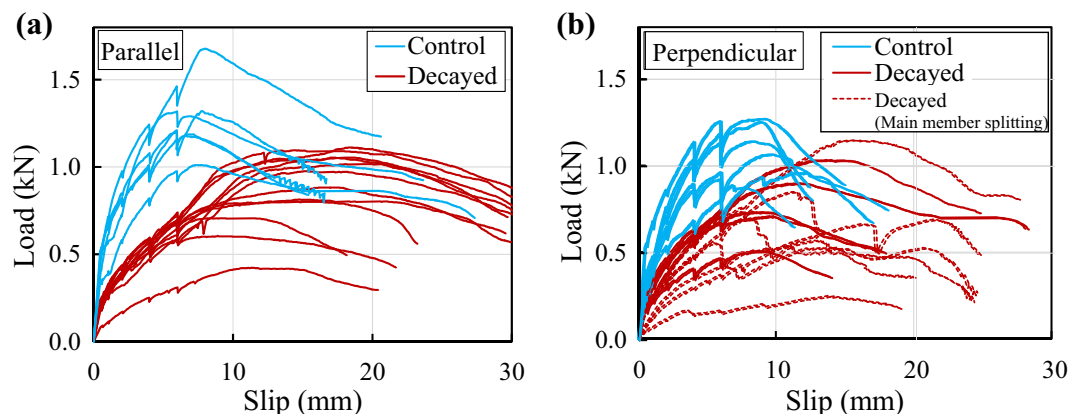


Fig. 10 Relationship between the load and slip of nailed joints parallel (a) and perpendicular (b) to the grain. The *solid line* curves are for the specimens that failed by nail withdrawal. The *broken line* curves are for the specimens that failed by main member splitting

5–21 mm. Both nailed joints parallel and perpendicular to the grain with decay showed a low load at the initial deformation and had a large variation in slip at the maximum load.

The nailed joints perpendicular to the grain exhibited two failure modes. In the case of un-decayed nailed joints perpendicular to the grain, nailed joints that failed by the main member splitting exhibited brittle load–slip curves [14]. However, decayed nailed joints perpendicular to the grain that failed by the main member splitting exhibited a somewhat lower load at initial deformation than nailed joints that failed by nail withdrawal, and the shapes of the load–slip curves were slightly different from that of the main member.

Shear properties of the nailed joints

The shear properties of the nailed joints were evaluated based on the initial stiffness (K_s), yield resistance (P_y), and maximum resistance (P_{max}). A perfect elastoplastic idealization scheme using 10, 40, and 90% of P_{max} [11, 20] was applied to the load–slip curves to obtain K_s and P_y . Figure 11 shows the values of K_s , P_y , and P_{max} of the nailed joints parallel and perpendicular to the grain. The values of K_s , P_y , and P_{max} were all significantly different between the control and decayed specimens in each loading direction at the 5% level. The K_s , P_y , and P_{max} values of the decayed specimen parallel to the grain were 68.4%, 39.2%, and 31.9% smaller, respectively, than those of the control specimen. For the nailed joints perpendicular to the grain, K_s , P_y , and P_{max} values of the decayed specimen were 60.2%, 40.3%, and 34.4% smaller, respectively,

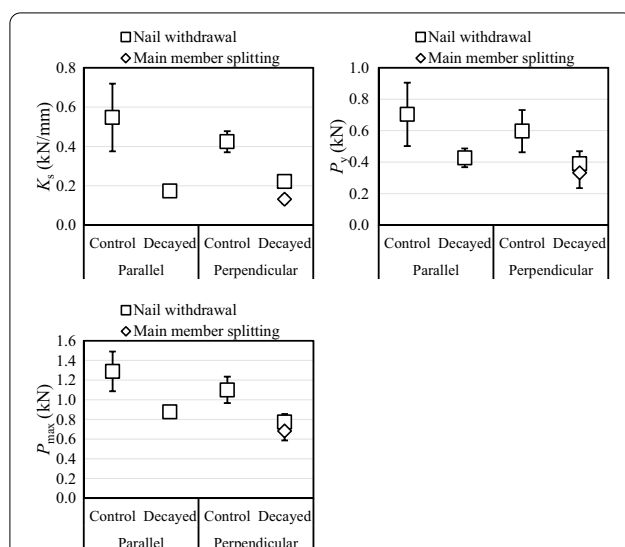


Fig. 11 Shear properties of nailed joints parallel and perpendicular to the grain. K_s , initial stiffness; P_y , yield shear resistance; P_{max} , maximum shear resistance

than those of the control specimen. There was no clear difference in the shear properties degradation of nailed joints depending on the loading directions. The value of K_s exhibited the largest decrease, followed by those of P_y and P_{max} for both the nailed joints parallel and perpendicular to the grain. On the other hand, some preceding studies on the nailed [2] and screwed [9, 11] joints parallel to the grain have reported that degradation of the initial stiffness was not present regardless of decay. In those studies, decay treatment was conducted on the surface of the specimens similarly as in this study; however, the effective length of the fasteners was 1.3–1.6 times that in this study. Presumably the long effective length of the fasteners maintained the initial stiffness in those studies, and the result in this study implied that degradation of the initial stiffness would be present if shorter fasteners were used. Compared to the failure mode of decayed specimens perpendicular to the grain, the decayed specimens that failed by the main member splitting showed lower K_s values than those that failed by nail withdrawal, and the former had almost the same P_y and P_{max} as the latter. The failure mode of the nailed joints perpendicular to the grain had little effect on the initial stiffness.

The values of K_s , P_y , and P_{max} of the decayed specimens were divided by the corresponding mean values of the control specimen, and the ratios of these shear properties were obtained. The relationship between the ratios of K_s and P_y and that of the ratios of P_{max} and P_y are shown in Fig. 12. The ratio of K_s did not exhibit an apparent correlation with the ratio of P_y , and the value of the former ranged from close to that of the latter to 73% lower than that of the latter. The ratio of P_{max} linearly decreased with decreasing P_y , and the value of the former was, on average, 10% higher than that of the latter. These tendencies did not change with the loading direction of the grains. When a wood member subjected to decay was divided into sound and decay regions and the yield mode of nailed joints was assumed according to the regions, the

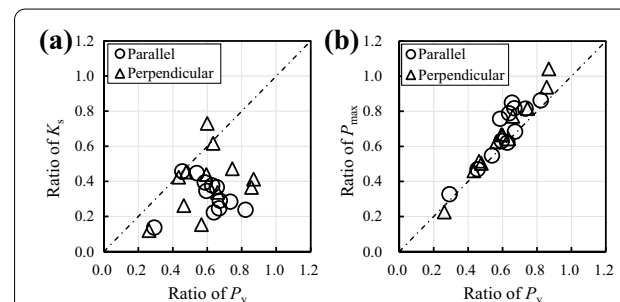


Fig. 12 Relationships between the ratio of initial stiffness (a) and the maximum resistance (b) and the ratio of yield resistance. K_s , initial stiffness; P_y , yield shear resistance; P_{max} , maximum shear resistance

yield resistance of the nailed joints with decay can be estimated using the European yield theory [8]. When calculated from the decayed state, the ratio of yield resistance is obtained from the theory, and the minimum ratio of initial stiffness and ratio of maximum resistance can be estimated from the results shown in Fig. 12.

Pilodyn penetration depth

The relationships between the shear properties of nailed joints parallel and perpendicular to the grain and d_p are shown in Fig. 13. The values of K_s , P_y , and P_{max} of the nailed joints parallel to the grain had a negative correlation with d_p , and P_y and P_{max} had a particularly significant negative correlation at the 5% level. The presence of negative correlation between d_p and P_y has been reported in preceding studies on nailed [7] and screwed [9, 10] joints parallel to the grain, and some compatibility of Pilodyn for the assessment of residual strength was similarly confirmed.

The d_p of the control specimens was ≤ 20 mm. The decayed specimens with $d_p \leq 20$ mm had smaller K_s , P_y , and P_{max} values than the control specimens, and the difference was significant at the 5% level. Nishino et al. [7] investigated the shear properties of nailed joints parallel to the grain with decayed main member and sound

side member, and reported that the nailed joints with decayed main member exhibited similar P_y to those with sound main member at d_p below 25 mm. This result is different from this study. Nishino et al. conducted the nailed joint tests using nails that have length of 50 mm and diameter of 2.75 mm, and the nails used in this study have the same length but a larger diameter, which was 2.87 mm. Because the cross-sectional dimensions greatly affect the geometrical moment of inertia and section modulus, those also would affect the change of shear properties of nailed joints by wood decay.

The values of K_s , P_y , and P_{max} of the nailed joints perpendicular to the grain with decay had no significant correlation with d_p at the 5% level, since those shear properties exhibited large variable with d_p . The decayed specimens perpendicular to the grain with $d_p \leq 20$ mm exhibited smaller K_s , P_y , and P_{max} values than the control specimens, and the difference was significant at the 5% level. The K_s , P_y , and P_{max} of decayed specimens with $d_p \leq 20$ mm had large variables, and some of them exhibited significantly small values. For some of the nailed joints perpendicular to the grain failed by the main member splitting, the load–slip curves exhibited large variables as shown in Fig. 10. Even if the d_p was within the range of those obtained from sound wood, the shear properties of nailed joints perpendicular to the grain subjected to wood decay might be significantly changed.

Decay depth

The relationships between K_s , P_y , and P_{max} of nailed joints parallel and perpendicular to the grain and decay depth (d_d) are shown in Fig. 14. The values of K_s , P_y , and P_{max} of the nailed joints parallel to the grain tended to decrease with increasing d_d . Those of the nailed joints perpendicular to the grain did not exhibit this tendency. Regardless of the loading direction to the grain, the values of K_s , P_y , and P_{max} of the decayed nailed joints with a small d_d greatly decreased. For example, when d_d was less than or equal to 2 mm, which is approximately 5% of the nail penetration length of the main member, the values of K_s , P_y , and P_{max} of the nailed joints parallel to the grain were 0.28–0.38, 0.63–0.73, and 0.62–0.85 times those of the control specimens, respectively. In the case of the decayed nailed joints perpendicular to the grain, the values were 0.12–0.73, 0.26–0.87, and 0.23–1.04 times the latter, respectively. The shear properties of nailed joints were significantly affected by a small decay depth, and the variable of decrease was larger for the nailed joints perpendicular to the grain than for those parallel to the grain.

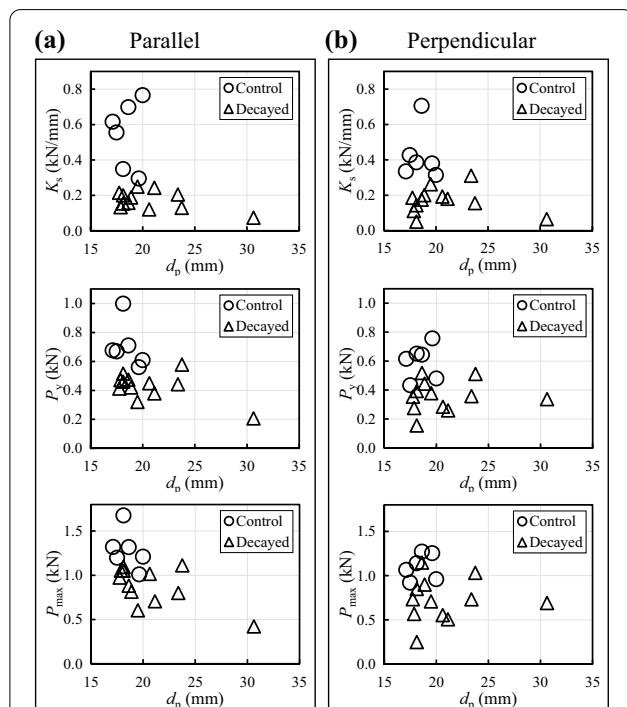
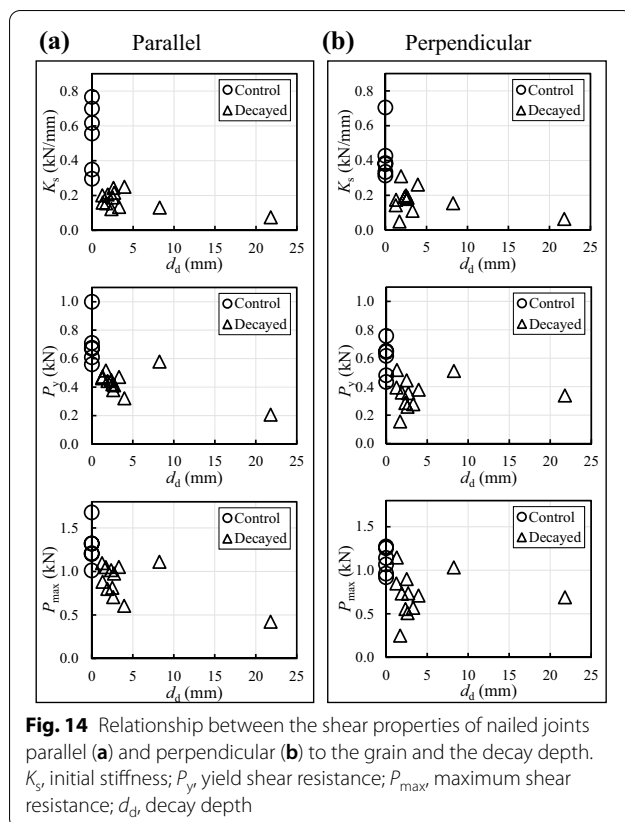


Fig. 13 Relationship between shear properties of nailed joints parallel (a) and perpendicular (b) to the grain and Pilodyn penetration depth. K_s , initial stiffness; P_y , yield shear resistance; P_{max} , maximum shear resistance; d_p , Pilodyn penetration depth



Conclusions

Shear tests were conducted on nailed joints parallel and perpendicular to the grain with a decayed main member, and the degradation of the shear properties of the nailed joints due to decay was investigated. The results can be summarized as follows:

1. The nailed joints with decay had a low load at the initial deformation, regardless of the loading direction to the grain. The failure modes of some of the decayed nailed joints perpendicular to the grain were different from those of the control nailed joints. The decayed nailed joints perpendicular to the grain that failed by the main member splitting mode exhibited a somewhat lower load at the initial deformation than the nailed joints that failed by nail withdrawal.
2. There was no clear difference in the shear properties degradation of nailed joints depending on the loading directions. The value of the initial stiffness exhibited the largest decrease, followed by the yield and maximum resistance for both the nailed joints parallel and perpendicular to the grain. Presumably in this study, the large decrease in the initial stiffness of the nailed joints resulted from the relatively short effective length of the nails. The initial stiffness did not

exhibit an apparent correlation with the decrease in yield resistance. The maximum resistance decreased linearly with decreasing yield resistance, and the former was approximately 10% higher than the latter.

3. The initial stiffness, yield resistance, and maximum resistance of nailed joints parallel to the grain were negatively correlated with the Pilodyn penetration depth, whereas those of nailed joints perpendicular to the grain exhibited large variation with the Pilodyn penetration depth and no significant correlation with the Pilodyn penetration depth at the 5% level. The Pilodyn penetration depth of the sound nailed joints was all not more than 20 mm. The initial stiffness, yield resistance, and maximum resistance of the decayed nailed joints with under 20 mm of Pilodyn penetration depth were significantly smaller than that of the sound nailed joints at the 5% level, for both those parallel and perpendicular to the grain. Some of the decayed nailed joints perpendicular to the grain with under 20 mm of Pilodyn penetration depth exhibited significantly low shear properties. Therefore, even if the obtained Pilodyn penetration depth was within the range of those obtained from sound wood, the shear properties of nailed joints perpendicular to the grain subjected to wood decay might be significantly changed.
4. The initial stiffness, yield resistance, and maximum resistance of nailed joints parallel to the grain tended to decrease with increasing decay depth, and those of nailed joints perpendicular to the grain did not exhibit a similar tendency. The shear properties of the nailed joints were significantly decreased by a small decay depth. The decrease in those perpendicular to the grain was larger than that in those parallel to the grain.

Abbreviations

K_s : Initial stiffness; P_y : Yield load; P_{max} : Maximum load; d_p : Pilodyn penetration depth; d_d : Decay depth.

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Authors' contributions

RU and KS performed plan building. RU and YS performed specimen preparation and test conduction. RU, KS, and TS performed discussion. RU and KS performed data analysis and manuscript writing. All authors read and approved the final manuscript.

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Availability of data and materials

The test materials, test method, and data were recorded as shown in the manuscript. Additional data are available from the corresponding author on reasonable request.

Declarations**Competing interests**

The authors declare no competing interest associated with this manuscript.

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