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Method for measuring the resistances produced on parallel and perpendicular veneers in plywood under nail embedment loading

Keita Ogawa*, Masaki Harada, Tatsuya Shibusawa and Kohta Miyamoto

Abstract

The resistance of wooden materials against embedment loading is an important property that governs the performance of timber joints with dowel-type fasteners including nails. When plywood is used as a sheet material in a nailed joint, veneers with different grain directions are simultaneously embedded. The resistance produced on individual veneers has to be measured to elucidate the embedment properties of plywood. This study proposes a method for measuring resistance on individual veneers. Embedment behavior was modeled using springs arranged in parallel, and the equations for calculating resistance on individual veneers were derived. Embedment tests were conducted using structural plywood composed of sugi or karamatsu. Mechanical behaviors of individual veneers were revealed as followings. In the initial range of deformation, the slope of the resistance–deformation relationship of the veneer with grain parallel to the load direction is higher than that of the resistance–deformation relationship of the veneer with grain perpendicular to the load direction. The parallel veneer began to yield under a low range of deformation, and the resistance of the perpendicular veneer under a high range of deformation became almost equal to that of the parallel veneer.

Keywords: Plywood, Embedment, Nail, Load–deformation relationship, Spring model

Introduction

Plywood-sheathed structural diaphragms with nailed joints are commonly used in the construction of light wooden frames or other types of structures. Past studies have shown that the in-plane shear resistance performance of the diaphragms is mainly dominated by the shear performance of the nailed joints [1–4]. The embedment behavior of wood by a nail is an important characteristic that strongly influences the shear performance of the joints. This characteristic has been used to analyze or predict shear performances on the basis of European Yield Theory [5, 6], elastic foundation model [7–12], and finite element method [13–15]. Therefore, the embedment behavior of wood and wood-based materials by a nail must be clarified. The embedment behaviors of various types of wooden materials by dowel-type fasteners have been investigated under different loading conditions. For example, Chui and Ni [16] conducted embedment tests on spruce, maple, and plywood specimens under reversed cyclic load. Jeon and Kong [17] evaluated the embedment behavior of glulam specimens made of Japanese cedar by ash pegs. Bal [18] investigated the characteristics of plywood reinforced with glass fiber fabric. Sawata and Sasaki [19] evaluated the embedment properties of decay-treated solid wood specimen.

When the load is applied to the structural diaphragms with nailed joints, the joints are loaded from many angles. Then, the influence of the grain direction of wood or wood-based material on the embedment behavior is of major concern. Jeong et al. [20] subjected glulam specimens made of Japanese cedar to embedment tests. They applied load on longitudinal, radial, and tangential directions and obtained the highest load capacity in the longitudinal direction. Bleron et al. [21] investigated the embedment characteristics of a gonfolo rose specimen with various grain directions. Under embedment

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load applied perpendicular to the grain direction, lower load at plastic threshold and higher maximum load were observed than the case of parallel.

Plywood is a wood-based panel material produced by alternately laminating veneers with parallel and perpendicular grain directions. The grain direction of each veneer may affect embedment behavior in plywood–solid wood nail joints. On the shear performance of plywood–solid wood nailed joints, the effect of the grain direction of plywood has been investigated under single-shear loading. Stewart [22] conducted a single-shear test with nailed joint specimens. He prepared two types of plywood joint specimens. In the joint specimes, the plywood was attached to become that the grain direction of surface veneer were parallel or perpendicular to the load direction. The load–deformation curves of the two types of specimens were not considerably different. Harada et al. [23] conducted the tests with similar types of specimen and reported no large difference in maximum load. However, the deformation at maximum load in the case of plywood with perpendicular grain of the surface veneer was higher than that of parallel grain. Meanwhile, Demirkir and Colakoglu [24] reported that stiffness was higher when the surface direction of plywood was parallel to the loading direction than when the surface direction of plywood was perpendicular to the loading direction. Hagiwara [25] reported no difference in shear performance between the parallel and perpendicular grain directions of plywood. However, when the angle between the grain and load directions was 30°, 45° or 60°, resistance performance decreased under a small load range.

The resistance of nailed joints under single-shear loading is determined by various factors, e.g., bending properties of nail, pull out strength of nail from wood, nail-head pull-through resistance. In addition, the combination of plywood embedment and solid wood embedment resistances is also one of the important factors for it; however, the above studies [22–25] did not ignore the resistance produced by solid wood. The authors posit that only the resistance produced in plywood should be considered to clarify the influence of the grain direction of plywood. Some studies have conducted embedment tests on plywood specimens [18, 26, 27], and Kamada [28] showed the experimental data of the two grain directions (i.e., the grain direction of surface veneer was parallel or perpendicular to the load direction) using 3-ply plywood made of larch. According to his data, the higher stiffness was observed when the grain direction of surface veneer was parallel to the loading direction, whereas almost same maximum load was observed in the two. In this study, an embedment test was conducted on plywood specimens with grain directions of surface veneers that are parallel and perpendicular to the load direction. Moreover, to understand the resisting mechanism of plywood precisely, the method for calculating the resistance–deformation relationship exhibited by individual parallel and perpendicular veneers was proposed.

Materials and methods

Plywood specimen

Structural plywood made of sugi (Japanese cedar, *Cryptomeria japonica* D. Don) and karamatsu (Japanese larch, *Larix kaempferi* Carr.) classified as Class 2 structural plywood in accordance with the Japanese Agricultural Standard [29] was used as the specimen. The plywood was made in Japan and had five plies and a thickness of 12 mm. Eight original sheets were produced by preparing four sheets from each species. Six specimens measuring 50 mm × 100 mm in size were removed from the original sheets. From one original sheet, three specimens with grain in the surface veneer parallel to the specimen's longitudinal direction (hereafter, longitudinal specimen) and three specimens with grain in the surface veneer parallel to the specimen's transverse longitudinal direction (transverse specimen) were obtained as shown in Fig. 1a. The provided original plywood sheets were composed of veneers with grain parallel and perpendicular to

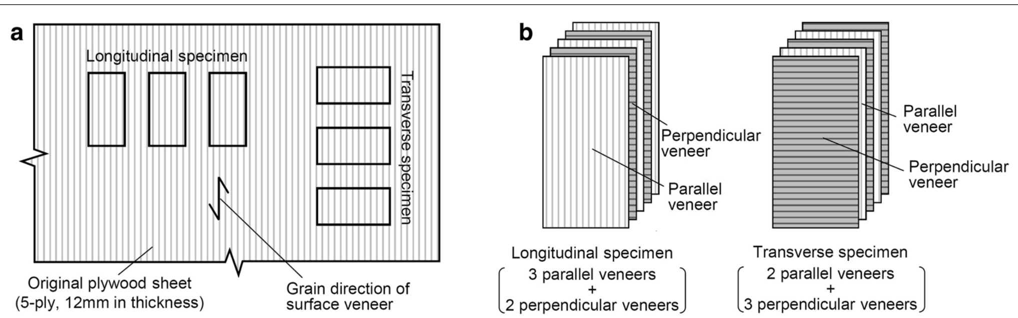

Fig. 1 Plywood specimens. **a** Sampling method of longitudinal and transverse specimens from an original sheet. **b** Veneer composition of longitudinal and transverse specimens

Table 1 Series of plywood specimens

Series	Species	Grain direction of surface veneer	Number of specimens
S_0	Sugi (Japanese cedar)	Parallel	12
S_{90}		Perpendicular	12
K_0	Karamatsu (Japanese larch)	Parallel	12
K_{90}		Perpendicular	12

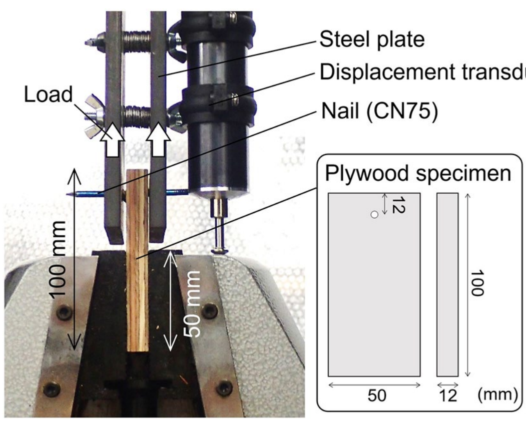

Fig. 2 Plywood specimen and experimental setup

the load direction (hereafter, parallel and perpendicular veneer). The composition of longitudinal and transverse specimens is shown in Fig. 1b. Table 1 presents the four series of specimens. The total number of specimens was 48. These specimens had been placed in a conditioning testing room at 20 °C and 65% relative humidity for more than 1 month. The sugi plywood specimen had a density of 423 ± 22 kg/m^3 (average ± standard deviation) and moisture content of 10.3 ± 0.3%; whereas, the karamatsu plywood specimen had a density of 626 ± 24 kg/m^3 and moisture content of 10.1 ± 0.3%.

Embedment test

The embedment test was conducted in accordance with the American Society for Testing Materials (ASTM) standard D1037-12 [30]. However, the specimen size was different from that recommended by the standard method. The experimental setup is shown in Fig. 2. A CN75 nail [31] with a trunk diameter of 3.76 mm was driven into the specimen at a point 12 mm below the top side. The specimen was set to an Instron-type tension–compression testing machine (MinebeaMitsumi, Inc., (formerly Shinko Co., Ltd.), TOM-5000X; capacity: 49.5 kN). The nail part of the specimen was hooked to the holes with diameter of 10 mm installed to two steel plates, and the gaps between the plates and plywood were maintained at 1 mm. The plywood part was grabbed with a chuck. The embedment load by the nail was applied to the plywood by moving up the steel plates. The load was measured with a load cell (MinebeaMitsumi, Inc., (formerly Shinko Co., Ltd.), TT3-5T; capacity: 49.5 kN), and deformation was measured with a displacement transducer (Tokyo Sokki Kenkyujo Co., Ltd., CDP-50, capacity 50 mm) connected to the steel plate (Fig. 2). The grabbed length in this setup exceeded 50 mm. In this grabbed length, the slip that occurred around the chuck was too small and the slip was ignored in the analysis. Load was applied at the speed of 0.5 mm/min. After reaching the maximum load, load was continuously applied until it decreased to 80% of the maximum.

Results and discussion

Embedment test results

Figures 3 and 4 present the load–deformation relationships. Each graph shows the results for three longitudinal and three transverse specimens obtained from one original structural plywood. The solid lines represent the longitudinal specimens (Series S_0 in Fig. 3 and Series K_0 in Fig. 4), whereas the dotted lines represent the transverse specimens (Series S_{90} in Fig. 3 and Series K_{90} in Fig. 4). The thin lines denote the experimental results, whereas the thick lines denote the average results obtained by averaging the value of the load of the three specimens under the same deformation. Comparing the averaged results of longitudinal and transverse specimens (solid and dotted thick lines) revealed that the longitudinal specimen has a slightly larger load value than the transverse specimen in the rage from the beginning of the testing to approximately 1 mm in deformation. The difference in the load value decreased as the deformation increased.

Failure mode observed around nail part is illustrated in Fig. 5. An embedment deformation was observed in parallel and perpendicular veneers. At the end of the loading, in parallel veneer, trapezoidal failure occurred; whereas in perpendicular veneer, only the embedment deformation was observed. The failure modes were observed in both longitudinal and transverse specimens.

Stiffness and maximum load were calculated from the load–deformation relationships of all the specimens. Stiffness was derived as the slope with linear regression to the data plots in the range of 10–40% maximum load through the least-squares method. Figure 6 depicts the average values and the standard deviations of stiffness and maximum load. For example, the average stiffness of Series S_0 was 3.23 kN/mm, whereas that of Series S_{90} was 1.99 kN/mm, which was considerably lower than that of S_0. In the case of Series K_0 and K_{90}, average values of

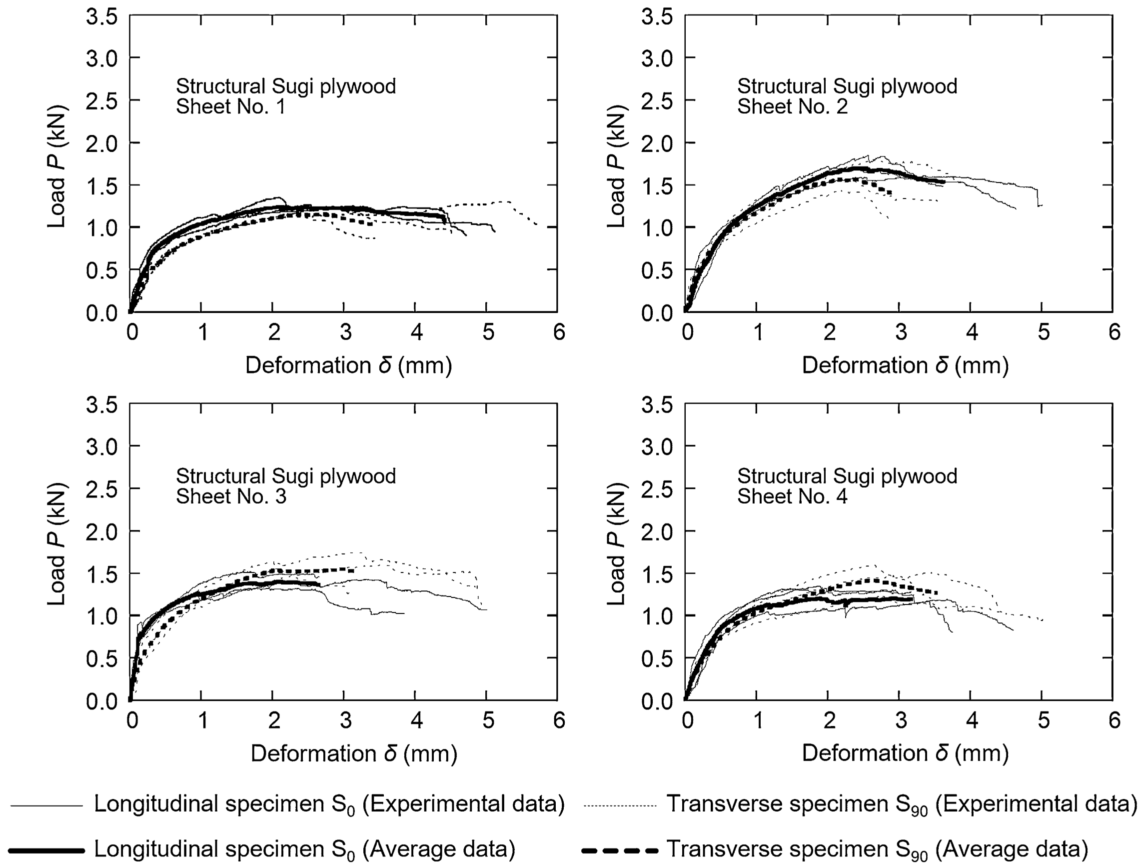

Fig. 3 Results of embedment test of nail in structural sugi plywood specimens (S_0 and S_{90})

stiffness were 3.24 and 2.25 kN/mm, respectively, which also had a large difference between the two. The calculation of the *t*-test showed that there were significant differences in stiffness between S_0–S_{90} and K_0–K_{90} at a significance level of 0.05. However, the average maximum load of series S_0 and S_{90} was 1.45 and 1.49 kN, indicating that the two series provide an almost equal value of maximum load. Similar results were observed for the karamatsu plywood: maximum loads of K_0 and K_{90} were 2.45 and 2.47 kN, respectively. The calculation of the *t*-test showed that there were no significant differences in maximum load between S_0–S_{90} and K_0–K_{90} at a significance level of 0.05. The results indicated that the grain direction of the surface veneer considerably affects stiffness but negligibly affects maximum load under embedment resistance.

Method for calculating the load–deformation relationships of parallel and perpendicular veneers

To understand the embedment behavior of plywood precisely, this section describes a method for calculating the resistance produced on individual veneers under embedment loading. This method uses the load–deformation relationships shown in Figs. 3 and 4. Figure 7 shows the model of specimen deformation under nail embedment load. The model was constructed with springs. Figure 7a shows the schematic of the nail region of the specimen. The nail was embedded in the plywood by moving up the steel plates. In the case that the plywood is sufficiently thin, two assumptions could be imposed on the model: First, the nail is bent at the plywood surface. Second, the shape of the nail in the plywood remains linear (i.e., embedment deformation is equal in the five veneers).

On the basis of these assumptions, the specimen was modeled with springs (Fig. 7b). The read value from the displacement transducer (Fig. 2) includes two deformations: the bending deformation of the nail [(A), Fig. 7b] and the embedment deformation of the plywood [(B), Fig. 7b]. The read value from the displacement transducer deformation δ is the sum of the bending deformation of the nail δ_{nail} and the embedment deformation of the plywood δ_{ply}:

$$\delta = \delta_{nail} + \delta_{ply} \tag{1}$$

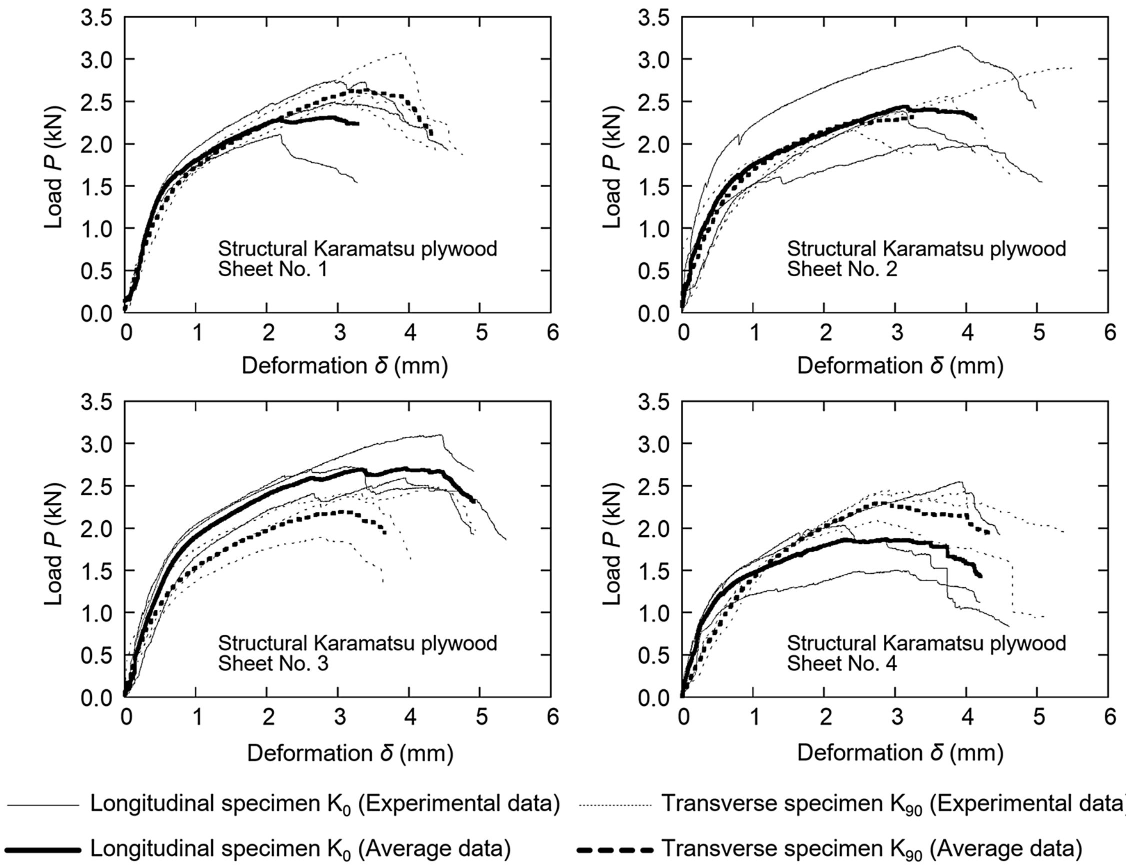

Fig. 4 Results of embedment test of nail in structural karamatsu plywood specimens (K_0 and K_{90})

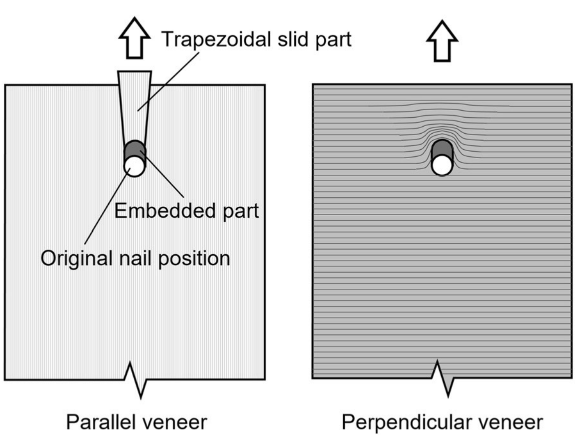

Fig. 5 Failure modes observed around nail part

Therefore, the relationship between load P and the embedment deformation of the plywood δ_{ply} [i.e., only the relationship in part (B)] could be calculated by obtaining the bending deformation of the nail δ_{nail}.

The five springs in the model of the embedment deformation of plywood indicate that each veneer was arranged in parallel. Here, the load value of the longitudinal specimen at deformation δ_{ply} was denoted as $P_{ply.0}$. Similarly, the load value of the transverse specimen at deformation δ_{ply} (same deformation with the case of $P_{ply.0}$) was denoted as $P_{ply.90}$. If the thicknesses of five veneers was equal, the two load values could be represented with the nail embedment resistances produced on the parallel $R_{ven.0}$ and perpendicular $R_{ven.90}$ veneers as follows:

$$P_{ply.0} = 3R_{ven.0} + 2R_{ven.90} \tag{2}$$

$$P_{ply.90} = 2R_{ven.0} + 3R_{ven.90} \tag{3}$$

The resistances $R_{ven.0}$ and $R_{ven.90}$ under the embedment deformation of plywood δ_{ply} are represented as the simultaneous solution to Eqs. (2) and (3) as follows:

$$R_{ven.0} = \frac{3P_{ply.0} - 2P_{ply.90}}{5} \tag{4}$$

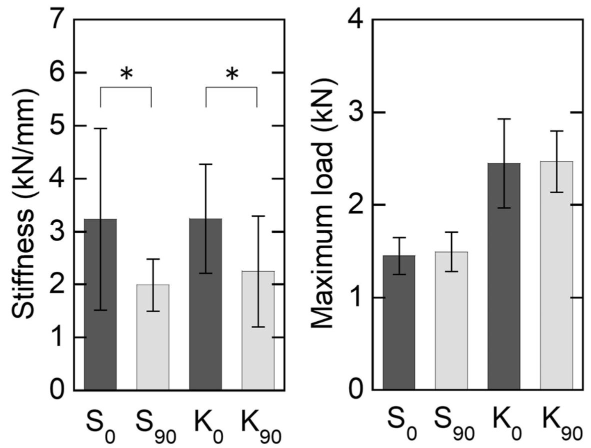

Fig. 6 Average values and the standard deviations of stiffness and maximum load obtained by the embedment test. *Significant difference observed at a significance level of 0.05

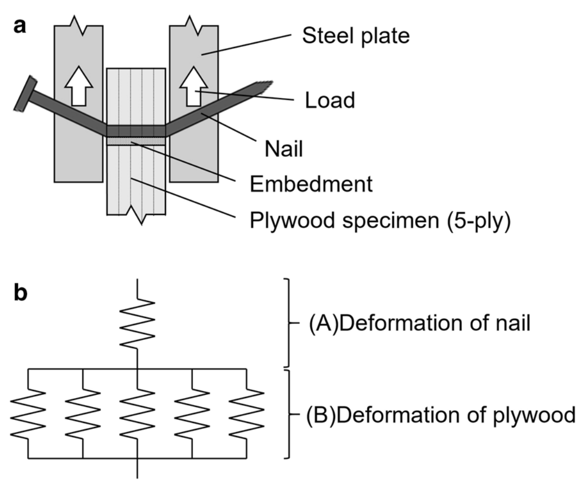

Fig. 7 A model of specimen deformation. **a** Schematic diagram of deformation. **b** A spring model

$$R_{\mathrm{ven.90}} = \frac{-2P_{\mathrm{ply.0}} + 3P_{\mathrm{ply.90}}}{5} \tag{5}$$

The relationships between the resistance and deformation of each veneer could be obtained by calculating the resistances under various δ_{ply}.

Figure 7 and Eqs. (2)–(5) were supposed that all of thickness of veneers in the provided plywood is equal. However, in the case that a plywood is applied surface smoothing, the assumption is not true because the thickness of surface veneer becomes thin. Although the Eqs. (4) and (5) cannot be used, the resistance produced at individual veneers can be calculated with alternative equations derived by the model similarly to the above. For this, the thickness of individual should be measured. The resistance can be calculated by following equations with the sum of thickness of parallel veneers t_0 and sum of thickness of perpendicular veneers t_{90}:

$$R'_{\mathrm{ven.0}} = \frac{t_0 \cdot P_{\mathrm{ply.0}} - t_{90} \cdot P_{\mathrm{ply.90}}}{t_0^2 - t_{90}^2} \tag{6}$$

$$R'_{\mathrm{ven.90}} = \frac{-t_{90} \cdot P_{\mathrm{ply.0}} + t_0 \cdot P_{\mathrm{ply.90}}}{t_0^2 - t_{90}^2} \tag{7}$$

It should be noted that $R'_{\mathrm{ven.0}}$ and $R'_{\mathrm{ven.90}}$ in Eqs. (6) and (7) are the resistances per thickness.

Resistance–deformation behavior of each veneer

The relationship between the load and deformation behavior of each veneer was graphed by the experimental results and the proposed model. The bending deformation of the nail has to be measured through an additional test to enable analysis with the proposed method. The additional test was conducted in the same setup as shown in "Embedment test" of "Materials and methods" section (Fig. 2). The plywood was replaced with a steel plate having a hole (12 mm in thickness). Therefore, the nail was fixed by the three steel plates, and bent by moving up the two steel plates. During the test, the nail was deformed similarly to the case of using plywood, i.e., it could be assumed that the nail kept lineally at the contacted area between the nail and the replaced steel plate. Figure 8 shows the relationship between load P and deformation δ_{nail} obtained through the test. The thin lines represent the experimental data, whereas the thick line represents the averaged data. The deformation of the plywood δ_{ply} was calculated using the results of the embedment test (relationship between P and δ shown in Figs. 3 and 4) and the nail test (relationship between P and δ_{nail} shown in

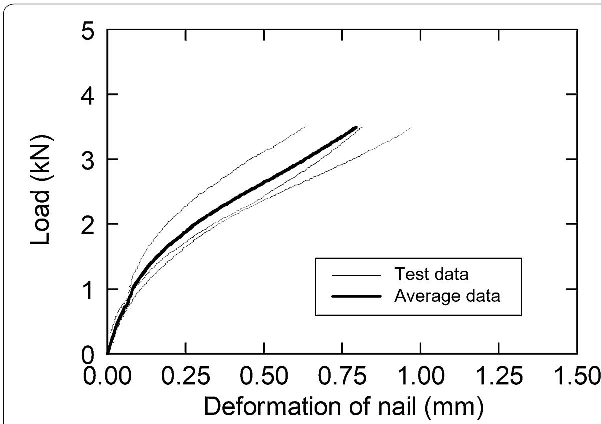

Fig. 8 Load–deformation relationship of nail

Fig. 8). Under the same load value P, the deformation of nail δ_{nail} (Fig. 8) was subtracted from the read value from the displacement transducer δ (Figs. 3 and 4) to calculate the deformation of plywood δ_{ply} [Eq. (1)]. The relationship between load P and deformation δ_{ply} was obtained by calculating deformation δ_{ply} under various load P values.

The relationships between resistances $R_{ven.0}$ and $R_{ven.90}$ and the deformation δ_{ply} of each veneer were calculated on the basis of the relationships between load P and deformation δ_{ply} (Load P was substituted to $P_{ply.0}$ and $P_{ply.90}$ in the cases of longitudinal and transverse specimens, respectively) using Eqs. (4) and (5). Herein, the relationships were calculated for each original plywood sheet, i.e., the result obtained for one original sheet (shown as solid and dotted thick lines in Figs. 3 and 4) was used for calculation, and the results for other original sheets were calculated through the same method. Four results for the sugi plywood and four results for the karamatsu plywood were obtained and are shown in Fig. 9. The solid lines denote the results for the parallel veneers, whereas the dotted lines denote those for the perpendicular veneers. The thin lines represent the calculated results for one original sheet, whereas the thick lines represent the averaged results obtained with the average value of resistance under the same deformation in four solid/dotted thin lines. Although there is no significant variation in the relationships of plywood specimens (Figs. 3 and 4), the relationships in Fig. 9 have a wide variation. The reason for it is assumed that Fig. 9 focused on the veneers having a characteristic in small thickness, i.e., it was discussed about resistance produced on very local area of wood. The subtle difference in wood properties (e.g., density, ring width, and so on) might influence the relationships of veneers largely. In the following, the relationships of veneers were discussed with average results; however, it is desired that the variation should be taken in consideration when discussing on the relationships in future study.

Comparing the results for parallel and perpendicular veneers (shown as solid and dotted thick lines) reveals that the resistance of the former had a larger slope than the that of the latter during the initial stage of the test. The slope of the parallel veneer began to become small gradually under approximately 0.3 mm of deformation, then kept the resistance after it. The perpendicular veneer increased its resistance until under approximately 2.0 mm of deformation. The two thick lines intersected when deformation reached approximately 2.0 mm (i.e., no difference attributable to the resistance contributed by the grain direction of the veneer was observed under such a large deformation).

Next, the obtained behavior (Fig. 9) was discussed by comparing with past reports on the anisotropic strength properties of plywood. Asano and Tsuzuki [32] attempted to reveal the compression properties of veneer by conducting compression tests on Lauan plywood specimens. They reported that perpendicular veneer shows low modulus of elasticity and strength. This tendency was experimentally confirmed by Kuwamura [33], who subjected veneer specimens to an in-plane compression test under steel-plate loading and found that the compression strength of parallel veneer was approximately 7.5 times higher than that of perpendicular veneer. Although the resisting behavior in this study (Fig. 9) revealed the difference between parallel and perpendicular veneers, the difference was not as large as the results of above reports [32, 33]. This result may be attributed to differences in loading conditions, loaded with steel plate or nail. Some researchers have reported [34, 35] that when fastener diameter is sufficiently small, the contribution of grain direction to differences in characteristics of embedment

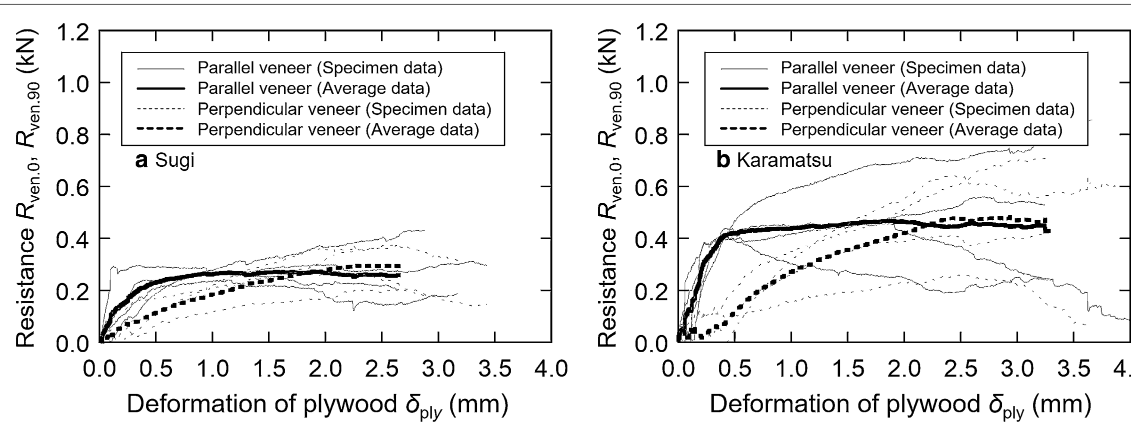

Fig. 9 Resistance–deformation relationship produced on parallel and perpendicular veneers

behavior decreases. The diameter of the nail used in this study is small enough to reduce the influence of grain direction. This effect, in turn, may have resulted in the smaller differences than compression results obtained under steel-plate loading.

Conclusion

To analyze the mechanical properties of nailed joint, precisely understanding of the deformation around nail is important. This study conducted the nail embedment test with plywood specimens for comparing the behaviors between different grain direction in surface veneer. Sugi and karamatsu plywood specimens with thicknesses of 12 mm (5-ply) were loaded by a CN75 nail in accordance with the ASTM setup. This test revealed that the grain direction of the surface veneer considerably affects stiffness but negligibly affects maximum load under embedment resistance.

Additionally, the authors tried to calculate the resisting behavior produced on individual veneers. The presented method clarifies the mechanical contribution of veneers with parallel and perpendicular grain to the resisting behavior of plywood under embedment loading by a nail, which helps to understand the deformation of plywood in detail. The proposed method was developed on the basis of a plywood deformation model constructed with springs arranged in parallel. The experimental results showed that under low deformation, the parallel veneer had a higher slope than the perpendicular veneer. The parallel veneer began to yield under approximately 0.3 mm of deformation, whereas the perpendicular veneer began to yield under approximately 2.0 mm of deformation. The deformation behaviors of the two veneers were negligibly different when deformation exceeded 2.0 mm. It is hoped that the results become one of the basic academic knowledge for evaluating the mechanical behavior of nailed joint under loading from many angles.

Future investigations are required to confirm the validity of the proposed method. The proposed method must be applied to plywood specimens with other thicknesses/compositions because this study focused on limited types of plywood specimens. Additionally, the proposed model assumes that the shape of the nail in plywood remains linear and embedment deformation is assumed equal in the five veneers. Under actual loading conditions (e.g., single-shear load), the model should be modified to consider the unequal embedment deformation among veneers in plywood. Therefore, future studies are required to use the presented results for analyzing the mechanical behavior of plywood-sheathed nailed joints.

Authors' contributions

KO performed the embedment test, and was a major contributor in writing the manuscript. MH was a co-performer of the test. TS and KM contributed to the interpretation of the data. MH, TS, and KM contributed to improve the quality of the manuscript. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

The test materials, test method, and the data we recorded are shown in the manuscript with uncolored descriptions.

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