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ORIGINAL ARTICLE

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Effects of density profile of MDF on stiffness and strength of nailed joints

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Abstract Nail-head pull-through, lateral nail resistance, and single shear nailed joint tests were conducted on medium density fiberboard (MDF) with different density profiles, and the relations between the results of these tests and the density profiles of MDF were investigated. The maximum load of nail-head pull-through and the maximum load of nailed joints were little affected by the density profile. However, the ultimate strength of lateral nail resistance, the stiffness, and the yield strength of nailed joints were affected by the density profile of MDF and showed high values when the surface layer of the MDF had high density. It is known that bending performance is also influenced by density profile. Therefore, the stiffness and the yield strength of nailed joints were compared with the bending performance of MDF. The stiffness of nailed joints was positively correlated with the modulus of elasticity (MOE); in the case of CN65 nails, the initial stiffness of joints changed little in response to changes in MOE. The yield strength of nailed joints had a high positive correlation with the modulus of rupture (MOR). The stiffness and the yield strength of nailed joints showed linear relationships with MOE and MOR, respectively.

Key words Press closing speed · Nail-head pull-through · Lateral nail resistance · Single shear joint · Density profile

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Introduction

Recently, there have been numerous examples of the use of wood-based panels for important structural parts like bearing walls, floors, and roof sheathings. While there are many kinds of wood-based panels, it is expected that more attention will focus on mat-formed materials such as medium-density fiberboard (MDF) and particleboards, because they have wide raw material selectivity that can utilize demolition residuals, factory waste, small-diameter logs, and low-quality wood.

The mechanical properties of MDF and particleboard depend on how they are manufactured. Therefore, research has been conducted on the influence of manufacturing methods on bending performance, internal bond strength, thickness swelling, and the linear expansion of MDF[1,2] and particleboard.[3–5]

Because these mechanical properties provide valuable information for evaluating the characteristics of wood-based materials, the authors had previously investigated the influence of the density profile of MDF on bending performance.[2] In order to utilize these mat-formed materials as structural members of wooden structures, it is important to evaluate the nailed joint performance.

Several research studies of nailed joint performance have been conducted on commercial mat-formed materials.[6,7] However, these studies mainly described the maximum load of nailed joints, and did not deal with the general shear performance of nailed joints, such as initial stiffness and yield strength. Furthermore, there is little research that has examined the relation between the manufacturing methods of the mat-formed materials and the performance of nailed joints, and there is only one such example for particleboard.[8]

In this study, nail-head pull through, lateral nail resistance, and nail joint shear tests were conducted on four types of MDF with different density profiles to examine the influence of density profile on nailed joint performance, and to consider the suitability of a method for estimating nailed joint performance from the bending performance.

Materials and methods

Preparation of the MDF test pieces

The raw material, consisting of wood fiber produced from sawmill waste of sugi (*Cryptomeria japonica* D. Don), was dried until the moisture content reached 6.8%. A melamine urea co-condensed resin (Honen, MB-240, solid content 60%) was used as a binder. A 20% ammonium chloride solution equivalent to 10% of the weight of adhesive was added to the adhesive as a curing agent. Distilled water was added to the adhesive to give the fiber mat a moisture content of 16% (including the ammonium chloride solution) after adhesive spraying.

The adhesive was sprayed until a fiber mat with 12% resin content and fiber mat was formed by hand. The fiber mat was hot-pressed in a one-step or two-step method with a positional control-type hot press (Yamamoto Eng. Works, TA-200-1W) at 180°C. The two-step method was adapted to form a high-density inner layer. Press closing speeds of the one-step method were set at 10.0, 2.0, and 0.5 mm/s, and the press time was set at 9 min after the mat thickness reached the target board thickness of 12 mm.

For the two-step method, press closing speed was set at 10.0 mm/s until the mat thickness reached 50% (540 mm) of its initial value. After maintaining this condition for 6.5 min, the press closing speed was changed to 2.0 mm/s and was maintained for 2 min after the mat thickness reached the target board thickness of 12 mm. Table 1 shows the hot press schedule and the names of sample panels.

The sample panel dimensions were 500 mm long × 500 mm wide × 12 mm thick, and the target panel density was 0.7 g/cm^3. The average density of the sample panels PCS10, PCS2, PCS0.5, and PCS10-2 were 0.72, 0.72, 0.71, and 0.70 g/cm^3, and the standard deviations were 0.02, 0.01, 0.03, and 0.02 g/cm^3, respectively.

Figure 1 shows the density profile of sample panels measured by density profiler (GreCon DA-X). The dimensions of the test pieces were 50 mm long × 50 mm wide × 12 mm thick, and six pieces were cut from the center and the edge of the sample panel. PCS10 and PCS2 had a high-density layer in the surface area. On the other hand, PCS0.5 and PCS10-2 had a low-density layer in the surface area while the density of the inner layer was high. The shapes of the density profiles of PCS10 and PCS2 were close to that of commercial MDF.[9]

Table 1. Symbols of specimens and press schedules of medium-density fiberboard

Symbol	Pressing method	Press closing speed (mm/s)	Press time (min)	Target thickness (mm)
PCS10	One step	10.0	9.0	12
PCS2	One step	2.0	9.0	12
PCS0.5	One step	0.5	9.0	12
PCS10-2	Two step	10.0 → 2.0	6.5 → 2.0	540 → 12

Figure 2 shows the average density of the layer from the surface of the panel to each position along the thickness direction (hereafter called the *average layer density*). The average layer density of sample panels PCS10 and PCS2 approached the target panel density from a state of high density as the distance from the surface increased. In contrast, the average layer density of sample panels PCS0.5 and PCS10-2 approached the target panel density from a state of low density as the distance from the surface increased. The average layer density of PCS0.5 became about 0.7 g/cm^3 when the distance from the surface was about 3 mm or more, while the average layer density of PCS10-2 became about 0.7 g/cm^3 when the distance from the surface was about 6 mm.

The test pieces of nailed joint were obtained from these sample panels. All test pieces were seasoned under conditions of 20°C and 65% relative humidity (RH) until they reached a constant mass in the environment.

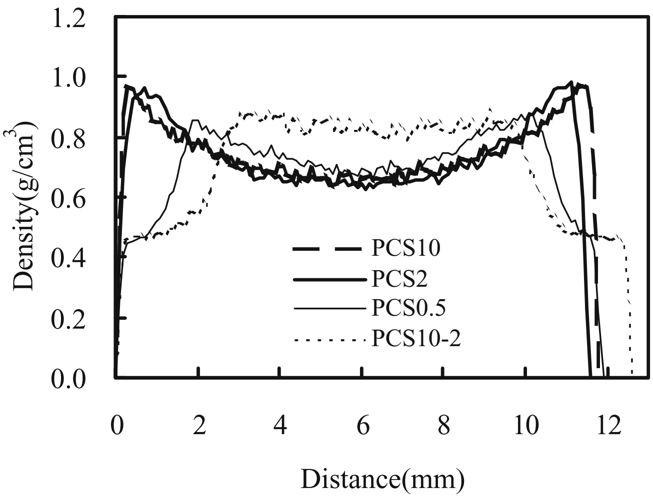

Fig. 1. Density profiles along the board thickness direction for 12-mm medium density fiberboard (MDF)

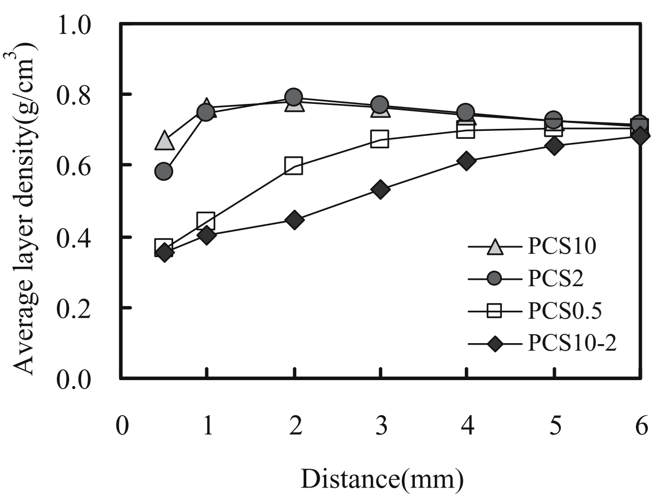

Fig. 2. Average layer density of the layer from the surface to various depths of 12-mm MDF

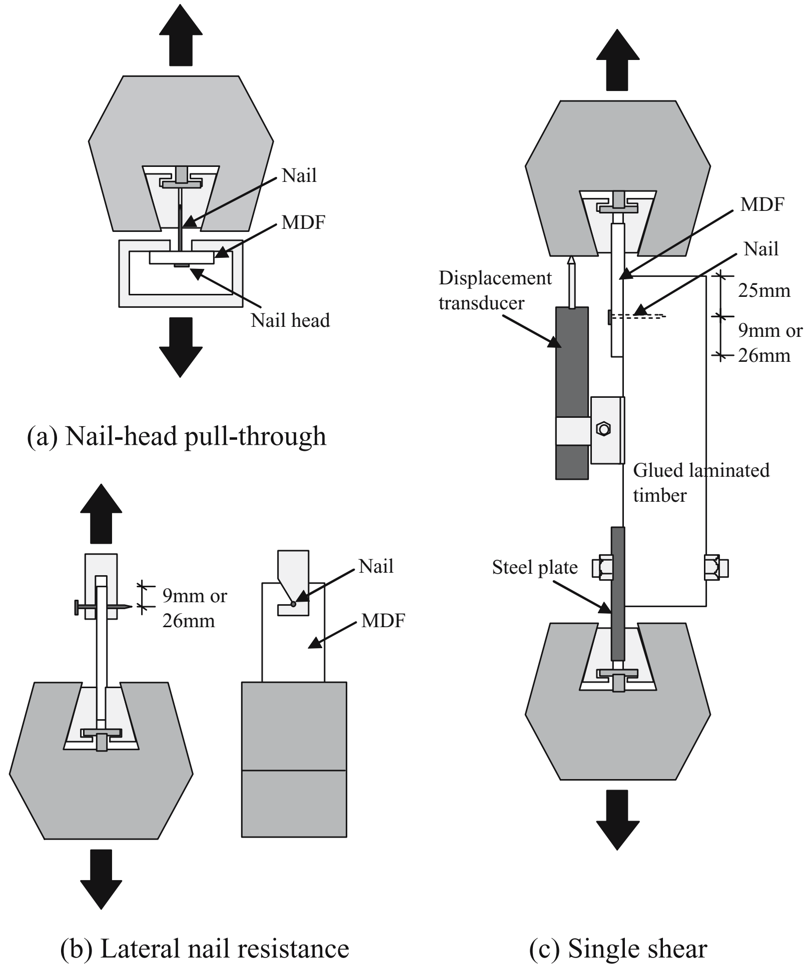

Fig. 3a–c. Configurations of nailed joint tests. **a** Nail-head pull-through test, **b** lateral nail resistance test, **c** single shear test

Nail-head pull-through test

Figure 3 shows the configuration of the nailed joint tests. The dimensions of the nail-head pull-through test pieces were 50 mm long × 50 mm wide × 12 mm thick, and the average moisture contents of the test pieces were: PCS10, 7.3%; PCS2, 7.5%; PCS0.5, 7.8%; and PCS10-2, 9.3%. CN50 or CN65 nails were used. Penetrated tip holes having diameters of 2.5 mm for CN50 (about 87% of the nail diameter) and 3.0 mm for CN65 (about 90% of the nail diameter) were installed before nailing because the nail could be driven at a right angle with the test piece surface. The nails were driven by hand hammering. Three or four test pieces were measured according to ASTM D1037.[10] The slit width of the specimen holding fixture was 25 mm.

A monotonic load was applied to the test pieces at an average deformation speed of 2.0 mm/min. The measurements ended when the load had decreased to 80% of the maximum load.

Lateral nail resistance test

The dimensions of the lateral nail resistance test pieces were 80–100 mm long × 50 mm wide × 12 mm thick, and the average moisture contents were: PCS10, 7.4%; PCS2, 7.6%; PCS0.5, 7.9%; and PCS10-2, 9.3%. Measurements were taken according to ASTM D1037.[10] The clearance between the test piece and the jig was 0.75 mm on one side. CN50 or CN65 nails were used. The edge distance of MDF was determined based on wood-framed houses and Japanese conventional post-and-beam houses. When MDF was jointed to the studs of 204 dimension lumber and to the posts of 105-mm square lumber, the edge distances of MDF were 9.5 and 26.25 mm, respectively. Therefore, the edge distance was set at 9 or 26 mm. Penetrated tip holes were installed in MDF similar to the nail-head pull-through test. Seven test pieces were examined.

A monotonic load was applied to the test pieces at an average deformation speed of 2.0 mm/min. When the load had decreased to 80% of the maximum load or deformation became twice the nail diameter, the measurements were ended.

Single shear test of nailed joints

Using the other end of the lateral nail resistance test pieces, a single shear test of nailed joints was carried out. Spruce (*Picea abies*) glulam samples 250 mm long × 50 mm wide × 50–70 mm thick, having an average air-dry density of 0.47 g/cm^3 and average moisture content of 12.5%, were used for the frame members. The grade of the glulam was E105-F345, according to Japanese Agricultural Standard. The glulam was grouped according to the mean value of the air-dry density so that standard deviations were uniform among the test pieces. CN50 or CN65 nails were used. In this study, nail heads were slightly floated to avoid a significant frictional force between the MDF and the glulam. The nails were arranged perpendicular to the interface of the lamina. The edge distance of MDF was assumed to be one of the two possibilities (9 and 26 mm). Penetrated tip holes were installed in MDF similar to the nail-head pull-through test.

A monotonic load was applied to the test pieces at an average deformation speed of 2.0 mm/min. The relative displacement between the glulam and the tensile jig was measured with a displacement transducer. The measurements were ended when the load had decreased to 80% of the maximum load or when relative displacement reached 30 mm.

Results and discussion

Nail-head pull-through maximum load

The nail-head pull-through test pieces showed three types of failure. PCS10 and PCS2 showed caving of nail heads, PCS0.5 showed both caving of nail heads and bending between nailed joint parts and tensile jigs, and PCS10-2 showed bending.

The nail-head pull-through load was evaluated by maximum load ($P_{max,p}$).[10] Figure 4 shows the relation between the bearing force of CN50 joints and the average board density. There was a positive correlation between $P_{max,p}$ and the average board density. The experimental value was corrected based on the standard density, 0.7 g/cm^3, to examine the influence of the density profile on the experimental value.

Figure 4 also shows the ultimate lateral nail resistance load ($P_{u,l}$) and maximum single shear load ($P_{max,s}$) of the 9-mm edge distance with CN50. A similar density correction of the bearing force was done for the initial stiffness and the bearing force that had been obtained from the lateral nail resistance test and single shear test of nailed joints. Table 2 shows all test results.

Figure 5 shows $P_{max,p}$ of the four types of MDF. Although PCS0.5 had a much different density profile from PCS10 and PCS2 (Fig. 1), the $P_{max,p}$ values were almost the same. PCS10-2 showed the lowest value among the four types of MDF. This tendency was the same regardless of the nail type.

Because the bending strength[2] of PCS10-2 [modulus of rupture (MOR) 8.4 MPa] was extremely low [about 0.3

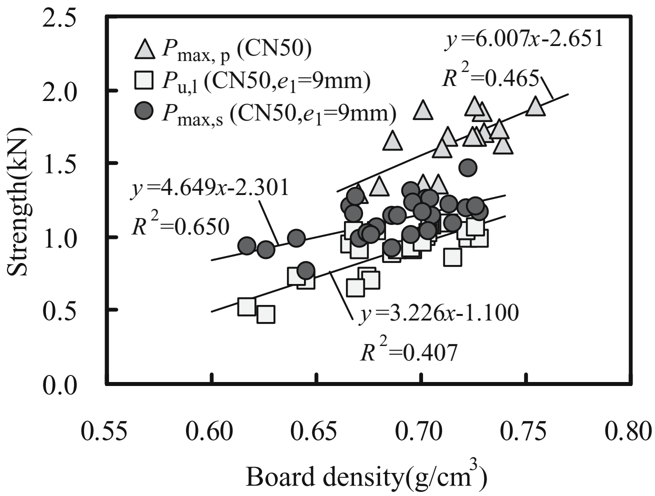

Fig. 4. Relations between strengths of nailed joint (CN50 nails) obtained from three load tests and board density. $P_{max,p}$, Maximum pull-through load; $P_{u,l}$, ultimate lateral nail resistance load; $P_{max,s}$, maximum single shear load

Table 2. Results of nail-head pull-through tests, lateral nail resistance tests, and single shear tests of nailed joints

Nail	Board	$P_{max,p}$ (kN)[a]	$F_{e,l}$ (N/mm^2)[b]		$K_{s,s}$ (kN/mm)[c]		$P_{y,s}$ (kN)[c]		$P_{max,s}$ (kN)[c]	
			e_1 = 9 mm	e_1 = 26 mm	e_1 = 9 mm	e_1 = 26 mm	e_1 = 9 mm	e_1 = 26 mm	e_1 = 9 mm	e_1 = 26 mm
CN50	PCS10	1.61 (0.04)	29.51 (1.88)	40.50 (2.45)	0.91 (0.24)	0.89 (0.14)	0.65 (0.04)	0.67 (0.05)	1.14 (0.07)	1.75 (0.13)
	PCS2	1.66 (0.07)	30.58 (1.63)	38.57 (1.99)	0.96 (0.22)	0.78 (0.11)	0.70 (0.07)	0.63 (0.03)	1.20 (0.12)	1.69 (0.10)
	PCS0.5	1.79 (0.08)	26.83 (1.32)	34.65 (4.28)	0.79 (0.15)	0.68 (0.05)	0.65 (0.09)	0.62 (0.04)	1.15 (0.14)	1.74 (0.08)
	PCS10-2	1.61 (0.02)	18.73 (2.75)	22.67 (2.88)	0.52 (0.10)	0.61 (0.07)	0.55 (0.03)	0.51 (0.03)	1.06 (0.14)	1.72 (0.11)
	Sign.	**	**	**	**	**	**	**	NS	NS
CN65	PCS10	1.74 (0.14)	25.39 (2.83)	29.48 (5.00)	0.62 (0.21)	0.67 (0.15)	0.75 (0.09)	0.70 (0.07)	1.12 (0.08)	2.01 (0.25)
	PCS2	1.83 (0.13)	25.02 (1.66)	31.79 (2.31)	0.59 (0.19)	0.87 (0.17)	0.71 (0.06)	0.73 (0.07)	1.25 (0.14)	2.02 (0.25)
	PCS0.5	1.80 (0.11)	21.23 (2.46)	27.47 (2.42)	0.53 (0.08)	0.64 (0.07)	0.67 (0.06)	0.68 (0.04)	1.16 (0.11)	2.08 (0.25)
	PCS10-2	1.35 (0.04)	17.16 (2.61)	21.03 (2.88)	0.48 (0.11)	0.58 (0.11)	0.61 (0.05)	0.55 (0.04)	1.07 (0.10)	1.99 (0.28)
	Sign.	**	**	**	NS	**	**	**	*	NS

Numbers in parentheses show standard deviations

* Significant at 95% confidence level; ** significant at 99% confidence level; NS, not significant at 95% confidence level

$P_{max,p}$, Maximum pull-through load; $F_{e,l}$, ultimate strength obtained from lateral nail resistance tests; $K_{s,s}$, initial stiffness; $P_{y,s}$, yield load; $P_{max,s}$, maximum single shear load; e_1, end distance of medium-density fiberboard

[a] Nail-head pull-through test

[b] Lateral nail resistance test

[c] Single shear of nailed joint

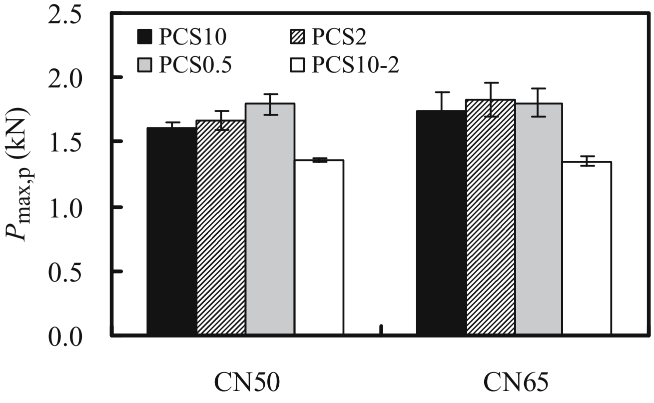

Fig. 5. Maximum loads obtained from nail-head pull-through tests with CN50 and CN65 nails. *Bars* indicate standard deviations

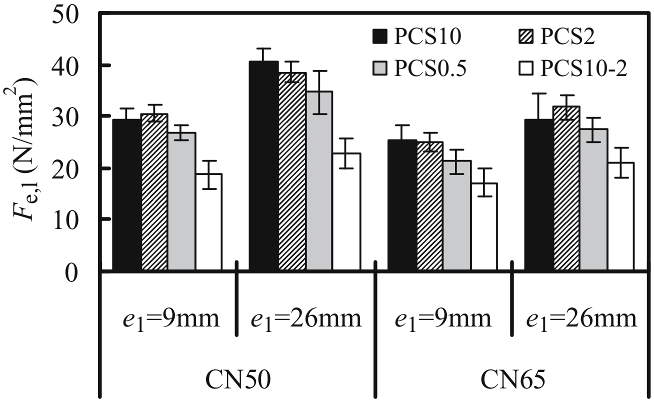

Fig. 7. Ultimate strength obtained from lateral nail resistance tests. e_1, End distance of MDF. *Bars* indicate standard deviations

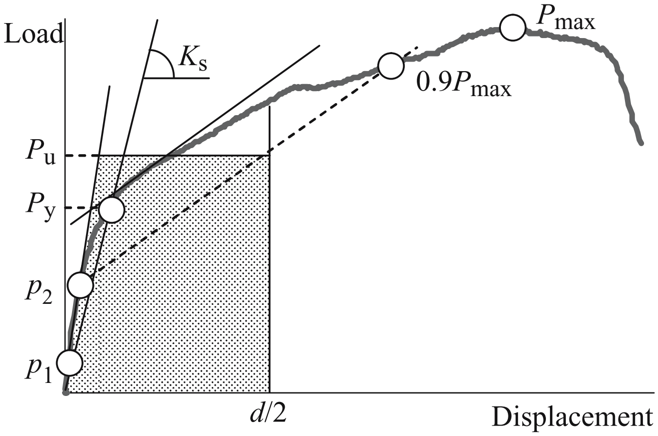

Fig. 6. Definition of stiffness and strengths of nailed joints. P_{max}, Maximum load; P_u, ultimate load; P_y, yield load; K_s, initial stiffness; d, nail diameter; p_1, 5% or 10% of P_{max}; p_2, 20% or 40% of P_{max}

times that of PCS10 (26.9 MPa) and PCS2 (28.3 MPa) and about 0.4 times that of PCS0.5 (19.8 MPa)], it is thought that PCS10-2 failed in bending mode rather than from caving of the nail head, and the $P_{max,p}$ value of PCS10-2 became lower than the other MDF values as a result. This indicates that $P_{max,p}$ would not be greatly influenced by the density profile if the bending strength of MDF is not extremely low. One-way analysis of variance (ANOVA) revealed that the differences among the four types of MDF were significant at a 99% confidence level regardless of the nail type (Table 2).

Lateral nail resistance yield load

All lateral nail resistance test pieces showed caving of nail trunks bent by applied load regardless of the specifications. The load–displacement curve obtained in the lateral nail resistance test was substituted in the perfect elasto-plastic model as shown in Fig. 6. This model enclosed the line that passes through the points on the curves corresponding to 0.1 and 0.4 times the maximum load until 0.5 times deformation of the nail diameter, the line parallel to the x-axis, 0.5 times deformation of the nail diameter, and the x-axis. The area of this model becomes equivalent to absorbed energy until 0.5 times deformation of the nail diameter is reached. Ultimate load ($P_{u,l}$) is defined as the line parallel to the x-axis.[11] Ultimate strength ($F_{e,l}$) was obtained by dividing the ultimate load by the nail diameter and thickness of MDF.

Figure 7 shows the $F_{e,l}$ values of the four types of MDF. The influence of the density profile was observed; the value of PCS10 and PCS2 was the highest in $F_{e,l}$, and decreased in the order of PCS0.5 and PCS10-2. In the lateral nail resistance test, the surface area of MDF received most of the partial compressive stress when the nail was deformed by bending. PCS10 and PCS2 with the high-density layer in the surface area seemed to have the largest values of $F_{e,l}$. One-way ANOVA revealed that the differences among the four types of MDF were significant at a 99% confidence level regardless of the kind of nail and edge distance (Table 2).

Single shear performance of nailed joints

The 9-mm edge distance test pieces showed failure in which the edge of the MDF could be pulled out by the caving of the trunk of the nail in MDF, regardless of the type of MDF. The 26-mm edge distance with CN50 test pieces showed three types of failure: nail withdrawal (PCS2, PCS0.5), a combination of nail withdrawal and layer peeling (PCS10), and a combination of nail withdrawal and bending (PCS10-2). The 26-mm edge distance with CN65 test pieces showed two types of failure: nail withdrawal (PCS2) and a combination of nail withdrawal and bending (PCS10, PCS0.5, PCS10-2).

Figure 8 shows examples of load–displacement curves obtained from the examination (PCS2 and PCS10-2). Yielding part load for the same kind of nail was almost a constant value, regardless of the edge distance, but there was significant influence of the edge distance on the shape of the load–displacement curve after yielding.

The obtained load–displacement curve was substituted in the perfect elasto-plastic model (Fig. 6) to calculate the

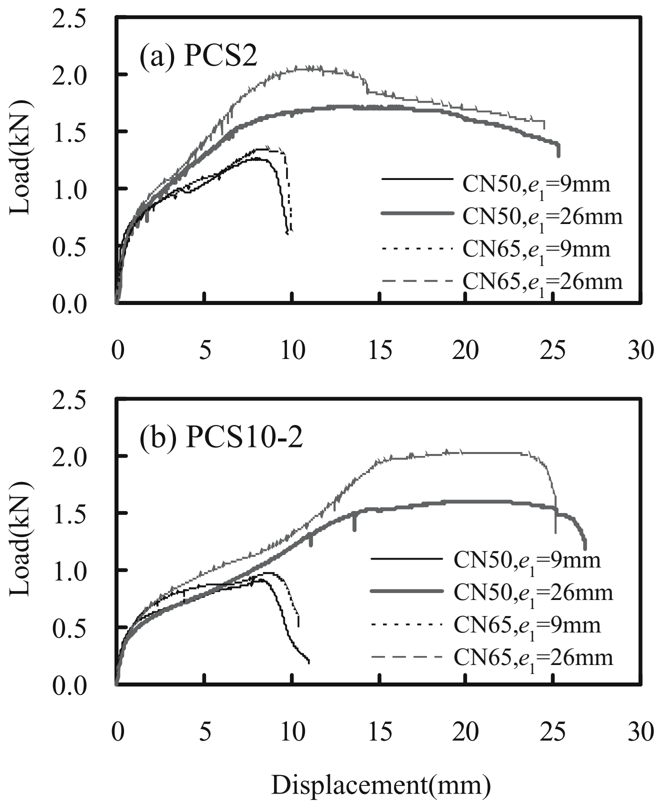

Fig. 8a,b. Load–displacement diagrams for single shear joints. **a** PCS2; **b** PCS10-2

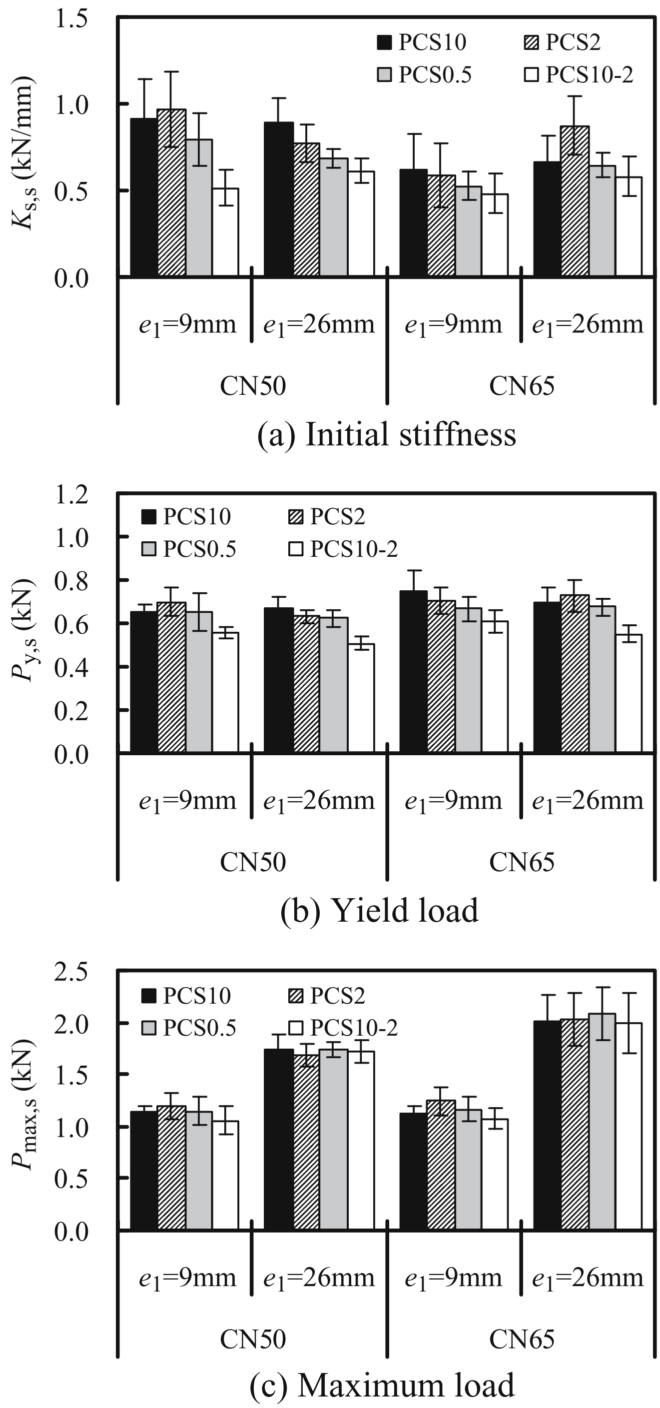

Fig. 9a–c. Single shear performance of nailed joints. **a** Initial stiffness; **b** yield load; **c** maximum load. *Bars* indicate standard deviations

following values: initial stiffness ($K_{s,s}$), yield load ($P_{y,s}$), maximum load ($P_{max,s}$).[11] Although 0.1 times and 0.4 times the point of maximum load are generally connected as a straight line in this evaluation method, the authors assumed the first straight line as follows: 0.1 times and 0.4 times the point of maximum load for the edge distance of 9 mm, and 0.05 times and 0.2 times the point of maximum load for the edge distance 26 mm. The second straight line has the same slope as the line that passes through the points on the curves corresponding to *p*2 (Fig. 6) and 0.9 times the maximum load and is the tangent to the curve. The load corresponding to the intersection of the first and second straight lines is defined as yield load, and the displacement on the curve corresponding to yield load is defined as yield displacement. The line that passes through the origin and the coordinate yield load and yield displacement is defined as initial stiffness.

Figure 9 shows $K_{s,s}$, $P_{y,s}$, and $P_{max,s}$ of the four types of MDF. For $K_{s,s}$, PCS10 and PCS2 having high surface densities, were the highest, followed by PCS0.5 and PCS10-2, usually in that order. $P_{y,s}$ values of PCS10, PCS2, and PCS0.5 were approximately the same, and only PCS10-2 was low.

When shear force was applied to a nailed joint, it appears that the bearing stress on the panel material and lumber (caving stress on the members by nail trunk) was concentrated on the boundary surface between the panel material and lumber during initial deformation, as shown in Fig. 10. After that, as deformation of the member progressed, the area from the boundary surface toward the member section may have increased until a yielding condition was reached.[12] Therefore, there were differences in $K_{s,s}$, which expresses initial deformation behavior among the four types of MDF, due to the influence of the density profile.

$P_{y,s}$ values of PCS10, PCS2, and PCS0.5 did not differ because the average layer density eventually stabilized at 0.7 g/cm^3 after a certain threshold distance from the surface was reached (Fig. 2). However, it appears that PCS10-2 with

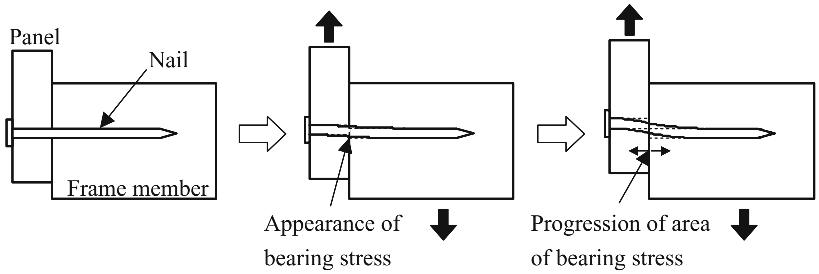

Fig. 10. Notional deformation of single shear joint

a wide low density layer from the surface to the core layer showed lower $P_{y,s}$ than the other three types of MDF. One-way ANOVA for $K_{s,s}$ and $P_{y,s}$ revealed that the differences among the four types of MDF were significant at a 99% confidence level for nailed joint type except for $K_{s,s}$ for the 9-mm edge distance with CN65 (Table 2).

$P_{max,s}$ values of the four types of MDF were very close. It seems that the density profile had little effect on $P_{max,s}$ if the average board density, the board thickness, etc., were equal, because the four types of MDF with 9-mm edge distance showed caving of overall nail to MDF and pulling out from the edge of the MDF. For the edge distance of 26 mm, three failure modes were observed, but all modes involved the withdrawal of the nail. It is thus thought that the decrease of the nail-holding resistance of the lumber influenced $P_{max,s}$. One-way ANOVA for $P_{max,s}$ revealed that the differences among the four types of MDF were not significant at a 95% confidence level for the nailed joint except for the type with 9-mm edge distance with CN65. In the case of the joint with 9-mm edge distance with CN65, the difference was significant at a 95% confidence level.

The nailed joint with CN65 showed 0%–20% higher $P_{max,s}$ values than the nailed joint with CN50 (Figs. 8 and 9). However, future investigations must examine the influence of the performance of nailed joints on the structural performance of wooden constructions.

Yanaga et al.[13] reported that it is suitable to set the edge and end distances at six times or more of the nail diameter to prevent the nail-holding resistance from decreasing in the nailed joints. In this research, only the edge distance of 26 mm satisfied this condition. Thus, $K_{s,s}$, $P_{y,s}$, and $P_{max,s}$ values for the edge distance of 9 mm were divided by the respective shear performance values for the 26-mm edge distance to examine the decreasing rate of initial stiffness, yield load, and maximum load for the 9-mm edge distance.

Figure 11 shows the ratio of each shear performance value. In the initial stiffness ratio, no clear trend was seen with decreasing edge distance because of the wide fluctuation in $K_{s,s}$. The yield load and maximum load ratio of the four types of MDF were almost the same value, with average yield load ratio falling in the range of 0.97–1.11 regardless of the kind of the nail, and the average maximum load ratio was 0.62–0.71 for CN50 and 0.55–0.62 for CN65. With the edge distance of 9 mm assuming nail joints on 204 dimension lumber, it should be noted that $P_{max,s}$ with CN50 was about 35% lower, and $P_{max,s}$ with CN65 was about 45% lower than the value of nailed joints with sufficient edge distance.

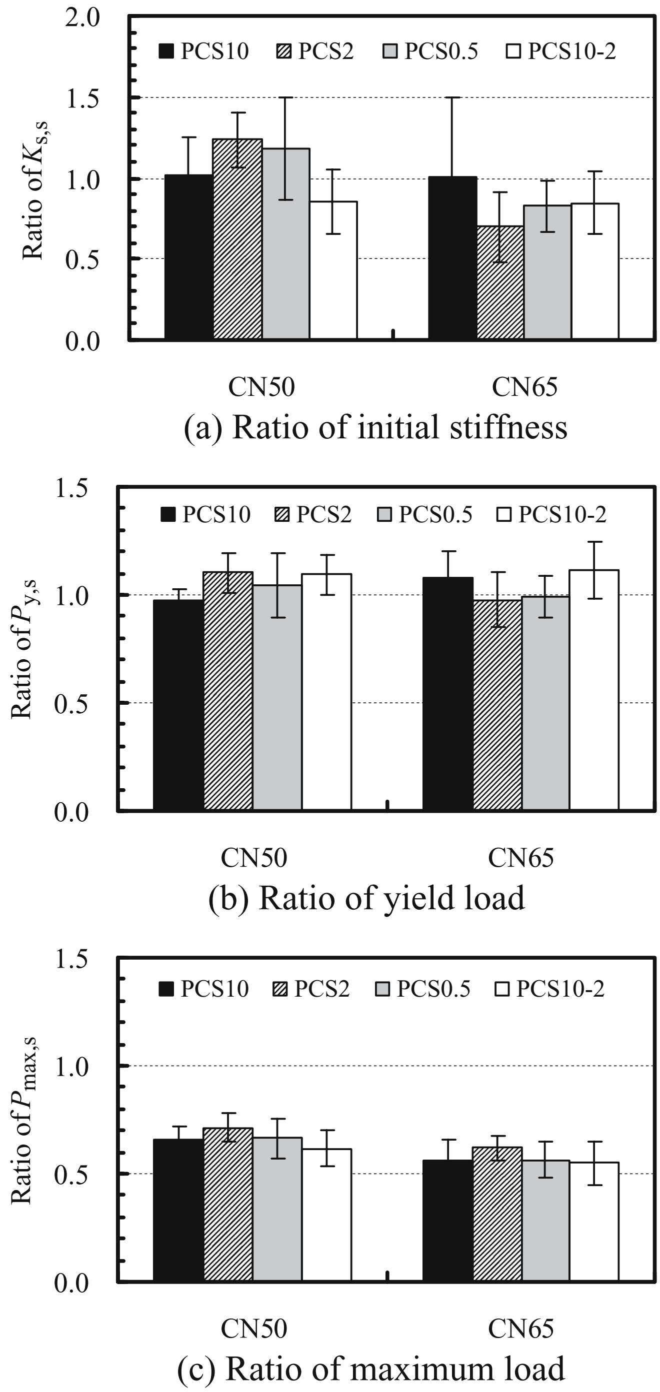

Fig. 11a–c. Ratio of single shear performance of nailed joints with end distance of 9 mm to that with end distance of 26 mm. **a** Initial stiffness; **b** yield load; **c** maximum load

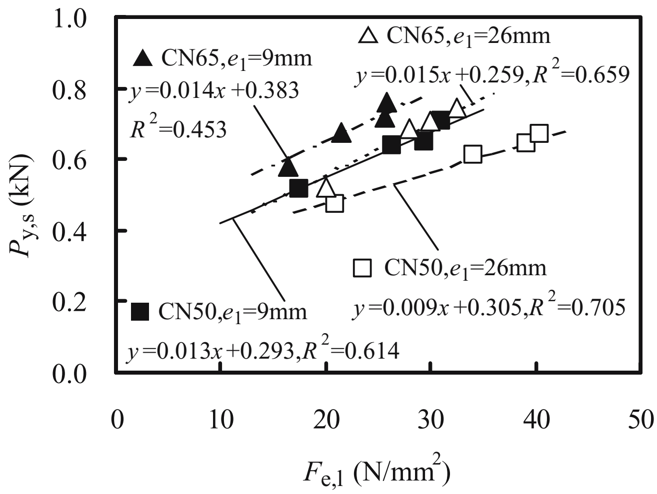

Fig. 12. Relations between the yield load of single shear joints and ultimate strength obtained from lateral nail resistance tests

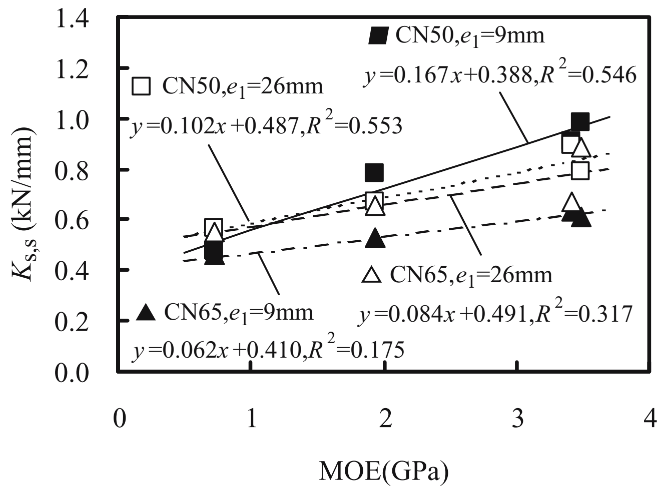

Fig. 13. Relations between the initial stiffness of single shear joints and the modulus of elasticity (*MOE*)

Single shear performance, lateral nail resistance, and bending performance

Because $P_{y,s}$ in the nailed joint can be estimated from $F_{e,l}$ of the panel material and the yield bending moment of the nail,[11] $P_{y,s}$ is dominated by $F_{e,l}$. Thus, the relation between $P_{y,s}$ and $F_{e,l}$ of MDF in Fig. 12 is shown by the mean value of each type of MDF. Here, each performance value was compared without correction based on the density, including the effect of the average board density and the density profile. The edge distance/nail diameter ratio of the lateral nail resistance specimen differs depending on the test conditions, and $F_{e,l}$ depends on the nail diameter even if the edge distance is sufficient.[14] Therefore, $F_{e,l}$ between each test condition cannot be compared directly.

There was a close positive relation between $P_{y,s}$ and $F_{e,l}$, but this relation differed depending on the test condition. The reason for this was that $P_{y,s}$ for each condition was almost the same (Fig. 9), while $F_{e,l}$ differed depending on the test condition (Fig. 7). From this result, even if the lateral nail resistance test was conducted according to the actual edge distance of the nailed joint and $P_{y,s}$ were estimated using $F_{e,l}$ obtained from that test, there is a possibility that $P_{y,s}$ might not be expressed in an actual nailed joint.

The nail-head pull-through performance was not related to the shear performance of nailed joints. Failure of the nail-head penetration generally occurs when the thickness of the panel material is insufficient.[15] In this study, failure of nail-head penetration was not observed in any type of MDF.

It was found that $K_{s,s}$ and $P_{y,s}$ reached high values if a high-density layer was formed near the surface. Previously, the authors revealed that a high bending performance could be obtained when a high-density layer was formed near the surface of MDF.[2] Consequently, the single shear performance of nailed joint was compared with the bending performance.

The relations between $K_{s,s}$ and modulus of elasticity (MOE) are shown in Fig. 13 by the mean value of each type of MDF. $K_{s,s}$ with CN50 and CN65 showed almost the same value for the 26-mm edge distance. For the 9-mm edge distance, $K_{s,s}$ with CN50 was higher than that with CN65 for the same MOE. Also in the case of the 9-mm edge distance, the edge distance/nail diameter ratio with CN50 was about 3.14 and that with CN65 was about 2.70. $K_{s,s}$ for large-diameter nails was generally higher,[16] suggesting that the results of this study were affected by a decrease in the edge distance/nail diameter ratio.

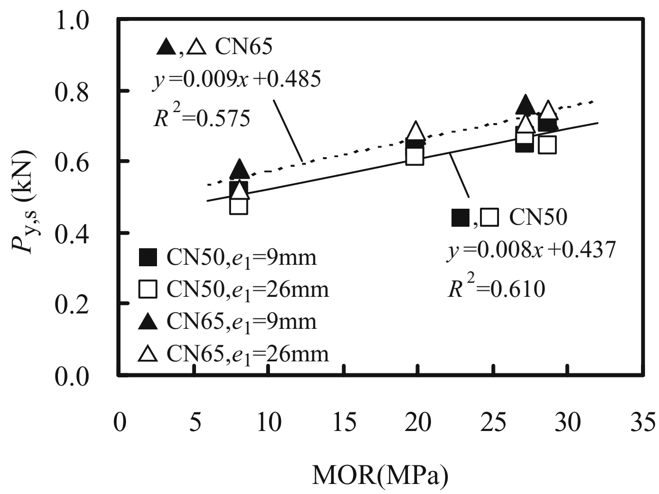

Fig. 14. Relations between the yield load of single shear joints and the modulus of rupture (*MOR*)

The decision coefficient of the relation between $K_{s,s}$ and MOE with CN50 was higher than that for the case with CN65. This is because there was relatively little change in $K_{s,s}$ with CN65. The correlated straight line in Fig. 13 provides a good illustration of the relation between $K_{s,s}$ and MOE.

Figure 14 shows the relations between $P_{y,s}$ and MOR. Because there was little influence of edge distance on $P_{y,s}$, there was a straight regression line bringing the data for edge distances of 9 and 26 mm together, depending on the nail type. $P_{y,s}$ and MOR showed a close positive relation; $P_{y,s}$ with CN65 reached a value about 1.1 times higher than in the case with CN50 for the same MOR. When a nailed joint reaches a yielding condition, the moment on the member subject to bearing stress is balanced by the bending yield moment of the nail. Given that the yield moments calculated from the nominal yield strength of CN50 and CN65[11] are 2.75 and 3.63 kN mm, respectively, it is considered that the difference between the $P_{y,s}$ of nailed joints with CN50 and CN65 was due to the yield moments of these nails.

Single shear performance of nailed joints is a significant parameter that has influence on the structural performance of constructions. However, obtaining shear performance of nailed joints is not simple as compared with the case of bending performance. Using the regression lines in Figs. 13 and 14, $K_{s,s}$ and $P_{y,s}$ of various MDF of 12 mm in thickness could be easily estimated from the MOE and MOR, respectively.

Conclusions

Tests on nail-head pull-through, lateral nail resistance, and single shear of nailed joints were conducted using MDF with different density profiles to examine the influence of density profile on nailed joint performance. The following results were obtained:

1. The effect of density profile on nail-head pull-through maximum load was small, but the average board density did show a significant effect.
2. The effect of density profile on the ultimate lateral nail resistance strength was strong and ultimate strength increased with increasing density near the board surface.
3. The influence of the density profile was most remarkable in first-stage rigidity, although initial stiffness and the yield load in the nail joint shear test showed a high value when there was a high-density layer near the board surface. The density profile did not influence the maximum load.
4. The initial stiffness showed a positive correlation with MOE, and there was little change in the initial stiffness with CN65 compared with the amount of change in MOE. The yield load of nailed joints showed a strong positive correlation with MOR. Because a straight-line relation was seen, the nail joint shear performance of MDF of 12 mm in thickness can be estimated from bending performance.

References

1. Wong ED, Zhang M, Han G, Kawai S, Wang Q (2000) Formation of the density profile and its effects on the properties of fiberboard. J Wood Sci 46:202–209
2. Ohashi K, Castellianos JRS, Hatano Y, Shibusawa T (2006) Mechanical properties of MDF having differed density profile and its nondestructive assessment with ultrasonic wave (in Japanese). Mokuzai Kogyo 61:12–6
3. Kawai S, Sasaki H (1986) Production technology for low-density particleboard I. Forming a density gradient and its effect on board properties. Mokuzai Gakkaishi 32:324–330
4. Wong ED, Zhang M, Wang Q, Kawai S (1998) Effects of mat moisture content and press closing speed on the formation of density profile and properties of particleboard. J Wood Sci 44: 287–295
5. Miyamoto K, Suzuki S, Inagaki T, Iwata R (2002) Effects of press closing time on mat consolidation behavior during hot pressing and on linear expansion of particleboard. J Wood Sci 48:309–314
6. Fujimoto Y, Sekino N, Korai H, Nogami H, Ohashi K (2005) Nail joint performance of several wood-based panels subjected to outdoor exposure and accelerated aging tests. Proceedings of International Symposium on Wood Science and Technologies (IAWPS 2005), Yokohama, Japan, vol 2, pp 143–144
7. Sekino N, Korai H (2006) Nail joint durability of wood-based panels – correlations between outdoor exposure and laboratory aging tests. Conference Proceedings of Wood Resources and Panel Properties, COST Action E44-E49, Valencia, Spain, pp 113–122
8. Sekino N, Morisaki S (1987) The effects of board density and board-edge distance of nails on lateral nail-resistance of low-density particleboards (in Japanese). Mokuzai Gakkaishi 33: 694–701
9. Wang SY, Chen TY, Fann JD (1999) Comparison of internal bond strength and compression shear strength of wood-based materials. J Wood Sci 45:396–401
10. American Society for Testing and Materials (ASTM) (1996) Standard test methods for evaluating properties of wood-based fiber and particle panel materials. ASTM D-1037. ASTM, West Conshohocken, PA, USA
11. Japan 2 × 4 Home Builders Association (2002) Structural design guidelines for wood frame construction (in Japanese). Japan 2 × 4 Home Builders Association, Tokyo, p 66, pp 233–241, 253–259
12. Sawata K, Yasumura M (2003) Estimation of yield and ultimate strengths of bolted timber joints by nonlinear analysis and yield theory. J Wood Sci 49:383–391
13. Yanaga K, Mochida T, Sasaki Y, Hirai T (2004) Allowable margins of nailed joints with wood-based structural panels subjected to lateral forces (in Japanese). Mokuzai Gakkaishi 50:30–36
14. Whale LRJ, Smith I, Larsen HJ (1987) Design of nailed and bolted joints proposals for the revision of existing formulae in draft Eurocode 5 and the CIB code. Proceedings of the CIB-W18 Meeting, Dublin, Paper 20-7-1
15. Architectural Institute of Japan (2006) Standard for structural design of timber structures (in Japanese). Architectural Institute of Japan, Tokyo, pp 266–278
16. Sonoda S, Kamiya F, Oshiumi S, Nakatani H, Wakashima Y (2002) Effects of member characteristics on the shearing resistance of plywood-lumber nailed joints (I) (in Japanese). In: Summaries of technical papers from the Annual Meeting. Architectural Institute of Japan, Tokyo, C-1(III), pp 45–46