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Determination of embedding strength of wood for dowel-type fasteners

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Abstract Embedding tests parallel and perpendicular to the grain were conducted to produce a database of embedding strength of wood for the design of dowel-type joints. Dowel diameters were 8, 12, 16, and 20 mm. Embedding strength was evaluated by the 5% off-set method and a maximum load up to 5 mm displacement according to EN383. The embedding strength parallel to the grain evaluated by the former method showed values close to those obtained with the latter method, but they showed a significant difference in tests conducted perpendicular to the grain. The embedding strength parallel to the grain was 0.9 times as large as the compressive strength parallel to the grain regardless of the evaluation method. The embedding strength perpendicular to the grain evaluated by the 5% off-set method was four times as large as the compressive strength perpendicular to the grain. When the embedding strength perpendicular to the grain was evaluated by a maximum load up to 5 mm displacement according to EN383, the ratio of embedding strength perpendicular to the grain to the compressive strength perpendicular to the grain decreased as the dowel diameter increased.

Key words Embedding strength · Compressive strength · Density · 5% Off-set method

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Introduction

Johansen's yield theory[1] is widely used for estimating the yield strength of dowel-type joints. According to this theory, the embedding strength of wood and the yield moment of the fastener governs properties for determining the strength of joints with dowel-type fasteners. Numerous studies have been performed on embedding characteristics of wood and wood-based materials with dowel-type fasteners.

Hirai[2,3] investigated the influence of the embedding test method and round bar diameter on embedding strength and stiffness. Fujita et al.[4] examined the effect of edge-distance and end-distance on the bearing characteristic of glued laminated timber and laminated veneer lumber. These studies were based on the embedding tests in tension, and the ultimate embedding strength obtained in these studies might include the effects of the fracture of wood.

Whale et al.[5] conducted a comprehensive investigation of the embedding strength of softwood, hardwood, plywood, and tempered hardboard with nails and bolts; and Ehlbeck and Werner[6] carried out embedding tests on hardwood under various loading angles to the grain. These studies, being the basis of the design of dowel-type joints in Eurocode 5,[7] dealt only with ultimate embedding strength; they did not look at the yield embedding strength.

Kawamoto et al.[8] carried out the embedding tests perpendicular to the grain of glued laminated timber; and Harada et al.[9] and Hwang and Komatsu[10] investigated the relations between the dowel diameter and the embedding properties obtained by the embedding tests of glued laminated timber and some engineered woods, respectively. These studies were based on compressive tests with cube-shaped specimens, and ultimate embedding strength was not considered. Therefore, we conducted the embedding tests parallel and perpendicular to the grain according to EN383[11] to examine both yield and ultimate embedding strengths.

Although numerous studies[3–6,8–10] have been reported on the relations between the embedding strength of wood or wood-based materials and round bar diameter, few data on the variance of embedding strength have been sought. Reliability-based design is one of the most efficient methods for evaluating the mechanical performance of timber structures. A statistical approach when considering the variance of embedding strength might be required to adapt the yield theory to reliability-based design. Therefore, embedding tests were conducted on a thousand laminae with different grades, dowel diameters, and loading directions to produce a database for the design of dowel-type joints.[12,13] Estimating the embedding strength from the compressive strength of wood was also proposed by comparing the embedding test results with those of compressive tests.

Materials and methods

Specimens

Embedding and compressive tests were conducted on ezomatsu (*Picea jezoensis* Carriere) and todomatsu (*Abies sachalinensis* Fr. Schmidt) laminae, which had four grades (L90, L100, L110, L125) according to the Japanese Agricultural Standard.[14] Approximately 1000 specimens were cut from more than 300 laminae. Dowel diameters (d) were 8, 12, 16, and 20mm. The number and densities of embedding specimens for each dowel diameter and grade are shown in Table 1. The dimensions of the embedding specimen according to EN383[11] were 14d in length, 6d in width, and 32mm in thickness, as shown in Fig. 1. The thickness of our specimen was within the range of that defined in EN383, which was $\geq 1.5d$ and $\leq 4d$.

Compressive specimens were cut near the embedding specimens. The dimension of compressive specimens was 32mm square in the loading section and 64mm in height.

Embedding tests

Embedding tests according to EN383 were conducted as shown in Fig. 1. Steel side plates 12mm thick were placed on both sides of the wooden member and were connected with a dowel. There was no clearance between the steel plates and the specimen. The embedding stress increment parallel to the grain was 10–30MPa/min for the elastic area. Embedding tests parallel to the grain were terminated when the embedding displacement was equal to the dowel diameter or when the load decreased to half the maximum load. The embedding stress increment perpendicular to the grain was 3–10MPa/min for the elastic area. Embedding tests perpendicular to the grain were stopped when the embedding displacement was equal to the dowel diameter or when the crack reached the end of the wood.

Compressive tests

Compressive tests parallel and perpendicular to the grain were conducted on the specimens cut from the wood near

Table 1. Number and density of embedding specimens

Grade	Parallel to the grain			Perpendicular to the grain		
	No. of specimens	Density		No. of specimens	Density	
		Mean (kg/m^3)	CV (%)		Mean (kg/m^3)	CV (%)
d = 8mm						
Total	57	391	11.4	57	387	10.9
L90	14	381	11.0	14	373	9.57
L100	14	369	8.36	14	364	7.10
L110	15	399	9.58	15	398	9.13
L125	14	414	12.3	14	412	12.0
d = 12mm						
Total	117	394	10.2	119	389	10.3
L90	30	359	6.47	30	351	5.05
L100	30	393	12.0	30	383	9.36
L110	30	394	6.05	30	401	9.87
L125	27	422	8.26	29	420	6.89
d = 16mm						
Total	212	399	11.1	212	403	11.1
L90	50	350	10.2	50	357	7.64
L100	56	389	4.99	56	392	4.45
L110	56	411	7.52	56	404	7.73
L125	50	448	5.33	50	460	6.08
d = 20mm						
Total	117	403	10.7	118	401	12.2
L90	29	372	7.05	30	361	6.26
L100	30	381	9.65	30	372	8.50
L110	30	419	5.63	30	418	5.68
L125	28	441	9.67	28	450	11.1

d, dowel diameter; CV, coefficient of variation

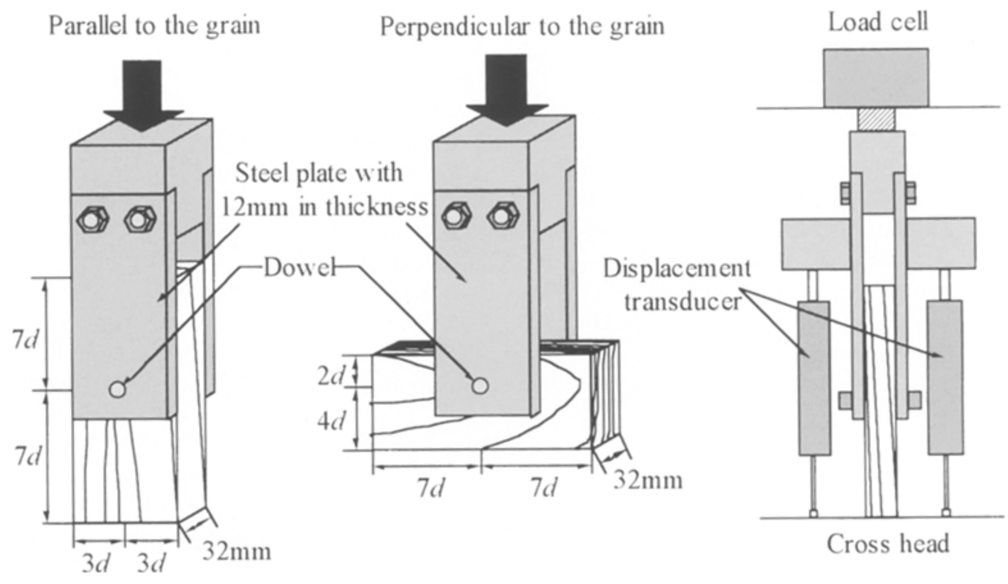

Fig. 1. Configuration of embedding test. *d*, dowel diameter (millimeters)

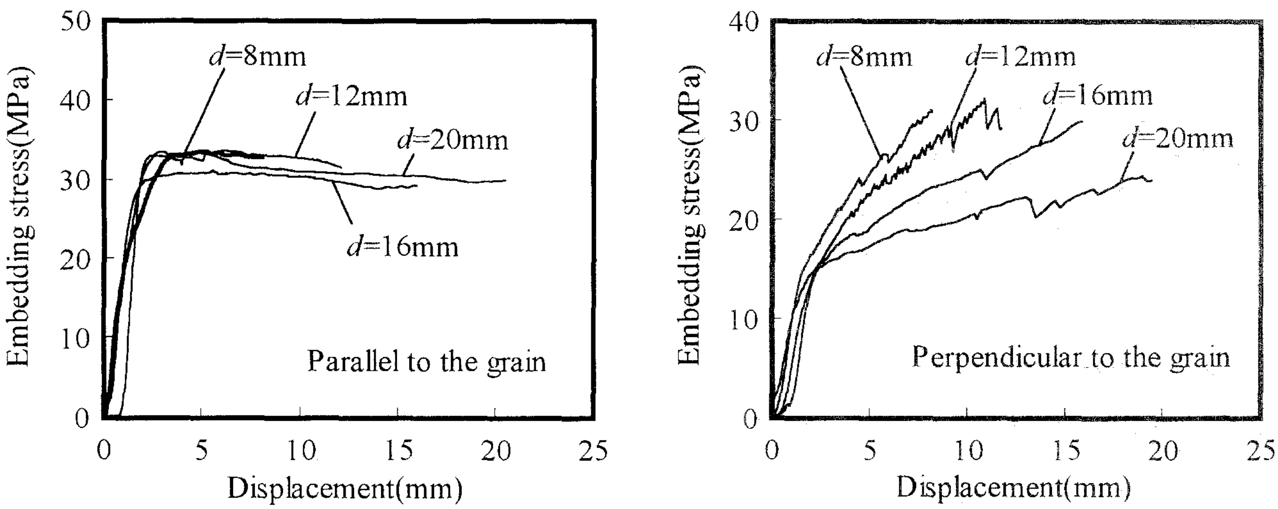

Fig. 2. Relations between embedding stress and displacement

the embedding specimen according to the Japanese Industrial Standard.[15] Approximately 500 specimens with a density (±10%) close to that of the embedding specimens were tested. Compressive tests parallel to the grain were terminated after the maximum load was attained, and those perpendicular to the grain were stopped when the displacement was >10% of the height of the specimen.

Results and discussion

Evaluation methods of embedding strength

The typical embedding stress-displacement curves are shown in Fig. 2. The embedding stress parallel to the grain showed a linear increase up to the yielding of wood and was almost constant after yielding regardless of the increase in displacement. The embedding stress perpendicular to the grain showed a liner a increase up to the yielding of wood and a continuous increase after yielding. The increment ratio after yielding was smaller as the dowel diameter was increased. Embedding strengths were evaluated by the 5% off-set method and according to EN383, as shown in Fig. 3. The 5% off-set method was adopted to evaluate the yield embedding strength. With the former method the line that goes through the points on the curves corresponding to 10% and 40% of the maximum load up to 5 mm displacement was moved 5% of the dowel diameter parallel to the X-direction, and embedding strength is defined as the intersection of this line and the load-displacement curve. The latter is defined as the maximum load up to 5 mm displacement. The former and the latter are expressed as 5% embedding strength and 5 mm embedding strength in

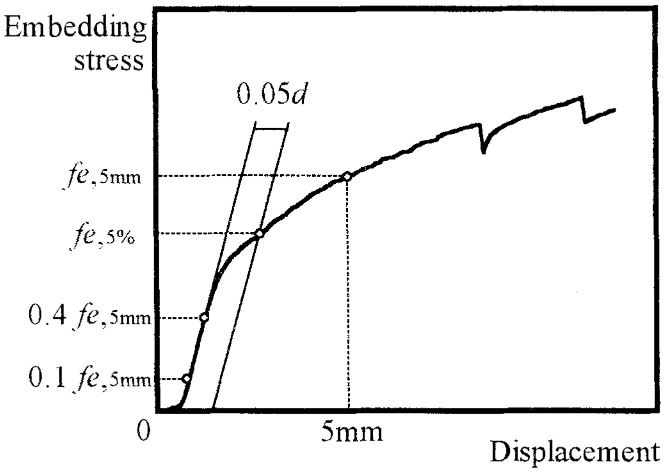

Fig. 3. Method for evaluating embedding strength (*fe*)

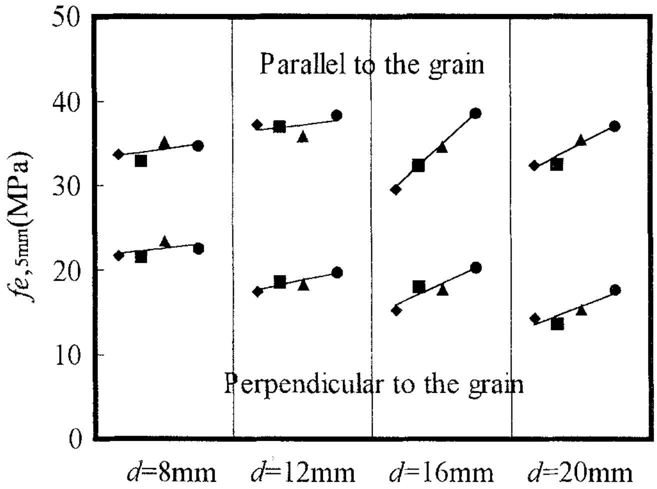

Fig. 4. Relations between 5 mm embedding strength and lamina grade. *Diamonds*, L90; *squares*, L100; *triangles*, L110; *circles*, L125

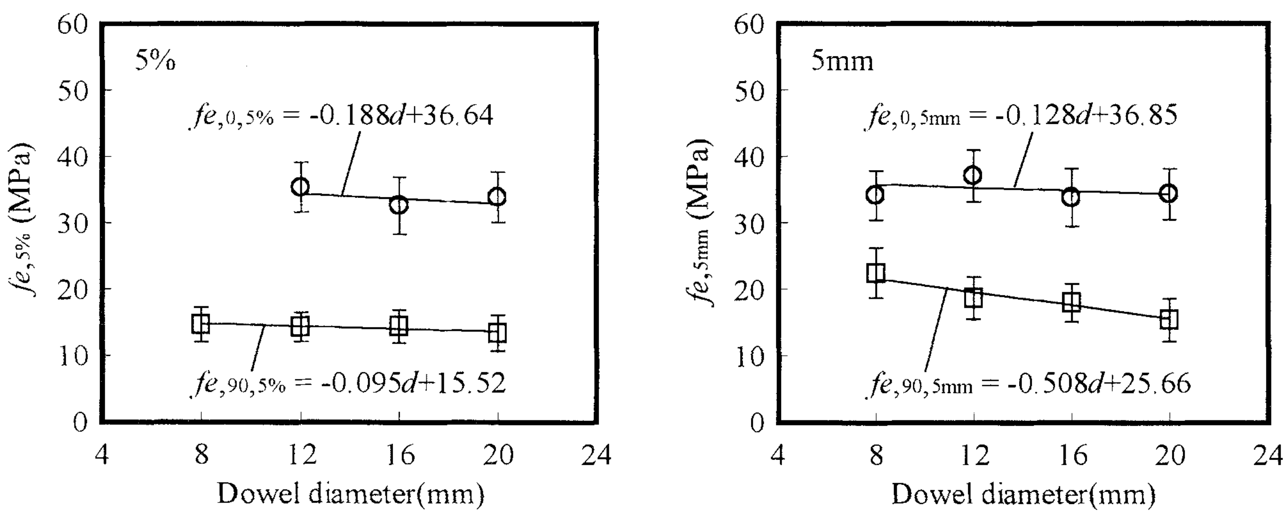

Fig. 5. Embedding strength as a function of dowel diameter. *Circles*, parallel to the grain; *squares*, perpendicular to the grain; symbols and vertical bars denote the mean value and standard deviation, respectively

this paper, respectively. Embedding strength was calculated as follows.

$$fe_{\alpha,\beta} = \frac{P}{td} \tag{1}$$

where fe is the embedding strength, α is the loading angle to the grain, β is the evaluation method (i.e., 5% or 5 mm), P is the load, t is the thickness of the specimen, and d is the dowel diameter.

Embedding strength

Table 2 shows the mean values and the coefficient of variation of the embedding strength parallel and perpendicular to the grain for each dowel diameter and lamina grade. The density increased as the lamina grade was higher, as shown in Table 1. Some studies[3,8] reported that the embedding strength had a positive correlation with the density. The 5 mm embedding strength for each lamina grade are shown in Fig. 4. As the grade increased, the 5 mm embedding strength with dowels of 8 and 12 mm diameter showed a slight increase. The increase in the 5 mm embedding strength due to lamina grade was more significant in the specimens with a 16 or 20 mm diameter dowel. The same tendency was observed with the 5% embedding strength. This might be caused by the fact that there was little difference in average density among each lamina grade used for specimens with dowels 8 or 12 mm in diameter, whereas the average density was larger with higher lamina grade for dowels 16 or 20 mm in diameter. The data from the various lamina grades were combined in this study to simplify the analysis.

The embedding strengths parallel and perpendicular to the grain for each dowel diameter are shown in Fig. 5. Although yielding of the dowel does not occur with a slen-

Table 2. Results of embedding test

Evaluation method	Parallel to the grain		Perpendicular to the grain	
	Mean (MPa)	CV (%)	Mean (MPa)	CV (%)
5% Embedding strength				
$d = 8$ mm				
Total	26.7	17.1	14.6	17.7
L90	26.8	8.42	15.0	10.8
L100	25.1	11.6	13.5	14.7
L110	28.8	23.3	15.3	20.8
L125	25.9	15.1	14.4	19.4
$d = 12$ mm				
Total	35.4	10.5	14.2	15.5
L90	36.4	9.81	14.1	8.84
L100	35.6	12.0	14.2	19.5
L110	33.6	7.43	14.0	15.1
L125	36.2	11.0	14.7	15.8
$d = 16$ mm				
Total	32.6	13.2	14.3	17.3
L90	28.4	10.4	12.7	16.8
L100	31.3	7.81	14.5	13.6
L110	33.9	9.61	14.2	20.1
L125	36.7	9.74	15.9	10.7
$d = 20$ mm				
Total	33.9	11.2	13.3	20.3
L90	31.9	8.18	12.5	14.6
L100	31.9	9.51	11.8	17.1
L110	35.1	7.18	13.3	12.3
L125	36.6	11.9	15.4	21.8
5 mm Embedding strength				
$d = 8$ mm				
Total	34.2	10.8	22.4	16.9
L90	33.8	6.26	21.8	10.4
L100	32.9	6.11	21.6	16.7
L110	35.3	14.1	23.6	18.7
L125	34.7	11.9	22.5	18.2
$d = 12$ mm				
Total	37.1	10.6	18.6	17.4
L90	37.3	9.83	17.6	11.9
L100	37.0	12.8	18.7	19.0
L110	36.0	7.43	18.5	16.9
L125	38.3	11.0	19.7	18.1
$d = 16$ mm				
Total	33.8	12.9	17.9	16.1
L90	29.6	11.6	15.4	16.3
L100	32.4	6.98	18.1	10.1
L110	34.7	9.42	17.9	16.1
L125	38.5	7.84	20.3	10.1
$d = 20$ mm				
Total	34.3	11.1	15.3	20.9
L90	32.5	7.63	14.5	14.2
L100	32.5	9.61	13.7	17.7
L110	35.6	7.64	15.5	14.6
L125	37.0	12.0	17.7	22.9

derness ratio of 4, the effects of bending the dowel on the load-displacement curve cannot be ignored. The regression equation of the 5% embedding strength parallel to the grain was obtained from the experimental results with dowels 12, 16, and 20 mm in diameter, excluding those with dowels 8 mm in diameter. Whale et al.[5] reported that the embedding strength parallel to the grain decreased as the dowel diameter increased. Hirai[3] and Harada et al.[9] reported that the embedding strength was almost constant regardless of dowel diameter. In our study, the 5% and 5 mm embedding strengths parallel to the grain were almost constant regardless of dowel diameter, which agreed with the latter study. For conditions perpendicular to the grain, numerous studies[3,4,6,9] reported that embedding strength decreased as the dowel diameter increased, which may be caused by the effects of crack propagation.[3] The 5% embedding strength perpendicular to the grain decreased slightly as the dowel diameter increased but could be considered almost constant regardless of dowel diameter for practical purposes. It was obvious that the 5 mm embedding strength perpendicular to the grain decreased as the dowel diameter increased.

Figure 6 shows the embedding strength parallel to the grain/perpendicular to the grain ratio for each dowel diameter. The ratio for the 5% embedding strength was almost

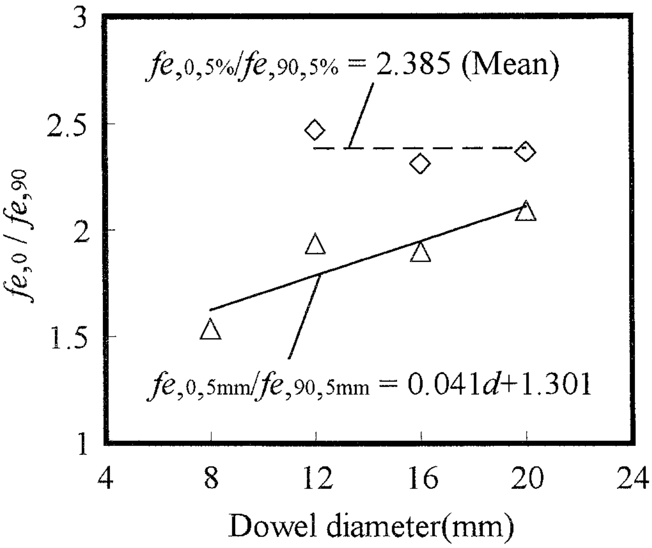

Fig. 6. Ratio of embedding strength parallel to the grain to that perpendicular to the grain for each dowel diameter. *Diamonds*, ratio for 5% embedding strength; *triangles*, ratio for 5 mm embedding strength

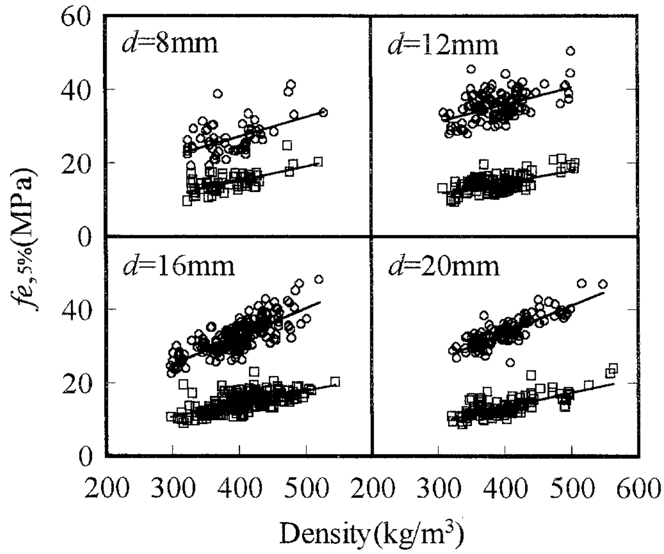

Fig. 8. Relations between 5% embedding strength and density. Symbols are the same as in Fig. 5

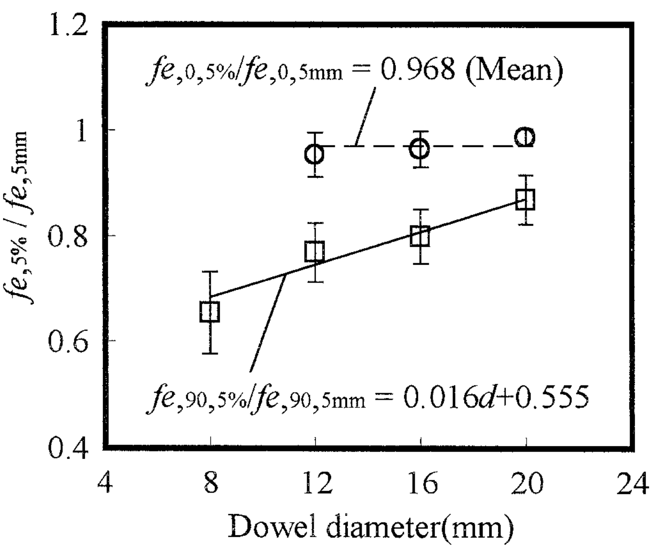

Fig. 7. Ratio of 5% embedding strength to 5 mm embedding strength for each dowel diameter. Symbols and vertical bars are the same as in Fig. 5

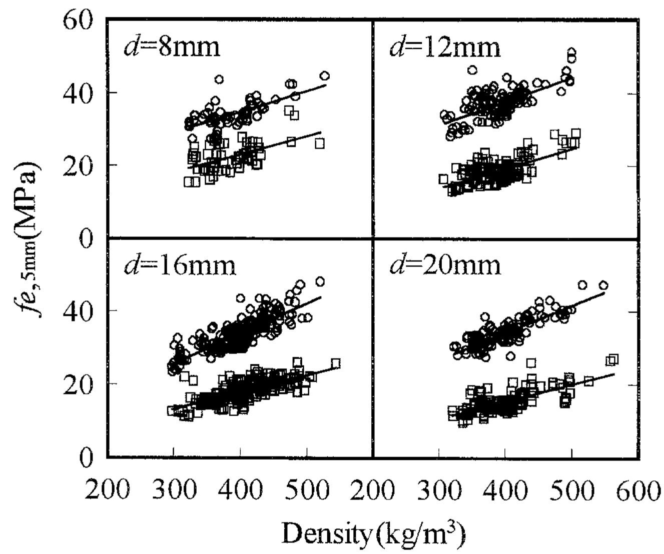

Fig. 9. Relations between 5 mm embedding strength and density. Symbols are the same as in Fig. 5

constant, averaging 2.4, regardless of dowel diameter. The ratio for the 5 mm embedding strength decreased as the dowel diameter decreased. This indicates that 5 mm embedding strength perpendicular to the grain becomes close to that parallel to the grain when the dowel diameter is small. This coincides the fact that there is no effect of the loading direction in the case of softwood with a round bar of small diameter, such as a nail fastener.[5]

Figure 7 shows the ratio of the 5% embedding strength and the 5 mm embedding strength for each dowel diameter. The 5% embedding strength parallel to the grain was almost equal to the 5 mm embedding strength. Perpendicular to the grain, the difference between the 5% and 5 mm embedding strengths decreased as the dowel diameter increased. The embedding strength parallel to the grain is not affected by the evaluation method because the embedding stress-displacement curve parallel to the grain indicates a perfectly elastic-plastic pattern. However, a proper evaluation method should be used to obtain the yield and ultimate embedding strength for conditions perpendicular to the grain.

Effect of density

The relations between the 5% and 5 mm embedding strengths and the density are shown in Figs. 8 and 9, respectively. The 5% and 5 mm embedding strengths were

Table 3. Coefficients of regression line and lower limit of 90% confidence interval between embedding strength and density

Loaded direction	Evaluation method	d (mm)	a_1	a_2	b_1 ($\times10^{-3}$)	b_2	b_3
Parallel to the grain	5% Embedding strength	8	0.053	6.15	0.394	−0.308	104.66
		12	0.049	16.04	0.146	−0.115	50.34
		16	0.076	2.15	0.046	−0.037	26.95
		20	0.073	4.26	0.054	−0.044	20.72
	5mm Embedding strength	8	0.057	11.79	0.181	−0.142	48.16
		12	0.068	10.21	0.115	−0.091	39.63
		16	0.082	1.11	0.038	−0.031	22.20
		20	0.074	4.55	0.054	−0.044	20.72
Perpendicular to the grain	5% Embedding strength	8	0.039	−0.53	0.112	−0.087	28.13
		12	0.032	1.98	0.048	−0.037	16.41
		16	0.036	−0.20	0.023	−0.019	13.56
		20	0.040	−2.80	0.033	−0.027	14.86
	5mm Embedding strength	8	0.049	3.35	0.283	−0.219	71.27
		12	0.055	−2.60	0.084	−0.065	28.65
		16	0.047	−0.92	0.026	−0.021	15.19
		20	0.047	−3.67	0.048	−0.038	21.31

Coefficient of regression line: $fe = a_1\rho + a_2$
Lower limit of 90% confidence interval: $fe_L = fe - \sqrt{b_1\rho^2 + b_2\rho + b_3}$
Embedding strength (fe), in MPa
Density: [ρ(kg/m^3)]
ρ, density of the wood; a_1, a_2, b_1, b_2, b_3, constants

positivly correlated with the density regardless of the dowel diameter, the evaluation method, or the loading angle to the grain. These results agreed well with reports[3,8] that embedding strength had a positive correlation with density. The regression line and lower limit of the 90% confidence interval between embedding strength and density were calculated. The lower limit equation of the confidence interval was as follows.[16]

$$fe_L = fe - t(\phi, \omega)\sqrt{\left\{1 + \frac{1}{n} + \frac{(\rho - \mu_\rho)^2}{S_{\rho\rho}}\right\}Ve} \quad (2)$$

where fe_L is the lower limit of 90% confidence interval, fe is the regression line, $t(\phi, \omega)$ is the value of t-distribution with the degree of freedom (ϕ) and significance level (ω), n is the number of specimens, ρ is the density of wood, μ_ρ is the mean value of the density, $S_{\rho\rho}$ is the sum of squares of the density, and Ve is the residual variance. The following equation was obtained by transformation of Eq. (2).

$$fe_L = fe - \sqrt{b_1\rho^2 + b_2\rho + b_3} \quad (3)$$

where fe_L, fe, and ρ are the same as in Eq. (2); and b_1, b_2, and b_3 are constant values.

The coefficients of regression line and Eq. (3) are shown in Table 3. The inclination of the regression line between the 5mm embedding strength and the density was larger than that between the 5% embedding strength and the density. The variance of the embedding strength can be estimated by the density from Table 3.

The embedding strength divided by the density (fe/ρ) for each dowel diameter is shown in Fig. 10. These figures also show the values of (fe/ρ) obtained by Harada et al.[9] and Kawamoto et al.[8] and the design values of embedding strength according to Eurocode 5[7] standard. For the values of (fe/ρ) by Harada et al., the density of sugi (*Cryptomeria japonica* D. Don) and karamatsu (*Larix leptolepis* Gordon) were assumed to be 430 and 510kg/m^3, respectively based on unpublished data. In the Eurocode 5 standard, embedding strength is calculated from the dowel diameter and the density. The equation in the Eurocode 5 standard is defined as follows.

$$fe_\alpha = \frac{0.082(1 - 0.01d)\rho}{(1.35 + 0.015d)\sin^2\alpha + \cos^2\alpha} \quad (4)$$

where fe_α is the embedding strength (MPa), d is the dowel diameter (mm), ρ is the density (kg/m^3), and α is the loading angle to the grain.

As is shown in the relations between the embedding strength and the dowel diameter (Fig. 5), the slope of the regression line of the 5mm embedding strength perpendicular to the grain divided by the density was smaller than others. When embedding strength was evaluated by the 5% off-set method, the values for (fe/ρ) parallel and perpendicular to the grain obtained by this study showed good agreement with those reported by Harada et al. and Kawamoto et al. This indicates that 5% embedding strength of softwood would be estimated from dowel diameter and density. When embedding strength was evaluated for the maximum load up to 5mm displacement according to EN383, the values of (fe/ρ) parallel to the grain were 23%–29% larger than that derived by Eq. (4). The values of (fe/ρ) perpendicular to the grain were close to that of Eq. (4).

Relations between embedding strength and compressive strength

Compressive strength parallel to the grain was evaluated with maximum stress according to the Japanese Industrial

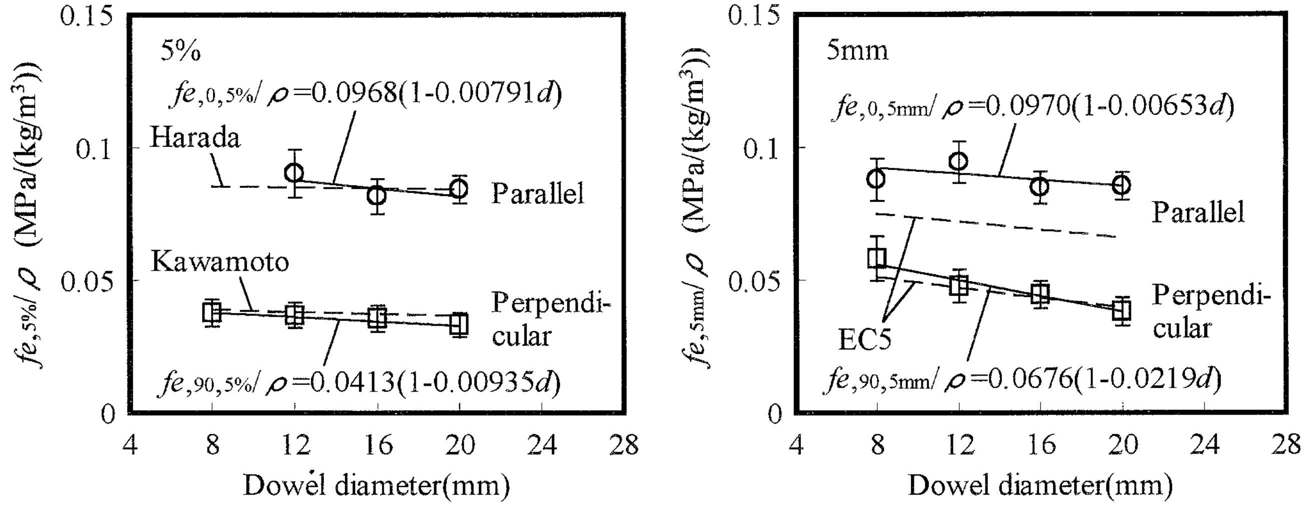

Fig. 10. Embedding strength divided by density as a function of dowel diameter. Symbols and vertical bars are the same as in Fig. 5. *EC5*, design value in Eurocode 5

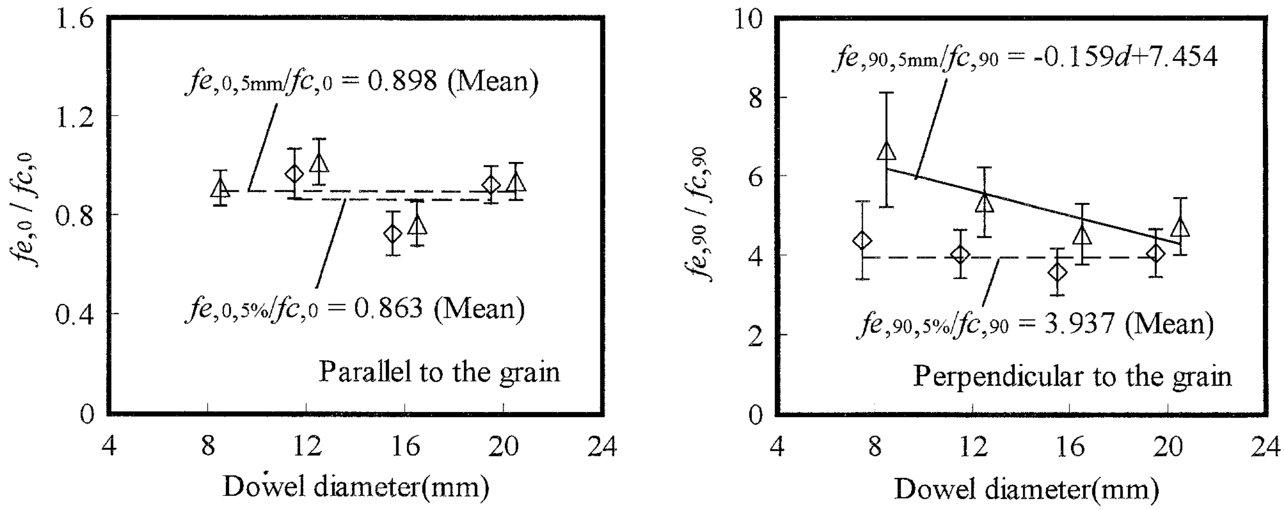

Fig. 11. Relations between the ratio of the embedding strength to compressive strength and dowel diameter. *Diamonds*, ratio for 5% embedding strength; *triangles*, ratio for 5 mm embedding strength. Symbols and vertical bars denote the mean value and standard deviation, respectively

Standard.[15] That perpendicular to the grain was evaluated according to EN1193;[17] the elastic line was moved 0.01 strain parallel toward X-direction, and the compressive strength was defined as the intersection of this line and the stress–strain curve.

Based on compressive tests, the regression line through the origin point between the compressive strength and the density was obtained as follows.[18]

$$fc_0 = 0.0973\rho$$
$$fc_{90} = 0.00932\rho \qquad (5)$$

where fc_0 and fc_{90} are the compressive strengths (MPa) parallel and perpendicular to the grain, respectively, and ρ is the density (kg/m^3).

The embedding strength divided by the compressive strength (*fe*/*fc*) for each dowel diameter is shown in Fig. 11. The values of (*fe*/*fc*) parallel to the grain was almost constant regardless of dowel diameter or evaluation method. The embedding strength parallel to the grain was about 0.9 times as large as the compressive strength parallel to the grain. When the embedding strength perpendicular to the grain was evaluated by the 5% off-set method, the values of (*fe*/*fc*) perpendicular to the grain were almost constant regardless of dowel diameter. The 5% embedding strength perpendicular to the grain was about four times as large as the compressive strength perpendicular to the grain. When the embedding strength perpendicular to the grain was evaluated by the maximum load up to 5 mm displacement according to EN383, the values of (*fe*/*fc*) perpendicular to the grain decreased as the dowel diameter increased.

From the result described above, 5% and 5 mm embedding strengths can be estimated by the following equation using Eq. (5) and the equations in Fig. 11.

Embedding strength parallel to the grain:

$$fe_{0,5\%} = fe_{0,5\text{mm}} = 0.9fc_0 \quad (6)$$

Embedding strength perpendicular to the grain:

$$fe_{90,5\%} = 0.4fc_0 \quad (7)$$

$$fe_{90,5\text{mm}} = (-0.016d + 0.745)fc_0 \quad (8)$$

where $fe_{0.5\%}$ and $fe_{0.5\text{mm}}$ are the embedding strengths (MPa) parallel to the grain evaluated by the 5% off-set method and the maximum load up to 5 mm displacement according to EN383, respectively, $fe_{10.5\%}$ and $fe_{90.5\text{mm}}$ are those perpendicular to the grain, respectively, fc_0 is the compressive strength (MPa) parallel to the grain, and d is the dowel diameter (mm).

Conclusions

The following conclusions can be drawn from this study.

1. The coefficient of variation of the embedding strength from all lamina grades varies from 10% to 17% and 15% to 21%, respectively, in the parallel and perpendicular directions. There is a significant correlation between embedding strength and density.

2. The embedding strengths parallel to the grain evaluated by the 5% off-set method and the maximum load up to 5 mm displacement according to EN383 shows close values that are scarcely influenced by dowel diameter. The embedding strength perpendicular to the grain evaluated by the 5% off-set method is little influenced by dowel diameter as well. However, the embedding strength evaluated by the maximum load up to 5 mm displacement decreases as the dowel diameter increases.

3. Embedding strength evaluated by the 5% off-set method can be estimated from the dowel diameter and the density of the wood. The design value of embedding strength in the Eurocode 5 standard is useful for the embedding strength evaluated by the maximum load up to 5 mm displacement according to EN383.

4. The embedding strength for the dowel-type fastener can be estimated by Eqs. (6) to (8) using the compressive strength parallel to the grain of wood.

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