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EXPERIMENTAL STUDY ON CHARACTERISTIC VALUES OF PARTIAL COMPRESSION PERPENDICULAR TO THE GRAIN OF HARDWOOD WITH EDGE DISTANCE ORTHOGONAL TO THE LONGITUDINAL DIRECTION

Hiroto Suesada[1], **Kohta Miyamoto**[2]

ABSTRACT: The use of hardwoods for wooden joints is advantageous because of their higher density and superior structural performance compared to softwoods, which are generally used as construction materials in buildings. However, the effects of the dimensions of the hardwood specimens and wood species on the partial compression performance perpendicular to the grain are unclear. In this study, we conducted partial compression tests perpendicular to the grain of hardwoods clarify the effect of edge distance that is orthogonal to the longitudinal direction and wood species on the characteristic values. The tendencies of the relationships between the partial compression performance perpendicular to the grain and the edge distance perpendicular to the grain of hardwoods were found to be similar to those of softwoods. The effect of wood species on characteristic values needs to be examined in more detail.

KEYWORDS: Hardwood, Partial compression perpendicular to the grain, Edge distance in two directions

1 INTRODUCTION

The compression performance of wood perpendicular to the grain was considerably lower than that of wood parallel to the grain. Partial compressive deformation perpendicular to the grain is one of the primary causes of deformation of wooden joints.

In Japan, most planted forests are in the mature and utilisation stages [1]. In addition, the environmental advantages of wooden buildings have led to an increase in the number of mid-rise and large-scale non-residential wooden buildings. These buildings require higher structural performance than low-rise buildings.

Some hardwood species have a higher density and superior compression performance perpendicular to the grain compared with softwoods, which are generally used as construction materials in buildings. Therefore, it is advantageous to utilise such hardwoods in wooden joints. The estimation of the performance of hardwoods is essential for their utilisation as structural materials but not yet for the partial compression performance of hardwoods perpendicular to the grain. Furthermore, the effects of the dimensions of the hardwood specimens and wood species on the partial compression performance perpendicular to the grain is unclear.

Previously, the relationships between the partial compression performance perpendicular to the grain and the edge distance in the longitudinal direction were determined [2]. In this study, partial compression tests perpendicular to the grain were conducted to clarify the effect of the edge distance orthogonal to the longitudinal direction and wood species on the characteristic values.

2 MATERIALS AND METHODS

2.1 TEST SPECIMENS

Table 1 presents the specifications of the test specimens. Eight hardwood species were used as test specimens. Itayakaede (IT, *Acer mono Maxim.*), Udaikamba (UD, *Betula maximowicziana*), and Buna (BN, *Fagus crenata*) are diffuse-porous woods. Shirakashi (SR, *Quercus myrsinifolia*) is radial-porous wood. Kuri (KR, *Castanea crenata*), Keyaki (KY, *Zelkova serrata*), Yachidamo (YC, *Fraxinus mandshurica*), and Mizunara (MZ, *Quercus crispula Blume*) are ring-porous woods.

The height of each sample was fixed at 40 mm. Specimens with three different widths (*w*) (40, 60 and 80 mm) and two different lengths (*l*) (40 and 120 mm) were

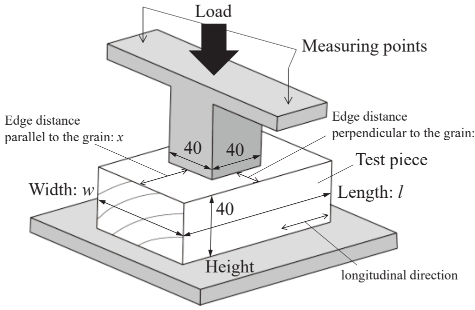

***Figure 1**: Schematic of partial compression test perpendicular to the grain (dimensions in mm)*

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[1] Hiroto Suesada, Shinshu univ., Japan, suesada@shinshu-u.ac.jp

[2] Kohta Miyamoto, Forestry and Forest Products Research Institute, Japan, mkohta@ffpri.affrc.go.jp

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***Table 1**: Specification of the test specimens*

wood species	length (mm)	width (mm)	n [a)]	ρ [b, c)] (kg/m^3)	MC [c, d)] (%)
Itayakaede (IT, *Acer mono Maxim.*)	40 / 120	40 / 60 / 80	6	734 ± 32.8	10.9 ± 0.89
Shirakashi (SR, *Quercus myrsinifolia*)	40 / 120	40 / 60 / 80	3	890 ± 59.5	12.6 ± 0.20
Udaikamba (UD, *Betula maximowicziana*)	40 / 120	40 / 60 / 80	4	707 ± 71.9	12.1 ± 0.72
Kuri (KR, *Castanea crenata*)	40 / 120	40 / 60 / 80	6	575 ± 73.7	13.9 ± 0.88
Keyaki (KY, *Zelkova serrata*)	40 / 120	40 / 60 / 80	6	747 ± 67.7	12.2 ± 1.93
Yachidamo (YC, *Fraxinus mandshurica*)	40 / 120	40 / 60 / 80	6	571 ± 80.4	13.3 ± 0.48
Mizunara (MZ, *Quercus crispula Blume*)	40 / 120	40 / 60 / 80	6	732 ± 59.7	12.4 ± 0.91
Buna (BN, *Fagus crenata*)	40 / 120	40 / 60 / 80	6	687 ± 17.8	12.9 ± 0.31

Notes: a) Number of specimens, b) Density, c) The values mean Average ± Standard variation, d) Moisture content

made. Thus, each wood specimen had 6 dimensional specifications, which are indicated by a four-digit number. For example, 4040 represents a width of 40 mm and a length of 40 mm, whereas 6120 represents a width of 60 mm and a length of 120 mm. For each species, six specimens of different widths and lengths were obtained from a single piece of wood in the longitudinal direction.

2.2 COMPRESSION TEST PERPENDICULAR TO THE GRAIN

Figure 1 shows a schematic of the partial compression test perpendicular to the grain. The tests were conducted according to Japanese Industrial Standards (JIS) Z 2101 [3]. Figure 1 shows that the centre of the specimen was loaded with a metal bearing plate with a length and width of 40 mm. Therefore, the edge distances parallel (x) and perpendicular (y) to the grain were represented by $(l-40)/2$ and $(w-40)/2$, respectively. Accordingly, x is 0 mm (4040, 6040, 8040) and 40 mm (4120, 6120, 8120), and y is 0 mm (4040, 4120), 10 mm (6040, 6120) and 20 mm (8040, 8120). When both x and y were 0 mm (4040), the tests were full-area compression tests perpendicular to the grain tests.

A tensile and compression testing machine (MAEKAWA MFG. CO., LTD. A-300-B4) was used for loading.

Vertical displacements of the bearing metal plate were measured at two points using displacement transducers (Tokyo Measuring Instruments Laboratory Co., Ltd., CDP-25), and the average value was considered as the test displacement. The ratio of the displacement to height was considered as the test strain. The load was measured using a testing machine. The load divided by the loading area (1,600 mm^2) was considered as the test stress.

The method of calculating the characteristic values was the same as that used in a previous study [2]. The elastic stiffness (E_e), plastic stiffness (E_p), yield stress (σ_y), and yield strain (ε_y) were calculated from the stress–strain curves. E_e was calculated following Inayama's study [4] and E_p, σ_y and ε_y were calculated following Fujita's study [5].

3 RESULTS AND DISCUSSION

3.1 DIFFERENCE IN STRESS-STRAIN CURVE DUE TO POROUS STRUCTURES

Figure 2 shows examples of stress-strain curves of the compression test perpendicular to the grain for diffuse-porous wood (Itayakaede) and ring-porous wood (Keyaki), each taken from the same piece, for each dimensional specification. In diffuse-porous wood, the stiffness gradually decreases after the yield point. The stiffness decreased more clearly in ring-porous wood than in diffuse-porous wood at the yield point. In the specification without the edge distance (4040), the load increased and decreased repeatedly after the yield point. This behaviour may be due to the sequential failure of vessels in the pore zone of ring-porous wood. The load increase/decrease behaviours were milder for the specifications with edge distance than for those without edge distance. Such behaviour was less apparent for the specifications with an edge distance parallel to the grain (4120, 6120, and 8120). The edge distance is considered to constrain the fracture of the vessels in the pore zone. For the edge distance perpendicular to the grain, shear failure occurred at the edge of the loading area, which may have weakened this effect compared with the edge distance parallel to the grain. The other diffuse-porous and radial-porous wood specimens showed similar trends to the example of diffuse-porous wood, and the other ring-porous wood specimens showed trends similar to those of ring-porous wood.

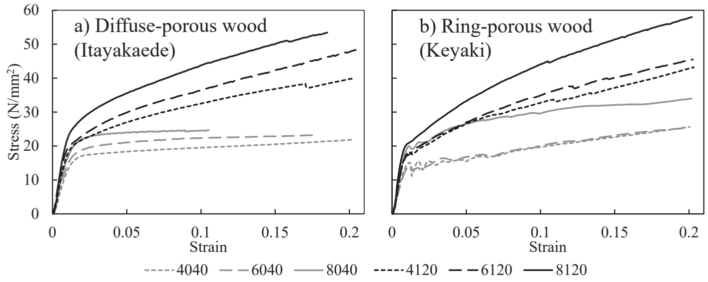

***Figure 2**: Example of stress-strain curves of compression test perpendicular to the grain for each porous structure.*

***Table 2**: Summary of results of partial compression test perpendicular to the grain*

	size	E_e a, b) (kN/mm^2)	E_p b, c) (kN/mm^2)	σ_y b, d) (N/mm^2)	ε_y b, e) (%)		size	E_e a, b) (kN/mm^2)	E_p b, c) (kN/mm^2)	σ_y b, d) (N/mm^2)	ε_y b, e) (%)
IT	4040	1.52 (0.146)	0.088 (0.016)	14.3 (1.79)	1.07 (0.071)	KY	4040	1.44 (0.267)	0.073 (0.034)	12.0 (1.25)	0.98 (0.135)
	6040	1.82 (0.277)	0.137 (0.028)	17.3 (2.93)	1.04 (0.069)		6040	1.67 (0.192)	0.116 (0.052)	14.5 (2.15)	0.98 (0.092)
	8040	1.88 (0.214)	0.167 (0.019)	17.3 (1.29)	1.01 (0.081)		8040	1.85 (0.387)	0.153 (0.045)	15.7 (2.96)	1.00 (0.146)
	4120	2.27 (0.209)	0.215 (0.025)	18.9 (2.18)	0.92 (0.065)		4120	1.89 (0.278)	0.200 (0.040)	17.0 (2.09)	1.04 (0.188)
	6120	2.64 (0.284)	0.267 (0.034)	20.7 (2.54)	0.85 (0.039)		6120	2.39 (0.342)	0.263 (0.053)	17.3 (2.12)	0.83 (0.036)
	8120	2.69 (0.273)	0.288 (0.041)	21.2 (1.89)	0.91 (0.099)		8120	2.50 (0.466)	0.294 (0.062)	18.4 (3.92)	0.87 (0.077)
SR	4040	1.29 (0.194)	0.138 (0.006)	13.3 (1.57)	1.12 (0.032)	YC	4040	0.95 (0.172)	0.004 (0.010)	5.86 (0.84)	0.71 (0.035)
	6040	1.75 (0.231)	0.214 (0.006)	16.9 (1.70)	1.12 (0.107)		6040	1.04 (0.236)	0.025 (0.017)	6.66 (0.93)	0.72 (0.062)
	8040	1.76 (0.031)	0.252 (0.024)	17.1 (0.36)	1.11 (0.027)		8040	1.08 (0.208)	0.032 (0.015)	6.73 (0.51)	0.74 (0.078)
	4120	1.94 (0.284)	0.283 (0.038)	18.9 (1.95)	1.06 (0.069)		4120	1.32 (0.239)	0.068 (0.032)	7.30 (0.82)	0.67 (0.041)
	6120	2.61 (0.212)	0.386 (0.045)	21.3 (2.20)	0.92 (0.125)		6120	1.53 (0.243)	0.093 (0.040)	7.38 (0.76)	0.58 (0.037)
	8120	2.41 (0.012)	0.403 (0.031)	22.7 (2.17)	1.05 (0.103)		8120	1.54 (0.212)	0.101 (0.030)	7.85 (1.01)	0.63 (0.052)
UD	4040	1.00 (0.284)	0.057 (0.011)	10.4 (1.98)	1.15 (0.098)	MZ	4040	1.02 (0.294)	0.040 (0.013)	8.67 (1.93)	0.95 (0.084)
	6040	1.40 (0.079)	0.078 (0.003)	13.0 (0.74)	1.01 (0.078)		6040	1.29 (0.418)	0.064 (0.012)	10.6 (3.27)	0.92 (0.075)
	8040	1.25 (0.051)	0.120 (0.022)	12.6 (0.27)	1.11 (0.065)		8040	1.26 (0.373)	0.096 (0.017)	11.4 (3.59)	0.99 (0.057)
	4120	1.52 (0.376)	0.164 (0.017)	13.7 (2.32)	1.04 (0.047)		4120	1.52 (0.357)	0.152 (0.050)	11.4 (2.81)	0.85 (0.052)
	6120	2.11 (0.081)	0.198 (0.024)	15.9 (0.72)	0.84 (0.041)		6120	1.89 (0.537)	0.193 (0.051)	12.4 (3.85)	0.75 (0.063)
	8120	2.02 (0.163)	0.229 (0.024)	16.3 (0.94)	0.90 (0.050)		8120	1.92 (0.463)	0.228 (0.060)	13.4 (3.87)	0.81 (0.047)
KR	4040	0.88 (0.480)	0.024 (0.011)	5.15 (1.62)	0.72 (0.211)	BN	4040	0.79 (0.069)	0.072 (0.013)	6.77 (0.52)	0.95 (0.079)
	6040	1.04 (0.517)	0.036 (0.025)	6.26 (2.20)	0.76 (0.197)		6040	0.97 (0.138)	0.097 (0.012)	8.43 (0.26)	0.99 (0.181)
	8040	1.04 (0.349)	0.040 (0.028)	6.46 (1.55)	0.77 (0.106)		8040	1.04 (0.129)	0.124 (0.014)	8.70 (0.61)	0.98 (0.071)
	4120	1.24 (0.411)	0.085 (0.026)	6.91 (1.47)	0.65 (0.109)		4120	1.20 (0.124)	0.143 (0.007)	9.92 (0.76)	0.94 (0.128)
	6120	1.49 (0.522)	0.113 (0.041)	7.15 (1.90)	0.57 (0.081)		6120	1.43 (0.240)	0.190 (0.012)	10.6 (0.46)	0.86 (0.144)
	8120	1.47 (0.479)	0.127 (0.030)	7.63 (1.72)	0.66 (0.109)		8120	1.43 (0.235)	0.192 (0.013)	10.9 (1.00)	0.90 (0.072)

Notes: a) Elastic stiffness, b) The values mean Average (Standard deviation), c) Plastic stiffness, d) Yield stress, e) Yield strain, size shows dimensional specifications

3.2 RESULTS OF COMPRESSION TESTS

Table 2 shows the mean values and standard deviations of E_e, E_p, σ_y and ε_y. The mean values of E_e, E_p and σ_y were higher for partial compression than for full-area compression for all the species. For the edge distance perpendicular to the grain, the values tended to be higher with increasing edge distance; however, little differences were noted between 6120 and 8120. The mean values of ε_y were higher for specimens without an edge distance parallel to the grain than for those with an edge distance parallel to the grain.

The coefficients of variation for E_e and E_p were 0.49–54.8% and 2.77–245% respectively. E_e for Kuri and Mizunara were particularly high. E_p for Kuri and Yachidamo were particularly high. Ring-porous wood tended to show a higher variation than diffuse- and radial-porous wood. Ring-porous wood is considered more affected by the annual ring angle than diffuse- and radial-porous wood because of the fracture of vessels in the pore zone. There is also the possibility of the influence of an increase/decrease in the load on the stress-strain curve after the yield point.

3.3 RELATIONSHIP BETWEEN THE CHARACTERISTIC VALUES AND DENSITY

Figure 3 shows the relationship between E_e and the density of each specimen. Figure 4 shows the relationship between σ_y and density for each dimensional specification. Figures 3 and 4 represent the regression line calculated for

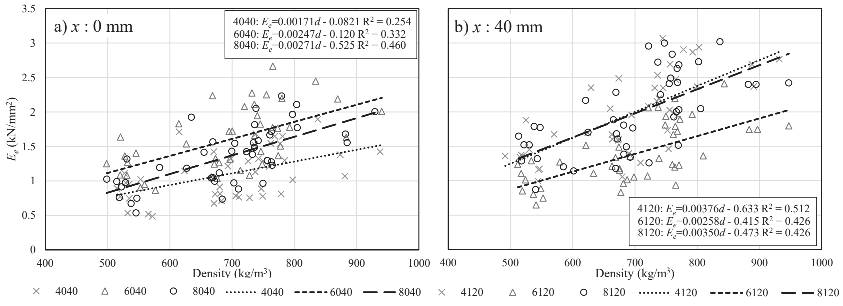

***Figure 3**: Relationship between E_e and density (d) of each specimen.*

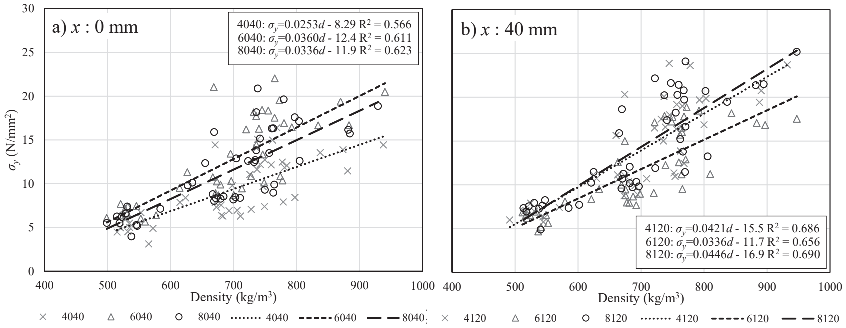

***Figure 4**: Relationship between σ_y and density (d) of each specimen.*

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each dimensional specification for the relationships between E_e and density and σ_y and density.

For E_e and σ_y, a significant positive correlation was observed ($p < 0.01$) with density for all dimensional specifications. In both cases, the correlation was stronger in the specifications with edge distance than in those without it. A possible explanation for this is that the effect of factors other than density, such as the annual ring angle, was less affected by the partial compression specifications because the deformation was constrained by the edge distance. For σ_y, the correlation was stronger than that for E_e for all dimensional specifications. The effect of density may have been greater for σ_y than for E_e, while the effects of other factors may have been relatively less.

3.4 EFFECT OF EDGE DISTANCE ON INCREASE RATIOS OF CHARACTERISTIC VALUES

Figure 5 shows the relationship between the increase ratios of E_e and σ_y and the edge distance perpendicular to the grains. The increase ratios of E_e and σ_y are defined as the average of the ratio of the characteristic value of a specimen to that of the full compression specimen without both edge distances being prepared from the same material.

As shown in Figure 5, the increase ratios of E_e and σ_y were higher for the partial compression specimens than for the full compression specimens. Irrespective of the edge distance parallel to the grain (0 mm or 40 mm), the increase ratios of E_e and σ_y tended to increase with increase in the edge distance perpendicular to the grain. In contrast, at an edge distance perpendicular to the grain longer than 10 mm, the increase ratios of E_e and σ_y increased only slightly or remained constant depending on the wood species. It is suggested that the effect of the edge distance parallel to the grain on the improvement in the characteristic values converged. These trends agree with a previous study on softwood reported by Inayama [4].

3.5 DIFFERENCES IN INCREASE RATIONS BY WOOD SPECIESE

As shown in Figure 5, the increase ratios of E_e and σ_y tended to be higher for Shirakashi and Udaikamba and lower for Yachidamo compared to other species. These results suggest that there are differences among the wood species. However, further studies are needed to clarify the effects of the annual ring angles and other factors.

3.6 RELATIONSHIPS BETWEEN CHARACTERISTIC VALUES

Figures 6 and 7 show the relationships between E_e and E_p and σ_y and ε_y, respectively, and indicate that both relationships are significantly positively correlated. However, the relationships between σ_y and ε_y had a smaller correlation coefficient than E_e and E_p and were not strongly correlated. Figure 7 shows that the plots for each tree species fell within certain ranges, and the all ranges appeared to be different from the regression line for all specimens. Therefore, although a positive correlation was observed for all specimens, the relationship may be different for each tree species.

Table 3 summarizes the linear regression equations calculated for each tree species, the dimensional specifications for the relationships between E_e and E_p, σ_y and ε_y, and their coefficients of determination. For the relationship between E_e and E_p, significant positive correlations were found for all tree species and dimensional specifications. Therefore, there is a positive

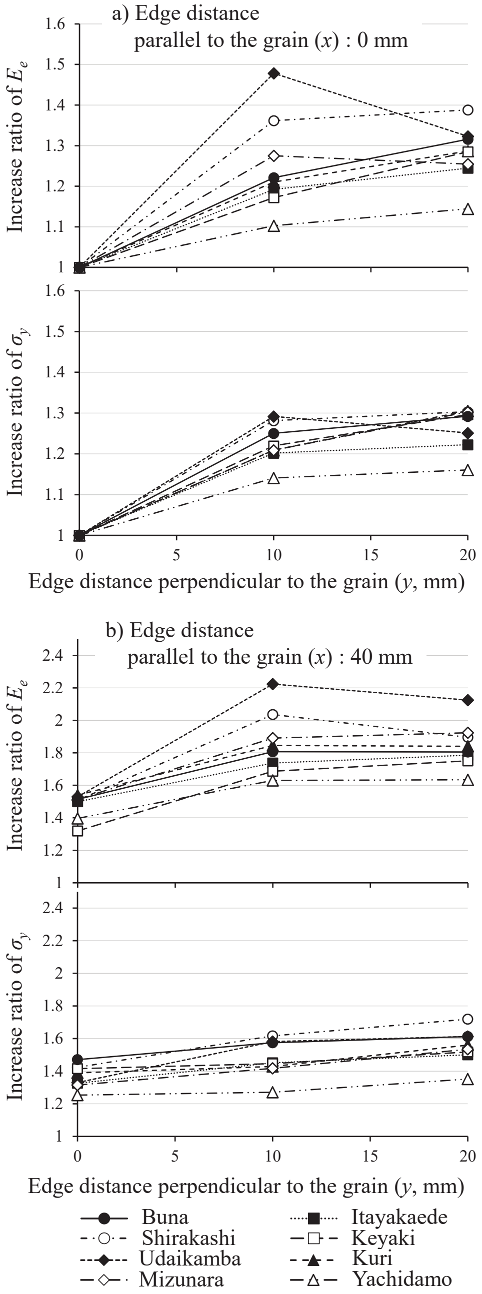

***Figure 5**: Relationships between the increase ratio of E_e and σ_y and edge distance perpendicular to the grain*

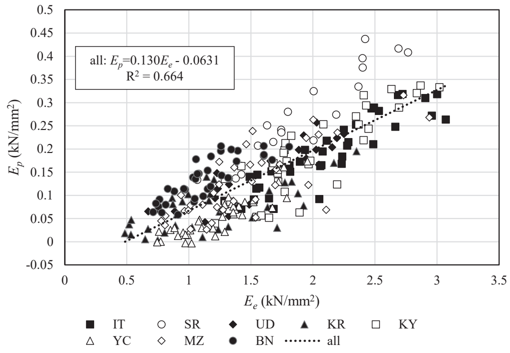

Figure 6: *Relationship between E_e and E_p.*

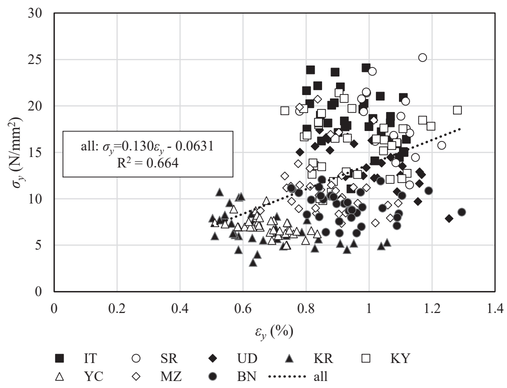

Figure 7: *Relationship between σ_y and ε_y.*

Table 3: *Results of correlation analysis for each specification in the relationship between characteristic values.*

	Relationship between E_e and E_p		Relationship between σ_y and ε_y	
	The linear regression equation	R²	The linear regression equation	R²
IT	$E_p = 0.139E_e - 0.103$	0.806^{**}	$\sigma_y = -12.2\varepsilon_y + 30.0$	0.165^{*}
SR	$E_p = 0.193E_e - 0.0981$	0.875^{**}	$\sigma_y = -10.7\varepsilon_y + 29.7$	0.0948^{**}
UD	$E_p = 0.123E_e - 0.0493$	0.701^{**}	$\sigma_y = -14.7\varepsilon_y + 28.5$	0.606^{**}
KR	$E_p = 0.0658E_e - 0.00741$	0.451^{**}	$\sigma_y = -5.84\varepsilon_y + 10.6$	0.234^{**}
KY	$E_p = 0.160E_e - 0.130$	0.747^{**}	$\sigma_y = 1.61\varepsilon_y + 14.3$	0.00464
YC	$E_p = 0.125E_e - 0.101$	0.791^{**}	$\sigma_y = -6.65\varepsilon_y + 11.5$	0.253^{**}
MZ	$E_p = 0.119E_e - 0.0472$	0.604^{**}	$\sigma_y = -5.56\varepsilon_y + 16.2$	0.0285
BN	$E_p = 0.134E_e - 0.0175$	0.681^{**}	$\sigma_y = -2.72\varepsilon_y + 11.8$	0.0437
4040	$E_p = 0.0404E_e + 0.0124$	0.141^{*}	$\sigma_y = 11.9\varepsilon_y - 1.89$	0.373^{**}
4120	$E_p = 0.110E_e - 0.0202$	0.551^{**}	$\sigma_y = 18.9\varepsilon_y - 3.99$	0.465^{**}
6040	$E_p = 0.0812E_e - 0.0206$	0.380^{**}	$\sigma_y = 15.8\varepsilon_y - 3.31$	0.339^{**}
6120	$E_p = 0.123E_e - 0.0404$	0.646^{**}	$\sigma_y = 26.3\varepsilon_y - 6.55$	0.465^{**}
8040	$E_p = 0.106E_e - 0.0317$	0.492^{**}	$\sigma_y = 18.0\varepsilon_y - 5.43$	0.356^{**}
8120	$E_p = 0.128E_e - 0.0314$	0.641^{**}	$\sigma_y = 27.3\varepsilon_y - 8.34$	0.458^{**}

Notes: R^2 shows coefficient of determination, ** significant at $p<0.01$, * significant at $p<0.05$

correlation between elastic stiffness and plastic stiffness in the compression strength of wood perpendicular to the grain, regardless of the wood species and dimensional specifications. For the dimensional specifications, the slope and coefficient of determination of the linear regression equation were the smallest for the full-area compression specification (4040), and each value increased with an increasing edge distance perpendicular to the grain. In addition, they tended to be even larger for specifications with the edge distance parallel to the grain. The slope is because the plastic stiffness is close to zero for the full-area compression specification (4040) and the stiffness increases with increasing the edge distance. The coefficient of determination is due to the constraining effect of the edge distance on the deformation and fracture of the specimens, which reduces the variation between the elastic and plastic stiffnesses. In the relationship between σ_y and ε_y, significant positive correlations were found for each dimensional specification; however, significant negative correlations were found for many wood species. Previous studies on softwoods [4] and hardwoods [2] have shown that for the same species, loading area dimensions and specimen height, relationships between σ_y and ε_y are inversely related. This may also be true for the results of this study, as the relationship is not clear but is close to inversely proportional when the same wood species, loading area dimensions, and specimen height are held constant. However, the relationship between σ_y and ε_y was significantly positively correlated for each dimensional specification. Although the coefficient of determination was smaller than that in the relationship between E_e and E_p, the slope and coefficient of determination in the relationship between σ_y and ε_y were similar to those in the relationship between E_e and E_p. These results suggest that there is a positive correlation between σ_y and ε_y for dimensional specifications regardless of the species.

4 CONCLUSIONS

The aim of this study was to investigate the effect of edge distance orthogonal to the longitudinal direction and wood species on the compression performance of hardwoods perpendicular to the grain.

The results of this study are as follows.

(1) The behaviour of the stress-strain curve after the yield point might differ depending on the porous structure.

(2) With respect to the edge distance parallel to the grain, the variation in the elastic stiffness and yield stress can be

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reduced by constraining the deformation and fracture with the edge distance perpendicular to the grain.

(3) The elastic stiffness and yield stress are significantly correlated with density, and specifications with an edge distance perpendicular, parallel, or both to the grain have a stronger correlation than those without it.

(4) The effect of the edge distance perpendicular to the grain on the increase ratio of elastic stiffness and yield stress tends to be similar to that of softwood [4] and may vary between wood species.

(5) The relationships between elastic stiffness and plastic stiffness, yield stress and yield strain tend to be similar to those for softwood.

These results support the conclusions of a previous study in which hardwoods were able to estimate the same degree of denting performance as softwoods [4]. However, some species showed greater variability in their characteristic values, particularly in ring-porous wood. More detailed studies are needed on the effects of different species, especially on the porous structure, and on the effects of the annual ring inclination angle.

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