EFFECTS OF COMPONENT RATIO OF THE FACE AND CORE LAMINAE ON STATIC BENDING STRENGTH PERFORMANCE OF THREE-PLY CROSS-LAMINATED WOOD PANELS MADE WITH SUGI (*CRYPTOMERIA JAPONICA*)

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ABSTRACT

In order to improve the bending strength performance of three-ply laminated wood panels and use them as construction-grade panel materials, twelve types of three-ply cross-laminated wood panels whose percentages of core lamina thickness versus total lamina thickness were 33%, 50%, and 80% were made with sugi (Japanese cedar), and the effect of component ratio of the face and core laminae on their static bending strength performance was investigated.

The moduli of elasticity (MOE), proportional limit stresses and moduli of rupture (MOR), perpendicular ($C_\perp$ type) and parallel ($C_\parallel$ type) to the grain of face laminae markedly increased or decreased with increasing percentage of core lamina thickness. The percentages of core lamina thickness at which each strength property value of $C_\parallel$ type became equal to that of $C_\perp$ type ranged from 65% to 80%. At each percentage of core lamina thickness, the MOE and proportional limit stress of $C_\parallel$ type were higher in $C_\parallel$(45) specimens having perpendicular-direction lamina of 45° annual ring angle in the core than in $C_\parallel$(90) specimens having perpendicular-direction lamina of 90° in the core, whereas there was little difference in MOR between $C_\parallel$(45) specimens and $C_\parallel$(90) specimens. For 45° specimens having the core lamina thickness from 60% to 70%, MOE as well as MOR parallel and perpendicular to the grain of face laminae exceeded the corresponding requirement values of structural plywood with 21.0-mm thickness specified in Japanese Agricultural Standards.

The measured MOEs of $C_\perp$ type were nearly equal to those calculated from true MOEs of individual laminae, whereas the measured MOEs of $C_\parallel$ type were smaller than the calculated MOEs, owing to the effect of deflection caused by shear forces. The percentages of deflection caused by shear force versus total deflection (Y_s) were much greater in $C_\parallel$(90) specimens than in $C_\parallel$(45) specimens. The Y_s for the $C_\parallel$(45) specimen decreased with increasing percentage of core lamina thickness, while *Y*s for the $C_\parallel$(90) specimen minimally varied.

Keywords: Anisotropy, annual ring angle, cross-laminated wood panels, modulus of elasticity, shear force.

INTRODUCTION

Sugi trees are the most commonly occurring species in Japanese forests. A very low modulus of elasticity at the annual ring angle of 45° perpendicular to the grain of sugi wood, which results from its low shear modulus in cross-section (G_{RT}), becomes a problem when used for a panel product. It is assumed that the strength performance perpendicular to the grain can be improved by cross-laminating each layer so that the grain direction is at a right angle to that of the adjacent layer. Recently, cross-laminated wood panels have been developed and used for applications such as wall and floor sheathing in wood construction. In addition, cross-laminated wood panels are expected to be superior in dimensional stability and warp resistance. However, there has been no research on the effect of percentage of face and core lamina thickness on the static bending strength performance of cross-laminated wood panels.

In a previous report on three-ply cross-laminated wood panels that were composed of three laminae with the same thickness (Park et al. 2001), it was found that static bending strength performance perpendicular to the grain was markedly improved by cross-laminating, and bending strength performance was markedly influenced by annual ring angles of perpendicular-direction laminae used for the core as well as the face. Moreover, for the cross-laminated wood panels whose core was composed of lamina perpendicular to the grain, the measured values of modulus of elasticity (MOE) were much lower than those calculated from the true MOE of individual laminae. It was clarified that this could be explained in terms of the effect of deflections caused by shear forces owing to a very small shear modulus in cross-section (G_{RT}) of sugi. This result for cross-laminated wood panels that had three laminae of the same thickness was expected to be varied by changing the percentage of faces and core lamina thickness.

The degree of anisotropy of strength properties for plywood that was expressed as ratios of strength properties perpendicular to the grain of face veneer versus those parallel to the grain of face veneer of plywood can be varied over a wide range by changing the percentage of face and core veneer thickness (Asano and Tuzuki 1963; Okuma 1966).

In order to improve the bending strength performance of cross-laminated wood panels and use them as construction-grade panel materials, in this study, three-ply cross-laminated wood panels whose core lamina thickness versus total lamina thickness was 33%, 50%, and 80% were made with sugi; and the effect of core lamina thickness on the degree of anisotropy of bending strength performance and the change in effect of the deflection caused by shear forces on bending MOE with increasing percentage of core lamina thickness were investigated. It is very difficult to measure the bending strength properties perpendicular to the grain of veneer constituting plywood, but the bending strength properties perpendicular to the grain of lamina constituting cross-laminated wood panel can be measured. This is very advantageous to investigate the bending strength performance of cross-laminated wood panels.

MATERIALS AND METHODS

Specimens

Sugi (Japanese cedar, *Cryptomeria japonica* D. Don) with densities in the range of 0.358-0.417 Mg/m^3 and having annual rings with radii of curvature of more than 110 mm was used as a raw material. A resorcinol-phenol resin type adhesive formulated for a room temperature cure was used, and the amount of spread was 300 g/m^2. Cross-laminated wood panel specimens and their preparation are shown in Fig. 1. The longitudinal-direction laminae and perpendicular-direction laminae were made with sugi. The longitudinal-direction laminae whose long axes were parallel to the grain had dimensions of 2, 5, 6.7, 10, and 16 mm(T) × 20 mm(R) × 360 mm(L), and the annul ring angles of the laminae were 90°. The perpendicular-direction laminae whose long axes were perpendicular to the grain had 45° and 90° annual ring angles. The perpendicular-direction lamina with 45° had the lowest MOE and the highest shear modulus in cross-section ($G_{45°}$), while those with 90° had the highest MOE and the lowest shear modulus in cross-section (G_{RT}) as described in Park et al. (2001). As shown in Fig. 1, the perpendicular-direction laminae had the dimensions of 2, 5, 6.7, 10, and 16 mm (45°) × 20 mm (L) × 360 mm (45°) and of 2, 5, 6.7, 10, and 16 mm (T) × 20 mm (L) × 360 mm (R), and were prepared as follows; the elements of 2, 5, 6.7, 10, and 16 mm

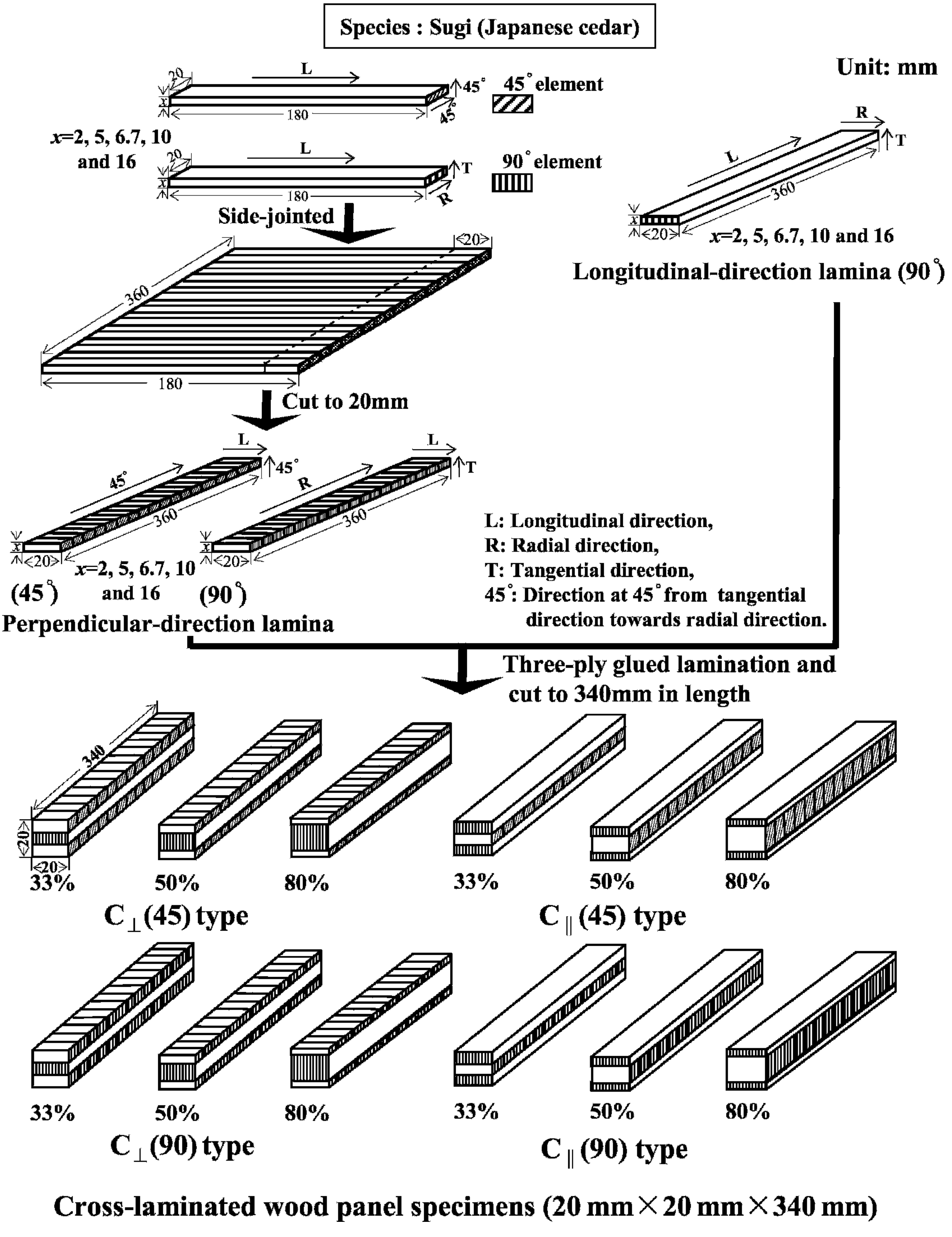

FIG. 1. Cross-laminated wood panel specimens and their preparation. 33%, 50%, and 80% are the percentage of core lamina thickness versus total thickness for cross-laminated wood panel specimens. 45 and 90 are annual ring angle in degrees.

(45°) × 20 mm (45°) × 180 mm (L) and of 2, 5, 6.7, 10, and 16 mm (T) × 20 mm (R) × 180 mm (L) were made. Eighteen elements of each thickness were side-jointed and then cut to 20 mm (L) size in width. By combining these longitudinal- and perpendicular-direction laminae, the following twelve types of three-ply cross-laminated wood panel specimens (20 mm × 20 mm × 340 mm) were manufactured; $C_{\|}(45)33\%$, $C_{\|}(45)50\%$, $C_{\|}(45)80\%$, $C_{\|}(90)33\%$, $C_{\|}(90)50\%$, $C_{\|}(90)80\%$, $C_{\perp}(45)33\%$, $C_{\perp}(45)50\%$, $C_{\perp}(45)80\%$, $C_{\perp}(90)33\%$, $C_{\perp}(90)50\%$ and $C_{\perp}(90)80\%$. For $C_{\|}$ type, the faces were composed of longitudinal-direction laminae and the core was composed of perpendicular-direction lamina. For $C_{\perp}$ type, the faces were composed of perpendicular-direction laminae and the core was composed of longitudinal-direction lamina. Forty-five and 90 indicated annual ring angles of perpendicular-direction laminae. 33%, 50%, and 80% indicated percentage of core lamina thickness versus total lamina thickness, which was the thickness of the finished cross-laminated wood panel. $C_{\|}$ and $C_{\perp}$ types were the specimens used to measure the static bending properties parallel and perpendicular to the grain of face laminae of cross-laminated wood panels. The number per each type of specimen was four.

Bending strength properties test

Static bending tests for cross-laminated wood panel specimens were conducted using four-point loading according to Japanese Agricultural Standards (JAS) for structural laminated veneer. The span was 300 mm, the distance between a loading point and a supporting point was 100 mm, and the cross-head speed was 5.0 mm/min. The deflection at the mid-span between the supporting points was measured with a dial gauge, and load-deflection curves were recorded with an X-Y recorder. The schematic diagram of bending test is shown in Fig. 2. The measured deflection was apparent deflection containing deflection caused by shear forces. The calculated MOE for each specimen was obtained using the equivalent cross-section method expressed in Eq. (1) from true MOE of individual laminae (Utokuchi et al. 1998), and compared with measured values of the cross-laminated wood specimens.

$$E = \frac{E_1 I_1 + E_2 I_2 + E_3 I_3}{I} \qquad (1)$$

where E is the modulus of elasticity of the laminated wood beam and E_1, E_2, and E_3 are the moduli of elasticity of individual laminae. I is the moment of inertia for the cross-section of laminated wood beam, and I_1, I_2 and I_3 are the moments of inertia of individual laminae about the neutral axis of their cross-section.

RESULTS AND DISCUSSION

Modulus of elasticity of laminae

The averaged moduli of elasticity (MOE) of longitudinal- and perpendicular-direction laminae are shown in Table 1. The average MOE for the longitudinal-direction laminae with 90° annual ring angle was 10.2 GPa, and the average MOE values of the perpendicular-direction laminae with 45° and 90° annual ring angles were 0.0817 GPa and 0.738 GPa, respectively. The MOE of the perpendicular-direction lamina with 45° annual ring angle was considerably smaller than that of 90° annual ring angle.

Stress-strain curves of cross-laminated wood panels

Typical examples of stress-strain curves for cross-laminated wood specimens are shown in Fig. 3. The stress-strain curve of $C_{\perp}$ type exhibited a distinct change in shape with increasing thickness of longitudinal-direction laminae used for the core. Large plastic deformations were observed beyond the proportional limit at 33% and 50% of core lamina thickness, whereas there was little plastic deformation at 80% of core lamina thickness. The breaking strain, which was defined as strain generated when stress reached the maximum value, decreased with increasing thickness of longitudinal-direction lamina used for the core. For $C_{\perp}(90)$ specimens

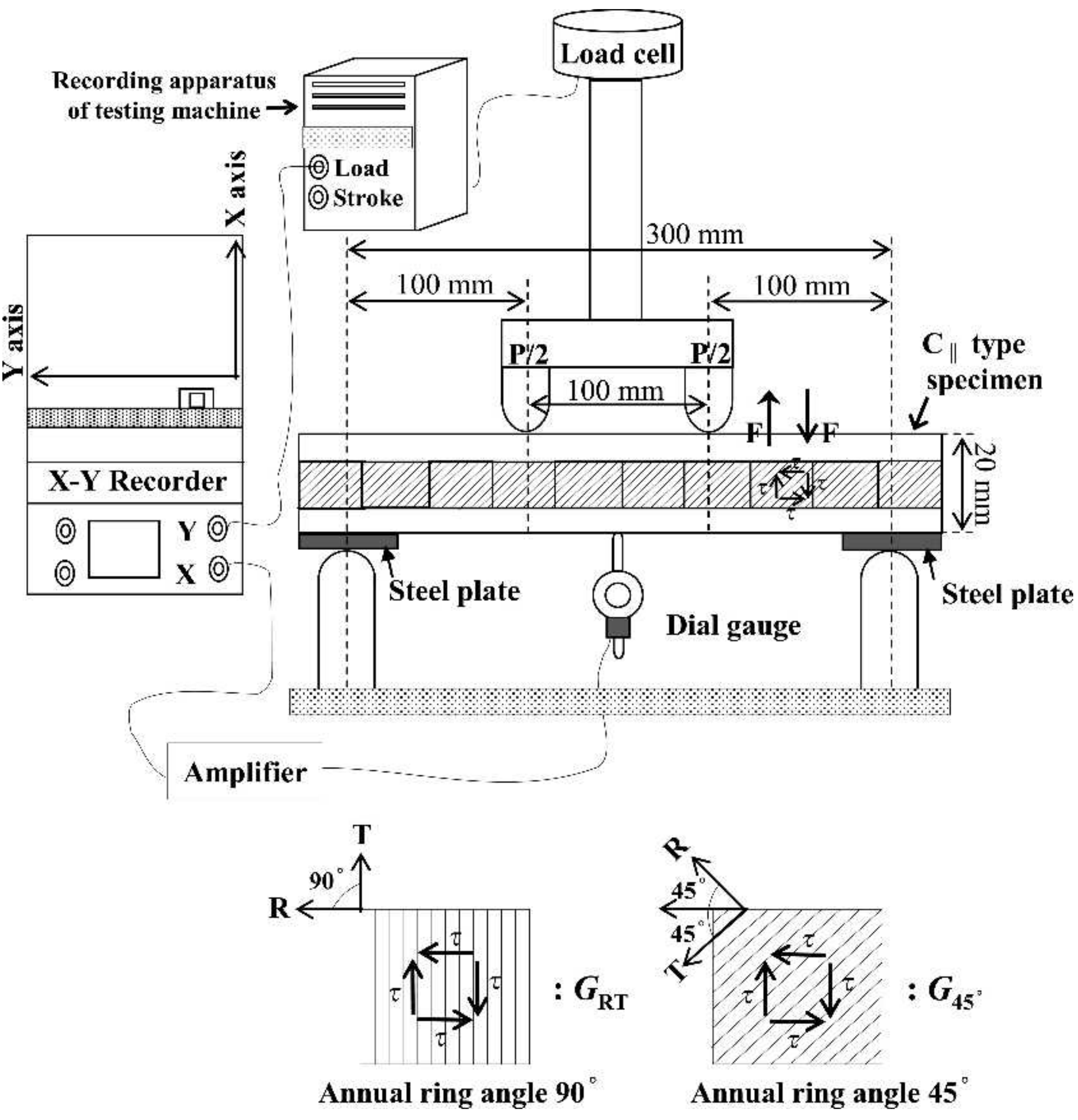

FIG. 2. Schematic diagram of static bending test for cross-laminated wood panel specimen. F is shear force (= P/2) and τ is shear stress generated in beam of specimen.

having perpendicular-direction laminae of 90° in the faces, numerous cracks occurred in specimens beyond the proportional limit, whereas for $C_{\perp}(45)$ specimens having perpendicular-direction laminae of 45° in the faces, there were no apparent cracks of perpendicular-direction lamina in the faces until breaking point. This is considered to be due to considerably greater breaking deflection of perpendicular-direction laminae of 45°. Unlike $C_{\perp}$ types, the MOEs within the proportional region for $C_{\parallel}$ types were higher in $C_{\parallel}(45)$ specimens having perpendicular-direction lamina of 45° in the core than in $C_{\parallel}(90)$ specimens having perpendicular-direction lamina of 90° in the core, regardless of core lamina thickness. The breaking strain for

TABLE 1. *Density and MOE of longitudinal- and perpendicular-direction laminae.*

Type	Annual ring angle(°)	Thickness (mm)	Density(Mg/m^3) AV	Density(Mg/m^3) CV(%)	MOE(GPa) AV	MOE(GPa) CV(%)	Number of lamina
Longitudinal-direction lamina	90	2	0.403	3.5	10.3	10.4	16
		5	0.383	3.4	9.87	8.9	16
		6.7	0.394	2.8	11.2	7.2	24
		10	0.391	3.3	9.60	11.9	8
		16	0.389	2.3	9.70	6.3	8
	Average		0.392		10.1		
Perpendicular-direction lamina	45	2	0.387	3.4	0.0833	6.0	8
		5	0.396	2.0	0.0788	3.8	8
		6.7	0.395	2.8	0.0792	5.1	12
		10	0.393	0.3	0.0875	2.3	4
		16	0.388	0.3	0.0815	2.5	4
	Average		0.392		0.0821		
	90	2	0.388	3.9	0.750	9.6	8
		5	0.388	2.8	0.708	7.6	8
		6.7	0.394	2.3	0.772	3.6	12
		10	0.396	0.3	0.718	2.2	4
		16	0.387	0.5	0.725	3.6	4
	Average		0.391		0.735		

AV: Average value, CV: Coefficient of variation.

33% of core lamina thickness had lower values in $C_{\|}(45)$ specimens than in $C_{\|}(90)$ specimens, whereas values for 50% and 80% of core lamina thickness were found to be greater in $C_{\|}(45)$ specimens. As shown in Fig. 3, for $C_{\|}(45)$ specimens, the stress-strain curves for 50% and 80% of core lamina thickness showed long and essentially straight lines beyond the proportional limit. For $C_{\|}(90)$ specimens, numerous cracks occurred, except for 80% of core lamina thickness.

Modulus of elasticity of cross-laminated wood panels

Results of bending tests for cross-laminated wood panel specimens are shown in Table 2.

Modulus of elasticity

The relationship between the MOE and the percentage of core lamina thickness of cross-laminated wood panels is shown in Fig. 4. The ratios of MOE of each core lamina thickness versus MOE of 33% and the ratios of MOE of 90° specimens versus MOE of 45° specimens were calculated from the average values of MOE shown in Table 2 and are mentioned below. For $C_{\perp}$ type, the MOE increased distinctly with increasing thickness of longitudinal-direction lamina used for the core from 33% to 80%. MOE values of cross-laminated wood panels were greater in $C_{\perp}(90)$ specimens than in $C_{\perp}(45)$ specimens, regardless of core lamina thickness. The ratios of MOE of each core lamina thickness versus MOE of 33% core lamina thickness were 1 : 2.80 : 10.4 for $C_{\perp}(45)$ specimens and 1 : 1.55 : 4.41 for $C_{\perp}(90)$ specimens; and the extent of the increase was much greater in $C_{\perp}(45)$ specimens than in $C_{\perp}(90)$ specimens. The MOE values for $C_{\perp}(45)$ specimens were compared with those for $C_{\perp}(90)$ specimens at each percentage of core lamina thickness, and the ratios of the MOE for $C_{\perp}(90)$ specimens to those for $C_{\perp}(45)$ specimens were 2.50 for 33%, 1.38 for 50%, and 1.06 for 80%. It was found that the ratio decreased considerably with increasing percentage of core lamina thickness. This is because the MOE values of $C_{\perp}$ types are gradually ruled by longitudinal-direction lamina used for the core with an increase in thickness of longitudinal-direction lamina with a high MOE, and

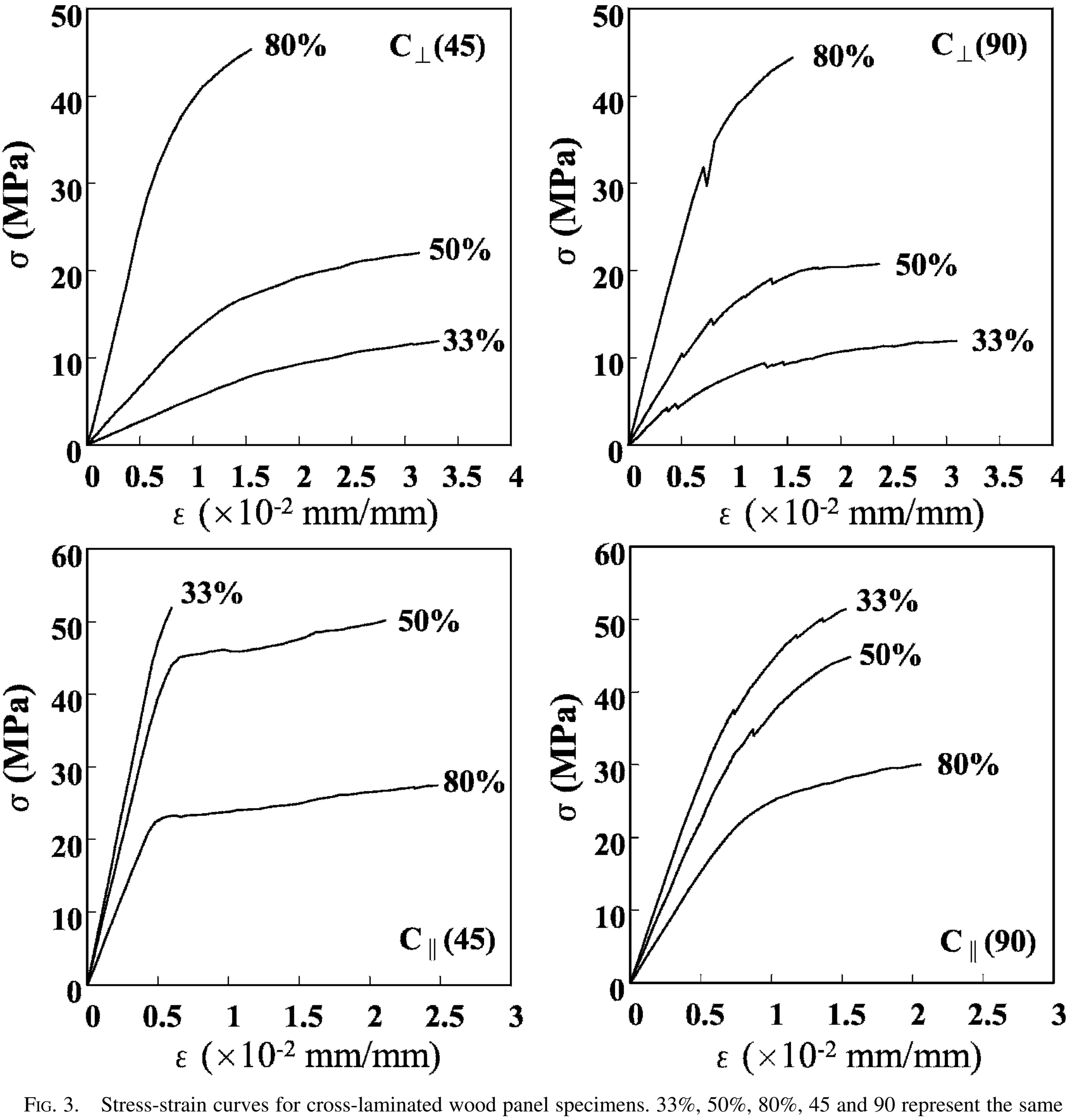

FIG. 3. Stress-strain curves for cross-laminated wood panel specimens. 33%, 50%, 80%, 45 and 90 represent the same parameters as in Fig. 1.

at 80%, there is little influence of perpendicular-direction laminae used for the faces.

MOEs of $C_{\|}$ types decreased linearly with increasing thickness of perpendicular-direction lamina used for the core in both annual ring angles. However, unlike $C_{\perp}$ types, their values were higher in $C_{\|}(45)$ specimens than in $C_{\|}(90)$ specimens. The ratios of MOE of each core lamina thickness versus MOE of 33% core lamina thickness were 1 : 0.84 : 0.52 for $C_{\|}(45)$ specimens and were 1 : 0.79 : 0.54 for $C_{\|}(90)$ specimens, and it was found that there was little difference in the extent of the decrease between both annual ring angles. The ratios of the MOE for $C_{\|}(90)$ specimens to those for $C_{\|}(45)$ specimens were 0.61 for 33%, 0.56 for 50%, and 0.64 for 80%, which minimally varied with the core lamina thickness.

TABLE 2. *Results of bending tests for cross-laminated wood panel specimens.*

Types	*T* (%)	Density (Mg/m^3)	MOE (GPa)	PLS (MPa)	MOR (MPa)	BS (10^{-2} mm/mm)
$C_\perp$(45)	33	0.412 (1.0)	0.492 (7.8)	6.08 (3.6)	11.8 (5.6)	3.83 (12.1)
	50	0.411 (1.8)	1.38 (5.3)	12.3 (2.5)	21.3 (6.7)	2.96 (21.4)
	80	0.402 (1.8)	5.12 (4.5)	31.1 (5.7)	46.5 (7.2)	1.67 (20.2)
$C_\perp$ (90)	33	0.413 (1.8)	1.23 (2.8)	5.53 (31.4)	11.1 (9.3)	2.61 (39.7)
	50	0.405 (3.2)	1.91 (10.3)	9.48 (21.4)	19.1 (13.6)	1.94 (22.1)
	80	0.401 (2.6)	5.42 (7.3)	31.1 (3.7)	46.8 (4.9)	1.61 (12.7)
$C_\parallel$ (45)	33	0.408 (0.9)	9.19 (3.7)	42.9 (4.5)	51.7 (1.7)	0.873 (33.9)
	50	0.401 (1.3)	7.86 (7.0)	37.8 (8.5)	49.1 (7.0)	2.20 (11.7)
	80	0.409 (1.1)	4.76 (6.6)	19.7 (7.6)	27.5 (6.4)	2.58 (2.7)
$C_\parallel$ (90)	33	0.411 (2.4)	5.62 (5.4)	28.9 (7.0)	50.8 (3.5)	1.44 (4.0)
	50	0.399 (1.8)	4.44 (5.1)	22.9 (8.0)	44.8 (6.5)	1.55 (8.6)
	80	0.409 (0.8)	3.03 (3.4)	17.2 (2.2)	28.2 (6.7)	1.75 (13.5)

T is the percentage of core lamina thickness. MOE is bending modulus of elasticity, PLS is proportional limit stress, MOR is bending modulus of rupture, BS is breaking strain. Each value is the average of four measurements, and each value in parentheses is the coefficient of variation (%). 45 and 90 in parentheses are annual ring angle(°).

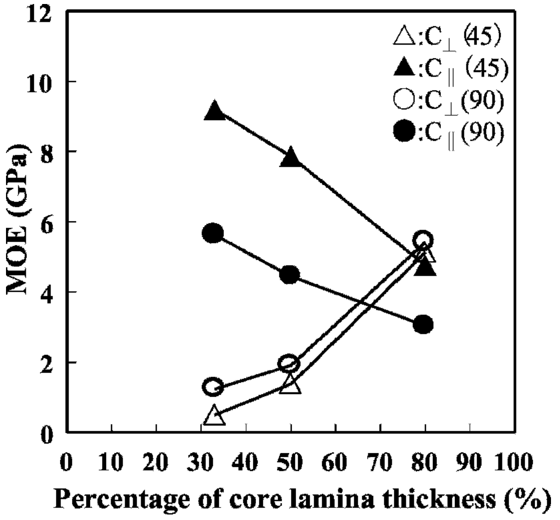

FIG. 4. Relationships between MOE and percentage of core lamina thickness of cross-laminated wood panel specimens. Each value is the average of four measurements.

The degree of anisotropy of MOE was expressed as a ratio of MOE perpendicular to the grain of face lamina (for $C_\perp$ type) versus MOE parallel to the grain of face lamina (for $C_\parallel$ type) of cross-laminated wood panels. These values were calculated using average values of MOE shown in Table 2 and were 0.053 for 33%, 0.179 for 50%, and 1.08 for 80% in 45° specimens, and were 0.220 for 33%, 0.430 for 50%, and 1.79 for 80% in 90° specimens. Their values for both annual ring angles were distinctly varied by changing core lamina thickness, and the extent of the change was greater in 45° specimens than in 90° specimens. In the case of cross-laminated wood panels with 80% core lamina thickness, the MOE value of $C_\perp$ type was greater than that of $C_\parallel$ type for both annual ring angles, and the values of anisotropy were found to be greater than 1.

For 45° specimens, as shown in Fig. 4, MOE value of $C_\perp$ type became nearly equal to that of $C_\parallel$ type at 80% core lamina thickness, which indicated the isotropy of MOE. On the other hand, the isotropy of MOE for 90° specimens was shown to occur at 65% core lamina thickness. The value for 45° specimens agreed with the percentages for the isotropy of plywood reported by Asano and Tuzuki (1963) and Okuma (1966), whereas the value for 90° specimens was lower than those in their report. It was found that MOE values for 45° specimens and 90° specimens at which the $C_\perp$ type was equalized to the $C_\parallel$ type were 4.9 GPa and 3.7 GPa, respectively; and the MOE value which yielded isotropy was greater in 45° specimens than in 90° specimens. It is specified in the requirement of MOE for structural plywood of JAS that MOEs parallel and perpendicular to the grain of face veneer of plywood with 21.0-mm thickness are 55 kgf/cm^2 (5.4 GPa) and 35 kgf/cm^2 (3.4 GPa), respectively. For 45° specimens, MOE parallel to the grain of face laminae exceeded the former value and MOE perpendicular to it exceeded the latter value over the core lamina thickness from 60% to 70%. For 90° specimens, both of the MOE values did not exceed the requirement values at any core lamina thickness.

Effect of deflection caused by shear forces on bending MOE

Deflection of beam for four-point bending is shown as follows

$$y_\alpha = y_m + y_s = \frac{Pl_1(3l^2 - 4l_1^2)}{4bh^3E} + \frac{kPl_1}{2bhG} = \frac{Pl_1(3l^2 - 4l_1^2)}{4bh^3E}\left[1 + \frac{2.4h^2}{3l^2 - 4l_1^2}\cdot\frac{E}{G}\right] \quad (2)$$

where y_m is the deflection caused by bending moment; y_s is the deflection caused by shear force; E is the true MOE; G is the shear modulus; P is the applied load; b and h are the width and height of the beam, respectively; l is the span; l_1 is the distance between the loading point and the supporting point ($l/3$); k is 6/5 in the case of a rectangular cross-section (Sakai 1970).

From Eq. (2), MOE calculated from the deflection caused by bending moment is as follows

$$E = E_\alpha\left[1 + \frac{2.4h^2}{3l^2 - 4l_1^2}\cdot\frac{E}{G}\right] \quad (3)$$

where E_α is the apparent MOE.

The E/G values are required for obtaining the true MOE from apparent MOE. The true MOEs for longitudinal-direction lamina and perpendicular-direction laminae of both annual ring angles were calculated using Eq. (3). E/G values of longitudinal-direction lamina ($E_L/G_{LR} = 18.1$) and perpendicular-direction lamina ($E_R/G_{RT} = 35.3$) of 90° annual ring angle were calculated from the relation between the square of the height/span ratio and the compliance ($1/E$) as was reported in a previous report (Park et al. 2003); and the E/G value ($E_{45°}/G_{45°} = 0.585$) of perpendicular-direction lamina of 45° annual ring angle was calculated from the two equations between $1/E$ and $1/G$ and annual ring angle as were reported in a previous paper (Park et al. 2001). The averaged density and MOE of laminae used for obtaining E/G values described above were 0.382 Mg/m^3 and 9.04 GPa for longitudinal-direction lamina, 0.378 Mg/m^3 and 0.074 GPa for perpendicular-direction lamina of 45°, and 0.387 Mg/m^3 and 0.690 GPa for perpendicular-direction lamina of 90°. The values were close to those of laminae used for this study. The calculated MOE values of cross-laminated wood panels were obtained using the equivalent cross-section method (Eq. (1)) from the true MOE of individual laminae. Figure 5 shows the ratios of the measured MOE to calculated MOE of cross-laminated wood panels. For $C_\perp$ type whose faces were composed of perpendicular-direction laminae, the ratios were 0.97–1.07, and there was little difference between the measured values and the calculated values. However, for $C_\parallel$ type whose faces were composed of longitudinal-direction laminae, the ratios were 0.84–0.93 for $C_\parallel(45)$ specimens and 0.51–0.55 for $C_\parallel(90)$ specimens, and it was found that for $C_\parallel(90)$ specimens, the measured values were considerably lower than calculated values. As described in previous reports (Park et al. 2001, 2003), this can be explained in terms of the effect of deflection caused by shear forces, depending on E/G ratio of Eqs. (2) and (3). In the previous report (Park et al. 2001), the contribution of glueline to MOE of parallel-laminated woods was investigated in order to obtain the effect of deflection caused by shear forces on MOEs of cross-laminated wood panels. However, in this study, there was no investigation on the contribution of glueline to MOE of parallel-laminated woods because the effect of the percentage of core lamina thickness of cross-laminated wood panels was the focus of this research. Hence, the contribution of glueline to MOE was discussed using the result of the previous paper. The contribution can be expressed by the following equation:

$$C_g = \frac{E_\gamma - E_\beta}{E_\beta} \times 100(\%) \quad (4)$$

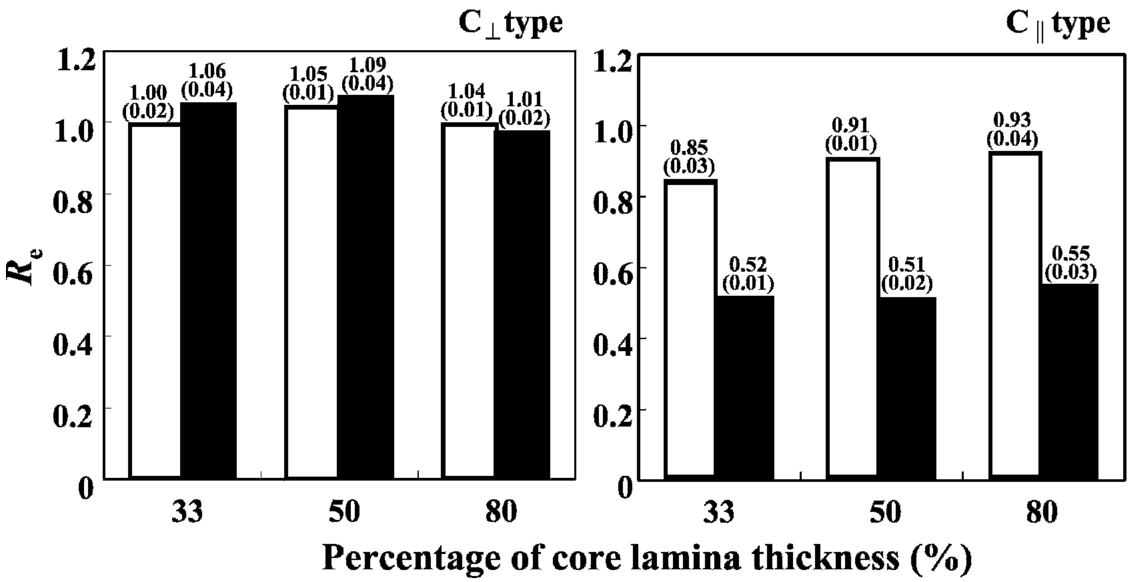

FIG. 5. R_e (ratio of measured value of MOE to value calculated from true MOE of laminae) for cross-laminated wood panel specimens. Each value is the average of four measurements, each value in parentheses is the standard deviation. Open poles: 45° annual ring angle; filled poles: 90° annual ring angle.

where E_β was the MOE calculated from the true MOE of individual laminae, and E_γ was the MOE calculated from the measured MOE (E_α) of laminated wood panels and included the contribution of glueline. In the previous report (Park et al. 2001), the ratio (R_g) of E_γ/E_β, was proportional to the reciprocal of E_β, and the regression equation between them was as follows: $R_g = 2.91 \times 10^{-2} E_\beta^{-1} + 1.050$ (correlation coefficient $r = 0.823^{**}$, where ** is significant at 1% level). R_g can be calculated from E_β using this equation and E_γ was obtained, where $E_\gamma = R_g \cdot E_\beta$.

Table 3 shows E_α, E_β, E_γ, the percentage of deflection caused by shear forces versus total deflection caused by bending moment and shear force (Y_s), and the percentage of contribution of

TABLE 3. *Effect of deflection caused by shear forces and glueline on MOE for cross-laminated wood panel.*

Types	T (%)	E_α (GPa)	E_β (GPa)	E_γ (GPa)	Y_s (%)	C_g (%)
C⊥(45)	33	0.492 (7.8)	0.493 (6.8)	0.530	10.2	10.9
	50	1.38 (5.3)	1.32 (5.1)	1.49	3.5	7.2
	80	5.12 (4.5)	5.08 (5.8)	5.52	6.1	5.6
C⊥(90)	33	1.23 (2.8)	1.17 (5.1)	1.29	2.4	7.5
	50	1.91 (10.3)	1.79 (13.2)	2.00	0.0	6.6
	80	5.42 (7.3)	5.50 (8.2)	5.67	8.1	5.5
C∥ (45)	33	9.19 (3.7)	10.9 (6.9)	11.5	20.1	5.3
	50	7.86 (7.0)	8.69 (8.0)	9.16	14.3	5.3
	80	4.76 (6.6)	5.15 (9.7)	5.44	12.7	5.6
C∥ (90)	33	5.62 (5.4)	10.9 (6.8)	11.6	51.6	5.3
	50	4.44 (5.1)	8.74 (9.4)	9.21	51.8	5.3
	80	3.03 (3.4)	5.54 (9.5)	5.85	48.2	5.5

E_α is measured value of MOE, E_β is the MOE calculated from true MOE of laminae. E_α and E_β are the average of four measurements, and each value in parentheses is the coefficient of variation (%). E_γ is the value of true MOE calculated from the measured MOE (E_α) averaged from four measurements. Y_s is the percentage of deflection caused by shear forces versus total deflection by bending moment and shear force and is obtained using Eq. (4). C_g indicates contribution of glueline to MOE of cross-laminated wood panel and is obtained using Eq. (5). T and 45, 90 in parentheses are the same as in Table 2.

glueline to MOE (C_g). Y_s can be obtained by the following equation.

$$Y_s = \frac{y_\alpha - y_m}{y_\alpha} \times 100 = \frac{E_\gamma - E_\alpha}{E_\gamma} \times 100(\%) \quad (5)$$

Y_s for $C_\perp$ type were 0%–10.2%, and the effect of deflection caused by shear force was small. However, Y_s values for $C_{||}$ types were 12.7%–20.1% for $C_{||}(45)$ specimens and 48.2%–51.8% for $C_{||}(90)$ specimens, and it was found that the effect of deflection caused by shear force was much greater in $C_{||}(90)$ specimens than in $C_{||}(45)$ specimens. From the previous report (Park et al. 2001), shear moduli in cross-section of perpendicular-direction laminae were 126 MPa in 45° annual ring angle and 19.1 MPa in 90° annual ring angle; and it was found that the shear modulus of perpendicular-direction lamina of 45° was 6.6 times greater than that of perpendicular-direction lamina of 90°. Beams with perpendicular-direction lamina of 45° annual ring angle in the core had shear modulus 4.2–6.4 times greater than the beams with that of 90° annual ring angle. Therefore, Y_s values for $C_{||}(45)$ specimens were much smaller than those of $C_{||}(90)$ specimens, regardless of core lamina thickness. Y_s values for $C_{||}(90)$ specimens hardly varied with increasing core lamina thickness. This is considered to be the reason that the change in *E/G* was small because both shear modulus and MOE decreased with increasing core lamina thickness as described in Table 4. Y_s values for $C_{||}(45)$ specimens decreased with increasing core lamina thickness. This was due to the decreased *E/G* value because MOE decreased markedly with increasing core lamina thickness and the decrease in shear modulus was small.

TABLE 4. *Change of E/G with increasing percentage of core lamina thickness of cross-laminated wood panel specimens.*

Type	*T* (%)	*E* (GPa)	*G* (MPa)	*E/G*
$C_{\|\|}(45)$	33	11.5	191	60.2
	50	9.15	230	39.8
	80	5.47	157	34.8
$C_{\|\|}(90)$	33	11.6	45.5	255
	50	9.18	33.5	274
	80	5.87	26.2	224

E means E_γ value (the value of true MOE calculated from measured MOE). *G* is shear modulus in cross-section. *T* and 45, 90 in parentheses are the same as in Table 2.

Proportional limit stress of cross-laminated wood panels

The relationships between proportional limit stress and percentage of core lamina thickness of cross-laminated wood panels are shown in Fig. 6. The proportional limit stress for $C_\perp$ type increased markedly with increasing core lamina thickness, and unlike MOE, the value was higher in $C_\perp(45)$ specimens than in $C_\perp(90)$ specimens, except for 80% core lamina thickness. In contrast, the proportional limit stress for $C_{||}$ type decreased markedly with increasing core lamina thickness, and it was found that the value was higher in $C_\perp(45)$ specimens than in $C_\perp(90)$ specimens, regardless of core lamina thickness.

The degrees of anisotropy of proportional limit stress, which were expressed as ratios of proportional limit stress perpendicular to the grain to the grain of face laminae versus that parallel to the grain of face laminae of cross-laminated wood panel, were 0.142 for 33%,

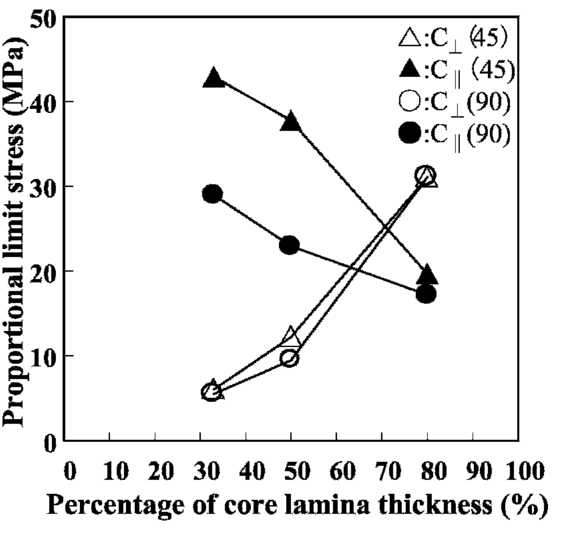

FIG. 6. Relationships between proportional limit stress and percentage of core lamina thickness of cross-laminated wood panel specimens. Each value is the average of four measurements.

0.325 for 50%, and 1.58 for 80% in 45° specimens, and 0.191 for 33%, 0.414 for 50%, and 1.81 for 80% in 90° specimens. These values were distinctly different when changing the percentage of core lamina thickness, and there were little differences in the extent of the change between both annual ring angles. As shown in Fig. 6, the percentages of core lamina thickness at which the proportional limit stress of $C_{\perp}$ type was equalized to that of $C_{\|}$ type was 75% for $C_{\|}(45)$ specimens, and was 65% for $C_{\|}(90)$ specimens. And the average proportional limit stresses for $C_{\|}(45)$ specimens and $C_{\|}(90)$ specimens at which $C_{\perp}$ type was equalized to $C_{\|}$ type were 24 MPa and 20 MPa, respectively.

Modulus of rupture of cross-laminated wood panels

The relationships between the modulus of rupture (MOR) and the percentage of core lamina thickness of cross-laminated wood specimens are shown in Fig. 7 and the breaking strain of cross-laminated wood specimens is shown in Table 2. For $C_{\perp}$ type, the MOR increased markedly with increasing thickness of longitudinal-direction lamina used for the core. Unlike MOE,

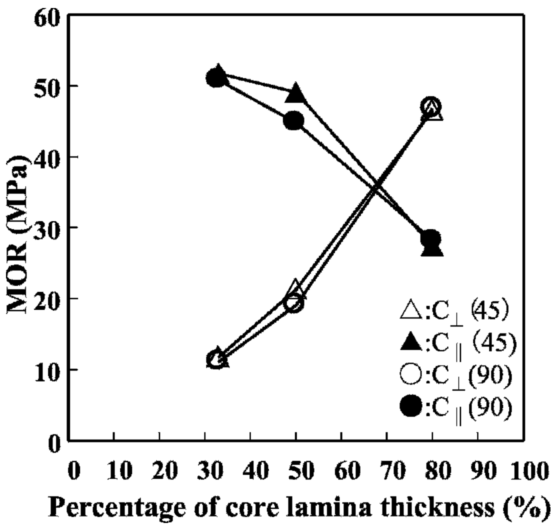

FIG. 7. Relationships between MOR and percentage of core lamina thickness of cross-laminated wood panel specimens. Each value is the average of four measurements.

the MOR values for 33% and 50% core lamina thickness were slightly higher in $C_{\perp}(45)$ specimens than in $C_{\perp}(90)$ specimens, whereas the value for 80% core lamina thickness was higher in $C_{\perp}(45)$ specimens. The ratios of MOR of each core lamina thickness versus MOR of 33% core lamina thickness were 1 : 1.81 : 4.00 for $C_{\perp}(45)$ specimens and were 1 : 1.72 : 4.20 for $C_{\perp}(90)$ specimens. The extent of the increase was lower than that of MOE because the breaking strain decreased considerably with increasing core lamina thickness as shown in Table 2. The MOR value for $C_{\perp}(45)$ specimens was compared with that for $C_{\perp}(90)$ specimens at each percentage of core lamina thickness, and the ratios of the MOR value for $C_{\perp}(90)$ specimen to that for $C_{\perp}(45)$ specimen were 0.94 for 33%, 0.90 for 50%, and 1.01 for 80%. Unlike MOE, there was little difference in MOR values between both annual ring angles.

The MOR values of $C_{\|}$ types decreased markedly with increasing thickness of perpendicular-direction lamina used for the core in both annual ring angles. The values for 33% and 50% of core lamina thickness were slightly higher in $C_{\|}(45)$ specimens, whereas values for 80% core lamina thickness were higher in $C_{\|}(90)$ specimens. The ratios of MOR of each core lamina thickness versus MOR of 33% core lamina thickness were 1 : 0.95 : 0.53 for $C_{\|}(45)$ specimens and were 1 : 0.88 : 0.56 for $C_{\|}(90)$ specimens. As shown in Table 2, the breaking strain for $C_{\|}(45)$ specimens increased markedly with increasing thickness of perpendicular-direction lamina used for the core, but there was little difference in the extent of the decrease between the MOR and the MOE. The ratios of the MOR for $C_{\|}(90)$ specimens to those for $C_{\|}(45)$ specimens were 0.98 for 33%, 0.91 for 50% and 1.03 for 80%.

The degrees of anisotropy of MOR, which were expressed as ratios of MOR perpendicular to the grain of face laminae versus that parallel to the grain of face laminae of cross-laminated wood panel, were 0.228 for 33%, 0.434 for 50%, and 1.69 for 80% in 45° specimens, and were 0.219 for 33%, 0.426 for 50%, and 1.66 for 80% in 90° specimens. Values for both annual ring angles varied distinctly by changing core lamina thickness, and there was little difference in the degree of anisotropy of MOR between both annual ring angles, regardless of core lamina thickness. The degree of anisotropy of MOR decreased with increasing core lamina thickness from 33% to 50% in both annual ring angles, but at 80% the MOR of $C_\perp$ type was greater than that of $C_\parallel$ type, and the extent of the change was greater than that of MOE.

As shown in Fig. 7, the MOR values for $C_\perp$ and $C_\parallel$ types for both annual ring angles were equalized at about 70%, and for 45° specimens, the value was lower than that of MOE, and for 90° specimens, the value was slightly higher than that of MOE. It was found that their values were lower than 80% of the percentage for the isotropy of plywood reported by Asano and Tusuki (1963) and Okuma (1966). The MOR values that yielded isotropy were 36 MPa for 45° specimens and 35 MPa for 90° specimens and this difference was very small. It is specified in the requirement of MOR for structural plywood of JAS that the MORs parallel and perpendicular to the grain of face veneer of plywood with 21.0-mm thickness are 260 kgf/cm^2 (25.5 MPa) and 180 kgf/cm^2 (17.7 MPa). For both 45° and 90° specimens, MOR parallel to the grain of face laminae exceeded the former value and MOR perpendicular to it exceeded the latter value over the core lamina thickness from 50% to 80%.

CONCLUSIONS

In order to improve the performance of three-ply cross-laminated wood panels made with sugi and use them as construction-grade materials, the effects of component ratio of the face and core lamina on their static bending strength performance were investigated. The MOE proportional limit stresses, and MOR perpendicular ($C_\perp$ type) and parallel ($C_\parallel$ type) to the grain of face laminae were distinctly varied by changing the percentage of core lamina thickness, and the extent of the change in MOE of $C_\perp$ type was greater in $C_\perp(45)$ specimens than in $C_\perp(90)$ specimens. It was found that the degrees of anisotropy of static bending strength properties of $C_\perp/C_\parallel$ for cross-laminated wood panels can be varied over a wide range by changing the component ratio of the face and core laminae. At each percentage of core lamina thickness, the MOE and proportional limit stress of $C_\parallel$ type were higher in $C_\parallel(45)$ specimens than in $C_\parallel(90)$ specimens, whereas there was little difference in MOR between $C_\perp(45)$ specimens and $C_\perp(90)$ specimens. For 45° specimens, there were no apparent cracks of perpendicular-direction lamina in the faces until breaking point. MOEs parallel and perpendicular to the grain of face laminae exceeded the requirement values of MOE of structural plywood with 21.0-mm thickness specified in JAS over the core lamina thickness from 60% to 70% and for both 45° and 90° specimens, MORs parallel and perpendicular to it exceeded the requirement values of MOR over the core lamina thickness from 50% to 80%.

The MOE for $C_\perp$ type was minimally affected by the deflections caused by shear forces, whereas that for $C_\parallel$ types was distinctly affected by it, and the effects were considerably greater in $C_\parallel(90)$ specimens than in $C_\parallel(45)$ specimens. It was found that for $C_\parallel(90)$ specimens, its effect was hardly varied and was very great because of a very high and nearly constant ratio of E/G, even by changing the percentage of core lamina thickness.

Therefore, it was found from the results of this study that construction-grade cross-laminated wood panels were possible to be made even with sugi having low density. It is suggested that cross-laminated wood panels are necessary to have about 70% core lamina thickness if they are required to behavior like isotropic material in bending strength. The reduction in MOE due to deflection caused by shear forces can be smaller by using the perpendicular-direction lamina with 45° annual ring angle for the core. Cross-laminated wood panels are considered to be materials whose excellent strength properties parallel to the grain of wood are taken full advantage of. Strip and plank having very various dimensions can be shown as possible elements constituting cross-laminated wood panels. Very long finger-jointed elements are possible. Hence, log with a small diameter and residual wood can be also used as their raw material.

REFERENCES

ASANO, I., AND K. TUZUKI. 1963. Some anisotropic properties on the strength of the plywood. J. Soc. Mater. Sci. Jpn 12(121):761–768.

JAPANESE AGRICULTURAL STANDARDS. 1993. Structural laminated veneer lumber. Bending test. Japanese Agricultural Standards Association, Tokyo, Japan. Pp. 18–20.

———. 1994. Structural plywood. Bending test. Japanese Agricultural Standards Association, Tokyo, Japan. Pp. 18–21.

OKUMA M. 1966. Studies on mechanical properties of plywood II. Young's modulus in bending. Mokuzai Gakkaishi 12(1):15–20.

PARK H. M., M. FUSHITANI, T. OHTSUKA, T. NAKAJIMA, K. SATO AND H. S. BYEON. 2001. Effect of annual ring angle on static bending strength performances of cross-laminated woods made with sugi wood. Mokuzai Gakkaishi 47:22–32.

———, ———, K. SATO, T. KUBO AND H. S. BYEON. 2003. Static bending strength performances of cross-laminated woods made with five species. J. Wood Sci. 49:411–417.

SAKAI J. 1970. Strength of structures. Gihodo, Tokyo. P. 77.

UTOKUCHI T., Y. KAWADA, M. KURANISHI. 1998. Strength of materials. Shokabo. Pp. 270–271.