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Static bending strength performances of cross-laminated woods made with five species

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Abstract Thirty types of three-ply parallel- and cross-laminated woods were prepared from five species, and their static bending strength performance were investigated. The modulus of elasticity (MOE), proportional limit stress, and modulus of rupture (MOR) perpendicular to the grain were increased by cross-laminating, and the extent of the increase increased with decreasing density of the species. The measured values of MOE parallel and perpendicular to the grain of parallel-laminated woods and perpendicular to the grain of face laminae of cross-laminated woods were approximately equal to those calculated from true MOEs of individual laminae. However, the MOE parallel to the grain of face laminae of cross-laminated woods was much lower than the calculated MOE owing to the effect of the deflection caused by shear force on the MOE. The percentage of deflection caused by shear force versus total deflection (Y_s) showed high values, from 16.1% (buna) to 40.5% (sugi), and it decreased linearly with increasing shear modulus in the cross section of the core. In addition, there was an extremely high positive correlation between the MOR and the measured MOE parallel to the grain of face laminae of cross-laminated woods. The MOR was also highly dependent on the shear modulus in cross section of the core.

Key words Cross-laminated woods · Species · Modulus of elasticity · Shear force · Modulus of rupture

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Introduction

In a previous report,[1] we investigated the static bending strength performances of three-ply cross-laminated woods to study the use of sugi wood as a material for wide boards. As a result, the static bending strength performances perpendicular to the grain have been markedly improved by cross-laminating. In the cross-laminated woods whose core was composed of lamina perpendicular to the grain, it was found that the measured values of the modulus of elasticity (MOE) are much lower than those calculated from the true MOE of laminae. We determined that this can be explained in terms of the effect of deflection caused by shear force due to an extremely small shear modulus in cross section of sugi wood.

In this study, three-ply parallel- and cross-laminated woods were prepared from five species of two softwoods and three hardwoods. We investigated the improvement in static bending strength performances perpendicular to the grain by cross-laminating and the influence of density and shear modulus in cross section in the element placed perpendicular to the long axis of the specimen.

Materials and methods

Specimen preparation

Five species with different densities and shear moduli in cross section were selected for this study. They included two softwoods: sugi (Japanese cedar, *Cryptomeria japonica* D.Don) and hinoki (Japanese cypress, *Chamaecyparis obtusa* Endl.); and three hardwoods: kiri (royal paulownia, *Paulownia tomentosa* Steud.), katsura (katsura, *Cercidiphyllum japonicum* Sieb. et Zucc.), and buna (beech, *Fagus crenata* Blume). Longitudinal laminae of 6.7 (T) × 20 (R) × 360 (L) mm were made with sugi and buna. Elements of 7.5 (T) × 20 (R) × 180 (L) mm were cut from each of the five species; 18 elements from each species were side-jointed

Table 1. Density and MOE for parallel-direction and perpendicular-direction laminae of five species

Species	Longitudinal-direction lamina		Perpendicular-direction lamina	
	Density (Mg/m^3)	MOE (GPa)	Density (Mg/m^3)	MOE (GPa)
Kiri	0.254	5.55	0.254	0.460
Sugi	0.382	9.04	0.387	0.690
Hinoki	0.464	12.8	0.463	0.760
Katura	0.483	8.91	0.463	1.22
Buna	0.579	8.57	0.538	1.46

Each value for longitudinal-direction lamina of kiri, hinoki, and katsura is the average of 9 measurements, and that for longitudinal-direction lamina of sugi and buna is the average of 54 measurements. Each value for perpendicular-direction lamina is the average of 27 measurements
MOE, modulus of elasticity

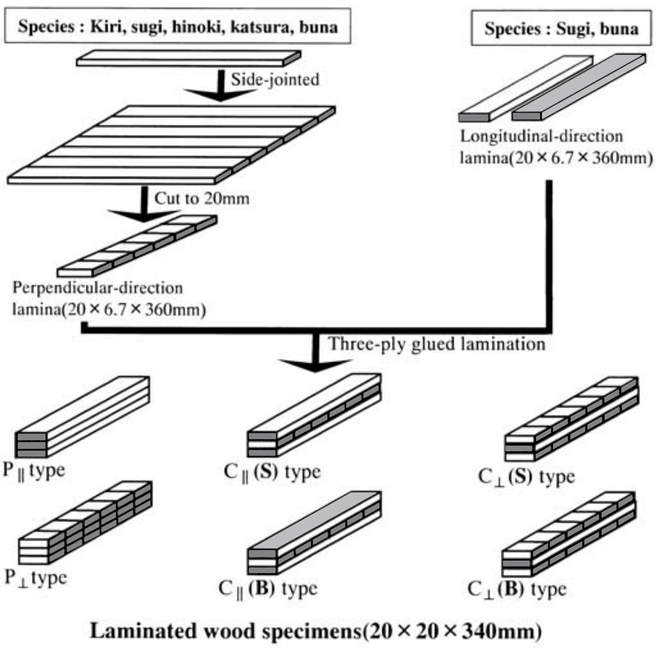

Fig. 1. Parallel- and cross-laminated wood specimens

Table 2. Arrangement of laminae and combination of species for 30 types of laminated wood specimen

Types	F:C	Types	F:C
$P_{\parallel}$ (KI)	KI(L):KI(L)	$C_{\parallel}$ (BKI)	BU(L):KI(P)
$P_{\parallel}$ (SU)	SU(L):SU(L)	$C_{\parallel}$ (BSU)	BU(L):SU(P)
$P_{\parallel}$ (HI)	HI(L):HI(L)	$C_{\parallel}$ (BHI)	BU(L):HI(P)
$P_{\parallel}$ (KA)	KA(L):KA(L)	$C_{\parallel}$ (BKA)	BU(L):KA(P)
$P_{\parallel}$ (BU)	BU(L):BU(L)	$C_{\parallel}$ (BBU)	BU(L):BU(P)
$P_{\perp}$ (KI)	KI(P):KI(P)	$C_{\perp}$ (SKI)	KI(P):SU(L)
$P_{\perp}$ (SU)	SU(P):SU(P)	$C_{\perp}$ (SSU)	SU(P):SU(L)
$P_{\perp}$ (HI)	HI(P):HI(P)	$C_{\perp}$ (SHI)	HI(P):SU(L)
$P_{\perp}$ (KA)	KA(P):KA(P)	$C_{\perp}$ (SKA)	KA(P):SU(L)
$P_{\perp}$ (BU)	BU(P):BU(P)	$C_{\perp}$ (SBU)	BU(P):SU(L)
$C_{\parallel}$ (SKI)	SU(L):KI(P)	$C_{\perp}$ (BKI)	KI(P):BU(L)
$C_{\parallel}$ (SSU)	SU(L):SU(P)	$C_{\perp}$ (BSU)	SU(P):BU(L)
$C_{\parallel}$ (SHI)	SU(L):HI(P)	$C_{\perp}$ (BHI)	HI(P):BU(L)
$C_{\parallel}$ (SKA)	SU(L):KA(P)	$C_{\perp}$ (BKA)	KA(P):BU(L)
$C_{\parallel}$ (SBU)	SU(L):BU(P)	$C_{\perp}$ (BBU)	BU(P):BU(L)

F, face; C, core; L, longitudinal-direction lamina; P, perpendicular-direction lamina; KI, kiri; SU, sugi; HI, hinoki; KA, katsura; BU, buna

and then cut to 20 mm width; perpendicular-direction laminae with 6.7 (T) × 20 (R) × 360 (L) mm were then prepared. A resorcinol-phenol resin-type adhesive formulated for room temperature cure was used, and the amount of spread was 300 g/m^2. The density and MOE of longitudinal-direction and perpendicular-direction laminae are shown in Table 1. The three-ply laminae were pressed under a pressure of 0.34 MPa for 24 h in a room maintained at 20°C and 65% relative humidity (RH). Three-ply parallel- and cross-laminated wood specimens were manufactured as shown in Fig. 1. $P_{\parallel}$ and $P_{\perp}$ types were the specimens used to measure bending strengths parallel and perpendicular to the grain of parallel-laminated woods, respectively. $C_{\parallel}$ and $C_{\perp}$ types were the specimens used to measure those of the face laminae of cross-laminated woods, respectively. Table 2 shows the arrangement of laminae and combination of species for 30 types of laminated wood specimens. There were three of each type of specimen, for a total of 90 specimens.

Bending strength test

The static bending test for all laminated wood specimens was conducted by four-point loading. The span was 300 mm, the distance between a loading point and a supporter was 100 mm, and the crosshead speed was set at 5.0 mm/min. The deflection of the mid-span was measured with a dial gauge, and load–deflection curves were recorded with an X-Y recorder. The calculated MOE for each specimen was obtained by the equivalent cross-section method from the true MOE of the individual laminae and compared with measured values of laminated wood specimens.

Shear modulus measurement

The static three-point bending test was conducted to obtain the shear modulus (G) for parallel-laminated wood specimens. The relation between the square of the height/span ratio and the compliance ($1/E_{\alpha}$) is expressed by the following equation[2]

$$\frac{1}{E_{\alpha}} = \frac{1}{E} + \frac{k}{G}\left(\frac{h}{l}\right)^2 \tag{1}$$

where E_α is the measured MOE; E is the true MOE; G is the shear modulus; k is 6/5 in the case of a rectangular cross section[3]; and h and l are the height and span of the specimen.

The span was decreased from 300mm to 120mm in decrements of 20mm; and the MOE corresponding to each span was calculated. The regression line was described from the relation between the square of the height/span ratio and the compliance ($1/E_\alpha$). The shear modulus and true MOE for $P_\parallel$ and $P_\perp$ types were calculated using Eq. (1).

Results and discussion

Modulus of elasticity of laminated woods

The density and MOE of the tested specimens are shown in Tables 3 and 4, respectively. For the $C_\perp$ (S) type, the MOE for buna [$C_\perp$ (SBU)] had the highest value (1.82GPa), whereas that for kiri [$C_\perp$ (SKI)] had the lowest value (0.79GPa). The MOEs of the $C_\perp$ (S) type were increased to 1.13 [$C_\perp$ (SBU)] to 1.54 [$C_\perp$ (SKI)] times those for the $P_\perp$ type by using longitudinal-direction lamina of sugi in the core. The extent of the increase increased with decreasing density and MOE of species. A similar result was found for $C_\perp$ (B) type.

In contrast, for $C_\parallel$ (S) type the MOE for buna [$C_\parallel$ (SBU)] had the highest value (7.68GPa), whereas that for sugi [$C_\parallel$ (SSU)] had the lowest value (5.68GPa). The $C_\parallel$ (S) type, with the higher density of perpendicular-direction lamina in the core, tended to show a higher MOE; but kiri, with the lowest density, had a higher MOE than sugi. This is explained in detail in the next section. MOEs of laminated woods decreased to 0.63 (sugi) to 0.86 (buna) times that for the $P_\parallel$ (SU) type. The $C_\parallel$ (S) type, having lamina of buna or katsura with high density in the core, showed a high value. A similar result was obtained for the $C_\parallel$ (B) type.

The degree of anisotropy of MOE perpendicular to the grain of face laminae versus that parallel to the grain of face laminae was decreased from 0.082 to 0.186 in sugi and from 0.185 to 0.242 in buna by cross-laminating. The extent of the decrease for sugi was higher than that for buna.

Furthermore, the specific MOE (MOE/specific gravity) values of the $C_\parallel$ (SSU) and $C_\parallel$ (BBU) types, whose layers were composed of the same species of sugi and buna, were 13.6 and 12.0GPa, respectively. The values were lower than the 22.0GPa of three-ply lauan plywood (composed of veneers with the same thickness) reported by Okuma[4] and the 13.9GPa of commercial three-ply lauan plywood (composed of veneers with the same thickness) reported by Sawada et al.[5] In contrast, the values for the $C_\perp$ (SSU) and $C_\perp$ (BBU) types were 2.53 and 3.03GPa, respectively, which were higher than the 1.32GPa for plywood reported by Okuma[4] and the 1.06GPa for plywood reported by Sawada et al.[5]

Table 3. Density of laminated wood specimens

Type	Density (Mg/m^3)				
	KI	SU	HI	KA	BU
$P_\parallel$	0.276	0.402	0.487	0.496	0.602
$P_\perp$	0.283	0.389	0.502	0.514	0.611
$C_\parallel$ (S)	0.357	0.417	0.438	0.438	0.473
$C_\parallel$ (B)	0.495	0.544	0.583	0.577	0.635
$C_\perp$ (S)	0.318	0.418	0.466	0.475	0.544
$C_\perp$ (B)	0.407	0.494	0.534	0.554	0.607

Each value is the average of three measurements
KI, SU, HI, KA, and BU: see Table 2

Table 4. MOE of laminated wood specimens

Type	MOE (GPa)				
	KI	SU	HI	KA	BU
$P_\parallel$	5.69	8.98	12.5	8.80	8.67
$P_\perp$	0.510	0.735	0.872	1.31	1.60
$C_\parallel$ (S)	5.83	5.68	6.25	7.52	7.68
$C_\parallel$ (B)	5.78	5.31	6.06	7.08	7.60
$C_\perp$ (S)	0.787	1.06	1.14	1.59	1.82
$C_\perp$ (B)	0.821	1.04	1.15	1.60	1.84

Each value is the average of three measurements

Effect of deflection caused by shear force on MOE of laminated woods

Deflection of beams for four-point bending is as follows

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

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 supporter; and k is 6/5 in the case of a rectangular cross section.[3]

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

$$E = E_\alpha\left(1 + \phi\right) \tag{3}$$

where E_α is the apparent MOE; and ϕ is $2.4h^2/(3l^2 - 4l_1^2)\cdot(E/G)$.

As described in the Materials and methods section, the three-point bending test was conducted to obtain the E/G ratio. Figure 2 shows typical examples of the regression lines calculated from the relation between the apparent compliance ($1/E_\alpha$) and the square of the height/span ratio for parallel-laminated woods. Because there were high correlations between the two values, this method was useful for obtaining the shear modulus in cross section of perpendicular-direction lamina with a low MOE.

The shear moduli for parallel-laminated wood specimens calculated from Eq. (1) are given in Table 5. These values

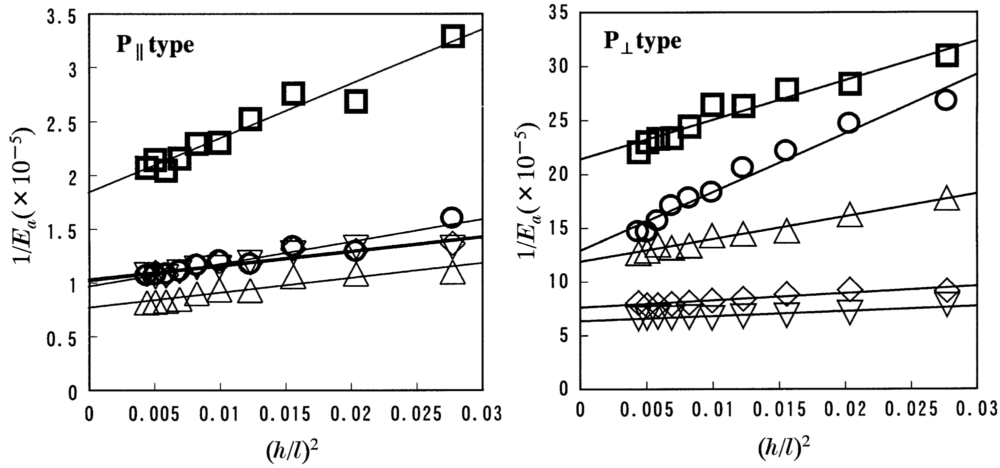

Fig. 2. Regression line between $1/E_\alpha$ and $(h/l)^2$ for parallel-laminated wood specimens. *Squares*, kiri: $f(x) = 0.504 \times 10^{-3}x + 0.184 \times 10^{-4}$, $r = 0.974$**($P_\parallel$ type); $f(x) = 3.64 \times 10^{-3}x + 2.13 \times 10^{-4}$, $r = 0.969$**($P_\perp$ type). *Circles*, sugi: $f(x) = 0.209 \times 10^{-3}x + 0.096 \times 10^{-4}$, $r = 0.924$**($P_\parallel$ type); $f(x) = 5.44 \times 10^{-3}x + 1.28 \times 10^{-4}$, $r = 0.982$**($P_\perp$ type). *Triangles*, hinoki: $f(x) = 0.138 \times 10^{-3}x + 0.076 \times 10^{-4}$, $r = 0.947$**($P_\parallel$ type); $f(x) = 2.10 \times 10^{-3}x + 1.18 \times 10^{-4}$, $r = 0.989$**($P_\perp$ type). *Diamonds*, katsura: $f(x) = 0.133 \times 10^{-3}x + 0.103 \times 10^{-4}$, $r = 0.947$**($P_\parallel$ type); $f(x) = 0.664 \times 10^{-3}x + 0.750 \times 10^{-4}$, $r = 0.941$**($P_\perp$ type). *Inverted triangles*, buna: $f(x) = 0.135 \times 10^{-3}x + 0.101 \times 10^{-4}$, $r = 0.947$**($P_\parallel$ type); $f(x) = 0.457 \times 10^{-3}x + 0.625 \times 10^{-4}$, $r = 0.932$**($P_\perp$ type). **Significant at 1% level

Table 5. Effect of deflection caused by shear force and glue line on MOE for parallel-laminated wood specimens

Type	E_α (GPa)	E_β (GPa)	E_γ (GPa)	G (MPa)	Y_s (%)	C_g (%)
$P_\parallel$ (KI)	5.69	5.73	6.21	284	8.5	8.4
$P_\parallel$ (SU)	8.98	9.19	9.66	533	7.1	5.1
$P_\parallel$ (HI)	12.5	12.9	13.5	750	7.1	4.5
$P_\parallel$ (KA)	8.80	8.81	9.21	864	4.5	4.5
$P_\parallel$ (BU)	8.67	8.96	9.18	726	5.6	2.5
$P_\perp$ (KI)	0.510	0.470	0.537	40.2	5.0	14.4
$P_\perp$ (SU)	0.735	0.697	0.833	23.6	11.8	19.4
$P_\perp$ (HI)	0.872	0.774	0.928	56.4	6.0	19.9
$P_\perp$ (KA)	1.31	1.23	1.36	170	3.1	10.6
$P_\perp$ (BU)	1.60	1.48	1.65	215	3.0	11.7

E_α, measured value of MOE; E_β, value calculated from true MOE of laminae; E_γ, value of true MOE calculated from measured MOE; G, for $P_\parallel$ type shear modulus in radial section, and for $P_\perp$ type shear modulus in cross section; Y_s(%), percentage of deflection caused by shear force versus total deflection by bending moment and shear force $(100(E_\gamma - E_\alpha)/E_\gamma)$; C_g(%) is $100(E_\gamma - E_\beta)/E_\beta$ and means contribution of glue line to MOE of parallel-laminated member

increased with increasing density of species in the $P_\parallel$ type; but in the $P_\perp$ type it was found that hardwoods had markedly higher values for their density than softwoods. We did not succeed in obtaining the E/G for $C_\perp$ types because the extremely small slope of the regression line between $1/E_\alpha$ and $(h/l)^2$ for the $C_\perp$ types was affected by the variation in the deflection measurements. Therefore, the percent deflection caused by shear force for cross-laminated woods were calculated by a method described later.

The true MOE of individual laminae for three-ply laminated wood was calculated by Eq. (3) using the E/G ratio obtained. The ratio (Re) of measured/calculated MOE, calculated from the true MOE of individual laminae was obtained. Because space here is limited, the Re only for four types of cross-laminated wood specimen are shown in Fig. 3.

The Re values for $P_\perp$, $C_\perp$ (S), and $C_\perp$ (B) types in which perpendicular-direction laminae were placed in the faces were 1.00–1.13, and the measured value was slightly higher than the calculated value. For $P_\parallel$ type with longitudinal-direction laminae in all layers, the measured value was slightly lower than the calculated value, but the measured values for $C_\parallel$ (S) and $C_\parallel$ (B) types were much lower than the calculated values. For the $C_\parallel$ (S) type, buna (SBU) had the highest value (0.87), katsura (SKA) had the second highest value (0.85), and the values for hinoki, kiri, and sugi were 0.71, 0.67, and 0.65, respectively. A similar result was found for the $C_\parallel$ (B) type. As described in the previous report,[1] this can be explained in terms of the effect of deflection caused by shear force, depending on the E/G ratio of Eqs. (2) and (3).

Table 5 shows the measured value of MOE (E_α), the value calculated from the true MOE of laminae (E_β), the value of the true MOE calculated from the measured MOE (E_γ), the percentage of deflection caused by shear force

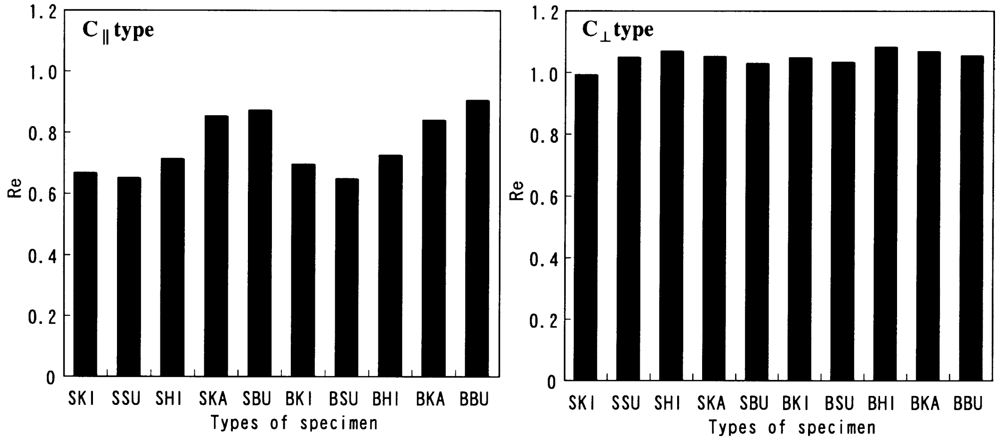

Fig. 3. Ratio (*Re*) of the measured value of the modulus of elasticity (MOE) to the value calculated from the true MOE of laminae for $C_{\parallel}$- and $C_{\perp}$ type specimens, respectively: SKI, SSU, SHI, SKA, SBU, BKI, BSU, BHI, BKA and BBU: see Table 2

versus total deflection by bending moment and shear force (Y_s), and the contribution of the glue line to the MOE (C_g) for parallel-laminated woods. E_γ is the value of the true MOE calculated from the measured MOE of laminated wood using the E/G ratio obtained. Y_s is obtained by the following equation.

$$Y_s = 100(y_\alpha - y_m)/y_\alpha = 100(E_\gamma - E_\alpha)/E_\gamma(\%) \tag{4}$$

The Y_s for $P_{\parallel}$ type was the highest in kiri (8.5%) and the lowest in katsura (4.5%). For $P_{\perp}$ type, sugi had the highest value of Y_s (11.8%) and buna the lowest (3.0%). In contrast, the contribution of the glue line to MOE (C_g), expressed as the percent difference between E_γ and E_β versus E_β, was 2.5%–8.4% for $P_{\parallel}$ type and 10.6%–19.9% for $P_{\perp}$ type. In the $P_{\parallel}$ type, C_g decreased with increasing density.

Next, the contribution of the glue line to MOE for parallel-laminated wood was investigated by the same method as described in the previous report[1] to examine the effect of the deflection caused by shear force on the MOE for cross-laminated wood. R_g ($= E_\gamma/E_\beta$) is considered inversely proportional to E_β, and the relation between R_g and $1/E_\beta$ for parallel-laminated wood specimens is shown in Fig. 4. It also had a high correlation coefficient between the two values. In general, the contribution of the glue line to the MOE increased with decreasing MOE of laminated wood.

If it is assumed that cross-laminated wood specimens have the same relation between them, R_g corresponding to the value of $1/E_\beta$ was calculated from this regression line. Based on the R_g value, we can obtain E_γ ($= R_g \cdot E_\beta$) in which the contribution of the glue line to the true MOE is taken into consideration. The values for E_α, E_β, E_γ, Y_s, and C_g for cross-laminated wood specimens are shown in Table 6. The Y_s values for $C_{\perp}$ (S) type were 4.6% (KA) to 13.1% (KI), and that for $C_{\perp}$ (B) type was 3.3% (KA) to 8.6% (KI). The deflection by shear force had small effect. On the other hand, $C_{\parallel}$ (S) types had Y_s values of 18.2% (BU) to 38.9% (SU), and the $C_{\parallel}$ (B) types had Y_s values of 16.1% (BU) to 40.5% (SU). The effect of the deflection caused by shear force was the highest in sugi, whose shear modulus in the cross section is the lowest of the five species, whereas buna and katsura were found to have about one-half the Y_s value for sugi. Kiri, with a lower density, showed a smaller value

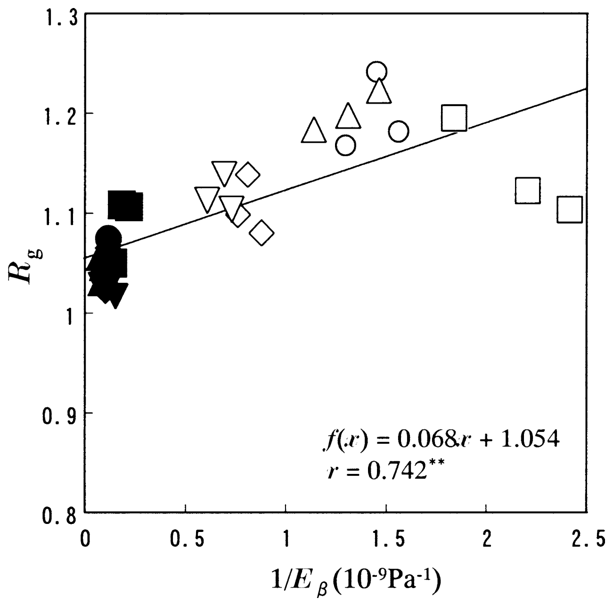

Fig. 4. Relation between R_g and $1/E_\beta$ for parallel-laminated wood specimens ($P_{\parallel}$, $P_{\perp}$ type). R_g is E_γ/E_β. E_γ is the value of the true MOE calculated from the measured MOE of laminated wood. E_β is the value calculated from the true MOE of laminae. *r*, coefficient of correlation; **significant at 1% level. *Filled symbols*, $P_{\parallel}$ type; *open symbols*, $P_{\perp}$ type. *Squares*, kiri; *circles*, sugi; *triangles*, hinoki; *diamonds*, katsura; *inverted triangles*, buna

of Y_s than sugi. The reason for this is discussed below. For the $C_{\perp}$ type with perpendicular-direction laminae in the faces, the effect of the deflection caused by shear force was small because E/G in the right-hand side of Eq. (2) was decreased owing to the high shear modulus of the core lamina parallel to the grain and the low MOE of the face laminae perpendicular to the grain. In contrast, for the $C_{\parallel}$ type with parallel-direction laminae in the faces and with laminae perpendicular to the grain in the core, its effect was great because E/G was increased owing to the low shear modulus of the core lamina perpendicular to the grain and the high MOE of the face laminae parallel to the grain. Figure 5 shows the relation between Y_s for the $C_{\parallel}$ type and the shear modulus in the cross section of the core. The Y_s values decreased linearly with increasing shear modulus in

Table 6. Effect of deflection caused by shear force and glue line on MOE for cross-laminated wood specimens

Type	E_α (GPa)	E_β (GPa)	E_γ (GPa)	Y_s(%)	C_g(%)
$C_\parallel$ (SKI)	5.83	8.75	9.29	37.3	6.2
$C_\parallel$ (SSU)	5.68	8.75	9.29	38.9	6.2
$C_\parallel$ (SHI)	6.25	8.80	9.35	33.1	6.2
$C_\parallel$ (SKA)	7.52	8.85	9.40	20.0	6.2
$C_\parallel$ (SBU)	7.68	8.84	9.39	18.2	6.2
$C_\parallel$ (BKI)	5.78	8.33	8.85	34.7	6.3
$C_\parallel$ (BSU)	5.31	8.39	8.92	40.5	6.3
$C_\parallel$ (BHI)	6.06	8.48	9.01	32.8	6.2
$C_\parallel$ (BKA)	7.08	8.54	9.07	21.9	6.2
$C_\parallel$ (BBU)	7.60	8.52	9.05	16.1	6.2
$C_\perp$ (SKI)	0.787	0.794	0.906	13.1	14.0
$C_\perp$ (SSU)	1.06	1.01	1.14	7.1	12.2
$C_\perp$ (SHI)	1.14	1.07	1.20	4.9	11.8
$C_\perp$ (SKA)	1.59	1.51	1.66	4.6	9.9
$C_\perp$ (SBU)	1.82	1.77	1.94	6.2	9.3
$C_\perp$ (BKI)	0.821	0.786	0.898	8.6	14.4
$C_\perp$ (BSU)	1.04	1.01	1.13	8.6	12.3
$C_\perp$ (BHI)	1.15	1.07	1.20	4.0	11.9
$C_\perp$ (BKA)	1.60	1.50	1.65	3.3	10.0
$C_\perp$ (BBU)	1.84	1.75	1.91	3.9	9.3

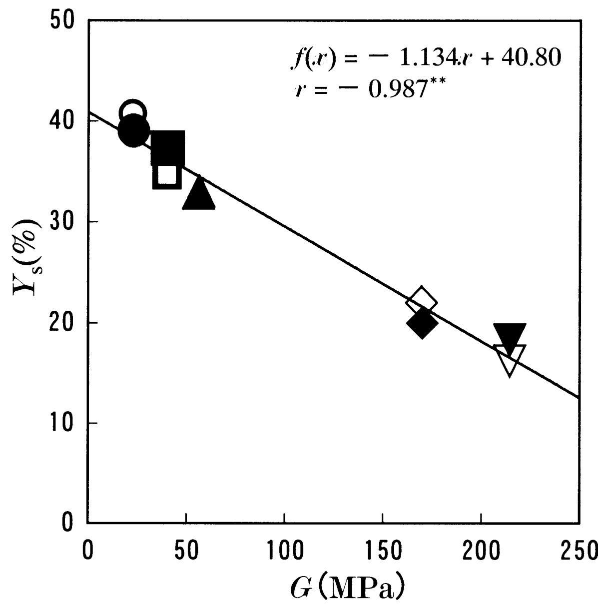

Fig. 5. Relation between Y_s (%) of $C_\parallel$-type specimens and shear modulus in cross section of core lamina. *Filled symbols*, $C_\parallel$(S) types; *open symbols*, $C_\parallel$(B) types. *Squares*, SKI and BKI; *circles*, SSU and BSU; *triangles*, SHI and BHI; *diamonds*, SKA and BKA; *inverted triangles*, SBU and BBU

cross section of the core. Therefore, it can be said that Y_s is higher in species with a low shear modulus in cross section (e.g., sugi), whereas it is lower in species with a high shear modulus in cross section (e.g., buna and katsura).

Proportional limit stress of laminated woods

Table 7 shows the proportional limit stresses on the tested specimens. The proportional limit stress is equal to the product of MOE and proportional limit strain. By replacing parallel-direction lamina in the core, the proportional limit stresses for $C_\perp$ (S) and $C_\perp$ (B) types were increased to 1.16–3.13 times those for the $P_\perp$ types. In contrast, those for $C_\parallel$ (S) and $C_\parallel$ (B) types were decreased to 0.58–0.85 times those for the $P_\parallel$ type by using perpendicular-direction lamina in the core.

The degree of anisotropy of proportional limit stress perpendicular to the grain of face laminae versus that parallel to the grain of face laminae was markedly decreased from 0.085 to 0.194 in sugi and from 0.260 to 0.371 in buna by cross-laminating. The extent of the decrease for sugi with lower density was higher than that for buna.

Table 7. Proportional limit stress of laminated wood specimens

Type	Proportional limit stress (MPa)				
	KI	SU	HI	KA	BU
$P_\parallel$	25.7	41.4	51.6	42.6	36.7
$P_\perp$	1.84	3.50	4.31	9.51	9.78
$C_\parallel$ (S)	23.9	24.2	29.8	35.3	35.3
$C_\parallel$ (B)	22.2	22.1	24.2	32.0	30.7
$C_\perp$ (S)	5.77	4.68	7.05	13.0	12.1
$C_\perp$ (B)	4.84	4.66	7.09	11.7	11.4

Each value is average of three measurements

Table 8. MOR of laminated wood specimens

Type	MOR (MPa)				
	KI	SU	HI	KA	BU
$P_\parallel$	40.3	74.7	93.2	87.2	80.0
$P_\perp$	3.87	5.52	6.54	15.7	18.2
$C_\parallel$ (S)	43.7	46.6	54.2	58.9	58.5
$C_\parallel$ (B)	46.1	47.5	57.4	66.7	69.5
$C_\perp$ (S)	10.7	11.6	12.8	17.7	18.1
$C_\perp$ (B)	11.4	11.1	10.9	16.1	19.3

Each value is average of three measurements
MOR, modulus of rupture

Modulus of rupture of laminated woods

Moduli of rupture (MORs) of the tested specimens are shown in Table 8. For the $C_\perp$ (S) type, the MOR of buna was the highest (18.1 MPa) and that of kiri was the lowest (10.7 MPa). The MORs increased to 1.00 (BU) to 2.76 (KI) times those of the $P_\perp$ type by using parallel-direction lamina of sugi in the core. The extent of the increase increased with decreasing density of species. A similar result was found in the $C_\perp$ (B) type. In contrast, for the $C_\parallel$ (S) type, katsura and buna had high values (58.9 and 58.5 MPa, respectively), and kiri had the lowest value (43.7 MPa). The value was decreased to 0.59 (KI) to 0.79 (KA) times that for $P_\parallel$ (SU). The extent of the decrease was less in species with higher density. The $C_\parallel$ (B) type had a tendency similar to the $C_\parallel$ (S) type, but buna and katsura had values 0.87 and 0.83 times that for $P_\parallel$ (BU) respectively and had much higher values than the other species.

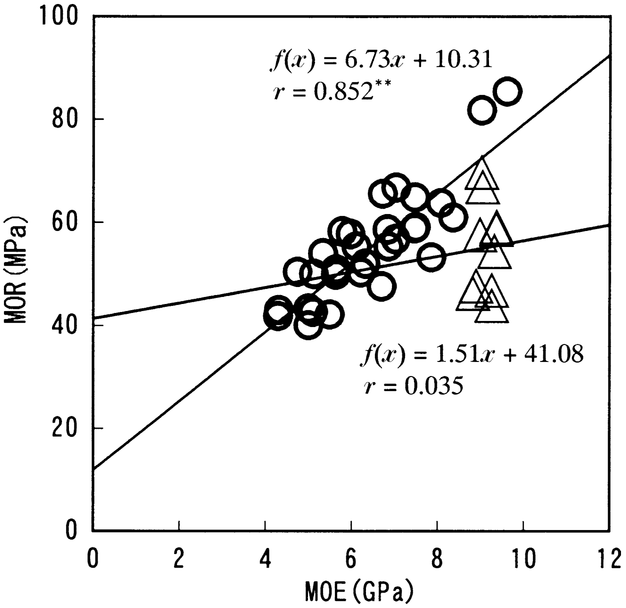

Fig. 6. Relations between MOE and modulus of rupture (MOR) for $C_{\parallel}$ type specimens. *Cricles*, measured MOR and measured MOE (E_{α}) for each specimen; *triangles*, average measured MOR and true MOE (E_{γ}) calculated from the average E_{α}

Like MOE, this can be explained by the effect of the deflection caused by shear force. Figure 6 shows the relation between the measured MOR and the measured MOE for each $C_{\parallel}$ type specimen and that between the average MOR and the true MOE (E_{γ}) calculated from the average MOE (E_{α}) of three measurements for each $C_{\parallel}$ type. There was a high correlation between the MOR and the measured MOE depending on the deflection caused by shear force (correlation coefficient r = 0.852), but there was no correlation between the average MOR and the average true MOE (r = 0.035). The measured MOR had lower values than the MOR calculated from the section modulus of laminated woods with a hollow core; and the ratios of the former to the latter had markedly higher values in buna (0.81) and katsura (0.82) with a high shear modulus in cross section than in kiri (0.61) or sugi (0.65) with a low shear modulus in cross section. In addition, the MOR of $P_{\parallel}$ (BU) (80.0 MPa) was higher than that of $P_{\parallel}$ (SU) (74.7 MPa); but $C_{\parallel}$ (SBU), whose core of $P_{\parallel}$ (SU) was replaced by perpendicular-direction lamina of buna with a high shear modulus in cross section, had a higher value (58.5 MPa) than $C_{\parallel}$ (BSU) (47.5 MPa), whose core of $P_{\parallel}$ (BU) was replaced by perpendicular-direction lamina of sugi with a low shear modulus in cross section. Therefore, it can be said that the MOR and the MOE are greatly influenced by the deflection caused by shear force.

The degree of anisotropy of MOR perpendicular to the grain of face laminae versus that parallel to the grain of face laminae was decreased from 0.074 to 0.248 in sugi and from 0.227 to 0.278 in buna by cross-laminating. The extent of the decrease was found to be markedly higher in sugi than in buna.

Furthermore, the specific MOR (MOR/specific gravity) of $C_{\parallel}$ (SSU) and $C_{\parallel}$ (BBU) types, whose layers were composed of the same species of sugi and buna, were 112 and 109 MPa respectively, which were higher than the 106 MPa of commercial three-ply lauan plywood.[5] On the other hand, those for $C_{\perp}$ (SSU) and $C_{\perp}$ (BBU) types were 27.8 and 31.8 MPa, respectively, and were higher than the 24.2 MPa of plywood.[5]

Conclusions

The MOE, proportional limit stress, and MOR perpendicular to the grain were increased by cross-laminating, and the extent of the increase increased with decreasing density of species. The MOE for $P_{\parallel}$, $P_{\perp}$, and two $C_{\perp}$ types were little influenced by the deflection caused by shear force, whereas two $C_{\parallel}$ types were markedly affected by it. The percent deflection by shear force for two $C_{\parallel}$ types decreased linearly with increasing shear modulus in the cross section of the core. For $C_{\parallel}$ types, the MOR had a high positive correlation with the measured MOE; and both MOR and MOE were greatly affected by deflection caused by shear force.

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