STATIC BENDING STRENGTH PERFORMANCES OF CROSS-LAMINATED WOOD PANELS MADE WITH SIX SPECIES

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Abstract. In this study, with a view to effectively use small- and medium-diameter Korean woods as structural materials, cross-laminated wood panels were manufactured using six species of Korean softwoods and hardwoods and static bending strength performances were investigated for each species. Static bending strength performances of parallel- and cross-laminated wood panels generally improved in proportion to the density of the wood species. Bending strength performances perpendicular to the grain were improved by cross-laminating the longitudinal-direction lamina in the core. The improvement was greater for softwoods than for hardwoods. The measured modulus of elasticity (MOE) of parallel- and cross-laminated wood panels perpendicular to the grain of face laminae showed little difference from those calculated from true MOE of individual laminae. However, the measured MOE of cross-laminated wood panels parallel to the grain of face laminae were much lower than the estimated MOE because of the effect of deflection caused by shear force. The percentage of deflection caused by shear force vs total deflection (Y_s) showed high values of 9.8-34.0%, with markedly higher values observed for cross-laminated wood panels made with softwoods than those made with hardwoods.

Keywords: Species, cross-laminated wood panels, modulus of elasticity, deflection, shear force.

INTRODUCTION

Approximately 64% of South Korea is under forest cover, which is the fourth greatest forest area after Finland, Japan, and Sweden among

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the 30 members of the Organisation for Economic Cooperation and Development countries. Forest conservation and afforestation projects have been continuously carried out, and the growing stock has considerably increased since 1996. At present, extending the use and technical development of wood are required. Recently, there have been various motions proposing the use of cross-laminated timber (CLT) in South Korea.

CLT is a wood-based material that is manufactured with wide and thick panels by cross-laminating the longitudinal directions of wood to effectively use the high-strength performances of the longitudinal direction of wood and to decrease anisotropy of wood. Therefore, CLT is a superior material with regard to durability and functionality and can be applied to important structural parts of buildings such as floors and walls as well as nonbearing parts such as ceilings and roofs. Since its development in Europe, CLT has increased in use and gradually extended to North America and Asia.

Recently, research has been conducted regarding the mechanical properties of CLT, including bending properties (Gülzow et al 2011; Stelger et al 2012; Okabe et al 2014; Goto et al 2014), shear properties (Gülzow et al 2011; Okabe et al 2014; Nakashima et al 2014), compressive properties (Ido et al 2014; Oh et al 2015), and torsion properties (Sebera et al 2015), and regarding the connectors such as typical metal and screwed connectors (Gavric et al 2015a, 2015b). However, there is little research available on the relationship between estimated values and measured values of bending strength performances of CLT panels made with various species, and in particular, no research is available on the influence of deflection caused by shear force on bending strength properties. In previous studies, we manufactured cross-laminated wood panels made with Japanese cedar (Park et al 2001, 2002; Park and Fushitani 2006, 2014) and with five species including two softwoods (Japanese cedar and Japanese cypress) and three hardwoods (royal paulownia, katsura, and beech) (Park et al 2003, 2006, 2009) and investigated the effects of annual ring angles, densities, shear moduli, and thicknesses of constitution laminae on the bending strength and bending creep properties. As a result, it was found that the bending strength and creep properties were considerably affected by the annual ring angles, densities, shear moduli, and constituent thicknesses of perpendicular-direction laminae positioned in the core as well as the face of panels. In particular, with placement of perpendicular-direction laminae with low shear modulus in the cross section in the core, the effect of deflection caused by shear force was found to be especially great.

In this study, cross-laminated wood panels made with six Korean species were prepared and the effects of densities and shear moduli of the constitution laminae on static bending strength performances were investigated.

MATERIALS AND METHODS

Specimen Preparation

Six species of Korean softwoods and hardwoods were selected for this study. They included three softwoods: Japanese cedar, Japanese cypress, and Japanese larch, and three hardwoods: chestnut, tulip tree, and oriental oak. Longitudinal-direction laminae of 6.7 (T) $\times$ 20 (R) $\times$ 360 (L) mm with their long axes parallel to the grain were made with six species (T, R, and L are tangential, radial, and longitudinal directions, respectively). Samples of 7.5 (T) $\times$ 20 (R) $\times$ 180 (L) mm were cut from each of six species, 18 samples from each species were side jointed and then cut to 20 mm wide, and perpendicular-direction laminae of 6.7 (T) $\times$ 360 (R) $\times$ 20 (L) mm were made with long axes perpendicular to the grain. The annual ring angles of both laminae were 90°. Water based polymer isocyanate adhesive (MPU-500, Okong Co., Ltd.), formulated for a room temperature cure, was used and the amount of spread was 300 g/m^2. The three-ply laminae were pressed at 0.34 MPa for 24 h in a room maintained at 20°C and 65% RH. Figure 1 shows the three-ply parallel- and cross-laminated wood panel specimens tested. $P_{||}$ types ($P_{||}$[S], $P_{||}$[H], $P_{||}$[L], $P_{||}$[C], $P_{||}$[T], and $P_{||}$[O]) and $P_{\perp}$ types ($P_{\perp}$[S], $P_{\perp}$[H], $P_{\perp}$[L], $P_{\perp}$[C], $P_{\perp}$[T], and $P_{\perp}$[O]) were the specimens used to measure the bending strength performances parallel and perpendicular to the grain

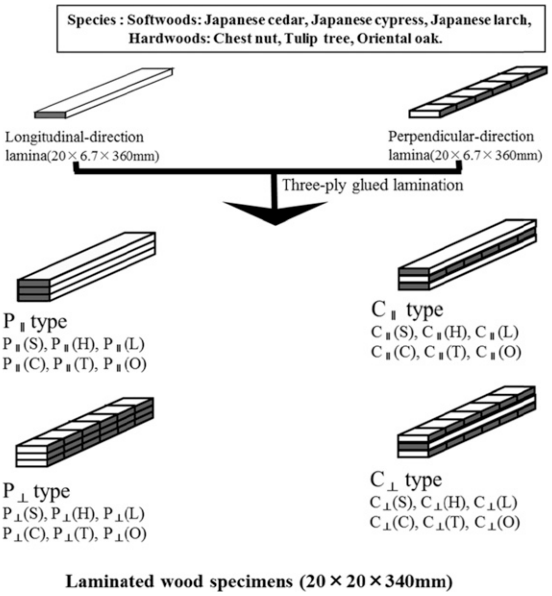

Figure 1. Parallel- and cross-laminated wood panels made with six species (S, H, L, C, T, and O are Japanese cedar, Japanese cypress, Japanese larch, chestnut, tulip tree, and oriental oak, respectively).

of parallel-laminated wood panels, respectively (S is Japanese cedar, H is Japanese cypress, L is Japanese larch, C is chestnut, T is tulip tree, and O is oriental oak). $C_{\parallel}$ types ($C_{\parallel}$[S], $C_{\parallel}$[H], $C_{\parallel}$[L], $C_{\parallel}$[C], $C_{\parallel}$[T], and $C_{\parallel}$[O]) and $C_{\perp}$ types ($C_{\perp}$[S], $C_{\perp}$[H], $C_{\perp}$[L], $C_{\perp}$[C], $C_{\perp}$[T], and $C_{\perp}$[O]) were the specimens used to measure the bending strength performances parallel and perpendicular to the grain of the face laminae of cross-laminated wood panels, respectively. Four specimens for measuring bending strength performances and three specimens for measuring shear modulus were prepared, respectively, for a total of 168 specimens.

Bending Strength Properties Test

A static bending test for parallel- and cross-laminated wood panel specimens was conducted by four-point loading according to the Japanese Agricultural Standards (JAS 2008) for laminated veneer lumber. The span was 300 mm, the distance from a loading point to a supporting point was 100 mm, and the cross-head rate was set at 5.0 mm/min. The midspan deflection was measured using the linear variable differential transformer, and stress–strain curves were plotted. The bending test was conducted in a room maintained at 20°C and 65% RH. The estimated modulus of elasticity (MOE) of each specimen was calculated using the equivalent cross-section method expressed in Eq 1 from true MOE of individual laminae (Utokuchi et al 1998) and was compared with measured values.

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

where E is the MOE of the laminated wood beam; E_1, E_2, and E_3 are MOE of individual laminae; I is moment of inertia for the cross section of laminated wood beam; and I_1, I_2, and I_3 are moments of inertia of individual laminae for the neutral axis of the cross section.

Shear Modulus Measurement

A static three-point bending test was conducted to obtain shear moduli (G) for parallel-laminated wood panel specimens with all layers composed of laminae parallel and perpendicular to the grain. The relationship between the square of the height/span ratio ($[h/l]^2$) and the compliance ($1/E_\alpha$) is expressed by the following equation (Yoshihara and Kubojima 2002):

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

where E_α is the measured MOE; E is true MOE; G is shear modulus; k is 6/5 in the case of a rectangular cross section (Sakai 1970); and h and l are height and span of the specimen, respectively.

A static three-point bending test for parallel-laminated wood panel specimens was conducted by center-point loading according to the JAS (2008) for laminated veneer lumber. The span of each specimen was decreased from 300 to 120 mm in decrements of 20 mm, 10 bending tests per specimen were taken, and the MOE corresponding to each span was set to keep the same strain rate from 5.0 to 0.8 mm/min. The regression line was described from the relation between the square of the height/span ratio and the compliance ($1/E_\alpha$), and the regression equations were obtained. By applying the regression equation to Eq 2, shear moduli (G) and true MOE (E) for $P_{||}$ and $P_\perp$ types were calculated and the E/G values were obtained.

RESULTS AND DISCUSSION

Stress–Strain Curves of Parallel- and Cross-Laminated Wood Panels

Typical examples of stress–strain curves of parallel- and cross-laminated wood panels made with the six species are shown in Fig 2. In the case of $P_{||}$ type, which were composed of longitudinal-direction laminae in all layers, the curves were similar to that of solid wood parallel to the grain. In the case of $P_\perp$ types, which were composed of perpendicular-direction laminae in all layers, softwood laminated panels failed after short curve regions or without curve regions when beyond proportional limits, and hardwood laminated panels showed much more deformation than softwood laminated panels.

In the case of $C_\perp$ type, which were composed of perpendicular-direction laminae in the faces and longitudinal-direction lamina in the core, specimens failed after numerous cracks appeared in the faces when beyond proportional limits, as observed in previous studies (Park et al 2001, 2003; Park and Fushitani 2006). In the case of $C_{||}$ type, which were composed of longitudinal-direction laminae in the faces and perpendicular-direction lamina in the core, the curves were similar to those observed for $P_{||}$ type, although the declination of the curve and the amount of strain were lower than that of $P_{||}$ type. There was more strain in hardwoods than in softwoods on the whole.

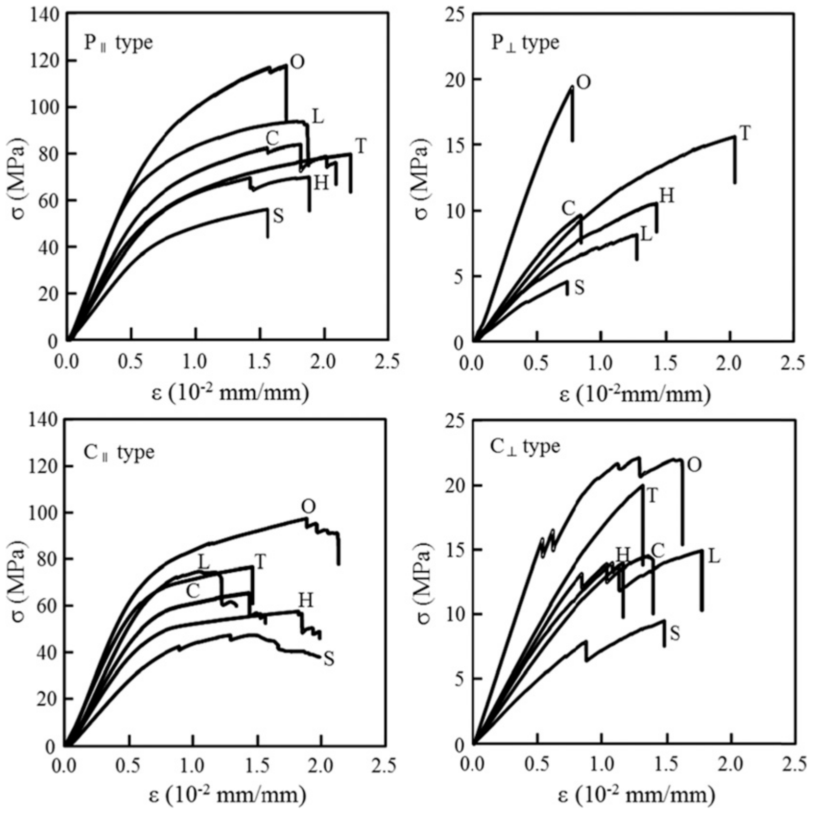

Figure 2. Stress–strain curves for parallel- and cross-laminated wood panels (S, H, L, C, T, and O are Japanese cedar, Japanese cypress, Japanese larch, chestnut, tulip tree, and oriental oak, respectively).

Bending MOE of Cross-Laminated Wood Panels

Results of bending tests for parallel- and cross-laminated wood panels are shown in Table 1.

Bending MOE. Static bending MOE of parallel- and cross-laminated wood panels are shown in Fig 3. For $P_{||}$ type, $P_{||}$(O) had the highest value (15.0 GPa) and $P_{||}$(S) had the lowest value (6.79 GPa). For $P_{\perp}$ type, $P_{\perp}$(O) had the highest value (2.90 GPa), whereas $P_{\perp}$(S) had the lowest value (0.779 GPa). The values increased with increasing density of the wood species. The density dependence of parallel-laminated wood panels was greater in the perpendicular direction than in the parallel direction, corresponding to the results of Sawada et al (1959) and Park et al (2003).

For $C_{\perp}$ type, $C_{\perp}$(O) had the highest value (3.30 GPa) and $C_{\perp}$(S) had the lowest value (1.11 GPa). The values were in the order of $C_{\perp}$(O) > $C_{\perp}$(L) > $C_{\perp}$(T) > $C_{\perp}$(C) > $C_{\perp}$(H) > $C_{\perp}$(S). Values tended to increase with increasing density of the wood species on the whole. The values were 1.3-1.5 times higher than those observed for $P_{\perp}$ type, given the cross-laminating longitudinal-direction laminae of each species in the core of $P_{\perp}$ type. For $C_{||}$ type, $C_{||}$(O) had the highest value (13.9 GPa) and $C_{||}$(S) had the lowest value (5.36 GPa). The values were in the order of $C_{||}$(O) > $C_{||}$(L) > $C_{||}$(T) > $C_{||}$(C) > $C_{||}$(H) > $C_{||}$(S). The values were 0.80-0.93 times lower than that of $P_{||}$ type, although the density dependence for MOE tended to be similar to $P_{||}$ type.

The degree of anisotropy of MOE perpendicular to the grain of face laminae compared with parallel to the grain of face laminae was markedly decreased from 0.079-0.193 to 0.150-0.237 by cross-laminating. The decrease was greater for low-density wood species. This corresponded to the results of a previous study by Park et al (2003).

Furthermore, the specific MOE (MOE/specific gravity) value of the laminated wood panels was 16.4-23.7 GPa for $P_{||}$ type, 1.88-3.34 GPa for

Table 1. Results of bending tests for parallel- and cross-laminated wood panels.[a]

Type	ρ (kg/m^3)	MOE (GPa)	PLS (MPa)	MOR (MPa)	BS (10^{-2} mm/mm)
$P_{\|\|}$(S)	413 (4.6)	6.79 (7.6)	33.8 (4.7)	56.8 (5.6)	1.48 (6.1)
$P_{\|\|}$(H)	450 (1.9)	10.4 (12.1)	47.0 (6.2)	70.9 (5.1)	1.60 (13.9)
$P_{\|\|}$(L)	571 (5.5)	13.6 (17.3)	65.0 (17.7)	94.5 (9.0)	1.71 (15.5)
$P_{\|\|}$(C)	563 (2.5)	9.97 (12.3)	51.6 (11.3)	77.8 (9.8)	1.68 (23.0)
$P_{\|\|}$(T)	580 (3.5)	10.9 (16.0)	48.9 (17.8)	79.0 (9.6)	1.98 (37.0)
$P_{\|\|}$(O)	864 (1.3)	15.0 (7.7)	73.9 (6.9)	114 (10.0)	1.54 (14.1)
$P_{\perp}$(S)	398 (3.3)	0.779 (7.1)	2.96 (14.7)	4.83 (14.2)	0.818 (12.2)
$P_{\perp}$(H)	466 (2.0)	0.924 (6.5)	5.72 (6.3)	10.0 (12.2)	1.46 (12.4)
$P_{\perp}$(L)	573 (4.5)	1.08 (11.4)	4.39 (9.2)	7.74 (8.4)	1.08 (17.2)
$P_{\perp}$(C)	561 (3.4)	1.24 (13.0)	6.57 (11.7)	9.81 (10.0)	1.06 (11.0)
$P_{\perp}$(T)	608 (7.5)	1.36 (8.0)	8.43 (8.3)	15.4 (9.5)	1.6 (24.8)
$P_{\perp}$(O)	869 (1.3)	2.90 (1.7)	11.6 (6.9)	18.0 (17.6)	0.739 (19.4)
$C_{\|\|}$(S)	423 (5.7)	5.63 (19.5)	30.6 (13.5)	47.7 (9.4)	1.55 (25.3)
$C_{\|\|}$(H)	456 (2.6)	8.64 (9.5)	41.7 (5.4)	57.6 (5.2)	1.80 (1.6)
$C_{\|\|}$(L)	572 (3.4)	10.9 (12.3)	52.9 (13.1)	73.2 (4.2)	1.52 (42.0)
$C_{\|\|}$(C)	555 (2.5)	9.08 (10.1)	49.5 (6.7)	66.2 (4.6)	2.13 (20.0)
$C_{\|\|}$(T)	591 (4.7)	9.81 (15.5)	48.5 (19.8)	67.8 (16.1)	2.01 (34.9)
$C_{\|\|}$(O)	856 (1.4)	13.9 (6.0)	68.5 (6.6)	98.6 (4.8)	1.81 (8.1)
$C_{\perp}$(S)	413 (3.3)	1.11 (8.4)	6.85 (13.6)	9.93 (3.5)	1.54 (17.4)
$C_{\perp}$(H)	460 (5.2)	1.33 (7.7)	12.1 (8.1)	13.5 (4.8)	1.75 (56.6)
$C_{\perp}$(L)	568 (3.0)	1.64 (6.2)	11.1 (9.7)	15.6 (8.7)	1.59 (19.6)
$C_{\perp}$(C)	569 (2.7)	1.68 (5.3)	9.88 (12.4)	14.0 (9.5)	1.59 (24.9)
$C_{\perp}$(T)	580 (4.6)	1.77 (9.5)	13.5 (9.3)	21.3 (7.9)	1.61 (12.4)
$C_{\perp}$(O)	853 (2.3)	3.30 (6.0)	18.6 (12.9)	23.4 (6.2)	2.08 (24.3)

[a] ρ is the density, PLS is proportional limit stress, and BS is breaking strain. Each value is the average of four measurements, and each value in parentheses is the coefficient of variation (%).

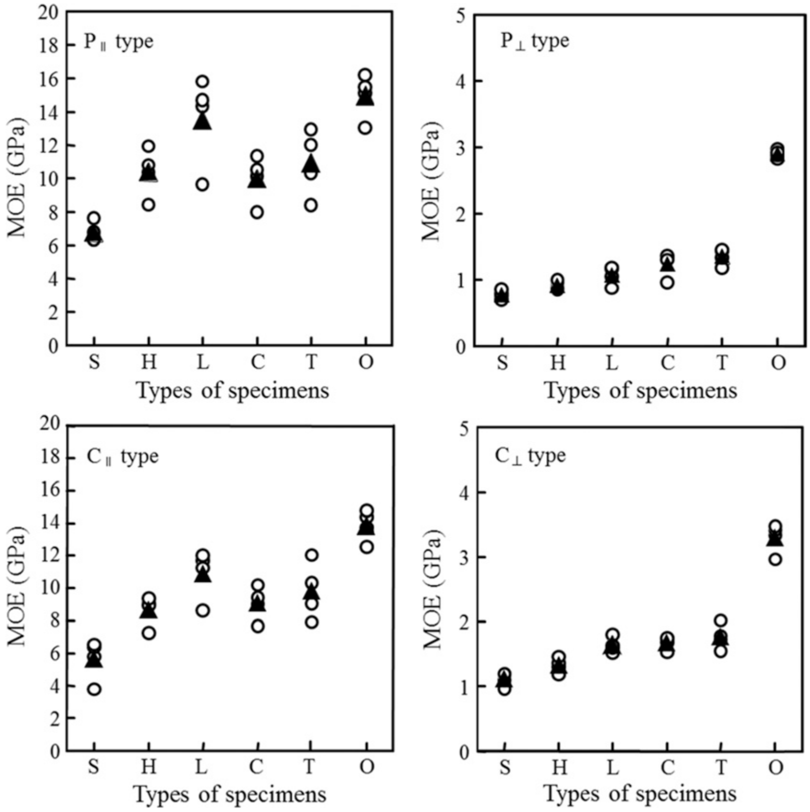

Figure 3. Effect of wood species on bending MOE of parallel- and cross-laminated wood panels (S, H, L, C, T, and O are Japanese cedar, Japanese cypress, Japanese larch, chestnut, tulip tree, and oriental oak, respectively).

$P_\perp$ type, 2.70-3.86 GPa for $C_\perp$ type, and 13.3-19.0 GPa for $C_{||}$ type. The values were approximately 1.2-1.5 times greater than the MOE, and the increase was greater in softwoods than in hardwoods. The values for $C_{||}$ type were lower than the 22.0 GPa of the three-ply lauan plywood reported by Okuma (1966) and greater than the 13.9 GPa of commercial three-ply lauan plywood reported by Sawada et al (1959), with the exception of cross-laminated wood panels made with Japanese cedar. In addition, these values were considerably greater than the 9.62 GPa of lauan oriented strandboard (OSB) reported by Muraue et al (1999). The values for $C_\perp$ type were greater than the 1.32 GPa of lauan plywood reported by Okuma (1966), the 1.06 GPa of commercial lauan plywood reported by Sawada et al (1959), and the 1.61 GPa of lauan OSB reported by Muraue et al (1999) for all species.

Relation between estimated value and measured value of bending MOE. The ratios (R_e) of measured MOE to estimated MOE calculated by the equivalent cross-section method of Eq 1 from true MOE of each lamina of parallel- and cross-laminated wood panels are shown in Fig 4.

The R_e of $P_{||}$ type ranged from 0.84 to 0.93, with the measured values slightly lower than the estimated values. There was little difference between softwoods and hardwoods. The R_e of $P_\perp$ type ranged from 1.07 to 1.26, with the measured values higher than the estimated values. This was considered because the contribution of glue line was greater in the measured values compared with the estimated values, which were not affected by glue line. The percentages of the contribution of glue line of the parallel-laminated wood panels are shown in Table 1. The contribution of glue

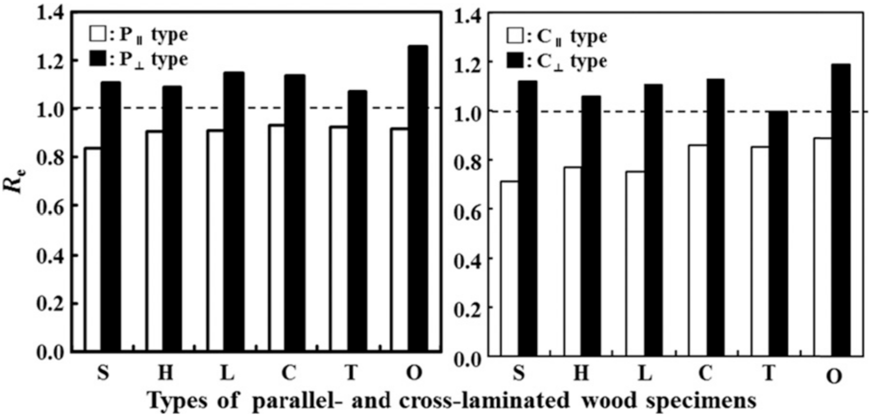

Figure 4. Ratio (R_e) of the measured MOE to the estimated MOE calculated from the true MOE of laminae (S, H, L, C, T, and O are Japanese cedar, Japanese cypress, Japanese larch, chestnut, tulip tree, and oriental oak, respectively).

line was markedly greater in $P_\perp$ type than in $P_{||}$ type.

For $C_\perp$ type, the R_e values ranged from 0.99 to 1.18 and the measured values were greater than the estimated values, as was observed for $P_\perp$ type. This was also considered to be caused by the contribution of glue line as previously mentioned. For $C_{||}$ type, the R_e values ranged from 0.71 to 0.77 for softwoods and 0.85 to 0.89 for hardwoods and it was found that the measured values were considerably lower than the estimated values. Also, the values for softwoods were markedly lower than those for hardwoods. This was considered to be from the effect of deflection caused by shear force as verified in several previous studies (Park et al 2001, 2003, 2009; Park and Fushitani 2006, 2014).

Deflection of the beam for four-point bending is as follows:

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

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

From Eq 3, MOE calculated from the deflection caused by bending moment is as follows:

$$E = E_\alpha(1 + \varphi) \quad (4)$$

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

Total deflection of a beam was composed of the deflections caused by bending moment and shear force, and the deflection caused by shear force was proportional to the E/G ratio, as shown in Eq 3. Therefore, as previously described, the three-point bending test was conducted to obtain the E/G ratio and the shear moduli of $P_{||}$ and $P_\perp$ type were calculated from the regression line between the square of the height/span ratio and the compliance ($1/E_\alpha$) of Eq 2, as shown in Table 2.

For $P_{||}$ type, shear moduli were greatest (786 MPa) in $P_{||}$(O) and lowest (560 MPa) in $P_{||}$(S). The values tended to increase with increasing density of species. The E/G ratio ranged from 14.1 to 25.3. For $P_\perp$ type, shear moduli were greatest (322 MPa) in $P_\perp$(O) and lowest (31.7 MPa) in $P_\perp$(S). The value tended to increase with increasing density of species. The E/G ratio ranged from 4.3 to 24.8, and the parallel-laminated wood panels composed of softwoods showed considerably greater values than those composed of hardwoods.

Table 2. Effect of deflection caused by shear force and glue line on MOE for parallel- and cross-laminated wood panels.

Type	ρ (kg/m^3)	E_α (GPa)	E_β (GPa)	E_γ (GPa)	G (MPa)	Y_s (%)	C_g (%)
$P_{\|}$(S)	413	6.79	8.10	7.19	560	5.6	−11.2
$P_{\|}$(H)	450	10.4	11.5	11.3	588	7.6	−1.9
$P_{\|}$(L)	571	13.6	14.8	15.0	600	9.6	1.7
$P_{\|}$(C)	563	9.97	10.7	10.6	619	6.3	−0.7
$P_{\|}$(T)	580	10.9	11.8	11.6	684	6.3	−1.6
$P_{\|}$(O)	864	15.0	16.3	16.3	786	7.9	−0.2
$P_{\perp}$(S)	398	0.779	0.704	0.860	31.7	9.4	22.1
$P_{\perp}$(H)	466	0.924	0.846	0.982	61.5	5.9	16.0
$P_{\perp}$(L)	573	1.08	0.938	1.14	81.2	5.2	21.5
$P_{\perp}$(C)	561	1.24	1.09	1.26	291	1.7	15.4
$P_{\perp}$(T)	608	1.36	1.27	1.39	274	2.0	9.2
$P_{\perp}$(O)	869	2.90	2.31	3.02	322	4.1	30.9
$C_{\|}$(S)	423	5.62	7.94	8.53	65.4	34.0	7.4
$C_{\|}$(H)	456	8.64	11.3	12.1	120	28.4	7.2
$C_{\|}$(L)	572	10.9	14.5	15.2	153	28.6	5.0
$C_{\|}$(C)	555	9.08	10.6	10.1	415	9.8	−5.1
$C_{\|}$(T)	591	9.83	11.6	11.0	409	10.7	−4.9
$C_{\|}$(O)	856	13.9	15.6	15.8	475	12.2	0.9
$C_{\perp}$(S)	413	1.11	0.992	1.17	90.9	5.0	17.7
$C_{\perp}$(H)	460	1.33	1.26	1.37	166	3.4	9.2
$C_{\perp}$(L)	568	1.64	1.49	1.69	211	3.2	13.9
$C_{\perp}$(C)	569	1.68	1.49	1.70	477	1.4	14.5
$C_{\perp}$(T)	580	1.77	1.78	1.80	501	1.6	0.6
$C_{\perp}$(O)	853	3.29	2.78	3.37	513	2.3	21.2

ρ is the density, E_α is the measured MOE, E_β is the value calculated from true MOE of the laminae, E_γ is the true MOE calculated from the measured MOE, G is shear modulus, Y_s is the percentage of deflection caused by shear force vs total deflection ($100\,(E_\gamma - E_\alpha)/E_\gamma$), and C_g is the percentage of contribution of glue line to MOE ($100(E_\gamma - E_\beta)/E_\beta$). Each value is the average of the four measurements.

We did not succeed in obtaining the E/G for $C_\perp$ type because the extremely small slope of the regression line between $1/E_\alpha$ and $(h/l)^2$ was affected by the variation in the deflection measurements, as reported in a previous study (Park et al 2003). Therefore, the percentage of deflection caused by shear force for cross-laminated wood panels was calculated by the following method. First, to obtain the E/G value, R_g ($=E_\gamma/E_\beta$) was considered inversely proportional to E_β which was calculated from the true MOE of individual laminae, and the relation between R_g and $1/E_\beta$ for parallel-laminated wood panels was plotted, as is shown in Fig 5. A high correlation coefficient between the two values was observed. Assuming that cross-laminated wood panels also show the same relationship between them, R_g corresponding to the value of $1/E_\beta$ was calculated from this regression line. On the basis of the R_g value, E_γ ($= R_g \times E_\beta$) in which the contribution of the

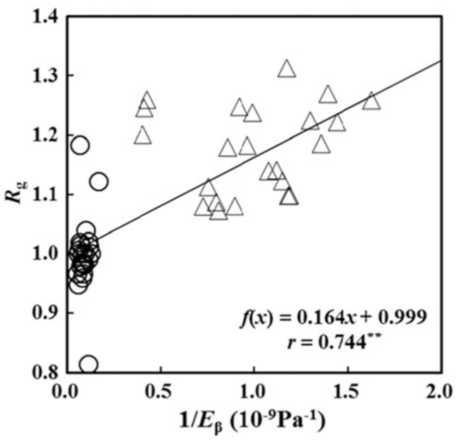

Figure 5. Relation between R_g and $1/E$ for parallel-laminated wood panels. (R_g is E_γ/E_β; E_γ is the true MOE calculated from the measured MOE of laminated woods; E_β is the value calculated from the true MOE of the laminae; r is coefficient of correlation, ** indicates significance at 1% level, $P_{\|}$ type represented by open circles, $P_\perp$ type represented by open triangles).

glue line to the true MOE was taken into consideration was obtained. And, shear moduli of cross-laminated wood panels were calculated by substituting the shear moduli of each lamina in Eq 5, which were derived for the calculation of the shear modulus of laminated woods from the shear modulus of each lamina in a previous report (Park et al 2009).

$$G = \frac{h^3 E}{6X} \tag{5}$$

where

$$X = \frac{E_1}{G_1}\left[(h-\eta){h_1}^2 - \frac{{h_1}^3}{3}\right] + \frac{E_1}{G_2}\left[2(h-\eta)^2 h_1 - 3(h-\eta){h_1}^2 + {h_1}^3\right] + \frac{2}{3}\times\frac{E_2}{G_2}(h-\eta-h_1)^3 + \frac{2}{3}\times\frac{E_2}{G_2}(\eta-h_3)^3 + \frac{E_3}{G_2}\left(2\eta^2 h_3 - 3\eta {h_3}^2 + {h_3}^3\right) + \frac{E_3}{G_3}\left(\eta {h_3}^2 - \frac{{h_3}^3}{3}\right)$$

where η is the distance from the base axis ZZ to neutral axis NN as shown in Fig 6; E is MOE of the laminated wood beam; E_1, E_2, and E_3 are MOE of each layer (E_1 is MOE of bottom lamina, E_2 is MOE of core lamina, and E_3 is MOE of top lamina); G_1, G_2, and G_3 are shear modulus of each layer (G_1 is shear modulus of bottom lamina, G_2 is shear modulus of core lamina, and G_3 is shear modulus of top lamina); h is thickness of the laminated wood beam; h_1 is thickness of the bottom lamina; and h_3 is thickness of the top lamina.

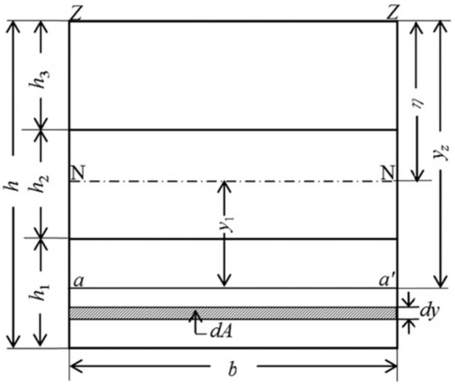

Figure 6. Configuration of cross section for obtaining shear stress and shear strain of three-ply laminated material beam (NN is the neutral axis, η is the distance from ZZ axis to neutral axis, y_1 is the distance from neutral axis to *aa'* horizontal line, y_z is the distance from ZZ axis to *aa'* horizontal line, h is the thickness of three-ply laminated material beam, h_1, h_2, and h_3 are the thicknesses of individual laminae of three-ply laminated material beam, b and is the width of three-ply laminated material beam).

For $C_\perp$ type, the shear moduli were greatest (513 MPa) in $C_\perp$(O) and lowest (90.9 MPa) in $C_\perp$(S). By cross-laminating longitudinal-direction lamina in the core, the shear modulus increased 2.6-2.9 times in softwoods and 1.6-1.8 times in hardwoods. The E_γ/G ratios showed small values of about 10. For $C_{||}$ type, the shear moduli were greatest (475 MPa) in $C_{||}$(O) and lowest (65.4 MPa) in $C_{||}$(S). These values increased with increasing density of species. By cross-laminating perpendicular-direction lamina in the core, the shear moduli decreased 0.1-0.7 times and the decrease was considerably greater in softwoods than in hardwoods. The E_γ/G values of $C_{||}$ type were 95.1 to 123.7 for softwoods and 26.0 to 33.3 for hardwoods, with the values of softwoods markedly greater than those of hardwoods. The E_γ/G values increased 3.8-8.8 times for softwoods and 1.6-1.8 times for hardwoods. The increase was considerably greater in softwoods than in hardwoods. The true MOE (E_γ) of the laminated wood panels by bending moment including the contribution of glue line was calculated by substituting the E/G (= E_γ/G) values obtained in Eq 3. The percentages of deflection caused by shear forces (Y_s) of cross-laminated wood panels were calculated by substituting the true MOE (E_γ) and the apparent MOE (E_α) in Eq 6 and are shown in Table 2.

$$Y_s = (y_\alpha - y_m)/y_\alpha \times 100 = \left(E_\gamma - E_\alpha\right)/E_\gamma \times 100(\%) \tag{6}$$

where y_α is the total deflection caused by bending moment and shear forces and y_m is the deflection caused by bending moment.

As shown in Table 2, the Y_s values for $P_{||}$, $P_\perp$, and $C_\perp$ types were less than 10%. However, the Y_s values of $C_{||}$ type showed very high values of 9.8 to 34.0%. These values were similar to the results of previous reports (Park et al 2001, 2003, 2009; Park and Fushitani 2014), which showed high percentages of deflection caused by shear force of 16.1-51.8%. Especially, it was found that the values were greater in softwoods with low shear moduli in cross section than in hardwoods, shown by the results of cross-laminated wood panels made with five species (Park et al 2003). This is considered an important factor when this material is used as a structural material.

Proportional Limit Stress of Cross-Laminated Wood Panels

As shown in Fig 7, the proportional limit stresses of parallel- and cross-laminated wood panels were greatest in the laminated wood panels composed of oriental oak and were lowest in the laminated wood panels composed of Japanese cedar. These values increased with increasing density of wood species. The density dependence of parallel-laminated wood panels was markedly greater in the perpendicular direction than in the parallel direction. The values of $C_\perp$ type increased from 1.6 to 2.5 times by cross-laminating longitudinal-direction laminae of each species in the core of $P_\perp$ type. Conversely, the values for $C_{||}$ type were 0.81-1.01 times lower than that of $P_{||}$ type, and the density dependence tended to be similar to $P_{||}$ type.

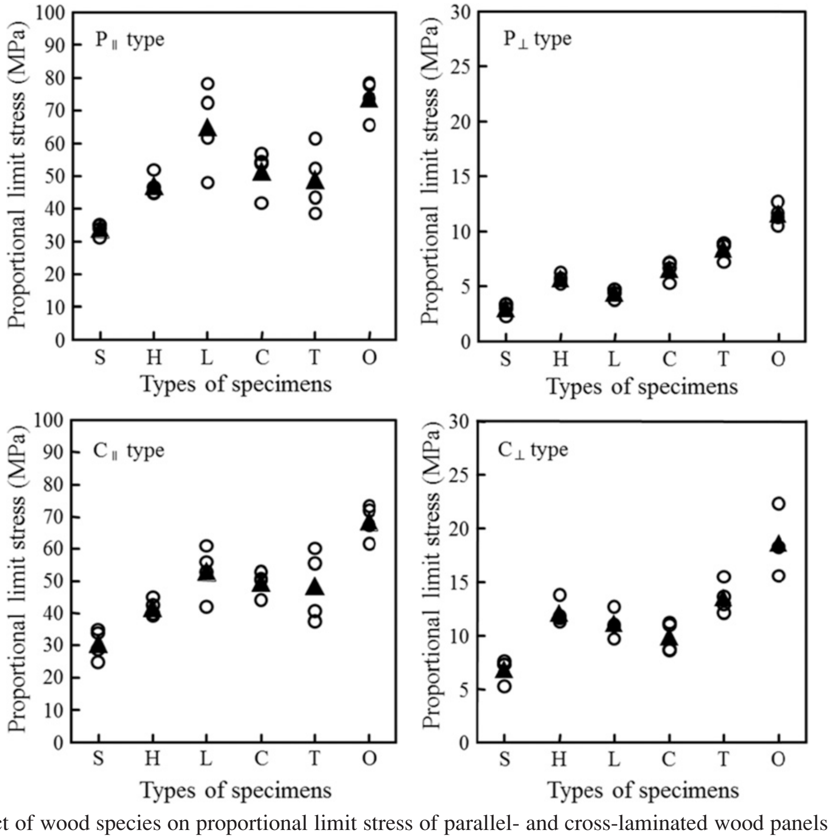

Figure 7. Effect of wood species on proportional limit stress of parallel- and cross-laminated wood panels (S, H, L, C, T, and O are Japanese cedar, Japanese cypress, Japanese larch, chestnut, tulip tree, and oriental oak, respectively).

The degree of anisotropy of proportional limit stress perpendicular to the grain of face laminae vs that parallel to the grain of face laminae was markedly decreased from 0.068-0.172 to 0.200-0.290 by cross laminating. The decrease was greater than the MOE of cross-laminated wood panels previously explained.

Modulus of Rupture (MOR) of Cross-Laminated Wood Panels

MOR of parallel- and cross-laminated wood panels are shown in Fig 8. For $P_{||}$ type, the values were greatest in $P_{||}$(O) (114 MPa) and lowest in $P_{||}$(S) (56.8 MPa). For $P_{\perp}$ type, the values were greatest in $P_{\perp}$(O) (18.0 MPa) and lowest in $P_{\perp}$(S) (4.83 MPa). These values increased with increasing density of the wood species, demonstrating an apparent density dependence, and showed a very small value of 0.1-0.2 times that of $P_{||}$ type.

For $C_{\perp}$ type, values were greatest in $C_{\perp}$(O) (23.4 MPa) and lowest in $C_{\perp}$(S) (9.93 MPa). The values were in the order of $C_{\perp}$(O) > $C_{\perp}$(T) > $C_{\perp}$(L) > $C_{\perp}$(C) > $C_{\perp}$(H) > $C_{\perp}$(S), and these values tended to increase with increasing density of wood species on the whole. Values for $C_{\perp}$ type were increased from 1.2 to 2.1 times by cross-laminating longitudinal-direction lamina of each species in the core of $P_{\perp}$ type. Conversely, for $C_{||}$ type, the values were greatest in $C_{||}$(O) (98.6 MPa) and lowest in $C_{||}$(S) (47.7 MPa). The values were in the order of $C_{||}$(O) > $C_{||}$(L) > $C_{||}$(T) > $C_{||}$(C) > $C_{||}$(H) > $C_{||}$(S). These values increased with increasing density of the wood species and were 0.77-0.86 times lower than that of $P_{||}$ type. The decrease was lower in hardwood than in softwood.

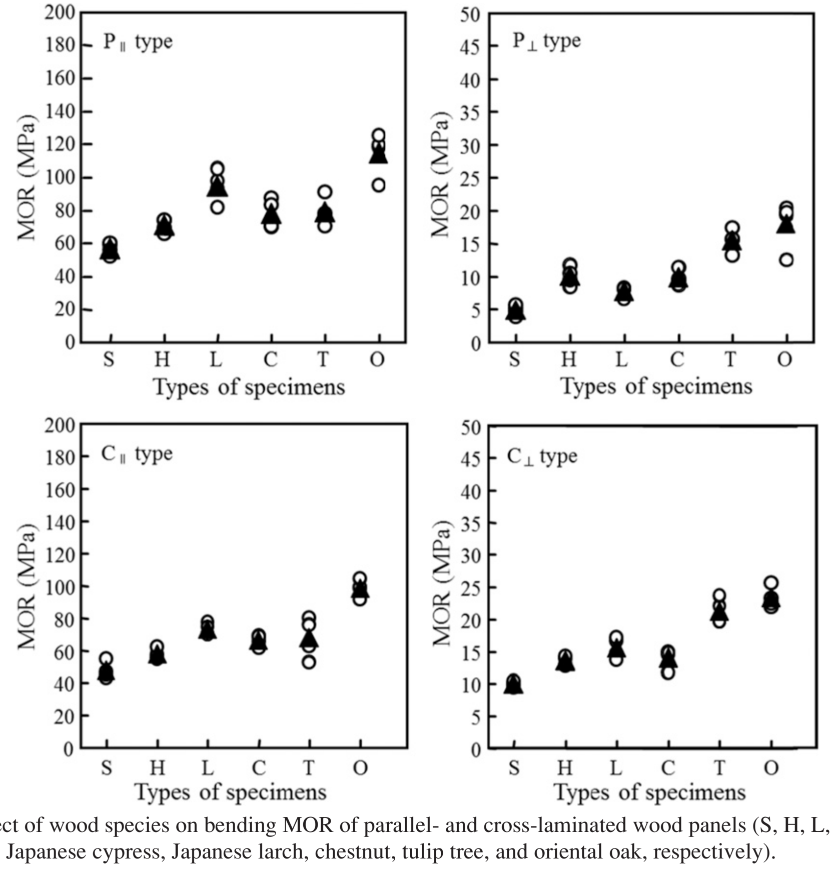

Figure 8. Effect of wood species on bending MOR of parallel- and cross-laminated wood panels (S, H, L, C, T, and O are Japanese cedar, Japanese cypress, Japanese larch, chestnut, tulip tree, and oriental oak, respectively).

The degree of anisotropy of MOR perpendicular to the grain of face laminae vs that parallel to the grain of face laminae was markedly decreased from 0.085-0.195 to 0.208-0.314 by cross-laminating, and the decrease was greater than that of the MOE of cross-laminated wood panels previously mentioned.

Furthermore, the specific MOR (MOR/specific gravity) value of the laminated wood panels was 133-165 MPa for $P_{||}$ type, 12.1-25.6 MPa for $P_{\perp}$ type, 112-128 MPa for $C_{||}$ type, and 24.1-36.7 MPa for $C_{\perp}$ type. The values were 1.2-2.5 times higher than the MOR.

CONCLUSION

In this study, with a view to effectively use small- and medium-diameter Korean wood as structural materials, cross-laminated wood panels were manufactured using six species of Korean softwoods and hardwoods and the effects of wood species on static bending strength performances were investigated. The conclusions obtained were as follows:

1. Static bending strength performances of parallel- and cross-laminated wood panels showed the greatest values for those made with oriental oak and the lowest values for those made with Japanese cedar. It was found that the MOE and MOR increased with increasing density of the wood species overall.
2. The MOE, the proportional limit stress, and the MOR perpendicular to the grain were considerably improved by cross-laminating longitudinal-direction lamina in the core of $P_{\perp}$ type, and the extent of the improvement was greater in panels made with softwoods with a low density than in those made with hardwoods.
3. Shear moduli of cross-laminated wood panels were greatest in those made with oriental oak and lowest in those made with Japanese cedar. The values for $C_{\perp}$ type increased 1.6-2.9 times by cross-laminating longitudinal-direction lamina in the core, and those for $C_{||}$ type decreased 0.1-0.7 times by cross-laminating perpendicular-direction lamina in the core. The extents of increase and decrease were found to be greater in panels made with softwoods than in those made with hardwoods.
4. The measured MOE of $P_{||}$, $P_{\perp}$, and $C_{\perp}$ types were similar to the estimated MOE. However, the measured MOE of $C_{||}$ type was considerably lower than the estimated MOE because of the effect of deflection caused by shear forces. The percentage of deflection caused by shear force vs total deflection (Y_s) was less than 10% for $P_{||}$, $P_{\perp}$, and $C_{\perp}$ types. However, that of $C_{||}$ type demonstrated very high values of 9.8-34.0%.

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