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Measurement of Dynamic MOE of 3-Ply Laminated Woods by Flexural Vibration and Comparison with Bending Strength and Creep Performances*[1]

Han-Min Park*[2] and Hee-Seop Byeon*[2]†

ABSTRACT

To estimate nondestructively strength performances of laminated woods, 3-ply parallel- and cross-laminated wood specimens exposed under atmosphere conditions after bending creep test were prepared for this study. The effects of density of species, arrangement of laminae and lamination types on dynamic MOE obtained by flexural vibration were investigated, and regression analyses were conducted in order to estimate static bending strength and bending creep performances.

Dynamic MOE of parallel-laminated woods showed 1.0~1.2 times higher values than static bending MOE, and those of cross-laminated woods showed 1.0~1.4 times higher values than static bending MOE. The degree of anisotropy of dynamic MOE perpendicular to the grain of face laminae versus that parallel to the grain of face laminae was markedly decreased by cross-laminating. There were strong correlations between dynamic MOE by flexural vibration and static bending MOE (correlation coefficient r = 0.919~0.972) or bending MOR (correlation coefficient r = 0.811~0.947) of 3-ply laminated woods, and the correlation coefficient were higher in parallel-laminated woods than in cross-laminated woods. It indicated that static bending strength performances were able to be estimated from dynamic MOE by flexural vibration. Also, close correlations between the reciprocal of dynamic MOE by flexural vibration and initial compliance at 0.008 h of 3-ply laminated woods were found (correlation coefficient r = 0.873~0.991). However, the correlation coefficient between the reciprocal of dynamic MOE and creep compliance at 168 h of 3-ply laminated woods was considerably lower than those between dynamic MOE and initial compliance, and it was hard to estimate creep compliance with a high accuracy from dynamic MOE due to the variation of creep deformation.

Keywords : *laminated wood, dynamic MOE, static bending MOE, bending MOR, compliance*

1. INTRODUCTION

Nondestructive evaluation (NDE) of wood was generally conducted by an organic function of experts for wood processing. However it has been gradually changed with the evaluation by

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[1] Received on January 5, 2006; accepted on March 6, 2006.

[2] Institute of Agriculture & Life Science, College of Agriculture & Life Science, Gyeongsang Nat'l Univ., Jinju 660-701, Korea.

† Corresponding author : Hee-Seop Byeon (hsbyeon@gnu.ac.kr)

using machines owing to various facts such as the request for the guarantee of quality and stability for wood materials, the increase of the demand of wood in building construction field and the necessity of quality control for wood as a raw material with the development of engineered wood products (EWP). There are various nondestructive evaluation (NDE) techniques such as machine stress rated (MSR), longitudinal and flexural vibrations, acoustic emission, acousto ultrasonic, and x-ray. Also, various studies for assessment of strength properties of wood and wood-based materials by NDE techniques have been conducted (Matsumoto and Tsutsumi, 1968; Murakami *et al.*, 1971; Cha, 1996; Jang, 2000; Byeon *et al.*, 2005a, b). The researches for free-free beam vibration (flexural vibration) in the NDE have been extensively conducted for detecting the characterization of solid wood and chemically modified wood for musical instruments (Kataoka and Ono, 1975, 1976; Norimoto, 1982; Tonosaki *et al.*, 1983; Sobue *et al.*, 1984; Hong, 1985; Yano *et al.*, 1986; Beall and wilcox, 1987; Wilcox, 1988; Akitsu *et al.*, 1991), and there are little researches for laminated woods.

In previous reports (Park *et al.*, 2003, 2006), we investigated static bending strength and bending creep performances of three-ply parallel and cross-laminated woods made with various species through static bending test and bending creep test to study the use as a material for building construction. From the results, we clarified various facts on the static bending strength and bending creep performances of cross-laminated woods such as the improvement of strength performances and the decrease of anisotropy by cross-laminating, the relation between the estimated values and the measured values on static bending MOE and bending creep deformation.

In this study, following the previous reports (Park *et al.*, 2003, 2006), 30 types of parallel- and cross-laminated wood specimens exposed under atmosphere conditions after bending creep test were prepared in order to estimate nondestructively static bending strength and creep performances by dynamic MOE of 3-ply laminated woods. We investigated the effect of density of species, arrangement of laminae and lamination types on dynamic MOE obtained by flexural vibration. And regression analyses were conducted to clarify the relations between dynamic MOE and static bending strength or bending creep performances.

2. MATERIALS and METHODS

2.1. Specimen

Five species with various densities and shear moduli in cross section were selected for this study. They included two softwoods: Japanese cedar (*Cryptomeria japonica* D. Don) and Japanese cypress (*Chamaecyparis obtusa* Endl.); and three hardwoods: royal paulownia (*Paulownia tomentosa* Steud.), katsura (*Cercidiphyllum japonicum* Sieb. et Zucc.), and beech (*Fagus crenata* Blume). They were air-dried more than one year in a room without the humidity control system. Longitudinal-direction laminae of 6.7(T) × 20(R) × 360(L) mm whose long axes were parallel to the grain were made with Japanese cedar and beech. Elements of 7.5(T) × 20(R) × 180(L) mm were cut from each five species, 18 elements from each species were side-jointed by a butt joint method, and were pressed for 24 hours in a room maintained at 20°C and 65%RH. And then they were cut to 20 mm size in width direction and perpendicular-direction laminae of 6.7(T) × 360(R) × 20(L) mm whose long axes were perpendicular to the grain were made. The annual ring angles of both laminae were 90°. A resorcinol-phenol resin type adhe-

Table 1. Arrangement of laminae and combination of species for thirty types of laminated wood specimens

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

Notes; F: Face, C: Core, L: Longitudinal-direction lamina; P: Perpendicular-direction lamina, KI: Royal paulowina, SU: Japanese cedar, HI: Japanese cypress, KA: Katsura, BU: Beech.

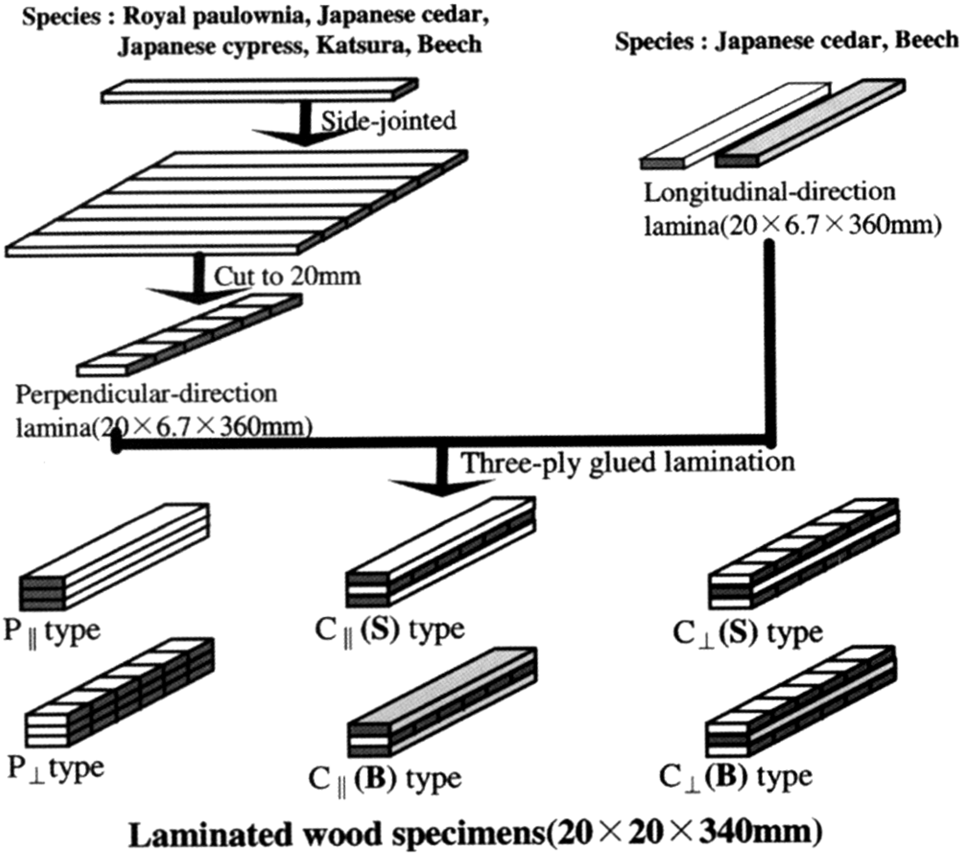

Fig. 1. Parallel- and cross-laminated wood specimens.
Note: "S" and "B" of cross-laminated woods mean that Japanese cedar and beech were used as longitudinal-direction lamina, respectively.

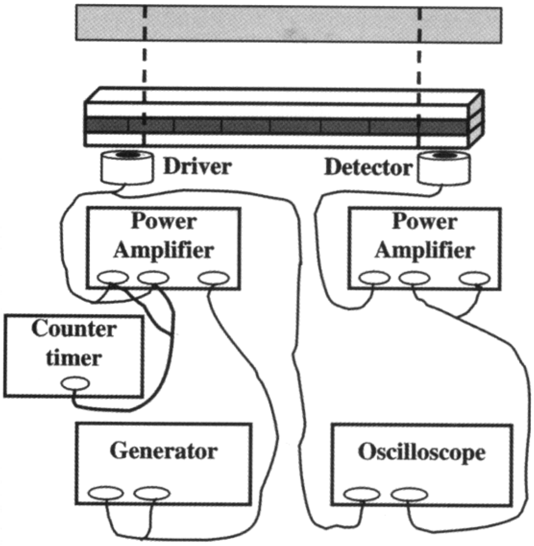

Fig. 2. Schematic diagram of free-free beam vibration (flexural vibration) of laminated wood specimens.

sive formulated for a room temperature cure was used, and the amount of spread was 300 g/m^2. The three-ply laminae were pressed under pressure of 0.34 MPa for 24 hours in a room maintained at 20°C and 65%RH. Fig. 1 shows three-ply parallel- and cross-laminated wood specimens. $P_{\parallel}$ and $P_{\perp}$ types were the specimens used to measure the dynamic MOE parallel and perpendicular to the grain of parallel-laminated woods, respectively. $C_{\parallel}$ and $C_{\perp}$ types were the specimens used to measure the dynamic MOE parallel and perpendicular to the grain of the face laminae of cross-laminated woods, respectively. Table 1 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.

2.2. Static Bending Test

Static bending test for laminated wood specimens was conducted by four-point loading. The span was 300 mm, the distance between a loading point and a supporting point was 100 mm, and the cross-head speed was set at 5.0 mm/min. The deflection of mid-span was measured with a dial gauge type displacement transducer, and load-deflection curves were recorded with an X-Y recorder.

2.3. Bending Creep Test

Bending creep test for parallel- and cross-laminated wood specimens was conducted by four-point loading. The span was 300 mm, and the distance between a loading point and a supporting point was 100 mm. The stress corresponding to 20% of breaking stress obtained from static bending test was applied to each specimen. The creep test was conducted for 168 hr (7 days) in a constant atmosphere maintained at 20°C and 65%RH. The deflection of the mid-span was measured with a dial gauge type displacement transducer. Total creep compliance $D(t)$ and creep compliance $D_c(t)$ (total creep compliance except for initial compliance) were obtained using Eqs. (1) and (2) as follows:

$$D(t) = \frac{4bh^3 y(t)}{Pl_1(3l^2 - 4l_1^2)} \qquad (1)$$

where P is the applied load; l is the span; b, h are the width and depth of the beam; l_l is the distance between a loading point and a supporting point; and $y(t)$ is the apparent deflection at time(t) between both supporting points and contains the deflection caused by shear force. Therefore, $D(t)$ is the apparent total creep compliance obtained from the apparent deflection containing the deflection caused by shear force.

$$D_c(t) = D(t) - D(0.008) \qquad (2)$$

where $D(0.008)$ is initial compliance at t = 0.008 hr (30 s).

2.4. Dynamic MOE Measurement by Flexural Vibration under Free-Free Beam Condition

Vibration was induced via a small steel plate attached to the bottom end of 3-ply laminated wood specimens suspended by two threads at the magnetic driver as shown in Fig. 2. The vibration was received at a small steel plate attached to the other end. The test was made with both ends free condition. The test apparatus consisted of a sine wave generator (Type 1023, B&K), a universal counter timer (Type 5001, GSP) and an oscilloscope (Type 1740A, HP). The value of the frequency counter timer was recorded when the relative amplitude indicated the highest value on the oscilloscope. Resonance frequency (f) and dynamic MOE (MOE$_d$) were calculated by the following equations (Kataoka and Ono, 1975):

$$f = f_0(1+\alpha h^2/l^2) \qquad (3)$$

where f_0 is the value obtained from frequency counter timer, α=8.2 is the value according to chosen vibration type, h is the thickness of specimen (mm), l is the length of specimen (mm).

$$\mathrm{MOE_d} = 48\pi^2 \rho l^4 f^2 / m^4 h^2 \qquad (4)$$

where ρ is density (Mg/m^3), m=4.73 is the value according to the chosen basic vibration, h is the thickness of specimen (mm), l is the length of specimen (mm).

3. RESULTS and DISCUSSION

3.1. Dynamic Modulus of Elasticity (MOE) of Laminated Woods

Dynamic MOEs by flexural vibration under free-free beam condition of parallel- and cross-laminated woods made with five species are shown in Table 2, and static bending strength and bending creep performances were contained in Table 2 from the previous reports (Park *et al.*, 2003, 2006) in order to compare with them. For P$_{\parallel}$ type parallel-laminated woods composed of longitudinal-direction laminae for three layers, Japanese cypress had the highest dynamic MOE and royal paulownia had the lowest dynamic MOE. These values showed 1.0～1.1 times higher values than static bending MOE. And density dependence of dynamic MOE was not found like static bending strength performances reported in the previous paper (Park *et al.*, 2003). For P$_{\perp}$ type parallel-laminated woods composed of perpendicular-direction laminae for three layers, beech had the highest dynamic MOE and royal paulownia had the lowest dynamic MOE. The values increased with increasing density of species, and showed very small values of 0.08～0.20 times that of P$_{\parallel}$ type. Also, they were found to be about 1.2 times higher values than static bending MOE, and agreed with the report which dynamic MOE exceeded static MOE by a factor of 1.2 (Norimoto, 1982). For C$_{\perp}$ type cross-laminated wood whose faces composed of perpendicular-direction laminae of five species, C$_{\perp}$ (BBU) cross-laminated woods with beech perpendicular-direction lamina used for faces had the highest values, and C$_{\perp}$ (SSU) cross-laminated woods with Japanese cedar perpendicular-direction lamina used for faces had the lowest values. The values increased to 1.1～2.2 times that of P$_{\perp}$ type by arranging longitudinal-direction laminae in the core, and cross-laminated woods with beech longitudinal-direction laminae in the core had the slightly higher values than in that with Japanese cedar longitudinal-direction laminae on the whole. The values were found to be 1.0～1.4 times higher than static bending MOE. They increased mostly with

Table 2. Results of dynamic MOE measurement by flexural vibration and static bending strength and bending creep tests

Type	ρ (Mg/m^3)	E_s (GPa)	σ (MPa)	R_{fr} (Hz)	E_d (GPa)	$1/E_d$ (10^{-11} Pa^{-1})	$D(0.008)$ (10^{-1} ^{1}Pa^{-1})	$D_c(168)$ (10^{-11} Pa^{-1})
$P_{\parallel}$(KI)	0.264(4.3)	5.69(16.2)	40.3(9.4)	826(3.3)	5.71(9.0)	17.7(9.2)	19.4(9.0)	1.52(28.2)
$P_{\parallel}$(SU)	0.397(2.7)	8.98(7.9)	74.7(4.0)	874(1.4)	9.18(5.0)	10.9(5.1)	12.2(4.6)	0.964(16.6)
$P_{\parallel}$(HI)	0.480(1.0)	12.5(7.7)	93.2(3.4)	943(1.5)	12.8(3.4)	7.81(3.5)	8.79(6.3)	0.581(42.2)
$P_{\parallel}$(KA)	0.503(2.8)	8.80(9.0)	87.2(12.9)	795(0.4)	9.62(3.1)	10.4(3.1)	12.0(2.4)	1.11(10.7)
$P_{\parallel}$(BU)	0.578(2.1)	8.67(26.7)	79.9(25.0)	723(8.0)	9.31(15.4)	11.0(16.8)	12.5(20.4)	1.76(51.5)
$P_{\perp}$(KI)	0.275(6.1)	0.510(15.2)	3.87(2.3)	267(5.1)	0.596(15.7)	172(16.1)	195(11.1)	104(25.7)
$P_{\perp}$(SU)	0.419(0.2)	0.735(7.1)	5.52(4.6)	260(2.8)	0.866(5.3)	116(5.2)	138(2.3)	61.6(17.6)
$P_{\perp}$(HI)	0.500(2.0)	0.829(9.0)	6.54(11.8)	261(1.9)	1.01(3.1)	98.9(3.0)	119(3.7)	53.9(24.3)
$P_{\perp}$(KA)	0.509(0.5)	1.31(6.9)	15.7(5.9)	314(2.3)	1.53(4.9)	65.6(4.8)	76.4(2.3)	34.5(9.6)
$P_{\perp}$(BU)	0.617(3.4)	1.60(7.8)	18.2(21.5)	319(3.3)	1.87(7.8)	53.7(7.6)	64.8(1.7)	32.0(21.4)
$C_{\parallel}$(SKI)	0.369(2.2)	5.83(11.7)	43.7(5.7)	798(2.5)	7.07(7.0)	96.9(22.4)	16.6(7.1)	2.90(19.8)
$C_{\parallel}$(SSU)	0.420(0.8)	5.68(8.7)	46.6(10.7)	722(2.9)	6.79(5.0)	94.8(5.8)	17.1(2.7)	3.73(10.2)
$C_{\parallel}$(SHI)	0.448(2.9)	6.25(7.9)	54.2(6.6)	746(1.7)	7.47(6.0)	88.1(11.5)	15.0(8.4)	2.78(22.2)
$C_{\parallel}$(SKA)	0.434(3.0)	7.52(6.6)	58.9(5.8)	801(1.4)	8.33(6.1)	55.3(3.2)	13.2(5.5)	1.59(11.2)
$C_{\parallel}$(SBU)	0.478(2.3)	7.68(7.2)	58.5(2.9)	773(1.9)	8.57(6.0)	47.8(4.0)	13.4(8.1)	1.67(15.1)
$C_{\parallel}$(BKI)	0.505(2.3)	5.78(26.5)	46.1(10.3)	665(6.2)	6.77(13.4)	82.4(23.4)	17.5(13.2)	3.95(50.0)
$C_{\parallel}$(BSU)	0.562(1.1)	5.31(15.7)	47.5(9.3)	600(4.8)	6.32(11.4)	92.2(9.8)	19.4(10.4)	5.63(27.1)
$C_{\parallel}$(BHI)	0.567(2.6)	6.06(18.6)	57.4(10.3)	641(5.2)	7.01(12.9)	78.0(6.1)	16.6(13.7)	4.24(25.2)
$C_{\parallel}$(BKA)	0.560(2.0)	7.08(21.5)	66.7(17.0)	695(4.7)	8.22(11.8)	56.3(5.1)	13.5(12.2)	2.38(34.4)
$C_{\parallel}$(BBU)	0.620(1.0)	7.60(20.1)	69.5(16.5)	662(6.2)	8.17(12.5)	46.1(4.5)	16.6(7.3)	3.50(36.9)
$C_{\perp}$(SKI)	0.317(2.3)	0.787(11.9)	10.7(15.5)	335(12.0)	1.10(25.9)	14.2(7.3)	117(7.5)	31.7(25.5)
$C_{\perp}$(SSU)	0.422(1.8)	1.06(6.0)	11.6(15.0)	285(2.4)	1.06(5.8)	14.8(5.1)	89.0(5.8)	32.9(7.2)
$C_{\perp}$(SHI)	0.478(0.8)	1.14(8.9)	12.8(7.9)	285(5.3)	1.15(11.4)	13.4(6.2)	82.4(6.2)	28.9(17.1)
$C_{\perp}$(SKA)	0.477(2.8)	1.59(4.5)	17.7(13.5)	355(1.3)	1.81(3.1)	12.1(6.3)	51.9(26.2)	18.2(9.5)
$C_{\perp}$(SBU)	0.552(1.2)	1.82(7.4)	18.1(23.5)	355(0.8)	2.09(3.9)	11.7(6.2)	55.2(3.8)	21.5(14.3)
$C_{\perp}$(BKI)	0.381(3.2)	0.821(19.9)	11.4(20.8)	355(11.9)	1.30(28.0)	15.1(14.5)	120(11.3)	41.5(43.2)
$C_{\perp}$(BSU)	0.480(4.3)	1.04(12.5)	11.1(24.0)	273(3.9)	1.10(10.1)	16.1(12.2)	94.2(8.9)	46.8(30.8)
$C_{\perp}$(BHI)	0.552(2.2)	1.15(12.7)	10.9(20.8)	279(2.4)	1.29(6.4)	14.5(13.5)	83.1(6.2)	34.6(29.5)
$C_{\perp}$(BKA)	0.556(2.3)	1.60(8.6)	16.1(21.5)	325(3.0)	1.78(5.0)	12.4(12.8)	60.4(2.9)	20.6(23.5)
$C_{\perp}$(BBU)	0.607(3.8)	1.84(10.7)	19.3(23.7)	344(1.4)	2.17(4.4)	12.4(11.6)	56.5(7.8)	23.4(24.3)

Notes; ρ: Density, E_s: Static bending MOE, σ: Bending MOR, E_d: Dynamic MOE, R_{fr}: Resonance frequency, $D(0.008)$: Initial compliance at 0.008 h, $D_c(168)$: Creep compliance at 168 h ($D(168)$-$D(0.008)$). Each value is the average of three measurement, the values in parentheses are coefficients of variation (%).

increasing density of species, whereas Japanese cedar with the higher density than in royal paulownia showed the lower dynamic MOE.

On the other hand, for $C_{\parallel}$ type cross-laminated woods whose core was composed of perpendicular-direction lamina of each species, $C_{\parallel}$ (SBU) had the highest dynamic MOE and $C_{\parallel}$ (BSU) had the lowest values. The values decreased to 0.58～0.92 times that of $P_{\parallel}$ type by arranging perpendicular-direction lamina in the core except for P (KI) with a low density, whereas in the case of arranging beech and katsura with high densities of five species in the core, they showed the higher values than in other types with low densities. Cross-laminated woods with Japanese cedar longitudinal-direction

Table 3. Results of regression analyses between dynamic MOE and static bending strength and bending creep performances

	Type	Regression model	r
E_s vs. σ	$P_{\parallel}$	y=7.50x + 8.16	0.885**
	$P_{\perp}$	y=14.2x − 4.20	0.953**
	$C_{\parallel}$	y=6.73x + 11.3	0.852**
	$C_{\perp}$	y=9.61x + 1.63	0.876**
E_d vs. E_s	$P_{\parallel}$	y=1.00x − 0.438	0.948**
	$P_{\perp}$	y=0.836x + 0.020	0.972**
	$C_{\parallel}$	y=1.17x − 2.30	0.919**
	$C_{\perp}$	y=0.802x + 0.124	0.941**
E_d vs. σ	$P_{\parallel}$	y=7.91x + 1.32	0.881**
	$P_{\perp}$	y=12.3x − 4.45	0.947**
	$C_{\parallel}$	y=8.18x − 6.18	0.811**
	$C_{\perp}$	y=7.58x + 3.01	0.811**
$1/E_d$ vs. $D(0.008)$	$P_{\parallel}$	y=1.08x + 0.445	0.991**
	$P_{\perp}$	y=1.05x + 11.6	0.990**
	$C_{\parallel}$	y=1.07x + 1.21	0.873**
	$C_{\perp}$	y=0.926x + 9.93	0.895**
$1/E_d$ vs. $D_c(168)$	$P_{\parallel}$	y=0.0972x + 0.0626	0.536*
	$P_{\perp}$	y=0.562x − 0.338	0.850**
	$C_{\parallel}$	y=0.585x − 4.76	0.751**
	$C_{\perp}$	y=0.369x + 1.66	0.707**

Notes; r: Correlation coefficient, **, *: Significant at 1% and 5% level, respectively, E_s, σ, E_d, $D(0.008)$ and $D_c(168)$: See notes in Table 2.

laminae in the faces had the slightly higher values than that with beech longitudinal-direction laminae on the whole. They were found to be 1.1~1.2 times higher than static bending MOE, and it was similar to the result for the relation between dynamic MOE and static MOE reported by Norimoto (1982). The values increased with increasing density of species, whereas cross-laminated woods with Japanese cedar perpendicular-direction lamina in the core had the lower values than that with royal paulownia with the lowest density of five species in the core. This is considered because the effect of deflection caused by shear forces increased due to a very low shear modulus in cross section of Japanese cedar like the previous reports (Park *et al.*, 2003, 2006). Namely, the deflection caused by shear force which depends on the ratio (*E/G*) between MOE and shear modulus is much greater in Japanese cedar than in royal paulownia because Japanese cedar has about 2 times lower shear modulus in cross-section than in royal paulownia, thus the dynamic MOE of cross-laminated woods with Japanese cedar perpendicular-direction lamina in the core having the lower density than in royal paulownia was smaller than in cross-laminated wood with royal paulownia perpendicular-direction lamina. Therefore, it can be said that dynamic MOE of cross-laminated woods depends on shear modulus in cross section in the core than density like static bending MOE.

The degree of anisotropy of dynamic MOE perpendicular to the grain of face laminae versus that parallel to the grain of face laminae was decreased from 0.094 to 0.156 in Japanese cedar

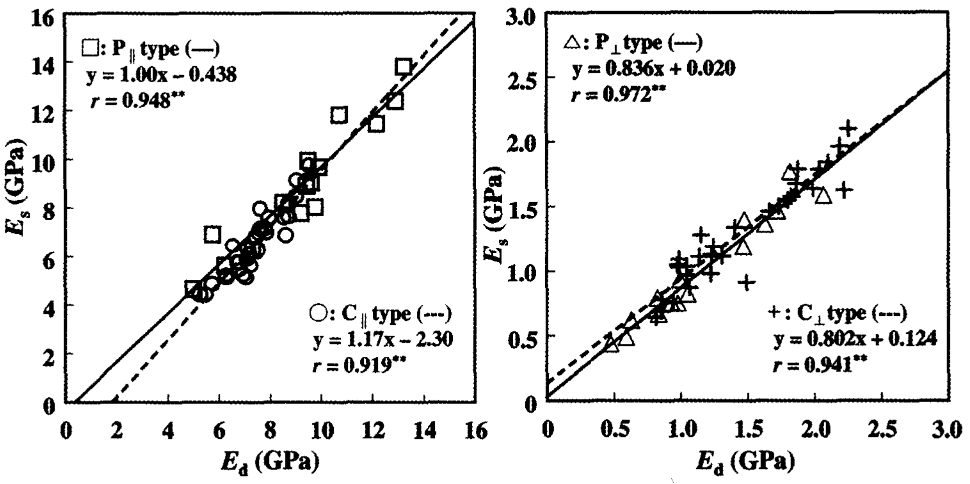

Fig. 3. Relationships between dynamic MOE (E_d) and static bending MOE (E_s) of parallel- and cross-laminated woods.

Notes; *r*: Correlation coefficient, **: Significant at 1% level.

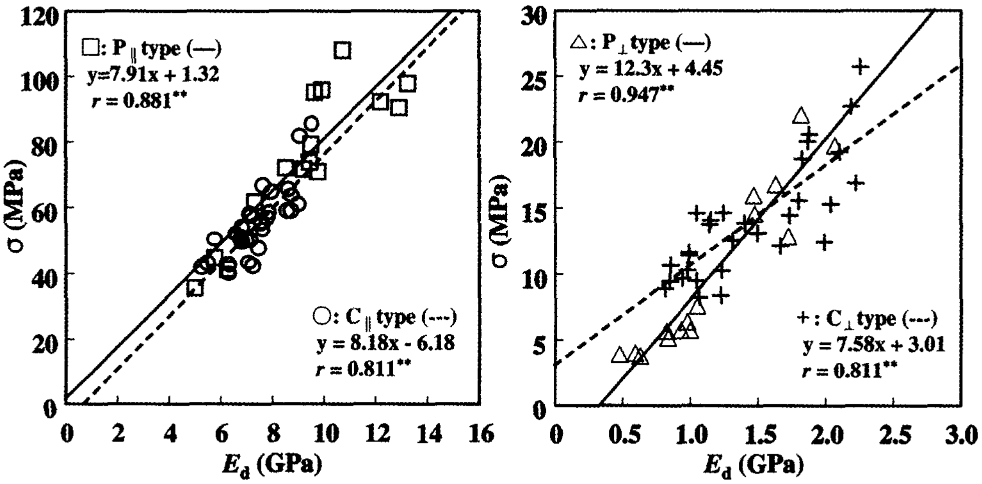

Fig. 4. Relationships between dynamic MOE (E_d) and bending MOR (σ) of parallel- and cross-laminated woods.

Notes; *r*: Correlation coefficient, **: Significant at 1% level.

and from 0.201 to 0.266 in beech by cross-laminating. There was little difference of the extent of the decrease for both species unlike previous results (Park *et al.*, 2003, 2006) for static bending MOE and creep compliance which the extent of decrease were higher in Japanese cedar than in beech.

3.2. Relations between Dynamic MOE and Static Bending Strength Performances for Laminated Woods

Least squares regression analyses were performed to examine the relation between dynamic MOE by flexural vibration and static bending strength performances. The derived regression

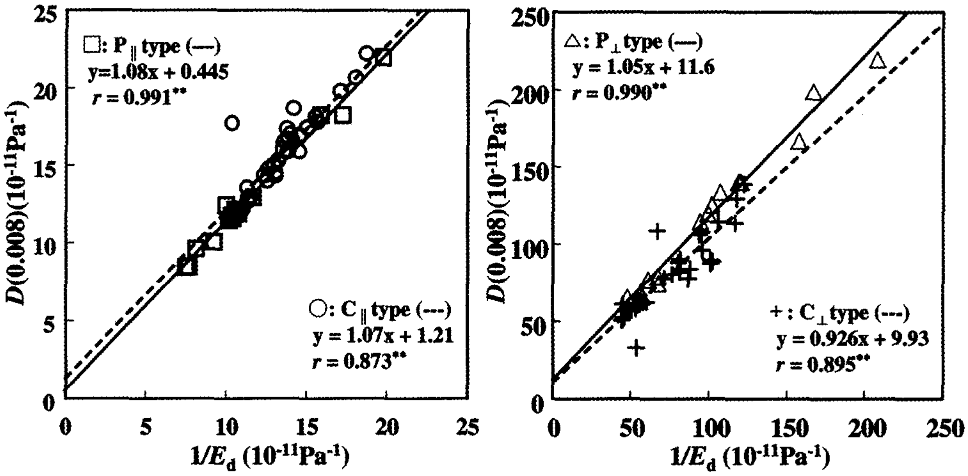

Fig. 5. Relationships between the reciprocal of dynamic MOE ($1/E_d$) and initial compliance at 0.008 h ($D(0.008)$) of parallel- and cross-laminated woods.
Notes; r: Correlation coefficient, **: Significant at 1% level.

parameters are summarized in Table 3. Relationships between dynamic MOE of each type laminated wood as calculated from their resonance frequencies and static bending MOE are shown in Fig. 3. The correlation coefficients for the regression of dynamic MOE and static MOE were 0.948 for $P_{\parallel}$ type, 0.972 for $P_{\perp}$ type, 0.919 for $C_{\parallel}$ type and 0.941 for $C_{\perp}$ type. Parallel-laminated woods had the higher value than in cross-laminated woods, and cross-laminated woods with perpendicular direction lamina in the faces had the higher value than in that with longitudinal direction lamina in the faces. The results agreed with various results for solid wood and finger-jointed woods which there was a high correlation between both MOEs (Matsumoto and Tsutsumi, 1968; Norimoto, 1982; Bender *et al.*, 1990; Lee *et al.*, 1997; Ayarkwa *et al.*, 2001; Park *et al.*, 2004; Byeon *et al.*, 2005a). It is considered that static bending MOE can be estimated by dynamic MOE because there were very strong correlations more than 0.9 for both MOEs.

On the other hand, regression relationships between dynamic MOE and bending MOR for parallel- and cross-laminated woods are shown in Fig. 4. The correlation coefficient for the regression between dynamic MOE and bending MOR were 0.881 for $P_{\parallel}$ type, 0.947 for $P_{\perp}$ type, 0.811 for $C_{\parallel}$ type and 0.811 for $C_{\perp}$ type. Like the relations between dynamic MOE and static bending MOE, parallel-laminated woods had the higher values than in cross-laminated woods, however the difference of correlation coefficient for both cross-laminated woods was not found. These values were slightly lower than those between static bending MOE and MOR which the correlation coefficients showed 0.885, 0.852, 0.953 and 0.876 for $P_{\parallel}$ type, $P_{\perp}$ type, $C_{\parallel}$ type and $C_{\perp}$ type, respectively, whereas they had high values more than 0.8 for all types. This result indicated that bending MOR can be estimated from dynamic MOE by flexural vibration, and agreed with various reports for wood and wood based materials (Nakayama, 1975; Bender *et al.*, 1990; Ayarkwa, 2001; Park *et al.*, 2004, Byeon *et al.*, 2005a).

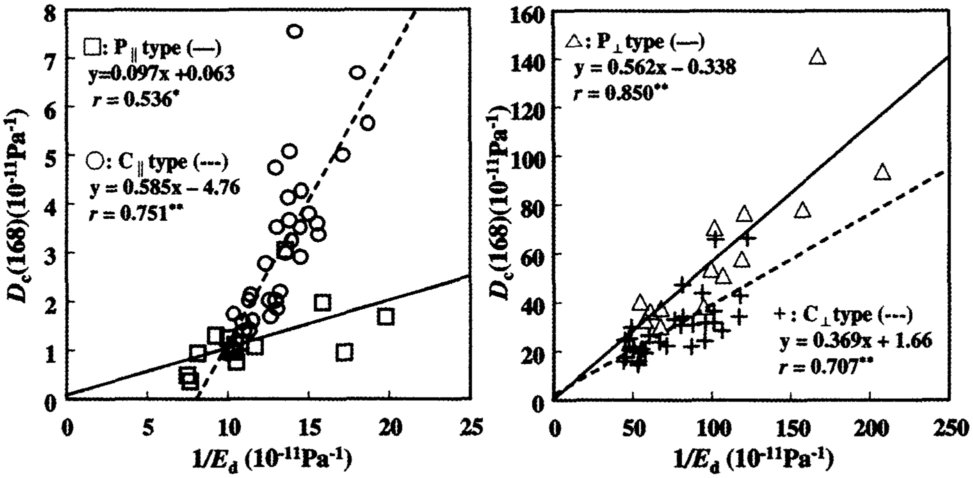

Fig. 6. Relationships between the reciprocal of dynamic MOE ($1/E_d$) and creep compliance at 168 h ($D_c(168)$) of parallel- and cross-laminated woods.

Notes; r: Correlation coefficient. **, * are significant at 1% level and 5% level, respectively.

3.3. Relations between Dynamic MOE and Initial Deformation for Laminated Woods

To investigate the relation between dynamic MOE and initial deformation for parallel- and cross-laminated woods, the regression relationships between the reciprocal of dynamic MOE by flexural vibration and initial compliance at 0.008 h ($D(0.008)$) for parallel- and cross-laminated woods are shown in Fig. 5, and the regression parameters are summarized in Table 3. The correlation coefficients for the regression between the reciprocal of dynamic MOE and initial compliance at 0.008 h ($D(0.008)$) were 0.991 for $P_{\parallel}$ type, 0.990 for $P_{\perp}$ type, 0.873 for $C_{\parallel}$ type and 0.895 for $C_{\perp}$ type. Parallel-laminated woods had the higher values than in cross-laminated woods, however the difference of correlation coefficient both parallel-laminated woods was small. For cross-laminated wood, $C_{\perp}$ type had the higher value than that of C type. They showed high values close to 0.9 for all types. This result indicated that initial deformation at 0.008 h can be estimated from dynamic MOE by flexural vibration.

3.4. Relations between Dynamic MOE and Creep Deformation for Laminated Woods

The regression relationships between the reciprocal of dynamic MOE and creep compliance at 168 h ($D_c(168)$) to investigate the relation between dynamic MOE and creep deformation for parallel- and cross-laminated woods are shown in Fig. 6, and the regression parameters are summarized in Table 3. The correlation coefficients for the regression between the reciprocal of dynamic MOE and creep compliance at 168 h ($D_c(168)$) were 0.536 for $P_{\parallel}$ type, 0.850 for $P_{\perp}$ type, 0.751 for C type and 0.707 for $C_{\perp}$ type. These values were considerably lower than those for the regression between the reciprocal of dynamic MOE and initial deformation. For cross-laminated wood, $C_{\parallel}$ type was higher than that of $C_{\perp}$ type unlike the relation between dynamic MOE and initial deformation. This indicates the difference for creep deformation of laminated woods with the lapse of time. The correlation coefficient between both values until 168 h was significant at 1% and 5% level, whereas it was considered that it would be hard to estimate creep compliance for a long time with a high accuracy from dynamic MOE due to the variation of creep deformation.

4. CONCLUSIONS

Dynamic MOE of three-ply parallel- and cross-laminated wood was measured by flexural vibration, and the effect of density of species, arrangement of laminae, lamination types on the dynamic MOE were investigated. Regression analyses were conducted in order to estimate static bending strength and bending creep performances.

Dynamic MOE were 1.0～1.2 times greater than static bending MOE for parallel-laminated woods and 1.0～1.4 times greater than static bending MOE for cross-laminated woods. The degree of anisotropy of dynamic MOE perpendicular to the grain of face laminae versus that parallel to the grain of face laminae was markedly decreased by cross-laminating, whereas the difference for species was small unlike their bending MOE and creep compliance. Static bending strength performances and initial compliance were able to be estimated from dynamic MOE calculated from resonance frequency by flexural vibration, whereas the correlation coefficient between the reciprocal of dynamic MOE and creep compliance at 168 h was considerably lower than those between the reciprocal of dynamic MOE and initial compliance, thus it was hard to estimate creep compliance for a long time with a high accuracy from dynamic MOE due to the variation of creep deformation.

REFERENCES

1. Ayarkwa, J., Y. Hirashima, and Y. Sasaki. 2001. Predicting modulus of rupture of solid and finger-jointed tropical African hardwoods using longitudinal vibration. Forest Prod. J. 51(1): 85～92.
2. Akitsu, H., M. Norimoto, and T. Morooka. 1991. Vibrational properties of chemically modified wood. Mokuzai Gakkaishi 37(7): 590～597.
3. Beall, F. C. and W. W. Wilcox. 1987. Relationship of acoustic emission during radial compression to mass loss from decay. Forest Prod. J. 37(4): 38～42.
4. Bender, D. A., A. G. Burk, S. E. Taylor, and J. A. Hooper. 1990. Predicting localized MOE and tensile strength in solid and finger-jointed laminating lumber using longitudinal stress waves. Forest Prod. J. 40(3): 45～47.
5. Byeon, H. S., H. M. Park, C. H. Kim, and F. Lam. 2005a. Nondestructive evaluation of strength performance for finger-jointed woods using flexural vibration techniques. Forest Prod. J. 55(10): 37～42.
6. Byeon, H. S., S. Y. Ahn, and H. M. Park. 2005b. Nondestructive evaluation of bending strength performances for red pine containing knots using flexural vibration technique. Mokchae Konghak 33(5): 13～20.
7. Cha, J. K. 1996. Study on stress waves for development of glulam from domestic small diameter log(1). Mokchae Konghak 24(3): 90～100.
8. Hong, B. H. 1985. The dynamic mechanical properties of *paulownia coreana* used for sounding boards. Mokchae Konghak 13(3): 34～40.
9. Jang, S. S. 2000. Evaluation of lumber properties by applying stress waves to larch logs grown in Korea. Forest Prod. J. 50(3): 44～48.
10. Kataoka, A. and T. Ono. 1975. The relations of experimental factors to the vibration and the measuring values of dynamic mechanical properties of wood I. The experimental errors due to the measuring apparatus. Mokuzai Gakkaishi 21(10): 543～550.
11. Kataoka, A. and T. Ono. 1976. The dynamic

mechanical properties of sitka spruce used for sounding boards. Mokuzai Gakkaishi 22(8): 436 ~443.

12. Lee, D. S., J. S. Jo, and G. H. Kim. 1997. Evaluation of static bending properties for some domestic softwoods and tropical hardwoods using sonic stress wave measurements. Mokchae Konghak 25(1): 8~14.
13. Matsumoto T. and J. Tsutsumi. 1968. Elastic properties of plywood in dynamic test I. Relation between static Young's modulus and dynamic Young's modulus. Mokuzai Gakkaishi 14(2): 65 ~69.
14. Murakami, R., H. Yamada, and K. Mori. 1971a. The dynamic viscoelasticity of hardboard pulp sheets I. Relation between hot pressing temperature and dynamic viscoelasticity. Mokuzai Gakkaishi 17(6): 243~248.
15. Nakayama, Y. 1975. Non-destructive test of wooden beam by vibrational method. Estimation of modulus of rupture in bending of beam containing an artificial circular hole. Mokuzai Gakkaishi 21(7): 402~409.
16. Norimoto, M. 1982. Structure and properties of wood used for musical instruments I. Mokuzai Gakkaishi 28(7): 407~413.
17. Park, H. M., M. Fushitani, K. Sato, T. Kubo, H. S. Byeon. 2003. Static bending strength performances of cross-laminated woods made with five species. Journal of Wood Science 49: 411~417.
18. Park, H. M., G. P. Lee, T. S. Kong, H. S. Ryu, and H. S. Byeon. 2004. Effect of finger profile on static bending strength performance of finger-jointed wood. MokchaeKonghak 32(6): 57~66.
19. Park, H. M., M. Fushitani, K. Sato, T. Kubo, H. S. Byeon. 2006. Bending creep performances of three-ply cross-laminated woods made with five species. Journal of Wood Science. (in press).
20. Sobue, N., H. Nakano, and I. Asano. 1984. Vibrational properties of spruce plywood for musical instruments. Mokuzai Gakkaishi 31(1): 93~97.
21. Tonosaki, M., T. Okano, and I. Asano. 1983. Vibration properties of sitka spruce with longitudinal vibration and flexural vibration. Mokuzai Gakkaishi 29(9): 547~552.
22. Wilcox, W. W. 1988. Detection of early stage of wood decay with ultrasonic pulse velocity. Forest Prod. J. 38(5): 68~73.
23. Yano, H., T. Yamada, and K. Minato. 1986b. Changes in acoustical properties of sitka spruce due to reaction with formaldehyde. Mokuzai Gakkaishi 32(12): 984~989.