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Bending creep performances of three-ply cross-laminated woods made with five species

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Abstract To improve the performance of cross-laminated woods, 30 types of three-ply parallel-laminated and cross-laminated woods were prepared from five species with various densities and shear compliances in cross section, and their bending creep performances were investigated on the basis of our previous research in cross-laminated wood made with sugi (Japanese cedar). The creep deformation perpendicular to the grain was decreased by cross laminating. The creep deformation perpendicular to the grain of parallel-laminated woods ($P_{\perp}$ type), that perpendicular to the grain of face laminae of cross-laminated woods ($C_{\perp}$ type), and also that parallel to the grain of face laminae of cross-laminated woods ($C_{\parallel}$ type) tended to decrease with increasing density of species used for perpendicular-direction lamina. It was found that the extent of the decrease was greater in creep deformation than in initial deformation. The degrees of anisotropy for both deformations of laminated wood were markedly decreased by cross laminating. The extent of the decrease was much greater in creep deformation than in initial deformation and considerably smaller in buna with higher density than in sugi with lower density. The measured values of initial deformation and creep deformation of $C_{\perp}$ type were almost equal to the calculated values obtained from the measured values of parallel-laminated woods, whereas the measured values of both deformations of $C_{\parallel}$ type were much greater than their calculated values and increased markedly with increasing shear compliance in cross section of perpendicular-direction lamina used for core. The ratios of the average of measured values to the calculated value of $C_{\parallel}$ type ranged from 1.05 (katsura) to 1.50 (sugi) in initial deformation and from 1.30 (katsura) to 3.69 (sugi) in creep deformation. This result can be explained as the effect of deflection caused by shear force.

Key words Cross-laminated woods · Initial deformation · Creep · Anisotropy · Shear force

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Introduction

Recently, cross-laminated woods have been developed and used in building applications such as wall construction and flooring. Creep performance of materials in use as structural members is very important because they are subjected to load for a long period. There has been much research on the creep of wood-based boards such as plywood,[1–5] particleboard,[2–8] and fiberboard.[2–5,9,10] However, there has been only one article on the creep of cross-laminated wood.[11]

In a previous report,[11] we investigated the bending creep performances of three-ply parallel-laminated and cross-laminated woods to study the use of sugi wood as a material for wide boards. As a result, the creep compliance perpendicular to the grain of laminated wood and the degree of anisotropy of creep deformation were markedly decreased by cross laminating, and the extent of the decrease was the greatest at 45° annual ring angle. In the cross-laminated wood with core composed of lamina perpendicular to the grain, it was found that the measured values of initial compliance and creep compliance were much greater than their calculated values owing to the influence of deflection caused by shear force. This influence was considerably higher in creep deformation than in initial deformation, and was the lowest at 45° annual ring angle of lamina in the core. Furthermore, in another report[12] on the static bending strength performances of cross-laminated woods made with five species, it was found that the effect of deflection caused by shear force on the modulus of elasticity (MOE) decreased linearly with increasing shear modulus in cross section of the core.

In this study, three-ply parallel-laminated and cross-laminated woods were prepared from five species (two softwoods and three hardwoods) with various densities and shear compliances in cross section. We investigated the improvement of bending creep performances perpendicular to the grain by cross laminating, the effects of the density and the shear compliance in cross section of perpendicular-direction lamina on the bending creep performances of cross-laminated wood, and the relation between the measured and the calculated values of initial compliance and creep compliance.

Materials and methods

Specimens

Five species with various densities and shear compliances 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). Sugi used in this study had different growing districts from that in the previous report, but both had almost the same values of density and MOE. Longitudinal-direction laminae of 6.7 (T) × 20 (R) × 360 (L) mm with long axes parallel to the grain were made with sugi and buna. Elements of 7.5 (T) × 20 (R) × 180 (L) mm were cut from each five species, 18 elements from each species were side jointed and then cut to 20-mm size in width direction and perpendicular-direction laminae of 6.7 (T) × 360 (R) × 20 (L) mm were made with the long axes perpendicular to the grain. The annual ring angles of both laminae were 90°. A resorcinol–phenol resin adhesive formulated for a room temperature cure was used, and the amount of spread was 300 g/m^2. Figure 1 shows the three-ply parallel-laminated and cross-laminated wood specimens tested. The specimens used to measure the bending creep parallel and perpendicular to the grain of parallel-laminated woods were designated as $P_{\parallel}$ and $P_{\perp}$, respectively, while the specimens used to measure the bending creep parallel and perpendicular to the grain of the face laminae of cross-laminated woods were designated as $C_{\parallel}$ and $C_{\perp}$, respectively. Table 1 shows the arrangement and designations of laminae and combination of species for 30 types of laminated wood specimens. There were 3 of each type of specimen, for a total of 90 specimens.

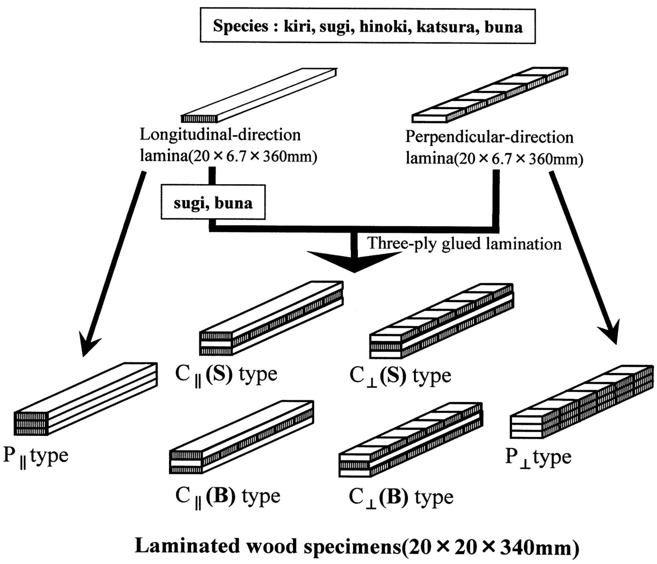

Fig. 1. Parallel-laminated and cross-laminated wood specimens. *S* and *B* of cross-laminated woods mean that sugi and buna, respectively, were used as longitudinal-direction laminae

Bending creep test

The bending creep test for parallel-laminated 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 the breaking stress obtained from a static bending test was applied to each specimen. The applied stresses are shown in Table 2. The creep test was conducted for 168 h (7 days) in a constant atmosphere maintained at 20°C and 65% relative humidity (RH). The deflection of the midspan was measured with a dial gauge. Total creep compliance $D_a(t)$ and creep compliance $D_{ca}(t)$ (total

Table 1. Arrangement of laminae and combination of species for 30 types of laminated wood specimens

Type	F : C	Type	F : C	Type	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)

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

Table 2. Applied stress for bending creep test of parallel-laminated and cross-laminated wood specimens

Type	Stress (MPa)				
	KI	SU	HI	KA	BU
$P_{\parallel}$	8.06 (9.4)	14.9 (4.1)	18.6 (3.4)	17.4 (12.9)	16.0 (25.0)
$P_{\perp}$	0.774 (2.3)	1.10 (4.6)	1.31 (11.8)	3.15 (5.6)	3.63 (21.5)
$C_{\perp}$(S)	2.15 (15.5)	2.31 (15.0)	2.55 (7.9)	3.55 (13.5)	3.62 (23.5)
$C_{\perp}$(B)	2.28 (20.8)	2.21 (24.0)	2.17 (20.8)	3.22 (21.5)	3.86 (23.7)
$C_{\parallel}$(S)	8.74 (5.7)	9.33 (10.7)	10.8 (6.6)	11.8 (5.8)	11.7 (2.9)
$C_{\parallel}$(B)	9.22 (10.3)	9.50 (9.3)	11.5 (10.3)	13.3 (17.0)	13.9 (16.5)

Each value is the average of three measurements; values in parentheses are coefficients of variation (%)

creep compliance except for initial compliance) were obtained using Eqs. 1 and 2 as follows:

$$D_a(t) = \frac{4bh^3 y_a(t)}{Pl_1\left(3l^2 - 4l_1^2\right)} \quad (1)$$

where P is the applied load; l is the span; b, h are the width and depth of the beam; l_1 is the distance between a loading point and a supporting point; and $y_a(t)$ is the apparent deflection at time t between both supporting points and contains the deflection caused by shear force. Therefore, $D_a(t)$ is the apparent total creep compliance obtained from the apparent deflection containing the deflection caused by shear force.

$$D_{ca}(t) = D_a(t) - D_a(0.008) \quad (2)$$

where $D_a(0.008)$ is the total creep compliance at $t = 0.008$ h (30 s) and is called initial compliance.

Results and discussion

Bending creep curves of laminated woods

Figure 2 shows the double logarithm plots of creep compliance and time for typical examples of each type of laminated wood specimen. There were differences in creep curve among $P_{\perp}$, $P_{\parallel}$, $C_{\perp}$, and $C_{\parallel}$ types. For $C_{\perp}$ types, SSU and BSU types with perpendicular-direction laminae of sugi in the faces had the highest creep compliance, whereas SKA and BKA types with perpendicular-direction laminae of katsura in the faces had the lowest creep compliance (see Table 1 for sample designations). For $C_{\parallel}$ types, SSU and BSU types with a perpendicular-direction lamina of sugi in the core had the highest creep compliance, whereas SKA and BKA with a perpendicular-direction lamina of katsura in the core had the lowest compliance. The creep compliance perpendicular to the grain was decreased by cross laminating. Every creep curve showed linear behavior beyond about 1 h. The creep curve $[D_{ca}(t)]$ was expressed by the following equation (power law):

$$D_{ca}(t) = At^N \quad (3)$$

where A and N are constants, and t is time.

It has been reported in many articles[3–5,8,10,13–18] that the creep curves of wood and wood-based materials fitted the power law.

In the logarithmic regression of Eq. 3, the correlation coefficients were in the range of 0.967–0.996. The fitted values of N and A are shown in Table 3. For every type, buna showed the highest value of N and katsura tended to have a lower value. There was little relation between the value of N and the density of species. On the other hand, the value of A varied markedly with the types of laminated wood and the density of species. The N values of sugi were found to be nearly equal to those of $P_{\parallel}$, $P_{\perp}(90)$, $C_{\parallel}(90)$, and $C_{\perp}(90)$ (90 means the annual ring angle is 90°) reported in the previous study.[11] The N values of $P_{\parallel}$(SU) and $P_{\parallel}$(KA) were nearly equal to those of solid sugi and kastura woods under constant humidity, respectively, whereas the value of $P_{\parallel}$(HI) was higher than that of solid hinoki wood.[4] The N value of every $P_{\parallel}$ type was considerably smaller than those of solid wood and glulam beams of sugi and Douglas-fir under variable humidity.[15–18] The values of $C_{\parallel}$ type were slightly higher than that of five-ply lauan plywood[3] under constant humidity and were nearly equal to that of commercial three-ply plywood[4] under constant humidity.

Initial deformation and creep deformation of laminated woods

The initial compliance (total creep compliance at 0.008 h) and creep compliance (total creep compliance except for initial compliance at 168 h) are shown in Table 3. For $P_{\parallel}$ type, kiri had the greatest initial compliance and buna had the greatest creep compliance, whereas hinoki showed the smallest initial compliance and creep compliance. For $P_{\perp}$ type, both initial compliance and creep compliance were the greatest in kiri with the lowest density, whereas they were the smallest in buna with the highest density. They decreased markedly with increasing density.

Like $P_{\perp}$ type, the initial compliance of $C_{\perp}$(S) type decreased with increasing density of perpendicular-direction laminae used for the face. Its creep compliance tended to decrease with increasing density of perpendicular-direction laminae of the faces, but $C_{\perp}$(SSU) type with faces composed

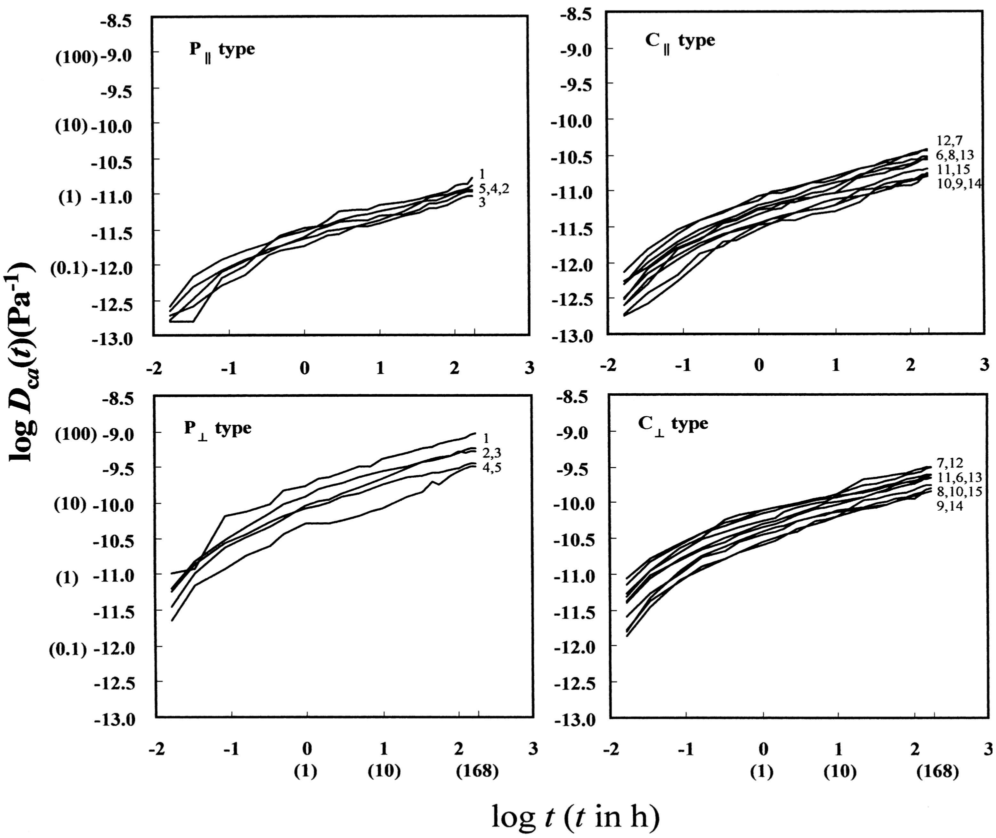

Fig. 2. Double logarithm plots of creep compliance and time for typical examples of each type of laminated wood type specimens. *1*, KI; *2*, SU; *3*, HI; *4*, KA; *5*, BU; *6*, SKI; *7*, SSU; *8*, SHI; *9*, SKA, *10*, SBU; *11*, BKI; *12*, BSU; *13*, BHI; *14*, BKA; *15*, BBU. *1–5*, $P_{\parallel}$ and $P_{\perp}$ types; *6–15*, $C_{\parallel}$ and $C_{\perp}$ types. Numbers in parentheses on *x* axis and *y* axis are values of time (h) and creep compliance (10^{-11} Pa^{-1}), respectively, before being transformed into logarithm. See Table 1 for explanation of abbreviations

of perpendicular-direction laminae of sugi had the highest value, and $C_{\perp}$(SKA) type with faces composed of perpendicular-direction laminae of katsura had the lowest value.

On the other hand, for $C_{\parallel}$(S) type, $C_{\parallel}$(SSU) type with a perpendicular-direction sugi core showed the highest values of both compliances, and $C_{\parallel}$(SKA) type with a perpendicular-direction katsura core showed the lowest values. It was found that both compliances tended to decrease with increasing density of perpendicular-direction lamina. However, kiri, which had a lower density than sugi, showed small creep compliance rather than sugi.

Next, the changes in initial compliance and creep compliance perpendicular and parallel to the grain of faces of laminated wood were examined by transforming from parallel-laminated type to cross-laminated type. The ratios of initial compliance or creep compliance for $C_{\perp}$ type to $P_{\perp}$ type and that for $C_{\parallel}$ type to $P_{\parallel}$ type are shown in Table 4.

By replacing the perpendicular-direction lamina of each species in the core with longitudinal-direction lamina of sugi, the initial compliance for $C_{\perp}$(S) type was decreased to 0.60–0.85 times that for the $P_{\perp}$ type and the creep compliance for $C_{\perp}$(S) type was decreased to 0.30–0.67 times that for the $P_{\perp}$ type. It was found that the extent of the decrease tended to decrease with increasing density of $P_{\perp}$ type in both compliances and the extent of the decrease in creep compliance was greater than that in initial compliance. A similar result was found in $C_{\perp}$(B) type.

In contrast, by replacing the longitudinal-direction lamina of sugi in the core with the perpendicular-direction lamina of each species, the initial compliance for $C_{\parallel}$(S) type was increased to 1.08–1.40 times that for the $P_{\parallel}$(SU) type and the creep compliance for $C_{\parallel}$(S) type was increased to 1.65–3.87 times that for the $P_{\parallel}$(SU) type. It was found that the extent of the increase tended to increase with decreasing density of perpendicular-direction lamina in the core in both compliances and the extent of the increase for creep compliance was greater than that for initial compliance. A similar result was found in $C_{\parallel}$(B) type.

The degrees of anisotropy of initial compliance or creep compliance perpendicular to the grain of face laminae versus that parallel to the grain of face laminae of laminated wood are shown in Figs. 3 and 4. For parallel-laminated wood shown in Fig. 3, the degrees of anisotropy for both initial compliance and creep compliance showed the highest value in hinoki, and the degree of anisotropy for creep compliance was considerably higher than that for initial compliance in every species. This corresponded to the result reported by Schniewind and Barratt[19] that relative creep of Douglas-fir was greater in the perpendicular direction than in the longitudinal direction. Hardwood such as buna and katsura with higher density had a much lower degree of anisotropy than the other tested species, and the differences in the degree of anisotropy between the initial compliance and the creep compliance of buna and katsura were smaller.

As shown in Fig. 4, the degrees of anisotropy for initial compliance and creep compliance of sugi were decreased to 0.46 and 0.14 times those of parallel-laminated wood, re-

Table 3. Results of creep tests for each type of laminated wood specimen

Type	Density (Mg/m^3)	N	A ($10^{-11}Pa^{-1}$)	$D_a(0.008)$ ($10^{-11}Pa^{-1}$)	$D_{ca}(168)$ ($10^{-11}Pa^{-1}$)
$P_{\parallel}$(KI)	0.264 (5.3)	0.253 (28.6)	0.361 (3.3)	19.44 (11.0)	1.52 (34.5)
$P_{\parallel}$(SU)	0.397 (3.3)	0.254 (23.8)	0.234 (14.3)	12.17 (5.6)	0.96 (20.4)
$P_{\parallel}$(HI)	0.480 (1.3)	0.230 (26.5)	0.156 (27.5)	8.79 (7.8)	0.58 (52.0)
$P_{\parallel}$(KA)	0.503 (3.5)	0.249 (5.8)	0.305 (9.4)	11.98 (3.0)	1.11 (13.2)
$P_{\parallel}$(BU)	0.578 (2.6)	0.292 (20.0)	0.360 (61.7)	12.46 (25.0)	1.76 (63.0)
$P_{\perp}$(KI)	0.275 (7.5)	0.319 (10.2)	20.1 (15.1)	194.60 (13.6)	104.10 (31.5)
$P_{\perp}$(SU)	0.419 (0.3)	0.347 (12.6)	9.85 (14.8)	137.60 (2.8)	61.60 (21.5)
$P_{\perp}$(HI)	0.500 (2.5)	0.339 (21.6)	10.2 (32.5)	119.40 (4.5)	53.93 (29.8)
$P_{\perp}$(KA)	0.509 (0.6)	0.301 (15.6)	7.49 (15.6)	76.43 (2.9)	34.52 (11.7)
$P_{\perp}$(BU)	0.617 (4.1)	0.361 (13.5)	4.83 (30.8)	64.83 (2.0)	31.99 (26.2)
$C_{\perp}$(SKI)	0.317 (2.8)	0.283 (5.0)	7.46 (28.7)	117.30 (9.2)	31.67 (31.2)
$C_{\perp}$(SSU)	0.480 (2.2)	0.318 (8.1)	6.47 (11.4)	89.02 (7.1)	32.92 (8.8)
$C_{\perp}$(SHI)	0.478 (1.0)	0.347 (8.9)	4.65 (11.1)	82.43 (7.6)	28.88 (20.9)
$C_{\perp}$(SKA)	0.552 (3.0)	0.295 (12.4)	3.93 (7.7)	59.81 (5.0)	18.15 (11.7)
$C_{\perp}$(SBU)	0.552 (1.5)	0.369 (11.0)	3.30 (20.4)	55.15 (4.7)	21.45 (17.5)
$C_{\perp}$(BKI)	0.381 (3.9)	0.291 (24.2)	8.03 (13.4)	119.90 (13.9)	41.48 (53.0)
$C_{\perp}$(BSU)	0.562 (5.2)	0.330 (22.1)	7.49 (16.5)	94.24 (10.8)	46.77 (37.7)
$C_{\perp}$(BHI)	0.552 (2.7)	0.346 (21.8)	5.18 (15.7)	83.06 (7.6)	34.59 (36.1)
$C_{\perp}$(BKA)	0.556 (2.8)	0.277 (14.7)	4.61 (15.1)	60.36 (3.6)	20.59 (28.8)
$C_{\perp}$(BBU)	0.607 (4.7)	0.376 (12.2)	3.02 (4.5)	56.45 (9.5)	23.38 (29.7)
$C_{\parallel}$(SKI)	0.369 (2.6)	0.330 (9.8)	0.512 (13.2)	16.56 (8.7)	2.90 (24.2)
$C_{\parallel}$(SSU)	0.422 (1.0)	0.309 (11.0)	0.726 (10.8)	17.08 (3.3)	3.73 (12.4)
$C_{\parallel}$(SHI)	0.448 (3.6)	0.325 (7.8)	0.477 (15.8)	15.04 (10.2)	2.78 (27.2)
$C_{\parallel}$(SKA)	0.434 (3.7)	0.311 (9.7)	0.326 (21.9)	13.21 (6.7)	1.59 (13.7)
$C_{\parallel}$(SBU)	0.478 (2.9)	0.372 (22.6)	0.247 (39.1)	13.39 (9.9)	1.67 (18.5)
$C_{\parallel}$(BKI)	0.505 (2.8)	0.318 (18.1)	0.672 (23.9)	17.49 (16.1)	3.95 (61.3)
$C_{\parallel}$(BSU)	0.420 (1.4)	0.357 (17.4)	0.846 (17.1)	19.37 (12.8)	5.63 (33.2)
$C_{\parallel}$(BHI)	0.567 (3.1)	0.339 (19.9)	0.658 (24.9)	16.60 (16.7)	4.24 (30.9)
$C_{\parallel}$(BKA)	0.560 (2.5)	0.298 (10.6)	0.488 (28.6)	13.51 (14.9)	2.38 (42.1)
$C_{\parallel}$(BBU)	0.620 (1.2)	0.377 (18.2)	0.437 (27.0)	14.60 (8.9)	3.50 (45.1)

Each value is the average of three measurements, values in parentheses are coefficients of variation (%)

N and A, constant values in the exponential regression equation between creep compliance and time [$D_{ca}(t) = At^N$]; $D_a(0.008)$, initial compliance (total creep compliance at 0.008 h); $D_{ca}(168)$, creep compliance (total creep compliance except for initial compliance at 168 h)

Table 4. Comparison of initial compliance and creep compliance between $C_{\perp}$ type and $P_{\perp}$ type and between $C_{\parallel}$ type and $P_{\parallel}$ type

Species	$C_{\perp}(S)/P_{\perp}$		$C_{\perp}(B)/P_{\perp}$		$C_{\parallel}(S)/P_{\parallel}(SU)$		$C_{\parallel}(B)/P_{\parallel}(BU)$	
	$D_a(0.008)$	$D_{ca}(168)$	$D_a(0.008)$	$D_{ca}(168)$	$D_a(0.008)$	$D_{ca}(168)$	$D_a(0.008)$	$D_{ca}(168)$
KI	0.60	0.30	0.62	0.38	1.36	3.00	1.40	2.13
SU	0.65	0.53	0.69	0.76	1.40	3.87	1.55	3.19
HI	0.69	0.54	0.70	0.64	1.24	2.88	1.33	2.41
KA	0.78	0.53	0.79	0.58	1.08	1.65	1.08	1.35
BU	0.85	0.67	0.87	0.73	1.10	1.73	1.17	1.99

Each value is the ratio of average value of three measurements

spectively, by cross laminating. Those of buna were decreased to 0.65 and 0.37 times those of parallel-laminated wood, respectively, by cross laminating. It was found that the extent of the decrease was much greater in creep compliance than in initial compliance and considerably smaller in buna with higher density than in sugi with lower density.

Relation between calculated and measured values of laminated woods

Equation 4, which can be used for calculating the total creep compliance of three-ply laminated beam composed of laminae with the same thickness from those of individual laminae, can be derived using the equivalent cross-section method.[20]

$$D(t) = \frac{\frac{3}{4}h^2}{\frac{1}{D_1(t)}\left(3\eta^2 - h\eta + \frac{h^2}{9}\right) + \frac{1}{D_2(t)}\left(3\eta^2 - 3h\eta + \frac{7}{9}h^2\right) + \frac{1}{D_3(t)}\left(3\eta^2 - 5h\eta + \frac{19}{9}h^2\right)} \quad (4)$$

$$\eta = \frac{h}{6} \times \frac{\left(\frac{1}{D_1(t)}\right)+\left(\frac{3}{D_2(t)}\right)+\left(\frac{5}{D_3(t)}\right)}{\left(\frac{1}{D_1(t)}\right)+\left(\frac{1}{D_2(t)}\right)+\left(\frac{1}{D_3(t)}\right)} \tag{5}$$

where $D_1(t)$, $D_2(t)$, and $D_3(t)$ are the total creep compliances of the face, core, and back lamina, respectively; h is the depth of laminated wood, the depth of individual lamina is $h/3$, and η is the distance from the base line passing through the upper edge of beam to the neutral axis.

This total creep compliance corresponds to the true deflection caused by bending moment. The measured deflection in this creep test contained the deflection caused by shear force. However, from the result of the previous report,[11] the percentages of deflection caused by shear force versus total deflection at 0.008 h and 226 h of laminated wood made with sugi were 4.5% and 6.0% for $P_{\parallel}$ type, and 10.1% and 11.3% for $P_{\perp}(90)$ type, respectively, so that the effect of deflection caused by shear force is considered to be small for these types. Hence, using Eq. 4, we calculated the values of $D_a(0.008)$ and $D_a(168)$ for cross-laminated woods from their measured values [$D_a(0.008)$ and $D_a(168) = D_a(0.008) + D_{ca}(168)$ shown in Table 3] for $P_{\parallel}$(SU) type or $P_{\parallel}$(BU) type and each $P_{\perp}$ type of five species, and then obtained the calculated values of $D_{ca}(168)[D_a(168) - D_a(0.008)]$. The measured values of $D_a(0.008)$ and $D_a(168)$ for the parallel-laminated woods that were used as the values for laminae contained the contribution of glue line to their values. In the previous report,[12] the contribution of glue line to the MOE for parallel-laminated woods was found to increase from 2.5% to 19.9% with decreasing MOE. Therefore, it was considered that the $D_a(t)$ of laminated woods was decreased by the contribution of glue line and the extent of the decrease increased with increasing $D_a(t)$.

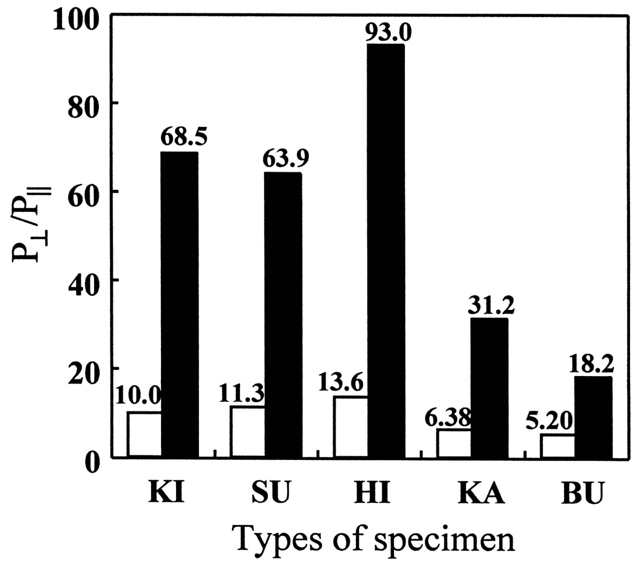

Fig. 3. Anisotropy of initial compliance and creep compliance for parallel-laminated wood specimens. $P_{\perp}/P_{\parallel}$ is the ratio of initial compliance or creep compliance of $P_{\perp}$ type to $P_{\parallel}$ type. *Open rectangular bars*, initial compliance [$D_a(0.008)$]; *filled rectangular bars*, creep compliance at 168 h [$D_{ca}(168)$]

Figure 5 shows the effects of density of the perpendicular-direction lamina on the measured and calculated values for $C_{\perp}$ and $C_{\parallel}$ types, and the relation between their measured and calculated values. For $C_{\perp}$ type, both measured and calculated values of initial compliance and creep compliance decreased with increasing density of perpendicular-direction laminae used for the face. The coefficient of correlation between the measured initial compliance and its density was much higher than that between the measured creep compliance and its density. However, the measured value was in good agreement with the calculated value in not only initial compliance but also in creep compliance. On the other hand, for $C_{\parallel}$ type, the measured values of both compliances tended to decrease with increasing density of perpendicular-direction lamina used for the core, but the coefficients of correlation for $C_{\parallel}$ type had lower values than those for $C_{\perp}$ type. Their calculated values hardly depended on its density and the differences between the calculated and the measured values decreased with an increase in its density.

Figure 6 shows the effects of shear compliance in cross section of perpendicular-direction lamina used for the core on the measured and calculated values of $D_a(0.008)$ and $D_{ca}(168)$ for $C_{\parallel}$ type and the relation between the measured and the calculated values. The values of shear compliances

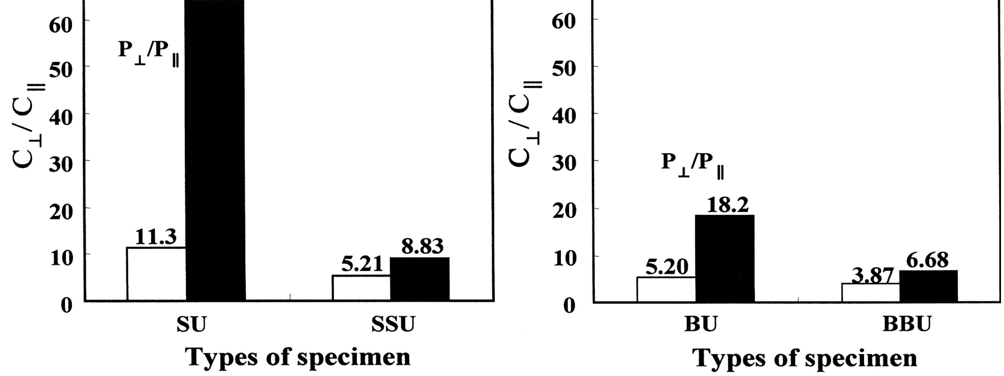

Fig. 4. Anisotropy of initial compliance and creep compliance for parallel-laminated and cross-laminated woods made with sugi or buna. The values for $P_{\perp}/P_{\parallel}$ are the same as shown in Fig. 3. $C_{\perp}/C_{\parallel}$ is the ratio of initial compliance or creep compliance for $C_{\perp}$ type to $C_{\parallel}$ type. *Open rectangular bars*, initial compliance [$D_a(0.008)$]; *filled rectangular bars*, creep compliance at 168 h [$D_{ca}(168)$]

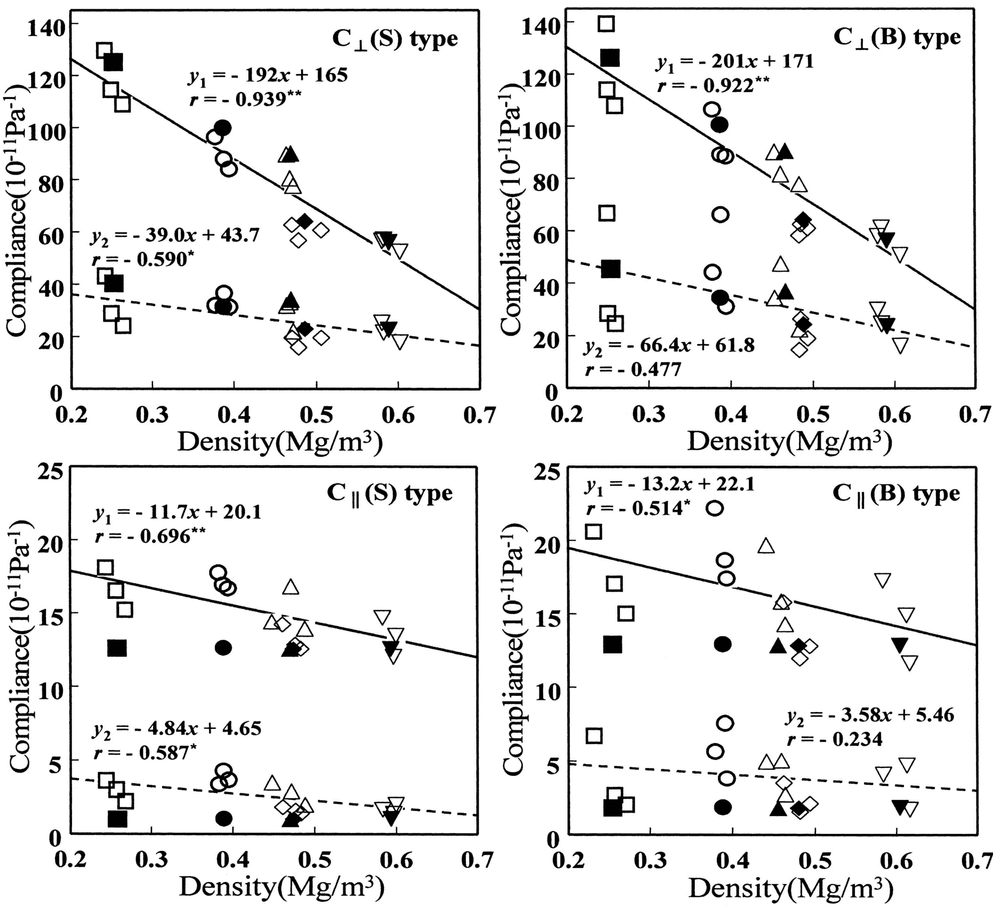

Fig. 5. Effects of density of perpendicular-direction lamina on measured and calculated values of initial compliance and creep compliance at 168h for $C_\perp$ and $C_\parallel$ types, and relation between their measured and calculated values. Calculated values were obtained from the average measured values of initial compliance and creep compliance at 168h for $P_\parallel$ and $P_\perp$ types, using Eq. 4. Measured value of each specimen was plotted. y_1, initial compliance; y_2, creep compliance at 168h; *open squares*, *open circles*, *open triangles*, *open diamonds*, and *open inverted triangles*: measured values of initial compliance and creep compliance at 168h for kiri, sugi, hinoki, katsura, and buna, respectively; *filled squares*, *filled circles*, *filled triangles*, *filled diamonds*, and *filled inverted triangles*: calculated values of initial compliance and creep compliance at 168h for kiri, sugi, hinoki, katsura, and buna, respectively. *Double asterisk*, significant at 1% level; *asterisk*, significant at 5% level

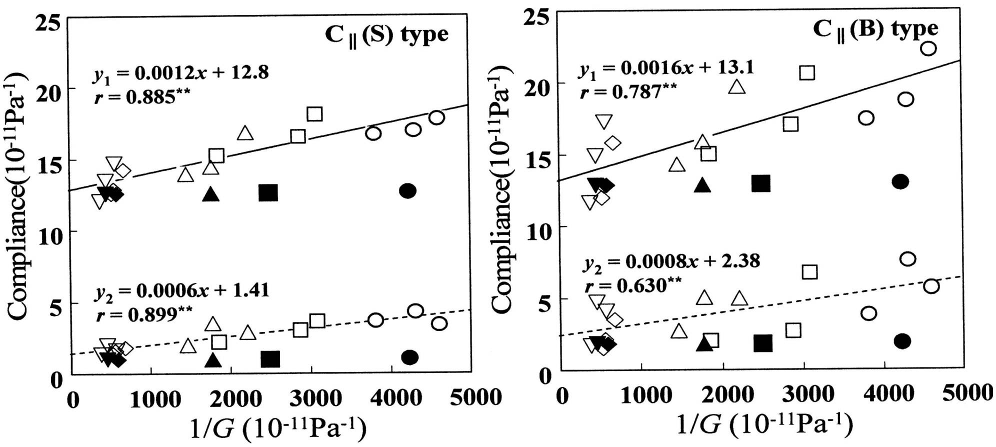

Fig. 6. Effects of shear compliance in cross section of perpendicular-direction lamina used for the core on measured and calculated values of initial compliance and creep compliance at 168h for $C_\parallel$ type, and relation between their measured and calculated values. Legends are the same as in Fig. 5

in cross section of five species were the reciprocal of shear modulus in cross section obtained from the relation between the square of depth/span ratio and the compliance ($1/E_a$) reported previously.[12] The shear compliance in cross section of $P_\perp$ type specimen having a value of MOE closest to that of the perpendicular-direction lamina of each $C_\parallel$ type specimen was used as the value for its lamina. The average values were 2490×10^{-11} Pa^{-1} for kiri, 4240×10^{-11} Pa^{-1} for sugi, 1770×10^{-11} Pa^{-1} for hinoki, 588×10^{-11} Pa^{-1} for katsura, and 465×10^{-11} Pa^{-1} for buna, showing considerable variation with species. As shown in Fig. 6, the measured values of $D_a(0.008)$ and $D_{ca}(168)$ for $C_\parallel$(S) and $C_\parallel$(B) increased with increasing shear compliance in cross section and were found to be much more closely correlated with the shear compliance in cross section than with the density. However, their calculated value hardly depended on the shear compliance in cross section. Table 5 shows the ratios of the average of measured values to the calculated value for initial compliance and creep compliance of $C_\parallel$ type. The ratios ranged from 1.05 (katsura) to 1.50 (sugi) in initial compliance and from 1.30 (katsura) to 3.69 (sugi) in creep compliance. The ratio increased markedly with increasing shear compliance

Table 5. Ratios of measured values to the calculated values of initial compliance and creep compliance for $C_{\parallel}$ types

Type	$D_a(0.008)$ (10^{-11}Pa^{-1})	$D_{ca}(168)$ (10^{-11}Pa^{-1})	$D'_a(0.008)$ (10^{-11}Pa^{-1})	$D'_{ca}(168)$ (10^{-11}Pa^{-1})	Ratio of $D_a(0.008)$ to $D'_a(0.008)$	Ratio of $D_{ca}(168)$ to $D'_{ca}(168)$
$C_{\parallel}$(SKI)	16.56	2.90	12.61	1.01	1.31	2.87
$C_{\parallel}$(SSU)	17.08	3.73	12.60	1.01	1.36	3.69
$C_{\parallel}$(SHI)	15.04	2.78	12.59	1.01	1.19	2.74
$C_{\parallel}$(SKA)	13.21	1.59	12.57	1.02	1.05	1.56
$C_{\parallel}$(SBU)	13.39	1.67	12.55	1.02	1.07	1.63
$C_{\parallel}$(BKI)	17.49	3.76	12.91	1.83	1.35	2.05
$C_{\parallel}$(BSU)	19.37	5.63	12.90	1.83	1.50	3.07
$C_{\parallel}$(BHI)	16.60	4.24	12.89	1.84	1.29	2.31
$C_{\parallel}$(BKA)	13.51	2.38	12.86	1.84	1.05	1.30
$C_{\parallel}$(BBU)	14.60	3.50	12.85	1.84	1.14	1.90

$D'_a(0.008)$, initial compliance calculated from measured initial compliance of parallel-laminated woods; $D'_{ca}(168)$, creep compliance at 168h calculated from measured total creep compliance of parallel-laminated woods

in cross section and was much higher in creep compliance than in initial compliance. This can be explained in terms of the deflection caused by shear force as described in the previous report.[11]

The apparent deflection $y_a(t)$ of beam for four-point bending can be expressed by the following equation:

$$y_a(t) = y_m(t) + y_s(t) = \frac{Pl_1(3l^2 - 4l_1^2)}{4bh^3} \cdot D(t) + \frac{kPl_1}{2bh} \cdot J(t) = \frac{Pl_1(3l^2 - 4l_1^2)}{4bh^3} \cdot D(t)\left[1 + \frac{2.4h^2}{3l^2 - 4l_1^2} \cdot \frac{J(t)}{D(t)}\right] \quad (6)$$

where $y_m(t)$ is the deflection caused by bending moment, $y_s(t)$ is the deflection caused by shear force, $D(t)$ is the creep compliance in the case of strain caused by normal stress, $J(t)$ is the creep compliance in the case of strain caused by shear force, P is the load, b and h are the width and depth of the beam (20mm, respectively), l is the span (300mm), l_1 is the distance between a loading point and a supporting point (l/3), and k is 6/5 in the case of a rectangular cross section.[21]

The shear total creep compliance in cross section of perpendicular-direction lamina was high and the shear total creep compliance of beam [$J(t)$] for $C_{\parallel}$ type increased with increasing shear total creep compliance in cross section of perpendicular-direction lamina used for the core subjected to a higher shear stress, whereas its total creep compliance [$D(t)$] was low and hardly varied with species used for the core. Therefore, $J(t)/D(t)$ on the right side of Eq. 6 becomes higher and the effect of deflection caused by shear force is considered to increase with an increase in shear total creep compliance in cross section of perpendicular-direction used for the core.

From Eq. 6, the true total creep compliance of $D(t)$ was expressed by the following equation:

$$D(t) = D_a(t)\left[1 + \frac{2.4h^2}{3l^2 - 4l_1^2} \cdot \frac{J(t)}{D(t)}\right]^{-1} = D_a(t)\left[1 + 0.00417\frac{J(t)}{D(t)}\right]^{-1} \quad (7)$$

where $D_a(t)$ is the apparent total creep compliance.

The percentage of deflection caused by shear force versus total deflection in total creep compliance (Y_{TS}) and creep compliance (Y_{CS}) can be calculated by Eqs. 8 and 9:

$$y_{TS} = \frac{y_a(t) - y(t)}{y_a(t)} \times 100 = \frac{D_a(t) - D(t)}{D_a(t)} \times 100\,(\%) \quad (8)$$

$$y_{CS} = \frac{D_{ca}(t) - D_c(t)}{D_{ca}(t)} \times 100\,(\%) \quad (9)$$

where $D_{ca}(t)$ is the apparent total creep compliance and $D_c(t)$ is the true creep compliance.

Using the data of our previous report[11] on bending creep of sugi laminated wood, the percentages of deflection caused by shear force versus total deflection of $C_{\parallel}$ type in initial compliance, total creep compliance at 226h, and creep compliance at 226h were calculated by Eqs. 8 and 9 and discussed. The calculation method is explained as follows.

First, using the data of the previous report,[11] the values of $J(t)$ and $D(t)$ of parallel-laminated woods were calculated. Like modulus of elasticity, the total creep compliance in the direction of an angle θ from the tangential direction toward the radial direction [$D_\theta(t)$] can be expressed by following equation:

$$D_\theta(t) = D_T(t)\cos^4\theta + D_R(t)\sin^4\theta + \left(J_{RT}(t) - 2\nu_{TR}(t) \cdot D_T(t)\right)\sin^2\theta\cos^2\theta \quad (10)$$

where $D_T(t)$ and $D_R(t)$ are the true total creep compliances in tangential direction and radial direction, respectively, $J_{RT}(t)$ is the shear total creep compliance in cross section, and $\nu_{TR}(t)$ is the Poisson's ratio.

The shear total creep compliance in the direction of an angle from the tangential direction toward the radial direction can be expressed by the following equation:

$$J_\theta(t) = \left(D_T(t) + D_R(t) + 2\nu_{TR}(t) \cdot D_T(t)\right)\sin^2 2\theta + J_{RT}(t)\cos^2 2\theta \quad (11)$$

Substituting the measured values of $D_{a45}(226)$, $D_{aT}(226)$ and $D_{aR}(226)$ shown in Table 6, $\nu_{TR}(226)$ = 0.46 (the value

Table 6. Data of bending creep of sugi laminated woods reported in previous article[11]

Type	$D_a(0.008)$ ($10^{-11}Pa^{-1}$)	$D_a(226)$ ($10^{-11}Pa^{-1}$)	$D_{ca}(226)$ ($10^{-11}Pa^{-1}$)	$D(0.008)$ ($10^{-11}Pa^{-1}$)	$D(226)$ ($10^{-11}Pa^{-1}$)	$D_c(226)$ ($10^{-11}Pa^{-1}$)	$J(0.008)$ ($10^{-11}Pa^{-1}$)	$J(226)$ ($10^{-11}Pa^{-1}$)	$J_c(226)$ ($10^{-11}Pa^{-1}$)
$P_{\parallel}$	12.84	13.74	0.90	12.26	12.92	0.66	153.1	223.6	70.50
$P_{\perp}(0)$	254.6	422.0	167.4	239.2	396.7	157.5	3691	6049	2358
$P_{\perp}(45)$	964.5	1577	612.1	962.0	1573	611.0	597.3	1034	436.7
$P_{\perp}(90)$	153.1	223.6	70.50	137.7	198.3	60.60	3691	6049	2358
$C_{\parallel}(90)$	20.03	24.95	4.92	12.69	13.39	0.70			

$D_a(t)$ and $D(t)$ of $P_{\perp}(0)$ correspond to $D_{aT}(t)$ and $D_T(t)$, respectively. $D_a(t)$ and $D(t)$ of $P_{\perp}(90)$ correspond to $D_{aR}(t)$ and $D_R(t)$, respectively. $J(t)$ of $P_{\perp}(0)$ corresponds to $J_{RT}(t)$, and $J(t)$ of $P_{\perp}(90)$ corresponds to $J_{RT}(t)$

D_a (0.008), measured initial compliance at 0.008 h; $D_a(226)$, measured total compliance at 226 h; D_{ca} (226), measured creep compliance at 226 h; $D(0.008)$, true initial compliance at 0.008 h; $D(226)$, true total compliance at 226 h; $D_c(226)$, true creep compliance at 226 h; $J(0.008)$, shear initial compliance at 0.008 h; $J(226)$, shear total creep compliance at 226 h; $J_c(226)$, shear creep compliance at 226 h; 0, 45, and 90 are annual ring angles of perpendicular-direction laminae

calculated from that reported in literature[22]) and $\theta = 45°$ into Eq. 10, $J_{RT}(226)$ was obtained. Furthermore, substitution of the measured values of $D_{aT}(226)$, $D_{aR}(226)$, $\nu_{TR}(226) = 0.46$ and $J_{RT}(226)$ and $\theta = 45°$ into Eq. 11 yielded $J_{45}(226)$.

Next, substituting the values of $J_{RT}(226)/D_{aT}(226)$, $J_{RT}(226)/D_{aR}(226)$, and $J_{45}(226)/D_{a45}(226)$ into $J(t)/D(t)$ of Eq. 7, respectively, the corrected values of $D_T(226)$, $D_R(226)$, and $D_{45}(226)$ were obtained. Because the value of $0.00417\,J(t)/D(t)$ was small and $D_a(t)$ showed the value close to $D(t)$, $D_a(t)$ was used instead of $D(t)$. Using the stepwise corrected values of $D_T(226)$, $D_{45}(226)$, and $D_R(226)$, the above calculation were repeated three times and then $D_T(226)$, $D_{45}(226)$, $D_R(226)$, $J_{RT}(226)$, and $J_{45}(226)$ were obtained.

For the true total creep compliance in longitudinal direction of parallel-laminated wood, assuming that as for $G_{LR} \fallingdotseq E_R$, $J_{LR}(226) \fallingdotseq D_{aR}(226)$ held, $D_{aR}(226)$ was used instead of $J_{LR}(226)$, and $D_L(226)$ was obtained by Eq. 7 in a manner similar to the direction perpendicular to the grain. The value of each initial compliance at 0.008 h also was obtained by the same method. The obtained values are shown in Table 6.

From the obtained values of $D_L(0.008)$ and $D_R(0.008)$, $D(0.008)$ of $C_{\parallel}$ type was calculated by Eq. 4 and $D(226)$ of $C_{\parallel}$ type was calculated by the same method. $D_c(226)$ of $C_{\parallel}$ type was obtained from $D(226)$ and $D(0.008)$ of $C_{\parallel}$ type. These obtained values of $C_{\parallel}$ type are shown in Table 6.

From $D_a(0.008)$ and $D(0.008)$ of $C_{\parallel}$ type, Y_{IS} was calculated by Eq. 8. From $D_a(226)$ and $D(226)$, Y_{TS} at 226 h was calculated by Eq. 8. From $D_{ca}(226)$ and $D_c(226)$, Y_{CS} was calculated by Eq. 9.

On the other hand, the calculated values of $C_{\parallel}$ type, which were obtained from the measured values of $P_{\parallel}$ and $P_{\perp}$ type by Eq. 4, were substituted into Eqs. 8 and 9. The effects of deflection caused by shear force on their calculated values were examined.

The percentages of deflection cause by shear force versus total deflection of $C_{\parallel}$ type made with sugi were 4.5% for the calculated initial compliance and 36.6% for the measured initial compliance, 6.0% for the calculated total creep compliance and 46.3% for the measured total creep compliance at 226 h, and 25.5% for the calculated creep compliance and 85.8% for the measured creep compliance at 226 h. The percentage for each calculated value was equal to each of the measured values of $P_{\parallel}$ type. Because the effect of deflection caused by shear force was much greater in the measured values than in the calculated values estimated using Eq. 4, the measured values were much higher than the calculated values. The measured value of creep compliance was considered to be much more affected by deflection caused by shear force than that of initial compliance. The creep of wood is said to be due to the breaking and remaking of hydrogen bonds under stress. The reason why the effect of deflection caused by shear force on creep deformation is much greater than that on initial deformation is considered to be that hydrogen bonds play much more important roles in shear deformation than in deformation in longitudinal direction by bending moment.

For the bending modulus of elasticity (corresponds to the reciprocal of initial compliance) of $C_{\parallel}$ types of cross-laminated woods made with five species, the percentage of deflection caused by shear force versus total deflection ranged from 16.1% (buna) to 40.5% (sugi) (G_{RT} was obtained from the relation between the square of depth/span ratio and $1/E_a$), and it decreased linearly with increasing shear modulus in the cross section of perpendicular-direction lamina used for the core.[12] The marked variation in the ratios of measured/calculated value of initial compliance and creep compliance is also considered to result from the effect of deflection caused by shear force.

References

1. Okuma M, Tashiro H (1968) Effect of adhesive on creep of plywood (in Japanese). Wood Ind Jpn 23:168–170
2. Nakai T (1978) Bending creep test on wood-based boards I (in Japanese). Wood Ind Jpn 33:158–160
3. Nakai T (1978) Bending creep test on wood-based boards II (in Japanese). Wood Ind Jpn 33:247–249
4. Arima T, Sato M, Mashita K (1981) Studies on evaluation method for long-term performance of wood-based materials and elements (in Japanese). Report of the Building Research Institute No. 95:25–80
5. Moriizumi S (1981) Creep properties of wood-based boards under plate shear test (in Japanese). J Hokkaido Forest Prod Res Inst 359:6–14
6. Bryan EL, Schniewind AP (1965) Strength and rheological properties of particleboard. Forest Prod J 15:143–148
7. Halligan AF, Schniewind AP (1972) Effect of moisture on physical and creep properties of particleboard. Forest Prod J 22:41–48

8. Saito F, Ikeda M, Ogawa K (1980) Time-related flexural behavior of particleboards under long term load (in Japanese). Mokuzai Gakkaishi 26:714–718
9. Moslemi AA (1964) Some aspects of viscoelastic behavior of hardboard. Forest Prod J 14:337–342
10. Kitahara K, Perng WT (1965) On the creep of hardboard (in Japanese). Mokuzai Gakkaishi 11:88–92
11. Park HM, Fushitani M, Sato K, Kubo T, Byeon HS (2002) Bending creep performances of cross-laminated sugi wood (in Japanese). Mokuzai Gakkaishi 48:166–177
12. Park HM, Fushitani M, Sato K, Kubo T, Byeon HS (2003) Static bending strength performances of cross-laminated woods made with five species. J Wood Sci 49:411–417
13. Kitahara K, Okabe N (1959) The influence of temperature on creep of wood by bending test (in Japanese). Mokuzai Gakkaishi 5:12–18
14. Schniewind AP (1968) Recent progress in the study of the rheology of wood. Wood Sci Technol 2:188–206
15. Hoyle RJ, Itani RY, Anderson JT (1994) The effect of moisture cycling on creep of small glued laminated beams. Wood Fiber Sci 26:556–562
16. Aratake S, Arima T (1995) Creep of sugi sawn lumber in process of humidity changes (in Japanese). Mokuzai Gakkaishi 41:359–366
17. Aratake S, Morita H, Arima T (2002) Creep of various structural members in ambient conditions I. Estimation of future deflections considering the longevity of wooden structures (in Japanese). Mokuzai Gakkaishi 48:233–240
18. Aratake S, Arima T (1996) Creep of sugi full size members II. Behaviors under various loading conditions of loads and estimations by deformation models (in Japanese). Mokuzai Gakkaishi 42:755–761
19. Schniewind AP, Barrett JD (1972) Wood as a linear orthotropic material. Wood Sci Technol 6:43–57
20. Fushitani M, Bono Y (1975) Bending creep of laminated woods (in Japanese). Wood Ind Jpn 30:22–24
21. Sakai J (1970) Strength of structures (in Japanese). Gihodo, Tokyo, p 77
22. Park HM, Fushitani M, Ohtsuka T, Nakajima T, Sato K, Byeon HS (2001) Effect of annual ring angle on static bending strength performances of cross-laminated woods made with sugi wood (in Japanese). Mokuzai Gakkaishi 47:22–32