EFFECT OF SHEAR DEFLECTION ON BENDING PROPERTIES OF COMPRESSED WOOD

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ABSTRACT

We investigated the bending properties of compressed Japanese cedar (*Cryptomeria japonica* D. Don). The specimens were compressed in the radial direction under 180°C for 5 h. Compression ratios (the ratio of deformation to the initial thickness) were 33% and 67%. Young's modulus was measured by flexural vibration test and static bending test. As a result, the Young's modulus obtained by loading in the radial (R) and tangential (T) directions approached the value without shear influence as the length-to-depth ratio and the span-to-depth ratio increased. In the same compression ratio, the Young's modulus was closer to the value without shear influence in loading in the T-direction than in the R-direction. This is because the Young's modulus to shear modulus ratio of the tangential section was smaller than that of the radial section. In the static bending test, the Young's modulus at the span-to-depth ratio of 14 used in major standards was not appropriate.

Keywords: Compressed wood, shear deflection, bending properties, Young's modulus-to-shear ratio, span-to-depth ratio.

INTRODUCTION

The surface, mechanical, and processing properties of wood are improved by compressing. Hence, there are various uses for compressed wood.

As for the mechanical properties, since Young's modulus and strength in bending are improved by compressing, compressed wood is used in applications that need high strength qualities such as flooring boards, handrails, and frames of furniture. Studies have focused mainly on the manufacturing and dimensional stability of the compressed wood; nevertheless, there has not been extensive research on the mechanical properties (Asaba and Nishimura 2001; Hayashi and Nishimura 2001; Iida et al. 1986; Inoue and Norimoto 1991; Inoue et al. 1990, 1991a,b, 1993a,b).

The static bending test is one of the most important mechanical testing methods because wood materials are frequently subject to bending stress in everyday uses, and the static bending test is easy to conduct. In the static bending test, there is the value of span-to-depth ratio (*l/h*) used in the major standards, that is to say, *l/h* in the three-point bending test should be at least 14

(ASTM 2000; JIS 1994). This value is based on the contribution of the shear deflection to the total measured deflection in the static bending test, which corresponds to the Young's modulus to shear modulus ratio of each specimen (Baumann 1922; Timoshenko 1955).

Properties of compressed wood differ from those of untreated wood. Since it appears that the influence of shear deflection is also changed markedly by compressing, we think that the bending properties cannot be evaluated properly under the major standards.

In this study, bending tests were conducted using specimens with various *l/h* and compression ratios. Then, the Young's modulus thus derived was compared to Young's modulus without the effect of shear deflection.

EXPERIMENT

Specimen

Japanese cedar (*Cryptomeria japonica* D. Don) conditioned at 20°C, 65% relative humidity was used as the experimental material. The specimens were divided into 4 groups by loading directions in the vibration and static bending tests (radial (R) and tangential (T) directions) and compression ratio (the ratio of deformation in the R-direction to the initial dimension in the R-direction, 33% and 67%). The dimensions of the cross sections were 15 mm (R) × 30 mm (T) (Loading direction: R-direction, Compression ratio 33%), 30 mm (R) × 30 mm (T) (R-direction, 67%), 22.5 mm (R) × 25 mm (T) (T-direction, 33%), and 45 mm (R) × 25 mm (T) (T-direction, 67%). The specimens were compressed in the R-direction at a temperature of 180°C for 5 h using heated roller press. After compression, the specimens were processed to 15 mm (T) × 10 mm (R) × 130, 170, 230, 330, and 430 mm in longitudinal (L) for the specimens loaded in the R-direction and 15 mm (R) × 10 mm (T) × 130, 170, 230, 330, and 430 mm (L) for the specimens loaded in the T-direction. These specimens were applied to the free-free flexural vibration and static bending tests to obtain the properties of compressed wood. Five specimens were used for each group. The specimens with 25 mm (T) × 10 mm (R) × 300 mm (L) and 25 mm (R) × 10 mm (T) × 300 mm (L) were also made and used for controls without compression.

Vibration test

To obtain Young's modulus and shear modulus, a free-free flexural vibration test as undertaken by the following procedure. Figure 1 shows the apparatus of the vibration test. Each specimen was suspended by threads at the nodal positions of a free-free vibration corresponding to each resonance mode. Lateral vibration was excited by impacting one end of each specimen in the R- and T-directions with a small hammer. The motion of the specimen was detected by a microphone at the other end. The signal was processed by a fast Fourier transform (FFT) signal analyzer to yield resonance frequencies.

From the first resonance mode, Young's modulus of Euler-Bernoulli's elementary theory (E_{EB}) was obtained as follows:

$$E_{EB} = \frac{48\pi^2 \rho L^4}{m_1^4 h^2} f_1^2$$

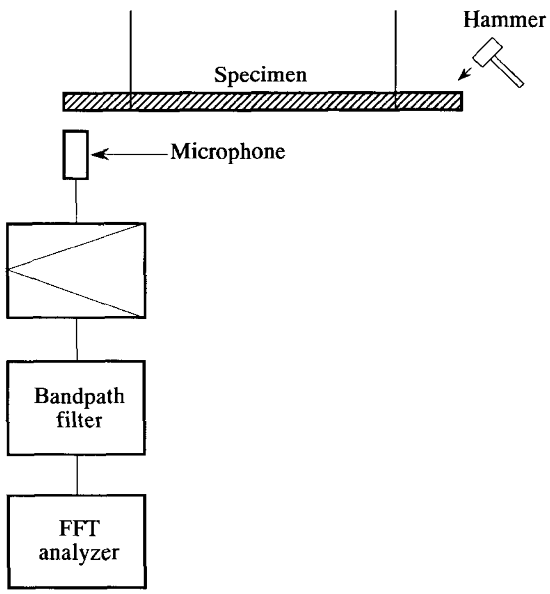

FIG. 1. Apparatus for vibration test.

where ρ, L, f_1 and m_1 are density, length, resonance frequency of the first mode and constant (= 4.73), respectively. This Young's modulus contains the contribution of shear deflection and rotary inertia in flexural deflection.

Next, Young's modulus(E_{TGH}) and shear modulus were calculated by Goens-Hearmon regression (Goens 1931; Hearmon 1958) based on Timoshenko's bending theory (Timoshenko 1921). By this regression, the Young's and shear moduli are separated from each other using several resonance modes, and the contribution of shear deflection and rotary inertia are eliminated from the Young's modulus. The resonance modes used for the calculation were 1st–10th ones. By vibrating a specimen in the R- and T-directions, the shear moduli of the LR-plane (G_{LR}) and LT-plane (G_{LT}) were obtained, respectively. The calculation procedure is described in Kubojima et al. 1996.

Static bending test

The static bending test was performed using centerpoint loading over 100-, 140-, 200-, 300-, and 400-mm spans with the load applied in the R- and T-directions. The crosshead speed was 5 mm/min. Load (P) and loading period were simultaneously recorded by a measuring system (Instron Corporation, Universal Material Test System Model 5569) at intervals of 0.1 s. Loading point displacement (y) was calculated by multiplying the crosshead speed with the loading period. From the load-deflection diagram, the static bending Young's modulus (E_{sb}) was obtained by

$$E_{sb} = \frac{l^3}{4bh^3}a$$

where l, b, h and a are span, width, and depth of the specimen and slope of linear part of the P-y relation, respectively (JIS 1994). This Young's modulus is an apparent value that contains the contribution of shear deflection like E_{EB}.

RESULTS AND DISCUSSION

Vibrational properties

Table 1 shows the vibrational properties of the compressed wood and controls. Young's and shear moduli were increased by compressing in almost all of the cases. The increase in Young's modulus in vibrating in the R-direction was similar to that in the T-direction, whereas G_{LT} increased much more than G_{LR}.

In the compressing process, the surface part of a specimen is compressed first. Hence, the density around the surface is increased but that around the neutral axis does not change markedly. Young's and shear moduli tend to increase with this increase in density. In bending on the cross section of the specimen, the axial stress is maximum on the surface of the specimen and 0 on the neutral axis, while shear stress is maximum on the neutral axis and 0 on the surface. Therefore, the surface and center parts bear the axial stress and shear stress, respectively, in the case of vibrating in the R-direction. This explains why Young's modulus was increased while shear modulus did not change noticeably and why the Young's modulus to shear modulus ratio (*E/G*) increased.

TABLE 1. *Vibrational properties of compressed wood and control.*

Loading direction	Compression ratio	Density [g/cm³]	E_{TGH} [GPa]	G [GPa]	sE_{TGH}/G
R	Control	0.38 (0.01)	10.8 (0.9)	0.66 (0.06)	19.5 (3.2)
R	33%	0.52 (0.04)	12.1 (2.8)	0.60 (0.10)	24.5 (7.3)
R	67%	0.97 (0.10)	21.4 (5.6)	0.91 (0.24)	30.0 (11.8)
T	Control	0.36 (0.01)	10.4 (0.2)	0.60 (0.03)	20.5 (0.8)
T	33%	0.54 (0.08)	14.8 (2.8)	1.38 (0.26)	12.9 (2.5)
T	67%	0.94 (0.09)	22.7 (4.5)	2.58 (0.52)	10.7 (2.4)

Note: E_{TGH} is Young's modulus with the contributions of shear deflection and rotary inertia eliminated and G is shear modulus of the LR- and LT-planes when loading in the R- and T-directions, respectively. s is the shear deflection constant, which is 1.18 in vibration of wood (Nakao et al. 1984). Values are of 5 specimens averages and standard deviations are shown in parentheses.

In contrast, when vibrating in the T-direction, density can be regarded as uniform in the vibrating direction, and the high density part bears both the axial and shear stresses. Thus, Young's and shear moduli were increased, and then, *E/G* was not increased.

The length-to-depth ratio (*L/h*) and *E/G* relate to the contribution of shear deflection to the total measured flexural deflection: Young's modulus by Euler-Bernoulli's elementary theory (E_{EB}) cannot be obtained appropriately in the flexural vibration test when *L/h* is small and *E/G* is large because the contribution of shear deflection to the flexural deflection is large (Kubojima et al. 1996, 1997; Matsumoto 1956; Mead and Joannides 1991).

As shown in Fig. 2, E_{EB} obtained by the first resonance mode approached the Young's modulus without shear deflection and rotary inertia by the Goens-Hearmon regression (E_{TGH}) as *L/h* increased in vibrating in both the R- and T-directions. In the same compression ratio, E_{EB}/E_{TGH} was larger in vibrating in the T-direction than in the R-direction. This was because the Young's modulus to shear modulus ratio of the LT-plane (E/G_{LT}) was smaller than that of the LR-plane (E/G_{LR}). Vibrating in the R-direction, E_{EB}/E_{TGH} was larger for the 33% compression ratio than for the 67% ratio. This is because *E/G* at 33% compression was smaller.

Static bending properties

We think that the findings obtained by the flexural vibration test mentioned above are applicable to the static bending test. The contribution of shear deflection to bending deflection in static bending using center point loading that affects the Young's modulus is estimated as follows (Baumann 1922):

$$\frac{y_s}{y_b} = \frac{sE}{G}\left(\frac{h}{l}\right)^2$$

where y_s and y_b are shear deflection and bending deflection, respectively. This equation is not perfect (Yoshihara et al. 1998; Yoshihara and Matsumoto 1999) because additional deflection is produced by the distorted stress distribution near

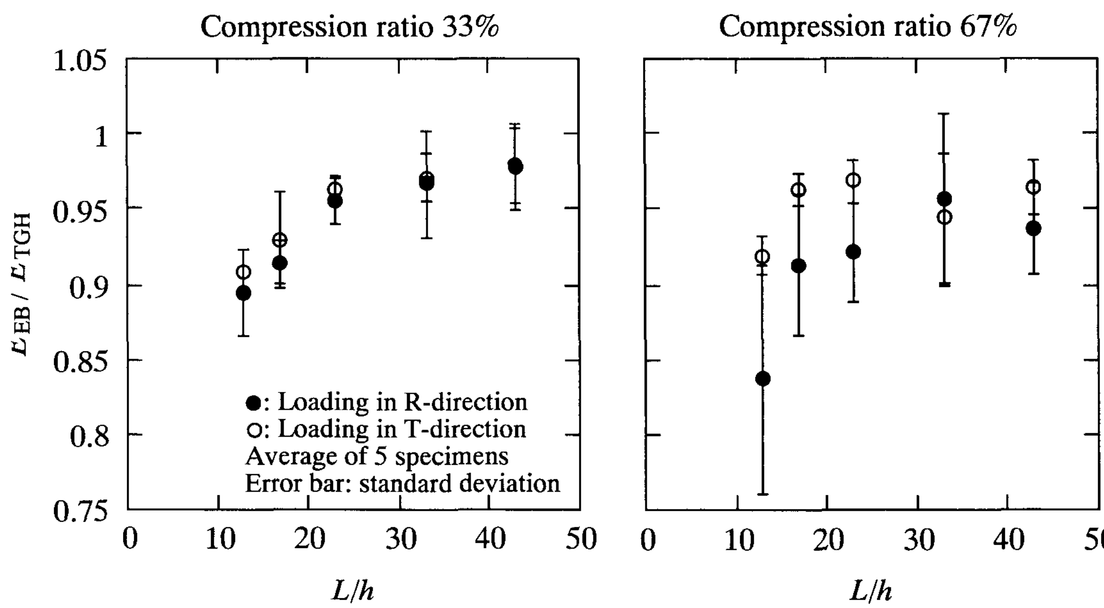

FIG. 2. Changes in Young's modulus of compressed wood by Euler-Bernoulli's elementary theory (E_{EB}) at various length-to-depth ratios (*L/h*).

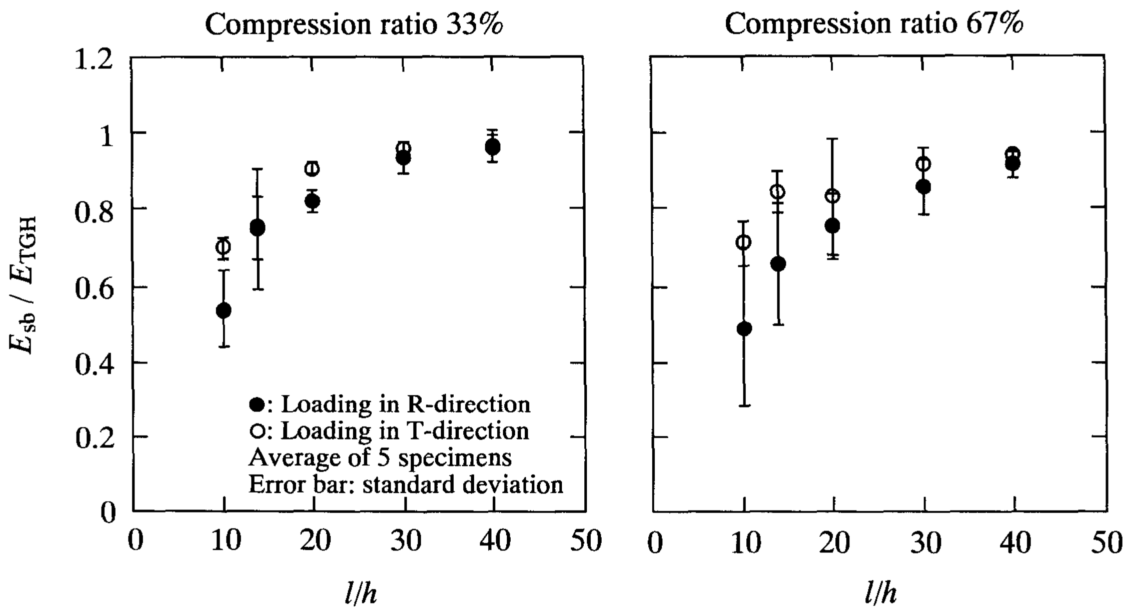

FIG. 3. Changes in Young's modulus of compressed wood by static bending test (E_{sb}) at various span-to-depth ratios (l/h).

the leading point derived from the stress concentration (Uemura 1981; Dong et al. 1994). However, it is understood qualitatively that large E/G and small l/h (thick beams) make the contribution of shear deflection to bending deflection large.

According to the relationships of E_{sb}/E_{TGH} - l/h shown in Fig. 3 corresponding to each compressing ratio, E_{sb} became stable around E_{TGH} when l/h was large in loading in both the R- and T-directions. At the same compression ratio, E_{sb}/E_{TGH} was larger in vibrating in the T-direction than in the R-direction. This is because the Young's modulus to shear modulus ratio of the LT-plane was smaller than that of the LR-plane as was the case with E_{EB}/E_{TGH}. Loading in the R-direction, E_{sb}/E_{TGH} was larger for 33% compression ratio than 67%, because Young's modulus to shear modulus ratio for 33% compression was smaller. Therefore, we concluded that specimens with high l/h, that is to say, thin beams and long beams, could obtain appropriate Young's modulus of compressed wood.

Here, the value of span-to-depth ratio of 14, which is effective to measure static bending in Young's modulus without the influence of shear deflection in ASTM (2000) and JIS (1994) was examined. For this purpose, the average of E_{sb}/E_{TGH} at l/h = 40 when E_{sb} was closest to E_{TGH} was compared to that at l/h = 14 using a t-test. The t-values in Table 2 show that they were different at 1% significant level in any loading direction and compression ratio. Hence, E_{sb} at l/h = 14 in the major standards was too small to be accurate. Further experiments are needed to obtain the proper values of l/h for various compressing ratios or Young's modulus to shear modulus ratios.

CONCLUSIONS

We examined the Young's modulus of compressed wood using the flexural vibration test

TABLE 2. *T-values in comparing the average of E_{sb}/E_{TGH} at l/h = 40 to that at l/h = 14.*

Loading direction	Compression ratio 33%	Compression ratio 67%
R	8.852**	4.460**
T	12.497**	8.955**

**1% significant level.

and the static bending test. The results were as follows.

(1) The value of E_{EB} approached E_{TGH} as L/h increased in vibrating in vibrating in both the R- and T-directions. In the same compression ratio, E_{EB}/E_{TGH} was larger in vibrating in the T-direction than in the R-direction. This is because E/G_{LT} was smaller than E/G_{LR}. (2) The value of E_{sb} became close to E_{TGH} when l/h was large in static loading in both the R- and T-directions. At the same compression ratio, E_{sb}/E_{TGH} was larger in loading in the T-direction than in the R-direction. This is because E/G_{LT} was smaller than E/G_{LR}, as was the case with E_{EB}/E_{TGH}. In the static bending test of the compressed wood, the Young's modulus at $l/h = 14$ used in major standards was not appropriate.

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