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ORIGINAL ARTICLE

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Acoustoelastic birefringence effect in wood III: ultrasonic stress determination of wood by acoustoelastic birefringence method

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Abstract Stress conditions produced in wood were analyzed by means of the acoustoelastic birefringence method. Bending load was applied against a wood beam specimen. Under loading, ultrasonic shear waves were propagated through the breadth direction of the wood beam specimen. The velocities of shear waves polarized in the longitudinal or tangential direction of the wood beam specimen were measured with the sing-around method. Bending stresses were determined by dividing the difference between the acoustic anisotropy and the texture anisotropy by the acoustoelastic birefringence coefficient. Shear stresses were also determined. These stress distributions of the beam specimen were in good agreement with those obtained by the strain gauge method and mechanical calculation.

Key words Acoustoelasticity · Acoustoelastic birefringence · Ultrasonic wave velocity · Stress determination

Introduction

The shear wave velocities along two principal directions of polarization, under the influence of initial stresses, are slightly different from the wave velocity in an unstressed medium.[1,2] This phenomenon, which is analogous to the changing of light speed in a stressed transparent body (called the photoelastic effect), has received much attention from the engineering viewpoint, not only as a new technique for experimental stress analysis but also as a nondestructive technique for measuring residual stresses in metals and ceramics.[3–7]

Since the discovery of the birefringence phenomenon of acoustic waves by Bergman and Shahbender[1] and by Benson and Raelson,[2] many experimental and theoretical works on acoustoelasticity have been carried out.[8–12] Crecraft[8] compared photoelastic and acoustoelastic phenomena and showed that acoustoelasticity could indeed be used in engineering as a practical method with reasonable accuracy. He measured the velocity change due to uniaxial stress for each independent mode of the principal wave, and verified the linear relationship between the velocity and the stress. He also measured residual stresses in a bent bar and a distorted ring. As reviewed by Pao et al.,[13] ultrasonic techniques have been successfully developed to measure the applied stresses in an elastically deformed medium. The general formulas for the stress dependence of the velocity have been linearized with respect to the stress. For the birefringence of a transverse principal wave, the birefringence gives the relation that the velocity difference between two polarized transverse constituents is proportional to the difference between the principal stresses. Imanishi et al.[14] and Blinka and Sachse[11] examined experimentally the relation in the acoustical birefringence. Based on their findings, many research studies on stress measurement in metals were carried out using the effect of acoustoelastic birefringence.[3–7]

In our previous report,[15] the bending stress distribution of a bent wood beam was estimated by using the acoustoelastic phenomena of wood. In this method, however, information for the unstressed state of the material was needed. This was a demerit for the practical application of this method to the stress determination in wood, because such information could not be obtained in most cases for members of timber structures. To overcome this demerit, the acoustoelastic birefringence effect of wood should be investigated, because the acoustoelastic birefringence phenomena may be used to evaluate stress states without information concerning the unstressed state of the material.

The final objective of our study is to develop a new method for evaluating stress states in wood using ultrasonic techniques. The experimental results of acoustoelastic birefringence studies of wood shown in previous reports[16,17] revealed that by measuring the stress-induced velocity changes of the ultrasonic shear waves, two coefficients of

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acoustoelastic birefringence were obtained, namely, the acoustoelastic coefficient of the texture-induced birefringence and that of the stress-induced birefringence. In addition, the influence of texture anisotropy on the polarization direction of shear waves was investigated.[17] It was found that the polarization direction of shear waves coincided with the orthotropic direction of wood and not with the principal stress direction.

In the present study, the measurement method and the results for the estimated stress state in a bent wood beam are shown using the results of the acoustoelastic birefringence effects presented in previous reports.[16,17] Ultrasonic shear waves are transmitted across the breadth of the elastically bent wood beam. The wave speeds for two shear waves oscillated in perpendicular directions were measured with the sing-around method.

Materials and methods

The material used was sapwood of Japanese magnolia (*Magnolia obovata* Thunb.). The wood beam specimen was processed from an air-dried lumber. The density and moisture content of the specimen were 0.51 g/cm^3 and 6.92%, respectively. The dimensions (length × height × breadth) of the specimen were 1300 × 105 × 15 mm.

Approximately 2 kN of bending load was centrally applied using an Instron-type testing machine, over a loading span of 350 mm, in four-point bending over a 1100 mm span, as shown in Fig. 1. According to this loading method, only the bending stress was produced inside loading points of a bent beam, and the bending and shear stresses were produced outside loading points.

Ultrasonic waves were propagated across the breadth (radial) direction of the bent wood specimen, and ultrasonic velocity was measured at seven points along the height direction of the beam at 100, 150, 200, and 250 mm from the support, as shown in Fig. 2. The seven points were at −37.5, −22.5, −7.5, 0, +7.5, +22.5, and +37.5 mm from the neutral axis in the height direction of the beam. As shown in Fig. 2, the oscillation direction of the shear wave was aligned with the longitudinal and tangential directions of the wood, that is, the length and height directions of the wood beam specimen, and the velocities were given by V_1 and V_2, respectively. The previous report confirmed that the shear wave that propagated through the stressed wood was polarized along the anisotropic axis of the wood and not along the principal stress direction.[17] The ultrasonic velocity propagating through the wood during loading was measured with the sing-around method, using a UVM-2 unit (Ultrasonic Engineering, Tokyo). The number of repetitions of the sing-around method was adjusted to 10 000 in this experiment. Piezoelectric transducers with a natural frequency of 0.5 MHz and a diameter of 25.4 mm (CR-0016-SA, Harisonic Laboratories, CT, USA) were used to detect the ultrasonic waves. A special holder shown in Fig. 3 was used to facilitate attachment of the ultrasonic transducers to the beam specimen with constant pressure at all measuring positions, and to allow them to rotate by 90° at each point to measure the velocities V_1 and V_2 of the shear waves oscillated in two perpendicular directions. Epoxy resin (AR-R30) was used as coupling media to improve bonding between the transducers and the wood specimen.[18,19]

For comparison with the acoustoelastic birefringence method, stress values were also estimated by the strain gauge method. Three-element rectangular rosette gauges (3 mm long) were placed at all points along the ultrasonic measurement positions, as shown in Fig. 1. Equipment for bending load, strain, and velocity measurements was connected to a personal computer, and data were automatically recorded. Figure 4 illustrates a setup for the applied load, strain, and ultrasonic velocity measurements in the specimen under bending. The above procedures were carried out

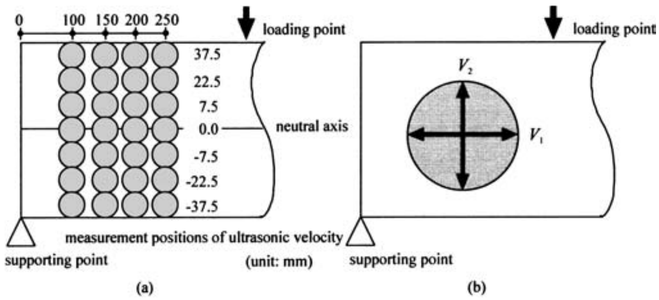

Fig. 2a,b. Illustrations of ultrasonic velocity measurement. **a** Measurement positions of shear wave velocity. **b** Oscillation direction of shear wave. V_1, wave velocity for oscillation in the longitudinal direction; V_2, wave velocity for oscillation in the tangential direction

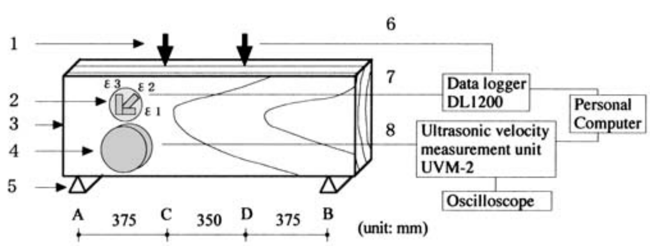

Fig. 1. Setup for ultrasonic velocity measurement. *1*, Loading points (*C* and *D*); *2*, three-element rectangular rosette gauge; *3*, wood beam specimen; *4*, ultrasonic sensors; *5*, supporting points (*A* and *B*); *6*, load; *7*, strains (*ε*1, *ε*2 and *ε*3); *8*, sing-around periodic time

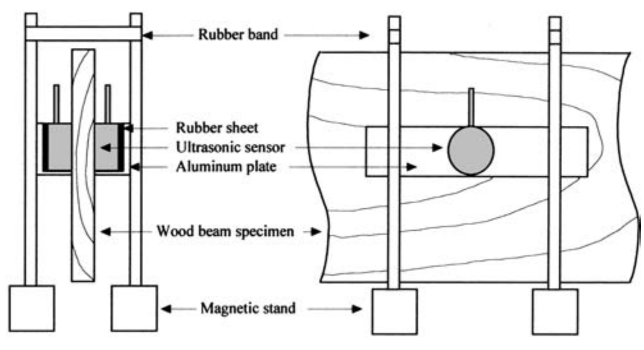

Fig. 3. Setup for fastening ultrasonic sensors to wood beam specimen

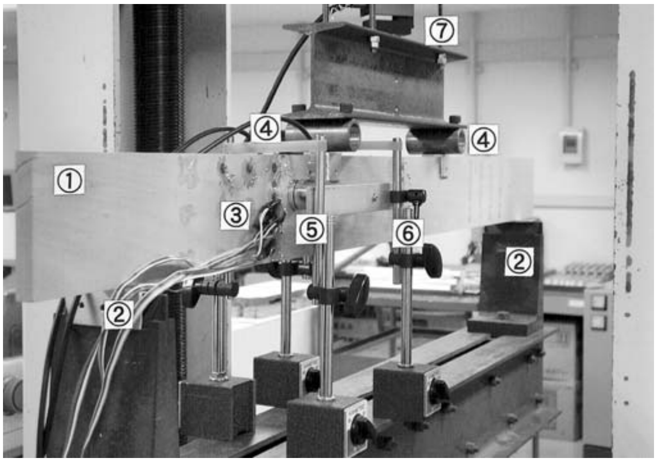

Fig. 4. Setup for ultrasonic velocity measurements under bending. *1*, Wood specimen; *2*, supports; *3*, strain gauges; *4*, loading points; *5*, ultrasonic transducers; *6*, holder; *7*, load cell

in an air-conditioned chamber at 24°C and 55% relative humidity.

Stress analysis

Stress estimation by acoustoelastic birefringence method

It is well known that even in materials such as metals, which are generally considered to be isotropic, texture anisotropy due to processing during manufacturing and thermal treatment is present, and therefore the material exhibits slight anisotropy. When such a material is stressed in-plane, the principal directions of the texture-induced anisotropy and the stress-induced anisotropy, in general, do not coincide with each other. The polarization of shear wave direction depends on the resultant effect of both texture- and stress-induced anisotropies. Therefore, the polarization direction is at an angle ϕ to the orthotropic axis. According to the theory of the acoustoelastic birefringence by Iwashimizu and Kubomura regarding the plane stress state,[20,21] the acoustic anisotropy (i.e., the relative difference of the velocity) and the polarization angle ϕ of shear wave are expressed as follows:

$$\frac{V_1 - V_2}{V_T} = \sqrt{\alpha^2 + 2\alpha Ca(\sigma_1 - \sigma_2)\cos 2\theta + [Ca(\sigma_1 - \sigma_2)]^2} \qquad (1)$$

$$\tan 2\phi = \frac{Ca(\sigma_1 - \sigma_2)\sin 2\theta}{\alpha + Ca(\sigma_1 - \sigma_2)\cos 2\theta} \qquad (2)$$

where V_T is the average of velocities V_1 and V_2, α is the texture anisotropy, Ca is the acoustoelastic birefringence coefficient, σ_1 and σ_2 are the principal stresses, and θ is the direction of the principal stress with respect to the orthotropic axis.

On the other hand, when the texture anisotropy of the material is strong compared with the stress-induced anisotropy, the polarization direction of shear waves does not correspond with the direction of principal stress. In such a case, Eq. 1 can be rewritten as follows:

$$\frac{V_1 - V_2}{V_T} = \alpha + Ca(\sigma_1 - \sigma_2)\cos 2\theta \qquad (3)$$

The difference between the plane stress components σ_x and σ_y, and the shear stress τ_{xy} are expressed by using σ_1, σ_2, and θ, as Eqs. 4 and 5.[22,23]

$$\sigma_x - \sigma_y = (\sigma_1 - \sigma_2)\cos 2\theta \qquad (4)$$

$$\tau_{xy} = \frac{(\sigma_1 - \sigma_2)}{2}\sin 2\theta \qquad (5)$$

Equation 3 can be rewritten as Eq. 6.

$$\frac{V_1 - V_2}{V_T} = \alpha + Ca(\sigma_x - \sigma_y) \qquad (6)$$

In the plane stress state in this study, σ_x is equal to the bending stress σ_b. Because no stress is produced in the height direction of the beam specimen, σ_y is zero. Equation 6 can be written as Eq. 7.

$$\frac{V_1 - V_2}{V_T} = \alpha + Ca \cdot \sigma_b \qquad (7)$$

Therefore, the bending stress was estimated by dividing the difference between the acoustic anisotropy and the texture anisotropy α by the acoustoelastic birefringence coefficient Ca, as shown in Eq. 8.

$$\sigma_b = \frac{\dfrac{V_1 - V_2}{V_T} - \alpha}{Ca} \qquad (8)$$

On the other hand, the shear stress was also estimated by the acoustoelastic birefringence theory. Equations 2, 3, and 5 yield Eq. 9.

$$\tau_{xy} = \frac{\tan 2\phi \cdot \dfrac{V_1 - V_2}{V_T}}{2Ca} \qquad (9)$$

As shown in Eq. 9, the shear stress was obtained using the values of the polarization angle ϕ, the acoustic anisotropy $[(V_1 - V_2)/V_T]$, and the acoustoelastic birefringence coefficient Ca. The polarization angle ϕ is approximately zero as reported in the previous study,[17] and is difficult to measure with high accuracy. In this study, the shear stress (τ_b) was estimated using Eq. 10 for convenience.[22] The principal stress direction θ in the equation was obtained by mechanical calculation.

$$\tau_b = \frac{\tan 2\theta}{2}\sigma_x \qquad (10)$$

As shown in the previous study,[17] the principal stress direction (θ) equals $\pi/4$ rad on the neutral axis of the bent beam. In this case, substituting $\pi/4$ into θ in Eqs. 1 and 5 yields Eq. 11.

$$\tau_b = \frac{\sqrt{\left(\frac{V_1 - V_2}{V_T}\right)^2 - \alpha^2}}{2Ca} \tag{11}$$

With prior knowledge of two acoustoelastic constants, that is, the texture anisotropy (α) and the acoustoelastic birefringence coefficient (Ca), the measurement of the shear wave velocities (V_1, V_2) yields the bending and shear stresses. In this study, these stresses were estimated using the values of the acoustoelastic constants obtained in the previous study.[16]

Stress estimations by strain gauge method and mechanical calculation

For comparison with the acoustoelastic birefringence method, the bending and shear stresses were evaluated by the strain gauge method and by mechanical calculation. For the strain gauge method, the bending stress (σ_g) and the shear stress (τ_g) in this study were obtained as follows:[23,24]

$$\sigma_g = \frac{E_x\left(\varepsilon_x + \mu_{yx}\varepsilon_y\right)}{1 - \mu_{xy}\mu_{yx}} \tag{12}$$

$$\tau_g = G\gamma_{xy} \tag{13}$$

where E_x is Young's modulus in the longitudinal direction, μ_{xy} and μ_{yx} are Poisson's ratios, and ε_x and ε_y are strains in longitudinal (length) and tangential (height) directions, respectively. Young's modulus was obtained as $E_x = 9.9$ GPa by the uniaxial loading test in the previous report.[16] In Eq. 13, G is shear modulus, and γ_{xy} is shear strain. These elastic moduli used in Eqs. 12 and 13 were obtained by separately conducted compression and torsion tests.[25,26] Strains were measured using three-element rectangular rosette gauges attached on the wood beam specimen, as shown in Fig. 4. They were measured at the same positions as those for ultrasonic measurements.

For the mechanical calculation, the bending stress σ_c and the shear stress τ_c were calculated by Eqs. 14 and 15.[22]

$$\sigma_c = \frac{6Pxy}{bh^3} \tag{14}$$

$$\tau_c = \frac{3P}{4bh}\left[1 - \left(\frac{2y}{h}\right)^2\right] \tag{15}$$

where P is the bending load, x is the distance from the support, y is the distance from the neutral axis, and b and h are the width and height of the wood beam specimen, respectively.

Results and discussion

Velocities of shear waves oscillated parallel or normally to the applied stress direction

Table 1 shows examples of results of ultrasonic measurements of shear wave velocities (V_1, V_2) in the wood beam specimen under a 2-kN bending load. The measurements were performed at a distance of 250 mm from the supporting point of the specimen. The measurement position of 0.0 mm in the table corresponds to the neutral axis of the wood beam specimen. The values of the velocity V_1 ranged from 1581.9 to 1680.4 m/s and those of V_2 from 706.6 to 817.0 m/s. The values of V_1 were larger than those of V_2 at each measurement position because the shear wave for V_1 was oscillated along the longitudinal direction of the wood. Because of measurement positions, the velocities showed different values; however, no distinct relationship was observed.

The acoustic anisotropy, that is, the relative differences between the shear wave velocities [$(V_1 - V_2)/V_T$], in Table 1 showed smaller values at the upper positions of the specimen (7.5, 22.5, and 37.5 mm from the neutral axis) than those at the lower positions (−7.5, −22.5, and −37.5 mm). The differences between the acoustic anisotropy and the texture anisotropy [$(V_1 - V_2)/V_T - \alpha$] were negative at the upper positions and positive at the lower positions.

Table 1. Results of shear wave velocities, acoustic anisotropy, texture anisotropy, and predicted stress

Measurement position[a] (mm)	Shear wave velocities		Acoustic anisotropy $(V_1 - V_2) / V_T$	Texture anisotropy α	$(V_1 - V_2) / V_T - \alpha$	Predicted stress
	V_1 (m/s)	V_2 (m/s)				
37.5	1680.4456	816.9842	0.6915	0.6960	−0.0046	Compressive
22.5	1661.5672	813.5791	0.6852	0.6879	−0.0027	Compressive
7.5	1667.2096	814.4889	0.6872	0.6879	−0.0007	Compressive
0.0	1611.6206	754.4075	0.7246	0.7246	0.0000	−
−7.5	1587.5171	706.8644	0.7677	0.7673	0.0003	Tensile
−22.5	1581.9129	706.8541	0.7647	0.7641	0.0005	Tensile
−37.5	1595.7586	706.5676	0.7724	0.7706	0.0018	Tensile

[a] Measurement position of ultrasonic shear wave velocity from the neutral axis

Our previous study showed that the acoustic anisotropy decreased with increasing compressive stress and increased with increasing tensile stress.[16] According to those results, the compressive bending stresses were understood to distribute on the upper side of the wood beam specimen, and the tensile bending stresses on the lower side. Therefore, it can be predicted that in the wood beam specimen under loading as shown in Fig. 1, compressive bending stress is produced at the upper position, and tensile stress at the lower position. The stress (compression or tension) estimated in the wood beam specimen coincided clearly with the predicted one.

Stress distribution of wood beam

According to Eq. 8, the bending stress values can be obtained by dividing the difference between the acoustic anisotropy and the texture anisotropy $[(V_1 - V_2)/V_T - \alpha]$ in Table 1 by the acoustoelastic birefringence coefficient (Ca). The values of the coefficient obtained in the previous study[16] are shown in Table 2. They are the experimental values for each specimen cut from near the measurement positions for the ultrasonic velocities in the beam specimen. The averaged values of α and Ca were not used for the calculation, because large variations in the constants were observed due to the measuring positions. The bending stress values (σ_b) estimated by the acoustoelastic birefringence method are also shown in Table 2. For comparison with the acoustoelastic birefringence method, the bending stresses were also estimated by the strain gauge method and mechanical calculation, and are shown as σ_g and σ_c in Table 2, respectively. They were obtained by Eqs. 12 and 14, respectively. Bending stress (σ_b) estimated by the acoustoelastic birefringence method showed 0.0 MPa at the measurement position of 0.0 mm, and the compressive and tensile stress increased with increasing distance from the neutral axis. The stress values estimated by the three methods were in good agreement with each other. Figure 5 shows the distributions of the bending stresses obtained by the three methods in Table 2. As shown in Fig. 5, there are only slight differences in the stress values obtained by the three methods, and they almost coincide. This suggests that the bending stress is adequately estimated by the acoustoelastic birefringence method.

It is an advantage of the acoustoelastic birefringence method that the stress states can be determined by measuring the velocities (V_1 and V_2) of shear waves under the stressed state, without having to determine the velocities in the unstressed state. According to the method shown in a previous report,[15] the velocities in the unstressed state had to be known for the estimation of the stress states. The results shown above suggest that the difference between the acoustic anisotropy and the texture anisotropy gives the compressive or tensile stress by determining the texture anisotropy beforehand.

Shear stresses were also estimated by the acoustoelastic birefringence method using Eqs. 10 and 11. They are shown as τ_b in Table 3. In Table 3, the shear stresses obtained by the mechanical calculation and the strain gauge method are

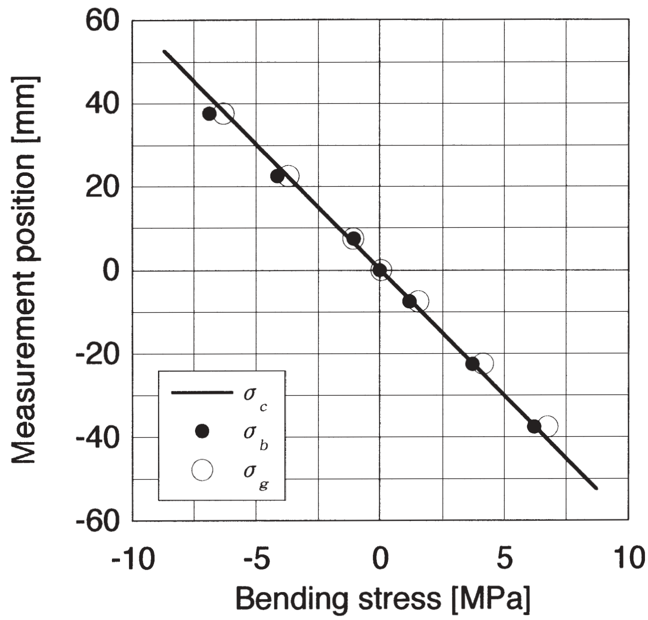

Fig. 5. Bending stress distribution obtained by three methods. *Solid line*, mechanical calculation; *filled circles*, acoustoelastic birefringence method; *open circles*, strain gauge method

Table 2. Acoustoelastic birefringence coefficient (Ca) and estimated stress values

Measurement position[a] (mm)	Ca ($\times 10^{-4}$/MPa)	Estimated bending stress		
		σ_b^b (MPa)	σ_c^c (MPa)	σ_g^d (MPa)
37.5	6.64	−6.88	−6.23	−6.32
22.5	6.57	−4.14	−3.74	−3.71
7.5	6.62	−1.09	−1.25	−1.10
0.0	8.31	0.00	0.00	−0.20
−7.5	2.88	1.11	1.25	1.51
−22.5	1.46	3.70	3.74	4.12
−37.5	2.88	6.19	6.23	6.73

[a] Measurement position of ultrasonic shear wave velocity from the neutral axis
[b] Bending stresses obtained by acoustoelastic birefringence method
[c] Bending stresses obtained by mechanical calculation
[d] Bending stresses obtained by strain gauge method

Table 3. Estimated values of shear stress

Measurement position[a] (mm)	Estimated shear stress		
	τ_b^b (MPa)	τ_c^c (MPa)	τ_g^d (MPa)
37.5	0.50	0.46	0.52
22.5	0.85	0.76	0.79
7.5	0.80	0.91	0.87
0.0	1.13	0.93	0.89
−7.5	0.86	0.91	0.83
−22.5	0.76	0.76	0.65
−37.5	0.46	0.46	0.40

[a] Measurement position of ultrasonic shear wave velocity from the neutral axis
[b] Shear stresses obtained by acoustoelastic birefringence method
[c] Shear stresses obtained by mechanical calculation
[d] Shear stresses obtained by strain gauge method

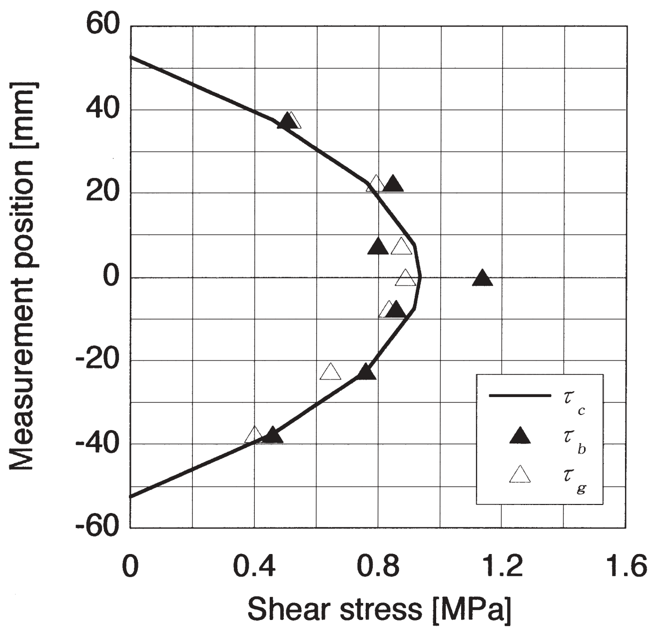

Fig. 6. Shear stress distribution obtained by three methods. *Solid line*, mechanical calculation; *filled triangles*, acoustoelastic birefringence method; *open triangles*, strain gauge method

also shown as τ_c and τ_g, respectively. They were obtained using Eqs. 15 and 13, respectively. Regarding the strain gauge method, the shear modulus (G) was needed in Eq. 13, and obtained as $G = 0.94\,\text{GPa}$ by a torsion test conducted separately.[25,26] Stress values obtained by the three methods were in relatively good agreement with each other, and showed a maximum at the neutral axis and a minimum at the outermost positions. Figure 6 shows the distributions of the shear stresses obtained by the three methods. They are also in good agreement with each other, and show a parabolic distribution.

In the acoustoelastic birefringence method, shear stresses were evaluated by using the calculated values of the principal stress direction (θ) as shown in Eq. 10. In general, the principal stress direction is not known. In the case of isotropic materials, it is possible to confirm the principal stress direction by determining the direction in which the shear wave velocity shows a peak value using the rotating ultrasonic sensor. In the case of wood, however, it is difficult to determine the principal stress direction because of the strong anisotropy in texture as mentioned in a previous report.[17] The establishment of a reliable ultrasonic measurement system will enable the determination of the principal stress direction, and from this it will be possible to evaluate shear stress directly by the acoustoelastic birefringence method.

Conclusions

Ultrasonic shear waves were propagated through the breadth direction of a bent wood beam. The velocities of shear waves oscillated in the longitudinal or tangential direction of the wood beam specimen were measured using the sing-around method.

The difference between the acoustic anisotropy (the relative difference between two perpendicular shear wave velocities) and the texture anisotropy was confirmed to indicate the bending stress (compression or tension). Bending stresses were determined by dividing the difference between the acoustic anisotropy and the texture anisotropy by the acoustoelastic birefringence coefficient, without having to determine the velocities in the unstressed state. Shear stresses were also determined. The stress distributions of the bent beam specimen were in good agreement with those obtained by the strain gauge method and mechanical calculation.

The results of this study suggest that the acoustoelastic birefringence method is advantageous for stress determination, because there is no need to determine information in the unstressed state. The application of the acoustoelastic birefringence effect as a new method for stress measurement in wood is expected.

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