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Acoustoelastic effect of wood III: effect of applied stresses on the velocity of ultrasonic waves propagating normal to the direction of the applied stress

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Abstract Changes in the velocity of ultrasonic waves propagating in wood normal to the direction of applied stresses are discussed. The ultrasonic modes considered here are longitudinal waves and shear waves with particle motion along the direction of the applied stress. The ultrasonic velocities in wood were measured by the sing-around method. From the results of the acoustoelastic experiments in wood, changes in the ultrasonic velocities were expressed as a function of the applied stress. For the shear waves, the ultrasonic velocities decreased with an increase in compressive stress from the initial stress level. On the other hand, the ultrasonic velocities under tensile stress increased with an increase in stress at low stress levels and then gradually decreased with further a increase in the stress. In contrast, the longitudinal wave velocities increased with an increase in compressive stress at low stress levels and then decreased with additional increase in the stress. The wave velocities under a tensile stress decreased with an increase in the stress. The proportional relations between velocities and stresses at low stress levels are confirmed, and acoustoelastic constants were obtained from these relations. Their absolute values were smaller than those reported in previous studies but larger than those of metals. The acoustoelastic effect seemed to be almost equivalent on the sensitivity for stress measurement as the strain-gauge method.

Key words Acoustoelasticity · Acoustoelastic effect · Ultrasonic wave velocity

Introduction

An isotropic material under stress, either internally generated or externally applied, becomes double refracting; that is, the velocity of shear waves normal to the direction of the stress is dependent on whether its direction of oscillation is parallel or normal to the direction of the stress. This phenomenon is the acoustic counterpart of the photoelastic effect used for investigating specimens in the form of transparent models; and the term acoustoelasticity has been coined in a manner similar to photoelasticity.[1–6]

Ever since an acoustoelastic birefringent effect of ultrasonic shear waves in a stressed metal specimen was found, this phenomenon has been accepted with much enthusiasm for its potential use in experimental stress analysis techniques.[7–13] Moreover, it was expected that the phenomenon would lead to the development of nondestructive techniques for measuring residual stresses in metal.[14,15]

As regards wood, however, the acoustoelastic effect has yet to be confirmed in tests of wood samples. An acoustoelastic effect of wood was found for the first time in our previous reports.[16–18] The results of an experimental investigation of changes in the velocity of ultrasonic longitudinal waves propagating parallel to the direction of the applied compressive stress were previously reported.

The purpose of this study was to investigate the effect of uniaxial stress on the ultrasonic velocity propagating normal to the direction of the applied stress. Compressive and tensile stresses were applied in the longitudinal direction of the wood specimen, and ultrasonic waves were propagated normal to the direction of the stress. This experimental procedure was considered to be reasonable in applications of the acoustoelastic technique to the stress analyses of structural components (e.g., posts and beams in timber construction). The ultrasonic modes considered in this study were longitudinal waves and shear waves with particle motion along the direction of the applied stress. Stress-induced velocity changes of the ultrasonic waves for some wood species were measured, and acoustoelastic constants were

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Table 1. Properties of the specimen used in the acoustic experiment

Species	Average moisture content (%)	Average specific gravity	Average Young's moduli (GPa)
Alaska cedar	6.8 (0.9)	0.45 (0.02)	9.57 (1.25)
Japanese cypress	6.6 (0.6)	0.40 (0.01)	10.1 (1.72)
Ash	6.4 (1.4)	0.53 (0.07)	10.5 (4.25)
Japanese magnolia	6.5 (0.4)	0.42 (0.04)	7.10 (1.22)

Numbers in parentheses denote standard deviations

obtained from experimentally observed relations between velocity changes and stress. In addition, the possibility of using the acoustoelastic technique for stress measurement of wood is discussed by comparing it to an existing strain-gauge method.

Materials and methods

Table 1 shows the four species of wood used in the experiment and their properties. Two softwood and two hardwood species were used: Alaska cedar [*Chamaecyparis nootkatensis* (D.Don) Spach.], Japanese cypress [*Chamaecyparis obtusa* (S. and Z.) Endl.], ash (*Fraxinus excelsissima* Koidz.), and Japanese magnolia (*Magnolia obovata* Thunb.). Small, clear specimens were processed from air-dried lumber samples of the selected timbers. At least 10 specimens of each species were prepared for the test. The dimensions of the test specimens were 6cm (longitudinal) × 3cm (tangential) × 2cm (radial) for compressive loading tests and 29 × 5 × 1.5cm for tensile loading tests. The longitudinal axis of each specimen coincided with the longitudinal direction of the wood. The test specimens were kept under an air-dried condition prior to the tests.

Both compressive and tensile loads were applied parallel to the longitudinal axis of the wood specimens using an Instron-type testing machine. Cross-head speeds of 0.3mm/min and 1.0mm/min were applied to the specimen during the compressive and tensile loading tests, respectively. The length for chucking a tensile loading specimen was 8cm. The ultrasonic waves were propagated along the radial direction of the wood normal to the direction of loading. The ultrasonic velocities in both compressive and tensile loading tests of the wood were measured by the sing-around method, using a model UVM-2 (commercially available sing-around unit made by Ultrasonic Engineering Co., Tokyo, Japan). Transducers used in the tests were commercially available piezoelectric type for shear and longitudinal waves with a center frequency of 0.5MHz and a diameter of 1 inch (models CR-0016-S for longitudinal waves and CR-0016-SA for shear waves made by Harisonic Laboratories, CT, USA). Figure 1 shows the setup for acoustoelastic measurements in wood specimens. Coupling media such as silicone grease for longitudinal wave transducers and epoxy resin for shear wave transducers were used to ensure bonding of the transducers to the wood specimen, and rubber bands were used to fix the transducers to the specimen.

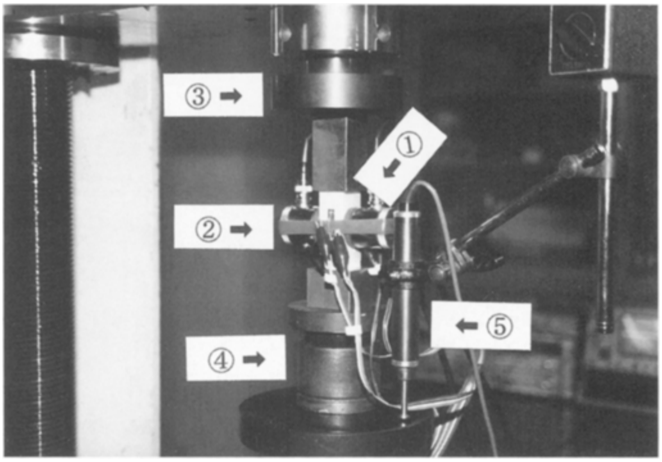

Fig. 1. Setup for ultrasonic wave velocity measurement in wood under compressive loading. *1*, Wood specimen with strain gauges; *2*, ultrasonic transducers held by rubber band; *3*, cross-head of testing machine; *4*, load-cell with rolling attachment; *5*, displacement meter

As mentioned before, the ultrasonic waves considered in this study were shear and longitudinal waves. For the shear waves, only the mode with particle motion in the direction of loading was considered; the other mode, with particle motion normal to the direction of loading, was not considered because in this direction the transducer was not able to receive signals traveling through the specimens owing to the high attenuation.[19]

The ultrasonic velocity was calculated by dividing the periodic time of the sing-around by the distance between the transducers. The distance, however, was changed by Poisson's effect during the loading. To correct the change in distance for calculation of the velocity, strains in the radial direction of the wood specimen were measured by strain gauges during the loading. Strain gauges (5 or 10mm long) were attached to the symmetrical surfaces of the radial section of the specimen, as shown in Fig. 1, for measuring the strains along the directions of loading and wave propagation. Figure 2 shows the setup used for acoustoelastic measurements. The data from the stress, strain, and velocity transducers were digitally recorded on a personal computer. The experiments were conducted in an air-conditioned chamber at 24°C and 55% relative humidity.

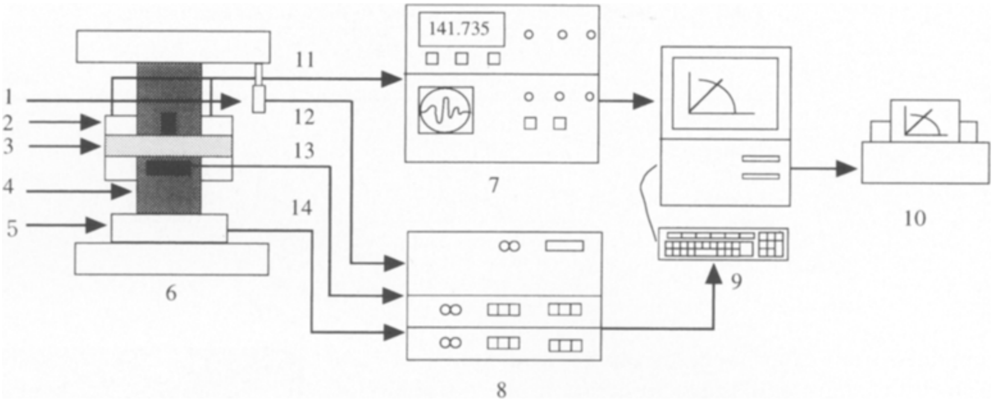

Fig. 2. Stress, strain, and velocity measurements. *1*, Electric displacement meter; *2*, ultrasonic transducer; *3*, rubber band; *4*, wood specimen with strain gauges; *5*, load cell; *6*, cross-head of testing machine; *7*, ultrasonic velocity measurement unit "UVM-2"; *8*, data logger "7V-14"; *9*, computer; *10*, printer; *11*, periodic time of sing-around; *12*, displacement of specimen; *13*, strain; *14*, load

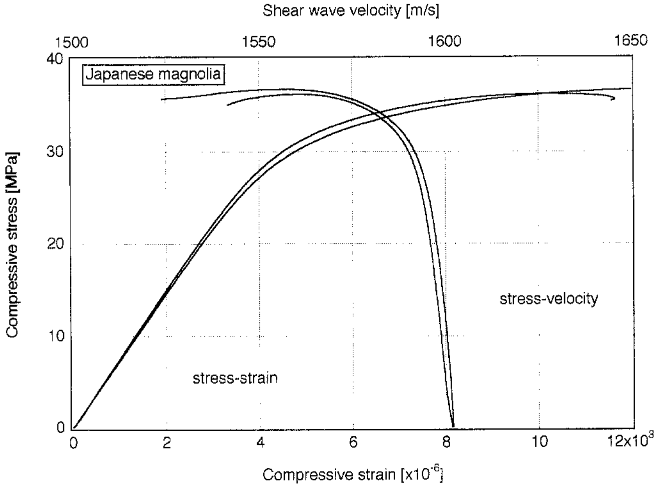

Fig. 3. Relations between compressive stress, strain, and shear wave velocity for Japanese magnolia

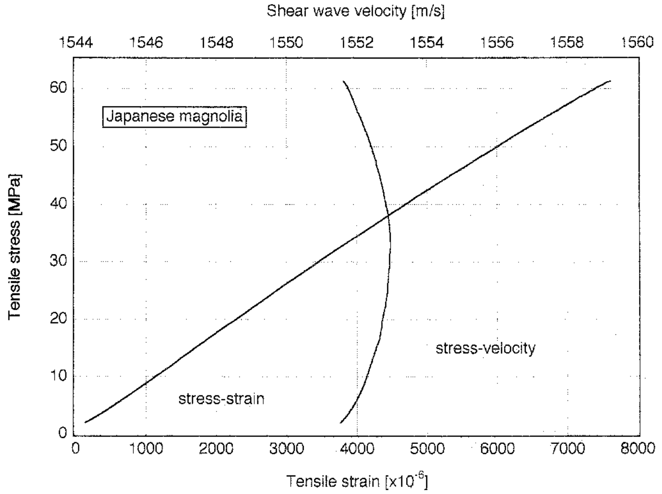

Fig. 4. Relations between tensile stress, strain, and shear wave velocity for Japanese magnolia

Results and discussion

Changes in ultrasonic wave velocities propagating normal to loading direction

Some differences in the experimental results were noted depending on the mode of ultrasonic wave and the magnitude and nature of applied stresses. The experimental results are summarized into four phenomena, as shown in Figs. 3–6. Figure 3 shows the experimentally obtained relations between stress, strain, and changes in ultrasonic velocity of a shear wave under compressive loading for Japanese magnolia. The ultrasonic velocity decreased with increases in compressive stress and strain from the beginning of the compressive loading. As the deformation became more severe (i.e., at strain levels of around 0.7%), the decline in ultrasonic velocities was even more steep. Similar phenomena were obtained with other species of wood for ultrasonic shear waves under compressive stress. The range of the change in velocity observed in this study was, however, smaller than those reported in previously published results.[16–18]

On the other hand, the results under tensile stress were different from those under compressive stress. Figure 4 shows the stress–strain relation and change in the ultrasonic velocity of shear waves for Japanese magnolia under tensile stress. The stress–strain relation can be represented by a straight line. At an initial stress level of less than 30–35 MPa, the strain and ultrasonic velocity increased with an increase in tensile stress. The velocity then gradually decreased with an increase in stress and strain at stress levels greater than 35–40 MPa. Similar results were obtained with other species for ultrasonic shear waves under tensile stress, as was also the case in our previous reports.[16–18] This behavior of ultrasonic shear waves was common to softwood and hardwood species.

Figure 5 shows the stress–strain curves and changes in ultrasonic longitudinal wave velocities for Alaska cedar under a compressive stress. The ultrasonic velocities increased with increases in compressive stress up to a stress level of less than 25 MPa, beyond which the velocities gradually decreased with increases in compressive stress. A similar behavior is obtained with other species in this experimental mode.

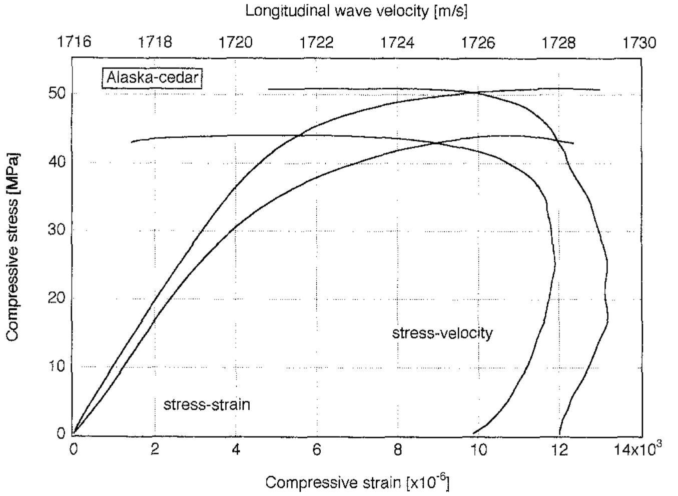

Fig. 5. Relations between compressive stress, strain, and longitudinal wave velocity for Alaska cedar

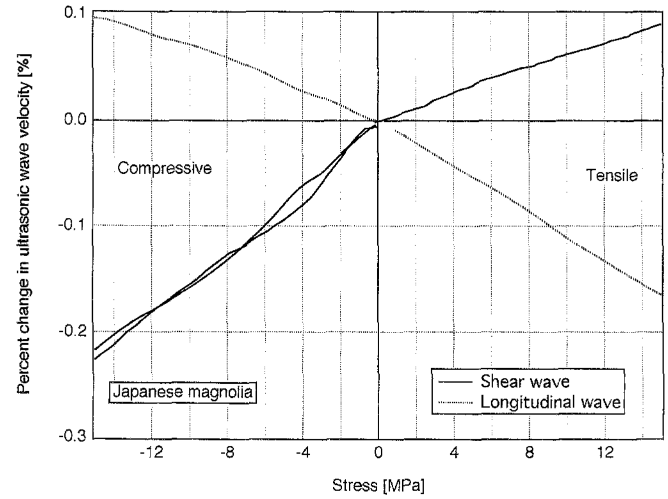

Fig. 7. Relations between percent change in velocity of ultrasonic wave and stress for Japanese magnolia

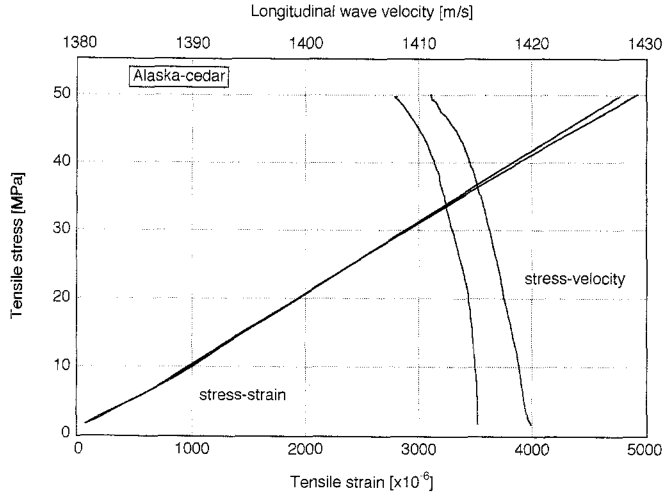

Fig. 6. Relations between tensile stress, strain, and longitudinal wave velocity for Alaska cedar

Figure 6 shows the relations between stress, strain, and changes in velocity of ultrasonic longitudinal waves for Alaska cedar under tensile stress. The stress–strain relations in Fig. 6 can be represented by essentially straight lines, as was the case in Fig. 4. The ultrasonic longitudinal wave velocity continued to decrease with increases in tensile stress and strain, unlike the case in Fig. 5. Similar results were obtained with other species in this mode of testing irrespective of whether the specimen was a softwood or a hardwood.

Changes in velocity in magnitude and sign with applied stress were due to differences in the materials, mode of ultrasonic wave, direction of wave propagation, and so on. In metals, for example in 99.9% pure copper and 0.01% carbon iron, ultrasonic longitudinal wave velocities decreased only slightly with increased application of tensile stresses.[20] Similar behavior was obtained in the present study. However, ultrasonic shear waves in 0.01% carbon iron and 99.5% pure aluminum and ultrasonic longitudinal waves in 99.5% pure aluminum showed behavior inverse to that seen at low stress levels in this study. As in the case of wood, metals exhibit obvious linear relations between the velocities and stresses, but the magnitude of the changes in the velocities in these materials was smaller than those seen in wood.

The changes in the propagation velocities of ultrasonic waves can be accounted for by the changes in the densities and elastic moduli of the materials as a consequence of the application of stress.[2,13] However, in the case of wood, such changes in density or elastic moduli with the application of stress or deformation have not yet been confirmed; and as described in previous reports, these changes could also result from the complexity in the cellular structure of wood.[16–18]

Relative changes of ultrasonic velocities and acoustoelastic constants

From the results depicted in Figs. 3–6, relations between the relative changes of ultrasonic velocities and stresses were obtained at stress levels of less than 15–20MPa. Following our previous reports,[16–18] the percent changes in velocity were calculated as follows.

$$(V - V_0) \times 100/V_0(\%) \qquad (1)$$

where V is the velocity for an arbitrary stress and V_0 is the initial velocity for the natural state (zero stress, zero strain).

Figure 7 shows the percent changes in ultrasonic wave velocity due to applied stresses for Japanese magnolia. The relations for shear wave in Fig. 7 were obtained by combining the data plotted in Figs. 3 and 4. As seen in Fig. 7, the magnitude of the shear wave velocity changes increased with increased application of tensile stress, revealing a proportional relation. With compression the relations between velocity changes and stress were essentially straight lines, which clearly indicated inverse relations. In contrast, the results for longitudinal waves showed quite the opposite behavior.

Figure 8 shows the percent changes in ultrasonic wave velocity due to applied stresses for Alaska cedar. The results in Fig. 8 showed the same behavior as in Fig. 7, regardless of species in this experimental mode. The relations for longitudinal waves in Fig. 8 were obtained by combining the data depicted in Figs. 5 and 6. Unlike the case of shear wave velocity under compressive stress, the magnitude of longitudinal wave velocity changes increased with increased compressive stress, and the relations between velocity change and compressive stress are represented by essentially straight lines. Similar straight-line relations between velocity changes and stress were exhibited under tensile stress.

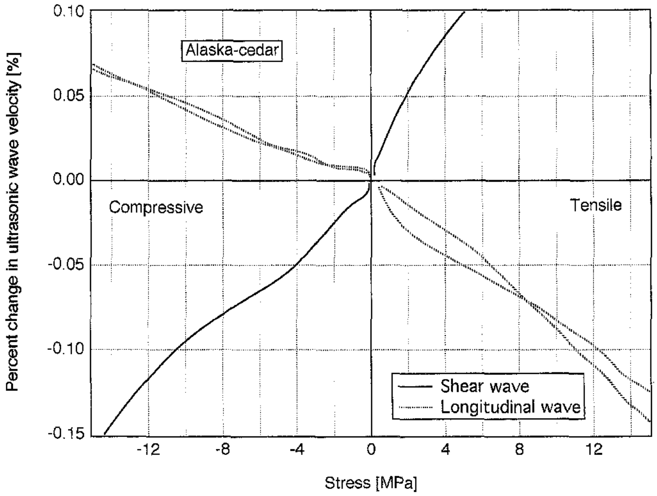

Fig. 8. Relations between percent change in velocity of ultrasonic wave and stress for Alaska cedar

As seen in Figs. 7 and 8, the lines of the relative changes at an ultrasonic velocity had different slopes due to the types of applied stress.

The proportional constants in the relations between the ultrasonic wave velocity changes and stresses were used to obtain acoustoelastic constants. The relations between the velocity changes and applied stresses were expressed as follows:

$$(V - V_0)/V_0 = K \cdot \sigma \qquad (2)$$

where K is the acoustoelastic constant and σ the applied stress. The averaged values of K for each species of wood are shown in Table 2. Values of K for other materials are shown for the sake of comparison. The signs of the constants obtained in this study depended on the ultrasonic mode and the type of applied stress. As seen in Table 2, the constants for all species of wood for a given mode of ultrasonic wave were all of the same sign regardless of the type of applied stress. Constants for ultrasonic shear waves were all positive in sign, and those for longitudinal waves were negative. This meant that different types of acoustoelastic behavior were observed depending on the mode of the ultrasonic wave.

The magnitude of the constants in Table 2 are about two digits smaller than those published in previous reports.[16–18] The differences in the results can be partially explained by the differences in the manner in which this experiment and the earlier ones were conducted. The ultrasonic waves in this study propagated along the radial direction of the wood specimen normal to the direction of the applied stress, whereas the waves in the previous study[18] propagated along the same (radial) direction, which corresponded to the direction of application of stress. Therefore, it became clear that the magnitude of the acoustoelastic constants depend also on the relation between the direction of propagation of ultrasonic waves and that of the applied stress. The con-

Table 2. Acoustoelastic constants of wood obtained from this experiment and of some other materials

Species	Mean value (MPa^{-1})	Wave	Stress
Alaska cedar	1.36×10^{-4} (0.54×10^{-4})	Shear	Compressive
	0.49×10^{-4} (0.44×10^{-4})	Shear	Tensile
	-0.43×10^{-4} (0.15×10^{-4})	Longitudinal	Compressive
	-0.98×10^{-4} (0.59×10^{-4})	Longitudinal	Tensile
Japanese cypress	0.95×10^{-4} (0.31×10^{-4})	Shear	Compressive
	0.77×10^{-4} (0.88×10^{-4})	Shear	Tensile
	-0.60×10^{-4} (0.37×10^{-4})	Longitudinal	Compressive
	-2.12×10^{-4} (1.59×10^{-4})	Longitudinal	Tensile
Ash	1.01×10^{-4} (0.24×10^{-4})	Shear	Compressive
	0.52×10^{-4} (0.36×10^{-4})	Shear	Tensile
	-0.27×10^{-4} (0.27×10^{-4})	Longitudinal	Compressive
	-1.30×10^{-4} (0.65×10^{-4})	Longitudinal	Tensile
Japanese magnolia	1.30×10^{-4} (0.41×10^{-4})	Shear	Compressive
	0.46×10^{-4} (0.24×10^{-4})	Shear	Tensile
	-0.71×10^{-4} (0.18×10^{-4})	Longitudinal	Compressive
	-1.59×10^{-4} (0.82×10^{-4})	Longitudinal	Tensile
Carbon iron[21]	1.96×10^{-7}	Longitudinal	Tensile
Aluminum[21]	1.56×10^{-5}	Longitudinal	Tensile
Soft steel[21]	3.00×10^{-6}	Longitudinal	Tensile

Numbers in parentheses denote standard deviations stants evaluated in this study, though smaller than those found in earlier studies, are still larger than those of metals, as can be seen in Table 2. This means that the velocity of ultrasonic waves in wood change with greater sensitivity to the applied stress than it does in metals. These findings suggest that the acoustoelastic effect could be applied to determine the stress condition of wood samples.

As can be seen in Table 2, the absolute values of the constants for shear wave under compression were larger than those under tension. In contrast, those for longitudinal waves under compression were smaller. The standard deviations of the acoustoelastic constants had large values, as shown in Table 2. Large variations in the constants have also been reported in previous studies.[16–18] The origins of the large variations may be considered to be a natural, intrinsic property of wood.

Comparison of acoustoelastic effect for stress measurement with strain-gauge method

The acoustoelastic effect was evaluated and compared with that determined by strain-gauge method for the purpose of stress measurement in wood. The strain-gauge method has been a useful, general technique for stress measurement of solid materials. The fundamentals of the strain-gauge method are expressed as follows:

$$\Delta R/R = K_g \cdot \varepsilon \qquad (3)$$

where ε is the strain, R the electric resistance, $\Delta R/R$ is the relative change of the resistance due to the deformation, and K_g is the so-called gauge factor whose values generally lies in the range 2.0–4.0.[22,23]

In contrast to the above equation, for strain and electric resistance the acoustoelasticity equation is expressed as follows:

$$\Delta V/V = K \cdot \sigma = K \cdot E \cdot \varepsilon \qquad (4)$$

where $\Delta V/V$ is the relative change of the wave velocity, and E is the modulus of elasticity. Comparing the two equations, the term $(K \cdot E)$ in the acoustoelasticity equation can be considered to be equivalent to the gauge factor K_g in the strain gauge equation. Supposing K and E assume values of $2.00 \times 10^{-4}\,\mathrm{MPa}^{-1}$ and 10GPa for wood, then the $(K \cdot E)$ value for wood is 2.00. In comparison, for metals the values of K and E are $1.56 \times 10^{-5}\,\mathrm{MPa}^{-1}$ and 71GPa, respectively, for aluminum, and $3.00 \times 10^{-6}\,\mathrm{MPa}^{-1}$ and 210GPa for soft steel. Their $(K \cdot E)$ values are 1.10 and 0.63, respectively. Comparing the values of $(K \cdot E)$ in the acoustoelastic equation to that of K_g in the strain-gauge equation, it is seen that the acoustoelasticity gives more or less the same degree of sensitivity for stress measurement as does the strain-gauge method.

Conclusions

The effect of uniaxial stresses on ultrasonic wave velocity propagating in wood specimens normal to the direction of the applied stress was investigated experimentally. The results obtained can be summarized as follows: At low stress levels, different acoustoelastic behaviors were observed depending on the mode of ultrasonic waves as a result of the application of stresses. For example, shear wave velocity decreased with increases in compressive stress and increased with increases in tensile stress.

The absolute values of the acoustoelastic constants obtained in this study were smaller than those reported in previous studies but were still larger than those of metals. Experimental conditions, such as the type of ultrasonic wave being considered and the direction of propagation vis-à-vis the direction of applied stress, were seen to affect the acoustoelastic behavior of wood. The ultrasonic wave velocity propagating through wood changed with the application of stress; and the sensitivity of the acoustoelastic effect, as measured by $(K \cdot E)$, was seen to be more or less of the same magnitude as that of the gauge factor in the strain-gauge method.

These findings suggest that the acoustoelastic technique could potentially be applied to determination of the stress conditions of wood. However, the values of the acoustoelastic constants showed large variations, and the origins and the mechanism of the changes in ultrasonic velocities have not yet been explained for wood. Further experimental and theoretical investigations are needed to understand this mechanism so as to be able to develop further the acoustoelastic technique for stress measurement in wood.

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