# EFFECTS OF CYCLIC LOADING ON VELOCITIES OF ULTRASONIC WAVES PROPAGATING THROUGH WOOD

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ABSTRACT

The aim of this study was to determine the acoustoelastic phenomenon of wood under cyclic loading–unloading processes. Compression or tension load was repeatedly applied to wood specimens within an elastic range. Ultrasonic waves used in this study were shear and longitudinal waves, and their propagation directions were normal to, and along, the loading directions. The ultrasonic wave velocities were obtained by the sing-around method, which is a method for measuring transit time of ultrasonics. The experimental results revealed that change in the velocity of ultrasonic waves passing through wood under axial stress was a nearly linear function of applied stress level with similar slope for both loading and unloading cycles. The acoustoelastic effect of wood was found to be a repeatable and reversible phenomenon. The acoustoelastic constant seemed to maintain a fixed value regardless of the number of loading cycles. The acoustoelastic technique could be used in the determination of stress conditions of structural components in timber construction.

*Keywords:* Acoustoelastic effect, ultrasonic wave velocity, shear wave, longitudinal wave, wood.

## INTRODUCTION

Since Benson and Raelson proposed a new method for experimental stress analysis using ultrasonic waves (Benson and Raelson 1959), much attention from an engineering viewpoint has been given to the physical phenomenon, that is, the stress dependence of the propagation velocity of ultrasonic waves. They called this phenomenon "acoustoelasticity" or "acoustoelastic effect" for the first time. Many research results of the acoustoelastic effect and its engineering applications were reported for metallic materials, such as aluminum, copper, and iron (Clark et al. 1983; Fukuoka et al. 1983; Hsu 1974; Imanishi et al. 1982; Okada 1981). This phenomenon, which is analogous to the change of light speed in a stressed transparent body (the photoelastic effect), was accepted as the basis of not only a new technique for experimental stress analysis but also a nondestructive technique for measuring residual stress in metals and ceramics. The nondestructive evaluation of residual stress, for example, is one of the paramount features of this technique (Arai and Kobayashi 1990; Fukuoka et al. 1983). Recently, the word "acoustoelasticity" has been used to indicate the ultrasonic characterization of stress and materials.

As regards wood, experimental studies were carried out by the authors for the first time. The results revealed the existence of acoustoelastic phenomenon in wood, and changes in ultrasonic wave velocities were given as a function of the applied stresses (Hasegawa et al. 2000; Sasaki et al. 1995, 1997, 1998). In addition, the estimation of bending stress distribution in wood beams as a construction

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member was attempted by measuring ultrasonic wave velocities, that is, by means of the acoustoelastic method. The possibility of stress measurement was discussed (Sasaki et al. 2001).

Wood is a living material that exists naturally. As building material, wood is one of the simplest, most easily used products. At the same time, wood is one of the most complex materials. Sometimes wood shows an interesting physical phenomenon. For example, an irreversible dimensional change occurs when green wood is heated in water. This irreversible phenomenon is discussed in relation to the recovery of growth strains and is called "thermal recovery" (Kübler 1959, 1973; Kübler et al. 1973; Perkitny and Helinska-Raczkowska 1966; Sasaki and Okuyama 1983; Sharma et al. 1978; Yokota and Tarkow 1962).

To apply the acoustoelastic effect in the stress determination of wood, the acoustoelastic phenomenon is required to be reversible and to show the same behavior throughout the loading–unloading cycle in wood as a construction member. In the present study, the aim was to investigate the acoustoelastic phenomenon of wood under cyclic loading. This research focused on the influence of the loading–unloading cycle on the acoustoelastic phenomenon of wood, the results of which should confirm the application of this technique to the determination of the stress condition in wood.

## MATERIALS AND METHODS

### *Specimens*

The materials used in this experiment comprised four species, i.e., two softwood and two hardwood species: 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 each test. The dimensions of the test specimens were 6 cm (longitudinal) × 3 cm (tangential) × 2 cm (radial) for compressive loading tests and 25 cm (longitudinal) × 3 cm (tangential) × 1.5 cm (radial) 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. The properties of the specimens are shown in Table 1.

TABLE 1. *Properties of specimens used in this study.*

| Specimen | Average moisture content (%) | Average air-dried density ($g/cm^3$) | Average Young's modulus (Gpa) |
|---|---|---|---|
| Alaska cedar | 8.52 (1.36) | 0.46 (0.02) | 9.71 (0.84) |
| Japanese cypress | 8.41 (0.81) | 0.41 (0.01) | 10.6 (1.35) |
| Ash | 8.64 (2.07) | 0.53 (0.05) | 10.4 (2.68) |
| Japanese magnolia | 7.90 (0.60) | 0.45 (0.02) | 9.21 (1.44) |

Numbers in parentheses denote standard deviations.

### *Loading–unloading operation*

Axial (compressive or tensile) load was applied parallel to the longitudinal axis of the wood specimen using an Instron-type testing machine. The loading–unloading operation was continuously repeated ten times, within an elastic range of 0–10 MPa. Stress level of 10 MPa was considered to be enough within elastic limit to avoid change in the microstructure of wood. This was the reason for selecting 10 MPa as the uploading limit on the loading–unloading cycle. The length for chucking a tensile loading specimen was 8 cm. Ultrasonic waves were propagated along the radial or longitudinal direction of the wood, that is, normally or parallel to the loading direction. In this report, the former condition is called "perpendicular mode" and the latter, "parallel mode." The experimental design is summarized in Table 2.

### *Measurement of ultrasonic wave velocity*

Ultrasonic wave velocities of the wood loading tests were measured by the sing-around method, using the UVM-2 model (a commercially available sing-around unit made

TABLE 2. *Experimental design of this study.*

| Propagation mode | Wave | Stress |
|---|---|---|
| Perpendicular[a] | Shear, Longitudinal | Compressive, Tensile |
| Parallel[b] | Longitudinal | Compressive |

[a] Ultrasonic wave was propagated normally to the stress direction.
[b] Ultrasonic wave was propagated parallel to the stress direction.

by Ultrasonic Engineering Co., Ltd., Tokyo). This method is used for measuring the transit time with very high accuracy and high sensitivity (Negishi and Takagi 1984; Toda 1993). The principle of the method is as follows. An electric signal is transmitted from a generator to an emitter, and is transformed into an ultrasonic pulse. The ultrasonic pulse travels through the specimen, is received by a receiver, and is transformed to an electric signal, which is visualized by an oscilloscope. Triggered by this received pulse, the next pulse transmission waits for a fixed delay time until reverberation of the ultrasonic wave vanishes. After waiting for a fixed delay time, the next pulse is transmitted. This operation is repeated many times and is called "sing-around." The periodic time of the sing-around operation is counted by a counter, and then the elapsed time between transmission and reception is measured. The UVM-2 sing-around unit performs these procedures automatically. In this experimental procedure, the repetition number of sing-around operations is adjusted to 10,000. Transducers used in the tests were of the commercially available piezoelectric type for shear and longitudinal waves with a center frequency of 0.5 MHz and a diameter of 1 inch (models CR-0016-SA for shear waves and CR-0016-S for longitudinal waves, made by Harisonic Laboratories, CT). Frequency also affects ultrasonic velocities. High-frequency is better for velocity measurement accuracy. However, transceiver can not receive high-frequency signals traveling through specimens because of the great attenuation of wood. The frequency of 0.5 MHz was selected for this experiment. Coupling media such as epoxy resin AR-R30 for shear wave transducers and silicone grease SH-111 for longitudinal wave transducers were used to ensure bonding of the transducers to the wood specimen (Bucur 1995; Toda 1993). The ultrasonic wave velocity was calculated by dividing the periodic time of the sing-around operation by the distance between the transducers.

The ratio of a specimen's width to the transducer's diameter will have some effect on the magnitude of velocities. However, it will have no effect on the qualitative tendencies of acoustoelastic effect. The measurement of ultrasonic velocities is different whether the transducers are mounted opposite on tangential or radial faces owing to the anisotropy of wood. In this current study, the tangential direction of wood was not selected as the propagation direction of ultrasonic wave. The propagation direction was made to coincide with the radial or longitudinal direction. That is, the transducers were mounted opposite on tangential face or cross-cut area. Because the ultrasonic measurements could not be performed well in the tangential direction as shown in the previous report (Sasaki et al. 1998), transducers could not receive the ultrasonic pulse traveling through in the tangential direction. The highest attenuation is expected in this direction in which no continuous structural elements exist (Bucur 1995).

The equipment for stress, strain, displacement, and velocity measurements was connected to a personal computer, and all data were digitally recorded. The experiments were conducted in an air-conditioned chamber at 24°C and 55% relative humidity.

### *Perpendicular mode*

Throughout the loading–unloading cycles, cross-head speeds of 0.3 mm/min and 1.0 mm/min were applied to the specimen under compressive and tensile loading tests, respectively. In the perpendicular mode, the ultrasonic waves were propagated along the radial direction of the wood, normal to the loading direction. Figure 1 shows a photograph of the setup for acoustoelastic measurements in wood

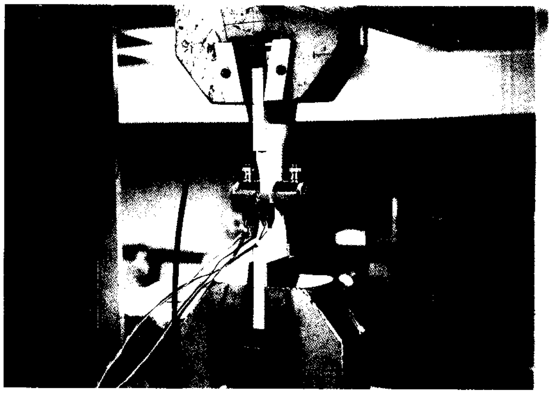

FIG. 1. Setup for acoustoelastic measurement in wood specimen under tensile loading.

FIG. 2. Duralumin holder protecting transducer from compressive load in the parallel mode experiment. Left: ultrasonic transducer; center: ultrasonic transducer inserted in the duralumin holder; right: wooden cube sample 3 × 3 × 3 $cm^3$ (not used here).

specimens. Rubber bands were used to fix the transducers to the specimen.

The ultrasonic waves considered in this mode were shear and longitudinal waves. For the shear waves, the mode with particle motion in the loading direction was considered.

During the loading–unloading operation, the distance between the transducers was changed by Poisson's effect. To correct the change in distance for the calculation of velocity, strains in the radial direction of the wood specimen were measured by strain gages during loading. Strain gages (5 or 10 mm long) were attached to the symmetrical surfaces of the radial section of the specimen for measuring strains along the wave propagation and loading directions. Using these strain gages and the load cell, the stress–strain relationships were also obtained.

### *Parallel mode*

In the parallel mode, only compressive load was applied to the wood specimen. Throughout the loading–unloading cycles, a cross-head speed of 1.0 mm/min was applied to the specimen. The ultrasonic waves considered in this mode were longitudinal waves and were propagated along the longitudinal direction of the wood, parallel to the loading direction. To protect the transducers from compressive loading, special holders made of duralumin were used, as shown in Fig. 2. Compressive load against a wood specimen was applied through these holders. The ultrasonic wave velocity traveling through these duralumin holders is also influenced slightly by the load. To prevent this influence on ultrasonic wave velocity measurements, the propagation time of the ultrasonic pulse through the duralumin holders was measured as a function of the load in advance, without the wood specimen. The propagation time through the specimen and the holders was then measured by subtracting the time without the specimen as a function of load.

For stress–strain measurements, load cell and strain gages were used. Strain gages (10 mm long) were attached to the center of the symmetrical surface along the stress axis of the specimen. Longitudinal dimensional changes of the specimen during the test were measured by a high-sensitivity electric displacement meter. For the calculation of the ultrasonic wave velocity, the distance between the ultrasonic transducers was corrected by this measurement.

## RESULTS AND DISCUSSION

Figures 3–7 show typical results of experimentally obtained relationships between stress and strain and between stress and ultrasonic wave velocities under cyclic loading. The re-

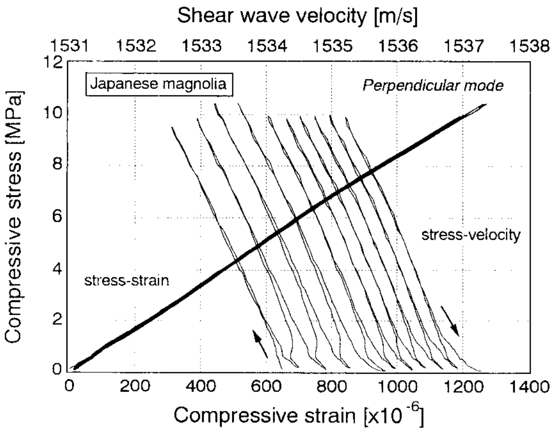


FIG. 3. Relationships between compressive stress and strain, and between stress and velocity of shear wave propagating perpendicular to the loading direction for Japanese magnolia.

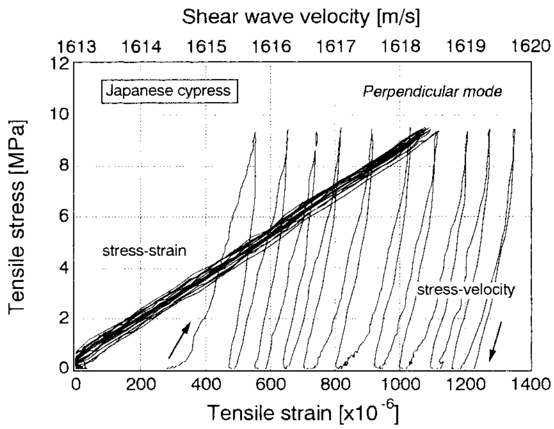


FIG. 4. Relationships between tensile stress and strain, and between stress and velocity of shear wave propagating perpendicular to the loading direction for Japanese cypress.

sults were dependent on the wave mode (shear or longitudinal) and the applied stress (compressive or tensile), but independent of the wood species. The stress–strain relationships and stress–velocity relationships were represented by nearly straight lines, and showed almost the same tendency regardless of the loading–unloading cycle.

### *Changes in shear wave velocities in perpendicular mode under cyclic loading*

Figure 3 shows the relationships between stress and strain and between stress and shear wave velocity for Japanese magnolia under cyclic compressive loading. The shear wave velocity decreased with increasing compressive stress. After the stress reached approximately 10 MPa, the shear wave velocity increased with decreasing stress, following almost the same path in the stress–velocity relationship. The trend of velocity change during the second loading–unloading cycle was similar to that seen in the first loading–unloading cycle. The phenomenon of velocity decrease that was shown during compressive loading in the perpendicular mode was also observed in our previous report (Hasegawa et al. 2000).

Figure 4 shows the stress–strain curves obtained and changes in ultrasonic shear wave velocities for Japanese cypress under cyclic tensile loading. The velocity increased with increasing tensile stress and decreased with decreasing stress. This trend of velocity change was in contrast to that shown in Fig. 3. The stress–velocity relationships showed almost the same tendency during the loading and unloading process. The relationship between velocity and stress shifted to the right in each figure with an increasing number of loading–unloading cycles. However, the degree of shift seemed to become small gradually. A similar behavior was obtained with other species in this experimental mode.

### *Changes in longitudinal wave velocities in perpendicular mode under cyclic loading*

Figures 5 and 6 show relationships between stress and strain and between stress and longitudinal wave velocity for ash. The results for the longitudinal wave were different from those for the shear wave. As shown in Fig. 5, the velocity increased with increasing compressive stress and decreased with decreasing stress. On the other hand, as shown in Fig. 6, the velocity decreased with increasing tensile stress. The relationship between velocity and stress shifted to the right in the figures, in the same manner as shear waves. The relationship

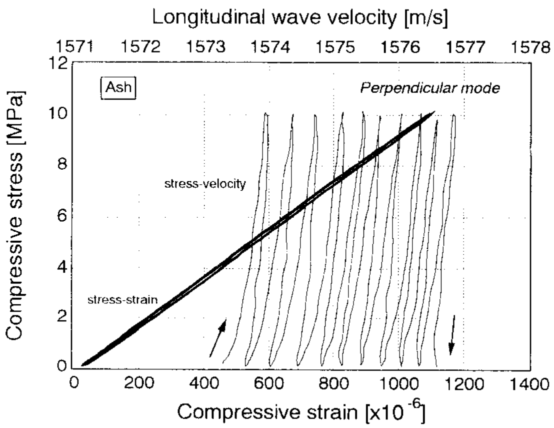


FIG. 5. Relationships between compressive stress and strain, and between stress and velocity of longitudinal wave propagating perpendicular to the loading direction for ash.

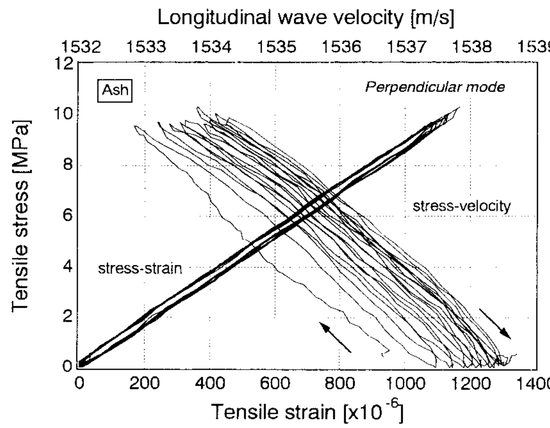


FIG. 6. Relationships between tensile stress and strain, and between stress and velocity of longitudinal wave propagating perpendicular to the loading direction for ash.

between applied stress and ultrasonic wave velocity in the perpendicular mode was reproducible under the cyclic loading–unloading process, and a reversible phenomenon was observed.

### *Changes in longitudinal wave velocities in parallel mode under cyclic loading*

Figure 7 shows relationships between stress and strain and between stress and longitudinal wave velocity in the parallel mode for Japanese cypress under cyclic loading. The wave velocity increased with increasing compressive stress and decreased with decreasing stress, forming a loop. The relationship between stress and velocity shifted to the right in the figure; however, the degree of shift seemed to become small gradually. The velocities of longitudinal waves in the parallel mode were approximately five times as high as those in the perpendicular mode, as shown in Figs. 5 and 6. Changes in velocity due to stress in the parallel mode were large compared with those in the other experimental mode shown in Figs. 3–6. This means that the ultrasonic wave velocity in the parallel mode shows greater sensitivity to the applied stress than in the perpendicular mode.

From these experimental results, it was found that the acoustoelastic effect of wood was a reproducible and reversible phenomenon.

Changes in velocity with applied stress were due to differences in material, ultrasonic wave mode, and wave propagation direction, among others. The magnitude and sign of velocity changes also varied markedly. For metallic materials, the velocities of ultrasonic waves under uniaxial stress change slightly with increasing stress. There exists an obvious linear relationship between them, and changes

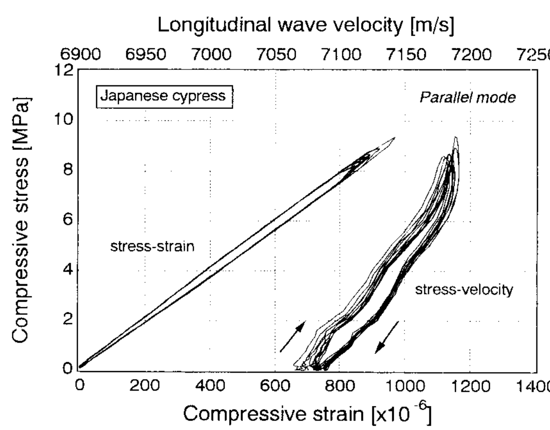


FIG. 7. Relationships between compressive stress and strain, and between stress and velocity of longitudinal wave propagating parallel to the loading direction for Japanese cypress.

in the velocities for these materials are smaller than those for wood (Hsu 1974). The origin of the changes in the propagation velocities of ultrasonic waves is said to be the changes in the densities and the elastic moduli of the materials (Iwashimizu 1994). As a result of stress application to an elastic material, the density and the elastic modulus of the material are considered to change. This change is considered to lead to a change in the propagation velocity of ultrasonic waves. In addition to this, the phenomenon observed in wood is considered to be related to its complex cellular structure. However, the reason for the shift of the stress–velocity relationship to the right in the figures with increasing number of loading cycles remains unknown.

### *Changes in acoustoelastic constants under cyclic loading*

From the results depicted in Figs. 3–7, the relationship between the relative change in ultrasonic wave velocity and the applied stress can be obtained. The relative change in velocity is expressed as $(V - V_0)/V_0$, where $V$ is the velocity for an arbitrary stress and $V_0$ is the velocity for the natural state (zero stress and zero strain). The acoustoelastic constant is also expressed as a proportional constant in the relation between the relative change in velocity and stress, and is shown as follows: $(V - V_0)/V_0 = K \cdot \sigma$, where $K$ is the acoustoelastic constant and $\sigma$ is the applied stress. To determine the stress condition of a material by the strain gage method, for example, Young's modulus is always necessary. Similar to this, the acoustoelastic constant is just as necessary for the acoustoelastic technique. In this section, the effects of cyclic loading on the acoustoelastic constants are discussed.

Figure 8 shows an example of the relationship between the acoustoelastic constant and the number of loading–unloading cycles in tension for Japanese cypress in the perpendicular mode. The relationships in the figure were obtained from the data plotted in Fig. 4. A difference in the acoustoelastic constants between loading and unloading processes can be found in Fig. 8. The difference became smaller with an increasing number of loading cycles and seemed to converge to a constant value. When the two values of the constants in each loading–unloading cycle were averaged, the averaged acoustoelastic constants were found to be almost fixed values regardless of the number of cycles, as shown in Fig. 8.

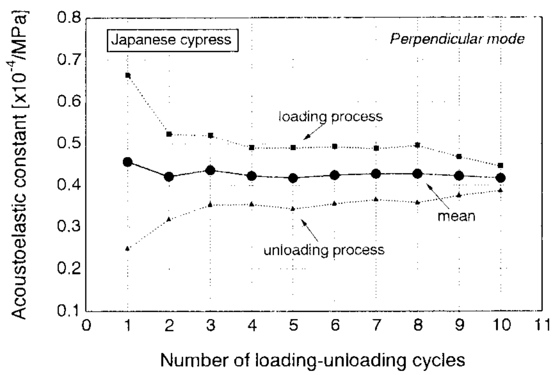


FIG. 8. Changes in acoustoelastic constants of shear wave propagating perpendicular to the loading direction in tension for Japanese cypress.

Figure 9 shows the relationships between the averaged acoustoelastic constants and the number of loading cycles. Data shown in Fig. 9 are the plot of all 4 wood species in the perpendicular mode. In Fig. 9, S and L following species name denote shear and longitudinal waves, respectively, and C and T denote compression and tension, respectively. The averaged acoustoelastic constant for each species showed almost fixed value regardless of the number of cycles, as shown in the figure. It was found in a previous study that the sign of the acoustoelastic constant in the perpendicular mode depended on the wave type, being positive for shear waves and negative for longitudinal waves, regardless of the applied stress (Hasegawa et al. 2000). Similar results on the signs of the constants were also obtained in this study.

Figure 10 shows the relationships between the averaged acoustoelastic constants and the number of loading cycles in the parallel mode. The same tendency as that shown in Fig. 9

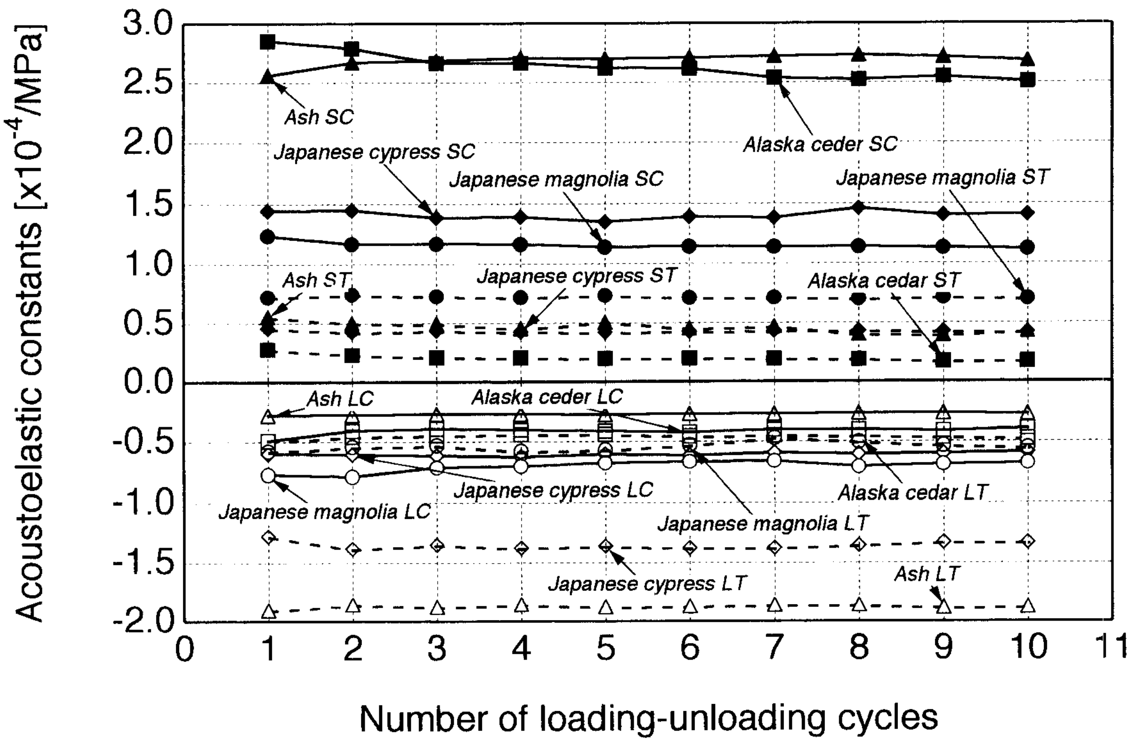


FIG. 9. Changes in mean values of acoustoelastic constants in the perpendicular mode. The symbols S and L following species denote shear and longitudinal waves, respectively, and C and T denote compression and tension, respectively.

was observed. The average values of the acoustoelastic constants in that loading–unloading process seemed to remain constant regardless of the number of cycles, and the same result as that shown in Fig. 9 was observed.

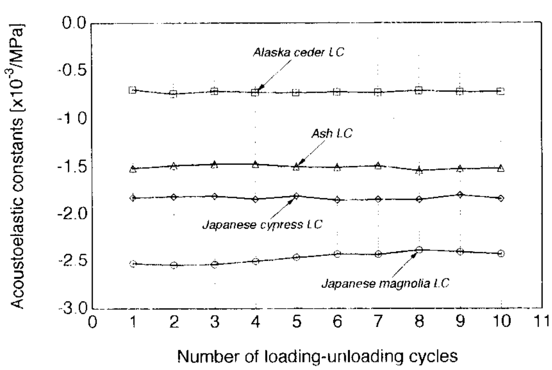


FIG. 10. Changes in mean values of acoustoelastic constants in the parallel mode. The symbols L and C following species denote longitudinal wave and compression, respectively.

The mean values and standard deviations for the acoustoelastic constants for each wood species as plotted in Figs. 9 and 10 are summarized in Table 3, including their testing method and mode. The absolute values of the constants in the parallel mode were about one order of magnitude larger than those in the perpendicular mode. Variance of the mean values is small, and the averaged acoustoelastic constants are confirmed to keep constant for each loading–unloading cycle. As shown in the previous paper, the magnitude of the acoustoelastic constants depended on the relationship between the propagation direction of ultrasonic waves and the direction of the applied stress (Hasegawa et al. 2000; Sasaki et al. 1997). It was also confirmed that the loading–unloading process had no influence on the acoustoelastic effect. The acoustoelastic phenomenon of wood was reproducible, and the acoustoelastic constants showed almost

TABLE 3. *Acoustoelastic constants of wood obtained from this experiment.*

| Species | Mean value (×10 ⁻⁴/MPa) | Wave | Stress | Propagation mode | Remarks |
|---|---|---|---|---|---|
| Alaska cedar | 2.63 (0.12) | Shear | Compressive | Perpendicular | Fig. 9 |
| | 0.20 (0.03) | Shear | Tensile | | |
| | −0.41 (0.03) | Longitudinal | Compressive | | |
| | −0.46 (0.02) | Longitudinal | Tensile | | |
| Japanese cypress | 1.41 (0.03) | Shear | Compressive | | |
| | 0.43 (0.01) | Shear | Tensile | | |
| | −0.60 (0.01) | Longitudinal | Compressive | | |
| | −1.36 (0.03) | Longitudinal | Tensile | | |
| Ash | 2.67 (0.05) | Shear | Compressive | | |
| | 0.46 (0.05) | Shear | Tensile | | |
| | −0.27 (0.00) | Longitudinal | Compressive | | |
| | −1.87 (0.01) | Longitudinal | Tensile | | |
| Japanese magnolia | 1.15 (0.03) | Shear | Compressive | | |
| | 0.71 (0.01) | Shear | Tensile | | |
| | −0.71 (0.04) | Longitudinal | Compressive | | |
| | −0.54 (0.03) | Longitudinal | Tensile | | |
| Alaska cedar | −7.22 (0.12) | Longitudinal | Compressive | Parallel | Fig. 10 |
| Japanese cypress | −18.3 (0.19) | | | | |
| Ash | −15.0 (0.22) | | | | |
| Japanese magnolia | −24.7 (0.59) | | | | |

Numbers in parentheses denote standard deviation.

fixed values regardless of the number of loading cycles. These findings suggest that the acoustoelastic effect may be used to determine stress conditions in wood samples.

As mentioned before, acoustoelastic phenomena depend on the combination of ultrasonic wave mode, wave propagation direction, and stress direction. The determination of acoustoelastic constant is influenced by acoustic anisotropy. For the application of acoustoelastic effect on the stress analysis in solid-sawn lumber members commonly used in the building construction, further investigations concerning the effects of acoustic anisotropy on the acoustoelastic constants should be made.

## CONCLUSIONS

Stress–strain relationships and velocity–stress relationships were found to be represented by almost straight lines, and followed almost the same path regardless of the loading–unloading cycle. The acoustoelastic effect of wood was found to be a reproducible and reversible phenomenon. The averaged values of the acoustoelastic constants in the loading–unloading process seemed to remain the same regardless of the number of loading cycles. The absence of an effect of the loading–unloading process on the acoustoelastic phenomenon of wood was confirmed. These findings suggest that the acoustoelastic technique may be used in the determination of stress conditions of structural components in timber construction.

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