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Hasegawa, Masumi

Department of Forest and Forest Products Science, Faculty of Agriculture, Kyushu University

Matsumura, Junji

Department of Forest and Forest Products Science, Faculty of Agriculture, Kyushu University

Kusano, Ryoichi

Kumamoto Prefectural Forestry Research Guidance Place

Tsushima, Syunji

Oita Prefectural Agriculture, Forestry, Fisheries Research Center, Forestry Research Institute

他

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Acoustoelastic effect in *Melia azedarach* for nondestructive stress measurement

Masumi Hasegawa ^{a,*}, Junji Matsumura ^a, Ryoichi Kusano ^b, Syunji Tsushima ^c, Yasutoshi Sasaki ^d, Kazuyuki Oda ^a

^a Department of Forest and Forest Products Science, Faculty of Agriculture, Kyushu Univ., 6-10-1 Hakozaki Higashi-ku Fukuoka 812-8581, Japan

^b Kumamoto Prefectural Forestry Research Guidance Place, Japan

^c Oita Prefectural Agriculture, Forestry, Fisheries Research Center, Forestry Research Institute, Japan

^d Graduate School of Bioagricultural Science, Nagoya Univ., Japan

Abstract

The acoustoelastic effect in Japanese fast growing trees was experimentally investigated in order to apply the acoustoelastic technique to nondestructive stress analysis in a timber structure. The velocities of the shear waves propagated through *Melia azedarach* changed depending on the applied stress type (compression or tension). The longitudinal stresses produced in a wood beam under static bending were measured by using the acoustoelastic constants obtained in pure tension and compression tests. The stress values obtained by the acoustoelastic method were in good agreement with those obtained by the strain gauge method and strength of materials formulae. These findings suggested the potential of applying the acoustoelastic effect to determine the stress condition of *M. azedarach*.

Keywords

Acoustoelasticity; Fast growing tree; *Melia azedarach*; Stress analysis; Nondestructive testing;

Shear wave velocity

Main text

1. Introduction

Wood is a natural material that absorbs and assimilates carbon dioxide during the growth process. After a tree is cut, its wood can continue stocking carbon dioxide over a long period. In Japan, *Melia azedarach* and *Choerospondias axillaris* are known as fast growing trees. *M. azedarach* is a broad-leaved deciduous species that grows in the warm regions (distributed in the southwest of Japan, the southern part of the Korean Peninsula and China). These could contribute to the prevention of global warming due to their high ability to stock carbon. Generally, fast growing trees are used as pulping materials due to their high productivity. The fast growing trees rapidly grow for a short period, and have a large diameter of trunk. The utilization of such fast growing trees as a new building material (e.g., posts and beams in timber construction) is expected. Many researchers have investigated the physical and mechanical properties of the *Eucalyptus* species, *Acacia* species, amongst others [1-4]. Matsumura et al. [5,6] reported mechanical properties and variations in the stems of *M. azedarach* and *C. axillaris* and suggested the possibility of using them as new timber materials.

A timber construction can sustain static, dynamic, earthquake load, and wind loads. The stresses resulting from these affect the structure over its entire life. It is thus necessary to evaluate the safety of an existing timber construction for long term use. It is difficult to measure the stress state of structural components by the current technique. The information about the collapse of the timber structures can be known by the current seismic diagnosis system, but not be known which parts of

structures should be repaired. The only members with high-risk condition may be identified by the acoustoelastic technique. This technique is best suitable to maintain the timber structures. Therefore Sasaki et al. [7-10] and Hasegawa et al. [11] have considered the application of the acoustoelastic technique to nondestructive stress measurement in a timber construction.

The acoustoelastic technique is a method for analyzing the stress state in materials using ultrasonic waves. Benson and Raelson [12] reported that the velocities of ultrasonic waves propagated through an elastic material under stress conditions changed due to the applied stress. They called this effect acoustoelasticity in an analogy with photoelasticity, which is used in the analysis of stress distributions in transparent materials by employing light waves. In metals, this method is expected to lead to a commercially viable nondestructive stress analysis for the residual stress [13-15] and axial stress in bolts [16-19]. In the field of wood science, Sasaki et al. [7-9] showed the existence of acoustoelastic phenomena in wood for the first time. These phenomena are dependent on several factors, including the ultrasonic waves, wave propagation direction, and applied stress direction. They also reported that these phenomena were found to be repeatable and reversible against cyclic loading [10]. They indicated that the acoustoelastic technique could be applied to a timber construction with a loading history.

The goal of this study is to estimate the longitudinal stress under static bending in wood beams made of the Japanese fast growing trees of the *M.azedarach* species using the acoustoelastic technique. In a previous study [20], we reported that the acoustoelastic phenomenon in *M. azedarach* for the longitudinal wave mode were not affected by the type of loading (tension or compression). This result

meant that only the stress values could be determined. This was the disadvantage of applying longitudinal waves to estimate the stress condition in *M. azedarach*. In the first series of experiments (tension and compression test), variation in the velocity of ultrasonic shear waves propagating in wood normal to the direction of applied stresses were investigated. In addition, the acoustoelastic constants for this wood species were determined from the relations between velocity changes and stress. In the second series of experiments (beams under static bending), the longitudinal stresses distributions were estimated using the acoustoelastic constants obtained beforehand.

2. Experimental Procedure

2.1 Tension and compression tests

The specimens were processed from air-dried lumber of *M. azedarach*. At least ten specimens were prepared for each one of the test conditions. The dimensions of the test specimens were 60 mm (longitudinal) × 30 mm (tangential) × 20 mm (radial) for the compressive loading test and 250 mm (longitudinal) × 30 mm (tangential) × 15 mm (radial) for the tensile loading test. The test specimens were kept in an air-dried condition prior to the tests.

Both compressive and tensile loads were applied parallel to the longitudinal axes of the wood specimens using an Instron-type testing machine. Crosshead speeds of 1.0 mm/min and 2.0 mm/min were applied to the specimens in the compressive and tensile loading tests, respectively. For the tensile testing, the splints were attached to the both edges of testing specimens by the epoxy resin not to collapse by the

chuck. The length of chuck is 8 cm. As shown in Fig. 1, the ultrasonic shear waves propagated along the radial direction of the wood, i.e., normal to the direction of loading. Under these conditions, the shear waves oscillated parallel to the longitudinal direction of the wood, i.e., the loading direction [9]. The ultrasonic velocities in both the compressive and tensile loading tests for the wood were measured by the sing-around method, using a model UVM-2 unit (Ultrasonic engineering, Tokyo). Piezoelectric transducers with a natural frequency of 0.5 MHz and diameter of 12.7 mm (model S-0008 made by Staveley Instruments, USA) were used to detect the ultrasonic waves. Epoxy resin (AR-R30) was used as a coupling medium to improve the bonding between the transducers and the wood specimen, and a rubber band was employed to press the transducers against the specimen [21]. The equipment for the load, strain and velocity measurements was connected to a personal computer, and the data were automatically recorded.

The sing-around method is a technique for measuring the transit time of ultrasonic waves propagating through a material with very high accuracy. The principle of the method is explained as follows. An electric signal is transmitted from a generator to an emitter, and transformed into an ultrasonic pulse. The pulse travels through the specimen and is received by a transducer, which transforms the mechanical vibration into an electric signal. The signal can then be visualized on an oscilloscope. Because of triggering by this received pulse, the next pulse transmission waits for a fixed delay time until the ultrasonic reverberation vanishes. After waiting for a fixed delay time, the next pulse is transmitted. This operation is repeated many times, and this repeated operation is the so-called

“sing-around”. In this experiment, the number of repetition set out 10000 times. The sing-around periodic time was given by the average values. The sing-around periodic time is counted by a counter, and the elapsed time between emission and reception is measured. The UVM-2 sing-around unit conducts these procedures fully automatically.

The ultrasonic velocity was calculated by dividing the distance between the transducers by the sing-around periodic time. This distance, however, was changed by Poisson's effect during loading. Strains in the radial direction of the specimen were measured with strain gauges during loading to correct the distance between the transducers. Strain gauges (5 or 10 mm long) were attached to the center of the symmetrical surfaces of the radial section of the specimen to measure the strains along the direction of loading and wave propagation.

After tension or compression tests, each specimens were dried in a constant temperature oven at 105 °C overnight. The moisture content (MC) can be calculated as equation (1).

$$MC[\%] = (W_a - W_o) / W_o \times 100 \quad (1)$$

where W_a is the weight in air-dried condition and W_o is the weight in oven-dried condition. The average \pm standard deviations (SD) of the moisture content, Young's modulus, and density were $11.3 \pm 0.41\%$, 12.6 ± 2.09 GPa, and 520 ± 32 kg/m³, respectively.

2.2. Bending tests

The wood beam specimens to be tested under bending processed from the same lumber used in characterization procedure (section 2.1). The dimensions (length \times height \times width) of the specimen were 920 mm \times 70 mm \times 15 mm. Fig. 2 illustrates the bending setup for the ultrasonic velocity measurements

in the wood beam specimen. First, ultrasonic waves were propagated across the width (radial) direction of the wood specimen with no loading. The ultrasonic wave velocity measurement positions were located at seven points at mid-span, as shown in Fig. 2. These seven points were at 0, ± 10 , ± 20 and ± 30 mm from the neutral axis in the height direction of the beam. The oscillation direction of shear waves was aligned with the longitudinal direction of the wood as in the characterization tests (section 2.1).

Following, a load was applied by hanging weights of 196 N at the each specimen edges, as shown in Fig. 2. The length of the span was 200 mm, and the distance between the loading points was 900 mm. Based on this loading method, only bending stresses were created inside the span of the beam. Under loading, the velocity of the ultrasonic waves propagating through the wood was measured at the same positions as in the tests with no loading. The experimental procedures for ultrasonic velocity measurement were identical to section 2.1. Strains were also measured by strain gauges (10 mm long) to compare with the stress values from the acoustoelastic method. They were placed at the 7 points mentioned, alongside the ultrasonic measurement positions (Fig. 2). The above procedures were carried out in an air-conditioned chamber at 24°C and 55% of relative humidity.

3. Stress analysis

According to the acoustoelastic technique, the relation between the ultrasonic wave velocity and applied stress can be expressed as equation (2) [12]. Sasaki et al. [7,8] and Hasegawa and Sasaki [9] also used the same formula to describe the acoustoelastic effects in wood.

$$(V - V_0)/V_0 = K \cdot \sigma_a \quad (2)$$

where V , V_0 , K , and σ_a are an arbitrary velocity, the initial velocity in the un-stressed state, the acoustoelastic constant, and the applied stress, respectively. As observed in eq. (2), the relative velocity variation $[(V - V_0)/V_0]$ is proportional to the applied stress. The proportional constant is called the acoustoelastic constant (K). K is equivalent to Young's modulus, which is used by the strain gauge method, and is very important in the acoustoelastic technique. If the value of K is known beforehand, the stress condition in a material can be estimated by eq. (2). In this study, the values of K were initially determined by the tension and compression tests. In the next step, the longitudinal stresses in a wood beam under static bending were estimated from the two measured velocity values (V , V_0), using the pre-determined values of K .

Using the strain gauge method and strength of materials formulae, the longitudinal stresses

(σ_g , σ_c) were obtained as follows [22,23]:

$$\sigma_g = E \cdot \varepsilon, \quad (3)$$

$$\sigma_c = \frac{12Pay}{bh^3}, \quad (4)$$

where E is Young's modulus in the longitudinal direction, ε is the strain in the longitudinal direction,

P is the bending load, a is the distance between the loading point and supporting point, y is the

vertical distance from the neutral axis, and b and h are the width and height of the wood beam

specimen, respectively. Values of $E_t = 11.4$ GPa (tension) and $E_c = 13.9$ GPa (compression) were

obtained for Young's modulus from the tension and compression tests. E_t was used at the upper half of

the beam and E_c at the lower half. For the strain gauge method, strains were obtained from strain gauges attached to the wood beam specimen, as shown in Fig. 2.

4. Results and Discussion

4.1. Changes in ultrasonic wave velocities propagated transversely to the loading direction

Fig. 3 shows a typical experimental result indicating the relationships between the stress, strain, and shear wave velocity under compressive loading. The shear wave velocity decreased with the increases of compressive stress. As the deformation became more severe beyond the strain level of 0.4%, the decline in ultrasonic velocities was even steeper. Fig. 4 shows a typical experimental result under the tensile stress. It shows the relations between tensile stress and strain, and between tensile stress and shear wave velocity. The stress-strain relation in Fig. 4 can be described by an essentially straight line. The ultrasonic shear wave velocity increased with the increases of the tensile stress from the beginning of the tensile loading. As compared to the acoustoelastic phenomenon in the previous reports [9-10], those of *M. azedarach* for the shear wave mode showed no difference. The average \pm SD of the initial velocities were 1529.8 ± 30.4 m/s and 1574.3 ± 31.7 m/s for the compressive and tensile tests, respectively. This difference in the initial velocities was not an effect of the applied stress type but rather the result of using different specimens. In the range of 0 to 10 MPa, the wave velocities decreased by 0.04% with the increases of compressive stress and increased by 0.08% with the increases of tensile stress (Figs. 3 and 4). The variation of shear wave velocity under tensile stress was larger than that under compressive stress,

thus depending on the type of applied stress (compression or tension). The variation per unit stress, i.e., the relative velocity variation, is explained in detail in the next section.

For the longitudinal wave technique, the velocity decreased with the increase of the compressive or tensile stress from the beginning of the loading, as mentioned in the work of Hasegawa et. al[20]. The longitudinal wave velocity variation is independent of the applied stress type (tension or compression). As shown in Figs. 3 and 4, the shear wave velocity was observed to be dependent on the applied stress type. These results indicate that the shear wave technique is a more suitable tool than that of longitudinal waves for analyzing stresses type in wood structures.

The variations of the shear wave velocity with the applied stress were due to differences in the materials, wave propagation direction and loading, as well as the mode of the ultrasonic waves. In the case of wood, when the wave propagation direction agrees with the loading direction (longitudinal wave), the wave velocity increases with the applied compressive stress. In the radial or tangential direction, i.e., perpendicularly to the longitudinal axis of the wood, it decreases [7,8]. In metals such as 99.9% pure copper, the ultrasonic shear wave velocity is known to decrease only slightly with an increasing magnitude of compressive stresses [24]. A similar behavior was obtained in the present study. However, ultrasonic shear waves in 0.01% carbon iron and 99.5% pure aluminum have shown behaviors that were the inverse to that seen at low stress levels in this study [24]. Metals clearly exhibit linear relations between the wave velocities and stresses, but the wave velocity variation in metals is typically smaller than in wood.

The ultrasonic velocity is given as the square root of the Young's modulus divided by the density. Bergman and Shahbender [25] reported that the velocity variation of ultrasonic waves propagated through metals could be explained as changes in Young's modulus and density due to the applied stress. In the field of wood science, such changes in Young's modulus or density as a function of the applied stress have not yet been confirmed. The velocity changes in wood may be closely connected with the structure of the natural anisotropic material, as mentioned in previous studies [7-9]. Further research is needed to clarify these acoustoelastic effects in wood.

4.2. Relative changes in ultrasonic velocities and acoustoelastic constants

To determine the acoustoelastic constants, the relationships between the relative velocity variation and stress were established (Fig. 5). This figure shows the typical relationships between the per centile variation of the shear wave velocity and the applied stress. In the range of stress evaluated under both tension and compression (between -10 and 10 MPa), these relations varied linearly with the applied stress. Positive correlations were thus found between the shear wave velocity changes and the applied stress.

As explained in eq. (2), the slopes of these relationships correspond to the acoustoelastic constants. The average values of these constants are shown in Table 1. Values for other wood species (e.g., *Chamaecyparis nootkatensis* and *Fagus crenata*) [9,10] and metals [24] are also shown in the table for comparison. The constants obtained in this study were positive in sign for both tension and compression tests. This meant that different types of acoustoelastic behavior were observed depending on the applied

stress, as shown in Figs. 3 and 4. The calculated constants for *M. azedarach* are in good agreement with other wood species from previous reports [9,10]. The absolute values were larger than those of metals.

However, the velocity of the ultrasonic waves propagating through *M. azedarach* was more sensitive to the applied stress than in metals, as with the other wood. These findings indicated that the acoustoelastic effect is particularly suited to determine the stress condition of timber from fast growing species such as *M. azedarach*. However, the SD values of the acoustoelastic constants were quite large, as shown in Table

1. Large variations in these constants have been reported in previous reports [7-9]. These large variations may be considered to be a natural, intrinsic property of wood.

4.3. Stress measurement due to a bending load by acoustoelastic method

Table 2 shows an example of the results of shear wave velocities in wood specimens under bending, for unstressed and stressed conditions, considering the geometry of Fig. 2. The measuring position of 0.0 mm in the table corresponds to the neutral axis of a wood specimen under static bending. The values of the initial velocities (V_0) at the compression regions of the beam (-10, -20, and -30 mm from the neutral axis) were bigger than those at the tensile regions (10, 20, and 30 mm). The relative in velocity variations $[(V - V_0)/V_0]$ were positive at the tensile regions of the beam and negative at the compression ones.

The previous section reported that the shear wave velocity decreased under compressive stresses and increased under tensile ones (Figs. 3 and 4). According to these results, the upper half of the beam was judged to be under tension and the lower one under compression. The estimated stresses in the wood beam specimen under bending were in those agreement with the predicted ones. Assessment of a tension

or compression loading could be expressed in terms of a positive or negative relative variation of wave velocity, respectively.

Fig. 6 shows the distributions of the longitudinal stresses due to the bending load obtained by the acoustoelastic method, the strain gauge method and strength of materials formulae (σ_a , σ_g and σ_c , respectively). For the acoustoelastic method, the average values of K for a tensile load were used at the upper half of the beam, and those for a compressive load at the lower half. As shown in Fig. 6, there are only minor differences in the stress values obtained by the three methods. This suggests that stresses due to the bending load were adequately estimated by the acoustoelastic method.

5. Conclusions

The effect of the type of applied longitudinal stress and respective magnitude on the velocity of ultrasonic waves propagating transversely to the stress application direction in *M. azedarach* was investigated experimentally in specimens under pure tension and compression. The shear wave velocities decreased with an increase in compressive stress, and increased with an increase in tensile stress. The shear wave velocities variation changed depending on the applied stress. The absolute values of the acoustoelastic constants obtained in this study were identified to other wood species but were bigger than those of metals.

These constants were then applied to predict the longitudinal stresses in a wood beam under static bending. The stress type, i.e., compression or tension could be distinguished from a negative or

positive variation of shear wave velocity, respectively. The magnitude of stresses found with the acoustoelastic method was in good agreement with those obtained by the strain gauge method and strength of materials formulae. These results showed the potential of applying the acoustoelastic effects experimentally to determine the stress condition of *M. azedarach*.

The above findings expand the application capabilities of the acoustoelastic method as a new stress analysis technique in timber construction. However, most timber structures are subjected to loads that are more complicated than the simple bending investigated in this study. We have reported the effects of simple stress states, i.e., pure compression and, tension and bending stresses, on the acoustoelastic behavior of the beam [7-11]. Further research on the influence of complicated stress state, such as combined stress, may also be needed to work toward the practical use of the acoustoelastic technique in the future.

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References

- [1] Yang JL, Waugh G. Potential of plantation-grown eucalypts for structural sawn products. I. *Eucalyptus globulus* Labil. ssp. *globulus*. Australian Forestry 1996; 59(2): 90-98.
- [2] Yang JL, Waugh G. Potential of plantation-grown eucalypts for structural sawn products. II. *Eucalyptus nitens* (Dean & Maiden) Maiden and *E. regnans* F. Muell. Australian Forestry 1996; 59(2): 99-107.
- [3] NK Shukla, Mohan Lal, RS Singh, AK Khanduri. Physical and mechanical properties of *Acacia auriculiformis*, *Fernandoa adenophlla* and *Melia azedarach*. J Timb Dev Assoc 1990; 36(2): 31-45.
- [4] SR Shukla, RV Rao, SK Sharma, P Kumar, R Sudheendra, S Shashikala. Physical and mechanical properties of plantation-grown *Acacia auriculiformis* of three different ages. Australian Forestry 2007; 70(2): 86-92.
- [5] Matsumura J, Inoue M, Yokoo K, Oda K. Cultivation and Utilization of Japanese Fast Growing Trees with High Capability for Carbon Stock I: Potential of *Melia azedarach* (in Japanese). Mokuzai Gakkaishi 2006; 52(2): 77-82.
- [6] Matsumura J, Tanoue M, Ogata R, Gyokusen K, Muta S, Kamiwaki K, Hasegawa M, Oda K. Cultivation and Utilization of Japanese Fast Growing Trees with High Capability for Carbon Stock II: Potential of *Choerospondias axillaris* (in Japanese). Mokuzai Gakkaishi 2007;

53(3): 127-133.

- [7] Sasaki Y, Iwata T, Kuraya K, Ando K. Acoustoelastic effect of wood I. Effect of compressive stress on the velocity of ultrasonic longitudinal waves parallel to the longitudinal direction of the wood (in Japanese). *Mokuzai Gakkaishi* 1997; 43(3): 227-234.
- [8] Sasaki Y, Iwata T, Ando K. Acoustoelastic effect of wood II. Effect of compressive stress on the velocity of ultrasonic longitudinal waves parallel to the transverse direction of the wood. *J Wood Sci* 1998; 44(1): 21-27.
- [9] Hasegawa M, Sasaki Y. Acoustoelastic effect of wood III. Effect of applied stresses on the velocities of ultrasonic waves propagating normal to the direction of the applied stress. *J Wood Sci* 2000; 46(2): 102-108.
- [10] Sasaki Y, Hasegawa M, Iwata Y. Acoustoelastic stress measurement of wood in bending. *Holz Roh- Werkst* 2001; 59(4): 237-243.
- [11] Sasaki Y, Hasegawa M. Effects of cyclic loading on velocities of ultrasonic waves propagating through wood. *Wood Fib Sci* 2003; 35(1): 110-119.
- [12] Benson RW, Raelson VJ. Acoustoelasticity. *Prod Eng* 1959; 30:56-59.
- [13] Crecraft DI. The measurement of applied and residual stresses in metals using ultrasonic waves. *J Sound and Vibration* 1967; 5(1): 173-192.
- [14] Fukuoka H, Toda H, Naka H. Nondestructive residual-stress measurement in a wide-flanged rolled beam by acoustoelasticity. *Exp Mech* 1983; 23(1): 120-128.

- [15] King RB, Fortunko CM. Determination of in-plane residual stress states in plates using horizontally polarized shear waves. *J Appl Phy* 1983; 54(6): 3027-3035.
- [16] Heyman JS, Chern EJ. Ultrasonic measurement of axial stress. *Journal of Testing and Evaluation* 1982; 10(5): 202-211.
- [17] Joshi SG, Pathare RG. Ultrasonic instrument for measuring bolt stress. *Ultrasonics* 1984; 22(6): 270-274.
- [18] Johnson GC, Holt AC, Cunningham B. Ultrasonic method for determining axial stress in bolts. *Journal of Testing and Evaluation* 1986; 14(5): 253-259.
- [19] Chaki S, Corneloup G, Lillamand I, Walaszek H. Combination of longitudinal and transverse ultrasonic waves for in situ control of the tightening of bolts. *Journal of Pressure Vessel Technology* 2007; 129(3): 383-390.
- [20] Hasegawa M, Matsumura J, Oda K, Sasaki Y. Acoustoelastic Effect in Fast Growing Tree for Ultrasonic Stress Measurement, In: *Proceedings BB103-CD of the 9th European Conference on Non-Destructive Testing*. Berlin, 2006; P210.
- [21] Bucur V. *Acoustics of Wood* (2nd ed.), Berlin: Springer-Verlag, 2006. p.80-82.
- [22] Potma T. *Strain gauges: theory and application* (in Japanese), Sekiya T, Sumi S, Sugiyama Y, Sumi N, translator. Tokyo: Kyoritsu Shuppan, 1974. p.107-108.
- [23] Kawada Y. *Strength of materials* (in Japanese), Tokyo: Shokabo, 1984. p.46-55.
- [24] Fukuoka H, Toda H. Preliminary experiment on acoustoelasticity for stress analysis.

Arch Mech 1977; 29(5): 671-686.

- [25] Bergman RM, Shabbender RA. Effect of statically applied stresses on the velocity of propagation of ultrasonic waves. J Appl Phys 1958; 29(12): 1736-1738.

Figure Captions

Fig. 1. Setup for ultrasonic velocity measurement and three orthotropic axes of wood: 1, Loading direction; 2, propagation direction of ultrasonic waves; 3, longitudinal direction of wood; 4, radial direction of wood; 5, tangential direction of wood; 6, electric signal; 7, strain; 8, load; 9, sing-around periodic time.

Fig. 2. Setup for ultrasonic velocity measurement in a wood beam under static bending: 1, Loading direction by hanging weights; 2, electric signal; 3, strain; 4, sing-around periodic time; Numbers $(0, \pm 10, \pm 20, \pm 30)$ in figure show the distance from the neutral axis.

Fig. 3. Relations between compressive stress, strain, and shear wave velocity for *M. azedarach*.

Solid line, stress-velocity curve; *dotted line*, stress-strain curve.

Fig. 4. Relations between tensile stress, strain, and shear wave velocity for *M. azedarach*.

Solid line, stress-velocity curve; *dotted line*, stress-strain curve.

Fig. 5. Relations between the percentile variation of the shear wave velocity and the applied stress for

M. azedarach.

Fig. 6. Longitudinal stresses obtained by the three methods.

Table 1

Calculated acoustoelastic constants of *M.azedarach* and those of other wood species and metals.

Species		Average value [MPa ⁻¹]	Type of stress
Wood	<i>Melia azedarach</i>	0.50×10^{-4} (0.15×10^{-4})	Compressive
		0.77×10^{-4} (0.20×10^{-4})	Tensile
	<i>Chamaecyparis nootkatensis</i> ⁹	1.36×10^{-4} (0.54×10^{-4})	Compressive
		0.49×10^{-4} (0.44×10^{-4})	Tensile
	<i>Fagus crenata</i> ¹⁰	0.78×10^{-4} (0.98×10^{-4})	Compressive
		0.65×10^{-4} (0.54×10^{-4})	Tensile
Metal	Iron ²⁴	-0.95×10^{-5}	Compressive
	Copper ²⁴	-4.52×10^{-5}	Tensile

Numbers in parentheses denote standard deviations.

Table 2

Results of shear waves, relative velocity variations, acoustoelastic constants, and predicted type of stress.

Measuring position* [mm]	V_0 [m/s]	V [m/s]	$(V - V_0) / V_0$	$K [\times 10^{-4} \text{ MPa}^{-1}]$	Predicted type of stress
30	1389.39	1389.94	0.00040	0.77	Tensile
20	1385.55	1385.86	0.00022	0.77	Tensile
10	1397.17	1397.31	0.00010	0.77	Tensile
0	1481.55	1481.58	0.00002	0.77	-
-10	1532.10	1531.97	-0.00009	0.50	Compressive
-20	1593.35	1593.13	-0.00014	0.50	Compressive
-30	1610.93	1610.59	-0.00021	0.50	Compressive

* Measurement position of ultrasonic shear wave velocity from the neutral axis (see Fig. 2)

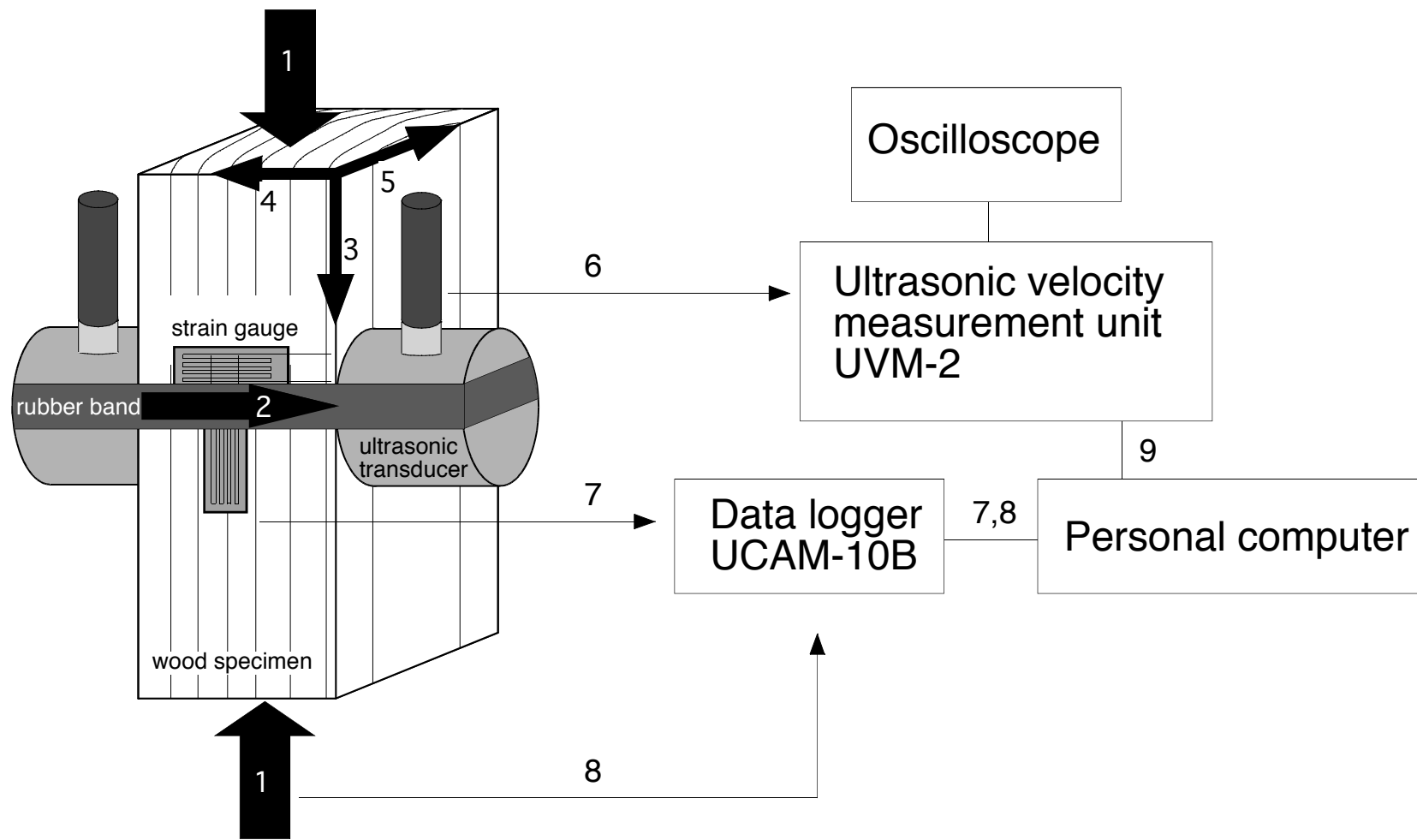


Fig. 1. Setup for ultrasonic velocity measurement and three orthotropic axes of wood: 1, Loading direction; 2, propagation direction of ultrasonic wave; 3, longitudinal direction of wood; 4, radial direction of wood; 5, tangential direction of wood; 6, electric signal; 7, strain; 8, load; 9, sing-around periodic time.

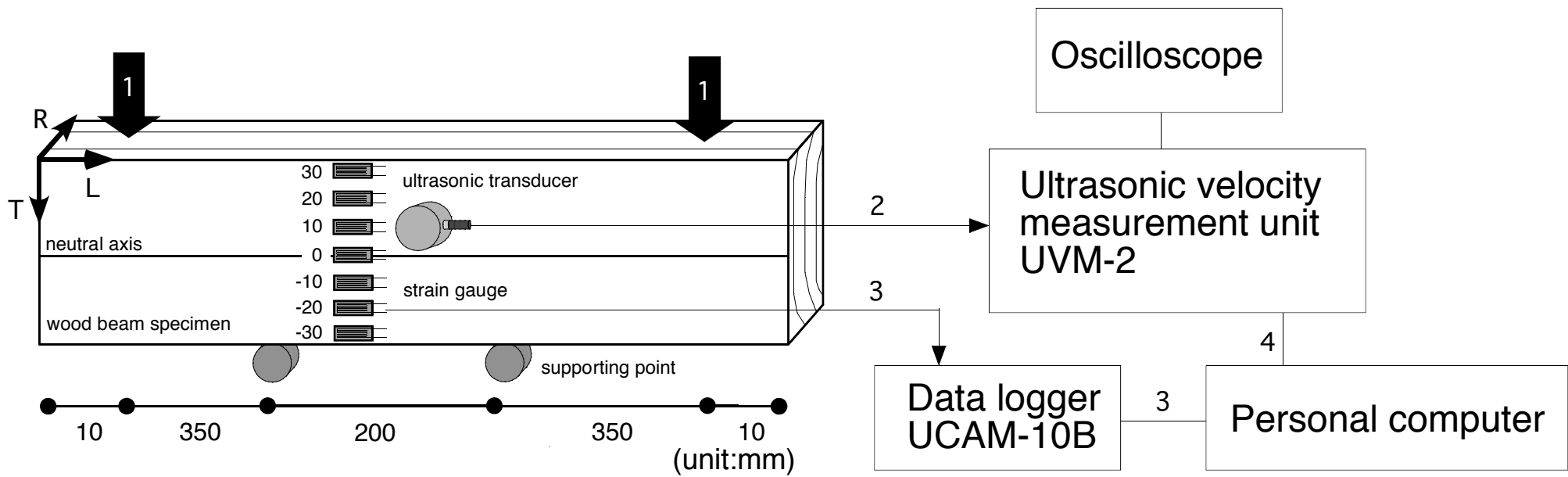


Fig. 2. Setup for ultrasonic velocity measurement in a wood beam under static bending:
 1, Loading direction by hanging weights; 2, electric signal; 3, strain; 4, sing-around periodic time;
 Numbers (0, ± 10 , ± 20 , ± 30) in figure show the distance from the neutral axis.

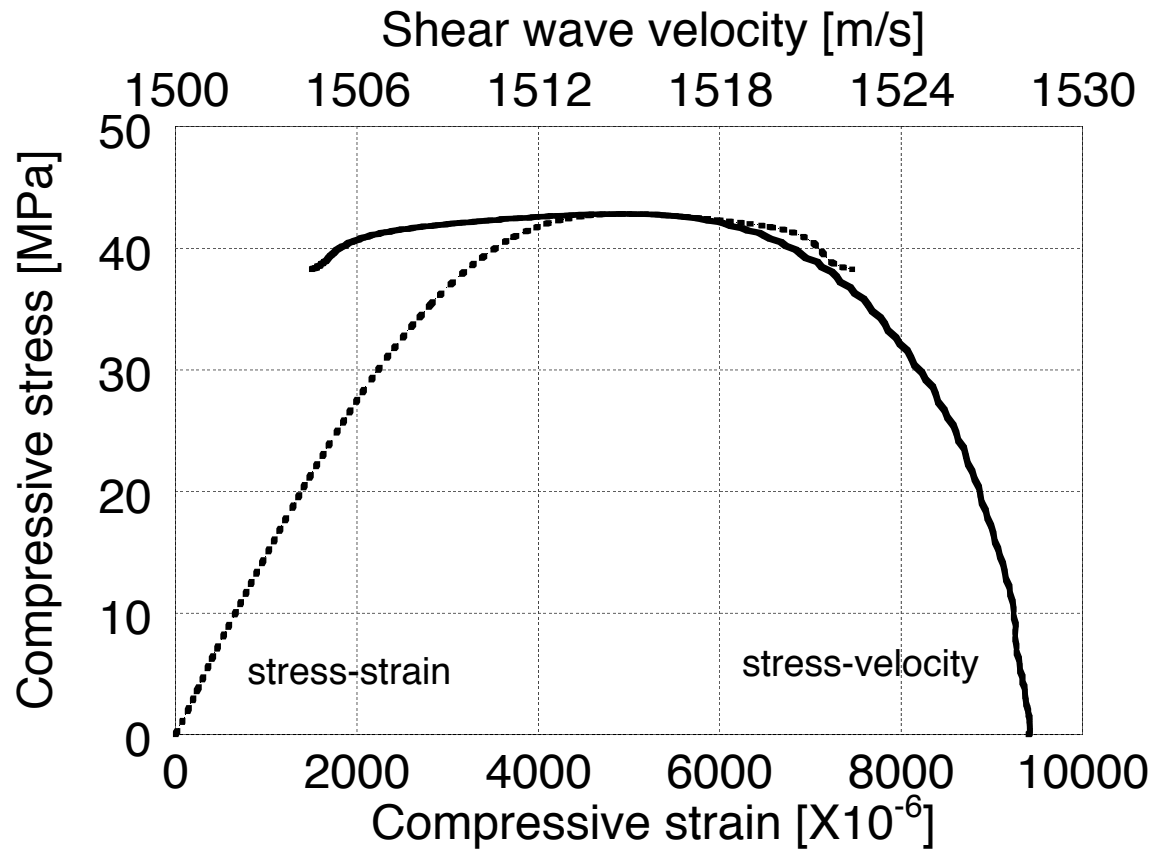


Fig.3. Relations between compressive stress, strain and shear wave velocity for *M. azedarach*. *Solid line*, stress-velocity curve; *dotted line*, stress-strain curve.

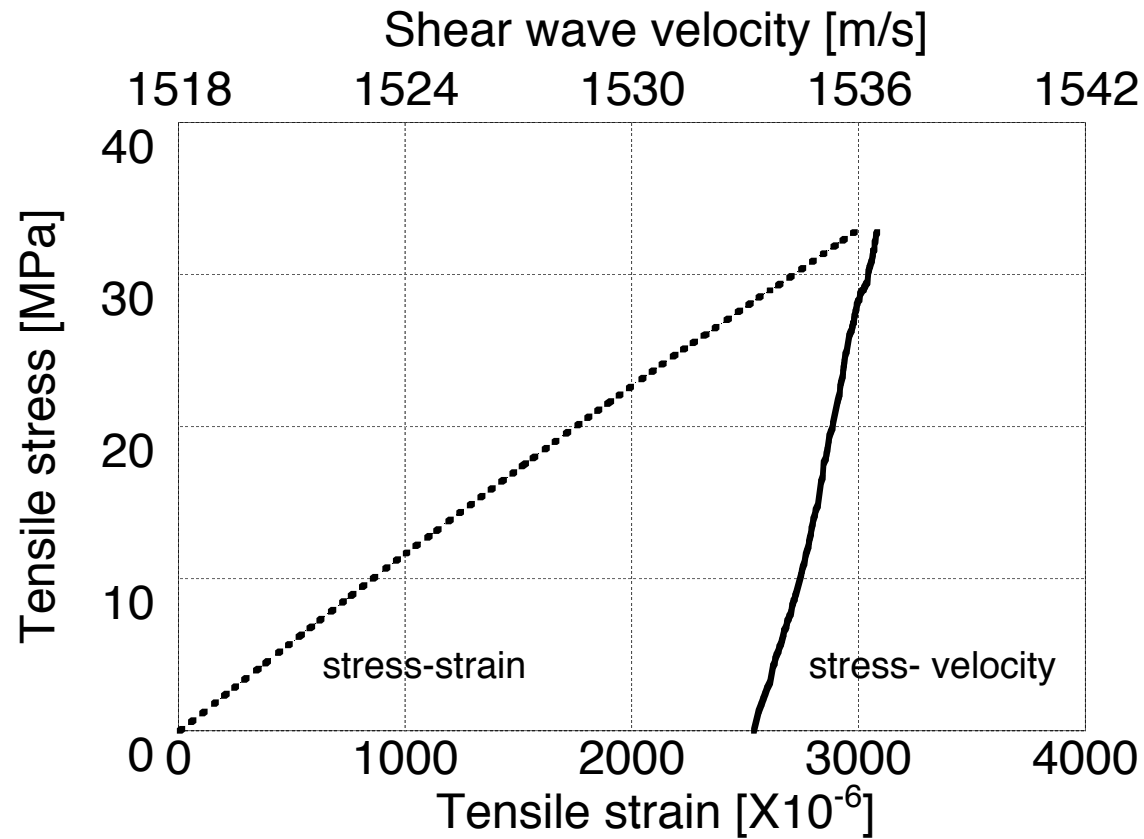


Fig.4. Relations between tensile stress, strain and shear wave velocity for *M. azedarach*. *Solid line*, stress-velocity curve; *dotted line*, stress-strain curve.

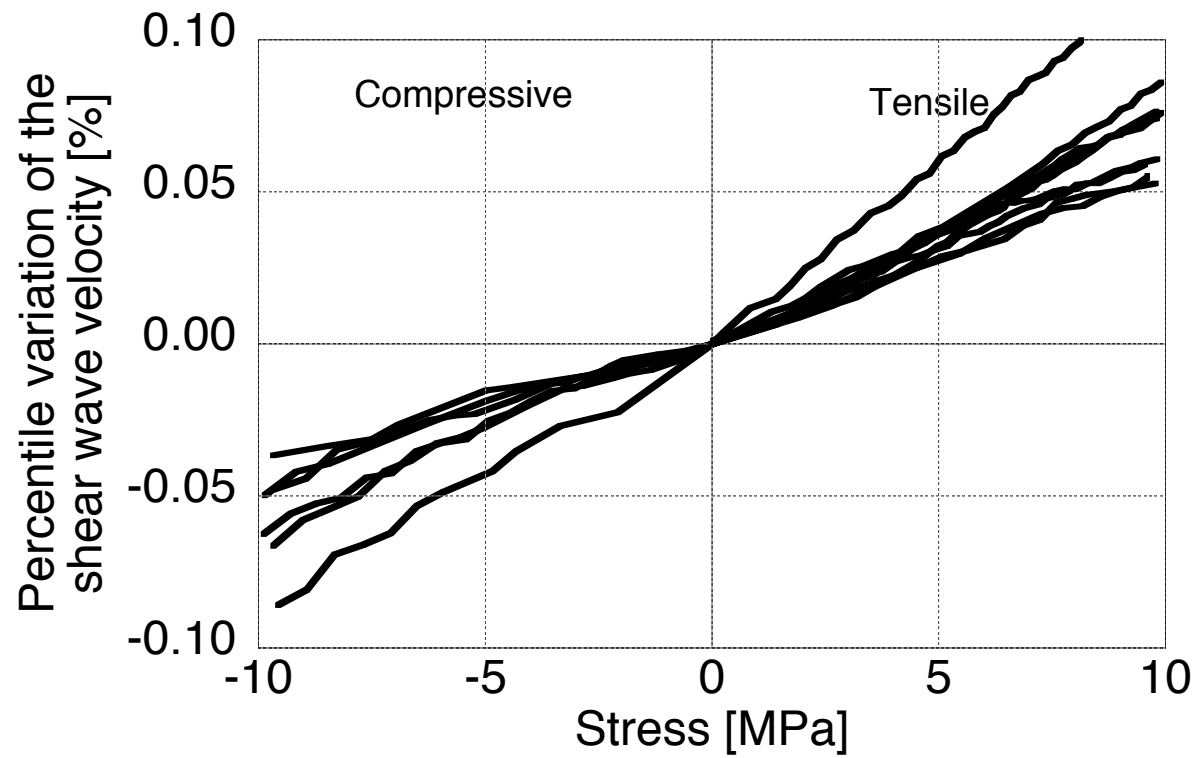


Fig. 5. Relations between the percentile variation of the shear wave velocity and the applied stress for *M. azedarach*.

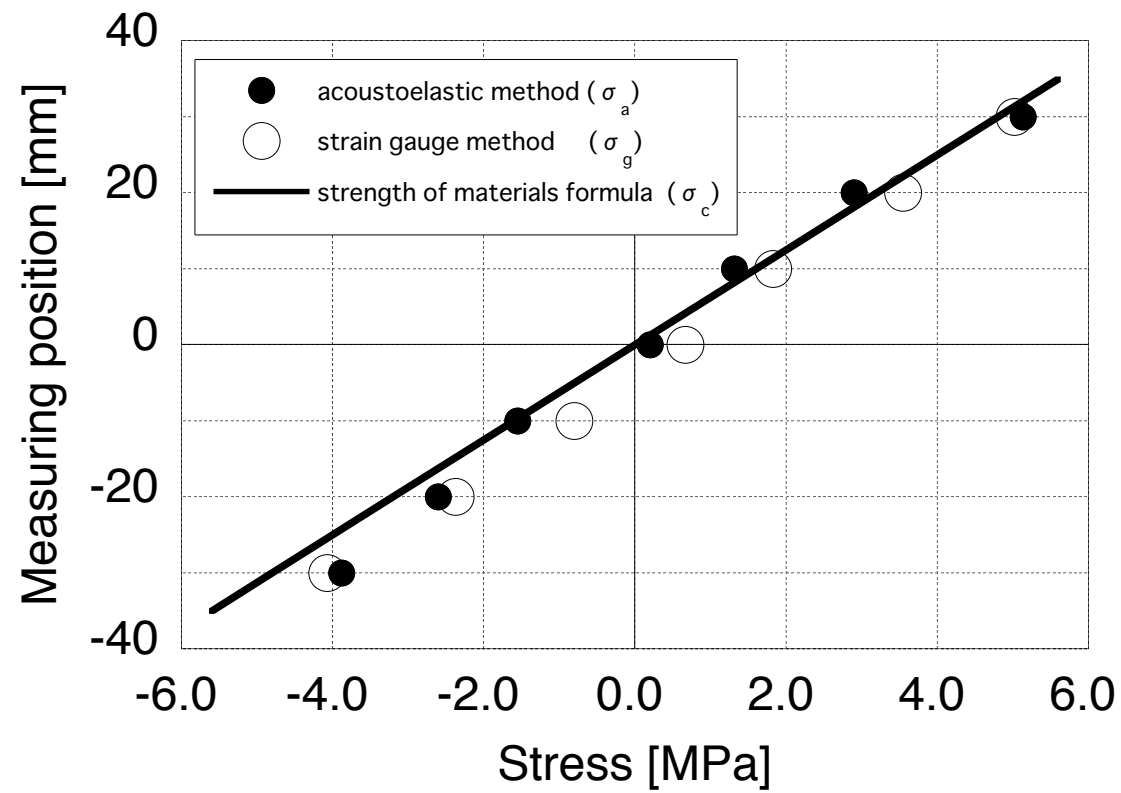


Fig. 6. Longitudinal stresses obtained by the three methods.