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RAPID COMMUNICATION

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Relationship between piezoelectric behavior and the stress – strain curve of wood under combined compression and vibration stresses

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Key words Wood · Natural cellulose crystals · Piezoelectric voltage · Stress – strain curve · Combined compression and vibration stresses

Introduction

It is generally thought that the piezoelectric effect of wood results from natural cellulose crystals in the cell wall. However, natural cellulose cannot exist as a molecule in wood. Many molecular chains of cellulose form fiber structures in bundles with hemicellulose and lignin, i.e., microfibrils. The cell wall can be considered as a frame for these microfibrils. Hence, the increase and decrease of the piezoelectric voltage during the deformation of wood originates from the dynamic deformation of the cell wall.

Many studies of the piezoelectric effect in wood have examined the physical properties of small specimens of wood under a minute load, but there is very little research on deformation.[1–3] Therefore, we examined test specimens subjected to combined compression and vibration stresses at a 45-degree angle to the fiber direction and load direction, to clarify the relationship between the piezoelectric voltage and deformation. This study elucidated the relationship between piezoelectric behavior and the initial shape of the stress-strain curve.

Materials and methods

The specimens used were made of kiln-dried hinoki (*Chamaecyparis obtusa* Endl.); the external dimensions were 3.0 × 3.0 × 9.0 cm. The ten specimens were first conditioned in a room at a constant temperature of 20°C and a constant humidity of 60% for 6 months. The average moisture content and density of the specimens before testing were 11.0% (standard deviation: 0.01%) and 0.48 g/cm^3 (standard deviation: 0.02 g/cm^3), respectively. We placed the plane electrodes on a radial section in which the angle between the axial direction and the fiber direction of the specimen was 45 degrees. The electrodes used to detect the piezoelectric voltage were 3 cm × 3 cm × 100-μm pieces of aluminum foil (length × width × thickness) bonded with double-sided tape to the center of opposite sides of the specimen. The lead wires were bonded to the electrodes using electrically conductive paint.

The piezoelectric voltage generated by the wood was detected by the electrodes and amplified. Noise was removed with a 1/3-octave band-pass filter with an input impedance of 10 MΩ (NEC Sanei), and the signal was measured using a highly sensitive alternating current voltmeter with a built-in AC-DC converter (NF). In this study, the piezoelectric voltage measured with this apparatus was extremely small. The piezoelectric voltage (load, displacement) was stored in a data acquisition controller (NEC Sanei) at 2-s intervals, and input to a personal computer.

A hydraulic testing machine (servo pulser, EHF-UG100kN-20L, full-scale range = ± 100 kN, Shimadzu) was used to apply the load. Specimens were set in a jig, and static compression with the superimposed minute sinusoidal load (F) given by Eq. 1 below, was applied. Loads were applied in the following order: first, a compression load F_1 = 0.2 kN was applied, followed by a sinusoidal load with frequency $f = 30$ Hz and amplitude $a = 0.2$ kN. Finally, a static compression load, F_n, was applied until it reached 60% of the proportional limit compression load of the specimen. A sinusoidal load made it possible for the apparatus to detect the piezoelectric voltage. The combined load, F, is given by:

$$F = F_n + a \sin((2\pi f)t) \tag{1}$$

where t is the time (10 s).

In this study, the piezoelectric voltage generated with the load output of the servo pulsar was monitored using a storagescope, as shown in Fig. 1.

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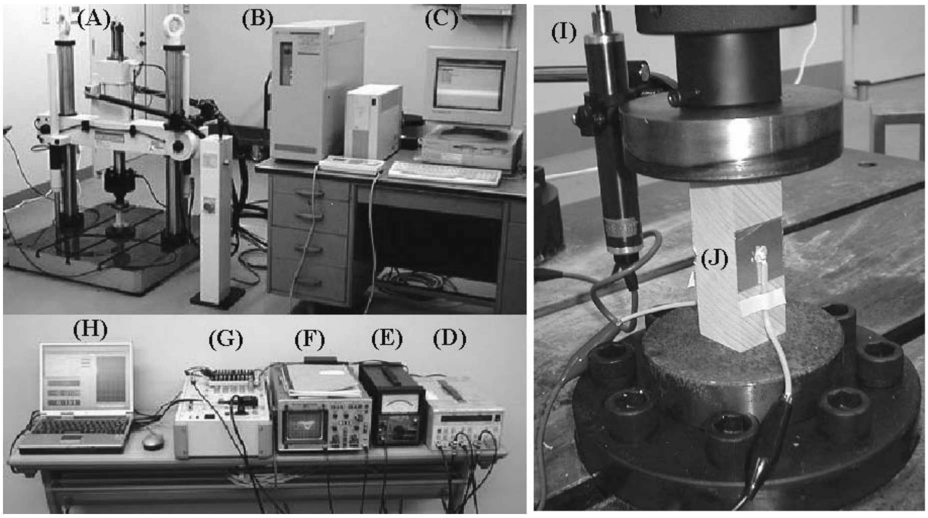

Fig. 1. The apparatus used to measure the piezoelectric voltage (load, displacement) showing a test specimen ready for measurement: *A*, servo pulser, which applies a load to the test specimen; *B*, controller for the servo pulser; *C*, personal computer for the controller; *D*, 1/3-octave band-pass filter with an input impedance of 10 MΩ; *E*, highly sensitive alternating current voltmeter with a built-in AC-DC converter; *F*, storagescope; *G*, data acquisition controller; *H*, personal computer for recording the output from *G*; *I*, displacement transducer; *J*, test specimen

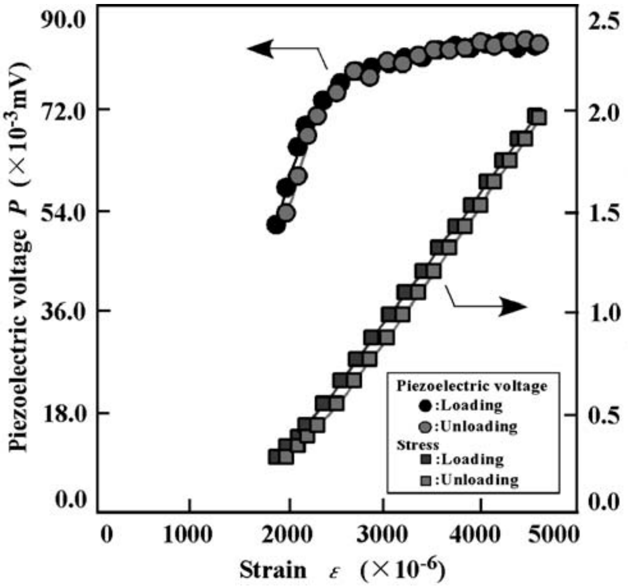

Fig. 2. Examples of piezoelectric voltage–strain (P–ε) curves and stress–strain (σ–ε) curves with repeated combined compression and vibration stresses. *Arrows* show the vertical axis of each curve

Results and discussion

Typical piezoelectric voltage–strain (P–ε) and stress–strain (σ–ε) curves obtained in the combined compression and vibration tests are shown in Fig. 2. The figure clearly shows that initially the piezoelectric voltage was proportional to the strain; then, the P–ε curve became convex, with the maximal point on the convex curve. In this case, when a stress was applied to the specimen, most of the P–ε curve was nonlinear, because the load of proportional limit of the P–ε curve was only 20% of the maximum stress used in this study. That is, it appeared that the mechanical response of natural cellulose crystals is nonlinear elasticity. The P–ε

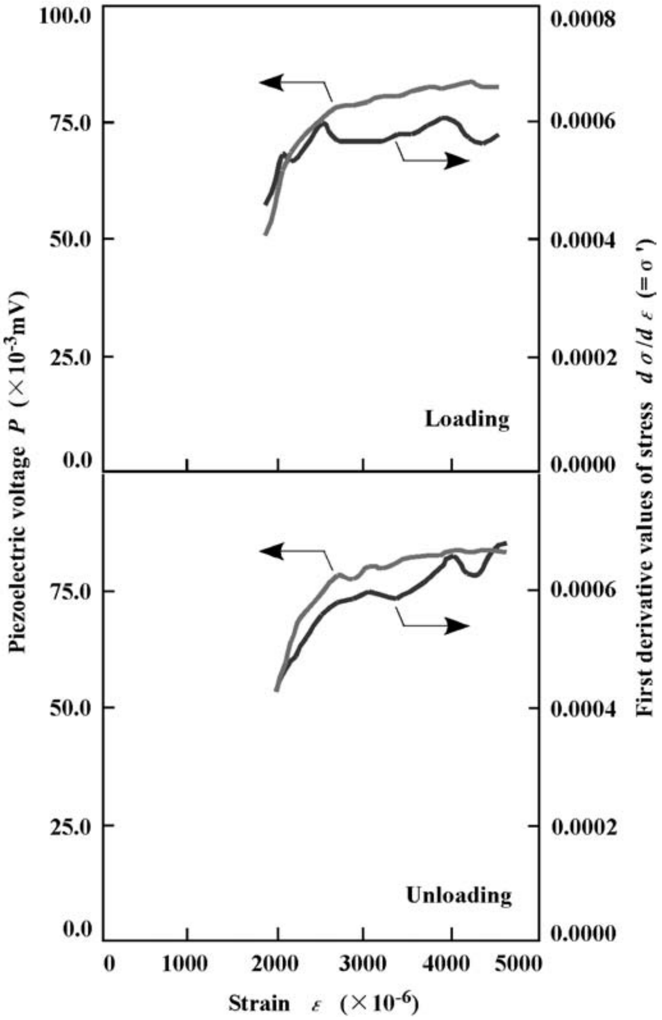

Fig. 3. Examples of piezoelectric voltage–strain (P–ε) curves and the first derivative of the stress–strain ($d\sigma/d\varepsilon$ $(=\sigma')$ $-$ ε) curves for loading and unloading, respectively, under combined compression and vibration stresses. *Arrows* show the vertical axis of each curve

curve had almost the same shape during loading and unloading. The piezoelectric behavior in the elastic region resulted from electrical and elastic phenomena, which do not show hysteresis.

In the σ–ε curve, the stress increased with strain. The first derivative of the stress ($d\sigma/d\varepsilon$ $(= \sigma')$) was calculated, and corresponds to Young's modulus of the test specimen. Each value of P and σ' obtained from the calculation was plotted against the strain, as shown in Fig. 3. The value of σ' was not constant against the strain and the σ'–ε curve was convex. The P–ε and σ'–ε curves were fairly similar. The correlation coefficients for the regressions for both relationships were 0.91 and 0.95 for loading and unloading, respectively.

These results suggest the following hypothesis. When the behavior of microfibrils under loading in previous reports[4–6] is considered, it is estimated that the orientation of single cellulose crystals in the cellulose microfibrils is disturbed to some extent in unloaded wood, and on applying a load, the orientation of the cellulose microfibrils improves. In the meantime, the experimental fact obtained from this study is that the piezoelectric voltage and Young's modulus of the test specimens increase with load. There seems to be a close relation with the increase of piezoelectric voltage and Young's modulus on improving the orientation of the cellulose microfibrils by applying a load.

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