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RAPID COMMUNICATION

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The relationship between macroscopic strain and crystal lattice strain in wood under uniaxial stress in the fiber direction

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Introduction

Wood, a natural composite material, is composed mainly of cellulose and noncellulose matrix. The native natural cellulose that forms the skeleton comprises about half of the components (crystallinity: about 50%–60%). Although it is probable that natural cellulose greatly affects the dynamic behavior of wood, there have been few reports[1–3] on the effects of the crystalline and noncrystalline regions in wood on the macroscopic and semi-microdynamic behaviors in small clear specimens. In the present study, X-ray stress measurements were performed by applying uniaxial compression stress and tensile stress to test specimens in the direction of the fibers. The relationship between the crystal lattice strain and the macroscopic strain in the test specimens (hereafter referred to as the surface strain) was investigated in detail. Meridional (004) diffraction was used to calculate the crystal lattice strain. The experiment was carried out taking into account the microfibril inclination angle (MFA, by Cave's method) of the test piece, because it is thought that the orientation of the fibers greatly affects the dynamic behavior.

Materials and methods

Wood from Japanese cypress (*Chamaecyparis obtusa* Endl.) was first conditioned at a constant temperature of 20°C and a constant humidity of 60% for 6 months before being used as a test specimen. Before testing, the specimens had the following characteristics: density, 0.33 ± 0.01 g/cm^3 (mean ± S.D.); annual ring width, 1.5 ± 0.02 mm; percent late wood, 23.8% ± 0.15%; microfibril angle, 12.0°–16.8°; crystallinity, 54% ± 1.5%; and moisture content, 11.9% ± 0.1%. Straight-grained pieces of wood were used to measure the X-ray stress. The pieces used for the compressive tests had external dimensions of 2 × 20 × 50 mm (thickness × width × length) and those used for the tensile tests had dimensions of 600 μm × 10 mm × 60 mm. In this case, the thickness of the compressive specimen was set to the dimension at which the effect of buckling and bending was not generated with the simulation using the finite element method. Arches were cut in both sides of the center of each test specimen to form a constriction, and beech wood was glued to the specimens with epoxy resin as a reinforcement. A 5-mm-diameter hole was drilled in each test specimen to fix it to the jig and thus prevent slippage. To measure the macroscopic surface strain of the test specimens, a 5-mm-long strain gauge (Tokyo Sokki Kenkyujo Japan) was glued to the center of the specimen using cyanoacrylate adhesive. In this case, the experimental value of the surface strain was corrected by taking the MFA into consideration.

Native cellulose, the main constituent of wood, crystallizes in the cell wall to form rigid microfibrils. The microfibrils are aligned roughly parallel to the direction of the fibers in the middle layer of the secondary wall, which constitutes the majority of the cell wall. The change in the spacing of the crystal lattice caused by stress loading in the fiber direction (i.e., the crystal lattice strain) can be measured using X-ray diffraction.[1–3] A (004) diffraction peak cannot be measured by conventional reflection optics unless a thin cross-sectional plate made from wood is prepared, in such a case it is impossible to stretch in the longitudinal direction. It is therefore required to use transmission optics. A jig constructed for this experiment was attached to the rotating part of the sample holder on a goniometer. Each test specimen was attached to the jig with screws, and a load was placed on it via a bar for compressive tests or a wire for tensile tests under the control of a small desktop material-testing machine. An X-ray diffractometer (XD-D1w,

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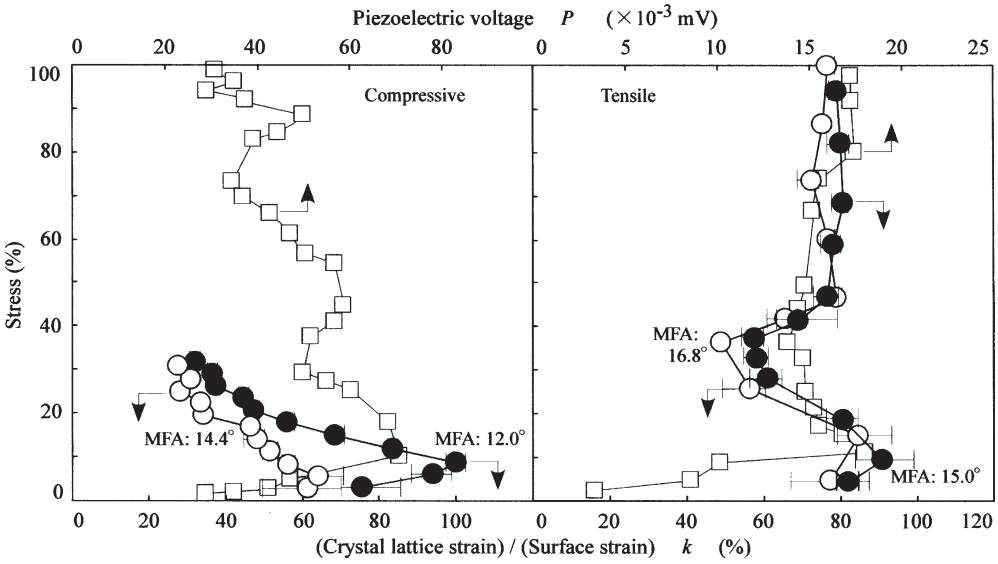

Fig. 1. Relationships between the ratios of the crystal lattice strain to the surface strain, the piezoelectric voltage, and the stresses. *open circles*, ○; *filled circles*, ●; value of *k* for each MFA. *Squares*, □; piezoelectric voltage. The stress values given on the vertical axis are given as the percentage of the breaking stress. *Bars* of each plot show the maximum and minimum values. *Arrows* show the horizontal axis of each curve. *MFA*, microfibril angle

Shimadzu, Japan) was used to measure the crystal lattice strain. In addition, the diffraction intensity profile was measured around the diffraction peak of the (004) plane, and the diffraction angle was approximated using an asymmetric Gaussian curve. After attaching the specimen to the tensile jig, the diffraction intensity profile was first measured with no load, and then measured at constant intervals until the specimen failed. When a specimen is loaded with a constant stress, the stress actually decreases owing to stress relaxation. To prevent the decrease in stress, the X-ray stress was measured while monitoring the stress, on the personal computer, and adjusting the stress manually. The piezoelectric voltage generated by the wood was transmitted via the electrodes and amplified by a 1/3-octave band pass filter with an input impedance of 10 MΩ (NEC Sanei) to remove noise. The voltage was then measured with a highly sensitive alternating current voltmeter with a built-in AC-DC converter (NF Circuit Design Block). In this study, the measured piezoelectric voltage had an extremely high signal-to-noise ratio. The specimens were attached to the jig, and static load with a minute superimposed sinusoidal load was applied.

Results and discussion

The ratio of the crystal lattice strain to the surface strain, *k*, was plotted for the stress applied to the test specimens in Fig. 1. Up to a stress level of about 35%, the dynamic behavior of the crystalline region in the wood showed very similar qualitative tendencies under uniaxial compression stress and uniaxial tensile stress. That is, *k* changed from an increase to a decrease with increased stress. At the same time, quantitatively, average values of *k* were about 70% and about 80% for the uniaxial compressive stress and tensile stress, respectively, at the initial stress level, and the values of *k* were about 30% and about 45% for the uniaxial compressive stress and tensile stress, respectively, at a stress level of around 35%. The relative deformation of the crystalline region decreased under both stresses, and was especially remarkable under uniaxial compressive stress.

In the stress range beyond the stress level of about 35%, *k* increased to a stress level of about 45% under uniaxial tensile stress, after which its value was almost constant. Under uniaxial compressive stress, *k* could not be measured after a stress level of about 35% owing to measurement problems. The piezoelectric voltage[4–6] determined using a different measurement system was plotted to predict the behavior of *k* in the stress range (squares in Fig. 1). As shown in Fig. 1, both correspondences were good in all stress ranges under uniaxial tensile stress. It is thought that the fluctuation behavior of *k* appears to be predictable from that of the piezoelectric voltage. In short, in the stress level range from about 35% to failure under uniaxial compressive stress, from the piezoelectric voltage behavior it can be predicted that *k* increases up to a stress level of about 45%, after which it declines in the form of a curve. It is anticipated that after a stress level of about 45%, the relative deformation of the crystalline region differs under the two types of stress.

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