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ORIGINAL ARTICLE

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Mechanism for deformation of wood as a honeycomb structure I: Effect of anatomy on the initial deformation process during radial compression*

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Abstract The mechanism for radial compression of coniferous wood was examined from the viewpoint of the porous structure of wood. The compressive test was carried out in a wet-type scanning electron microscopy (WET-SEM) chamber to observe continuously the deformation process of wood. The initial stress–strain relation of the cellular solids or single cell was measured with image analyses of SEM photographs. The first fracture occurred in one tangential row of earlywood tracheids just after the load–displacement curve exceeded the proportional limit. The fracture occurred because of abrupt breaks of the radial cell walls. The first fractured cells had a tendency to have the smallest percentage of cell wall within an annual ring, and the cells suffered shearing deformation in a radial direction until the occurrence of the first fracture. On the basis of the results of image analyses, it was concluded that this shearing deformation of cells was almost linearly related to the compressive load.

Key words Radial compression · Cellular solids · Porous structure · Image analysis · Stress-strain diagram

Introduction

When compressive load is applied to wood in a transverse direction, the wood has high deformation capacity (low stiffness) and superior ability to absorb the kinetic energy produced by the shock. Because the high deformation capacity is a major characteristic of wooden construction materials, it is important to elucidate its mechanism. However, few studies have helped explain the mechanism for development of the high transverse deformation capacity.

This characteristic seems to be mainly due to the elaborate geometrical arrangements of various macrostructural and microstructural units that constitute wood. There have been some anatomical studies on transverse compression of wood.[1-11] Wang[4] observed the appearance of hinoki wood tissues compressed radially with an optical microscope. He found that strain was concentrated on the tracheids of earlywood adjacent to the boundary of annual ring when strain exceeded the proportional limit in the stress-strain diagram. This concentration caused crushing of the tracheids. Aiuchi and Ishida[7] observed continuously the appearance of the tissues of todomatsu wood during radial compression by a scanning electron microscope (SEM) and reported that the area of first fracture was located in the tracheids of earlywood and that the first fracture started from both sides of the specimen and immediately occurred successively in a tangential direction. Other studies have also reported on the first fracture under radial compression. These studies pointed out the shear buckling of the tracheid of earlywood,[1] the buckling of the ray,[2] and the sliding of the tracheid of earlywood in a tangential direction after the first fracture.[3]

The deformation behavior of the cellular solids or cell unit after the first fracture has been demonstrated by the studies mentioned above. In contrast, fewer studies have shown the behavior prior to the first fracture.

In this study, we analyzed the deformation behavior of the cellular solids or cell unit of coniferous wood, especially the behavior prior to the first fracture, under radial compression. The machine for material tests was incorporated into an SEM to carry out the radial compression test within the SEM chamber. Changes in stages of the deformation and fracture of wood were observed continuously. The images were recorded on video tapes or photographs. Image analyses were carried out to measure the changes in the area or length of the various macrostructural and microstructural units that constitute wood.

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Materials and methods

Coniferous woods were used for this study because of the relatively simple structure of their tissues, and hinoki (*Chamaecyparis obtusa* Endl.), sugi (*Cryptomeria japonica* D. Don), and kuromatsu (*Pinus thunbergii* Parl.) were chosen as specimens. The shapes and sizes of the specimens are shown in Fig. 1.

The middle of both longer edges of each specimen were cut off in a semicircular shape to concentrate stress on the center and offer easier observation of its deformation. The direction of compression is the radial direction.

The section to be observed (cross section) was finished with a microtome, and the humidity was controlled to attain a moisture content that kept the weight of the specimen constant before and after the compression test, which was carried out in an SEM chamber. The average specific gravity and moisture content for hinoki, sugi, and kuromatsu were 0.38 and 1.8%, 0.37 and 3.0%, and 0.52 and 2.5%, respectively.

The equipment for this study was a WET-SEM servopulser (Shimadzu, Kyoto, Japan), combined with a machine for material tests. We could observe under low vacuum condition (0.8 ± 0.2 Torr, 20°C) because of use of the wet-type SEM. The specimens were bolted with attachments at the top and bottom of the cross section, up to 20mm away from the each end of the specimens. The cross sections were observed in the SEM chamber while compressive force was applied to the specimens at a crosshead speed of 0.3mm/min. The accelerating voltage was 15kV.

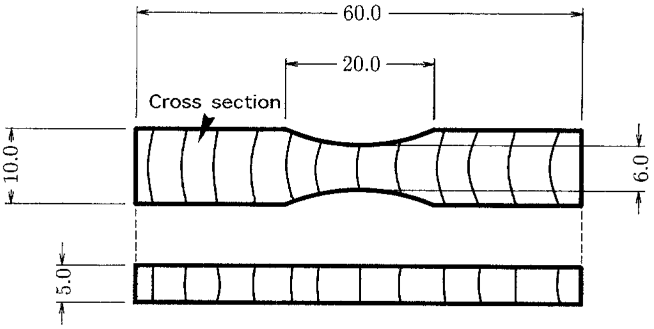


Fig. 1. Test specimen. Units in millimeters. The specimen was bolted with attachments at the top and bottom of the cross section up to 20mm away from the both ends of the specimen

A television (TV)-scanning device was used for continuous observation. The frame speed of the device is 0.06s. The process of deformation was continuously observed on a monitor and recorded with a video cassette recorder (HV-MX1; Aiwa, Tokyo, Japan).

Sharper photographs were obtained at the different stages of radial compression. Each of the negatives (Neopan SS; Fuji Film, Tokyo, Japan) was translated into numerical data for computer analysis using an image scanner (IX-4015; Canon, Tokyo, Japan). The data were input into a personal computer (Power Macintosh 7100/66AV; Apple Japan, Tokyo, Japan) at 1200dpi, and image analyses were carried out using the translated data to measure the changes in the area or length of the various macrostructural and microstructural units that constitute wood.

Results and discussion

Deformation and fracture of specimens

A typical load-displacement curve of each species is shown in Fig. 2. Displacement is defined as the length of movement of an actuator. SEM photographs show the process of the deformation and fracture of hinoki (Fig. 3). Each letter on the photographs corresponds to those on Fig. 2.

The first fracture occurred abruptly in one tangential row of earlywood tracheids just after the load-displacement curve deviated from the proportional limit (Figs. 2, 3B). Simultaneously, each ray in the earlywood was observed to buckle sideways. It was noted that earlywood tracheids in one tangential row were abruptly crushed owing to the breaks in their radial cell walls. In this study, this first fracture from broken radial walls of tracheids was called "the first break." The earlywood had "the first break" at the cells close to the boundary of an annual ring. The first

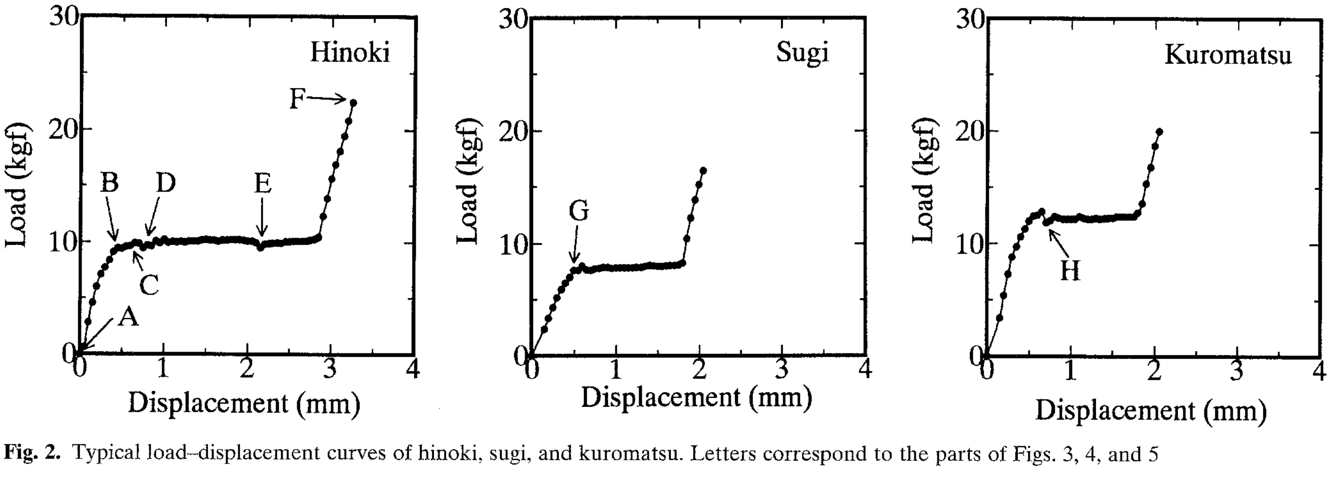


Fig. 2. Typical load–displacement curves of hinoki, sugi, and kuromatsu. Letters correspond to the parts of Figs. 3, 4, and 5

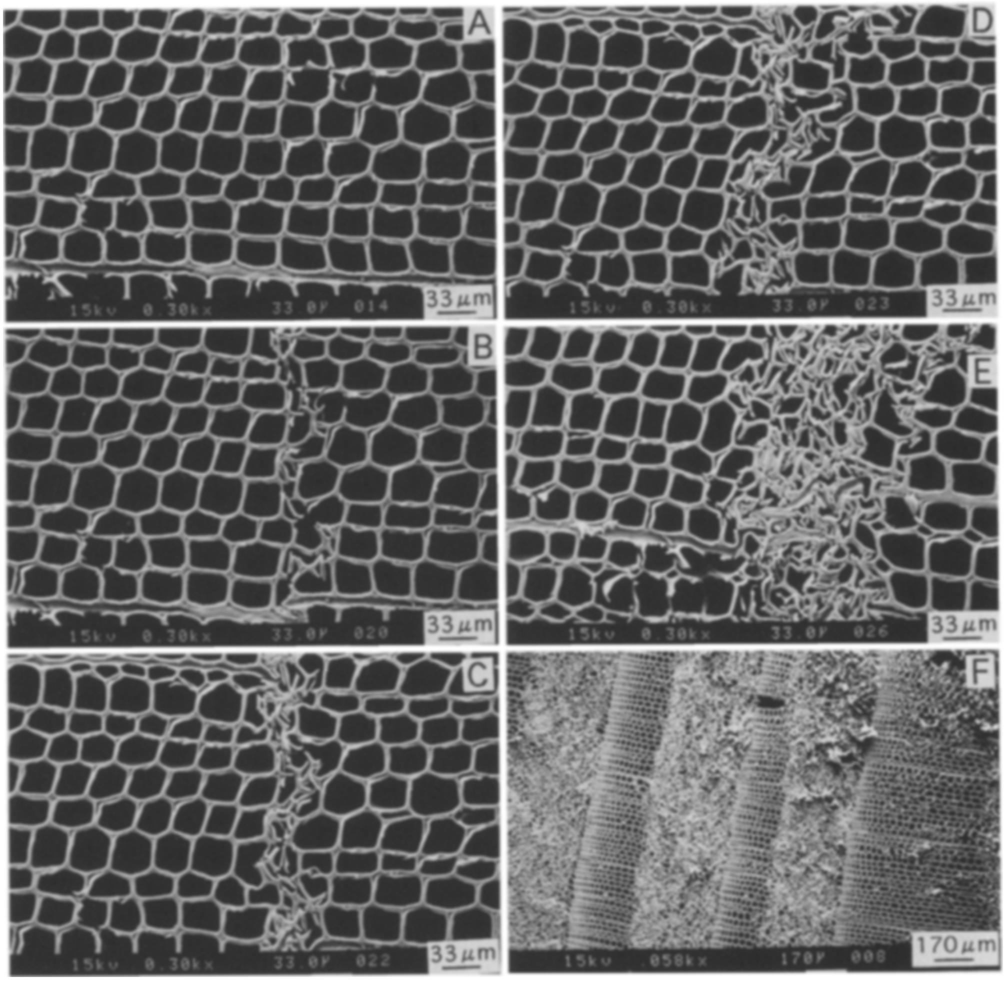


Fig. 3. Deformation process of hinoki in radial compression. Figure parts A–F correspond to those in Fig. 2

broken row of tracheids was the tenth one from the boundary of an annual ring. Because it was observed simultaneously on both side (radial) sections of the specimen, the first break is assumed to have occurred on the same section (tangential section) at the same time.

The appearance of the first break was similar to that pointed out by other studies.[2–4,7] The first break was an abrupt event, which is an outstanding feature of the wood under radial compression. Aiuchi and Ishida[7] explained that the first break started from both side sections of the specimen and immediately occurred successively in a tangential direction. This sequence, however, has not been confirmed in this study.

In the subsequent stage, cells next to the first broken cells were stratified one after another in a radial direction (making tangential walls closer) (Figs. 2, 3C–E). The cells were observed to be stratified relatively gradually. This stratification stage corresponds to the flat area of a load-displacement curve shown in Fig. 2. After most of the cells in earlywood were stratified, cell-wall substances were compressed. Their compression stage corresponds to the area where load is rapidly increasing again (Figs. 2, 3F).

The appearances of the first breaks of sugi and kuromatsu are shown in Figs. 4 and 5, respectively. Each letter in these figures corresponds to those in Fig. 2. The processes of deformation up to the ultimate stage in sugi and kuromatsu were the same as those observed in hinoki. It was noted, however, that most of the first broken cells of these species were closer to the boundary of the annual ring than those of hinoki.

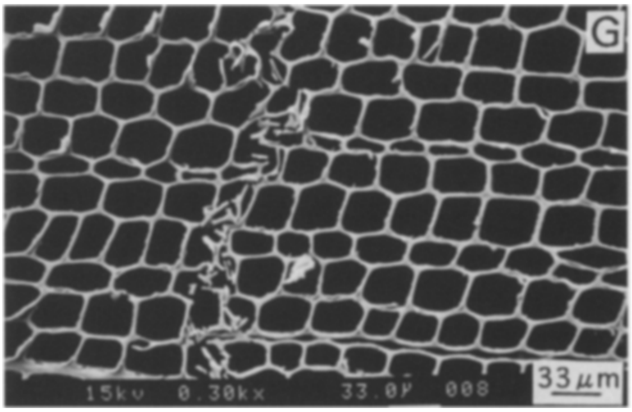


Fig. 4. Appearance of the first break of sugi in radial compression. Letter G corresponds to that in Fig. 2

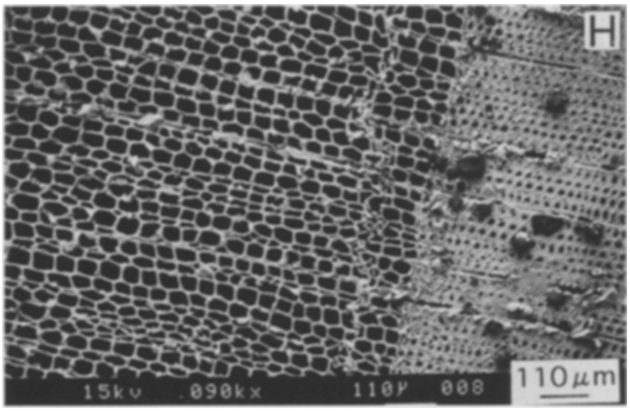


Fig. 5. Appearance of the first break of kuromatsu in radial compression. Letter H corresponds to that in Fig. 2

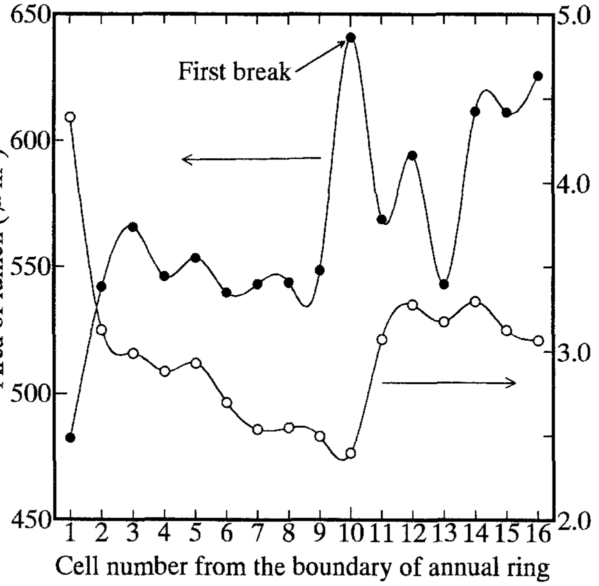


Fig. 6. Transitions of the area of the cell lumen and the thickness of the cell wall of hinoki. Horizontal axis represents the number of tracheids from the pith-side boundary of an annual ring

As observed in this study, the deformation behavior of the cellular solids or cell unit after the first break has been demonstrated by many other studies,[3,4,10,11] because the cells were deformed relatively slowly. In contrast, fewer studies have shown the behavior prior to the first break, and so the process of deformation of the cellular solids or cell unit prior to the first break is discussed here.

Influence of percentage of cell wall on the first break

Figure 6 shows the changes in the area of the cellular lumen and the thickness of the cell wall of individual cells within an annual ring of hinoki. No. 1 cell is defined as a tracheid adjacent to the pith-side boundary of the annual ring. A cell with a higher number is closer to the bark of the wood. No. 10 cell was the first broken tracheid. Figure 6 demonstrates that the cell with the biggest cellular lumen and the thinnest wall suffered the first break.

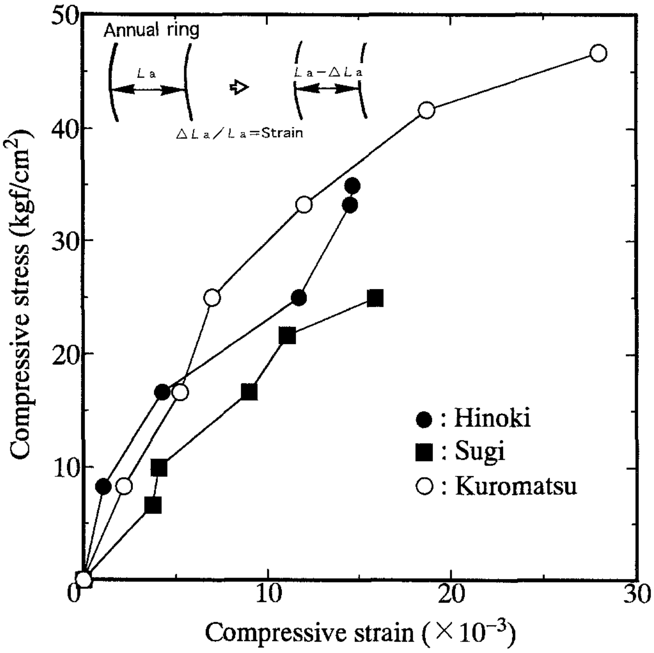


Fig. 7. Typical compressive stress/compressive strain curves of single annual rings up to the first break. The strain was obtained from the results of image analysis of the pictures taken with scanning electron microscopy (SEM)

Although the change in density of the cells arranged in a radial direction within an annual ring depends on the species and the specimen, either No. 10 cell or its adjacent cells had the smallest percentage of cell wall within the researched annual ring. It can be said that such a cell suffered the first break. It is interesting to note that Bodig[2] used Douglas fir as a specimen and reported either the fourth cells from the boundary of the annual ring or their adjacent cells suffered the first break by radial compression. Wang[4] concluded that the first break occurred at the cells with the larger-diameter lumens and the thinner walls.

Relation between stress and strain

Behavior of a single annual ring

Typical compressive stress/compressive strain curves of the single annual rings inclusive of the first broken cells are shown in Fig. 7. Compressive stress was defined as a nominal stress calculated on the assumption that the specimen had uniform stress on the section perpendicular to the direction in which load was applied. Strain was obtained by measuring the change in the gauge length (width of an annual ring) of the specimen using image analysis of its SEM photographs. Figure 7 shows the results of measurements obtained until just before the first break occurred.

Each species had either a linear or a parabolic change. In an annual ring level of structure, the relation between stress

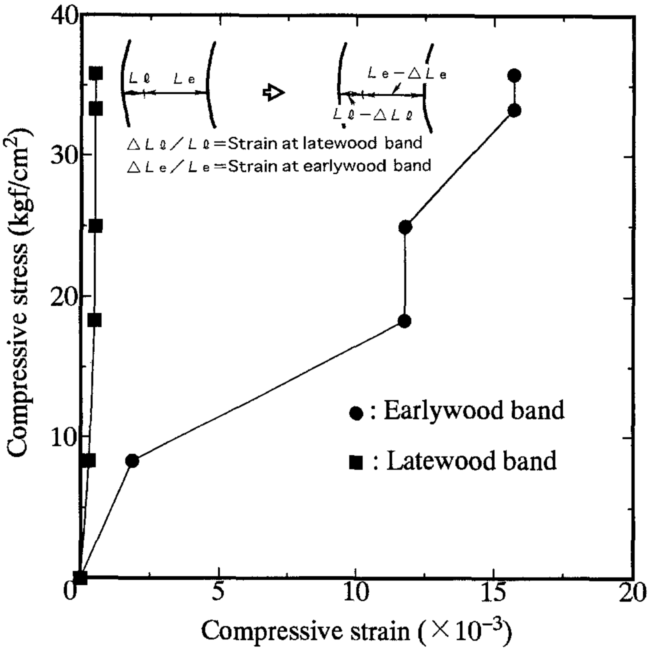


Fig. 8. Typical compressive stress/compressive strain curves of an earlywood band and a latewood band of hinoki up to the first break. The strain was obtained from the results of image analysis of the pictures taken with SEM

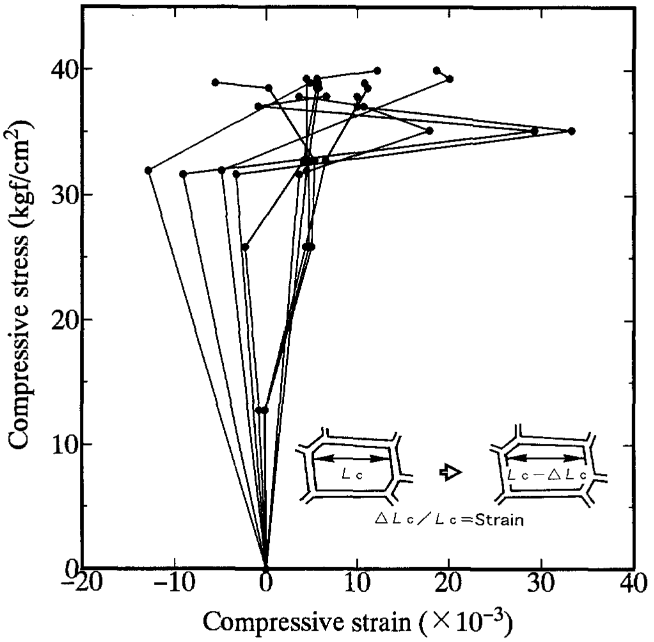


Fig. 9. Examples of compressive stress/compressive strain curves of the first broken single cells of hinoki up to the first break. The strain was obtained from the results of image analysis of the pictures taken with SEM

and strain up to the first break is thought to be almost linear. The modulus of elasticity was calculated from the inclination of its curve. The modulus of elasticity of hinoki, sugi, and kuromatsu averaged 4×10^3, 3×10^3, and 8×10^3 kgf/cm², respectively. The results were almost the same as those

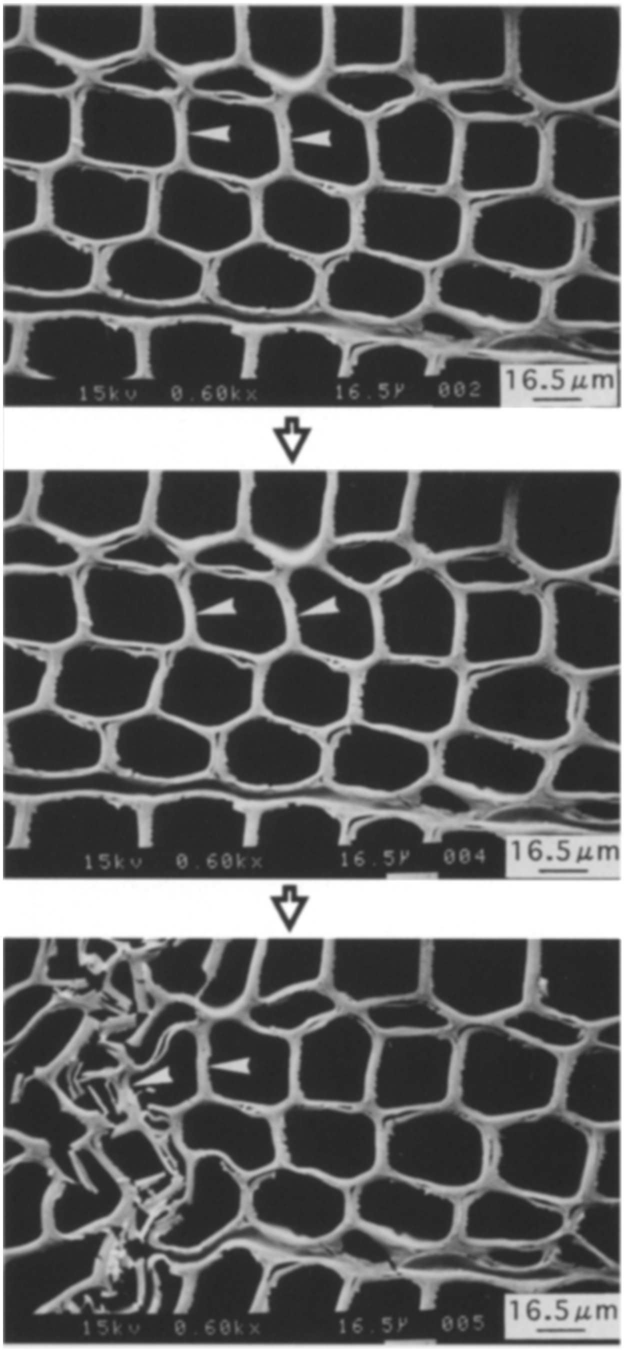
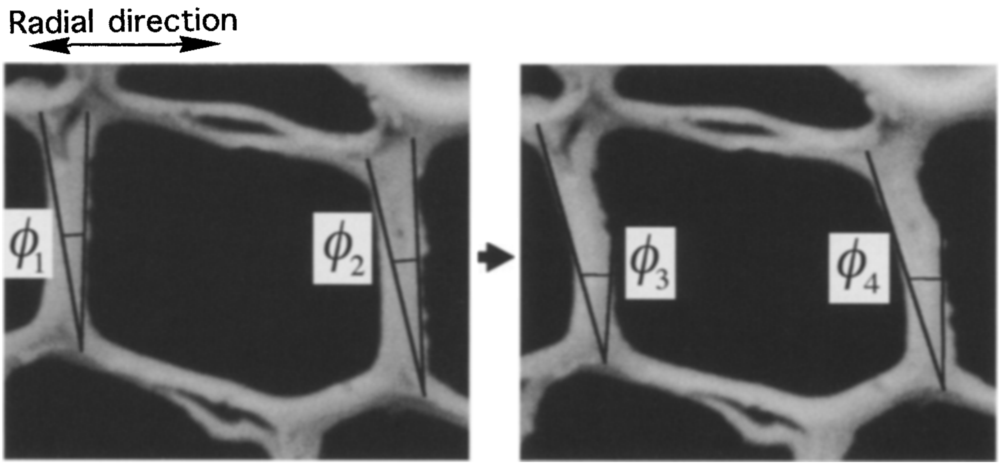


Fig. 10. Shear deformation process of the first broken tracheid of hinoki. This phenomenon was observed before the first break. *Arrows* indicate the phenomenon

reported in previous studies on whole woods.[12] This evidence suggests that the deformation behavior of a single annual ring up to the first break is almost equal to that of the whole wood.

Considering a porous structure of wood, Liu et al.[13] examined experimentally the relation between stress and strain under radial compression and reported that the relation was expressed by Hooke's law when the strain was less than the yield point.

Fig. 11. Definition of the shearing strain (γ) of tracheids in this study



$$\gamma = \phi$$

$$\phi = \frac{(\phi_3 - \phi_1) + (\phi_4 - \phi_2)}{2}$$

Behavior of an earlywood and a latewood

Typical compressive stress/compressive strain curves of an earlywood band inclusive of the first broken cells and a latewood band of hinoki are shown in Fig. 8. This figure shows the results of measurements up to just before the first break. Strains were obtained by measuring the changes in the gauge lengths of both bands (widths of an earlywood and a latewood) with image analysis of SEM photographs. Much less strain was produced on the latewood, and much more strain was produced on the earlywood with a curve similar to that of the single annual ring in Fig. 7.

Behavior of the first broken single cell

Focus was placed on the first broken cells. Figure 9 shows the compressive stress/compressive strain curves for some hinoki cells. This figure demonstrates the behavior of each cell observed up to just before its first break. Strain was obtained by measuring the change in the gauge length (radial length) of a cell with image analysis of SEM photographs. The accuracy of the measurement was ±3 × 10^{-2} μm. The assumption that the strain increased with the increase of stress was not observed. In contrast, some cells had negative strain as stress increased. Based on this evidence, it can be assumed that not only a uniaxial compressive strain is produced in the first broken cell, but the change in cell shape is associated with the stress-strain behavior of the cell. We discuss here the deformation of cell shape that occurred in the first broken cells up to just before the first break.

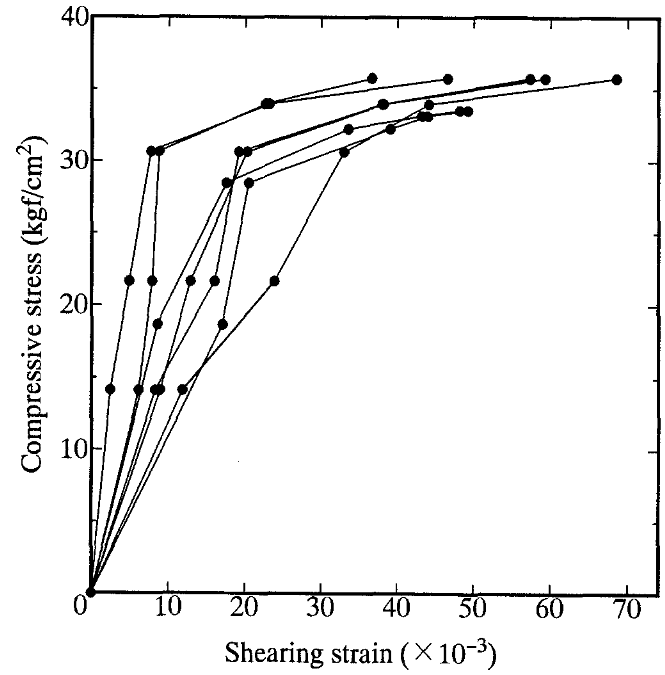


Fig. 12. Examples of compressive stress/shearing strain curves of the first broken single cells of hinoki up to the first break. Shearing strain of the cell was defined in Fig. 11

Various kinds of changes in cell shape were observed at the stage where the cells were stratified in a radial direction after the first break. Until the occurrence of the first break, however, the cells had characteristic shearing deformation in a radial direction, as shown in Fig. 10. An equation was determined for shearing strain (γ) and is shown in Fig. 11. Shearing strain (γ) was calculated according to the equation with image analysis of SEM photographs. The relation between the compressive stress and the shearing strain of hinoki is shown in Fig. 12, which illustrates the deformation behavior of single cells until just before the first break. Figure 12 shows that the shearing strain increased almost linearly with a inflection point when compressive stress increased. This evidence suggests that the deformation of cells prior to the first break is largely related to the changes in cell shape, mainly the shear deformation of the cells in a radial direction, rather than a uniaxial compressive strain. We think that such a change of cell shape is a important factor in relaxing the stress concentration of wood.

The remarkable change in cell shape before the first break, except for shear deformation in a radial direction, was not confirmed in this study. However, when cells were stratified in a radial direction subsequent to the first break, cells were deformed exclusively because of the bending of their radial walls. This bending deformation of cells will be reported in a succeeding paper.

Conclusions

The mechanism for radial compression of coniferous wood was examined in this study and the following conclusions were obtained.

1. The first break occurred abruptly in one tangential row of earlywood tracheids from broken radial walls just after the load-displacement curve exceeded the proportional limit.
2. The tracheids with the smallest percentage of cell wall within an annual ring had a tendency to suffer the first break.
3. The initial stress-strain relations for a single annual ring, an earlywood and a latewood, and a single cell were measured using image analyses of SEM photographs. The relation for a single annual ring is similar to that for the whole wood. For the first broken single cell, a linear relation between compressive stress and compressive strain was not noted; in contrast, a positive relation was noted between the compressive stress and the shearing strain.
4. The characteristic change in cell shape because of the shearing deformation of cells in a radial direction was observed up to the occurrence of the first break. From the results of image analysis, this shearing deformation of cells was found to be almost linearly related to the compressive load. We think that such a change of cell shape is a important factor in relaxing the stress concentration of wood.
5. Changes in cell shape due exclusively to the bends of radial walls were rarely observed up to the first break.

The first break was found to be an abrupt event. This is an outstanding feature of the wood under compression in a radial direction.[2-4,7] With this characteristic taken into consideration, the theoretical analysis and experimental verification concerning the first break will be reported in a next paper.

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