J Wood Sci (2009) 55:100–106
DOI 10.1007/s10086-008-1002-4

ORIGINAL ARTICLE

Masamitsu Nakajima · Yuzo Furuta · Yutaka Ishimaru
Makoto Ohkoshi

Cooling set and its recovery in water-saturated bamboo under large bending deformation

Received: June 13, 2008 / Accepted: October 1, 2008 / Published online: December 18, 2008

Abstract To clarify the bending properties and cooling set for bamboo under large deformation, the relationship between applied deflection and residual deflection was investigated, and comparison was made with the results of thermal recovery and anatomical changes due to deformation. No clear effect of initial deflection on set measured after a long time was found for wood and bamboo loaded on the epidermis side (B_{epi}). On the other hand, set for bamboo loaded on the endodermis side (B_{endo}) increased with deformation level. Recovery from the deformation with time for B_{endo} was almost complete at around 1000 min after unloading in the three-point bending method. This recovery behavior was not seen for B_{epi} or wood. It was considered that no failure was caused in the bent specimen, because most of the deformation was completely recovered by reheating to the temperature at which the specimens were deformed before cooling. The recovery from deformation for B_{endo} loaded by the four-point bending method continued even after 1000 min. From microscopic observations, shearing deformations were seen for B_{endo} loaded by the three-point bending method. From these results, it can be considered that shearing deformations between the two loaded points effectively contribute to decreased recovery force from deformations for B_{endo}.

Key words Bamboo · Plastic working · Cooling set · Thermal recovery · Bending

M. Nakajima (✉) · Y. Ishimaru
Research Division of Agriculture, Graduate School of Kyoto Prefectural University, 1-5 Shimogamo-hangicho, Sakyo-ku, Kyoto 606-8522, Japan
Tel. +81-75-703-5637; Fax +81-75-703-5637
e-mail: a0011125@kpu.ac.jp

Y. Furuta · M. Ohkoshi
Research Division of Life and Environmental Sciences, Graduate School of Kyoto Prefectural University, Kyoto 606-8522, Japan

Part of this report was presented at the 54th Annual Meeting of the Japan Wood Research Society in Sapporo, August 2004

Introduction

Generally, not only lowering temperature but also decreasing moisture content is essential for the fixing of wood deformation such as drying set.[1–3] In the practical plastic working of bamboo, the traditional techniques used by skilled craftsman to straighten bamboo are a combination of loading with heating and cooling.[4] In these traditional methods, it is empirically recognized that the cooling process is important to fix the deformation. Although both bamboo and wood are classified as wooden resources, it is scientifically interesting to clarify why the actual working methods between wood and bamboo are so different.

In the previous report, to clarify the characteristics for plastic working of bamboo and the differences between wood and bamboo, the thermal-softening properties and fixation by cooling of bamboo within proportional limits were investigated in comparison with those of wood.[5] A close relationship between cooling set and the thermal softening of lignin and a clear difference in recovery from deformation with time between bamboo and wood were found. However, as shown in studies on bent wood or compressed wood, information about the fixation of large deformations is important for practical plastic working. Iida et al.[2] investigated the hygrothermal recovery from large compression set of rakuusho wood (*Taxodium distichum* Rich.). They showed the reduction of cell cavity and the folding of the cell wall in proportion to the amount of compression, but failure and separation of the cell walls could not be detected even in the specimen compressed by 68.4%.[2] Iida et al.[2] also found that the dimensions and cell shapes of the compressed specimens almost returned to their original state by heating and/or increasing the moisture content. The anatomical characteristics of bent wood were reported by Imamura et al.[3] On the other hand, few investigations from the viewpoint of the plastic working of bamboo have been performed except for reports by Mori[6] and others. However, the investigation of large deformations in bamboo including changes in the tissues is essential for not only utilizing bamboo but also to clarify the mechanism of cooling set.

In the present study, to clarify the mechanism of fixing the deformations in bamboo, the bending properties and fixation by cooling of bamboo with a large deformation were investigated in comparison with wood. The results were examined through the contrasts in anatomical characteristics, recovery from the deformation with time, and thermal recovery.

Materials and methods

Materials

For bamboo samples, 4-year-old madake (*Phyllostachys bambusoides*) from Oita, felled in November, was used in this study. Specimens were taken at 3400–4400 mm culm height from the ground, and oily components adhering to the outer surface of the culms were removed by boiling (0.05% NaOH).[7] Wood specimens were obtained from the outer part of heartwood with straight grain in a log of Japanese cypress (hinoki: *Chamaecyparis obtusa*). For both bamboo and wood, the dimensions of the specimens were 140 mm (longitudinal, L) × 8 mm (tangential, T) × 4 mm (radial, R). The endodermis plane of the bamboo culm was flattened but the outer side was not flattened, as shown in the previous report.[5] Specimens were oven-dried at 50°C for 24 h, and then for 80°C for 12 h, and 105°C for 6 h. After drying, specimens were boiled at 100°C for 2 h and left in water at 20°C over 2 months to saturate with water.

Measurements

Residual deflection and its recovery with time

As in the preceding study,[5] the specimen was supported on a stand with a span of 80 mm, and the initial deflection was applied to the center of the span in a water bath at 20°C using a material testing instrument (Tensilon UTM-4L, Toyo Measuring Instruments). The bamboo samples were loaded on the endodermis (B_{endo}) or the epidermis side (B_{epi}). The water temperature was elevated to 90°C at the rate of 1°C /min and then cooled to 20°C by leaving at room temperature. After the cooling process, the specimen was unloaded and the residual deflection was read from the chart. The proportion of the residual deflection to the initial deflection was defined as the set ratio. After the removal of loading, the recovery from deformation with time (R_T) was followed without moving the set specimen in water at 20°C. The residual deflection was read from the chart at predetermined periods after the removal of loading; a crosshead was moved down until it touched the specimen, and the displacement was read from the chart. Then relative recovery with time (relative R_T) was defined as in following equation:

$$\text{Relative} \quad R_T = \frac{S_0 - S_T}{S_0}$$

where, S_0 is the set ratio measured immediately after unloading, S_T is the set ratio at predetermined time after loading.

To examine the effect of shearing force during loading on the set and its recovery with time, four-point bending (B_{4pb}) with a constant bending moment between two central loaded points was also employed for the B_{endo} specimen. In this case, a load was applied to cause the same maximum bending moment in the specimens as in the three-point bending (B_{3pb}).

Thermal recovery

Six thousand minutes after unloading, the water temperature was heated to 90°C from 20°C, again at a rate of 1°C/min. In this heating process, residual deflections were read from the chart at 10°C intervals, and thermal-recovery values at predetermined temperatures (relative R_H) were evaluated by the following equation:

$$\text{Relative} \quad R_H = \frac{S_{20} - S_H}{S_{20}}$$

where, S_{20} is the set ratio at 20°C at 6000 min after unloading, S_H is the set ratio at predetermined temperature in the heating process.

Microscopic observation

A microscope (digital microscope KH-1300, Hirox) was employed for observations of bamboo specimens. Because bamboo has many more parenchyma cells than wood, which frequently collapse in the drying process, water-saturated bamboo was used for microscopic observations without drying. The radial plane of specimens was marked with stain at several points prior to the experiment and was observed before deforming and after cooling set.

Results and discussion

Effects of tissue and structure on the fixation of deformation

Figure 1 shows the effects of the initial deflection on the set ratio measured immediately (Set_0) and 6000 min after unloading (Set_{6000}). Differences between Set_0 and Set_{6000} indicate the recovery from the deformation over 6000 min at 20°C. Set_0 increased with the initial deflection for B_{epi} (bamboo specimens loaded on the epidermis side), B_{endo} (bamboo specimens loaded on the endodermis side), and wood. However, Set_{6000} was almost constant for B_{epi} and wood regardless of the initial deflection. Because both bamboo and wood are viscoelastic materials, it can be considered that the dependence of Set_0 on the initial deflection was caused by the increase in delayed deformation before unloading. On the contrary, for B_{endo}, both Set_0 and Set_{6000} depended on the initial deflection. This cannot be considered to result only from the increase in delayed deformation

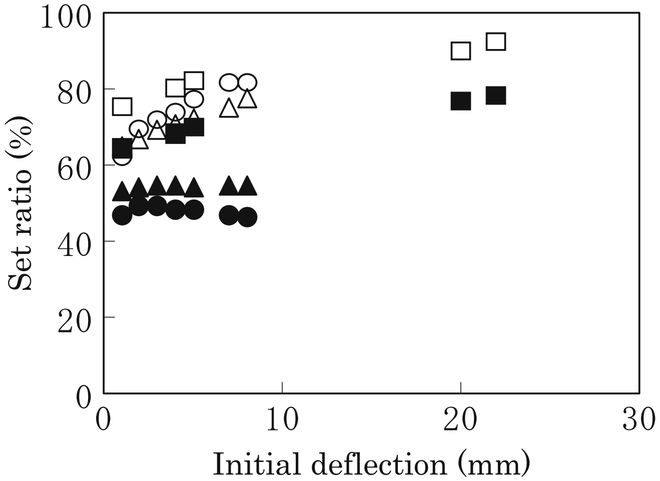

Fig. 1. Effect of initial deflections on sets measured immediately after (Set_0) and at 6000 min after unloading (Set_{6000}). The deflections were applied by the three-point bending method. *Open symbols*, Set_0; *filled symbols*, Set_{6000}; *squares*, loaded on the endodermis side of bamboo; *circles*, loaded on the epidermis side of bamboo; *triangles*, wood

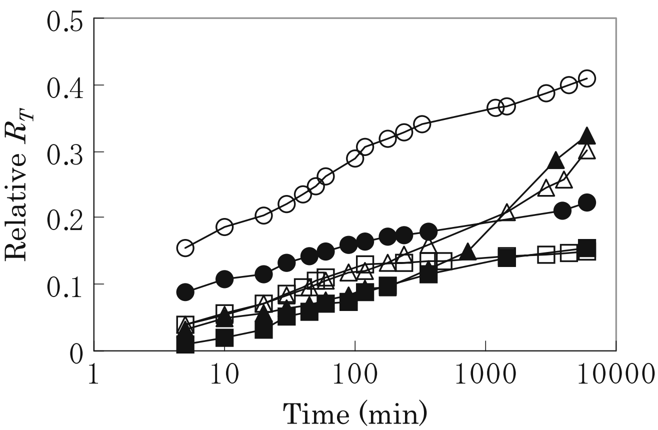

Fig. 2. Recovery over time from deformation (R_T) applied by the three-point bending method beyond (*open symbols*) and within (*solid symbols*) the proportional limits. *Squares*, loaded on the endodermis side of bamboo; *circles*, loaded on the epidermis side of bamboo; *triangles*, wood

with the initial deflection and suggests that there are other factors with respect to the dependence of the set ratio on the initial deflection.

Figure 2 shows recovery from deformation with time (R_T) for bamboo (B_{endo} and B_{epi}) and wood in wet condition. To investigate the effect of the initial deflection on the recovery behavior, the recovery from deformation for specimens deformed within their proportional limit (R_{within}) and beyond their proportional limit (R_{beyond}) was compared. In this case, the deflections within the proportional limit and beyond the proportional limit were two thirds of the proportional limit deflection (around 1 mm) and 80% of the breaking deflection (B_{endo}, 22 mm; B_{epi}, 8.6 mm; wood, 7.8 mm), respectively.

In the preceding report, it was clarified that the values of R_{within} after a long period were different between wood and bamboo. This was also the case for the present results; a larger rate of recovery in deformation for wood was found than that for B_{endo} beyond 1000 min after unloading. With regard to B_{epi}, R_{beyond} was considerably larger than R_{within}. This means that the relative recovery from deformation depended on the initial deflection. For B_{endo}, no clear difference between R_{within} and R_{beyond} was found in the later stage of recovery, although a small difference was found in the early stage. Moreover, R_{within} and R_{beyond} were almost constant in the later stage of recovery. These results mean that the recovery from deformation in B_{endo} was nearly complete within 1000 min, even for largely deformed specimens. These recovery behaviors corresponded well with the result shown in Fig. 1; Set_{6000} of B_{epi} and wood were almost constant regardless of the initial deflection. It can be considered that larger degrees of recovery from deformation were induced by larger delayed deformations before unloading. However, the result for B_{endo}, for which little difference in the behavior between R_{within} and R_{beyond} was found, cannot be explained from the viewpoint of delayed deformations. In addition, comparing the relative recovery between largely deformed B_{endo} and B_{epi}, recovery from the deformation in B_{endo} was nearly complete within 1000 min, but the recovery of B_{epi} continued longer. Thus, it was obvious that the effect of the initial deflection on recovery behavior was different between B_{endo} and B_{epi}. This suggested that set varies whether the bamboo specimen is loaded on the endodermis or epidermis side, and that B_{endo} has advantageous characteristics for the fixation of the deformation.

Bamboo culms primarily consist of parenchyma cells with embedded vascular bundles composed of metaxylem vessels, and the content of vascular bundle generally decreases from the outside to the inside across the culm wall.[8–11] It is commonly considered that the elastic modulus for the epidermis side is much larger than that for the endodermis side, and a neutral axis for bending exists between the central axis in the radial direction and the convex face. With increasing applied load, more conspicuous differences in the stress levels between the concave and convex faces will be generated for B_{endo}, and the neutral axis moves toward the epidermis side because the elastic modulus is greatly different between parenchyma cells and vascular bundles.[12–15] Thus, for B_{endo} it can be considered that large compressive deformations are generated in parenchyma cells near the concave face, and the result of set and its recovery should be investigated in more detail.

In addition, the recovery from deformation of wood immediately after unloading is considered to be caused by the elastic potential stored in cellulose microfibrils.[2] For drying set, this potential is frozen by hydrogen bonding in the matrix that develops with drying. In the case of compressed wood or bent wood, when the specimen was deformed beyond the proportional limit, conspicuous macroscopic deformation of the tissue including the cell lumens has been seen in largely deformed wood.[2] Considering these reports, the result of the increase in the set ratio with the initial deflection seen for B_{endo} is important for clarifying the mechanism of cooling set in bamboo and suggests a significant relationship between macroscopic deformation of the tissue and cooling set in largely deformed regions.

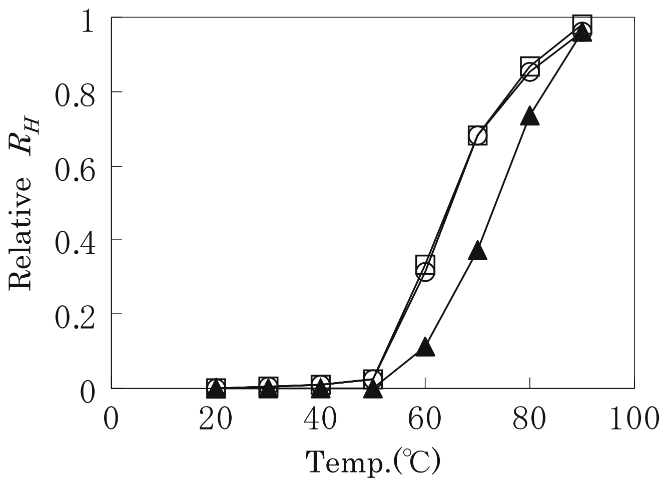

Fig. 3. Comparison of thermal recovery of cooling set between bamboo (*open symbols*) and wood (*solid symbols*) in the case of the three-point bending method. *Squares*, loaded on the endodermis side of bamboo; *circles*, loaded on the epidermis side of bamboo; *triangles*, wood

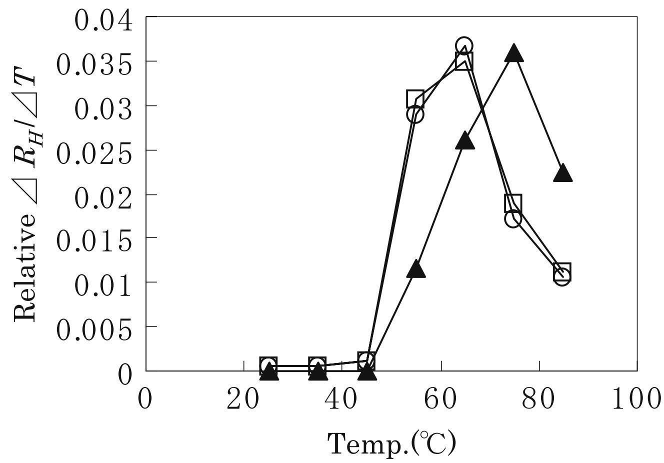

Fig. 4. Differential curves of relative recovery with heating in the case of the three-point bending method. *Squares*, loaded on the endodermis side of bamboo; *circles*, loaded on the epidermis side of bamboo; *triangles*, wood; R_H, relative recovery by heating; *T*, temperature

Thermal recovery of cooling set

Figure 3 shows the relationship between temperature and relative recovery from deformation in the heating process (R_H) from 20° to 90°C for the specimens deformed to 80% of breaking deflections. A unitary value for relative R_H means complete recovery of deformation. As shown in Fig. 3, 96%–99% of relative R_H was found by elevating the temperature to 90°C for all specimens. Iida et al.[2] investigated the hygrothermal recovery of deformation for compressed wood, and found that most of the deformation fixed by drying was recovered by hygrothermal treatment. However, they also suggested that drying set was not absolutely recovered by only moisture treatment. In the present work, for both bamboo and wood, the deformation fixed by cooling was completely recovered when the water temperature was elevated to 90°C again as shown in Fig. 3. This means that no failures are caused in specimens fixed by cooling.

Figure 4 shows differential curves of the relative R_H shown in Fig. 3. Steep recovery rates were found around 65°C for B_{epi} and B_{endo}, and at 75°C for wood. Given that the viscoelastic properties for highly polymeric materials like bamboo and wood depend on not only temperature but also relaxation time or frequency, it should be noted that the recovery behavior shown in Fig. 4 changes slightly with the heating rate. In the preceding study, a steep decrease in relaxation modulus, which is principally attributable to thermal softening by micro-Brownian motion of lignin, was found around 60°C for bamboo and 80°C for wood.[16–18] Considering this, it can be interpreted that the steep recovery rates around 65° and 75°C shown in Fig. 4 are due to the micro-Brownian motion of lignin, in other words, by the breaking of temporary hydrogen bonds produced in the set specimen. In the preceding section, the set ratio measured immediately after unloading and the recovery from deformation with time were different not only between bamboo and wood but also between B_{epi} and B_{endo}. However, as shown in Figs. 3 and 4, it was considered that cooling set was principally caused by the freezing of micro-Brownian motion of lignin through lowering the temperature below the glass transition temperature. Hence, further studies on higher order changes, such as microscopic characteristics of the specimen caused by large bending deformation, are necessary to clarify the facility of fixation shown for B_{endo}.

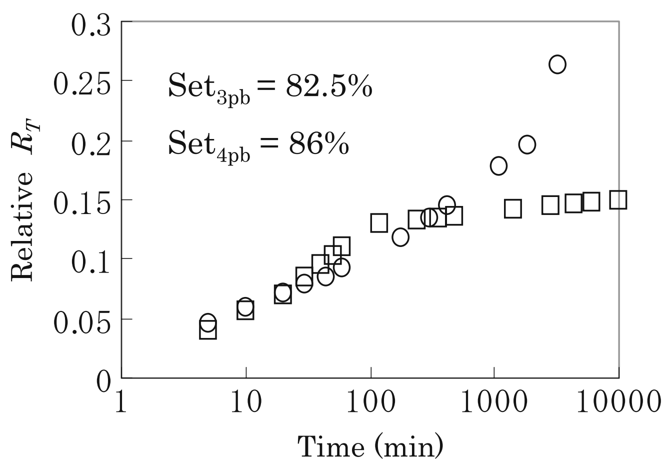

Fig. 5. Recovery from deformation for specimens loaded by the three-point bending and four-point bending methods on the endodermis side. *Squares*, three-point bending; *circles*, four-point bending; Set_{3pb}, set ratio measured immediately after unloading for specimens loaded by three-point bending; Set_{4pb}, set ratio measured immediately after unloading for specimens loaded by four-point bending

Effect of shearing deformation on recovery behavior

In Figure 5, the recovery from deformation with time for B_{endo} specimens loaded by three-point bending (B_{3pb}) and four-point bending (B_{4pb}) are compared. To clarify the effect of shearing stress, a load to cause the same maximum bending moment between B_{3pb} and B_{4pb} was calculated and applied. The set ratios measured immediately after unloading for B_{3pb} and B_{4pb} were 82.5% and 86%, respectively. As shown in Fig. 5, the R_T for B_{3pb} and B_{4pb} were quite different. While the recovery for B_{3pb} was almost finished at around 1000 min after unloading, that for B_{4pb} kept increasing after 1000 min. The recovery behavior for B_{4pb} was quite similar to that of wood shown in Fig. 2. It is well known that, in the four-point bending method, no shearing stress occurs between the two central loaded points. Considering this, it is suggested that shearing stress plays a significant role in the difference between the recovery behaviors of B_{endo} specimens loaded by three-point bending and four-point bending.

Microscopic observation

Imamura et al.[3] investigated the anatomical characteristics of some softwoods bent under microwave heating, and found that anatomical changes of the tracheid walls on the compression side varied with the radius of curvature of the bend and the susceptibility of wood species to microwave heating. Based on the above results and microscopic observation of wood specimens straightened by moisture treatment, they concluded that the softening of wood-matrix substances by microwave heating results in easy bending of wood specimens, and that wood-matrix substances are fixed in the bent wood after cooling and drying. Thus, the anatomical changes in bamboo caused by large bending deformation and cooling set should be examined to obtain new information about the mechanism of cooling set for bamboo. However, bamboo specimens loaded on the epidermis side broke before sufficient deflection was obtained to detect visible anatomical changes. Therefore, significantly bent bamboo loaded on the endodermis side was observed using a microscope.

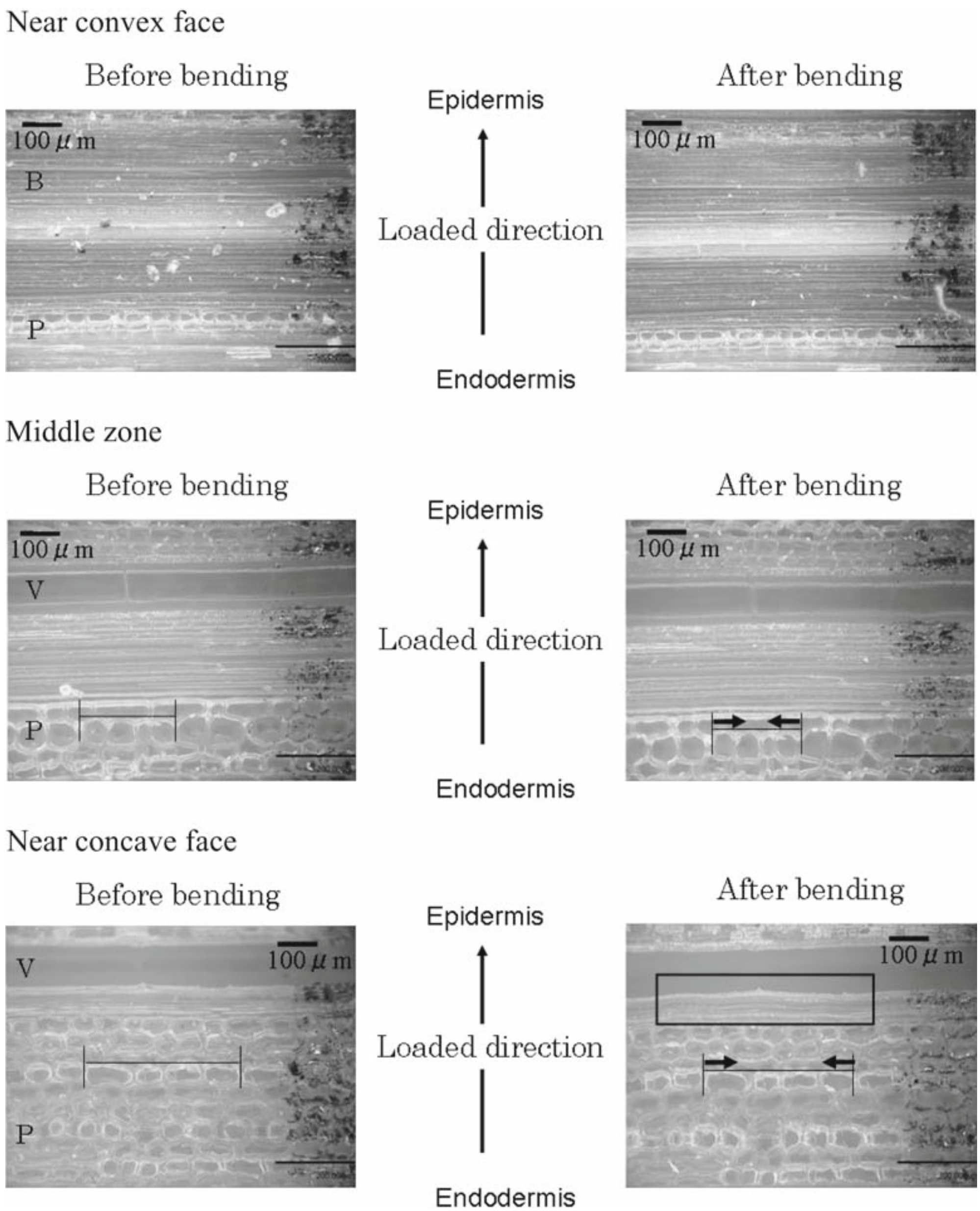

Fig. 6. Anatomical changes of tissues with deformation when the specimen was loaded on the endodermis side by the four-point bending. *Top*, convex face; *middle*, middle zone; *bottom*, radial plane near the concave face; *left*, before bending; *right*, after bending; *P*, parenchyma cell; *V*, vascular bundle; *B*, bast fiber

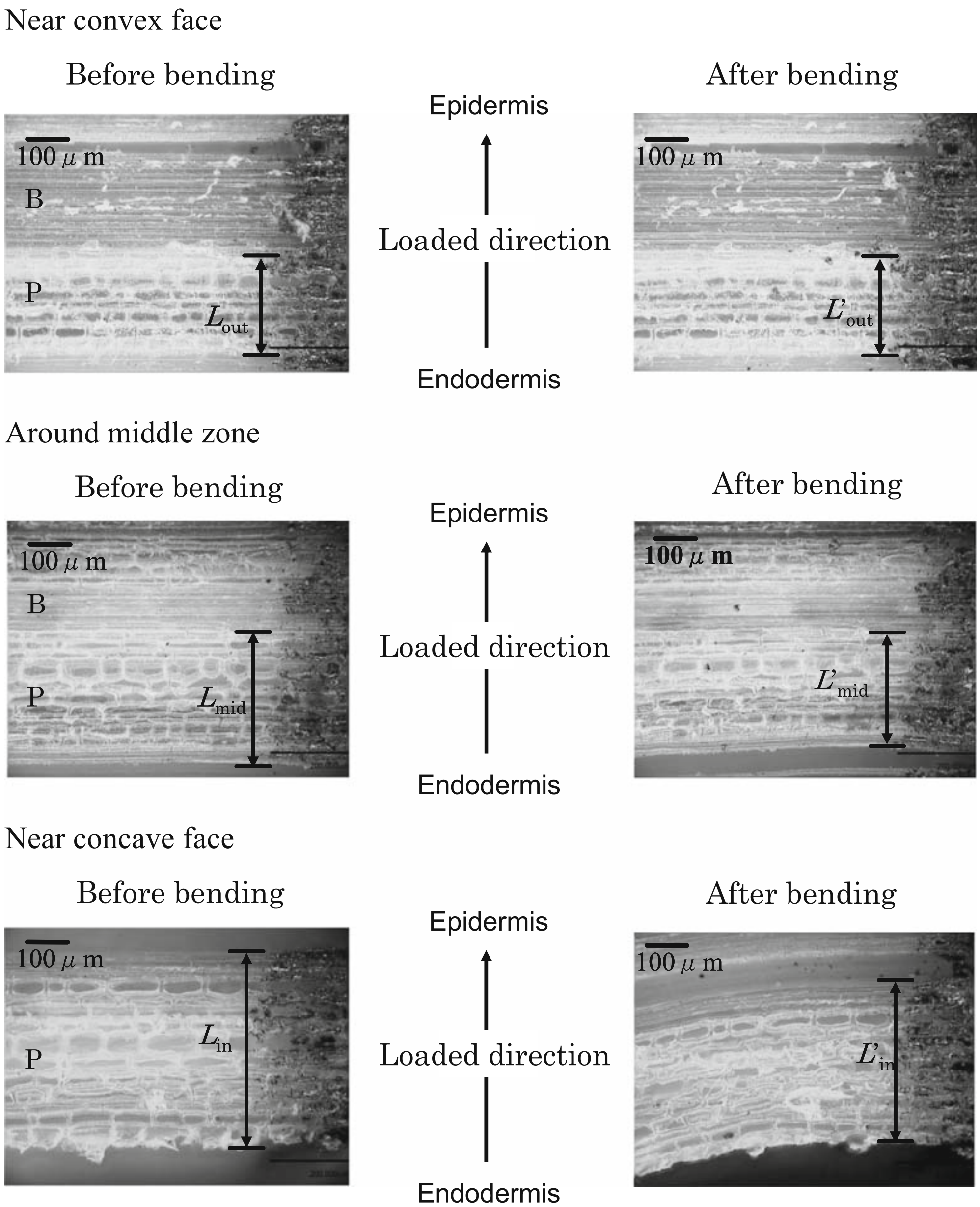

Fig. 7. Anatomical changes of tissues with deformation when the specimen was loaded on the endodermis side by the three-point bending method. *Top*, convex face; *middle*, middle zone; *bottom*, radial plane near the concave face; *left*, before bending; *right*, after bending; *P*, parenchyma cell; *V*, vascular bundle; *B*, bast fiber; *L*, length of parenchyma cell zone before bending; *L*', length of parenchyma cell zone after bending. Subscripts: *out*, near the convex face; *mid*, middle zone; *in*, near the concave face

For the B_{4pb} and B_{3pb} used in the above investigation (Fig. 5), the anatomical changes in tissues with bending near the convex face, middle zone, and concave face are shown in Figs. 6 and 7. In Fig. 6, remarkable compressive deformation of parenchyma cells (arrows) and wavy deformed bast fibers (rectangles) were observed near the concave face and middle zone. On the other hand, no clear changes in the tissue were found around the convex face even for a 3-cm radius of curvature. Nakato[10,11] investigated the proportion of microscopic elements in the transverse section of moso bamboo and found that the proportion of vascular bundles was about 57.2% in the outer part but only 26.2% in the inner part. Chuma et al.[12] showed that the mechanical properties of bamboo could be evaluated from its specific gravity using the rules of mixture between the volume fraction of bundle sheath and the Young's modulus. They determined that the Young's modulus of parenchyma and bundle sheath are 0.26 and 48 GPa, respectively.[12] Thus, the Young's modulus of the epidermis side is much larger than that of the endodermis side. In this manner, it is plausible that large deformations are applied to the parenchyma cells and bundle sheaths near the concave face while only slight deformation is caused near the convex face. This was also shown in the present microscopic observations. In Fig. 7, near the concave face and middle zone, shearing deformations and decrease in radial dimension were observed. Generally, compressive deformations and tensile deformations are caused by bending near the concave face and convex face, respectively. Considering the Poisson effect, the length of tissue in the radial direction near the concave face should be extended corresponding to compressive deformations in the longitudinal direction with bending. However, as shown in Fig. 7, L'_{in} and L'_{mid} (after bending) were clearly shorter than L_{in} and L_{mid} (before bending) at the concave face and in the middle zone. This was not seen for B_{4pb} at all. Hence, this decrease in radial dimensions is considered to be partially caused by shearing forces. Such a decrease in the radial dimension as well as shearing deformations should make it easy to bend the specimen and to reduce the recovery force from deformation.

From the above results, it can be considered that the characteristic recovery behavior found for B_{endo} given by three-point bending, which nearly finishes around 1000 min after unloading, is attributable to large deformations of parenchyma cells in the direction of the thickness of the beam and shear deformations of parenchyma cells in the direction of the length of the beam.

Conclusions

The bending properties and cooling set for bamboo under large deformations were investigated in comparison with wood. While no clear effect of the initial deflection on the set measured after a long period for bamboo loaded on the epidermis side (B_{epi}) was found, as also observed for wood, that for bamboo loaded on the endodermis side (B_{endo}) increased with the deformation level. Recovery from deformation with time for B_{endo} was almost complete at around 1000 min after unloading in the case of three-point bending. This recovery behavior was not observed for B_{epi} or wood. With most of the deformation recovered completely by reheating the specimen to the temperature at which it was deformed before cooling, it was considered that no failure occurred in the bent specimens. The deformation for B_{endo} loaded by four-point bending continued to recover, even after 1000 min. From microscopic observations, shearing deformations in parenchyma cells were observed.

From these results, the contribution of shearing deformations to the characteristic recovery behavior seen for B_{endo} was suggested. Thus, it can be considered that shearing deformations effectively contribute to a decrease in recovery force from deformations when bamboo specimens are loaded on the endodermis side by three-point bending.

References

1. Norimoto M, J Gril (1989) Wood bending using microwave heating. J Microwave Power Electromagn Energ 4:203–212
2. Iida I, Norimoto M, Imamura Y (1984) Hygrothermal recovery of compression wood (in Japanese). Mokuzai Gakkaishi 30:354–358
3. Imamura Y, Wada H, Norimoto M, Hayashi S (1982) The anatomical characteristics of softwood bent by utilizing microwave heating (in Japanese). Mokuzai Gakkaishi 28:743–749
4. Sato S (1974) Takekougei (in Japanese). Kyoritsu Shuppan, Tokyo, pp 73–78
5. Nakajima N, Furuta Y, Ishimaru Y (2008) Thermal-softening properties and cooling set of water-saturated bamboo within proportional limit. J Wood Sci 54:278–284
6. Mori M (1987) Process of flattening bamboo pieces utilizing microwave heating (in Japanese). Mokuzai Gakkaishi 33:630–636
7. Sato S (1974) Takekougei (in Japanese). Kyoritsu Shuppan, Tokyo, pp 35–38
8. Liese W (1987) Research on bamboo. Wood Sci Technol 21: 189–209
9. Nomura T (1980) Growth of bamboo (in Japanese). Mokuzai Kennkyuu Siryou 15:6–33
10. Nakato K (1959) On the cause of the anisotropic shrinkage and swelling of wood XVII. On the anisotropic shrinkage of bamboo. (1) (in Japanese). Bull Kyoto Pref Univ For 11:95–104
11. Nakato K (1959) On the cause of the anisotropic shrinkage and swelling of wood XVII. On the anisotropic shrinkage of bamboo. (2) (in Japanese). Bull Kyoto Pref Univ For 11:105–113
12. Chuma S, Hirohashi M, Ohgama T, Kasahara Y (1990) Composite structure and tensile properties of Mousou bamboo (in Japanese). Zairyou 39:847–851
13. Fujii T (2001) Natural fibers and environmentally gentle composite (in Japanese). Zairyou 50:556–557
14. Deshpande AP, Bhaskar RM, Lakshmana RC (1999) Extraction of bamboo fibers and their use as reinforcement in polymeric composites. J Appl Polym Sci 76:83–92
15. Sato S (1974) Takekougei (in Japanese). Kyoritsu Shuppan, Tokyo, pp 16–17
16. Sarkanen KV, Ludwig CH (1971) Lignins – occurrence, formation, structure, and reactions. Wiley, New York, pp 729–733
17. Salmen NL (1984) Viscoelastic properties of in situ lignin under water-saturated conditions. J Mater Sci 19:3090–3096
18. Furuta Y, Imanishi H, Kohara M, Yokoyama M, Obata Y, Kanayama K (2000) Thermal-softening properties of water-swollen wood VI. The change of thermal-softening properties due to lignification with moso bamboo as a model material (in Japanese). Mokuzai Gakkaishi 45:193–198