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Deformation under a repetition of moisturizing and drying of bamboo subjected to a set in bending

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Abstract The aim of this study was to elucidate the mechanisms of deformation change of bamboo set during bending with repeated moisturizing and drying. Deformation was represented by the set ratio, defined as the camber height normalized by the initial value of the fixed set. Susceptibility to deformation from moisture changes was estimated by the slope of the plot of the set ratio versus the moisture content. The set ratio decreased gradually during the repetition of moisturizing and drying, a property consistent with general wood materials. When the specimens were previously extracted in hot water, the set ratio increased but the slope did not change. On the other hand, a previous thermal treatment at more than 230°C or a set at less than 60°C affected both the set ratio and the slope: The set ratio decreased, and the slope increased. It is known that at 60°C hemicellulose starts to soften and at 230°C thermal degradation occurs. Thus, hemicellulose may play a role in the deformation properties of bamboo set during bending.

Key words Bamboo · Set in bending · Extraction · Thermal treatment · Hemicellulose

Introduction

Bamboo is widely available in Asia, as it is both fast-growing and mechanically strong.[1] Recently, bamboo has been used for construction, similar to plywoods.[2] There are traditional uses as well, such as for handicrafts or the interior of Japanese tea ceremony rooms. This is partially because bamboo is easily split longitudinally and has tough fibers. The set during bending is one way to manufacture bamboo, as it takes into account its characteristic mechanical properties. The deformation of set during bending of bamboo should be examined to ascertain the practical application of its use in moisturized conditions. However, there have been few reports on the deformation of bamboo set during bending under changing moisture conditions, whereas considerable study has been undertaken for wood.[3–5] Bamboo might be a good model for the mechanism of the mechanosorptive phenomenon, as it has a simple composition,[6] consisting mainly of only two constituents: the bundle sheath and parenchyma.

In this study we investigated what affects the set during the bending of bamboo by examining deformation under repeated drying and wetting conditions. The deformation was compared between specimens from the inner and outer layers, previously extracted and unextracted, and between previously thermally treated and nonthermally treated specimens.

Experimental

Specimen

Bamboo madake (*Phyllostachys bambusoides*) from Miyazaki, with 8 cm diameter, was used in this study. After removing the nodes, the inner surface, and the outer surface, the stem wall was cut into two layers longitudinally. They were cut into specimens of 110 mm (length) × 1 mm (radial) × 5 mm (tangential) and pretreated by hot water extraction or by a thermal treatment (Table 1). For the extraction treatment, the untreated specimens were boiled in water for 2 h. This treatment caused a weight loss of 1.6% in the outer layer specimen and 2.9% in the inner layer specimen. For the thermal treatment, the unextracted specimens were heated at a rate of 5°C per minute up to 140°, 170°, 200°, or 260°C and held at the temperature for 1 h in a

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vacuum. The specimens after the pretreatments were then completely dried.

Before setting, the specimens were softened in water at 60°, 80°, or 100°C and them set while bending fixed at both ends with 15 mm of camber (Fig. 1). They were left fixed overnight in a vacuum at the same temperature for softening. After setting, the keepers were removed and the specimens put into a desiccator with silica gel and cooled to room temperature. They were then exposed to repeated moisturizing and drying. Three to six specimens were measured for each procedure.

Repetition of moisturizing and drying

Moisturizing at 20°C in 98% relative humidity (RH) for several days and drying at 40°C overnight in a vacuum was repeated several times. During the repetition, the moisture contents and set ratios of the specimens were measured. The moisture contents were estimated by weighing, without considering the gradation of moisture inside the specimen. The set ratio represents the height of the camber normalized to that of the initial state just after the keeper was removed. The specimens were so thin the moisture severely affected the deformation of the specimen; and even a slight difference in the processing of each specimen affected the setting considerably.

Table 1. Overview of the treatments of bamboo samples

Previous treatment	Set treatment temperature
None	60° or 80°C
Extraction by boiling water for 2 h	100°C
Heating at 140°, 170°, 200°, 230°, or 260°C in a vacuum	100°C

Set treatment includes immersing in water for softening and drying in a vacuum under set during bending

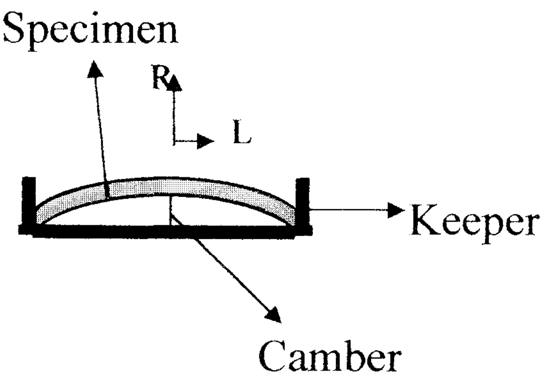

Fig. 1. Set of a bamboo specimen while bending

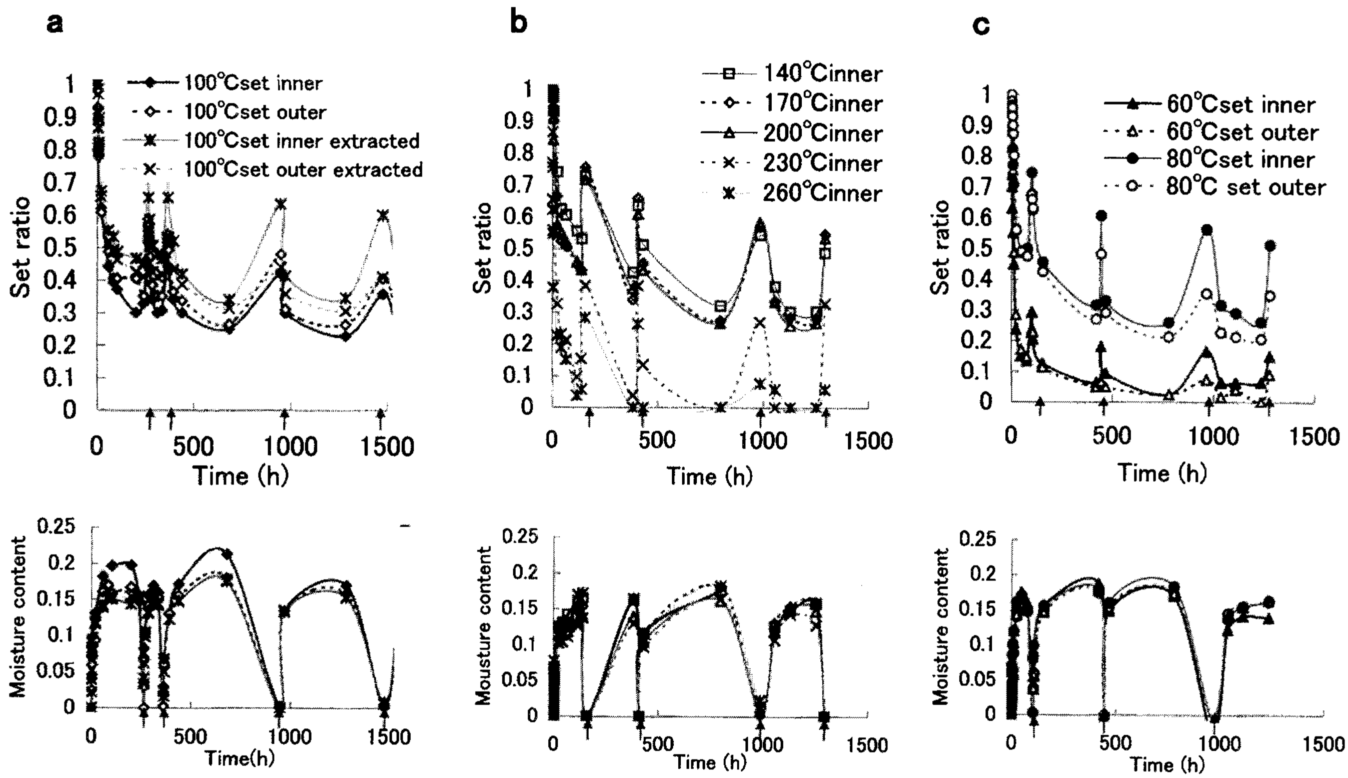

Fig. 2. Set ratios and moisture contents plotted against time when the bamboo specimens were exposed to repeated moisturizing and drying. The plotting started when the set specimens were initially exposed to humid air of 98% relative humidity (RH) at 20°C. **a** Untreated and previously extracted specimens set at 100°C. **b** Thermally pretreated specimens at 140°–260°C set at 100°C. **c** Untreated specimens set at 60° and 80°C. Note that the specimens moisturized successively at 20°C and 98% RH were dried overnight in a vacuum at 40°C at the time indicated by the *arrows*. Data points are connected as expedient lines for sake of appearance, although the lines might depart slightly from the real set ratios and moisture contents

Results and discussion

Change of set ratio during repeated moisturizing and drying

The change in the set ratio during the repeated moisturizing and drying versus time duration was plotted after initial exposure to a moisture content of 98% RH at 20°C (Fig. 2). At the time indicated by the arrows, the specimens were dried overnight. The set ratio decreased with moisturizing and increased with drying, but it generally decreased as the moisturizing and drying cycles were repeated. This creep tendency is similar to that of other wood-based materials. When the set ratio under the drying condition was large, it was also large under moisturizing conditions. The slopes of the plots of the set ratio versus the number of repetitions of moisturizing and drying became similar after the second cycle, possibly because the remaining stress had been released by the first cycle of moisturizing and drying.

The inner layer maintained the set better than did the outer layer, and the extracted specimen had a larger set ratio than did the unextracted specimen (Fig. 2a). Bamboo's inner layer includes more extractives than its outer layer because the inner layer has more abundant parenchyma cells.[7] Removal of the extractives might encourage formation of new bondings that constitute the set.

The set ratio of specimens treated at 100°C (Fig. 2a) was smaller than that of pretreated specimens at 140°–200°C, and those pretreated at >230°C were particularly low (Fig. 2b). It is believed that thermal degradation of wood hemicellulose occurs mainly at 180°C and achieves a maximum at 330°C,[8] although another report indicated that wood hemicellulose has a small thermal degradation peak at 140°C as well.[9] If the result with wood hemicellulose is applicable to bamboo, because their components are similar the degradation of hemicellulose at around 140°C may have caused the increased set ratio. At around 230°C, where the set ratio decreases significantly, hemicellulose has a second exothermal peak, whereas cellulose and lignin do not change.[10] These facts indicate the possibility that hemicellulose is related to the setting mechanism.

As for the setting temperature, the set ratio of specimens set at 80°C was far larger than those set at 60°C (Fig. 2c). This is consistent with the fact that the deformation of water-saturated wood increases drastically at temperatures >60°C.

Relation between set ratio and moisture content

The set ratio is believed to be affected by the susceptibility of the specimen to moisture. A plot of the set ratio of the extracted outer layer specimens versus the moisture content of the specimen showed a linear relation (Fig. 3). Only a plot of the outer layer specimen is shown in Fig. 3 because whole specimens had similar tendencies. The linearity between the set ratio and moisture content is usual for the creep properties of other wood materials.[11] The apparent slope of the plot became less steep as the cycle of moisturizing and drying was repeated (Fig. 3a). However, those normalized to the initial set ratio of each cycle were similar, apart from the first cycle, which had the steepest slope (Fig. 3b). This might be because some kind of stress was released at the first cycle.

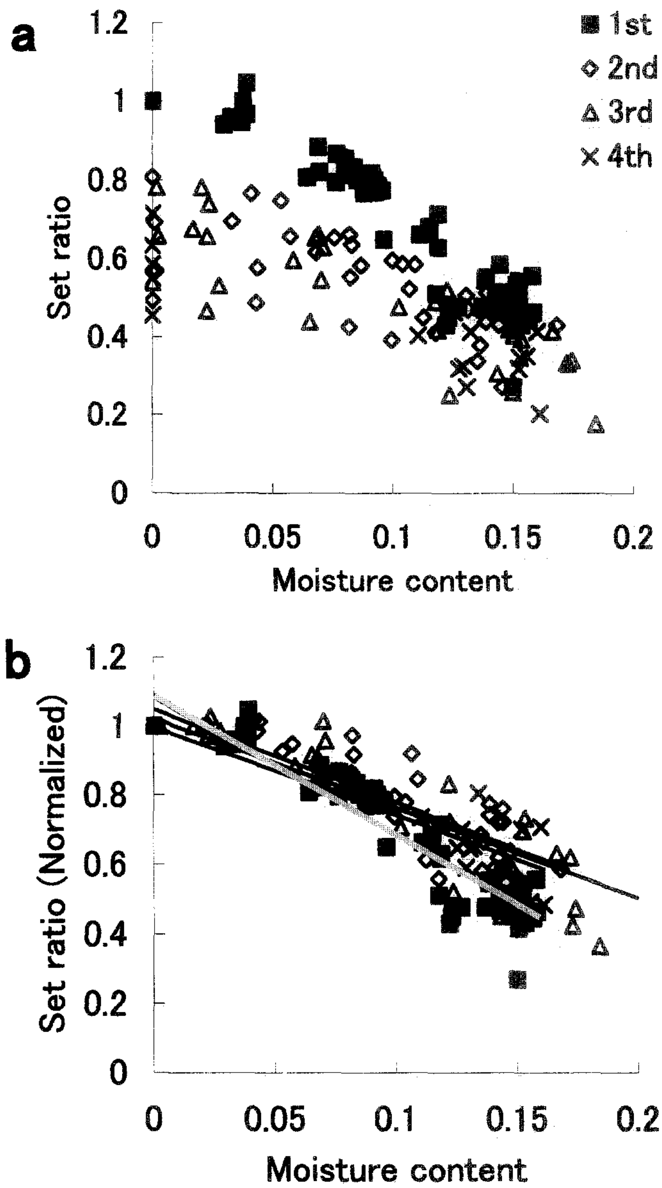

Fig. 3. **a** Set ratios of the first to fourth cycles were plotted versus moisture content. **b** As in **a**, but the set ratio was normalized by the initial set ratio of each cycle. *Gray line*, approximation to the first cycle; *black lines*, approximation to the second, third, and fourth cycles. As an example, only an extracted specimen from the inner layer set at 100°C is shown here

The slope of the set ratio plotted against moisture content is thought to represent the extent to which the set is affected by moisture. The change of the set ratio of variously treated specimens at the first cycle is examined in Fig. 4. As for the specimens set at 100°C, the slopes were similar among the specimens from the inner layer, outer layer, and extracted and unextracted specimens (Fig. 4a). In this case, the set is achieved by the same mechanism regardless of the

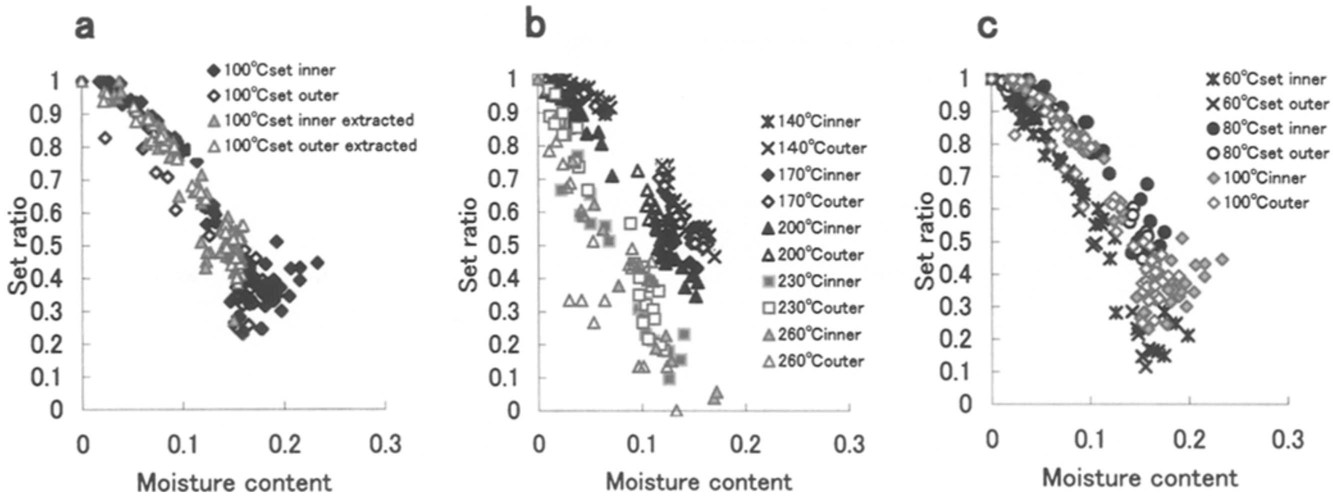

Fig. 4. Set ratio plotted versus moisture content. **a** Untreated and extracted specimens were set at 100°C. **b** Thermally pretreated specimens set at 100°C. **c** Specimens set at 60° and 80°C

Table 2. Comparison of set ratios and the slope of the plot of set ratio versus moisture content, among various conditions of set during bending

Factor	Set ratio	*d*(set ratio)/*d*(moisture content)
Sampled layer of specimen	Outer > inner	Inner ≒ outer
Extraction in boiling water before set	Extracted > untreated	Untreated ≒ extracted
Thermal pretreatment at 100°–260°C before set	140°, 170°, 200°C > 100°C > 230°, 260°C	230°, 260°C > 100°, 140°, 170°, 200°C
Temperature for setting	80°C > 60°C	60°C > 80°C

amount of extractives in the specimens. This fact indicates that the extractives do not act as the binder for the set. On the other hand, the temperature during setting affected the slope; when the set was achieved at lower temperatures the slope was steeper (Fig. 4c). Thus, the set at lower temperatures is more affected by moisture than that at higher temperatures. In the case of the specimens previously treated thermally (Fig. 4b), no difference in the slope was observed among the specimens treated at 100°–170°C, whereas for those treated at more than 200°C the slope became steeper as the temperature of the previous thermal treatment increased. To clarify the cause of the difference in the slopes, correlations were examined between the slope and the following factors: (1) the gravity; (2) Young's modulus for bending; (3) the decrease in weight by previous thermal treatment; and (4) the decrease in weight during softening in boiling water for the set. Only the decrease in weight by previous thermal treatment had a correlation with the slope ($R = 0.89$). Hemicellulose might affect the slope because it is the most degradable of the three main components of wood at temperatures between 170° and 260°C.

Comparison of set ratios and slope of the plot of set ratio versus moisture content, among various conditions of set during bending are summarized in Table 2. Hemicellulose might relate significantly to the efficiency of moisture to decrease the set ratio in this study. The decrease in the set ratio was severely affected by moisture in two cases: (1) when the specimens were set at quite low temperatures under the point of hemicellulose softening; and (2) when the specimens were previously treated at quite high temperatures above the point of hemicellulose degradation. This indicates that the set by hemicellulose bonding is hardly affected by the moisture content. These results were from an analogy of components between wood and bamboo. The effect of hemicellulose on the setting mechanism of bamboo should be studied more vigorously. The effect of lignin on the setting at lower temperature than 80°C must also be investigated because the thermal softening point of green wood possible due to lignin was found using the forced-vibration test in the temperature range 10°–95°C.[12] Further investigations into the mechanism of set will be reported in the future based on the anatomical differences between wood and bamboo.

Conclusions

Deformation during moisture adsorption and desorption of bamboo subjected to set during bending was investigated, and the results are summarized as follows.

1. The set of the specimen previously extracted in boiling water was more stable than that of the intact specimen.
2. However, the extractives did not make bondings for the set.
3. The set ratio was severely decreased and the susceptibility by water was increased when the specimens were set at quite low temperatures (below the point of hemicellulose softening). This was also the case when the specimens were previously treated at quite high temperatures (above the point of hemicellulose degradation).

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