The Influence of Repeated Thermal Shock on the Mechanical Properties of Mongolia Scotch Pine and Moso Bamboo

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The sharp temperature changes in nature (*e.g.*, forest fires, ice, and snow) can cause mechanical damage to trees and bamboo. The mechanical properties of Mongolia Scotch pine (*Pinus sylvestris* L. *var. mongolica*) and Moso bamboo (*Phyllostachys edulis*) were investigated by a three-point bending test with a repeated thermal shock process (*i.e.*, sudden changes of temperature). The experimental results indicated that the flexural modulus, flexural strength, and deformation work *per* volume decreased almost linearly with the increased repetition of thermal shock treatment for both Mongolia Scotch pine and Moso bamboo. The damage caused by repeated thermal shock was stronger for Mongolia Scotch pine, as compared to Moso bamboo, under the same thermal shock treatment. Thus, the experimental results provided basic data for engineering applications of Mongolia Scotch pine and Moso bamboo after natural disturbances.

Keywords: Mongolia Scotch pine; Moso bamboo; Thermal shock; Three-point bending; Mechanical properties

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INTRODUCTION

Natural disturbances, such as earthquakes, forest fires, ice, snow storms, and hurricanes, happen widely and frequently in nature (Chen 1996; Aszalós *et al.* 2012). As a result of these natural disturbances, trees and bamboos can experience damage such as bending, snapping, uprooting, branch loss, and crown damage (Prouix and Greene 2001; Zhou *et al.* 2011). The effect of natural disturbances on tree recovery, land restoration, ecosystem change, and forest management have been extensively studied as a function of the species, density, size, and growth factor of trees, climate factors, and physiographic factors (DeWalle *et al.* 2003; Marilou *et al.* 2007; Goodnow *et al.* 2008; Zhou *et al.* 2011). Few investigations have been carried out on the possible changes in mechanical properties of trees or bamboos after severe and abrupt temperature change caused by such widespread and common disturbances as fire, ice, and snow. Such abrupt changes in temperature is termed thermal shock and it is expected that the reaction of wood to quick changes and cycles in temperature could be different than what has been observed in traditional laboratory studies. In addition, substantial evidence has demonstrated that mechanical properties of woods or bamboos are affected by temperature, especially high temperatures, which can dry out the plants (Oltean *et al.* 2007; Borrega and Kärenlampi

2010; Goodrich *et al.* 2010). This drying process is rather slow, while it is abrupt and dynamic when caused by forest fires, ice, and snow. Therefore, it is necessary to characterize the influences on the mechanical properties of wood and bamboo with exposure to thermal shock treatment (or thermal shock resistance) (Monteverdew 2007), either in the management of forest recovery or regarding the engineering applications of trees and bamboos after the disturbances. The thermal shock resistance of materials is the comprehensive reaction of mechanical properties and thermal properties when the heating conditions suddenly change (Hasselman 1985). Damage as a result of thermal shock can be divided into two categories. One is the transient fracture, called the thermal shock fracture, while the other is the cracking and spalling due to thermal shock cycles. Fragmentation and deterioration resulting from these forces cause thermal shock damage. For lignocellulosic materials, thermal degradation of the organic materials should be considered as another category (Rowell 2012). Many factors influence the thermal shock resistance of materials, such as the mechanical and thermal properties of the materials, material geometry, environment medium, and heating mode. In addition, several methods are used to evaluate thermal shock resistance of different materials. The residual strength of thermal shock resistance is the most commonly used laboratory evaluation method for materials (Schön *et al.* 1994). With this method, the samples are first heated to a specified constant temperature, then quickly immersed in a cooling medium for immediate thermal shock and then the samples are placed under a constant temperatures during the thermal shock process. The thermal shock resistances are then evaluated by measuring the remaining moduli, strengths, and deformation of the materials (Johnson-Walls *et al.* 1985).

Most of these current thermal shock studies have focused on ceramic or metal materials. The unique features of this work were that the biomaterials such as wood and bamboo were investigated. The purpose of this study was to investigate the influences of repeated thermal shocks on the mechanical properties of two plant materials commonly growing in forests, Mongolia Scotch pine (*Pinus sylvestris* L. *var. mongolica*) and Moso bamboo (*Phyllostachys edulis*). Pine and bamboo samples were exposed to repeated thermal shocks ranging from 200 °C to -65 °C. Three-point bending tests were then carried out to determine the mechanical properties (flexural modulus, flexural strength, and deformation work *per* volume) of the thermal shock-treated pine and bamboo samples. The experimental results showed that the mechanical properties decreased almost linearly with an increased repetition of thermal shock treatment for both species. This study provides basic data for engineering applications of Mongolia Scotch pine and Moso bamboo, and a reference for forest recovery and management after natural disturbances.

EXPERIMENTAL

Materials

Mongolia Scotch pine (*Pinus sylvestris* L. *var. mongolica*) samples were collected from the Greater Khingan Range in China. The age of the trees ranged from 10 to 12 years, with an average diameter at breast height of 120 mm. The air-dried density of the samples was 422 kg/m^3, and the average water content was about 14%. Moso bamboo (*Phyllostachys edulis*) samples were gathered from the Laoshan forest farm of the Qiandao Lake in Zhejiang Province of China. The bamboo was 6 years old, and the samples were cut from the middle and distal culms. The diameter of the stalks was 85 to 95 mm, and the wall thickness 8 to 10 mm. The bamboo strips were sliced in the longitudinal direction of the culms. According to the national standards of China (GB/T 1927 2009; GB/T 1936.1 2009; GB/T 1936.2 2009), three-point bending specimens of Mongolia Scotch pine and Moso bamboo were prepared with a length, width, and height of 140 mm, 8 mm, and 8 mm, respectively. More than three replicates are required according to the standards.

Methods

Repeated thermal shock treatments on Mongolia Scotch pine and Moso bamboo samples were performed to simulate the sudden temperature changes of natural disturbances within the forest. For repeated thermal shock treatments, the specimens were placed in a heating furnace with the heating rate of 12 °C/min from room temperature to 200 °C, just below the ignition temperatures of Mongolia Scotch pine and Moso bamboo. After being maintained for 30 min at 200 °C, the samples were quickly removed from the 200 °C furnace and placed into a -65 °C medium, dynamically controlled by a mixture of liquid nitrogen and alcohol for 5 min to cool. Once cooled, the samples were removed from the cold medium and then placed into the heating furnace at 200 °C for another cycle. This hot/cold process was repeated to expose the specimens to the impact of a 265 °C temperature difference. The number of cycles in the study were 1, 20, 40, 60, and 80.

Three-point bending tests on the specimens, before and after thermal shock, were performed using a WDW-3020 electronic universal testing machine (Changchun Testing Machine Co., Changchun, China) at ambient conditions, with a loading rate of 2 mm/min was. The load-deflection curves were automatically recorded. The parameters characterizing the flexural properties were then obtained for the flexural modulus, flexural strength, and deformation work *per* volume. Three to five samples were measured to yield an average for the different repeated thermal shock times for both Mongolian pine and Moso bamboo.

RESULTS AND DISCUSSION

Mechanical property test results are shown in Figs. 1 and 2.

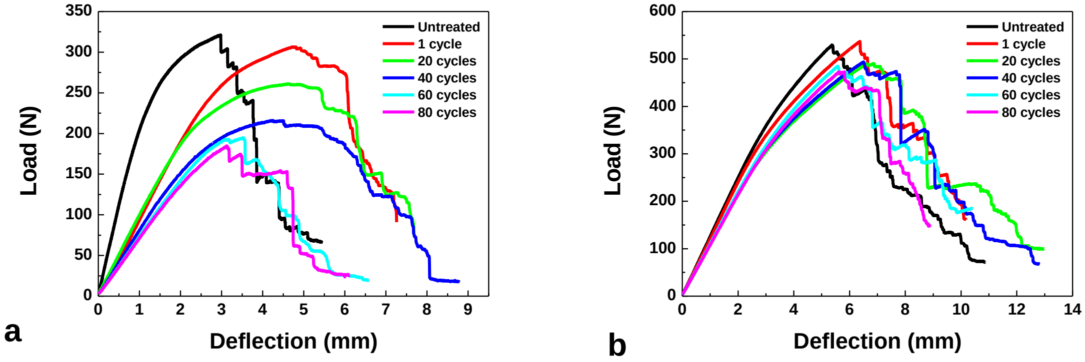

Fig. 1. Typical three-point bending load and deflection curves under before and after different thermal shock treatment times for (a) Mongolia Scotch pine and (b) Moso bamboo

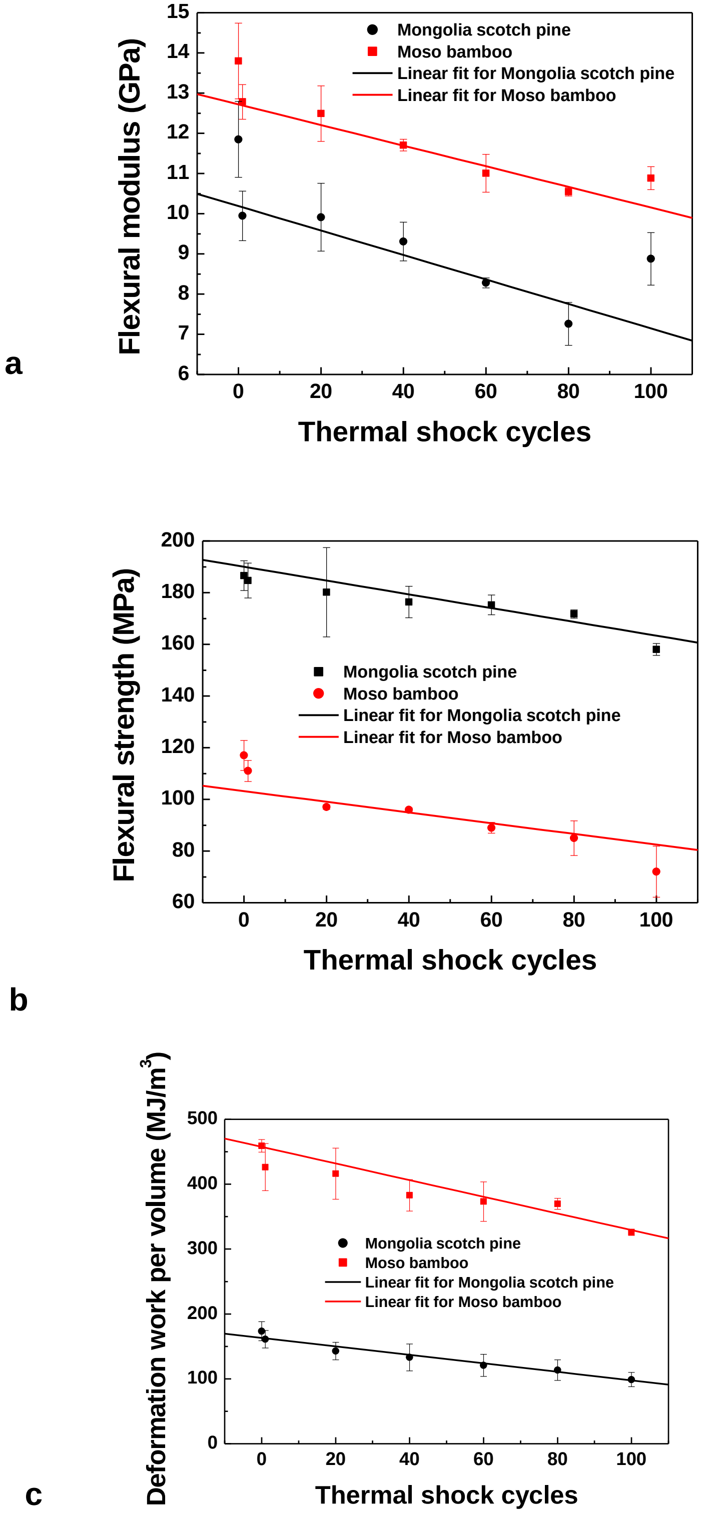

Fig. 2. Property variations of the (a) flexural modulus, (b) flexural strength, and (c) deformation work *per* volume for Mongolia Scotch pine and Moso bamboo

Three-point bending tests were performed to determine the influences on the mechanical properties of both Mongolia Scotch pine and Moso bamboo with varying cycles of thermal shock treatment. The representative flexural load-deflection curves are shown in Fig. 1 for both the Mongolia Scotch pine and Moso bamboo samples before and after thermal shock treatment. The average flexural modulus, flexural strength, and deformation work per volume and their standard deviations are given in Fig. 2.

Mongolia Scotch pine and Moso bamboo were found to behave as typical plant cellular biocomposites, before and after the thermal shock treatments, as shown in Fig. 1; *i.e.*, the load in the three-point bending increased non-linearly to a peak and then decreased gradually. Furthermore, it is obvious that the maximum load decreased with the increased number of cycles of thermal shock treatment, for both Mongolia Scotch pine and Moso bamboo. After 80 thermal shock cycles, the load on the Mongolia Scotch pine sample decreased by about 40%, whereas that of the Moso bamboo sample decreased by about 10%.

Figure 2 shows the dependence of the flexural modulus, flexural strength, and deformation work *per* volume on the repeated cycles of thermal shock treatment. It is clear that all three mechanical parameters of Mongolia Scotch pine and Moso bamboo exhibited distinct effects with repeated thermal shocks; *i.e.*, they decreased almost linearly with increased repetition of thermal shock treatment. Similar results were detected from ceramics or metal materials (Hasselman 1985; Johnson-Walls *et al.* 1985). The decrease in flexural properties was gradual for both the Moso bamboo and Mongolia Scotch pine samples. Meanwhile, after one thermal shock, there was an obvious decrease in flexural modulus, while no distinct change for flexural strength and deformation work *per* volume were seen. After 80 thermal shock cycles, the flexural modulus, flexural strength, and deformation work *per* volume of Mongolia Scotch pine sample decreased by about 39%, 39%, and 35%, respectively, while these values decreased by about 24%, 8%, and 29%, respectively, for the Moso bamboo sample. The damage caused by the same repeated thermal shock was stronger for the Mongolia Scotch pine samples than for the Moso bamboo samples (Figs. 1 and 2). One reason may be that bamboo, a member of the grass family, contains highly aligned long cellulosic fibers that make up the woody stem coupled with higher density than wood (Byrne and Nagle 1997).

Figure 3 shows photographs of the tested pine wood and bamboo samples before and after 1 to 80 thermal shock cycles.

Fig. 3. Samples after flexural tests for (a) Mongolia Scotch pine and (b) Moso bamboo. The six tested samples depicted from top to bottom were treated with 0, 1, 20, 40, 60, and 80 thermal shock treatments.

The specimen surface color became darker with an increasing number of thermal shocks. All the samples failed at the mid-span with a concentrated load, and the lower surfaces of all samples were damaged with maximum tensile stresses during bending. The experimental results provide basic data for engineering applications of Mongolia scotch pine and Moso bamboo, and a reference for forest recovery and management after natural disturbances. The temperature influences mechanical properties should be considered when wood or bamboo materials are used, especially in the environments with sharp temperature changes.

CONCLUSIONS

1. The mechanical properties of wood or bamboo materials are influenced by sharp temperature changes.
2. The flexural modulus, flexural strength, and deformation work *per* volume decreased almost linearly with increased repetition of thermal shock treatment number of thermal shock treatment for both Mongolia Scotch pine and Moso bamboo.
3. The damage caused by the same repeated thermal shock was greater for the Mongolia Scotch pine sample than it was for the Moso bamboo sample.

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