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Experimental study on compressive and tensile properties of a bamboo scrimber at elevated temperatures

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HIGHLIGHTS

- Stress-strain relationship of bamboo scrimber at elevated temperatures were reported.
- Failure mechanisms of each stress state at elevated temperatures were analyzed.
- The equations with reduction factors for strength and modulus of elasticity were established.

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ABSTRACT

To understand the stress-strain relationship and failure mechanism of bamboo scrimber at elevated temperatures, both parallel and perpendicular to grain properties in tension and compression at temperatures from 20 °C to 270 °C were experimentally studied. A total of 90 tensile coupon specimens and 60 compressive specimens were tested during heating at temperatures ranging from 20 °C to 270 °C. The experimental results indicated that tensile stress-strain relationships of a bamboo scrimber parallel to grain at elevated temperatures were linear from the beginning of loading to failure, and the tensile strength and modulus decreased with increasing the temperature from 20 °C to 270 °C, except at 200 °C. Perpendicular to grain direction, the tensile stress-strain relationships exhibited nonlinear behaviour, and the ultimate strengths were very small. Accordingly, it was observed that the modulus decreased to zero from 20 °C to 180 °C. The compressive stress-strain curves of bamboo scrimber exposed to elevated temperatures were divided into a linear branch and a nonlinear branch beyond proportional limit for both grain directions. The equations with reduction factors for strength and modulus of elasticity were established by regression analysis of the test data. Parallel to grain of a bamboo scrimber, the values from fitting formulas were mostly larger than those from Eurocode 5, and the maximum differences between reduction factors were 0.31, 0.04, 0.23, and 0.24. This study provides a valuable reference for potential application of bamboo scrimber in structural engineering.

1. Introduction

Bamboo is a rapidly renewable sustainable material that is globally available [1–5]. Across Asia, Africa, and Latin America, there are over 1200 recognized species with an estimated growing area of approximately 36 million hectares [6]. Bamboo grows very rapidly and usually takes 3–6 years to harvest, as opposed to traditional timbers, which take decades [7,8]. Worldwide, there is a growing interest in development of bamboo products as a sustainable, cost-effective and ecologically responsible alternative constructive material. While the potential of bamboo is promising, more widespread applications are limited by the diameter of the bamboo and the variation in the geometric and mechanical properties [9].

Generally, natural bamboo can be idealized as a 2-phase composite consisting of longitudinal cellulose fibres within a ligneous matrix [10]. The mechanical properties of bamboo are based on the distribution of fibres. To decrease the flaws and enhance dimensional consistency, strength and uniformity of bamboo, the bamboo culm can be split to strips, fluffed to bamboo fibre bundles, dried until the moisture content is less than 11%, and then saturated in phenolic resin to form the desired specific gravity and thickness under high pressure. The composite material is called bamboo scrimber. Therefore, bamboo scrimber has highly

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distinctive microstructure and favourable mechanical properties, particularly a lower variability of both strength and modulus [11]. Furthermore, the manufacturing technical process of bamboo scrimber is gradually improving, and bamboo scrimber is becoming an increasingly attractive structural material for use in construction engineering [12].

Kumar et al. studied the influence of bamboo scrimber density on the mechanical properties, including compressive strength, tensile strength, shear strength, flexural strength and elastic modulus for compression, tension and flexure and compared the results with existing results in the literature [13]. They revealed that all of the mechanical properties significantly varied with the density of bamboo scrimber. Huang [14] investigated the uniaxial compressive and tensile stress-strain relationship of parallel strand bamboo at room temperature and found that the strength of tension parallel to grain was nearly twice that of compression parallel to grain, but it was much lower than that of compression perpendicular to grain. Yu et al. tested bamboo scrimber with different weight percentages of phenol formaldehyde resin and different heat treatments of bamboo bundles [15]. The effects of thermal treatment and PF loading on the dimensional stability and mechanical properties of a bamboo scrimber were also evaluated. Chen et al. investigated the effect of the holes in the web on the mechanical properties of the OSB webbed bamboo scrimber I-joists [16]. It was found the strengths of the specimens were considerably influenced by holes in the web. Sharma et al. reported the mechanical properties of bamboo scrimber parallel to grain direction and compared them with those of laminated bamboo sheets [17].

To date, many knowledge gaps remain in the understanding of the mechanical behaviour of bamboo scrimber as a common construction material [18]. One important issue is the stress-strain relationship of bamboo scrimber at elevated temperatures. Bamboo scrimber is combustible. Fire is destructive in bamboo structures and can significantly reduce the strength and stiffness of bamboo scrimber when exposed to elevated temperatures [19–21]. However, few studies have been conducted on the mechanical properties of bamboo scrimber at elevated temperatures. Therefore, it is essential to understand the effect of temperature on the mechanical properties of bamboo scrimber, especially the compressive and tensile stress–strain relationships. It can be used to predict the behaviour of a structure during the fire damage process, which is important in structural design.

The purpose of this paper is to understand the effects of grain direction and heating temperature on the mechanical properties (strength, modulus, ultimate strain, stress-strain curve characteristic) of bamboo scrimber. Based on the experiment results and regression analysis, the reduction factors for strength and modulus of bamboo scrimber with elevated temperatures are proposed. The results provide a valuable reference for the application of bamboo scrimber in structural engineering.

2. Experimental program

2.1. Fabrication of specimen

In this study, the commercially produced bamboo scrimber products, also known as parallel strand bamboo, strand woven bamboo, or restructured bamboo, supplied from China were used [22]. Approximately four- to five-year-old Moso bamboo culms were split longitudinally into 2-m-long strips. Next, each strip was pushed into the fluffer to form net-structured bamboo bundles. Subsequently, bamboo fibre bundles were saturated in phenolic resin and then compressed to the desired specific section of 140 mm × 140 mm under high pressure. The average density of bamboo scrimber specimen is 1060 kg/m^3, with a moisture content of 10%.

According to ASTM D143-14 [23] and the configuration of the testing furnace, the size and shape of the specimens designed for tensile and compressive experiments are shown in Fig. 1. To investigate the effect of temperature and grain direction on the mechanical properties of bamboo scrimber, 11 types of tensile coupon specimens in parallel to grain, 7 types of tensile coupon specimens in perpendicular to grain, and 10 types of compressive specimens for both grain directions were prepared. Three specimens for each type of compressive test and 5 specimens for the tensile test were adopted.

2.2. The uniaxial loading system

The uniaxial compressive and tensile tests were performed on a testing machine, UTM5105, with a capacity of 300 kN. The strain of the specimens was measured using a high-temperature extensometer, which was made of high resisting ceramic tubes that range from 0 to 10 mm. Two ceramic tubes were fixed on the specimens with a standard distance of 50 mm along the vertical direction. The load was applied monotonically for compressive specimens by the motion of the movable crosshead of the test machine at a rate of 0.02 mm/min; for the tensile specimens, a pair of jigs was used with the same velocity. The data for load, displacement, strain, temperature and time were recorded during the loading process at a frequency of 50 Hz. The layout of the loading system is illustrated in Fig. 2. For the tensile test, a pair of jigs, which were used to fix specimens, were set outside the testing furnace and the middle of the specimens. A high temperature head was adopted for all of the specimens in the compressive test at high temperature. The corresponding loading system and testing furnace are shown in Fig. 2.

2.3. Heating regimes

The steady state test method was employed to examine the properties of the bamboo scrimber material. The testing furnace with a maximum temperature of 1200 °C was used to specify the required temperatures with an accuracy of 1 °C. The specimens were heated up to a specified temperature and then loaded until they failed. The heating treatment was performed utilizing the testing furnace at 11 different target temperatures: 20 °C, 50 °C, 80 °C, 100 °C, 120 °C, 150 °C, 180 °C, 200 °C, 220 °C, 250 °C, and 270 °C. The tensile strength parallel to grain is nearly 0 as the temperature exceeds 180 °C; thus, the target temperatures ranged only from 20 °C to 180 °C. The temperature was applied at a rate of 10 °C/min, except for the temperature case of 20 °C. To improve stability and homogeneity of temperatures in the testing furnace, the target temperature was sustained for 30 min before loading. The temperature was maintained when the load was applied during testing. The location of the specimens and testing furnace are presented in Fig. 2.

3. Experimental results and discussion

3.1. Stress-strain relationships

The typical tensile stress-strain relationships of bamboo scrimber specimens at different temperatures are shown in Fig. 3. The bamboo scrimber specimens show nearly linear behaviour parallel to grain at different temperatures. As presented in Fig. 3(a), with temperature increasing from 20 °C to 270 °C, the peak stress decreases gradually except for an abrupt change at 200 °C. The peak strain and slope of the curves exhibit the same change tendency with peak stress. Fig. 3(b) shows that nonlinear behaviour can be observed in the stress-strain relationship perpendicular to grain from the initial loading stage to final failure. The tensile strength is very small at elevated temperatures. The peak stress, strain and slope of the curves decrease gradually with increasing temperature.

As Fig. 4 shows, the typical compressive stress-strain relationships of bamboo scrimber specimens can be divided into a linear branch and a nonlinear branch within and beyond the proportional limit for both parallel to grain and perpendicular to grain directions. It can be observed that in the earlier loading stage, the specimens were in the linear state and the stress was proportional to the strain; subsequently, the specimens exhibited distinct nonlinearity exceeding the point of proportional limit. After the peak point, the curves turned into a descending branch and the slope of the curves became negative. When the temperature was at 20 °C, the platform of the curve in parallel to grain was short. As the temperature increases from 20 to 270 °C, the platform and strain area of the curves become longer, resulting in good ductility of the bamboo scrimber. Above 270 °C, the curves decrease evidently. The peak stress and slope of each curve with temperature