Construction and Building Materials 182 (2018) 178–187

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Experimental study on thermal performance of bamboo scrimber at elevated temperatures

Zhaoyan Cui [a,b], Ming Xu [a,b,*], Zhongfan Chen [b], Jinhua Xiang [b]

[a] Key Laboratory of RC & PC Structures of Ministry of Education, Southeast University, 02, Sipailou, Nanjing 210096, PR China
[b] School of Civil Engineering, Southeast University, 02, Sipailou, Nanjing 210096, PR China

HIGHLIGHTS

- The specific heat of bamboo scrimber exhibits two peaks in the temperature range of 20–500 °C.
- The change tendencies of density ratio of bamboo scrimber and timbers are similar to each other from 20 °C to 900 °C.
- The thermal conductivity ratios for the two grain directions of bamboo scrimber are between 1.26 and 1.63.
- The measured thermal properties of bamboo scrimber have good accuracy and are suitable for numerical simulation.

ARTICLE INFO

Article history:
Received 15 October 2017
Received in revised form 11 June 2018
Accepted 15 June 2018

Keywords:
Specific heat
Density ratio
Conductivity
Charring depth
Bamboo scrimber

ABSTRACT

To understand the thermal performance of bamboo scrimber at elevated temperatures, its specific heat, density ratio and conductivity were measured using TGA-DSC and Hot Disk. With temperature increasing from 20 °C to 100 °C, the specific heat and conductivity of bamboo increase gradually. The density ratio decreases to about 0.25 at 500 °C and stays constant until 900 °C. The conductivity of bamboo scrimber parallel to grain is 1.26–1.63 times the conductivity perpendicular to grain. Due to the high density and content of phenolic resin, the conductivity of bamboo scrimber is higher than those of glued laminated timber and timbers in Eurocode 5 and the literature. Charring models of bamboo scrimber parallel to grain and perpendicular to grain exposed to one-sided fire were simulated and compared with experimental results. The relative difference in charring depth is less than 10%. A 3D finite element model of bamboo scrimber beams exposed to four-sided fire was established based on the measured thermal parameters. The results indicate that the measured specific heat, density ratio and conductivity of bamboo scrimber have good accuracy and are suitable for numerical simulation. Therefore, the reliable thermal parameter data can be used in fire resistance analysis.

1. Introduction

Bamboo is a high potential building material that has a long history in construction engineering due to its significant features: it is a rapidly renewable, sustainable, green and widespread resource in Latin America and Asia [1]. The diameter of culms and variability of material properties of raw bamboo limit its widespread use for building applications. To solve shape limitations and improve consistency, four- to five-year-old Moso bamboo culms are split into 2-m-long strips and each strip is pushed into the fluffer to form net-structured bamboo bundles. Next, bamboo fibre bundles are saturated in phenolic resin and then compressed into a dense block under high pressure. The composite material is called bamboo scrimber (Fig. 1). Because of the standard shape and relatively low variability, bamboo scrimber is becoming an increasingly attractive structural material [2].

However, bamboo scrimber is a combustible bio-material, similar to traditional timbers. It is important to investigate the performance of bamboo scrimber at elevated temperatures. Xu M. [3] et al studied the effects of grain direction and heating temperatures on the mechanical properties of bamboo scrimber and established equations with reduction factors for the strength and modulus of elasticity at elevated temperatures. Xu Q. [4] et al investigated the charring rates of engineered bamboo (bamboo scrimber and laminated bamboo) using a cone calorimeter. The measured results were transformed into equivalent charring rates for standard furnace tests and compared with those promulgated by European and Australian standards. Mena [5] et al studied the

* Corresponding author at: Key Laboratory of RC & PC Structures of Ministry of Education, Southeast University, 02, Sipailou, Nanjing 210096, PR China.
E-mail address: xuming@seu.edu.cn (M. Xu).

https://doi.org/10.1016/j.conbuildmat.2018.06.124
0950-0618/

Fig. 1. Bamboo scrimber.

fire resistance and fire reaction of *Guadua a.k.* based on fire ignition and flame spread. They revealed that either round or laminated *Guadua a.k.* performs better than plywood, and most were comparable to those commonly indicated for different wood species. Xiao [6] et al. studied the fire safety of lightweight glue-laminated bamboo frame buildings using a full-scale room model test. It was proven that numerical simulation using the Fire Dynamic Simulator can provide similar results and a good visual illustration of experimental results.

Furthermore, to make valid predictions of temperature in bamboo scrimber exposed to fire, reliable thermal property data of bamboo scrimber at elevated temperatures are required [7]. These thermal properties include thermal conductivity, specific heat and the density ratio [8]. They are necessary to analyse thermal degradation and to model complex heat transfer phenomena.

The thermal conductivities of wood samples measured with a steady state method have been published in the literature. The results of studies by Fredlund [9], Knduson [10], and Janssens [11] et al. are widely used in finite element models of fire resistance simulation. However, the Hot Disk method as an alternative transient technique for conductivity measurement has gained popularity since 1991 because of its accuracy and speed. The principles of the Hot Disk method were described by Gustafsson [12]. Thermal conductivity and diffusivity were measured simultaneously at room and elevated temperatures. The key part of the Hot Disk is a flat sensor that acts as a heater and a temperature increase detector. Sensors insulated with Kapton are used in the temperature range of 20–200 °C, and mica-insulated sensors are used for temperatures up to 700 °C. Moreover, the anisotropy of wood samples can be measured by the method [13]. White [14] reported that the thermal conductivity of wood parallel to the grain is 1.5–2.8 times the conductivity perpendicular to grain, and the conductivity in the radial direction is approximately 5%-10% greater than that in the tangential direction. Eurocode 5 [15] gives the values of conductivity for wood and char layers at 20 °C, 200 °C, 350 °C, 500 °C, 800 °C and 1200 °C. Adl-Zarrabi [16] et al. used the Hot Disk method to determine the conductivity and diffusivity of spruce and compared them with fire test measurements. Their results are the same magnitude as the results found in the literature and verify the feasibility of the method. Shah [17] et al tested the thermal conductivity of engineered bamboo composites using the transient plane source method and confirm a linear relationship between density and thermal conductivity. The density-conductivity relationship in bamboo and engineered bamboo products was compared with common wood species.

The specific heat and density ratio can be measured simultaneously using the thermal gravimetric analyser with differential scanning calorimeter (TGA-DSC) method [18]. The DSC method has been frequently used to measure the specific heat of biomass materials, i.e., softwood bark [19], wood pellets [20], bamboo [21], etc. The advantage of the DSC method over conventional methods is the accuracy and speed with which data can be obtained and the small sample size required for measurement. Moreover, the dynamic nature of DSC allows the determination of specific heat as a function of temperature. Huang [21] measured the specific heat of Moso bamboo in three directions of the cylindrical coordinate system and studied the influences of temperature, cutting position and anatomical features on the specific heat capacity. Mehaffey [22] and Janssens [11] established a formula of wood among specific heat, temperature, moisture content and relevant parameters. König [23] reported specific heat-temperature curves that abruptly change points between 100 and 120 °C due to the evaporation of inherent water and energy consumption. When the temperature exceeds 350 °C, the specific heats of different wood samples tend to coincide in different studies within the literature.

The purpose of this paper is to determine the thermal conductivity, specific heat and density ratio of bamboo scrimber at elevated temperatures. These reliable thermal property data can be used to make valid predictions of the temperature distribution when bamboo scrimber is exposed to fire. Furthermore, comparison with the charring depths of experimental results can confirm the adaptation for numerical simulation and fire resistance analysis. The thermal property results can provide a valuable reference for the application of bamboo scrimber in structural engineering.

2. Materials and methodology

2.1. Bamboo scrimber

In this study, five-year-old Moso bamboo culms were used to fabricate bamboo scrimber by a standard process for experiments in Shang Hai, China. Bamboo scrimber relies on a binding agent for its performance. The bamboo scrimber had about 10% resin content by volume. The adhesive used in the bamboo scrimber was a commercially available low molecular weight water-soluble impregnated phenolic resin (PF16L510, Beijing Dynea Chemical Industry Co., Ltd., Beijing, China). The thermosetting phenolic resin was a brown liquid obtained by the reaction of phenol with formaldehyde and caustic soda. The solid content of phenolic resin was 46–49%. The solubility in water was greater than 7 multiples with pH of 10.5 to 11.5. The viscosity was 157 mPa·s (25 °C, 25 rpm). The manufacturing pressure for the cold pressing process is approximately 50 MPa. Bamboo scrimber products were tested with an average density of 1050 kg/m^3, and the moisture content was 8%. The experimental specimens were cut from bamboo scrimber products and were made into the necessary sizes and shapes on the basis of the experimental objectives.

2.2. Measurement of the specific heat and relative density-ratio by TGA-DSC

According to ASTM E 1269-11 [24], bamboo scrimber specimens were measured using the TGA-DSC technique. The experimental device was a Netzsch STA 449 F3, which was made in Germany (Fig. 2). The test specimens were ground and mixed homogeneously with a mass of 10–20 mg (Fig. 3). Sapphire with a mass of 64 mg was employed as a reference. The test was carried out under a dry nitrogen environment with a heating rate of 5 °C/min. When the temperature of the DSC test program exceeds 500 °C, errors generated by the test instrument and reference would significantly increase. So the measured temperature of the DSC test was set from 20 °C to 500 °C. TGA tests were performed