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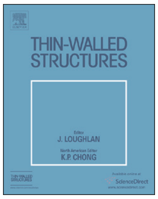

The energy absorption of bamboo under dynamic axial loading

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ABSTRACT

The energy absorption characteristics and material parameters of the bamboo species *Phyllostachys pubescens* are studied by drop-weight and dynamic tensile tests. The dynamic tensile test shows that 1-year-old bamboo has the greatest tensile strength (251 MPa), which is 1.85 times that of a 2A12 aluminium alloy. The drop-weight test shows that the energy absorption of nodal samples is greater than that of the internode samples, and the specific energy absorption (SEA) values of the nodal and internode samples are 11.85 kJ/kg and 9.78 kJ/kg, respectively. The SEA of nodal samples is close to that of aluminium alloy and steel tube, and the SEA of the internode samples is close to that of copper tube. The energy absorption increases with increasing moisture content and decreases with growth age. Analyses show that the bamboo nodes and the vascular bundle are the main factors affecting bamboo energy absorption. The results indicate that bamboo is a tubular structure with excellent mechanical and energy absorption properties.

1. Introduction

Crashworthiness means that moving structures, such as vehicles, spacecraft, weapons and aircraft, rely on buckling, fracture and other acts of energy-absorbing components to buffer the impact load and dissipate impact energy to protect people and valuables in an accident [1]. Currently, the main energy-absorption components include thin-walled metal tubes, composite material tubes, foam materials, honeycomb materials and matrix materials [2], with the thin-walled metal tube being most widely used as an energy-absorbing component [3]. However, energy-absorbing components such as thin-walled tubes are not generally used as additional structures in practical application but are integrated with other structures to achieve carrying capacity, support and decorative functions under normal operating conditions [4,5]. Therefore, studies to improve the energy absorption capacity of thin-walled tubes must at the same time ensure that the rigidity and strength of the thin-walled tube structure is maintained.

The single thin-walled tube has many disadvantages, such as lower energy-absorption efficiency, instability on impact and weak rigidity and strength in the radial direction [6–8]. In the natural environment, biological structures need to bear their own weight and load exerted by the surrounding growth environment. Many biological structures are tubular and have excellent mechanical properties that effectively save on raw materials and allow transport of water and nutrients [9]. Bamboo is one such typical tubular structure with good mechanical properties in the natural environment and which has a multi-level composite structure from the cellular level to the organisational level on the macroscopic scale [10]. Bamboo's excellent mechanical properties of high strength and good toughness are determined by its hollowness, tubular shape, the discrete distribution of nodes, and the gradient distribution of vascular bundles and the multilayer structure of sclerenchyma cells [11]. The similarity between bamboo and thin-walled tubes in loading, structure and function provides inspiration and reference for optimisation of the crashworthiness of thin-walled tubes [12]. Previous research has focussed on the mechanical properties of bamboo in static and fracture mechanics or on its light weight and strength in bionic applications [13–20]. To our knowledge, the dynamic mechanical properties, and particularly the crashworthiness of bamboo, have not been studied in detail prior to this research.

In this study, *Phyllostachys pubescens* was selected as the research object. The material parameters of the bamboo were obtained under intermediate strain rate by using a tensile test, and the characteristics of energy absorption were tested under axial impact by using drop-weight device. The influences of nodes, moisture content and growth ages of the bamboo were analysed to determine the mechanism by which bamboo absorbs energy. The results are expected to provide several design parameters for optimisation of the bionic design of thin-walled structures.

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2. Materials and experiment

2.1. Material

The test samples were bamboo of the species *Phyllostachys pubescens* with growth ages of 1, 3 and 5 years. They were collected in Caochang town of Fenyi County, located in the west midlands of Jiangxi Province, near the middle Yuan River, an area with subtropical monsoon humid weather, as shown in Fig. 1(a). The diameter of the bamboo at breast height was close to 50 mm, and its thickness was about 12 mm. The bamboo was felled at a length of 1.5 m above the ground and then measured upward of 2 m from the cross-section where it was cut to include complete nodes. The bamboo specimens were numbered and sealed before being mailed to the test site. The samples used for the drop-weight test were divided into nodal samples and internode samples. The average length of the samples was 160 mm, and the node was located in the centre of the nodal samples, as shown in Fig. 1(b), whereas the internode samples were selected from bamboo between two nodes (Fig. 1(c)).

Previous tests on the structure of bamboo have mostly focussed only on its static tensile strength, and little attention has been paid to its dynamic tensile strength. Dynamic tensile tests on samples of 1.5 mm × 3.0 mm in cross-section (Fig. 2(a)) and 46% moisture content were performed at a constant stretching speed of 2.2 m/s using the medium-speed strain tensile testing machine shown in Fig. 2(b). We also performed dynamic tensile tests on a 2A12 aluminium alloy tube 1.37 mm × 3.06 mm in cross-section as a comparison test. The 2A12 aluminium alloy is a high-strength duralumin with excellent plastic deformation characteristics.

2.2. Axial crushing tests

Drop-weight testing was carried out on the test rig of an automobile crash laboratory in Tsinghua University (Fig. 3a). A high-speed camera system and dynamic image sequence system mounted on the test rig obtained compression deformation data of the samples (Fig. 3b). The bamboo sample was mounted on a base with a fixture (Fig. 3c), and an acceleration sensor on the drop hammer recorded axial dynamic loads during the process of sample deformation. The drop height of the hammer was chosen on the basis of the bamboo outside diameter and results of pre-experimentation. The bamboo sample mounted at the base used a fixture avoid to slip, and the rolling friction between the guile rail and the hammer was ignored when the hammer dropped.

The specific energy absorption (*SEA*), the peak load (F_p) and the mean load (F_m) were applied to evaluate the energy-absorbing characteristics of the bamboo samples. *SEA* is the energy absorbed per unit mass of the structure, and it represents the utilisation rate of the material in the energy absorption during the collision process of a structure [21]. The expression of *SEA* is shown by Eq. (1):

$$SEA = \frac{E_{\mathrm{total}}}{\Delta M} = \frac{\int F ds}{A \Delta l \rho}, \tag{1}$$

where E_{total}=total energy absorbed by the sample, ΔM=mass of the destroyed sample, F=instantaneous impact load, s=crushing displacement of the sample, A=cross-sectional area of the sample, Δl=effective amount of sample deformation and ρ=pogmo07 density of the sample.

The average load (F_{m}) is shown in Eq. (2):

$$F_{\mathrm{m}} = \frac{E_{\mathrm{total}}}{\Delta l} \tag{2}$$

The load–displacement curves were recorded by the drop-weight test, but the energy absorption per unit structure from the load–displacement curves could not be directly compared because it was difficult to find very similar bamboo samples as it is a natural biological material. Therefore, we defined the instantaneous specific load as the instantaneous load divided by the product of the sample cross-sectional area and sample density [21]. The instantaneous specific load ($F_s(t)$) is shown in Eq. (3).

$$F_s(t) = \frac{F(t)}{\rho A} \tag{3}$$

In addition, the application of *SEA* and unit load is convenient for comparison with other materials and structural forms of energy-absorbing components, such as tube made from metal.

3. Results and analysis

3.1. Dynamic tensile tests

Dynamic tensile tests can obtain the basic material parameters of the test samples, which can then be used in the crush test. Fracture deformation occurred when the bamboo structure reached its ultimate strength in the dynamic tensile tests. The corresponding damage patterns observed in the bamboo and aluminium alloy samples are compared in Fig. 4. The damage patterns indicated that the bamboo underwent brittle fracture (Fig. 4(a)), whereas those of the aluminium were dominated by plastic deformation (Fig. 4(b)), which reflected the difference in failure modes between the respective bio-composite and metallic materials in the dynamic tensile tests.

The stress–strain curves from the dynamic tensile tests are depicted in Fig. 5(a). The tensile strengths of the 1-, 3- and 5-year-old samples were 251 MPa, 158 MPa and 103 MPa, respectively, indicating that the dynamic tensile strength decreased as the age

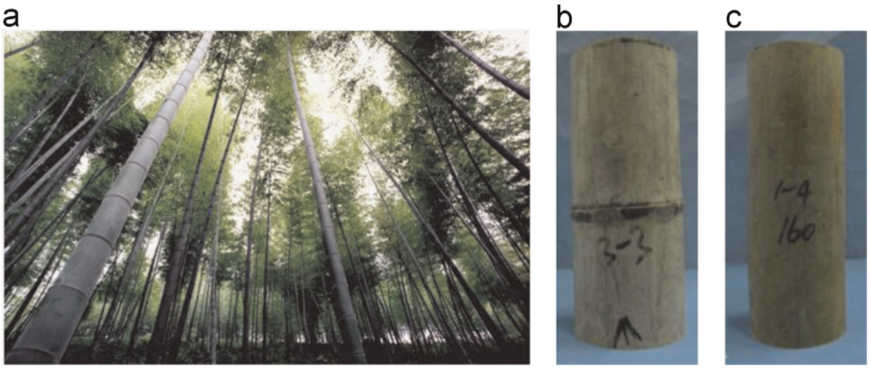

Fig. 1. (a) Collection site of bamboo and (b) nodal and (c) internode samples.