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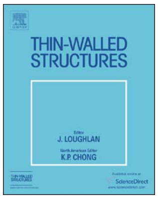

Full length article

Bionic design and multi-objective optimization for variable wall thickness tube inspired bamboo structures

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ABSTRACT

This study introduces an energy absorbing structure called a variable thickness structure (VTS) inspired by the gradient of thickness and the inter-nodal distance along the growth direction of bamboo. A series of VTSs under axial impact load were investigated to study the influence of the bionic factors on the energy absorption through a simulation analysis. It was determined that the wall thickness ratio and inter-nodal length ratio of a VTS have a significant effect on the crashworthiness of the structure. In order to obtain an optimal VTS, these factors were optimized through a multi-objective optimization method and polynomial regression (PR) meta-model. We found that the crashworthiness of some VTSs are better than that of a circular tube. In addition, a VTS with an inter-nodal length ratio of 1/2/1 and wall thickness of 3/2.47/1.78 mm was shown to be the optimal structure. A comparison between the optimal VTS and circular tube showed that the specific energy absorption of the VTS increased by 6.2%, whereas the peak crushing force showed a 28.23% decrease. Moreover, the crushing force efficiency increased by 7.48%, the mass decreased by 19.3%, and the VTS deformed more stably in terms of the overall crashing behaviours or collapse modes.

1. Introduction

Thin-walled structures have been widely used in automotive, aerospace, and military equipment. Previously, thin-walled structures were investigated by employing experimental, analytical, and numerical methods. In addition, a number of studies on the energy absorption characteristics of thin-walled structures under axial and lateral impact loadings have been conducted. Different thin-walled structures with different cross sections have been investigated. Nia [1] conducted numerical simulations and experiments to investigate the deformations and energy absorption capacity of thin walled tubes with various sectional shapes (circular, square, rectangular, hexagonal, triangular, pyramidal, and conical), and found that the section geometry has a considerable effect on the energy absorption. Fan [2] studied hexagonal, octagonal, 12-sided, and 16-sided tubes experimentally and numerically under axial compression. The increase in the number of corners of a thin-walled tube can help improve the energy absorption. Some researchers have also introduced other types of thin-walled tubes. Tang [3] studied a type of cylindrical multi-cell column equipped with a number of corners on the cross section and the angles between neighbour flanges. Nagel [4] conducted a numerical study on tapered thin-walled tubes, the results of which indicate that the energy absorption response of tapered tubes can be controlled through their wall thickness and taper angle, which highlights their potential use as an energy absorber. In addition, Morris [5] compared the lateral crushing of circular and non-circular tube systems under quasi-static conditions, and discussed how such a modified shape can exhibit greater crushing efficiencies than their circular-shaped counterparts. Some other researchers designed different cross-sections to improve the crashworthiness; for example, Kim [6] designed a new type of trigger and multi-cell profile with four square elements at the corner, and showed dramatic improvement over a conventional square box column. According to a study by Fan [7], multi-cell tubes with triangular and Kagome lattices can effectively increase the mean crushing forces under quasi-static axial compression experiments, and thus multi-cell lattice tubes are more weight efficient in terms of energy absorption. Liu et al. [8] added bulkheads in the column to improve the energy absorption property, and found that this structure shows a higher energy absorption than a similar column without such bulkheads, the existence of which changes the deformation mode from an expansion-contraction mode to a progressive mode, while the bulkheads themselves absorb little energy. Eyvazian [9] investigated the effect of corrugations on the crushing behaviour, energy absorption, and failure mode of a circular aluminium tube subjected to axial compressive loading.

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In the field of material filled structures, Shojaeifard and Zare [10,11] studied the bending collapse of empty thin-walled and foam-filled structures with different cross-sections (circular, square, elliptic). In their experimental study, they found that foam-filled hat profiles can achieve a 45–73% increase in specific energy absorption (SEA). For the graded thickness, Ghosh et al. [12] analysed the deformation response of mild steel rings and short tubes of various thicknesses and lengths, which were loaded centrally using opposed conically headed cylindrical punchers both theoretically and experimentally. Sun [13] introduced functionally graded structures with a changing wall thickness along the longitudinal direction in a certain gradient, namely, functionally graded thickness (FGT). The results yielded from the optimization indicate that an FGT tube is superior to its uniform thickness counterparts in terms of the overall crashing behaviours. In addition, the maximum crushing force of an FGT column is always smaller than that of the corresponding uniform thickness counterparts. For a variable thickness structure, Zhang [14,15] investigated the energy absorption characteristics of tapered circular tubes with graded thickness (TCTGT) under axial loading. The energy absorption efficiency of the TCTGT was found to be considerably higher than that of straight tubes. The mean crushing force of TCTGT was generally 30–40% higher than that of a circular tube. In addition, the performance of TCTGT under oblique loading was investigated, and the results indicate that the TCTGT achieves a much better performance against oblique loads than an original straight circular tube. Moreover, the TCTGT can sustain more than 80% of the axial crushing force at an angle of 15°. Zhang [16] investigated square tubes with two types of thickness distribution through both a simulation and an experimental method. Both the experimental and numerical results show that this structural design can lead to a 30–35% increase in energy absorption efficiency. Above all, the energy absorption was found to be significantly dependent on the foam density and cross section.

It is still a challenge to design a lightweight structure with better crashworthiness. Nowadays, bionic structures have gained the attention of researchers owing to their excellent crash performance. In nature, after billions of years of evolution, natural biotechnology achieves a high crash performance exceptionally well, and to a greater extent than engineering structures. Such biotechnologies may have given us the inspiration for a thin-walled structure design owing to an excellent property that adapts to various extreme conditions. In recent years, some researchers have designed a lightweight thin-walled structure with good crashworthiness using a bionic method. Zhao [17] extracted the structural characteristics of water lily leaf ribs and cactus stems to design a new gantry machining centre crossbeam, which has a better load-carrying capacity than a conventional distribution. Ma [18] designed a bionic structure to mimic the gradient distribution of vascular bundles of bamboo, the simulation results of which show that the load-bearing capacity of a bionic shell is increased by 124.8%. The optimal distribution of the reinforcing fibers for stiffening hollow cylindrical composites was explored by M. Sato et al. [19]. using the linear elasticity theory. The spatial distribution of the vascular bundles in wild bamboo, a nature-designed functionally graded material, is the basis for the bionic design. And results suggested that wild bamboos maximize their flexural rigidity by optimally regulating the radial gradation of their vascular bundle distribution. Based on that fact, they have developed theory that can predict the most effective distribution of reinforcing fibers in the radial direction, then it can switch from a parabolic to a linear gradation with increasing the mean volume fraction of the fibers. This theoretical consequence matches quantitatively with the real vascular bundle distribution observed in sections of the wild bamboos. Their result give us a new avenues in the bio-inspired optimal design of cylindrical tube endowed with high-stiffness and lightweight properties.

In nature, bamboo not only supports its own weight, but also withstands external pressure of the wind and snow. Moreover, it is light-weight [20,21], which is relatively rare in the field of engineering. A bionic structure is a combination of biological structure research and basic methods of engineering mechanics, among other factors. Through a modification and optimization of the original structure, a device with a better performance can be achieved.

The purpose of this research is to improve the energy absorption characteristics of a thin-walled tube structure under the precondition of lightness in weight, and mainly includes the following three aspects: (1). According to the gradient change rule of the wall thickness and the inter-nodal length of a bamboo section along the growth direction, we designed a variable thickness structure based on a bionic structure method. (2). We analysed the influence of the wall thickness ratio and inter-nodal length ratio of the energy absorption through a drop weight impact test and finite element simulation. Finally, (3) we optimized the VTS through the response surface of a multi-objective optimization method and polynomial regression (PR) meta-model.

2. Design of VTS based on bamboo

2.1. Structural characteristics of bamboo

Bamboo has a high strength, good elasticity, stability, and low density, and is considered to be the most effective natural structure. In addition, its strength is 3–4 times higher than that of steel [22]. At the same time, bamboo has excellent energy absorption efficiency. Zou [23] studied the energy absorption characteristics of bamboo using a drop weight test. The drop weight test shows that the energy absorption of a nodal sample is greater than that of the inter-nodal samples, and the SEA is 11.85 kj/kg, which is close to that of aluminium alloy and a steel tube. In addition, a bamboo node can not only increase the bending strength of bamboo but also greatly improve the lateral compression and shearing ability. Owing to the tapering structure and gradient wall thickness, the compressive stress of each section is equal under the influence of gravity, and the ability to resist the bending deformation for each section is also equal under a wind load. Moreover, the slenderness ratio of bamboo reaches up to 1/150 to 1/250, which is very difficult for a normal structure [24–27]. Therefore, based on the macro- and micro-structures of bamboo, the bionic design method for the crashworthiness of a thin-walled structural is proposed, which can provide new ideas for the energy absorbing structure of a thin-wall design.

As shown in Fig. 1, we obtained 16 pieces of bamboo (*Phyllostachys pubescens*), which were 5 years old, from Fenyi city in Jiangxi Province, China, and divided the bamboo samples into internode and nodal samples. The external diameters of the culms were between 60 to 70 mm, and their density was 0.82 g/cm^3. By measuring the size parameter of the bamboo, we can obtain its relationship among the wall thickness, inter-nodal length, and nodes, as shown in Fig. 2.

As shown in Fig. 2(a), the wall thickness becomes gradually thinner along the growth direction, and the wall thickness from the second node to the 20th node can be described using Eq. (1).

$$y = 8.90244 - 0.12664 * x \tag{1}$$

where “x” indicates the nodes of bamboo along the growth direction,

Fig. 1. Jiangxi Bamboo and bamboo with joint.