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Energy absorption characteristics of bio-inspired honeycomb structure under axial impact loading

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ABSTRACT

Honeycomb structures are widely used in automotive and aerospace applications because of their outstanding characteristics of high strength and light weight. In this paper, a new honeycomb structure named as bionic honeycomb thin-walled structure (BHTS) which filled the column in different way inspired by the internal structure of the ladybeetle is proposed. The energy absorption characteristics of two kinds of BHTSs have been investigated comparing an original honeycomb structure with the same type of material under axial impact loading using nonlinear finite element software LS-DYNA. Dynamic loading has been carried out under the weight of 500 kg and the speed of 10 m/s. The results show that the energy absorption characteristic of BHTS which filled columns on its walls is better than that filled columns in its walls. Then the parameter studies in energy absorption of BHTS-2 have been carried out. It is found that energy absorption performance of BHTS-2 is best when the filled column number is 6 and diameter is 8 mm.

1. Introduction

Nowadays, thin-walled structures with various cross-sectional geometries are widely used as energy absorbers in aeronautics and astronautics applications because of their low price, simple manufacture technology and higher energy absorption efficiency. Many relevant works have been carried out using combinations of theoretical researches [1], numerical simulations [2,3] and experimental studies [3–5].

Different cross-sectional shapes of the single thin-walled tube have significant differences on the energy absorption characteristics. Several cross-sectional figures such as hexagon, octagon, 12-sided and 16-sided star have been already studied experimentally [6]. The results revealed that the increase of the number of inward corners showed a notable change in energy absorption. More tubes with different shapes such as square tubes [7,8], circular tubes [9,10], rectangular tubes [11–13], pyramidal tubes [14], hexagonal tubes [15–17] and conical tubes [18–20] have been investigated widely. Two kinds of creative configurations including pentagon and cross section with different materials have also been studied [21]. Another novel cross-sectional shapes was proposed, which combines the square section and circular section [22]. A new method has been proposed to enhance energy absorption characteristic of structure by adding corners in the cross-section of the tube. Several kinds of multi-corner thin-walled columns used this way have been tested experimentally [23]. Some parametric studies of the longitudinally grooved square tubes under axial crushing have been carried out recently. It is found that the grooves could obviously increase the specific energy absorption of the structures [24–27]. Bi-tubular thin-walled column is another high-performance energy absorption structure. A wide variety of bi-tubular thin-walled column design has been reported in the literature. Several geometry parameters of bi-tubular tubes have been numerically investigated, including radial distance of concentric cylindrical tubes [28], the shape of the inner tubes and the location of diaphragms [29]. The simulation results showed that the efficiency of energy absorption could be improved by introducing interlayer to the tubes. Many foam-filled bi-tubular circular tubes have been investigated under axial loading and the parameter studies such as cross-sectional configurations and loading conditions have been carried out [9,30,31]. Rabczuk et al. [32] have proposed a homogenization method for sandwich structures consisting of two plates interlaced with beams and shells in a periodic, lattice structure. It could achieve a significant reduction in computation and modeling time for the analysis of sandwich structures by this computational method. They also have developed a simplified method for estimating the impulsive load in sandwich structures submerged in water due to a dynamic wave loading that accounts for fluid-structure interaction [33].

More previous studies have focused on the thin-walled structures and conventional honeycombs, while relatively less works have been done on the bionic honeycomb structures. However, because of the

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extremely low densities, the conventional honeycomb cell walls buckle easily under axial impact loading, which limits axial energy absorption capacity. It is found that the sandwich walls with core struts in honeycomb structures have superior mechanical properties to that with solid walls in conventional honeycomb structures [34]. In this paper, the energy absorption capability of this bionic honeycomb thin-walled structure (BHTS) were analyzed to reveal pathways to structures with superior characteristics [35]. The elytra of beetle possesses the characteristics of light weight and impact resistance because of thin-walled tube exists in the elytra's honeycomb structure [36–38]. A novel bionic integrated honeycomb plate has been designed based on internal structure of beetle elytra [39,40]. The shear and compressive mechanical properties of this bio-mimetic structure made of composite materials have been studied experimentally [41,42]. The bionic honeycombs' material components processing good performances have also been obtained by experimental tests [43]. However, the existing forms and geometric parameters of the thin-walled tubes which could make a significant effect on crashworthiness performance have been seldom researched.

In this paper, two kinds of filling modes of thin-walled columns were studied, which named as Bionic Honeycomb thin-walled Structure (BHTS). The BHTS imitating the structural characteristic of elytra from different species of beetles were investigated under axial impact loading using finite element software LS-DYNA. The energy absorbing characteristics of different filling methods were compared and the BHTS with good performance was put forward. In addition, the effects of design variables of the filling tube such as filling density and filling tube diameter were studied on BHTS numerically.

2. Beetle-based BHTS

2.1. The internal structural characteristics of beetles' elytra

Beetles are a group of insects which have the elytra to protect their bodies. Figs. 1 and 2 show two kinds of beetles (i.e. *Coccinella septempunctata* and *Allomyrina dichotoma*) which all have the elytra. The adult *C. septempunctata* ladybeetle was used as shown in Fig. 1(a). There are many honeycombs in the internal structure of its elytra, as shown in Fig. 1(b). In each honeycomb structure, there is a hollow column structure, as shown in Fig. 1(c) and (d). Due to the internal structure of *C. septempunctata* is quite complicated, the model of its structure is proposed, as shown in Fig. 1(e). The irregular honeycombs are green, while the hollow columns are yellow. The adult *A. dichotoma* beetle was used as shown in Fig. 2(a). Unlike the inside structure of *C. septempunctata*, in *A. dichotoma* elytra the hollow columns are on the wall of honeycombs, as shown in Fig. 2(b). Fig. 2(c) and (d) are the microstructure of hollow column. The schematic of internal structure of *A. dichotoma* elytra is shown in Fig. 2(e).

2.2. Description of the beetle-based BHTS

By imitating the inside structural characteristics of beetle elytra, two different forms of BHTSs were designed, as shown in Fig. 3(b) and (c). The bionic honeycomb structure (BHS) in Fig. 3(a) is entirely composed of honeycombs. The BHTS-1 in Fig. 3(b) is composed of honeycombs and circular tubes, while the circular tubes are all in the center of honeycombs. The BHTS-2 in Fig. 3(c) is also composed of honeycombs and circular tubes, however, the circular tubes are on the wall of honeycombs. In order to investigate the energy absorption performances of the different forms of the BHTSs, the equivalent cross-sectional size of different components (i.e. honeycomb and tube) and the same length of the BHTSs are obtained.

2.3. Material properties of bionic structure

The single-wall tubes were prepared using aluminum alloy AA6063 T6. The specific alloy has a density $\rho = 2.7 \times 10^3$ kg/m^3, a Young's modulus E = 68.2 GPa, the initial yield stress $\sigma_y = 162$ MPa, the ultimate stress $\sigma_u = 192$ MPa, and Poisson's ratio $\upsilon = 0.3$ (see Table 1) [44]. The tubes were modeled with the MAT_24 material law in LS-DYNA971. Because the aluminum alloy was considered insensitive to the strain rate, the strain rate was ignored. The fracture behavior of the aluminum alloy was neglected during these analyses [45].

2.4. Structural crashworthiness criteria

Four indicators are used to define the crashworthiness performance of the BBTS. The first indicator to estimate the energy absorption capabilities of the structure is the special energy absorption (SEA) defined as the ratio of the total energy EA absorbed by a structure to its mass M [46]:

$$\mathrm{SEA} = \frac{\mathrm{EA}}{\mathrm{M}} \tag{1}$$

The area under the force-displacement curve represents the amount of absorbed energy EA [47]:

$$\mathrm{EA} = \int_0^d \mathrm{F(x)dx} \tag{2}$$

Where *d* is the axial crushing displacement and *F* denotes the axial crushing force. For an energy absorption structure, a high value of crash load efficiency (CLE) is expected [48]:

$$\mathrm{CLE} = \frac{\mathrm{MCF}}{\mathrm{MIF}} \times 100\% \tag{3}$$

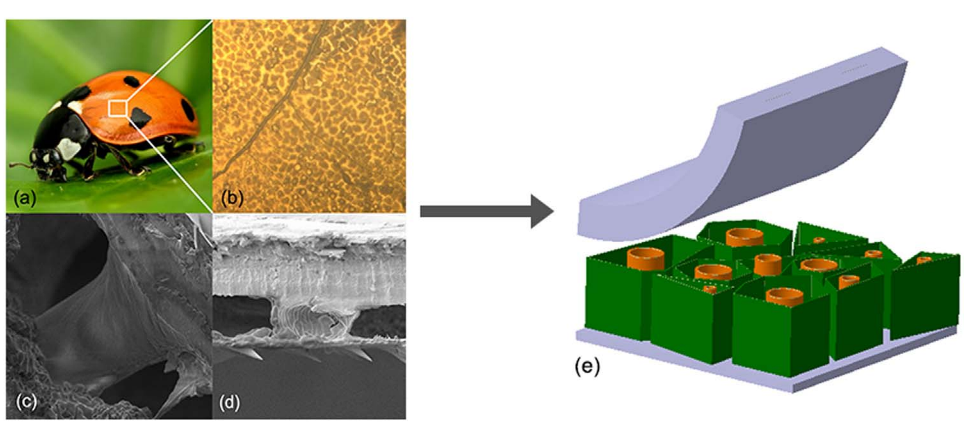

Fig. 1. Internal structure of elytra: (a) The adult *C. septempunctata* ladybeetle, (b) the microscopy of internal structure of elytra, (c) the tubular structure in the elytron, (d) the internal hollow structure of the tube and (e) schematic of the internal structure of *C. septempunctata* elytra. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).