Thin-Walled Structures 122 (2018) 42–51

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

Crashworthiness design for bio-inspired multi-cell tubes with quadrilateral, hexagonal and octagonal sections

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ARTICLE INFO

Keywords:
Microstructure
Bionic multi-cell tube
Theoretical validation
Crashworthiness
Multiobjective optimization

ABSTRACT

Multi-cell tubes have been widely used in vehicle engineering for their excellent energy absorption capacity. In this paper, a group of bionic multi-cell tubes (BMCTs) with quadrilateral, hexagonal and octagonal sections were proposed. The BMCTs were constructed by filling the cylindrical tubes into different position of multi-cell tubes (MCTs), which was inspired by the microstructure of beetle forewings. The finite element (FE) models under axial impact loading were established and then validated by the Simplified Super Folding Element (SSFE) theory. The crashworthiness of different BMCTs and MCTs was compared, and the results showed that the sixth type of bionic multi-cell tube with octagonal section (O-BMCT-6) has the best crashing performance. Then, the multi-objective optimization design of O-BMCT-6 was conducted by using non-dominated sorting genetic algorithm II (NSGA-II) and radial basis function (RBF) metamodels. The optimal O-BMCT-6 showed superior crashworthiness and could be used as an energy absorber.

1. Introduction

Thin-walled tubes as effective energy absorbers characterized by being cost-efficient, lightweight and crashworthy have been widely utilized in the vehicle engineering [1–3]. Over the past decades, extensive research efforts were conducted to investigate the crashworthiness of thin-walled tubes with various cross-sectional shapes [4], such as circular [5–7], quadrilateral [8–10], hexagonal [11–13] and octagonal [14–16], etc. In addition, Yamashita et al. [17], Nia et al. [18], Fan et al. [19] and Ali et al. [20] compared the crashworthiness of thin-walled tubes with different cross-sectional shapes. According to these previous studies, it can be found that the cross-sectional configuration has a significant influence on the crashworthiness of thin-walled tubes.

Recently, multi-cell thin-walled tubes have been widely studied for improving the crashworthiness [21–29]. Chen and Wierzbicki [30] proposed the Simplified Super Folding Element (SSFE) theory to predict the mean crushing forces of single-cell, double-cell and triple-cell tubes and found that the energy absorption efficiency of triple-cell tubes is superior to the single-cell tubes. Zhang et al. [31] improved Chen and Wierzbicki's theoretical solution [30] by dividing the cross-section of the tube into basic elements and demonstrated that the energy absorption efficiency of multi-cell tubes is 50% higher than the single-cell tubes. Zhang and Zhang [32–34] further studied the theoretical models for different basic elements of multi-cell tubes and indicated that the theoretical models are agreed well with both numerical and experimental results. Qiu et al. [29] applied the theoretical formulas in [32] to make a comparative analysis on the crashworthiness of hexagonal multi-cell tubes with different cross-sections, which showed that the W2W hexagonal multi-cell tubes (the inner and outer tubes are connected by the ribs at the mid-walls) are the most efficient configuration among them. Nia and Parsapour [35] investigated the crashworthiness of single-cell and multi-cell tubes with triangular, square, hexagonal and octagonal sections by using the experimental and numerical methods, and revealed that multi-cell tubes with inner ribs connected at the mid-walls of the outer tubes are more efficient than those at the corners. Based on the above investigations, it can be seen that the multi-cell thin-walled tubes have excellent energy absorption capacity and exhibit better performance with the ribs connected at the mid-walls.

The above studies mainly focus on the conventional single-cell and multi-cell tubes. However, thin-walled tubes with other complicated cross-sections may have even better crashworthiness since cross-sectional configurations have a significant influence on crashworthiness. But, how to design a thin-walled tube with better crashworthiness remains a topic of further studies. Nowadays, many researchers have paid attention to the use of bionic methods to design engineering structure [23,36]. Chen and co-workers [37–39] investigated the three-dimensional structures and mechanical properties of beetle forewings and

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http://dx.doi.org/10.1016/j.tws.2017.10.010
Received 8 June 2017; Received in revised form 3 October 2017; Accepted 4 October 2017

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found that the beetle forewings have characteristics of high strength and lightweight. Chen and co-workers [40,41] proposed an integrated honeycomb structure with reinforced trabeculae inspired by the microstructure of beetle forewings and confirmed that the integrated honeycomb structure exhibits excellent mechanical properties through the experimental study [42]. Xiang and Du [43] employed the microstructure of beetle forewings to design a bionic honeycomb structure and showed that the energy absorption of the bionic honeycomb structure, which filled columns on its walls is better than that filled columns in its walls. From the above studies, it can be observed that the bionic structures have the better energy absorption capacity than traditional thin-walled structures. However, few studies have been made to investigate the crashworthiness of bionic multi-cell tubes based on the microstructure of beetle forewings and systematically compare the crashworthiness of bionic multi-cell tubes with different cross-section shapes.

In this paper, eighteen kinds of bionic multi-cell tubes (BMCTs) based on the microstructure of beetle forewings were proposed. The finite element (FE) models of these tubes were established by using the explicit FE code LS-DYNA and then validated by the Simplified Super Folding Element (SSFE) theory. The comparison was made between the crashworthiness of traditional multi-cell tubes (MCTs) and BMCTs with different cross-sectional shapes, and the best possible BMCT structure was determined. To find the optimal design of BMCT, the multi-objective optimization was realized by adopting the non-dominated sorting genetic algorithm II (NSGA-II) and radial basis function (RBF) metamodels.

2. The bionic multi-cell tube based on the microstructure of beetle forewing

2.1. Structural characteristics of the beetle forewing

Fig. 1(a) shows the adult *Allomyrina dichotoma* beetle [41]. Fig. 1(b) shows the beetle forewing [38]. Fig. 1(c) and (d) show the microstructure of the beetle forewing [40]. From Fig. 1(c), we can find that there exist multi-cell structures in the internal structure of beetle forewing, and there are many hollow cylindrical tubes located at the multi-cell structures. Fig. 1(d) shows the microstructure of the cylindrical tube. Since natural evolution is a self-optimizing process, the structural characteristics of the beetle forewing may be reasonable. In nature, the beetle forewing can resist the impact load represented by droplets of rain, or produced by the opponent. Therefore, the bionic thin-walled structure based on the microstructure of beetle forewing may be an excellent energy absorber when subjected to impact loading.

2.2. Description of the bionic multi-cell tube inspired by the beetle forewing

By imitating the structural characteristics of the beetle forewing, eighteen kinds of BMCTs with quadrilateral, hexagonal and octagonal sections were designed and compared with the traditional MCTs with the ribs connected at the mid-walls, as shown in Fig. 2. Fig. 2(a), (h) and (o) show the cross-section of traditional quadrilateral, hexagonal and octagonal multi-cell tube, and the rest is bionic multi-cell tube. The bionic multi-cell tubes were constructed by filling the cylindrical tubes in the different position of multi-cell tubes. The bionic multi-cell tubes were named to distinguish from each other, and codes for the simple specimen were as follows: quadrilateral (Q), hexagonal (H) and octagonal (O). And the numbers denoted different types of bionic multi-cell tubes. Taking BMCTs with quadrilateral section as an example: (a) Q-MCT: traditional quadrilateral multi-cell tube, in which the ribs are connected at the mid-walls, (b) Q-BMCT-1: filling the cylindrical tubes into the center of the gaps between the inner and outer tube, (c) Q-BMCT-2: filling the cylindrical tubes into the center of mid-ribs, (d) Q-BMCT-3: filling the cylindrical tubes into the mid-walls of inner tube, (e) Q-BMCT-4: filling the cylindrical tubes into the corners of inner tube, (f) Q-BMCT-5: filling the cylindrical tubes into the corners of outer tube, (g) Q-BMCT-6: filling the cylindrical tubes into the mid-walls of outer tube. The length and the circumcircle diameters of the inner and outer tube for MCTs were 240 mm, 50 mm and 100 mm, respectively. The diameters of cylindrical tubes for BMCTs were 12 mm, and the wall thickness for all tubes was set to be 2 mm initially.

3. Numerical simulation and crashworthiness indicators

3.1. Finite element model

Fig. 3 shows the finite element (FE) model of the bionic multi-cell tube subjected to axial impact loading. The explicit FE code LS-DYNA was used to simulate the crashing process. The four-node Belytschko-Tsay shell elements with five integration points through thickness were employed to model the tube wall. The bottom end of the tube was fixed, and the top end of the tube was compressed by a rigid plate with a constant velocity of 10 m/s. When the deformation displacement of the tube reached 168 mm (70% of the tube length), the tube was unloaded and the simulation stopped. The contact between the rigid plate and the tube was modeled as 'node to surface'. The 'automatic single surface' was applied to the tube to avoid interpenetration. The static and dynamic frictional coefficients were 0.3 and 0.2, respectively [44,45]. The element size of the tube was 2 mm × 2 mm in the FE model.

The material of the tube was aluminum alloy AA6060 T4 with the following properties: $\rho = 2700\ kg/m^3$, Young's modulus $E = 68.2$ GPa, Poisson's ratio $\nu = 0.3$, the power law exponent $n = 0.23$, initial yield strength $\sigma_y = 80$ MPa, and ultimate stress $\sigma_u = 173$ MPa [46]. The engineering stress-strain curve of the tube material was shown in Fig. 4 [31,46]. The constitutive behavior of the aluminum material was based upon the piecewise linear elastic-plastic material model. As the aluminum is insensitive to the strain rate, the strain rate effect was neglected in the FE model [45].

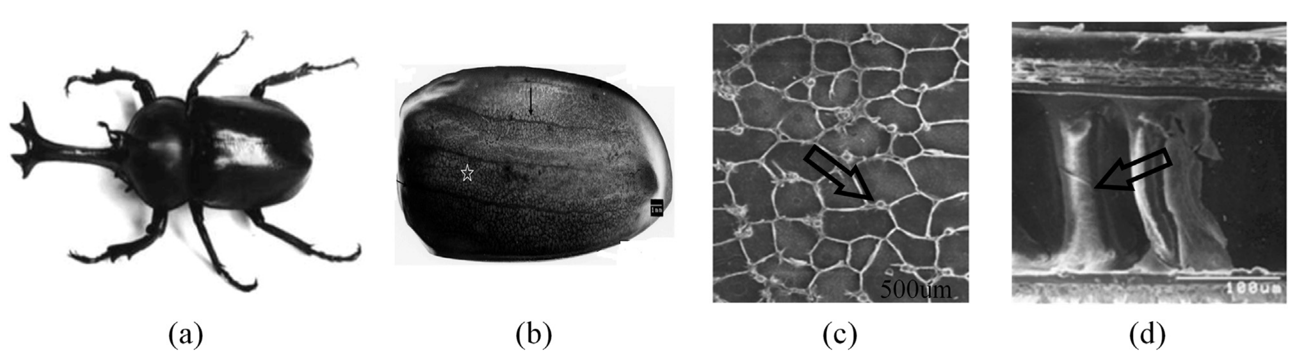

Fig. 1. Microstructure structure of the beetle forewing: (a) the adult *Allomyrina dichotoma* beetle [41], (b) the beetle forewing [38], (c) internal structure of the beetle forewing filled with cylindrical tubes [40] and (d) the microstructure of the cylindrical tube in the beetle forewing [40].