EXPERIMENTAL INVESTIGATION INTO ENERGY-ABSORBING BEHAVIOR OF HIERARCHICAL HONEYCOMB COMPOSITE TUBES

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ABSTRACT

This paper investigates the energy-absorbing behavior of hierarchical honeycomb composite tube (HHCT) which inspired by both the microstructural features of a beetle's forewing and geometrical features of a spider's web. Multi-mold combination vacuum bag moulding method was used to manufacture the Biomimetic Multi-Cell Tubes (BMCTs). Quasi-static axial crush load and low velocity crush load tests were conducted to study. The BMCT-MA2 structure demonstrates a 6.5% higher dynamic energy-absorbing capability compared to its quasi-static counterpart. In contrast, the specific energy absorption (SEA) of BMCT-MA1 remains nearly unchanged under both loading regimes. On the other hand, the quasi-static SEA of the plain circular tube is 13.8% lower than its dynamic counterpart. These findings provide valuable insights for the design of crash-resistant hierarchical honeycomb composite structures, particularly for applications that involve extreme crush conditions.

1 INTRODUCTION

Passive safety protection relies heavily on energy absorption devices, which have garnered increasing research interest with the rise in vehicle speeds [1]. In the event of a frontal crash, the bumper system comprising a bumper beam, crash box, and front rail plays a crucial role by absorbing approximately 70% of the total impact energy [2]. Among these components, the crash box serves as a vital energy-absorbing element, connecting the bumper beam to the front rail, and effectively dissipating energy through progressive crushing deformations [3]. Multi-cell thin-walled structures have gained significant attention for their exceptional crashworthiness capabilities, making them increasingly utilized in innovative lightweight body structures.

Through hundreds of millions of years of evolution, biological structures such as plants and animals exhibit unique features and remarkable mechanical properties. Use of the biomimetic approach for designing novel lightweight structures with excellent energy absorption capacity has been increasing in engineering fields in recent years [4-11]. For example, Zhang et al [12] proposed eighteen kinds of bionic multi-cell tubes (BMCTs) with quadrilateral, hexagonal and octagonal sections inspired by the microstructure of beetle forewings. It was shown that the octagonal cross-section and the middle wall of the outer tube filled with the cylindrical tubes were the best structural configuration to achieve higher SEA. Fu et al [5] designed six kinds of bionic-bamboo tube structures with different cross-sectional configurations. The numerical results showed that the bionic-bamboo tubes with the ribs of 'X' shape had the highest energy absorption capacity with SEA value of 31.51 J/g. Yin et al [8] proposed six kinds of bionic thin-walled structures (BTSs) with different cross-sectional configurations based on the structural characteristics of horsetails. They investigated the influence of the cell number, inner wall diameter and wall thickness on the crashworthiness of the structure using nonlinear finite element method using LSDYNA.

This paper investigates the energy-absorbing behavior of hierarchical honeycomb composite tubes under axial quasi-static compression and dynamic impact conditions. The hierarchical honeycomb composite tube (Fig. 1) inspired by the structure of spiderweb and beetle forewing was proposed to enhance structural crashworthiness performance.

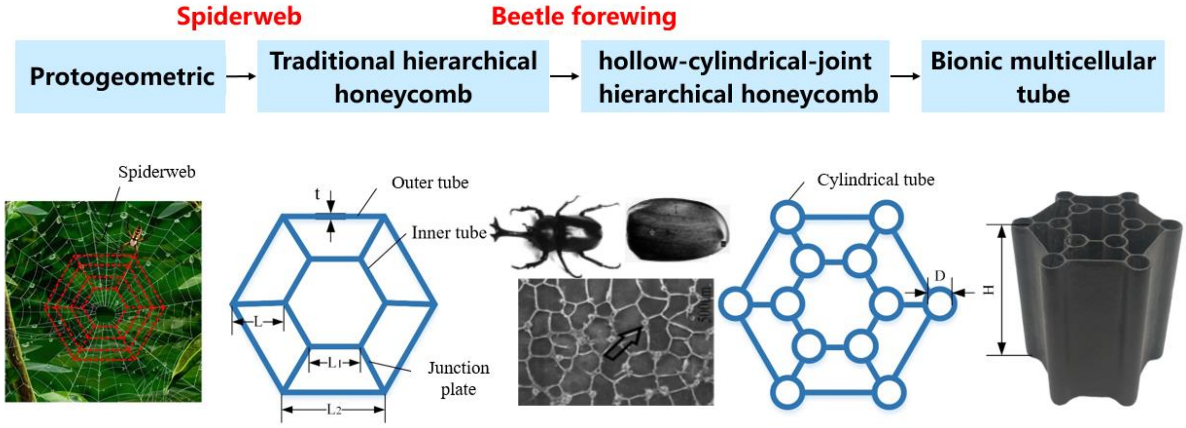

Fig. 1. The evolution of hierarchical honeycomb CFRP tube

2 EXPERIMENTAL PROCEDURE

The bionic multi-cell tubes (BMCTs) made of carbon fiber reinforced plastic (CFRP) were manufactured using the vacuum bag molding method shown in Fig.2. Samples were then cut from the tubes and inspected in an X-ray computed tomography machine prior to testing. Quasi-static axial compression and low speed impact tests were carried out to study the energy absorption characteristics.

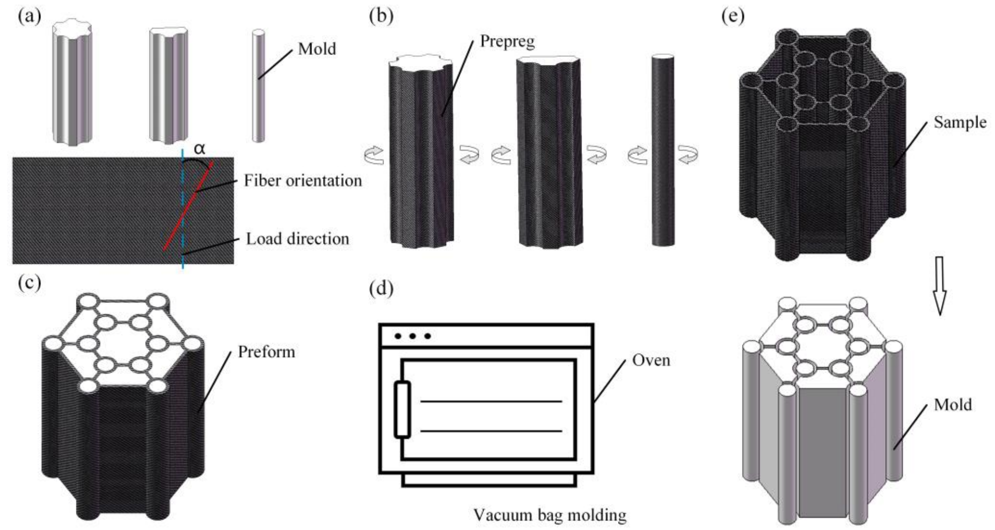

Fig. 1. Manufacturing processes of biomimetic multi-cell tube: (a) Preparation of mold and prepreg strips, (b) Wrapping of prepreg, (c) Mold assembly, (d) Curing, (e) Demold

2.1 Quasi-static axial compression testing

An MTS (SANS) UTM5305X screw-driven electromechanical test-machine, with a 300 kN load-cell, was used to perform quasi-static axial compression the tests. The samples were compressed between two steel platens at a displacement rate of 2 mm/min. The force and displacement for three samples based on each of the designs were recorded to determine the crashworthiness characteristics of the BMCTs. The absorbed energy was determined from the area under the load–displacement trace up to the point where the curve begins to rise rapidly (densification point). For simplicity, the densification threshold in all samples tested was assumed to occur at a crosshead displacement of 60 mm. Therefore, the absorbed energy was calculated between the initial (zero) displacement and 60 mm.

2.2 Low velocity impact testing

Axial impact tests were carried out using the drop-weight system shown in Fig. 3. The maximum impact velocity of the drop hammer is 14 m/s, and the mass of drop hammer up to 200 kg, resulting in the maximum impact energy of 19600 J. Table 1 shows the mass 'm' and height 'h' of the hammer in these tests, as well as the impact velocity 'v' and impact energy 'E'.

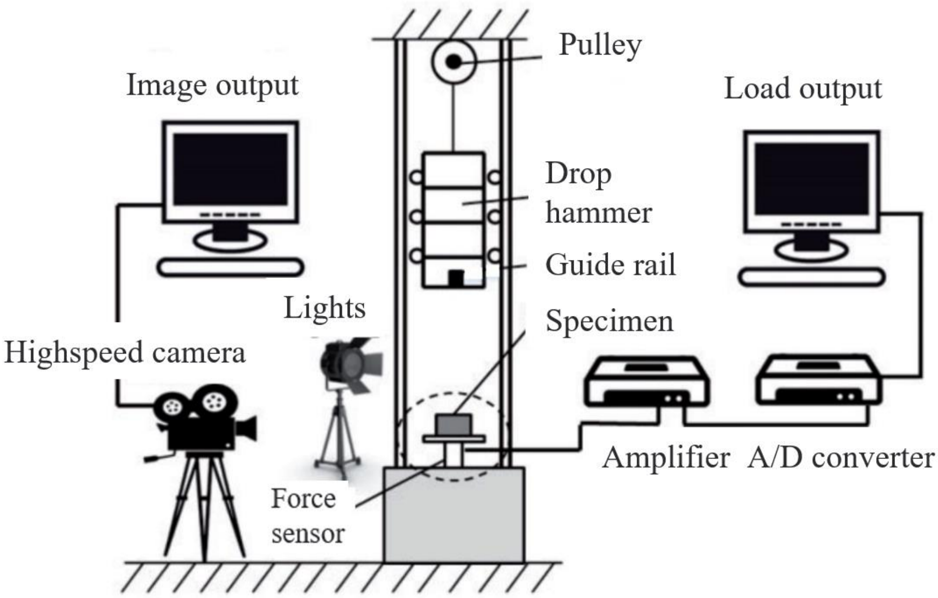

Fig. 3. Impact test system

Table 1. The experimental test conditions for the impact tests.

Specimen ID	Sample mass (g)	Sample height (mm)	*Drop mass* (kg)	*Drop height* (m)	*Impact velocity* (m/s)	*Impact energy* (J)
C-Dy	26.5	79.8	59.81	2	6.26	1172
BMCT-MA1-Dy	26.5	80.2	119.74	4.5	9.39	5281
BMCT-MA2-Dy	86.2	80.0		8	12.52	9388

3 RESULTS AND DISCUSSION

Fig. 4 shows the crush zone morphologies of BMCT-MA2 after quasi-static crushing and dynamic crushing. As observed in Fig. 4, it is clear that BMCT-MA2 exhibits the "splaying" mode identified by Hull [26] or the "lamina bending crushing" mode described by Farley and Jones [27] under both dynamic and quasi-static compression. The splaying mode is a matrix-controlled crushing mode, characterized by the progressive end crushing with internal and external fronds forming as a petal-like shape. From the top view, the sample BMCT-MA2 is clearly divided into internal and external parts based on specimen outline, where the outside one is with curved fronds and the interior one is with small fragments. The presence of such debris and dust suggests that a significant amount of energy has been absorbed during the failure process. As shown in the lower view, BMCT-MA2 remains almost the original texture after crushing, filled with small debris and wedges caused by friction between inward fronds. Meanwhile, the layers splayed parallel to their corresponding fibre orientation, such as ± 15◦, ±30◦, and ± 45◦. In addition, axial splitting can be observed in the cylindrical tube area, due to local stress concentrations.

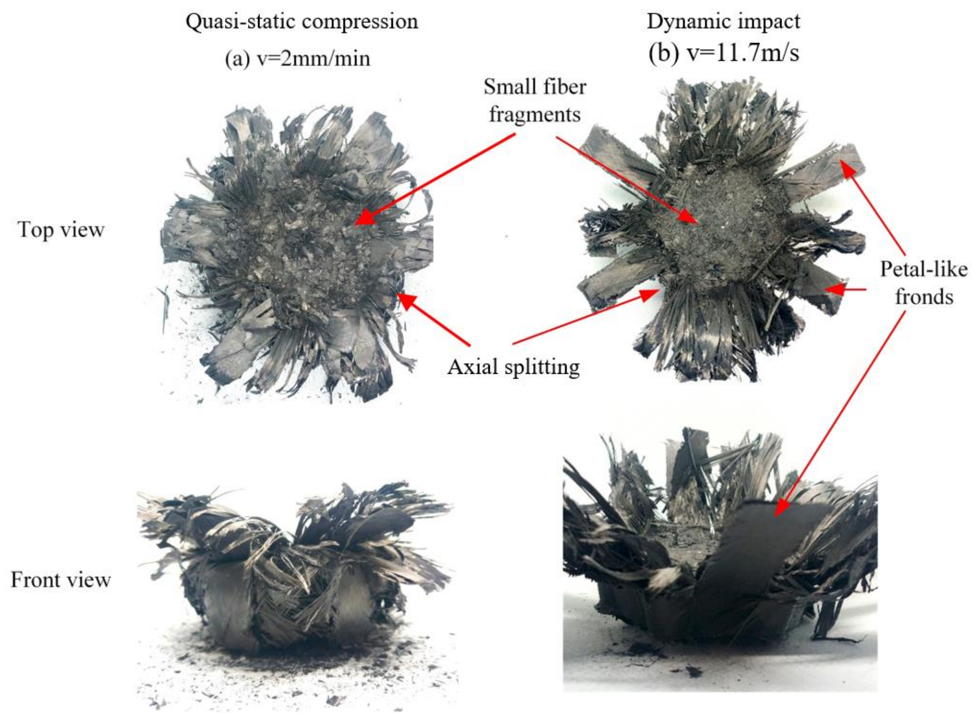

Fig. 4. Photograph of BMCT-MA2 after quasi-static crushing and dynamic crushing

Figure 5 illustrates a comparison between the load-displacement curves of the circular tube, BMCT-MA1, and BMCT-MA2 structures under both quasi-static and dynamic loading conditions. The quasi-static responses exhibit significantly reduced load fluctuations when compared to the impact curves. Furthermore, the quasi-static responses demonstrate a single peak load, whereas the impact curves display multiple peak loads. These distinctions in performance can be attributed to the influence of strain-rate effects.

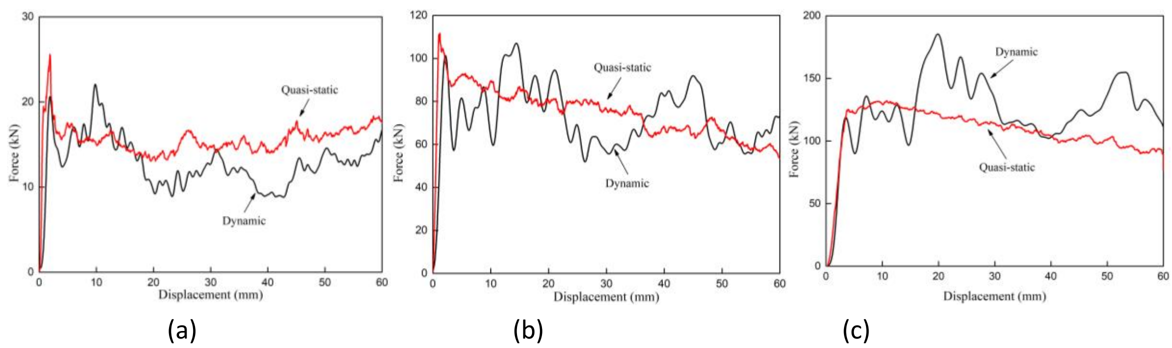

Fig. 5 Comparison of force-displacement curves of (a)circular tube, (b)BMCT-MA1 and (c)BMCT-MA2 under quasi-static compression and dynamic impact

From Fig. 6(a), it is evident that the initial peak loads for both ordinary tubes and multicellular tubes subjected to impact loading are lower than their quasi-static counterparts. Comparing the impact crushing to quasi-static crushing, the circular tube experiences a 26%

decrease in the initial peak load, while the BMCT-MA1 and BMCT-MA2 structures exhibit a decrease of 13%. Notably, the drop in the initial peak load for the BMCT-MA1 and BMCT-MA2 structures is smaller than that of the ordinary circular tube, indicating a superior dynamic response of the BMCT structures.

In Fig. 6(b), the specific energy absorption values for the composite tubes under quasi-static and impact crushing are presented. For the plain tubes, the specific energy absorption under impact loading is 14% lower than the quasi-static value. However, for the multicellular BMCT-MA1 structure, the specific energy absorption remains similar between quasi-static and dynamic loading conditions, with values of 49.4 J/g and 49.8 J/g, respectively. On the other hand, the multicellular tube BMCT-MA2 demonstrates a 6.5% increase in specific energy absorption under impact loading. Hence, the BMCT-MA2 exhibits the highest dynamic energy absorption performance, which can be attributed to its multiple cell design, providing enhanced damage resistance during crush.

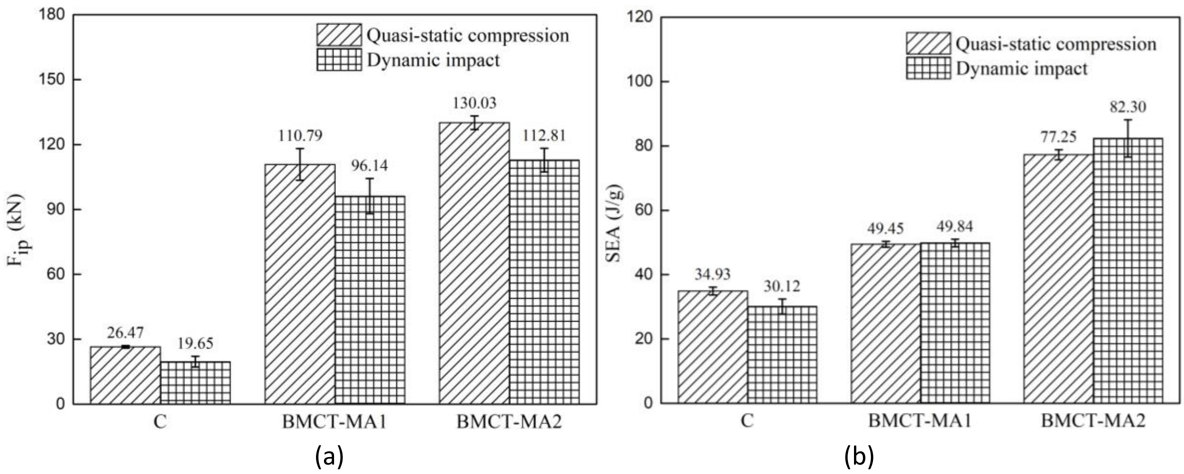

Fig. 6 The comparison of (a)initial peak force and (b)specific energy absorption for circular tubes and BMCTs under quasi-static compression and dynamic impact

4. CONCLUSIONS

In the study, the Biomimetic Multi-Cell Tubes inspired by the structure of spiderweb and beetle forewing were successfully manufactured using the Multi-mold combination vacuum bag moulding method. The crashworthiness of BMCTs under both quasi-static compression condition and dynamic impact condition was evaluated. It showed that the BMCT-MA2 exhibit an impressive energy-absorbing capability relative to plain composite tubes, with SEA values up to 86.7 kJ/kg being recorded under dynamic testing conditions. the BMCT-MA2 structure exhibits a notable 6.5% improvement in dynamic energy-absorbing capability compared to its quasi-static counterpart. In contrast, the BMCT-MA1 structure demonstrates consistent specific energy absorption (SEA) values under both loading regimes. Conversely, the quasi-static SEA of the plain circular tube is observed to be 13.8% lower than its dynamic counterpart. These findings hold significant implications for the design of crash-resistant hierarchical honeycomb composite structures, particularly in applications that involve extreme crush conditions. The study provides valuable insights for advancing the development of such structures and optimizing their performance in real-world scenarios.

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