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Crashworthiness of hierarchical circular-joint quadrangular honeycombs

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ABSTRACT

The new hierarchical circular-joint quadrangular honeycomb is proposed by iteratively replacing the edge-junctions of regular honeycomb with a circular joint. Firstly, the nonlinear finite element analysis is performed through LS-DYNA and the results are validated by experimental data. Then, analytical solutions to crushing resistance of the hierarchical honeycomb are obtained based on the Simplified Super Folding Element (SSFE) theory. The results between the numerical and analytical method are in good agreement, which indicates that the analytical solutions are reliable. Furthermore, parametric studies of the first and second hierarchical order structures are conducted numerically. The results show that the specific energy absorption of the first and second-order hierarchical honeycomb is improved by up to 81.8%, 115.3% respectively compared with the regular honeycomb. It is also found that the out-of-plane crashworthiness performance of the second-order hierarchical honeycomb can be enhanced by increasing relative density. However, the peak crushing force would also increase with the increase in relative density. The findings of this study show that the proposed hierarchical honeycomb is a structural configuration with high energy absorption capacity.

1. Introduction

The honeycomb structure, which is inspired from the natural honeycomb in a nest, has been widely used in many engineering applications, such as automotive components [1–4], aerospace components [5–7], railway structures [8] and offshore structures [9], due to their lightweight, high specific strength and stiffness [10,11], as well as outstanding energy absorption performance [12–15]. Different unit cell topologies have been used to develop the common honeycomb structures, such as hexagonal [16,17], triangular [18], square [19,20] and circular [21]. Numerous work on exploring both out-of-plane and in-plane crushing resistance of honeycomb structures have been conducted using analytical [22–24], numerical and experimental [25–29] methods.

Nature is a great and successful laboratory with effective solutions for material and structure design [30]. There are many materials with structural hierarchy available in nature, such as bones and teeth [31], wood [32] and tendons [33]. Over millions of years of evolution, hierarchical design is able to achieve mechanically efficient materials and structures. In recent years, such hierarchical design has drawn increasing attention to artificial materials and structures. Banerjee [34] analytically studied the in-plane and out-of-plane mechanical characteristics of the four types of hierarchical lattices. Sun et. al [35,36] investigated the in-plane and out-of-plane compression behaviour and energy absorption of the hierarchical lattice tubes (HLTs). Compression test results showed that the HLTs have higher mean crushing forces (MCF) than single-cell tubes. Li et. al [37] studied the crushing mechanisms of the hierarchical hexagonal multi-cell tube structures through finite element analyses and axial compression experiments. The results show that the hierarchical tube is a more weight-efficient energy absorber. Xu et. al [38] presented a novel self-similar hierarchical hexagonal columns (HHC) by iteratively adding sub-hexagons at the corners of the regular hexagons. Experimental and numerical results indicated that the hierarchical design can significantly enhance the crashworthiness performance compare with multi-cell structures. Zhang et. al [39] proposed a novel hierarchical circular tube to improve structural crushing characteristics. The finite element analyses and experimental tests were conducted to investigate the crashworthiness performance. The results indicated that the second-order structure can improve the energy absorption efficiency. An analytical model of the second-order hierarchical circular tube was presented based on the super folding element method. To obtain the optimal design of the second-order hierarchical circular tube, multi-objective optimization was performed through multi-objective particle swarm optimization (MOPSO).

To enhance mechanical properties, structure hierarchy has already

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been introduced to honeycombs. For example, Zhang et. al [40] presented a new self-similar regular hexagonal hierarchical honeycomb (HHH) by iteratively adding a smaller regular hexagon to a three-edge vertex of primary hexagons. They found that the hierarchical design can improve crashworthiness performance efficiency. Sun et. al [4] proposed a novel hierarchical honeycomb and considered the oblique-wall angles of the honeycomb. The specific energy absorptions of the first-order and second-order hierarchy honeycombs were improved 81.3% and 185.7%, respectively. Qiao and Chen [41] investigated the in-plane uniaxial crushing response of the second-order hierarchical honeycomb using finite element simulations and analytical solutions. Fang et. al [42] proposed a new hierarchical honeycomb by iteratively adding smaller hexagons to the sides of hexagons. The crushing behaviours of the hierarchical honeycomb were studied by quasi-static tests and finite element analyses. The analytical solution to crushing resistance also presented based on the simplified super folding element method. Zhang et. al [43] proposed a fractal-like hierarchical honeycomb and investigated the out-of-plane crushing performance using numerical and analytical methods. He et. al [44] presented a new spider-web hierarchical honeycomb to improve the out-of-plane crashworthiness performance. The crushing behaviours of this structure were investigated using numerical, analytical and experimental methods. Taylor et. al [45] investigated effects of adding hierarchy to a honeycomb with hexagonal, triangular or square sub-structure cells. Chen et. al [46,47] presented hierarchical honeycombs by replacing cell walls of regular honeycomb with hexagonal, kagome, and triangular lattices, respectively. Numerical and analytical studies revealed that hierarchical honeycombs with triangular lattice exhibit enhanced mechanical properties and energy absorption. Dong et. al [48–50] proposed a series of hierarchical re-entrant honeycomb structures and the mechanical behaviours of the structures were studied using the finite element method.

Generally, the circular tubes possess greater energy absorption capacity than other types of polygon tubes because the severe deformation in polygon tubes is concentrated in the zones near to the corner [51]. Chen et. al [52,53] proposed a new cylindrical shell-plate periodic honeycombs by adding a hollow cylinder to the three-edge joint of regular honeycomb. Out-of-plane and in-plane mechanical behaviours were investigated by experiments and finite element analyses. However, these studies only investigated this configuration up to the first-order. It is worth studying the effects of hierarchical circular-joint on the out-of-plane crashworthiness of higher orders.

In this study, we present a novel hierarchical honeycomb by iteratively replacing the edge-junctions of regular quadrangular honeycombs with a smaller hollow cylinder, and the crashworthiness performance of this honeycomb structure is investigated using numerical and analytical methods. Section 2 gives the description for the hierarchical circular-joint quadrangular honeycomb. Finite element models are developed and validated by experimental results in Section 3. Section 4 introduces the analytical solutions of mean crushing forces for hierarchical circular-joint quadrangular honeycombs. Section 5 presents the crashworthiness behaviours and parametric studies of hierarchical circular-joint quadrangular honeycombs. Some concluding remarks are stated in Section 6.

2. Problem description

2.1. Geometrical configuration

In this study, a novel hierarchical circular-joint quadrangular honeycomb is constructed by iteratively replacing the edge-junctions of regular honeycomb with a circular joint. Fig. 1 shows a regular quadrangular honeycomb, and a cross-shaped unit cell extracted from the regular quadrangular honeycomb. Because of the periodicity of the honeycomb, the mechanical characteristics of the honeycomb can be simulated using the unit cell for simplicity. Here, the regular

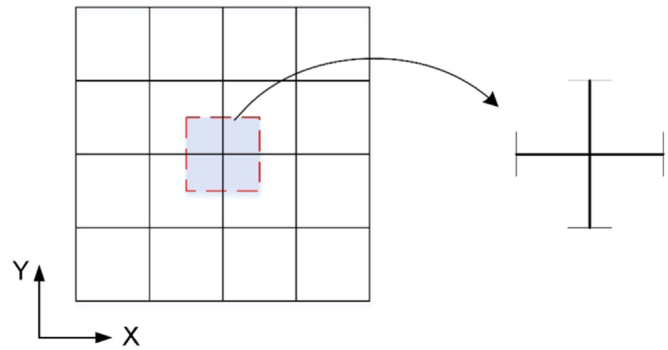

Fig. 1. Illustration of the unit cell of a regular square honeycomb.

quadrangular honeycomb is defined as the zeroth-order. Fig. 2 shows the evolution of the hierarchical sub-structure, where the hollow cylinders are added to the edge-junctions of honeycombs. The high order (first and second) hierarchical honeycombs can be obtained by repeating this process.

The hierarchical length ratios $\gamma_i = D_i/B_0 (i = 1, 2)$ are defined to characterize the geometry topology of hierarchical honeycombs, where the edge length of the regular honeycomb is defined as B_0 and the diameters of newly added circular-joint are defined as D_1, D_2 as shown in Fig. 2. In order to avoid overlapping of the newly added circular-joint with the pre-existing edges, geometric constraints should be imposed as follows,

$$\begin{cases} 0 < \gamma_1 + \gamma_2 < 1 \\ 0 < \gamma_2 < \frac{\sqrt{2}}{2}\gamma_1 \end{cases} \tag{1}$$

For simplicity, the wall thickness of the hierarchical honeycombs is prescribed to be uniform. The relative densities $\bar{\rho}_i$ of the i th order hierarchical honeycomb are introduced to compare between the hierarchical and regular honeycombs, which are defined as the ratio of the apparent density of the honeycomb to the density of its base material. The relative densities can be calculated as follows,

$$\bar{\rho}_0 = 2\cdot\frac{t_0}{B_0}$$
$$\bar{\rho}_1 = (2(1-\gamma_1) + \pi\gamma_1)\cdot\frac{t_1}{B_0}$$
$$\bar{\rho}_2 = \left(2(1-\gamma_1-\gamma_2) + \pi\gamma_1\left(1 - 4\frac{\eta}{\pi}\right) + 4\pi\gamma_2\right)\cdot\frac{t_2}{B_0} \tag{2}$$

where t_i is the wall thickness of the i th order hierarchical honeycomb. η is the centre angle of the first order sub-circle as shown in Fig. 3, which can be calculated as,

$$\eta = 2\cdot\arcsin(D_2/2D_1) = 2\cdot\arcsin(\gamma_2/2\gamma_1) \tag{3}$$

2.2. Crashworthiness indicators

It is necessary to predefine the crashworthiness indicators to study the crushing performance of hierarchal circular-joint quadrangular honeycombs. Specific energy absorption (SEA), mean crushing force (MCF) and peak crushing force (PCF) are used to measure crashworthiness characteristic of the hierarchal circular-joint quadrangular honeycombs [54–56].

The specific energy absorption (SEA) is energy absorbed per unit mass. The SEA can be used to evaluate energy absorption capabilities of different materials and weights, and it can be formulated as,

$$SEA = \frac{EA}{m} \tag{4}$$

where m is the mass of the structure, EA is the total absorbed energy during the crushing process, which can be expressed mathematically as,