Composite Structures 194 (2018) 36–48

Contents lists available at ScienceDirect

Composite Structures

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

Crashworthiness design of novel hierarchical hexagonal columns

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ARTICLE INFO

Keywords:
Hierarchical structure
Hexagonal columns
Crashworthiness
Energy absorption

ABSTRACT

Self-similar hierarchical structures are widely observed in nature, and have been credited with superior mechanical properties. In this paper, a novel self-similar hierarchical hexagonal columns (HHC) is proposed to improve structural crashworthiness performance. The self-similar hierarchical hexagonal columns are constructed by iteratively adding sub-hexagons at the corners of primary hexagon. To investigate the crashworthiness of HHC, the nonlinear finite element model is first developed and validated against experimental data obtained from 1st order HHC. Numerical investigations of 1st and 2nd order hierarchical hexagonal columns with different hierarchical levels are performed to compare with 0th order HHC, the results show that 1st and 2nd order hierarchical hexagonal columns improve the energy absorption and crush force efficiency by governing the material distribution, especially, 2nd order HHC exhibits significant advantage for energy absorption. In addition, parametric designs of 2nd order HHC are carried out to explore crashworthiness effect on hierarchical size ratio, cell wall thickness and impact velocity. The significant effects on both specific energy absorption (SEA) and the peak crushing force (PCF) are observed. The findings of this study offer a new route of designing novel crashworthiness structure with highly energy absorption capacity.

1. Introduction

Thin-walled structures have been widely used in vehicle and aerospace engineering as energy absorbers due to their lightweight properties and high energy absorption efficiency [1–3]. The crashworthiness of thin-walled structures with different cross-sections such as square [4–5], circular [6–7], and hexagonal section [8–9] was extensively studied using analytical, numerical and experimental methods in the past decades. Among these polygon columns it was identified that hexagonal cross-section was credited with superior crashworthiness performance due to the desirable folding manner [10].

Therefore, researchers focused on exploring design parameters and principles that governed the crashworthiness performance of hexagonal columns. Alkbir [11] studied hexagonal columns with different oblique wall angle and found peak specific energy absorption occurs at 60°, meaning a regular hexagon was preferable for energy absorption. Tarlochan [12] compared different cross sectional shapes of single cell tubes subjected to oblique loads, and found the hexagonal profile was a better concept for energy absorption application. Furthermore, multi-cell hexagonal columns with more weight efficient attracted the attention. For example, A. Alavi Nia [9] (Fig. 1(a)) compared hexagonal, square and triangular multi-cell columns and confirmed the merits of hexagonal cross-sections. Moreover, it was recognized that double-walled hexagonal hybrid structure has important effect to improve energy absorption performance of thin walled structure [13]. Qiu [14–15] performed crashworthiness investigation for double-walled hexagonal columns (Fig. 1(b)), Pirmohammad [16] analyzed the energy absorbing influence of the inner connecting wall size for double-walled hexagonal columns (Fig. 1(c)). They found that number of corners also played a significant role in enhancing energy absorption by altering the relative position between inner column and external column. From these studies, it was well known that multi-cell hexagonal columns were capable of dissipating impact energy by an efficient manner, and their crashworthiness performance could be improved through designing corner connections and internal cell layouts.

A recent trend for improving structural performance was adopting nature-inspired design principles. Biological materials exhibited superior mechanical performance and multi functionality with respect to their ambient environment [17–18]. A notable characteristic widely demonstrated among load-bearing biomaterials, such as shell, mineralized tendon and bone, was a multi-level, hierarchical organization of materials [19], as shown in Fig. 1(d). To dig such unique properties, emerging studies were carried out to examine the effects of structural hierarchy, most of which were associated with cellular materials. One popular scheme of hierarchical honeycomb construction was by replacing the solid cell walls of the original honeycomb with sub-structures.

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https://doi.org/10.1016/j.compstruct.2018.03.099
Received 18 June 2017; Received in revised form 22 March 2018; Accepted 28 March 2018

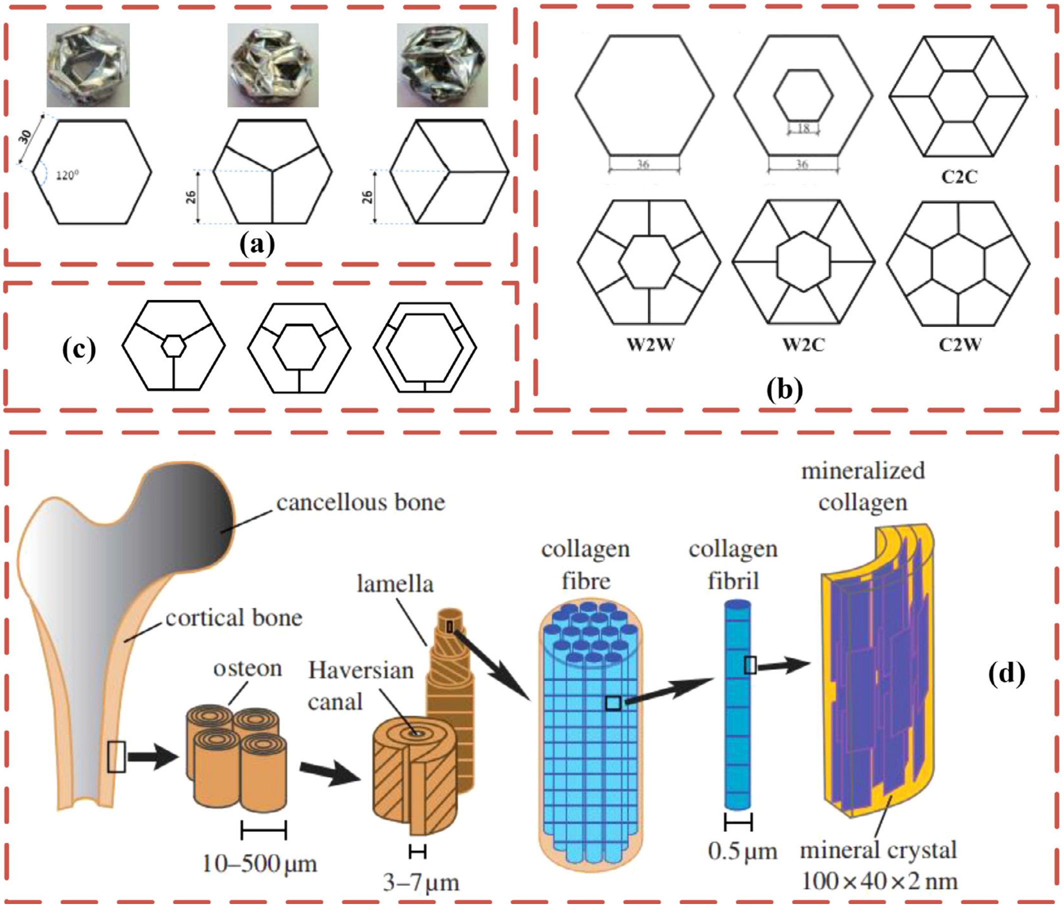

Fig. 1. Hexagonal structures and hierarchy concept reported in literature: (a) Ref. [9]; (b) Ref. [14–15]; (c) Ref. [16]; (d) Ref. [19].

Sun [20–22] realized significant improvement of in-plane stiffness of anisotropic hierarchical honeycombs using triangular, Kagome and negative Poisson's ratio sub-structures. Chen [23] calculated the in-plane elastic properties of hierarchical honeycomb materials, and identified key parameters that govern linear-elasticity and elastic buckling. Taylor [24] attempted to introduce functional grading in hierarchical honeycombs without causing a reduction in Young's modulus. Chen [25] studied hierarchically architected metamaterials using hexagonal, kagome, and triangular lattices as sub-structures, and found improved heat resistance and load-carrying capacity. Another scheme for hierarchical honeycomb construction was achieved by replacing each three-edge vertex of a base hexagonal network with a smaller hexagon of the same orientation, thus forming a self-similar structure. Haghpanah [26] first identified a wide variety of specific stiffness and specific strengths achievable for this novel class of self-similar hierarchical honeycombs. Ajdari [27] investigated in-plane elastic properties and found improvement of the stiffness by up to 2.0 and 3.5 times comparing with regular honeycomb at the same mass. Oftadeh [28] found that anisotropic hierarchical honeycombs of first to fourth order can be 2.0–8.0 times stiffer than regular honeycomb at the same wall angle and the same average density. Besides, hierarchical honeycombs also exhibited superior plastic properties and energy absorption. Qiao [29] investigated the in-plane crushing of hierarchical honeycombs, and found improved collapse stress over traditional honeycombs especially for low velocity impact. Zhang [30] and Sun [31] studied the out-of-plane crashworthiness of self-similar vertex based hierarchical honeycombs, and identified significant improvement in energy absorption with respect to traditional honeycombs given the same density. Though self-similar hierarchical organization was proven effective in promoting the mechanical characteristics of cellular materials, unfortunately, little was done to adopt this design principle to improve the weight efficiency and performance of thin-walled columns.

The paper proposes a novel self-similar hierarchical column (HHC) to improve the crashworthiness performance of thin-walled structure. Section 2 gives a brief summary of self-similar hierarchy and crashworthiness indictors. Finite element model of HHC is developed and experimental test of 1st order HHC is performed to validate the numerical model in Section 3. The crashworthiness comparison of HHCs with different orders is discussed in Section 4. Section 5 conducts the parametric studies of 2nd order HHC to identify the effects of hierarchical size ratio, cell wall thickness and impact velocity. Several interest conclusions are drawn in Section 6.

2. Problem description

2.1. Geometrical properties

In this study, a novel self-similar hierarchical hexagonal structure is constructed by iteratively adding sub-hexagons at the corners of the primary hexagon, and the vertex of two adjacent sub-hexagon is connected with an internal rib, as shown in Fig. 2, in which newly added cell walls and ribs are marked in red. By repeating this process, the 1st and 2nd order self-similar hierarchical structures are generated.

The geometric topology of hexagonal structure at each hierarchy can be characterized by the hierarchical size ratio of higher order hexagonal edge length L_N to the lower order hexagonal edge length $L_{N\text{-}1}$ ($N \geqslant 1$). Where N is the order of self-similar hierarchical structure ($N \geqslant 1$). The edge length of primordial hexagonal structure is denoted as L_0. Here, the hierarchical size ratio ψ_N can be formulated as follows: