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On hierarchical honeycombs under out-of-plane crushing

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ABSTRACT

Hierarchy has been introduced to honeycomb structures in pursuing ultralight materials with outstanding mechanical properties. Nevertheless, the hierarchical honeycombs under the out-of-plane loads have not been well studied experimentally and analytically for energy absorption to date. This study aimed to apply a special structural hierarchy to the honeycomb by replacing the sides of hexagons with smaller hexagons. The quasi-static test of the hierarchical honeycomb specimen was first conducted experimentally to investigate the crushing behaviours; and then the corresponding finite element (FE) analyses were performed. Finally, the analytical solutions to the mean crushing force and plateau stress were derived based on the simplified super folding element (SSFE) method. It was shown that the experimental data and numerical results agreed well in terms of crushing force versus displacement relation and energy absorption characteristics; and the analytical results were validated by the experimental test. Importantly, the hierarchy could improve the energy absorption; and the increase in the order and number of replacement hexagons could excavate the advantage even further. Specifically, the second order honeycomb characterized by five smaller replacement hexagons at each order can yield a plateau stress 2.63 and 4.16 times higher than the regular honeycomb and the aluminium foam, respectively. While it might lead to global bending, structural hierarchy provides new architectural configurations for developing novel ultralight materials with exceptional energy absorption capacity under out-of-plane loads.

1. Introduction

Lured by their excellent mechanical properties and lightweight, cellular materials, such as metallic foams and honeycombs, have been widely used in crashworthiness applications through severe plastic deformation inside the structure (Banhart, 2001; Gibson and Ashby, 1999; Lu and Yu, 2003). Different from the stochastic nature of metallic foams, honeycombs possess a relatively simple and ordered structural feature by comprising an array of open cells formed with thin walls in axial direction. Compared with foam materials, honeycombs have a better mechanical performance in terms of strengths and moduli in both compression and shear conditions with the same density (Banhart, 2001). The study on honeycomb crushing can be traced back to McFarland's work in the early 1960s (McFarland, 1963), in which an analytical formula was derived to approximate the mean crushing stress of the hexagonal honeycomb. Since then, numerous studies on out-of-plane energy absorption of honeycombs have been conducted by using experimental (e.g., Goldsmith and Sackman, 1992; Hussein et al., 2016; Sun et al., 2016b; Wang et al., 2014; Wu and Jiang, 1997; Xu et al., 2012; Yamashita and Gotoh, 2005; Zhao and Gary, 1998), analytical (e.g., Cote et al., 2004; Feli and Pour, 2012; Wierzbicki, 1983; Zhang et al., 2006) and numerical (e.g., Aktay et al., 2008; Wang et al., 2014; Yamashita and Gotoh, 2005) methods.

Driven by public concerns in environmental preservation and sustainability, significant endeavours have been recently made in pursuing previously unachieved ultralight materials and structures (Schaedler et al., 2011; Zheng et al., 2014). In fact, over millions of years of evolution, nature has taught us a way to achieve mechanically efficient materials (Lakes, 1993; Meza et al., 2015): introducing architectural hierarchy to materials and structures. As shown in Fig. 1a, grass takes advantage of hierarchical configuration to be highly efficient in performing its function, by introducing a honeycomb-like core to its tubular structure naturally (Gibson, 2005). Hierarchical structures have also arisen in manmade systems intentionally or unintentionally. Typical macroscopic examples include the Eiffel tower and Sydney Harbour Bridge (Fig. 1b).

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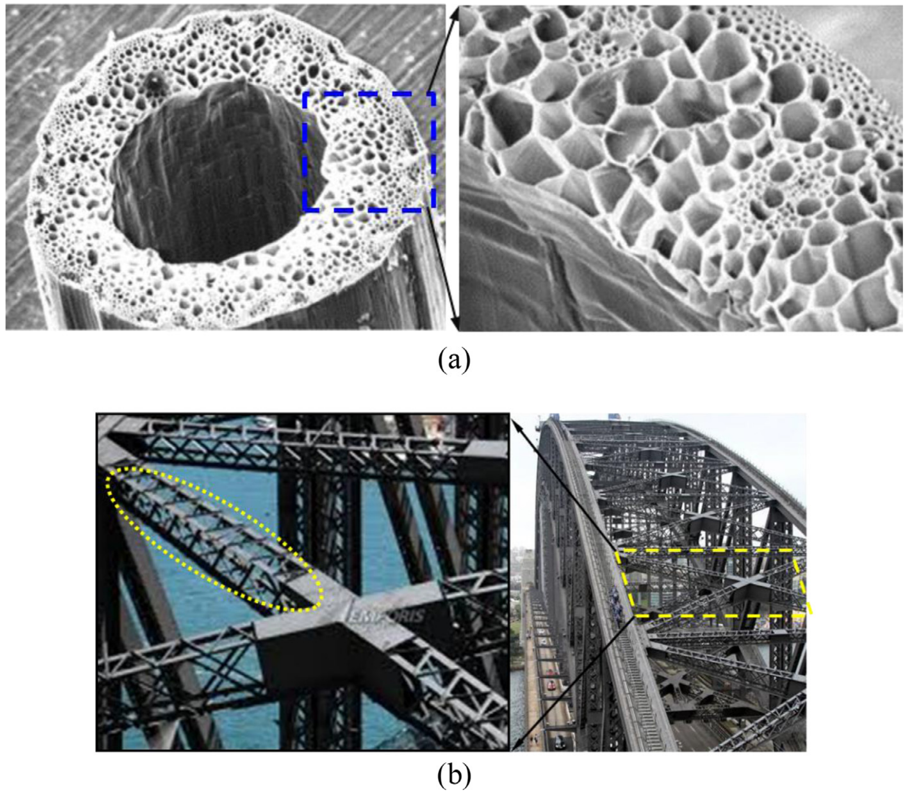

Fig. 1. (a) Natural hierarchical material (grass stem (Gibson, 2005)); (b) man-made hierarchical structure (Sydney Harbour Bridge).

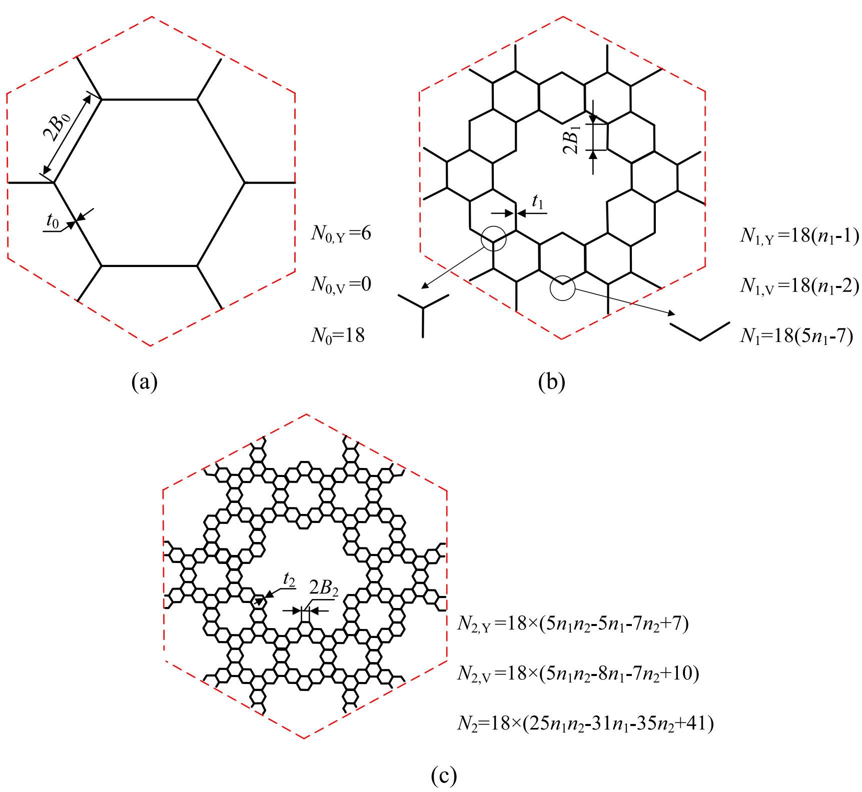

Fig. 2. Cross sectional configurations of (a) zeroth-order (regular), (b) first-order, and (c) second-order hierarchical honeycombs.