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In–plane dynamic crushing behavior and energy absorption of honeycombs with a novel type of multi-cells

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ABSTRACT

In order to pursue better crashworthiness and higher energy absorption efficiency, a new type of multi-cell honeycomb (quadri-arc) was designed and followed by a series of numerical studies on in-plane dynamic crushing behavior and energy absorption property under different impact loading. Meanwhile, simulations of a regular circular single-cell honeycomb were also conducted as comparisons. Three distinct deformation modes were identified from the observation of deformation profiles: quasi-static, transition and dynamic, respectively. Simulations indicate that deformation modes are not only influenced by impact velocity but also sensitive to relative density of the honeycomb, based on which a deformation map was summarized. Furthermore, the plateau stress and energy absorption of the quadri-arc honeycomb as well as the circular honeycomb were explored and compared, during which effects of impact velocity and relative density of the honeycomb were discussed in detail. The results show that a much higher plateau stress and better energy absorption efficiency for the quadri-arc honeycomb are predicted compared to the circular honeycomb, especially in the quasi-static case. The investigation suggests that design of the quadri-arc multi-cell will enhance the crashworthiness and energy absorption capacity of honeycombs.

1. Introduction

As one typical type of cellular material, honeycomb structures have been widely employed in many engineering applications, including personal protective equipment, automotive industry, transportation and aeronautics engineering due to their desirable mechanical properties such as outstanding lightweight, high strength, heat insulation and excellent performance in energy absorption [1]. With increase of safety requirements, optimization and improvement of honeycomb structures for pursuing better crashworthiness and higher energy absorption efficiency have become advanced research hotpots recently [1–3].

Generally, the stress-strain curve of a honeycomb structure subjected to in-plane impact loading contains three distinct regimes: a linear elastic regime, a plateau regime and a densification regime. Among the three regimes, energy capacity of the structure mainly relies on the plateau regime, which is dominated by elastic buckling, plastic buckling and plastic collapse of the unit cells [4]. Therefore, geometry sensitivity is a very important characteristic of honeycombs, the mechanical properties of a honeycomb structure are not only determined by the matrix material, but also extremely be sensitive to cell topology properties [5–9]. By changing the geometrical parameters of the cells such as cell type, cell size, and ratio of wall thickness-to-length and so on, the honeycombs may show a different mechanical property and energy absorption capacity [5]. As is well known, honeycomb cellular structure is one classic biomimetic material, which was first developed originating from the nature honeycomb in a nest. So honeycomb structure with hexagonal cells have drawn the most attention of researchers. However, hexagonal honeycombs are not suitable for all applications, many other types of simple cells have been introduced and designed for specific purpose, including circular, triangular and square cells. Mechanical characteristics and energy absorption capacity of honeycomb structures with different simple types of single cells have been fully researched theoretically, experimentally and numerically [4,5,8–16]. Gibson and Ashby [4] systematically studied the fundamental mechanical properties of honeycomb structures with hexagonal cells as well as triangular and square cells based on micro-structure model and theoretically derived the equation to predict the plateau stress of honeycombs. Ruan et al. [9] numerically investigated the in-plane dynamic behavior of hexagonal honeycomb structures, they observed three deformation modes and discussed the

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Nomenclature

R_B,R_C	Constitutive cell Radius of honeycomb	$\overline{V}$	Relative impact velocity
l_B	Cell length of the quadri-arc honeycomb	V_y	Yield velocity
t_B,t_C	Cell thickness	c_0	Elastic wave speed in the matrix material
κ_B,κ_C	Cell thickness-to-length ratio	ε_Y	Yield strain of the matrix marital
ρ_B,ρ_C	Density of the honeycomb	ε	Nominal compressive strain
$\overline{\rho}_B$,$\overline{\rho}_C$,$\overline{\rho}$	Relative density of the honeycomb	δ	Vertical displacement
ρ_s	Density of matrix material	V_{C1}, V_{C2}	Critical velocity
V_0	Impact velocity	$\sigma(\varepsilon)$	Nominal compressive stress
E_s	Young's modulus of matrix material	V_B	Wave speed
μ_s	Poisson's ratio of matrix material	ε_{cr}	Nominal strain at initial stress peak
σ_{ys}	Yield stress of matrix material	ε_d	Locking strain
		λ,C, C_1, C_2, C_3	Constants
		σ_p^d,σ_p^q	Plateau stress

influences of cell wall thickness and impact velocity on localized deformation and plateau stress of the honeycomb. Papka et al. [10,11] conducted experimental and numerical studies of uniaxial and biaxial crushing of a honeycomb with circular cells, they presented a full scale numerical simulation method which can successfully predict the major material parameters of interest and compared well with the experimental results. An analytical model was established by Hu et al. [12,13] to deduce the crushing strength of the hexagonal honeycombs and was in good agreement with the numerical simulation results. Besides, a lot of works were presented to discuss the crushing behavior of honeycombs with different cell micro-topologies. Wang et al. [14,15] investigated the in-plane mechanical properties of periodic honeycomb structures with seven different single cell types and derived initial yield surfaces of periodic metal honeycombs under a combined in-planes stress state. The empirical equation for honeycomb structures filled with equilateral triangular or quadratic cells and regular or staggered micro-arrangement at high impact velocities were formulated in terms of impact velocity, cell geometric and topology parameters by Liu et al. [16].

Studies mentioned above mainly focused on the honeycombs with simple single-cells. However, honeycomb structures with multi-cells were found to be highly efficient energy absorption structures and received more and more research interests recently [17–23]. A multi-cell honeycomb structure is usually constituted by a number of simple cells with various angles and by different connection factors. Kagome honeycomb as shown in Fig. 1(a) is one typical multi-cell honeycomb constructed by a combination of hexagon and triangle cells. A lot of works have been presented [17–20] to research the mechanical characteristics of Kagome honeycombs under impact loading and it was found that Kagome honeycombs are better choice under the targets of energy absorption capacity compared with honeycombs with simple single-cells. Besides, other types of multi-cell honeycomb structures such as diamond cell honeycombs [19,20] and chiral cell honeycombs [21–23] have also been introduced and studied. Generally, multi-cell honeycomb structures show considerably desirable mechanical properties and energy absorption capacity compared with the single-cell honeycombs.

Fig. 1 shows a Kagome honeycomb structure and a diamond honeycomb structure, their micro-structures are magnified and given as well as the constitutive cells. It is noticed from the figure that a multi-cell honeycomb is essentially constructed by cross connection, combination or superimposition of simple single-cells. For Kagome honeycomb, the single-cells are triangular cells while for diamond honeycomb, the single-cells are triangular or hexagonal cells. In this paper, a new type of multi-cell honeycomb as shown in Fig. 2 is introduced and followed by a serious of numerical analyses on dynamic behavior and energy absorption properties under in-plane impact loadings. The new multi-cell honeycomb is constructed from circular cells and named as quadri-arc multi-cell honeycomb based on the geometry of its unit cells.

This paper is organized as follow. In Section 2, details of the micro-structure of quadri-arc honeycomb is described. Finite element (FE) model of the honeycomb is established and validated. During which, a FE model of regular circular honeycomb is established as comparison. In Section 3, deformation modes of the quadri-arc honeycomb are investigated and compared with the circular honeycomb. Moreover, an overall deformation map of the quadri-arc honeycomb is summarized and the critical velocities of different deformation modes are proposed based on analysis of deformation profiles of honeycombs with different relative densities under different impact velocities. In Section 4, the dynamic impact response of the quadri-arc honeycomb is investigated by analyzing the reaction stress-strain curve of the impact plate, during which effects of impact velocity and relative density are discussed. Meanwhile, the plateau stress of the quadri-arc honeycomb is compared with the circular honeycomb. In Section 5, energy absorption property of the quadri-arc honeycomb is further studied and compared with the regular circular honeycomb.

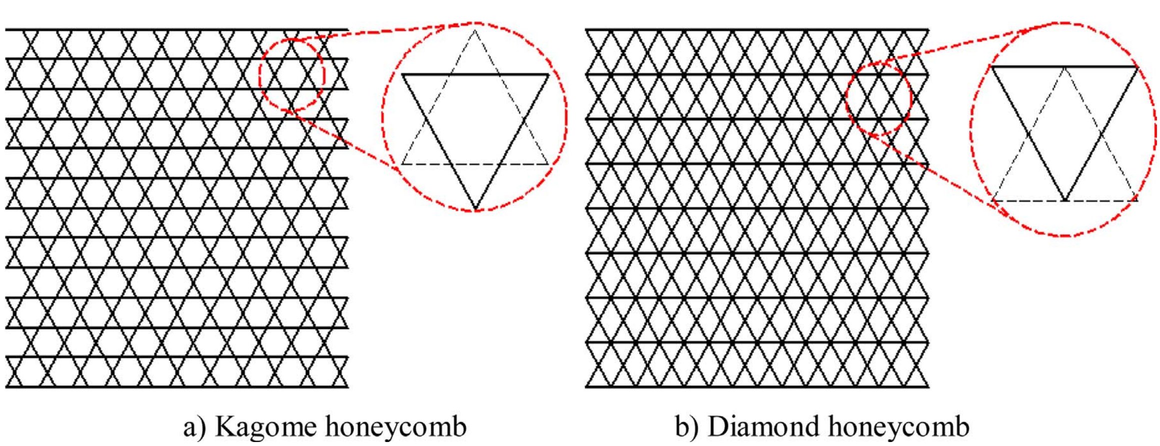

Fig. 1. Two typical multi-cell honeycombs and their constitutive cells.