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The influence of cell micro-topology on the in-plane dynamic crushing of honeycombs

Ying Liu*, Xin-Chun Zhang

Institute of Mechanics, Beijing Jiaotong University, Beijing 100044, PR China

A R T I C L E I N F O

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A B S T R A C T

The influence of the cell micro-topology on the in-plane dynamic crushing of honeycombs is studied by means of explicit dynamic finite element simulation using ANSYS/LS-DYNA. Firstly, under the assumption that the edge length and thickness are the same, the dynamic properties of the honeycombs filled by cells with different shapes (equilateral triangular or quadratic cells) and micro-arrangements (regular or staggered arrangement) are numerically analyzed. The full-scale in-plane dynamic crushing of the specimen, as well as the micro-structure transformation during the deformation, is discussed. Based on these, the influence of the cell micro-arrangement on the energy absorption ability of the honeycombs is clarified. The results show that owing to the differences in the micro-topology, triangular or quadratic honeycombs display different local deformation properties during the crushing. The variation of the cell arrangement patterns changes the local dynamic evolution characteristic of stress waves. '>' and '<' mode local deformation bands form at the sides of the stagger-arranged honeycombs, which results in lateral compression shrinkage during the crushing. The plateau stresses also increase with the impact velocity by a square law. The empirical equations for honeycombs filled with different cells (equilateral triangular or quadratic cells) and micro-arrangements (regular or staggered arrangement) at high impact velocities are formulated in terms of impact velocity, and the cell geometrical (edge length and thickness) and topology (edge connectivity) parameters.

1. Introduction

As one kind of low weight, physical and structural function integrated novel engineering materials, honeycombs have been widely applied in chemical engineering, electrical techniques, architecture, aeronautics, and biomechanics [1,2]. Different from pure solid materials, topology sensitivity is a distinct characteristic of honeycombs. The mechanical responses of honeycombs are not just a material behavior, but also determined by the local topological properties. How to establish the relations between material topology and performance, and realize the self-design of micro-topology of honeycombs according to applicable demands is always the frontier [1].

By now, the relation between the micro-topology and static or quasi-static macro-responses (mainly about the elastic moduli and plastic collapse strength) of honeycombs has been basically established. For example, Gibson and Ashby [2] obtained the fundamental mechanical parameters of honeycombs based on the discrete cell structural models. Shi and Tong [3] derived the equivalent transverse shear modulus and in-plane modulus of honeycombs based on a two-scale method for the homogenization of periodic media. Grenestedt [4] gave the analytical models for regular periodic elastic cellular materials. Hohe et al. [5,6] discussed the elastic responses of hexagonal, triangular or quadratic filling honeycombs. Fortes and Ashby [7] analyzed the effect of non-uniformity on the in-plane Young's modulus of 2D foams with a distribution of the cell wall lengths and thicknesses. Chen et al. [8] studied systematically the influence of six types of morphological imperfection on the yielding of 2D cellular solids under biaxial loading. The research results indicate that the micro-structure has decisive effects on the macro- or local damage modes of materials. It is also seen that the morphology, such as porosity, cell shape and its stability, side length and thickness, is mainly concentrated. In fact, other minor topological aspects of cell shapes, such as the edge connectivity, number of contact neighbors and so forth, will vary from one structure to another, and influence the properties in important ways [2,9]. Especially when the impact loading is applied, the high frequency components will control the dynamic response of the structures. The influence of the cell topology on the local stress dynamic evolution becomes more dominant. As such, clarification of the relation between the cell local arrangement and material dynamic behavior is also an important task in the dynamic description of honeycombs.

In fact, impact deformation mechanism is important in the design of honeycombs. Only after the relation between the

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* Corresponding author. Tel./fax: +86 10 51682094.
E-mail address: yliu5@bjtu.edu.cn (Y. Liu).

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Nomenclature

A	a parameter (Eq. (10))
A_Q	a parameter for quadratic honeycomb (Eq. (14))
A_T	a parameter for triangular honeycomb (Eq. (13))
a	original width of the honeycomb specimen along the x direction (Fig. 1)
b	original height of the honeycomb specimen along the y direction (Fig. 1)
E_s	Young's modulus of cell wall material
h	honeycomb cell wall thickness (Fig. 2)
l	length of honeycomb cell edge (Fig. 2)
N_Q	filling number of quadratic cells (Eq. (3))
N_T	filling number of triangular cells (Eq. (3))
v	impact velocity
W	absorbed energy per unit volume of honeycomb (Eq. (17))
Z_Q	topology factor for quadratic honeycomb (Eq. (16))
Z_T	topology factor for triangular honeycomb (Eq. (15))

Greek letters

δ	displacement
ε	strain of honeycomb
ε_d	locking strain of honeycomb
ρ_s	density of matrix material
ρ^*	density of honeycomb
ρ^*_T	density of triangular honeycomb
ρ^*_Q	density of quadratic honeycomb
σ	plateau stress of honeycomb
σ_0	static plateau stress of honeycomb
σ_Q	plateau stress of quadratic honeycomb
σ_T	plateau stress of triangular honeycomb
σ_{Qe}	elastic buckling stress of quadratic honeycomb
σ_{Te}	elastic buckling stress of triangular honeycomb
σ_c	compression stress of honeycomb
σ_{Qp}	yielding stress of quadratic honeycomb
σ_{Tp}	yielding stress of triangular honeycomb
σ_{ys}	yielding stress of cell wall material

micro-topology and macro-dynamic responses is fully established, and the material performance could be forecast just by its local structures, the honeycomb could be applied widely and safely. Up to now, a lot of research has been carried out. Papka and Kyriakides [10–14] analyzed the full-scale in-plane uniaxial and biaxial crushing behavior of circular polycarbonate honeycombs experimentally and numerically. Hönig and Stronge [15,16] discussed the crush band initiation and wave trapping during the in-plane crushing of honeycombs. Ruan et al. [17] numerically discussed the influences of the cell wall thickness and the impact velocity on the mode localization and the plateau crush of hexagonal honeycombs. Karagiozova and Yu [18] gave the plastic deformation modes of regular hexagonal honeycombs under in-plane biaxial compression. Zheng et al. [19] investigated the influences of cell irregularity and impact velocity on the deformation mode and plateau crush pressure of 2D cellular structures. As a result, some basic rules about the material microstructure and macro-dynamic performance have been obtained. However, the present analysis is mainly focused on materials with circular or hexagonal cells. The research about the honeycombs with other cell shapes is just carried out [20–23]. Moreover, although the results of Shim and Stronge [9] indicated that the cell arrangement pattern had a great influence on the dynamic performance of honeycombs, less attention has been paid. The abundant dynamical evolution characteristic in honeycombs caused by the variation of the local topology should be further clarified.

In this paper, the in-plane dynamic crushing of the honeycombs filled with triangular or square cells is studied. The distinct deformation modes of honeycombs with the same cell geometrical parameters (edge length and thickness) but different spatial topological structures (edge connectivity) are discussed numerically with the aim to disclose the intrinsic relation between the macro-dynamic responses and cell shapes, as well as cell micro-arrangement patterns.

2. Computational models

2.1. Finite element models

Fig. 1 is the diagrammatic sketch of honeycombs under in-plane impact. The size of the honeycomb specimen is $a \times b = 58.5\ \text{mm} \times 70.2\ \text{mm}$, and filled by equilateral triangular or quadratic cells with regular or staggered arrangements, which is shown in Fig. 2. In the filling, the cell edge length and thickness are constant. For triangular cell filling, the cell numbers along the x and y directions are $N_T = 13 \times 18$. For quadratic cell filling, the cell number is $N_Q = 13 \times 16$. The matrix material is aluminum and taken to be elastic–perfectly plastic. The material parameters are Young's modulus 69 GPa, yielding stress 76 MPa, Poisson's ratio 0.3 and mass density 2700 kg/m^3, which are the same as those used in Ref. [17]. ANSYS/LS-DYNA explicit code is adopted to carry out the calculation. Each edge of the cell is modeled with 16 shell elements of type Shell163 (a 4-node quadrilateral shell element), and five integration points are determined along the shell thickness direction to keep convergence. Each cell is defined as a single self-contact surface. Self-contact is also specified between the outside faces of a cell that may contact other cells during crushing. Moreover, the surfaces of the rigid plate and the honeycomb specimen are treated as frictionless planes during the crushing.

In order to analyze the influence of the impact velocity, the velocity v is changed in the calculation. All of the nodes used in each FE model are constrained from the displacement in the out-of-plane direction to ensure the plane strain state of deformation. Moreover, in order to make the comparison with the results of hexagonal honeycombs given in Ref. [17], the same boundary conditions are adopted in the present calculation, that is, when the rigid plate impacts the honeycomb specimen along the y direction,

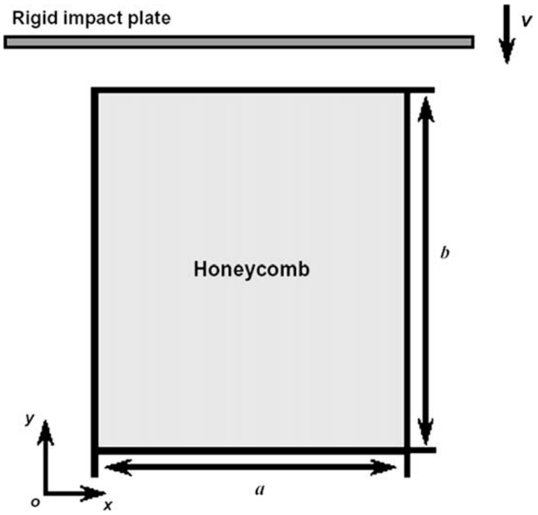

Fig. 1. Diagrammatic sketch for the honeycomb under in-plane impacting. The velocity of the rigid plate remains constant during crushing.