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Effects of defects on the in-plane dynamic crushing of metal honeycombs

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ABSTRACT

The effects of defects and their distributions on the in-plane dynamic crushing of honeycomb panels were studied using explicit finite element modeling. The influence of defect locations and ratios is investigated on the deformation modes and the plateau stresses with respect to the impact velocity. Numerical results show that the dynamic performance of honeycomb displays a high sensitivity on the defect location, especially under low and moderate impact velocities. By introducing a defect correction factor β_m and using the one-dimensional shock wave theory, an empirical formula is given for the variation of honeycomb's plateau stress with respect to the impact velocity and the defect ratio.

1. Introduction

Metallic honeycombs have been widely applied in the industry due to their multi-functional performance and good design ability. A large number of models have been established based on the unit cell approach to predict the macro-mechanical performance of perfect honeycombs [1,2]. Defects have not been considered in most of these models, but are, for practical reasons, difficult to avoid. Interest, thus, arises on the capability to estimate the reduced capacities of honeycombs due to the existence of defects for design purpose. This is particularly crucial for applications in pivotal fields, such as the aerospace industry.

A number of studies about defected honeycombs can be seen in open literacy. Silva and Gibson [3] studied the effects of non-periodic microstructure and defects on compressive failure of Voronoi honeycombs by using the finite element method. Guo and Gibson [4] gave the Young's moduli, the uniaxial or biaxial elastic buckling and post-yielding behavior of regular hexagonal honeycomb with defects. Fortes and Ashby [5] analyzed the non-uniform distribution of the cell wall thickness. Simone and Gibson [6,7] discussed the cell wall curvature and corrugation on the Young's modulus and plastic collapse strength of two-dimensional regular honeycombs. Chen et al. [8] systematically studied the influence of six types of morphological imperfection (waviness, non-uniform thickness of cell edges, cell-size variations, fractured cell walls, cell-wall misalignments, and missing cells) on the yielding strength of 2D cellular solids under biaxial loading. Chung and Waas [9] analyzed the elastic imperfection sensitivity of hexagonally packed circular cell honeycombs. Li et al. [10] discussed the effect of irregular cell shapes and non-uniform cell wall thickness on the elastic modulus of two-dimensional (2D) cellular solids. Prakash et al. [11] and Chen et al. [12] studied the local strengthening of honeycomb structures with inclusions. It is seen that the relation between the defects and the static or quasi-static responses of honeycombs has been basically established.

However, in the dynamic response of honeycombs where impact loading is applied, the inertial effect causes variation in the deformation mechanism, which is characterized by the progressive collapse and localized deformation [13–19]. The influence of defects on the dynamic performance of honeycombs differs from that in static or quasi-station situations. Hönig and Stronge [20] studied the location of the initial crushing bands and the wave propagation in aluminum honeycombs with misaligned cell walls. Zheng et al. [21] investigated the influences of the cell irregularity and the impact velocity on the deformation modes and the plateau stresses. Zhu et al. [22] analyzed the effect of cell irregularity on the high strain compression of 2D Voronoi honeycombs with periodic boundary conditions. Li et al. [23] discussed the effects of the irregular cell shapes and non-uniform cell wall thickness. Wang and McDowell [24] have discussed the effects of missing or fractured cell walls on the in-plane effective Young's modulus, shear modulus, and initial yield strength of metal honeycombs. Nakamoto et al. [25] studied the in-plane impact behavior of honeycomb structures randomly filled with rigid inclusions. These results help to explain the influence of the defect type and the defect ratio on the dynamic responses of honeycombs. However, another parameter, the location, or to some extent, the distribution of the defects, which also plays an important role in determining the local dynamic stress

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evolutions, as evidenced by the work of Nakamoto et al. [26], has not been fully studied.

This paper, aiming to clarify the influence of defects (in the format of missing cell walls in this paper) locations, discusses numerically the dynamic response and energy absorption of honeycomb panels with defects under impact loads. A computational model is first introduced. It is followed by discussions on the effect of the defect ratio and the location, and the impact velocity on the plateau stress of the material. Empirical formulae are provided to evaluate the plateau stress for design purpose.

2. Computational models

2.1. Finite element models

For perfect hexagonal honeycombs, three main deformation modes (X-, V- or I-mode) may forms in the material which depend on the impact velocity [27]. The locations where such modes are formed are termed as PLBs (perfect local bands). Defects may exist at such locations, or in the band, and one would expect that the effect would yield in a change of the mode. To facilitate descriptions, we divide a rectangular honeycomb panel into 9 equal sub-regions, as

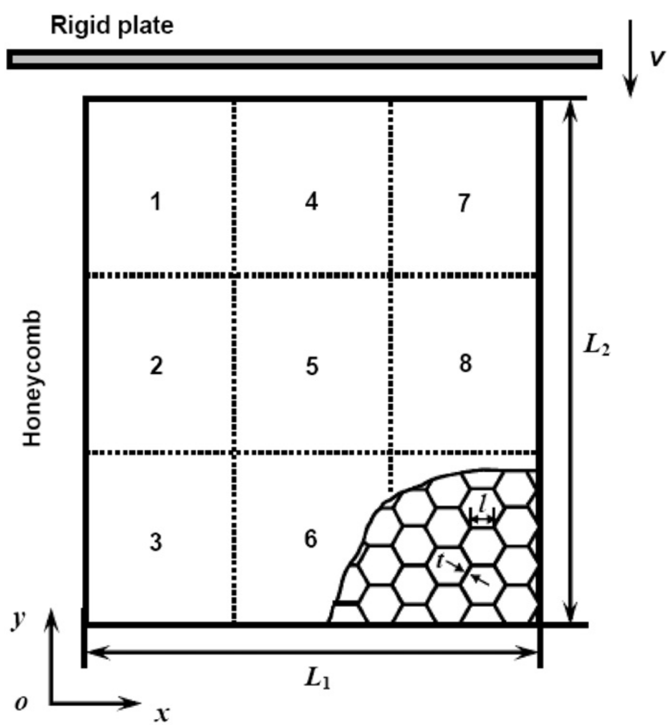

Fig. 1. Model of the honeycomb panel and division of the sub-domains.

shown in Fig. 1. For perfect honeycombs, the X-mode, when forms, will be in the diagonal sub-regions 1, 5, 9, 3, and 7, and the V-mode in sub-regions 1, 5, and 7. Defects are placed in different sub-domains (in or out of PLB), respectively, to see their effects on the deformation behavior of materials. Without losing generosity, the overall size of the honeycomb panel in the present model is $L_1 \times L_2 =$ 58.5 mm × 70.2 mm, and each side is filled by 15 regular hexagons in both the x and y directions, respectively. The cells are uniform with an edge length $l=2.7$ mm and a cell wall thickness $t=0.3$ mm.

Explicit finite element analysis was conducted to simulate the dynamic crushing behavior of honeycomb by using code LS-DYNA [28]. Each edge of the cell was modeled with element type Shell163, a 4-node quadrilateral shell element. Five integration points along the cell wall thickness, as well as the full integrated element formulation were adopted. These were found to be sufficient to provide good accuracy. The matrix material is aluminum and was modeled as elastic–perfectly plastic with material parameters given as: the Young's modulus $E=69$ GPa, the yielding stress $\sigma_y=76$ MPa, Poisson's ratio $\upsilon=0.3$, and a density $\rho=2700$ kg/m^3 [27]. Each surface of the cell was defined as a single self-contact one. Self-contacts were also defined for the outside faces of a cell for interactions with other cells during crushing. All contacts were assumed to be frictionless. Crushing was assumed in the y direction, and a plane strain state of the deformation is assumed. All degrees of freedom at the bottom of the model were fixed, with both the left and right sides of the panel kept free.

Defects were introduced in the form of missing cell walls. Due to the symmetry of the specimen, only sub-domains 1–6 are modeled. MATLAB was used to generate random numbers, which were used to delete cell walls through a user defined pre-processing code during mesh generation. Moreover, in order to eliminate the influence of the cell-wall missing patterns, the same defects (given in Fig. 2) are placed into different sub-domains, subsequently.

In Fig. 2, the local defect ratio φ in a sub-domain is defined as

$$\phi = \frac{\overline{N}}{N/n} = n\Phi, \tag{1}$$

where $\overline{N}$and N are the number of the missing cell walls in the sub-domain and the total cell wall number of the honeycomb panel, respectively, $n=9$, is the number of the sub-domains, and Φ the total defect ratio. Since a connected gap may be formed in the sub-domain when the local cell wall missing ratio is more than 35% [1], the values for φ varying from 0% to 35% is considered in the present discussion.

2.2. The relative density

When cell walls are missing randomly, the relative density $\Delta\rho$ becomes a function of the local defect ratio, specified as

$$\Delta\rho(\varphi) = \frac{\rho^*(\varphi)}{\rho_s} = \sum_{i=1}^{N-\overline{N}} l_i t_i/(L_1 L_2), \tag{2}$$

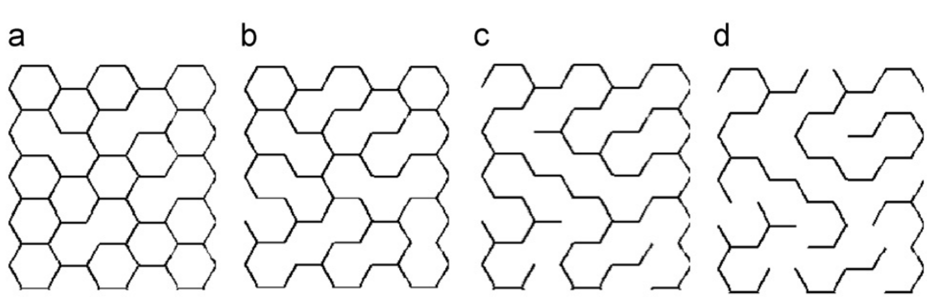

Fig. 2. Patterns (cell wall missing) of defect ratios: (a) φ=5%, (b) φ=15%, (c) φ=25%, and (d) φ=35%.