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Dynamic crushing behavior of honeycomb structures with irregular cell shapes and non-uniform cell wall thickness

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Abstract

Dynamic crushing responses of honeycomb structures having irregular cell shapes and non-uniform cell wall thickness are studied using the Voronoi tessellation technique and the finite element (FE) method. FE models are constructed for such honeycomb structures based on Voronoi diagrams with different degrees of cell shape irregularity and cell wall thickness non-uniformity. The plateau stress, the densification strain energy and the initiation strain are determined using the FE models. Simulation results reveal that the "X" and "V" shaped deformation modes evident in a perfectly ordered honeycomb at low or moderate impact velocities are disrupted as cell shapes become irregular and/or cell wall thickness gets non-uniform. The "I" shaped deformation mode is clearly seen in all honeycomb structures at high impact velocities. Both the plateau stress and the densification strain energy are found to decrease as the degree of cell shape irregularity or the degree of cell wall thickness non-uniformity increases, with the weakening effect induced by the presence of non-uniform cell wall thickness being more significant. When the two types of imperfections co-exist in a honeycomb structure, the interaction between them is seen to exhibit a complicated pattern and to have a nonlinear effect on both the plateau stress and the densification strain energy. It is also found that stress waves propagate faster in a honeycomb structure having irregular cell shapes and slower in a honeycomb structure having non-uniform cell wall thickness than in a perfectly ordered honeycomb. Finally, the strain hardening of the cell wall material is seen to have a strengthening effect on the plateau stress, which is more significant for perfectly ordered honeycombs than for imperfect honeycomb structures.

Keywords: Cellular solids; Dynamic crushing; Honeycombs; Voronoi tessellation; Irregular cell shapes; Non-uniform cell wall thickness; Finite element method

1. Introduction

Unit cell based micromechanics models have often been used to predict mechanical properties of cellular solids (e.g., Gibson and Ashby, 1997). Although these models are simple and cost-effective, they are signifi-

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cantly limited by their inability to account for microstructural imperfections inherently present in most real cellular materials, whose cell structures are typically non-periodic, non-uniform and disordered (e.g., Silva and Gibson, 1997; Chen et al., 1999; Guo and Gibson, 1999). Hence, models that incorporate microstructural imperfections and contain a large number of cells are needed for improved predictions. Such a model has recently been developed by Li et al. (2005) for two-dimensional (2D) cellular solids having irregular cell shapes and non-uniform cell wall thickness, which are two types of imperfections commonly present in such solids. Their simulation results indicated that the elastic moduli increase as cell shapes become more irregular, but decrease as cell wall thickness gets less uniform. The effect of the interaction between the two co-existing imperfections on the elastic moduli was found to be weak. However, only static loading was considered in Li et al. (2005).

Very limited attention has been paid to the effect of microstructural imperfections on dynamic responses of cellular solids. Papka and Kyriakides (1998) performed a full-scale FE simulation of quasi-static crushing of aluminum honeycombs and found the initiation stress and the plateau (crushing) stress to be, respectively, 14% and 8% above those experimentally measured values. They attributed these differences to the imperfections induced during fabrication of the honeycombs, which were not included in their FE model. Hönig and Stronge (2002a) reported that misalignment of cell walls affected the location of initial crushing bands in an aluminum honeycomb. The FE study of Tan et al. (2005) revealed that cellular microstructural irregularities had insignificant effect on the internal energy density at three velocities (100, 150, and 200 m/s). However, Zheng et al. (2005) showed that increasing the cell irregularity leads to an increase in the plateau stress, thereby improving the energy absorption capacity. A common feature of these earlier investigations is that in each study only one type of imperfection was included at a time. Since several types of imperfections are generally co-existent in the microstructure of a typical honeycomb structure, models incorporating two or more types of imperfections are still in need.

The objective of this paper is to study the combined effect of two co-existing imperfections—irregular cell shapes and non-uniform cell wall thickness—on dynamic crushing behavior of honeycomb structures. The rest of this paper is organized as follows. In Section 2, honeycomb structures with different degrees of cell shape irregularity and cell wall thickness non-uniformity are first constructed using the Voronoi tessellation technique. Finite element (FE) models are then developed using the constructed Voronoi diagrams to predict the plateau stress, densification strain energy and initiation strain of the honeycomb structures. In Section 3, a mesh sensitivity study is first performed to determine the appropriate number of cells to be included in each diagram. This is followed by an investigation of the plateau stress of the honeycomb structures based on the Voronoi diagrams and the FE models. Then, parametric studies for sample cases involving different values of five controlling parameters (i.e., the impact velocity, cell shape irregularity amplitude, cell wall thickness non-uniformity amplitude, relative density, and strain-hardening index) are conducted, with the simulation results presented and discussed. The paper concludes with a summary in Section 4.

2. Analysis

2.1. Model construction

Each honeycomb structure with microstructural imperfections is built by starting from a reference model, which is a perfectly ordered hexagonal honeycomb with regular cell shapes and uniform cell wall thickness. This reference model is constructed from a set of regularly packed seeds using the Voronoi tessellation technique. 2D Voronoi diagrams with irregular cell shapes are then generated by introducing perturbation to the reference model.

Since the irregularity of cell shapes is determined by the irregular distribution of the seeds, the locations of the seeds used to construct Voronoi diagrams with irregular cell shapes can be perturbed from a regular lattice of seeds. Fig. 1 shows the coordinate perturbations of a regularly packed seed $(\bar{x}_1^i, \bar{x}_2^i)$. The perturbed coordinates of seed i, x_1^i and x_2^i, can be represented by

$$\begin{aligned} x_1^i &= \bar{x}_1^i + a(d_0 \cos\theta_i)\varphi_i, \\ x_2^i &= \bar{x}_2^i + a(d_0 \sin\theta_i)\varphi_i, \end{aligned} \tag{1}$$