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Dynamic crushing of 2D cellular structures: Local strain field and shock wave velocity

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ABSTRACT

Continuum-based shock models have been proposed by different authors to understand the strength enhancement and deformation localization phenomena observed in the dynamic response of cellular materials, but their applicability is still debatable due to continuum-based stress wave theory being used to cellular materials with finite cell sizes. A method based on the optimal local deformation gradient is developed to calculate the local strain field of a deformed cellular structure using a cell-based finite element model. The strain field provides evidences of the existence of a plastic shock front in cellular materials under a high or moderate velocity impact. Due to the feature of shock front propagation, the 2D strain fields are simplified to one-dimensional distributions of strain in the loading direction. Shock wave velocity is measured by an approach that gives the location of the shock front varying with the impact time. A comparison of the cell-based finite element model with continuum-based shock models indicates that the shock model based on a material accounting for the post-locking behaviour is more accurate in predicting the shock wave velocity. Finally, stress–strain states ahead of and behind the shock front are obtained. These results provide an explanation in terms of deformation mechanism for the stress reduction at the support end with increasing impact velocity, which was previously observed in experimental and numerical studies.

1. Introduction

Cellular materials, such as metallic foams and honeycombs, have attracted considerable research interests because of their extensive applications in impact energy absorption and shock mitigation [1]. Their dynamic crushing behaviours have been extensively studied and much knowledge has been achieved, but some fundamental problems have not been satisfactorily solved due to the technical difficulties such as the measurement of local stress and strain states.

Strength enhancement is a typical feature of cellular materials under dynamic impact. Significant enhancement in the crushing strength of woods under high impact velocities was observed by Reid and Peng [2]. It was found that the deformation of wood specimens was localized, like a shock propagates through the material. Enhancement of dynamic plastic collapse strength of aluminium foams was observed by Tan et al. [3]. Inertia effect associated with the 'shock' formation was suggested to be responsible for the enhancement measured at super-critical impact velocities. Strength enhancements accompanied with the 'structural shock' were also experimentally observed in Refs. [4–6]. Additionally, even under a rather moderate impact velocity, there exists strength enhancement as shock fronts propagate in Alporas foams and nickel hollow spheres [7]. Meanwhile, cell-based finite element models approximating 2D or 3D cellular materials were proposed to investigate their dynamic crushing behaviours. By discretely modelling cell walls and cell faces, these finite element models can accurately represent the microstructural deformation mechanisms. Dynamic crushing of regular honeycombs was studied by Ruan et al. [8] and a deformation in a manner of shock wave propagation was observed under high impact velocities. Discontinuities in strains and stresses across the shock front propagating through the regular honeycombs were examined by Zou et al. [9], who introduced particular definitions of strain and stress. Dynamic crushing of irregular honeycombs was investigated by Zheng et al. [10] and the existence of shock front propagation under an impact velocity exceeding a critical value was revealed.

Several crushing models have been developed to understand the physical mechanisms of the strength enhancement, such as mass-spring models [11,12], shock models [2,4,13–15] and cell-based finite element models [8,10,16]. Recently, Harrigan et al. [17] suggested that mass-spring models should be used with

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caution because they are not capable of modelling the discontinuities that exist in shock wave propagation. Shock models, on the contrary, have been shown to be successful for a number of cellular materials. A shock model based on a rate-independent, rigid–perfectly plastic–locking (R–P-P–L) material idealization was first proposed by Reid and Peng [2]. This model gives good predictions of shock enhancement of crushing strength of woods. Some other more realistic material idealizations have been used by different authors [4,13,15,17,18] to get much understanding of the dynamic responses of cellular materials.

However, it is still debatable whether or not the continuum-based shock wave theory is applicable to cellular materials [13]. The argument is that solutions based on discontinuities at shock front in solid continua are now used to cellular materials with finite cell sizes. The aim of this paper is to present evidences of the existence of discontinuities at shock front in cellular materials as that in solid continua. A numerical method is developed to construct the strain field of Voronoi structures during their dynamic crushing. It allows for evaluating quantitatively the deformation and strain localization mechanisms of cellular materials.

In this paper, local strain fields corresponding to various impact velocities are calculated. One-dimensional distributions of strain in the loading direction are further obtained from two-dimensional strain fields. Shock wave velocity is then measured and compared with that predicted by one-dimensional shock models. Finally, the stress–strain states ahead of and behind the shock front are obtained.

2. Numerical models

Irregular honeycombs, any of which is an assembly of basic cells with different geometry, are used to model cellular structures in this study. They are constructed by using 2D random Voronoi technique [10]. Firstly, N nuclei are randomly generated in a given area by constraining the minimum distance between any two nuclei. Secondly, the nuclei are translated to the surrounding neighbouring regions. Thirdly, the Delaunay triangulation and the Voronoi diagram are constructed. Finally, the part of the Voronoi diagram in the given area is reserved to form the Voronoi structure. The degree of cell irregularity used to create Voronoi structures is set as 0.6 in this study. A sample is illustrated in Fig. 1. The Voronoi structure is placed against a fixed rigid plate at one end (support end) and crushed along the x direction by a rigid plate with constant velocity V at the other end (impact end). The relative density of all Voronoi structures used in numerical simulations is taken to be $\rho_0/\rho_s = 0.1$, where ρ_0 is the initial density of the Voronoi structures and ρ_s the density of the cell-wall material. The average cell size of the Voronoi structures is kept constant, i.e. $d = 7.28$ mm, which is defined as the diameter of a circle whose area equals the average area of Voronoi cells. The length and width of a Voronoi structure are denoted as L and H, respectively.

Numerical simulations were performed by using explicit finite element code ABAQUS/Explicit. The cell-wall material was assumed to be elastic, perfectly plastic with $E = 66$ GPa, $Y = 175$ MPa, $\rho_s = 2700$ kg/m^3 and $\nu = 0.3$, where E, Y and ν are the Young's modulus, yield stress and Poisson's ratio, respectively. The cell walls of Voronoi structures were modelled with S4R (A 4-node doubly curved, reduced integration, hourglass control, finite membrane strains) shell elements, of which the size was set to be about 0.6 mm in-plane and 1 mm out-of-plane through a mesh sensitivity analysis. Self-contact within each cell and contact between the Voronoi structure and the rigid plates were considered by defining general contact in ABAQUS/Explicit code. The friction coefficient of contact was assumed to be 0.02 as used in Ref. [10]. All the nodes were constrained in the out-of-plane direction to simulate an in-plane strain state.

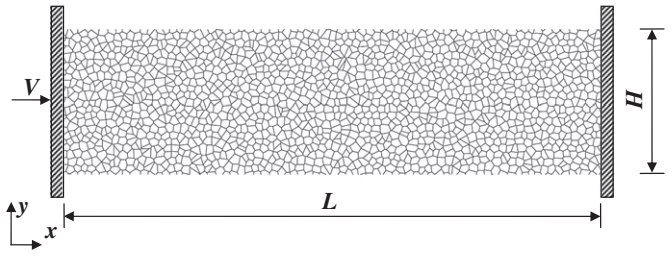

Fig. 1. Finite element model of Voronoi structure.

3. Local strain formulation

The cell-based finite element models cannot directly provide strain fields of cellular materials, though they can accurately represent the microstructural deformation at the cell level. This brings difficulty in verifying the continuum-based shock models. Several methods for calculating strain have been proposed in the literature but they are either not satisfactory even limited for regular honeycombs [9] or based on small strain definition [19]. Zheng et al. [18] suggested that strain should be defined as statistical average measured over a range of at least one cell size because of the cellular nature of the materials.

In the continuum mechanics, strain tensors are the primary measure of local deformations. The Lagrangian or Green strain tensor, $\mathbf{E}$, is defined with respect to the reference configuration as

$$\mathbf{E} = \frac{1}{2}\left(\mathbf{F}\cdot\mathbf{F}^{\mathrm{T}} - \mathbf{I}\right), \tag{1}$$

where $\mathbf{F}$ is the deformation gradient, $\mathbf{I}$ the identity matrix and superscript T denotes the transpose of a matrix. Thus, if a local deformation gradient is determined, a local strain field can be obtained. However, the cellular nature of the materials allows for only discrete displacement field of nodes, which prevents direct calculation of the deformation gradient. In this study, a discrete local deformation gradient based on the least square error defined in Refs. [20–22] was employed.

The Voronoi structure in the numerical simulation is discretized as a series of corner nodes (vertices of Voronoi cells) and other nodes on the cell walls, as illustrated in Fig. 2. Interior strain of the Voronoi structure is discretely represented by the local strain at each corner node, which is regarded as a statistical average of the strain over the neighbourhood of each corner node. The nodal configurations at $t = t_0$ and $t = t_1$ are called reference configuration and current configuration, respectively. A corner node i and its neighbouring node j are located at the position $\mathbf{x}_i^0$ and $\mathbf{x}_j^0$ at $t = t_0$,

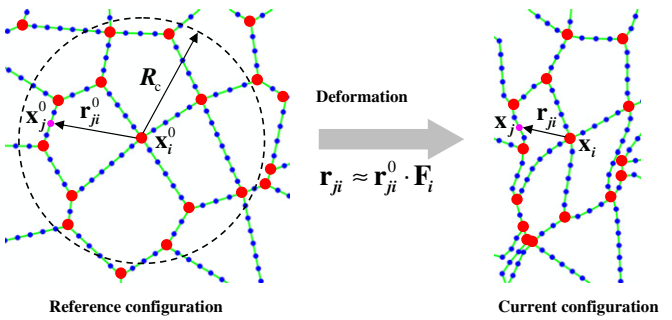

Fig. 2. Motion in the neighbourhood of a corner node i with position vectors $\mathbf{x}_i^0$ and $\mathbf{x}_i$ in the reference and current configurations, respectively.