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Impact resistance of graded cellular metals using cell-based finite element models

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Abstract. A varying cell-size method based on Voronoi technique is extended to construct 3D graded cellular models. The dynamic behaviors of graded cellular structures with different density gradients are then investigated with finite element code ABAQUS/Explicit. Results show that graded cellular materials have better performance as energy absorbers. Graded cellular structures with large density near the distal end can protect strikers, and those with low density near the distal end can protect structures at the distal end. It is concluded that graded cellular materials with suitable design may have excellent performance in crashworthiness.

Introduction

Cellular metal possesses good mechanical properties, such as light weight, high specific strength, high specific stiffness and high energy absorption. These properties make cellular metal being widely used in auto-mobile, high-speed train and other transportation industries [1], 2]. Microscopic heterogeneity of cells in size, shape and wall thickness affects the macroscopic properties of cellular metals and makes them designable. Previous researches showed that density gradient affects the mechanical properties of graded cellular materials under quasi-static compression [3], 4]. It is possible to take full advantages of the potential of cellular material with reasonable design.

Preliminary studies on the impact behaviors of graded cellular materials have been reported in the literature. The properties of graded cellular materials, such as the energy absorption, impact resistance and heat-insulating, could be improved by changing the density distribution. Because of limitations of manufacturing technology, most of the investigations about graded cellular materials were carried out using finite element method [5-7]. Voronoi structures [8], which can well reflect the microstructure of cellular material, are widely used to simulate cellular materials. Two-dimensional random honeycombs constructed by Voronoi technique have been employed to investigate the dynamic crushing behaviors of cellular metals and understandings of its mechanism have been achieved [9], 11]. With computer efficiency improving, three-dimensional Voronoi technique is used to construct cellular structures and to study their static and dynamic mechanical behaviors [13].

In this study, 3D Voronoi models are employed to investigate the impact behaviors of graded cellular materials. A numerical method is introduced to construct graded cellular structures with different density gradients. Results and discussion of the impact resistance of graded cellular structures are presented, followed by conclusions.

Numerical method

A varying cell-size method based on Voronoi technique has been developed to construct 2D graded cellular structures by Wang et al. [14, 15]. It is extended to construct 3D graded cellular structures in this study. Cellular structures with a relative density distribution along the Z-direction, ρ(Z), are generated by using the Voronoi technique with a new principle of random seeding nuclei that the distance between any two nuclei i and j, δ_{ij}, is not less than the local minimum allowable distance δ_{ij}^{min}, written as

$$\delta_{ij} \geq \delta_{ij}^{min} = (1-k) \cdot \frac{3(6+\sqrt{3})h}{8\rho(Z_i+Z_j)/2}, \tag{1}$$

where k is the cell irregularity, h the cell-wall thickness and (X_i, Y_i, Z_i) the location of nucleus i.

In this study, the density distribution of cellular specimens is assumed to be linear in the Z-direction, given by

$$\rho(Z) = \rho_0[1 + \gamma(Z/L - 1/2)], \tag{2}$$

where γ is the gradient parameter, ρ_0 the relative density and L the length of the cellular specimen. Five specimens with γ = 1, 0.5, 0, −0.5 and −1 are investigated. Specimens are in the size of 40×40×50 mm^3, consist of about 3,000 cells with a uniform cell-wall thickness. The schematic diagrams of cellular specimens with γ = 1, 0.5 and 0 are shown in Fig. 1. In this study, we take ρ_0 = 0.12, k = 0.4 and h = 0.19 mm. The cell-wall material of the cellular specimens is taken to be elastic-perfectly plastic with the density, Young's modulus, Possion's ratio and yield stress being 2700 kg/m^3, 69 GPa, 0.3 and 165 MPa, respectively. Cell walls are modeled with hybrid shell elements of types S4R and S3R. General contact with slight friction is specified.

Inverse impact tests of the cellular specimens, as represented schematically in Fig. 1a, are performed by using finite element code ABAQUS/Explicit. The striker with a mass of M = 0.5 kg impacts a cellular specimen at an initial velocity of V_0 = 120 m/s.

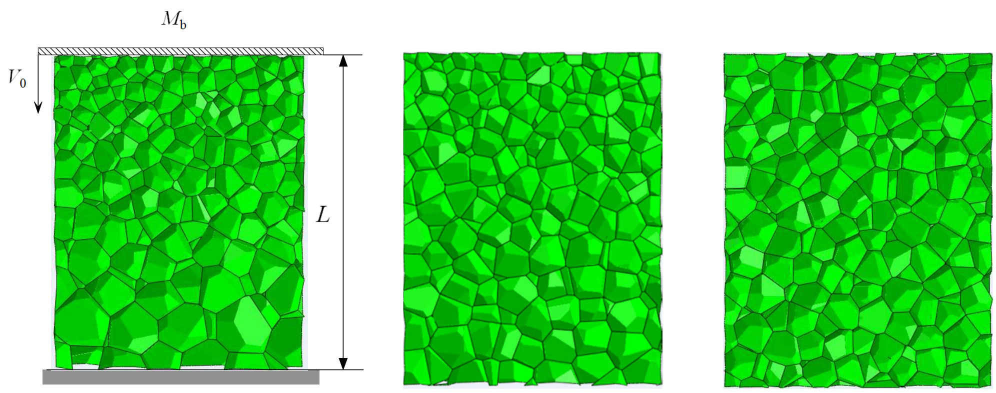


Fig. 1. Schematic diagrams of impact test and cellular specimens with the gradient parameters of (a) γ = 1, (b) γ = 0.5 and (c) γ = 0.

Results and discussion

Forces at the proximal end and at the distal end. In practice, a structure which may be subjected to impact or explosive loads needs to be protected by an energy absorber. Thus, as an element of energy absorber, the reaction force at the proximal/distal end of graded cellular structures is necessary to be evaluated. Deformation patterns of specimens with γ = 0, −1.0, 1.0 are shown in Fig. 2, while force-time curves of graded cellular structures are shown in Figs. 3 and 4. All the force-time curves have oscillation due to cell collapsing. For specimen with $\gamma = 0$, the reaction force at the proximal end has a descending trend and then rises, as shown in Fig. 3(a). This is because of the impact velocity decreasing at first, but the specimen is not long enough and the cells near the distal end are suffered by the action of a reflected shock wave, as shown in Fig. 2(a3). The reaction force at the distal end changes slightly at the first stage as materials crushed and then significantly increases due to compaction, see Fig. 4(a).

For specimens with $\gamma < 0$, the reaction force at the proximal end is less than the one with $\gamma = 0$ at first, then increases gradually, as shown in Fig. 3(a). The reason is that cellular layers with lower density and strength crushed before those with higher density and strength. The reaction forces at the distal end have a rising trend for all curves with obvious fluctuation at first, as shown in Fig. 4(a). Because cells with big size collapse at first and cellular layers with lower density and strength crushed before those with higher density and strength.

For specimens with $\gamma > 0$, the reaction force at the proximal end decreases from a high level at the beginning gradually and then increases before the end of response, as shown in Fig. 3(b). Under high velocity impact, specimens are crushed at the proximal end with higher density. As the impact velocity of the striker decreases, a shock wave also appears at the distal end, as shown in Fig. 2(c3). The stress behind this shock front increases with time as the strength of the crushing layer increases, leading to the rising of reaction force at the distal end, as shown in Fig. 4(b).

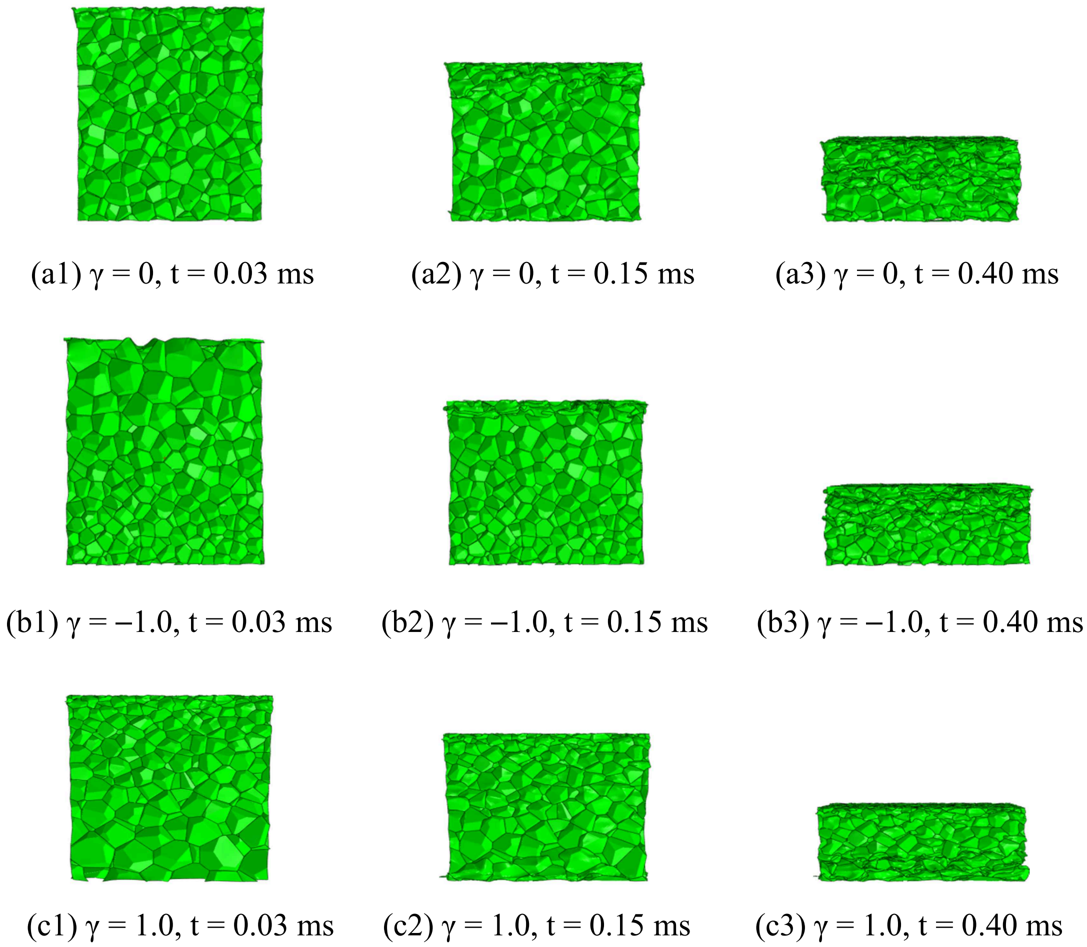
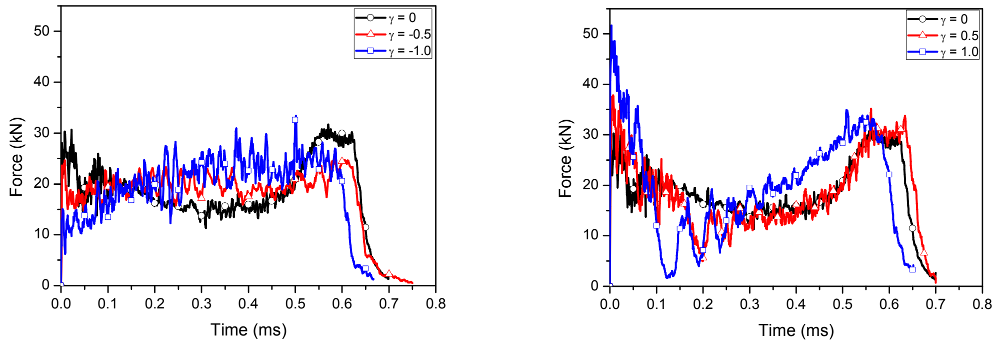
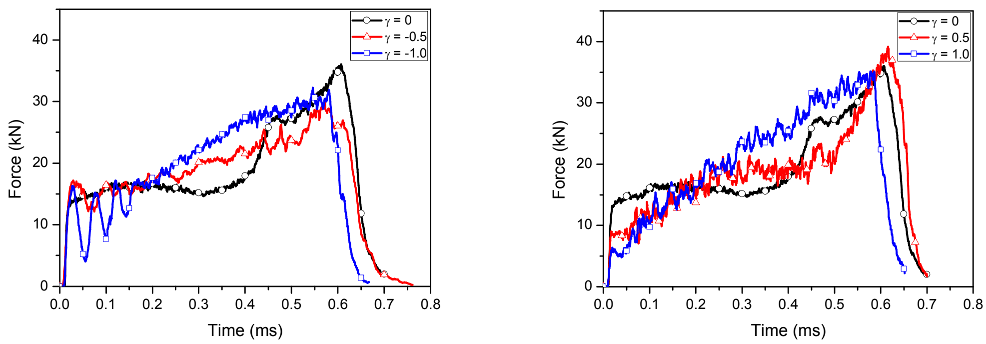


Fig. 2. Deformation patterns of graded cellular structure with different gradients at different time: (a) $\gamma = 0$, (b) $\gamma = -1.0$ and (c) $\gamma = 1.0$



(a) (b)

Fig. 3. Reaction forces at the proximal end of graded cellular structures with different gradients: (a) $\gamma \leq 0$ and (b) $\gamma \geq 0$

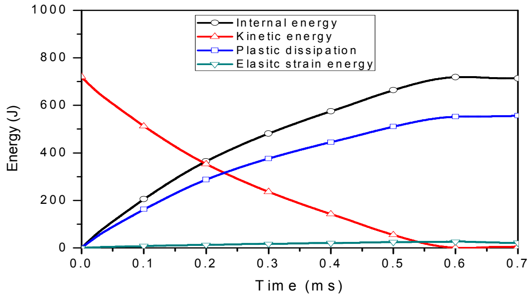


(a) (b)

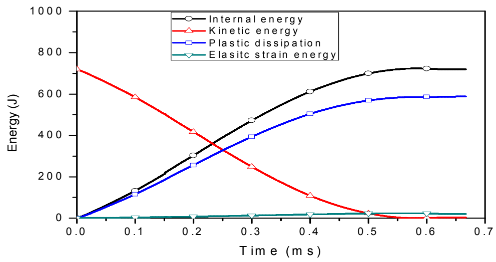
Fig. 4. Reaction forces at the distal end of graded cellular structures with different gradients: (a) $\gamma \leq 0$ and (b) $\gamma \geq 0$

In summary, the reaction force at the proximal end of specimens with $\gamma < 0$ are more stable and the force levels are relatively lower than others. Therefore, they can be used to protect the striker. If the structure being protected is located at the distal end, the graded cellular structures with $\gamma > 0$ perform better than others, as the force at the distal end is lower at first and the maximum value is less than those of others.

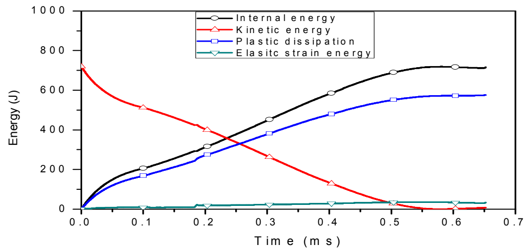
Energy absorption. Energy absorption capacity is an important index to evaluate the crashworthiness of structures. The kinetic energy of system is absorbed by graded cellular materials mainly in the form of plastic dissipation due to collapse of cell-walls. The time history of energy absorption of cellular specimens with $\gamma = 0$, -1.0 and 1.0 are shown in Fig. 5. It is seen that for specimens with $\gamma = -1.0$, the internal energy and plastic dissipation increase more slowly than those with $\gamma = 0$ at first while for specimens with $\gamma = 1.0$, and the internal energy and plastic dissipation increase more quickly than those with $\gamma = 0$ at first and then slow down. And specimens with $\gamma \neq 0$ absorb more energy than the uniform one. As mentioned before, for specimens with different γ, the sequences of cellular layer crush lead to the differences of energy absorption history. At last, all materials are compacted and the values of energy components no longer change. The energy curves with $\gamma = -0.5$ are similar with those of $\gamma = -1.0$, while the energy curves with $\gamma = 0.5$ are similar with those of $\gamma = 1.0$.



(a)



(b)



(c)

Fig. 5. Typical energy absorption curves for graded cellular specimens with different gradients: (a) $\gamma = 0$, (b) $\gamma = -1.0$ and (c) $\gamma = 1.0$

Conclusions and Discussion

A series of 3D graded cellular structures with different density gradients were generated by a varying cell-size method based on Voronoi technique. The impact resistance and energy absorption of the graded cellular structures are investigated by finite element method. It is found that the energy absorption capability of graded cellular structures are better than that of the uniform cellular structure.

Graded cellular structures with different density gradient have different deformation modes, which have significant influence on the reaction forces at the two ends of graded cellular structures. For $\gamma = 0$, the reaction force at the proximal end has a descending trend at first and then has a rising trend with fluctuation. The force at the distal end changes slightly at the beginning but has a sudden increase at the final stage. For $\gamma < 0$, the reaction force at the proximal end is less than that for $\gamma = 0$ at first, and it increases gradually. The reaction force at the distal end has a rising trend for each curve with obvious fluctuation. For $\gamma > 0$, the reaction forces at the proximal end have a great peak value at the beginning as the collapse of cell starts from the proximal end which has the highest density. And then the force decreases in a short time, followed by an increasing at last. At the distal end, the reaction forces rising with fluctuation. It is found that graded cellular structures with large density near the distal end can protect strikers, those with low density near the distal end can protect structures at the distal end.

It can be seen from Figs. 3 and 4 that the reaction force levels of specimens with $\gamma = 0.5$ and $\gamma = -0.5$ are lower than those with $\gamma = 1$ and $\gamma = -1$, respectively. This indicates that graded cellular materials with suitable design may have excellent performance in crashworthiness. The meso-structure generating technique and the finite element method developed in this study may help to guide the design of graded cellular materials.

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