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Study of cell irregularity effects on the compression of closed-cell foams

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ABSTRACT

Closed-cell aluminum foam is widely used as energy absorbing material. The cell regularity profoundly affects the mechanical behavior of this material. To investigate the influence of irregularity on elastic and plastic behavior of closed-cell foams, the compression behavior of Voronoi foams was simulated using the finite element method. The results show that with the increasing randomness of the foam, the elastic modules decrease a little while the collapse-strength decrease considerably. A theoretical analysis is conducted with the simple springs model. The results match well with simulation which shows theoretical analysis is reasonable. The Voronoi models were also compressed under different loading velocities and with different relative densities in simulation. The results reveal that foams with low regularity are more suitable for application in protective structures.

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1. Introduction

As a lightweight energy-absorbing material, foam has been widely used in engineering structures such as sandwich panels, anti-blast structures. [1,2] The interests on mechanical properties of foam have been growing for decades. Since these properties are affected by micro-structure parameters such as relative density, cell size and cell morphology, it is necessary to analyze these effects using a micro-structure model.

Gibson and Ashby [1] used a cubic cell model to investigate elastic and plastic properties of different foams. They deduced the relationship between relative density and Young's modulus as well as the plastic-collapse strength of metallic foam, and used finite element analysis of tetrakaidecahedral cells to obtain the constants in their formula. However, this model overestimated mechanical properties of metallic foam as the real foam cell usually has a random size and configurations. [2]

An ideal method to realistically construct the geometry of foams is to create 3-D volumes using computed tomography (CT) technique. For example, Sun et al. [3] constructed a closed-cell foam model using this method to investigate the strain-rate effect on its compressive behavior. Unfortunately, this method usually results in complicated model and takes a long simulation time. To represent the morphology of cellular materials in a more efficient way, the Voronoi tessellation technique was used. However, few researches can be found about the role cell regularity played on the mechanical performance of foams.

In fact, the cell regularity profoundly determines the topology of 2-D honeycomb and 3-D foams and hence affects their mechanical behavior. Zhu et al. [4–7] indicated that the effective Young's modulus and shear modulus increase with increasing irregularity of both 2-D Voronoi honeycomb and open-cell foams. On high strain compression, a more irregular honeycomb supports a lower compressive stress and the same phenomenon can be found in open-cell foams. However, opposite opinion was expressed by Luxner [8] and Sotomayor [9]. Their calculation revealed that the Young's modulus of open-cell foams decreases as irregularity increases. Song's [10] and Li's [11] research on closed-cell Voronoi foams indicates the plateau stress of foam decreases with increase of cell shape irregularity (In publication [10], authors made a mistake to treat regularity as irregularity and made an opposite conclusion). Moreover, most of these conclusions were drawn only from FEM calculation, and theoretical support was lacking, especially in closed-cell foams.

In this work, an FE model of closed-cell Voronoi foam with different irregularity parameters was constructed. The influences of cell regularity on both elastic and plastic behavior of closed-cell Voronoi foams were investigated. Closed-cell foam with relative density of 10% was used as an initial target of simulations based on commercial foam ALPORAS. Theoretical analysis was then conducted to explain the simulation results. Finally, the effects of compression velocity and relative density of the foams were also investigated.

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2. Finite element simulations

2.1. Construction of Voronoi foam

Voronoi foams are usually formed by nuclei and growth of cells. A 3-dimensional Euclidean space V_0 which is a cube was established in this study. A right-handed Cartesian coordinate was chosen with its origin located at one corner of the cube. The nuclei were then generated in V_0 at random positions with coordinate *x, y* and *z* independently. After the first nucleus was located, the newly generated nucleus is accepted only if the distance between other nuclei and itself is greater than a minimum distance δ ($\delta \geqslant 0$). The nucleus generation process continues until the number of nuclei reaches a referred number *n*. A Matlab® code is developed to generate all nuclei in space V_0. The growth of cell is implemented in C++ code using Voro++ open source software [12]. Information of vertices and faces in the model was read by an in-house C++ program. The short edges (edge length < 0.1 mm) on the faces were eliminated to improve the computational efficiency. Similar methods have been applied in other researchers' work [10,13,14].

2.2. Regularity parameter

A fully regular Voronoi foam is known as Kelvin foam which consists of cubic arranged tetrakaidecahedral cells. To construct a Kelvin foam model with N cells in the cubic volume V_0, the distance d_0 between any two adjacent nuclei can be presented as [5]

$$d_0 = \frac{\sqrt{6}}{2}\left(\frac{V_0}{\sqrt{2}N}\right)^{\frac{1}{3}} \tag{1}$$

To construct a random Voronoi foam model with N cells in V_0, the minimum distance δ between any two adjacent nuclei should be less than d_0. The regularity of a random Voronoi foam model can be defined by [5]:

$$\beta = \frac{\delta}{d_0} \tag{2}$$

For a fully regular Kelvin foam model, the regularity β is 1 as the minimum distance δ between any two adjacent nuclei equals d_0. For a complete random Voronoi foam model, δ is 0 and the regularity β is 0. However, natural and conventional foams are neither fully regular nor fully irregular. Their regularity is somewhere in between these two limits. [1]

2.3. Finite element modeling

The number of cells in the model must be large enough to represent the continuum foam while a too large number will cause issues in FEM calculation. According to other researchers' work [15], the ratio of the specimen size to cell size equaling to ~6 accurately predicts the elastic modulus and presents a tolerable difference in the prediction of the plastic collapse strength of aluminum foams. As the general cell size of commercial foam ALPORAS is ~3.5 mm, the size of the specimen was then designed as 20 × 20 × 20 mm. The cell walls are made up of S4R and S3R elements in ABAQUS software. The thickness *h* of the cell walls is related to the relative density $\bar{\rho}$ of the foam as

$$\bar{\rho} = \frac{h\sum A_i}{V_0} \tag{3}$$

where A_i is the area of cell walls. Models with regularity $\beta = 0.2$, 0.4, 0.6, 0.8 and 1 were generated. The geometries of these models are presented in Fig. 1. The properties of the cell wall material were selected to be those of aluminum alloy. The bilinear elastic-perfectly plastic model was employed for the cell wall material. Its density, Young's modulus, Poisson's ratio and yield stress were assigned as 2700 Kg/m^3, 69 GPa, 0.33 and 76 MPa, respectively.

In some researches on Voronoi foams [6,16], periodic boundary conditions were used to describe the behavior of a large block of foam. While in this study, the boundary condition is more likely to be that in a uniaxial compression test. The models were sandwiched between two rigid plates and the other four faces of the specimen is free in the simulation. During the compression process, the top rigid plate moved downward with an initial velocity while the bottom rigid plate kept stationary. To avoid the convergence issues in this complicated contact problem using implicit FEM method, Abaqus/Explict was used. Mass scaling technique was implemented in simulating the quasi-static compression process and the compression velocity was set as 50 mm/s which can minimize the inertia effect of the cell walls and meanwhile improve the calculation efficiency. Non-friction condition was employed between the Voronoi foam and the rigid plates and General Contact in Abaqus was applied to all the cell surfaces in the model.

3. Computational results and discussion

3.1. Validation of Voronoi model

The Voronoi cell nuclei were located randomly in a given space, and the geometry generated by these nuclei may cause different mechanical properties in different direction. To verify the isotropic property of the model, compression simulation on a Voronoi model was conducted. The relation between Young's modulus and the relative density of the foam was deduced as follow:

$$\text{In the X direction: } E^*/E_s = 0.306(\bar{\rho}^2 + \bar{\rho})$$
$$\text{In the Y direction: } E^*/E_s = 0.310(\bar{\rho}^2 + \bar{\rho})$$
$$\text{In the Z direction: } E^*/E_s = 0.302(\bar{\rho}^2 + \bar{\rho})$$

where E^* is the Young's modulus of Voronoi foam and E_s is the Young's modulus of cell wall material which is aluminum in this model. Simone and Gibson [17] found that the Young's modulus is nearly equal for loading in all the three directions. Therefore, the Kelvin model and Voronoi model can both be treated as isotropic model. The following equation was deduced in their research:

$$E^*/E_s = 0.32(\bar{\rho}^2 + \bar{\rho}) \tag{4}$$

Therefore, in the following calculation, only Z direction was considered.

The plateau stress is very important in evaluating plastic properties of foam material. The normalized compression stress (defined by *F/A*, where *F* is the compression force and *A* is the section area of the specimen) and normalized compression depth (defined by *d/h*, where *d* is the compression depth and *h* is the height of the specimen) curve of Voronoi model is shown in Fig. 2. The plateau stress obtained by Eq. (5) proposed by Simone and Gibson [17] is also marked in the figure. These results are close to each other which calibrated the FE model.

$$\sigma^*_{pl}/\sigma_{ys} = 0.44\bar{\rho} \tag{5}$$

3.2. Effect of regularity on elastic behavior of Voronoi foam

To study the effect of regularity on compression behavior of Voronoi foams, five random samples were investigated for each different regularity parameter: $\beta = 0.2$, 0.4, 0.6 and 0.8. Each Voronoi foam sample was generated by using a different list of random nuclei, and had the same relative density of 0.1. The average reduced elastic modulus for Voronoi foams with different regularity was marked in Fig. 3 together with the result calculated by Eq. (4), and the standard deviation is given as well. There is a little increase on the reduced elastic modulus, though not so significantly with increasing regularity of the Voronoi foam model. A similar phenomenon can be found in Sotomayor's [9] research on 3-D open cell Voronoi foam but opposite to Zhu's [6] work of open-cell

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