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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.

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).

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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.

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 ($\delta \geq 0$). 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]

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

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]:

$$\beta = \frac{\delta}{d_0} \quad (2)$$

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 $20 \times 20 \times 20$ 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

$$\bar{\rho} = \frac{h \sum A_i}{V_0} \quad (3)$$

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/Explicit 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:

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

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

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

Fig. 1. The geometries of Voronoi models with different regularity: (a) $\beta = 0.2$; (b) $\beta = 0.4$; (c) $\beta = 0.6$; (d) $\beta = 0.8$; (e) $\beta = 1.0$.

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:

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

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.

$$\sigma_{pl}^*/\sigma_{ys} = 0.44\bar{\rho} \quad (5)$$

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 foam and Babier's [16] work on closed-cell foam where elastic modulus decreases with

Fig. 2. Normalized force varying with normalized compression depth.

Fig. 3. Effect of regularity on reduced elastic modulus of Voronoi foam.

increasing regularity. This difference could be a result of periodic boundary condition in compression which used in Zhu's and Babier's work but not employed in Sotomayor's research and the present research.

As shown in Fig. 3, the standard deviation decreases as the Voronoi foam becomes more regular and the simulation result is quite close to the reduced elastic modulus predicted by Simone and Gibson [17] in Eq. (4).

To explain this result, we assume that the strain of each cell is equal in very small strain range, which means we can treat the cells in the Voronoi foam as springs in parallel when considering the elastic property of the foam. The same model was used in Zhu's [6] study on open-cell foams. For a spring-in-parallel system with N springs (or cells), the relation between the spring stiffness of the system and the stiffness of each spring is

$$k = \sum_{i=1}^N k_i \quad (6)$$

As all springs have the same length and elongation, in the whole model, the elastic modulus E^* can be presented as

$$E^* = \frac{F/A}{\epsilon l} \quad (7)$$

where A is the sum of cross-section areas of springs (or cells), F is the sum of force that applied on each spring and l is the length of the spring. For each single spring,

$$E_i = \frac{F_i/A_i}{\epsilon l} \quad (8)$$

where E_i is the elastic modulus for the i th cell.

Combining Eqs. (7) and (8) gives

$$E^* = \sum_{i=1}^N E_i \left(\frac{A_i}{A} \right) \quad (9)$$

In the springs in parallel model, all the springs share the same length, then Eq. (9) can be written as

$$E^* = \sum_{i=1}^N E_i \left(\frac{V_i}{V} \right) = \sum_{i=1}^N E_i P_v(E_i) \quad (10)$$

where $P_v(E_i)$ is the volume probability of the cells having elastic modulus E_i . To simplify the analysis, the cubic cell model proposed by Gibson and Ashby [1] was used. The elastic modulus of foam is

$$\frac{E^*}{E_s} = C\phi\bar{\rho}^2 + C'(1-\phi)\bar{\rho} \quad (11)$$

where E_s is the elastic modulus of cell wall material, C and C' are constant relating with cell shape, ϕ is the volume fraction of the solid contained in the cell edges and $\bar{\rho}$ is the relative density of the foam. In a foam, each cell wall is shared by two cells and hence the relative density of a cell is one-half of the total cell wall area of the cell, multiplied by the area of the cell wall cross-section and divided by the cell volume. Assuming that relation (11) can be used in each Voronoi cell, Combining Eqs. (10) and (11) gives

$$\frac{E^*}{E_s} = C\phi \sum \left(\bar{\rho}_i^2 \right) P_v(\bar{\rho}_i) + C'(1-\phi) \sum \bar{\rho}_i P_v(\bar{\rho}_i) \quad (12)$$

which can also be written as

$$\frac{E^*}{E_s} = C\phi\bar{\rho}_0^{-2} \sum (d_i)^2 P_v(d_i) + C'(1-\phi)\bar{\rho}_0 \quad (13)$$

where $\bar{\rho}_0$ is the relative density of the foam, d_i is the normalized cell relative density defined by $\bar{\rho}_i/\bar{\rho}_0$ and $P_v(d_i)$ is the volume probability of the cells having a normalized cell relative density d_i . The cell density distribution of Voronoi foam is given in Fig. 4 which was based on the analysis of 10^4 cells of varying degrees of regularity. The cell density distribution in Fig. 4 varies significantly with the foam regularity that it gets more concentrated as the foam being more regular. As a result, Eq. (13) gives the relationship between the foam regularity and its elastic property through $P_v(d_i)$. In elastic range, cell-edge bending and cell-face stretching are main deformation mechanism of closed-cell foam which refer to the quadratic term and linear term in Eq. (13) respectively. It can also be found in Eq. (13) that the regularity of the foam only affects the cell-edge bending behavior. In elastic deformation of foam with low relative density ($\bar{\rho}_0 < 0.2$), the cell-face stretching plays more important role. [1] This may cause the effect of foam regularity on elastic modulus of Voronoi foam not so significant.

3.3. Effect of regularity on plastic behavior of Voronoi foam

The normalized compression stress and normalized compression depth curves of Voronoi model with different regular-

ity are shown in Fig. 5. Each curve presents the average value of five samples. There is an clear increase on plastic-collapse stress as the regularity of the foam increases. This result can also be found in Zhu's [5] and Sotomayor's [9] work on open-cell foams and Li's [11] and Babier's [16] on closed-cell foams. In the Kelvin model ($\beta = 1$), regular tessellation causes an equal sum of section area of cell walls in any cross-section of foam model. In a Voronoi model, there are always some cross-sections in which the sum of section area of cell walls is smaller than the average value. These sections may cause a lower strength in Voronoi foam.

In plastic deformation range of foam, we can treat the cells in the Voronoi foam as springs in series, because they collapse locally and progressively. This spring-in-series model has also been used in Zhu's [5] work in open cell foams. According to Gibson and Ashby's [1] work, the plastic-collapse strength σ_{pl}^* of the closed-cell foam and the yield strength σ_{ys} of cell wall material are related as

$$\frac{\sigma_{pl}^*}{\sigma_{ys}} = C\bar{\rho}_0^{-3/2} + C'\bar{\rho}_0 \quad (14)$$

where $\bar{\rho}_0$ is the relative density of the foam, C and C' are constant. For Kelvin foam with low relative density, this equation can be simplified as

Fig. 4. The volume probability of the cells having a normalized cell relative density d_i in Voronoi foams with different regularity parameters: (a) $\beta = 0.2$; (b) $\beta = 0.4$; (c) $\beta = 0.6$; (d) $\beta = 0.8$.

Fig. 5. Effect of regularity on plastic behavior of Voronoi foam.

$$\frac{\sigma_{pl}^*}{\sigma_{ys}} = K \bar{\rho}_0 \quad (15)$$

where K is a constant. Assuming this relation can be used in each single cell in Voronoi foam, the plastic-collapse strength of the i th cell can be written as

$$\frac{\bar{\sigma}_{ipl}}{\sigma_{ys}} = K \bar{\rho}_i \quad (16)$$

where $\bar{\rho}_i$ is the relative density of the i th cell. Combining Eqs. (15) and (16) gives

$$\bar{\sigma}_{ipl} = \sigma_{pl}^* \left(\frac{\bar{\rho}_i}{\bar{\rho}_0} \right) \quad (17)$$

Assuming this relation can be used in the whole plastic range of the foam, we can write Eq. (17) as

$$\bar{\sigma}_i = \sigma_0 \left(\frac{\bar{\rho}_i}{\bar{\rho}_0} \right) \quad (18)$$

where $\bar{\sigma}_i$ is the normalized force (compression force on the cell divided by the cross-section of the cell) of the i th cell and σ_0 is the normalized force of Kelvin foam. The following derivation is similar as presented in Zhu's [5] work. We assume the following relationship can be used in Kelvin foam

$$\sigma_0 = f(\epsilon) \quad (19)$$

which can be rewritten as

$$\epsilon = F(\sigma_0) \quad (20)$$

where F is the inverse of function f . We can obtain the following equation after the combination of Eqs. (18) and (19)

$$\bar{\sigma}_i = f(\epsilon_i) d_i \quad (21)$$

where d_i is the normalized cell relative density as defined

before. Also, this equation can be rewritten as

$$\epsilon_i = F \left(\frac{\bar{\sigma}_i}{d_i} \right) \quad (22)$$

Each spring in series shares the same force. We can assume the normalized force on each cell is equal to the normalized force of Voronoi foam $\bar{\sigma}_s$

$$\epsilon_i = F \left(\frac{\bar{\sigma}_s}{d_i} \right) \quad (23)$$

Then the normalized compression depth of the foam can be obtained

$$\epsilon = \sum_{i=1}^n \epsilon_i P_v(d_i) = \sum_{i=1}^n F \left(\frac{\bar{\sigma}_s}{d_i} \right) P_v(d_i) \quad (24)$$

If we know the function F of Kelvin model, we can use Eq. (24) and the result in Fig. 4 to obtain the relation between the normalized compression depth and the normalized force of Voronoi foams with varying regularity.

To calculate the inverse function F , the normalized force-normalized compression depth curve should be simplified so that the function is a monotonic. Fig. 6 shows the result of this simplification. The plastic-collapse strength and the normalized force-normalized compression depth curves of Voronoi foam with different regularity obtained by Eq. (24) are shown in Figs. 7 and 8.

The theoretical result and numerical result in Fig. 7 are close, and both show that the plastic-collapse strength of the Voronoi foam is larger for a more regular model. Li's [11] simulation result on closed-cell foams and Sotomayor's [9] results on open-cell foams are also presented. To eliminate the effect of foam density on the result, the reduced plastic collapse strength in this study and Li's [11] study was obtained through dividing the plastic collapse strength of the foam by $\sigma_{ys} \bar{\rho}^3$ and in Sotomayor's [9] result by $\sigma_{ys} \bar{\rho}^2$. In Eq. (24), $\frac{\bar{\sigma}_s}{d_i}$ sometimes becomes larger than the maximum value of normalized force in Fig. 6, so a maximum value of $F \left(\frac{\bar{\sigma}_s}{d_i} \right)$ was assumed as 0.75. This assumption may underestimate the normalized compression depth of the Voronoi foam which inversely enhance the strength of the foam. This may explain why the theoretical re-

Fig. 6. The simplification of function f in Kelvin model.

Fig. 7. The plastic-collapse strength of the Voronoi foam with varying regularity.

Fig. 8. Normalized force-normalized compression depth curves of Voronoi foams with different regularity calculated by Eq. (24).

sults in Fig. 7 are always a little higher than the numerical results.

Through the analysis, we can find that the irregularity of the Voronoi foam can cause different deformation for each cell under the same compression force. When Voronoi foams are compressed under the same force, deformation of a more random foam is more severe than a regular one. This finally causes the increasing plastic-collapse strength with increasing foam regularity.

Comparing Fig. 5 with Fig. 8, we can find the results in these two figures are close when the normalized compression depth is less than 0.02. After that, the normalized force of Voronoi foam model decreases and that of Kelvin model increases in numerical results in Fig. 4. It increases in all models in theoretical results in Fig. 8. To investigate this difference, the deformation process of Kelvin model and a Voronoi model with regularity parameter $\beta = 0.2$ are shown in Fig. 9. The deformation of Kelvin model is uniform through the whole compression process, and the deformation of each cell is very close. This deformation pattern results in the increase of compression force. The Voronoi model shows a complete different deforma-

tion pattern. The randomness in geometry may cause a very weak cross-section with the minimum cross-section area, and this leads to a localization on deformation pattern. As shown in Fig. 9, one layer of cells below the middle of model firstly collapse and a localized deformation then formed and the compression force on the Voronoi model began to decrease. Before this localized deformation, the theoretical results predict the numerical results well.

3.4. Effect of relative density of foams and loading velocity

Relative density plays an important role in mechanical behavior of foams. Compression behavior of Voronoi models with relative density of 0.1, 0.15, 0.2 and 0.25 were investigated. The loading velocity was set at 30 m/s. Compression force of these samples are shown in Figs. 10–13. Both the initial peak stress and the plateau stress increase with the increasing relative density of the foams. In all the figures, compression force increases as the foam becomes more regular. The strain energy per unit volume of the foam is shown in Fig. 14. The strain energy keeps a linear relationship with relative density in all the Voronoi foam models and the slopes seems the same in spite of different regularity of the foams.

To investigate the effect of regularity under different loading velocities, compression simulation of Voronoi foam model was conducted under 30 m/s, 70 m/s and 150 m/s respectively. All the foams are with the same relative density 0.1. The simulation results are shown in Figs. 15–17. To investigate the strain hardening effect of basic material on dynamic compression, foams with bi-linear elastic-plastic aluminum model were also considered. The plastic modules of the material is 1400 MPa. The increasing plastic modules results in the increase of both peak stress and plateau stress of the foam. Under the loading velocity of 30 m/s, strain hardening behavior can be observed on the foams with higher regularity while for higher loading velocity, difference caused by foam regularity on the plateau stress seems similar for both foams made of different plastic hardening aluminum model. In all scenarios, the initial peak stress and plateau stress increase with increasing cell regularity. As the loading velocity increases, the difference between the plateau stress of Voronoi foams with different regularity decreases, while the difference in the initial peak stress becomes larger. Deformation propagation of Voronoi foam with regularity 0.2 and 0.8 were compared in Table. 1. Both of Voronoi foams show different deformation patterns under different loading velocities. The collapse of cells happened in the weakest layer of the foam under 30 m/s. Due to different regularity of foams, the plastic deformation area are different. But when it comes to 150 m/s, both two foams show the same deformation pattern, the cells near the moving rigid plate collapses first due to the inertia effects of cell walls, the plastic deformation is confined in a small area near the moving rigid plate. The same deformation pattern explains why the difference between plateau stress of Voronoi foam with varying regularity is quite small under high loading velocity. Researchers [18] have revealed that the increase of initial peak stress of cellular materials under dynamic loading is due to the inertia effect of cell structures. The result in this study implies the randomness of the foam structure can reduce this inertia effect. The increase of plateau stress under dynamic loading seems dominated by other mechanism which cause a different behavior from the initial peak stress. As most recently found in Ozdemir's [19] research in lattice structure, the structure made

Fig. 9. The deformation process of Kelvin model (a) and Voronoi model with regularity parameter $\beta = 0.2$ (b).

Fig. 10. Normalized Force of Voronoi foams with relative density of 0.10.

Fig. 13. Normalized Force of Voronoi foams with relative density of 0.25.

Fig. 11. Normalized Force of Voronoi foams with relative density of 0.15.

Fig. 14. Strain energy per unit volume of Voronoi foams with different relative densities.

Fig. 12. Normalized Force of Voronoi foams with relative density of 0.20.

Fig. 15. Normalized Force of Voronoi foams under compression velocity of 30 m/s.

Fig. 16. Normalized Force of Voronoi foams under compression velocity of 70 m/s.

Fig. 17. Normalized Force of Voronoi foams under compression velocity of 150 m/s.

up over multiple layers of unit cells can be rate sensitive in spite of the fact that each individual lattice cell is relatively rate insensitive, the relative lower rate sensitivity of the plateau stress may have caused by an overall mechanism other than the behavior of each single cell. This mechanism is yet to be investigated.

The strain energy per unit volume of the foam under compression shown in Fig. 18 was calculated by integrating the curves in Figs. 5, 15–17. The energy increases with the loading velocity, which agrees with the phenomenon observed in our previous experimental study [20]. However, the difference between the strain energy of the foams with different regularity

seems unchanged under different loading velocity. An ideal energy absorption material should have a relative low initial peak stress and high energy absorption capability under dynamic loading. [21] The initial peak stress of foams with low regularity increase less with increasing loading rate and the plateau stress is close to the regular foam under high velocity impact. This result reveals that the foam with low regularity is more suitable for engineering application in energy-absorbing structures.

4. Conclusions

The effects of cell irregularity on the compression of closed-cell foams were investigated in this work. The Voronoi models with different regularity parameters were constructed and Abaqus/Explicit software was employed in numerical simulation. The result indicates that the reduced elastic modulus increases a little with increasing regularity of the Voronoi foam model which agrees with Sotomayor's [9] work but is opposite from Zhu's [6] and Babier's [16] results. Different boundary condition may have caused this difference. There is an significant increase on plastic-collapse stress as the regularity of the foam increases. The result can be also found in other researchers' [5,9,11,16] work.

Springs-in-parallel model was used to explain the effect of irregularity on elastic modulus of Voronoi foam. The result reveals that the irregularity only affects the cell-edge bending behaviour in elastic range. As the cell-wall stretching domains in this range, the effect of irregularity on elastic modulus of Voronoi foam is not so significant. Springs-in-series model was used to analysis the plastic behaviour of Voronoi foam. The theoretical results well predict the simulation results. The irregularity causes more severe deformation when the foam is compressed under the same force. This makes the random Voronoi foam weaker than a regular one.

The effect of loading velocity and the relative density of the foams was also investigated. Both the initial peak stress and the plateau stress of the foam increase with the increasing loading velocity and relative density of the foam, but the foams with low regularity show relative lower rate sensitivity on initial peak stress which makes them more suitable for engineering application in protective structures.

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Table 1

Deformation propagation Voronoi foam under loading velocity of 30 m/s and 150 m/s, the counter shows PEEQ (Effective Plastic Strain) in Abaqus.

Fig. 18. Strain energy per unit volume of Voronoi foams at different compression velocities.

References

- [1] L.J. Gibson, M.F. Ashby, Cellular solids: structure and properties, 2nd ed. Cambridge University Press, Cambridge; New York, 1997.
- [2] A.E. Simone., L.J. Gibson, The effects of cell face curvature and corrugations on the stiffness and strength of metallic foams, *Acta Mater* 46 (1998) 3929–3935.
- [3] Y. Sun, Q.M. Li, T. Lowe, S.A. McDonald, P.J. Withers, Investigation of strain-rate effect on the compressive behaviour of closed-cell aluminium foam by 3D image-based modelling, *Mater Des* 89 (2016) 215–224.
- [4] H.X. Zhu, J.R. Hobdell, A.H. Windle, Effects of cell irregularity on the elastic properties of 2D Voronoi honeycombs, *J Mech Phys Solids* 49 (2001) 857–870.
- [5] H.X. Zhu, A.H. Windle, Effects of cell irregularity on the high strain compression of open-cell foams, *Acta Mater* 50 (2002) 1041–1052.
- [6] H.X. Zhu, J.R. Hobdell, A.H. Windle, Effects of cell irregularity on the elastic properties of open-cell foams, *Acta Mater* 48 (2000) 4893–4900.
- [7] H.X. Zhu, S.M. Thorpe, A.H. Windle, The effect of cell irregularity on the high strain compression of 2D Voronoi honeycombs, *Int J Solids Struct* 43 (2006) 1061–1078.
- [8] M.H. Luxner, J. Stampfl, H.E. Pettermann, Numerical simulations of 3D open cell structures – influence of structural irregularities on elasto-plasticity and deformation localization, *Int J Solids Struct* 44 (2007) 2990–3003.

- [9] O.E. Sotomayor, H.V. Tippur, Role of cell regularity and relative density on elastoplastic compression response of 3-D open-cell foam core sandwich structure generated using Voronoi diagrams, *Acta Mater* 78 (2014) 301–313.
- [10] Y. Song, Z. Wang, L. Zhao, J. Luo, Dynamic crushing behavior of 3D closed-cell foams based on Voronoi random model, *Mater Des* 31 (2010) 4281–4289.
- [11] Z. Li, J. Zhang, J. Fan, Z. Wang, L. Zhao, On crushing response of the three-dimensional closed-cell foam based on Voronoi model, *Mech Mater* 68 (2014) 85–94.
- [12] <http://math.lbl.gov/voro++/>.
- [13] Z. Zheng, J. Yu, J. Li, Dynamic crushing of 2D cellular structures: a finite element study, *Int J Impact Eng* 32 (2005) 650–664.
- [14] G. Schaffner, X.-D.E. Guo, M.J. Silva, L.J. Gibson, Modelling fatigue damage accumulation in two-dimensional Voronoi honeycombs, *Int J Mech Sci* 42 (2000) 645–656.
- [15] E.W. Andrews, G. Gioux, P. Onck, L.J. Gibson, Size effects in ductile cellular solids. Part II: experimental results, *Int J Mech Sci* 43 (2001) 701–713.
- [16] C. Barbier, P.M. Michaud, D. Baillis, J. Randrianalisoa, A. Combescure, New laws for the tension/compression properties of Voronoi closed-cell polymer foams in relation to their microstructure, *Eur J Mech* 45 (2014) 110–122.
- [17] A.E. Simone, L.J. Gibson, Effects of solid distribution on the stiffness and strength of metallic foams, *Acta Mater* 46 (1998) 2139–2150.
- [18] H. Zhao, I. Elnasri, S. Abdennadher, An experimental study on the behaviour under impact loading of metallic cellular materials, *Int J Mech Sci* 47 (2005) 757–774.
- [19] Z. Ozdemir, A. Tyas, R. Goodall, H. Askes, Energy absorption in lattice structures in dynamics: nonlinear FE simulations, *Int J Impact Eng* 102 (2017) 1–15.
- [20] X.P. Shi, Y.G. Miao, S.Y. Liu, Y.L. Li, G.X. Lu, Indentation of aluminium foam at low velocity, In: *Epj Web Conf*, 2015, p. 94.
- [21] G. Lu, T.X. Yu, *Energy absorption of structures and materials*, 2003, Woodhead, Cambridge, 2003.