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Multiaxial creep of transversely isotropic foams

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ABSTRACT

Based on the method of the geometric stretch, the elongated tetrakaidecahedron and Voronoi models in the rise direction have been established to investigate the multiaxial creep behavior of approximately transversely isotropic open-cell foams. A stretch factor R (the ratio of the cell length in the rise direction to that in the transverse direction) is introduced to quantificationally characterize the degree of transverse isotropy. Uniaxial simulation results indicate that, for the open-cell foams, the relative density has significant influence on the secondary creep rate and the effects of the microstructure cannot be ignored. Additionally, a modified phenomenological model is proposed to predict the multiaxial secondary creep rate of transversely isotropic foams, and the corresponding material constants are determined as a function of the stretch factor R by modifying the theoretical equations or fitting the FEA results. Then, the capability of the modified model is examined by simulating the creep behavior under axisymmetric loading. The simulation results indicate that the modified phenomenological model can give a good description of the uniaxial/multiaxial creep response of the transversely isotropic foams.

1. Introduction

Foam materials are widely used in various engineering applications such as lightweight structures of autos and aircrafts, protective packaging and heat exchanger, due to their high specific strength, excellent energy absorption capability and superior thermal shock resistance characteristics [1,2]. Many practical applications of foam materials are usually designed for long-term service under high environment temperature [3,4], where their creep response is relevant. Therefore, creep constitutive model of foam materials becomes increasingly important to be able to predict the creep behavior so as to allow confidence in service life and informed design choice. Many micromechanics models have been developed to investigate the creep behavior of the foam materials. Based on a bending dominated cubic model and an axial compression dominant foam model, Andrews et al. [3,4] and Hodge et al. [5] derived the uniaxial secondary creep rate for the open-cell cellular materials, respectively. In addition, finite element analysis(FEA) are also increasingly applied to study the mechanical behavior of cellular materials. Many simulation models have been employed for metallic foams by establishing the realistic architectures or regular unit cell. Andrews et al. [6] simulated the secondary creep rate of 2D Voronoi model and analyzed the effects of the boundary condition and cell wall curvature on the uniaxial creep behavior. Huang et al. [7] presented a new numerical method by 3D Voronoi model with periodic boundary conditions to redetermine the dimensional arguments for the theoretical formula. Dunand et al. [8] have adopted unit cell models with different microstructures to compare the distribution characteristics of the stress and the deformation mechanisms of foam materials under different stress states. Su et al. [9] studied defect-effect on the creep behavior of the cellular materials by using 2D honeycombs and 3D tetrakaidecahedron models, and proposed an empirical model to predict the uniaxial creep rate of cellular materials as a function of the ratio for different types of missing struts.

However, the previous works only focused on the uniaxial creep of the isotropic cellular materials. In fact, the materials always subjected to multiaxial loading in practical engineering applications [10–13]. Meanwhile, as we all known, many natural cellular materials like balsa wood, bone and pumice are anisotropic [1,2,14]. For the artificial materials, the micro-structure is inevitably elongated in the rise direction due to the foaming and rising process [15]. It leads the mechanical behavior of the cellular materials to be transversely isotropic. Ridha et al. [16] and Sullivan

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et at. [17] have adopted an elongated tetrakaidecahedron as the repeating unit cell and derived the equations for the Young's modulus, Poisson's ratio and yield strength in the principal directions. So far, most studies for the transversely isotropic cellular materials are limited to investigating their compressive response, crushing behavior and yield criterion [18–22]. Therefore, it is very necessary to further explore the multiaxial creep of the transversely isotropic foams. The main aim of this paper is to establish the elongated tetrakaidecahedron and Voronoi models to investigate the uniaxial/multiaxial creep behavior of approximately transversely isotropic foams and explore the influence of the microstructure. For further analyzing the multiaxial creep, the characteristic stress in the phenomenological constitutive modeling [23] is extended to include the degree of transverse isotropy. Subsequently, the uniaxial/multiaxial creep responses of two types of models are compared with the predictions of the modified phenomenological model.

2. Finite element models for cellular material

2.1. Periodic isotropic models

It is well-known that the mechanical behavior of foams strongly depends on their cell structure [1,2,6–8]. Zhu et al. [24] and Li et al. [25] have investigated the mechanical properties of open-cell foams by using the tetrakaidecahedron and Voronoi cell, respectively. And they treat the tetrakaidecahedron cell and Voronoi cell as nearly isotropic models. Therefore, in this paper, the periodic tetrakaidecahedron model and Voronoi model are employed to investigate the creep response of the open-cell foams. To construct a tetrakaidecahedron model with K cells in the volume V_0, the minimum distance between any two adjacent nuclei in a regular lattice is given by Zhu et al. [26].

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

And to establish a Voronoi model, a dimensionless variable α is defined as the degree of irregularity of the cellular material [27].

$$\alpha = \frac{d}{d_0} \tag{1b}$$

Here, d is the minimum distance between any two adjacent nuclei in a random Voronoi model. α represents the degree of cell irregularity for the Voronoi model, hereinafter, and it is set to be 0.8. Particularly, the value of α is equal to 1 for the regular tetrakaidecahedron model.

2.2. Transversely isotropic models

Many natural and artificial cellular materials are transversely isotropic [1,2]. Generally speaking, transversely isotropic properties are caused by two aspects. One is the transverse isotropy for matrix material, and the other one is transversely isotropic microstructure which relies in the geometry shape and topological pattern of the cell. Especially, the cell shape has dominant influence on the degree of the transverse isotropy for the majority of cellular materials. For the sake of illustration convenience, the geometric stretch factor R, which represents the ratio of the length of the cells in the rise direction to that in the transverse direction, is introduced to quantificationally characterize the degree of transverse isotropy [1,15–21], as shown in Fig. 1. The above method leads to 1–2 is the plane of isotropy, and 1–3/2–3 plane is the plane of anisotropy. In addition to the stretch factor R, for the elongated tetrakaidecahedron model, a cell shape parameter Q has introduced by Sullivan et al. [17] and defined as $Q = b/(a\cos\theta)$. In this paper, the parameter Q is set to be $\sqrt{2}$ [15,16] and the range of stretch factor R varied from 1 to 1.4. Noted that, based on the conclusion in previous Ref. [29,30], the elongated models should be treated as approximately transversely isotropic. Particularly, R=H/L=1 means isotropic cellular materials.

The finite element analysis code ABAQUS is adopted to simulate the creep behavior of the open-cell foams. All of the FE models have been performed with a fixed relative density (ρ=0.08) by adjusting the strut diameter. The struts are assumed to have a constant circular cross sectional area and meshed by the Timoshenko beam elements (i.e. B32). It should be noted that the nonlinear shear responses of beam elements are neglected in ABAQUS. It may result in additional errors in nonlinear/viscoelastic regime. Accordingly, the beam elements must be used carefully in the nonlinear analysis [31]. Meanwhile, mesh sensitivity analysis is executed to make sure that the number of elements is capable to produce reliable results. As shown in Fig. 1, two types of models are established with $5\times5\times5$ cells in geometric space. The periodic boundary conditions [27] should be applied to the boundary nodes of the model to eliminate any potential size effect [6,7] and simulate the uniaxial/multiaxial behavior [12,28]. Additionally, the bilinear strain-hardening model is employed for the matrix material with a Young's modulus E=69 GPa, a Poisson's ratio μ=0.35, a yield stress σ_y=70 MPa and a hardening tangent modulus of 0.69 GPa. And the matrix material is assumed to follow power law creep (Eq. (2)) with the creep parameters: n=4, $\dot{\varepsilon}_0/\sigma_0^n = 2.5\times10^{-9}\,\mathrm{MPa}^{-4}\mathrm{s}$, a typical value for aluminum [6].

$$\dot{\varepsilon}^* = \dot{\varepsilon}_0\left(\frac{\sigma^*}{\sigma_0}\right)^n \tag{2}$$

where $\dot{\varepsilon}^*$ is the uniaxial secondary creep rate; σ^* is the creep stress; $\dot{\varepsilon}_0$, σ_0 and n are the creep constants. In this paper, axisymmetric loading is applied to the FE models along the 1, 2 and 3-directions, as shown in Fig. 2. Obviously, σ_3 is the longitudinal loading and $\sigma_1=\sigma_2$ (i.e. $k_1=k_2$) refer to the transverse loading. In other words, σ_1, σ_2, σ_3 denote not only the macroscopic stresses in the 1, 2 and 3-directions but also the principal stresses [27]. In the following simulations, the constant load, corresponding to an overall stress of 0.1 MPa, is applied to each node in the longitudinal direction. In addition, nominal stress and nominal strain are used to calculate the deformations of the open-cell foams.

3. Results and discussion

3.1. Uniaxial creep for isotropic foams

It is well-known that the relative density has dominated influence on the mechanical properties of cellular materials. Thus, the effect of relative density on the creep behavior is firstly studied. It should be noted that the error increases as the material relative density is increased, because the volume of junctions is calculated repeatedly [12,27]. Therefore, the low density (from 6% to 10%) open-cell foams are adopted in current study. Gibson and Ashby [4] developed the expression of the displacement rate $\dot{\delta}$ through the creep bending of struts:

$$\dot{\delta} = \frac{1}{n+2}\dot{\varepsilon}_0\frac{l^2}{t}\left(\left(\frac{2n+1}{n}\right)\frac{Fl}{\sigma_0 t^3}\right)^n \tag{3}$$

Here, F represents the creep loading, l and t^2 are the length and cross-section area of the strut, respectively. Then, the uniaxial secondary creep rate can be derived as a function of the relative density for open-cell foams by setting $F\propto\sigma^* l^2$, $\dot{\varepsilon}^*\propto\dot{\delta}/l$ and