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Axisymmetric plastic expansion of a cylindrical hole in isotropic metallic foam

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ABSTRACT

By combining a finite element simulation with an analytical treatment, this paper provides quantitative information on the stress, strain and deformation states induced during the axisymmetric expansion of a cylindrical hole of an initial radius, located at the center of a block of closed-cell metallic foam of infinite size. Uniformly distributed radial loading is applied on the surface of the hole. A macroscopic phenomenological constitutive model of metal foam is first introduced, considering the initial and subsequent yielding surfaces in the space of the effective stress and hydrostatic stress. Isotropic hardening model is incorporated into the material property of the crushable foam. Two deformation stages are revealed from the numerical simulation, i.e. the initial yielding and then subsequent expansion of the hole accompanied with hardening. Preliminary analytical formulation is performed with respect to the pressure at the initial yielding and the size of the subsequent plastic deformation zone. It is found that after the onset of initial yielding, the maximum pressure is identical to that from the finite element analysis. The evolution of plastic zone during the expansion is discussed in terms of the results from the analytical and finite element studies. Furthermore, foam densification is observed from finite element analysis and a map is obtained showing the evolution of the three deforming zones, i.e. elastic, plastic and densification of the foam, when the applied pressure increases.

1. Introduction

With the increasing demand for energy and concern for environment, much research attention has been paid to developing and assessing light-weight structures and materials. Thin-walled structures and metallic foams are two examples. The solid expandable tubular is an emerging and promising technology in petroleum industry [1,2]. Much more effective and efficient protective structures against impact and blast loadings are required due to enhanced chance of terroristic attacks and natural disasters. Thin-walled metal tubes are common energy absorption components since they are relatively cheap, versatile and efficient for absorbing energy [3]. Apart from traditional metals, metallic foams are one type of novel materials with the advantage of being light weight, recyclable, non-flammable, and they have the most attractive capability of energy absorption; hence they have great potential to serve as core materials for protective structures [4,5]. Thus, taking advantages of both tubes and foams, sandwich tube structures filled with metallic foams have attracted research interest [6,7] for designing protective structures against impact, including those subjected to internal explosion [8] resulting from heated gas or terrorist attack.

In order to assess the energy dissipation characteristics of sandwich structure under dynamic loading, an understanding of the quasi-static response of such structure is essential. On one hand, the mechanical behavior and energy absorption characteristics of each component are crucial, including the deformation and interaction effect among each component in the sandwich tube design. The plastic behavior of monolithic expandable tubes subjected to large plastic deformation has been studied in detail [2,9–10]. It is concerned with increasing the diameter of a tube by hydraulically pushing or mechanically pulling a conical mandrel through the inner tube. On the other hand, due to the wide applications of metallic foams in engineering fields, much attention has been paid to the closed-cell metallic foams' mechanical properties and design [5,11]. However, since the yielding, hardening and the associated plastic flow rule are different from the conventional isotropic elastic–plastic metal [12], the plastic behavior of metallic foams under large deformation still requires further understanding [13]. Two typical macroscopic material models have recently been developed for aluminum foams. One continuum plastic model was proposed by Miller [14] based on the Drucker–Prager [15] yield criterion for soil. Due to the difficulties in distinguishing elastic and plastic stages as well as

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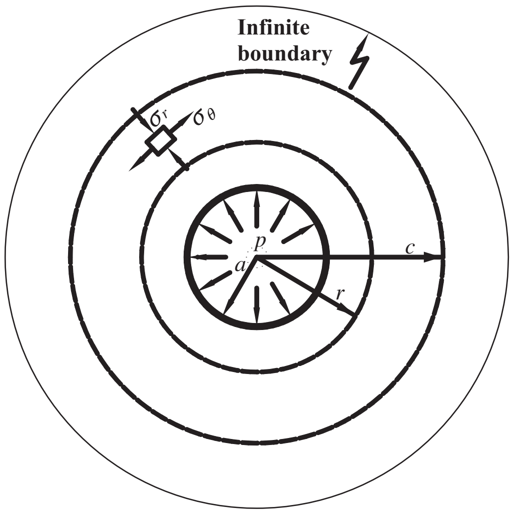

Fig. 1. Schematic representation of the hole expansion under internal pressure p. The initial radius of the hole is $a=16$ mm at the inner boundary. r is the radius for a generic layer and c is the radius of the plastic zone.

the inhomogeneities of metallic foam, the initial yielding function and the shape of the subsequent yield surface may not be reliable. The other model is the crushable foam model based on the proportional loading experiments, proposed by Deshpande and Fleck [16]. This isotropic constitutive model has an elliptical yield surface defined in terms of the effective stress and hydrostatic stress, with the assumption of associated flow. One of the advantages of the model is that only one uniaxial compressive or hydrostatic test is required to calibrate it. It could be used to evaluate the response of foams under general loading with reasonable results.

A system of two concentric monolithic metal tubes with metal foam sandwiched may be used as a protective structure to contain, for example, explosives inside. The response of such a structure subjected to internal pressure should be understood and hence the resistance of the metal foam as well as each of the two monolithic tubes needs to be assessed. As a first step, in this paper a numerical analysis using ABAQUS/Explicit [17] is conducted to study the expansion of a cylindrical hole in an infinite block of closed-cell metallic foam, as shown in Fig. 1. Detailed deformation history and stress history at the inner boundary are explored. The evolution and the size of plastic zone are discussed during the expansion. Based on the isotropic constitutive models with inelastic, linear hardening with densification, the evolution of the plastic zone is then compared with the simplified analytical solution proposed in this paper.

2. Finite element analysis

A finite element model of the pressure-loaded foam is given below, where the foam is simplified as a continuum of an inelastic, linear hardening with densification, represented by a uniaxial compressive constitutive relationship. Previous studies [18] have found that the plastic deformation occurs locally even before the stresses reach the plastic collapse strength, and so the elastic stage of crushing metallic foam would be very short. Therefore, the main research focus of our study will be on the plastic response in the expansion. Due to the axisymmetry of the problem, including the circular hole and the loading, an axisymmetrical model is employed. The initial radius of the hole in the infinite block of foam is assumed to be $a=16$ mm. Using the convention for foams, a compressive stress is regarded as positive while tensile stress is negative.

2.1. Foam constitutive relationship

The crushable foam model assumes uniaxial loading in any principal direction while insignificant deformation occurs in the other directions. Besides, Poisson's ratio in plastic regime is assumed to be non-zero and the load conditions in principal directions are interdependent [16]. According to the conventional Prandtl–Reuss J_2 flow theory [19], the quadratic yield surface is written in the form of

$$\sigma_e^2+\alpha^2\sigma_m^2=\left[1+\left(\frac{\alpha}{3}\right)^2\right]\sigma_y^2 \tag{1}$$

where σ_y is the absolute value of yield stress under uniaxial compression, and the effective stress σ_e is a scalar measure of the deviatoric stress, also called von Mises stress. σ_m is the mean stress (or hydrostatic stress) and α is the aspect ratio of the yield surface, namely the shape factor of the ellipse. The hardening law of the material is written in the incremental form as

$$\sigma_y=\sigma_y^0+H(\varepsilon_{pl}) \tag{2}$$

where H is the hardening modulus and σ_y^0 is the initial yield stress of foam under uniaxial compression. Typical yield surface of elliptical shape in the $(\sigma_m-\sigma_e)$space [20] is shown in Fig. 2. Isotropic hardening model is adopted for the metallic foam in the current study, where the yield ellipse is centered at the origin in the stress space.

2.2. Material property

Typical properties for commercial Alporas® aluminum foam of the relative density (ρ^*) of 8% are used in the FE analysis. The elastic properties of the foam are given as Young's modulus $E=1.1$ GPa and Poisson's ratio $\nu=0.3$. The uniaxial compressive constitutive relation is assumed to govern the quasi-static response of the foam under internal pressure, which is idealized in Fig. 3 with initial yield stress $\sigma_y^0=1.2$ MPa, the linear hardening modulus $E_1=1.2$ MPa and, after the locking strain $\varepsilon_D=0.65$, the densification modulus $E_D=120$ MPa. In addition, to determine the shape factor of the yield ellipse that defines the relative magnitudes of the axes, the value of compression yield stress ratio k should be defined first. This is taken as 1.21. The shape factor is then 1.32 by using

$$\alpha=\frac{3k}{\sqrt{9-k^2}} \text{ with } k=\frac{\sigma_y^0}{p_c^0} \tag{3}$$

where p_c^0 is the initial yield stress under hydrostatic compression.

2.3. Finite element model

This study treats the present hole expansion problem as quasi-static. To explore the plastic deformation behavior of the foam

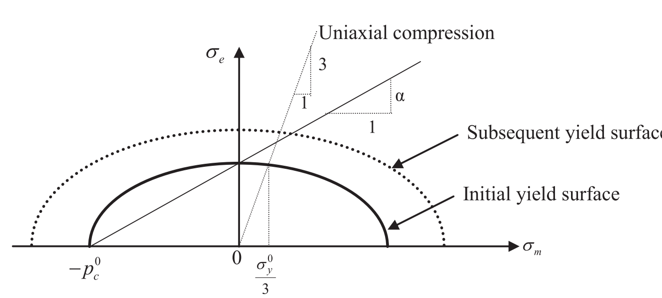

Fig. 2. Yield surface for metallic foam in effective–hydrostatic stress space. *Note*: Different from the conventional notion, the hydrostatic axis positive direction represents compression.