ICPS5

Design, Experiment and Analysis of Protective Structures

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Application of the shock wave theory for the assessment of crushing force in the open-cell copper foams

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1 Introduction

Metallic open cell foams materials have excellent potential characteristics as impact energy absorbers due to their ability to deform over a long stroke at an almost constant load. Under intensive dynamic load, the compaction waves travelling through the open-cell metallic foam cause a strength and energy absorption enhancement. The subject of the study is the model of virtual metallic foam with the skeleton formed of convex cells, cf. [1]. The computed tomography made the basis for the formulation of numerical model of the foam and the finite element discretization of skeleton. The present study aims to examine the propagation of compaction waves in metal foams that exhibit strain hardening. In the paper it is considered the problem of a rigid mass striking a stationary foam block. The emphasis is on explaining the compaction under decreasing impact velocity. The state variables derived from Hugoniot relation for shock wave and the conservation laws are used for the comparison with the results of FEM simulations.

The goal of the presented investigations is to study the propagation of compaction waves, the impact limits and absorption energy of open cell copper foam.

2 Propagation of compaction waves

In this paper it is considered a rigid mass striking a stationary copper foam block. The emphasis is on explaining the compaction under decreasing impact velocity. The increase in strength under dynamic loading conditions may be attributed to three main factors: (i) strain rate sensitivity of the cell wall material, (ii) micro-inertial effects and (iii) shock wave propagation. The shock wave means the motion of an interface, measured with reference to the initial undeformed configuration of the specimen, which separates crushed and uncrushed cells, during an impact loading process. The basic jump condition can be used to describe the dynamical conditions across the crushing wave, see [2, 3].

Classical jump conditions representing conservation of the mass, momentum and energy applied to plane longitudinal shocks leading to:

$$V_b - V_a = V_S(\varepsilon_b - \varepsilon_a) \tag{1}$$

$$\sigma_b - \sigma_a = \rho_0 V_S(V_b - V_a) \tag{2}$$

$$U_b - U_a = \frac{1}{2}(\sigma_b + \sigma_a)(\varepsilon_b - \varepsilon_a) \tag{3}$$

The equations (1-3) describe the shock compression of the metal foam above a critical impact velocity. In Eqs. (1-3) V, ε, σ, U and ρ_0 are material velocity, engineering strain, engineering stress, internal energy density and initial density of the foam, respectively. The subscript s, a and b denote the shock front, the material ahead of the shock front and the material behind the shock front, respectively. It is evident that the correct application of the shock wave model for a description of cellular material compaction is strongly related to the rate of loading and material properties.

In the formulation of the response of metal foams to dynamic loads the following assumptions is applied:

(i) it still lacks a strict definition of the shock front boundary and a jump in the velocity distribution defines a shock front,

(ii) the state variables in the crushed zone are obtained in the averaging process of its computed values,

(iii) the finite element mesh should be sufficiently fine to not degenerate significantly the elasto-viscoplastic wave character (e.g., speed, distribution).

3 Material model

For numerical simulations the constitutive elasto-viscoplasticity model for the foam skeleton is applied that defines the dynamic behaviour of oxygen-free high conductivity (OFHC) Cu using the experimental data reported in the literature, [4, 5]. The chosen material description for the numerical simulation is based on the Cowper-Symonds model. The elasto-viscoplasticity material model with Huber-Mises-Hencky yield criterion is used in the numerical simulations of the impact compression processes.

The Cowper-Symonds material constitutive equation offers an overstress power law model of the tensorial form

$$\dot{\varepsilon}^{vp} = D\left(\frac{\sqrt{J_2}}{\sigma_y(\varepsilon^{pl})} - 1\right)^p \frac{\sigma'}{\sqrt{J_2}} \tag{4}$$

where D and p are material parameters, J_2 is the second invariant of the Cauchy stress deviator tensor $\sigma' = \sigma - \frac{1}{3}\sigma_{kk}$ and σ_y is the quasi-static yield stress. Equation (4) leads to the following relation for dynamic yield function depending on the equivalent strain rate $\dot{\bar{\varepsilon}}^{vp}$

$$\sigma_y^d = \sigma_y(\varepsilon^{pl})\left(1 + \left(\frac{\dot{\bar{\varepsilon}}^{vp}}{D}\right)^{\frac{1}{p}}\right). \tag{5}$$

The elastic modulus, Poisson's ratio, density and material parameters D and p for copper (OFHC) are taken to be 110.0 GPa, 0.34, 8960 kg/m^3, D=20000 1/s and p=2.41, respectively.

4 Computational examples

In numerical simulations using ABAQUS finite element program [6] a rigid plate strikes a stationary copper foam block, see Fig. 1 (left). The bottom displacement in the impact direction is fixed and initial velocity V_0 on the top surface and general contact (steel wall-Cu foam and selfcontact Cu foam) with the friction coefficient 0.35 is assumed. The numerical analysis of dynamic compression test and prediction of axial force (crushing force) within the wide range of velocity: from 50 to 300 m/s are discussed. In Fig.1 (right) the equivalent plastic strain distribution for rigid plate impact with V_0=300 m/s and t=5.0 μs is presented. The finite elements model for convex cell foam consists of 129720 nodes and 506747 elements.

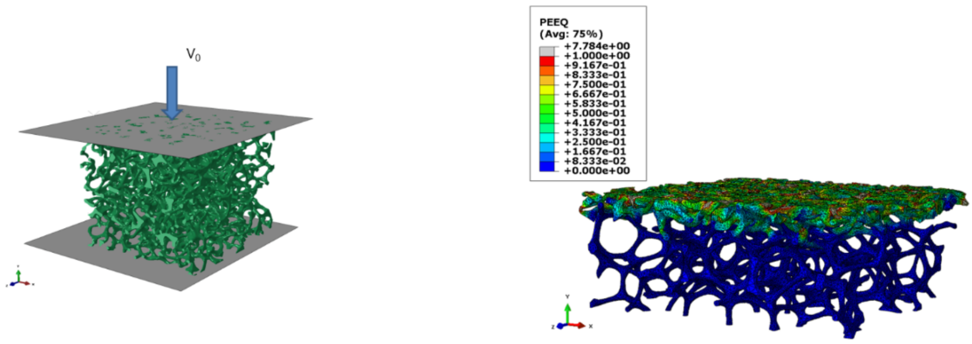

Figure 1: Numerical model for rigid mass impact testing of open-cell 96% porosity convex foam (left) and the equivalent plastic strain distribution for rigid plate impact with V_0=300 m/s and t=5.0 μs (right).

5 Conclusions

The numerical impact resistance of the convex open cell copper foam is analysed using ABAQUS finite element program. Using the numerical models, a parametric study has been carried out to examine the effect of impact velocity on the absorbed energy of this type of foam. The shock compression occurs above a critical impact velocity, which can be estimated by Hugoniot relations. The plastic deformation in the cell wall are enhanced when the impact velocity increases. The shock state variables derived from analytical Hugoniot relation and the conservation laws can be used for comparison with FEM simulations. The primary outcome of this research is new information on the assessment of the crushing force in the open-cell copper foams that is obtained on the basis of virtual material concept with application of the shock wave theory.

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