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Numerical simulation of drop weight impact behaviour of closed cell aluminium foam

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ABSTRACT

Numerical simulation is carried out using ANSYS/LS-DYNA for closed cell aluminium foam undergoing axial impact due to free fall of a drop hammer. Quasi-static axial crushing tests carried out on foams of three different densities were applied to derive the material properties. Mesh refinement results showed that coarse mesh was sufficient to predict the results accurately. Simulation was validated with published experimental results. Parametric study was carried out on foams of various densities for different impact velocities.

1. Introduction

Aluminium foam has been investigated as a potential candidate for energy absorption for nuclear transportation cask [1,2]. During accidental fall of the cask, the kinetic energy of fall introduces transient dynamic stress of very high magnitude that can impair the integrity of the cask. International Atomic Energy Agency (IAEA) safety standard series [3] has stipulated that the nuclear transportation cask has to withstand a free fall of 9 m on a rigid surface simulating the most detrimental drop for a transportation speed of 48 kmph.

Free fall impact experiments are carried out on a scaled model of the cask to simulate the drop condition [4–6]. Introduction of aluminium foam between the model and the unyielding surface greatly reduces the force acting on the model due to which the stress developed on the model is much less in comparison with the permissible stress.

Numerical simulation of aluminium foam deformation was carried out by various authors. Meguid et al. [7] developed three dimensional non-linear finite element model for the quasi-static crushing of foam filled aluminium box assuming a Mises type material that follows isotropic hardening criterion for the aluminium box and the foam was modeled as a series of horizontal layers, each layer consisting of a single layer of solid elements. The nodes of the elements of one layer were collated with the nodes of the adjacent layer. The nodes were then tied together with a tie break contact criterion available in LS-DYNA. Aktay et al. [8] carried out experimental and numerical quasi-static crushing of extruded polystyrene foam filled thin walled aluminium tubes. The numerical solutions were carried out using the explicit finite element code PAM-CRASH. Aluminium tubes were modeled using Belytschko-Tsay-4 node thin shell elements and the polystyrene foam was modeled using a crushable foam solid model. Rizov [9] investigated elastic–plastic behavior of closed cell cellular foams subjected to point and line loads both experimentally and numerically. The numerical simulation was carried out using ABAQUS. The plastic behaviour of the foam was described using crushable foam hardening material model. A good agreement between modeling and experimental data was observed. Zhang and Cheng [10] carried out a comparative study of energy absorption characteristics between foam filled square columns and multi-cell square columns by using LS-DYNA. A self-similar isotropic constitutive model for metal foam developed by Deshpande and Fleck [11] was used. Masso-Moreu and Mills [12] carried out numerical assessment of compressive impact response of pyramidal polystyrene foam shapes used in protective package industry. The results were validated through the experimental testing of physical components.

Present investigation brings out a finite element simulation of closed cell aluminium foam cylinder undergoing axial impact crushing by a free fall drop hammer using ANSYS/LS-DYNA. The simulation was validated with the experimental results presented in Ref. [1]. Parametric studies are carried out on the foam for various impact velocities and foam densities.

2. Experimental details

A detailed procedure on the impact experiments of hammer on the foam is given in Ref. [1]. A mild steel hammer of 155 mm

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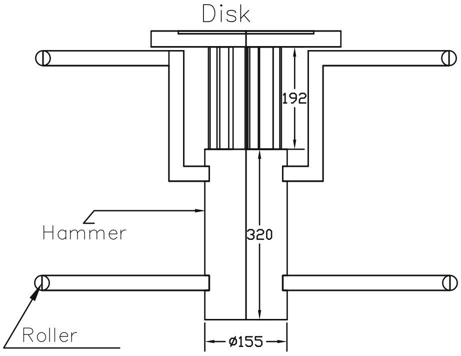

Fig. 1. Schematic of the hammer that was used for drop test.

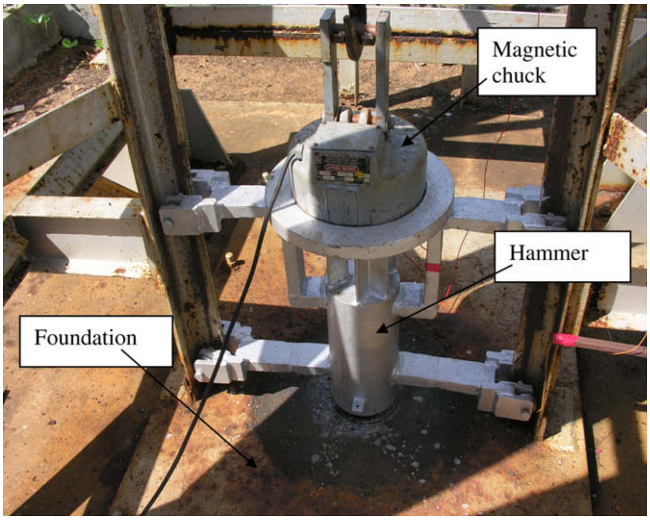

Fig. 2. Photographic view of the experimental set up for foam impact tests.

diameter and 320 mm height was attached with rollers and a disk for attaching the hammer with the electromagnet. The total weight of the hammer was 106 kg. A schematic of the hammer used for drop experiments is shown in Fig. 1. The foam was kept axially vertical on the foundation of the drop tower. A photographic view of the experimental set up is shown in Fig. 2. Drop experiment was carried out for various drop heights to measure the final axial deformation of the foams of various densities.

3. Material parameters

Load–deflection tests were carried out on aluminium foams of densities 292, 471 and 760 kg/m^3 which were translated to true stress (σ)–true strain (ε) diagram. The behaviour of 292 kg/m^3 foam was used as reference to establish the variation of difference in true stress ($\Delta\sigma$) as a function of true strain (ε) for the densities (ρ) 471 and 760 kg/m^3:

$$\Delta\sigma(\rho,\varepsilon) = m(\rho)\varepsilon + c(\rho) \tag{1a}$$

where m is the slope. The trend shows a linear variation of $\Delta\sigma$ with respect to ε up to the region of densification but at the same time $\Delta\sigma$ increased with respect to increasing density. This attribute is utilized for deriving the material model. Since the fit is perfect only up to densification, the material model becomes less accurate after that. The slope m of $\Delta\sigma$ a function of foam density ρ is given as

$$m(\rho) = a_1(\Delta\rho)^2 + b_1(\Delta\rho) + c_1 \tag{1b}$$

The intercept c as a function of foam density ρ is given as

$$c(\rho) = a_2(\Delta\rho)^2 + b_2(\Delta\rho) + c_2 \tag{1c}$$

Second order function of density was chosen for m and c to minimize the error in the predicted $\Delta\sigma$. Fig. 3a shows the true stress–true strain diagram for the tested foams. Legends ‘P’ indicates prediction and ‘M’ indicates measurement. Predicted values compared well with the measurement but as the density of the foam increased the true stress–true strain line deviated from the measurement after densification.

True volumetric strain ε_V is numerically equal to the true strain ε since the change in area of cross-section of the foam is negligible. Therefore,

$$\varepsilon_V = \varepsilon \tag{1d}$$

Densification nominal strain e_D for foams of different densities is given as [13]

$$e_D = 1 - 1.95\left(\frac{\rho}{\rho_s}\right) \tag{2a}$$

From which densification true strain ε_D is given as

$$\varepsilon_D = \ln(1 + e_D) \tag{2b}$$

where ρ_s is the density of the solid material.

Simulated true stress–true strain diagram for the foam densities 380, 450, 570 and 579 kg/m^3 which will be used for the validation of the numerical simulation is shown in Fig. 3b. Simulated true stress–true strain diagram for the foam densities 300, 400, 500, 600, 700 and 800 kg/m^3 which will be used for the parametric studies is shown in Fig. 3c.

4. Finite element modeling

ANSYS/LS-DYNA was used for the numerical analysis. The kinetic energy of the 106 kg hammer is imparted to the foam through its base of 155 mm diameter while it is freely falling from a specified height at the drop tower. Therefore, the hammer with rollers and holding disc is modeled as a single cylinder of an equivalent length of 720.2 mm retaining its diameter. Eight noded hexahedral solid elements with bilinear material model (Table 1) were applied.

The foam had a dimension of 100 mm length and 80 mm diameter and was modeled using eight noded hexahedral solid elements. Clamped boundary condition was applied to the bottom surface of the foam. Crushable foam material model was applied. Automatic node to surface contact algorithm was used between the foam top surface and the hammer. Initial velocity computed from the free fall height was employed to the hammer. Elastic modulus of closed cell foam varies linearly with its density as brought out by Olurin et al. [13]. However, sensitivity study revealed that the change in elastic modulus did not alter the response of the foam. Poisson’s ratio is taken as zero. A tension cut off of 4 MPa and a viscous damping factor of 0.05 are applied.

5. Mesh refinement studies

Mesh refinement study was carried out on the foam for mesh edge lengths of 2, 4, 5, 10, 15 and 20 mm. Displacement–time history of the node on the top surface of the foam and reaction force on the bottom surface of the hammer were studied. Both the displacement–time history (as shown in Fig. 4) and the reaction force–time history (as shown in Fig. 5) were almost insensitive to the mesh size. Therefore an edge length of 10 mm was chosen for the foam element. A finite element model of the hammer and the foam chosen for further analysis is shown in Fig. 6.