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EFFECT OF RELATIVE DENSITY AND VELOCITY TOWARDS DYNAMIC RESPONSE OF METAL FOAM

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Graphical abstract

Abstract

Dynamic response of ALPORAS aluminium foam has been investigated experimentally and numerically. The dynamic response is quantified by the force produced as the foam deforms as a function of time. Quasi-static tests are conducted to determine the quasi-static properties of the foam. In the impact test, the aluminium foams are fired towards a rigid load-cell and the force signals developed are recorded. Experimental dynamic stress is also compared with theoretical prediction using existing theory. Finite element model is constructed using LS-DYNA to simulate the impact test. Results from the experiment, finite element analysis and theoretical prediction are in acceptable agreement. Finally, parametric studies have been conducted using the verified model to investigate the effect of impact velocity and relative density towards the dynamic response of the foam projectile. It is found that the dynamic response of the foam is more sensitive towards impact velocity as compare with the foam relative density.

Keywords: Metal foam projectile, dynamic load cell, high strain rate

1.0 INTRODUCTION

Cellular solids are becoming popular due to their wide potential for diverse engineering applications such as in the automotive, naval and aerospace industries. A good understanding of how the cellular materials behave under a given load is important to avoid catastrophic failure. Limited knowledge about the mechanics of foam impact in 2001 caused 7 astronauts to lose their lives when foam debris hit Colombia space shuttle Reinforced Carbon-Carbon wing at high speed during takeoff [1]. The dynamics stresses, σ_d, of cellular material such as aluminium foam at different velocities are calculated using the shock wave theory introduced by Reid *et al*. [2].

$$\sigma_d = \sigma_{pl} + \frac{\rho v^2}{\varepsilon_d} \qquad \text{(Eq.1)}$$

where σ_{pl} is the plateau stress of the material measured during a quasi-static test, ρ is the material density, v is the impact velocity and ε_d is the densification strain.

The dynamic (impact) force, F_d, can be estimated as,

$$F_d = \sigma_d (A_c) \qquad \text{(Eq. 2)}$$

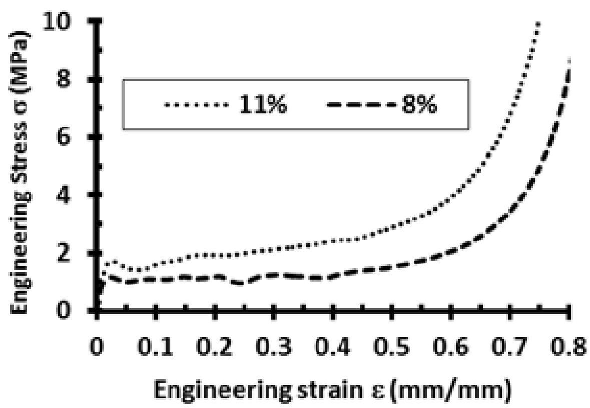
where A_c is the cross section area of the foam projectile.

The current study investigates dynamic response of 37 mm diameter and 50 mm length cylindrical ALPORAS aluminium foam at a strain rate between 2700 s^{-1} to 6800 s^{-1}. The composition of ALPORAS foam is Al-Ca 5-Ti 3 (wt.%) and the average cell size is 4 mm. Quasi-statics tests were conducted to determine the foam properties. Impact test were carried out by using a gas gun and a load-cell that records the impact force. A finite element model was constructed using LS-DYNA and validated with the experimental data. The results are also compared with theoretical prediction by using existing theory as in Eqn.1. Finally, parametric studies were carried out by employing the verified model to determine the effect of relative density and impact velocity towards impact force.

2.0 EXPERIMENT

A quasi-static test was conducted using MTS universal testing machine to determine the foam properties such as the plateau stress and densification strain. Two cylindrical foam specimens with a length of 50 mm and a relative density of 8% and 11% were cut using a wire-cutting machine. The relative density is defined as the density ratio of the foam relative to the solid material. The quasi-static tests were conducted at a cross-head velocity of 0.005 ms^{-1}. Results of the quasi-static tests were shown in Figure 1(a) and (b).

Impact tests were conducted to study the deformation of foam projectiles at different strain rates. The impact experimental set up was shown in Figure 2. During the experiment, the minimum dimension requirement of the specimen, which is 7 cell sizes in all directions, was maintained. Five foam projectiles were fired towards a load-cell manufactured by Kitsler Germany. The gas gun pressure was adjusted at 300 kPa, 600 kPa, 900 kPa, 1200 kPa and 1500 kPa and the resultant impact velocities were 135 m/s, 229 m/s, 277 m/s, 314 m/s and 340 m/s respectively. The load-cell has a built in piezoelectric force transducers that converts a force into an electrical charge. The charge is then converted into a voltage by a charge amplifier [3]. A clamp for the load cell was manufactured in order to protect the load cell from the foam impact and to apply a preload. The graphs of force versus time at different gas gun pressures were shown in Figure 3 (a). A projectile image before and after the test was shown in Figure 3(b). A high speed camera was installed to capture images during the experiment and some of the images were shown in Figure 4.



(a)

Foam Density	8%	11%
Weight (g)	5.4	10.8
Height (mm)	50	50
Diameter (mm)	36.92	36.95
Densification Strain	0.66	0.56
Plateau Stress (MPa)	1.1658	2.1253

(b)

Figure 1 (a) Engineering stress-strain curve of ALPORAS foam, (b) dimension and properties of the foam as extracted from the engineering stress-strain curve

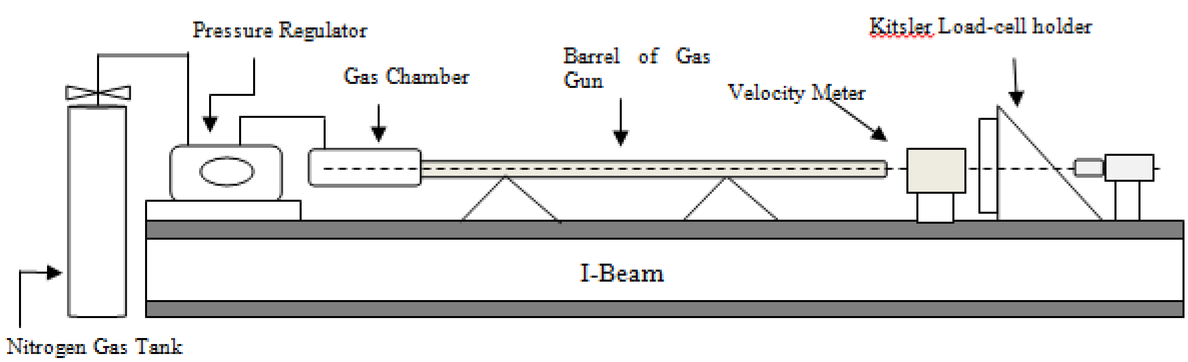
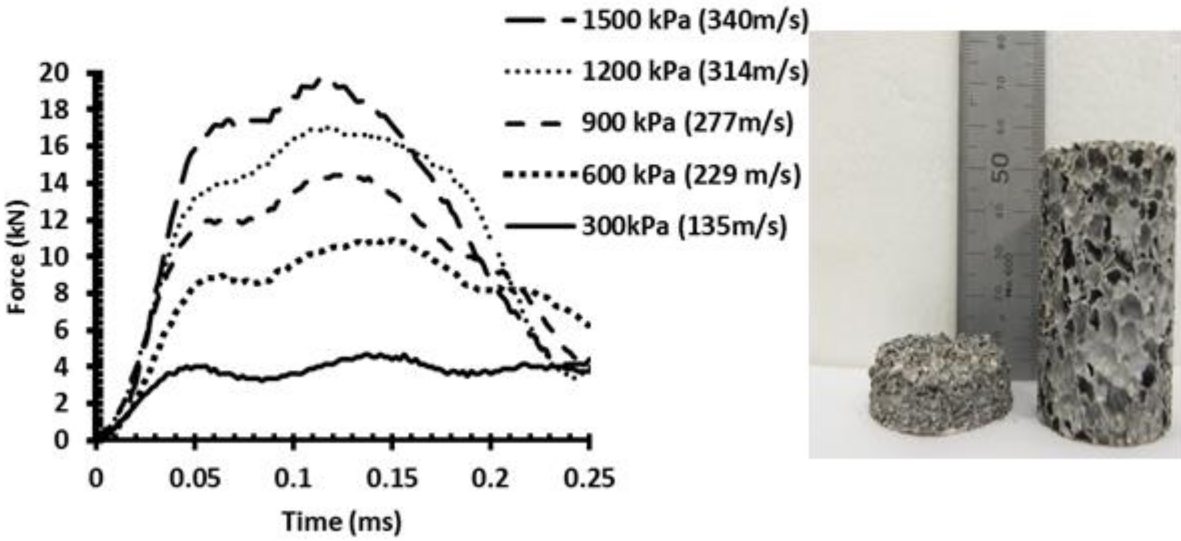


Figure 2 Impact experimental set-up



(a) (b)

Figure 3 (a) Force versus time of specimens at different gas gun pressure, (b) image of sample before and after the impact test (1200 kPa)

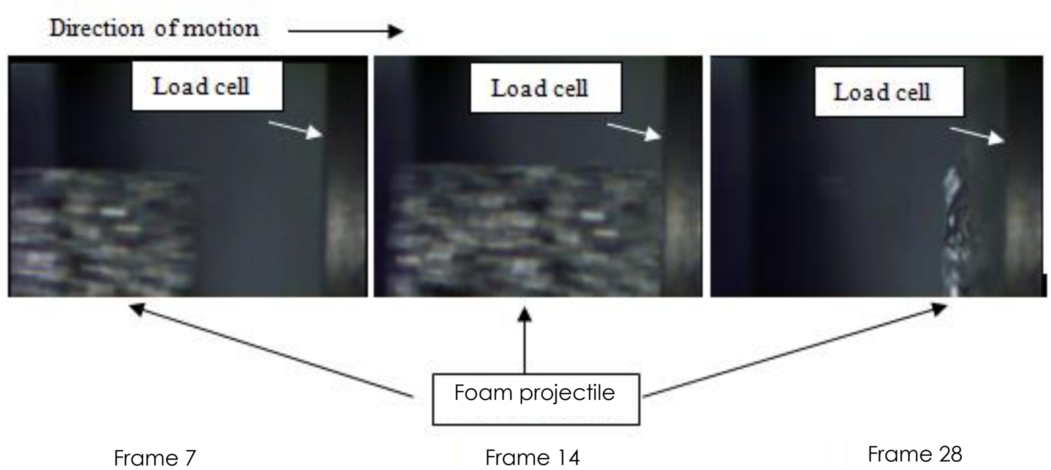
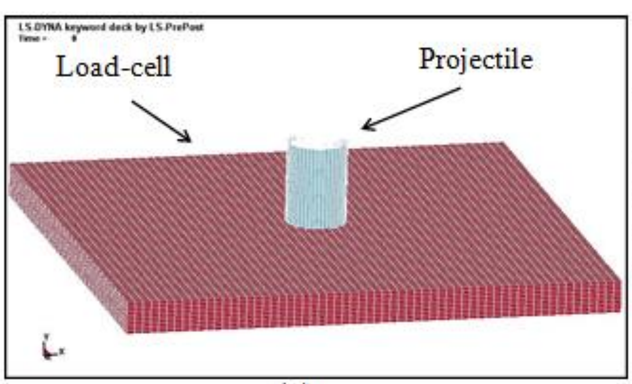


Figure 4 High-speed camera images of the foam projectile impacting a load cell at 277 ms^{-1} ($\dot{\mathcal{E}}$ =4800 s^{-1})



Mass density (ρ)	2.510 x 10^{-7} (kg/mm^3)
Young's modulus (E)	0.072 GPa
Poisson's ratio (v),	0
Tensile Stress Cut-off	0.00218 GPa
Rate Sensitivity effect	0.01

(a) (b)

Figure 5 (a) The FEA model in LS-DYNA software, (b) foam properties as loaded in LS-DYNA [5]

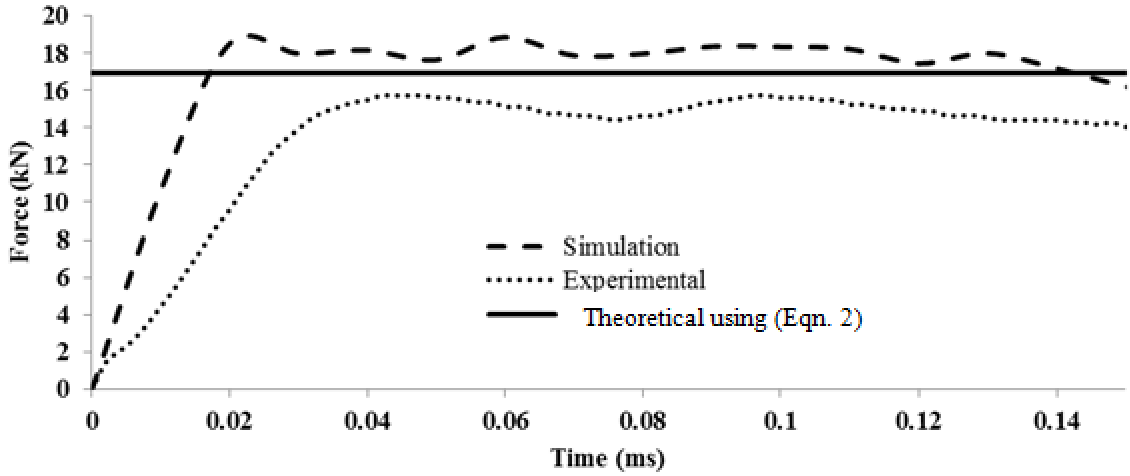


Figure 6 Comparison between experimental simulation, and theoretical analysis of foam response

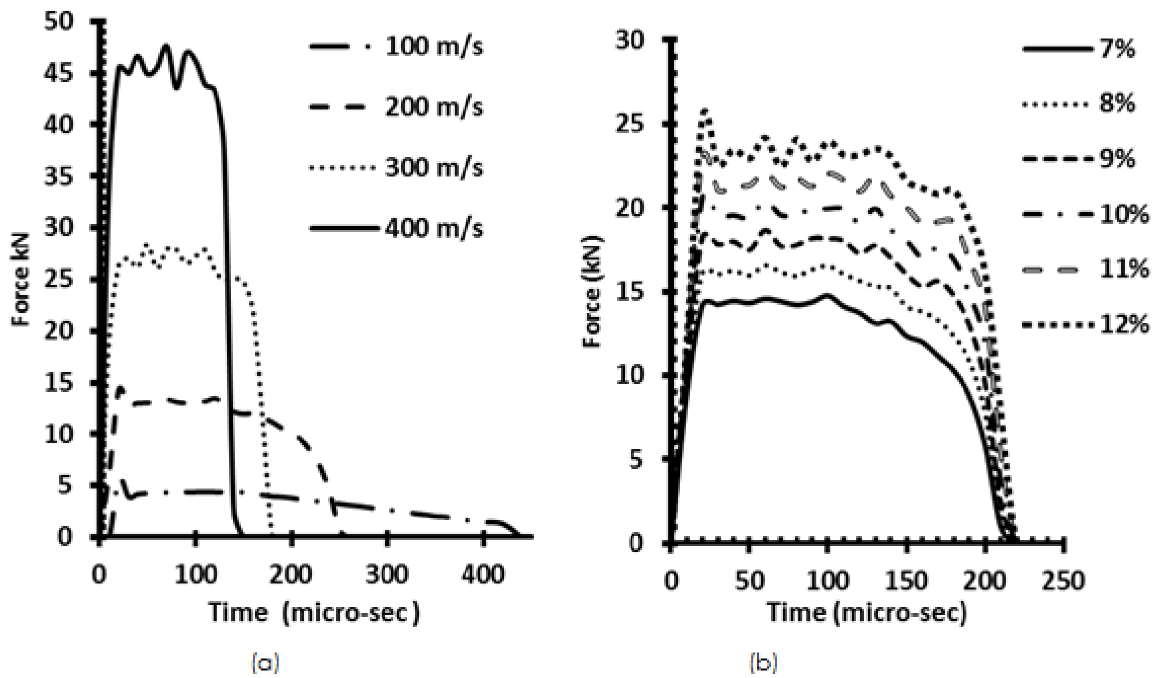


Figure 7 Parametric studies, (a) effect of increasing impact velocity, (b) effect of increasing relative density

3.0 NUMERICAL SIMULATION

The foam projectile that was fired at 1200 kPa during the impact test was simulated in LS-DYNA [4]. The full finite element model for the foam projectile and the load-cell were shown in Figure 5(a). Solid element was applied to both models. The material model for the foam projectile and the plate representing the load-cell were material type 63 *MAT_CRUSHABLE _FOAM and material type 20 *RIGID respectively. The input parameters of the foam projectile were shown in Figure 5(b). Automatic_Surface_to_Surface contact definition had been applied to the models.

4.0 RESULTS AND DISCUSSIONS

The experimental dynamic stress was compared with numerical and theoretical prediction of dynamic stress as shown in Figure 6. The impact forces from the three methods show good agreement. The contact duration between the foam and the load-cell was 240 mili-sec in the experiment and 220 mili-sec in the numerical analysis. The final length of the projectile was 11.30 mm in the experiment while 9.06 mm in the numerical analysis. By using the verified model, parametric studies were conducted to determine the effect of impact velocity and relative density. Results from the parametric studies were shown in Figure 7.

As observed in Figure 7, impact force is more sensitive to velocity than relative density of the foam. The sensitivity of the impact velocity towards impact force is more significant at higher impact velocity, e.g. the force increased by 30 kN when the velocity was increased from 300 ms^{-1} to 400 ms^{-1} compared with 13 kN when the velocity was increased from 100 ms^{-1} to 200 ms^{-1}.

5.0 CONCLUSIONS

The effect of relative density and impact velocity towards impact force has been studied. Impact force is more sensitive to impact velocity compared with relative density. However, the sensitivity increases when the velocity is high.

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