QUASI-STATIC UNIAXIAL AND BIAXIAL LOADING OF ALUMINIUM FOAMS

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Abstract

Aluminium foams are now being considered for use in lightweight structural sandwich panels such as aircraft body and in energy absorption systems for protection from impacts. In both cases, the aluminium foams may be subjected to uniaxial and as well as biaxial compression loadings. In this study, the uniaxial compression loading at a rate of 5 mm/min is performed to find the crushing characteristics and their directional dependency. Eight specimens are used in the uniaxial compression. The load responses are recorded and compared with the biaxial compression loading. Biaxial compression tests are conducted in a custom testing facility between rigid platens, which can be moved independently in two principles direction at the same speed. Five specimens in biaxial compression loading in various densities are used. Considerable enhancement in collapse loads and lead to higher energy absorption is seen in biaxially compression loaded metallic foams in comparison with uniaxial compression loading. The refined empirical relationship for uniaxial loading is also developed.

Keywords: Aluminium foams, uniaxial compression, biaxial compression, quasi static loading

Introduction

In recent years, renewed interest has been observed in the application of cellular materials such as aluminium honeycombs and foams as materials for energy absorption devices and lightweight structural sandwich panels. Besides as high specific energy absorption ability, it provides the stable deformation behaviour.

Much effort has been devoted to the study of mechanical properties of foams. Based on the pioneering work of Maiti *et al*. (1984), Gibson and Ashby (1998) provided a semi-empirical formula for plastic collapse stress, σ^*_{pl} of foam, using an isotropic behaviour, as

$$\left(\frac{\sigma^*_{pl}}{\sigma_{ys}}\right) = 0.3\left(\frac{\rho^*}{\rho_s}\right)^{1.5} \qquad (1)$$

where,

$\frac{\sigma^*_{pl}}{\sigma_{ys}}$ is the ratio of plastic collapse stress over plastic yield stress

$\frac{\rho^*}{\rho_s}$ is the ratio of density of cellular to density of cell wall material

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Collapse is initiated in a weak row of cells and progresses to the rest of the material at this σ^*_{pl}. A rapid increase in the slope of load-displacement curve was seen when the crushed zones have covered all the initial volume of a cell wall material. The strain at transition from the cell wall collapse process at a constant stress to solid phase compression of the cell wall material is called a locking strain, ε_l. The locking strain was also seen by Maiti *et al.* (1984), who introduced an empirical constant, α, which is determined experimentally, as in Equation 2.

$$\varepsilon_l = 1 - \alpha\left(\frac{\rho *}{\rho_s}\right) \tag{2}$$

Foams with closed cells structure are more difficult to analyse, since they contain a thickness variation from cell edges to cell faces. There are also entrapped gases in these cells and the flow of these gases during compression.

Santosa and Wierzbicki (1998) are studied the behaviour of closed-cell metallic foams. They compared the published experimental results on aluminium foams under compression with their numerical analysis. They used finite element code by modelling the foams as a truncated cube to simulate the deformation mechanism. They also developed a semi-empirical relationship for the crushing stress given by,

$$\frac{\sigma^*_{pl}}{\sigma_o} = 1.05\left(\frac{\rho^*}{\rho_s}\right)^{1.52} \tag{3}$$

which is as good as $\left(\frac{\rho^*}{\rho_s}\right)^{1.5}$, giving an error of < 2% at $\left(\frac{\rho^*}{\rho_s}\right) = 0.5$. They used a constant flow stress of σ_o = 139.2 MPa for the aluminium material and obtained a crushing stress from their model.

However, no work has been done on aluminium foams subject to biaxial compression loading. This paper describes the experimental work on uniaxial and biaxial loading with a particular interest in energy absorption during quasi-static compression of aluminium foams specimens. The energy absorbed is found by calculating the area under load-compression curve.

Experimental Developments

There are two types of compression have been performed during experiment: uniaxial and biaxial compression.

Uniaxial Compression of Aluminium Foams

A limited number of aluminium foams specimens of different densities were tested under quasi-static axial loading condition. To find the uniaxial crushing characteristics and their directional dependent, simple compression tests in different directions were carried out under quasi-static condition at crosshead speed of 5 mm/min. Eight smaller specimens were cut from an original cubic block (of 70 mm side) of aluminium foams with a specified density, ρ^*_o of 458 kg/m^3 as shown in Figure 1.

Figures 2 and 3 show the nominal stress-strain curves for the aluminium foams specimens under quasi-static uniaxial compression. The detailed of the results can be found in Said (2000). Generally these exhibit elastic, perfectly-plastic-locking characteristics. The orientations and the positions are shown in the insert and the densities are also indicated in the graphs. In all the cases, a linear-elastic region precedes a short elastic-plastic zone before collapse. Just after the initial collapse, there is always a drop in load

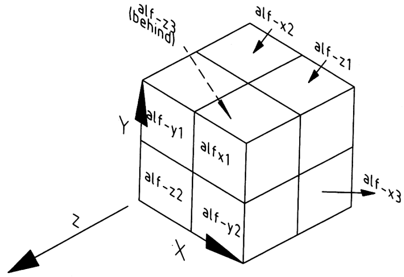


Figure 1. A schematic showing eight smaller specimens with the orientation and direction of compression

before the plateau starts and the magnitude of this drop also appears to depend on densities. The collapsed loads generally increased with density. Post-collapse compression occurs at either a nearly steady or a very mildly increasing load producing a plateau (especially for lower density foams) in the stress-strain curve as seen in Figures 2 and 3.

The plateau gradually terminates with the start of an ever-stiffening zone. The extent of the plateau from collapse to the start of the ever-stiffening zone is seen to reduce with increasing density. The zone most useful for energy absorption can ba defined as the stress-strain curve up to the locking strain, ε_1 defined earlier. The energy absorption obtained as the area under the load-deflection curve up to a displacement consistent with locking strain is shown in column 8 of Table 1. Table 1 shows the summary of results of aluminium foam under biaxial test.

Biaxial Compression of Foams

Biaxial crushing tests were conducted in a purpose built rig as shown in Figure 4. Twelve aluminium honeycomb specimens each of the same density and five aluminium foams

Table 1. A summary of result of aluminium foams under biaxial compression

Density ρ^* (kg/m^3)	Collapse load (kN) F_c		Mean load, F_m (kN) up to 10 mm displacement		Energy absorption, W up to 10 mm displacement (Nm)		Total energy, W absorbed (Nm)
	vertical direction	horizontal direction	vertical direction	horizontal direction	vertical direction	horizontal direction	
152	4	3.5	3.1	3.2	31	32	63
175	6	4.3	4.9	4.2	49	42	91
280	17	15.6	12.5	14.1	125	141	266
303	15	24.0	14.0	21.0	142	202	344
429	34	38.0	30.0	35.0	241	310	551

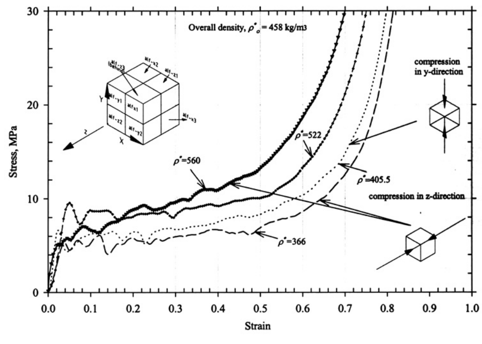


Figure 2. Stress-strain of characteristics aluminium foams of different density under quasi-static uniaxial compression. The orientation and the direction of compression are also indicated

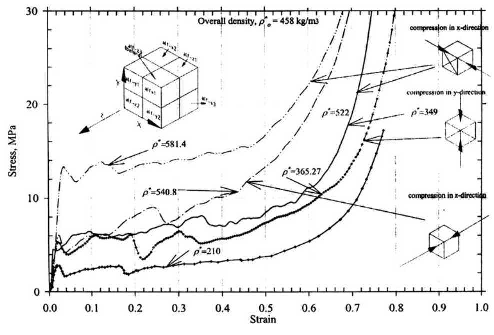


Figure 3. Stress-strain of characteristics aluminium foams of different density under quasi-static uniaxial compression. The orientation and the direction of compression are also indicated

specimens of different densities were compressed biaxially. Five aluminium foams specimens of various overall densities, ρ_o^* were compressed under quasi-static biaxial compression loading condition. The densities of aluminium foams were varied from 152 to 429 kg/m^3. Figures 5(a) and 5(b) show the vertical and horizontal load-displacement curves (or stress-strain curves) under biaxial compression loading. As in the case of simple compression, the curves show a linear-elastic region followed by elastic-plastic zone before initial collapse. These are seen in all densities. A sudden drop in load (just after the peak load) also appears in the curves in all cases. This may indicate localised deformation. As refer to Table 1, the total energy absorbed is noted in the fifth column.

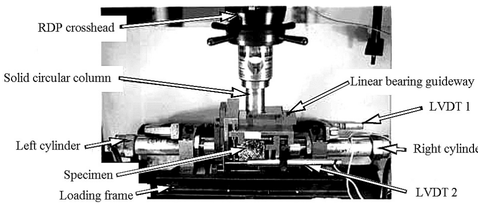


Figure 4. The arrangement of biaxial rig, showing the components

Discussion

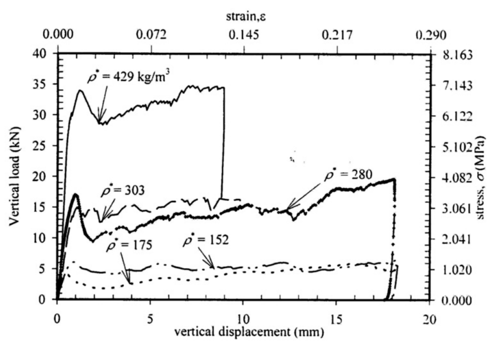
Uniaxial Compression of Aluminium Foams

The normalised yield stress and the normalised density for aluminium foams is plotted in Figure 6a and is compared with the semi-empirical relationship developed by Gibson and Ashby (1998). Experimental results from the present investigation as well as those due to Thornton and Magee (1975a) are used in this plot. The empirical relationship is that for open-cell aluminium foams. The present experimental data is close to Gibson and Ashby's (1998) empirical relationship shown on the graph. However, if the previous work done by Thornton and Magee (1975b) is included, this relationship can be refined to,

$$\frac{\sigma_{pl}^*}{\sigma_{ys}} = 0.4\left(\frac{\rho^*}{\rho_s}\right)^{1.5} \tag{4}$$

This refined relationship is shown in Figure 6(a) if cell wall material density, ρ_s is taken as 2,730 kg/m^3 and yield stress, σ_{ys} as 290 MPa from the manufacturer's data. For example, the predicted crushing stress, σ_{pl}^* for foam density, ρ^* of 406 kg/m^3 is 6.7 MPa. It is worth noting that Gibson and Ashby's expression based on the polymeric foams while the data in Figure 6(a) is for aluminium (metallic) foams. The locking strain

(a)



(b)

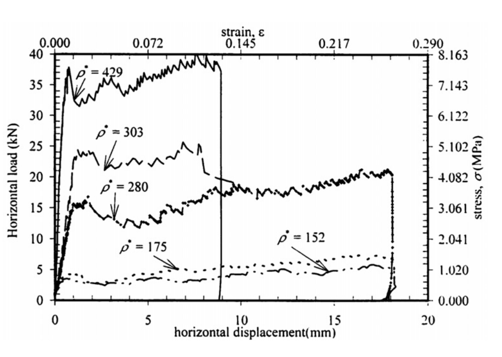


Figure 5. Graph of load-displacement curves (or stress-strain) for aluminium foam specimens (70 mm cube) with various densities during biaxial compression (a) Vertical load against vertical displacement (b) Horizontal load against horizontal displacement

against relative density is plotted in Figure 6(b). The best fitting straight line is given by the

$$\varepsilon_l = 1 - 2\left(\frac{\rho^*}{\rho_s}\right) \tag{5}$$

It is interesting to note that this relationship (Equation 5) is identical to that of Maiti *et al.* (1984), which is based on the data for balsa wood.

Biaxial Compression of Aluminium Foams

The energy absorbed-displacement histories for biaxially crushed foam specimens are area under the two load-displacement plots. They are shown in Figure 7(a). It is obvious that, the higher density foams absorb more energy than the lower density ones. Figure 7(b) show the corresponding energy absorption curves under biaxial loading for relative densities of 0.056, 0.10, 0.11, and 0.16. The normalised stress is chosen from an average stress.

(a) (b)

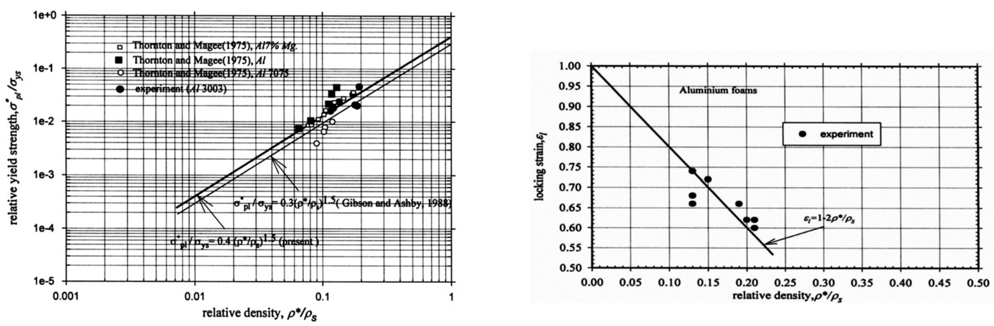


Figure 6. (a) Normalised yield strength versus normalized density for aluminium foams under quasi-static uniaxial compression;
(b) The locking strain, ε_l plotted against the relative density

(a) (b)

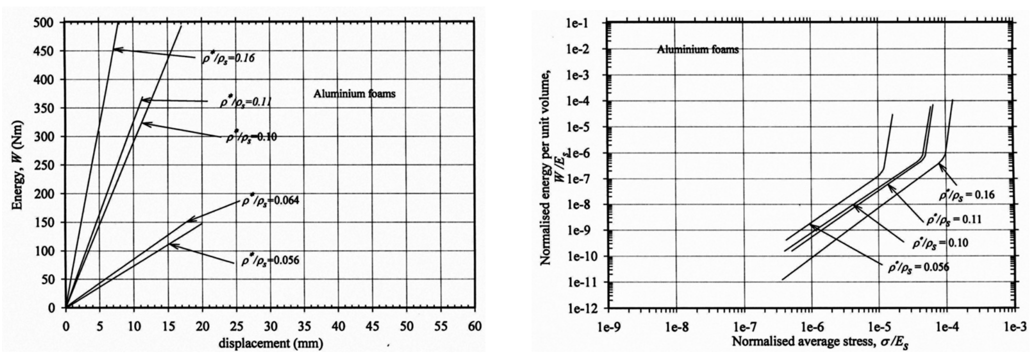


Figure 7. Experimental energy-absorption curve for foams curves under biaxial loading
(a) energy-absorbed against displacement
(b) normalised energy per unit volume against normalised average stress

Conclusions

Two different types of tests, i.e. uniaxial and biaxial compression, were conducted. Uniaxial compressive tests were conducted to obtain the uniaxial compressive strength for the aluminium foams. Biaxial compressive tests were conducted on aluminium foams specimens by a purpose built test rig. In this experiment, the crushing characteristics of aluminium foams and their directional dependency had been determined. It is noticed that a considerable enhancement in collapse loads in biaxially loaded metallic foams in comparison with uniaxial loading. This leads to higher energy absorption. The refined empirical relationship for uniaxial loading is also developed and is satisfactory well in experiment.

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