# THE RESPONSE OF ALUMINIUM FOAMS UNDER QUASI-STATIC LOADING.

M. R. Said
[1]Faculty of Mechanical Engineering, Kolej Universiti Teknikal Kebangsaan Malaysia,Locked bag 1200, Ayer Keroh, 75450 Melaka.
*Email : radzai@kutkm.edu.my*

Ir Tan Chee Fai
Faculty of Mechanical Engineering, Kolej Universiti Teknikal Kebangsaan Malaysia,Locked bag 1200, Ayer Keroh, 75450 Melaka

A Alias
Faculty of Mechanical Engineering, Universiti Teknologi Malaysia

A. Ibrahim
Faculty of Technology Management, Universiti Utara Malaysia

**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, they may be subject to uniaxial and as well as biaxial loadings. In this study, the uniaxial loading at a rate of 5 mm/min is performed to find the crushing characteristics and their directional dependency. Eight specimens are used in uniaxial compression. The load responses are recorded and compared with the biaxial loading. Biaxial 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 loading in various densities are used. Considerable enhancement in collapse loads and lead to higher energy absorption is seen in biaxially loaded metallic foams in comparison with uniaxial loading. The refined empirical relationship for uniaxial loading is also developed and is satisfactory well in experiment.*

**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. Beside a high specific energy, 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) provide a semi-empirical formula for plastic collapse stress, $\sigma^*_{pl}$ 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, $\frac{\rho^*}{\rho_s}$ is the ratio of density of cellular to density of cell wall material. Collapse is initiated in a weak row of cells and progresses to the rest of the material at this $\sigma^*_{pl}$. 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, $\varepsilon_l$ .The locking strain was also seen by Maiti et. al (1984), who introduced an empirical constant, $\alpha$, which is determined experimentally, as in equation 2.

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

Foams with closed cells structure are more difficult to analyse, as 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 will have to be considered.

Santosa and Wierzbicki (1998) have 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,

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

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 $\sigma_o$ = 139.2 MPa for the aluminium material and obtained a crushing stress from their model that agree well with experiment.

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

## EXPERIMENTAL DEVELOPMENT

### Uniaxial compression of aluminium foams.

A limited number of aluminium foam specimens of different overall densities were tested under quasi-static axial loading condition. To find the uniaxial crushing characteristics and their directional dependency, 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 foam with a specified overall density, $\rho^*_o$ of 458 kg/m$^3$ as shown in Figure 1.

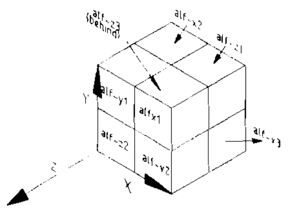


Figure 1: A schematic showing eight smaller specimens
with the orientation and direction of compression.

Figure 2a-b show the nominal stress-strain curves for the aluminium foams specimens under quasi-static uniaxial compression. The detailed of the result can be found in Said (2000). Generally these exhibit elastic, perfectly-plastic-locking characteristics. The orientations and the positions are shown in the inset 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 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 2a and Figures 2b.

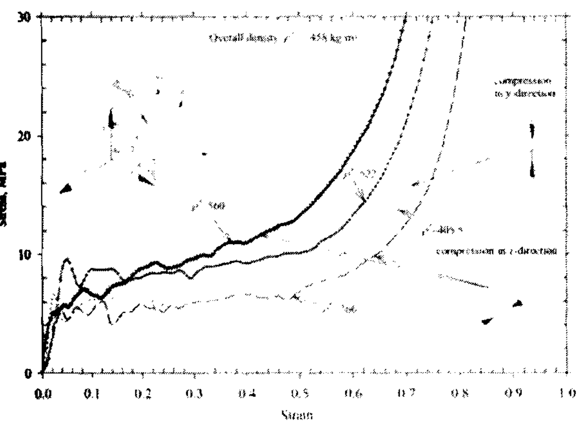



**Figure 2a** : Stress-strain of characteristics aluminium foams of different density under quasi-static uniaxial compression. The orientation and the direction of compression are also indicated

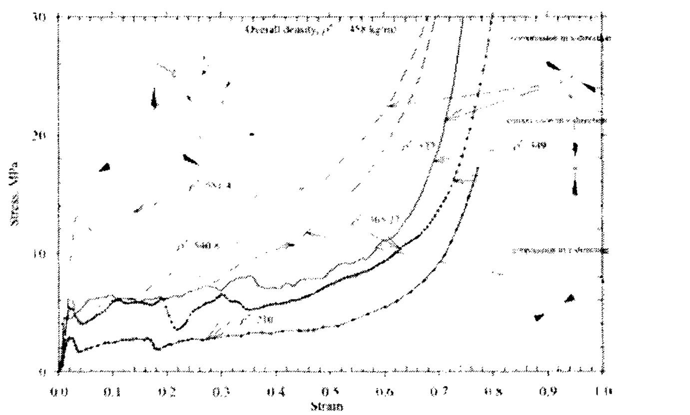



Figure 2b Stress-strain of characteristics aluminium foams of different density under quasi-static uniaxial compression. The orientation and the direction of compression are also indicated

The plateau region 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 be defined as the stress-strain curve up to the locking strain, $\varepsilon_l$ 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.

**Biaxial compression of foams.**

Biaxial crushing tests were conducted in a purpose built rig as shown in Figure 3. The frictional behaviour of the rig is also examined. Twelve aluminium honeycomb specimens each of the same density and five aluminium foam specimens of different densities were compressed biaxially. Five aluminium foam specimens of various overall densities, $\rho_o^*$ were compressed under quasi-static biaxial loading condition. The densities of foams were varied from 175 kg/m$^3$ to 429 kg/m$^3$. Figure 3a and Figure 3b show the vertical and horizontal load-displacement curves (or stress-strain curves) under biaxial 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. Table 1 shows the summary of results of aluminium foams under biaxial test. The total energy absorbed is noted in the fifth column.

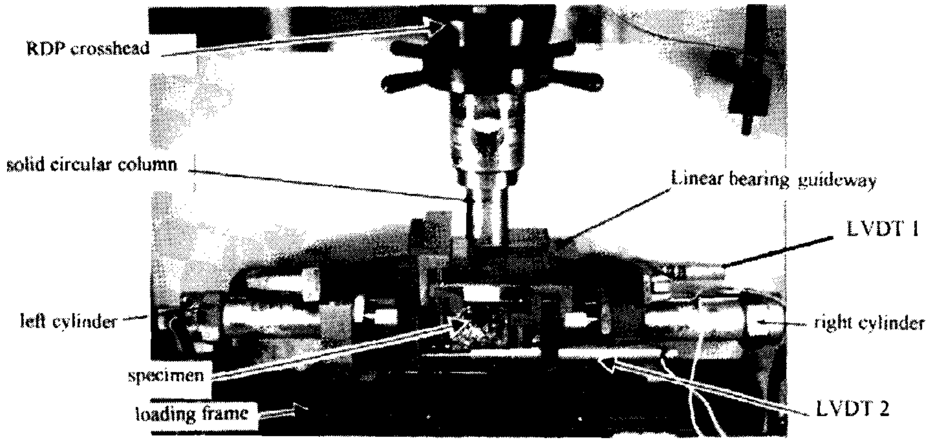
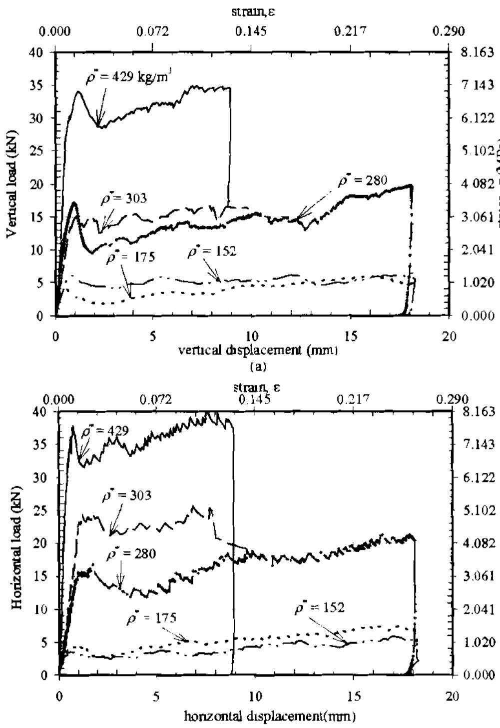



Figure 3 : The arrangement of biaxial rig, showing the components.

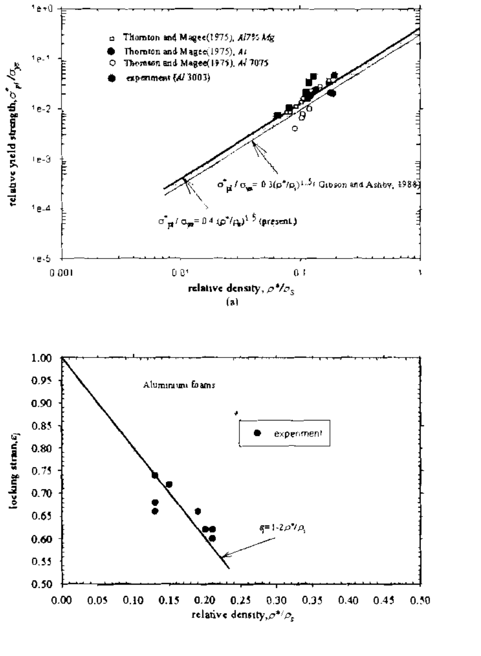
Table 1: A summary of result of aluminium foams under biaxial compression

| Density $\rho^*$ (kg/m$^3$) | Collapse load (kN) $F_c$ | | Mean load, $F_m$ (kN) up to10mm displacement | | Energy absorption, $W$ up to 10mm displacement (Nm) | | Total energy, $W$ absorbed (Nm) |
|---|---|---|---|---|---|---|---|
| | vertical direction | horizontal direction | vertical direction | horizontal direction | vertical compression | horizontal compression | |
| 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 | 14 | 21 | 142 | 202 | 344 |
| 429 | 34 | 38 | 30 | 35 | 241 | 310 | 551 |




(b)

Figure 4 Graph of load-displacement curves (or stress-strain) for aluminium foam specimens (70 mm cubes) with various densities during biaxial compression (a) Vertical load against vertical displacement (b) Horizontal load against horizontal displacement




(b)

Figure 5 (a) Normalised yield strength versus normalized density for aluminium foams under quasi-static uniaxial compression (b) The locking strain, $\varepsilon_l$ plotted against the relative density

## DISCUSSION

### Uniaxial compression of aluminium foams

The normalised yield stress and the normalised density for aluminium foams is plotted in Figure 5a 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 (1975) are used in this plot. The empirical relationship is that for an open-cell foam. The present experimental data is close to Gibson and Ashby's empirical relationship shown on the graph. However, if the previous work done by Thornton and Magee (1975) 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 satisfactory well in experiiment as shown in Figure 3a if cell wall material density, $\rho_s$ is taken as 2730 kg/m$^3$ and yield stress, $\sigma_{ys}$ as 290 MPa from the manufacturer's data. For example, the predicted crushing stress, $\sigma_{pl}^*$ for foam density, $\rho^*$ of 406 kg/m$^3$ is 6.7 MPa, which is less than 3% deviation with experiment. It is worth noting that Gibson and Ashby's expression based on the polymeric foams while the data in Figure 5a is for aluminium (metallic) foams.The locking strain against relative density is plotted in Figure 5b. 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 6a. It is obvious that, the higher density foams absorbs more energy than the lower density ones. Figure 6b 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.

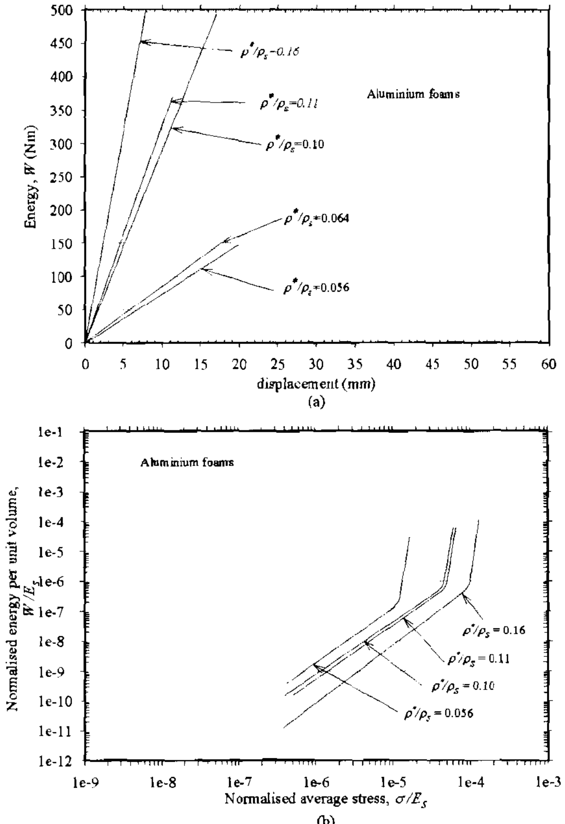



Figure 6 : Experimental energy-absorption curve for foams curves under biaxial loading. (a) Energy-absorbed against displacement (b) Normalised energy per unit volume against normalised average stress.

## CONCLUSION

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.

## REFERENCES.


Maiti, S.K., Gibson, L.J. and Ashby, M.F "Deformation and energy absorption diagrams for cellular solids" *Acta Metall.*, Vol. 32, No.11, pp 1963-1975,1984

Gibson, L.J and Ashby, M.F "Cellular Solids: Structures and Properties", 2nd ed., Cambridge University Press, 1998

Santosa, S and Wierzbicki, T "On the modelling of crush behaviour of a closed-cell aluminium foam structure" *J.Mech. Phys. Solids*, vol. 46, no.4, pp. 645-669, 1998

Thornton, P. H. and Magee, C. L. Met. Trans., 6A, 1253, 1975a

Thornton, P. H. and Magee, C. L. Met. Trans., 6A, 1801,1975b

Said, M. R "Energy absorption in certain cellular structures under uniaxial and biaxial loading" PhD. Thesis, UMIST, 2000.