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Contributed Paper

The Response of Aluminium Foams Under Quasi-Static Loading

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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, 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 was performed to find the crushing characteristics and their directional dependency. Eight specimens were used in uniaxial compression. The load responses were recorded and compared with the biaxial loading. Biaxial tests were 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 were used. Considerable enhancement in collapse loads and lead to higher energy absorption was seen in biaxially loaded metallic foams in comparison with uniaxial loading. The refined empirical relationship for uniaxial loading was also developed and was satisfactory well with the experiment.

Keywords: aluminium forms, compression, quasi-static loading.

1. 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. [1], and Gibson and Ashby [2] 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, $\frac{\rho^*}{\rho_s}$ 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 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, e_l. The locking strain was also seen by Maiti et al. [1], who introduced an empirical constant, a, which is determined experi-mentally, 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, 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 [3] 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,

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

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 s_o = 139.2 MPa for the aluminium material and obtained a crushing stress from their model that agreed 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

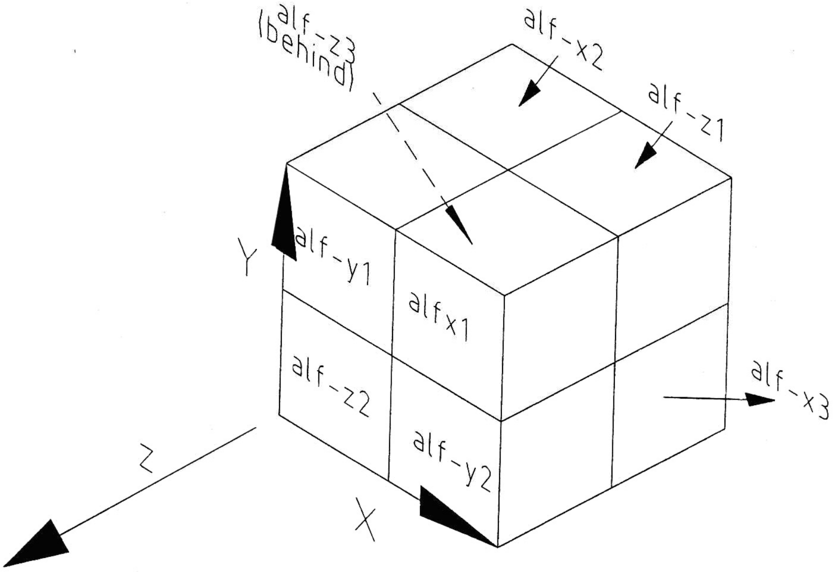

Figure 1. A schematic showing eight smaller specimens with the orientation and direction of compression.

compression. The energy absorbed was found by calculating the area under load-compression curve.

2. EXPERIMENTAL PROCEDURE

2.1. Uniaxial Compression of Aluminium Foams

A limited number of aluminium foam specimens of different 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, ρ_o^* of 458 kg/m^3 as shown in Figure 1.

Figure 2 and figure 3 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 [4]. 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 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 Figure 2 and figure 3.

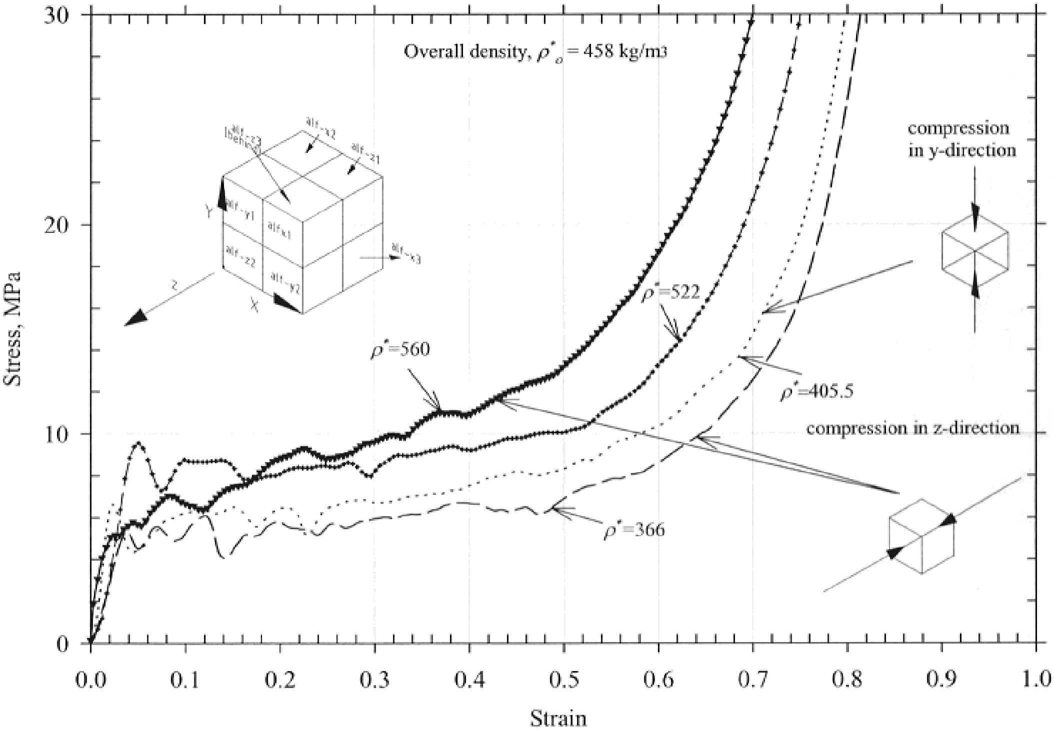

Figure 2. Stress-strain of characteristics aluminium foams of different density under quasi-static uniaxial compression. The orientation and the direction of compression are also indicated.

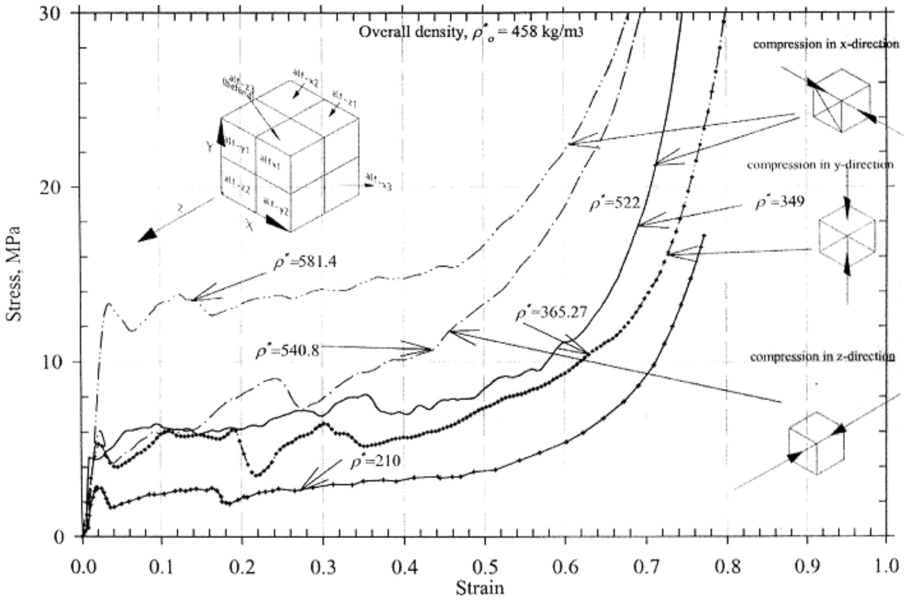

Figure 3. Stress-strain of characteristics aluminium foams of different density under quasi-static uniaxial compression. The orientation and the direction of compression are also indicated.

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, ε_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.

2.2 Biaxial Compression of Foams

Biaxial crushing tests were conducted in a purpose built rig as shown in Figure 4. The frictional behaviour of the rig is also examined. Twelve aluminium honeycomb specimens

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 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

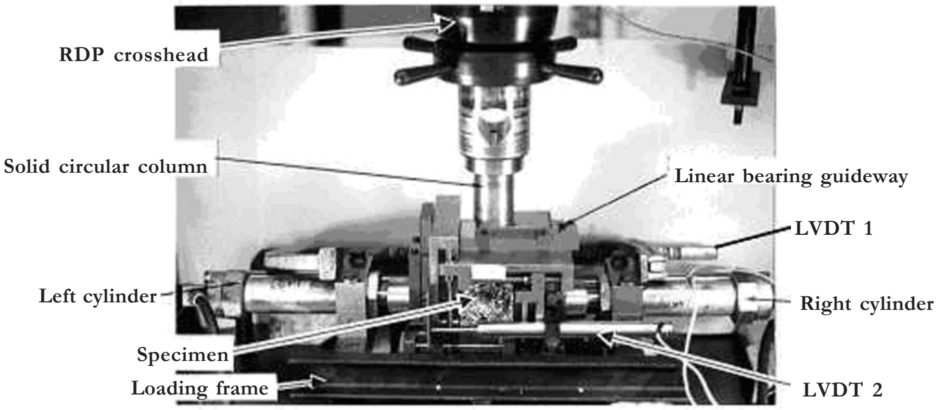

Figure 4. The arrangement of biaxial rig, showing the components.

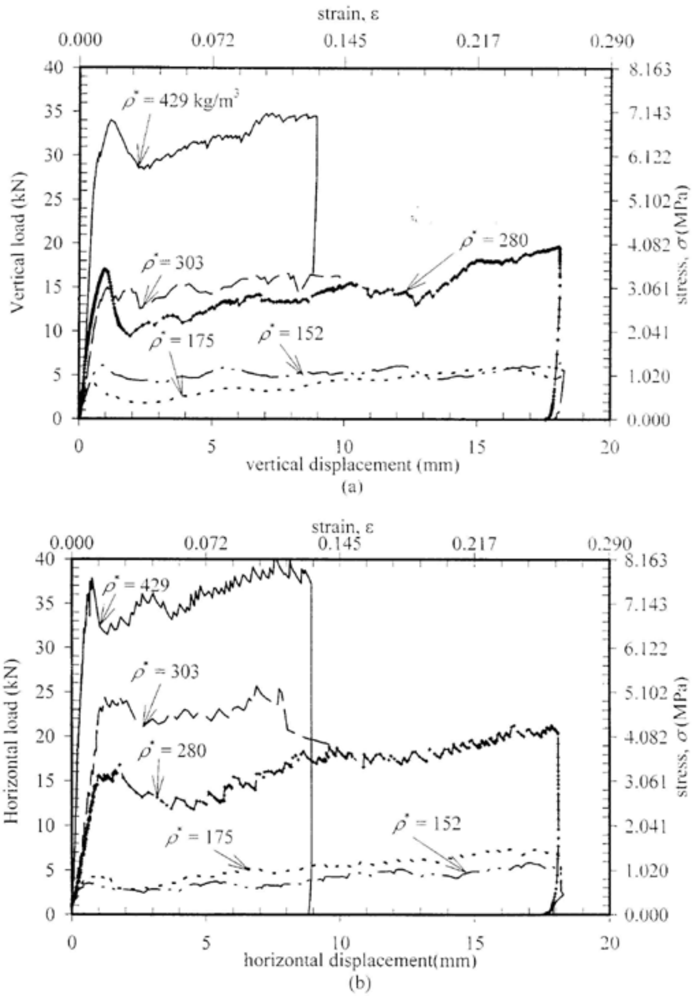

Figure 5. Graphs of load-displacement curves (or stress-strain) for aluminium foam specimens (70 mm cubes) with various densities during biaxial compression (a) Vertical load against vertical displacement (b) Horizontal load against horizontal displacement.

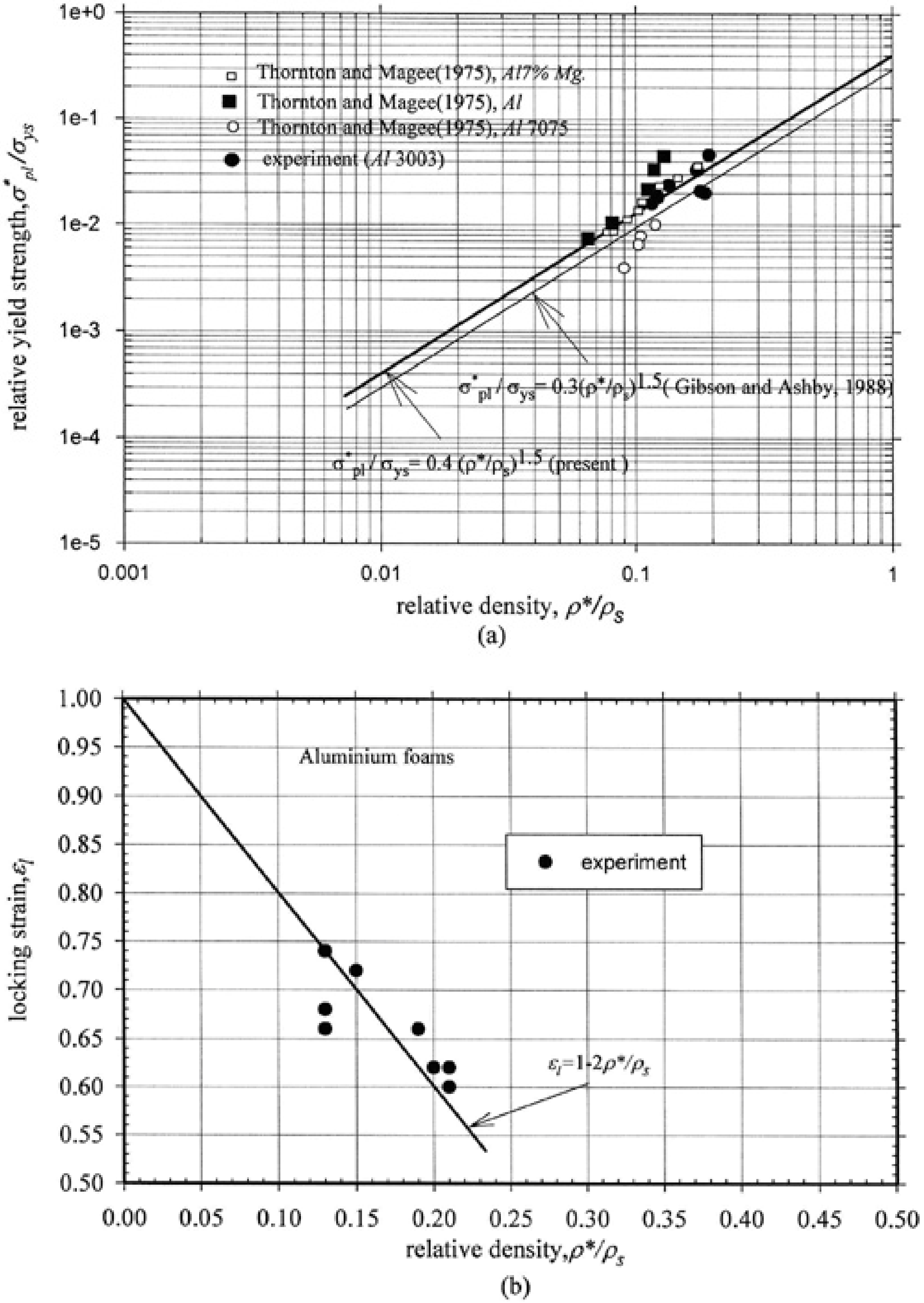

Figure 6. (a) Normalised yield strength versus normalized density for aluminium foams under quasi-static uniaxial compression.

(b) The locking strain, e_l plotted against the relative density.

each of the same density and five aluminium foam specimens of different densities were compressed biaxially. Five aluminium foam specimens of various overall densities, ρ_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 5 (a) and figure 5 (b) 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.

3. DISCUSSION

3.1. 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 [2]. Experimental results from the present investigation as well as those due to Thornton and Magee [5] were used in this plot. The empirical relationship is that for 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 [6] 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 was satisfactory well in experiment as shown in Figure 3a if cell wall material density, ρ_s is taken as 2730 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 was 6.7 MPa, which was 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 6a is for aluminium (metallic) foams. The locking strain against relative density is plotted in Figure 6b. The best fitting straight line is given by the following equation.

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

It is interesting to note that this relationship (equation 5) is identical to that of Maiti et al. [1], which is based on the data for balsa wood.

3.2. Biaxial Compression of Aluminium Foams

The energy absorbed-displacement histories for biaxially crushed foam specimens are area under the two load-displacement plots as shown in Figure 7a. It is obvious that, the higher density foams absorb more energy than the lower density ones. Figure 7b shows 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.

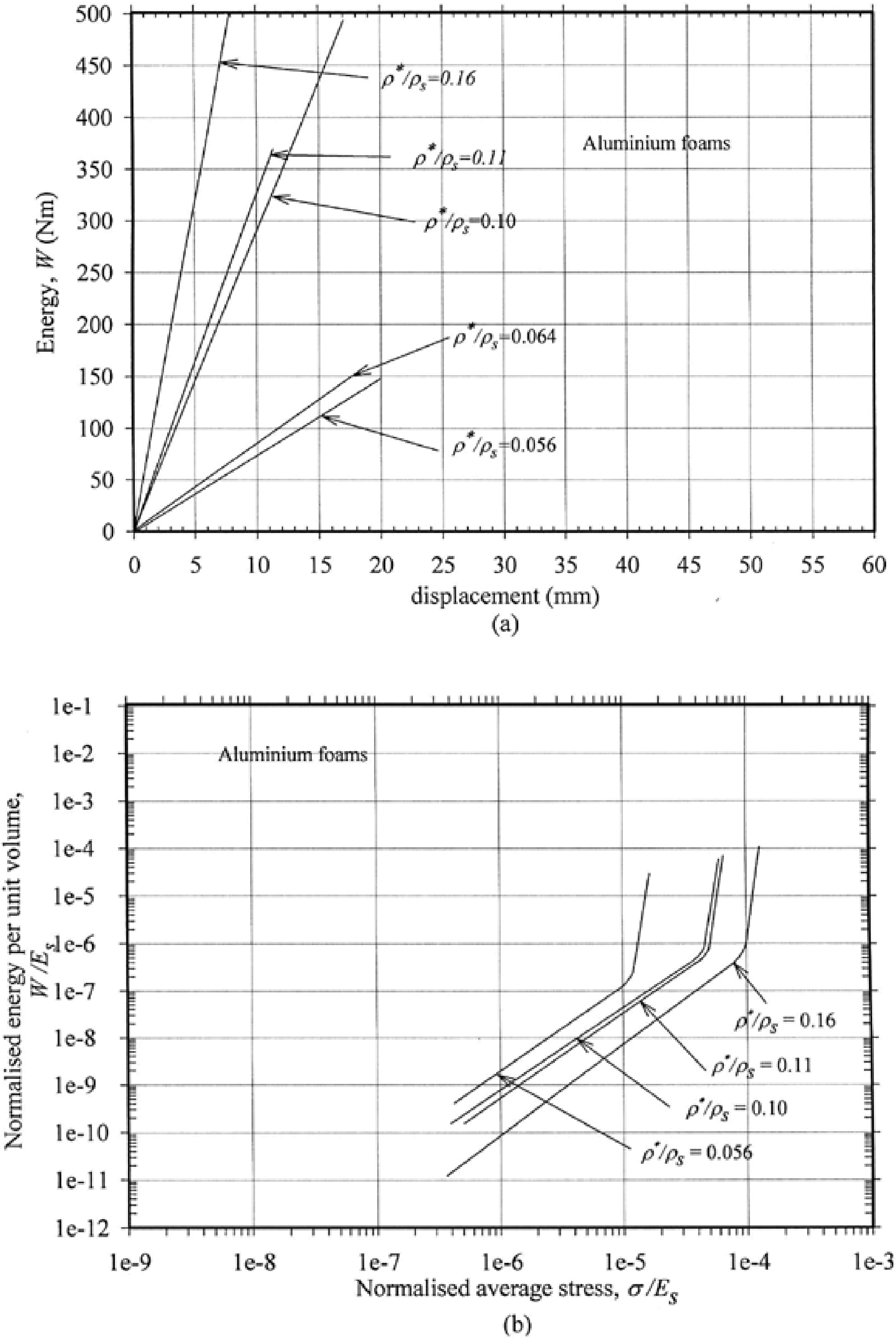

Figure 7. Experimental energy-absorption curve for foams curves under biaxial loading.
(a) Energy-absorbed against displacement and
(b) normalized energy per unit volume against normalized average stress.

4. CONCLUSIONS

In this experiment, the crushing characteristics of aluminium foams and their directional dependency were determined. It was noticed that a considerable enhancement in collapse loads in biaxially loaded metallic foams in comparison with uniaxial loading. This led to higher energy absorption. The refined empirical relationship for uniaxial loading was also developed and was satisfactory well with the experiment.

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