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UNIAXIAL AND BIAXIAL CRUSHING CHARACTERISTICS OF ALUMINIUM HONEYCOMB

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ABSTRACT

Quasi-static uniaxial loading of aluminium honeycomb is reported, along with biaxial loadings. The load-displacement curves show an initial collapse occurs at a peak load, then followed by the amplitudes of the little peaks, which signify progressive folding collapse. The area under the curve is an energy absorbed during the loading.

Keywords: quasi-static, aluminium honeycomb and cellular structure.

INTRODUCTION

Pioneering works on the plastic crushing of honeycombs under axial loads were reported from California Institute of Technology by McFarland (1964). Wierzbicki (1983) has provided an improved model for crushing of honeycombs. Axial loading of cellular material has received a great deal of attention, in the context of impact energy absorption Reid and Peng (1997) and Gibson and Ashby 1998). Many aspects of the behaviour of cellular solids are summarized well in the book by Gibson and Ashby (1998). Wu and Jiang (1997) have performed tests on aluminium honeycombs under axial compression and compared the results with theoretical predictions. However, they wrongly quoted that *H* depends on the wall thickness, *t* and minor diameter, *s*.

The response of honeycombs under lateral compression has been studied by Klinworth and Stronge (1989; 1988). More recent studies are due to Triantafyllidis and Schraad (1998), Papka and Kyriakides (1994). However, Gibson *et al.* (1982) first derived the expressions for the linear-elastic modulus and for the elastic and plastic collapse stresses for honeycombs under lateral loading. They assumed beam theory analysis for elastic region and large deformation theories for plastic region. The elastic analysis only includes the bending action of the walls of the cells. Masters and Evans (1996) included the effect of bending and stretching mechanism. This leads a conclusion that these properties can be related to cell-wall properties (elastic modulus Young, Es and yield stress, σ_{ys}), the cell shapes (cell wall angle, θ and the ratio of cell face length to cell side length, *h/l*) and density (the ratio of thickness to cell side length, *t/l*). Recently Galehdari *et al*. (2015) and Ashab *et al.* (2016) have investigated in-plane loading on graded and aluminium honeycomb structure, respectively

This paper presents the results of the crushing load-displacement characteristic and the mode of deformation of honeycomb of biaxial loading.

METHODOLOGY

Specimens made of aluminium honeycombs, AL3003-H19 were used. The honeycomb had a side length 100 mm or 80 mm and an overall density of 83 kg/m3. The cells of the honeycomb supplied by the manufacturer were slightly irregular hexagons with face length, *h* of 4.38 mm, side length, *l* of 3.1 mm and wall thickness; *t* was 0.0635 mm, as shown in Figure-1. The properties of the aluminium as specified by manufacturer are Modulus of Elasticity, E = 69 MPa, Yield stress, σ_y =165 MPa, Poisson's ratio, ν = 0.33 and ultimate tensile strength, σ_{ult} = 200 MPa. The 100 mm-cube specimens (Figure-1a) consisted of 190 cells with 15 rows and 17 columns. The 80 mm-cube (Figure-1b) had 168 cells, 12 rows by 14 columns. The specimens were carefully prepared so that the edges of the cross sections were clean.

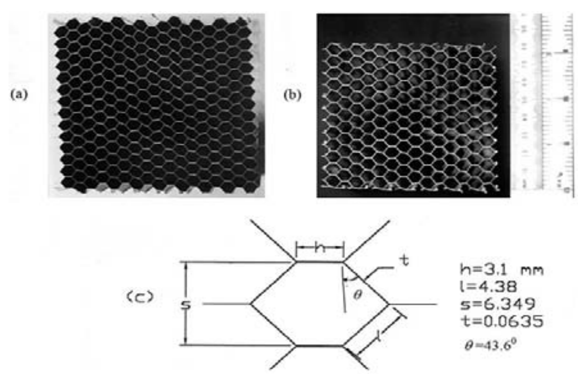

Figure-1. An undeformed Aluminium honeycomb with irregular cell.

Uniaxial loading

The honeycomb specimens were compressed between two rigid platens along the direction of cell axis using an Instron Universal Testing Machine.

Biaxial loading

The aluminium honeycomb specimens were compressed biaxially in axial and lateral directions. Loading in lateral compression had two directions: one was lateral compression across faces and other was lateral compression across corners. In most cases, axial compression was produced by vertical compression while

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compression across faces was produced by horizontal. However, some of the specimens were arranged in the specimen chamber such that the cell specimen axes were in horizontal direction. This examined the repeatability of results.

RESULTS AND DISCUSSIONS

Uniaxial loading

The load-displacement curves were obtained from the displacement controlled at crosshead speed of 10 mm/min. Figure-2 shows typical load-displacement curves for honeycombs under axial compression for 100mm-cube and 80mm-cube specimens. Two curves are given in each case to show the repeatability. The curves for each specimen show an elastic, perfectly plastic, and locking type characteristics. A sharp reduction of load separates the elastic and plastic regions.

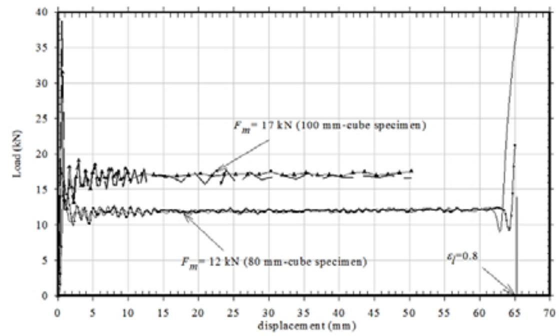

Figure-2. Load against displacement traces for axially compressed honeycomb repeatability.

The single tubes of the honeycomb deformed in diamond mode, adjacent cell walls connected to each other deforming out of phase without any triggering. In axial loading for 80 mm cube specimen, the mean load (*Fm* =12 kN) is about 60 times higher compared with simple lateral loading across faces (Said and Tan, 2009). This shows the energy absorbed of 300 Nm. It was found that the average λ_p (=2H) is 3 mm. A summary of experimental results for honeycombs is presented in Table-1.

Table-1. A summary of result of aluminium honeycombs under uniaxial compression for 80mm-cube.

Spec. No.	**Peak load,** (kN)	**average λ_p at mid face** (mm)	**Mean Load, F_m** (kN)	**Energy absorbed, W** (Nm) **at δ =25mm**
h3com1	17.4	3	12	300
h3com2	18.1	2.8	12	302
h3com3	16.8	2.8	12	305
h3com4	18.8	3	12	302

Biaxial loading

(i) Biaxial loading in axial and across faces directions.

Figure-3a and Figure-3b shows a typical axial load-displacement curves (for specimens under biaxial loading) when the specimens were arranged with their axes in the vertical and horizontal direction, respectively, along with the mean curves. A summary of result of aluminium honeycomb 80mm-cube-specimen under biaxial compression is illustrated in Table-2.

The mean curves shown in Figure-3a and Figure-3b include frictional forces. The mean curves without frictional forces for the two cases (specimens with cell axes in horizontal and vertical directions) are plotted and compared in Figure-3a, which show that the difference in mean loads is less than 10%. The collapse load shown for both cases is about 15 kN (Figure-3c). Overall, their behaviours in both cases are also repeatable. The summary of results of mean and collapse load are shown in Table-2, along with the energies absorbed.

There are slight differences in curves, before the collapse, between these cases. The initial stiffness is smaller when the cell axes are horizontal (forces applied by the hydraulic plungers). This and the initial nonlinearity may be due to inconsistency of the loading devices. The hydraulic cylinders are single acting and the rate of compression is not constant. This may be one of the reasons. The load is applied in the vertical direction by Universal Testing Machine (UTM). Figure-3d compares the axial crushing loads under biaxial condition with those under simple uniaxial loading. The mean load is about the same considering the differences in friction characteristics of the rig. This indicates that the axial crushing load is not affected by the lateral loading.

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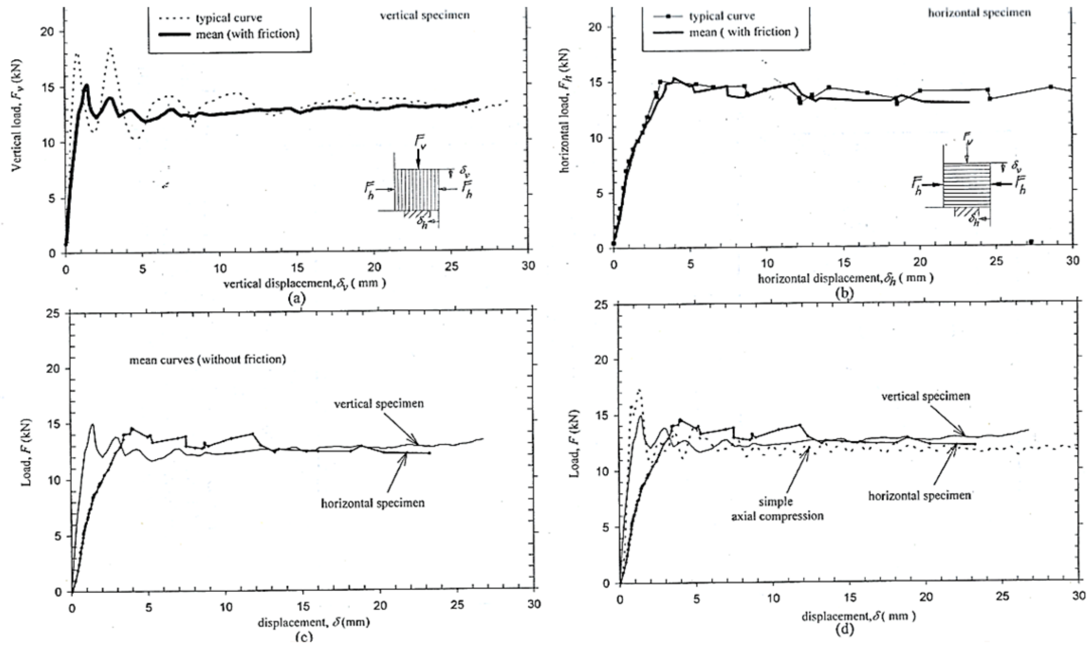

Figure-3. Typical axial load-displacement curve in biaxial compression of honeycomb in 1-4 and 2-3 directions (a) Compression in 2-3 direction of rig (b) Compression 1-4 direction produced by pump (c) Comparison of cases a & b (d) Comparison of average curves in a & b with simple axial compression.

Table-2. A summary of result of aluminium honeycomb (80 mm cube specimen) under uniaxial and biaxial compression. (a) h1- compressed across faces only (b) h2-compressed across faces only (c) h3-axial compression (d) h13-compressed across faces and axially (e) h23-compressed across corners and axially.

Specimen number.	Collapse load (kN) F_c				Mean load, F_m (kN) (up to 25 mm displacement)						Energy absorption, *W* up to 25 mm displacement (Nm)				Total energy absorbed, *W* (Nm)	
	Uniaxial compression	Biaxial compression			Uniaxial compression			Biaxial compression			Uniaxial compression	Biaxial compression			Uniaxial compression	Biaxial compression
		F*	C*	A*	F	C	A	F	C	A		F	C	A		
a) h1	0.2	-	-	-	0.16	-	-	-	-	-	3.9	-	-	-	3.9	-
b) h2	0.3	-	-	-	-	0.24	-	-	-	-	6	-	-	-	6	-
c) h3	18	-	-	-	-	-	12	-	-	-	300	-	-	-	300	-
d) h13	-	2.2	-	15	-	-	-	2.7	-	12.2	-	66		305	-	371
e) h23	-	-	2.36	15.1	-	-	-	-	1.4	12	-	-	33	287	-	320

*F indicates compression across faces, C- compression across corners and A- axial compression

Figure-4a shows a typical lateral load-displacement curve under biaxial loading, together with an average curve. In all cases, an initial linear elastic region at the beginning is followed by elastic-plastic state, which ends when collapse load is reached. It shows that the collapse load is about 3 kN. As further deformation continues, the load gradually increases with non-uniform load fluctuation. The load starts to increase more rapidly at about 15 mm as local densification takes place. This is due to the fact that a part of the face is denser as result of compression in a perpendicular (axial direction). The compression was terminated at displacement of 27 mm. The mean load after friction effects were deducted (Figure-4b) was seen to be 2.7 kN. This gives the energy absorption of 86 Nm if calculating up to displacement of 25 mm. Figure-4b is a comparison of the lateral load-compression curve with under biaxial loading curve with that under simple compression across faces. A significant increase of energy absorbed (by about 17 times) is noticed in biaxial loading compared with simple compression.

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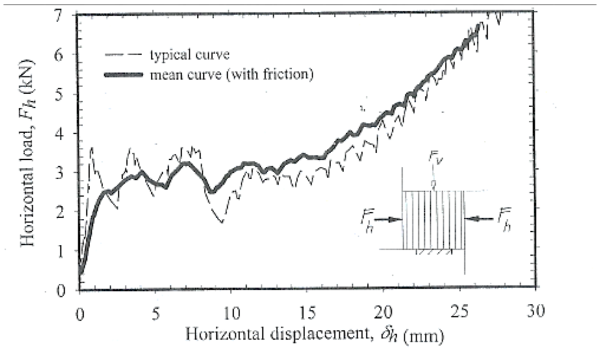
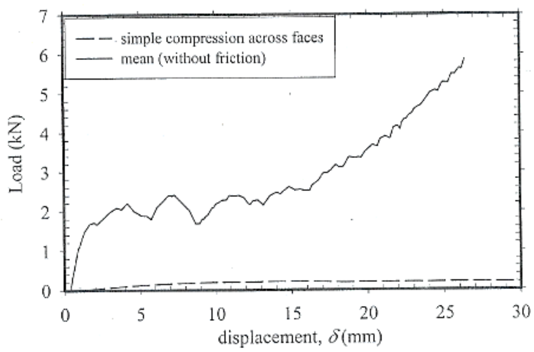


(a)



(b)

Figure-4. Typical lateral load-displacement curves in biaxial loading in 1-4 and 2-3 direction (a) Compression in 1-4 direction produced by pump (b) Comparison an average curve with simple compression across faces.

In lateral direction (compression across faces), all specimens deformed in progressive manner, i.e. collapse in the first row of cells, and followed by subsequent rows. Four view of a typical deformed (cell axes were horizontal in this case) is shown in Figure-5. From close examination, the axial deformation mechanism of honeycombs under biaxial compression was found to be a diamond mode, the same as in honeycombs under simple axial compression. The plastic fold length estimated was also the same (i.e. ʎp ~ 3 mm).

Figure-5 shows no shear band forms in the specimens, as observed under simple compression across faces. This may be due to simultaneous axial compression along the cell axis, preventing the localisation of deformation. Table-2 shows the summary results of aluminium honeycombs under biaxial test in which loading are compressed across faces and axially (indicated as h13) along with simple compression (h1).

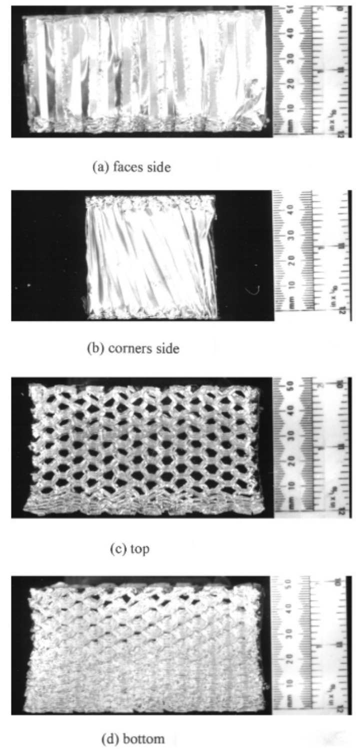


Figure-5. Photographs of deformed specimens.

(ii) Biaxial loading in axial and across corner directions.

Figure-6a and Figure-7a show the average vertical and horizontal load-displacement curve of biaxial compression of honeycomb in the direction of and normal to cell axis, respectively.

Figure-6b shows a comparison of the curve with that under simple axial compression. The mean load is not affected by the transverse load in the case of biaxial compression. Figure-7b indicates that the transverse crushing mean load increases by about 6 times compared with simple compression across corners.

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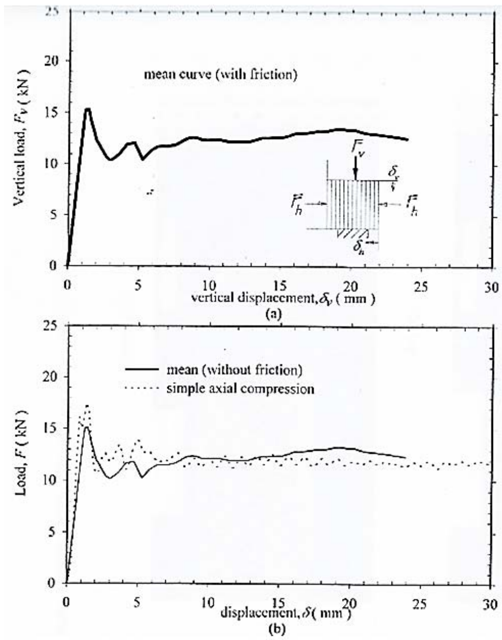

Figure-6. a) Typical axial load-displacement curve during biaxial compression of honeycomb in 2-3 direction (b) Comparison with simple axial compression.

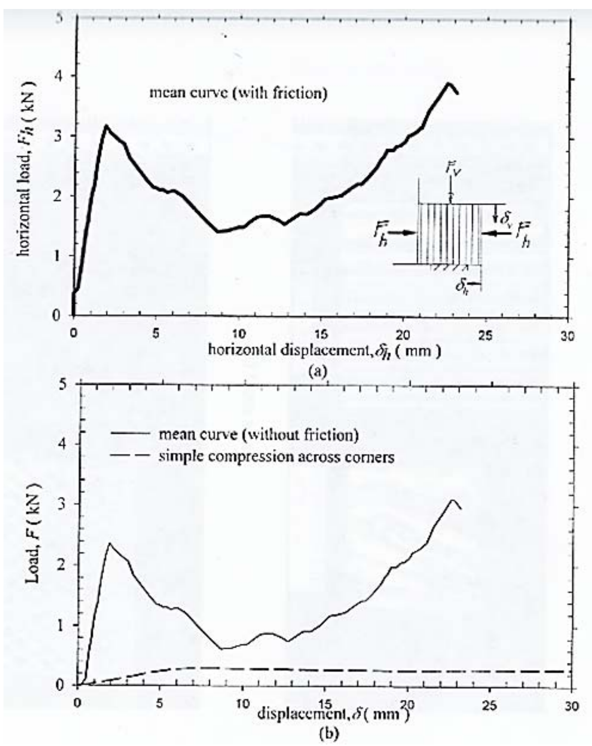

Figure-7. a) Typical transverse load-displacement curve during biaxial compression of honeycomb in 1- 4 direction along with average curve (b) Comparison with simple compression across corners.

Table-2 shows the summary results of aluminium honeycombs under biaxial test in which loading are compressed across faces and axially (indicated as h23) along with simple compression (h2).

Figure 8a-c show three views of specimens deformed under biaxial along with of the undeformed specimens.

Figure-9 shows a typical axial load-displacement curves (for specimens under biaxial loading) when the specimens were arranged with their axes in the vertical and horizontal direction, respectively, along with the mean curves. The collapse load and energy absorbed shown for both cases are about 15 kN (Figure-9) and 300 Nm, respectively. Overall, their behaviours in both cases are also repeatable. Two view of a typical deformed (cell axes were horizontal in this case) is shown in Figure-10.

From close examination, the axial deformation mechanism of honeycombs under biaxial compression was found to be a diamond mode, the same as in honeycombs under simple axial compression. The plastic fold length estimated was also the same (i.e. $\ell_p \sim 3$ mm).

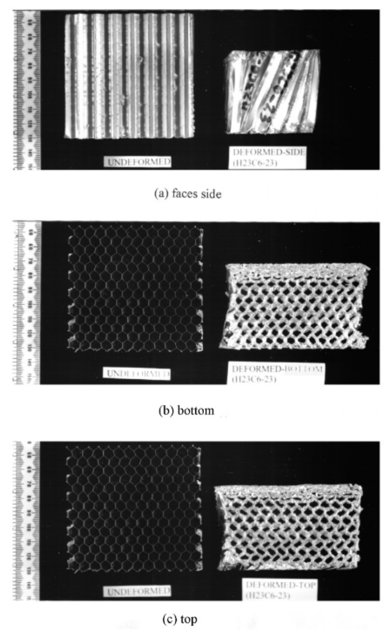

Figure-8. Photographs of deformed specimen under along with the undeformed specimens.

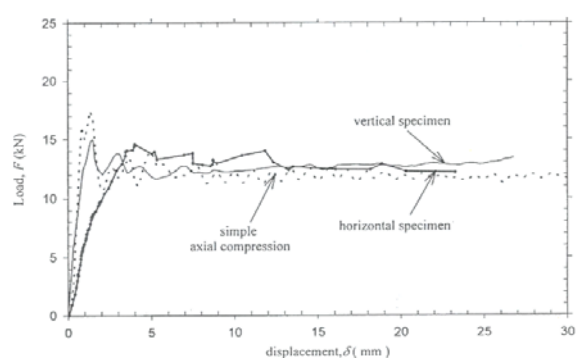

Figure-9. A typical axial load-displacement in biaxial loading.

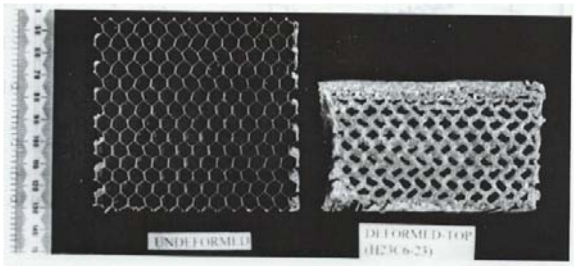

Figure-10. Undeformed and deformed specimen.

CONCLUSIONS

A significant increase of collapse load in lateral direction is noticed under biaxial loading. However, the difference in axial collapse loads between uniaxial and biaxial loading cases is insignificant. The plastic fold length, λ_p was ~ 3 mm and the same for the both uniaxial and biaxial cases.

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