THE ENERGY ABSORPTION OF ALUMINIUM HONEYCOMB UNDER QUASI-STATIC LOADING

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Abstract Experimental results for aluminium honeycomb under quasi-static axial loading is reported, along with computer simulation results. The specimens under axial compression 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 which show is similar amount compared with Finite Element Analysis.

Keywords: Energy absorption, Cellular structure/solid, Aluminium honeycomb, Quasi-static.

INTRODUCTION

Axial crushing of cellular solids has received a great deal of attention, in the context of energy absorption [Reid and Peng,1997, Gibson and Ashby,1998]. Reid et al.,(1993) have recently reviewed the literature on the crushing of wood under dynamic loading conditions and have provided formulae for the crushing stress versus displacement for wood. Many aspects of the behaviour of cellular solids are summarized well in the book by Gibson and Ashby(1998). There is a great interest in the current and potential use of these materials for packaging, as impact energy absorbers and their use as core material in lightweight sandwich structures. Honeycomb in particular, has been used as a protective material for high velocity impact and is often used as an impact energy absorbing material. This paper presents the results of one such study in which specimens of aluminum honeycomb were subjected to axial compression under quasi-static loading.

Pioneering investigations on the plastic crushing of honeycombs under axial loads were reported from California Institute of Technology by McFarland(1963,1964). He developed a semi-empirical formulae for the mean crushing stress for honeycomb under axial compression, which depend on the ratio of thickness and side length, t/b. He concluded that, for t/b ratios $\leq$ 0.07, a shear failure mode is the one that essentially produces a gross progressive collapse. The mechanics of deformation were seen to be unchanged under impact loads. Even though his model is not totally compatible with the experimentally observed collapse modes and his approach is of a semi-empirical nature, he provided a great trust into research of hexagonal honeycombs.`

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Wierzbicki,(1983) has provided an improved model for crushing of honeycombs. By incorporating both bending and extension in the deformation mechanism, he produced an expression for the mean crushing stress, $\left(\sigma_{cr}^{*}\right)_m$ for regular hexagons and also for honeycombs in which two of six sides of a cell have double thickness due to forming process. He obtained the expressions by minimising the mean crushing stress with reference to half wavelength of plastic fold, H. The most recent paper, 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.

In this paper, the computer simulation results [Said,2000] are compared with the experimental works. The main body of this work is concerned with the crushing load-displacement characteristic and the mode of deformation of honeycomb under quasi-static loading. These include the comparison with computer simulation results.

EXPERIMENTAL DEVELOPMENTS.

Cubic specimens of side length 100 mm or 80 mm made of aluminium honeycombs manufactured by CIBA-GEIGY (AL3003-H19) were used. This honeycomb had an overall density of 83 kg/m^3. The cells of the honeycomb supplied by the manufacturer were slightly irregular hexagons (Figure 1a and 1b) 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 1c. The properties of the material (aluminium alloy) 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.

Axial compression of honeycombs.

The honeycomb samples described in above were compressed between two rigid platens in each of the three principal directions: lateral compression across faces, lateral compression across corners and compression along the direction of cell axis. The load-displacement traces obtained from the displacement controlled at 10 mm/min, quasi-static experiments are presented. The deformation patterns are described and a comparison of the behaviour of honeycomb compressed in different directions is made.

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.

Initial collapse occurs at a load, which is about twice the average steady load causing progressive crushing. The amplitudes of the little peaks, which signify progressive folding collapse, are higher initially and gradually decrease as shown in Figure 2. Plastic collapse always occurred at one (usually top) end and the deformation front gradually progressed with continued crushing until the plastic folding deformation approached the lower end of the specimen. Then the load increased very rapidly indicating the densification of the specimen. The locking strain is 0.8.

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 (F_m=12 kN) is about 60 times higher compared with simple lateral loading across faces [Said,2000]. This shows the energy absorbed of 744 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

Spec. no.	Peak load, (kN)	average λ_p at mid face (mm)	Mean Load, F_m (kN)	Energy absorbed, W (Nm)
h3com1	17.4	3	12	744
h3com2	18.1	2.8	12	744
h3com3	16.8	2.8	12	744
h3com4	18.8	3	12	744
h3com-1	38.8	3.4	17	850
h3com-2	31.5	3.4	17	850

FINITE ELEMENT MODELLING AND DISCUSSION

The properties of aluminium sheets used were obtained from the manufacturers. The material for the ABAQUS/Explicit model was taken as elastic-strain hardening. A model having 15 rows by 17 columns of cells was considered, which was equivalent to 100 mm x 100 mm as was used in experiments for lateral compression. Each cell has four sides with a single thickness and two sides with double thickness and the connected angle is chosen as 133.6^0 as given by the manufacturer. The single thickness sides (oblique walls) were 0.0635 mm, hence the double thickness (horizontal walls) was taken as 0.127 mm. The effects of the adhesive were ignored. The length of the side walls of the cells were also different, making cells an irregular hexagonal. The common interfaces (the two double thickness sides) were smaller than the rest. Typically the average side lengths were 1.55 mm (double thickness side) and 2.19 mm (single thickness side).

Figure 3 shows an isometric view of a typical junction of those cells (one-sixth cell mesh) 20 mm in height extracted from the top end of the honeycomb specimen. The total number of one-sixth cells was 373, including the extreme end cells. The total height of one-sixth cell mesh model was 80 mm. This was equivalent to 80 mm-cube specimen tested in experiment. The model comprised of 480 shell elements (type S4R) of single thickness and 240 shell elements for double thickness. The circumferential length of single thickness element was 0.5475 mm and that of double thickness element was 0.3875 mm both being 0.333 mm in height. To economise on the run time, the second quarter of the model consisted of 1 shell element of 1.55 mm by 20 mm and 2 shell elements of 2.19 mm by 20 mm. The other half (remaining 40 mm in height) was modelled by 3 elements of 2 sizes - 1.55 mm by 40 mm and 2.19 mm by 40 mm.

The base of the model was constrained completely while a rigid body element type R3D4 was used to model the platen that effected the compression axially from the top. Compression speed of 9.8 m/s was chosen in the analyses. The speed was a relatively high compared with the physical speed of 10 mm/min. However, it was the suitable artificial speed in the analysis as the speed is too small compared with the wave speed of aluminium, 5000 m/s. A coefficient of friction of 0.3 was also used between the top platen and model and between cells wall.

Figure 4a shows the comparison between experimental and FE load-displacement curves of honeycomb under axial compression. The sequences of deformations of the model mesh shown in Figure 4a at points 0-20 in this figure are shown in Figure 4b. The mesh deforms in diamond mode, as also observed in the experiment. An elastic strain-hardening model was used for the material and this gives a load-displacement characteristic in agreement with the experimental results except in the elastic region (0-1 in Figure 4) and up to collapse. The overall form of curve is quite similar with experiment. The fluctuation indicates the formation of plastic folds. From mesh modelling in ABAQUS/Post package, it was found that the plastic fold length, $2H$ is approximately 3 mm, which compares very well with the experiment. In contrast, Wu and Jiang,(1997) found that the experimental plastic fold,$2H$ significantly overestimate the theoretical as they wrongly quoted the cell size. In fact, the cell size in the theoretical plastic fold developed by Wierzbicki,(1983) must depend on the cell side,b not minor diameter,s as they cited. The FEA mean load is 11 kN, which gives 682 Nm of energy absorption. This underestimates experiment by 10%.

CONCLUSION.

The FEA prediction of the energy absorbed for honeycombs under axial compression overestimates the experimental result by 10% (Figure 4a) while the analytical energy absorbed done by Wierzbicki,(1983) underestimates the experiment by about 20% assuming the flow stress to be equal to the ultimate tensile stress, σ_{ult} . The plastic fold length due to Wierzbicki,(1983) underestimates the experiment by 50%. The side hexagonal, b is taken by averaging of cell side, l and cell face, h length. However, the FEA plastic fold length is in good agreement with experiment.

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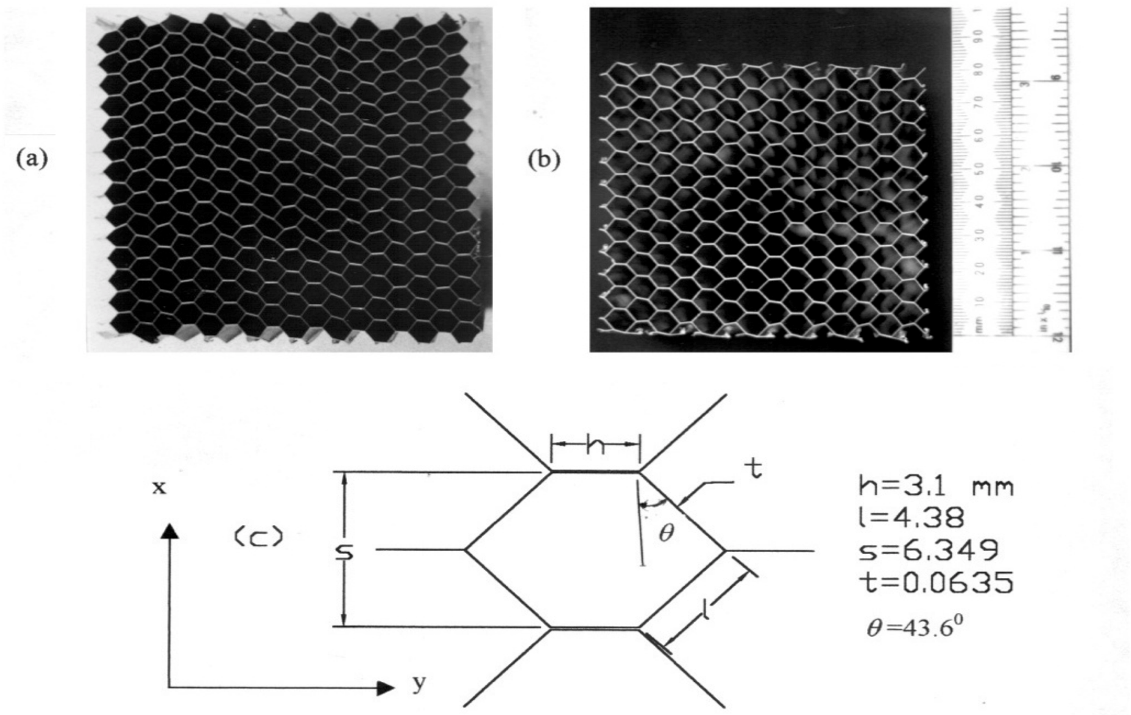

Fig . 1 : An undeformed Aluminium honeycomb with irregular hexagonal cell (a)100 mm x 100 mm x 100 mm, with 15 rows and 17 columns (b) 80 mm x 80 mm x 80 mm, with 12 rows and 14 columns (c) dimension of hexagonal cells (in mm)

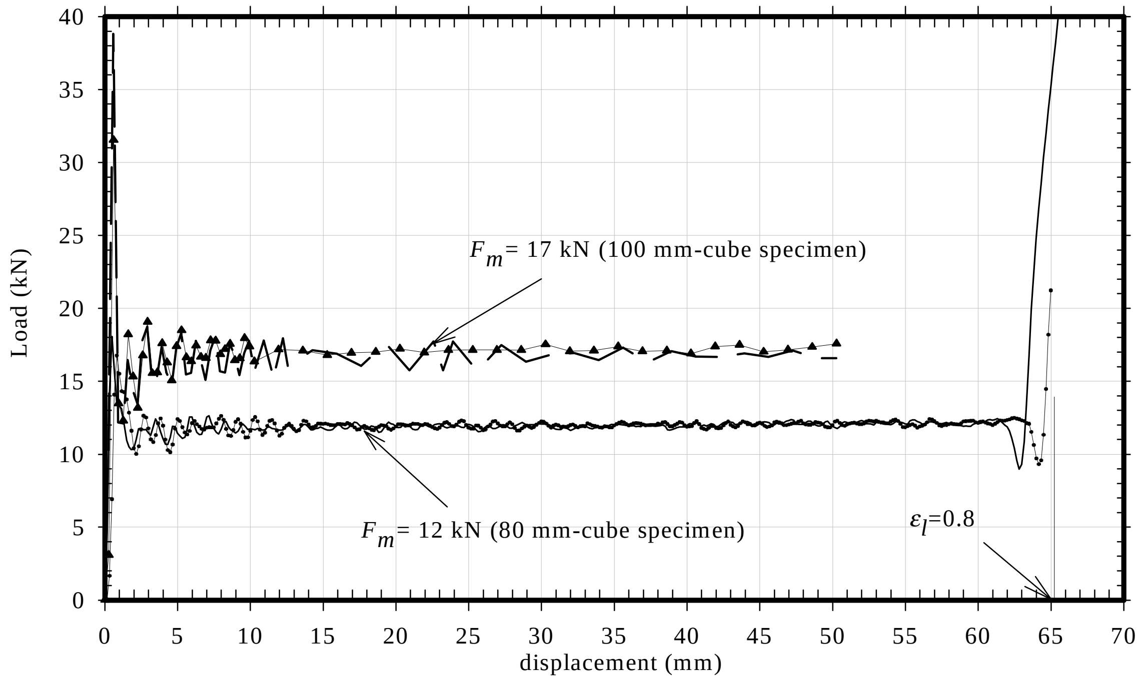

Fig. 2 : Load against displacment traces for axially compressed honeycombs showing repeatability. The top traces are for 100 mm cube and the bottom for 80 mm cube specimens.

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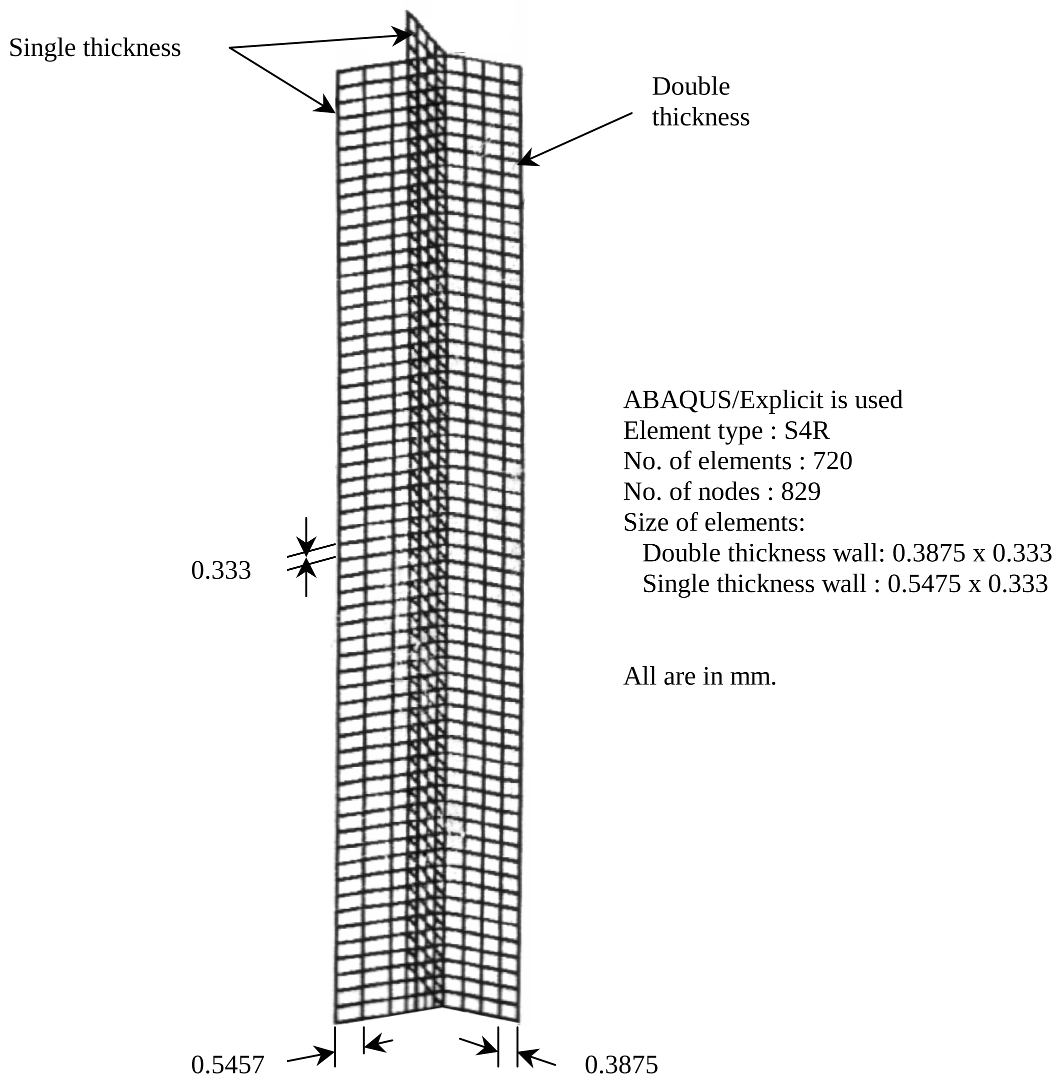

(b)

Fig. 3 : Typical mesh modeling of honeycombs. Isometric view of one sixth cell mesh, 20 mm in height extracted from top end of honeycomb.

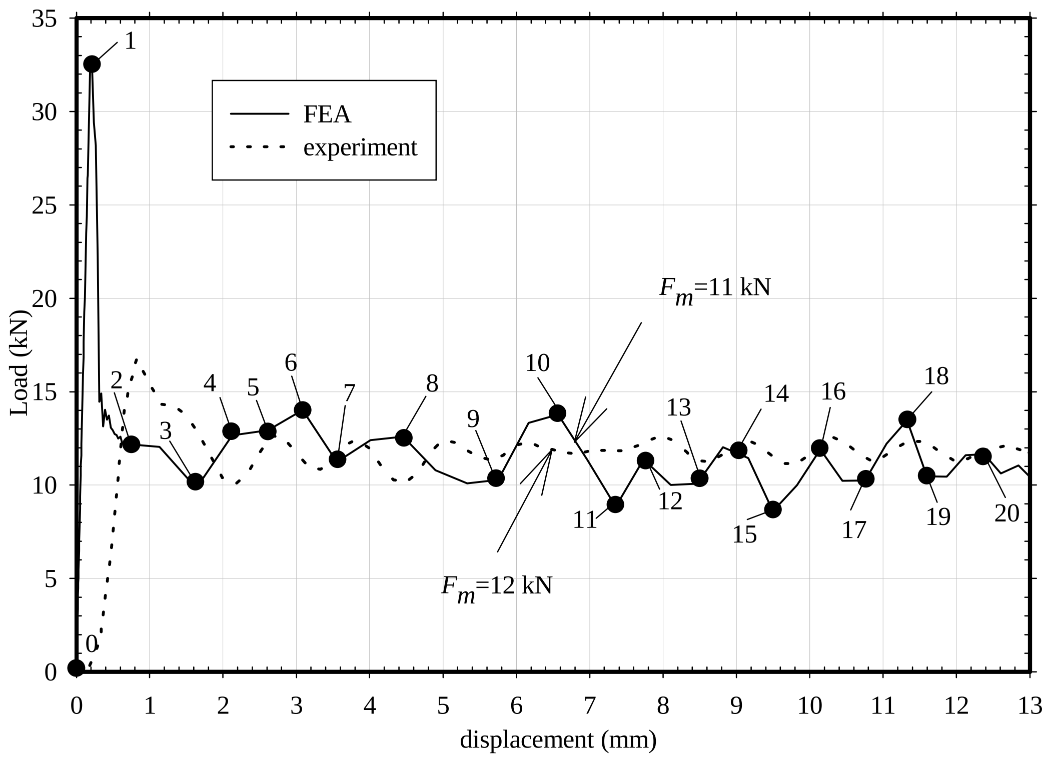

Figure 4a : Comparison between FEA and experimental load-displacement curves of aluminum honeycomb under axial compression. Points 1-20 show the sequence of deformations of the model mesh as shown in Figure 5.23. Dimension of specimen is 80mm x 80 mm x 80 mm.

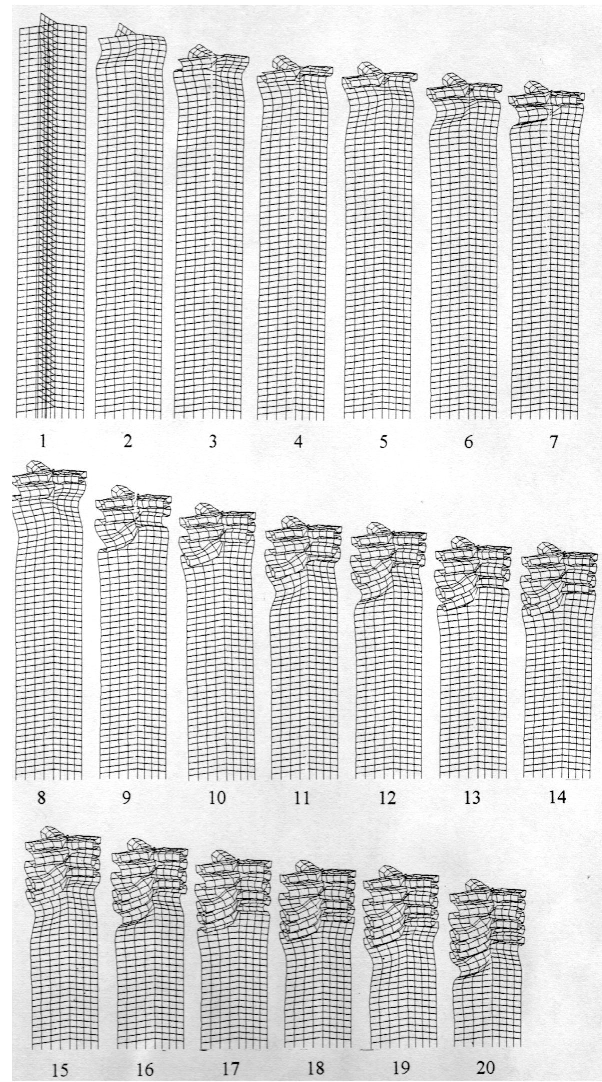

Figure 4b: A sequence of the deforming mesh of the honeycomb model under quasi-static axial compression (material model: elastic strain-hardening)