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Strength enhancement of aluminium honeycombs caused by entrapped air under dynamic out-of-plane compression

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ABSTRACT

The out-of-plane crushing behaviour of aluminium hexagonal honeycombs containing different percentages of holes (i.e., the fraction of penetrated cells to the total) was extensively investigated over a wide range of strain rates where each test was conducted at constant compression velocity. Strength enhancement due to the increase of the strain rate and the entrapped air was studied. It is found that the strain hardening of honeycomb structures during the dynamic crush is mostly attributed to the pressure change caused by the entrapped air. The leaking rate, $\dot{\delta}$, was then studied and found to be dependent on the strain and strain rate, and independent of the wall thickness to edge length ratio, t/l. An empirical constitutive relation describing the plastic collapse stress in relation to the t/l ratio, the strain and strain rate is proposed, which agrees well with the experimental results.

1. Introduction

Cellular solids, including foams and honeycombs, are widely used as energy absorbers and protective components in automotive, aerospace and other engineering sectors because of their high energy absorption capacity and high strength-to-weight ratio. Due to the increasing demands in safety and energy saving of vehicles, research on the mechanical properties of metallic foams and honeycombs has become more and more attractive in the past decades [1,2]. Since the impact of vehicles is of great interest, e.g. the structural response in a car crash, numerous studies have been conducted focussing on the dynamic behaviour of these materials and structures, especially on their strain rate sensitivity.

It has been found that some closed-cell foams exhibit strain rate sensitivity [3–7], while open-cell foams do not [7–9]. The studies on the dynamic out-of-plane compression of honeycombs also showed strain rate sensitivity [10–15]. Due to the complexity of cellular materials, the causes of this macroscopic strain rate sensitivity are still in debate. In summary, the strength enhancement under high strain rate compression may come from four sources; i.e., strain rate sensitivity of cell wall material, micro-inertia effect, entrapped air and shock wave (for high velocity impact only). The rise of the internal pressure caused by the entrapped air during the dynamic compression is believed to be one of the main reasons to the strength enhancement by some researchers [1,15]. Gibson and Ashby [1] proposed a method to evaluate the strength enhancement due to the air pressure increase for foam materials. However, few experimental studies on this issue have been conducted so far. Zhang and Yu [16] studied pressurised thin-walled circular tubes under axial crushing and found that the strength enhancement resulted from a direct effect of the air pressure increase and an indirect effect caused by the interaction between air pressure and tube wall buckling. Dawson et al. [17] developed a comprehensive boundary value model for the contribution of viscous Newtonian fluid flow to the stress–strain response of a fluid-filled, elastomeric open-cell foam under dynamic compression and verified it with experiments on low-density polyurethane foams.

In a parallel study of the out-of-plane dynamic behaviour of hexagonal honeycombs by Xu et al. [13], a strong strength enhancement was observed when the compressive velocity increased from 5×10^{-5} to 10 m/s, especially when the deformation occurred in the region close to the densification strain. The present paper will focus on the effect of entrapped air aiming at a better interpretation of the relationship between the entrapped air and

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the strength enhancement. In the present paper, honeycomb specimens were sandwiched between two thin fibre reinforced sheets, one of which contained a certain amount of holes. First, the leakage of the entrapped air was studied by using specimens with different percentages of holes in one of the thin sheets. Then, the strain rate sensitivity was studied via a series of compression tests under crushing velocities ranging from 5×10^{-5} to 5 m/s. Finally, a constitutive relation is proposed which reflects the relation between the dynamic plateau stress and the relative density, strain and strain rate.

2. Experiments

2.1. Materials and specimens

The honeycomb materials used in this work were commercial HexWeb® CR III corrosion specification aluminium honeycombs. The cell wall material was aluminium alloy 5052 with a H39 temper. Four types of honeycombs were tested and their properties are listed in Table 1, as supplied by the manufacturer.

In a parallel study [13], it was experimentally demonstrated that honeycomb specimens with 9 × 9 cells are sufficient to represent a large block of honeycomb. Therefore, using the same method, honeycomb specimens were carefully cut by sharp, thin knives to contain 9 × 9 cells for honeycombs 3.1-3/16-5052-.001N, 4.5-3/8-5052-.001 and 8.1-1/8-5052-.002N 3N. Honeycomb 4.2-3/8-5052-.003N had large cell size. The loading platen of the testing machine could only accommodate 5 × 5 cells for this honeycomb. Thus, specimens containing 5 × 5 cells were used for this type of honeycomb only.

In order to study the effect of the entrapped air on the honeycomb properties during dynamic crushing, every specimen was sealed by a layer of GMS Composites EP-280 films, whose properties are listed in Table 2, on each end. Honeycomb specimens covered by EP-280 films were sandwiched between two aluminium sheets (splints), and then kept in a heating furnace at 150 °C for 20 min with a weight standing on the aluminium sheet to achieve a good bonding and seal (Fig. 1a). The difference of the stress–strain curves for specimens with and without the heating treatment was experimentally investigated and it was proved that the effect of such heat treatment (150 °C for 20 min) was negligible. Thereafter, one layer of EP-280 film at one end of honeycomb specimen was penetrated by a sharp ended heated tool to obtain a certain number of holes. For simplification, in the following, η is defined as the *hole percentage*, i.e., the number of penetrated cells divided by the total number of cells. The 5 × 5 cells 4.2-3/8-5052-.003N specimen shown in Fig. 1b has a hole percentage of 52%. One layer of strong double sided glue was used to cover each end of the specimen (Fig. 1c). Then the glue covered on the EP-280 film with holes was penetrated again by the heated tool (Fig. 1d). Fig. 1e shows a 9 × 9 cells 3.1-3/16-5052-.001N specimen with nominal 51% penetrated cells at one end. In the test, the end with holes was sitting on the support with many small holes (Fig. 2), from which the air could easily leak out of the specimen during a crushing test.

2.2. Equipment and test set-up

Quasi-static and low strain rate tests were conducted on an MTS machine. The MTS machine has a load capacity of 250 kN and can reach a velocity of up to 0.2 m/s for compression tests. Specimens were sitting on the lower fixed platen. During the compression, the upper platen moved downwards to crush specimens. Velocities of 5×10^{-5}, 5×10^{-3} and 5×10^{-2} m/s, respectively, were applied to specimens corresponding to nominal strain rates of 10^{-3}, 10^{-1} and 1 s^{-1}, respectively, for specimens 50 mm thick.

Dynamic compression tests were conducted on an Instron 8800 hydraulic high rate testing system (Fig. 3). The Instron is equipped with VHS software, which helps to maintain a constant velocity during the compression of the specimens. The Instron can achieve a maximum velocity of 10 m/s in compression and has a load capacity of 100 kN. In our experiments, the Instron was used for tests under crushing velocities of 0.5 and 5 m/s, the corresponding nominal strain rates were 10 and 10^2 s^{-1}, respectively, for specimens 50 mm thick. A high speed camera was used to record the deformation process of honeycomb specimens in the dynamic out-of-plane compression.

In the parallel study [13], experimental data obtained from the MTS and Instron testing machines at a velocity of 5×10^{-2} m/s were in good agreement with each other. Therefore, the experimental data obtained from the two machines in the present study are comparable and can be analysed together. Moreover, Ref. [13] showed a good agreement for repeated tests, so that only one test was conducted for each test condition in the present study, unless otherwise stated.

The set-up of the present tests is sketched in Fig. 2. A specially designed support with holes was riveted to the lower load piston. The holes in the support had a diameter of 3.2 mm. While honeycomb specimens were placed on the support, the holes on one end of the specimen were against the holes in the support, which allowed the air in the specimens to escape easily.

2.3. Data processing

Periodical "*Y*" unit structures, which compose the cell structure around each triple point, were used to deal with the experimental data in the same way as that in the parallel study [13]. The relative density (ρ^*/ρ_s) of perfect hexagonal honeycomb is related to the wall thickness to edge length ratio, t/l, for perfect hexagonal honeycombs ($h = l$, $\theta = 30^\circ$) [1]

Table 1
HexWeb® CR III 5052 aluminium hexagonal honeycomb.

Designation[a]	Nominal density, ρ^* (kg/m^3)	c (mm)	t (mm)	Compressive					Crush strength (MPa)
				Peak		Stabilised			
				Strength (MPa)		Strength (MPa)		Modulus (GPa)	
				Typ	Min	Typ	Min		
4.5-1/8-5052-.001N	72.09	3.175	0.0254	3.79	2.59	3.93	3.28	1.03	1.79
8.1-1/8-5052-.002N	129.75	3.175	0.0508	10.34	6.89	10.76	7.58	2.41	5.17
3.1-3/16-5052-.001N	49.66	4.763	0.0254	2.00	1.38	2.31	1.48	0.52	0.90
4.2-3/8-5052-.003N	67.28	9.525	0.0762	3.59	2.31	3.86	2.45	0.93	1.52

[a] In designation "4.5-1/8-5052-.001N", 4.5 is the nominal density in pounds per cubic foot, 1/8 is the cell size in inches, 5052 is aluminium alloy, .001 is the nominal foil thickness in inches and N indicates the cell walls are not perforated. "Typ" is the typical value and "Min" is the minimum value. (Data supplied by the manufacturer).