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Experimental investigation of the mechanical behavior of aluminum honeycombs under quasi-static and dynamic indentation

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ABSTRACT

The present paper details the first extensive study of the dynamic out-of-plane indentation of aluminum honeycombs at a range of different loading velocities. Dynamic and quasi-static mechanical properties of honeycombs were comparatively analyzed to investigate the strain rate effect on both mean plateau stress and energy absorption. Indentation and compression tests of three types of HEXCELL® 5052-H39 aluminum hexagonal honeycombs were tested using MTS and high speed INSTRON machines at strain rates from 10^{-3} to 10^{2} s^{-1} respectively. The tearing energy was calculated as the difference in energy dissipated in indentation and compression of the same type of honeycomb. It was found that tearing energy was affected by strain rate and nominal density of honeycomb. Empirical formulae were proposed for tearing energy in terms of strain rate.

1. Introduction

Aluminum hexagonal honeycombs are widely known for their excellent properties such as high strength to weight ratio. They can undergo large plastic deformation to absorb high energy. Owing to their distinctive mechanical properties, aluminum honeycombs have been used as energy absorber material since the last few decades in different industrial applications. For example in the aerospace industry, shock absorber located inside the primary strut of the landing gear in Apollo 11 lunar module was made from crushable aluminum honeycomb and the conical pressure vessel named Command Module (CM) was made of aluminum honeycomb sandwich bonded between aluminum alloy sheets [1]. In modern automotive industry, the chassis is made out of a combination of aluminum honeycombs and carbon fiber for optimal weight distribution and safety concern [2]. Today the safety and energy saving of automobiles are of great concerns to researchers. For this reason, the use of lightweight cellular materials such as metallic foams and honeycombs is increasing. In naval architectures where the ships are in high intensity pressure, this type of cellular material has been used in sandwich structures to enhance the performance.

A number of studies [3–12] have been carried out to study the deformation mechanism of aluminum honeycombs theoretically, experimentally and numerically in the two in-plane (L-ribbon or W-transverse) directions and one out-of-plane (T) direction of honeycombs. These investigations mainly focused on the failure and crushing mechanisms of honeycomb materials under quasi-static and dynamic compressive loading conditions. Gibson et al. [3] described the deformation mechanism of honeycomb structures in terms of elastic buckling and plastic collapse and the formation of plastic hinges of the cell walls. Wierzbicki [4] proposed a half wavelength formula of plastic buckling for a metal honeycomb structure, which was related to cell wall thickness and edge length of the honeycomb. Wu and Jiang [5] compared their experimental analysis under quasi-static and dynamic compressive loadings with the theoretical predictions of Wierzbicki's model. They observed significant discrepancies between theoretical model and experimental results in terms of progressive plastic buckling and buckling wavelength of honeycomb specimens, which might be caused by the difference in progressive plastic-buckling mechanism of honeycomb structures or in the material data of aluminum honeycombs. Zhang and Ashby [6] experimentally studied the mechanical behavior of different types of aluminum honeycombs used as a core material in sandwich panels under pure compression. They observed two types of plastic collapse modes in honeycomb structure: honeycomb collapsed through buckling for lower density material and collapsed through fracture for higher density material. Aktay et al. [7] reported experimental and finite element

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analyses of transverse crushing behavior of aluminum honeycomb materials. They employed different finite element modeling techniques for numerical crushing analyses of honeycombs in investigating of appropriate honeycomb models for structural simulations. Gibson and Ashby [8] summarized the mechanical properties of honeycombs in their book and stated that the stiffness and strength of honeycombs materials were much larger in the out-of-plane direction compared to the two in-plane directions. Khan et al. [9,10] also found that the out-of-plane is the strongest direction among the three directions of honeycomb. They also observed that the stress–strain curves were similar for both in-plane directions but the crushing strength in the ribbon direction was double of that in the transverse direction. Hu et al. [11,12] reported experimental and numerical analysis on in-plane crushing of aluminum honeycombs. They proposed a dynamic sensitivity index to discuss the effect of impact velocity on the crushing strength and the energy absorption.

The large plastic deformation under a compressive load for hexagonal honeycombs takes place in the plateau phase, which absorbs the predominant portion of energy in crushing. The stress over this region is known as the plateau stress, σ_{pl}. The important parameters that affect plateau stress as well as mechanical response of aluminum honeycombs are the cell size, cell wall thickness, nominal density and strain rate [7]. McFarland [13] conducted the pioneer work and derived a semi-empirical formula to calculate the mean crushing strength of honeycomb structures under axial compression. Yang and Qiao [14] studied, both experimentally and numerically, the uniaxial crushing behavior of aluminum honeycombs in the out-of plane directions. They proposed two semi-empirical equations that could be used to determine the crushing strength of honeycombs. Yamashita and Gotoh [15] conducted quasi-static and dynamic compression tests on aluminum 5052 honeycombs to study the compressive strength and energy dissipation in the out-of-plane direction. They found that the crushing strength increased with the cell wall thickness, which also followed the power of 5/3 of wall thickness as derived by Wierzbicki [4].

To investigate the effect of impact velocity on crushing strength of aluminum honeycombs Goldsmith and Sackman [16] conducted dynamic crushing tests at different velocities up to approximately

Table 1
Specification of aluminum honeycombs.

Type	Material description[a]	Cell size, D (mm)	Single cell wall thickness, t (mm)	Cell wall thickness to edge length ratio, t/l	Nominal density, ρ (kg/m^3)	Young's modulus (GPa)	No. of cells under the indenter or platen
H31	3.1-3/16-5052-.001N	4.763	0.0254	0.00924	49.66	0.52	19 × 19
H42	4.2-3/8-5052-.003N	9.525	0.0762	0.0139	67.28	0.93	9 × 9
H45	4.5-1/8-5052-.001N	3.175	0.0254	0.0139	72.09	1.03	28 × 28

[a] In the material description, 3.1, 4.2 and 4.5 are the nominal densities in pounds per cubic foot, 3/16, 3/8 and 1/8 are the cell size in inches, 5052 is the aluminum alloy grade, 0.001 or 0.003 is the nominal foil thickness in inches and N denotes non-perforated cell walls. Data were provided by the manufacturer.

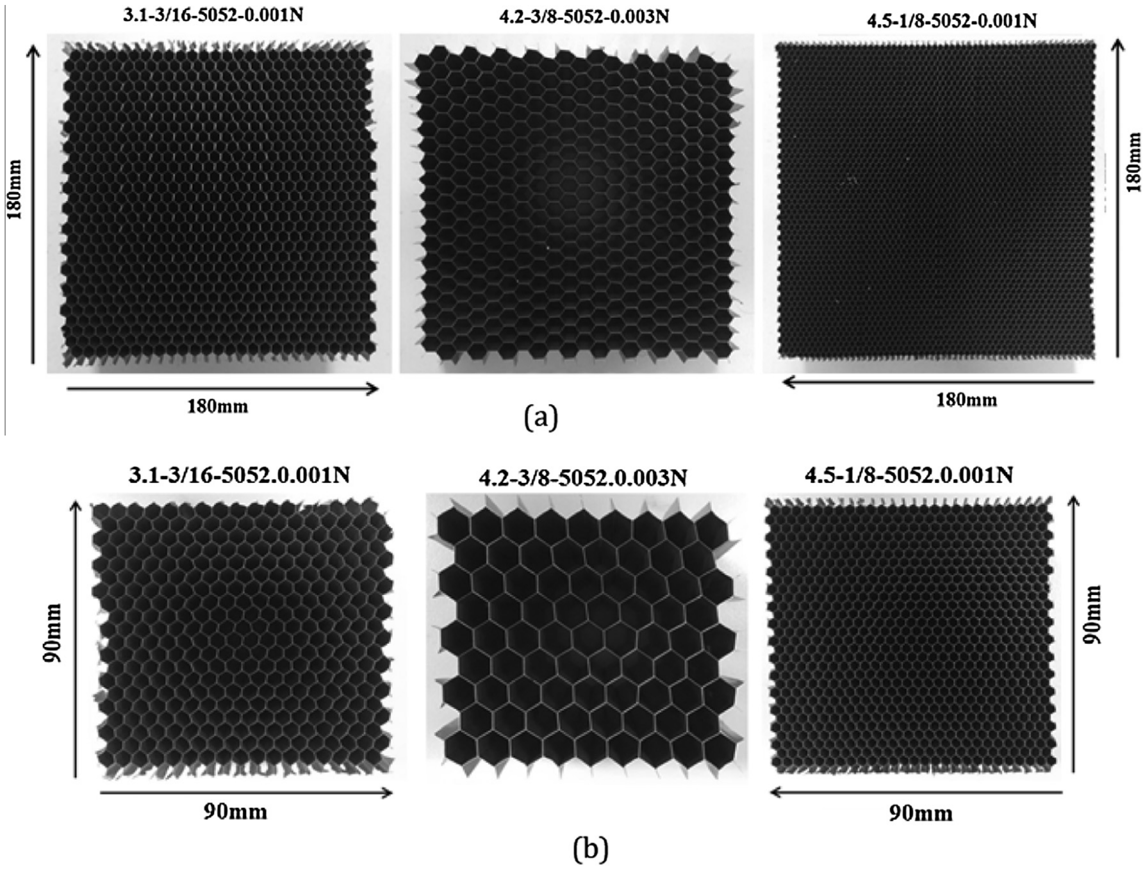

Fig. 1. Three types of hexagonal aluminum honeycomb specimens used in (a) indentation tests and (b) compressive tests.