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Quasi-static and dynamic experiments of aluminum honeycombs under combined compression-shear loading

ASM Ashab, Dong Ruan *, Guoxing Lu, Yat Choy Wong

Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, VIC 3122, Australia

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ABSTRACT

In this paper, aluminum hexagonal honeycombs are experimentally studied for their mechanical behavior under combined compression-shear loads. Quasi-static and dynamic tests were conducted at five different loading velocities ranging from 5×10^{-5} ms^{-1} to 5 ms^{-1} using MTS and INSTRON machines, among which tests at 0.5 ms^{-1} and 5 ms^{-1} were conducted for the first time. Specially designed fixtures were employed to apply combined compression-shear loads to honeycombs at angles of 15°, 30° and 45° respectively. Three types of HEXCELL® 5052-H39 aluminum honeycombs with different cell sizes and wall thicknesses were crushed in two different plane orientations (TL and TW). The deformation, crushing force, plateau stress and energy absorption of aluminum honeycombs are presented. The effects of loading plane, loading angle and loading velocity are discussed. An empirical formula is proposed to describe the relationship between plateau stress and loading angle.

1. Introduction

Lightweight aluminum honeycombs are commonly used in aerospace, automotive, naval and other industries for their excellent energy absorption capabilities and high strength-to-weight ratio. A honeycomb structure has one out-of-plane (T) and two in-plane (L and W) directions, as shown in Fig. 1.

The mechanical behavior of aluminum honeycombs under quasi-static and dynamic uniaxial compression loads has been extensively investigated [1–12]. Gibson and Ashby [1] studied the deformation mechanism of honeycombs loaded in both the in-plane and out-of-plane directions. They found that honeycombs were much stiffer and stronger in the out-of-plane direction than in the in-plane directions [1,2]. When honeycombs were compressed in the out-of-plane (T) direction, it was found that they could undergo large deformations under almost constant force/stress. This relatively constant stress was defined as the plateau stress, σ_{pl}. Honeycomb cell length (l), cell wall thickness (t) and strain rate ($\dot{\varepsilon}$) were found to affect the plateau stress [1]. A semi-empirical formula to determine plateau stress of hexagonal honeycomb cells was derived by McFarland [3]. Later on, the effect of cell wall thickness to edge length ratio (t/l) on the plateau stress was theoretically derived by Wierzbicki [4], where the plateau stress was found to increase with t/l ratio by a power law with an exponent of 5/3. Yamashita and Gotoh [5] and Xu et al. [6] found good agreement of their experimental results with the theoretical prediction as proposed by Wierzbicki [4].

Wu and Jiang [7] tested aluminum honeycombs at different loading velocities in the out-of-plane (T) direction and found that crushing strength increased proportionally with initial striking velocity. The effect of strain rate on the plateau stress of honeycombs loaded in the out-of-plane (T) direction was experimentally and numerically investigated by Zhou and Mayer [8], Yamashita and Gotoh [5], Xu et al. [6,9], Hou et al. [10], Wang et al. [11], Ashab et al. [12,13], Li et al. [14], Foo et al. [15] and Akatay et al. [16] and so on. They all observed a power law relationship between the plateau stress and strain rate. Xu et al. [9] also reported that entrapped air enhanced the plateau stress of aluminum honeycombs loaded in the out-of-plane (T) direction.

The in-plane mechanical properties of aluminum honeycombs have been studied by many researchers [1,8,17–28]. Gibson and Ashby [1] reported that with an increase of relative density (ρ^*/ρ_s) or t/l ratio, the in-plane plateau stress increased. Hönig and Stronge [17,18] found that the effect of impact velocity on the stress enhancement of honeycombs under in-plane uniaxial compression was due to increasing translational micro-inertia with impact velocity. Ruan et al. [19] employed finite element software ABAQUS to investigate the effects of t/l ratio and impact velocity on the in-plane deformation mode and plateau stress. They derived an empirical formula to describe the relationship between plateau stress, t/l ratio and velocity. Other researchers, Zhou and Mayer [8], Khan et al. [2], Zhu and Mills [20], Hu et al. [21–24], Ali et al. [25],

* Corresponding author.
E-mail addresses: aashab@swin.edu.au (A.S.M. Ashab), druan@swin.edu.au (D. Ruan), glu@swin.edu.au (G. Lu), ywong@swin.edu.au (Y.C. Wong).

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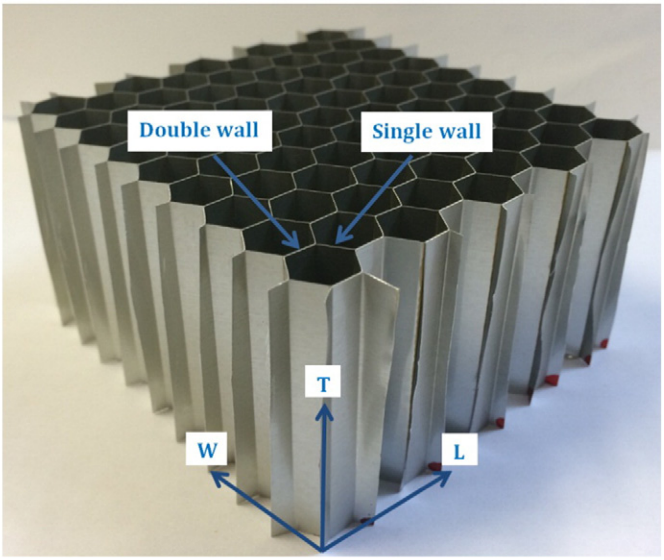

Fig. 1. Photograph of aluminum honeycomb (4.2–3/8–5052–0.003 N). T is the out-of-plane direction. L and W are the in-plane directions.

Papka and Kyriakides [26–28] also studied the in-plane mechanical properties of hexagonal honeycombs theoretically, experimentally and numerically.

In real world applications of aluminum honeycombs, they may be subjected to a pure compressive load or a combined compression-shear load. A limited number of studies [29–40] have been conducted to analyze the deformation mechanism and mechanical properties of honeycombs under combined compression-shear loads. Mohr and Doyoyo [29] used an ARCAN apparatus in their experimental work to measure the normal and shear stresses. They also conducted theoretical and numerical analysis to derive equations for normal and shear stresses under such loading. Later, Mohr and Doyoyo [30, 31] introduced a modified universal biaxial testing device (UBTD) in their experiments to study the mechanical response of aluminum honeycombs under combined compression-shear loads. They employed different loading angles, ranging from 0°–90°. They classified the deformation into five regions as Elastic I, Elastic II, Nucleation, Softening and Crushing. They described the correlation between normal and shear stresses for each of the different deformation regions. They also suggested an elliptic envelope in the nucleation region on the normal and shear stress planes.

Hong et al. [32,33] applied quasi-static and dynamic horizontal and vertical loads simultaneously by means of two actuators to conduct combined compression-shear tests of aluminum honeycombs. Their experimental results showed that for both normal and shear stresses, in proportional and non-proportional combined compression-shear loads, the stresses were identical; that is they did not find any effect of loading path on the crushing stress. However, under non-proportional combined compression-shear loads, different stacking fold patterns were observed. Furthermore, they observed that with an increase of impact velocity only the normal stress increased, but not the shear stress. They also proposed a relationship between the macroscopic yield criterion and the impact velocity. Hou et al. [34,35] conducted experimental and numerical analysis of combined compression-shear loading of aluminum honeycombs at high strain rate using a split Hopkinson pressure bar (SHPB). They reported on the crushing behavior of aluminum hexagonal honeycombs under combined compression-shear loads at various loading angles from 0° to 60° in the TW plane. They also observed crushing strength enhancement at a high velocity (15 ms^{-1}). Hou et al. [36] employed finite element analysis to investigate the normal and shear crushing of honeycombs under combined compression-shear loading. They found good agreement between numerical results and experimental results. Moreover, they found elliptical envelopes on the normal stress and shear stress plane for both the quasi-static and dynamics loading cases. Ashab et al. [37] conducted quasi-static combined compression-shear tests on aluminum honeycombs and observed similar deformation patterns of crushing for honeycombs loaded in the TL and TW planes.

Tounsi et al. [38] developed a numerical model of honeycombs to investigate the effects of loading angle and in-plane orientation on the crushing response of aluminum honeycomb at 15 ms^{-1} loading velocity. Most recently, Tounsi et al. [39] conducted experiments to study the effects of loading angle and in-plane orientation angle on the deformation mode of honeycombs subjected to a mixed shear-compression loading. They observed three different deformation modes: Mode 1 (Fold formation on a single side), Mode 2 (Fold formation on both sides) and Mode 3 (combination between Mode 1 and Mode 2). Zhou et al. [40] conducted quasi-static combined compression-shear tests on Nomex honeycombs to study their macroscopic yield criteria.

The previous studies of aluminum honeycombs under combined compression-shear loads are briefly summarized in Table 1. Those previous dynamic combined compression-shear tests were conducted using either gas gun or split Hopkinson pressure bar and the loading velocity decreased in a single test. In the present study, an MTS and a high speed INSTRON machines are employed, which are capable of applying quasi-static and dynamic loads at constant cross-head velocities of up to

Table 1
A brief summary of the studies of aluminum honeycombs subjected to combined compression-shear loads.

Researchers	Velocity (ms^{-1})	Loading angle	Equipment and method used	Percentage of crushing displacement with respect to specimen height	Type of honeycombs	
					Cell size, D (mm)	Cell wall thickness, t (mm)
Mohr and Doyoyo (2003–2004) [30–31]	1.67×10^{-5}	0°–90°	Arcan apparatus, universal biaxial testing device	67%	8.3 and 5.36	0.033 and 0.033
Hong et al. (2006) [32]	1×10^{-4}	15°	INSTRON	80%	9.5	0.025
Hong et al. (2008) [33]	6.7–6.8	15°	Gas gun	88%	9.5	0.025
Hou et al. (2010 − 2011) [35,36]	15 and 1×10^{-4}	0°–60°	SHPB and FEA	52%	6.35	0.076
Tounsi et al. (2013) [38]	15	0°–60°	FEA	60%	6.35	0.076
Tounsi et al. (2016) [39]	15	0°–60°	SHPB	56%	6.35	0.076
Current work	5×10^{-5} 5×10^{-4} 5×10^{-3} 5×10^{-1} and 5	15°, 30° and 45°	MTS and high speed INSTRON	90%	3.175, 4.763 and 9.525	0.0254, 0.0254 and 0.0762