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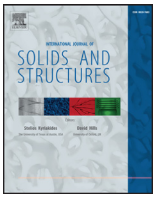

Dynamic behaviour of honeycombs under mixed shear-compression loading: Experiments and analysis of combined effects of loading angle and cells in-plane orientation

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ABSTRACT

Cellular materials such as aluminium honeycombs combine lightweight challenges with high mechanical performance for crash energy absorption regulations. This paper investigates experimentally the dynamic behaviour of an aluminium alloy honeycomb under mixed shear-compression loading with a special attention on the combined effects between the cells in-plane orientation and the loading angles. An improvement of an existing experimental SHPB set-up is proposed and an original measurement technique based on an electro optical extensometer is used to overcome a separation phenomenon observed during the test. A significant effect of the loading angle ψ is reported in the crushing responses. The in-plane orientation angle β effects become more significant when the loading angle increases. An investigation of collapse mechanisms is also presented. Three deforming pattern modes are identified and it is shown that their distribution is related to the combined effects of the in-plane orientation angle β and the loading angle ψ.

1. Introduction

Cellular materials are increasingly used in the transportation industry due to their high strength/weight ratio which contribute to develop environmentally friendly vehicles. Among this class of materials, aluminium alloy honeycombs have an outstanding capability in absorbing energy. Several studies reported by Gibson and Ashby (1997), Gibson et al. (1989), Papka and Kyriakides (1999), Yang and Huang (2005) have investigated quasi-static and dynamic behaviour of honeycombs under uni-axial compression loading. However, in real situations of crash events, the load direction is rarely uni-axial. More recently, Doyoyo and Mohr (2003), Hong et al. (2008), Bing (2011), Tounsi et al. (2012) have investigated honeycomb behaviour under more realistic conditions mixed shear-compression loading. In this case of mixed loading, two angles are defined : the loading angle ψ is the angle between load direction and out-of-plane direction and the in-plane orientation angle β is the angle between shear load direction and ribbon direction in the cell plane.

The experimental techniques and methods to study the crushing response of aluminium honeycomb under quasi-static mixed shear-compression loadings with respect to out-of-plane loading are investigated by Doyoyo and Mohr (2003) and Mohr and Doyoyo (2004b). An Enhanced Arcan Apparatus (EAA) (Arcan et al. (1978)) was used to apply a controlled biaxial displacement field to the boundaries of a butterfly-shaped 5056-H39 aluminium alloy honeycomb specimen. Their experimental tests have been however realised for only one specific in-plane orientation angle $\beta = 90°$. Recently, Zhou et al. (2012) investigated experimentally the quasi-static behaviour of Nomex honeycombs under mixed shear-compression loading using the Arcan set-up. They were interested to analyse the in-plane orientation angle effects. Four in-plane orientation angles with various loading angle were tested. A significant effect of the in-plane orientation angle β is reported on their experimental results under quasi-static loading.

Hong et al. (2003, 2004, 2006a, 2006b) have investigated the quasi-static and dynamic behaviour of 5052-H38 aluminium alloy honeycomb under mixed shear-compression loading taking into account the in-plane orientation angle effects. Quasi-static tests were performed using a bi-axial testing machine. Dynamic tests at a loading velocity of 6.7 m/s were performed using an impact testing machine with a gas gun. However, only one loading angle ψ fixed at 15° was investigated. A significant effect of the in-plane orientation angle β on the crushing responses was reported. However, under

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Table 1
Honeycomb behaviour studies summary.

Authors (year)	ψ	β	QS	DYN
Hong et al. (2002–2004)	Yes	No	Yes	Yes
Hong et al. (2006–2008)	No	3 angles	Yes	Yes
Hou et al. (2010–2011)	Yes	2 angles	Yes	Yes
Zhou et al. (2012)	Yes	4 angles	Yes	No

dynamic loading, as the loading angle was fixed the combined effects with the in-plane orientation angle were not investigated. The collapse mechanisms under quasi-static mixed shear-compression loading were also analysed. An inclined stacking patterns of folds due to the asymmetric location of horizontal plastic hinge lines is reported. Under dynamic loading, due to the weak fixed value of ψ angle, a similar progressive folding mechanism as that observed for uni-axial compression is reported.

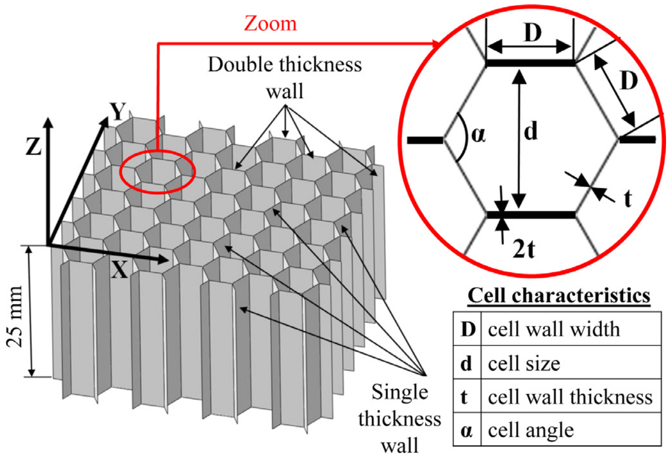
In order to perform dynamic experiments at a higher impact velocity and to study the effect of the loading angle ψ on a larger range, Hou et al. (2011a) developed new experimental techniques for testing the aluminium honeycomb behaviour under mixed quasi-static and dynamic shear-compression loadings. It is composed by two short cylindrical bars with one bevel end. Specimens made of 5052 aluminium alloy honeycomb are crushed under quasi-static loading conditions using the mixed shear-compression loading device on a universal tension/compression machine with a loading velocity of about 1 mm/min. The experiments were performed under dynamic loading conditions at the impact velocity of about 15 m/s by introducing the mixed shear-compression loading device on a large-diameter Nylon Split Hopkinson Pressure Bar system (SHPB) with beveled ends of different angles. The loading angle ranged from $\psi = 0°$ that presents the uni-axial compression loading case to $\psi = 60°$ by steps of 10° with two in-plane orientation angles $\beta = 0°$ and $\beta = 90°$. It was reported that the loading angle ψ has a strong effect on both the initial peak and the average crush strength that decrease with increasing loading angles. Two co-existing deforming pattern modes under combined shear-compression were identified. The origin of the two co-existing modes was however not further explained. Concerning the influence of both tested in-plane orientation angles ($\beta = 0°$ and $\beta = 90°$) no significant effect was reported.

Table 1 summarizes the state of the art on the behaviour of honeycombs under quasi-static and dynamic combined shear-compression loadings. It appears that the combined effect of ψ and β angles was not deeply investigated especially under dynamic loadings.

In this paper, we propose to investigate the combined effects of the in-plane orientation angle and the loading angle on the dynamic crushing responses of a Al5056 honeycomb. The paper is organized as follows. Section 2 presents the specimens and materials preparation. Section 3 is dedicated to experimental techniques and methods used to perform crushing tests. In particular, an improvement of an existing set-up based on FE simulation and an original measurement technique to overcome a separation phenomenon between the input bar and the input beveled bar are proposed. Section 4 presents and analyses the experimental results not only in terms of crushing responses but also in terms of collapse mechanisms.

2. Specimens and materials preparation

The specimen is an Al5056-N-6.0-1/4-0.003 aluminium alloy honeycomb. The relative density (the ratio of the honeycomb density and the base material density) is $\rho^* = 3\%$. The cell wall width is D = 3.67 mm, the single cell wall thickness is t = 76 µm , the cell angle is $\alpha = 120°$ and the cell size is d = 6.35 mm (Fig. 1). It contains 39 full cells on the honeycomb cross-section. The specimen



Cell characteristics

D	cell wall width
d	cell size
t	cell wall thickness
α	cell angle

Fig. 1. The honeycomb specimen geometry and cell parameters.

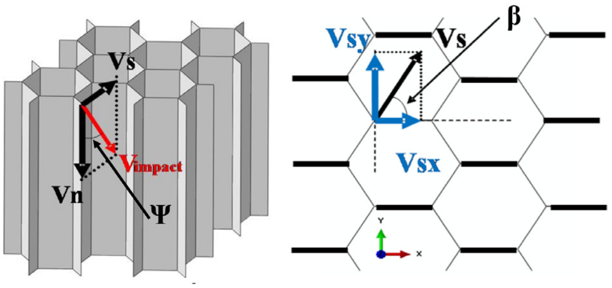


Fig. 2. The loading angle ψ and the in-plane orientation angle β.

dimensions are 44 × 41 × 25 mm in the directions of X, Y and Z respectively. The X and Y directions are the in-plane directions. X is the ribbon direction and Y is the width direction. Z direction is the strongest direction of honeycomb structure commonly used for the improvement of energy absorption capabilities. It is defined by the out-of-plane direction. Aluminium honeycomb specimens are extracted from a commercial sandwich panel core using an Electrical Discharge Machining (EDM) to avoid any influence of the cutting technique.

The dimensions of the specimen are chosen so that the specimen is a representative elementary volume as reported by Hou et al. (2011a). Under mixed loading, the loading angle ψ and the in-plane orientation angle β are presented in Fig. 2.

The influence of the in-plane orientation angle (four different angles $\beta = 0°$, $\beta = 30°$, $\beta = 60°$ and $\beta = 90°$) is studied by changing the cutting direction of the specimens (Fig. 3).

3. Experimental techniques and methods

Based on a combined shear-compression device developed by Hou et al. (2011a) introduced in a SHPB set-up, numerical simulations are carried in order to analyse in details the whole testing system.

3.1. Mixed shear-compression loading device

A new combined shear-compression loading device was developed by Hou et al. (2011a) to be introduced in a SHPB set-up and to realise mixed loading experiments. It is based on two short beveled bars inclined with different angles in order to achieve five loading angles ψ from 0° to 60° with a step close to 15°. The device is positioned between two large diameter bars made of Pa66 with 3 m in length and 60 mm in diameter (Fig. 4).

The two short cylindrical beveled bars are made of the same material and diameter than the Hopkinson bars. A Teflon sleeve with

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