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Numerical investigation, experimental validation and macroscopic yield criterion of Al5056 honeycombs under mixed shear-compression loading

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A B S T R A C T

Numerical simulations of honeycomb behaviour under mixed shear-compression loading are performed to overcome a limitation of the experimental measurements and to investigate the normal and the shear honeycomb behaviours separately. A detailed FE model allowing to simulate the mixed shear-compression honeycomb behaviour is presented. A validation between numerical and experimental results in terms of crushing responses and collapse mechanisms allows to dissociate the normal and shear forces components. They are used to identify the parameters of a macroscopic yield criterion expressed as a function of the impact velocity, the loading angle and the in-plane orientation angle. A well known dynamic enhancement phenomenon is confirmed by this macroscopic yield criterion. However, as a new result, this dynamic enhancement is reversed when the loading angle reaches a critical value. An analysis of the collapse mechanisms is carried out under both quasi-static and dynamic loading conditions in order to explain this inversion.

1. Introduction

Cellular materials are increasingly used in the transportation industry due to their high strength/weight ratio which contributes to the development of environmentally friendly vehicles. Among this class of materials, aluminium alloy honeycombs have an outstanding capability for absorbing energy. Several studies reported by Gibson and co-workers [1–9] have investigated the quasi-static and dynamic behaviours of honeycombs under uni-axial or bi-axial compression loadings (out-of-plane or in-plane loadings).

A limited number of studies reported by Doyoyo and co-workers [10–21] have investigated honeycomb behaviour under more realistic working conditions that occur in crash events where shear and compression loadings are mixed. In this case, 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.

Aluminium alloy honeycombs are considered as materials for different applications including lightweight structures combining a high stiffness and energy absorption capabilities under dynamic loading. The state of the art of all experimental studies and numerical studies on honeycombs allows concluding that a macroscopic yield criterion expressed as function of the impact velocity, the loading angle and the in-plane orientation angle is required to provide a constitutive description of the yield behaviour of honeycomb structures.

For that, Mohr and Doyoyo [11] suggested a linear fit for the crushing envelope obtained from their honeycomb specimens tested with only one in-plane orientation angle $\beta = 90°$. Hong et al. [12,13] developed a quadratic yield criterion that gives a good description of the macroscopic crush behaviour of honeycomb specimens under quasi- static and dynamic loading conditions with different in-plane orientation angles ($\beta = 0°$; $\beta = 30°$ and $\beta = 90°$). However, they investigated the impact velocity for only one loading angle $\psi = 15°$. An elliptical yield envelope is found for both the quasi-static and dynamic loading cases by Hou et al. [15] using the Levenberg–Marquardt Algorithm (LMA). Their macroscopic yield criterion takes into account the loading angle ψ and the impact velocity but without any influence reported on the in-plane orientation angle for $\beta = 0°$ and $\beta = 90°$. However, a significant effect of this in-plane orientation angle was reported by Zhou et al. [16] on the experimental yield surface of Nomex honeycombs.

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In this paper we propose to investigate the combined effects of the in-plane orientation angle, the loading angle and the impact velocity on the macroscopic yield criterion of an Al5056 honeycomb. The paper is organized as follows. Section 2 presents the experimental set-up and limitations. Section 3 is dedicated to numerical simulations used to perform virtual crushing tests. Comparative studies between numerical and experimental results are proposed in Section 4. In particular, a validation is performed in terms of both crushing responses and collapse mechanisms under both quasi-static and dynamic loadings. Section 5 presents separately the numerical shear and normal honeycomb behaviours based on the validated numerical model. The shear and normal crushing responses are used in Section 6 in order to present the macroscopic yield criterion as function of ψ, β and the impact velocity.

2. Experimental set-up and measurement limitations

2.1. Specimens and experimental set-up

Al5056-N-6.0-1/4-0.003 aluminium alloy honeycomb specimens are considered. 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. The specimen contains 39 full cells on the honeycomb cross-section. The specimen dimensions are 44 × 41 × 25 mm in the directions of X, Y and Z respectively. X and Y directions are the in-plane directions. Z direction is the out-of-plane direction (Fig. 1). Under mixed shear-compression loading, the loading angle ψ is defined by the angle between the out-of-plane direction and the load direction. The in-plane orientation angle β is defined by the angle between the ribbon direction and the shear load direction (Fig. 1). Five loading angles are considered for the experimental study. $\psi = 0°$ corresponds to uniaxial compression loading and $\psi = 15°$ / $\psi = 30°$ / $\psi = 45°$ / $\psi = 60°$ correspond to mixed shear-compression loadings. For every loading angle ψ, the in-plane orientation angle β is varied. Four in-plane orientation angles ($\beta = 0°$ / 30° / 60° / 90°) are considered. The experimental program is divided into 2 parts : The specimens are crushed with an impact velocity of 15 m/s for the dynamic experiments and with a loading speed of 1 mm/min for the quasi-static experiments. A mixed shear-compression loading device is introduced in a Nylon SHPB set-up to perform the dynamic experiments and is adapted to a universal tensile/compression machine to perform the quasi-static ones (Fig. 2).

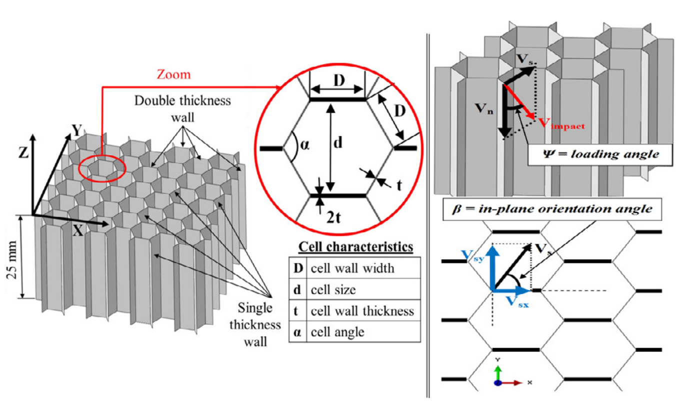

Fig. 1. The honeycomb specimen geometry, cell parameters, loading angle and in-plane orientation angle. [20].

As detailed in Tounsi et al. [19] a high strength steel sleeve of 10 mm thick with a Teflon sleeve of 5 mm thick put inside are used in the experiments in order to limit the expansion phenomenon and to ensure a good alignment during tests (Figs. 2 and 3).

In the following, analyses are focused on the initial peak force F^{Peak} and the average crushing force $F^{Average}$ (plateau) that characterise a typical response of honeycomb under impact loadings.

2.2. Experimental set-up limitations

In order to investigate in detail the mixed shear-compression behaviour of honeycombs and to develop a macroscopic yield criterion taking into account the loading angle ψ, the in-plane orientation angle β and the impact velocity, the normal and shear responses should be dissociated. However, the device used to load the specimens (Fig. 3) leads to a transverse component force F_Y which can not be measured experimentally. Indeed, the SHPB set-up only provides the axial component force (F_Z) of the crushing responses of aluminium honeycomb under mixed shear-compression loadings. The relationship between the forces obtained by the experimental set-up and the normal and shear forces on honeycomb specimen are presented by Fig. 3 and by the following equations :

$$F_X \approx 0 \tag{1}$$

$$F_Y = F_N \sin(\psi) - F_S \cos(\psi) \tag{2}$$

$$F_Z = F_N \cos(\psi) + F_S \sin(\psi) \tag{3}$$

So, the normal and the shear force components respectively F_N and F_S , which are required for the macroscopic yield criterion, can not be calculated directly using Eqs. (2) and (3).

One way to overcome this limitation is to simulate the experimental tests in order to have access to local force components. That is why, numerical simulations are carried out taking the effect of the loading angle ψ and the in-plane orientation angle β into consideration. In addition, an analysis of the crushing responses and the collapse mechanisms is realised.

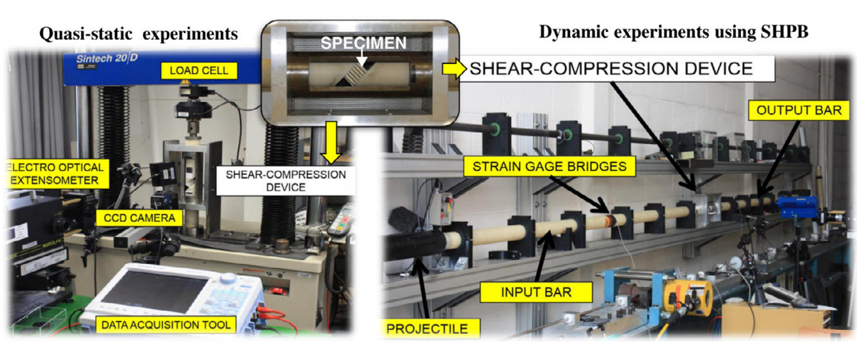

Fig. 2. The quasi-static and dynamic experimental set-up. [20].