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Reduced numerical model to investigate the dynamic behaviour of honeycombs under mixed shear–compression loading

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ABSTRACT

Cellular materials such as aluminium honeycombs combine lightweight with an efficient crash energy absorption capability. They have a major role in a wide range of transport applications to reduce gas emission by the design of lighter structures but remaining safe in accident case. Many investigations on the honeycomb behaviour have been performed, under uni-axial compression loading and more recently under mixed shear–compression loading. The influence of the in-plane orientation has not been however considered. The objective is to develop a reduced numerical model able to investigate, with a reduced cost of calculations, the dynamic behaviour of honeycomb under mixed shear–compression loading and taking into account of the in-plane orientation angle. Reduced model based on the periodicity procedure is developed and its validity range is evaluated. The numerical results show that in terms of pressure–crush curve and collapse mechanisms, the reduced model is consistent with a complete FE model composed of 39 cells with a CPU-time gain efficiency about 97.17%. The reduced model is valid from a loading angle $\psi = 0^\circ$ to a loading angle ψ_{limit} contained between $\psi = 30^\circ$ and $\psi = 45^\circ$. The reduced model allows investigating in depth the influence of the in-plane orientation and the loading angles on the crush behaviour with minimum time calculations in accord with the validity range.

1. Introduction

In order to improve sustainable development in the transport sector by reducing vehicle mass while maintaining the same safety level, one way is the use of cellular materials such as honeycombs. Due to a well balanced energy absorption capability-to-mass ratio (specific energy), aluminium honeycombs are frequently used as crash energy absorbing structures in vehicle application. In this context, several studies have been developed in the open literatures to understand their mechanical behaviour under quasi-static and dynamic loading conditions. The mechanical behaviour of honeycomb used for energy absorption applications under uni-axial loading conditions have been investigated numerically, experimentally and analytically by many authors such as McFarland [1,2], Wierzbicki [3], Wierzbicki and Abramowicz [4], Gibson and Ashby [5], Zhao and Gary [6], and Aktay et al. [7].

An analytical and experimental study under uni-axial loading conditions has been realized by Wu and Jiang [8] in order to investigate the effects of cell size, the specimen height and material strength in the crushed specimen. Their results suggest that a honeycomb structure with a smaller cell size and core height, and made of a stronger material gives a better energy-absorbing capability per areal density. An increase of up to 74% of the crush strength was observed between dynamic and quasi-static loading conditions. The simulation parameters such as element size, impact velocity and material properties on the crush behaviour of honeycomb have been introduced in a numerical model developed by Chawla et al. [9]. An increase in impact velocity increases the initial peak load of honeycomb but does not significantly alter the crushing strength. The effect of the cell shape and the cell wall thickness through FE models describing the quasi-static crush behaviour under uni-axial compression in the out-of-plane direction has been investigated by Yamashita and Gotoh [10]. Their numerical simulations suggest that the crush strength is higher for smaller branch angle and it increases with the foil thickness. They showed that the maximum crush strength value is obtained for a regular hexagon cell shape. A large enhancement of crushing strength between static and dynamic out-of-plane compression loadings has been reported by Wu and Jiang [8], Zhao et al. [6,11], Goldsmith and Sackman [12], and Schreyer et al. [13].

Many authors such as Doyoyo and Mohr [14], Mohr and Doyoyo [15–17], and Hong et al. [18–20] have investigated the honeycomb

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behaviour under quasi-static and dynamic multi-axial loading conditions. These studies were motivated by the fact that in the real crash events the shear and compression loads are combined. Both experiments and numerical simulations have been adapted and validated under quasi-static combined shear–compression loading by Mohr and Doyoyo [15], but in their analysis of collapse mechanisms, the effect of the in-plane orientation angle β (the in-plane orientation angle is defined by the angle between the double wall thickness direction and the shear load direction in the cell plane) is not considered. Nevertheless, a significant effect of this in-plane orientation angle β on the mechanical behaviour of aluminium honeycombs and the collapse mechanism has been reported by Hong et al. [18,20]. Their quasi-static experimental results indicated that the energy absorption rate depends on the in-plane orientation angle β and on the ratio of the shear stress to the compressive stress. The effect of dynamic loading is however reported for only one loading angle. Recently, Hou et al. [21] proposed a new experimental set-up for investigating the dynamic behaviour of honeycombs under mixed shear–compression loading. Their study combines the experiments based on a large-diameter Nylon Split Hopkinson Pressure Bar (SHPB) technique and the FEM analyses. A strong effect of the loading angle on the pressure–crush curve and on the collapse mechanisms has been reported. Indeed, two co-existing deforming patterns have been observed. In order to distinguish the normal and the shear behaviour under multi-axial loading, Hou et al. [22] exploit the results of a simplified honeycomb finite element model without taking the effect of the in-plane orientation angle β into consideration. For numerical simulations, as found in the open literature, a virtual honeycomb specimen called ‘cell-model’ may be considered as a three conjoint half wall in a “Y” configuration model. This configuration is however only valid for uni-axial compression loading. In their numerical study, Mohr and Doyoyo [15], as well as Hou et al. [22], used a virtual honeycomb specimen called a ‘row-model’ made up of a row of cells. Unfortunately, their model is only valid under combined shear–compression loading with a single in-plane orientation angle ($\beta = 90^\circ$) and the influence of this angle β is not investigated. The existing simplified finite element models in the open literature are summarized in Table 1.

Table 1
Existing simplified models.

Existing simplified models	Boundary conditions	Uni-axial $\psi = 0^\circ$	Mixed	
			ψ	β
Cell model	Local symmetric BC's	Yes	No	No
Row model	Local symmetric BC's	Yes	Yes	No

These simplified models are unable to simulate correctly the mixed shear–compression behaviour by taking the in-plane orientation angle β into account. The goal of the present study is to develop a reduced finite element model which allows one to study numerically the influence of the loading angle ψ and the in-plane orientation angle β on the honeycomb crush behaviour under mixed shear–compression loading. A reduced model involving a representative elementary cell of honeycomb structure, based on the periodicity procedure, is proposed in order to reduce the CPU-time of calculations. Different loading configurations are carried out in order to evaluate the validity range of the reduced model and to test its performances under mixed loading.

2. FE model and experimental validation

2.1. FE model

2.1.1. Honeycomb specimen and materials

The specimen used in this study is an Al5056-N-6.0-1/4-0.003 aluminium alloy honeycomb. It contains 39 cells on the honeycomb cross-section. The specimen dimensions are 44*41*25 mm in the directions of X, Y and Z respectively. It is chosen such that the specimen is a representative elementary volume in real applications as referred by Hou et al. [21]. The cell has a regular hexagonal shape, an angle of 120°, with a cell wall thickness $t = 76$ μm, a cell size $d = 6.35$ mm, and a cell wall width $D = 3.67$ mm (Fig. 1).

The aluminium alloy behaviour is assumed to be elastic–plastic. Its constitutive model parameters was determined using an inverse method from uni-axial quasi-static crushing test of aluminium honeycomb structure [23]. By this way, the identified mechanical behaviour takes into account the local hardening in the folded parts, the glue effects of bonded parts and any geometry imperfections.

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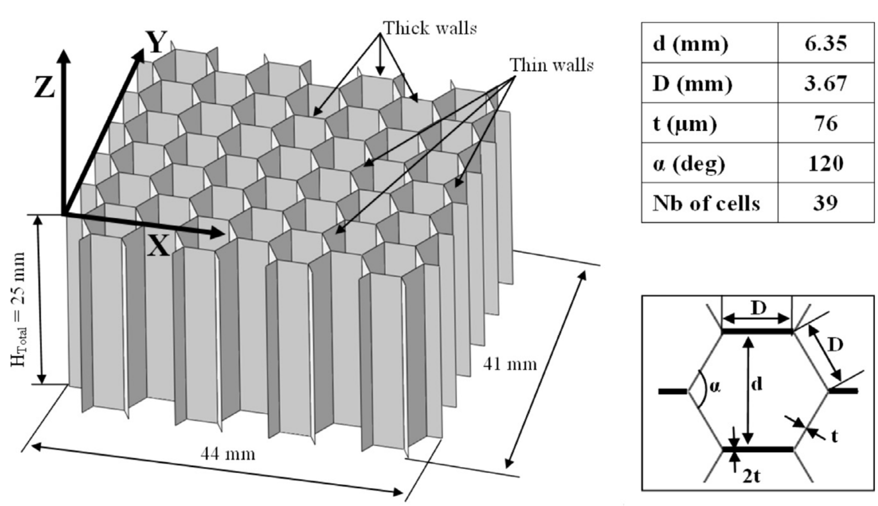

Fig. 1. The honeycomb specimen.