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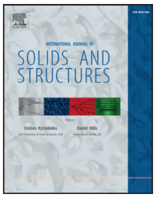

Compressive crushing of novel aluminum hexagonal honeycombs with perforations: Experimental and numerical investigations

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ABSTRACT

The quasi-static compressive behavior of novel aluminum hexagonal honeycombs with perforations on the cell wall is investigated experimentally and numerically. Compressive experiments on the perforated honeycombs with different cell numbers are conducted to study the effect of specimen sizes. The measured collapse stress is almost insensitive to the specimen sizes, while the crushing stress increases with the cell numbers and finally converges to a stable plateau for the specimens beyond 15 × 15 cells. Finite element simulations are performed to study the effects of perforation size, spacing and shape on the mechanical properties of honeycombs. The results reveal that perforation size is a key parameter that affects the compressive mechanical properties and deformation patterns of honeycombs. The perforation number along the height direction of a cell has nearly no influence on the collapse stress, and only affect the crushing stress when the perforation size is large. The perforation shape impacts the collapse of honeycombs but has minor effect on the subsequent crushing stage.

1. Introduction

Honeycombs are widely used in various engineering applications, such as aerospace, high speed train and automotive industries, due to their high strength-to-weight ratio, high energy absorption capacity, cost efficiency and multifunctionality (Gibson and Ashby, 1997; Yamashita and Gotoh, 2005; Feng et al., 2016; Liu et al., 2016). They are frequently used as core materials of sandwich structures to carry load (Zhang and Ashby, 1992), absorb energy (Goldsmith and Sackman, 1992), absorb radar wave (Feng et al., 2016), transfer heat/fluid (Liu et al., 2016), and so on. The cell geometries could be hexagonal, square, circular and other configurations including ones with negative Poisson's ratio (Gibson and Ashby, 1997; Chen et al., 2009; Karagiozova and Yu, 2005; Prall and Lakes, 1997). Honeycombs are made from metals, polymers and composites etc., according to their applications (Chen et al., 2009; Wu and Jiang, 1997; Wilbert et al., 2011; Foo et al., 2007). Of all honeycombs, metallic ones with hexagonal cell are most common (Wilbert et al., 2011).

The wide use of honeycombs in engineering has attracted many researchers to explore their mechanical properties and deformation mechanism. The elastic properties of honeycombs under different loading conditions have been well investigated (Gibson and Ashby, 1997; Zhang and Ashby, 1992; Zhang and Ashby, 1992; Grediac, 1993; Shi and Tong, 1995; López Jiménez and Triantafyllidis, 2013). For the energy absorption applications, they go through large deformation to absorb energy, so the out-of-plane crush behavior of honeycombs has also drawn much attention. Theoretical models have long been developed to predict the crushing stress and wavelength of honeycombs subjected to axial compression loading (McFarland, 1963; Wierzbicki, 1983). Massive experiments have been done to study the crush behavior of honeycombs under both quasi-static and impact loadings (Yamashita and Gotoh, 2005; Goldsmith and Sackman, 1992; Wu and Jiang, 1997; Wilbert et al., 2011; Mohr and Doyoyo, 2004, Xu et al., 2012, Wang et al., 2014; Tounsi et al., 2016; Papka and Kyriakides, 1998). The effects of strain rate (Tao et al., 2015; Alavi Nia and Sadeghi, 2013), inertia (Hou et al., 2012) and entrapped air (Xu et al., 2012) have been studied, trying to provide a deep understanding on the dynamic behavior of honeycombs. Through optimal design (Xie and Zhou, 2015; Caccese et al., 2013), the honeycombs may achieve better energy absorption performance.

Specimen dimensions are vital in mechanical testing of cellular materials. Elastic properties (Young's modulus and shear modulus) and collapse strength of hexagonal honeycombs under in-plane loadings were found to be highly depend on the ratio of the specimen size to the cell size and converge to the bulk properties for large specimens (Onck et al., 2001). Previous experimental results (Wu and Jiang, 1997; S. Xu et al., 2012) showed that spec-

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imen dimensions just had minor effect on the out-of-plane crushing strength. Xu et al. (2012) used specimens with 9 × 9 cells in their experiments to represent the bulk properties of honeycombs.

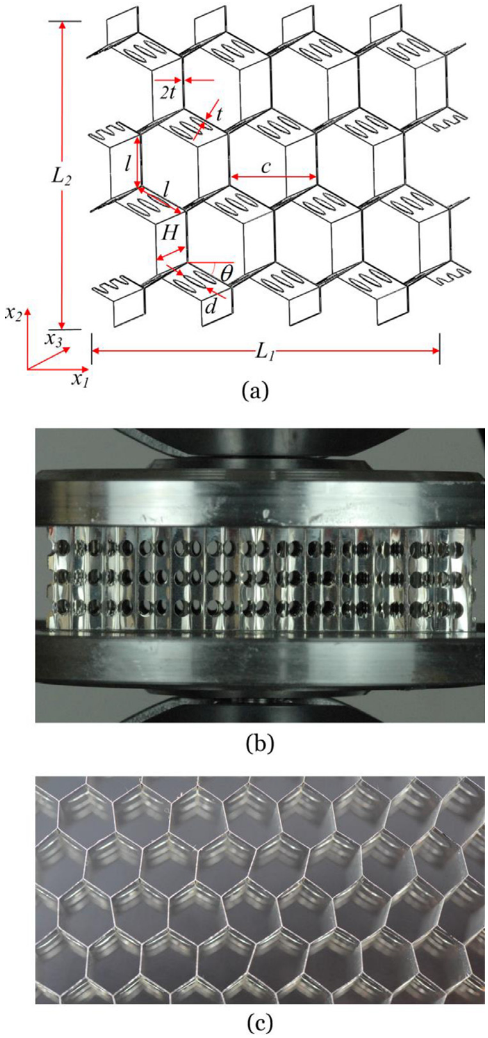
In addition to theoretical and experimental studies, finite element analysis (FEA) can be found in a mass of literature (Yamashita and Gotoh, 2005; Wilbert et al., 2011; Grediac, 1993; Papka and Kyriakides, 1998; Hou et al., 2012; Aktay et al., 2008; Deqiang et al., 2010; Mohr and Doyoyo, 2004, Jang and Kyriakides, 2015). Among which Wilbert et al. (2011) considered the collapse and crushing process in great detail and depth. Jang and Kyriakides (2015) numerically studied the effect of fabrication process on the onset of buckling and crushing of cold expanded honeycombs. Periodic unit-cells with different domain sizes were widely used to simulate the crush behavior of honeycombs (Yamashita and Gotoh, 2005; Wilbert et al., 2011; Hou et al., 2012). Full-scale model was also used to study the in-plane properties (Papka and Kyriakides, 1998) and out-of-plane properties under impact loadings (Deqiang et al., 2010). However, very fine meshes are required to simulate the honeycomb crush process with large strains, which lead the calculation to be time consuming. Especially for that under quasi-static loading condition, the calculation time will be much longer.

For conventional honeycomb heat/fluid exchanger (Liu et al., 2016), The honeycomb is put between two plates with the cells parallel to the plate for heat/fluid exchange. The honeycomb will be compressed in-plane under external mechanical load, which leads to a poor load-carrying capacity. The hexagonal honeycomb with perforations on the wall is an alternative core material for the sandwich construction, as shown in Fig. 1, which can carry load in its out-of-plane direction and provide heat/fluid exchange channels by the perforations on the wall. This configuration may enable good heat/fluid exchange performance as well as load-carrying capacity. In our previous study (Wang et al., 2013), we found that large perforations on the cell walls reduce the load-carrying capacity of honeycombs dramatically. Surprisingly, even though this design has been patented (Landi and Wilson, 1993; Landi and Wilson, 1998) and commercialized, there are few open literatures on this topic. It is still lacking of systematic understanding on how the perforations affect the mechanical behavior of honeycombs.

The aim of the present study is to investigate the quasi-static compressive behavior of novel aluminum hexagonal honeycombs with perforations. Emphasis is placed on how the perforations affect the mechanical properties of honeycombs. The article is organized in following manner. Compression experiments for the honeycomb specimens with various dimensions are conducted to study the effects of specimen sizes and circular perforations on the mechanical properties and failure patterns. The calculations of the compressive response are performed for aluminum hexagonal honeycombs with circular and elliptical perforations. Comparisons between the calculations and experiments are used to assess the fidelity of the simulation approach.

2. Experiments

In this work, the perforated aluminum alloy 3003 honeycombs were provided by Argosy XAC Composite Materials LTD in Shaanxi province, China. The honeycombs are fabricated by a commonly used gluing and expanding method. Circular holes are punched on the unglued part. The sketch and photos of a perforated honeycomb are shown in Fig. 1. The honeycomb is of nominal cell size c, edge length l and height H, with circular perforations on the slantwise walls. The thickness of cell walls in x_2 direction, $2t$, is double that of the slantwise walls. Three circular perforations of diameter d are uniformly distributed along x_3 direction on every slantwise cell wall, *i.e.* perforation number $n = 3$. The nominal geometric parameters of the perforated honeycombs are listed in Table 1. The real honeycombs have various imperfections (Fig. 1b and c), such as the cell twist, uneven or pre-buckled cell walls, irregular cell geometry. The effects of imperfections have been studied extensively (Wilbert et al., 2011; Hou et al., 2012), which is beyond our goal is this work.



(a)

(b)

(c)

Fig. 1. (a) Sketch of a perforated honeycomb specimen. (b) A specimen confined between two stiff plates mounted on the testing machine. (c) The top view of a specimen.

Table 1
Nominal geometric parameters of Aluminum alloy honeycombs used in the experiments.

l (mm)	c (mm)	t (mm)	H (mm)	d (mm)	n
5.50	9.53	0.05	30.00	5.00	3

The perforations on the cell walls may affect the relation between the mechanical properties and specimen dimensions. To investigate the size effect of hexagonal honeycomb with circular perforations and explore the critical minimum specimen dimensions for measuring the bulk properties, a series of crushing experiments on the honeycomb specimens with various cell numbers were performed. Eight groups of the honeycomb specimens are selected by changing the cell numbers: 3 × 3, 5 × 5, 7 × 7, 9 × 9, 11 × 11, 13 × 13, 15 × 15 and 17 × 17. Each group has three specimens with the same cell numbers. All the specimens were cut from the honeycomb blocks by wire-electrode cutting technology.