International Journal of Impact Engineering 66 (2014) 48–59

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Experimental and numerical studies on the crush resistance of aluminum honeycombs with various cell configurations

Xiong Zhang [a,c,*], Hui Zhang [b], Zhuzhu Wen [a]

[a] Department of Mechanics, Huazhong University of Science and Technology, Wuhan 430074, Hubei, PR China
[b] School of Mechanical Engineering and Automation, Wuhan Textile University, Wuhan 430073, Hubei, PR China
[c] Hubei Key Laboratory of Engineering Structural Analysis and Safety Assessment, Luoyu Road 1037, Wuhan 430074, PR China

ARTICLE INFO

Article history:
Received 23 May 2013
Received in revised form
16 August 2013
Accepted 28 December 2013
Available online 8 January 2014

Keywords:
Aluminum honeycombs
Crushing analysis
Energy absorption
Out-of-plane compression

ABSTRACT

Commercial aluminum honeycombs with various cell configurations are experimentally tested to study the influence of cell number and central angle on the out-of-plane crush resistance of the structures. The boundary effect is found to have significant impact on the crush strength of the structure when the number of cells is small and the central angle is observed to get a difference less than 10% in the strength of the honeycombs. Numerical analyses based on whole honeycomb model and Y-shaped element model are carried out to simulate the crush and deformation process of the specimens. The adhesive bonding of the double thickness foil is considered in the simulation and the numerical results show good agreement with the experimental data and theoretical predictions. Finally, the reason for the small influence of central angle on the out-of-plane strength of honeycombs is investigated and the interaction effect between wall thickness and central angle is believed to account for it.

1. Introduction

Metal honeycombs are widely applied as core of sandwich structures or filler of energy absorbers due to their excellent mechanical and energy absorption properties. As a typical lightweight cellular material, they have high specific strength to weight ratio and high specific energy absorption value. When crushed in different directions, the honeycombs have quite different energy absorption characteristics due to their anisotropic properties. The out-of-plane crushing resistance of honeycombs was found to be about two order of magnitude higher than their in-plane resistance [1]. The honeycombs may have various cell shapes such as square, triangle, rhomb or kagome and different cell shape may possess distinct advantages. For example, square honeycomb would be preferable to be used core of sandwich panels for intense impulsive loads because of good crushing resistance, considerable transverse shear strength and strong in-plane stretching strength [2,3].

Although metal honeycombs with different sections can be fabricated by various methods [4], the commercial hexagonal aluminum honeycombs (CHAHs) with two of the six cell walls having double thickness are the most extensively applied products due to its low-cost and mature fabrication technology. And accordingly, this type of honeycombs attracted the most extensive concerns in the research community. In the past decades, lots of numerical and experimental investigations are carried out to study the out-of-plane crushing properties of the commercial hexagonal honeycombs (CHHs), while relatively few theoretical works are available in the open literatures. Interestingly, the situation is quite different for honeycombs with other cell shapes. Most of studies were conducted numerically or theoretically and it is hard to find some relevant experiment results. The difficulties in the fabrication of specimens could be the primary reason for this.

In the theoretical aspect, an analytical model was firstly presented by McFarland [5] to predict the out-of-plane strength of CHHs in 1963 and an improved model was then offered by Wierzbicki [6] in 1983. The plateau stress predicted by the model of Wierzbicki was found to compare well with the experimental data and has been employed by researchers and engineers up to now. Based on the work of Wierzbicki, a formula was given by Gibson and Ashby [4] to predict the out-of-plane strength of hexagonal honeycombs with uniform wall thickness. Recently, the crush strength of square, hexagonal, rhombic and kagome honeycombs were analyzed by Zhang et al. [7–9] based on the Super Folding Element (SFE) method. The crush resistance of basic constitutive angle elements including Y-, T- and X-shaped elements was investigated. The influence of central angles between the plates of angle elements on the crush resistance was considered while the wall thickness of the structures was assumed to be uniform.

---

[*] Corresponding author. Department of Mechanics, Huazhong University of Science and Technology, Wuhan 430074, Hubei, PR China. Tel./fax: +86 27 87543501.
E-mail address: zhangxiong@hust.edu.cn (X. Zhang).

0734-743X/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijimpeng.2013.12.009

The quasi-static and dynamic experimental studies on the crush strength of CHHs were conducted by many researchers. Most of these studies were intended to investigate the dynamic enhancement effects. The ratio of dynamic crush strength to quasi-static strength can be defined as a dynamic enhancement coefficient and different values were reported by the researchers for different materials and under different loading conditions. The coefficient was reported to be of the range 1.33–1.74 by Wu and Jiang [10] and 1.12–1.4 by Zhao and Gary [11] and Zhao et al. [12]. It was also recorded by Baker et al. [13] to be about 1.5 for aluminum and stainless-steel honeycombs which were constrained by metal rings or tubes. Recently, Xu et al. [14] investigated experimentally the crushing strength of CHAHs over a wide range of strain rate. Semi-empirical expressions were proposed to predict the strength of honeycombs with different relative density and under various loading rate. The only experimental investigation on the influence of angle on the CHAHs was carried out by Yamashita and Gotoh [15] and interestingly the regular hexagonal honeycomb with central angles to be 120° was found to own the largest crush strength which was defined for the net cross-section of the material part.

The influence of cell configurations including cell number and central angle on the out-of-plane crushing strength of the CHAHs will be investigated in the present work. As we know, the dynamic effects under impact loading are quite involved and include many different factors [12] such as the air trapped in the cells, the strain rate effect, the shock enhancement and the inertia effect. The dynamic effects for honeycombs with different cell configurations are also expected to be different. To investigate the dynamic effects, the cell configurations should be kept uniform under different loading rates. Similarly, to investigate the influence of cell configurations, the same loading rate should be guaranteed. In the present work, quasi-static loading is employed in the experimental test to investigate the influence of cell configurations on the strength of CHAHs and the dynamic effects of honeycombs with different cell configurations will be investigated in further studies and be addressed somewhere else. The collapse characteristics of CHAHs identified quasi-statically might also provide some insights into their dynamic responses.

The numerical simulation of the CHHs under out-of-plane crushing was also carried out by researchers and the numerical results were frequently compared with experiment data. Actually, the simulation of CHHs is a quite difficult and challenging task. The numerical predictions were always reported to be inconsistent with the experimental results [16,17]. In the manufacture of CHHs, the two rows of cells are bonded by using adhesives. That is, the cell walls with double thickness in CHHs are not a simply plate but a composite structure. The strength of the bond is generally smaller than that of the material of cell walls and it will fail and break during the deformation of the honeycombs. The simulation of the adhesive and its failure is always difficult and sometimes it is omitted by the researchers [18,19]. Another problem is the high computational cost needed to simulate the honeycombs accurately. A detailed shell model is always needed to represent the honeycomb cell structures and the number of finite elements is generally very high. To solve the problem, the CHHs are always modeled with one single Y-shaped model with appropriate boundary conditions or the length of the structure is shortened artificially during simulation to reduce the computational cost [15].

The experimental and numerical investigations on the crushing resistance of CHAHs with various cell configurations are carried out in the present work. CHAHs with different number of cells and various central angles are experimentally tested to analyze the influence of cell number and central angle on the deformation and out-of-plane crushing property of the honeycombs. The axial crushing process is conducted quasi-statically to avoid the disturbance of dynamic effects on the above analyses. The loading process of CHAHs is numerically simulated by using non-linear finite element code LS-DYNA and both the single Y-shaped model and the whole honeycomb model are adopted. The out-of-plane strength of CHAHs is also theoretically predicted by the theory of Wierzbicki [6] and the theoretical results are then compared with the experimental and numerical results.

2. Experimental test and results

The CHAHs employed in the present test is made of AA3003 H18 with the thickness t of 0.075 mm. The honeycomb specimens can be divided into two groups: group I is the material with regular hexagonal cell but with different number of cells, and group II is of the same number of cells but with different central angles. The specimens are shown in Fig. 1(a) for group I and Fig. 1(b) for group II. The specimens in group II have different central angle for unit cells and a detailed illustration of the cell shapes is presented in Fig. 2. The engineering stress–strain curve of the AA3003 H18 aluminum foil with $t = 0.075$ mm is obtained by using the tensile specimens with dimensions as specified in the ASTM standard E8M-04. The tensile specimens and test machine are shown in Fig. 3(a) and the dimensions of the specimens are given in Fig. 3(b). The uniaxial tensile measurements were performed on a 10 KN capacity Zwick Z010 universal tensile tester and the tensile stress–strain curve of AA3003 H18 is shown in Fig. 3(c). The mechanical properties of the material are given here: Young's modulus $E = 69.0$ GPa, initial yield stress $\sigma_y = 115.8$ MPa, the ultimate stress $\sigma_u = 154.5$ MPa, Poisson's ratio $\nu = 0.33$.

The length L of all the honeycomb specimens is 100 mm and the width of cell wall D is 6 mm for each specimen. The number of cells for the honeycomb specimens in group I is $n \times n$ with n equal to 3, 5, 7, 9, 12 and 15. The specimens with a slightly different cell configuration are also tested for $n = 3$ and 5. Some cells are added to the honeycombs with 3 × 3 and 5 × 5 cells to make the structures have biaxial symmetry property as shown in Fig. 1(a) and the influence of this symmetry property is investigated. All the honeycomb specimens in group II have 15 × 15 cells and the central angle α is set to 60, 90, 120 and 180°. The net cross-section of the material part in all specimens in group II is the same and the crushing forces are compared directly. Three specimens are generally tested for each type and one or two specimens are used in some cases. The following test numbering system is applied for the specimens, e.g: For group I, H7x7s2 means specimen 2 of honeycomb with 7 × 7 cells, while the character S in "HS3x3s2" stands for biaxial symmetry. For group II, the specimen H90s3 indicate specimen 3 of honeycomb with $\alpha = 90°$. Quasi-static axial crush tests were carried out by using a 100 KN capacity INSTRON 5882 materials testing machine with computer control and data acquisition systems. The testing was displacement controlled with the top platen of the machine being moved vertically downward to compress the specimens and the loading speed was 0.5 mm/s. The experimental setups for axial compression test are shown in Fig. 2(a).

The deformed shapes of the honeycomb specimens are shown in Figs. 4 and 5 for group I and group II, respectively. As given in the figures, most of the specimens deformed progressively fold by fold in a regular manner and one specimen with regular deformed shapes are selected for each type of specimen to give an enlarged illustration. Some of the specimens deformed in global buckling mode or inclined during loading and showed obvious shear deformation. As denoted by the blue circle in Fig. 5, the specimen HS3x3s1 and HS3x3s2 switched to global bending during axial loading, while the specimen H5x5s2 and H180s1 suffered severe shear deformation as indicated by the red dashed circle in Figs. 5 and 6. The force–displacement curves of the specimens are plotted in Figs. 6–8. In Fig. 6, it can be found that the force level of