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Numerical and experimental study of crashworthiness parameters of honeycomb structures

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ABSTRACT

Crashworthiness parameters of aluminum hexagonal honeycomb structures under impact loads are investigated by using finite element methods and conducting experiments. To validate the finite element models, numerical results are compared with experimental measurements and theoretical results reported in literature. In numerical simulations of honeycomb structures, out-of-plane loads are considered while the aluminum foil thickness, cell side size, cell expanding angle, impact velocity and mass are varying, and dynamic behavior and crashworthiness parameters are examined. It is observed that there are good agreements between numerical, experimental and theoretical results. Numerical simulations predict that crashworthiness parameters depend on cell specification and foil thickness of the honeycomb structure and are independent of impact mass and velocity.

1. Introduction

Honeycomb structures are used in various industrial applications due to their low weight to strength ratio, high energy absorbing capacity, low cost and good crashworthiness characteristics. For instance, honeycomb structures can be used as shock absorbers in airplanes and high speed trains for energy absorption during crush [1–7]. In these events, impact energy is transformed into plastic strain energy and it is absorbed through large compressive strokes of materials. In case of out-of-plane impact, these structures are more effective in terms of energy absorption. The crashworthiness parameters under impact loads are strongly influenced not only by the mechanical properties of the honeycomb material and thickness of the cell wall, but also by the geometric parameters of the honeycomb cell. There are many theoretical, numerical and experimental investigations on honeycomb structures to determine the mean crush stress and crush behavior. Zhao and Gary [1] used Split Hopkinson viscoelastic pressure bar for dynamic test of aluminum honeycomb structure under out-of-plane and in-plane loads. The post-test observation reported in their study showed that only out-of-plane crushing behavior is affected by the loading rate and the mean crushing pressure was nearly the same for impact velocities from 2 to 28 m/s. In addition, the densification point seems independent of the loading rate (at 65% crush) and the mean crushing pressure for in-plane loading is the same for both dynamic and quasi-static loads. The densification point is between 70% and 80% crush in both directions, which is independent of the loading rate, e.g., see [1]. Zhang and Ashby [2] analyzed crushing behavior of honeycomb structures under both shear loads and simple compression in out-of-plane direction. They derived a theoretical model by consideration of buckling, debonding of adhesives and fracture as possible collapse mechanisms. Their experimental results and theoretical prediction showed that out-of-plane strength of a honeycomb structure is generally independent of the height of the cells and the cell expanding angle α (e.g., see Fig. 1) and highly sensitive to the density of the honeycomb material. By using the finite element (FE) method, Deqiang et al. [3] showed that in aluminum double-walled hexagonal honeycomb cores, for a given impact velocity, mean out-of-plane dynamic plateau stresses are related to the ratio between cell wall thickness and edge length. Mellquist and Wass [4] studied the effect of cell size and honeycomb size on energy absorption properties experimentally and numerically; their FE solutions and experimental measurements showed that energy absorption is independent of the number of cells and cell size. Hanfeng [5] proposed a new theoretical method to determine the mean crushing stress and folding wavelength for honeycomb structures having different cell specifications. He also simulated a honeycomb structure having the shape of a “Y” column by employing symmetric boundary conditions and bonds of the honeycomb by using a tie-break contact. He showed that numerical results are in good agreement with theoretical results. Gotoh et al. [6] studied the crush behavior of a honeycomb structure experimentally and numerically and showed that the crush strength increases slightly

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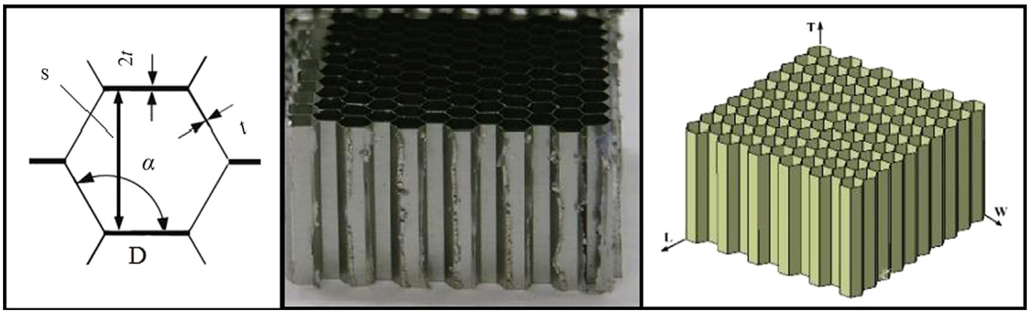

Fig. 1. (a) Geometric configuration of a hexagonal cell structure, (b) a sample for bare honeycomb core and (c) numerical model of a honeycomb core where $S=3.175$ mm and $t=0.025$ mm.

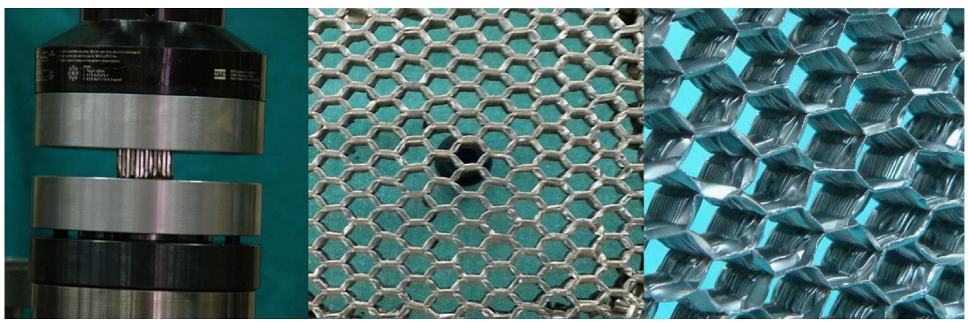

Fig. 2. Compressed honeycomb structure having regular hexagonal cells, which is crushed in out-of-plane direction where $S=3.175$ mm, $t=0.025$ mm and striking velocity is 0.1 mm/s. (a) The test specimen fixed to the MTS machine, (b) Top view of the compressed honeycomb and (c) enlarged view of the honeycomb after the test.

as the impact velocity and foil thickness increases. Yamashita and Gotoh [7] studied experimentally and numerically the effects of the cell shape and foil thickness on the crush behavior of a honeycomb structure. In numerical simulations, by using a single "Y" cross-sectional column model, they showed that crush strength per unit mass gets the largest value when the cell shape is a regular hexagon.

Although computational and experimental analyses of honeycomb structures are investigated by many researchers in literature [8–17], crashworthiness characteristics and associated parameters are not studied. Motivated by this fact, this study is undertaken to examine crashworthiness parameters and energy absorption characteristics of honeycomb structures.

In this paper, the crashworthiness parameters of honeycomb structures such as total energy absorption, specific energy absorption, crush force efficiency and energy absorber effectiveness factor are studied. By solving computational models, crashworthiness features of honeycomb structures are obtained where the software RADIOSS 11.0 is used. Following, numerical results are compared with experimental measurements and theoretical results to verify computational models. Thus, optimum parameters for improved crashworthiness and energy absorption are determined.

2. Out-of-plane loading of honeycomb structures

An experimental investigation on aluminum hexagonal honeycomb structures subjected to low velocity impact loading (i.e., velocities smaller than 20 m/s) is conducted. The dimension of test specimens used in the experiments has the height of 20 mm, square cross section of $30\times30\,\text{mm}^2$, foil thickness of 0.025 mm and cell size of 3.175 mm. The geometric configuration of a cell and sample honeycomb structure is shown in Fig. 1. The honeycomb cores used in tests are known as 1/8–5052–4.5 which was produced by the company HexWeb. The material of foil is an aluminum alloy labeled as A5052. The MTS universal testing machine is used for the tests. The crushing test is implemented by 0.1 mm/s striking speed in T-direction (i.e., see Fig. 1c). The measured data are the compressive force and stroke during the tests.

Fig. 2 shows the deformed honeycomb structure and progressive folding deformation pattern. It is observed in Fig. 2c that out-of-plane crushing mode (i.e., in the T-direction) is a regular localized folding.

In order to obtain stress–strain curves of the honeycomb structure during crushing, the nominal stress and crushing strain values are calculated by using the measured force and stroke data during experiments. Nominal stress is defined by Eq. (1) and crushing strain is defined by Eq. (2), where F is the compressive force, A is the gross cross-sectional area of the structure, ΔL is the stroke and L_0 is the initial length of the honeycomb structure. Furthermore, the crush strength is determined by averaging the oscillatory stress during cyclic collapse of the cells.

$$\sigma=\frac{F}{A} \tag{1}$$

$$\varepsilon=\frac{\Delta L}{L_0} \tag{2}$$

The gross stress–strain curves measured during out-of-plane loading of four specimens are shown in Fig. 3 where it is observed that the deviation between experimental measurements is very low; therefore, it is concluded that the reliability of experiment results is high.

The average crush strength σ_m is determined as 1.76 MPa by using experimental measurements which are shown in Fig. 4. In the published data of the honeycomb manufacturer, it is listed as 1.79 MPa. On the other hand, Wierzbicki′s theoretical solution for