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A study on the mean crushing strength of hexagonal multi-cell thin-walled structures

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ABSTRACT

This paper presents a study to extend a previously developed theoretical model to predict the crushing behavior of hexagonal multi-cell thin-walled structures, e.g. honeycombs under quasi-static loading. The low speed compressive tests were conducted on three types of aluminum honeycomb panels. Based on the test data and existing theoretical models, a new analytical model was developed to predict its mean crushing strength. Some key parameters in this new model were determined with the finite element (FE) method. Then the predictions based on the new model were compared with the results reported in the published literature. It has been shown that the new model has a similar or better performance compared to its counterparts. Considering its concise expression, the newly developed model can be deemed as a convenient computational tool in engineering practice.

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1. Introduction

Hexagonal multi-cell thin-walled structures have been widely used as lightweight energy absorbers to improve the crashworthiness and shock resistance of aircrafts, ships and vehicles [1–4]. To evaluate the energy absorption performance of such structures, the mean crushing strength should be calculated first, as it determines the energy dissipated until the material is compacted. Numerous studies have been conducted towards developing theoretical models to predict the mean crushing strength for thin-walled structures. For instance, Mc Farland [5] developed a semi-empirical model to predict the mean crushing strength of hexagonal cell structures. Gibson et al. [6] and Gibson and Ashby [7] developed another theoretical model for honeycombs, which was then validated against experimental data. De Oliveira and Wierzbicki [8], Wierzbicki [9], Wierzbicki and Abramowicz [10] introduced a super folding theory for predicting the mean crushing strength of thin-walled structures. Wu and Jiang [11] compared the predictions based on the theory by Wierzbicki and co-workers against the quasi-static compression test results on honeycombs. They found that the theoretical predictions underestimated the experimental data. Chen and Wierzbicki [12] simplified the super folding theory and improved its performance. This simplified model was then adopted by Zhang et al. [13] to successfully predict the mean crushing strength of multi-cell square columns. Zarei Mahmoudabadi and Sadighi [14–16] further improved Wierzbicki's super folding element theory by considering a more detailed geometric change during the structural deformation. Although a better accuracy was obtained, the equations have many parameters and they are not convenient to use in practice.

In this paper, a typical hexagonal multi-cell thin-walled structure, i.e. honeycombs were tested in the out-of-plane direction under quasi-static loading conditions. It was found that adhesive failure has significant effect on the folding behavior. However, such effect on energy dissipation was not considered in existing theoretical derivations. The simplified super folding element theory by Chen and Wierzbicki [12] was extended to derive the equation to calculate the mean crushing strength of hexagonal honeycombs. Double-thickness wall adhesive failure effect was considered in model development. Commercial nonlinear finite element (FE) code ABAQUS/EXPLICIT (Version6.10, 3DS SIMULIA, RI, USA) was employed to simulate quasi-static compressive response of honeycombs with different materials, foil thicknesses and cell sizes. Based on the simulation results, several parameters in the new formula for hexagonal aluminum honeycomb were determined. Finally, the performance of the new formula was compared with the predictions based on the theories by McFarland, Wierzbicki and Zarei Mahmoudabadi and Sadighi.

2. Experiment study

Quasi-static compression tests were conducted on three types of aluminum honeycomb samples using an Instron machine. The configurations of the samples were different in materials and cell

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sizes, as detailed in Table 1. The dimensions of specimen were L : 150 mm × W : 150 mm × H : 50 mm (shown in Fig. 1).

Because the mean crushing strength was the main focus in this study, the specimens were not compressed to the densification stage. The typical nominal stress–strain curves and the folding pattern of the three aluminum honeycomb samples are shown in Figs. 2 and 3, respectively. The mean crushing strength σ_m of each specimen was obtained by integrating the nominal stress σ with respect to nominal strain ε and then divided by the integration strain range (0.2–0.7), as shown in Eq. (1). Each type sample was tested three times, and the average mean crushing strengths were 0.240 MPa, 1.184 MPa and 0.398 MPa.

Table 1
Three types of aluminum honeycomb samples tested.

Type number	Material	Wall thickness, t (mm)	Length of cell edge, D (mm)	Nominal density (kg/m^3)
Type 1	Al3003	0.07	11.03	26.3
Type 2	Al3003	0.07	4.04	73.1
Type 3	Al5052	0.07	11.03	26.3

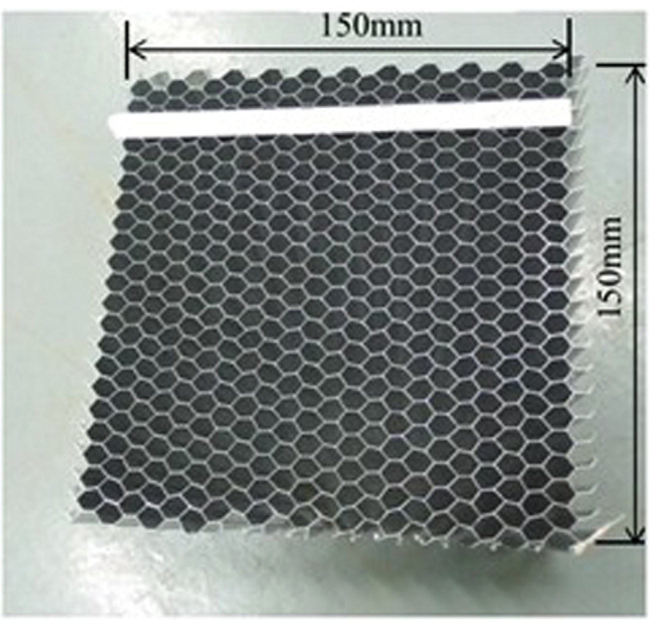

Fig. 1. A honeycomb specimen of Type 1 for compression tests.

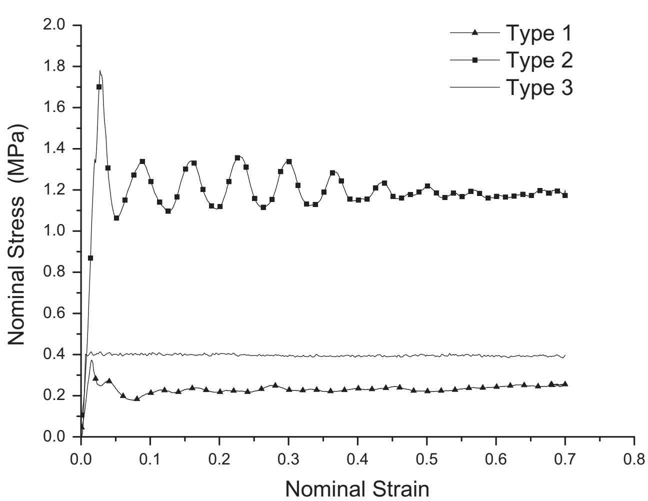

Fig. 2. Typical nominal stress–strain curves of three types of aluminum honeycomb samples under quasi-static compression.

$$\sigma_m = \frac{1}{\varepsilon_2 - \varepsilon_1} \int_{\varepsilon_1}^{\varepsilon_2} \sigma \, d\varepsilon \tag{1}$$

where ε_1 and ε_2 are the start and end point nominal strain of the densification stage, respectively; and σ is the nominal stress of densification.

During the compression, the folding pattern of the cells at the sample's boundary was irregular due to lack of constraints and thus it was not considered in the subsequent analysis. To investigate the crushing behavior in more detail, a piece of Type 2 aluminum honeycomb sample after test was taken and it was flattened for better examination as shown in Fig. 4a. Gibson and Ashby [7] pointed out that various deformation modes may be observed during the honeycomb out-of-plane compression, including linear elastic deformation, elastic buckling, plastic deformation and brittle fracture. In the current study, brittle deformation was not seen as the base material, i.e. aluminum is a ductile material. Since aluminum honeycombs were manufactured with expended/corrugated and adhesive [17,18], bending of both single-layered/double-layered wall and adhesive failure of double-thickness wall should be considered. In Fig. 4a, adhesive failure of double-layered wall and plastic hinge lines were clearly observed. The honeycomb was assumed to be made of an ideal rigid-plastic material [9]. The flattened cell walls generally consist of two types of planes: (1) pentagonal planes and triangular planes due to the adhesive failure (Fig. 4a). Fig. 4b is a sketch showing the detailed folding pattern, where the green transparent area represents an area with double-layered folding; the yellow area is a triangular plane which is dominated by adhesive failure; the khaki and blue areas are pentagonal planes and triangular planes on the single-layered wall. Comparison of all three type samples indicated that the area of yellow triangular plane had a great effect on the width of the adhesive failure region, and the height of yellow triangular plane was equal to the width of the adhesive failure region. Fig. 4c shows a paper model of folding process (the region enclosed by dotted line was the flattened area shown in Fig. 4a).

3. Theory

3.1. Super folding element theory

Super folding element theory was proposed by Wierzbicki [9]. In this theory, the cell was assumed to be made of an ideal rigid-plastic material [9]. Fig. 5 shows a cell which includes four trapezoidal planes moving as rigid bodies (areas 1–4) and two sections of curved surfaces. Based on the kinematic analysis of a basic folding element during crushing, the work of external force is equal to the energy dissipation by toroid shell extension and plastic hinge lines formation of on the curved surfaces. According to energy conservation law, the mean compressive crushing strength could be obtained using the following equation [9,10]:

$$\sigma_m = 16.56\sigma_0 \left(\frac{h}{s}\right)^{5/3} \tag{2}$$

where σ_0 is the flow stress of base material; s is the minor cell diameter which is the distance between the two parallel cell edges; and h is the cell wall thickness.

Chen and Wierzbicki [12] simplified the original super folding element theory in [9]. In the new theory, the total energy dissipation is separated into two parts: dissipation during the plastic hinge lines formation and during plastic flow. The simplified super folding element theory can be conveniently used to

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