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Experimental study on the effects of specimen in-plane size on the mechanical behavior of aluminum hexagonal honeycombs

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ABSTRACT

Specimen size affects the mechanical properties of hexagonal honeycombs. Out-of-plane and in-plane uniaxial compression tests are conducted on three kinds of honeycomb specimens with different relative densities to investigate the effects of specimen in-plane size on the mechanical properties of hexagonal honeycombs. Results indicate that an increase in specimen in-plane size causes a decrease in the macroscopic stiffness in the out-of-plane direction (x_3-direction) but an increase in that in the in-plane directions (x_1-direction and x_2-direction). Additionally, the macroscopic stiffness in out-of-plane direction decreases as in-plane size increases up to $N \times N = 13 \times 13$, beyond which the macroscopic stiffness becomes stable. The macroscopic stiffness in the in-plane directions increases with the specimen in-plane size up to $N \times N = 9 \times 9$. These results serve as bases for determining the minimum specimen in-plane size $N \times N \geq 13 \times 13$ of hexagonal honeycomb for measuring the effective mechanical properties of a bulk sample of honeycomb.

1. Introduction

Cellular solids are widely used in engineering as cores for sandwich structures, load-bearing insulation, and packaging for damage-critical components because of their high strength-to-weight ratio and high energy-absorption capacity [1–5]. Engineering design and application require an overall understanding of cellular solids mechanical properties, which were thus studied using various tests. Sugimura [6] examined the stiffness, yield strength and fracture resistance of closed cell Al alloy foams to provides goals for manufacturing strategies that enable attainment of good mechanical performance with affordable process technologies. Andrews [7] tested the uniaxial compressive and tensile modulus and strength of several aluminum foams and then compared them with models proposed by Gibson [8] for cellular solids. In addition, Andrews [7] found that the imperfections in the cellular structure result in the reduction in the measured values of Young's modulus and plastic collapse stress of closed cell aluminum foams below those predicted by models. Therefore, an improvement of processing techniques is required to improve the mechanical properties of cellular solids. Khan [9] studied the quasi-static in-plane and out-of-plane crushing properties of the honeycomb core by the experimental method to probe the global and local deformation mechanism of the honeycomb core. Balawi et al. [10–11] experimentally investigated the effect of honeycomb relative density on in-plane elastic modulus and proposed a refined model to predict the effective modulus of regular honeycombs with low relative densities.

The aforementioned literatures are helpful to improve the design and application in engineering. However, there is an important issue is in that the mechanical properties of cellular solids depend on the ratio of the sample size to the cell size at length scales where the two are of the same order of magnitude [12]. Moreover, given the cell size of many cellular solids used in engineering applications is between 1 and 10 mm, it is not uncommon to have components with dimensions of only a few cell sizes [12,13]. Hence, Onck et al. [14] theoretically analyzed size effects for the compression/shear modulus and strength in in-plane direction of regular hexagonal honeycombs under uniaxial and shear loadings. Consequently, the specimen to be tested is desired to have enough number of cells in in-plane directions of honeycomb for results to be representative of bulk because the specimen size has great effects on the mechanical behavior of cellular solids [15]. Alkhader [15] performed a series of FE simulations with Voronoi specimens of different sizes to identify the minimum specimen size representing and captureing the mechanical response of bulk material. Xu et al. [4] found that specimen size

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has no effect on the plateau stress in out-of-plane of honeycomb. However, an overall understanding of specimen size effects on the mechanical properties (the modulus, strength, plateau stress and densification strain) in out-of-plane and in-plane directions is still unclear. Therefore, this study aims to investigate the effects of specimen in-plane size on the mechanical properties of hexagonal honeycombs to find the smallest specimen size representing the mechanical response of bulk honeycomb.

2. Experimental procedure

2.1. Specimens

Three kinds of aluminum alloy (AA5052-H24) commercial hexagonal honeycombs with different relative densities of 2.5%, 3.1%, and 4.1% were used in the mechanical tests. For hexagonal honeycombs, the relative density (ρ^*) can be obtained as [8]

$$\frac{\rho^*}{\rho_s} = \frac{2t/D}{(1+\sin\theta)\cos\theta} \tag{1}$$

where D is the cell wall width, t is the single wall thickness, $\theta = 30^\circ$ is the expansion angle, and ρ_s is the density of the parent material. A schematic of a standard honeycomb with hexagonal cellular microstructure is shown in Fig. 1, where $d = \sqrt{3}D$ is the cell size, H is the height of specimens, and $W = Nd$ is the finite width of the honeycomb specimen in the x_1-direction and is expressed as N times the cell size d. Therefore, the value of N can be considered as the number of cells in the in-plane direction. Further more, the specimen in-plane size is quantified as $N \times N$ in this paper. The x_3-direction is the out-of-plane direction with the highest strength, whereas the x_2-direction is parallel to the direction of the double walls. In addition, the x_1-direction is perpendicular to the x_1-direction. In this study, the t/D ratio was used to represent the relative density for convenience of description.

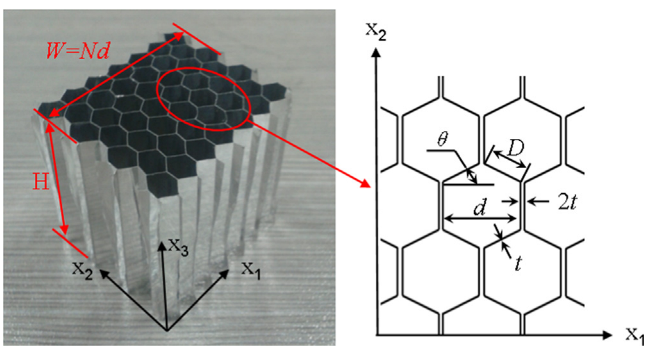

Fig. 1. Schematic of honeycombs with hexagonal microstructure.

Table 1 shows the geometric features of the three kinds of specimens. According to the manufacturer, the elastic modulus, yield strength, and ultimate tensile strength of AA5052-H24 are 69 GPa, 163 MPa, and 210 MPa, respectively. The specimen with the height $H = 30$ mm in the x_3-direction and in-plane size of $N \times N = 15 \times 15$ is used to represent the mechanical behavior of a bulk aluminum honeycomb. The specimens were prepared with a constant height of $H = 30$ mm but with different in-plane sizes, such as $N \times N = 5 \times 5$, 7×7, 9×9, 11×11, 13×13, and 15×15 in the in-plane directions to study the effects of specimen in-plane size on the overall compressive response.

Table 1
Geometric features of specimens.

Relative density (%)	D (mm)	d (mm)	t (mm)	θ (deg)	t/D
4.1	1.5	2.60	0.04	30	0.0267
3.1	2.0	3.64	0.04	30	0.0200
2.5	2.5	4.33	0.04	30	0.0160

2.2. Out-of-plane uniaxial compression tests

A universal testing machine (CMT5105A, SANS, Shenzhen, PRC) with a 50 kN load cell was used for the out-of-plane uniaxial compression tests. A computer was used to record the displacement and load signals from the universal testing machine during the entire loading process. Specimens were compressed between two pieces of metal plates. In addition, the upper surface of specimens was enforced and given normal displacement, whereas the bottom end surface had restricted movement in the compression direction. Three specimens of each size were tested, and the mean value was used for the following discussions. All out-of-plane uniaxial compression tests were conducted at a constant

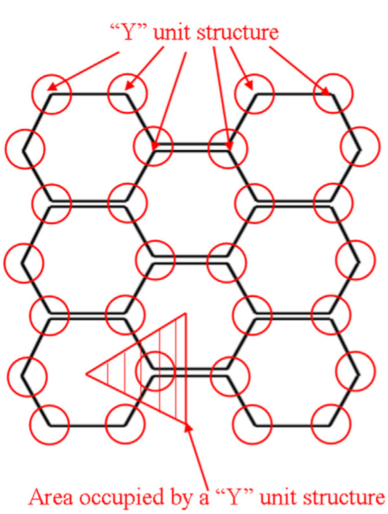

Fig. 2. Sketch of the periodic 'Y' unit structure and the corresponding occupied area sketch.

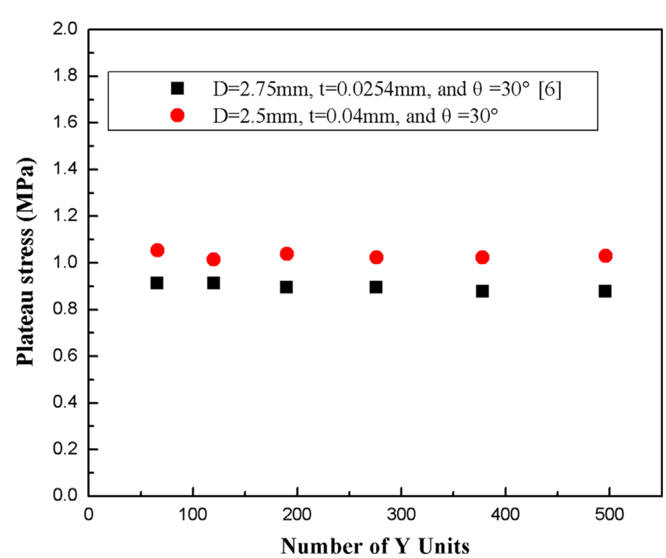

Fig. 3. Comparison of plateau stress in x_3-direction of specimens with the results reported in Ref. [6].