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COMPRESSIVE STRENGTH OF THIN-WALLED CELLULAR CORE BY INKJET-BASED ADDITIVE MANUFACTURING

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ABSTRACT: Lightweight honeycomb structures are widely used in aerospace industry and sporting protective equipment. Commercially available honeycomb cores often come in the basic hexagonal cell shape. In this present work, variation of unit cell shapes such as hexagons, triangles and circles were fabricated by inkjet-based additive manufacturing (AM) using photopolymer materials. Inkjet-based AM is able to manufacture thin walled products with high dimensional stability and hence it is suitable to fabricate thin-walled honeycomb core. In this paper, flatwise compression tests were performed on various geometrical parameters with constant relative density. The results obtained show that the compressive properties of honeycomb are largely affected by the cell shapes.

INTRODUCTION

Cellular materials are commonly used for lightweight structural components owing to their superior strength-to-weight ratios and excellent stiffness and buckling resistance (Gibson & Ashby, 1999). Currently, honeycombs, made of prismatic hexagonal cells, are widely used core panels in the structural sandwich applications. Owing to its excellent structural properties and lightweight, the honeycomb material has found many applications in the aerospace industry, for example, structurally critical area like fuselage, nacelle and radome as well as cabin flooring and interior fixtures in an aircraft.

Currently, metallic honeycomb and nonmetallic honeycomb such as Nomex and Fiberglass, are manufactured primarily using expansion and corrugation processes with the use of adhesives. Due to the nature of the expansion manufacturing process, the honeycomb panel produced could only have a uniform cell shape that allows only underexpanded, overexpanded and regular honeycomb cell configurations (Bitzer, 1997). Manufacturing of thermoplastic honeycomb core can be done using thermoforming of thermoplastics and heat fusing the bonded areas, without the use of adhesives.

Honeycombs sandwich materials are extremely strong and stiff when loaded along the X_3 direction in Figure 1 (Gibson & Ashby, 1999). The load applied onto the surface normal to X_3 direction is related to the out-of-plane stiffness and strength of the honeycomb while the much weaker in-plane properties can be derived from the load applied in the $X_1 - X_2$ plane, as shown in Figure 1. Certain geometric aspects of the honeycomb are crucial to understand the mechanical properties of the structure. Relative density, which is defined as the ratio of the honeycomb density to the solid material density, is one of the most important parameters in the structure characterization of cellular materials. This parameter is also related to the cell dimensions like cell edge length and cell wall thickness, and cell shapes (Gibson & Ashby, 1999). Effects of some other cell geometries, such as cell-wall angle of the hexagonal cells, variable thickness, curved cell edges, cell size and cell configuration, on the in-plane properties of cellular structure have been analyzed

by many researchers (Chuang & Huang, 2002; Dai & Zhang, 2009; Hu, You, & Yu, 2013; Li, Gao, & Subhash, 2005). For out-of-plane properties, previous research has shown that both compressive and shear strengths of honeycomb are independent of the height of the honeycomb panel; instead, they are highly sensitive to the honeycomb density (Zhang & Ashby, 1992). The solid distribution of cell edges also have significant effect in the out-of-plane elastic properties of hexagonal honeycombs (Lin, Yang, & Huang, 2013). Nevertheless, relatively little work has been carried out for the out-of-plane properties of honeycomb as compared to the in-plane properties. It is therefore the intention of this paper to study the effects of cell geometry on the out-of-plane compressive properties.

The primitive cell geometries, which include hexagon, circle and triangle, are adopted to analyze the out-of-plane behaviors of these honeycombs. Due to the limitation in the traditional manufacturing technology, the manufacturing of some of these cell shapes is often regarded as challenging as well as time and cost inefficient. It is, therefore, necessary to introduce Additive Manufacturing (AM) or 3D printing, for manufacturing of cellular materials of other shapes that are otherwise difficult, if not impossible to be fabricated using conventional manufacturing processes. AM allows rapid manufacturing of intricate geometry without the use of tooling through the addition of materials in a layer by layer manner.

Figure 1: A general honeycomb core with hexagonal cell configuration. The in-plane properties are those relating to load applied on the $X_1 - X_2$ plane while the out-of-plane properties are those relating to load applied onto the surface normal to X_3 direction.

METHODOLOGY

Honeycomb core specimens

Various AM systems have the capability of fabricating the thin-walled polymeric honeycomb cores, for example, Stereolithography (SLA), Fused Deposition Modelling (FDM), Selective Laser Sintering (SLS) and PolyJet. Among these AM systems, PolyJet, which jets layers of liquid photopolymers onto the build tray and cure the layer with UV light, was being chosen for the manufacturing of the honeycomb core because of its greater ability to manufacture the thin-walled features and the wide range of materials available for the PolyJet (Chua, Leong, & Lim, 2010). PolyJet has also very high accuracy of $16\mu\text{m}$, is able to produce the thin-walled honeycomb structures with excellent dimensional accuracy.

Primitive cell configurations, namely, hexagonal, equilateral triangle and circle were fabricated using Polypropylene-like material of the PolyJet (Eden350V) with the glossy surface finishing mode being selected to reduce the use of support material. The relative density of the honeycomb core was made constant to analyze the effects of cell geometry only. As hexagonal cell configuration is the most widely used cell shape in the honeycomb, additional hexagonal honeycomb with double cell length and wall thickness, was included to understand the effects of cell configuration and wall thickness on the out-of-plane compressive properties of honeycomb. The honeycomb geometries of 4 different cell configurations are listed in Table 1. The honeycombs have been sized to $75\text{mm} \times 75\text{mm} \times 12.7\text{mm}$ according to the dimensions given by the ASTM C365/C365M which is the standard test method for flatwise compressive properties of sandwich cores. The geometries of the honeycombs are shown in Figure 2.

Table 1: Dimensions of the 4 cell configurations used in the experiment

Cell configuration	Inner cell size (mm)	Cell wall thickness (mm)
Hexagon 1	length = 3.75	0.75
Hexagon 2	length = 7.5	1.5
Triangle	length = 10.97	0.75
Circle	radius = 5.875	0.75

Figure 2: Honeycomb core: (1) Hexagon 1, (2) Hexagon 2, (3) Triangle, (4) Circle

Flatwise Compression Test

The flatwise compression tests were performed using the Instron Testing Machine 5569 with a calibrated load cell of 50kN and loading rate of 0.5mm/min. The purpose of the flatwise compression tests is to determine the compressive strength of the honeycomb in relation to the out-of-plane direction. Three specimens were fabricated and included in the analysis for each of the cell-configurations.

The ultimate out-of-plane compressive strength of the honeycomb can be calculated by dividing the average yield load prior to failure ($P_{\max}$) by the load carrying cross-sectional area of the honeycomb specimen (A):

$$F^{cu} = P_{\max} / A \quad (1)$$

RESULTS AND DISCUSSION

The stress-strain curves of the honeycombs are shown in Figure 3 and the flatwise compressive strengths are tabulated in Table 2, for the cell configurations of hexagon 1, hexagon 2, triangle and circle, respectively. The shapes of the curves are generally in agreement with the plots reported by earlier research (Côté, Deshpande, Fleck, & Evans, 2004; Zhang & Ashby, 1992; Zhou, Wang, Zhao, & Shu, 2012). The hexagon 1, hexagon 2 and circle specimens demonstrate a linear elastic region followed by a peak strength, subsequently the peak begins softening and display a large plateau region followed by a densification region, as presented in Figure 3. However, densification region is not in the scope of the study for this paper hence the experiments were terminated after plateau. Triangle cell configuration has a relatively lower yield strength as compared to the other 3 configurations and displays a more abrupt softening after the peak. As the linear elastic behavior of the honeycomb terminates with the onset of fracture or elastic buckling of the thin cell walls, the abrupt reduction in the peak in triangle configuration honeycomb implies that the fracture of cell walls is critical to its stiffness and load bearing capacity, unlike hexagon and circle cell configurations honeycomb (Zhang & Ashby, 1992).

Table 2 shows that the out-of-plane compressive strength of circle cell configuration honeycomb is the highest among the 4 configurations. The compressive modulus of the circle configuration is also similar to that of hexagon 1 configuration. In the observation of the collapsing deformation of the cell walls in the 4 specimens, fracture tends to be the dominant failure mode for these honeycombs under compression. On the other hand, triangle cell configuration has the lowest compressive strength, attributed to the constraint in the higher number of connected cell wall that leads to greater probability and severity of plastic buckling and yielding of the cell walls near joints (Wang, Kumar, & McDowell, 2005).

Both hexagon 1 and hexagon 2 cell configurations have reasonable compressive strengths relating to the out-of-plane direction. Although these two configurations have different cell sizes while maintaining similar relative density, honeycomb with smaller cell size and wall thickness has a slightly higher out-of-plane compressive strength than that with larger cell size and wall thickness. However, it is noted that the flatwise compressive strength is reported as being insensitive to change of cell size at fixed relative density by earlier research (Wang et al., 2005; Zhang & Ashby, 1992).

Figure 3: Stress-strain curves of 4 cell-configuration honeycombs

Table 2: Out-of-plane compressive strength of honeycombs

	Hexagon 1	Hexagon 2	Triangle	Circle
Flatwise Compressive Strength F_{cu} (MPa)	6.68	6.11	3.80	8.06

CONCLUSION

The effects of the cell shape and cell geometry on the out-of-plane compressive strength of honeycombs have been reviewed in this paper. Using similar relative density, the circle cell configuration honeycomb displays the most excellent compressive strength in relating to the out-of-plane direction among the 4 cell configurations. However, the analysis of the cell size effect of the conventional hexagonal honeycomb may require further research because the current findings do not agree with previous findings. Future research could be performed on various cell configurations to analyze the effects of cell wall thickness and cell size on the out-of-plane properties of honeycomb.

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