Optimization of relative density to geometric parameter ratio for honeycomb structure using Finite Element Analysis

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Abstract. Honeycomb structures are becoming preferred choice for increasing the efficiency of automotive, aerospace, construction and other related industries as it provides low-density ratio to specific strength. Out-of-plane orientation honeycomb core structure has significant advantage in load-bearing and energy absorption. However, previous studies were mostly focusing on the specific strength of the structure. In this paper, optimization of relative density to geometric parameter ratio for honeycomb structure is conducted with the focus on compressive properties. It is expected that high compressive properties with low relative density can be achieved. Relative density and geometric parameter are obtained from RVE (Representative Volume Element) which affected by variable-thickness. Finite Element Analysis (FEA) using ANSYS software were conducted to simulate compression test with 300kN compressive load to the honeycomb structure with various ratios. FEM results illustrate that relatively higher geometric parameter tends to have higher compressive properties. Initial analysis shows that structure with the lowest ratio of relative density to geometric parameter of around 22.70% has higher equivalent elastic strain and equivalent stress around 0.50896 and 1.7152 GPa compared to other parameters.

1. Introduction

The demand of lightweight materials has been increased multi-fold in recent years due to environmental concern and consumer demand [1]. Lightweight materials becoming preferred choice for increasing the efficiency as they have low density ratio to the specific strength. Lightweight material has been used for increasing the efficiency of automotive, aerospace, construction and other related industries. One of the technologies used to fabricate lightweight material is by modifying the structure. The use of sandwich construction is prevalent in many structures due to the various advantages it offers in terms of weight-savings and high stiffness [2]. Sandwich structure generally consists of a core which bonded by two laminated face sheets on the two faces. Common core used on sandwich structure are made of cellular foams, trusses and honeycombs. Many studies have attempted to modify and develop the mechanical properties of the sandwich structure. Methods used for analyzing the behaviour of material are mathematical modeling and finite element analyses (FEA).

Common shape for core of sandwich material is hexagonal honeycomb structure. The advantage of the hexagonal honeycomb structure is high strength for load-barrier. The reason of honeycomb core become preferred choice is to achieve high stiffness with low density. Therefore, the structure is able to
be applied in weight sensitive applications such as aircraft, ships, and satellites [3]. Sandwich structures are basically constructed with thick and light core which bonded with two thin and strong sheet materials on both sides. The sandwich structure components are relatively weak, however as it is bonded together it provides a stiff, strong and lightweight structure as a composite structure.

The honeycombs structure has different mechanical properties along the in-plane and out-of-plane directions. Out-of-plane direction tends to have much higher stiffness and strength compared to in-plane due to the different in-plane and out-of-plane deformation mechanisms of honeycombs [4]. Investigations have been conducted by many researchers through experimental [5], numerical [6] and analytical [7] analysis. Some investigations demonstrate that the parent material property [8], topological configuration and relative density of honeycombs structure. Those factors have significant influence on the out-of-plane mechanical properties. Solid distribution on the structure affects the properties of both the in-plane and out-of-plane mechanical properties of honeycombs. The solid distribution of in-plane direction properties has been investigated by many researchers, but for out-of-plane it still not as many as them. This paper investigates the effect of solid distribution of out-of-plane mechanical properties of honeycomb structure with also considering about the relative density of the structure so that structure with high properties as well as low relative density can be achieved.

Recently, many honeycomb-like structures have been fabricated with additive manufacturing due to its excellent flexibility with complex geometric shapes compared with the conventional manufacturing methods [9], and honeycombs with variable thickness cell edges also can be easily fabricated using soft or hard elastic based materials. At present, there are few investigations devoted to the mechanical properties of additively manufactured honeycombs with variable-thickness cell edges. In this paper, the effects of solid distribution in hexagonal honeycomb cell edges on the out-of-plane mechanical properties are deliberately investigated. Firstly, hexagonal honeycombs structures were designed using SolidWorks with variable-thickness cell edges and tested by FEA in ANSYS software. The designs will be fabricated using 3D printer Anycubic Mega i3 with Polylactic Acid filament as the material.

2. Methodology
The idealized hexagonal honeycomb with variable thickness cell edges on the x-y plane is schematically illustrated in Figure 1, where \( h \) is the honeycomb width along the z direction and \( L_x \) and \( L_y \) are the length along x-y direction respectively. Representative Volume Element (RVE) is employed as it plays a central role in the mechanics of material to predict their effective properties. A representative volume element (RVE) model are used for Geometry configuration of the honeycombs are illustrated in Figure 2, where \( t \) is the thickness outside the intersection of the cell edges, \( R_p \) is the radius of the intersection, \( L_c \) is the length of the repeating cell element.

Figure 1. The configuration of honeycomb structure with variable thickness analyzed by RVE: \( h \) is the dimension along z axis, \( L_x \) and \( L_y \) are the dimension along x-y plane respectively.
Figure 2. Representative Volume Element (RVE) from Figure 1: \( L_c \) is the length of repeating element, \( t \) is the thickness of cell edges, \( R_p \) is the radius of fillet on each corner, \( A_p \) is the area on the cell edges within the intersection at the vertex, \( A_e \) is the area of the material in the cell outside the intersection and \( A_t \) is the area of RVE [10].

2.1. Relative density
Relative density is the most important structure characteristics of cellular material, which is dependent on the configuration of the cellular material. The relative density defined as the ratio of the density of a cellular material \( \rho^* \) (i.e., the honeycomb material) to the density of parent material \( \rho_s \) [4]. RVE is used in order to obtain the relative density of honeycomb structure geometrically based on Figure 2 with equation as:

\[
\frac{\rho^*}{\rho_s} = \frac{A_p + A_e}{A_t} = \frac{2}{\sqrt{3}} t \left( \frac{t}{L_c} \right)^2 + \frac{4}{3} - \frac{2\pi}{3\sqrt{3}} \left( \frac{R_p}{L_c} \right)^2
\]

Where \( A_p \) is the area on the cell edges within the intersection at the vertex, \( A_e \) is the area of the material in the cell outside the intersection and \( A_t \) is the area of RVE. Vertex areas can be computed as follows:

\[
A_p = \frac{(2R_p + t)^2}{4} - \frac{R_p^2\pi}{2}
\]

\[
A_e = 3t \left( \frac{L_c}{2} - \frac{R_p}{\sqrt{3}} - \frac{t}{2\sqrt{3}} \right)
\]

\[
A_t = 3\sqrt{3}L_c^2
\]

2.2. Geometric parameter
The geometric parameter \( \Phi_2 \) used for describing the proportion of the variable-thickness cell edges and the geometric parameter \( \Phi_2 \). The formula of the parameter was introduced by Simone and Gibson [11] in which the parameter defined as the area ration of intersection region \( A_p \) to the total solid region \( A_p + A_e \), given by:

\[
\Phi_2 = \frac{A_p}{A_p + A_e} = \frac{\rho_s}{\rho^*} \left[ \left( \frac{4}{3} - \frac{2\pi}{3\sqrt{3}} \right) \left( \frac{R_p}{L_c} \right)^2 + \frac{4}{3} \left( \frac{R_p}{L_c} \right) \left( \frac{t}{L_c} \right) + \frac{1}{3} \left( \frac{t}{L_c} \right)^2 \right]
\]

2.3. Design and preparation
In order to investigate the influence of the geometric parameter \( \Phi_2 \) on the out-of-plane mechanical properties of hexagonal honeycombs, four \( \Phi_2 \) values are selected. Two parameter variations were analyzed. The detailed dimensions and geometric parameter values of each honeycomb are listed in Table 1.
Table 1. Table of Parameter Variation with Relative Density and Geometric Parameter.

| Variation | \(L_x\) (mm) | \(L_y\) (mm) | \(h\) (mm) | \(L_z\) (mm) | \(t\) (mm) | \(r\) (mm) | \(\rho^*\) (%) | \(\Phi_2\) (%) |
|-----------|--------------|--------------|------------|--------------|-----------|-----------|---------------|---------------|
| HS-1      | 75           | 75           | 40         | 5            | 0.8       | 1         | 18.12         | 31.00         |
| HS-2      | 5            | 5            | 4          | 4            | 0.4       | 1.25      | 10.14         | 44.67         |

The honeycomb designs to be used for finite element analysis (FEA) are created based on the defined parameters in Table 1. The set up for the FEA was set to be similar with the out-of-plane compression test according to ASTM C365 [12]. Dimensions of the specimens were also designed according to ASTM C365: Standard Test Method for Flatwise Compressive Properties of Sandwich Cores. In this method, recommended minimum number of cells in the structure is 60 cells with largest practical facing area 5625 mm\(^2\) (7.5 × 7.5 mm\(^2\)). This method is used for uniaxial compressive force normal to the plane of the core structure. The force applied is transmitted from the machine to the structure through platens attached to the testing machine. Stress, strain, displacement and deformation of the samples were recorded. Deformation data can be obtained which then can be plotted into force vs deformation curve.

3. Result and discussion

In this study, the total deformation was obtained from compression test by Finite Element Analysis. Based on the two variations of parameters, the lowest relative density is achieved by sample HS-2. The ratio of relative density to the geometric parameter of HS-2 was relatively low around 1:4.4. As the compressive load applied, the displacement occurs to the structure is around 0.74 mm. The largest deformation of the specimen is located at the top surface of the specimen in contact with the load surface (Figure 3). The highest ratio of relative density to geometric parameter occurred on the HS-1 which was around 1:1.7. The deformation occurs at the structure was 0.43 mm lower than HS-2. The deformation of HS-1 was occurred at the top corner of the specimen (Figure 4). However, the density of HS-1 was still larger than HS-2.

![Figure 3. Total deformation of HS-1.](image-url)
The equivalent stress of the structure also has been obtained from Finite Element Analysis. The HS-1 as the lowest ratio has equivalent stress around 0.82847 GPa originated at the middle side of the specimen, means that the failure weight originated from the middle side of the specimen (Figure 5). Specimen HS-2 as the highest ratio has equivalent stress around 1.715 GPa occurred at the bottom of the specimen near to the fixed point (Figure 6). From this observation, the failure of the specimen was more likely to occur at the bottom part of the specimen.

**Figure 4.** Total deformation of HS-2.

**Figure 5.** Equivalent (Von-Mises) stress of HS-1.

**Figure 6.** Equivalent (Von-Mises) stress of HS-2.
The out-of-plane compression test will be conducted on Instron Universal Testing Machine with 300 kN load in order to validate the finite element results. The specimens of each configuration will be fabricated using an Anycubic Mega i3 printer with the PLA (Polylactic Acid) filament as the material. The samples of each configuration will be fabricated for compression test.

4. Conclusion
The finite element analysis on the optimization of honeycomb structure in the aspect of relative density to the geometric parameter ratio has been conducted. Two different geometric parameters were defined. It can be seen that specimen HS-2 with low relative density is more likely to have higher deformation compared to the specimen HS-1 with higher density. The magnitude of stress concentration of specimen HS-2 is also higher than specimen HS-1 which causes more possibility to fail. From this research, High geometric parameter is not necessary provided higher mechanical properties because the role of relative density affects more to the strength of the material. In order to validate the FEM result, the honeycomb structure will be fabricated using 3D printer with PLA filament and subsequently tested under compression test.

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