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Compression performance and analytical model of hexagonal-core sandwich panels fabricated by 3D printed continuous carbon fiber-reinforced thermosetting epoxy composites

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Abstract

Composite sandwich structures are widely used in a multitude of fields owing to their excellent properties, such as light weight and high strength. In this study, a series of hexagonal-core sandwich panels were integrally fabricated by three-dimensional (3D) printed continuous fiber reinforced thermosetting epoxy composites. The influence of the scaling effects that is, the side length and layer thickness on the compression performance of these structures was studied. The experimental results showed that the specific strengths of three different hexagonal-core sandwich panels with different side lengths of 5 mm, 10 mm and 20 mm side lengths is roughly maintained at 0.018 MPa/(kg m⁻³). In addition, doubling the wall thickness of the hexagonal core increases the compressive strength by only 38.9%. The performance characteristics of these hexagonal-core sandwich panels, which change with size, can provide a reference for designers and can be used for the preliminary prediction of the structural strength.

1. Introduction

Composite sandwich structures are characterized of high specific strength, high specific modulus, and low expansion coefficient. Such structures are widely used in transportation, aerospace, military protection, and civil buildings among other fields, playing the role of compression and energy absorption [1–3]. The core of the sandwich structure plays a critical role in the overall mechanical properties of these panels and various core design strategies for the compressive performance have been proposed, such as cellular [4], corrugated-cores [5], and lattice [6, 7].

The traditional hexagonal-core sandwich structures are also called honeycomb sandwich structures because their unit cells are much more close to the kind of honeycomb existing in nature [8]. The classical hexagonal honeycomb conjecture proved by Hales [9] further indicates that the hexagonal unit cell configuration is the most efficient structure in nature. In addition, the honeycomb has a periodic structure with two-dimensional arrays of unit cells in in-plane and parallel stacks in the out-of-plane, with tailorable anisotropic properties [10]. This allows the hexagonal honeycomb core to have more control over mechanical and crashworthiness characteristics than randomly-structured disordered and heterogeneous cores such as foam [11], voronoi lattice [12] and stochastic lattice [13, 14]. This also means that the design of the honeycomb sandwich structure under specific load conditions can more fully utilize the effectiveness of the material [15]. Alia et al. [16] prepared a honeycomb-core structure with infusing an epoxy resin through a carbon fiber fabric positioned in a dismountable honeycomb mould. These honeycomb-core exhibit impressive compression strength and energy-absorbing response. Compared with other sandwich structures, the hexagonal honeycomb sandwich structure is...
the first to appear [17] and is more widely used. For example, Vos et al [18] showed a pressure adaptive in-plane hexagonal honeycomb core morphing wing.

The mechanical properties of the sandwich structure have been investigated experimentally, simulated and analyzed theoretically [19], which indicate that the properties are closely related to the design parameters of the core material, such as cell size (length of hexagonal cell side), height and thickness. Ruan et al [20] investigated the in-plane dynamic response of hexagonal aluminum honeycomb structures based on ABAQUS finite element simulation. The results show that cell wall thickness and crushing velocity have a large effect on the deformation mode and platform stress. Gao et al [21] discussed the effect of geometric configuration on the mechanical properties of double arrowed sandwich structure.

Due to the traditional manufacturing process limitation, sandwich structures still cannot realize the integrated molding of core materials and panels [22, 23]. In recent years, advanced composite 3D printing technologies offer engineers new opportunities to produce greatly complex composite parts that were hitherto impossible to manufacture with traditional techniques [24]. In particular, the emergence of continuous fiber 3D printing technology has further improved their mechanical properties while ensuring manufacturing flexibility [25–27]. For example, Ming et al [28] printed thermostet continuous fiber specimens that achieved 58 wt% fiber content and exhibited maximum flexural strength and modulus of 952.89 MPa and 74.05 GPa, respectively. Moreover, complex parts with pentagonal and honeycomb structure were printed to verify their molding capabilities. Aziz et al [29] fabricated four different sizes of body-centered cubic lattice sandwich based on 3D printing. The experimental results showed that despite the similar failure modes observed in all samples, the compression strength increased by only 60% after four times the size.

In this paper, the hexagonal-core sandwich panels were prepared integrally, based on the 3D printed continuous carbon fiber-reinforced thermostetting epoxy composites process. Compression tests of these sandwich structures, with different side lengths and wall thicknesses, are carried out, and excellent agreement is found between the experimental results and the analytical model. The goal of this short communication is to obtain the law which describes the influence of the size on the performance of a hexagonal-core sandwich structure, in order to reduce the design cycle and the test cost, to provide the basis for the design of these panels, and to be used for the preliminary prediction of structural strength.

2. Material and methods

2.1. Material preparation
In this study, a continuous, fiber-reinforced composite 3D printer, based on a commercial fused deposition modelling (FDM) machine, has been adapted for the preparation of hexagonal-core sandwich panels. Continuous 3K carbon fibers (3000 fibers in a bundle, Tenax®-J, HTS40, 200 tex, Toho Tenax, Co., Ltd., Tokyo, Japan) with tensile strength and modulus of 4400 MPa and 240 GPa, respectively, were used as the reinforcement. EP (D.E.R. 671 (EP-671), 95 wt%, Dow, Pittsburg, CA, USA) and its curing agent [dicyandiamide (DICY), 5 wt%, Yongxin Plasticization, Guangzhou, China] were mixed uniformly to serve as the thermostetting matrix.

2.2. 3D printing procedures
The specimen is formed in two steps, printing and post-curing, as shown in figure 1. In the 3D printing process, continuous carbon fibers were firstly impregnated in a resin tank at 130 °C to fabricate them into continuous fiber reinforced thermostetting resin filaments [30]. Then the filament is extruded from the print nozzle (130 °C), rapidly cooled and attached to the glass print substrate or the previous layer. The printing nozzle can be moved in the X or Y direction along the contours of the section and the fill trajectory generated by the designed 3D model. During the post-curing process, the printed specimens were placed in silicone rubber moulds in order to avoid deformation of the specimens after warm-up. While the specimens were evacuated, it was put in an oven and heated to a temperature of 120 °C and maintained for 45 min for fiber densification, after which the temperature was adjusted to 170 °C and cured for 45 min for complete curing. Finally, demoulding was carried out to obtain the final specimen.

2.3. Experimental design
To study the effect of the thickness on the performance of these panels, two sandwich structure printing paths with different thickness were designed, as shown in figure 2. In particular, figures 2(a) and (b) illustrate a single- and a double-layer printing path, respectively. In order to ensure the continuity of the fibers, the printed path must be continuous during the printing process. In addition, the printed path should avoid intersections as much as possible to prevent local thickness unevenness caused by fiber intersection. At the same time, reducing the printing speed and adding a press command at the corner position optimizes the printing quality of the
corner position. The schematic diagram and the photograph of the final molded specimen are shown in figures 2(c) and (d), respectively.

In the experiment, the side length of the hexagonal-core was defined as the aperture size (s). The hexagonal-core sandwich samples with single- and double-layer walls, and with sizes of 5 mm, 10 mm, and 20 mm were printed and prepared. To ensure the same compression area of all sandwich panels with different apertures, the length and width of the compression surface of the designed structure were 103 mm and 20 mm, respectively. The specific parameters of the experimental samples are shown in table 1. An MTS (SANS) CMT4000 screw
driven electromechanical test machine with a 30 kN load cell was used to carry out all tests. The specimens were compressed between two steel cross heads at a displacement rate of 1 mm s$^{-1}$.

3. Results and discussion

3.1. Scaling effects in the compressive properties

The effect of varying the hexagonal-core size on the compressive properties of the sandwich samples, while keeping the total pressurized area constant, was assessed by crush tests. Figure 3 shows typical load-displacement traces following compression tests on the three scaled sample sizes. All three curves exhibit similar trends, increasing quickly to the initial peak after being loaded and subsequently dropping sharply. Loading further the three specimens, results in a second rising trend. The difference here is that, as the curve rises for a second time, the specimens with a side length of 5 mm are completely compacted, while the specimens with a side length of 10 mm, and 20 mm exhibit a second peak. After the second peak, the curve will rise again until the specimens are densified. However, in an intermediate loading regime between the initial peak and the second peak, the failure of the HPO-10 and HPO-20 specimens occurs at relatively low levels of force.

![Figure 3. Compression force-displacement traces for all samples, based on various aperture sizes.](image)

Table 1. Structural parameter values of the hexagonal-core sandwich panels which are studied.

| Specimen ID | Wall thickness ($t$, mm$^{-1}$) | Aperture size ($s$, mm$^{-1}$) | Number of hexagonal cell | Height ($H$, mm$^{-1}$) | Length ($L$, mm$^{-1}$) | Width ($W$, mm$^{-1}$) | Mass (M, g$^{-1}$) |
|-------------|--------------------------------|-------------------------------|--------------------------|------------------------|------------------------|------------------------|------------------|
| HPO-5–1     | 1                              | 5                             | 7                        | 37.6                   | 103.3                  | 20.4                   | 14.5             |
| HPO-5–2     |                                |                               |                          | 37.8                   | 103.5                  | 20.8                   | 14.3             |
| HPO-5–3     |                                |                               |                          | 37.8                   | 103                    | 20                     | 13.8             |
| HPO-10–1    | 10                             | 3.5                           |                          | 20.2                   | 104                    | 20.4                   | 14.0             |
| HPO-10–2    |                                |                               |                          | 21.2                   | 103.9                  | 20                     | 14.1             |
| HPO-10–3    |                                |                               |                          | 20.4                   | 103.9                  | 19.6                   | 13.9             |
| HPO-20–1    | 20                             | 2                             |                          | 11.2                   | 102.3                  | 20.3                   | 13.4             |
| HPO-20–2    |                                |                               |                          | 11.2                   | 101.9                  | 19.5                   | 13.5             |
| HPO-20–3    |                                |                               |                          | 11.4                   | 102.9                  | 19.7                   | 13.2             |
| HPT-10–1    | 2                              | 10                            | 3.5                      | 20.9                   | 103.4                  | 20.6                   | 23.7             |
| HPT-10–2    |                                |                               |                          | 21.2                   | 102.7                  | 20.7                   | 23.5             |
| HPT-10–3    |                                |                               |                          | 20.3                   | 102.7                  | 20.1                   | 24.4             |
Figure 4 depicts the typical photographs of the deformation evolutions for the three scaled sample sizes. A comparison suggests that the failure modes are similar in all of them, with the middle corner of the hexagonal-core cells failing in buckling and resulting in fracture. After the occurrence of the initial fracture, and under pressure, the entire sandwich structure continues to collapse downwards along the load direction, forming a new triangular cell sandwich structure. The reformed triangular cell exhibits improved compression capabilities and this can be considered as the main reason for the second rise in the force-displacement curve. However, it is important to note that when the side length of the hexagonal-core is 5 mm, the density of the structure increases and the cell is densified after the initial failure. Thus, this phenomenon does not appear on the force-displacement curve. These composite sandwich structures have similar failure modes at all three different scales, facilitating the prediction of structural failure.

After the test, the average initial peak forces of these sandwich with 20 mm, 10 mm, and 5 mm apertures are 6.6 kN, 13.1 kN, and 23.6 kN, respectively. Figure 5(a) illustrates the plot of the initial peak force versus the aperture size of the three hexagonal-core cells. It is evident that the compression properties seem to loosely follow a relationship based on the aperture size. The initial peak force shows a tendency to increase with the decrease of the aperture size. Combined with the specific experimental results, it can be approximated as,

$$\sigma_{20} : \sigma_{10} : \sigma_{5} = \frac{P_{20}}{A_{20}} : \frac{P_{10}}{A_{10}} : \frac{P_{5}}{A_{5}} \approx 1 : 2 : 3.5$$

where $\sigma$ is the compressive strength of honeycomb structures, $P_i$ and $A_i$ are the initial peak force and pressure area, respectively. The compression properties of these samples follow a simple law of proportionality, which can be used to initially estimate the shape of larger structures.

The strength of the structure can be defined as the strength of the structure over the density of the structure. It is used to measure the strength of the material per unit mass, and it can be expressed as,
\[ S_{\sigma} = \frac{\sigma}{M/V} \]  

where \( \sigma \) is structural strength, \( M \) and \( V \) are the mass and volume of the structure, respectively. Figure 5(b) summarizes the influence of the aperture size on a specific strength. An examination of figure 5(b) highlights the absence of any appreciable size effect on the specific strength of the hexagonal-core sandwich structure. Here, the specific strength of all specimens was roughly maintained in a constant range, being approximately 0.018 MPa/(kg m\(^{-3}\)).

### 3.2. The influence of the hexagonal-core thickness

Figure 6(a) shows typical force-displacement traces which follow compression tests on samples with single- and double-layer thicknesses. As expected, increasing the thickness leads to an increase of the compression capability of the sandwich structure. However, the variation trend of the force-displacement curve of the double-layer hexagonal-core sandwich, under compression, is still the same as that of the single-layer structure. Compared with the single-layer structure, the double-layer hexagonal-core wall thickness increased by 1 mm (see table 1). From figure 6(b), it can be seen that as the wall thickness increases, the compressive strength from 6.36 MPa to 10.38 MPa. The compression capability, in turn, increases by 63.2%. The compressive strength did not increase significantly with the increase of wall thickness. The specific strength of the sandwich with the two-layer thickness is depicted in figure 6(c), indicating that, for the double-wall sandwich, it is significantly smaller compared to the single-wall structure. The results show that the quality of the hexagonal-core sandwich increases when the wall thickness is increased. Nonetheless, the strength per unit mass decreases along with the material utilization rate. These results suggest that for composite structures, reducing the cellular aperture size can increase the compressive capacity of the structure significantly and achieve a higher material utilization compared to the one which is achieved by simply increasing the thickness.

The fracture of the double-thick sample during compression is shown in figures 7(a) and (b). Here, it is clear that the double-layer specimens exhibit the same failure mechanism as single-layer specimens. Figures 7(c) and (d) shows the interlayer damage of the specimens after testing. Cracks grow along the fibers in the interlayer direction and only a very small fraction of the fibers will fracture. In addition, it is important to note that defects in the 3D printing process can seriously affect the mechanical properties of the specimens [29]. Compared with the single-layer specimen, the printing path of the double-layer specimen is more complicated. Therefore, manufacturing defects, such as voids, are more likely to occur in 3D printed process, especially in the joint regions. This may be one of the reason for the lower-than-expected compressive strength of double-layer specimens.

### 3.3. Analysis of the Compression Strength

Consider the loading situation of the hexagonal-core sandwich panel with an applied compressive load, as shown in figure 8(a). Assuming that the total pressure is 3.5\( P \), the load on each hexagonal-core is \( P \), as illustrated in figure 8(b). After considering the sides of the hexagon as cantilever beams for force decomposition, \( P \) can be expressed via the relation,

\[ F_N \sin \theta + F_s \cos \theta = \frac{P}{2} \]

where \( F_N \) is the pressure along the hexagon side, \( F_s \) represents the shear force which is applied and \( \theta \) is the angle between the side edges of the hexagonal core and the top panels.
The displacement $D$ after compression is decomposed into the displacement components $d_1$ and $d_2$, along the beam and the direction perpendicular to the beam. The corresponding relationship can be expressed as,

$$d_1 \sin \theta + d_2 \cos \theta = \frac{D}{2}$$

Figure 7. Fracture of double-layers thickness samples. (a) and (b) Failure mechanisms in the compression process. (c) and (d) Manufacturing defects in the interlayer.

Figure 8. (a) Force diagram of hexagonal-core sandwich panel (HPO-10). (b) Free-body diagram of a single unit. (c) Fracture angle $\theta$ at initial failure. (d) The force of hexagonal core wall.
where,

\[ d_1 = \frac{F_N \cdot s}{tWE} \]

\[ d_2 = \frac{F_1 \cdot s}{12EI} = \frac{F_1 \cdot s}{EWt^3} \]

\[ \frac{d_1}{d_2} = \tan \theta \]

\( E \) is the Young’s modulus of the core and \( I \) is the moment of inertia. Using equations (3)–(7), the load \( P \) which is applied on each hexagonal-core can be expressed as:

\[ P = \frac{1}{s^3}tWED(s^2 \sin^2 \theta + t^2 \cos^2 \theta) \]

It is considered that the displacement \( D \), after loading, is closely related to the side length of the hexagon and is directly proportional to it. Assume that the ratio \( D_{20} : D_{10} : D_{5} \) is equal to 4:2:1. The first failure occurs when \( \theta \approx 50^\circ \) [figure8(c)] and the thickness of the single layer \( t \) is 1 mm. Combined with the data in table 1, equation (8) yield,

\[ P_{HPO-20} : P_{HPO-10} : P_{HPO-5} = 2P_{20,t=1} : 3.5P_{10,t=1} : 7P_{5,t=1} \approx 1 : 2 : 3.5 \]

The analytical results are in good agreement with the experimental results, supporting further that the compression strength is proportional to the edge length of the hexagonal-core.

Typically, the compressive structures exhibits two types of load-displacement curves during loaded [31]: One kind of load-displacement relationship curve is relatively flat. The other load-displacement curve rapidly descends to a flat plateau compression stage after a high initial peak. The difference is that the hexagonal sandwich panel has two peaks in the force-displacement curve after the test (shown in figure 3), which makes it have the potential to withstand the secondary loading. In addition, figure 9 shows the compression specific strength of the hexagonal-core sandwich structure compared to other materials. It can be seen that the compressive performance of the hexagonal core prepared from the 3D printed continuous carbon fiber reinforced thermosetting epoxy resin composites is significantly higher than that of the sinusoidal-shaped cores prepared by the co-curing process, and slightly lower than that of corrugated cores prepared by the molding process.

Figure 9. Comparison chart of hexagonal sandwich structure with other materials [5, 32, 33].
4. Conclusions

A range of all-composite sandwich structures based on a hexagonal-core have been manufactured by 3D printed continuous carbon fiber-reinforced thermosetting epoxy composites. According to the force-displacement curve, obtained from the test results, it can be concluded that the hexagonal-core sandwich shows more than one peak during the crushing process. The first peak is formed by the initial damage and the second peak is generated by the triangle-like structural damage, which is formed after the sustained compression. Three sandwich structures with the same compressed areas, but with different aperture sizes of 5 mm, 10 mm, and 20 mm, exhibited significant size scaling effects. The aperture ratio and the structural strength ratio show an almost consistent inverse relationship. However, the change of different aperture sizes does not drastically affect the specific strength of these hexagonal-core sandwich. Doubling the wall thickness of the hexagonal-core did not double the strength of the sandwich panels. On the contrary, as the layer thickness increased, the material utilization rate decreased. Therefore, the reduction of the aperture is more favorable to achieve structural strength improvement while maintaining the material utilization, compared to increasing the wall thickness of the hexagonal-core. The performance characteristics of the composite sandwich which change according to the law of size can provide a reference for designers and can be used for preliminary prediction of structural strength.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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