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Review Article

3D woven honeycomb composites: Manufacturing method, structure properties, and applications

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Abstract

Honeycomb is an advanced material that is preferred in many engineering applications due to its high weight/strength ratio. High toughness and cost competitiveness were achieved because of improved production technology and innovative honeycomb core-face sheet combinations. In this study, the basic concept of preparation of 3D woven honeycomb structure, the role of various honeycomb structural parameters, weave architecture, fabrication of honeycomb composites and their mechanical characteristics (compression, flexural, and impact), and applications of 3D woven honeycomb composites are discussed with experimental evidence. The results show that 3D woven honeycomb composite is a good energy absorber in flatwise compression and impact deformation. 3D woven honeycomb composites have a promising future in lightweight load-bearing applications mainly due to their structural integrity and therefore, they can be actual alternatives for aluminum and other metal alloys.

Keywords: honeycomb, woven, internal design, textile

Introduction

Lightweight engineering aims to find new ways to make items lighter without compromising their strength, and in some circumstances, even strengthening them. For lighter goods, one alternative is to use cellular structures and materials, such as honeycombs. Due to their superior mechanical performance, such as high stiffness to mass ratio and strong energy absorbing capacity, honeycomb structures are extensively used as sandwich panels in a variety of applications.[1–3] Sandwich panels with honeycomb cores with hexagonal structures have higher shear rigidity, higher crushing stress, longer stroke, lower weight, and continuous crushing force.[4]

The internal design of the 3D honeycomb structure has an inherent hollow space that decreases weight while maintaining the appropriate strength. For decades, cellular solids such as sandwich panels have been used as innovative materials in the aerospace, automobile, and marine industries due to their unique properties deriving from their cellular topologies.[5,6] There has been a lot of interest in figuring out how to weave this complex structure and how it functions mechanically under different stresses in recent years.[7] The fiber volume fraction and specific weight of the unit cell were determined using geometrical modeling of a 3D woven honeycomb.[8]

The impact point, core structure, panel geometry, and adhesion property all affect impact resistance.[9] By mathematical modeling of the 3D solid woven construction, some research has been done to anticipate the internal geometry, tensile behavior,[10] and impact behavior.[11] Xiaozhou Gong[12] investigated the mechanical performance of honeycomb textile composites with varied geometric structural characteristics, such as cell size, opening angle, wall-length ratio, and composites of the same thickness with varying cell sizes, using a low-velocity impact test. The researchers [13] tested a composite material consisting of a honeycomb core and sheets of reinforced glass fiber laminated with epoxy resin in an impact test.

The methodology for the test of edgewise compression of sandwich panels made of metals was previously described.[14] The buckling behavior of the square cell honeycomb was studied by Liang and Chen[15] and concluded that different buckling modes were shown by different kinds of cells and also developed a new iterative optimization method for the honeycomb panel. Honeycomb sandwich panels were studied numerically and experimentally under in-plane compression and bending loads.[16] Mamalis et al.[17] examined the in-plane compressive properties, collapse modes, and crushing characteristics of composite sandwich panels with various fiber-reinforced skins and core materials.

Sun et al.,[18]; Crupi et al.,[19]; Belouettar et al.[20] used three-point bending or four-point bending tests on sandwich constructions to examine the bending behaviors and fatigue life of aluminum honeycomb sandwiches. Giglio et al. used finite element simulations to investigate the behavior of sandwich constructions under flatwise compression and three-point bending simulations.[21,22]

Previous research has shown that honeycomb structures have high energy absorption properties, whereas woven honeycomb composites have received less attention. To give superior mechanical qualities such as tensile and shear strengths, 3D woven fabric provides a compact structure with no delamination or interlaminar separation. The structural parameters of 3D woven honeycomb composite, weave architecture, fabrication method, composite processing, mechanical behavior (compression, bending, and three-point bending test), and various applications were studied in depth in this research work.

Applications of 3D woven honeycomb structure

Honeycomb structures are utilized in the aerospace, marine, mantle, automotive high-speed trains, industrial structure, thermal management, or thermal insulation,[23] and packaging industries, particularly in the space and aviation industries. It is also utilized in sporting goods, furniture, doors, yachts, ships, and boats, as well as architectural projects and caravan décor. These honeycomb structures can also be employed as a buffer in buffer design, acting as an energy absorber and therefore reducing accidents.[1] Because of their increased weight/strength ratio, honeycombs are also used in the railway and automobile industries.[24] Honeycomb sandwich panels are widely utilized in the packaging sector because of their distinctive open pore structure, as well as in the furniture and construction industries due to their excellent cushioning capabilities. Paper honeycomb products are used to absorb energy and withstand shock and vibration, acting as a cushioning material and protecting objects from damage.[1]

The basic concept of textile-based honeycomb

Honeycomb is one of the types of cellular materials. Usually, it has a series of hexagonal cells which are arranged together and form cells that have a similar appearance to the cross-sectional slice of a beehive. Each cell in a regular honeycomb structure is symmetrical horizontally and vertically, but cells in an irregular structure are asymmetrical. Hollow cell architectures can be triangular, rectangular, or even circular, with hexagonal being the most prevalent due to geometrical and mechanical advantages. Honeycomb structures have long been utilized in weaving to create 2D cellular fabrics that absorb moisture. In recent years, 3D woven honeycomb structures have been created on traditional weaving machines with minor modifications. These structures are made to make lightweight high-volume constructions with various cell geometrical characteristics such as wall length, opening angle, cell size, number of layers, and cell height to achieve the appropriate thickness, areal density, and fiber volume fraction.

Structural parameters of 3D woven honeycomb

The number of picks in the required region of the honeycomb cell in the fabric can be altered to change the structural properties of the 3D woven honeycomb fabric. Free wall length (l_f), bonded wall length (l_b), free wall thickness (t_f), bonded wall thickness (t_b), cell opening angle (θ), and height of cell (h) are some of the structural parameters of 3D woven honeycomb fabric. Figure 1 depicts these factors.

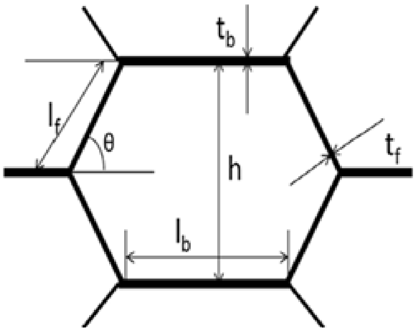

Figure 1 Parameters of unit honeycomb cell.[1]

Weave architecture of 3D woven honeycomb fabric

As shown in Figure 2, one repeat of a 3D woven honeycomb fabric can be separated into four sections: regions 1, 2, 3, and 4. Section I corresponds to the region of the 3D honeycomb structure where all of the fabric layers are separated from one another; section 2 is where adjacent layers join together at an alternate interval; section 3 is the same as section 1, and section 4 is the same as section 2 but with different joining layers.[1] Section 1 and 4 is showing the free wall length (l_f) zone, while sections 2 and 3 is showing bonded wall length(l_b) zone. In the cross-section diagram, the straight line represents the weft yarn, while the curved lines indicate the warp yarns (Figure 2).

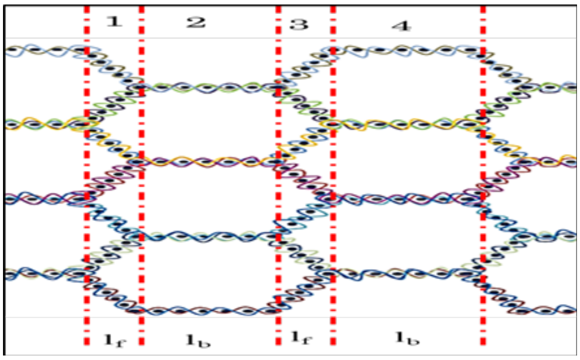

Figure 2 Cross-section representation of 3D woven honeycomb fabric.

Manufacturing of 3D woven honeycomb fabric

The 3D woven honeycomb samples in this study were made on a customized rigid rapier weaving machine. The machine is equipped with a four-beam setup with separate take-up and let-off mechanisms. The machine features 24 heald shafts with electronic dobby and a specialized CAD system for weaving diverse designs to generate textiles such as three-dimensional multilayer solid constructions, spacer fabrics, and three-dimensional honeycomb structures.

Weave design is the first and most important step in the weaving process. The designs must be compatible with a two-dimensional weaving technology. To achieve this criterion, designs are created using the double cloth principle, which consists of two unique layers that are separated from one another. Warp threads are drawn from four beams to make honeycomb fabric. The two layers of honeycomb fabric are then combined at a specific position to form a honeycomb structure. EPI (ends per inch) -10. Picks per inch (PPI)–10, the linear density of warp and weft –600 Tex. The connected wall of EPI is double that of the free wall, but the PPI remains constant. Figure 3 shows a honeycomb fabric sample with 5 picks in both the bonded and free wall zones and a 60-degree opening angle.

Figure 3 3D woven honeycomb fabric sample.

Processing of honeycomb composite

The vacuum-assisted resin infusion process was used to transform the fabric samples into composites. Epoxy LY556 (resin) and Aradur HY951 (hardener) were used to create composites. During resin impregnation and curing, the 3D shape of the preform had to be maintained. Wooden moulds were created to fit the desired shape of composites. Before putting it into honeycomb cells, a Teflon sheet was wrapped over it, as shown in Figure 4(a), so that it would not adhere to the fabric and could be easily removed once the composite was formed. Figure 4(b) depicts the successfully developed 3D woven honeycomb composite. The structural specifications of the developed composites are 12.7mm bonded wall and free wall lengths, 20mm cell height, 60-degree opening angle, 1.24mm bonded wall thickness, and 0.83mm free wall thickness.

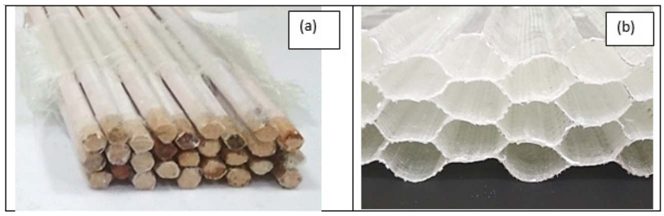

Figure 4 (a) Teflon wrapped wooden molds for composite making, (b) 3D woven honeycomb composite.

Result and discussion

Characterization of composite structures: compression, flexural and impact properties were studied to understand the effect of the structure of 3D woven honeycomb composite on mechanical properties.

Flatwise compression test

Flatwise compression testing of honeycomb composite was performed according to ASTM C365 using the Zwick/Roell universal testing equipment at a loading rate of 2mm/min (Figure 5 (a)). Sandwich panels were made using simple woven composites as upper

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and bottom sheets and an adhesive (Fast setting epoxy) to adhere the core to the face sheets, as shown in Figure 5(b). The core height (30 mm) and the number of cells (9) were consistent throughout the honeycomb sample. The average results are used to calculate the final findings after examining 5 samples. The energy absorption (W) of honeycomb structure was determined using equation 1 up to a strain (ε):

$$W=\int_0^{\varepsilon} \sigma(\varepsilon)d\varepsilon \qquad (1)$$

Where σ(ε) is the stress up to the strain (ε) in a deformed structure.[25] Load-deformation curve for the flatwise compression is shown in Figure 5(c). Ultimate load for flatwise compression of the sample is 15000N. The compressional energy of the honeycomb structure is 200J.

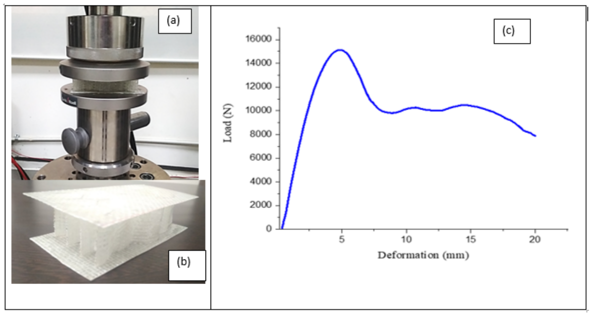

Figure 5 Flatwise compression test. (a) Experimental setup, (b) sandwich panel for compression test, (c) load-deformation curve.

Edgewise compression test

On the Zwick/Roell universal testing equipment, edgewise compression testing of honeycomb is performed according to ASTM C 364–99 with a crosshead movement of 0.5 mm/min (illustrated in Figure 6(a)). The core height (20 mm) and the number of cells (9) were consistent throughout the honeycomb samples. The average results are used to calculate the final findings after examining 5 samples. Figure 6(b) shows the load-deformation curve for the edgewise compression test. The ultimate load was determined using the edgewise compression load-deformation curve. The ultimate load of honeycomb structure for edgewise compression is 88N.

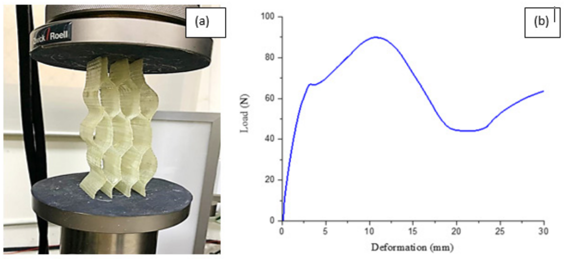

Figure 6 Edgewise compression test. (a) Experimental setup, (b)load-deformation curve.

Three-point bending test

For each honeycomb composite, ASTM C 393 was utilized to evaluate the bending performance of composite samples. A three-point bending test was done on the Zwick/Roell universal testing machine at a cross-head speed of 1mm/min with a span length of 150mm (Figure 7(a)). Three rollers with a diameter of 40mm were used for the bending test. The average results are used to calculate the final findings after evaluating 5 samples. The ultimate load for a 3D woven honeycomb composite was calculated using the load-deformation curve illustrated in Figure7 (b) for a three-point bending test. The maximum load for a three-point bending test in a honeycomb sample is 330 N.

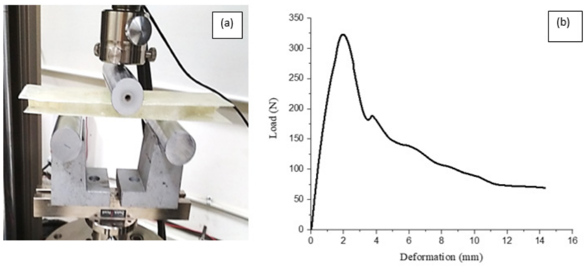

Figure 7 Three-point bending test. (a) Experimental set-up, (b)load-deformation curve.

Low-velocity in-plane impact test

A drop-weight impact facility (INSTRON CEAST 9350) was used to conduct low-velocity impact tests on sandwich specimens in the in-plane direction, as shown in Figure 8(a). In the following data analysis, the specimen cut in square shape of 14cmx14cm, peak force, and energy absorption were chosen as the most important performance indicators to determine the effectiveness of the textile honeycomb composites. The absorbed energy and response of the Load-displacement curve (Figure 8(b)) and energy-time curve Figure 8(c) were used to evaluate the impact characteristics of honeycomb composites. After testing the number of samples (five), average values are used to calculate the final results. The ultimate load, computed from the force-displacement curve, is 2700N, and the energy absorbed by the sample in the in-plane impact is 58J, as estimated from the force-displacement and energy-time curves.

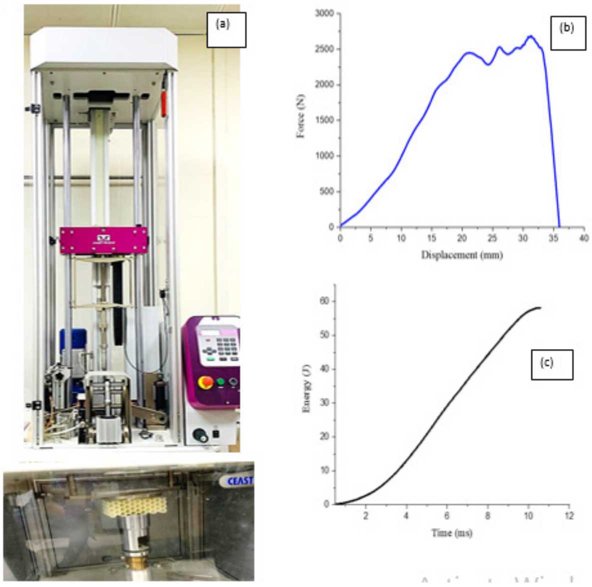

Figure 8 In-plane impact test (a) Experimental set-up for impact test in INSTRON CEAST 9350, (b)Force-displacement curve, (c) Energy-time curve.

Conclusion

Honeycomb geometric configuration has a significant effect on energy absorption qualities in impact and flatwise compression. Without modifying the constituent material, a wide range of mechanical properties (compression, flexural, and impact) can be achieved by varying the geometry of the cellular structure, allowing the designer to construct a large number of configurations. But there are some challenges to weave the honeycomb samples and to be considered during fabrication and optimization required for composite processing. This study gave a brief study of honeycomb structures, their structural variation, weave architecture, some mechanical behavior, and applications. The result of mechanical characteristics

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such as flatwise compression and impact analysis show that 3D woven honeycomb composite can be a good alternative to metal honeycomb and for some energy absorbing applications.

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Conflicts of interest

Author declares that there is no conflict of interest.

References

1. Tripathi L, Behera BK. Review: 3D woven honeycomb composites. *Journal of Materials Science*. 2021;56(28):15609–15652.
2. Domb R, Jadhav S, Gajare S, et al. Design of honeycomb sandwich panel and its validation with flooring plate of bus. *International Research Journal of Engineering and Technology*. 2018:490–495.
3. Sypeck DJ, Wadley HNG. Cellular metal truss core sandwich structures. *Adv Eng Mater*. 2002;4:759–764.
4. Wierzbicki T. Crushing analysis of metal honeycombs. *Int J Impact Eng*. 1983;1:157–174.
5. Torre L, Kenny JM. Impact testing and simulation of composite sandwich structures for civil transportation. *Compos Struct*. 2000;50:257–267.
6. Shin KB, Lee JY, Cho SH. An experimental study of low-velocity impact responses of sandwich panels for Korean low floor bus. *Compos Struct*. 2008;84:228–240.
7. Tan X, Chen X. Parameters affecting energy absorption and deformation in textile composite cellular structures. *Mater Des*. 2005;26:424–438.
8. Tripathi L, Neje G, Behera BK. Geometrical modeling of 3D woven honeycomb fabric for manufacturing of lightweight sandwich composite material. *J Ind Text*. 2020.
9. Crupi V, Epasto G, Guglielmino E. Comparison of aluminium sandwiches for lightweight ship structures: Honeycomb vs. foam. *Mar Struct*. 2013;30:74–96.
10. Jayan VR, Tripathi L, Behera PK, et al. Prediction of internal geometry and tensile behavior of 3D woven solid structures by mathematical coding. *J Ind Text*. 2021.
11. Tripathi L, Chowdhury S, Behera B. Modeling and simulation of impact behavior of 3D woven solid structure for ballistic application. *J Ind Text*. 2020.
12. Gong X. Investigation of different geometric structure parameter for honeycomb textile composites on their mechanical performance. United Kingdom: University of Manchester; 2011.
13. Petrescu HA, Hadăr A, Pastramă ȘD. Experimental program for impact tests on a honeycomb core composite material. *Proc Rom Acad Ser A - Math Phys Tech Sci Inf Sci*. 2017;18:150–157.
14. Ogorkiewicz RM. Analysis and design of structural sandwich panels. *Composites*. 1970;1:378.
15. Liang S, Chen HL. Investigation on the square cell honeycomb structures under axial loading. *Compos Struct*. 2006.
16. Sun G, Huo X, Chen D, et al. Experimental and numerical study on honeycomb sandwich panels under bending and in-panel compression. *Mater Des*. 2017;133:154–168.
17. Mamalis AG, Manolakos DE, Ioannidis MB, et al. On the experimental investigation of crash energy absorption in laminate splaying collapse mode of FRP tubular components. *Compos Struct*. 2005.
18. Sun G, Huo X, Chen D, et al. Experimental and numerical study on honeycomb sandwich panels under bending and in-panel compression. *Mater Des*. 2017.
19. Crupi V, Montanini R. Aluminium foam sandwiches collapse modes under static and dynamic three-point bending. *Int J Impact Eng*. 2007;34:509–521.
20. Belouettar S, Abbadi A, Azari Z, et al. Experimental investigation of static and fatigue behaviour of composites honeycomb materials using four point bending tests. *Compos Struct*. 2009.
21. Giglio M, Manes A, Gilioli A. Investigations on sandwich core properties through an experimental–numerical approach. *Compos Part B Eng*. 2012;43:361–374.
22. Giglio M, Gilioli A, Manes A. Numerical investigation of a three point bending test on sandwich panels with aluminum skins and NomexTM honeycomb core. *Comput Mater Sci*. 2012;56:69–78.
23. Dempsey BM, Eisele S, McDowell DL. Heat sink applications of extruded metal honeycombs. *Int J Heat Mass Transf*. 2005;48:527–535.
24. Nakada I, Eberhard H. Numerical simulation of crash behavior of composite structures for automotive applications. *Mater Tech*. 1994;82:33–38.
25. Gibson LJ, Ashby MF. Cellular solids. United Kingdom: Cambridge University Press; 1997.

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