THE ENERGY-ABSORBING CHARACTERISTICS OF HONEYCOMB CORES BASED ON CARBON FIBRE COMPOSITES

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ABSTRACT

This paper investigates the energy-absorbing behavior of two types of carbon fiber reinforced honeycomb core manufactured using the VARTM method. One type of honeycomb was based on an epoxy resin and the other on an infusible thermoplastic, ELIUM®. The honeycomb cores were produced using a steel onto which solid hexagonal blocks were secured. Carbon fiber fabrics were placed into the gaps between the blocks and the mold was subsequently vacuum-bagged and infused with either the thermoplastic or thermosetting resin. After manufacture, the steel blocks were removed from the samples giving a well-defined honeycomb structure. Test specimens were then removed from these honeycomb structures and inspected non-destructively using an X-ray computed tomography machine before testing at quasi-static rates of loading.

Compression tests on the two types of honeycomb structure resulted in a stable mode of crushing failure, with energy being absorbed in fiber fracture and splitting. Both the thermosetting and thermoplastic-matrix cores exhibited similar values of specific energy absorption (SEA) with this value exceeding 50 kJ/kg for a thermoplastic-matrix core based on a fiber weight fraction of approximately 57%. This evidence suggests that fiber-reinforced honeycomb cores offer significant potential for use in energy-absorbing applications.

1 INTRODUCTION

The use of sandwich composites has become a necessity in multiple structural components, especially in the aerospace industry where weight-saving and superior specific strengths are primary requirements. Another important use of sandwich structures includes blast protection, where plastic deformation and fracture in the face sheets combined with extensive crushing in the core frequently combine to offer a lightweight solution for various types of threat. Typically, the core material is based on a foam (polymeric or metallic) or a honeycomb (aluminum or Nomex™) [1,2]. Driven by sustainability and high-performance requirements, recent advancements in thermoplastic composites have led to the development of composite honeycombs cores. However, a very limited number of studies have been reported so far in the literature on composite cores, where continuous fibers are embedded in a polymeric matrix [3]. This is primarily due to the technical challenges associated with the manufacturing of complex composite structures with narrow tolerances.

Herein, we investigate the energy absorption characteristics of carbon fiber honeycomb cores for aerospace structures based on an epoxy resin and an innovative liquid thermoplastic resin (i.e., Elium®). Elium® resin is the first of its kind, liquid thermoplastic resin having a low viscosity of 0.1 Pa.s, that makes it compatible with liquid composite molding techniques [4–7]. Both types of composite core were manufactured using a simple resin infusion or vacuum-assisted resin transfer molding (VARTM) process at room temperature. The specific energy absorption characteristics of both honeycomb core variants were evaluated by compression testing of single-cell and five-cells specimens. The failure modes of fractured specimens were thoroughly investigated. The results are also compared with the findings reported in the literature on conventional honeycombs, polymeric foams and Nomex™ cores.

2 EXPERIMENTAL PROCEDURE

The honeycomb cores investigated in this study were manufactured from unidirectional (UD) carbon fibers supplied by Unitex UT-300/500 with an areal density of 291 g/m^2 and a nominal thickness of 0.25 mm. Two resin systems were used, one being a thermosetting epoxy (Prime^{TM} 20LV, with a slow hardener and was also supplied by Gurit Ltd.) and the other being an infusible thermoplastic (Elium® supplied by Arkema Ltd.).

The cores were produced using the mold shown in Figure 1a. Here, 39 honeycomb-shaped blocks, with a height of 29 mm and face-to-face distance of 22 mm, were located in slots machined into the base of the mold, as shown in Figure 1a. Short lengths of UD carbon fibers were placed vertically in the gaps between the blocks to serve as reinforcements after infusion. The weight fraction of fibers was varied by increasing the number of carbon fiber fabric plies from one to four. For infusion with epoxy, the resin and the hardener were mixed in a ratio of 100:28, whereas 2 wt.% benzoyl per oxide initiator was mixed with Elium® to initiate the in-situ polymerization of the thermoplastic resin. The mold was positioned on glass table and vacuum-bagged in preparation for infusion. After completing the infusion process, the cores were allowed to cure under vacuum of 24 h at room temperature. Following complete cure, the mold was removed from the bagging material and the steel blocks were removed from the core leaving a honeycomb structure similar to that shown in Figure 1b.

The composite cores were sectioned in order to create single cell and five cell samples. The microstructures of a number of samples were examined in a GE® Phoenix Nanotom X-ray computed tomography device. This machine has an X-ray capability up to 100 kV and a nominal resolution of one micron.

The energy-absorbing properties of the cores were determined through compression tests using a universal testing machine at a displacement rate of 2 mm/min. During the compression tests, the force and displacement data were recorded and then used to determine the specific energy absorption (SEA) characteristics of each sample. The absorbed energy was calculated from the energy under the load-displacement trace up to the densification threshold.

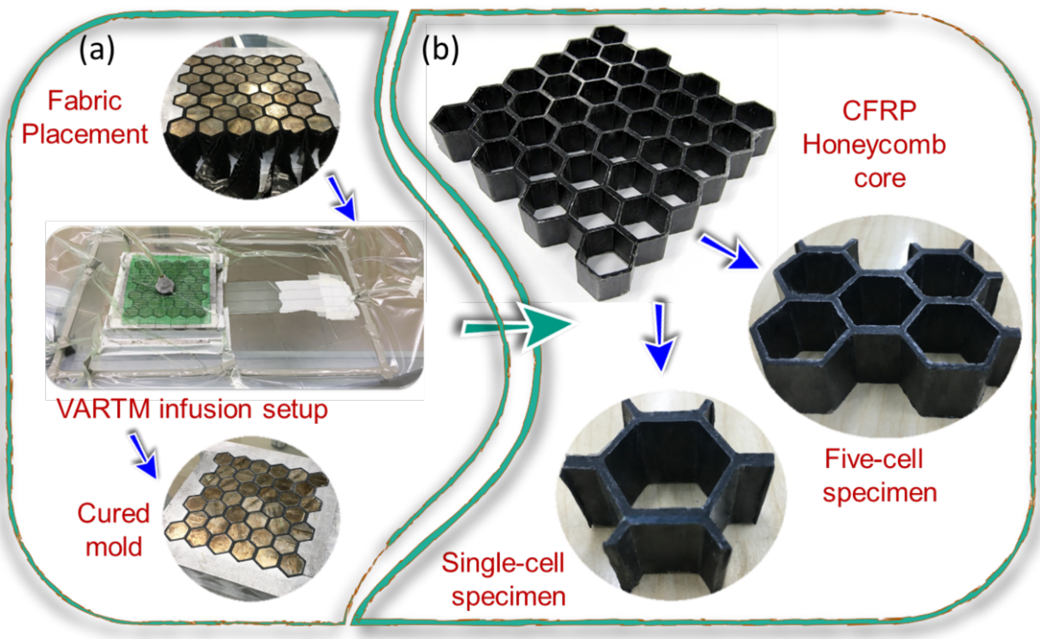

Figure 1: Manufacturing of composite honeycombs (a) mold preparation and infusion setup and (b) final composite specimens.

3 RESULTS AND DISCUSSION

3.1 Nondestructive Micro CT analysis

The quality of the composite honeycomb structures was evaluated through cross-sectional micro-CT (XCT) images, as shown in Figure 2. These micrographs showed that the resin rich areas were more prominent along the edges of the hexagonal cells where the single and double thickness regions merged. The scans also revealed defects in the form of mesoscopic voids, indicating that the porosity within the liquid resins was not fully removed by the VARTM process. Nonetheless, all of the composite specimens exhibited impressive energy absorption characteristics despite the presence of these defects. Similar microstructures were observed for both the thermosetting and thermoplastic composite honeycomb systems due to a similar viscosities and impregnation behavior of the liquid resins.

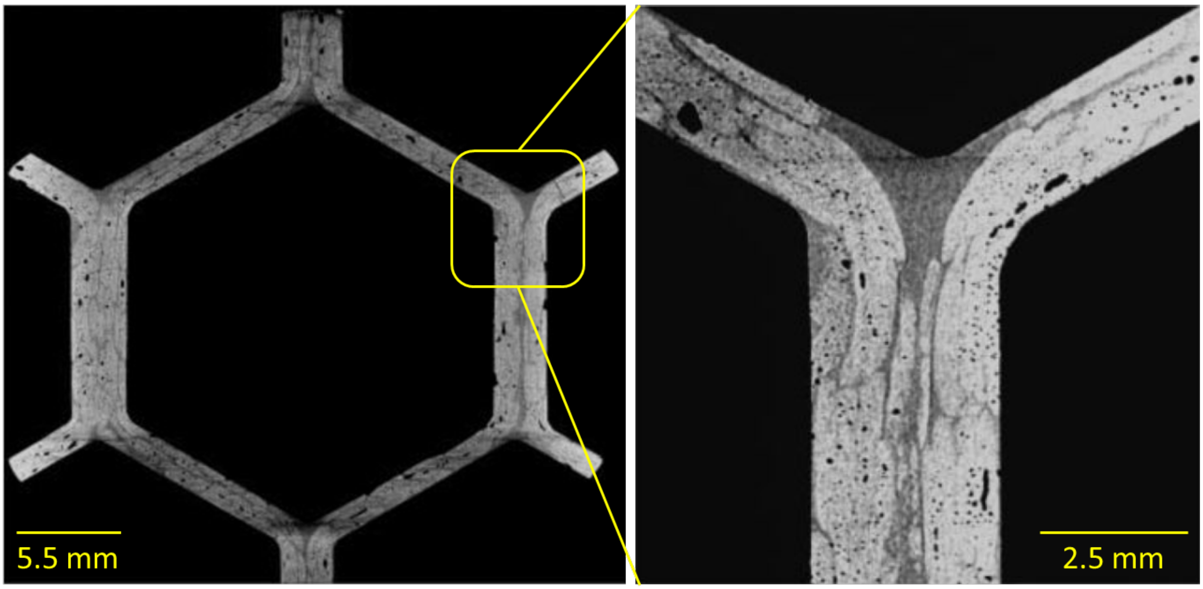

Figure 2. XCT cross-sectional images of the CFRP/epoxy honeycombs having four carbon fiber layers.

3.2 Energy absorption characteristics

The energy absorbing characteristics of the composite honeycombs, based on both thermosetting and thermoplastic liquid resins, were investigated through compression testing. The results of the compression tests in terms of load – displacement curves for both types of five-cell honeycomb cores are shown in Figure 3(a, b). In Figure 3(a, b) the first number represents the number of CF layers, and the second number represents the number of cells. For example, 3UD-1 refers to a one honeycomb cell with three unidirectional CF layers. The specific energy absorption (SEA) values for single-cell and five-cell honeycomb specimens at different fiber weight fractions are provided in Figure 3(c, d).

The results show that both epoxy and Elium® honeycombs exhibited similar compression peak load values. In terms of the epoxy-based honeycombs, the maximum performance was exhibited by those specimens incorporating three carbon fabric layers. The addition of another carbon fabric layer resulted in a decrease in performance. This was mainly attributed to an increase in the overall number of defects, due to an increase in the fiber weight fraction [8]. On the other hand, Elium®-based honeycombs exhibited almost a linear increase with increasing fiber weight fraction. Therefore, the highest peak load and SEA values were recorded for the five-cell specimens having a weight fraction of 0.55, these being 142 kN and 50 kJ/kg, respectively. A similar trend was observed in the compressive strength of the composite honeycombs. A comparison of both the thermosetting and thermoplastic cores revealed that the Elium®-based composites showed superior SEA characteristics and compression strengths compared to those of the CF/epoxy honeycombs. For example, the 4UD-5 CF/thermoplastic honeycombs exhibited a 29% higher compressive strength compared to those of their epoxy counterparts. Similarly, the 1UD-5 CF/thermoplastic honeycomb showed a 28% increase in the compressive strength compared to CF/epoxy system [9].

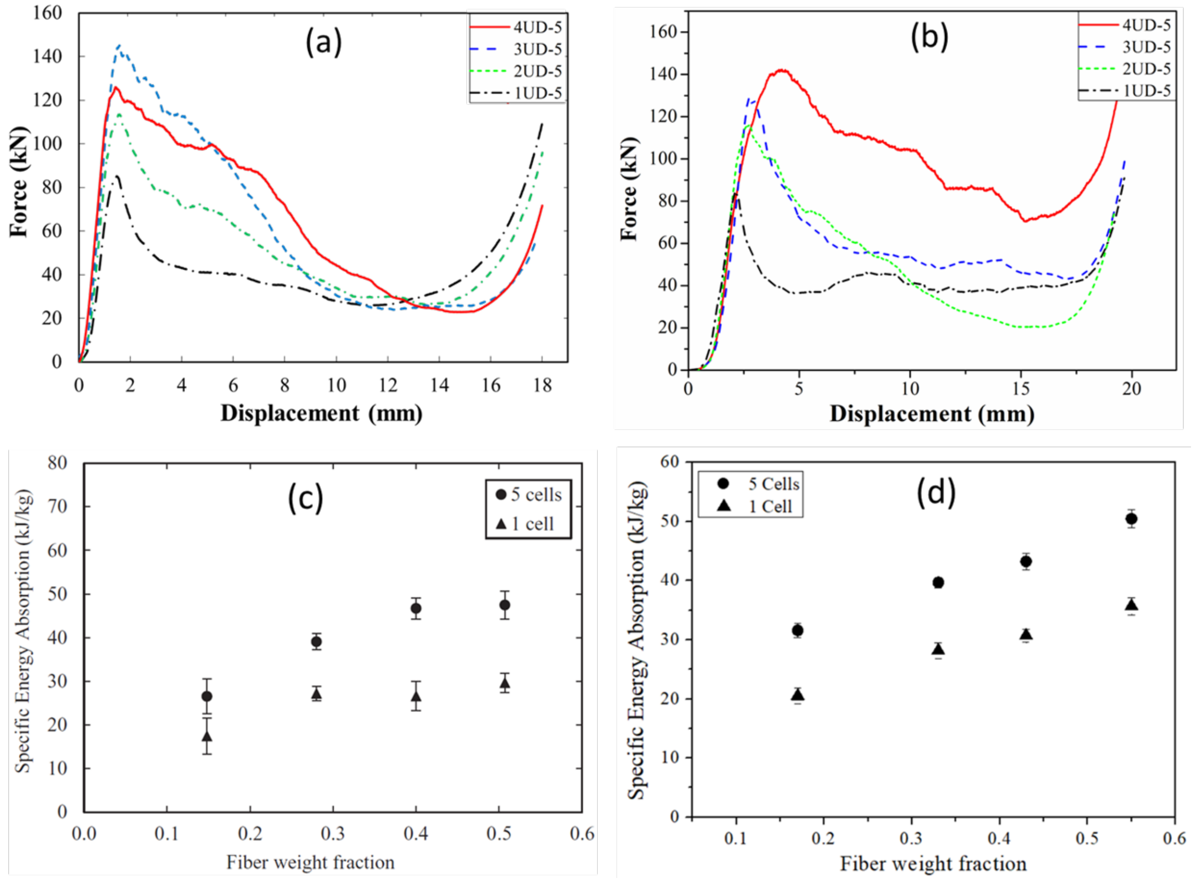

Figure 3. Compression test results (a) load-displacement curves for CF/epoxy honeycombs, (b) load-displacement curves for CF/Elium® honeycombs, (c) SEA for CF/epoxy honeycombs and (d) SEA for CF/Elium® honeycombs.

A detailed investigation showed that the enhanced performance of the thermoplastic specimens was primarily due to differences in the failure modes along with the inherited superior energy absorption characteristics of the thermoplastic polymers compared to that of the thermosetting polymers. In the case of the CF/epoxy honeycombs, failure was primarily comprised of premature delamination and longitudinal splitting during the compression test. This premature splitting of the cells compromised the overall performance of the CF/epoxy honeycombs. The failure modes in five-cell CF/epoxy specimens are shown in Figure 4-a.

In contrast, CF/Elium® honeycombs exhibited superior structural stability and SEA values, due to a uniform core crushing failure mode. The failure mode in a five-cell CF/Elium® honeycomb during compression loading is shown in Figure 4-b. These photographs show a clear contrasting failure mode dominated by uniform and stable core crushing, resulting in superior SEA characteristics of the thermoplastic honeycomb structures. Similar results were observed in specimens incorporating fewer carbon fabric layers i.e., having a lower fiber weight fraction. Additionally, single-cell CF/epoxy honeycombs also showed significant longitudinal splitting, whereas their Elium® counterparts again demonstrated a stable core crushing failure mode. This uniform core crushing in CF/thermoplastic honeycombs is associated with a higher energy absorption capability and a superior structural integrity of Elium composites compared to their epoxy counterparts [10].

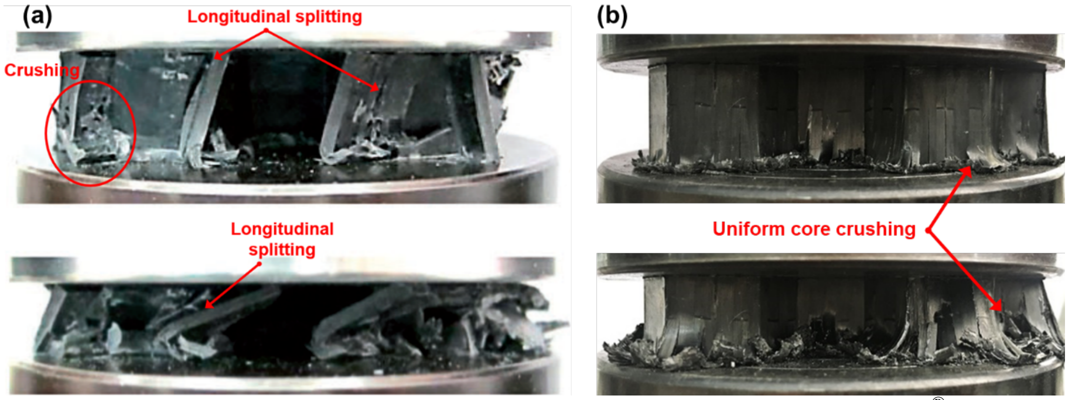

Figure 4. (a) failure in five-cell CF/epoxy honeycombs and (b) failure in CF/Elium® honeycombs.

The highest specific strength for Elium® specimens was found to be 0.14 MPa.m^3/kg for those specimens based on three CF layers, which is comparable to the CF/epoxy honeycombs with a specific strength of 0.15 MPa.m^3/kg, as listed in Table 1. Additionally, this value is much higher than other conventional core types, such as aluminum honeycombs exhibiting a value of 0.097 MPa.m^3/kg, crosslinked PVC with a specific strength of 0.026 MPa.m^3/kg and metallic foams typically around 0.008 MPa.m^3/kg [9].

Table 1. Compressive properties of five-cell CF/epoxy and CF/Elium® composite honeycombs

Matrix type	Sample ID	No. of Layers	Fiber weight fraction	Compressive strength (MPa)	Specific compressive strength (MPa.m^3/kg)	Avg. SEA (kJ/kg)
Elium®	4UD-5	4	0.55	39.5	0.111	50.5
	3UD-5	3	0.43	35.7	0.141	43.3
	2UD-5	2	0.33	32.2	0.129	39.7
	1UD-5	1	0.17	23.5	0.098	31.6
Epoxy	4UD-5	4	0.51	30.7	0.12	47.5
	3UD-5	3	0.4	35.4	0.15	46.7
	2UD-5	2	0.28	25.5	0.11	39.1
	4UD-5	4	0.51	30.7	0.12	47.5

4 CONCLUSIONS

In the study, carbon fiber honeycomb cores based on both thermosetting and thermoplastic resins, with variable fiber weight fractions were successfully manufactured using the VARTM approach. The performance of both types of specimen was evaluated by subjecting them to compression tests in single-cell and five-cell configurations. The compression test results revealed high SEA characteristics for both types of honeycomb, with the Elium® specimens outperforming their epoxy counterparts with SEA values over 50 kJ/kg. The high performance of the thermoplastic-based samples was primarily associated with their inherent superior energy absorption characteristics of the resin compared to the thermosetting resins. As a result, the fractured CF/Elium® specimens exhibited a dominant uniform core crushing failure mode, whereas their CF/epoxy counterparts showed a dominant longitudinal splitting and delamination failure mode.

In general, the properties of both types of honeycomb were significantly improved by increasing the fiber weight fraction. The XCT images showed the presence of mesoscopic voids in all the specimens. These defects increase with increasing fiber weight fraction in the densely packed honeycomb structures with the highest fiber contents and had a negative influence on their properties. Despite the presence of these defects, both types of composite honeycomb exhibited superior energy absorbing characteristics than all types of conventional core material. The results highlight the great potential of these composite honeycomb structures in multiple demanding applications, especially in the aerospace industry.

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