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Crushing behavior of hybrid hexagonal/octagonal cellular composite system: All made of carbon fiber reinforced epoxy

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ABSTRACT

Cellular carbon fiber-reinforced plastic (CFRP) composites, either unfilled or filled with foam, may be of interest for energy absorption application due to their improved crashworthiness. In the current paper, new combinations of octagonal and hexagonal cellular CFRP composites are introduced as energy absorption devices. Different arrangements of cells are tested. In addition, the effect of filling the structure with foam is studied. The well-known crashworthiness parameters are being used to compare the different configurations. In addition, 2 new parameters (crush load stability and springback coefficient) are introduced to assess both the difference between the peak and the average crushing load and the stability during the post crushing stage as well as the capability of the structure to retain its original height after crushing. The results show that the configurations with closed cells are advantageous in terms of the peak and the average crushing load and the energy absorption, whereas the open cells are of great interest when comparing the stability of the crushing load in the post-crushing stage.

1. Introduction

The ability of a structure to absorb impact energy is known as crashworthiness. Crashworthiness is concerned with the absorption of energy through controlled failure mechanisms and modes that enable sustainability of a stable load profile during the absorption process. Lighter and more deformable structural elements became the most important means to improve crashworthiness [1,2].

The ability to tailor composites, stiffness-to-weight and strength-to-weight ratios, fatigue resistance and corrosion resistance make them very attractive in terms of crashworthiness. The challenge is the use of specific features of geometry and materials to enable greater safety while simultaneously decreasing the weight, without negatively affecting the overall economics of fabrication and production [3,4]. Currently, these crushable elements are being made of thin-walled curved shells constructed from Fiber-Reinforced Polymers (FRP) due to its ability to withstand axial loading in a membrane manner rather than through bending [5]. In addition to the vehicle applications, FRP cylinders/tubes are now being used in chemical plants, oil and gas carriers and high pressure containers [6,7].

The geometry of the collapsible structure is one of the variables that affects the energy absorption capacity of the composite materials. Lau et al. [8] presented a review of the effect of geometrical designs and failure modes in composite axial crushing. Mahdi et al. [9] investigated the crushing behavior of collapsible energy absorber devices with circular and elliptical cross-sections when subjected to different loading conditions. Unstable interlaminar cracks, local buckling and brittle fracturing failure modes were reported. It is worth remarking that cross-sectional geometry significantly influenced the energy absorption capabilities. Subsequently, Mahdi and Hamouda [10] studied the energy absorption capabilities of composite hexagonal ring systems. They concluded that the ring geometry and arrangement significantly influenced the crashworthiness of composite hexagonal ring system. Elgalai et al. [11] studied the crashworthiness behavior of laminated corrugated tubes. Similar tubes were studied experimentally and numerically by Abdewi et al. [12,13]. The behavior of radially stiffened glass/epoxy tubes was studied by Mahdi and Sebaey [14]. Ajdari et al. [15] studied the in-plane dynamic crushing of 2D honeycombs with both regular hexagonal and irregular arrangements. Sun et al. [16] investigated the crushing of multi-layer regularly arranged circular honeycombs. More geometries can be found in [17,18]. These studies show the high dependency of the crushing behavior of the FRP on the geometrical properties of the crushable elements.

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Foams, as fillers, are low density, which make them attractive for energy absorption applications. In addition, foams can undergo great compressive strain (0.7 or more) at almost the same stress, so that large amounts of energy can be absorbed without generating high stress [20]. Costas et al. [21] studied the effect of filling steel tubes with different core materials. They compared the crushing parameters of the coreless tubes with CFRP-cored, GFRP-cored, foam-cored and cork-cored steel tubes. The results showed the advantages of using foam in comparison to the other fillers. Mamalis et al. [22] studied the effect of the foam type on the crushing behavior of the sandwich panels. Palanivelu et al. [19] studied the effects of filling crushable tubes with polyurethane foam. It was concluded that introducing the foam reduces the specific energy absorption of composite tubes.

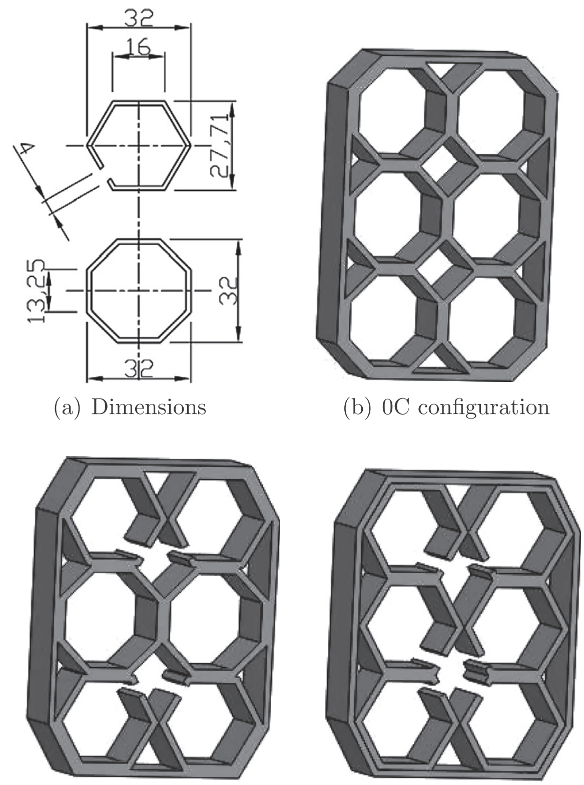
In the current paper, combinations of octagonal and hexagonal carbon fiber-reinforced epoxy cells were manufactured and tested. Each configuration was composed of 6 cells. In order to increase ductility, the hexagonal cells were opened from one side. The 6 cells were then packed by 3 layers of CFRP of the same material. Some of the specimens were filled by polyurethane foam and the others were tested without any filler. The specimens were tested under compression up to densification. The peak and mean crushing loads, the energy absorption, the specific absorbed energy and the percentage of springback were used to assess the crashworthiness of the different geometrical configurations.

2. Specimen fabrication

Carbon fiber-reinforced epoxy was used to manufacture the proposed energy absorption device. Plain weave 3 K carbon fibers and epoxy resin (epoxy resin A–B glue of $E = 3.35$ GPa, $\nu = 0.35$ and $\varepsilon_f = 1.7$) were used. The nominal ply thickness for this material was 0.25 mm. The epoxy to hardener ratio was 5:1.

A rotating mandrel was used to produce tubes of 1 m long of CFRP. The mandrel was partitioned in order to facilitate the extraction process. As the mandrel rotates, it pulls the carbon fiber sheet through the matrix basin. The carbon fiber sheet was used with its original orientations i.e. the resulting fiber orientations were 0° and 90°. The process continued until the desired number of layers was reached. The tubes were manufactured with 6 layers. The resulting wall thickness was 1.5 mm. After full curing, the mid-part of the wooden mandrel was simply extracted and, consequently, the upper and the lower parts were easily removed. The same process was used by the authors to produce other geometries and has been reported in [10,14,23].

2 tube cross-sections were manufactured: hexagonal and octagonal. In order to improve stability during the post-crushing stage, the hexagonal tubes were cut, as shown in Fig. 1(a). A matrix of 2×3 cells were joined together and packed using 3 layers of carbon fiber-reinforced epoxy of 450 gm/m^2 density. 3 configurations of the cells were checked: 0C, 2C and 3C, as illustrated in Fig. 1(b) and (c). In each configuration, 3 specimens were filled using polyurethane foam (of 25 kg/m^3 and 0.23 MPa compressive strength) and compared with the unfilled specimens. The polyurethane foam was delivered as a 2-part system. After joining all the cells together and packing them with the carbon/epoxy layers, the device was closed from one side by plastic film. Then, the 2 parts of the foam were mixed in a 1:1 ratio and poured into the device. The foam reached its full strength after 20 min. Finally, the plastic film was removed and the excess parts of the foam were cut using a handsaw. The resulting test matrix was composed of 6 configurations of 3 specimens each. A summary of the configuration of each specimen can be shown in Table 1. Specimens 0C and 0CF composed of 6 octagonal cells. The difference between them was the filler, i.e. 0C specimens had no filler whereas 0CF were filled with foam.



(a) Dimensions (b) 0C configuration
(c) 2C configuration (d) 3C configuration

Fig. 1. Cross-section properties of the examined configurations (all dimensions are in mm).

Table 1
Summary of the characteristics of the test matrix.

Configuration	Hexagonal	Octagonal	Foam	No. of specimens
0C		√		3
0CF		√	√	3
2C	√	√		3
2CF	√	√	√	3
3C	√			3
3CF	√		√	3

Specimens 2C and 2CF composed of 4 octagonal and 2 hexagonal cells. Specimens of 2CF were filled by foam whereas 2C were not. Each specimen of 3C and 3CF composed of 6 hexagonal cells. Specimens of 3CF were filled whereas 3C were not.

3. Crushing tests

Quasi-static crushing tests were carried out to assess crashworthiness and monitor the crushing mechanisms corresponding to each configuration. The tests were carried out using an Instron 8500 digital-testing machine with a full-scale load range of 250 kN. Steel platens were set parallel to each other prior to the initiation of the test. 3 tests were conducted for each configuration for data reproducibility. The average of the three tests was undertaken. The behavior of each configuration under compression loading was recorded using a camera. The acquisition system of the universal testing machine recorded the load–displacement data at a constant cross head speed of 5 mm/min. The test setup is shown in Fig. 2.

3.1. The well-known crashworthiness parameters

The parameters used to assess the crushing response are summarized in [10,24]. According to Mahdi and Hamouda [10], one