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Crushing behavior of a unit cell of CFRP lattice core for sandwich structures' application

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ABSTRACT

Sandwich structures made of composites are designed mainly for higher and efficient load capacity. Mostly, the use of composite materials in lattice core sandwich structures is limited to the face sheet; whereas, the core is usually made of metals due to the difficulty in producing the FRP lattice shape. A sandwich with a core made of FRP is believed to be lighter and better in terms of specific strength and absorbed energy. In order to manufacture the sandwich core, several methods and techniques were developed based on the designed core profile. In this paper, the core was extracted (using laser cutting) from the standard flame retardant carbon fiber hat stiffener. Four values of the strut angle α were considered (α = 45, 60, 75, and 90°). Crushing tests were performed using Instron Compression machine and a load cell of 5 kN capacity. Similar post crushing profiles were obtained for all the specimens. However, the peak load is being shifted upward. Improvements of 75% and 54% were recorded for the peak and the average crushing loads respectively. It is worth remarking that the crush load efficiency was kept constant during the tests. The energy and the specific energy absorption showed that the unit cells with 90° are at advantage since it is almost 53% higher than that of the 45°. For the effect of filler, the tests results show how important it is to fill such thin skeletal structures.

1. Introduction

Sandwich constructions comprise two thin but stiff skin layers separated by the lightweight core material. This allows the sandwich structures to possess a superior bending stiffness/strength to monolithic counterpart [1]. Lattice sandwich structures have been proven to have strong capacities in energy absorption, heat insulation and noise reduction [2]. Lattice cores made of CFRP have higher specific strength and stiffness [3]. Compared to metallic ones, energy absorption capabilities of CFRP lattice cores can be improved with proper design of the lattice geometry [4].

Previously, most publications used metallic lattice core with FRP face sheets due to the manufacturing constrains (see for example the work done by Zhang et al. [3]). Currently, several techniques are being developed to manufacture the core from FRP. Several researchers adopted cutting the core from composite sheets. Xiong et al. [5] used the laser cutting technique. Water jet cutting and circular traditional saw were used by Norouzi and Rostamiyan [6], and Schneider et al. [7] respectively. George et al. [8] used a braided approach for fabrication of the CFRP struts. In principle, this eliminates the delamination failure mode. In addition, all the fibers are aligned within a few degrees of the braid axis which may increase the axial compressive strength of the strut. Improved response was obtained, although the manufacturing feasibility of such a core is a questionable. Lost-mold manufacturing technique was also used to produce the whole sandwich structure without cutting in [9]. Xu et al. [10] proposed a new CFRP lattice core based on the idea of functional graded materials in order to reduce the structure's total weight. The authors tested 4 different types of cores under bending and presented the difference in the bending strength, damage propagation, and failure modes. Later on, the same authors [11] manufactured and tested graded lattice core with the structure presented by Xiong et al. [5].

In a previous study [12], the authors virtually tested the in-plane compression characteristics of the CFRP lattice core and its notch sensitivity. The numerical results showed that these structures are less sensitive to notches compared to the traditional composite plates. In the current paper, the laser cutting technique is used to produce the lattice core unit cell from the commercially available hat-section. Foam-filled and unfilled structures are considered equally. The strut angle varies from 45° to 90° which changes the relative density in addition to changing the whole structural response. To the authors, there is no detailed analysis of a single unit cell in crushing. For that reason, quasi-

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static crushing tests are performed at room temperature to assess the capability of such structures to be used in energy absorption applications.

2. Specimens fabrication

Carbon fiber hats contain plain weave carbon fiber both in 0°/90° and ± 45° orientations, with 0° unidirectional carbon fiber to add stiffness and strength along the length of the hat stiffener. The structure was delivered by Dragon Plate TM. To optimize the design, the unidirectional was added only to the cap of the hat stiffener. This fiber placement resulted in a stronger and firmer hat stiffener while minimizing the hat stiffener weight. The carbon fiber hat stiffener has a texture finish on the outside and on the flange surfaces to create an ideal bonding surface. The web is made of three layers [(0°/90°)/(± 45°)/(± 45°)] of 0.64 mm total thickness; while, the cap is made of four layers of [(0°/90°)/0°/(± 45°)/(± 45°)] of 0.81 mm total thickness. The fiber volume fraction was measured using the ignition test. The average volume fraction in both sections was 50%.

Laser cutting was adopted to form the geometry of the core unit cell. Laser cutting was selected due to its production rate and the relatively narrow damage induced cutting affected zone (about 0.4 mm of composite adjoining the cut was damaged) [5]. The process parameters were taken from Reference [5]. The final geometrical properties of the unit cell can be shown in Fig. 1. Two different studies were implemented. In the first one, the effect of the strut angle α is considered. The values considered for α are 45°, 60°, 75°, and 90°. For each value, the corresponding volume of the unit cell changes, which affects the value of the relative density (defined as the ratio between the volumes of the lattice structure to the volume of the whole sandwich [12]). The values of the relative densities are listed in Table 1. The volumes were extracted from a CAD software.

In the second study, the effect of filling the unit cell with foam is studied. The specimens with the angle α = 45° were selected for that purpose. Three specimens were filled using polyurethane foam (of 25 kg/m^3 and 0.23 MPa compressive strength) and they were compared with the unfilled specimens. The polyurethane foam was delivered as a 2-part system. The structure was closed from all sides using a plastic film. After which, the 2 parts of the foam were mixed in a 1:1 ratio and poured into the device. The foam attained 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 same technique was used earlier in [13].

3. Experimental protocol

Quasi-static crushing tests have been carried out to assess the crashworthiness and to monitor the crushing mechanisms corresponding to each configuration. The tests were carried out using an Instron digital-testing machine with 5 kN load cell. Tests were performed with control-displacement mode. Steel plates were set parallel to each other prior to the initiation of the test. Three tests were conducted for each configuration, for data reproducibility and the average of the three tests were 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 crosshead speed of 5 mm/min. In order to avoid sliding of the trusts and its ends on the lower plate, it was designed with a groove of internal dimensions to equate the plane dimension of the unit cell. Four pieces of the lower plate are designed to satisfy the dimensions of each specimen configurations. The schematic shown in Fig. 2 illustrates the test setup.

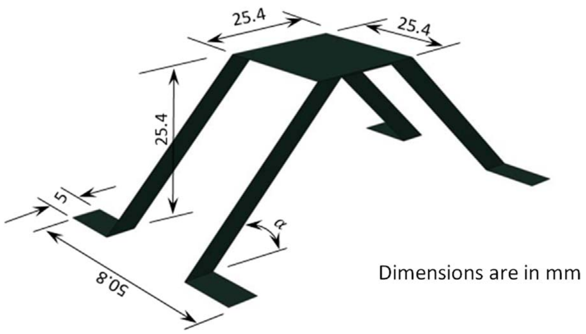

Fig. 1. Geometrical properties of the lattice unit cell.

Table 1
Relative density as a function of the angle α.

α	45°	60°	75°	90°
Relative density	1.02%	1.4%	2%	3.1%

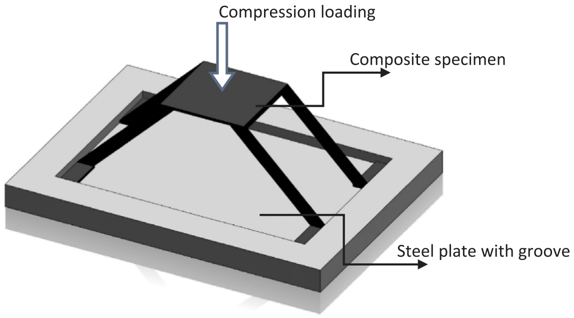

Fig. 2. Schematic sketch of the test setup.

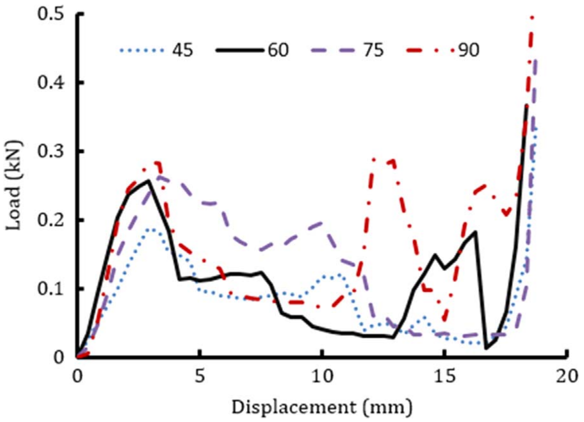

Fig. 3. Sample load displacement behavior of specimens with different strut angle.

The load at which the first significant damage occurs is characterized on the load-displacement diagram by the significant change in the slope and profile. This load is called the peak load ($P_{\max}$). After this loading level, the load displacement profile starts to fluctuate. The mean value of the load during the post crushing stage is the mean crushing load (P_{mean}). The crush force efficiency is the ratio between the mean crushing and the peak load is the crush force efficiency (CFE). This parameter measures how close the post crushing load readings is to the initial peak load. A value of unity is the target value of the CFE for the safety and comfort of the passengers.

The energy absorbed (E) by the specimen during the test can be divided into two main parts: before and after the peak load. Before the peak load, the energy is mainly absorbed in elastic and plastic deformation. After the peak load, the major part of the energy is consumed in fracture processes. The specific energy (E_S) absorption is also used to assess the crashworthiness of the unit cell. The specific energy absorption is the energy absorbed divided by the specimen weight. The higher values of the energy absorbed and the specific energy absorption reflect the capability of the structure to crush