ULTRA-LIGHTWEIGHT CFRP CORES MADE BY INTERLOCKING METHOD: FABRICATION AND EVALUATION

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Abstract

The development of ultra-light weight cores applied in sandwich structures, as the 3-dimensional carbon fiber reinforced polymer cores (CFRP), have the potential to reduce the structural mass of the upcoming vehicles used in the transportation and aerospace industry, increasing capabilities, performance and reducing fuel consumption. In this work, carbon fiber cores are obtained using a interlocking method from flat composite laminates. The mechanical performances such as the compressive and shear strength of three different geometries' cores are evaluated. Furthermore, failure modes are studied. Results are compared to those predicted by an analytical model and finite element method analysis (FEM). The research given provides useful insights on new ways to obtain 3D sandwich cores with very low density, for designers and future investigations.

1. Introduction

Lightweight construction is one of the most efficient way to improve performance of many vehicles or means of transport. The weight reduction is desirable to obtain the maximum payload capability, to increase the speed enhancing the driving performance or just to reduce the fuel consumption [1]. Thus, the demand for high stiffness and high strength to weight ratios in structural design has been posed by the automotive and aerospace since many years ago. Due to their great versatility, sandwich structures has been established as a validate candidate in minimum structural weight design. See [2] and [3]. Sandwich panels consist of two stiff skins, separated by a lightweight core. The core thickness will define the moment of inertia of the entire panel, giving an efficient structure for resisting bending and buckling loads, with little increase in weight [4]. The need for lightweight cores has stimulated the production of different polymeric and metallic foams [5]. Honeycombs are often applied for cores where a higher stiffness is required [2].
Recently, new concepts of honeycombs have emerged. For instance, the one proposed by Tochukwu G. et al. [6] where a hybrid CFRP pyramidal lattice/foam core structure is assembled and studied. Also, failure mode maps of CFRP egg and pyramidal honeycomb cores are been studied by Xiong et al. [7]. Russell et al. [8] has manufactured and tested CFRP square-honeycomb aiming to fulfill the gap in the strength/density material property space, previously given by Ashby and Bréchet [9] on the material properties' chart. Therefore, exists an increasing interest in ultra-light cores for weight sensitive structures [10]. These cores are focused as lower mass alternatives to traditional honeycombs or foams in composite sandwich panels.

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The aim of this work is to develop and study the compressive and shear behavior of three different geometries for ultralight-weight cores designs with a density lower than 48 kgm^{-3}, proposed as a true alternative for traditional honeycomb cores. An interlocking method also known as slotting method, for fabricating carbon fiber honeycomb cores is proposed for this project (Fig. 1b). This method has been mainly used to manufacture square honeycomb at lower cost compared to hot press and laser cutting techniques.

2. Materials and Methods

Square-honeycombs cores were obtained from a CFRP composite sheet material. The laminate was cut employing a CNC water-jet cutting machine (Fig. 1a). The cores were manufactured by slotting the composite sheets and bonding with epoxy resin in order to obtain the assembly. The interlocking method (Fig. 1b) applied for this work follows the one previously proposed by Côté et al. [11] where type 304 steel is employed for manufacturing metallic square-honeycomb cores.

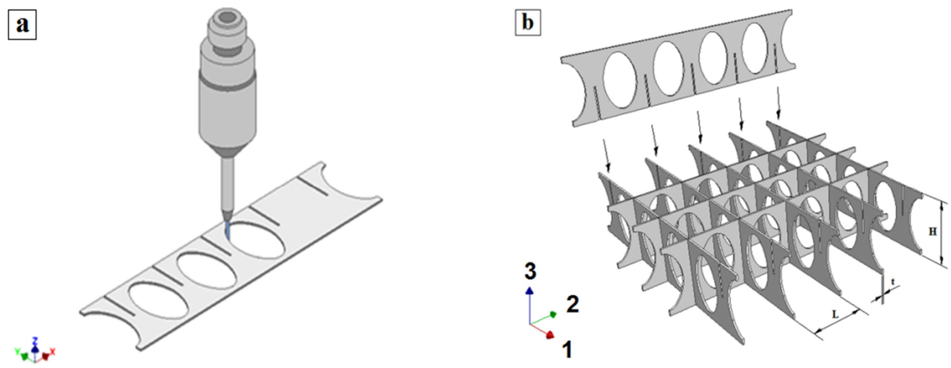

Figure 1. (a) Sketch of the cutting method employed for obtaining the proposed geometries. (b) Sketch of the square-honeycomb manufacturing method

2.1 Materials

CFRP composite laminate was obtained by Vacuum Assisted Resin Transfer Molding (VARTM) technique. The composite sheets were made from plain T300-3k, Hexcel fibers with a 3-ply [0°, 90°] lay-up, with filament diameter of 7 µm, density of 1.75 g cm^{-3}, 230 GPa of tensile modulus and 3530 MPa of tensile strength. The polymeric matrix employed was a DGEBA (DER 383, Dow Chemicals) having an epoxy equivalent of about 183 g eq^{-1} and a viscosity of 9000–10,500 mPa·s at 25 °C. For decreasing the viscosity of the resin it was used glycidyl aliphatic ether (Novarchem S.A.) as an epoxy reactive diluent, having an equivalent of about 255 g eq^{-1}. As hardener cycloaliphatic amine was employed (Air Products and Chemicals Inc.) having an amine equivalent of about 63 g eq^{-1}.

2.2 Manufacturing

The manufacturing process consisted in obtaining the CFRP composite laminate on a first step, and then cutting it by a CNC water-jet cutting machine (Fig. 1a). Three different core patterns were investigated.

2.2.1 CFRP composite sheet material

CFRP sheet material was obtained by VARTM technique. The resin was injected into the 3-ply lay-up assembly at room temperature by VARTM. The system was cured at 393K for 2 hours in an air-circulating oven.
The obtained laminate had an average thickness of t = 0.65 ± 0.05mm and a density of about 1300kgm^{-3}. The reached fiber volume content was in the range of 50 ±1%.

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2.2.2 Honeycomb cores

The composite sheets were cut into rectangles of height H = 25.4mm, a length of 100mm and 200mm for compressive and shear tests respectively. For cutting the CFRP material sheets it was employed a CNC water-jet cutting machine (Fig. 1a). The rectangles were shaped into 3 different geometries (Fig. 2a) and another one remained without shaping and were used as reference (Fig. 2b). Cross-slots of t = 0.65mm and spacing L = 20mm were obtained. The gap between sheet thickness and slot width was about 0.05mm. This clearance facilitated core assembly into a square-honeycomb pattern and also provided a suitable tight fit to improve stability. The cross-slots rectangles were bonded together using the same polymeric matrix used before. The nominal dimensions of the cores for compressive test were 100mm in length by 100mm in width and a height of 25.4mm (Fig. 2), containing an array of 5x5 of 20mm cells (Fig. 3). The resulting density of each core was less than 48kgm^{-3}. Shear samples used the same geometries as used for compressive loading, despite having dimensions 200mm in length, 100mm in width and 25.4mm in height.

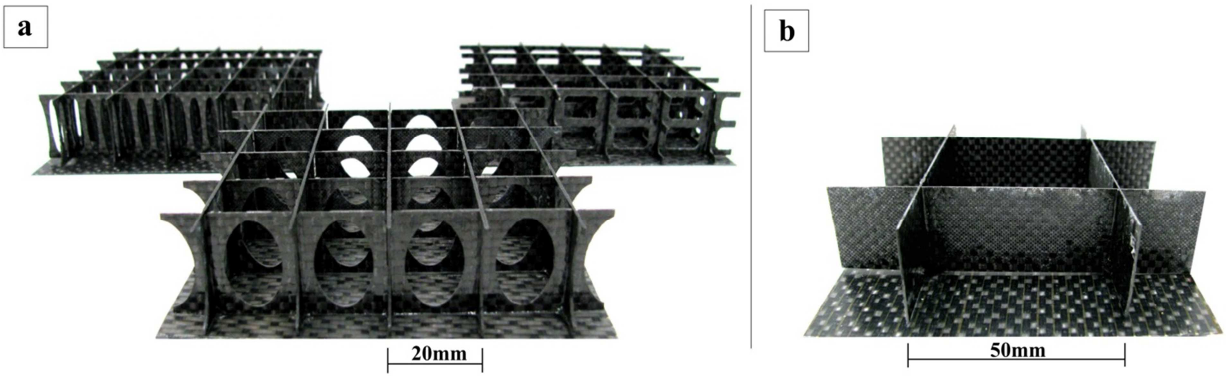

Figure 2. Different geometries employed for square-honeycomb cores. (a) Proposed geometries. (b) Reference core.

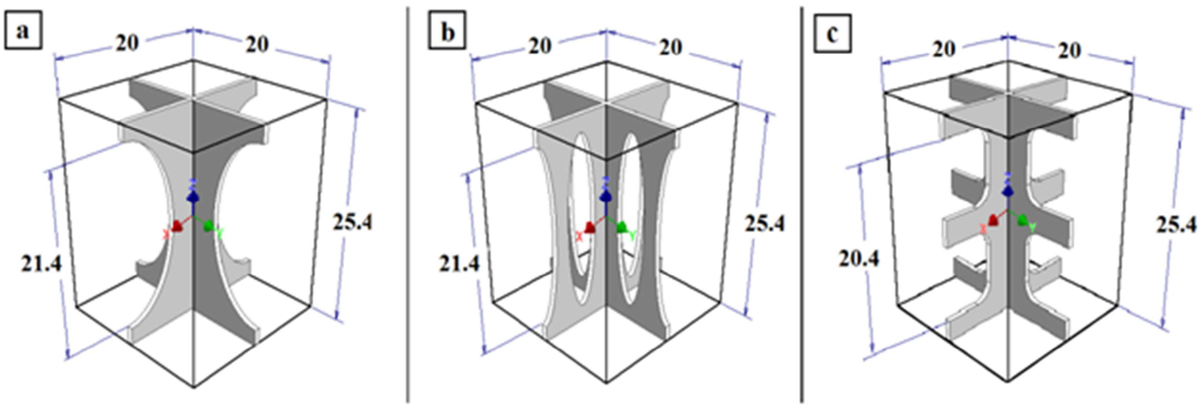

Figure 3. Sketches of unit cells of three different square-honeycombs designs. (a) Design 1: Large catenaries. (b) Design 2: Small catenaries. (c) Design 3: Two linear arrays of rectangles.

2.2.3 Square – honeycomb cores design

The obtained square-honeycomb cores can be assembled using unit cells of 20 by 20 mm, according three different designs (Fig. 2a and Fig. 3). For reference cores it was used unit cells of 50 by 50 mm (Fig. 2b) while maintaining core densities lower than 48 kgm^{-3}. Unit cells are symmetrical according to orthotropic

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reference axes (Fig. 3). This characteristic has many technological advantages such as an easier core design and manufacture.

3. Theoretical background

The core of a honeycomb structure firstly works as spacer between the two face sheets. While fulfilling this task, it has to transfer mainly shear and compression loads. As the lightweight core consists of thin-walled plates, stability phenomena probably are the main cause of failure. In the following analytical investigations, the unit cells shown in Figure 3 are considered as bars with axis 3 as bar axis.

3.1 Compression response.

In this work, the expected compressive failure of square-honeycomb is torsional buckling. Under compressive loading, the axis of the bar remains straight, while each flange buckles by turning about *z* axis. Honeycomb columns are considered as bars of cruciform section with four identical flanges of thickness t = 0.65mm and a width of 0.5 L. We have considered that cores were made from an orthotropic composite material for the analyses. The formula due to Timoshenko [12] was used to evaluate torsional buckling. In this case, shear center coincides with the centroid (Figure 3) and applying appropriate end conditions satisfied by sinusoidal solutions simplified equations are shown (Eq. 1, Eq. 2 and Eq. 3).

$$P_x = \frac{\pi^2 E_{3s}\, I_x}{H^2} \qquad (1)$$

$$P_y = \frac{\pi^2 E_{3s}\, I_y}{H^2} \qquad (2)$$

$$P_\varphi = \frac{A}{I_o}\left(C + C_1 \frac{\pi^2}{H^2}\right) \qquad (3)$$

Where P_x and P_y are critical loads due to Euler buckling behavior, about x and y axes, respectively and P_φ denotes the critical load for torsional buckling. Coefficient $C_1 = EC_w$ is called *warping* rigidity, where E is the elastic modulus of the column material and C_w is called the warping constant. See [12]. C_w is equal to zero for cruciform cross sections. I_o is the polar moment of inertia of the cross section about shear center [0; 0; 0], coinciding in this case with the centroid. Coefficient $C = GJ$ is called the torsional rigidity, where *G* is the shear modulus and *J* a torsion constant. For open-walled sections, *J* depends on 1/3 the wall thickness to the third exponent times the flange width, multiplied by the number of flanges. Coefficient *A* is the cross-sectional area and *H* is the height of the column.

Due to the involved geometries under uniformly compressed loading, elastic buckling of rectangular plates shall also appear. The formula presented by Ericksen [13] was used for evaluating elastic buckling of plates (Eq. 4):

$$P_b = \frac{K\pi^2 D}{H^2} \qquad (4)$$

Equation 4 represents the buckling load of thin rectangular plates. Coefficient *K* (Eq. 6) depends on the ratio H/L according to boundary conditions. Coefficient *K* lies in the range 22.2 to 3.29 for H/L ratio in the range of 0.2 to 3 for simply supported edges, while K lies in the range 9.44 to 7 for H/L ratio 0.4 to 0.7 for bottom and top edges built in and the rest free. Coefficient *D* is the represents the bending stiffness of the thin composite cell wall and it depends on the thickness *t*, Poisson's ratio and the Young's modulus *E* according to 1 and 3 directions plotted in Figure 1a. Stiffness *D* shall be written as Eq. (5) for orthotropic composite materials. See [8] and [14]. Coefficient α in equation 7 depends on shear modulus *G*, Poisson's ratio and Young's modulus of the composite.

$$D = \frac{\sqrt{E_{1s}E_{3s}}}{1 - \upsilon_{13s}\upsilon_{31s}}\,\frac{t^3}{12} \qquad (5)$$

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$$K = \frac{3H^2}{4L^2}\sqrt{\frac{E_{1s}}{E_{3s}}} + 2\alpha + 41\frac{L^2}{5H^2}\sqrt{\frac{E_{1s}}{E_{3s}}} \tag{6}$$

$$\alpha = \frac{1 - v_{13s}v_{31s}}{\sqrt{E_{1s}E_{3s}}}\left(\frac{E_{1s}v_{31s}}{1 - v_{13s}v_{31s}} + 2G_{13s}\right) \tag{7}$$

3.2 Shear response.

Analytical expressions for the shear failure loads and shear elastic modulus of the cores were obtained analyzing the behavior of a single strut of the square-honeycomb, neglecting the contribution of the cell walls in the plane normal to the loading vectors. Fig. 4 shows a diagram of a strut loaded in a combined bending and shear mode. The strut is loaded with a shear force *F* and the total displacement *w* is the sum of the bending deformation w_s and shear deformation w_b according to Eq. 8. Coefficient A_s is equal to *A/k* ratio, where *A* is the cross-section area and *k* a shear correction factor that takes the value 1.2 for rectangular shape struts. Then the failure load F_R is obtained from Eq.8, when the displacement *w* is maximum according to the nominal laminate shear strength.

$$w = w_b + w_s = \frac{F_R H^3}{3E_{3s}I} + \frac{F_R H}{GA_s} \tag{8}$$

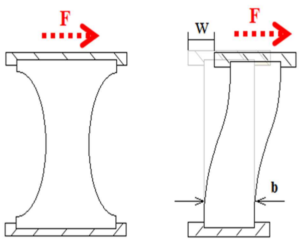

Figure 4. Sketch of core design 1 displacement due to a combination of bending and shear mode

4. FE modeling

Software FEMAP™ 10.3 with NX™ Nastran® [14] was employed for finite element analyses. The proposed cores under compressive and shear loading were modeled as a single and a two-material system respectively. FEM analyses combined with analytical calculations were used for predicting the elastic modulus in compression and shear modes.

Compressive tests were modeled using a single unit cell for each core case. Simulations were performed using the three different geometries of cores previously shown (Fig. 2a) and the reference core without shaping (Fig.2b). Unit cells were discretized using regular mesh of shell elements (S4R) with five integration points and a size of about 0.4 mm, representing in full detail the geometry of the studied cores. The employed elastic properties of core walls (CRFP sheet material) are specified in Table 1 according to Figure 3 coordinate system and considering the laminate as an orthotropic material.

Shear tests were modeled considering a two-material system. The performed simulation includes shell elements (S4R) for the composite sheet material of 0.65 mm in thickness, while bar elements (T1D2) for the bottom and top line nodes of the sheet material, simulating steel plates according to the real shear test setup. The material properties used for the thin core walls are shown in Table 1, while the applied material for bar elements was such as an AISI 1010 steel plate.

Table 1. Theoretical elastic properties of the laminate composite material made from T300/epoxy

	E_{1s} (GPa)	E_{3s} (GPa)	G_{31s} (GPa)	v_{31s}	F_v (%)	σ_{max} (MPa)	τ_{max} (MPa)
T300/Epoxy 0/90°	60.5	60.5	3.4	0.0366	50.8	680	110

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5. Test, results and discussion

5.1 Testing

Compressive properties of stabilized CF ultralight-weight composite cores were tested in accordance with ASTM Standard C365 – 03. The honeycomb core shear properties were obtained following ASTM Standard C273 -00. Compressive and shear tests were performed on a Zwick/Roell Z150 screw-driven universal testing machine.

5.2 Compressive response

Figures 6a and 6b represents the compressive loading test performed according to ASTM standard C365-03. The failure behavior resembled torsional buckling in each designed cores, but elastic buckling of the thin plates on reference cores. With an increasing load, the elastic instability arises at 23.7kN, 22.4kN and 26kN for design 1, 2 and 3 respectively. Design 3 showed the best compressive strength performance compared with the other designed cores (Fig. 5b)
The predicted Young's modulus and failure load from theoretical and FEM analyses are substantially higher than the measurements, due to imperfections in the manufacturing of the composite square-honeycombs (Table 2). Furthermore, design 2 presented the largest failure discrepancy. This could be attributed to Euler buckling behavior of the small columns that triggers premature torsional buckling behavior of the cross-shape columns. In addition, buckling behavior and imperfections reduced dramatically the Young's modulus comparing predicted properties.
Figure 6c shows the numerical results of core design 1. The render represents the elastic instability of a cross-shape column and its behavior in a 50 by 50mm unit cell. Comparing Figures 6b and 6c, it can be seen that the numerical results behavior fits with the performed test.
The compressive stress and strain response of the square-honeycomb cores can be seen on Fig. 5a.

Table 2. Experimental, analytical and FEM results from compression loading test

	ρ (kg/m^3)	F_{max} (kN)	σ_{comp} (MPa)	E_{comp} (MPa)	F_{theory} (kN)	F_{FEM} (kN)	$E_{predicted}$ (MPa)
Reference	35.46	21.74	2.17	536	27.2	25.3	1500
Design 1	46.73	23.7	2.37	615	31.2	32.5	1590
Design 2	46.44	22.4	2.24	560	38.5	39.7	1900
Design 3	46.61	26	2.6	930	32.7	37.5	1390

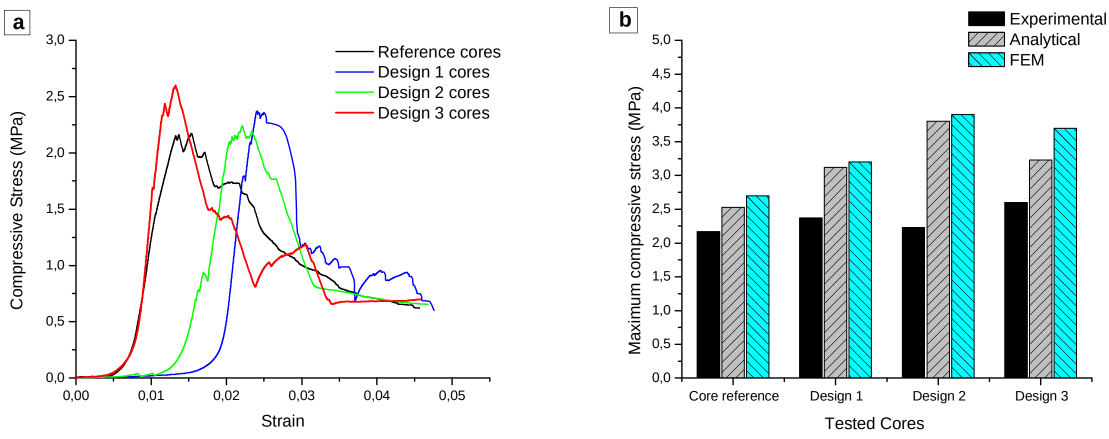

Figure 5. (a) Measured compressive stress versus strain response of the tested cores (b) Maximum compressive stresses according to analytical, FEM and experimental data

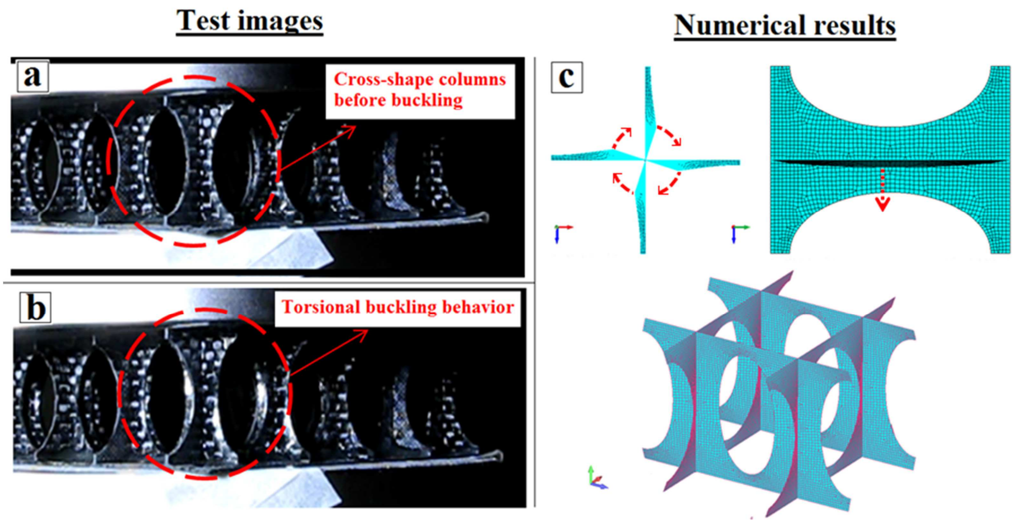

Figure 6. Images of compressive loading behavior according to core design 1. (a) Core sample between compression plates on loading. (b) Core sample failure by torsional buckling behavior. (c) FEM unit cell renders under loading showing torsional buckling behavior.

5.3 Shear response

Table 3 summarizes the honeycomb shear response according to tested cores, including density (ρ), failure load (F_{max}), maximum mean shear stress (τ) and resulting elastic modulus (G). Also analytical and FEM predictions are given. Experimental data has good agreement with the analytical and FEM results. Reference cores showed a premature failure due to debonding from the shearing plates, since the bonding area is dramatically reduced by the thin-walled composite sheets and the lower number of stripes. Figure 7a shows the shear response of loaded square-honeycomb cores. The predicted behavior of the cores Fig. 7b by numerical results fits quite well with the experimental images.

Table 3. Experimental, analytical and FEM results from shear loading test

	ρ (kg/m^3)	F_{max} (kN)	τ_{max} (MPa)	G_{max} (MPa)	F_{theory} (kN)	F_{FEM} (kN)	$G_{predicted}$ (MPa)
Reference	34.8	8.9*	0.445	55.6	24.1	27	42.6
Design 1	47.24	10.1	0.505	54.2	12.6	16.4	49.6
Design 2	46.09	6.74	0.337	19.75	7.5	10	23
Design 3	46.04	9.4	0.47	30.7	11.8	16.1	31.9

*Premature failure by debonding

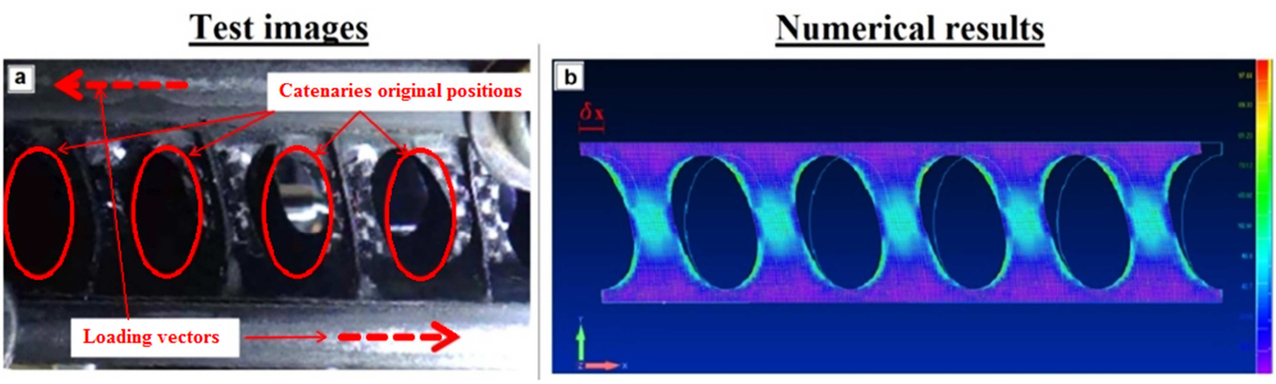

Figure 7. (a) Images of shear loading behavior according to core design 1. (b) FEM composite sheet render under shear loading.

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6. Concluding remarks

Three different geometries of square-honeycomb cores were manufactured with a density below 48kgm^{-3}. The compression and shear response of each core were evaluated and compared with low weight core taken as reference. Analytical and numerical models were developed and compared with experimental models. A good correspondence with the numerical values was obtained.
The experimental results were substantially lower than predicted strength and stiffness. The difference between these values can be attributed to imperfections in the manufacturing process of the main laminate composite material and the honeycomb cores. The highest compressive properties were exhibited due to core design 3 while the highest shear properties were showed by core design 1.
The reported manufacturing, measurement and predictions provide a first step for developing new cores for lightweight design. The current design of the cores according to shear elastic modulus *G* could be improved employing other ways for fiber orientations plies such as a ± 45°, enhancing the shear modulus of the core laminate.

7. Acknowledgements

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