Effect of Geometry on the Mechanical and Failure Properties of Cellular Core Structures

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Abstract Sandwich structures are commonly used for structural applications in the aerospace and automotive industry, in which the core geometry and material play an important role. Cores of sandwich composites have usually a two dimensional cellular structure with a regular honeycomb geometry. Additive manufacturing methods enable the production of samples with complex geometries and the bioinspired materials have arisen as alternatives to conventional designs. The purpose of this work is to analyse the effect of the geometry of the core on the mechanical properties of the structure. Three cellular solids geometry were considered, namely, regular honeycombs, lotus and hexagonal honeycombs with Plateau borders. Fused deposition modelling (FDM) was used to obtain samples in PLA (polylactic acid). The deformation and failure mechanisms of cellular structures were evaluated under experimental compressive loading, and finite element simulations were also undertaken. Compression results showed that, for the same relative density, the highest stiffness and strength were obtained for the lotus structure, although the absorbed energy remains larger for honeycomb at two loading directions. Failure modes depend on the loading direction angles. Alternative core geometries of sandwich composites may improve the design strategy, with the purpose of having structures with properties, such as, low weight and high stiffness.

Keywords: Cores of sandwich composites;mechanical properties; fracture; fused deposition modelling; finite element method.

1. Introduction

Sandwich panels consist of two skin sheets and a thicker core, which frequently has a two-dimensional cellular structure with regular honeycomb geometry. Composite cellular panels have applications in the field of transportation, mechanical engineering and aerospace industries, among others [1-3]. A honeycomb structure provides low density, high strength, high stiffness and capacity to absorb impact energy to the sandwich composite structures [1]. However, two dimensional cellular structures exhibit lower *in-plane* stiffness and strength when compared to the *out-plane* properties. Lately, research is focused on the design of new structures for developing low-weight cellular structures with tailorable properties [4].

The emergence of additive manufacturing has led to a new paradigm in the design of material structures. While with standard manufacturing processes, geometric structures were limited, advanced manufacturing methods are currently being used to produce new structures and complex shapes [5]. Among the various methods of additive manufacturing, fused deposition modelling (FDM) is by far the most common one [6-8]. In the FDM procedure, a filament of the raw material is taken through a heated extruder, after which is taken to a nozzle of a controlled diameter. The semi-melted material is deposited layer by layer, so that the required shape is obtained. The extruder movement is controlled by numerical control software. The FDM process allows the use of various polymeric materials, such as, ABS (acrylonitrile butadiene styrene), PMMA (poly(methyl methacrylate)), PCL (poly(ecaprolactone)), PLGA (poly(lactidecoglycolide)) and PLA (polylactic acid) [9-12]. PLA is a biodegradable aliphatic polyester with diverse applications from the biomedical field, as in scaffolds for tissue engineering, or orthopaedic fixation, to industry replacing conventional petrochemical-based polymers as in food packaging [13].

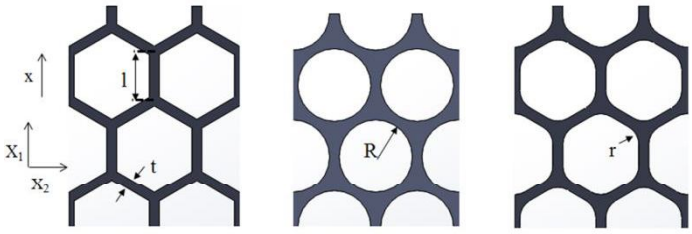
In the present paper, new core designs are introduced based on the two dimensional cellular microstructures proposed by Ronan et al [14], namely: hexagonal honeycomb, lotus material, and hexagonal honeycomb with Plateau borders. The purpose of this study is to investigate the strength and failure behavior of the several shape cores, by carrying out compression tests and simulating the test by developing a finite element model. Three *in-plane* loading directions, with cell axis at 0º, 90º and 45º angles were taken into account.

2. Materials and methods

2.1. Materials

The samples were created with the 3D CAD program Solidworks (SolidWorks, 2002). Three types of geometries, hexagonal honeycomb, lotus and hexagonal honeycomb with Plateau borders, as shown in Figure 1, were studied. The three structures have the same parameters l=11.26 mm and t=2.31mm, which enable similar relative densities (Table 1), as calculated in accordance with Ronan et al [14]. For the lotus structure the radius was R=8.66 mm and for the Plateau geometry the radius of the Plateau border was taken as r=0.4 × l. The three quasi-two dimensional structures were created with the same number of cells, which gives cellular structures with dimensions slightly different among each other around 118 × 136 × 10 mm. Besides the differences between geometries, anisotropy was also studied considering three loading directions. Cellular structures were drawn with cell axis x at 0º, at 90º and at 45º angles, regarding the axis X_1 (Figure 1). The structures will be nominated by the geometry type, Honeycomb, Lotus and Plateau, followed by the previously defined angle, 0, 90 and 45, in a total of nine examples.

Specimens were printed in a Ultimaker 3 device after being processed by the software CURA. The material used was PLA from ESUN. The temperature attained was 210°C and the layer thickness was 0.1 mm.



a) b) c)

Figure 1: Cells of a) regular hexagonal honeycomb, b) lotus material, and c) hexagonal honeycomb with Plateau borders of radius r = 0.4 × l (and relative density $\overline{\rho} \approx 0.2$)

2.2. Experimental tests

Compression tests were performed on an Instron 3369 universal testing machine with a load cell of 10 kN and a cross-head speed of 10 mm/min. The load- displacement curves were used to obtain the stress-strain curves using the Bluehill Software. From the compression results, the yield stress σ_Y, the yield strain ε_Y, the slope of the linear region of load-displacement curve, K, and the energy E_y until yield load, were assessed. The stress was calculated dividing the maximum load by the nominal contacting area between the plate and the specimen, while the strain was determined dividing the displacement by the length of the specimen.

2.3. Finite element modelling

In order to predict the failure mechanisms of the structure under uniaxial compression, a finite element (FE) model was developed using ABAQUS finite element software, version 6.16. The cellular structure was held between two plates, one fixed and the other moving with constant velocity of 10 mm/min. A contact interaction with a friction coefficient of 0.2 was applied. The cell-wall material was taken to be elastic-plastic and the properties of the PLA material, namely density, Young's modulus, Poisson's ratio and yield stress, were set as ρ_s =1252 kg/m^3, E =3.5 GPa, ν=0.36 and σ_{ys} =59 MPa, respectively [13]. Cell walls were meshed with elements of type C3D20R, i.e., 20-node quadratic brick, reduced integration.

The convergence test of the FE models was performed to verify the mesh quality, and the convergence criterion was set to be less than 7% changes in the highest von Mises stress.

3. Results and discussion

Figure 2a) exhibits the compression set-up used in the experimental tests. Figures 2b)-d) present the failure structures of Honeycomb_0, Lotus_0 and Plateau_0 respectively, while Figures 2e)-g) show the structures Honeycomb_45, Lotus_45 and Plateau_45. Finally, the geometries Honeycomb_90, Lotus_90

and Plateau_90 are revealed at Figures 2h)-j). The parameters assessed from the load-displacement curves are indicated in Table 1.

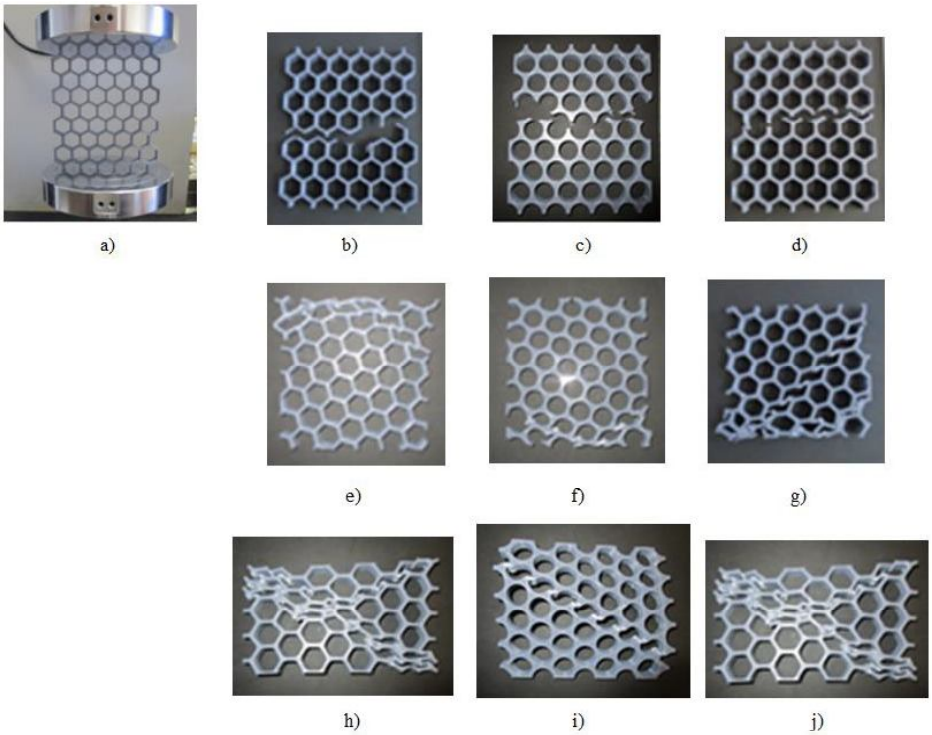


Figure 2: a) Experimental set-up for compression; failure of geometries b) Honeycomb_0; b) Lotus_0; c) Plateau_0; e) Honeycomb_45; f) Lotus_45; g) Plateau_45; h) Honeycomb_90; i) Lotus_90; j) Plateau_90.

Table 1. Relative density and experimental compression results.

Geometry	$\overline{\rho}$	σ_Y (MPa)	ε_Y (mm/mm)	K (N/mm)	E_y (J)	$E_y/\overline{\rho}$
Honeycomb_0	0.22	2.20	0.046	561.66	8.13	36.95
Lotus_0	0.28	4.37	0.027	1482.20	9.55	34.10
Plateau_0	0.24	2.98	0.037	850.12	8.67	36.12
Honeycomb_90	0.22	1.22	0.038	431.69	3.78	17.18
Lotus_90	0.28	2.64	0.034	1302.84	7.44	26.57
Plateau_90	0.24	1.46	0.033	739.67	3.98	16.58
Honeycomb_45	0.22	0.93	0.037	360.25	2.77	12.59
Lotus_45	0.28	1.20	0.026	686.27	2.54	9.07
Plateau_45	0.24	1.01	0.035	473.45	2.88	12.00

FE model deformation results are exhibited in Figure 3, for some specimens. Comparisons between the experimental (Figure 2) and FE results (Figure 3) enable to state that a good match is attained for the three configurations. The failure modes differ with the loading direction. In the honeycomb geometry, loads parallel to the axis X_1 (configurations _0) give rise to failure at mid-section, while loading at 90º leads to failure bands, at almost 45º with X_1.

This is in accordance with previous works [1]. The strength, evaluated by the maximum stress and the stiffness, measured by slope of the linear region of load-displacement curve, K, are both higher in the Lotus configurations, for all three loading directions. The energy absorbed until the maximum load, scaled to the relative density, is larger for honeycomb structures only in two directions, 0º and 45º, whilst lotus provides higher energy values at 90º.

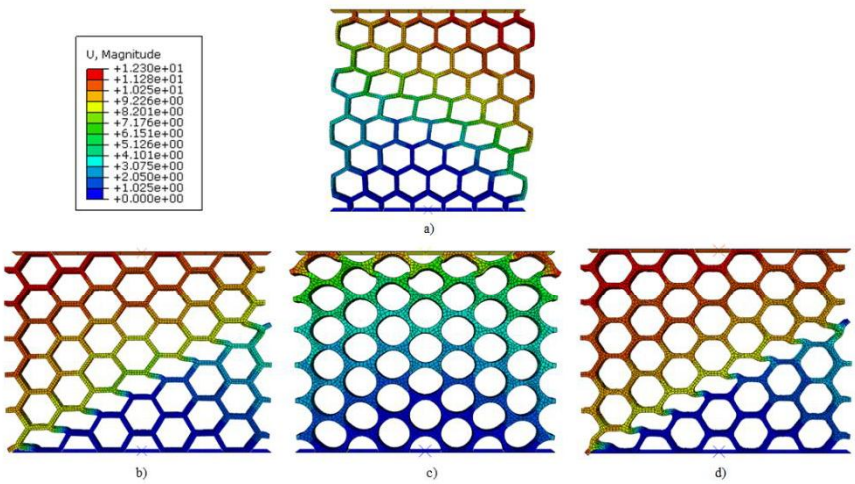


Figure 3: Finite element analysis of deformation under compression of geometries: a) Honeycomb_0, b) Honeycomb_90, c) Lotus_90, d) Plateau_90.

4. Conclusions

Sandwich panels are widely used in many applications as they are suitable for lightweight structures. However, regular honeycombs present lower *in-plane* stiffness and strength, due to bending of cell walls. The current work tries to improve the *in-plane* properties of the cellular structures by exploring new cell structure designs. Novel composite core models were drawn, simulated numerically, and prototypes fabricated by FDM were experimentally tested in compression. Results show that the lotus configuration may be a good alternative to regular honeycomb, showing larger strength and stiffness.

Acknowledgements

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