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# The in-plane compression performance of hierarchical honeycomb additive manufactured structures

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**Abstract.** Fused Deposition Modelling (FDM) is a simple additive manufacturing (AM) technology utilising fine filament extrusion of mainly thermoplastic materials to build 3D objects layer by layer. The focus of this paper is firstly to design hierarchical honeycombs and secondly to fabricate such structures using FDM with polylactic acid (PLA). The manufactured hierarchical honeycombs were tested under compression. The compression performance of the hierarchical honeycombs was assessed also with finite element analysis and the results were compared with the experimental derived properties in order to elucidate the mechanical behaviour of such honeycomb AM structures. The results reveal that for the 2nd order hierarchy of honeycombs the stiffness and the strength are increased in comparison with the 0th and the 1st hierarchies.

## 1. Introduction

Additive manufacturing/3D printing is at the forefront of research activities worldwide, as the commercial exploitation of this technology is expected to displace some traditional manufacturing methods over the next few years [1-2]. It is widely accepted that the 3D print materials currently available on the market have limited mechanical properties thereby it is necessary to develop printable materials for special applications with high performance [3-9]. It is quite common in nature to find structural components with impressive designs often hierarchically organized from the nanometer to the macroscopic length scales [10-11]. These materials frequently show complex hierarchical organization and usually every structural level of such materials contribute to the mechanical stability and toughness of the resulting design [12-13]. There are so many examples that prove the importance and necessity of hierarchy ranging from polymers with micro and nano level hierarchical structures and the Eiffel Tower [14], to sandwich panels having foams or composite lattice structures as cores. In such cases, the hierarchical structure can provide superior mechanical tailorable properties. In fact, the big diverse length of scales and levels of hierarchy govern the mechanical behavior of these structures. By increasing the levels of hierarchy lighter-weight structures with better mechanical performance can be obtained.

Honeycombs have been used in several applications including thermal insulation, impact energy absorption and structural protection, as well as the core of lightweight sandwich panels [15, 16]. The in-plane stiffness and strength of these cellular structures depend on the bending deformation of cell walls and strongly on the relative density of the honeycomb [17]. For such structures and under uniform transverse loading the maximum bending moment in each cell wall occurs at the honeycomb vertices (i.e., cell wall corners). Therefore, displacing material from the middle part of each wall closer to the vertices can potentially increase the transverse stiffness and strength [18-19].

The focus of this paper is to present a systematic way to incorporate hierarchy in honeycomb structures. Upon parametrically designing such structures, their response is assessed by uniaxial compression tests. The results from these tests are compared with predictions from finite element analysis. The reliable prediction of the mechanical behavior of the complex hierarchical structures is important for the design and development novel sandwich structures for real life components.

## 2. Design of Hierarchical Honeycombs

In the current work the vertices of a regular hexagonal lattice structure are replaced with smaller hexagons to achieve a shape with one level of hierarchy. Simultaneously the wall thickness is diminished so to maintain the overall density. It is anticipated that higher hierarchies will demonstrate stiffness superior to that of its regular hexagonal counterpart of equal relative density. Fractal appearing honeycombs can be achieved by such approach with higher orders of structural hierarchy, if this replacement procedure for three-edge vertices is repeated. figure 1(a) shows the regular, 1st and 2nd hierarchies of the hexagonal honeycomb cells.

According to A. Ajdari *et. al.* [19] for each level of hierarchy the structural organization of the honeycomb can be defined as the ratio of the introduced hexagonal edge length (b for the 1st order hierarchy and c for the 2nd order of hierarchy), to the original hexagon's edge length, (a), as described in figure 1(a) i.e., $\gamma_1 = b/a$ and $\gamma_2 = c/a$ . For a honeycomb with 1st order hierarchy, $0 \leq b \leq a/2$ and thus, $0 \leq \gamma_1 \leq 0.5$, where $\gamma_1 = 0$ denotes the regular honeycomb structure. For a honeycomb with 2nd order hierarchy, there are two geometrical constraints, $0 \leq c \leq b$ and $c \leq a/2 - b$. In terms of the ratio parameters, the constraints are $0 \leq \gamma_2 \leq \gamma_1$ if $\gamma_1 \geq 0.25$ and $0 \leq \gamma_2 \leq (0.5 - \gamma_1)$ if $0.25 \leq \gamma_1 \leq 0.5$. The dimensionless relative density, can be given in terms of t/a:

$$\rho = \frac{2}{\sqrt{3}} \times (1 + 2\gamma_1 + 6\gamma_2) \times \frac{t}{a} \tag{1}$$

where t is the thickness of the cell walls, from which the special cases of $\gamma_2$, $\gamma_1 = 0$ can be read off immediately. For regular honeycomb, $\rho = \frac{2}{\sqrt{3}} \times t/a$ and for honeycomb with first order hierarchy, $\rho = \frac{2}{\sqrt{3}} \times (1 + 2\gamma_1) \times t/a$ and finally for honeycomb with second order hierarchy, $\rho = \frac{2}{\sqrt{3}} \times (1 + 2\gamma_1 + 6\gamma_2) \times t/a$. This relation clearly shows that t/a must reduce to maintain fixed relative density as $\gamma_1$, $\gamma_2$ are increased.

## 3. Experimental Methods

### *3.1 Fabrication of 3D Printed Hierarchical Honeycombs*

The specimens of regular and hierarchical honeycomb structures were manufactured using the Fused Deposition Modeling (FDM) 3D printing method. All specimens tested in this study were fabricated on the commercial Ultimaker $2^+$ FDM open source printer with a 3 mm extrusion nozzle and using the Cura software as shown in figure 2. Furthermore, a nozzle extrusion temperature of 220 °C was used with a heat bed temperature of 60 °C and printing speed of 50 mm/s. The deposition speed was kept constant in order to avoid any variabilities in the 3D printed constructs. Additionally, all specimens were 3D printed in room temperature conditions without humidity control. PLA was selected as a 3D printing material, which is a biodegradable and compostable thermoplastic derived from renewable plant sources [20]. Moreover, all the specimens have relative density, $\rho=0.12$. The original hexagon's edge length, a=20mm and also the thickness of the cell wall measured t=2mm. Furthermore, the hierarchical honeycomb with 1st order hierarchy has $\gamma_1=0.3$ and t=1.25mm and at the same way the hierarchical honeycomb with 2nd order hierarchy has $\gamma_1=0.3$, $\gamma_2=0.12$ and t=0.86mm. Also, there was a reduction in the cell wall thickness for honeycombs with the increase in the hierarchy, so as to maintain the overall relative density constant, similar to the FEA calculations.

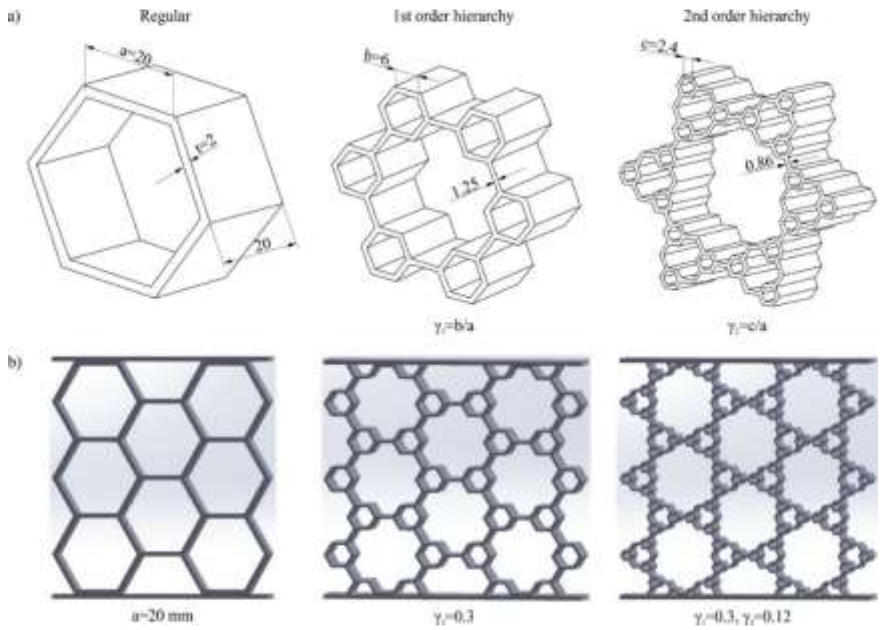


**Figure 1.** Hierarchical Honeycombs: a) cell of the regular and hierarchical honeycombs and b) design of the final specimens.

*3.2 Compression Testing*

Using a computer-controlled servo-hydraulic single axial test machine, Testometric (UK) equipped with a 50kN load cell the in-plane compression tests were conducted for the three different honeycomb structures. Specimens were compressed between hardened steel compression platens containing a spherical seat to overcome any small misalignment along the load train. The test specimens were placed between the moving head and fixed head of the test machine and lubrication was applied on the surfaces of both upper and lower platens. The cross-head speed was set at 5mm/min and at least three specimens of the same level of hierarchy were tested. Upon testing, the load-displacement curves were calculated in order to directly be compared with the predicted ones from the finite element tests.

## 4. Mechanical Behaviour of Hierarchical Honeycombs using FEA Supported Compression Tests

The typical load-displacement curves under compressive loading are illustrated in figure3. It is shown they have reached a peak compression load of 857 N, 1130.5 N and 1213 N for the regular honeycomb, the first order hierarchy and second order hierarchy, respectively. The ultimate deformation was 10 mm for all the samples. The results portray clearly that the second order hierarchy structure samples show higher stiffness than the first order hierarchy and the regular honeycomb. This phenomenon was expected since the effective elastic modulus is expressed as the ratio of mean stress and mean strain by this equation [19]:

$$\frac{E}{Es} = (t/a)^3 f(\gamma_1) \tag{2}$$

where

$$f(\gamma_1) = \sqrt{3}/(0.75 - 3.525\gamma_1 + 3.6{\gamma_1}^2 + 2.9{\gamma_1}^3) \tag{3}$$

According to A. Ajdari *et. al.* [19], in order to find the maximum normalized elastic modulus for 1st level of hierarchy structures with constant relative density, $t/a$ has to be excluded from Eq. (2), using through Eq. (1) the relative density expression. This expression for $E/E_S$ is a $\rho^3$ times function of $\gamma_1$, while setting $(\partial(\frac{E}{Es})/\partial\gamma_1)_\rho = 0$ leads to $E_1/Es = 2.97\rho^3$, two times the stiffness of the zeroth level of

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hierarchy honeycomb structure, for which $E_o/Es= 1.5\rho^3$ (HC0 effective modulus can be calculated by setting $\gamma_1 = 0$ in Eq. (2), and using Eq. (1) to eliminate $t/a$). For the 2nd order hierarchical structure [19], a stiffness almost three point five times that of HC0 (regular honeycomb) was observed. The experimental load-displacement results of the current work were in agreement with these theoretical values; 1.96 times higher stiffness for 1st level of hierarchy and 3.03 times for the 2nd level, compared with the stiffness of the regular honeycomb.

Overall, as the load increases and the honeycomb structure is under compression, the hierarchy cells tend to sustain deformation. This results in smaller yield displacement compared to the second order of hierarchy, first order of hierarchy and regular honeycomb. Therefore, hierarchical honeycombs resist higher values of applied loads compared to the regular honeycomb system and increase the stiffness.

The effect of hierarchy on the elastic properties of 3D printed hierarchical honeycombs has been also investigated in this paper. In order to accomplish that, the compression experimental results were simulated utilizing FEA. A computational model was introduced and a static structural analysis was performed using the commercial code ANSYS. Assumptions of initial material values for the tangent moduli $E_i$ of the multilinear stress-strain curves of the honeycombs' were made in the FEA model. On the top plate of each honeycomb structure, a vertical displacement was applied in steps and the reaction force was obtained at the bottom, which was considered with a fixed boundary condition. The values of this vertical displacement were acquired by the experimental results, figure 3. Considering the deformation, a static force was determined and compared to the experimental one. If the calculated force does not converge with the measured then the values $E_i$ are approximated and the finite element model is solved again. This procedure is repetitive until the last pair of values has converged and the loop ends. The final force-displacement values calculated from the FEA are illustrated in figure3, where it can be easily seen that these values converged with the experimental results. Thus, the assumptions of the multilinear material model of each hierarchy were considered accurate.

The $E_1$ value (initial slope) of the elastic modulus was determined to be 3500 MPa and this is in agreement with another work [3] on 3D printed PLA. The simulation results are illustrated in the form of a stress-strain curve in figure 4 along with a typical equivalent strain contour for each hierarchy. Finite Element Analyses were performed on honeycomb structures over three levels of hierarchy, as shown in figure 3, where the Young moduli of the hierarchical honeycombs were compared to that of a regular hexagonal honeycomb at the same relative density. It is shown in figure 4 that the level of hierarchy does not appear to have any significant effect on the Young's moduli in the elastic region. First order hierarchy and second order hierarchy structures show higher strength than the regular honeycomb without compromising their ultimate strain, even at higher levels of hierarchy.

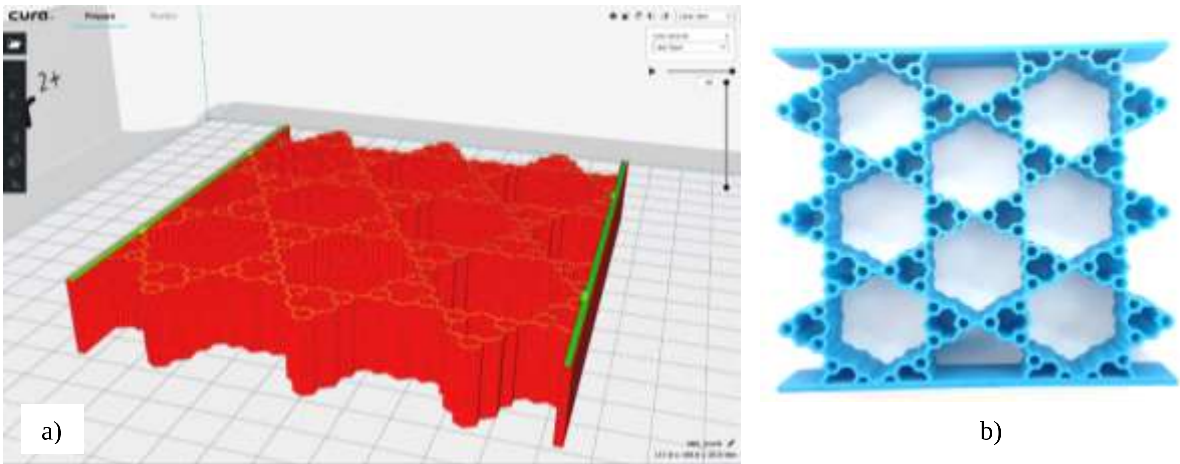


**Figure 2.** a) The virtual model on Cura software prior printing and b) The 3D printed specimen having 2nd order hierarchy.

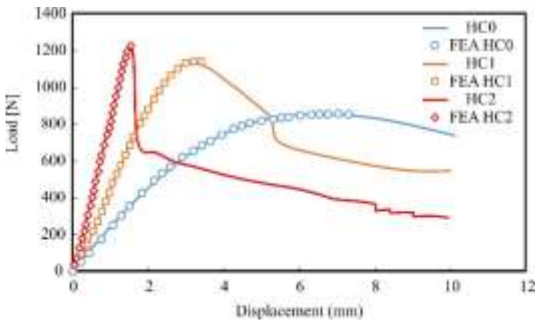


**Figure 3.** Typical experimental load-displacement curves and the curve-fit utilizing a FEA model of HC0, HC1 and HC2 structures.

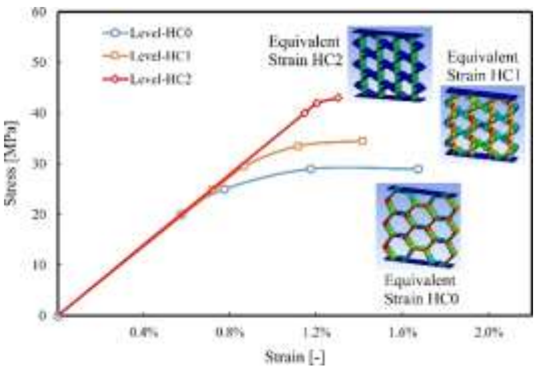


**Figure 4.** FEA-determined stress-strain behavior from compression tests through the developed FEM simulation and a typical strain contour.

## 5. Discussion

Increasing the level of hierarchy provides a wider range of achievable mechanical properties. The first and second order hierarchical honeycombs have shown stiffness up to two and three times of the regular hexagonal honeycomb. Furthermore, the compressive stress at yield is increased for HC1 and HC2 compared with regular honeycomb. The stiffness and strength of honeycombs is controlled by the bending of the cell walls when exposed to transverse loading. When the honeycomb is subjected to uniaxial loading, the maximum stress takes place at the corners of the cell walls, so the maximum bending occurs at the vertices of the honeycomb. Thus, replacing the corners of the cell walls with the material in the middle, it can decrease the deformation, and obtain less bending. Thus, it enables increase of the energy that can be absorbed. Further optimization should be possible by also varying the thickness of the hierarchically introduced cell walls, and thus the relative distribution of the mass, between different hierarchy levels. The current work focused only on the elastoplastic properties of hierarchical honeycombs, while the energy absorption and damping properties of these structures are currently under study.

## 6. Conclusions

The mechanical behaviour of the three level hierarchical honeycombs was evaluated through static compression tests. The results revealed increased stiffness and the strength for the 2nd order hierarchy of honeycombs in comparison with the 0th and the 1st hierarchies. A procedure is presented in order to extract the hierarchical honeycombs ' constitutive laws based on the evaluation of uniaxial compression test results through a developed FEA continuous simulation. The finite element analysis model utilizes the compression test results as input data to the described model and extracts the stress-strain curves of the 3D printed hierarchical honeycombs. The procedure followed showed that the presented compression test result evaluation method is a very efficient procedure to depict the stress-strain behaviour of the 3D printed hierarchical honeycombs.

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**References**

[1] Achillas C, Aidonis D, Iakovou E, Thymianidis M and Tzetzis D 2015 *J. Manuf. Sys.* **37** 328–339
[2] Raimondo M O, Achillas Ch and Tzetzis D 2017 *Int. J. Prod. Res.,* **55** (12) 3497–3509
[3] Mansour M, Tsongas K and Tzetzis D 2018, *Polym. Plast. Technol. Mat*. **58** 1715-1725
[4] Mansour M, Tsongas K, Tzetzis D and Antoniadis A 2018 *Polym Plast Technol Eng*, **57** 1715-1725.
[5] Kyratsis P and Tzetzis D 2018 *IOP Conf Ser Mater Sci Eng* **416** (1) 012086
[6] Gioumouxouzis C I, Baklavaridis A, Katsamenis O L, Markopoulou C K, Bouropoulos N, Tzetzis D and Fatouros D G 2018 *Eur J Hosp Pharm Sci* **120** 40–52
[7] Gioumouxouzis C I, Chatzitaki K, Karavasili C, Katsamenis O L, Tzetzis D, Bouropoulos N and Fatouros D G 2018 *AAPS Pharm Sci Tech* **19** (8) 3362-3375
[8] Fragkos S, Tzimtzimis E, Tzetzis D, Dodun O and Kyratsis P 2018 *MATEC Web of Conferences* **178**, 03013
[9] Efstathiadis A, Koidis C, Tzetzis D and Kyratsis P 2018 *Academic Journal of Manufacturing Engineering* **16** (4), 26-32
[10] Aizenberg J, Weaver J C, Thanawala M S, Sundar V C, Morse D E and Fratzl P 2005 *Science* **309** 275–278.
[11] Buehler M J 2006 *PNAS Journal* **33** 12285–290.
[12] Espinosa H D, Juster A L, Latourte F J, Loh O Y, Gregoire D and Zavattieri P D 2011 *Nat Commun* **178**
[13] Gibson L J, Ashby M F and Harley B A 2010 *Cellular materials in nature and medicine* (Cambridge *University* Press)
[14] Lakes R 1993 *Int. J. Sci* **361** 511–515.
[15] Lu T J and Chen C 1999 *Acta Mater* **47** 1469–85
[16] Ajdari A, Nayeb-Hashemi H and Vaziri A 2011 *Int J Solids Struct* **48** 506–516.
[17] Gibson L J and Ashby M F 1997 *Cellular solids: structures and properties* (Cambridge University Press second edition)
[18] Simone A E and Gibson L J 1998 *Acta Mater* **46** 2139–50.
[19] Ajdari A, Jahromi B H, Papadopoulos J, Nayeb-Hashemi H and Vaziri A 2012 *Int J Solids Struct* **49** 1413-19.
[20] Lim L T, Auras R and Rubino M 2008 *Prog. Polym. Sci.* **33** 820-852.