Design and Testing of 3D-Printed Elastomeric Honeycomb Structures for Energy Absorption Criteria

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Abstract: **Cellular structures resemble myriad of natural and biological structures such as Trabecular or Cancellous bone, Beehives, Cork and Wood. These structures have recently gained popularity in lightweight structures such as sandwich panels, in acoustic dampers and as thermal insulators. Development in Additive Manufacturing (AM), has rapidly grown in past few years. Hence, it has become easy to fabricate complex structures that could not be manufactured by any other fabrication process. Due to advancements in 3DP, the core lattice configurations can be designed to improve certain properties such as energy absorption by deformation mechanism, which could lead us to new sets of engineering structures altogether. In this paper, two hexagonal honeycomb structures with different cellular structure densities were designed and manufactured from TPU (Thermoplastic Poly Urethane) material using Fused Deposition Modelling, a 3D Printing technology. Deformation mechanics of these structures were studied under uniaxial in-plane compressive loading. Compressive tests were carried out on these structures to confirm the mechanical behavior of these structures by obtaining a Load-Displacement graph showing three regimes of deformation. Area under the curve of the Force-Displacement diagram represents the energy absorbing capacity of that respective structure which could be leveraged as per the requirement of any engineering application.**

Keywords — Compression test, Deformation mechanism, Hexagonal Honeycomb structures, Strain Energy Absorption, Thermoplastic Poly Urethane, 3D Printing.

I. INTRODUCTION

The mechanical properties of honeycomb in out-of-plane direction are typically higher than their in-plane properties. However, honeycombs are loaded in-plane in various natural structures like cancellous bone, wood and cork [1-2]. 3D Printing technology have made it possible to create scaffolds with precision. Therefore, many 3D unit cells have been tested mechanically and biologically when used as bone replacing scaffolds [3]-[4]. Singh showed that the microstructure of cancellous bone resembles that of a hexagonal honeycomb although in some areas only [5]. Papka and Kyriakides studied the crushing patterns obtained during the plateau regime of honeycombs that differed from specimen to specimen (caused by specimen size and geometric imperfections), though the cell failure mechanism is similar for all cases [6]. El-Sayed et al [7] published the first analytical study on the in-plane mechanical properties of hexagonal honeycombs along with the plastic deformation properties under in-plane axial loading. Sagar Sangale investigated the load-displacement behavior of five different lattice structures such as body centered cubic (bcc) diamonds without vertical struts, with vertical struts, tetras, tetrahedrons and pyramids[8]. Hedayati and Sadighi manufactured thick honeycombs with different wall thickness from PLA (Poly Lactic Acid) using Fused Deposition Modelling technique. Obtained samples were mechanically tested in-plane under compression to determine their mechanical properties [9]. Alexander Olsson and Mattias Naarttijarvi studied bio-inspired geometrical structures found in nature and theoretically optimized them to absorb as much energy as possible on impact by keeping the mass to a minimum[10].

The understanding of the mechanical behavior of the honeycomb structures and properties of these structures can lead us to the exploitation of these structures in the engineering applications. They are an important class of engineering material, yet a neglected one. The objective of this paper is to investigate the hexagonal honeycomb

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structures of two different structural densities for energy absorption criterion under uniaxial in-plane compression loading with a probability of leading us to the important conclusions on the nature of energy absorption zones of these two structures.

II. Standard Cellular Structures

Myriad cellular shapes are available such as triangular cells, circular cells, square cells, pentagonal cells, hexagonal cells and the list goes on. Now the question is which amongst the above geometries is more economical than others? Keeping the height and volume of all the standard structures constant, a comparative study between these structures on the basis of lateral surface area was done and it was then computed that which of these required the least amount of material to build a honeycomb structure of it? It is clearly observed from the figure that as the number of sides goes on increasing, the lateral surface area of the geometry goes on decreasing (keeping the height and volume of the geometries equal).

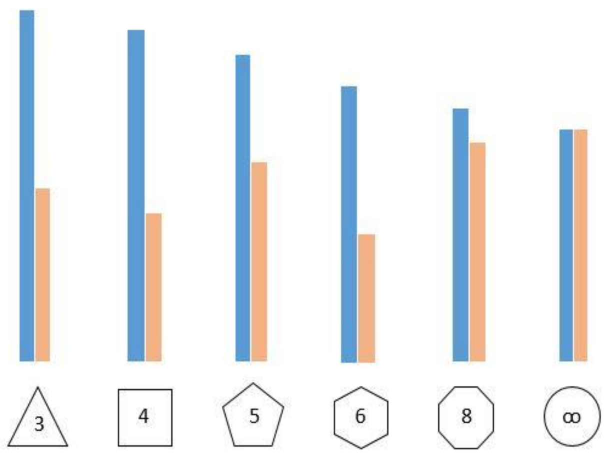

Fig 1: Comparison of Lateral surface area of standard geometries shown in blue and Comparison of geometries for material usage shown in orange with numbers indicating number of sides of the structure

So it is crystal clear now that circular geometry is the favorite for the selection amongst the geometries.

But cylinders are only economically effective when they are placed alone or if they are a single entity. Imagine if they are placed together, they leave large voids between them. Also, as no walls are shared between the cylinders meaning there is no compactness in the structure and hence both space and material is wasted tremendously. This reason is enough to discard the circular shape or the cylinders for the selection of cellular structure core. Sharing of two walls leads to saving of material as one wall is replaced by two. Thus the likes of octagon which share 4 of 8 sides save 25% of material while triangles, squares and hexagons having all of the sides being shared save 50% of the material. Sharing of the walls thus becomes an important criteria for material saving in the structure. Thus, the geometries under study were compared for lateral surface area as well as for the amount of material used for their production, as shown in figure 1.

The hexagonal structure provide the most economical, the strongest design, yet there was one more advantage of this structure i.e. the stress patterns when a load was applied on these structures.

Now, if we consider the load applied to the three most material saving structures i.e. triangular geometry, hexagonal geometry and square geometry then the stress patterns were quite striking. Square structure are unable to distribute load to its adjacent cell walls, increasing local stress concentration. Triangular cells does distribute load to its adjacent walls but horizontal cell walls of these triangles fail due to buckling. As far as hexagonal structure is concerned, the load is readily transferred to all the adjacent walls of the hexagonal unit cell. Hence, the load distribution of the hexagon honeycomb structure is better than triangular and square cellular structure.

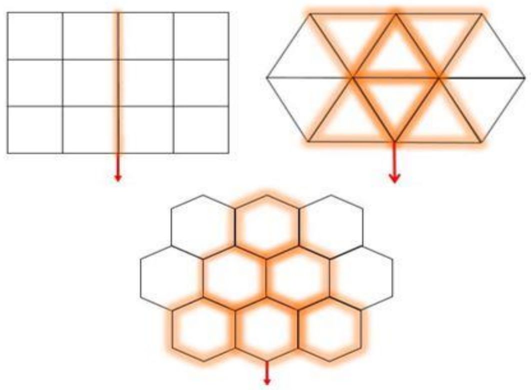

Fig 2: Comparison of square, triangular and hexagonal structure for load distribution amongst the structural walls

Hexagonal structure reigns superior amongst all the above standard geometries due to its material saving structure, compactness and also because of its stress distribution patterns that enhances its load carrying capabilities.

III. Geometry of Hexagonal Unit Cell

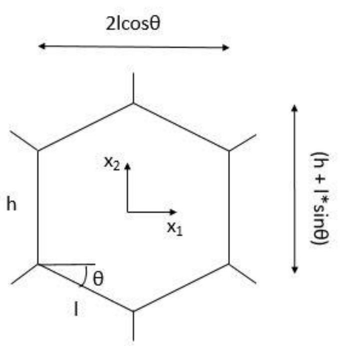

Fig 3 : 2D Unit cell of hexagonal structure with all dimensions.

As shown in the above figure 3, 'h' is the vertical wall length, 'l' is the inclined wall length of the hexagonal honeycomb structure.

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Here, in X_1 direction, length of unit cell is 2lcosθ.

In X_2 direction, length of unit cell is (h + lsinθ).

Depth of honeycomb is ‘b’ in the X_3 direction.

Thickness of the walls of the honeycomb structure is ‘t’.

Now, for a unit cell, when load ‘P’ is applied as shown in figure 4, normal stress in the X_1 direction is given by,

$$\sigma_1 = \frac{p}{(h + l\sin\theta)b} \qquad (1)$$

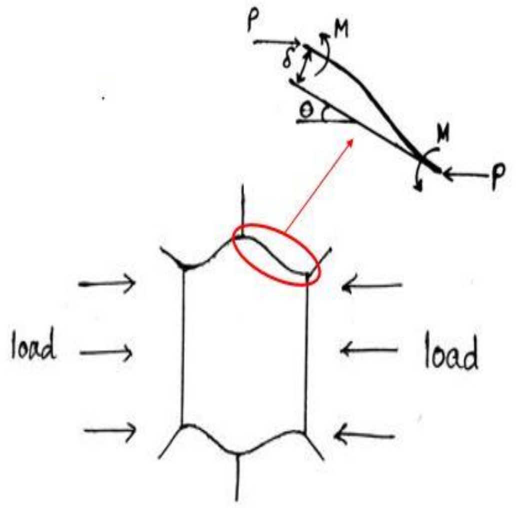

Fig 4 : In-plane load applied in x_1 direction causing bends at all ends of inclined wall members and free body diagram showing bending of inclined wall member due to loading in x_1 direction.

$$\varepsilon_1 = \frac{\delta\sin\theta}{l\cos\theta} \qquad (2)$$

Where (h + l*sinθ) is the projected area of unit cell.

If we closely observe figure 4, the inclined member behaves like two cantilever beams although not as exact.

For cantilever beam the deflection is given by,

$$\delta = \frac{PL^3}{3EI} \qquad (3)$$

Now, the inclined member of the honeycomb unit cell represents 2 cantilevers of length (l/2),

$$\delta = \frac{2P\sin\theta(l/2)^3}{3E_S I} \qquad (4)$$

Area moment of inertia of the inclined structure is given by,

$$I = \frac{bt^3}{12} \qquad (5)$$

Youngs Modulus is given by,

$$E_1^* = \frac{\sigma_1}{\varepsilon_1} = \frac{P}{(h + l\sin\theta)b} * \frac{l\cos\theta}{\delta\sin\theta} \qquad (6)$$

Putting eqn. (4) and (5) in (6),

$$E_1^* = E_s * [(\frac{t}{l})]^3 * \frac{\cos\theta}{[(\frac{h}{l} + \sin\theta)]\sin^2\theta} \qquad (7)$$

It can be observed from equation (7) that Moduli of Elasticity of the honeycomb structure depends upon the material from which it is made of (E_s), the thickness of the wall of the structure and the cell geometry (h, l and θ). Here relative density was varied to see the effect of its variation on energy absorption by the structure.

IV. Manufacturing of Honeycomb Structures

CAD modelling of honeycomb structure were designed according to the dimensions required for the application of soccer shin guard. The size of the specimens for testing are 50 mm length, 50 mm breadth and 6 mm height. The height of 6 mm is constrained as per the application. Accordingly the magnitude of inclined member of honeycomb unit cell length ‘l’ has been calculated as shown in Fig. 5. For a standard hexagon unit cell, l = h.

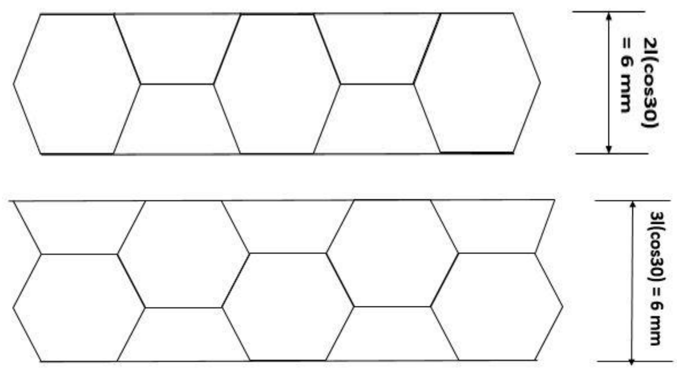

Fig 5: Dimensions of the core of two different honeycomb structures.

Fused Deposition Modelling (FDM), a 3D Printing technique was implemented in the fabrication of the honeycomb structure. The specifications of the instrument used are given below,

Technology	Fused Filament Fabrication
Print Head	Dual Extrusion Print
Build Volume	215* 215* 200 mm
Filament Diameter	2.85 mm
Nozzle Diameter	0.25 mm, 0.4mm
Print Head travel speed	30 to 300 mm/s
Build Speed	24 mm^3/s
Nozzle Temperature	180 to 260^{o}c
Build Plate temperature	20 to 100^{o}c
Supported Materials	PLA, ABS, TPU

Thermoplastic Polyurethane (TPU), a semi-flexible and abrasive resistant material that could take compressive loads and impacts was used as a feeding material spool in the

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FDM 3D Printer which printed out the CAD Model as shown in Fig. 6.

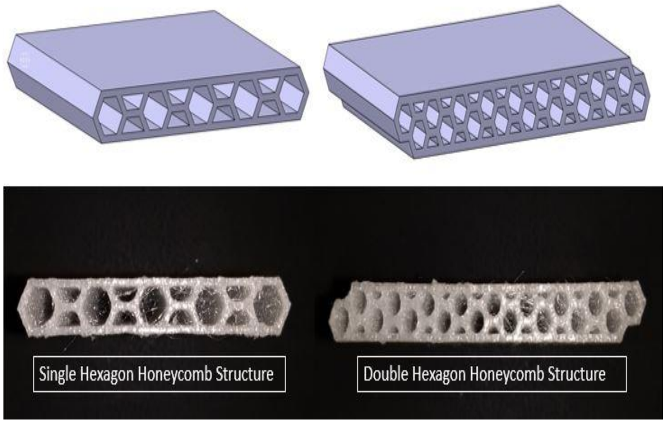

Fig 6 : CAD models of Honeycomb structures along with their 3D Printed representatives using semi-flexible TPU (Thermoplastic Poly Urethane) material.

V. IN-PLANE COMPRESSION TEST ON 3D PRINTED HONEYCOMB STRUCTURE

Different engineering applications demand different energy absorbing capacities of the structures but the common requirement is that the energy must be absorbed in a steady and controlled manner.

Ideally during the deformation of the energy absorbing structure, the reaction force which the structure generates, must remain constant for longer deformation zones. Also, the peak reaction force must be kept at such a magnitude above which there is a high chance of damage or injury for which this energy absorbing structures are used.

An in-plane compressive test is performed for Load-Displacement behavior of the structures, area under the curve will be the energy absorbed by the structures.

Energy absorbed = Force*displacement (8)

According to equation (8), in order to keep the reaction force to a minimum constant value, the deformation zone of the honeycomb structure must be as large as possible.

Thus, selection criteria of the optimum structure completely depends upon the application it is used for. For Packaging industry there are different mechanics, for defense industries there are different mechanics and similarly for sports there are different mechanics.

Tests were carried out at PRAJ Metallurgical lab, Pune. Specifications of the test instrument are given below,

Load Cell	9800 N
Temperature	25°c
Speed	5 mm/min
Pre tension load	0 N

3D Printed Honeycomb structure specimen were tested on UTM. Load-Displacement graph were obtained for the setup.

Fig 7: Compression test setup for single hexagonal honeycomb structure showing before compression and after compression state of the structure.

Following Load-Displacement curve was obtained for two honeycomb structures having two different relative densities

Fig 8: Load-Displacement curve for honeycombs showing different regions occurring due to mechanical behavior of these structure.

VI. RESULT AND DISCUSSION

Three clear distinct regions were obtained through In-Plane Compression testing namely – Linear Region, Plateau Region and Densification Region.

Linear Region – By compressing the honeycomb structure; a linear elastic region is obtained by resisting the deformation of cell walls to maintain equilibrium. In this region, as the relative density of the honeycomb structure

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increases from 0.5 to 0.7 (40 % increase), the overall stiffness of honeycomb structure increases up to 200 %.

Plateau region – Sudden but gradual collapsing of the cell walls leads to plateau region. At this critical point very less effort is required to further deform the cellular structure setting the tone for a steady and constant deformation zone. As we go on increasing the relative densities of the structure, the deformation zone goes on reducing, as the structure becomes more and more rigid leading to short deformation zones and high reaction forces.

Densification region – The graph roughly begins to shoot after a certain 3.5 mm of deformation value. This is an indication that the adjacent walls of honeycomb structure has started to touch each other, suddenly increasing the reaction force provided by the honeycomb structure. In this region, the honeycomb structure has completely become a solid structure, where there is no further absorption of strain energy by the structure.

VII. Conclusion

Three clear distinct regions were observed in the Load-Displacement diagram, out of which the densification region does not help in the absorption of strain energy due to deformation of honeycomb. Hence in order to set the criteria of energy absorbing structures like honeycombs, only first two regions must be considered. Area under the Load-Displacement curve up to deformation zone is the energy absorbed due to deformation in the honeycomb structure.

Having a longer deformation zone at constant peak load magnitudes is an indication of good strain energy absorbing structure. The peak load observed in the deformation zone must be below the critical load that can damage the part for which the application is to be used.

Increasing the relative density of honeycomb structure eventually makes the whole structure rigid. It is clear that the more material we add to the structure, the stiffer it is going to be, more reaction forces it is going to generate.

Thus depending upon the engineering application, different cellular structures can be designed as per requirement, keeping in mind the above criterions.

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