COMPRESSIVE PROPERTY CHARACTERIZATION OF FDM PRINTED CELLULAR STRUCTURES

Biranchi Narayan Panda\textsuperscript{1(*)}, Macro Leite\textsuperscript{1}, Andre Carvalho\textsuperscript{1}, Bibhuti Bhusan Biswal\textsuperscript{2}

\textsuperscript{1}Departamento de Engenharia Mecânica, Instituto Superior Tecnico, Universidade de Lisboa, Lisboa, Portugal
\textsuperscript{2}Department of Industrial Design, National Institute of Technology, Rourkela, India

\textsuperscript{(*)}Email: biranchipanda@tecnico.ulisboa.pt

ABSTRACT
Cellular structures with tailored mechanical properties are highly demanded in many areas of industrial applications such as thermal insulation, packaging, light weight structure, bone scaffolds etc. In recent years, additive manufacturing (AM) processes have been found to be a promising technology, capable of producing such products with precise porosity and pore sizes. In this regard, our present work is concerned with evaluation of compressive behavior of fused deposition modeling (FDM) printed cellular structures. Four different cellular structures such as Linear, Hexagonal, Catfill and Moroccanstar are analyzed with respect to infill density and material volume. The experimental results are compared with each other and a necessary tradeoff between infill density and material volume is established.

Keywords: Fused deposition modeling (FDM), Compressive strength, Cellular structures.

INTRODUCTION
Fused deposition modelling (FDM) process makes use of additive manufacturing (AM) technology to fabricate three-dimensional (3D) complex solid parts directly from computer aided design data, leading to shorter product development times and less human intervention. Due to several peculiar characteristics, it is finding applications in many diverse fields of the industry today (Mansour and Hague 2003, Hopkinson et al. 2006). However, machine and material cost associated with FDM is still remains the biggest barrier for widespread application of this promising technology. Though in these days, the machine cost has been reduced to a great extent, but the material used for printing has not been reduced to that level. Therefore use cellular structures instead of solid supports seem to be the only efficient approach to reduce the material consumption without affecting the component geometry and its application.

The concept of designed cellular lattice materials is motivated by the desire to put material only where it is needed for a specific application (Gibson and Ashby, 1997; Torquato et al., 1998; Ashby et al., 2000; Evans et al., 2001). From a mechanical engineering viewpoint, a key advantage offered by cellular materials is high strength accompanied by a relatively low mass. These materials can provide good energy absorption characteristics and good thermal and acoustic insulation properties as well. According to their relative densities and topology they of two types (stochastic and periodic).Fig. 1 shows the detailed classification of these structures according to their topology (Ashby et al. 2000). Cellular materials that are not produced using stochastic processes (e.g. foaming) are called designed cellular materials. Designed cellular structures typically exhibit high strength per unit weight than a typical foam structures. This paper focuses on evaluation of compressive property of four FDM made
cellular parts (periodic) in terms of its topology and infill density. The comparisons are done experimentally and it includes both infill density and topology effects on their compressive properties.

![Cellular Structures Classification](image)

**Fig. 1 - Classification of cellular structures (Asbhy et al. 2000)**

Literature reveals that the mechanical properties of simple hexagonal cells can be related to the cell geometry, volume fraction of solids, and cell wall properties (Amada et al. 1997, Ajdari et al. 2008). Two main methodologies such as unit cell and Super cell were used very frequently by researchers (Hodge et al. 2003, Chen et al. 2009, Grenestedt et al. 2000, Roberts et al. 2001, Roberts et al. 2002) in modeling cellular structures. The key idea of these investigations was to present the elastic modulus of highly porous materials as a function of the relative density. The unit cell method can be described as repeated arrangement of unit cell in a space such that its microstructure supposed to be regular. Due to regular patterns and ease to computation, this approach was popular among various authors. However, this method was not suitable for those cases where the pore size was smaller than the sample’s dimensions. To tackle this, Super cell approach came in to the field where a representative volume element (RVE) with more geometrical details is used to model the mechanical behavior of a porous specimen. In this perspective, several methods such as voronoi tessellation (Vander et al. 1997), the method of minimum energy (Weaire et al. 1994), removing or assigning zero stiffness to a number of elements (Panico et al. 2008) have been used to generate porous materials.

After successful fabrication of cellular lattice structures, researchers shifted their interest towards modeling their mechanical behavior. Labeas and Sunaric (Labeas et al. 2010) developed a new approach to study the buckling properties of lattice struts. They used this method to investigate the failure response of open lattice cellular cores. Campanelli et al. (Campanelli et al. 2014) investigated the fabrication of Ti6Al4V micro-lattices by means of selective laser melting. Then they performed compression tests to evaluate strength and energy absorption capacity of the lattice truss specimens. Brodin and Saarimäki (Brodin et al. 2013) fabricated some lattice truss structures, hollow rectangular tubes, and composites of tubes with an interior of lattice truss structures using selective laser melting (SLM). They also tested the samples for tensile strength to compare their mechanical behavior. Yan et al. (Yan et al. 2014) made diamond lattice structures using direct metal laser sintering (DMLS) to evaluate the manufacturability and performance of AlSi10Mg periodic cellular structures. Smith et al. (Smith et al. 2013) used both 3D and finite element (FEA) models to predict compressive response of the body-centered cubic lattice structure and a similar structure with
vertical pillars. Campoli et al. (Campoli et al. 2013) also developed some beam FEA model to study the elastic behavior of cellular lattices fabricated by SLM and electron beam melting.

Gumruk et al. (Gumruk et al. 2013) experimentally examined the static behavior of BCC and BCC-Z stainless steel micro-lattice structures manufactured by SLM under several loading types such as compression, shear, tension, and combined loadings. Later he joined with Mines (Gumruk et al. 2013) to investigate the mechanical behavior of 316 L stainless steel micro-lattice under the application of static compression. In addition to the mechanical behavior of cellular materials under static loading, there are number of investigations under dynamic loadings (Li et al. 2007, Kang et al.2008). Shaw and Sata (Shaw et al. 1966) measured the effect of combined stresses required on polystyrene foam which yields plastically under several loading conditions. Their results showed that the failure is governed by the maximum principal stress.

In this paper, the effect of infill density as well as material volume on the compressive strength of cellular lattices is analyzed. To this end, with the help of experimental observation a trade off in between these is established along with part build time. The more details about the complete setup can be found out in the following sections. Section “Materials and Methods” discusses in brief about the FDM experimental setup. In Section” Result and Discussion”, results are discussed with proper justifications and comments. Finally, “Conclusion” section concludes with recommendations for future works.

MATERIALS AND METHODS

Four different types of cellular structures such as Hexagonal, Linear, Catfill and Moroccanstar (Fig. 2), made with ABS-M30 material, are investigated in this paper. Replicator™ 2X made by makerboat is used to carry out the FDM process. The FDM parts are modeled in CATIA V5 setup and then send to the machine as .stl format for pre-processing operations. Dimension of the specimen (25.4mm in length and 12.7mm in diameter) is chosen according to ASTM D695 standard and an Instron 5582 is used to test the compressive strength at 2.0 mm/min loading rate. A sample during the test along with loading direction is shown in Fig. 3

![Fig. 2 - Different cellular structures: a) Hexagonal, b) Catfill, c) Linear, d) Moroccanstar](image)

A two-phase experimental method is proposed and implemented in this study for evaluating effective compressive strengths of the cellular structures. In the first phase the parts are tested with same infill density (0.5) but having different material volumes where as in later phase the infill densities are varied for different structures keeping the material volume fixed. In order to avoid experimental errors, five specimens per each pattern are tested for compressive strength and their average values are recorded.
RESULTS AND DISCUSSION

Effects of Material Volume (with constant infill density)

Figs. 4(a)-(b) show the experimental results obtained from the phase 1 and 2 respectively. The graph shown in Fig. 2 (a) indicates that the Catfill cellular structure has highest compressive strength followed by Hexagonal, Linear and Moroccanstar. However, it (Catfill) is consuming more material compare to others. In comparison, Hexagonal pattern is having good compressive strength with respect to its material volume, which is the lowest (2.95). Thus, there is no direct relationship between material volume and compressive strength of cellular structure. Though it is pre assumed that more material gives more strength, the part structure also takes an important role in deciding this factor. Introduction of cellular structure proved that proper distribution of material is much more important than adding material to the test specimen. Here Hexagoanl pattern consumes least material and provides relatively slight low strength compare to Catfill, which consumes highest material. In this situation, strength-to-weight ratio is only possible way to decide the best cellular structure. The slope value from Fig. 4 (a) indicates that the Catfill is still the best one since it has highest strength-to-weight ratio of 8.1.
Effects of Infill density (with constant material volume)

After concluding the effect of fixed infill density, it would be very interesting to see the response with fix material volume and varying infill density. Therefore in phase 2, material volume of the cellular structures are kept constant i.e 2.95g (minimum weight obtained for Hexagonal) by changing infill density percentage and tested for compressive strength. Data obtained from the results (plotted in Fig. 4(b)) implies that the Catfill structure is having higher compressive strength at lower infill density compare to other cellular structures. In comparison, Hexagonal is having lower strength with highest infill density. Linear and Moroccanstar structures lie in between the Catfill and Hexagonal with average compressive properties.

Regarding the part (cellular structures) build time, it’s worth mentioning that the time for four cellular structures in both phase 1 and 2 is found to be mostly equal (captured from the proprietary software). Therefore the authors conclude that, build time is not a significant factors in this study, rather focus should be given towards generation of new cellular structures, having high value of strength-weight ratio.

CONCLUSION AND FUTURE SCOPE

In this paper, some cellular structures are fabricated by FDM and their compressive properties are evaluated by varying infill density as well as the material volume. From the “Result and Discussion” section it is clear that Catfill is best cellular structures compared to others in terms of high strength against low mass. Hexagonal would stand next to it for relatively better performance at usual material consumption. In future, shell thickness and strut diameter (for lattice structure only) can be taken into consideration for characterizing mechanical behaviour. In addition, more tests should be performed to analyze other mechanical properties, such as tensile, bending and fatigue in both static and dynamic modes.

REFERENCES


