# Design and Development of Cellular Structures for Additive Manufacturing

Biranchi Narayan Panda
biranchipanda@tecnico.ulisboa.pt
Instituto Superior Técnico, Lisbon, Portugal
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## Abstract

This paper aims to take advantage of the additive manufacturing (AM) processes capabilities by providing a methodology to design parts for AM. Though AM have been established as an promising technology over last decades, material cost associated with the fabricated part is still present as a barrier for the wide spread application of this technology. In this regard, cellular structures have received considerable attention due to their high strength to weight ratio properties. However, due to their complexity, the design of these cellular structures has become a challenge task for current industrial designers. Therefore, current research presents an efficient approach to generate and design periodic lattice structures, especially honeycomb with the help of advanced CAD tools. In order to validate, robustness of the method is cellular resin transfer mold (RTM) is tested for fabricating boat oar paddle.

## Introduction

Additive manufacturing (AM), once referred to as Rapid Prototyping (RP), is a promising part building technology, enables to fabricate scaled prototype directly from 3D CAD model without the need of tooling and human intervention [1]. It started in the mid of 1980 with the advent of stereolithography (SL) process and since then it has been used in many diverse field of industry like medical, aerospace, automobile, construction, tooling and die making (Mansour and Hague 2003, Hopkinson et al. 2006).Past studies reveals that due to low part strength, at initial days this technology was used by artists and designers for verifying their concepts (concept modeling) prior to production. It was very much helpful for them in reducing manufacturing lead time and thus quick launch of products to the end use customers. However with advancement of time, this technology has been greatly improved in terms of dimensional accuracy, surface roughness and mechanical properties and now used for many more purposes. Most of the industries like, Siemens, Phonak, Widex use selective laser sintering (SLS) and SL machines to produce hearing aid shells, align technology uses SL to fabricate molds for producing clear braces (“aligners”), and Boeing as well as its suppliers use SLS to produce ducts and similar parts for F-18 fighter jets. Considering these recent applications, RP users realized that the term “RP” is inadequate in describing full scale application of the technology and therefore a new term called as Additive Manufacturing (AM) is adopted upon recommendation of ASTM International technical committee.

## Need For Designs for manufacturing (DFM)

Design for manufacturing (DFM) has typically meant that designers should tailor their designs to eliminate manufacturing difficulties and minimize manufacturing, assembly, and logistics costs. The great potential of AM removes nearly all limits in the manufacturing of parts. However, because of the enormous freedom conferred by AM, the challenge of AM is not the manufacturing of the part itself, but the design of component. Traditionally, the design methods are mainly focused on mold-based production systems, they do not allow designers to benefit from the opportunities AM has to offer. However, in the workflow based on DFM, the designer develops a customizable design by considering unique capabilities of AM process that enables improvement in product performance and lowers manufacturing costs. Introduction of cellular structures such as foam, honeycomb, in this regard, makes the design process easy in order to achieve DFM for various industrial applications, since a key advantage offered by cellular materials is high strength accompanied by a relatively low mass. These materials can also provide good energy absorption characteristics and good thermal and acoustic insulation properties. According to their relative densities and topology they are of two types (stochastic and periodic). The details about various types of cellular structures are discussed in [2].

Deshpande et al. [3] point out that stochastic cellular structures have strength that scales roughly to $\rho^{1.5}$, while the strength of lattice material scales to ρ, where ρ is the volumetric density of the structure's material. Therefore, a designed lattice structure with a volumetric density of 0.1 will be roughly three times stronger than its stochastic counterpart. It is hypothesized that this difference in strength occurs because stochastic cellular structures are dominated primarily by bending whereas periodic structures are dominated by compression and tension, thus resulting in higher failure stresses. Since designed cellular structures have such a significant strength advantage, scientists have shifted their research in developing synthesis methods for these structures. Rosen and his co-authors have explored this area from past ten years. Different new and improved methods have also been proposed to design cellular lattice structures. [4, 5, 6, 7, 8]. Despite of several approaches, FDM made cellular structure have not been evaluated yet in the literature survey. It appears that most of the work has been directed towards SLA and SLS process due to their wide range of material availability. Therefore present study introduces a new cad based design approach to synthesize hexagonal honeycombs and also evaluates their manufacturability by considering FDM as core production system.

## Design Methodology

Our proposed methodology for generating honeycomb structures consists of two design phases. Phase 1 is related to the hollowing process with uniform shell thickness, while phase 2 facilitates reinforcement of the honeycomb structure inside the hollow part body, generated in phase 1. Considering the system (here FDM) potential/limitation in terms of material availability, dimension accuracy and the highly significant support generation strategy, honeycomb pattern is designed in this work among the wide range of cellular structures (shown in Figure 1).

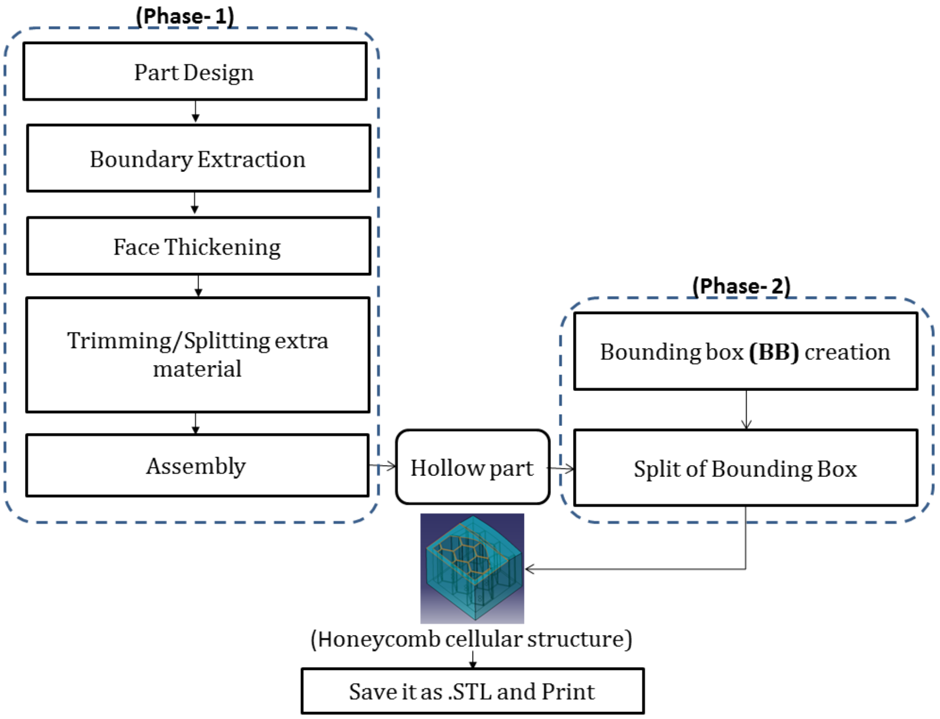


Fig. 1 Proposed Methodology

In the first step, a part is to be designed as per user requirements. Then boundary of part of the solid body is extracted into one or multiple faces with tangent continuity.Fig.2 represent a solid part and the extracted boundary with multiple surfaces is represented in Fig.3 as an exploded view.

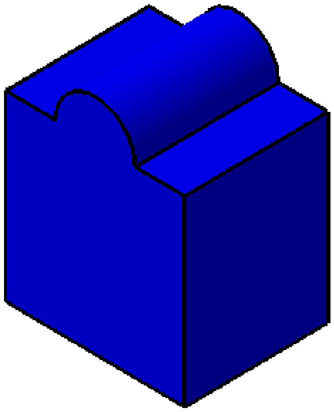


Fig.2The 3D solid part

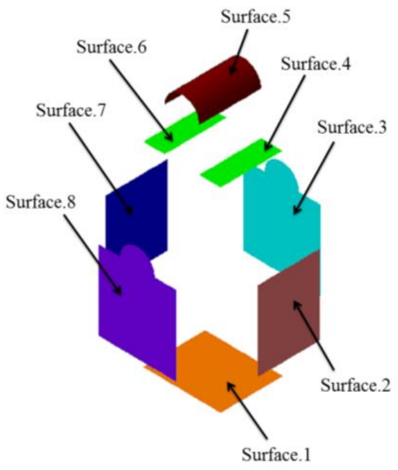


Fig.3 Exploded view of boundary surfaces

From this extracted surfaces solid bodies are created by thickening each surface to a specified thickness normal to the surface towards material direction. Designers have the rights to change this value (thickness) as per their need for application. Fig.4 represents the surface normals towards the material direction for all surfaces whereas Fig.5 represents the generated thickened body.

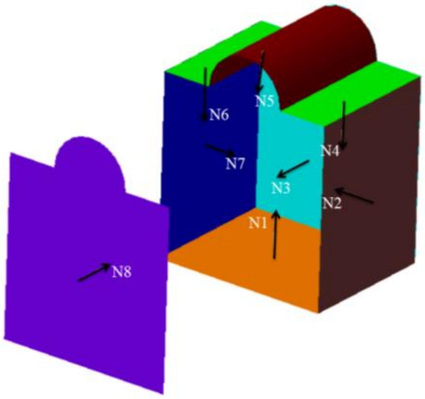


Fig.4 Direction of normal for each surface

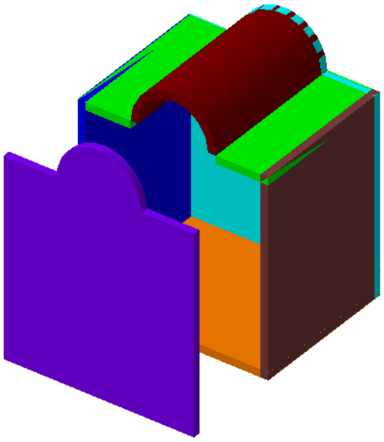


Fig.5 Thickened bodies

All thickened bodies are assembled together to generate a part with internal hollow space without any deviation in the physical appearance. Fig.6 represents the 3D hollow solid part created by using the proposed method, isometric view of the part, view from side with hidden lines andsection cut to represent the internal configuration.

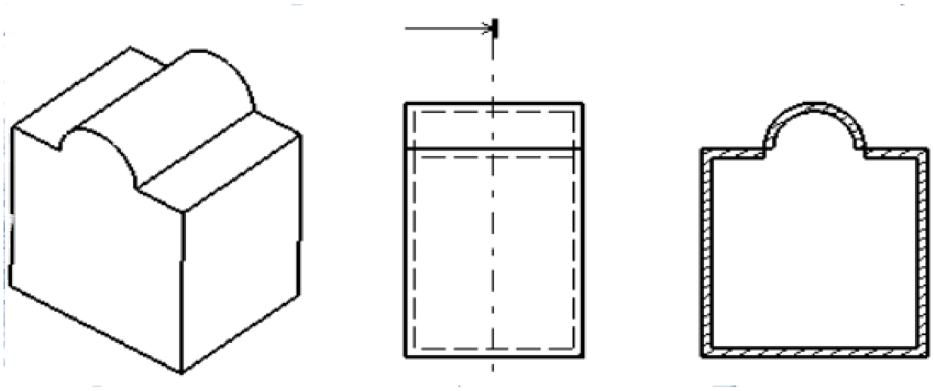


Fig.6 3D hollow solid part views (Isometric view, View from side, Section Cut view)

**Phase 2**

Bounding Box (BB) creation is our preliminary step towards generating cellular structures inside any complex geometry part. BB, as the name refers, it is the minimum enclosing box surrounding the (hollow) part body With the help of advanced CAD tools, a minimum oriented BB full of honeycomb structure is created (Fig. 7) for the hollow part shown in Fig. 6. The cell sizes of these honeycombs are controlled parametrically, in order to generate BB of different infill densities.

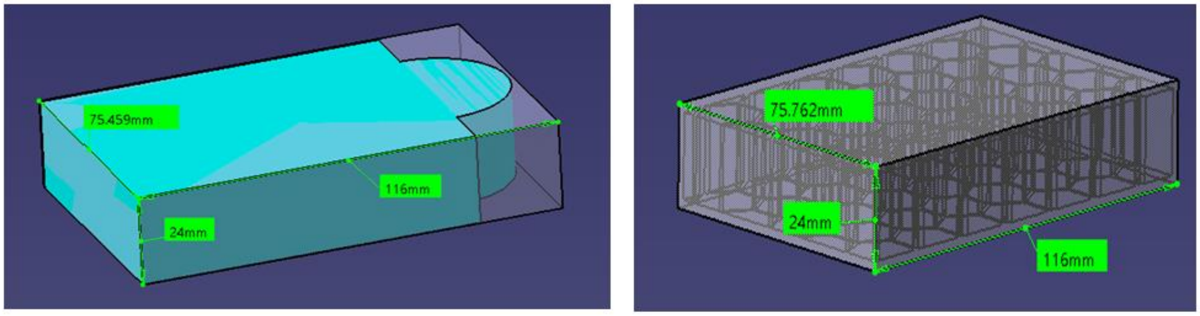
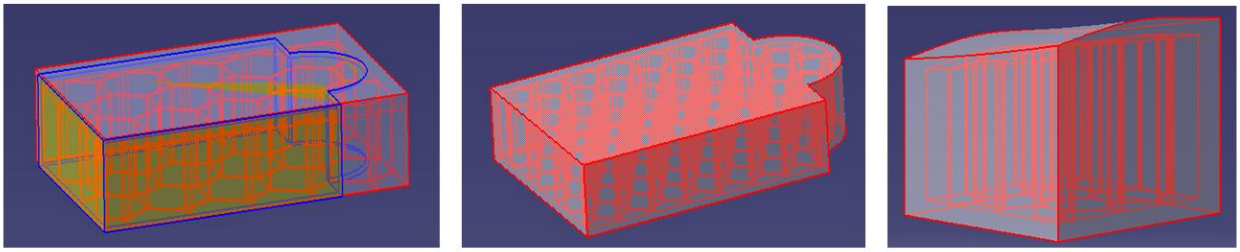


Fig.7 Bounding Box Creation

After creation of BB, internal honeycomb cellular structures for any complex shape part is generated by splitting the BB with respect to internal contour (marked in blue) of the hollow part. Figure 8(a) and (b) represents the splitting operation carried out to obtain internal honeycomb structure. In fig 8(c) (another part), the internal honeycomb structure is found to be a conformal one since it perfectly adapts to curve surface of the part body.



(a) (b) (c )

Fig.8 Splitting and generating honeycomb cellular structure

Using this method, CAD models of three honeycomb cellular structures with different volume fractions such as 25%, 30%, 35% created using this program (Fig. 9). Volume fraction is defined as the volume percentage of the solid material in the cellular structure. It is clear from this images that our proposed program is able to generate internal honeycomb structure for any complex part based on the values of wall thickness and cell size.

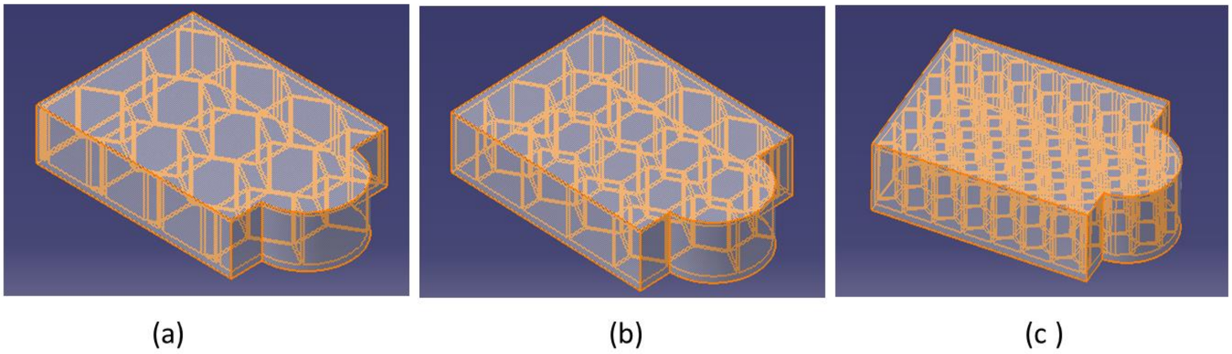


Fig. 9 Honeycomb structures with different volume fractions

## Mechanical Characterization

Microstructure and mechanical properties of hexagonal honeycomb cellular structures is thoroughly investigated with a wide range of cell size (5–15%) and wall thickness (1 &3 mm).

### *Material and Methods*

Five different cell sizes such as 5mm, 7.5mm, 10mm, 12.5mm, 15mm and two different wall thicknesses of 1mm and 3mm are designed and tested in compression for this purpose. The designed CAD model of the honeycomb structure with the cell size (5–15%) with wall thickness of 3.0 mm is shown in Fig. 10

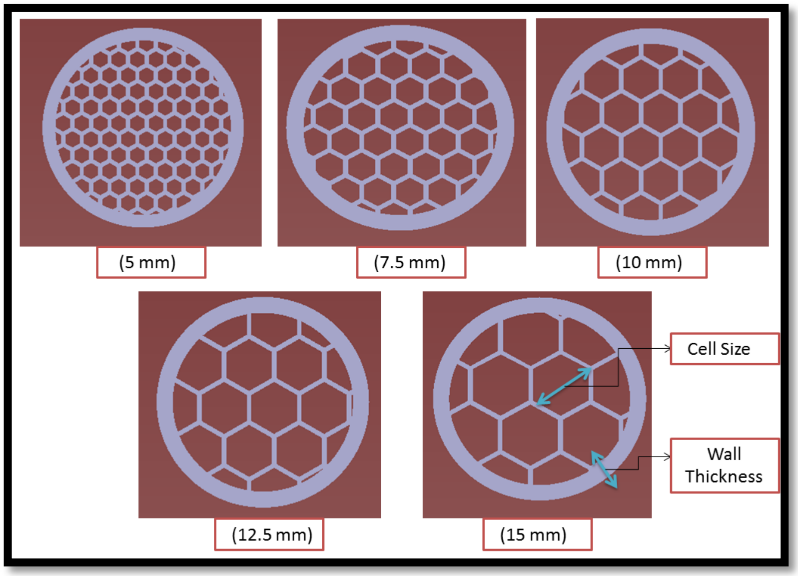


Fig. 10 CATIA modeled honeycomb cellular structure

Uniaxial compression tests are carried out using Instron 5582 at 1.0 mm/min loading rate. All the tests, done for measuring the compressive strength, are conducted in accordance with ASTM D1621 standards and results are displaced.

## Result and Discussion

### *Effect of unit cell size on the density*

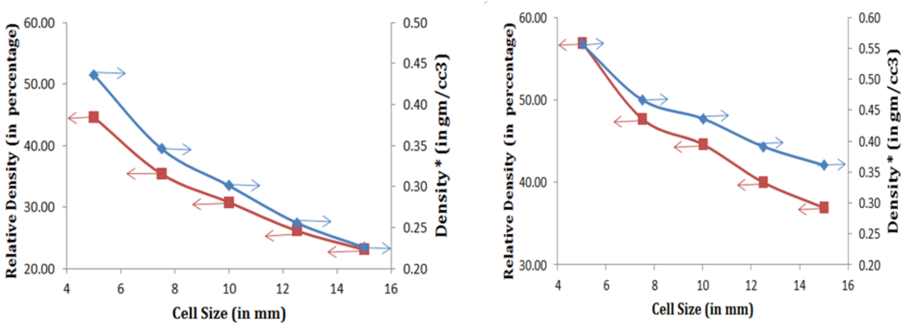


Fig. 11 (a) Wall thickness =1 mm (b) Wall thickness = 3 mm

Fig. 11 Variations of the relative density and density of cellular structure with cell size and wall thickness

The density as well as relative density of both wall thickness 1 and 3 mm decreases with increasing unit cell size. The honeycomb structure with the unit cell size of 5 mm has a relative density of 56%, which is higher than the relative density of the struts within the 15 mm cell size lattice structure, 36% (for 3 mm wall thickness). It is also noticed that the values of densities of 3 mm are higher than that of 1 mm thickness. This increasing trend may be the result of increase in material content for 3 mm thickness honeycomb structure in a defined volume.

### *Effect of unit cell size on the compressive properties*

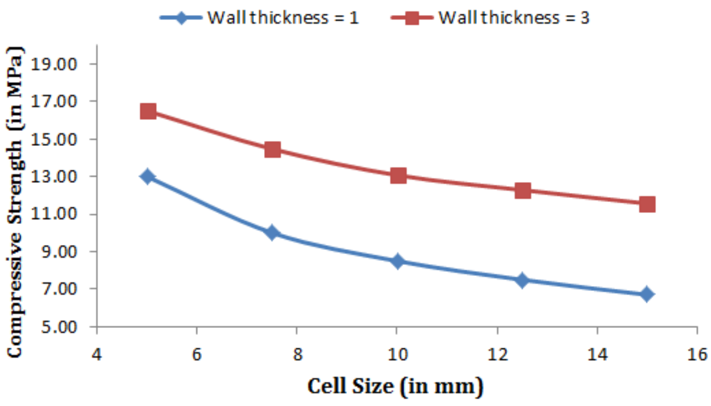


Fig. 12 Variations of the compressive strength with cell size at different wall thickness

Fig. 12 shows the compression strength of the honeycomb cellular structures as a function of cell sizes at the different wall thickness. It can be that at a fixed wall thickness, compressive strength increases with increase in cell, consistent with the Gibson–Ashby model [9].

## DESIGN EXAMPLE

In order to validate the proposed design methodology, it will be applied toward a design example of varying complexity. Here, we have considered the design of RTM for Boat Oar Paddle fabrication [10].

Fig. 13 Boat Oar Paddle

At first, both solid and sparse models of the mold are tested in compression by RTM unit. Later in order to save material consumption, CAD models for the honeycomb filled paddle's mold is designed in CATIA V5 and then it's scale down model is fabricated considering the FDM process capabilities and guidelines. The CAD modeled mold is shown in Fig. 14.

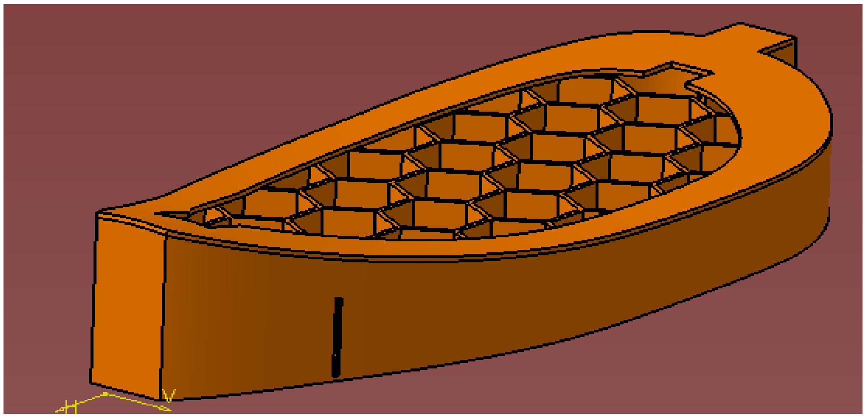


Fig. 14 Internal layout of honeycomb filled mold

For analysis, CATIA V5 structural analysis unit is used and results are displayed in Fig. 15

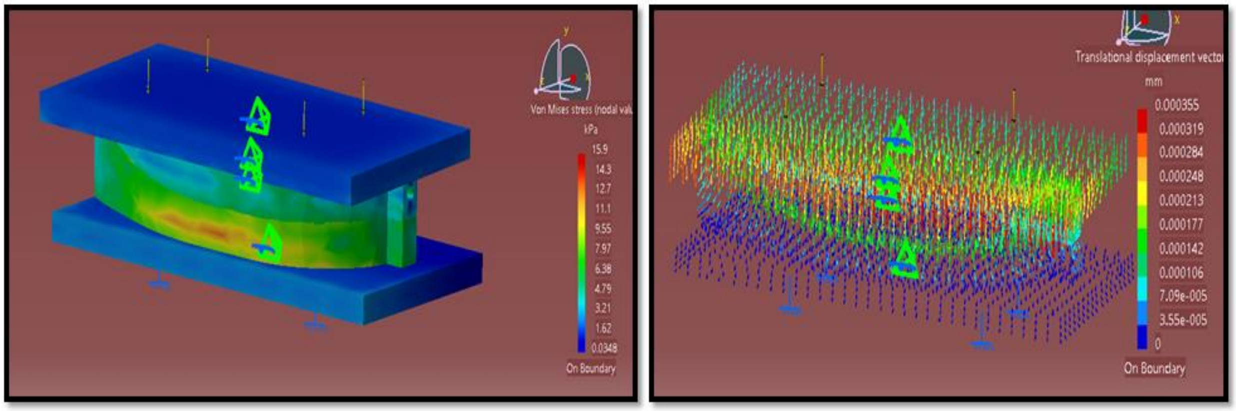


Fig. 15 (a) FEA stress analysis (b) FEA displacement analysis

It can be noticed that the obtained von mises stress at peak point (marked in red) is around 15.9 MPa, which is less than yield strength of the material. Similarly, from the displacement analysis (Fig. 15b) of the mold, a maximum deformation of 0.000335 mm is recorded which can be ignored compare to height of the mold.

From the above discussion, it can be concluded that our cellular mold design is safe and it can be tested for production of composite via RTM process. This test also confirms the potential of FDM process to create end use cellular solids without using of any tool and human interventions.

It has been also noticed that compare to solid (336gm) and sparse (104gm) mold, our designed honeycomb mold behaves well and good at 182 gm material. Thus, the potential of FDM made cellular structure has been proved with our RTM case study and in future this approach can be extended to other load bearing application for saving expensive build material without sacrificing the mechanical strength.

## Conclusion and Future work

The capabilities of AM processes have inspired many people to maximize the performance of their designs, while minimizing their weight. In this regard, a CAD based cellular structure designing approach is presented in this paper. Many DFAM examples along with their basic design guidelines are also explained in the introduction section which will serve as a benchmarking tool for future design engineers. Results from the honeycomb filled mold tool show that our proposed design approach can save 40% of expensive build material without sacrificing the functional application. However the design it not the optimal one, rather it is just an application. So, in near future, this design can be optimized with the help of structural analysis tools for better performance of the conformal honeycomb cellular structure.

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