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Bio-Mimetic Design with 3D Printable Composites

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BIO-MIMETIC DESIGN WITH 3D PRINTABLE COMPOSITES

BY

RAMYA MITRA PATNAM DAMODARAM

A thesis submitted in partial fulfillment of the requirements for the

Master of Science

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2018

BIO-MIMETIC DESIGN WITH 3D PRINTABLE COMPOSITES

RAMYA MITRA PATNAM DAMODARAM

This thesis is approved as a creditable and independent investigation by a candidate for the Master of Science in Mechanical Engineering degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidates are necessarily the conclusions of the major department.

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ABBREVIATIONS

AM	Additive Manufacturing
m	meter
mm	millimeter
N	Newton
GPa	Giga Pascal
MPa	Mega Pascal
ν	Poisson’s ratio
σ	Stress
ε	Strain
E	Young’s Modulus
DiFs	Discontinuous Fibers

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ABSTRACT

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2018

Weight and stiffness are key factors in the advancement of materials and parts for use in numerous industries. Lightweight cellular structures are broadly utilized for this reason. However, these structures must satisfy several key constraints: they should be light yet structurally safe, sustainable in different loading conditions, resource efficient and easy to maintain.

Bio-inspired materials/structures which results in desirable material features are a significant inspiration for engineered cellular structures. Cellular structures can be designed to have multifunctional properties along with lightweight characteristics. Currently, these structures with high strength to weight ratio are widely applied in many fields such as automotive, construction, and medical, among others.

In this research, the design and prototyping of cellular structures for high strength to weight ratio and stiffness to weight ratio reinforced by discontinuous fibers was studied. A computer modeled Truncated Octahedron structure is presented. With help of finite element analysis (FEA), compression testing was simulated on the cellular structure to estimate stiffness. 3D printing technique was used for prototyping the design, and experimental tests were carried out for validating the design methodology and simulations.

1. INTRODUCTION

1. Structural Design

In past 25 years, extraordinary advancement has been made in the improvement of new structural materials. These materials, which incorporate advanced ceramics, polymers, metals, and hybrid materials, called composites, open new engineering outcomes for the designer. Their prevalent properties like high temperature quality of ceramics, high stiffness, and light weight of composites, offer possibilities for more compact designs, greater fuel efficiency, and extensive lifespan in a wide category of products, from sports equipment to high potential aircraft. Furthermore, these materials can lead to new military and commercial applications that would not be possible with traditional materials [1].

Structural design is the methodological study of the strength, stability, and rigidity of structures. The fundamental aim in structural design and analysis is to build a structure efficient of resisting all applied loads without failure through its intended life. The basic role of a structure is to transmit or support loads. If the structure is improperly designed or fabricated, or if the applied loads exceed the design specifications, the device will most likely fail to perform its intended function, with feasible major effects. A well-designed structure significantly limits the likelihood of costly failures [2].

1.1 Philosophy of designing

The structural design of any structure initially includes setting up the loads and other design conditions, which must be upheld by the structure and thus should be considered in its design. This is followed by the analysis and computation of internal gross forces, (i.e. thrust, shear, bending moments and twisting moments), and stress, strain, deflections and reactions caused by loads, changes in temperature, shrinkage, creep and other design conditions. Eventually, proportioning and determination of materials is carried out for the members and joints to respond according to the impacts produced by the design conditions [2].

2. Biomimetics

The term ‘Biomimicry’ first appeared in scientific literature in 1962, developed in utilization especially among material researchers in 1980s. A few researchers favored the term ‘Biomimetics’ or less frequently ‘bionics'. There has been a huge surge of enthusiasm during the most recent ten years, brought about by individuals like biological-sciences author Janine Benyus, professor of biology Steven Vogel and professor of Biomimetics Julian Vincent, who have all composed widely in this branch. Julian Vincent characterizes it as ‘the abstraction of good design from nature’, while for Janine Benyus it is ‘the conscious emulation of nature’s genius’. There is no variation among 'Biomimicry' and 'Biomimetics', where Biomimicry is used for creating sustainable design solutions [3].

The biomimicry term appeared in 1982 and it was invented and published by the famous researcher Janine Benyus in her most significant book in 1997 entitled: Biomimicry Innovation Inspired by Nature. Biomimicry is presented in her book as the new science that reviews and imitates nature's models to solve human issues. She further looked to nature as a "Model, Measure, and Mentor" and she additionally recommended that the main aim of biomimicry is sustainability. Biomimicry is the most intense and intellectual approach to search for feasible answers for human's complications by imitating nature in its analogies, phenomenon, and patterns [3]. It is hard to improve on the real thing—nature has been engineering itself since the first life forms appeared on the planet. As human engineering solutions become more challenging, engineers are taking a closer look at how natural processes work, often at the molecular or atomic scale, such as the changing colors on a butterfly's wings, the motion of an insect's joint, or how termites build towering structures. These working prototypes have been with us all along, it's just a matter of recognizing them and studying their design and function [4].

Biomimicry's principle is to make appreciable designs by mimicking nature which has been evolving through 3.8 billion years [3] [4].

2.1 Methodology

While the utilization of biomimicry to address issues, and reveal opportunities is not new, but only recently has a methodology for applying the subject efficiently has emerged. The procedure can be utilized as a part of two distinctive courses: in the primary approach, the solution to a specific challenge is looked for in nature, which follows a Top-Down Approach. In the second approach, a study of biological organism(s) drives the best approach to inspiring designs, also referred to as a Bottom-Up Approach [5].

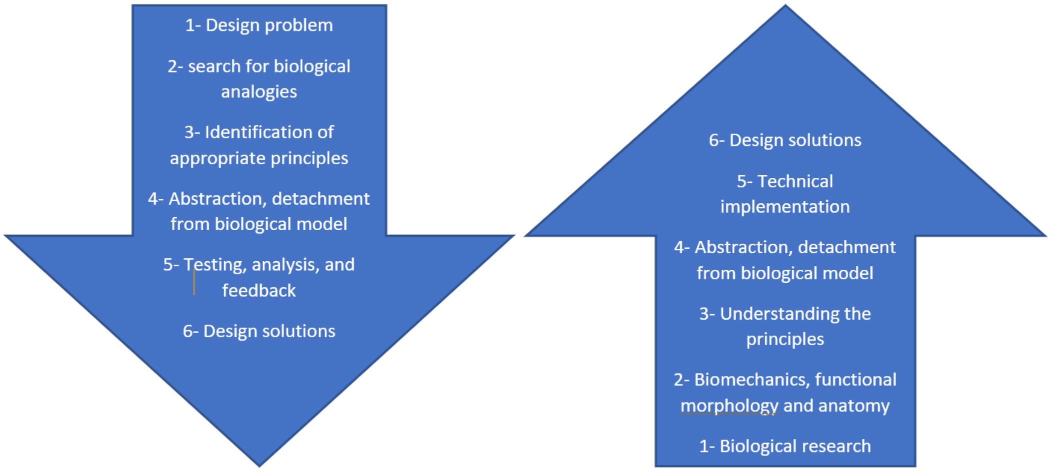


Figure 1: Biomimicry top-down and bottom-up approaches.

For this work, we utilized the primary approach, with the specific aim of discovering examples of cellular materials in nature that manage structural forces effectively. With this approach, multiple design principles will appear together to inspire the design space. For our purpose, we define 'cellular' materials as those materials with a specific, recurring structure that constructs the basis of the material itself. The specific steps we used in this work are as follows:

1. The "Challenge to Biology" approach empowers the discovery of natural models, which are significant to our functional needs within contextual considerations. Through a wide review of the accessible literature, we recognized approximately 70 distinct natural models that were developed at least partially of cellular materials, extending from the notable bee's honeycomb to the Venus' flower basket.
2. Having distinguished these models, we studied and reviewed our selection in the literature against the function and context of interest to build up the nature of the cellular material (design strategy), and in addition confirmation of the functional basis for the structure being referred to (i.e., the function of the material was for offering support to the structure). In some cases, this was a theory reinforced with circumstantial examination, in others the structure's functionality was validated through test or numerical methods. Some natural models were eliminated from consideration because the causality amongst structure and function could not be vigorously recognized.
3. The scope was limited to examine how these specific cellular design methodologies reacted to, and managed imposed loads. This is a non-trivial

characteristic of the work because numerous natural cellular models have emerged for more than one function, and a sub-optimal solution for managing forces may exist in exchange for another function, for example, buoyancy or thermal management [5].

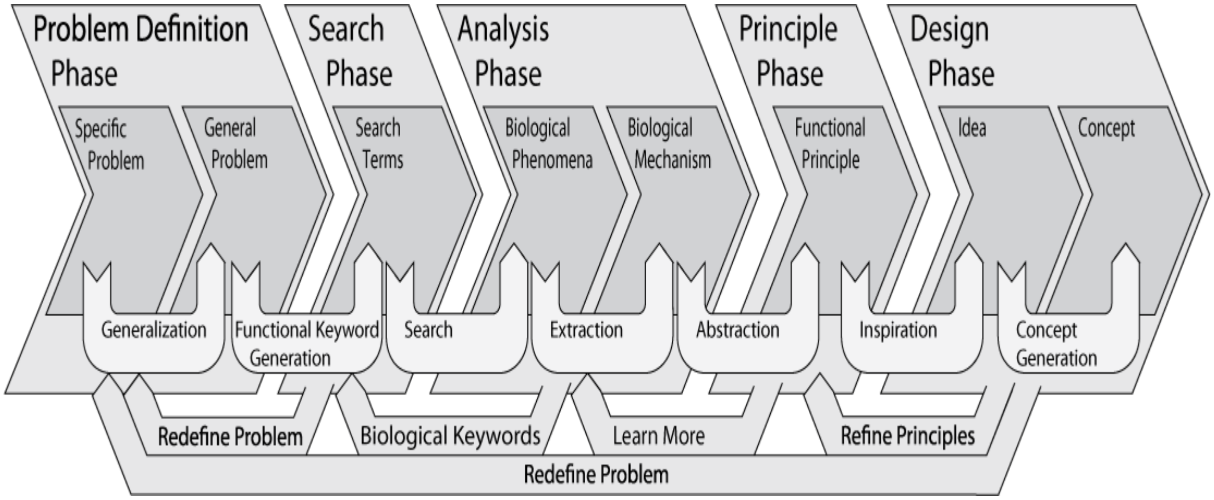


Figure 2: Proposed framework for implementing a biomimetic approach in the design problem solution [6]

Despite the incredible ingenuity and engineering ability humans have demonstrated over past millennia, we are continually looking for innovative ways to improve our designs. Given evolution has the benefit of millions of years of trial and error to perfect its designs in nature, it is logical that human construction can benefit in drawing from its influence. Biomimetic design has inspired many of our greatest creations - from buildings to bionic cars, here are some examples:

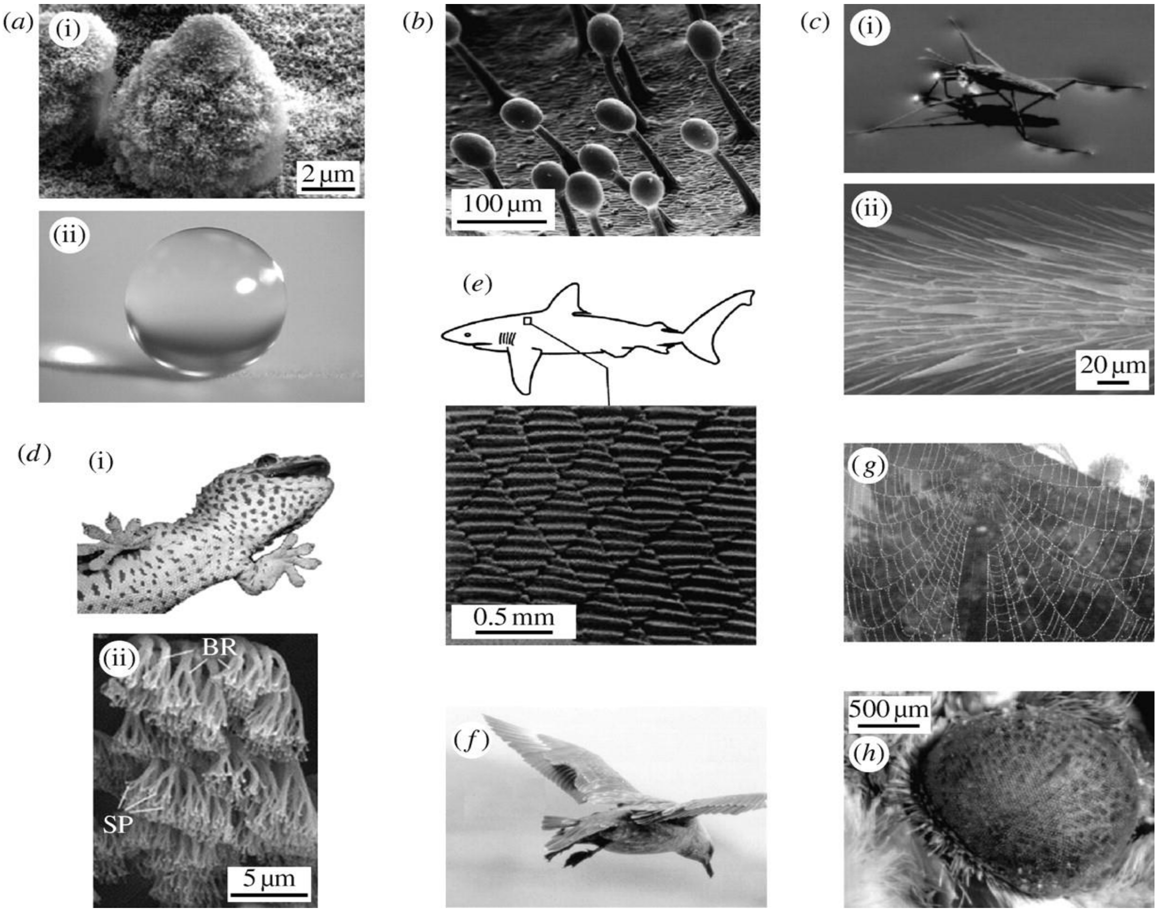


Figure 3: Montage of some examples from nature. (*a*) Lotus effect (Bhushan *et al.* in press), (*b*) glands of carnivorous plant secrete adhesive to trap insects (Koch *et al.* in press *c*), (*c*) pond skater walking on water (Gao & Jiang 2004), (*d*) gecko foot exhibiting reversible adhesion (Gao *et al.* 2005), (*e*) scale structure of shark reducing drag (Reif 1985), (*f*) wings of a bird in landing approach, (*g*) spiderweb made of silk material (Bar-Cohen 2006), and (*h*) antireflective moth's eye (Genzer & Efimenko 2006) [7].

2.2 Cellular Materials Design

The principle objective of this work is to propose a structure for the design of biomimetic cellular materials that can be incorporated into the larger design and manufacturing framework. Towards this end, we should recognize the basic patterns emerging from biological models by utilizing classifications that enable us to investigate both the design alternatives and the functional requirements. At last, we require a system that connects design and function to guide selection of a specific cellular design for a larger element. [5]

2.2.1 Classification of Design Options

There are several approaches to classify cellular materials. In the present work, we take our prompts from nature and propose a partition based principally upon the utilization of the material for either 2D (surface) or 3D (space-filling) purposes. This classification is arranged in Figure 4 and 5, with clear representations of the associated geometry. [5]

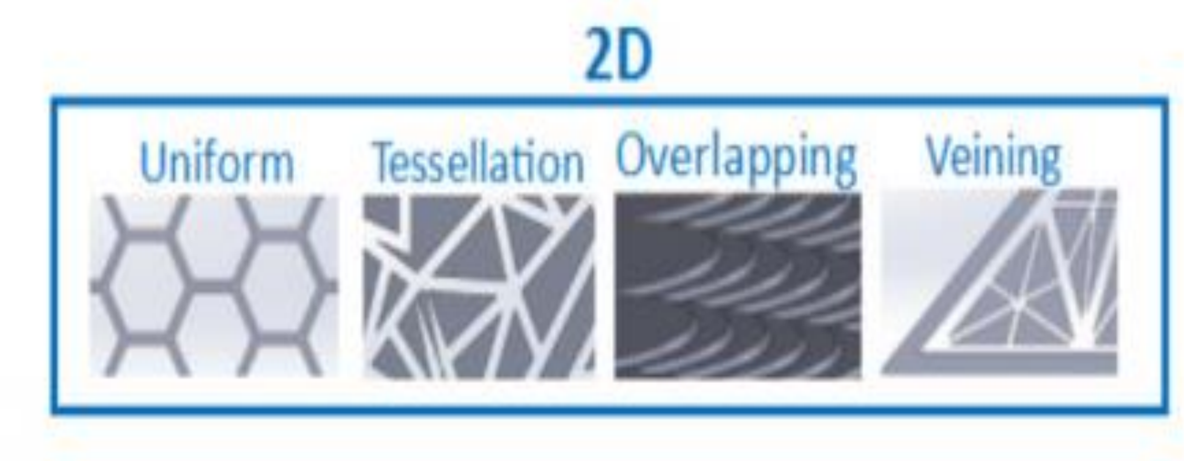


Figure 4: Proposed classification for 2-Dimensional cellular material designs [5]

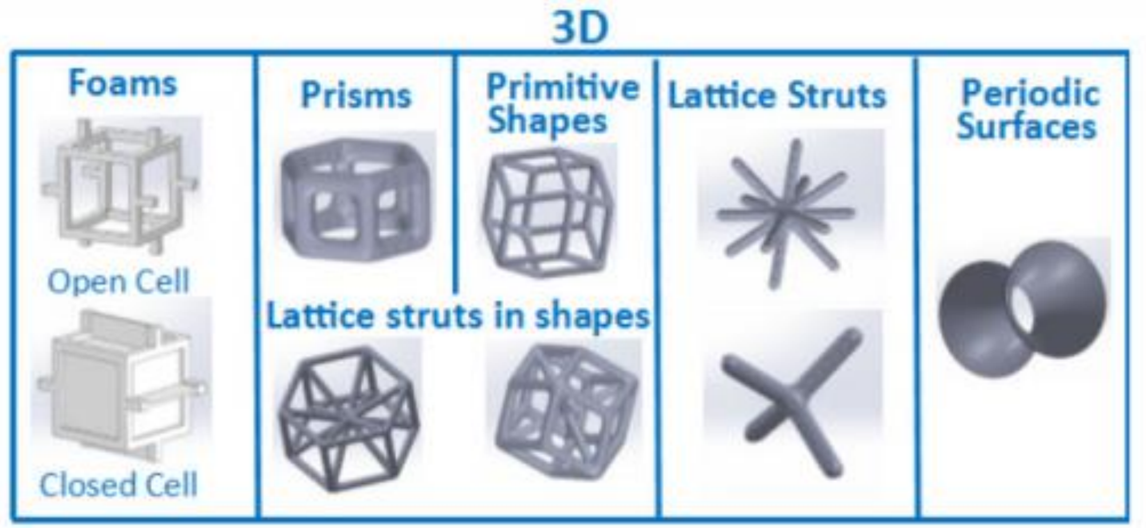


Figure 5: Proposed classification for 3-Dimensional cellular material designs [5]

3. Fabrication of Design

Factors that have an impact on the design fabrication are listed below

- Material
- Environment (Recycling / Efficient)
- Cost (Manufacture / Purchase)
- Ergonomics (Size / Form)
- Customer satisfaction
- Industrial production (Batch / Single item / Just in time)

3.1 Material Selection

3.1.1 Engineering Materials

Transportation, housing, textile, correspondence, entertainment, and food production - each portion of our regular daily routine is impacted to some degree by materials. In fact, early civilizations have been assigned by the level of their materials advancement. With time they found techniques for creating materials that had properties better than those of the characteristic ones; these new materials included ceramics and different metals. It was discovered that the properties of a material could be adjusted by heat treatments and by the expansion of different substances. Materials usage was a selection process that included choosing from a given, rather limited set of materials the one most appropriate for an application by its attributes. It was not until relatively recent times that researchers came to understand the connections between the auxiliary components of materials and their properties. This learning, procured over around the past 100 years, has helped them to mold the qualities of materials. Accordingly, a number of materials have developed with concentrated qualities that address the issues of our cutting edge and complex society that incorporate metals, plastics, glasses, and fibers. Numerous advancements are related to the accessibility of appropriate materials. For instance, automobiles would not have been conceivable without the accessibility of cheap steel. Additionally, electronic gadgets depend on parts that are made using semiconducting materials.

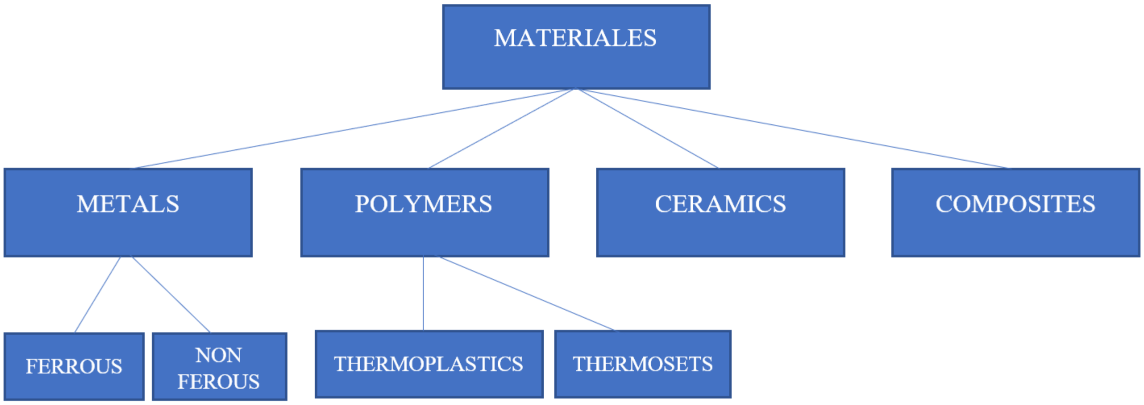


Figure 6: Classification of Engineering Materials

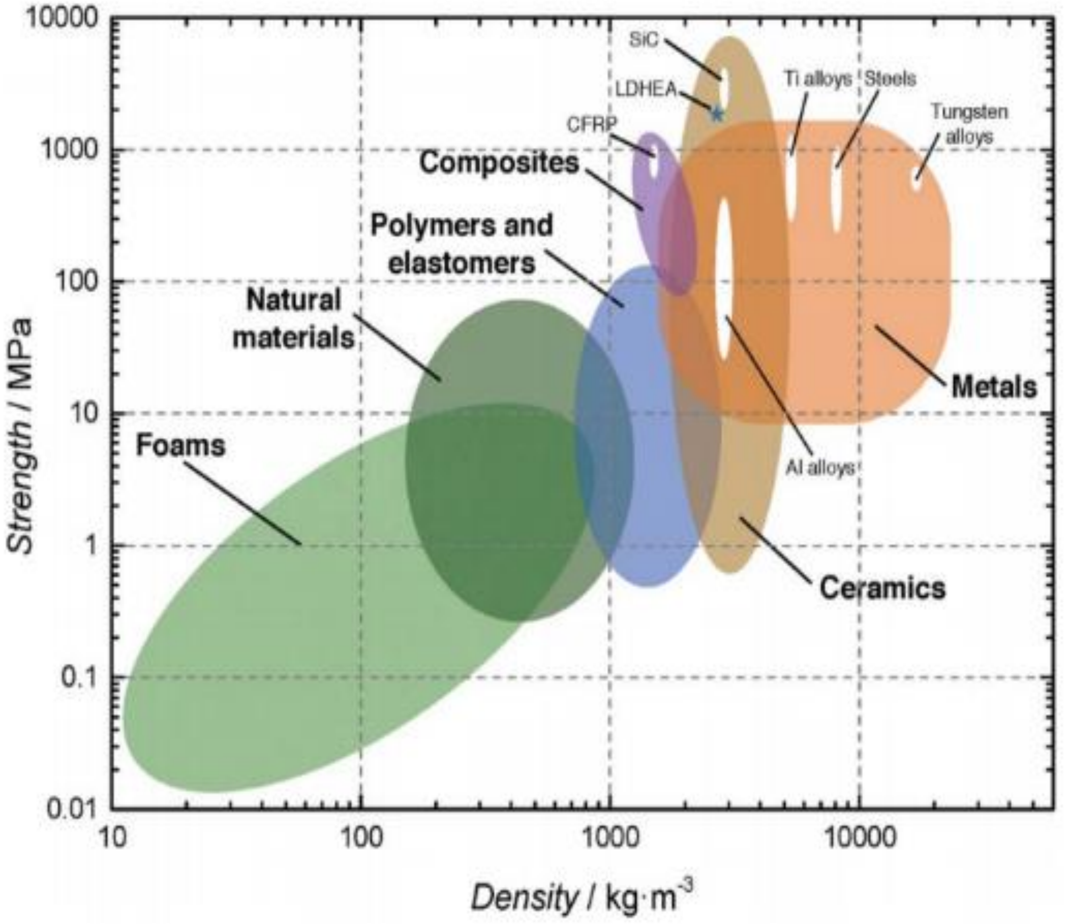


Figure 7: Ashby plot of strength vs. density for engineering materials [8]

From Figure 7, we observe strength to weight ratio of various engineering materials (e.g., Foams, Ceramics, Natural Materials, Polymers and elastomers, Composites and Metals). In comparison we find that ceramics have higher strength to weight ratio than the other materials. However, due to the brittle nature of ceramics, they are not suitable for structural appliances. After ceramics, metals and composites have similar strength with varying densities. When compared the composites have higher strength at lower densities than metals, which motivates preference for composite materials in structural designs and appliances.

Table 1. Mechanical Properties of Structural Materials and Fibers [9].

Materials	Ultimate Tensile Stress σ (MPa)	Young's Modulus E (GPa)	Density ρ (g/cm3)	Maximum Specific Strength K_{σ} x 10^3 (m)	Maximum Specific Modulus K_E x 10^3 (m)
Natural Fibers					
Wood	160	23	1.5	24.5	1564.6
Bamboo	550	36	0.8	44.9	4591.8
Cuttlefish Bone	0.40-0.52 (Compressive) [20]	4.4-8.0	0.67 [21]	0.036	1218.4
Cancellous Bone [9]	1.5-9.3 (Compressive) & 1.5-28 (Tensile)	0.01-1.57	1.0-1.4	0.9	160.2
Cortical Bone [22]	Transverse 35 (Tensile) & 160 (Compressive)	5 to 23	1.8-2.0	51.9	4.2
	Longitudinal 240 (Compressive) & 283 (Tensile)				
Jute	580	22	1.5	88.7	1496.6
Cotton	540	28	1.5	82.6	1904.8
Wool	170	5.9	1.32	22.9	456.1
Natural silk	400	13	1.35	55.0	982.6
Spider silk	1750	12.7	1.097	195.7	1181.3
Fibers for advanced composites (diameter, micro-meter)					
Glass (3-9)	3100-5000	72-95	2.4-2.6	1325.2	3728.4
Carbon (5-11)					
High Strength	7000	300	1.75	1248.7	17492.7
High Modulus	2700	850	1.78	489.9	48727.4
Boron (100-200)	2500-3700	390-420	2.5-2.6	980.6	16483.5

Thermoplastic Polymers					
Polyester (PC)	60	2.5	1.32	4.6	193.3
Polysulfone (PSU)	70	2.7	1.24	5.8	222.2
Polyamide-imide (PAI)	90-190	2.8-4.4	1.42	13.7	316.2
Polyetherether ketone (PEEK)	90-100	3.1-3.8	1.3	7.8	298.3
Polylactic Acid (PLA) [23]	53	3.5	1.25	8.2	285.7
Thermoset Polymers					
Epoxy	60-90	2.4-4.2	1.2-1.3	7.1	329.7
Polyester	30-70	2.8-3.8	1.2-1.35	5.3	287.2
Structural Materials - Metal Alloys					
Steel	400 -2200	180-210	7.8-7.85	28.8	2747.3
Aluminum	140-700	69-72	2.7-2.85	26.5	2721.1
Titanium	420-1200	110	4.5	27.2	2494.3
Structural Materials - Meatal wires (diameter, micro-meter)					
Steel (20-1500)	1500-4400	180-200	7.8-7.85	57.6	2616.4
Aluminum (150)	290	69	2.7-2.85	11.0	2607.7
Titanium (100-800)	1400-1500	120	4.5	34.0	2721.1

Maximum specific strength defines the length up-to which the material can carry its own weight or in simple terms strength to weight ratio. Similarly, Maximum specific modulus defines a material’s stiffness with respect to its density.

$$\text{Stress}, \sigma = \frac{F}{A}$$

$$\text{Maximum Specific strength}\,, K_\sigma = \frac{\sigma}{\rho}$$

$$\text{Young's Modulus}, \mathrm{E} = \frac{\sigma}{\varepsilon}$$

$$\text{Maximum Specific Modulus}, K_E = \frac{\mathrm{E}}{\rho}$$

3.1.2 Composite Materials

What are composite materials?

A composite is made by combining two or more other materials, so they improve one another but keep distinct and separate identities in the final product. So a composite isn't a compound (where atoms or molecules bind together chemically to make something quite different), a mixture (where one material is blended into another), or a solution (where something like salt dissolves in water and effectively disappears). The two materials work together to give the composite unique properties. However, within the composite you can easily tell the different materials apart as they do not dissolve or blend into each other. [10]

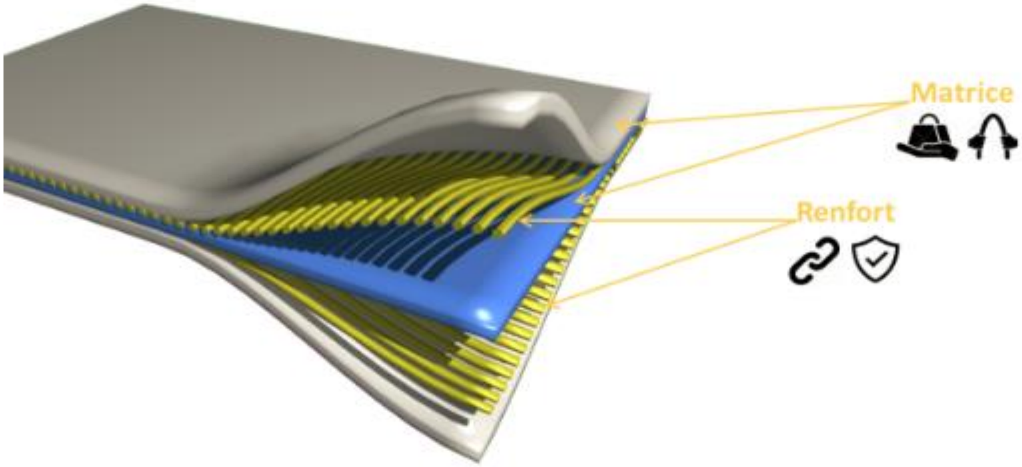


Figure 8: Detail view of matrix and reinforced material in composites [11]

How are composites materials manufactured?

Composites are generally made of two main materials (though there may be other additives as well): a "background" material called a matrix (or matrix phase) and, a *transforming* material called the reinforcement (or reinforcing phase). Although reinforcement is often thought of as being made up of fibers (as in fiberglass), that is not always accurate. In reinforced concrete, the "fibers" are large-scale, twisted steel rods; in fiberglass, they are tiny whiskers of glass. The reinforcement can be made of granules, particulates, or whiskers, but it can also be made of folded textiles [12].

The way the particles of reinforcement are arranged in the matrix determines whether a composite has the same mechanical properties in every direction (isotropic) or different properties in different directions (anisotropic). Fibers all pointing the same way will make a composite anisotropic: it will be stronger in one direction than another (e.g., wood). If particulates, whiskers, or fibers are randomly oriented in a composite it will be equally strong in all directions [12].

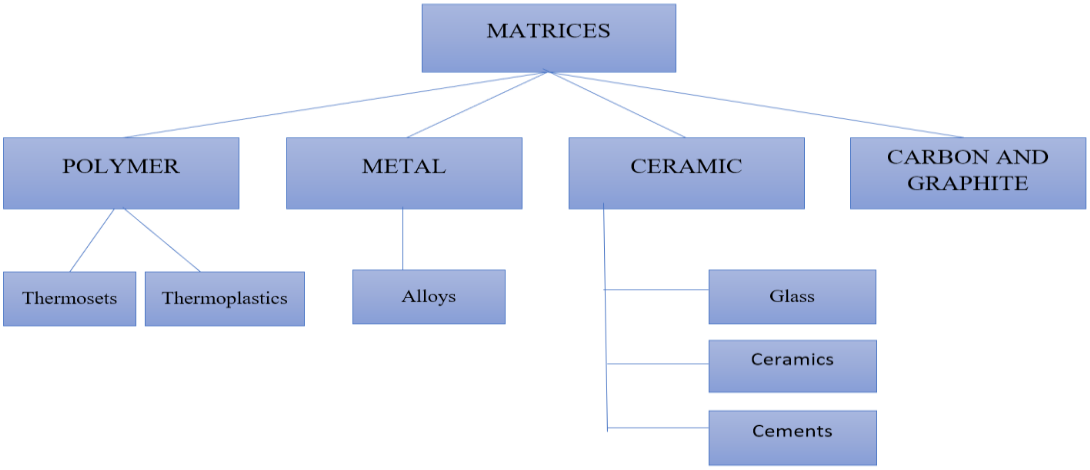


Figure 9: Classification of composites based on matrices

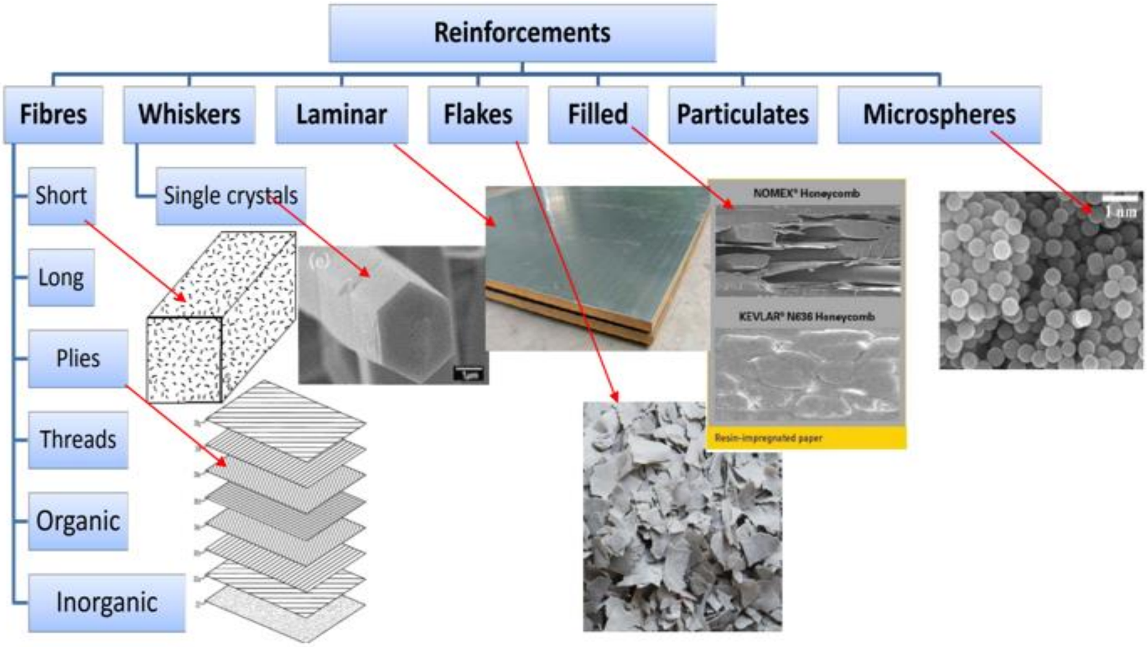


Figure 10: Classification of composites based on reinforcements

(*Composites lecture notes, slide share*)

Whatever form it takes, the reinforcement's job is to withstand forces placed on the material (adding strength or helping to stop cracks and fatigue), while the job of the matrix is to bind the reinforcement tightly in place (so it doesn't weaken) and protect it from heat, water, and other environmental damage.

Why use composite materials?

The biggest advantage of modern composite materials is that they are light as well as strong. By choosing an appropriate combination of matrix and reinforcement material, a new material can be made that exactly meets the requirements of an application. Composites also provide design flexibility because many of them can be molded into complex shapes. The downside is the cost. Although the resulting product is more efficient, the raw materials are often expensive.

3.2 Manufacturing

The manufacturing process is basically a complex activity. The process includes people from broad number of disciplines and a wide range of machinery, tools, and equipment with numerous levels of automation, such as computers and robots. Manufacturing pursuits must be receptive to several needs and developments.

3.2.1 Traditional Manufacturing Methods

There are four main families of standard manufacturing processes. Each manufacturing process has advantages and limitations.

- Injection Molding (IM)
- CNC Machining
- Plastic Forming (PF)
- Plastic Joining

3.2.2 Additive Manufacturing Methods

3D printing is also called AM. "Additive" refers to the successive addition of thin layers to create an object. In fact, all 3D printing technologies are similar, as they construct an object layer by layer to create complex shapes.

How does 3D Printing Work?

There are 3 main steps in 3D printing.

- The first step is the preparation before printing. A 3D file is created using CAD software, with a 3D scanner or simply download from an online marketplace. Once the file is accurately created, the printing process is initiated in the second step.
- The second step is the actual printing process. Printing material is chosen based on the specific properties required for the object. Potential materials includes plastics, ceramics, resins, metals, sand, textiles, biomaterials, glass, food, and even lunar dust. Most of these materials also allow for plenty of finishing options to achieve the desired. However, some materials like glass, are still being developed as 3D printing material and are not easily accessible yet.
- The third step is the finishing process. This step requires specific skills and materials. When the object is first printed, often it cannot be directly used or delivered until it has been sanded, lacquered, or painted.

3D Printing Techniques

The material chosen for the project will determine which printing methods are most suitable. Among these, the most commonly used techniques for each group of materials are described next.

Plastic or Alumide

Fused Deposition Modeling (FDM) Technology, is at the very entry of the market as it is mainly used by individuals. It is the most popular printing method due to the number of printers available on the market. FDM is an affordable 3D printing process compared to other 3D printing technologies. FDM works by the material being melted and extruded through a nozzle to 3D print a cross section of an object one layer at a time. The bed lowers for each new layer and this process repeats until the object is completed. Layer thickness determines the quality of the 3D print. Some FDM 3D printers have two or more print heads to print in multiple colors and use support for overhanging areas of a complex 3D print.

SLS Technology, Laser sintering is a 3D printing technique consisting of the fabrication of an object by melting successive layers of powder together to form an object. The process most notably facilitates in the creation of complex and interlocking forms. It is available for Plastic and Alumide .

Resin or Wax

Photo polymerization is a technique that involves the solidification of photo-sensitive resin by means of a UV light. It is used by different 3D printing processes including the following.

Stereolithography (SLA), uses a vat of curable photopolymer resin. The build plate descends in small increments and the liquid polymer is exposed to light where the UV laser draws a cross section layer by layer. The process is repeated until a model has been created. The object is 3D printed by pulling it out of the resin (bottom up), which creates space for the uncured resin at the bottom of the container and can then form the next layer of the object. Another method is to 3D print the object by pulling it downward into the tank with the next layer being cured on the top.

In Digital Light Processing (DLP), a projector is used to cure photopolymer resin. This is very similar to the SLA method except that instead of using a UV laser to cure the photopolymer resin, a safelight (light bulb) is used. Objects are created similarly to SLA with the object being either pulled out of the resin, or down into the tank.

Continuous Liquid Interface Production (CLIP) works by projecting a continuous sequence of UV images, generated by a digital light projector, through an oxygen-permeable, UV-transparent window below a liquid resin bath. The dead zone created above the window maintains a liquid interface below the part. Above the dead zone, the curing part is drawn out of the resin bath.

Similar to stereolithography, MultiJet and PolyJet 3D printing processes use a UV light to crosslink a photopolymer. However, rather than scanning a laser to cure layers, a printer jet sprays tiny droplet of the photopolymer (similar to ink in an inkjet printer) in the shape of the first layer. The UV lamp attached to the printer head crosslinks the polymer and locks the shape of the layer in place. The build platform then descends by one-layer thickness, and more material is deposited directly onto the previous layer.

Metal

DLP combined with the lost-wax casting technique allows objects to be printed in 3D. Sculpteo uses DLP technology for Silver and Brass 3D prints. First, a 3D wax model is printed. Then, a mold is made around the wax before it is melted and filled with silver, thus creating the object.

Direct Metal Laser Sintering (DMLS) uses a laser as a power source to sinter metal powder by aiming a laser and tracing a cross section of the object layer by layer. DMLS is like the selective laser sintering process.

Electron Beam Melting (EBM) uses an electron beam as the power source instead of a laser to 3D print metal. An electron beam melts metal powder layer by layer within a high vacuum and can achieve full melting of the metal powder. This method can produce high-density metal parts thus retaining the material's properties.

Multicolor

Binder Jetting is popular because detailed 3D prints with color can be created. An automated roller is used to spread a layer of powder onto the build platform. Excess powder is pushed to the sides and ensures that the bed is filled with a layer of packed powder. On a fast axis, the print heads apply a liquid binder and color simultaneously to create a cross section of the object on the powder.

Selective Deposition Lamination is a 3D printing process using paper. This process is like the Laminated Object Manufacturing (LOM) rapid prototyping method. The process involves layers of adhesive coated paper (or plastic or metal laminates) that are successively glued together with a heated roller and cut to shape with a laser cutter layer by layer. A roller with the material moves each new sheet of material over the last and repeats the process until the object is completed. This technology involves precise printing with three materials and thus makes three-color mixing possible.

Table 2. Comparison of Manufacturing Process

Process	Description	Details	Advantages	Disadvantages	Applications
Selective Laser Sintering	Laser fusion in a powder bed	Layers: 0.06-0.15 mm Features: 0.3mm Surface: rough	Strong Complex parts Large build volume Parts can be stacked in	Grainy surface finish	Electronics housing Mounts Custom consumer products

		Print speed: fast	build volume Living hinges and snap features possible		Aerospace hardware
Stereolithography	UV laser scanning vat polymerization	Layers: 0.06-0.15 mm Features: 0.1mm Surface: smooth Print speed: average	Fine detail Smooth surface finish	Weak parts Susceptible to sunlight and heat	Medical/dental products Electronics casings Investment casting patterns Art
Binder Jetting	Particle binding in a powder bed	Layers: 0.089-0.12 mm Features: 0.4mm Surface: rough Print speed: very fast	Multicolor prints Fast print speed	Very weak parts Rough surface finish	Full color prototypes and objects Figurines
Poly-jet	Jetted droplets of UV cross-linked polymer	Layers: 0.016-0.032 mm Features: 0.2mm Surface: smooth Print speed: fast	Fine detail High accuracy Multi-material capabilities	Low material strength Susceptible to sunlight and heat	Medical devices Complex and multi-material prototypes and objects Assembled prototypes
Fused Deposition Modeling	Extruded layers of thermoplastic	0.1-0.3 mm layers Surface: very rough finish Print speed: slow	High part strength Low cost	Poor surface finish Slow printing	Electronics housing Mounts Custom consumer products
Injection Molding	Material mixed and forced into a mold	Surface: excellent finish Tolerance: 50 µm	Broad material selection High volume	High start-up cost Long lead time	Automotive Aerospace Electronics Packaging Containers

			High tolerance Great surface finish	Thin walled parts only	
CNC Machining	Material removal	Surface: smooth Tolerance: 25 µm	All materials compatible Very high tolerances Reasonable turnaround	Difficulty with complexity High equipment cost Lot of scrap	Jigs and fixtures Automotive Aerospace
Plastic Forming	Stretched and formed plastic sheets	Surface: smooth Tolerance: typical 1mm	Very large parts Affordable price	Thermoplastics only Limited shape complexity Thin walled parts only One sided control	Packaging Containers Panels
Plastic Joining	Welded or adhered plastic parts	Dependent on semi-finished products	All materials	Time consuming High labor cost	Automotive Electronics Medical

Manufacturing Process Selection

For low volume manufacturing, high complexity parts, fully assembled components, customized parts, or time sensitive parts using a Professional 3D printer is the best choice. However, if material properties and surface finish are of critical importance, complexity is low, and manufacturing volume is low, then CNC machining may be a better option. For high volume manufacturing of relatively simple components, injection molding or forming is best.

Table 3. Comparison of Manufacturing Factors

	SLA	SLS	Poly-Jet	FDM/FFF	Binder Jetting	CNC	Injection Molding	Forming	Joining
Cost- Low Volume	✓	✓	✓	✓	✓	—	✗	✗	✗
Cost- High Volume	✗	✗	✗	✗	✗	✗	✓	✓	—
Lead Time	✓	✓	✓	✓	✓	✓	✗	✗	✗
Material Selection	—	—	—	—	✗	✓	✓	✓	✓
Surface Finish	—	—	—	✗	✗	✓	✓	✓	✓
Tolerance	✓	—	✓	✗	✗	✓	✓	✓	✓
Integrated Assembly	✓	✓	✓	✓	✓	✗	✗	✗	✗
Complexity	✓	✓	✓	✓	✓	—	—	✗	✗
Customizability	✓	✓	✓	✓	✓	✓	✗	✗	✗

✓ good, — fair, ✗ poor

4. Motivation

The cellular structures of biomaterials are of interest to scientists. Cellular materials offer high strength-to-weight ratio, high stiffness, high permeability, excellent impact-absorption, and thermal and acoustic insulation. Lightweight cellular composites, composed of an interconnected network of solid struts that form the edges or face of cells [13], are an emerging class of high performance structural materials that may find potential application in high stiffness sandwich panels, energy absorbers, catalyst support, vibration damping, and insulation [14-20]. Cellular composites provide the advantage of having a porous structure design and ability to alter properties as a composite. Cellular composites are of significant interest due to their wide applications in lightweight structural components and thermal structural materials and have the potential to revolutionize aerospace systems and capability [21]. Today the need for having a lightweight, high strength material is increasing in exponential manner.

Conventional design methods are cumbersome and time consuming. The conventional way of CFRP manufacturing is tedious in comparison to 3D printing. In addition, 3D printing allows the composite product to have a new degree of freedom that the conventional way of composite manufacturing lack.

An effective approach to design cellular periodic composites reinforced by discontinuous carbon fibers is to adopt the ideas behind biomimetics, which can encompass the essential aspects in materials design, system engineering, and even business models. The features in the model are listed below

- Resource efficiency
- Sustainability
- Multifunctional properties
- Light Weight Material Design
- Accessibility
- Durability
- Design Flexibility
- High strength to weight ratio

From Table 1, the carbon fiber has higher maximum specific strength than the conventional structural materials. Hence a combination of carbon fiber in cellular structures will lead to improved functionalities of products. Such innovative designs become complex and unconventional and creating a challenge for traditional subtractive manufacturing processes to realize these designs. AM techniques due to their unique additive nature becomes the best method to realize these designs with the highest level of details. These key subjects are taken as the motivation for this research and to achieve an optimized cellular structure design for a lightweight high strength material.

5. Literature Review

The focus of this study is on the honey bee’s architectural genius in designing its home — the hive, and in particular the “comb” part of the hive. With hundreds of bees inhabiting a hive, and with the weight of the honey they produce, it is necessary for their hives to be strong, light-weight and efficiently designed. Bee capability to design such a strong and efficient home and storage space has been replicated by humans in a wide variety of applications.

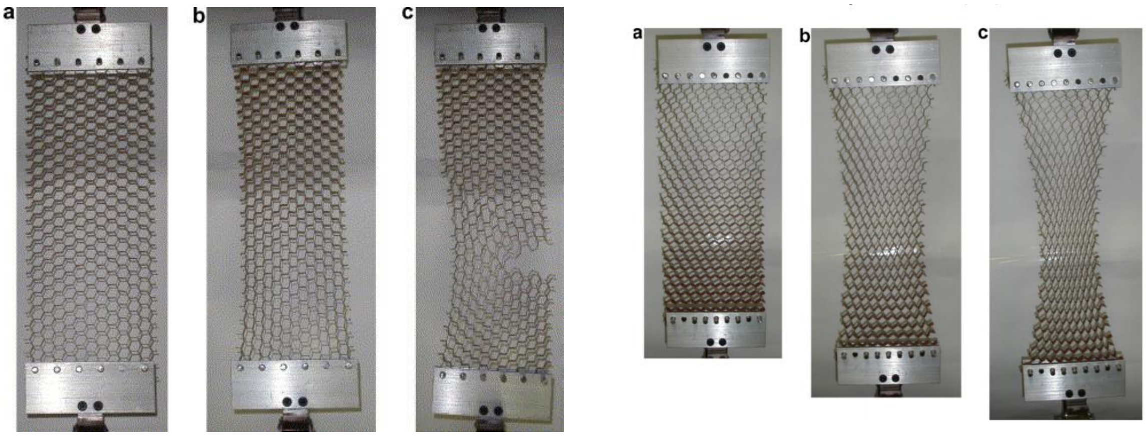
Scientists who have studied the physics and structural engineering aspects of the comb, which is made up of six-sided cells, have concluded that the hexagonal cells not only have superior strength to other shaped cells, but also greater efficiency in space usage, and are much lighter in weight. In addition to strength, efficiency, and weight, the honeycomb structure is also very shock absorbent, flexible, and wear resistant. This design is such a spectacular combination of desired design qualities, that man has copied the creation by replicating the honeycomb structure in applications including cardboard boxes, automotive and aircraft parts, window glass, floors, and insulation for homes, and shoes and sports gear.

Figure 11. Honey bee hive

Many researchers worked on various design methods to generate the topology of the highly porous composites with lightweight deign application requirements.

Design methods are adopted to generate topology of the highly porous composites, such as improved material bounds approach for multiphase, multi-dimensional, isotropic/anisotropic and periodic/nonperiodic composites with different physical properties. The topology optimization approach to material design which is frequently performed within a finite element framework and typically involves large number of design variables, homogenization or inverse homogenization approach in the design of microstructural materials which has permitted an increased level of design capability and understanding of underlying material mechanisms [22].

Choon Chiang Foo et al., studied the fundamental mechanical properties of the Nomex paper that are then used in the finite element modeling and analysis of the Nomex honeycomb structure [23].



(a) (b)

Figure 12. Tensile test of a Nomex honeycomb (a) X1-direction, (b) X2-direction [23]

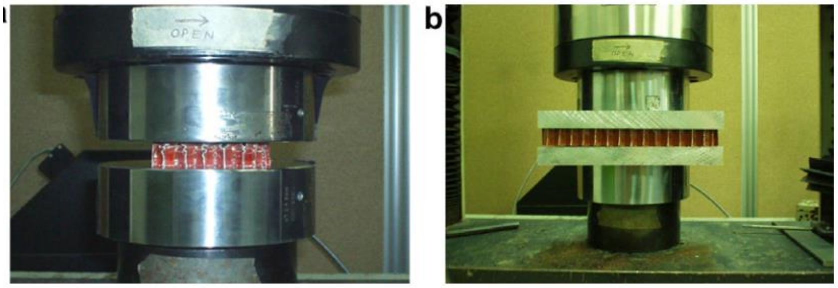


Figure 13. Compressive tests on bare honeycomb cores [23]

Epoxy-based ink which enables 3D printing of lightweight cellular composites with the controlled arrangement of multiscale, high-aspect ratio fiber support to make hierarchical structures propelled by balsa wood. Young's modulus esteems up to 10 times higher than existing industrially accessible 3D printed polymers while comparable strength values are maintained [24].

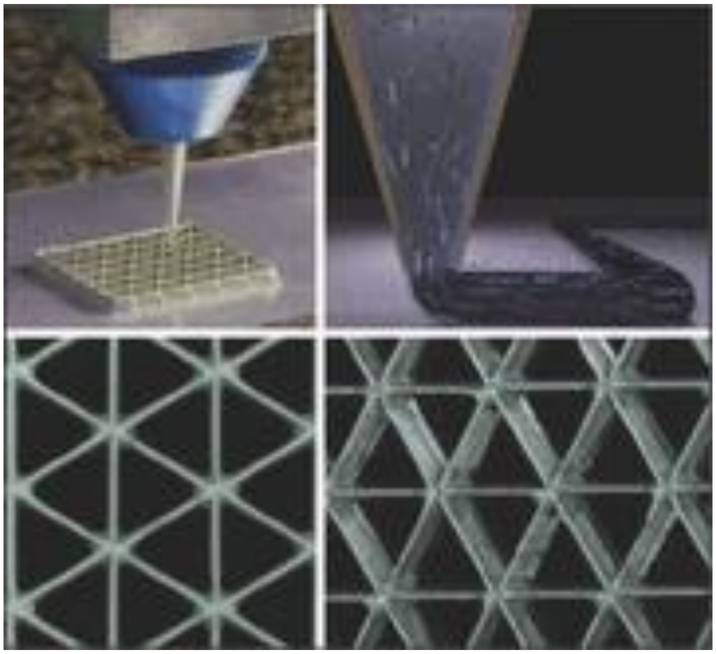


Figure 14. Fabrication of cellular composites [24]

Xin Wang et al., gave an overview on 3D printing techniques of polymer composite materials and the properties and performance of 3D printed composite parts as well as their potential applications in the fields of biomedical, electronics and aerospace engineering [25].

LA Hockaday et al., presented a novel simultaneous 3D printing/photo crosslinking technique for rapidly engineering complex, heterogeneous aortic valve scaffolds. Native anatomic and axisymmetric aortic valve geometries (root wall and tri-leaflets) with 12–22 mm inner diameters (ID) were 3D printed with poly-ethylene glycol-diacrylate (PEG-DA) hydrogels (700 or 8000 MW) supplemented with alginate [26].

In the present study, an approach involving homogenization, optimization, and validation of an efficient design of macro-/microcellular structural composites for AM will be presented for developing ultra-lightweight and high-strength cellular composites reinforced by DiFs. The topologies of the cellular composites will be designed based on the periodic structures inspired by biomimetics. Computer modeling will be conducted to characterize the performance and properties of the designed cellular structural composites, considering the materials' density/porosity. 3D printing techniques will be adopted.

6. Objectives

Nature has produced many light weight structural designs like human bone, cuttlefish bone, bamboo, wood, silk, and honeycomb. Nature inspired bio materials with optimized cellular structures will have high specific stiffness and will lead to light weight material. The three-dimensional cellular structure will exhibit an overall better isotropic property even with random distribution of the discontinuous fibers.

From the outcome of this study, a truncated octahedron structure with high strength to weight ratio, high specific strength, specific modulus, high specific stiffness was designed. Using AM, a 3D printed model was tested for required properties.

2. METHODS AND MATERIAL

The first developed AM techniques are typically applied to fabricate pure plastic parts mainly used as rapid prototypes for functional testing [27]. AM techniques include stereolithography apparatus (SLA) from photopolymer liquid [28], fused deposition modeling (FDM) from plastic filaments [29], laminated object manufacturing (LOM) from plastic laminations [30], and selective laser sintering (SLS) from plastic powders [31]. However, FDM is the most widely used method among all the AM techniques for fabricating pure plastic parts with low cost, minimal wastage, and ease of material change [32] [33]. In the AM technologies available to date, fusion deposition modelling technique was chosen for fabricating the designed Truncated Octahedron lattice structure in this research.

2.1 3D Printer & its Printing Technology

2.1.1 MARK TWO 3D printer

The Mark-forged MARK TWO 3D printer has been used for building experimental end parts for studying strength and stiffness of the parts. The MARK TWO is the only 3D printer manufacturer with a system on the market capable of 3D printing continuous carbon fiber. The MARK TWO 3D printer use a patented continuous filament fabrication (CFF) technology to reinforce plastic and composite parts with carbon fiber or other materials, making it what may be the most affordable method for producing carbon fiber–reinforced plastic parts available.

As the Mark Two is capable of reinforcing nylon and carbon fiber-nylon composite parts with carbon fiber, Kevlar, fiberglass and HSHT fiberglass, it offers several capabilities not possible with traditional desktop extrusion 3D printers. Carbon fiber reinforcement, for instance, results in parts stronger and lighter than aluminum.

The Mark Two is capable of 100-micron layer resolution when printing without reinforcement, as well as with fiberglass and Kevlar, and 125 microns for carbon fiber—all with a relatively substantial build volume of 320 mm x 132 mm x 154 mm (12.6 in x 5.2 in x 6.1 in). Due to the use of kinematic couplings, the printer's print-bed will remain level within 10 microns once first adjusted.

Table 4. Mark forged MARK TWO technical specifications

MARK TWO Technical Specifications	
Build Size	320 x 132 x 154 mm
Layer Resolution	0.1mm
Software	Browser Based
Supported OS	Windows 7+, Mac OS 10.7 Lion+, Linux
Supported File Types	.STL
Machine Size	575 x 322 x 360 mm
Power Supply	100–240 V 150 W

2.1.2 Fusion Deposition Modeling

Fused deposition modeling (FDM) is one of the most popular AM technologies for various engineering applications. FDM process was introduced commercially in the early

1990s by Stratasys Inc., USA. The quality of FDM processed parts mainly depends on careful selection of process variables. Thus, identification of the FDM process parameters that significantly affect the quality of FDM processed parts is important. In recent years, researchers have explored a number of ways to improve the mechanical properties and part quality using various experimental design techniques and concepts [34].

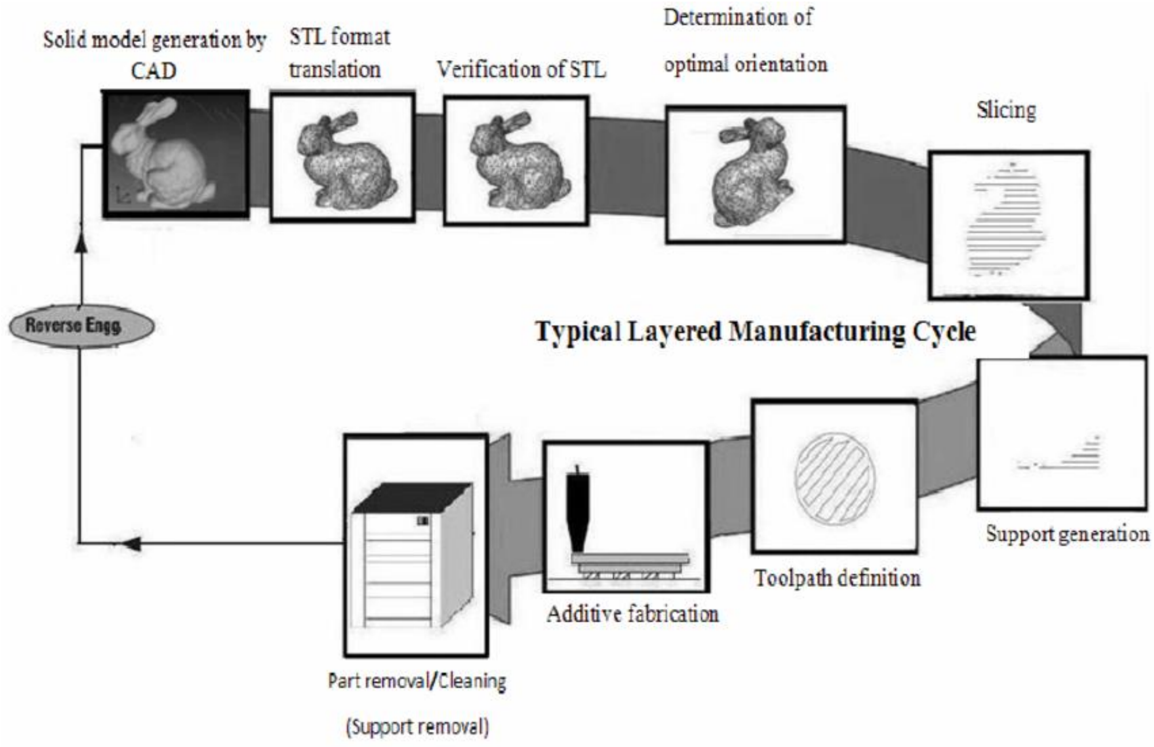


Figure 15. Generalized AM process [35]

Before FDM, the STL file generated by the CAD software is sliced into horizontal layers and the thickness of each layer can be set depending on the demands of customers. As shown in Fig. 16, in FDM processes, the filament on the spool is fed into the liquefier head with the aid of feeding pressure generated from a driver gear and a grooved bearing. Plastic parts can be built layer by layer through depositing the filament material that is heated to glass transition state and extruded through the extrusion nozzle at a constant temperature. The liquefier head moves on the X-Y plane as the tool path generated by the software and deposits the first desired layer onto the print bed to form a foundation for the part. When the layer is completed, the build platform moves downward one-layer thickness for the following layer of filament material fabrication. Each single layer will be deposited repeatedly on the previous one in the same way until the part is completed. In the FDM machine with dual extrusion nozzles, build filament material with another color or support filament material can be simultaneously extruded through the second nozzle if necessary. After FDM fabrication, the support material can be easily removed either mechanically or chemically (e.g., using solvent) [33].

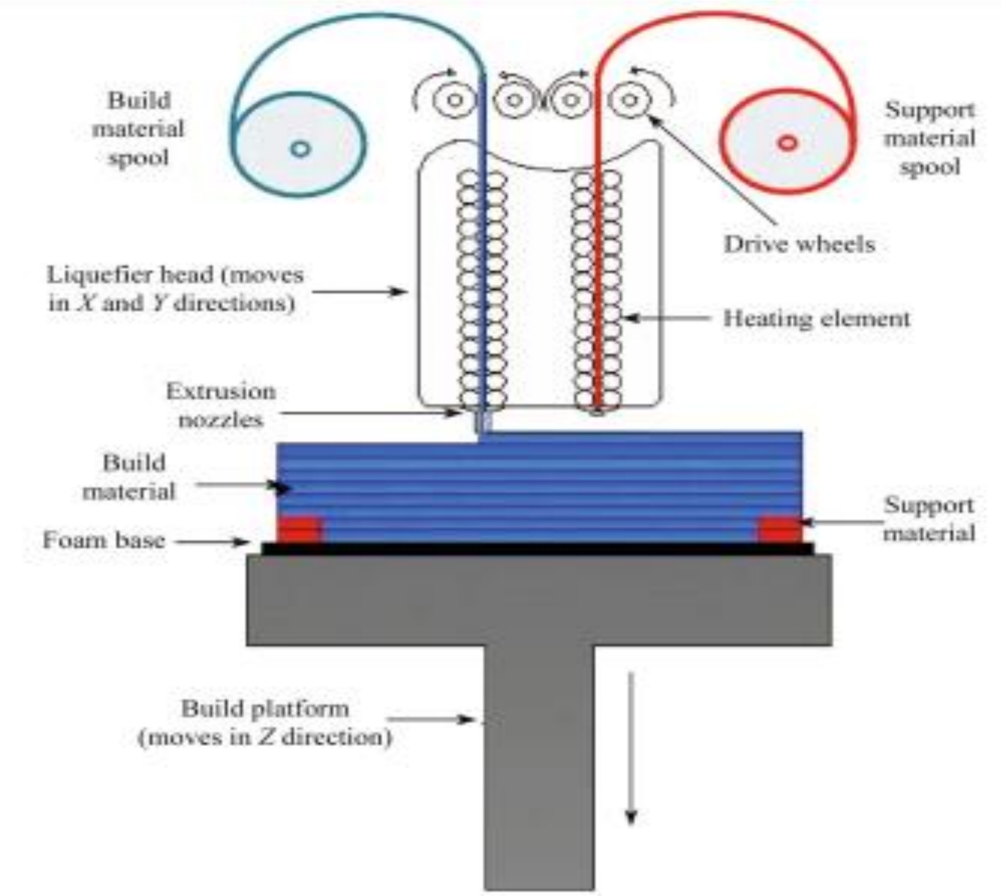


Figure 16. Schematic of FDM process [34]

It is crucial to deliver superior part quality, high productivity rate, safety, low manufacturing cost, and short lead time using AM technologies which include FDM. To meet the customer requirements, the AM process conditions must be established for each application. The key success of 3D printing depends upon the proper selection of process parameters. Optimum process conditions determination plays an important role in ensuring the quality of products, improved dimensional precision, avoidance of unacceptable wastes and large amounts of scraps, enhanced productivity rates, reduced production time, and cost. FDM is a complex process that includes difficulty in determining optimal parameters due to the presence of many conflicting parameters that will influence the part quality and material properties. The part quality and mechanical properties of the fabricated part can be attributed to proper selection of process parameters [36] [37].

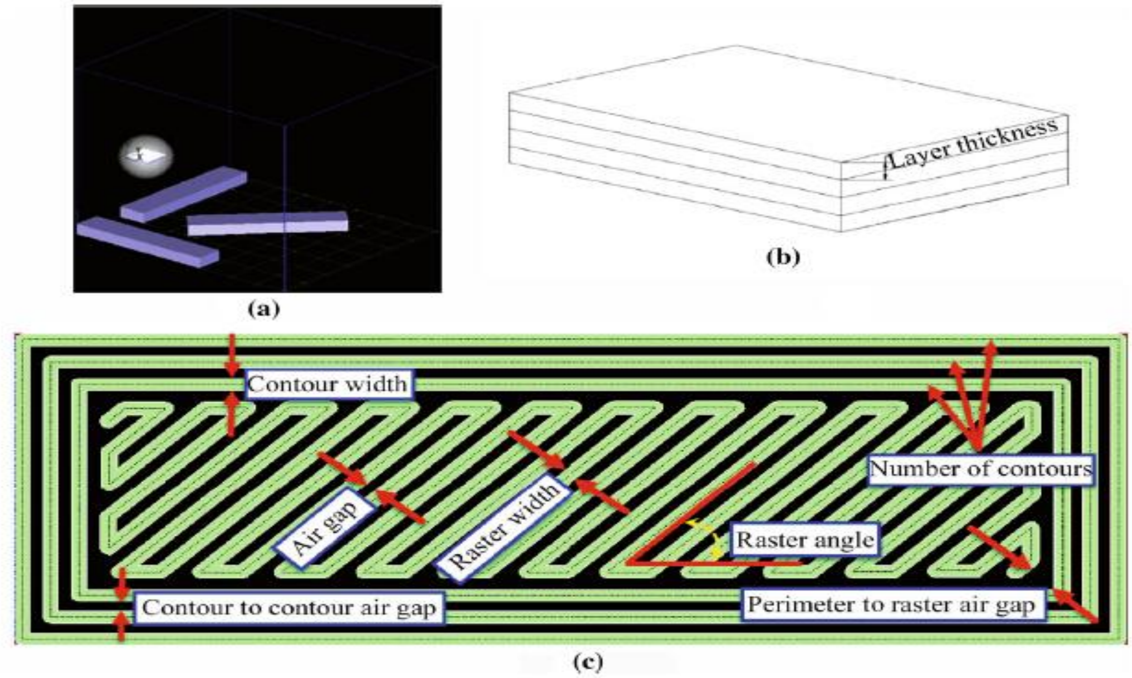


Figure 17. FDM Printing Process Parameters. (a) Build orientations, (b) layer thickness, and (c) FDM tool path parameters [34]

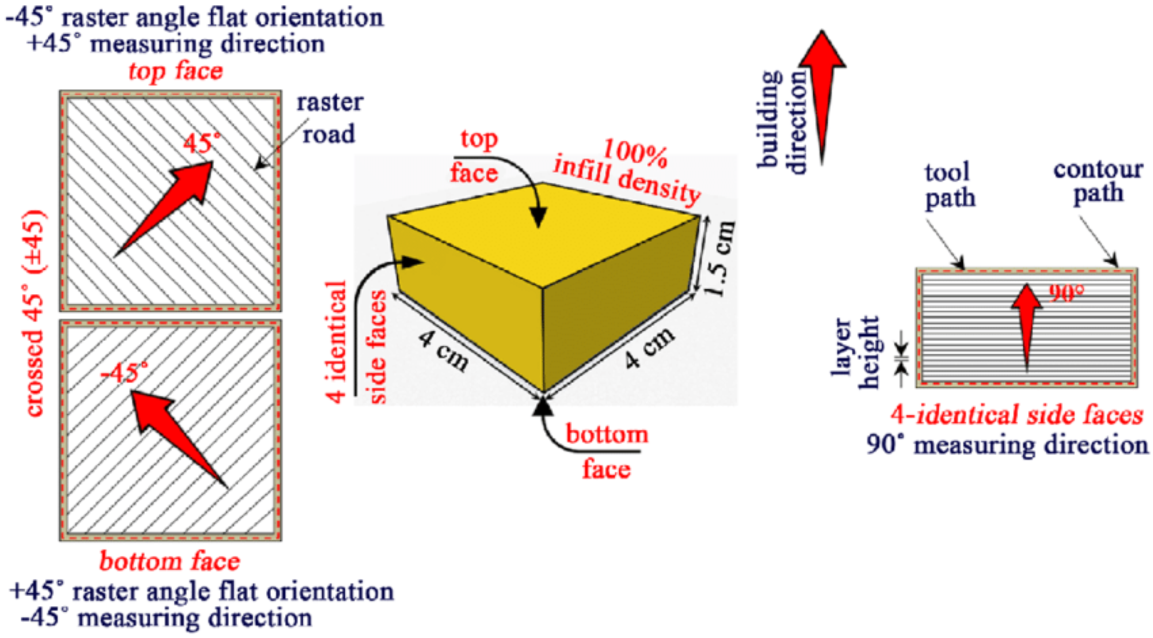


Figure 18. Proposed FDM 3D printed part, filament deposition patterns and measuring direction [38]

2.1.3 Mark Two Processing

The Mark Two is the first 3D printer of its kind to lay down continuous strands of fiber reinforcement material into a 3D printed object. The machine utilizes two print-heads: one for a traditional 3D printing filament and one for the continuous fiber. A layer of the traditional filament is printed before the reinforcement material is used to fill the inner cavity of a part. The print-bed lowers with each layer and the process is continued until the part is complete.

Figure 19. Printing pattern of MARK TWO printer *(Image courtesy of Mark forged)*

Essential to print composite parts with the Mark Two is the proprietary slicing software (called Eiger) used to calculate toolpaths for fiber and matrix material. Like other print preparation software, Eiger begins with uploading an STL file; however, because Eiger runs in the cloud, the process is quick and agile. After the print file is uploaded, the user can then determine the infill of the part, including density and pattern. When the "Use Fiber" option is switched on, Eiger automatically generates fiber reinforcement for the part. At this point, it's possible to get the internal view of the object and add more layers of fiber when required. One can also determine the way that the material is laid down, whether it should be printed in concentric circles or at a specific angle for optimized isotropic properties or both.

While there are many discontinues carbon fiber filaments on the market, these materials may only be about twice as strong as the base material due to the discontinues nature of the reinforcement material. CFF's greatest quality is the continuous nature of the reinforcement material, which sees thousands of continuous fibers spread evenly through an entire layer and allows a load to be carried throughout a part. This results in strengths five to ten times stronger than a nonreinforced part.

Carbon fiber reinforcement allows parts printed on the Mark Two to have a higher strength-to-weight ratio than aluminum and to be 27 times stiffer and 24 times stronger than ABS plastic. The material also maintains high thermal conductivity. As a result, users can 3D print lightweight, high-strength parts.

2.2 Onyx

The name Onyx comes from a mineral with the same name which is known for its surface finish. Mark forged, introduced Onyx which is strong 3D printing material. Onyx (the filament) is a fusion of engineering nylon and chopped carbon fiber. This chopped carbon fiber filament added stiffness to 3D printed parts, not only providing micro-carbon reinforcement to keep parts true to their dimensions, but also giving parts a smooth, matte black finish.

Even though Onyx filament contains none of the mineral, the properties like hardness, nice surface finish, and good adhesion so parts don’t split along layer seams are valued in 3D printing. Material Properties - Onyx is about 3.5 times stiffer than our standard nylon because of the micro-carbon reinforcement. Because it also contains nylon, the engineering toughness and wear resistance is comparable as well, and the material has a heat deflection temperature of 145C.

Onyx provides dimensional stability. The 3D printed parts with onyx will be more accurate to the CAD model. This means minimized warping, larger overhangs, and sharper edges. The micro-carbon reinforcement changes the way the material behaves once it comes out of the extruder and cools – there is less thermal deformation and faster heat dissipation within the material, so parts warp less on the build plate and can tolerate steeper overhang angles. As a result, the part comes out of the printer just as designed.

With the dimensional stability and the impeccable surface finish, post-process of parts is rarely needed. Unlike other 3D printed parts, Onyx needs no dyeing to hide internal honeycombs, no chemical baths or sanding to remove 3D printed ridges, and no filler putties or materials to fill in gaps from warping [39].

Mark Forged's Onyx is a material that is ideal for customer-facing parts that need to look good while standing up to industrial requirements. Onyx is based on a remarkably tough nylon, but also provides parts with stiffness equal to or greater than any pure thermoplastic material available for professional 3D printers. It’s easy to print and far more rigid in assemblies. Onyx can be used alone, or further reinforced with embedded continuous carbon fiber, Kevlar, or fiberglass layers [40]. Material specifications of onyx and nylon material are presented in the Table 5.

Table 5. Product specifications for Onyx and Nylon [40]

Property	**Test Standard**	**Onyx**	**Nylon**
Tensile Strength (MPa)	ASTM D638	36	54
Tensile Modulus (GPa)	ASTM D638	1.4	0.94
Tensile Strain at Break (%)	ASTM D638	58	260
Flexural Strength (MPa)	ASTM D790*	81	32
Flexural Modulus (GPa)	ASTM D790*	2.9	0.84
Flexural Strain at Break (%)	ASTM D790*	N/A**	N/A**
Heat Deflection Temperature (°Celcius)	ASTM D648 Method B	145	44-50
Density (g/cm^3)	N/A	1.18	1.10

2.3 Design of Structure

A Truncated Octahedron structure was designed with ANSYS with a verity of volume percentages from a solid 3D block shown in Figures (20-25).

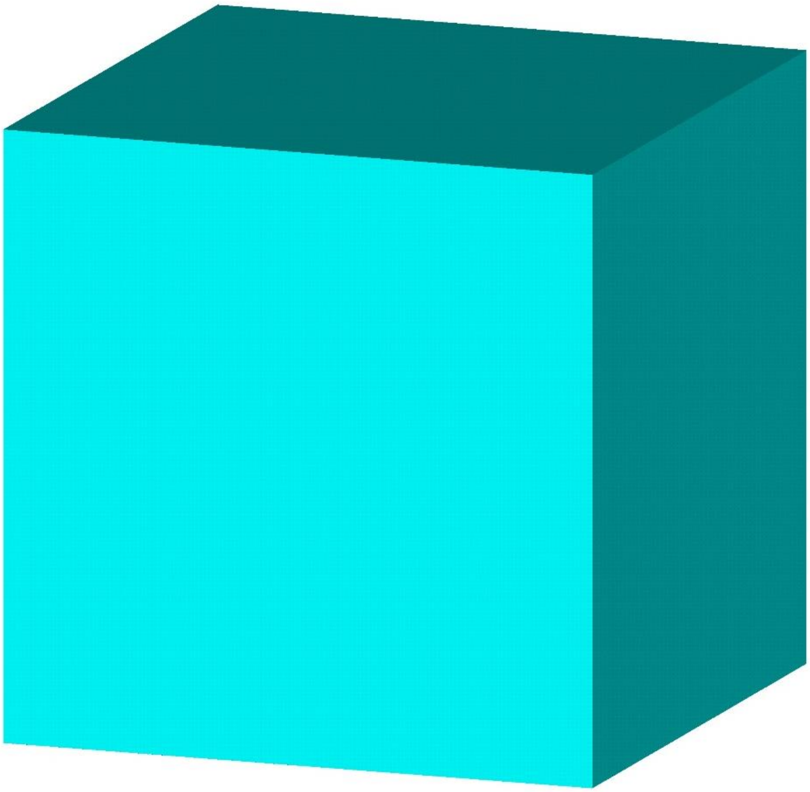


Figure 20. Solid block (100% volume occupied)

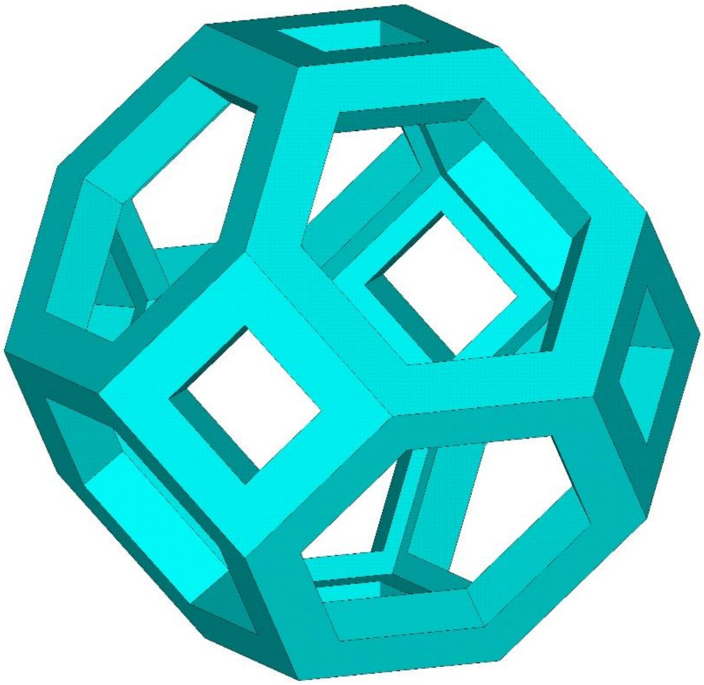


Figure 21. Truncated Octahedron Structure with 10% volume

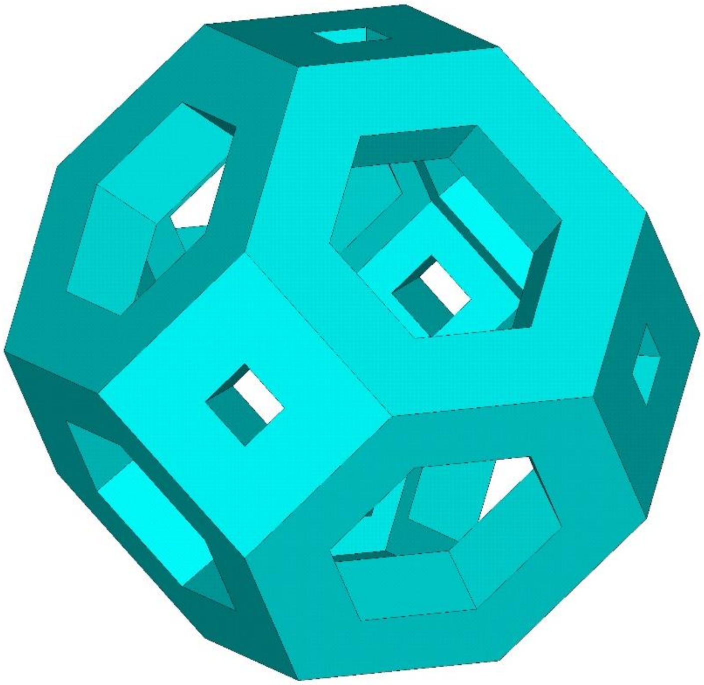


Figure 22. Truncated Octahedron Structure with 20% volume

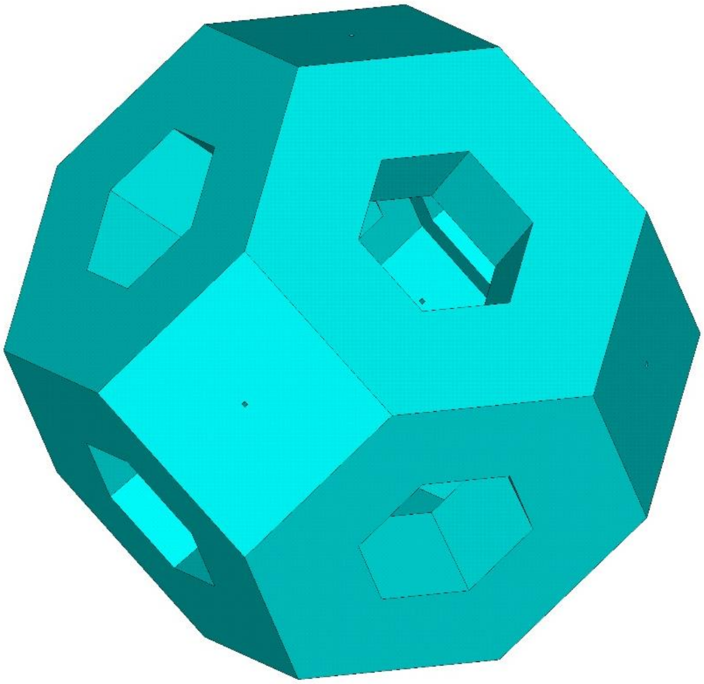


Figure 23. Truncated Octahedron Structure with 30% volume

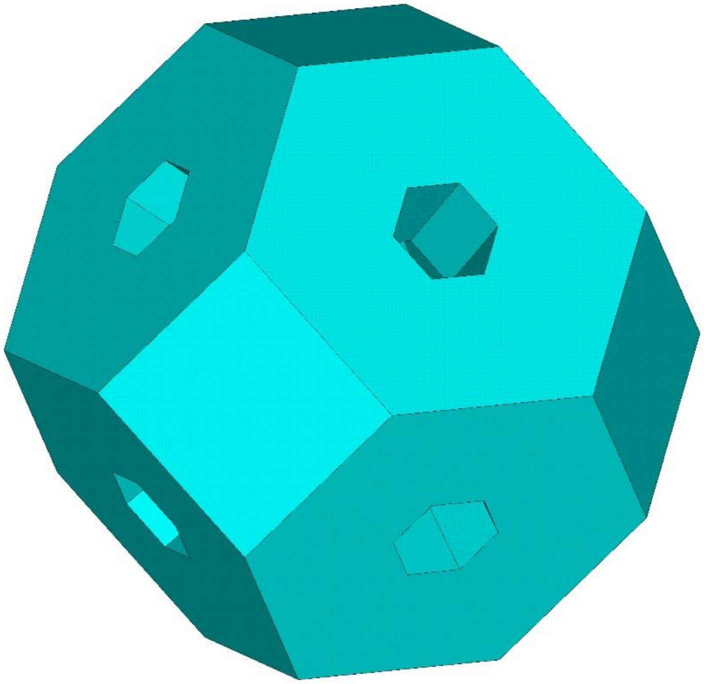


Figure 24. Truncated Octahedron Structure with 40% volume

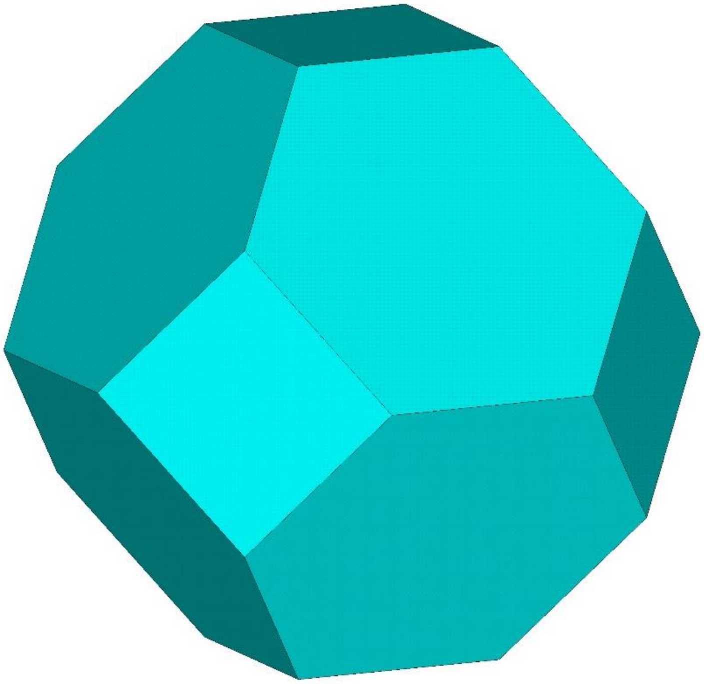


Figure 25. Truncated Octahedron Structure with 50% volume

A Truncated Octahedron lattice structure was designed for 3D printing shown in Figure 26,

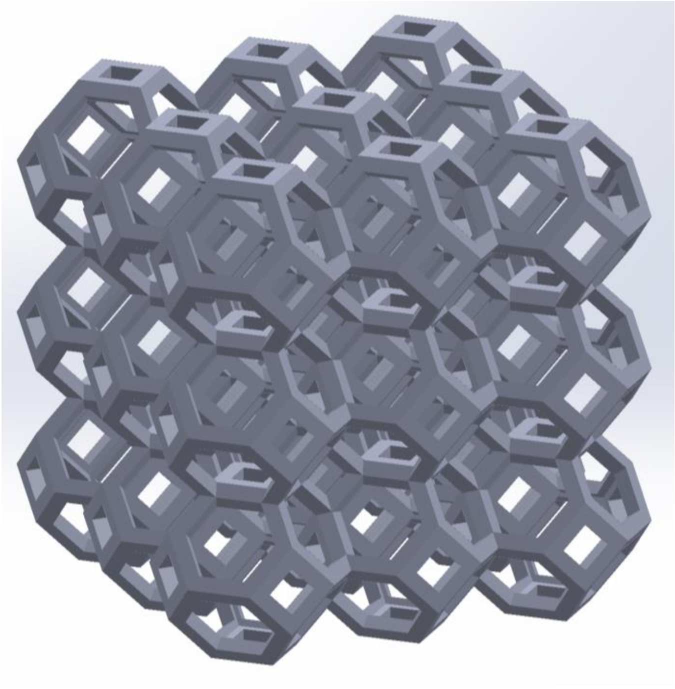


Figure 26. Truncated Octahedron Lattice Structure designed for 3D print

3. RESULTS

3.1 Properties of Onyx

For investigation of the properties of the bulk Onyx, specimens are prepared by 3D printing. Compression and tension tests have been conducted for Onyx block based on the relevant ASTM standards [41], as shown in Figures (29 and 30)

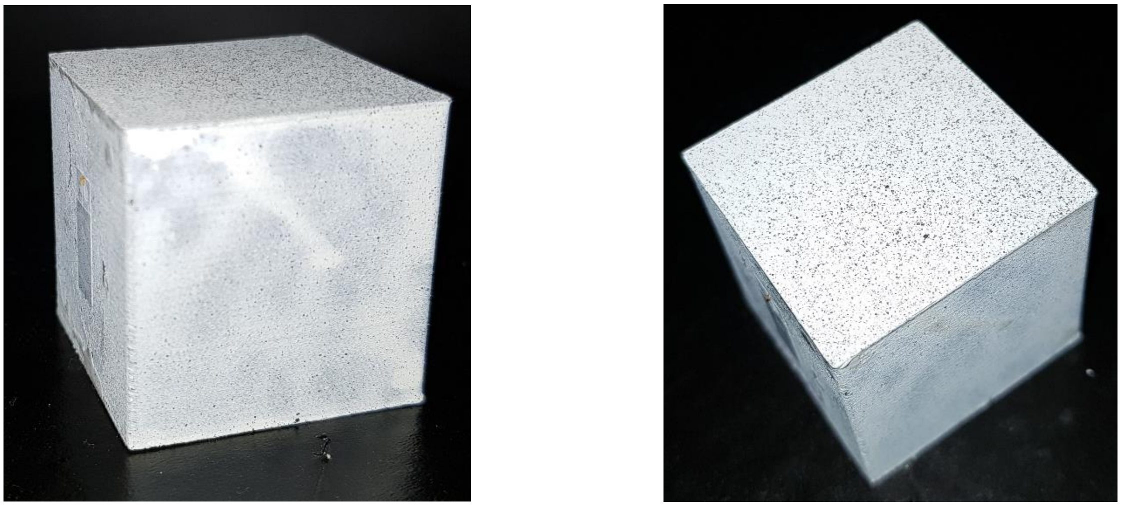


Figure 27. 3D printed samples (3D Onyx block) for compression test

Figure 28. 3D printed samples for Tension test

Figure 29. Tension test on 3D printed Onyx Samples

Figure 30. Compression test on 3D printed Onyx Samples

Table 6: Material Properties from testing.

Tensile test		Compression test	
(E) Young's modulus (GPa)	(ν) Poisson's ratio	(E) Young's modulus (GPa)	(ν) Poisson's ratio
1.4	0.3	1.4082	0.3

3.2 Mechanical Property Evaluation of the 3D Structure

For characterizing the mechanical properties of the 3D periodic lattice structures, a compression test was simulated using ANSYS. The testing model is shown in Figure 31. A vertical displacement constraint was applied on the bottom of the model so that it could not be moved vertically. The displacements on the four side faces were constrained so that the four side faces could only uniformly expand during a compression test as an applied periodic boundary condition, which simulates a compression test on a much larger structure consisting of many such 3D periodic lattice blocks. For testing the stiffness (Young's modulus) under the different load conditions, the top surface was subjected to a uniform pressure or uniform downwards displacement. The two test models are listed in Table 6. The test data, such as the total force applied or the average displacement on the top surface were extracted from the test and the Young's moduli were derived from the test data.

Table 7. The conditions setting for two different compression test models

Model #	Load type on top surface	Expansion type
1	Pressure	Uniform
2	Displacement	Uniform

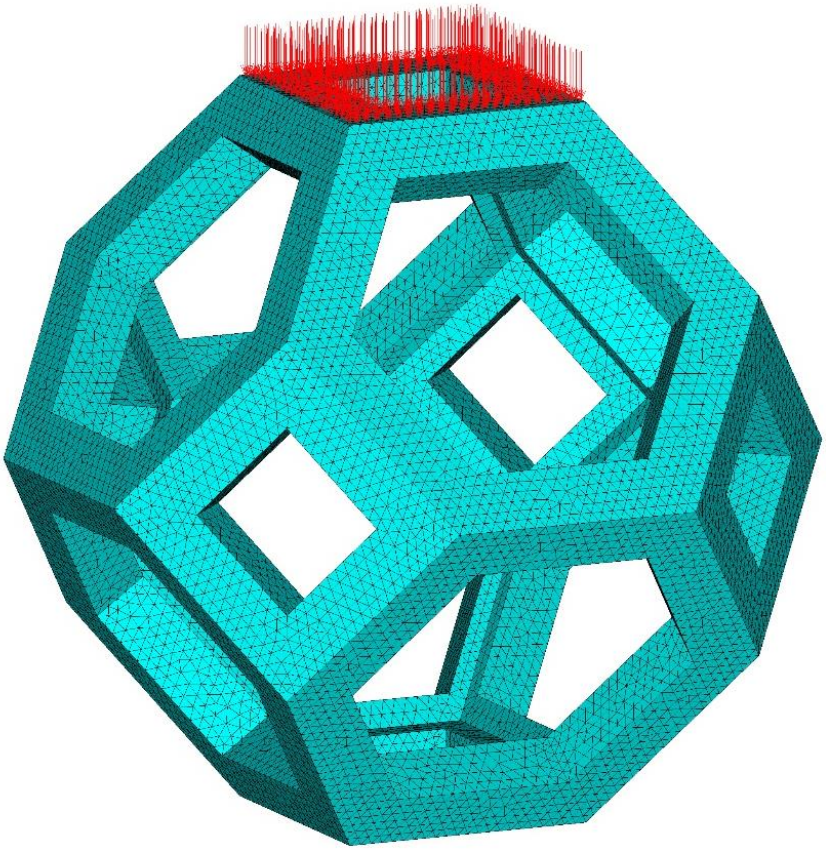
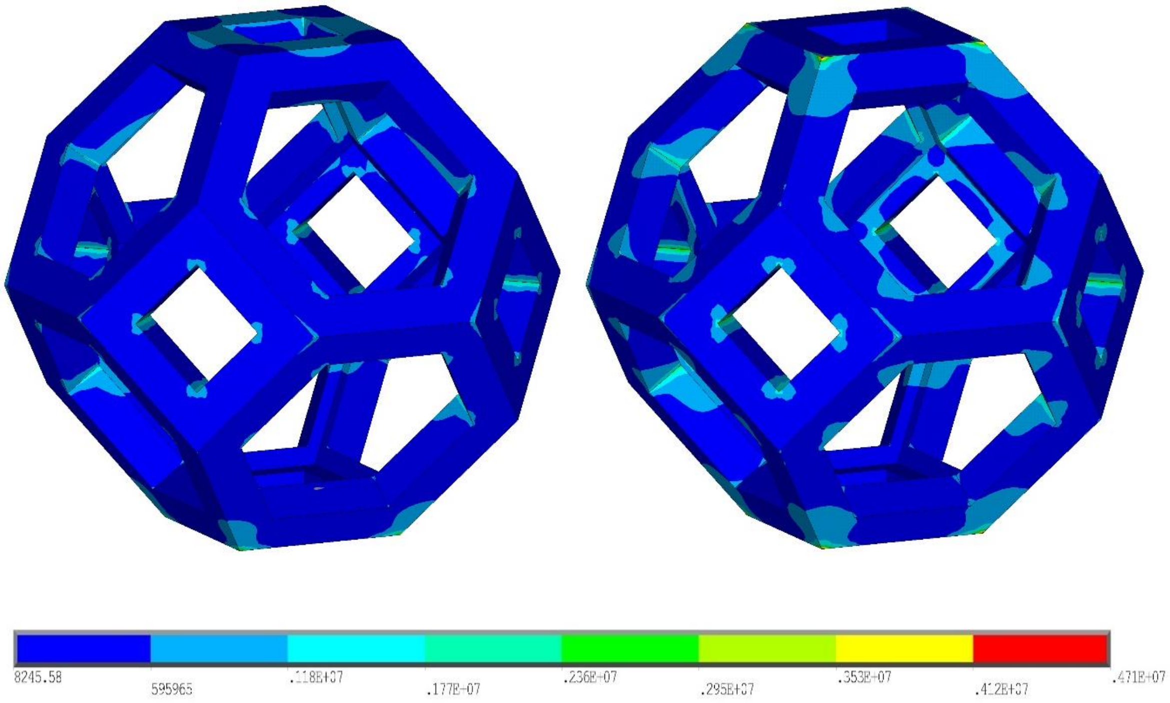


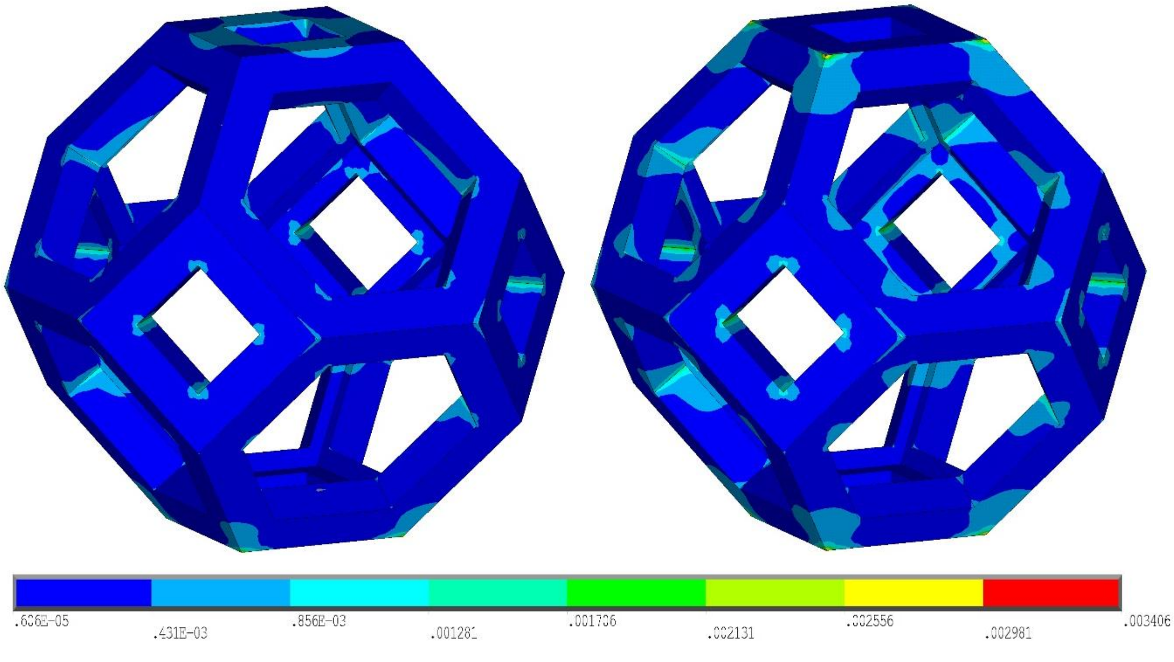
Figure 31. Meshed model for compression test simulation in ANSYS

The von Mises stress and strain distributions of two models with 10% volume under compression test are shown in Figures 32 and 33. The two models are experiencing similar stress and strain distributions. However, Model 2 is experiencing more stress and strain around the edges of the structure.



Model 1 Model 2

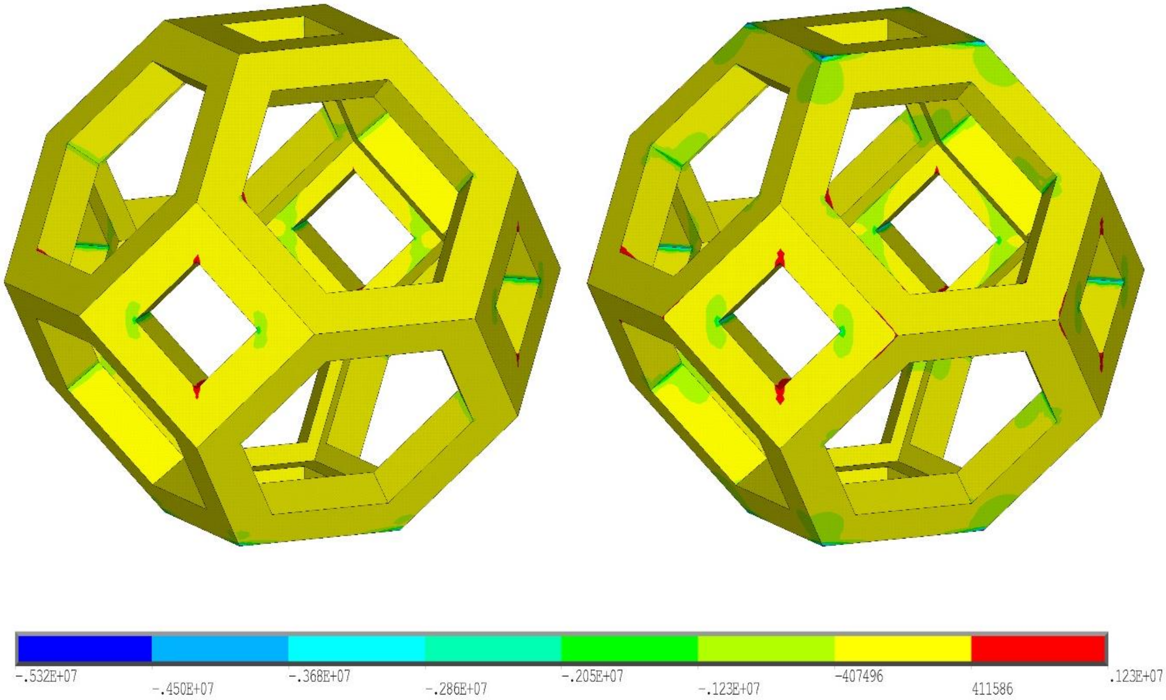
Figure 32: Von Mises stress distributions of 10% Volume.



Model 1 Model 2

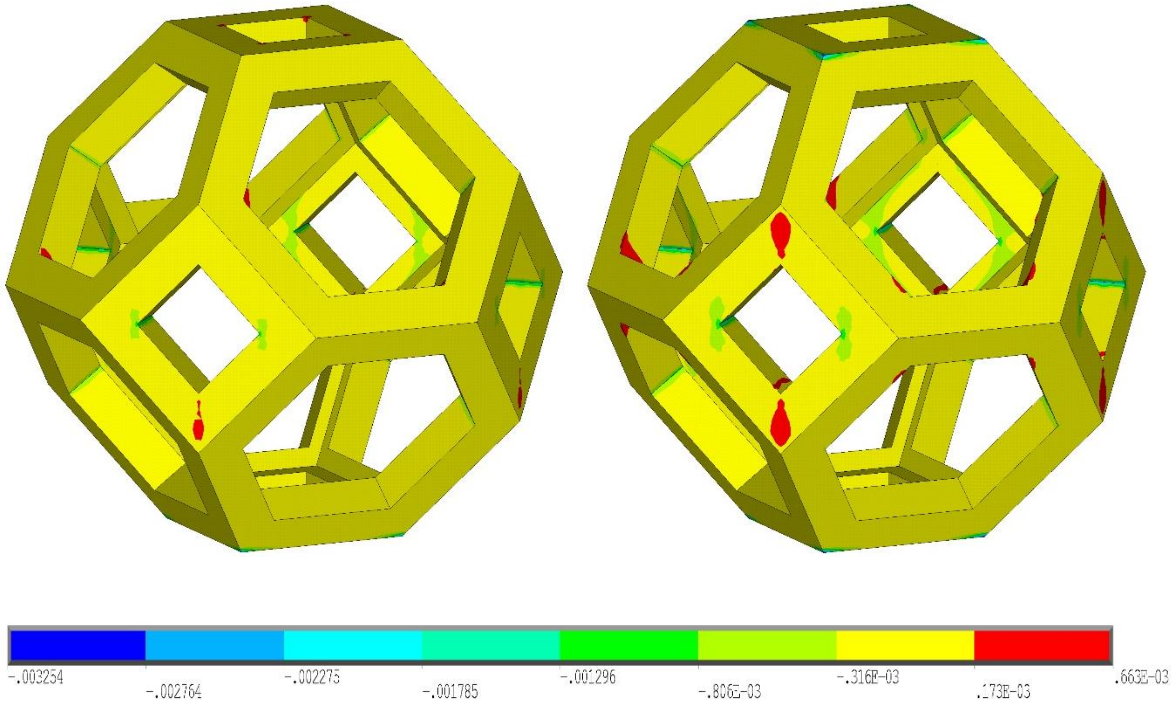
Figure 33: Von Mises strain distributions of 10% Volume.

The vertical stress and strain distributions of the two models with 10% volume under compression test are shown in Figures 34 and 35. The stress and strain are uniformly distributed all over the structure. Stress and strain for Model 2 is slightly more on the edges compared with Model 1.



Model 1 Model 2

Figure 34: Vertical stress σ_y distributions of 10% Volume.



Model 1 Model 2

Figure 35: Vertical strain ε_y distributions of 10% Volume.

The specific Young’s modulus (i.e., the ratio of Young’s modulus to density) and the specific square root Young’s modulus (i.e., the ratio of square root of Young’s modulus to density) vs. material volume percent occupied for the two models were derived from the testing data and are shown in Figures 37 and 38. At a higher material volume percent occupied, Model 1 and Model 2 have higher specific Young’s moduli. The specific Young’s moduli and specific square root Young’s moduli are nearly equal for Model 1 and Model 2. The maximum specific square root of Young’s modulus is achieved at around 20% material volume occupied.

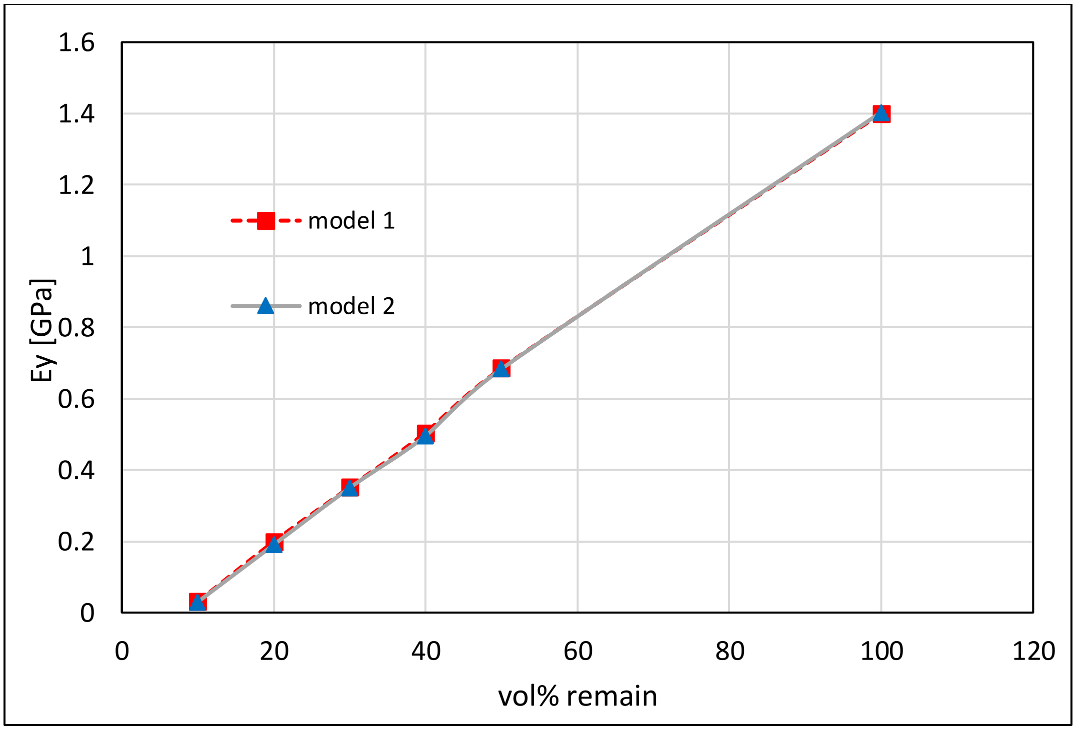


Figure 36: Young’s modulus vs. material volume percent occupied.

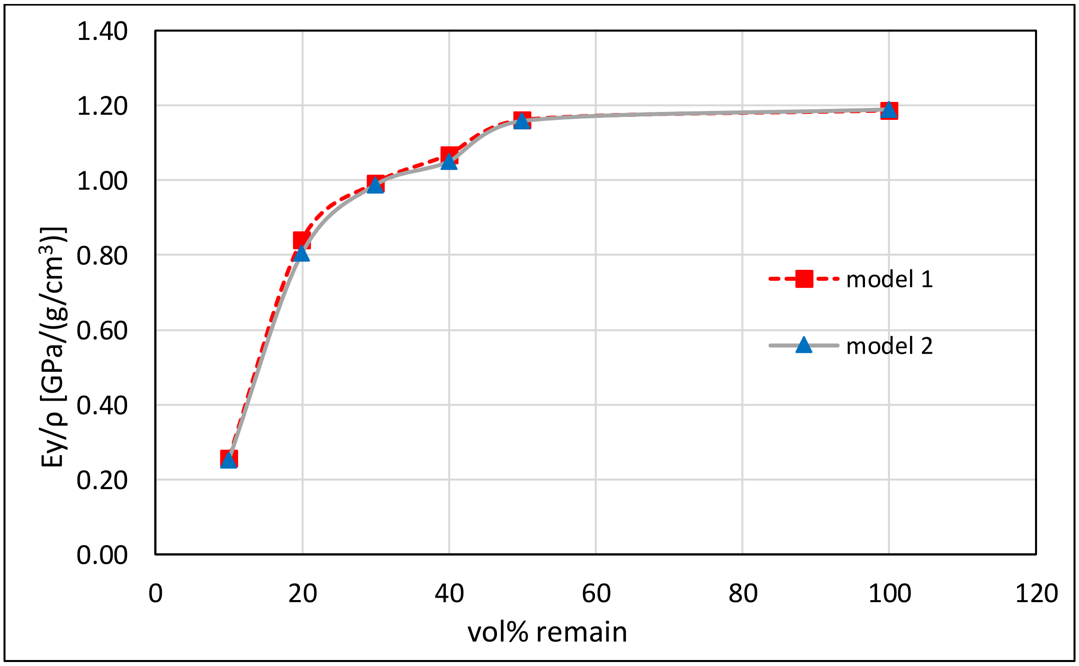


Figure 37: Specific Young’s modulus (ratio of Young’s modulus to density) vs. material volume percent occupied.

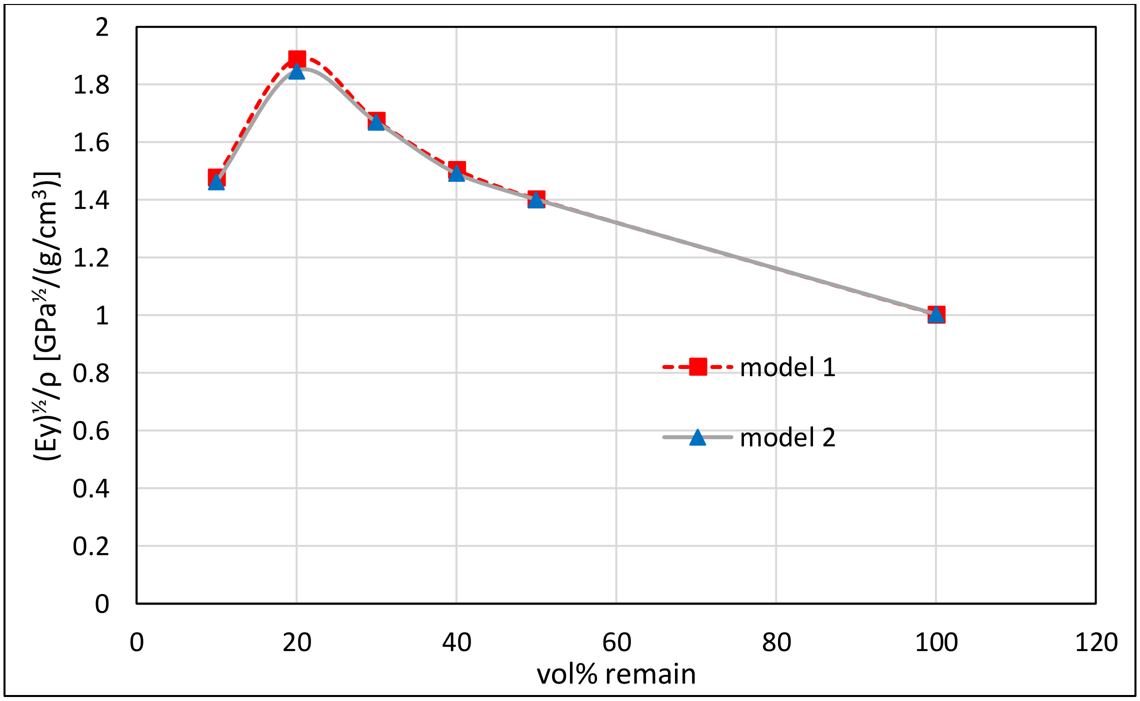


Figure 38: Specific square root of Young’s modulus (ratio of square root of Young’s modulus to density) vs. material volume percent occupied.

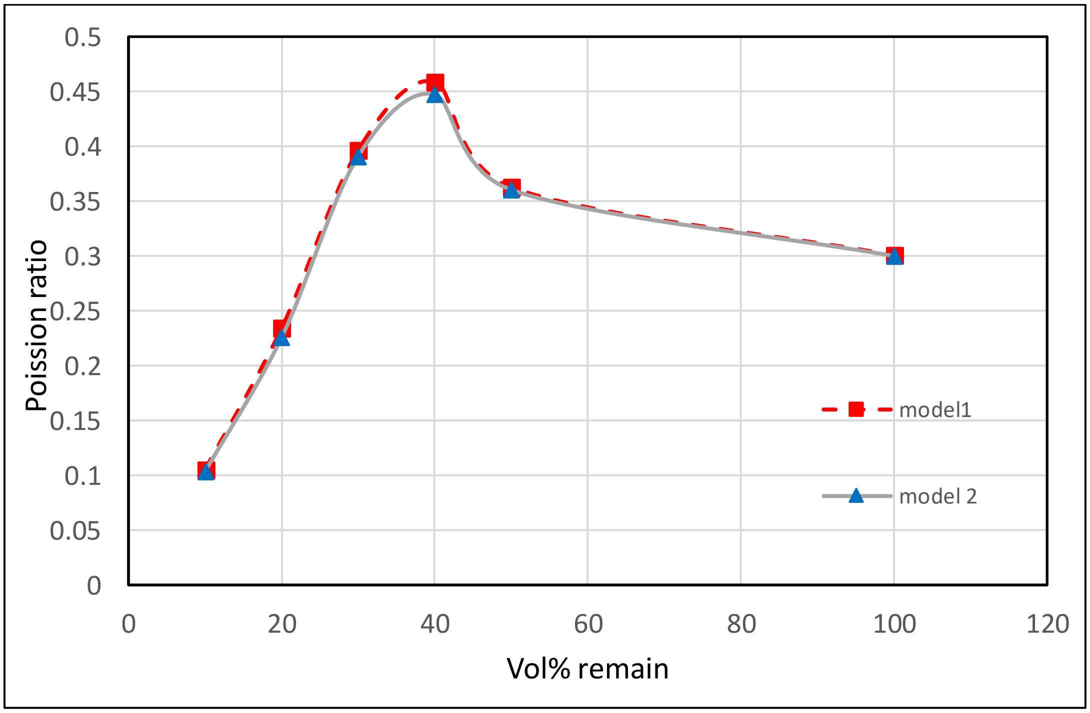


Figure 39: Poisson’s ratio vs. material volume percent occupied.

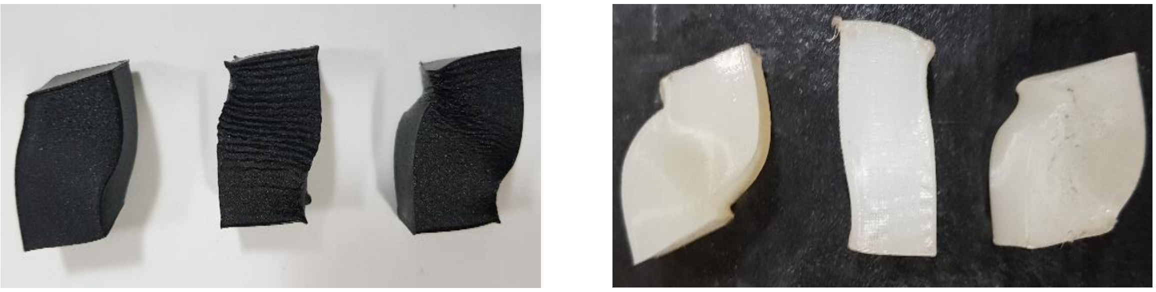
The Poisson’s ratio (the ratio of the strain in the transverse direction to the strain in the vertical direction under the vertical compression) vs. material volume percent occupied is shown in Figure 39. Poisson’s ratio increases as material volume percent occupied increases, the maximum value was reached at around 40% volume of material occupied, then decreased to the value of bulk material at 100% volume occupied.

3.3 Verification

3.3.1 Experimental setup procedures

ASTM D695-15 standard is followed for compression test respectively. Nylon and Onyx samples were prepared by FDM for the test. Proper dimensions of specimen are selected for compressive testing with respect to ASTM D695-15 standard. Compression test is conducted in a test machine MTS 858 - Universal Testing Machine which employs Model 359 load unit that has dynamic load rating of +/-5,500 lbs (+/-25 KN). In the Compression test setup, sample is conditioned prior to testing then the sample is placed between surfaces of compressive fixtures of machine. Ensure the center line of the sample aligns with the center line of plunger. Then proceeding towards test procedure, crosshead is adjusted until it contacts the compression fixture and sample is compressed at 1.3mm/min until failure. The relationships between force (N) and displacement (mm) were collected by computer with help of a data acquisition software.

Compression test was conducted to observe the difference in ultimate compressive strength and specific stiffness between Onyx and Pure Nylon, 3D printed onyx and pure nylon samples were fabricated; the images of the specimens are shown in Figure 40.



(a) (b)

Figure 40: Compression tested samples (a) Onyx (b) Pure Nylon

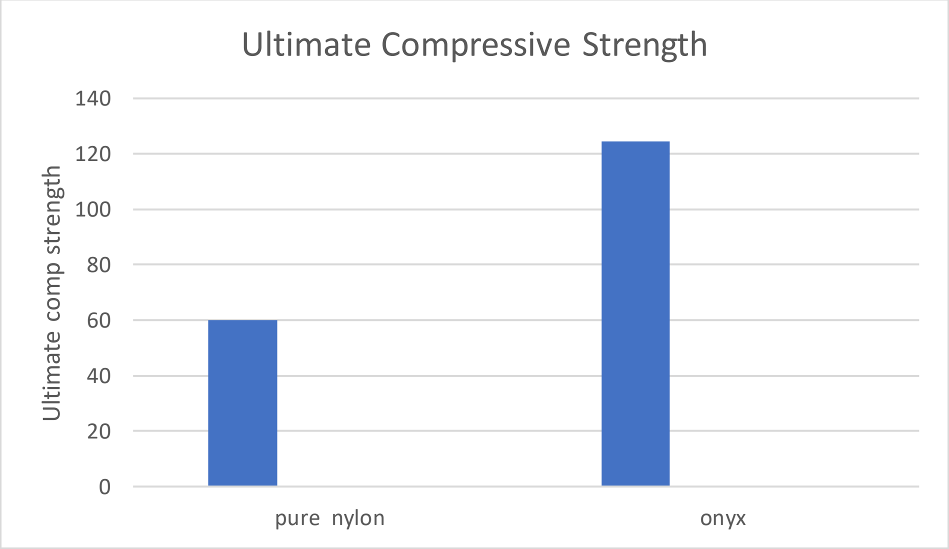


Figure 41: Ultimate Compressive Strength for Pure nylon and Onyx.

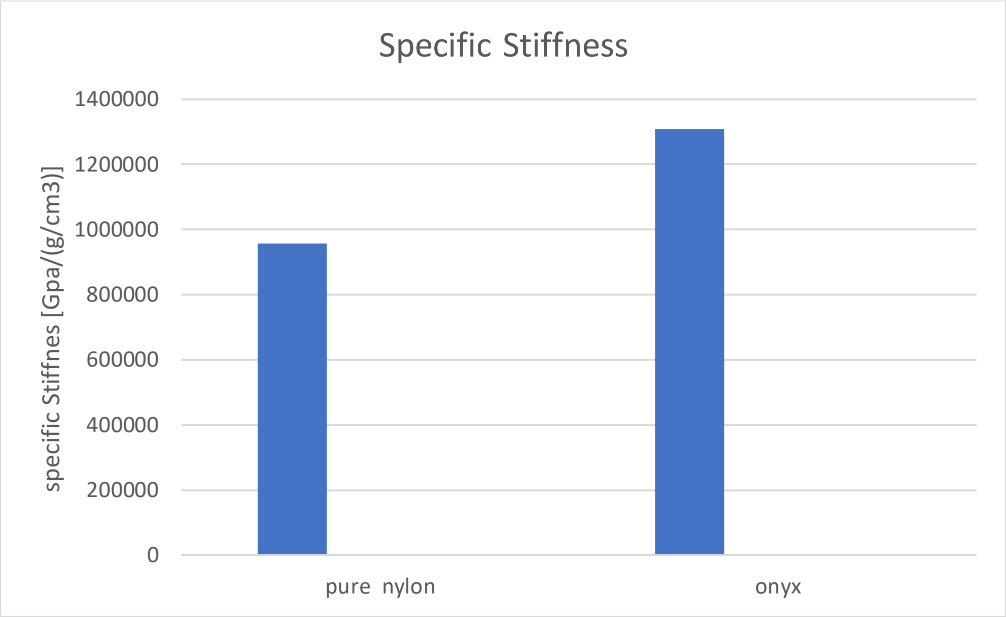


Figure 42: Specific Stiffness for Pure nylon and Onyx.

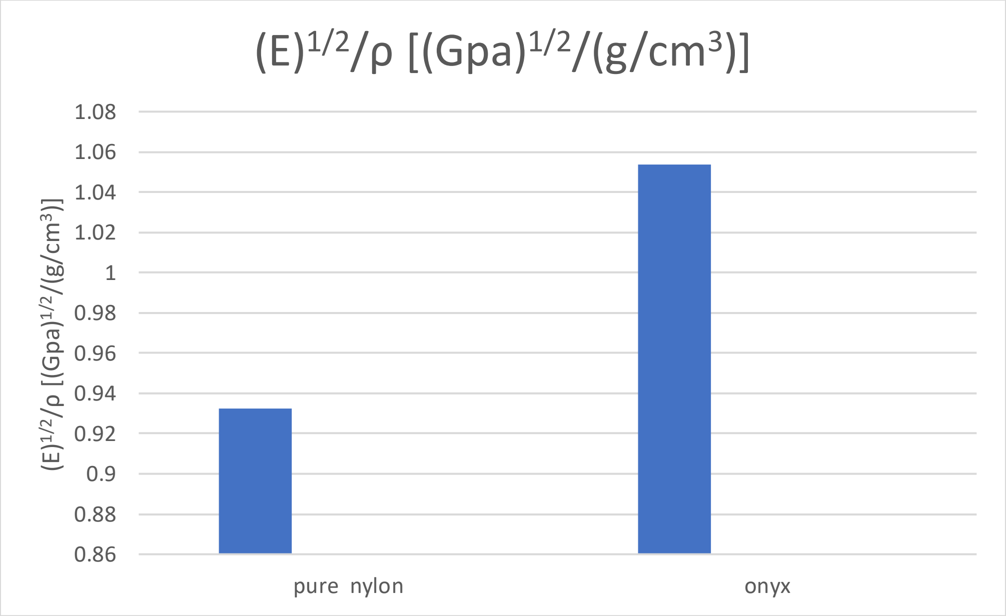


Figure 43: Square root of young’s modulus/density for Pure nylon and Onyx.

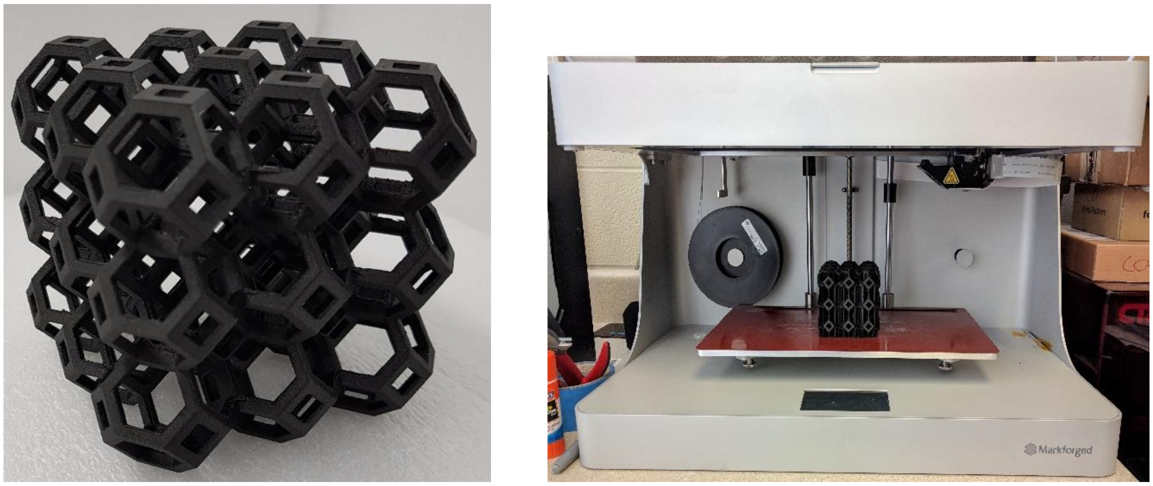
By observing above graphs between Onyx and Pure nylon, onyx is nearly 1.37% stiffer than pure nylon.

3.3.2 Structure Validation

For validating the model, 3D printing was used to fabricate the Truncated Octahedron samples with onyx material, images of the samples are shown in Figures 44 and 45.

(a) (b)

Figure 44: Truncated Octahedron samples (a) 10% volume material (b) 50% volume material.



(a) (b)

Figure 45: (a) Truncated Octahedron 3/3 Lattice structure sample (b) 3D printer printing 3D lattice structure.

Compression test was conducted on 3D printed Truncated Octahedron structures to evaluate mechanical properties of the structure using a test machine MTS 370 Landmark testing machine with dynamic load rating of +/-22,000 lbs (+/-100 KN). The samples are tested at compression rate of 1.5mm/min until failure. Images of the compression tests are shown in Figure 46.

(a) (b) (c)

Figure 46: Compression test on 3D printed samples (a) 10% volume, (b) 50% volume (c) 10% volume 3/3 lattice structure.

The testing and modeling data of Young's modulus, specific stiffness, and square root of Young’s modulus to density of specimens fabricated by 3D printing are listed in Table 8.

Table 8: Properties of Truncated Octahedron structure by compression test.

Volume	**Ey [Gpa]**			**Ey/ρ [GPa/(g/cm^3)]**			**(Ey)^{½}/ρ [GPa^{½}/(g/cm^3)]**		
	Experiment	***Simulation***	***Error %***	***Experiment***	***Simulation***	***Error %***	***Experiment***	***Simulation***	***Error %***
Single cell 10%	0.030430	0.030617	0.614%	0.257888	0.259467	0.612%	1.47834	1.48286	0.305%
Single cell 50%	0.685134	0.689413	0.624%	1.161245	1.168496	0.624%	1.40293	1.407303	0.311%
Single cell 100%	1.4082	1.403868	0.307%	1.19339	1.189719	0.307%	1.005658	1.00411	0.153%
3/3 matrix 10%	0.0711	0.0684	3.797%	0.602542	0.579661	3.797%	2.25971	2.216389	1.917%

3.4 Conclusion

In this research, light weight cellular structures are tested with compressive loads for required characteristics of high strength to weight ratio with high specific stiffness. Biomimetic designs that brings innovative solutions and sustainable design are preferred. The honeycomb structure is the bio-inspiration in the study. Freeing up the prismatic requirement on the honeycomb brings a fully 3-dimensional lattice or open-cell foam. Lattice designs tend to embody higher stiffness levels while open cell foams enable energy absorption. Structure is fabricated using AM technology and material to fabricate is chosen according to their properties which add value to the structural characteristics. Compression tests were carried out on various volumes percentage of the structure experimentally and compared with the simulated data. Specific square root Young's modulus is more for the 20% volume Truncated Octahedron structure compared with bulk materials

In the future, studies may be conducted on Truncated Octahedron structures with distinct load applications using different materials, various biomimetic structures, 3D printing lattice structures with carbon fibers reinforcement in onyx material.

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Appendex A

ANSYS APDL Code

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/UNITS,SI

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/PLOPTS,DATE,OFF

/PLOPTS,FILE,OFF

/TRIAD,OFF

JPEG,QUAL,100

/GFILE,2400

/PREP7

!################################################################

ET,1,SOLID95                ! Use 3-d 20-node solids. Type 1 is optimized

MP,EX,1,1.4E9

MP,PRXY,1,0.3

B_=0
```

```
H_=282.84*0.0354

W_=H_/2

BLC4,0,0,W_,H_,-W_

CSYS,5

VGEN,4,ALL,,,,90,,,0,0

CSYS,0

VADD,ALL

ALLSEL,ALL

SMRTSIZE,1

MSHAPE,1,3D

ESIZE,0.35

TYPE,1

VMESH,ALL

FINISH

/SOLU

ANTYPE,STATIC,NEW

NSEL,S,LOC,Y,B_         ! BOUNDARY CONDITIONS

D,ALL,UY,0
```

```
NSEL,S,LOC,X,-W_

D,ALL,UX,0

NSEL,S,LOC,X,W_

CP,10,UX,ALL

NSEL,S,LOC,Z,-W_

D,ALL,UZ,0

NSEL,S,LOC,Z,W_

CP,11,UZ,ALL

PRESSR = 10E4    ! Value of applied load

NSEL,S,LOC,Y,H_

SF,ALL,PRES,PRESSR

ALLSEL,ALL

SOLVE

fini

/post26

NSEL,S,LOC,Y,0

*GET,NODETOT,NODE,,COUNT

*GET,MINNODE,NODE,,NUM,MIN
```

```
NODENUM = MINNODE

RFORCE,3,NODENUM,F,Y,RFY

ADD,2,3,,,RFY,,,1

*DO,i,1,NODETOT-1,1

NODENUM=NDNEXT(NODENUM)

RFORCE,3,NODENUM,F,Y,RFY

ADD,2,2,3,,RFY,,,1,1

*ENDDO

ALLSEL,ALL

NSEL,S,LOC,Y,H_

*GET,NODETOT,NODE,,COUNT

*GET,MINNODE,NODE,,NUM,MIN

NODENUM = MINNODE

NSOL,5,NODENUM,U,Y,DISPY        !here the variable name should be disp1

ADD,4,5,,,DISPY,,,1

*DO,i,1,NODETOT-1,1

NODENUM=NDNEXT(NODENUM)

NSOL,5,NODENUM,U,Y,DISPY
```

```
ADD,4,4,5,,DISPY,,,1,1

*ENDDO

ALLSEL,ALL

ADD,4,4,,,DISPY,,,1/NODETOT,,,

NSEL,S,LOC,Z,W_

*GET,NODETOT,NODE,,COUNT

*GET,MINNODE,NODE,,NUM,MIN

NODENUM = MINNODE

NSOL,7,NODENUM,U,Z,DISPZ

ADD,6,7,,,DISPZ,,,1

*DO,i,1,NODETOT-1,1

NODENUM=NDNEXT(NODENUM)

NSOL,7,NODENUM,U,Z,DISPZ

ADD,6,6,7,,DISPZ,,,1,1

*ENDDO

ALLSEL,ALL

ADD,6,6,,,DISPZ,,,1/NODETOT,,,

NSEL,S,LOC,X,W_
```

```
*GET,NODETOT,NODE,,COUNT

*GET,MINNODE,NODE,,NUM,MIN

NODENUM = MINNODE

NSOL,9,NODENUM,U,X,DISPX

ADD,8,9,,,DISPX,,,1

*DO,i,1,NODETOT-1,1

NODENUM=NDNEXT(NODENUM)

NSOL,9,NODENUM,U,X,DISPX

ADD,8,8,9,,DISPX,,,1,1

*ENDDO

ALLSEL,ALL

ADD,8,8,,,DISPX,,,1/NODETOT,,,

*DIM,RFY,ARRAY,2

*DIM,TIME,ARRAY,2

*DIM,DISPY,ARRAY,2

*DIM,DISPZ,ARRAY,2

*DIM,DISPX,ARRAY,2

VGET,RFY(1),2
```

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VGET,DISPY(1),4
VGET,DISPZ(1),6
VGET,DISPX(1),8
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*VWRITE
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*VWRITE,TIME(1),100,RFY(1),RFY(1)/(W_*W_),DISPY(1),DISPZ(1),DISPX(1)
(7(F18.6))
/OUTPUT
/EOF
```