Design and Testing of Scalable 3D-Printed Cellular Structures Optimized for Energy Absorption

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DESIGN AND TESTING OF SCALABLE 3D-PRINTED CELLULAR STRUCTURES OPTIMIZED FOR ENERGY ABSORPTION

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering

By

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Abstract

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Sandwich panel structures are widely used due to their high compressive and flexural stiffness and strength-to-weight ratios, good vibration damping, and low through-thickness thermal conductivity. These structures consist of solid face sheets and low-density cellular core structures that are often based upon honeycomb topologies. Interest in additive manufacturing (AM), popularly known as 3D printing (3DP), has rapidly grown in past few years. The 3DP method is a layer-by-layer approach for the fabrication of 3D objects. Hence, it is very easy to fabricate complex structures with complex internal features that cannot be manufactured by any other fabrication processes. Due to the recent advancement of 3DP processes, the core lattice configurations can be redesigned to improve certain properties such as specific energy absorption capabilities. This thesis investigates the load-displacement behavior of 3D printable lattice core structures of five different configurations and rank them according to their specific energy absorption under quasi-static loads. The five different configurations are body centered cubic (bcc) diamonds without vertical struts; bcc diamonds with vertical alternate struts, tetras, tetrahedrons, and pyramids. First, both elastic and elastic-plastic finite element analysis (FEA) approach was used to find optimum cell dimension for each configuration. Cell size and strut diameter
were varied for each configuration, the energy absorption during compression were calculated, and the optimum dimension was identified for each configuration. Next, the optimized designs were printed using acrylonitrile butadiene styrene (ABS) polymer to evaluate their compression behavior. Fused deposition modeling based Stratasys uPrint printer was used for printing the samples. After printing the samples, all five designs of lattice structures were subjected to compression load and their load-displacement behavior were analyzed and compared. From both FEA calculations and experimental results, the five configurations can be placed as tetrahedrons, pyramids, tetras, BCC diamonds with struts, and diamonds without struts, the first one having the highest and the last one having the lowest energy absorption capabilities. A detailed discussion on the FEA modeling, sample fabrication, and testing of different configurations is presented in the thesis report.
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Nomenclature

D  Cross sectional diameter, mm
F  Force, N
K  Stiffness, N/mm
V  Volume, mm³
E  Energy absorbed, Joules
E₁  Energy absorbed per unit mass, J/kg
δ  Displacement, mm
δ₁  Displacement at the load location, mm
Y  Distance from the tetra structures open edges to the center, mm
H  Height of the structure analyzed
L  Length of the rod
Chapter 1. Introduction

1.1 Overview

This chapter discusses the importance of this project and its applications to various real world-engineering problems. It gives a motivation behind developing lattice structures. It also explains the need for additive manufacturing (AM) or 3D printing (3DP), its flexibility, and advantages for designing lightweight structures for impact loading.

1.2 Cellular Structures Background and Review

The demand for the ultralight sandwich structures for use in aerospace and other weight-sensitive applications has resulted in the need for developing light, but stiff and strong materials and structures. Magnesium, aluminum and titanium alloys are commonly used structural materials. These materials can be configured in sandwich core structures, which consist of light, stiff, and strong faces, with low-density cores; these types of configurations offer exceptional structural load support. This is one of the main reasons that core topologies have gained in importance [1].

Modulus-density space is an important factor in sandwich structures, as materials can be defined by their modulus and density. A plot that describes where materials stand
in terms of their modulus and density determines where there would be progress in the material development. Diverse materials have various characteristics, such as significant strength, lightweight, elastic properties, and plastic properties. The choice of material depends on which applications it is being used for. Therefore, researchers have long created hybrid materials to use respective material properties effectively where they are needed.

The creation of hybrid materials is like cooking food: If the significance of perfect ingredients is known, an optimum material can be developed. Figure 1 shows the categorization of different materials with respect to their modulus and density.

![Figure 1. Modulus-density space observing vector for material development.](image)

Figure 1 is a plot of Young’s modulus and density of a material. Metals and their alloys possess very high Young’s modulus, which means they have very high stiffness and
strength. However, it also indicates that their density is also high, so their applications are limited. These materials are carefully applied in the aerospace applications that require such materials, but their weight limits their use. Foams are depicted in the bottom left corner of Figure 1; they are incredibly light in weight but lack in strength and stiffness. Therefore, they cannot be used for applications for which strength is required. The “Holes” region in Figure 1 indicates that there is a large scope for vector development in the direction of the arrow shown. This research focuses on the upper left “Hole” where materials should have a high Young’s modulus, but should also be lightweight. This introduces the idea of creating cellular structures, which have void spaces like foams but are made up of high modulus materials. Creating such hybrid structures can benefit many weight-sensitive applications, mostly aerospace [2]. Creating such structures will use a fraction of the material conventionally or can be used in larger components with the same amount of material density, without stresses being compromised. Importance to 3D-printing rises as these complex structures are nearly impossible to manufacture by conventional techniques.

1.3 Importance and Need for 3DP

Many mechanical assemblies have such critical areas or components that require protection during operation. Therefore, casing, coating, and other sub-assemblies are manufactured for that purpose. However, these sub-assemblies or casings can add a
significant amount of weight, which has limited effect if the main assembly is fixed or stationary during operation. However, additional weight can create adverse effects for aircraft and other vehicles. In such cases, a lighter solution is required.

This thesis presents a solution for such complex structures that includes increasing the number and size of void spaces, decreasing a structure’s weight, or selectively using dense materials only where they are needed. There are various types of 3DP techniques that can be used to manufacture products, including Stereolithography (SLA), Digital Light Processing (DLP), fused deposition modeling (FDM), selective laser sintering (SLS), selective laser melting (SLM), electronic beam melting (EBM), and laminated object manufacturing (LOM) [3]. Chapter 2 includes a detailed literature review for this research.
Chapter 2. Literature Review

2.1 Overview

The demand for ultralight sandwich structures, which can be used in aerospace and other weight-sensitive applications, has resulted in the study of lightweight, stiff, and strong materials and structures. Alloys such as magnesium, aluminum, and titanium are highly valued, as their material properties are optimally suited for such applications. The sandwich structures consisting of light, stiff faces/members separated by low-density cores provide exceptional structural load support, especially in bending. Hence, these structures have rapidly grown in interest and importance. These structures’ strength, or energy absorption capacity, depend on the materials they are made of and the cell topology. For our study, we focus on the most common material for aerospace applications: Ti-6Al-4V.

This chapter addresses topics related to cellular structures and 3DP, which form the foundation of this research. We demonstrate how cellular structures can reduce the overall weight of a model while performing energy absorption. Furthermore, we will discuss the technology behind 3DP and will survey current types and techniques. We will then discuss the concepts and methods involved in this research. In the last section, a literature review on prior art in this field is provided.
2.2 Cellular Structures: Foams and Lattices

Cellular structures are cellular solids, which are classified into two types based on their mechanical properties. The first category of the foams is bending-dominated structures, and the second type is categorized as triangulated lattice structures. The difference between them can be explained with the following example: A foam with a relative density of 0.1 (which means that the solid cell members will occupy 10% of the total volume) is less stiff by a factor of 10 than a triangulated lattice of the same relative density (see Figures 2a and 2b).

![Figure 2a. Bending-dominated](#)  ![Figure 2b. Stretch-dominated](#)

According to Ashby’s book (2011), foaming creates bending-dominated structures with lower modulus and density [2]. Lattices that are stretch-dominated have much greater moduli than those foams of the same density [2].

2.3 Periodic Cellular Topologies

These topologies are usually stretch dominated structures whose strengths increase linearly with the relative density. As described in George’s paper [1], the topologies can
be broadly classified as sheets and truss members. Cores, which have cells, open in one direction and close in the other two directions (see Figure 3). Truss cores fully opened in all directions. Figure 3 explains all the periodic cellular topologies and their classification per their structure.

<table>
<thead>
<tr>
<th>i) Honeycomb</th>
<th>ii) Prismatic</th>
<th>iii) Truss</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Square</td>
<td>a) Triangular</td>
<td>a) Pyramidal</td>
</tr>
<tr>
<td>b) Hexagonal</td>
<td>b) Diamond</td>
<td>b) Tetrahedral</td>
</tr>
<tr>
<td>c) Triangular</td>
<td>c) Navtruss</td>
<td>c) Colinear (square)</td>
</tr>
</tbody>
</table>

*Figure 3. Schematic Illustration of Periodic Cellular Core Topologies [1]*

Figure 3 explains the different type of cellular topologies, which are built and applied for their respective functionalities and applications. For example, closed cell metallic foam can support bending loads and can mitigate impact loads well. However, open-celled topologies can provide cross-flow heat exchange in addition to good load support. Lattice truss core ligaments experience axial stress, which is either compression or tension, thus they are stretch dominated. The strength of these lattice structures scales linearly with the
relative density $\rho$ of the cellular structure until the buckling of the truss occurs. The mechanical performance of such lattice truss cores is therefore superior to those of the other stochastic foams that deform by bending. Mass required for truss members is also comparatively less. In the same material density, bigger and stiffer lattices could be made. These are the reasons why lattice truss cores are widely preferred over stochastic foams. These cores are further classified into different geometries to obtain the best energy absorption results [1]. In a subsequent section, we discuss how these core structures could be manufactured, given that these types of structures are almost impossible by conventional manufacturing processes.

2.4 Additive Manufacturing/3D Printing

Manufacturing processes have evolved since the emergence of 3DP. Therefore, it is necessary to understand where exactly additive manufacturing (AM) stands in various manufacturing processes. There are two categories of manufacturing processes, which are shown in Figure 4.

![Figure 4. Difference between subtractive manufacturing & additive manufacturing. [4]](image)

Subtractive manufacturing is the conventional manufacturing process in which undesired or excess material is removed from the raw material to form a product of desired
size and shape. Some examples of subtractive manufacturing include milling, drilling, turning, machining, and grinding. This process has many disadvantages, such as the waste of machined material, which leads to environmental issues. It also requires highly skilled labor, which increases the production cost of the product [5].

AM is a process that involves building the product layer by layer without wasting material. The manufacturing device is pre-programmed and therefore does not require highly skilled labor or supervision. This process gives immense flexibility to designers to design complex components because products can be built layer by layer. This process is also known as 3DP [4]. 3DP technology is already changing the way we produce different objects, from tools to toys and clothing, and even to body parts. This technology allows designers to create complex, lightweight designs for aerospace and other domains. The following sections will discuss the technology behind it and the different processes that work with this technology [6].

2.4.1 The Technology

3DP or AM is a process during which an object is created by adding material layer by layer. The first step in 3DP is to create a blueprint of the model/object to be printed. Various CAD modelling software can be used to create such models. Then, those models are saved as STereoLithography (.STL) file format which are accepted by 3D-printers. Alternatively, a standard model’s blueprint files found on the Internet can be used for direct printing. A ready STL file can be sent to the 3DP software, which further processes it. The imported file is then cut into n number of slices, making it ready for printing layer by layer [6].
2.4.2 The Processes

The American Society for Testing Materials (ASTM) has classified AM into seven categories according to standard terminology for AM technologies. These processes are briefly explained in the following sections.

2.4.2.1 Vat Photopolymerization

This type of 3D printer has a container filled with photopolymer resin that is then hardened with UV light. This concept is illustrated in Figure 5.

![Figure 5. Vat Photopolymerization. [7]](image)

The Y (build) platform can be lowered downwards from the top until the end after completion of each layer. The ultra violet light cures the resin layer by layer, the platform continues to move downwards, and additional layers are built on top of the previous one. Some variations of this process involve using a blade that moves on the cured layer to
provide a smooth resin base for the next layer [7]. On completion of the model, the vat is then drained of resin and the object is removed [7]. Vat polymerization has two sub types:

- **Stereolithography (SLA):** This technique is the same as described above with the following details. The platform, called the SLA’s elevator platform, descends downwards with a distance equal to the layer thickness. Layer thickness here ranges typically from 0.05mm to 0.15mm (0.002” to 0.006”). The stereolithography technique uses support structures when they are needed to prevent the object from floating [6]. These support structures are manually removed after the completion of the procedure. Charles Hull, who founded the company, 3D Systems, invented the technique in 1986 [6].

- **Digital Light Processing (DLP):** This method is a similar method and uses light and photosensitive polymers. The key difference in this method is its light source. DLP method uses traditional light sources such as arc lamps. Companies that specialize in the DLP technology include ONO and Carbon, who invented a subtype of DLP called CLIP. Envision Tec Ultra, MiiCraft High Resolution 3D printer, and Luna vast XG2 are some of the examples of this technique [6].

2.4.2.2 Material Jetting

This type of 3D printer has a different method of ink usage. This process involves material application in droplets through a small diameter nozzle using either a thermal or piezoelectric method. It has a similar process as a common ink jet paper printer. However, here the ink is applied layer by layer to build a 3D object, which is eventually hardened by UV light. The advantages of this process are high accuracy and good surface finish (see Figure 6).
Here, the support material is also a photopolymer, which is deposited from the second print head and is cured by UV lamp. Polymer and wax are the most suitable material for this type of printer because of their viscous nature and ability to form drops.

2.4.2.3 Binder Jetting

This type of 3D printer uses two materials, which are a powder-based material and a liquid binder. There are two platforms where powder material is stocked; one is the powder feeder, and the other is the build platform. The powder material is rolled over the build platform, and then the print head deposits the adhesive on top of the powder to glue the whole layer. Then, the build platform is lowered down with the distance equal to layer thickness. Again, the roller spreads the layer of powder material, and the process repeats. The remaining unbound powder remains as it is, surrounding the main object or supporting
it. The process repeats until the model is complete, and then unbound sand is removed manually (see Figure 7).

![Figure 7. Binder Jetting. [7]](image)

The Massachusetts Institute of Technology (MIT) was the first to develop this technology in 1993, and Z Corporation obtained an exclusive license in 1995 [6].

2.4.2.4 Fused Deposition Modelling (FDM)

This is the most common technology used, as it is the more consumer friendly. FDM works by using two materials in the form of a filament coiled in a cartridge: the main ink, which is usually a polymer or a metal wire, and the support material, which is other form of plastic [6]. The filament is extruded via a nozzle, which can turn the flow on and off [6]. The nozzle is set at a temperature and heats up and melts the filament before extrusion [6]. This nozzle is a numerically controlled mechanism, which is directly controlled by a computer-aided manufacturing software package (CAM), and can be moved in vertical and horizontal directions [6]. The material is extruded on the build plate
layer by layer with a predefined fill density that hardens instantly after extrusion from the nozzle (see Figure 8). The most commonly used materials are Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA) [6].

Figure 8. Fused Deposition Method (FDM). [8]

The extruder diameter determines the layer thickness and vertical dimensional accuracy, which ranges from 0.013 to 0.005 inches. A 0.001-inch resolution is achievable in the X-Y plane [6]. Other materials available with this technology include polyamide, polycarbonate, polyethylene, polypropylene, and investment casting wax [8].

2.4.2.5 Powder Bed Fusion

This technology is commonly used in metal 3DP. As previously mentioned, even this setup includes two containers: the build platform and a container involving a roller for rolling a new layer of material after each layer of fusion (see Figure 9) [7]. However, the
techniques used for fusing the top layer are different from the other methods discussed in this work [7].

![Figure 9. Powdered Bed Fusion. [7]](image)

The various techniques, which are used in this type of 3D printer, are direct metal laser sintering (DMLS), selective heat sintering (SHS), and selective laser sintering (SLS), selective laser melting (SLM), and electron beam melting (EBM). There are two methods used to fuse the powdered material together: laser or electron beam. These different techniques differ from one another with their approach to fusing the material. DMLS is the same as SLS (see Figure 10), but it is used for metals, not for polymers. Sintering is done layer by layer as the main model builds up [6]. SHS uses a heated thermal print head to fuse the layer of material powder, which is different from other processes.
Typically, a layer is about 0.1mm thick. The laser beam sinters each layer by fusing it together and then the next layer is added by the roller. The amount by which the fabrication piston goes down is equal to the amount the powder delivery piston raises, which is equal to the thickness of one layer [7]. The loose material is left as it is and is removed in the post processing process after the material is cooled down. The loose material is reused in the powder delivery system [7]. Dr. Carl Deckard developed and patented the SLS method at the University of Texas in the 1980s under the sponsorship of Defense Advanced Research Projects Agency (DARPA).

2.4.2.6 Sheet Lamination Method

SLM is a process that uses sheets made of metal, paper, or polymer. These sheets are bonded together with an external force in the fusion process, such as a rotating cylindrical sonotrode, ultrasonic welding for metal sheets, or adhesive glue for paper. Metal sheets are milled by a CNC into the proper shape, and paper is cut with precise blades [6]. See Figure 11 for a visual depiction of this process.
The laminated objects or models are typically used for aesthetic and visual models or small prototypes. Those are not applicable for structural use as yet. The ultrasonic method, which is used in metal 3DP, uses aluminum, copper, stainless steel and titanium. The ultrasonic process is operated at low temperature and requires relatively less energy, as the metal is not melted. Mcor Technologies is the industry leader in this technology.

2.4.2.7 Direct Energy Deposition

High tech companies use this technology when rapid 3D manufacturing is required for applications. This technology has two categories differentiated by the material used: direct energy deposition (DED) either uses powder or wire feedstock as its materials. A typical DED 3D printer consists of a nozzle that is mounted on a multi-axis arm. This nozzle deposits melted material on the desired location on the build surface, where it
solidifies instantly. This process is like the fused deposition method, except that this nozzle can move in multiple directions and not just in X and Y-axes. Since it has 4- to 5-axes machines, the material can be deposited in any angle. This technology can be used with metals and polymers, but is typically used with metal 3DP [11]. Figure 12 explains the wire DED process.

![Diagram of Direct Energy Deposition (Wire Method)](image)

*Figure 12. Direct Energy Deposition (Wire Method). [11]*

In the wire DED process, there is a wire feeder and an electron beam that work together to create layer-by-layer deposition. This method incorporates inert gas shielding in either an open environment or in a sealed gas chamber. This technique provides higher deposition rates as compared to powder DED process [11]. See Figure 13.
Although both methods use similar processes, the way by which material is added layer by layer is different in both cases. Here, the powder flows through the nozzle and is melted by a beam right on the surface of the treated part. This system is also known as Laser Cladding DED and Laser Metal Deposition [6]. This method uses the layer deposition, which varies from 0.1mm to several centimeters. Laser engineered net shaping (LENS) is the new development in this technology [6]. This method aids in adding material in an already existing part. This method is used to repair expensive metal products, which are worn out or damaged, such as chipped turbine blades [6]. This offers high flexibility and necessity wherever regular maintenance is required. Companies that use this technology include BeAM from France, Trumpf from Germany, and Sciaky from the USA [12].

2.5 Specifications of the 3D Printer Used

The 3D printer used for this research is a polymer printer, and its specifications and other details are provided in Figure 14.
Figure 14. Stratasys uPrint 3D Printer.

Figure 14 shows the printer used for this research: a Stratasys uPrint SE plus 3D printer. It uses FDM technology, but with polymer material only. The lower two compartments consist of the main material and the support material.

Figure 15. Configurations when STL files are processed.

Figure 15 shows the STL files being processed in the Catalyst software before being sent to the printer for printing. The red part is the main model sliced with the n number of
layers having thickness 0.254 mm (0.010 in.) or 0.330mm (0.013in.) [12], while blue part is the support material.

Following are the detailed specifications of the 3D printer used retrieved from [13] and the software installed and observations on operation.

- Model Material: ABS plus in white.
- Support material: SR-30 soluble
- Build size: 203 × 203 × 152 mm (8 × 8 × 6 in.)
- Layer thickness: 0.254 mm (0.010 in.) or 0.330mm (0.013in.)
- Layer Resolution: 0.01mm
- Model interior: High density (100% fill density)
- STL scale: 1.0
- Typical temperature recorded:
  - Model Head: 100° C
  - Support Head: 100° C
- Current Price in market: quote $20,900 USD
- Material usage for single configuration: Less than 1%.
- Support material usage for single configuration: Less than 1%
- Software used: Catalyst EX: This software provides the following features;
  - Provides a 3D view of the model
  - It has the ability to scale existing 3D models to desired printable size
  - Has complete control over the orientation in which model can be kept for building.
- Has flexibility for custom packs, also can build multiple packs in single operation on same build plate.
- Printing queue can be made for assigning multiple jobs in hierarchy; material consumption as well as required print time can be estimated.

2.6 Core Structures Studied in Literature

Core cellular structures are broadly classified as closed cell structures and open cell structures. These cores are normally sandwiched with different material face sheets to make a hybrid structure. The following subsections will discuss hybrids, but will focus on core structures.

2.6.1 Square Honeycomb Structure

Honeycomb structures are classified into three main types: square, hexagonal, and triangular honeycombs. Figure 16 depicts the square honeycomb cell topology.

![Figure 16. Square honeycomb cell topology. [1]](image)

This topology consists of four-sided unit cells, as shown in Figure 16. The unit cell is highlighted with the dotted red boundary. Typically, different topologies are compared with their relative density and the energy absorption or maximum load they can carry. The comparison depends on the applications. The relative density can be determined by
calculating the total volume contained by the truss within the unit cell, and then dividing it by volume of the unit cell. Failure that occurs in square honeycomb lattice structures is typically caused by elastic and plastic buckling of cell walls [1].

2.6.2 Hexagonal Honeycomb Structures

These structure lattices have six-sided unit cells. These honeycombs have an angle of 120° between the cell walls. The unit cell is highlighted with a red dotted boundary in Figure 17.

![Hexagonal honeycomb lattice structures](image1)

*Figure 17. Hexagonal honeycomb lattice structures. [1]*

2.6.3 Prismatic Structures

This type of lattice structure has open cells along one dimension and closed cells in all the other dimensions. These are further classified into triangular, diamond and nav-truss topologies [1]. Figure 18 depicts a prismatic structure.
Figure 18. Prismatic structures. [1]

The angle of inclination is typically between $45^\circ$ to $60^\circ$ [1]. Normally, closed cell structures were just compared with their relative density. However, they are not widely applied, as truss structures perform better in the same amount of density.

2.6.4 Truss Lattice Structures

Figure 19 illustrates different truss lattice structures that were developed to find the better structure for improved mechanical performance.

Figure 19. Octet lattice structure. [1]

Figure 19 illustrates the hybrid carbon fiber reinforced polymer (CFRP), which is fabricated from a braided IM7 carbon fiber with pre-machined polymer foam. Carbon fiber
members contain polymer foams for better mechanical performance. The failure modes observed in such hybrid structures are Euler buckling of slender struts. Delamination failure of stubby struts were observed in the laminated structures. The strength and the modulus of the overall structure increase with increase in foam density. Less susceptible elastic buckling is observed [1]. Different assembly techniques were observed using different materials to observe which hybrid performs better in the octet lattice structure.

2.6.4 Schoen Gyroid and Schwartz Diamond Lattice Structures

Different from all the previous designs, Gyroid and Schwartz structures have circular and smooth struts with a spherical core in between (see Figure 20). The inclination angle of the circular and smooth struts of the unit cell varies continuously along the spherical core, which makes layers build up gradually with slight changes in area and position between two adjacent layers [14].

![Image of Gyroid and Diamond lattice structures]

*Figure 20. CAD model of Gyroid and Diamond lattice structures. [14]*

The SLM process was used to build the structures in Figure 20. The two lattice structures were compared based on volume fraction and deformation analysis. Gyroid lattice structures were found to be better than diamond structure [14]. However, the
manufacturability was challenging because of their optimized topology having circular struts. The yield strength decreases with the increase in the unit cell size of the lattice structures [14]. The yield strength of the 2-mm unit cell size lattice structure is approximately 36% higher than that of the lattice structure with the unit cell size of 8 mm [15]. The modulus of the 2-mm unit cell size lattice structure is approximately 27% greater than that of the 8mm unit cell size lattice structure due to the strut density of the gyroid lattice structures decreasing with increasing unit cell size [15].

2.6.5 Lattice Structures Analyzed for Impact Resistance

Figure 21 illustrates the cellular structures that were manufactured using the SLM process and were analyzed for their impact resistance capability by Mackin T. J [17].

![Figure 21](image)

*Figure 21. Different types of unit cells analyzed for impact resistance. [16]*

The structures in Figure 21 are Body Centered Cubic (BCC), Body Centered Cubic with Z-truss (BCCZ), Face Centered Cubic (FCC), Face Centered Cubic with Z-truss (FCCZ), and Face and Body Centered Cubic with Z-truss (FBCCZ). The metal powder used for building these structures was AlSi10Mg [16]. The spherical shape of particles was produced using gas atomization technology in argon atmosphere [16].
The gyroid structure has a similar result as the BCC and BCCZ structures when they were tested for impact resistance. The advantage of the Gyroid is that its stiffness is the same for all loading directions. Long impact and depth of penetration are very important during impact loading for continuous absorption of the energy [16]. If the time of impact is very short and the depth of penetration is low, then the energy is only partly absorbed. Therefore, for measuring of exact values, a high-speed camera must be used. Calculated depth of penetration was evaluated with a 3D optical scanner.

2.6.6 Research on Hollow Core Structures

With the same mass used for solid members, hollow members should make lattice structures more efficient for energy absorption. Douglas and Haydn [17] stated that the compressive and shear strengths of the hollow pyramidal lattices with relative densities of 1 to 6% were three to five times those of solid pyramidal lattices of equivalent relative density and were accompanied by significant strength retention of the post buckled structures, resulting in very high specific energy absorption [17]. Here, lattice structures were made of stainless steel [17]. The hollow tubes were fabricated first, assembled into lattice structures, and bonded using a vacuum brazing approach [17]. See Figure 23 for a depiction of the hollow pyramidal unit cell.
Figure 23. Hollow pyramidal unit cell. [18]

Compressive tests were performed, and the following results were observed. The plot in Figure 24 shows energy absorption per unit mass of different lattice configurations.

Figure 24. Energy absorption per unit mass. [17]

The energy absorbed per unit volume, $W_v$ (Jm$^{-3}$) is defined from the area under the nominal stress-strain curve as: (equations retrieved from [17])

$$ W_v = \int_0^{\varepsilon_D} \sigma(\varepsilon) d\varepsilon $$

2.1
Where \( \sigma(\varepsilon) \) is the flow stress of the structure and \( \varepsilon_D \) is the densification strain. The corresponding energy absorption per unit mass, \( W_m \) (Jkg\(^{-1}\)), is calculated by dividing equation 2.1 by sample’s density that is product of the relative density \( \rho' \) and the parent alloy’s density \( \rho_s \):

\[
W_m = \frac{W_v}{\rho' \rho_s}
\]  \hspace{1cm} 2.2

The normalized energy absorption per unit mass for the hollow pyramidal lattice structures are compared with several other topologies schematically in Figure 24. In Figure 24, if the solid pyramidal lattice structures are modified with hollow cross sections, they absorb more energy per unit mass. But, the optimization of this configuration has not yet been researched, and confirming the optimal unit cell size has not been done.

Creating strong (as well as stiff) cellular materials requires the use of materials and topologies that delay the onset of failure modes, such as plastic buckling, plastic yielding of metals, delamination, and fiber micro buckling in fibrous composites. Figure 25 depicts different lightweight cellular lattice materials made from CFRP, light metals, titanium matrix composites that possess much higher strength than conventional foams [19].
**Figure 25.** Material Density space for lattice structures. [19]

### 2.6.7 Available Research Vs Current Research

The configurations under consideration followed typical dimensions. The geometries are not comprehensively varied to understand which unit cell is the optimum for its respective configuration. These points will be addressed in this research. Furthermore, new configurations will be introduced, such as a diamond with alternate vertical struts, which has not been researched until now. Compression tests will be performed at the rate of 0.5mm/min to provide a detailed load displacement curve, which will provide clarity on the energy absorption scenario. The following sections will illustrate the different configurations and their modeling and analysis procedures.
Chapter 3. Modeling

3.1 Overview

A unit cell had to be constructed such as it will involve sufficient void space and will include less physical mass. The main design objective was to absorb impact or incident energy. Secondly, the unit cell should have less mass. Thirdly, it should not be so stiff that it would not be able to absorb energy. Some of the initial designs are shown in Figure 26.

Figure 26. Introductory unit cell ideas.

The first unit cell seen in Figure 26 is just a normal unit cell with the boundaries kept and everything else is void. Therefore, the idea of a unit cell here is to construct such a skeleton structure that would satisfy the design requirements. The second design in Figure 26 has crossbars at the top and the bottom surface. Moreover, the unit cell should be constructed in a manner that it is going to be arrayed in the X, Y and Z direction. It implies that the vertical side members should be half the thickness compared to the regular bar.
thickness. At first, the structural lattice was to be built with 100mm*100mm*20mm, with 5mm cubes as a unit cell and 1mm bar members. Now as discussed, the side members were to be constructed as 0.5mm to make a whole 1mm when arrayed. (see figure 27)

Figure 27. A unit cell determining typical dimensions.

So now, it can be understood that constructing the unit cell in this way would make the structural lattice perfectly symmetrical. Additional designs with different styles were also modeled (see Figure 28).

Figure 28. Unit cells with tetra and pyramidal formations.
There is a possibility of combining different unit cell ideas to make a better unit cell instead. However, precaution must be taken that the main unit cell does not become very stiff, which would defeat the aim of energy absorption. So, some of those ideas could be seen in Figure 29.

*Figure 29. BCC with horizontal and vertical support, BCC, BCC with vertical struts.*

The unit cell is further analyzed for stress and displacement. Eventually, the energy absorbed per unit cell can be calculated. The best result could be multiplied in an array for 3DP. If the unit cells were arrayed, it would look like the array in Figure 30.

*Figure 30. Array of BCC with vertical and horizontal support.*
Categorizing and combining all the above ideas into specific configurations is done in the next section. The following section presents a detailed discussion about each configuration, its loading conditions, boundary conditions, and analysis discussions.

3.2 Configuration 1: The Diamond or BCC

This configuration consists of eight legs attached together like two diamonds, one above the other. Two unit cells make this configuration (see Figure 31):

![Figure 31. Configuration 1: The Diamond.](image)

For the configuration to have optimum geometry, some geometric parameters should be varied and analyzed to understand which specific geometric dimensions should be selected for further study. For this particular configuration, the cross-sectional diameter and overall unit cell size should be varied. A set of analyses should be done to understand which specific combination absorbs the most energy. This configuration can be arrayed in X, Y and Z directions to form its structural lattice formation, which can be used in the respective applications. Care should be taken while arraying such unit cells together, as the
joint which unites the two cells together should be merged together so as not leaving the joints double in size. This configuration, when arrayed in all the directions, is shown in Figures 32.

Figure 32. Configuration 1 BCC structural lattice.

For the analysis, if the model is symmetrical, a half model can be used. Since this model is perfectly symmetrical, just one fourth of the model can be taken in consideration. Figure 33 explains the geometry reduction.

Figure 33. Diamond geometry reduction for analysis. Here a is the strut length.
3.2.1 Boundary Conditions

After the breakdown, the configuration has to be analyzed for how much energy it can absorb on compression. For that, the geometry needs to be finalized. The variable parameters in such a case are cross-sectional diameter and the size of the unit cell. Therefore, keeping the resolution of the 3D printer in mind, we can approximate the smallest diameter possible. The diameter can be varied from 0.5mm to 0.8mm to 1mm, whereas the length of the cubic unit cell can be varied 5mm, 7.5mm, and 10mm. Next, all of the combinations should be analyzed for the optimum combination. The boundary conditions are shown in Figure 34. The bottom of the leg should be fixed in all translational degrees of freedoms. Therefore, the bottom of the leg cannot move in any direction on the application of any type of force. Now, the top of the leg should have roller support in X-direction or in the horizontal direction. Since the main loading/impact is going to be from the top and this particular unit cell is going to be surrounded by other unit cells, roller supports should be provided to constrain it in the horizontal direction.

Figure 34. Configuration 1 boundary and loading conditions.
3.2.2 Loading Conditions

There are two sets of analysis that should be carried out: (a) the vertical loading condition (in Y-axis) applied at the top of the leg and (b) the horizontal loading condition on the vertex in the middle of Z-direction. In both sets, the 4N force is applied on the configuration for the analysis. Then, another set of analysis is done where the boundary conditions and the loading conditions are kept the same in every combination of analysis and the force is increased bit by bit until the stress hits the yield point of the material, which is \(8.27 \times 10^8\) N/m\(^2\).

3.3 Configuration 2: Diamond with Vertical Struts

This particular configuration is a special case in which the two diamonds are combined together with a vertical rod on its side edges (see Figure 35).

*Figure 35.* Configuration 2 Diamonds with vertical struts.

The vertical struts add more stiffness to the configuration, helping it absorb more energy on compression. During analysis, the geometry variables are again the cross-
sectional diameter and the overall unit cell size. The cross-sectional diameter is varied as 0.5mm, 0.8mm, and 1mm, whereas the unit cell cube size is varied as 5mm * 5mm * 10mm, 7.5mm * 7.5mm * 15mm, and 10mm * 10mm * 20mm. Next, all of the possible combinations are tested to see which combination of the changed variables absorb the maximum energy. It has to be arrayed in X, Y and Z direction for the subsequent procedures and tests. Furthermore, care should be taken as it is arrayed; given that it has vertical members supporting the structure, the cross-sectional diameter must remain constant. That means that adjacent unit cells should have their vertical struts merged into each other to make it whole. When arrayed in all the three directions, it looks like the configuration in Figure 26.

![Figure 36. Configuration 2 structural lattice.](image)

Before going for actual analysis, a check is done to see if the geometry can be reduced for the ease of the procedure. For analysis, a similar breakdown in geometry must be performed as earlier for the ease of the whole analysis procedure. For this configuration,
reducing the main geometry to one fourth is a better decision for the ease of the analysis (see Figure 37).

**Figure 37.** Configuration 2 geometry reduction.

### 3.3.1 Boundary Conditions

In a similar way, two sets of analysis should be carried out to see how the configuration behaves when load is applied from the top that is in Y-direction and from the side that is in Z-direction. The bottom nodes of the configuration have to be fixed in all three translational degrees of freedom, i.e., X-, Y-, and Z-directions. Furthermore, the middle and top edges should have a roller support in the horizontal direction to explain the vertical compression (see Figure 38).
3.3.2 Loading Conditions

In a similar fashion, this configuration needs to be analyzed. Therefore, for the first set of analyses, a vertical loading on the top of 1N and similar loading on the side edge but in Z-direction are applied in the second set of analyses (see Figure 27).

3.4 Configuration 3: The Tetra structure

Only cubical structures have been observed to this point, but the tetra structure, another basic structure that is very good at supporting and requires less mass should be considered. It consists of just three legs instead of four, but performs the same function (see Figure 39).
Figure 39. The tetra structure.

This structure consists of a little less mass compared to the previous configurations, as it has one fewer leg and is made of just one unit cell instead of a combination of two. For testing purposes, the tetra structure needs to be arrayed to check the symmetry of the unit cell. The tetra structure has no symmetry in the X- and Y-axes. If it cannot be arrayed in a symmetric way, it would be very tedious to build this type of configuration. Since it cannot be patterned linearly, it has to be patterned in a circular way so that a rectangular section can be cut in such a way that it could be arrayed further in the X- and Y- directions and then flipped in vertical directions. When this particular unit cell is arrayed in X, Y and Z directions, it would look like the configuration in Figure 40.

Figure 40. Tetra structure arrayed in circular pattern.
Figure 30 depicts the different views of the arrayed tetra structure in the X- and Z-directions. Vertically, it can be flipped after it is arrayed in the X- and Z-directions to the desired amount. This structure is already very simple, so there is no specific need to reduce the geometry for the analysis. Because there is no symmetry, it was difficult to linearly pattern it and bring it to our desired lattice size. Therefore, a tetra structure was created and patterned circularly; we proceeded to pattern it three more times until it became large enough. Then, it is cut in a rectangular section to achieve the desired size of lattice structure (see Figure 41).

![Tetra structure cut in desired lattice form](image)

*Figure 41. Tetra structure cut in desired lattice form.*
Figures 42 demonstrates that the unit cell does not have a valid vertical symmetry to reduce. Therefore, it can only be reduced to a half model as shown above.

3.4.1 Boundary Conditions

In any analysis mode or analysis software, the configuration made or imported is in general space. So, it needs to constrained in such a way that it does not move in such specific directions that would give us the desired behavior after applying loading conditions. This configuration consists of just three legs; all three legs can be fixed at the bottom or just one needs to be fixed. To see how the configuration behaves under loads, it is recommended to perform analysis under both types of the loading conditions. That will help us understand the load bearing capacity of the configuration. However, in the real-time situation, the condition with all three legs fixed would not be a perfect loading condition because when this configuration is arrayed in all three axes and load is applied, the legs of each unit cell would displace from its original position and would not behave as a rigid boundary. Hence, keeping one leg fixed in all degrees of freedom with the other
two having roller vertical support should be the boundary condition to bring the analysis close to the real-time situation (see Figure 43).

![Figure 43. Boundary condition and loading conditions.](image)

### 3.4.2 Loading Conditions

The force is applied in the vertical downward direction at the top joint where the three legs meet. The magnitude of force is the unknown parameter for now. The first analysis in the set of simulations examines whether any arbitrary force can be given to check the possible deformation for that particular one. There are ways to find the magnitude of force that will let us find the yield capacity of the configuration. Repeated simulations were performed with same boundary conditions varying the magnitude of force, which gives the maximum stress. Increasing force above that value would let the stress increase above its yield strength. Thereafter that magnitude of force is taken in consideration for further simulations. Here, the force to be applied was 12 N. Now, for the boundary condition in which all three legs are fixed in all degrees of freedom, it takes a larger force to deform until its yield strength, which is 282 N. The results are tabulated and compared with other configurations in a subsequent chapter.
3.5 Configuration 4: The Tetrahedron

The tetrahedron is a further modification of the tetra structure. The three free ends are joined with rods to complete the tetrahedron structure. The geometry variables for this particular model can be the cross-sectional diameter of the rods and the length of the rods. Figure 44 depicts the completed model.

![Tetrahedron and its model reduction](image)

*Figure 44. Configuration 4 the tetrahedron and its model reduction.*

There are two different sets of analyses to be performed here: (a) keeping the load constant and varying the geometry to see which combination performs well and (b) varying the load by the trial method to find the energy absorbed at the yield strength of the model. The chosen diameters are 0.5mm, 0.8mm, and 1mm, according to the resolution of the available printers in the university. The reduced geometry will be similar to the tetra structure, which is shown in Figure 33. This tetrahedron has to be arrayed in all three axes. While arraying, the same difficulty was observed as for the tetra structure: It cannot be easily multiplied in the linear direction. Therefore, in the same way as Configuration 2, a circular pattern should be made first and then a rectangular pattern cut from it so that it can be arrayed in X-, Y- and Z-directions (see Figures 45 and 46).
3.5.1 Boundary Conditions

The same question arises as to whether the complete lower base should be fixed or not. However, the results of the earlier configuration confirm that it is not a correct boundary condition for the current design requirement. So, only one edge at the bottom of the tetrahedron is fixed, and all the lower body has the vertical roller support. See Figure 47.
3.5.2 Loading Conditions:

The tetrahedron structure has rods supporting its three legs to add more stiffness for the model. It implies that the force required would be larger than what was required for the tetra structure; analysis resulted in 73 N. This force is kept constant for the duration of the analyses despite changing the geometric variables. In the next set for the same combinations, force is varied and every combination is analyzed at their yield strength. The loading condition is vertically downwards on the top edge of the model as shown in Figure 47.

3.6 Configuration 5: The Pyramid

The pyramid structure has four legs supporting the structure and is a further modification of the tetrahedron structure. This configuration is another special case of Configuration One: “The Diamond” with just horizontal rods supporting it. However, this last configuration is stiffer compared to the previous configurations because it has one more
member supporting it. The geometric variables, which are the cross-sectional diameter and the length of the rods, would be similar. See Figure 48 for the geometry reduction.

*Figure 48. Configuration 5: The Pyramid and its model reduction.*

When arrayed the pyramid, structural lattice looks like the configuration in Figure 39.

*Figure 49. Pyramidal structural lattice.*

### 3.6.1 Boundary Conditions

Now that it is confirmed what type of boundary conditions are suitable for such structures, the same pattern could be followed for this configuration. The lower edge of the pyramidal structure is to be fixed in all degrees of freedom, and the complete lower body should have the roller support, supporting upward (see Figure 50).
3.6.2 Loading Conditions

The similar paradigm of the loading conditions continues, as this configuration is just a modification of the previous configurations. The load is applied vertically downwards on the top of the pyramid structure. The two sets of analysis are followed: (a) the constant force, which is found via the trial method and (b) the variable force, focusing on the yield strength of the model. In both sets, all the possible combinations are taken into concern by changing the geometric parameters of the configurations.

3.7 Finite Element Analysis (FEA) Modeling Approach

After modeling and simulating these configurations, their results were compared for energy absorption under the elastic limit. Determining which configuration absorbs the maximum energy is required before we can model them for plastic deformation. For plastic deformation, these configurations were modeled in ANSYS APDL. For analysis of any model for the plastic deformation, we need material details for its plastic region behavior.
Elastic modulus helps to understand elastic behavior of the material, whereas tangent modulus helps to understand the plastic behavior of the material (see Figure 51).

![Ti-6Al-4V Stress Strain Curve](image)

*Figure 51.* Reference stress strain curve Ti-6Al-4V [20].

The stress strain curve shown in Figure 51 for Ti-6Al-4V was used to calculate the elasticity and tangent moduli, and yield strength that were later used for elastic-plastic models. The graph points were approximated and plotted in Excel to calculate tangent and elasticity moduli. The slope of the stress strain curve at any specified stress or strain gives us the tangent modulus according to solid mechanics, which were used in the elastic plus plastic analysis.

### 3.7.1 Modeling Details

All the configurations were modeled in a similar pattern. The material properties were taken from Figure 41, and the analysis type was structural. The element type was taken as Beam 2 node 188. This typical element type does not require real constants. The
material properties were defined as Tangent Modulus at 643.32 MPa, Young’s modulus at 1.038e5 MPa, and Poisson’s ratio is taken as 0.31. Then, the section of the beam was assigned to be circular, which will vary with different configurations. Modeling was done by creating key points and joining them by straight lines to mesh them with a smart medium mesh size. This is how nodes and elements are created. Now, the loading conditions and the boundary conditions are applied on the nodes created in the same pattern as the elastic analysis. The only difference here is that there are roller supports on the top node for getting results that are more realistic. Some examples of the loading conditions and boundary conditions are shown in Figure 52.

![Figure 52. Boundary conditions and loading conditions for Configuration 4 and 5 ANSYS.](image)

The applied load was divided into 10 sub-steps and was determined by increasing it to the level above which the load steps fail due to plastic deformation. After simulation is done, we read the results stepwise and noted the deformation at each load step. Then, we plotted the load displacement graph in the Excel spreadsheet. We then calculated the area under the curve with the help of Excel. Dividing the area under the curve by its mass
resulted in the energy absorbed per unit mass. After the energy absorbed per unit mass was calculated, we compared the results for all configurations to see if the trend line was like the previous tested results. As the analysis exceeded the yield point, it became a nonlinear solution that could potentially differ from the elastic results. The details of the analysis are discussed in the next chapter. The details of the input program used for all of the configurations are attached in the appendix.
Chapter 4. Analysis and Discussion

4.1 Overview:

In this chapter, we will discuss the results of the simulations carried out in SOLIDWORKS and ANSYS for all configurations, which were discussed in chapter 3. Our goal is to select the configuration that absorbs maximum energy. First, we will look at the energy absorbed in the elastic limit, and then we will discuss the energy absorbed due to elastic and plastic deformation.

4.2 Elastic Energy Absorption

The general procedure followed in all sets of analyses that are carried out in this chapter will follow a certain pattern. First, the geometric variables are combined in all possible combinations. Next, the volume of one leg/member are recorded from the SOLIDWORKS tool. Then, the magnitude of force is found as discussed earlier for the set of constant loading. The applying material (Ti-6Al-4V in all cases), boundary conditions,
and loading conditions simulation is performed in SOLIDWORKS, and maximum displacement is calculated. The formula for energy absorbed is derived in n Joules:

\[
Energy\ absorbed\ E\ (elastic) = \frac{1}{2} \times \sigma \times \epsilon \times A \times L \quad 4.1
\]

\[
Energy\ absorbed\ E\ (elastic) = \frac{1}{2} \times F \times \delta \quad 4.2
\]

According to the finite element method, Force can be given as,

\[
Force\ F = Stiffness\ (K) \times \ Displacement(\delta) \quad 4.3
\]

\[
Energy\ absorbed\ E = \frac{1}{2} \times K \times \delta^2 \quad (Nmm) \quad 4.4
\]

\[
Energy\ absorbed\ E = \frac{\frac{1}{2} \times K \times \delta^2}{1000} \quad (Nm)\ Or\ (J) \quad 4.5
\]

Equation 4.1 retrieved from [17].

**4.2.1 Configuration 1: The Diamond**

The first set of analyses was carried out where the load was kept constant, which was 4N in this case. It can be seen from the following table that as the cross-sectional diameter increases from 0.5 to 1mm, the displacement reduces linearly. So, selecting the lowest possible cross-sectional diameter for a configuration is recommended. If the stiffness column is smaller than the unit cell and larger than the cross-sectional diameter, the structure is stiffer. Stiffness for Analyses 1, 4, and 7 are the smallest unit cells with increasing diameters that have increasing stiffness (see Table 1).
Table 1. Configuration 1: Results for energy absorption under constant load.

<table>
<thead>
<tr>
<th>Analysis #</th>
<th>D mm</th>
<th>Unit cell size mm</th>
<th>F N</th>
<th>δ mm</th>
<th>K N/mm</th>
<th>E Nm or J</th>
<th>mass 1/8th model, kg</th>
<th>E1 1/8th model, J/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>5×5×10</td>
<td>4</td>
<td>0.11</td>
<td>37.45</td>
<td>2.27E-04</td>
<td>7.533E-06</td>
<td>3.01E+01</td>
</tr>
<tr>
<td>2</td>
<td>0.8</td>
<td>7.5×7.5×15</td>
<td>4</td>
<td>0.14</td>
<td>28.27</td>
<td>2.77E-04</td>
<td>1.129E-05</td>
<td>2.45E+01</td>
</tr>
<tr>
<td>3</td>
<td>0.8</td>
<td>10×10×20</td>
<td>4</td>
<td>0.18</td>
<td>22.38</td>
<td>3.63E-04</td>
<td>1.507E-05</td>
<td>2.41E+01</td>
</tr>
<tr>
<td>4</td>
<td>0.8</td>
<td>5×5×10</td>
<td>4</td>
<td>0.02</td>
<td>242.28</td>
<td>4.85E-05</td>
<td>1.928E-05</td>
<td>2.51E+00</td>
</tr>
<tr>
<td>5</td>
<td>0.8</td>
<td>7.5×7.5×15</td>
<td>4</td>
<td>0.02</td>
<td>173.01</td>
<td>3.46E-05</td>
<td>2.893E-05</td>
<td>1.20E+00</td>
</tr>
<tr>
<td>6</td>
<td>0.8</td>
<td>10×10×20</td>
<td>4</td>
<td>0.03</td>
<td>133.02</td>
<td>5.99E-05</td>
<td>3.856E-05</td>
<td>1.55E+00</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>5×5×10</td>
<td>4</td>
<td>0.01</td>
<td>580.72</td>
<td>2.90E-05</td>
<td>3.013E-05</td>
<td>9.64E-01</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>7.5×7.5×15</td>
<td>4</td>
<td>0.01</td>
<td>401.04</td>
<td>2.01E-05</td>
<td>4.519E-05</td>
<td>4.44E-01</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>10×10×20</td>
<td>4</td>
<td>0.01</td>
<td>304.65</td>
<td>1.52E-05</td>
<td>6.026E-05</td>
<td>2.53E-01</td>
</tr>
</tbody>
</table>

However, if the diameter is constant and the unit cell size increases, the stiffness reduces. Conclusively, we can say the largest cross-sectional diameter with the smallest unit cell will be the stiffest, and smallest diameter with the largest unit cell will be the least stiff. For the energy absorption, as the cross-sectional diameter increases from 0.5 to 0.8 to 1mm, the energy absorption reduces. Whereas if the diameter is kept constant and unit cell size is increased, the energy absorption increases. However, for the energy absorbed per unit mass, the constant cross-sectional diameter energy absorption increases as the unit cell size is increased. Hence, for the behavior of different combinations of geometric variables to maximize energy absorption, we should select the smallest cross-section diameter and minimize the unit cell size. The best combination is Analysis 1 absorbing 3.01E+01 J/kg for one member, which is multiplied by number of legs for the required scaled structural lattice. If the force is not kept constant and is increased until the yield strength of the material is 8.27E+08 N/m², we will see changes occurred. Table 2 shows the tabulation of Configuration 1 at yielding.
Table 2. Configuration 1: Results for Energy Absorption at Yielding.

<table>
<thead>
<tr>
<th>Analysis #</th>
<th>D mm</th>
<th>Unit cell size mm</th>
<th>F N</th>
<th>δ mm</th>
<th>K N/mm</th>
<th>E Nm or J</th>
<th>mass 1/8th model, kg</th>
<th>E1 1/8th model, J/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>5×5×10</td>
<td>3.9</td>
<td>0.11</td>
<td>36.52</td>
<td>2.083E-04</td>
<td>7.533E-06</td>
<td>2.76E+01</td>
</tr>
<tr>
<td>2</td>
<td>1.96</td>
<td>7.5×7.5×15</td>
<td>1.96</td>
<td>0.18</td>
<td>10.78</td>
<td>1.782E-04</td>
<td>1.129E-05</td>
<td>1.58E+01</td>
</tr>
<tr>
<td>3</td>
<td>1.78</td>
<td>10×10×20</td>
<td>1.78</td>
<td>0.22</td>
<td>8.20</td>
<td>1.931E-04</td>
<td>1.507E-05</td>
<td>1.28E+01</td>
</tr>
<tr>
<td>4</td>
<td>23</td>
<td>5×5×10</td>
<td>23</td>
<td>0.04</td>
<td>580.81</td>
<td>4.554E-04</td>
<td>3.013E-05</td>
<td>1.51E+01</td>
</tr>
<tr>
<td>5</td>
<td>11.5</td>
<td>7.5×7.5×15</td>
<td>11.5</td>
<td>0.06</td>
<td>183.62</td>
<td>3.601E-04</td>
<td>4.519E-05</td>
<td>7.97E+00</td>
</tr>
<tr>
<td>6</td>
<td>8.7</td>
<td>10×10×20</td>
<td>8.7</td>
<td>0.11</td>
<td>80.56</td>
<td>4.698E-04</td>
<td>6.026E-05</td>
<td>7.80E+00</td>
</tr>
</tbody>
</table>

Therefore, we can understand that results are similar and behave linearly, but the energy absorption increases due to the increased force.

4.2.2 Configuration 2: Diamond with Vertical Struts

The second configuration has a set of vertical struts supporting the diamond structures. Does this make the configuration stiff; do the struts help in absorbing more energy? These questions could be answered with the results in Table 3. As the general procedure, the first set of analyses has constant load.

Table 3. Configuration 2: Results for Energy Absorption under Constant Load.

<table>
<thead>
<tr>
<th>Analysis #</th>
<th>D mm</th>
<th>Unit cell size mm</th>
<th>F N</th>
<th>δ mm</th>
<th>K N/mm</th>
<th>E Nm or J</th>
<th>mass 1/4th model, kg</th>
<th>E1 1/4th model, J/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>5×5×10</td>
<td>1</td>
<td>0.2906</td>
<td>3.44116</td>
<td>0.00015</td>
<td>1.848E-05</td>
<td>7.863E+00</td>
</tr>
<tr>
<td>2</td>
<td>1.2630</td>
<td>7.5×7.5×15</td>
<td>1</td>
<td>0.79177</td>
<td>0.00063</td>
<td>2.831E-05</td>
<td>2.231E+01</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>4.3740</td>
<td>10×10×20</td>
<td>1</td>
<td>0.22862</td>
<td>0.00021</td>
<td>3.802E-05</td>
<td>5.753E+01</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.3676</td>
<td>5×5×10</td>
<td>1</td>
<td>0.03676</td>
<td>27.20348</td>
<td>0.00002</td>
<td>4.596E-05</td>
<td>3.999E-01</td>
</tr>
<tr>
<td>5</td>
<td>0.1338</td>
<td>7.5×7.5×15</td>
<td>1</td>
<td>0.747384</td>
<td>0.00007</td>
<td>7.129E-05</td>
<td>9.384E-01</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.34740</td>
<td>10×10×20</td>
<td>1</td>
<td>0.28753</td>
<td>0.00017</td>
<td>9.611E-05</td>
<td>1.807E+00</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.01421</td>
<td>5×5×10</td>
<td>1</td>
<td>0.7037298</td>
<td>0.00001</td>
<td>7.037E-05</td>
<td>1.010E-01</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.05170</td>
<td>7.5×7.5×15</td>
<td>1</td>
<td>0.1934236</td>
<td>0.00003</td>
<td>1.101E-04</td>
<td>2.347E-01</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.13220</td>
<td>10×10×20</td>
<td>1</td>
<td>7.56430</td>
<td>0.00007</td>
<td>1.489E-04</td>
<td>4.439E-01</td>
<td></td>
</tr>
</tbody>
</table>
Here, the energy absorption reduces as the cross-sectional diameter increases from 0.5 to 0.8 to 1mm. Moreover, for a constant diameter, energy absorption increases as the size of the unit cell increases from 0.5 to 7.5 to 10mm. A changed pattern is observed, keeping the cross-sectional diameter lowest and unit cell size largest is recommended from the above results.

*Table 4. Configuration 2: Energy Absorption Results at Yielding.*

<table>
<thead>
<tr>
<th>Analysis #</th>
<th>D mm</th>
<th>Unit cell size mm</th>
<th>F N</th>
<th>δ mm</th>
<th>K N/mm</th>
<th>E Nm or J</th>
<th>mass 1/4th model, kg</th>
<th>E1 1/4th model, J/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>5×5×10</td>
<td>2.33</td>
<td>0.68</td>
<td>3.43</td>
<td>7.91E-04</td>
<td>1.848E-05</td>
<td>4.281E+01</td>
</tr>
<tr>
<td>2</td>
<td>7.5</td>
<td>7.5×7.5×15</td>
<td>1.35</td>
<td>1.26</td>
<td>1.07</td>
<td>8.53E-04</td>
<td>2.831E-05</td>
<td>3.011E+01</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>10×10×20</td>
<td>0.97</td>
<td>4.37</td>
<td>0.22</td>
<td>2.12E-03</td>
<td>3.802E-05</td>
<td>5.580E+01</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>5×5×10</td>
<td>21.8</td>
<td>0.37</td>
<td>58.93</td>
<td>4.03E-03</td>
<td>7.037E-05</td>
<td>5.730E+01</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>7.5×7.5×15</td>
<td>7.6</td>
<td>0.47</td>
<td>16.11</td>
<td>1.79E-03</td>
<td>1.101E-04</td>
<td>1.628E+01</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>10×10×20</td>
<td>8.1</td>
<td>1.37</td>
<td>5.90</td>
<td>5.56E-03</td>
<td>1.489E-04</td>
<td>3.734E+01</td>
</tr>
</tbody>
</table>

Table 4 gives the maximum energy absorption values each combination can have just before yielding. As we observed, including struts makes the model stiffer and will increase energy absorption in some combinations. Maximum energy absorption with best combination in Configuration 1 gave us 27.6 J/kg, whereas Configuration 2 gives us 57.30 J/kg. Further, we will see how much energy it can absorb when the orientation is changed to a tetra structure.

**4.2.3 Configuration 3: Tetra structure**

This configuration has fewer members compared to previous configurations. Here, we are interested in changes in energy absorption if the orientation of the model is a tetra structure. Cross-sectional diameters are 0.5 and 1mm, whereas distance between the members and center vary from 4, 5 and 7mm, and the height of the structure varies as 5, 8
and 10mm. Table 5 shows the results for their combinations when keeping the load constant.

Table 5. Configuration 3: Results for Energy Absorption under Constant Load.

<table>
<thead>
<tr>
<th>Analysis #</th>
<th>D mm</th>
<th>Y mm</th>
<th>H mm</th>
<th>F N</th>
<th>δ mm</th>
<th>K N/mm</th>
<th>E Nm or J</th>
<th>mass half model kg</th>
<th>E1 half model J/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>4</td>
<td>5</td>
<td>12</td>
<td>0.1505</td>
<td>79.734</td>
<td>9.030E-04</td>
<td>1.619E-05</td>
<td>5.578E+01</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>5</td>
<td>8</td>
<td>12</td>
<td>0.4303</td>
<td>27.888</td>
<td>2.582E-03</td>
<td>2.403E-05</td>
<td>1.074E+02</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>7</td>
<td>10</td>
<td>12</td>
<td>1.1740</td>
<td>10.221</td>
<td>7.044E-03</td>
<td>3.133E-05</td>
<td>2.248E+02</td>
</tr>
<tr>
<td>4</td>
<td>0.5</td>
<td>4</td>
<td>8</td>
<td>12</td>
<td>0.2753</td>
<td>43.589</td>
<td>1.652E-03</td>
<td>2.270E-05</td>
<td>7.276E+01</td>
</tr>
<tr>
<td>5</td>
<td>0.5</td>
<td>5</td>
<td>10</td>
<td>12</td>
<td>0.5761</td>
<td>20.830</td>
<td>3.457E-03</td>
<td>2.857E-05</td>
<td>1.210E+02</td>
</tr>
<tr>
<td>6</td>
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<td>7</td>
<td>5</td>
<td>12</td>
<td>0.5843</td>
<td>20.537</td>
<td>3.506E-03</td>
<td>2.187E-05</td>
<td>1.603E+02</td>
</tr>
<tr>
<td>7</td>
<td>0.5</td>
<td>4</td>
<td>10</td>
<td>12</td>
<td>0.4284</td>
<td>28.011</td>
<td>2.570E-03</td>
<td>2.740E-05</td>
<td>9.380E+01</td>
</tr>
<tr>
<td>8</td>
<td>0.5</td>
<td>5</td>
<td>5</td>
<td>12</td>
<td>0.2377</td>
<td>50.484</td>
<td>1.426E-03</td>
<td>1.801E-05</td>
<td>7.917E+01</td>
</tr>
<tr>
<td>9</td>
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<td>7</td>
<td>8</td>
<td>12</td>
<td>0.8668</td>
<td>13.844</td>
<td>5.201E-03</td>
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<td>1.906E+02</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>4</td>
<td>5</td>
<td>12</td>
<td>0.0084</td>
<td>1422.138</td>
<td>5.063E-05</td>
<td>6.305E-05</td>
<td>8.030E-01</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>5</td>
<td>8</td>
<td>12</td>
<td>0.0227</td>
<td>528.634</td>
<td>1.362E-04</td>
<td>9.423E-05</td>
<td>1.445E+00</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>7</td>
<td>10</td>
<td>12</td>
<td>0.0551</td>
<td>217.984</td>
<td>3.303E-04</td>
<td>1.234E-04</td>
<td>2.677E+00</td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>4</td>
<td>8</td>
<td>12</td>
<td>0.0140</td>
<td>859.599</td>
<td>8.376E-05</td>
<td>8.856E-05</td>
<td>9.458E-01</td>
</tr>
<tr>
<td>14</td>
<td>1</td>
<td>5</td>
<td>10</td>
<td>12</td>
<td>0.0248</td>
<td>483.286</td>
<td>1.490E-04</td>
<td>1.120E-04</td>
<td>1.330E+00</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>7</td>
<td>5</td>
<td>12</td>
<td>0.0442</td>
<td>271.309</td>
<td>2.654E-04</td>
<td>8.392E-05</td>
<td>3.162E+00</td>
</tr>
<tr>
<td>16</td>
<td>1</td>
<td>4</td>
<td>10</td>
<td>12</td>
<td>0.0177</td>
<td>677.966</td>
<td>1.062E-04</td>
<td>1.069E-04</td>
<td>9.931E-01</td>
</tr>
<tr>
<td>17</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>12</td>
<td>0.0152</td>
<td>791.557</td>
<td>9.096E-05</td>
<td>6.933E-05</td>
<td>1.312E+00</td>
</tr>
<tr>
<td>18</td>
<td>1</td>
<td>7</td>
<td>8</td>
<td>12</td>
<td>0.0455</td>
<td>264.026</td>
<td>2.727E-04</td>
<td>1.066E-04</td>
<td>2.559E+00</td>
</tr>
</tbody>
</table>

Because there are three geometry variables in (Y) and (H) and two variables in the cross-sectional diameters, we can have 18 possible combinations between them. For the cross-sectional diameter of 0.5mm, center to edge of the leg distance (Y) as 4mm energy absorbed continues increasing as the height of the cell increases from 5 to 10mm. A similar pattern is observed for 0.5 diameter Y as 5mm, as well as for 7mm. This pattern repeats if the cross-sectional diameter is changed to 1mm. The energy absorption results when the
force is not constant and every combination is analyzed until the yield strength of the material (see Table 6).

Table 6. Configuration 3: Results for Energy Absorption at Yielding.

<table>
<thead>
<tr>
<th>Analysis #</th>
<th>mm</th>
<th>Y</th>
<th>H</th>
<th>F</th>
<th>δ mm</th>
<th>KN/mm</th>
<th>E Nm or J</th>
<th>mass half model kg</th>
<th>E1 half model J/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>5</td>
<td>13</td>
<td>0.1630</td>
<td>79.755</td>
<td>1.060E-03</td>
<td>1.619E-05</td>
<td>6.544E+01</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5</td>
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<td>2.403E-05</td>
<td>6.454E+01</td>
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<td>1.491E-03</td>
<td>3.133E-05</td>
<td>4.758E+01</td>
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</tr>
<tr>
<td>4</td>
<td>4</td>
<td>8</td>
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<td>2.270E-05</td>
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<td>1.890E-03</td>
<td>2.857E-05</td>
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</tr>
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<td>21.337</td>
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<td>2.187E-05</td>
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<td>2.740E-05</td>
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<td>10</td>
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<td>6.352E+01</td>
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<tr>
<td>10</td>
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<td>6.305E-05</td>
<td>4.691E+01</td>
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<td>11</td>
<td>5</td>
<td>8</td>
<td>73</td>
<td>0.1381</td>
<td>528.602</td>
<td>5.041E-03</td>
<td>9.423E-05</td>
<td>5.349E+01</td>
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</tr>
<tr>
<td>12</td>
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<td>10</td>
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<td>217.996</td>
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<td>1.234E-04</td>
<td>4.106E+01</td>
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<td>13</td>
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<td>859.519</td>
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</tr>
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<td>6.257E-03</td>
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<td>5.585E+01</td>
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<tr>
<td>15</td>
<td>7</td>
<td>5</td>
<td>25</td>
<td>0.0922</td>
<td>271.267</td>
<td>1.152E-03</td>
<td>8.392E-05</td>
<td>1.373E+01</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>4</td>
<td>10</td>
<td>89</td>
<td>0.1532</td>
<td>580.940</td>
<td>6.817E-03</td>
<td>1.069E-04</td>
<td>6.375E+01</td>
<td></td>
</tr>
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<td>17</td>
<td>5</td>
<td>5</td>
<td>66</td>
<td>0.0834</td>
<td>791.652</td>
<td>2.751E-03</td>
<td>6.933E-05</td>
<td>3.968E+01</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>7</td>
<td>8</td>
<td>52</td>
<td>0.1970</td>
<td>263.959</td>
<td>5.122E-03</td>
<td>1.066E-04</td>
<td>4.806E+01</td>
<td></td>
</tr>
</tbody>
</table>

Table 6 demonstrates that the energy absorption increases linearly as height increases from 5 to 8 to 10mm, keeping D as 0.5mm, Y as 5mm similarly with D as 1mm, Y as 4 and 5mm. However, this pattern is not followed in the cases for which D is 0.5mm, Y is 4 & 7, and D is 1mm and Y is 7mm. For these cases, energy absorption is largest for heights of 8mm. There is an irregularity observed in these particular combinations of analysis for which the model is simulated at the yield strength of the material. Therefore, it is recommended that the model should not be considered further for testing as the results lack in stability and do not follow a constant pattern as in previous configurations.
4.2.4 Configuration 4: Tetrahedron Structure

Since the tetra structure does not give a regular constant pattern of energy absorption, this modified configuration adds three rods joining the free edges of that structure. Now, we are interested in whether the energy absorption scenario changes or follows a pattern like earlier configurations. Table 7 provides the results where the load is kept constant and different geometrical parameters are varied.

Table 7. Configuration 4: Results for Energy Absorption under Constant Loading.

<table>
<thead>
<tr>
<th>Analysis #</th>
<th>D mm</th>
<th>L mm</th>
<th>F N</th>
<th>δ mm</th>
<th>K N/mm</th>
<th>E Nm or J</th>
<th>mass half model, kg</th>
<th>E1 half model, J/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>5</td>
<td>73</td>
<td>0.010</td>
<td>7.14E+03</td>
<td>3.73E-04</td>
<td>2.461E-05</td>
<td>1.516E+01</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>8</td>
<td>73</td>
<td>0.016</td>
<td>4.50E+03</td>
<td>5.92E-04</td>
<td>4.018E-05</td>
<td>1.474E+01</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>10</td>
<td>73</td>
<td>0.026</td>
<td>2.79E+03</td>
<td>9.55E-04</td>
<td>5.057E-05</td>
<td>1.889E+01</td>
</tr>
<tr>
<td>4</td>
<td>0.8</td>
<td>5</td>
<td>73</td>
<td>0.004</td>
<td>1.91E+04</td>
<td>1.40E-04</td>
<td>6.125E-05</td>
<td>2.281E+00</td>
</tr>
<tr>
<td>5</td>
<td>0.8</td>
<td>8</td>
<td>73</td>
<td>0.006</td>
<td>1.12E+04</td>
<td>2.37E-04</td>
<td>1.012E-04</td>
<td>2.340E+00</td>
</tr>
<tr>
<td>6</td>
<td>0.8</td>
<td>10</td>
<td>73</td>
<td>0.008</td>
<td>9.05E+03</td>
<td>2.94E-04</td>
<td>1.278E-04</td>
<td>2.304E+00</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>5</td>
<td>73</td>
<td>0.003</td>
<td>2.78E+04</td>
<td>9.60E-05</td>
<td>9.375E-05</td>
<td>1.024E+00</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>8</td>
<td>73</td>
<td>0.004</td>
<td>1.72E+04</td>
<td>1.55E-04</td>
<td>1.562E-04</td>
<td>9.891E-01</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>10</td>
<td>73</td>
<td>0.005</td>
<td>1.40E+04</td>
<td>1.90E-04</td>
<td>1.978E-04</td>
<td>9.623E-01</td>
</tr>
</tbody>
</table>

Here, there are only two geometrical variables. For an analysis in which the diameter is 0.5mm, the energy absorption does not follow a regular pattern. The rod length of 10mm gives maximum energy absorption; 8mm length gives the least. When the diameter is 0.8mm, the rod length with 8mm gives maximum energy absorption, and the 5mm length gives the least. If we consider a 1mm diameter, the 5mm rod length gives maximum energy absorption, whereas the 10mm rod length gives the least. Overall, maximum energy absorption is achieved with a 0.5mm diameter and 10mm rod length. These results demonstrate that the whole set of analyses do not have any regular pattern.
followed. Therefore, it can be said if further geometry is varied, more irregular results would be achieved. This makes the configuration unreliable, and the best possible combination that would be fit for further testing could not be determined. Now, we will see what would be the energy absorption scenario if these sets of combinations are analyzed at the yield point of the material (see Table 8).

Table 8. Configuration 4: Results for Energy Absorption at Yielding.

<table>
<thead>
<tr>
<th>Analysis #</th>
<th>D mm</th>
<th>L mm</th>
<th>F N</th>
<th>δ mm</th>
<th>K N/mm</th>
<th>E Nm or J</th>
<th>mass half model, kg</th>
<th>E1 half model, J/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>138</td>
<td>0.020</td>
<td>7.00E+03</td>
<td>1.36E-03</td>
<td>2.461E-05</td>
<td>5.526E+01</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>8</td>
<td>124</td>
<td>0.028</td>
<td>4.43E+03</td>
<td>1.74E-03</td>
<td>4.018E-05</td>
<td>4.321E+01</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>10</td>
<td>125</td>
<td>0.035</td>
<td>3.56E+03</td>
<td>2.20E-03</td>
<td>5.057E-05</td>
<td>4.340E+01</td>
</tr>
<tr>
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<td>0.8</td>
<td>5</td>
<td>446</td>
<td>0.025</td>
<td>1.78E+04</td>
<td>5.60E-03</td>
<td>6.125E-05</td>
<td>9.138E+01</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>8</td>
<td>326</td>
<td>0.029</td>
<td>1.12E+04</td>
<td>4.74E-03</td>
<td>1.012E-04</td>
<td>4.686E+01</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>10</td>
<td>388</td>
<td>0.043</td>
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<td>8.35E-03</td>
<td>1.278E-04</td>
<td>6.535E+01</td>
</tr>
<tr>
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<td>5</td>
<td>649</td>
<td>0.023</td>
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<td>8.093E+01</td>
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<td>8</td>
<td>660</td>
<td>0.038</td>
<td>1.74E+04</td>
<td>1.25E-02</td>
<td>1.562E-04</td>
<td>8.013E+01</td>
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<tr>
<td>9</td>
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<td>10</td>
<td>639</td>
<td>0.046</td>
<td>1.40E+04</td>
<td>1.46E-02</td>
<td>1.978E-04</td>
<td>7.375E+01</td>
</tr>
</tbody>
</table>

As we see here also, no regular pattern is followed in the analysis with a 0.5mm diameter and 0.8mm diameter. Only the diameter with 1mm has energy absorption decreasing as the length of the rod increases. So, all together, a perfect combination could not be determined, as there is no proper flow in the result data. For now, the maximum energy absorbed by this configuration is 9.138E+01 J/m³.

4.2.5 Configuration 5: The Pyramid Structure

This configuration follows the same approach as earlier configurations, and is simply a modification of Configuration 1, which now has horizontal rods connecting the edges. We will determine how much energy the different combinations of the geometry variables
absorb. Until now, it was seen that in the first set of analyses, force was kept constant. Later sets of analyses were done at yield point. Therefore, there are no significant interpretations drawn doing both sets. So, for this particular structure, only one set of analyses is carried out at yielding. Here, geometry variables are cross-sectional diameter and unit cell size (see Table 9).

Table 9. Configuration 5: Results for Energy Absorption at Yielding.

<table>
<thead>
<tr>
<th>#</th>
<th>D mm</th>
<th>Unit cell size mm</th>
<th>F N</th>
<th>δ mm</th>
<th>K N/mm</th>
<th>E Nm or J</th>
<th>mass half model, kg</th>
<th>E1 half model, J/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>5×5×10</td>
<td>181</td>
<td>2.47E-02</td>
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<td>7.5×7.5×15</td>
<td>179</td>
<td>3.83E-02</td>
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<td>3.14E-03</td>
<td>7.522E-05</td>
<td>4.179E+01</td>
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<tr>
<td>4</td>
<td></td>
<td>5×5×10</td>
<td>388</td>
<td>2.20E-02</td>
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<td>4.27E-03</td>
<td>9.171E-05</td>
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<td>10×10×20</td>
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<td>9.66E-03</td>
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<td>9</td>
<td></td>
<td>10×10×20</td>
<td>534</td>
<td>3.74E-02</td>
<td>1.43E+04</td>
<td>9.99E-03</td>
<td>2.951E-04</td>
<td>3.387E+01</td>
</tr>
</tbody>
</table>

In this configuration, the energy absorption increases linearly in case of cross-sectional diameters 0.5, 0.8, 1mm as size of the unit cell increases. If we see a 0.5mm diameter, the unit cell size 5mm absorbs maximum energy, whereas the 10mm unit cell size absorbs the least energy. Similarly, if we look at an analysis for which the diameter is 0.8mm and 1mm, the energy absorption decreases with increase in size of the unit cell. First, second and 5th configurations are similar. First is having no vertical or horizontal support. Second configuration has vertical struts; third configuration has horizontal member supports. If all three are observed, the configurations with horizontal members absorb more energy compared to vertical support. This is because when there is a vertical load, the members try to stretch horizontally however horizontal members adds stiffness in
horizontal direction. Now, we can compare all configurations together with maximum energy absorption.

4.3 Elastic and Plastic Energy Absorption

Following are the details of the load steps and displacements and their graph plot for the load displacement curve. Every graph in the following section was plotted as a complete curve, and then it was cut short to the yield point. Energy absorbed by the configuration is equal to the area under the load displacement curve. Now, the same combinations are continued for elastic and plastic analyses. However, it is observed that the available 3D printer does not print a cross-sectional diameter below 1mm. So, because of this limitation, all the diameters will be kept as 1mm for all configurations.

4.3.1 Configuration 1: Diamond

A table was made with the help of ANSYS result and included force divided into 8 load steps and the displacement of the model at each load step. As we can see, the load increment is still 80 N. This magnitude of the load was reached by doing several trials. Above this value, the load step failure occurs. The load is quite low, as the model is reduced to 1/8th. Accordingly, the energy absorption that is displayed in the table will be only of one leg member. The following is the load displacement curve for all of the load steps until the yield point. The area under the curve was found to be 27.250 mm². Dividing this by its mass (0.0068gms) will give us the energy absorption per unit mass, which is found to be 9.93E+05 J/kg (see Figure 53).
4.3.2 Configuration 2: Diamond with Vertical Struts

The diamond with vertical struts adds a little more stiffness to the model. This will increase the maximum load step value. A table was tabulated from the results, which consists of nine step loads. This can take a larger load than the magnitude 331 N. This magnitude was found out with repeated trials. A load displacement graph is plot from the above-tabulated results, which is shown in Figure 54. The area under the curve is calculated with help of Excel. Further dividing it by mass gives 1.25E+06 J/kg energy absorbed per unit mass. This configuration is absorbing more than double energy than the first one.

Figure 53. Configuration 1: Elastic + Plastic Analysis, Load Displacement Curve.
4.3.3 Configuration 3: The Tetra Structure

This structure is like a tripod and has much greater stiffness compared to previous configurations. This will require much higher load since there are no edges or stress concentration areas in between the members as before. The following is the load displacement curve plotted from the above results. After a load of 665 N, the load steps fail and solution does not converge. The area under the curve can be calculated with the help of Excel and is found to be 92.23 mm$^3$. Dividing it by the mass, we will get the energy absorbed per unit mass of 1.30E+06 J/kg (see Figure 55).
4.3.4 Configuration 4: The Tetrahedron

The tetrahedron structure is the best configuration from the elastic analysis until now, so we evaluated the elastic plus plastic analysis. This configuration supports a maximum force of 20253 N, which is the highest load so far. This load is divided into 14 load steps, displacements are found out, and the graph is plotted for the same. The yield point occurs at 20197.63 N with a displacement of 0.735 mm. If we observe the following graph and calculate the energy absorption, it is absorbing a maximum energy per unit mass of 1.22E+08 J/kg. This means that the triangular horizontal members that support the tetrahedron structure adds a tremendous amount of stiffness, which increased the load value until 20253 N. The following is the load displacement curve for the tetrahedron structure (see Figure 56).
4.3.5: Configuration 5: The Pyramidal Structure

This is just a modification of Configuration 1. However, this configuration has horizontal members supporting the structure. As previously examined, it gives very good stiffness support to the main structure from deforming downwards. It was found that after the load of 9668 N, load step failure occurs. Dividing this load into 9 load steps and recording their respective stiffness, a graph was plotted for the calculation of the energy absorption (see Figure 57). The area under the curve was found to be 2730.58 mm$^2$. Dividing the area by its mass gives us 2.75E+07 J/kg of energy absorption, which is almost one and four times lower than the tetrahedron structure.

Figure 56. Configuration 4: Elastic + Plastic Analysis, Load Displacement Curve.
Until now, we have seen all the analysis results of the elastic and plastic analysis. These results imply that Configuration 4 (tetrahedron) is best in the elastic analysis performed in SOLIDWORKS. Therefore, following the same trend line, Configuration 4 (tetrahedron) is also best in the elastic plastic analysis performed in ANSYS APDL. Therefore, these configurations need to be 3D printed and practically tested for a better understanding of the best configuration among these five. The next chapter will give all the details of the testing part of the research, which will determine the best configuration.
Chapter 5 Compression Testing

5.1 Overview

Compression testing is the practical analysis in which all the models will be 3D printed and tested in a compression testing laboratory. Performing this practically would give us a better understanding of which configuration is the best for the energy absorption. This chapter addresses all the information regarding the 3D printing of the models, including the process of testing and analysis, as well as the discussion of the results. Furthermore, problems that occurred while printing or testing will also be discussed. For testing, all the lattice structures configurations were designed in SOLIDWORKS. The overall sample size was considered to be 25×25×20 mm³.

5.2 Printing Samples

For each configuration, the sample to be printed was selected from the combination of the elastic and elastic-plastic analyses tables, which has absorbed maximum energy. The lattice structure consisted of 5 unit cells by 5 unit cells by 4 layers upwards, which makes it 25×25×20. Now, some structures are easy to get in such a size requirement, such as Configurations 1, 2 and 5. Since they have similarity in the X- and Y-axes, they can be patterned in a rectangular way. For other configurations such as tetra structures and tetrahedrons, it is very difficult to arrange them in a rectangular pattern as they do not have any symmetry in the X- and Y-axes. Therefore, this problem was solved by creating
circular patterns that were later cut into a rectangular shape and size as needed for printing. The STL files were processed by the slicing software Catalyst. Furthermore, they were sent to the printer for building. There were some problems that occurred on printing: the cross-sectional diameters for some samples needed to be 0.5mm, but after observations of creating some samples, it was noticed that the available printer could not print 0.5mm diameters. Because the structures are complicated for a 3D printing approach, they require many support structures for building it (see Figure 58).

![Figure 58. Configurations 3, 4 and 5 with support structures.](image)

Figure 58 shows that the configurations are with support structure materials yet to be removed; the following procedure elaborates about how support material is to be removed for the further testing of the model.

5.3 Removing Support Material

After building it, the whole model was almost covered in support material. As these models, have so many void spaces, all the configurations were going to require such kind of support structures. Figure 59 is of the support cleaning apparatus used to dissolve all the support material on the main model.
This is a chemical bath for models that require removal of support material. This apparatus has cleaning agent mixed with water to form a solution. After immersing the samples in the apparatus, the bath must raise to a certain temperature for a certain duration of hours. For our procedure, the configuration required three and half hours for printing and four hours for cleaning support material. When cleaning is finished, the bath is at a high temperature. This solution at high temperature might be very harmful to the skin, so we had to wear special gloves and eye gear to use this apparatus [14]. After the support structures are removed, the models are identical to how they were built in the CAD software. Figures 60-64 are the pictures of all the configurations after support removal and cleaning.
Figure 60. Configuration 1 after removal of support material.

Figure 61. Configuration 2 after removal of support material.

Figure 62. Configuration 3 after removal of support material.
5.4 Compression Testing

Figure 65 shows the compression-testing machine. It performs different types of testing, but this project required only compression testing. The following provides the details in regards to the procedure used.
Figure 65. Compression testing machine.

Figure 65 depicts the image of INSTRON 5500 R universal testing equipment that was used for performing compression tests. This testing system represents a range of high performance load frames and high bandwidth (DSP) Digital Signal Processing-based electronics. The Bluehill modular application software is installed in a computer, allowing for running different tests [22]. Figure 66 shows the controller with which the load cell is controlled.
Figure 66. Controller testing machine.

Figure 67 depicts the load cell and plate arrangement on which the samples are kept for compression testing. The load cell is jogged down and fine-tuned until it touches the sample, and then the software controls the rest of the part.

The load cell has the maximum load capacity of 30,000 LB or can apply 150 KN of force (see Figure 67).
Before testing the samples, the weight of the samples was recorded to be used in the energy absorption calculations. The following sections provide the details of the applied load and displacements recorded for each configuration. Accuracy was a critical requirement, as there are about 15000 readings taken before the configurations break. With so many points, we can say that the load displacement curve can be highly reliable. If there are errors induced in the testing procedure, they would be in the printing part. For example, some members might not be properly printed, or some edges are not printed properly. These things can induce stress concentration areas, and the sample can quickly break there.

5.5 Compressi*n Test Results

The compression test results for all the five configurations in the form of a load-displacement curve are presented and discussed in the next sections.
5.5.1 Configuration 1: Diamond

The readings taken for this configuration are 14403. The load-displacement curve including all the readings is shown in Figure 68.

![Configuration 1 compression test complete curve](image)

*Figure 68. Configuration 1 load displacement curve complete curve.*

The dome-like curve at the start indicates that it required lot of load to break the last layer and that there was a gradual breakage of the rest of the layers, as evidenced by the dents in the curve that go down as the curve proceeds. Those are because of the layers that break in the testing. The load suddenly drops as the layer breaks. Also, the ones with the little notches are because of breakage of a few members at once. The load fluctuates at that moment. The curve that goes very high in the end implies that all the layers are broken down and the lattice structure has become a complete solid, which obviously requires the highest load to compress further. However, we are interested in the curve till yield point only, which is shown in Figure 69.
Figure 69. Configuration 1 until the yield point.

This configuration reached a maximum value of about 155 N, which is a quite good result, as the configuration does not have any vertical members or horizontal members to support it. Figure 70 shows the compression process of Configuration 1.

Figure 70. Compression testing process Configuration 1.

As load increases, the layer at the bottom breaks first, then the second last. After that, the first two break gradually and simultaneously. The area under the curve until the yield point was 123.37 J. The mass of the lattice structure was 2.2084 grams. The calculated energy absorbed per unit mass was found to be 5.59E+04 J/kg.
5.5.2 Configuration 2: Diamond with Vertical Struts

This configuration has vertical struts that add stiffness to the material. So, a higher load is expected in this analysis test. Figure 61 is the complete load-displacement curve from the testing process.

![Configuration 2 compression test complete curve](image)

*Figure 71. Configuration 2: Compression test complete curve.*

As we see, there are two peaks clearly visible. The first peak was the load required to break the middle layer first. After further members break, they form a horizontal surface, which further supports the structure. Therefore, an even higher load is required to break the next layer. The little fluctuations in the curve indicate breakage of the members. The process is seen in Figure 72.
As the load starts increasing beyond what the lattice structure can bear, the layer in the middle starts to collapse. Further increase in load makes the top and the bottom layer flat, leaving the layers, which have vertical struts, to bear further load. Further increase in load makes the bottom layer with the vertical struts to fail; eventually, the last one fails, making the lattice structure a completely solid block. Figure 73 shows the graph until the yield point and its results.

![Configuration 2 Compression test Graph till yield point](image)

**Figure 73.** Configuration 2: Compression test Graph till yield point.

There are no significant notes drawn as the graph gradually increases as the load increases. The only part where the load is constant and flat little parts in the curve is where some members break. The flat part at the start might be because there was a very small gap
between the sample and the load cell at the start of the test. Therefore, the area under the curve until the yield point is 161.34 J, whereas the mass of the lattice structure was 2.513 grams. The energy absorbed per unit mass was calculated to be 6.42E+04 J/kg.

5.5.3 Configuration 3: The Tetra Structure

From Configuration 3, there is complete change in the lattice formations. The lattices hereafter are in the tetrahedrons or pyramids. Let us see how it affects the energy absorption in practical testing. Figure 74 shows the complete load displacement curve for the compression test.

*Figure 74. Configuration 3: Compression test complete curve.*

In the plotted load displacement curve, we can see a sharp and big peak at the start, and then the load is quite low. This happened because the structure was quite stiff at the start. With further increase in load, some unit cells in the above two layers and some unit cells in the lower two layers fail all at once. Therefore, the load cell kept crushing the broken unit cells further. The process can be seen in Figure 75.
Figure 75. Compression process for Configuration 3.

The unit cells in different layers break at once because there is no vertical or horizontal support, which prevents them from breaking layer by layer. Therefore, the breaking behavior of such configuration is very unpredictable. After the random breakage of the unit cells, remaining unit cells fall on the same bottom layer, making it stiff again. This indicates the second peak in the graph in Figure 76.

Figure 76. Configuration 3: Compression test graph until yield point.

The graph until the yield point is shown in Figure 66. The model was quite unstable, which can be noticed from the above discussion. However, this lattice structure can support about 650 N load. The area under the curve until the yield point is 271.435 J. The mass
measured before testing was 2.99 grams. The energy absorbed per unit mass was calculated to be 9.07E+04 J/kg.

### 5.5.4 Configuration 4: The Tetrahedron Structure

The tetrahedron structure has been the best configurations in terms of elastic and plastic analyses. Now, let us see if the same trend follows in the actual testing too or not. Figure 77 shows the complete load displacement curve.

![Configuration 4 Compression test complete curve](image)

*Figure 77. Configuration 4: Compression test complete curve.*

The dome at the first portion until the displacement 2mm shows massive stiffness, which went up to 3500 N. This stiffness is added because of the horizontal triangular ring completing the tetrahedron structure. As the load increases, the top layer breaks, then the second, third, and then the last one. So, every layer breaks in order and gradually (see Figure 78). This indicates the load is distributed by the structure properly and can be an ideal model for the applications.
Figure 78. Configuration 4: Compression process.

Figure 79 is the graph plotted until the yield point, which explains additional details.

As we can see in Figure 79, the graph gradually proceeds and is quite smooth. This implies that there are no sudden load fluctuations until the yield point. The area under the curve until the yield point was recorded as 2121.2 J, which is the maximum until now. The mass was recorded as 3.63 grams. Finally, the energy absorbed per unit mass was calculated to be 5.84E+05 J/kg. This is the maximum energy absorption recorded in compression testing until now.
5.5.5 Configuration 5: The Pyramidal Structure

The pyramidal structure surprisingly does not absorb energy greater than the tetrahedrons, according to previous observations in elastic and plastic simulations. Figure 80 shows its testing load displacement curve.

![Configuration 5: Compression test, complete curve](image)

*Figure 80. Configuration 5: Compression test, complete curve.*

This graph has a similar peak as in the tetra structure. The maximum load reached for this configuration is about 2000 N, which is better than the tetra structure but not as good as the tetrahedron. Figure 71 addresses whether the layers broke like the tetra structure.

![Configuration 5: Compression process](image)

*Figure 81. Configuration 5: Compression process.*
As we can see, the breaking process is not as uncontrolled as the tetra structure. It happens layer by layer. A possible reason is because of the horizontal members supporting each unit cell. As the load increases above its bearing capacity, the last layer breaks, then second last, then second, and finally the first one. The similar pattern was observed in the second configuration. Figure 82 provides further details of the test results.

![Configuration 5 compression test, curve till yield point](image)

**Figure 82.** Configuration 5: Compression test, curve till yield point.

This curve is quite smooth and without any notches or fluctuations in load. In a complete curve, similar smoothness could also be found, which implies that the compression process was gradual and without sudden breakage into pieces. The total area under the curve until the yield point was recorded as 1215.94J. The mass of the lattice configuration was recorded before the test was 2.916 grams. Finally, the energy absorption per unit mass was calculated to be 4.17E+05 J/kg.

The pictures before and after were taken to observe what the lattice structure looks like after the compression tests. Figures 83-85 show the pictures of five configurations.
Figure 83. Configuration 1 before after.  Configuration 2 before after.

Figure 84. Configuration 3 before after.  Configuration 4 before after.

Figure 85. Configuration 5 before after.
Chapter 6. Summary and Conclusion

6.1 Overview

This chapter will summarize all the results and include the best combinations from all different configurations in the elastic analyses sets, plastic analyses sets, as well as the testing analysis to finalize the selected configurations.

6.2 Elastic Analysis Results Summary

The elastic analyses completed for all five configurations consist of tables tabulated by performing several sets of analyses by varying the geometry. Noting down Table 10 summarizes the best combinations that give maximum energy absorption and all the results.
Table 10. Summary for Elastic Energy Absorption Results.

<table>
<thead>
<tr>
<th>Configuration 1: Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis #</td>
</tr>
<tr>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Configuration 2: Diamond with vertical rods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis #</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Configuration 3: Tet legs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis #</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Configuration 4: Tetrahedron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis #</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Configuration 5: Pyramid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis #</td>
</tr>
<tr>
<td>1</td>
</tr>
</tbody>
</table>

Table 10 provides a hierarchy of energy absorbing capacity of the different configurations. Configuration 2 absorbs more energy compared to Configuration 1 due the vertical struts, which support the structure from deforming downwards. Further, we can see that the tetra structure absorbs more energy than Configurations 1 and 2. The tetrahedron configuration absorbs even more, specifically 9.14E+01 J/kg, which is the largest among all of them. Looking at the results and revising the concepts described in the literature survey, we can say that the tetrahedron structure belongs to the stretch dominated structures, whereas the diamond and diamond with struts belong to the bending dominated structures.
structures. In the following section, we will discuss the plastic deformation and its summary.

6.3 Elastic + Plastic Energy Absorption Results Summary

Table 11 summarizes the energy absorption per unit mass by each configuration. First, the graph for load displacement curve was plotted for all of the load steps. Then, the graph was reduced until the yield point as the scale of axes for all configurations were found to be very dissimilar.

Table 11. ANSYS Results Summary for Elastic and Plastic Analysis.

<table>
<thead>
<tr>
<th>Configuration #</th>
<th>Area under the load displacement curve, till yield point Ayp, J</th>
<th>Mass kg</th>
<th>Energy absorbed per unit mass J/gm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration 1: The Diamond</td>
<td>27.25</td>
<td>1.0977E-02</td>
<td>9.9299E+05</td>
</tr>
<tr>
<td>Configuration 2: Diamond with vertical struts</td>
<td>68.85</td>
<td>1.0981E-02</td>
<td>1.2540E+06</td>
</tr>
<tr>
<td>Configuration 3: The Tetra Structure</td>
<td>92.23</td>
<td>7.9459E-03</td>
<td>1.3000E+06</td>
</tr>
<tr>
<td>Configuration 4: The Tetrahedron Structure</td>
<td>7898.34</td>
<td>1.2904E-02</td>
<td>1.2242E+08</td>
</tr>
<tr>
<td>Configuration 5: The Pyramidal Structure</td>
<td>2730.58</td>
<td>9.9390E-03</td>
<td>2.7473E+07</td>
</tr>
</tbody>
</table>

As we see from the tabulated results in Table 11, the trend line is followed and found to be similar for Configuration 4, which absorbed the maximum energy per unit mass. After Configuration 4, the energy absorption drops in the fifth configuration. The actual practical results have much importance. Those results will confirm which configuration is better and if the trend line is followed. There was a difference observed in
the printed samples. The cross-sectional diameter of the printed samples were larger than they were supposed to be. The diameters in Configurations 1, 3, and 5 were 0.5mm, whereas Configuration 4 had a diameter of 0.8mm. However, the cross-sectional diameters, which were 3D printed, were more than 0.5mm, and some were more than 1mm. Observing this, we can understand that printer cannot print a cross-sectional diameter less than 1mm. This is the limitation of the 3D printer that was used for this thesis research. Moreover, tetra structures were very difficult to 3D print because of the angles of the members. However, after multiple modifications and trials, some testable samples were printed. So, considering all of the above-mentioned limitations, the trend line was somewhat expected to differ. The next section provides a testing summary.

6.4 ABS Compression Testing Results

The energy absorption was calculated in the same way as elastic plastic analyses; Table 12 is the summary of all the results.

<table>
<thead>
<tr>
<th>Configuration #</th>
<th>Area under the load displacement curve, till yield point Ayp, mm$^2$</th>
<th>Mass gms</th>
<th>Energy absorbed per unit mass J/gm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Configuration 1:</strong> The Diamond</td>
<td>123.37</td>
<td>2.2084</td>
<td>5.59E+04</td>
</tr>
<tr>
<td><strong>Configuration 2:</strong> Diamond with vertical struts</td>
<td>161.34</td>
<td>2.5129</td>
<td>6.42E+04</td>
</tr>
<tr>
<td><strong>Configuration 3:</strong> The Tetra Structure</td>
<td>271.44</td>
<td>2.99</td>
<td>9.07E+04</td>
</tr>
<tr>
<td><strong>Configuration 4:</strong> The Tetrahedron Structure</td>
<td>2121.20</td>
<td>3.63</td>
<td>5.84E+05</td>
</tr>
<tr>
<td><strong>Configuration 5:</strong> The Pyramidal Structure</td>
<td>1215.94</td>
<td>2.916</td>
<td>4.17E+05</td>
</tr>
</tbody>
</table>
From Table 12, we can see that Configuration 4 absorbs maximum energy per unit mass $5.84 \times 10^5$ J/kg, which is like previous sets of analyses. Table 13 summarizes comparison of all the procedures followed that are elastic analysis, elastic plastic analysis, and testing results.

Table 13. Comparison of all the procedures.

<table>
<thead>
<tr>
<th>Configuration #</th>
<th>Elastic analysis J/kg</th>
<th>Elastic + Plastic analysis J/kg</th>
<th>Compression tests J/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.23E+02</td>
<td>4.01E+06</td>
<td>5.59E+04</td>
</tr>
<tr>
<td>2</td>
<td>2.54E+02</td>
<td>4.33E+06</td>
<td>6.42E+04</td>
</tr>
<tr>
<td>3</td>
<td>3.24E+02</td>
<td>4.61E+06</td>
<td>9.07E+04</td>
</tr>
<tr>
<td>4</td>
<td>4.06E+02</td>
<td>3.73E+08</td>
<td>5.84E+05</td>
</tr>
<tr>
<td>5</td>
<td>2.69E+02</td>
<td>8.59E+07</td>
<td>4.17E+05</td>
</tr>
</tbody>
</table>

6.5 Trend Line

From all the above results, the energy absorbed per unit mass is calculated for each configuration. It is very necessary to observe if the trend line follows in respective sets of analyses. Until now, the elastic analysis was performed in SOLIDWORKS and the elastic + plastic analysis was performed in ANSYS APDL, whereas compression testing was performed in practical testing. Figures 86-88 plot the energy absorbed per unit mass versus configuration number to observe the trend line between the five configurations and can be compared to different means of analysis.
Figure 86. Trend line Elastic analysis.

Figure 87. Trend line Elastic + Plastic analysis.
6.5 Conclusion

Observing all the results and comparing them we can conclude the following. As the unit cell size increases it loses its stiffness as well as the energy absorption capacity. Stretch dominated structures are supposed to absorb more energy compared to bending dominated structures. We can conclude that Configuration 4 is the best among all, and the trend line follows in elastic, elastic + plastic as well as for compression testing practical.

6.6 Recommendations for future work:

After doing more than 200 analyses and 15 tests from which I drew my observations and conclusions, I can say there is a tremendous scope in this research. Some techniques, which were found during last stage of this thesis, leave more space for structural optimization. The density of the material at the stress concentration areas play a vital role in the whole analysis process. Use of HyperMesh software and tools like optistruct can further add topology optimization for the configurations. For optimizing and getting even
better results, the stress concentration areas should be made denser, which would give better results in terms of energy absorption. In addition, if the selected configuration is made hollow, it might optimize the model even further.
Bibliography


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Appendix

ANSYS input files for elastic + plastic analysis

Configuration 1

/PREP7

MPTEMP,1,0           ! Define temperatures for Young’s modulus
ET,1,BEAM188
!*               
!*               
rad=0.25
MPTEMP,1,0
MPDATA,EX,1,,1.038e5
MPDATA,PRXY,1,,0.31
TB,BKIN,1,2,2,1           ! Activate a data table with TBOPT=1
                       ! stress relaxation with temperature
TBTEMP,0.0                ! Temperature = 0.0
TBDATA,1,1080,643.32       ! Yield = 44,000; Tangent modulus = 643.32

SECTYPE, 1, BEAM, CSOLID, , 0
SECOFFSET, CENT
SECDATA,rad,0,0,0,0,0,0,0,0
A=3.54
B=2.5

k,1
K,2,A,B
K,3,,2*B

L,1,2
L,2,3
lesel,s,,,1,2,1
lesize,all,,4
lesel,all
LMESH,1,2

NSEL,S,LOC,X
NSEL,R,LOC,Y
D,ALL,ALL
NSEL,ALL

NSEL,S,LOC,X
NSEL,S,LOC,Y,2*B
D,ALL,UX,0
NSEL,ALL
FINISH

/SOLU
nsubst,10,1000,1
nlgeom,on
OUTRES, NSOL, 1,
F,6,FY,-83
!OUTPR,BASIC,1
solve

FINISH

Configuration 2:

/PREP7
MPTEMP,1,0 ! Define temperatures for Young's modulus
ET,1,BEAM188

*SET,rad,0.5
MPTEMP,1,0
MPDATA,EX,1,,1.038e5
MPDATA,PRXY,1,,0.31
TB,BKIN,1,2,2,1 ! Activate a data table with TBOPT=1
! stress relaxation with temperature
TBTEMP,0.0 ! Temperature = 0.0
TBDATA,1,1080,643.32 ! Yield = 44,000; Tangent modulus = 643.32
SECTYPE,  1, BEAM, CSOLID, , 0
SECOFFSET, CENT
SECDATA,rad,0,0,0,0,0,0,0,0,0

K,1,0,0,,
K,2,3.54,2.5,,
K,3,0,5,,
K,4,3.54,7.5,,
K,5,0,10,,
LSTR,   1,   2
LSTR,   2,   3
LSTR,   3,   4
LSTR,   4,   5
LSTR,   4,   2

SMRT,4
FLST,2,5,4,ORDE,2
FITEM,2,1
FITEM,2,-5
LMESH,P51X

D,1, , , , , , , ,ALL, , , , , , ,
D,5, , , , ,UX, , , , , , ,
D,11, , , , ,UX, , , , , , ,
FINISH

/SOLU

nsubst, 10, 1000, 1
nlgeom, on
OUTRES, NSOL, 1,
F, 11, FY, -337.5
!OUTPR, BASIC,
solve
FINISH

**Configuration 3**

/ PREP7
MPTEMP, 1, 0 ! Define temperatures for Young's modulus
ET, 1, BEAM188

*SET, rad, 0.25
MPTEMP, 1, 0
MPDATA, EX, 1,, 1.038e5
MPDATA, PRXY, 1,, 0.31
TB, BKin, 1, 2, 2, 1 ! Activate a data table with TBOPT=1
! stress relaxation with temperature

TBTEMP, 0.0 ! Temperature = 0.0
TBDATA,1,1080,643.32 ! Yield = 44,000; Tangent modulus = 643.32

SECTYPE, 1, BEAM, CSOLID, , 0
SECOFFSET, CENT
SECDATA,rad,0,0,0,0,0,0,0,0,0,0,0,0

*SET,A,2
*SET,B,3.46

k,1,A,-B
K,2,A,B
K,3,-2*A
K,4,4*A
L,1,4
L,2,4
L,3,4

lsel,s,,,1,3,1
lesize,all,,,4
lsel,all

LMESH,1,3

nsel,s,loc,y
d,all,all
nsel,all
finish

/SOLU

nsubst,10,1000,1
nlgeom,on
OUTRES, NSOL, 1,
F,2,FY,-559.6
!OUTPR,BASIC,1
solve
FINISH

Configuration 4

/PREP7
MPTEMP,1,0  ! Define temperatures for Young's modulus
ET,1,BEAM188

*SET,rad,0.4
MPTEMP,1,0
MPDATA,EX,1,,1.038e5
MPDATA,PRXY,1,,0.31
TB,BKIN,1,2,2,1  ! Activate a data table with TBOPT=1
! stress relaxation with temperature
TBTEMP,0.0  ! Temperature = 0.0
TBDATA,1,8.27e8,643.32  ! Yield = 44,000; Tangent modulus = 643.32
SECTYPE, 1, BEAM, CSOLID, , 0
SECOFFSET, CENT
SECDATA,rad,0,0,0,0,0,0,0,0,0

*SET,A,2.5
*SET,B,1.44

k,1,A,,B
K,2,-A,,B
K,3,-2.89
K,4,4.08

L,1,4
L,2,4
L,3,4
L,1,2
L,2,3
L,1,3

SMRTSIZE,6
FLST,2,6,4,ORDE,2
FITEM,2,1
FITEM,2,-6
LMESH,P51X
/CPLANE,1
/REPLOT,RESIZE
WPSTYLE,,,,,,,,0
/PREP7
MPTEMP,1,0 ! Define temperatures for Young's modulus
ET,1,BEAM188
*SET,rad,0.5
MPTEMP,1,0
MPDATA,EX,1,,1.038e5
MPDATA,PRXY,1,,0.31
TB,BKIN,1,2,2,1 ! Activate a data table with TBOPT=1
! stress relaxation with temperature
TBTEMP,0.0 ! Temperature = 0.0
TBDATA,1,8.27e8,643.32 ! Yield = 44,000; Tangent modulus = 643.32
SECTYPE, 1, BEAM, CSOLID, , 0
SECOFFSET, CENT
SECDATA,rad,0,0,0,0,0,0,0,0,0
*SET,A,2.5
k,1,A,,A
K,2,A,,A
K,3,-A,,A
K,4,-A,,A
K,5,,2*A
L,1,2
L,2,3
L,3,4
L,1,4
L,1,5
L,2,5
L,3,5
L,4,5
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FITEM,2,-8
LMESH,P51X
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D,5, , , , , , , ,UY, , , , ,
D,8, , , , , , , ,UY, , , , ,
D,13, , , , , , , ,UX, , , , ,
D,13, , , , , , , ,UZ, , , , ,
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!*  
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nlgeom,on
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FINISH
/SOL
/STATUS,SOLU
SOLVE
FINISH
/POSTI
SET,LIST,999
FINISH
! /EXIT,ALL