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Research Article

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Analysis of Compression Behavior of TPMS and Strut type Lattice Structures Using Finite Element Method

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Abstract

Latest developments in Additive Manufacturing have expedited the production of parts with complex structures and smaller sizes. Being a space-filling unit cell, lattice structures can be structured along any axis without any gap between them. As a solution to the weight, energy and advanced manufacturing challenges in the medical field, lattice structures have evolved as an advanced solution. In this work, the compressive properties of two classes of lattice structures have been studied and compared. The first class is the TPMS or Triply Periodic Minimal Surfaces (for example, Gyroid Diamond, etc.) and the second class is the Strut based lattice structures (for example, BCC, FCC, etc.). Implicit modelling approach has been adopted in this article to create different types of lattice structures using the nTopology software. This was followed by compression testing to determine the response of considered lattice structures using Finite Element Analysis ANSYS 2020 software. From the results obtained it can be concluded that TPMS based lattice structures exhibit superior mechanical properties than the strut-based lattice structures. Among them, the diamond TPMS has the maximum compressive load bearing capacity. It was also observed that with a decrease in volume fraction, the effect of geometry on the mechanical properties increases. This study is likely to assist in the design of improved modern day medical implants.

Keywords

Strut based lattice, Triply periodic minimal surfaces, Additive manufacturing, Medical implants, Finite element analysis

Introduction

In literature, lattice structure is specified as continuously repeating unit cells that are periodic in nature and interconnected in three dimensions. They can be made of trusses and minimal surfaces [1]. They possess multiple significant properties like high stiffness to weight ratio, high compressive load bearing capacity, heat dissipation, and heat transfer control. Due to the recent developments in Additive Manufacturing, lattice structure is becoming more significant in order to achieve the following objectives:

1. Decrease in amount of material used in fabrication.
2. High strength to weight ratio.
3. Decreased time taken and energy utilised in fabrication.

While manufacturing of a product, the main problems that arise are the optimisation of energy, material, and time. Such problems can be easily resolved by using the lattice structures. Lattice structures have a large number of appli-

cations in a variety of industries. For example, in biomedical implants as they mimic properties closer to that of bone [2, 3], scaffolds for tissue engineering [3] and bone replacement [4], lightweight bodies [5], heat exchangers [6 - 8], filters [9], in aerospace industries to enhance the performance to weight ratio by making lightweight parts in order to achieve the desired performance in aerospace vehicles [5], etc.

Lattice structure possess high energy-absorption capacity which makes them very useful in absorbing and distributing the shock across the whole body, as they have the property to propagate energy through their structure [10]. Micro-lattice structure possesses higher area density which makes them ideal for use in heat exchangers, thermal storage devices and heat sinks, etc. and they are also significant at places where heat dissipation and structural support are required simultaneously [11]. Cellular structures are generally periodic which includes two-dimensional cell configuration (such as honeycomb) or three-dimensional polyhedral layouts lattice structure - figure 1 [12, 13]. The properties of cellular structures can be defined as a function of relative density, architecture of the unit cell and the solid components. On applying an observable load on this structure, they tend to deform by the union of twisting, bending, or stretching of strut members [14]. Much research has taken place to find the optimum lattice structure which yields the best mechanical properties using lesser amount of material so as to improve the strength to weight ratio. And this resulted in many studies which mainly focussed on the cell topology, improving the mechanical properties [15]. Mainly in tissue engineering field, several research took place to find the best lattice structures which exactly represent the nature of bone and helps in regenerating the damaged tissue cells [16, 17].

Helou et al. [1], in his work, studied the different lattice structure and their scope in industries. In addition to highlighting the areas that require additional research in the design, simulation, fabrication, application, and characterization of lattice structures, this work compiles limitations and future work that may offer a better understanding of theoretical and technological restrictions of lattice structures.

Heinl et al. [2] studied cellular Ti-6Al-4V structures which was fabricated by employing selective electron beam melting (SEBM) for the orthopaedic applications. For demonstrating the properties of three-dimensional structures, Microcomputer tomography (μCT) analysis was used. The outcomes demonstrated that the manufactured structures' mechanical attributes, such as compressive strength and elastic modulus, were comparable to those of bone.

The work carried out by Al-Ketan et al. [6] illustrates the link between topology and properties of many kinds of periodic cellular materials. The cellular structures of different relative densities were created using powder bed fusion technique using maraging steel. The quality of the printed pieces was further evaluated using a scanning electron microscope (SEM). Compressive testing was carried out to assess the compressive characteristics. The results indicate that the Diamond TPMS with a sheet base exhibit the best mechanical performance.

Sur et al. [11] in his work, studied the thermal based applications of lattice structures. They have exceptional heat transmission, energy absorption, and vibration management properties. The micro-lattice structures, their production processes, and applications were examined. For thermal management system of battery in electric vehicles, a submissive heat transfer mechanism made of micro-lattice heat pipes is given in this work.

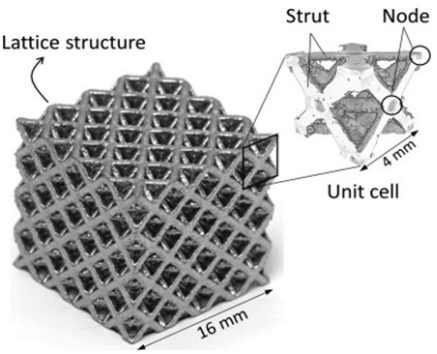


Figure 1: Regular three-dimensional arrangement of points in space [31].

Although much research has been done to find the best lattice structure but most of the studies evaluated the mechanical properties experimentally and usage of FEA to calculate the mechanical properties is still a novelty. Till now no study has been carried out on evaluating the mechanical properties of lattice structure considering polymer as material. In this study, compressive properties of lattice structures have been evaluated numerically using finite element method. This work has been carried out with the aim of reducing weight and obtaining higher strength-to-weight ratio. It allows the tuning of their architecture for various applications.

Types of lattice structures: strut-based and TPMS-based

Much research has been done on strut-based lattice structure like BCC, FCC, Kelvin cell, and hexagonal honeycomb as shown in the CAD models of figure 2 for cellular metals which exhibit cubic symmetry [18]. Strut-based lattice structure are the most common type structures which contain rod like structures periodically in the three perpendicular directions. The mechanical properties of these structures can be defined by the way in which these rods like structure are connected.

But now researchers are shifting their interest towards cellular structures whose architecture is mathematically defined such as TPMS. TPMS are cellular structures having complex 3D geometry with reduced surface area which can be repeated periodically in three directions [20 - 24]. There are various types of TPMS lattice structures such as Gyroid, Schwarz, Diamond and SplitP (Figure 3). TPMS lattice structure has two main advantages. The first is that they can be expressed by mathematical functions and the second is that the TPMS do not have sharp edges like other lattice structures [24]. There are many applications of TPMS in the field of engineering such as in tissue engineering [25 - 26] and structural engineering [27 - 29]. They are good conductors of heat and electricity, have tunable acoustic attenuation and fluid permeability and visible photonic crystal properties [30]. Much research took place, and it has been proved that the TPMS lattice structures have better mechanical properties than the conventional lattice structures [31].

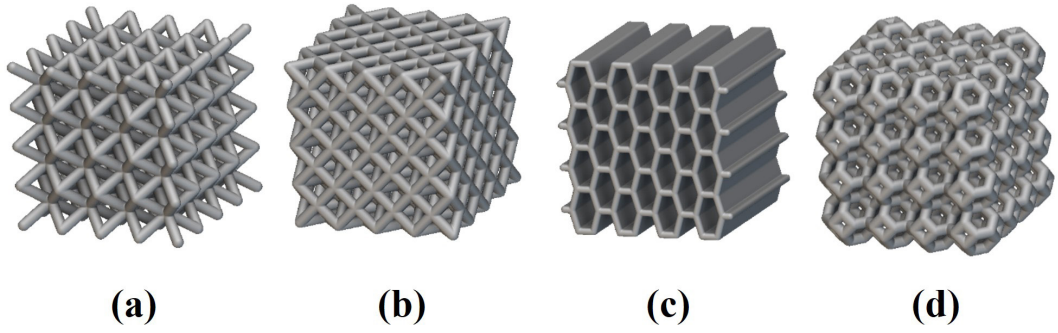


Figure 2: CAD model of different types of strut-based lattice structures **(a)** Body centered cubic (BCC), **(b)** Face centered cubic (FCC), **(c)** Hexagonal honeycomb, and **(d)** Kelvin cell.

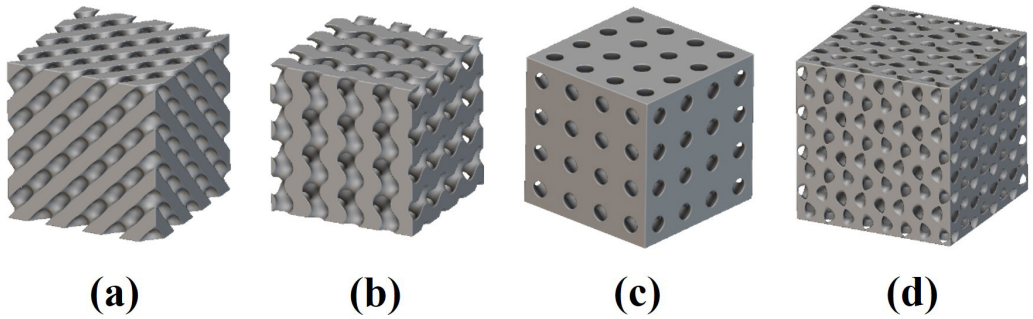


Figure 3: CAD model of different types of TPMS lattice structures **(a)** Diamond, **(b)** Gyroid, **(c)** Schwarz, and **(d)** SplitP.

Materials and Methodology

Compression test of material is a fundamental type of mechanical testing. A compressive force applies along the longer axis of a human bone to compress it. This is one of many uses for lattice structures, such as in tissue engineering (bone scaffolds). Compression fractures and impacting fractures are the results of compressive forces. Compression testing can be used to determine the mechanical behaviour and properties of the specimen by applying the crushing load on it. Also, it allows the manufacturers to figure out the safety and integrity of that material and product. Materials that demonstrate high tensile strength generally tend to exhibit low compressive strength and vice-versa. Therefore, compression testing is preferred for materials which have a brittle property. This test can also be used to illustrate the shock absorption properties of the material structure.

Materials

In this work, Polylactic Acid (PLA) is considered as the material for the lattice structure. PLA is a biodegradable thermoplastic polyester processed by the direct condensation reaction of lactic acid monomer, followed by a ring-opening polymerization. It is derived from organic as well as renewable sources such as sugar cane or corn starch, therefore it is also called 'Green Plastic'. It can be used as a replacement of petroleum-based polymers because of its good mechanical and processability properties (Table 1). Compared to other biodegradable polymers, PLA is the most promising replacement biopolymer due to its low melting point of around 150 °C to 160 °C, thus requiring less amount of energy being better in thermal processability to use in a wide range of Additive Manufacturing or injection moulding applications. Another reason to choose PLA is that it is environment friendly and can hence be used to preserve or store food items as it is non-toxic. PLA though is a brittle material having less than 10% elongation at break.

Table 1: Material properties of PLA.

Properties	Value
Density	1.24 g/cm^3
Tensile strength	61.5 MPa
Flexural strength	88.8 MPa
Impact strength	30.8 kJ/m^2
Heat resistance	110 °C
Thermal conductivity	0.13 W/m-K

Finite element modelling and analysis

This work is a comparative study of Strut-based and TPMS-based lattice structures to determine their behaviour under an applied crushing load. Compression test is performed on four types each of strut based and TPMS based latticesusing ANSYS Version 2020 FEA software to determine the compressive strength of these lattices. Different types of lattice structures are designed using their equations and nTopology software (Table 2, table 3, and table 4).

In ANSYS Workbench, the .inp meshed file of lattices along with the meshed file of top and bottom plates were imported as an external model under the component section and then structural analysis is done using the Static Structural

Table 2: Geometric dimensions of the cubical lattice structures.

Geometric parameter	Value
Cube Size	15 mm
Cell size	3 mm
Mid-surface offset (for TPMS)	0.1 mm
Thickness	0.5 mm
Tolerance	0.6 mm
Edge length	1 mm
Volume Mesh Shape	Tetrahedron

Table 3: Mathematical equation for two strut-based lattice structures.

Strut based lattice	Mathematical equations
BCC	$\sqrt{(3a)} = 4r$
Hexagonal Honeycomb	$g = 4\pi/a\sqrt{3}$

Table 4: Mathematical equation for two TPMS based lattice structures.

TPMS lattice	Mathematical equation
Gyriod	sin(x) cos(y) + sin(y) cos(z) + sin(z) cos(x)
Diamond	sin(x)*sin(y)*sin(z)+sin(x)*cos(y)*cos(z)+cos(x-)*sin(y)*cos(z)+cos(x)*cos(y)*sin(z)

module. Thereafter all the boundary conditions (bottom plate fully fixed) and load (1000 N on the top plate) are applied to the lattices and results are evaluated as per the methodology shown in figure 4.

Results and Discussion

The total deformation and equivalent von Mises stresses of compression testing are tabulated (Table 5) for strut-based lattices and shown in figure 5. Likewise, the FEA results for the TPMS lattices are presented in table 6 and figure 6. According to the results, the Kelvin cell among all Strut-based lattice structures has the lowest value of stress, which is 8.6 MPa, while the TPMS Diamond lattice among TPMS-based lattice structures has the lowest value of stress, which is 5.6 MPa. Hence it can be seen from the results that TPMS Diamond lattice structures are the least deformed lattice in comparison to all the other lattices which makes it the most resistive and applicable amongst the other lattices.

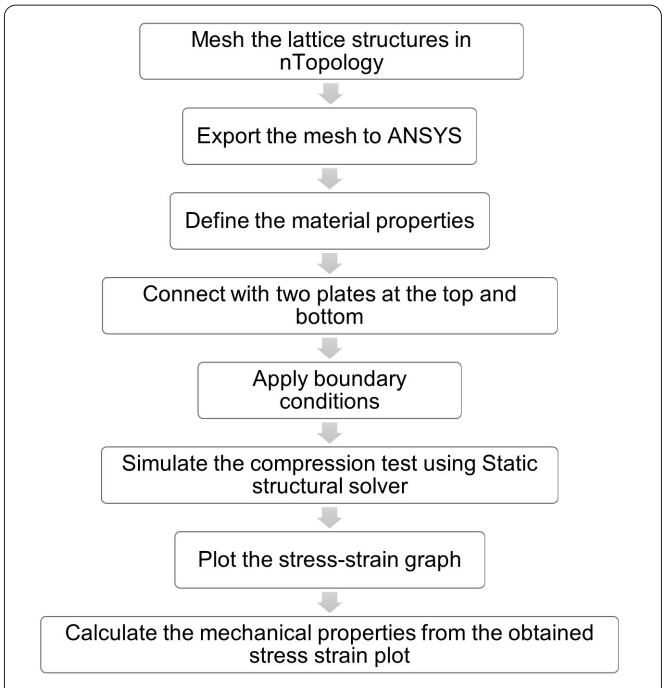


Figure 4: Methodology of FEA of lattice structures.

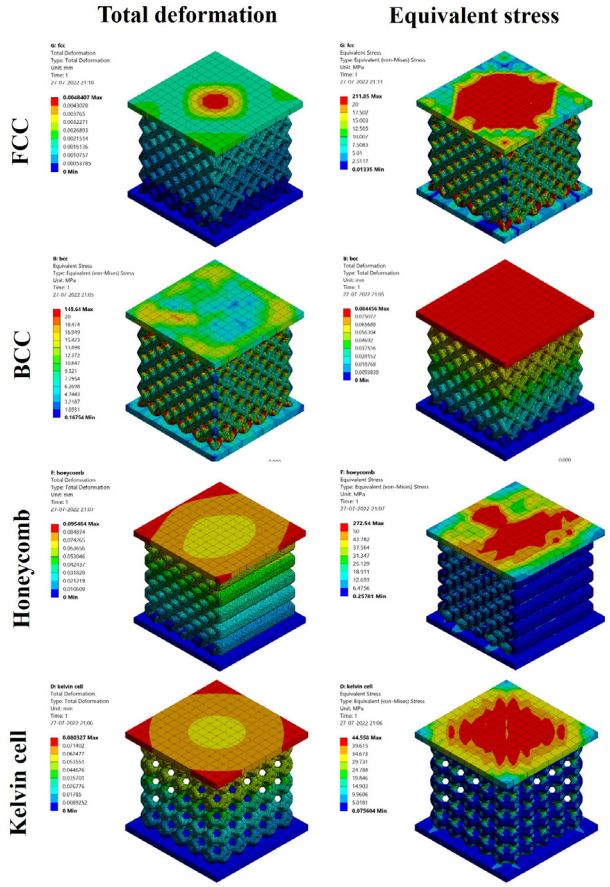


Figure 5: Deformation and stress results of compression test of strut-based lattice structures.

Table 5: Calculated values of strut-based lattice structures.

Lattice Structure	Total Deformation	Equivalent Stress	Equivalent strain
BCC	1.18E-01	20.127	6.46E-03
FCC	9.18E-04	11.372	3.1998e-003
Kelvin cell	3.33E-02	8.6805	2.62E-03
Honeycomb	4.08E-02	16.249	5.09E-03

Table 6: Calculated values of TPMS-based lattice structure.

Lattice Structure	Total Deformation	Equivalent Stress	Equivalent Strain
TPMS Gyroid	3.66E-02	10.685	3.20E-03
TPMS Schwarz	2.78E-02	8.9983	2.63E-03
TPMS Diamond	1.36E-02	5.6894	1.69E-03
TPMS SplitP	3.29E-02	9.7714	2.92E-03

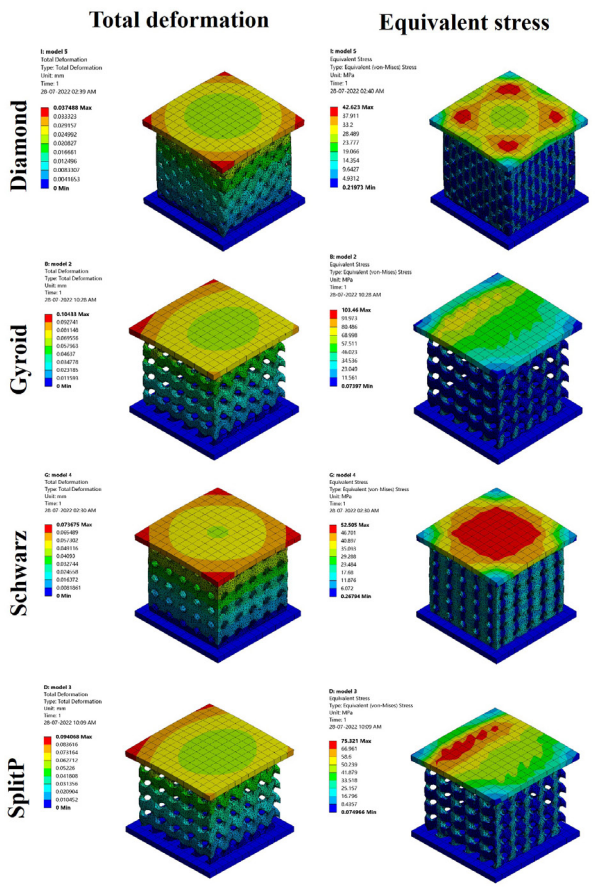


Figure 6: Deformation and stress results results of compression test of TPMS-based lattice structures.

Mesh convergence study and report

In convergence study, the sizing and configuration of FEA mesh varies. Using an iterative method, the increase in number of elements along each direction was done by refining mesh more and more and solved for every mesh. The response of number of elements vs deformation of model was recorded. Varying the number of elements, a table and graph of mesh size deflection were plotted in figure 7.

Conclusion

In this study, various lattice structures were CAD designed and FEA simulation was carried out on each lattice. The results such as total deformation, equivalent stress and equivalent elastic strain have been evaluated. And it can be concluded that the Diamond lattice exhibits superior compressive properties among all the lattices taken into consideration and stress bearing ability for use in tissue engineering, generative design and manufacturing applications. The adoption of lattice structure design is promising and still at an emerging stage. This study has offered a revised definition of lattice structures that takes into account newly published material. This will facilitate it for later researchers to accomplish the objectives set out for lattice structures, specifically to meet the objectives of a decrease in energy, material, and manufacturing time while optimizing the strength of a certain product that has been applied using lattice structures. While there are a few industries that are leveraging the prowess of lattice structures, there are still many areas in which its potential can be explored in the near future.

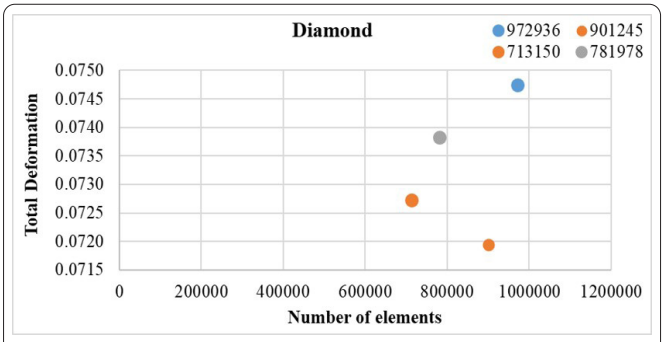


Figure 7: Total Deformation vs Number of elements comparison of TPMS-based Diamond lattice structure.

Acknowledgments

None.

Conflict of Interest

None.

Credit Author Statement

P. Yadav: Formal analysis, Investigation, Resources, Writing - original draft preparation; A. Kushwaha: Formal analysis, Investigation, Resources, Writing - original draft preparation; Mukul Shukla: Conceptualization, Methodology, Writing - review and editing, Supervision. All the authors read and approved the manuscript.

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