Finite Element Modeling and Analysis of Three Anatomically Shaped Scaffold Models

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Abstract

The fabrication of porous scaffolds is a significant challenge in orthopedic applications. Bone fractures can be repaired using porous biomaterial scaffolds. In addition to promoting bone growth, they also aid in the tissues' ability to osseointegrate. Porous scaffolds are increasingly being made using Additive Manufacturing (AM) methods. Modeling and finite element analysis (FEA) allow for more affordable exploration of the mechanical and biological behavior of patient-specific implants. In this study, we have used the CAD programme Creo to construct a scaffold lattice structure with three different unit cells triangular, hexagonal, and octagonal, and finite element analysis (FEA) of the compressive strength of these unit cells has been carried out using the Abaqus software. Compressive strength of lattice structures based on these three-unit cells was studied for the biocompatible PLA thermoplastic polymer with a strut size of 2mm.

Keywords
Anatomically shaped scaffold, additive manufacturing, lattice structures, FEA, and SA/V ratio.

4. Introduction
Bone implants are necessary for new bone to grow on the surface of the bone, which then helps to repair the damaged bone that is too large to mend on its own. Metal biomaterials are utilized in orthopedics, and implants are made from biocompatible materials Wang et al. (20!6). The most common cause of implant failure is aseptic loosening which is caused by the stress shielding effect Hedayati et al. (2016). Porous characteristics in implants are primarily designed to reduce the implant's stiffness, as stated by Singh et al. (2017). It is feasible to get rid of stress shielding effects by altering the elastic modulus of the implant. It has been reported that the elastic modulus of cortical and trabecular bones is in range from 3 to 30 GPa, while that of trabecular bones is in range from 0.02-2 GPa Chen and Thouas (2015). Low dense porous scaffolds that provide cell adhesion, mechanical stability, and fluid perfusion are developed to counteract the stress shielding, (Bandyopadhy.et al. 2010). Maintaining a porous geometry in bone implants is considered beneficial for nutrient transport, osseointegration, and enhanced bone ingrowth. Patient-specific implants can be made by altering the strut size of open porous scaffolds to control porosity. Manufacturing open cell porous scaffolds is attainable with the use of AM methods.

Aerospace, automotive, and medical industries are just a few of the many that have embraced AM as a result of its many advantages, such as shortened product development cycles, the capacity to make components with complicated geometry, decreased fabrication costs, and shorter lead time Sulaiman et al. (2021) and Zhang et al. (2019). The AM method is frequently used to manufacture cellular-patterned components. This is due to the fact that the AM technique offers a distinct advantage over more conventional manufacturing procedures by allowing the fabrication of complex geometries in the form of finished products Alfaify et al. (2020). One of the most popular additive manufacturing procedures is the Fuse Deposition Modelling (FDM) method due of its low price, high efficiency, and low learning curve. In most cases, FDM is used with thermoplastic polymers like polylactic acid, acrylic butadiene styrene (ABS), and recycled plastic Ford and Despeisse (2016).

The modern term for the design of cellular patterns is "lattice structure." Using lattice structures in additive manufacturing helps to increase the amount of energy that can be absorbed by the component while decreasing the amount of time required for the printing process. There are two types of lattice structures; those with a random structure are called stochastic, while those with a regular pattern are called non-stochastic Niu et al. (2018). Modern CAD modelling software is frequently used for the design of a lattice-structured component. The FEA simulation allows researchers to analyze the lattice's mechanical behavior before the structure is actually produced into a genuine part. The influence of the lattice structure and lattice parameter on the mechanical properties of the specimen was studied by Choo et al. (2017)] using finite element analysis simulation. By employing FEA simulation, the researchers were able to determine the lattice structure with the optimal stiffness-to-weight ratio.

As a result, the current work employs FEA simulation to assess the mechanical qualities of a lattice structure made from PLA filament.

This study makes use of finite element analysis (FEA) simulation to examine the mechanical properties of the lattice structure built from PLA filament. These properties include effective young modulus and maximal von Misses stress.

5. Methodology
5.1 Modeling of Lattice Structures

The four different unit cell structures were created using the computer-aided design (CAD) tool CREO. Their inspiration came from previously researched designs found in literature. However, adjustments have been made to the topography and parameters in order to enhance the printing quality and decrease the amount of time required for manufacture. Repetition of unit cells, which are struts of a circular shape constructed in a variety of orientations and connected through nodes, results in the formation of lattice structures. In order to facilitate meaningful comparisons, a predetermined envelope with dimensions of 22.22 and 20.30 mm in width and height is utilized.

Each of the four unique lattice structures (22.98mm diameter base, 20.30mm height and 22.22mm thickness) triangular, square, hexagonal, and octagonal has been built using struts that are 2 mm in diameter, beam cross section type circular and beam size 2 mm, unit cell size 5mm, position of beams in unit cell, ball diameter of 2mm and position of beams are outer horizontal beams and outer vertical beams only. The STL file format was utilized for the export of the final designs of the lattice scaffold.

Unit cells of various shapes, including triangular, hexagonal, and octagonal, as shown in Figure 1, were built with struts along their edges. During this investigation, the Creo software was utilized to produce a three-dimensional model of the lattice structures. To begin, a single unit cell of each of the three possible lattice structures—triangular, hexagonal, and octagonal—was selected. The anatomically shaped bone model is then substituted with the unit cell in both the in-plane and out-plane directions to produce the anatomically shaped scaffold models with a variety of lattice structures, as shown in Figure 2.
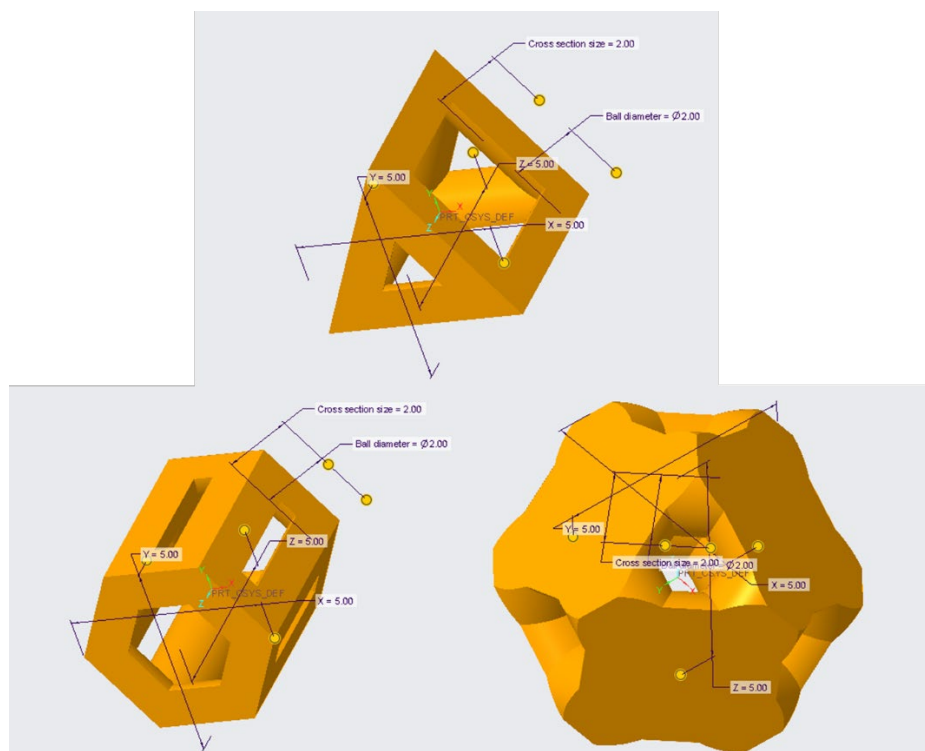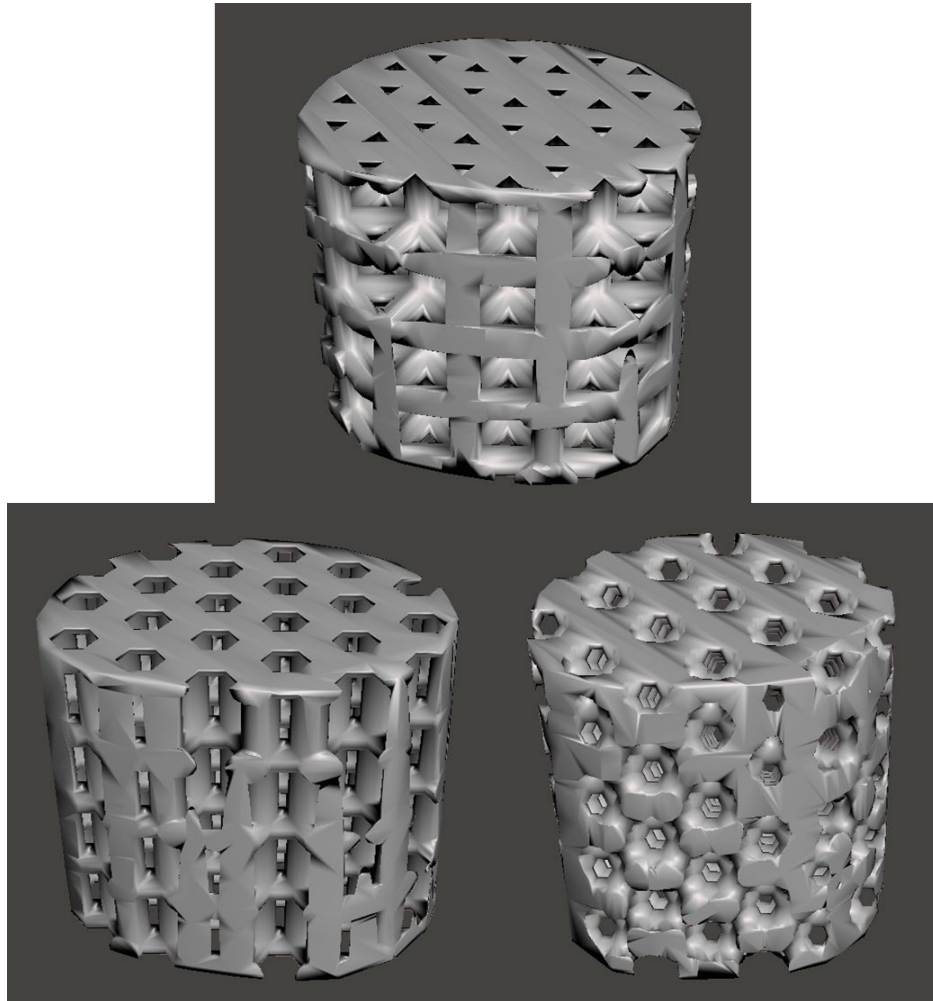

Figure 1. Unit Cells

Figure 2. Scaffold models

5.2 Finite element analysis

To estimate the compressive behavior of the three lattice structures based on unit cells, a linear static FEA is performed with the Abaqus 6.14 software Elastic modulus is 342 MPa, and Poisson's ratio is 0.3; both of these values are assigned to imported parts with a PLA material type. In order to properly assign the boundary conditions, The top and bottom struts' linear and angular degrees of freedom are locked down, preventing any rigid body motion. In addition, the other surfaces of the lattice structure are not subjected to the boundary conditions. Similarly, applying a displacement to the model's upper faces results in motion toward the lower faces and the base. Compression model loads and boundary conditions are shown in Figure 3.
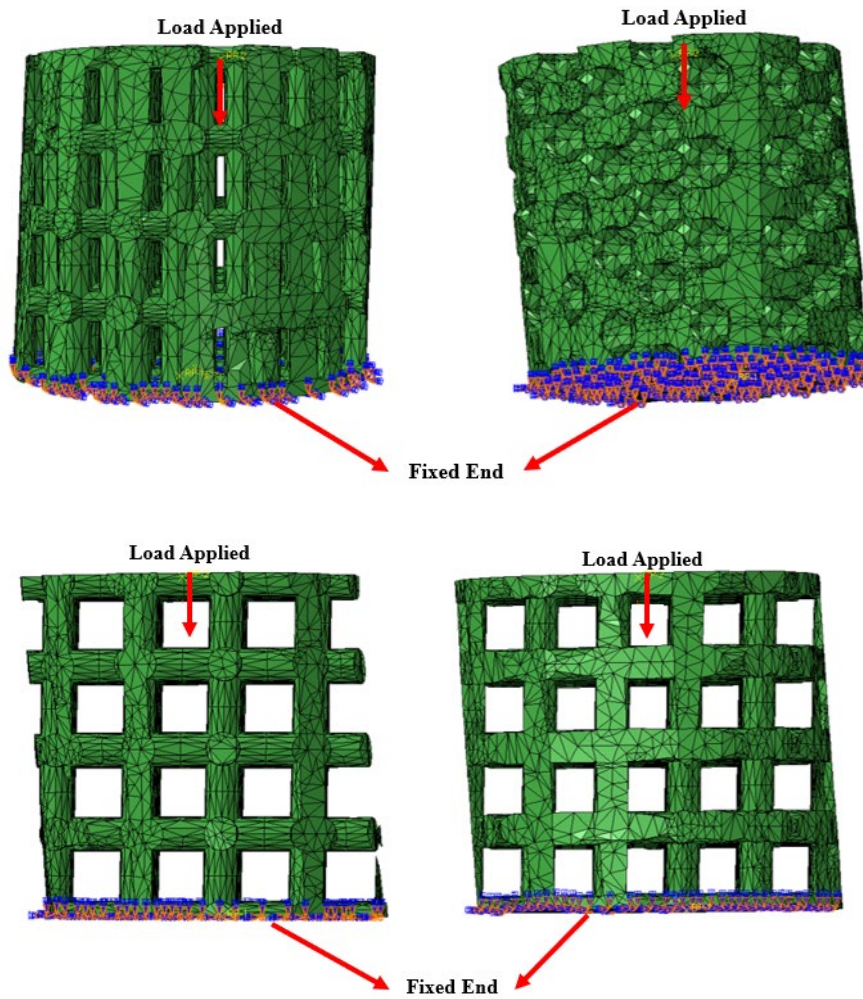
Figure 3. Boundary conditions of lattice structures for FEA models

6. Result and Discussion

Predictions have been made on the stress distribution in triangular, hexagonal, and octagonal lattice structures (Table 1), each of which has struts that are 2 millimeters thick. According to the findings that were derived from the FEA predictions, the compressive stresses for triangular, hexagonal, and octagonal lattice structures, respectively, are 830 MPa, 277 MPa, and 155 MPa at strut thicknesses that are each 2 mm, as depicted in Figure 4.

Table 1. Mathematical Analysis of different lattice structure scaffolds

Sl. No.	Lattice Structure	Porosity (%)	Volume (mm³ ×10³)	Surface Area (mm² × 10³)	Young's Modulus (MPa)
1.	Triangular	60.08	2.674	5.319	626.29
2.	Hexagonal	52.06	3.165	6.153	244.40
3.	Octagonal	41.57	3.892	5.893	239.27

(a)

STRESS VS STRAIN

(b)

STRESS VS STRAIN
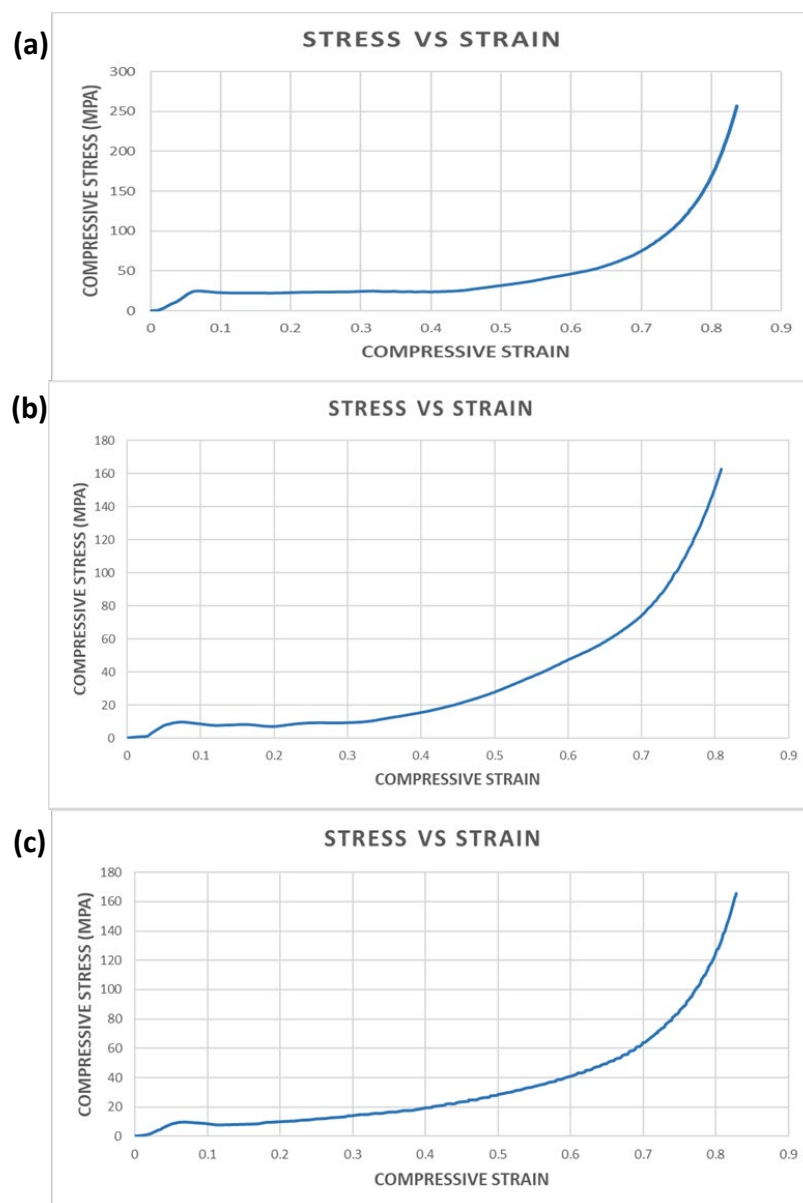
(c)

STRESS VS STRAIN

Figure 4. Stress-Strain graph (a). Triangular lattice (b). Hexagonal lattice (c). Octagonal lattice

The SA/V ratio is the primary factor to consider while choosing the most effective scaffold design from the three lattices structures. For the same amount of scaffold volume, the SA/V ratio of the triangular (60.08 percent porous) comes out to be 1.98, 1.94 for the hexagonal (52.06 percent porous), and 1.51 for the octagonal (41.57 percent porous). The SA/V ratio should be increased because this would result in greater vascularization and cell proliferation. As a result, the triangular design with strut thickness of 2 millimeters is the most appropriate for achieving the requisite porosity and compressive strength.

7. Conclusion
In this study, modelling of porous structures made of biocompatible PLA material (triangular, hexagonal, and octagonal) and their FEA have been undertaken to simulate the compressive behavior of the material under uni-axial load. Compressive stresses, porosity, surface area, and volume of all scaffolds were analyzed and compared. Elastic moduli were determined by the FEA to be 240 MPa for the hexagonal lattice structure scaffold, 235 MPa for the octagonal scaffold, and 687 MPa for the triangular scaffold. The SA/V ratio of the triangular lattice structure is higher than that of the other lattice structures, hence it is recommended as the optimal choice. Fabrication of all scaffolds will be done in the future as part of the planned activity in order to validate the results

of the FEA. In-vitro and in-vivo testing for biomechanical qualities can also be carried out to confirm that triangular structures promote faster rates of bone formation.

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