Department of Mechanical Engineering

Indian Institute of Technology Tirupati

B.Tech. Project Phase-I Report

NOVEL ORGANIC BIOMIMETIC LATTICE STRUCTURES FOR BONE ANALOGOUS APPLICATIONS

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1. Introduction

Bone replacement and reconstruction following trauma, disease, or surgical procedures such as tumour resection remains a major challenge in biomedical engineering. One of the primary difficulties in implant design is achieving mechanical compatibility between artificial implants and natural bone. Conventional solid implants often possess significantly higher stiffness than biological tissue, resulting in stress shielding, which leads to bone resorption and long-term implant failure. In recent years, lattice structures have emerged as a promising alternative due to their ability to tailor mechanical properties and promote biological integration.

This project focuses on the design and preliminary evaluation of biomimetic lattice structures for bone-analogous applications, with a particular emphasis on developing a robust workflow for lattice generation and comparing different lattice topologies. Cylindrical scaffold specimens of dimensions 20 mm × 20 mm were designed and populated with different lattice configurations: Simple Cubic (SC), Body-Centred Cubic (BCC), Face-Centred Cubic (FCC) and Fluorite Lattice. Two strut thickness values, 0.75 mm and 1.0 mm, were implemented to study the effect of geometric variation on mechanical behaviour. The base material for the scaffold models was assumed to be structural steel.

Static structural analysis was performed using nTop software by applying a compressive load on the top surface of the cylinders, while the bottom surface was fully constrained. Stress, strain, and displacement distributions were obtained for each configuration, allowing for a qualitative and comparative evaluation of stiffness and deformation characteristics across different lattice designs.

The femoral diaphysis was chosen as the primary anatomical focus for this project due to its critical role as a major load-bearing component of the human skeletal system. The shaft of the femur experiences significant axial compressive forces during activities such as walking, running, and jumping; therefore, any implant or scaffold designed for this region must achieve an appropriate balance between strength and compliance. Excessive stiffness may result in stress shielding, while insufficient stiffness may lead to mechanical failure. Consequently, the femoral diaphysis presents an ideal case study for evaluating the potential of lattice structures in bone-analogous applications

The present project focuses on developing a structured workflow for lattice generation and evaluation as a foundation for biomimetic bone scaffold design. In this initial phase, simplified cylindrical specimens representing a segment of the femoral diaphysis were created and populated with different lattice topologies, namely Simple Cubic, Body-Centred Cubic, and Face-Centred Cubic unit cells. Static structural analyses were performed to evaluate stress, strain, and displacement responses under physiological-level compressive loading. Rather than aiming for final implant optimisation, the emphasis of this phase is to understand how lattice geometry influences mechanical response and to establish a methodology that can later be extended to functionally graded and anatomically realistic scaffolds.

This work serves as a preliminary but essential step towards the long-term goal of designing implants and scaffolds that exhibit improved mechanical compatibility, reduced stress shielding, and enhanced biological integration. Future stages of the project will include graded lattice development, experimental validation through fabrication, and mechanical testing, ultimately contributing to the design of patient-specific and biologically effective bone scaffolds.

2. Literature Review

Bone is a naturally occurring hierarchical composite material that exhibits remarkable mechanical efficiency due to its graded and cellular structure. The femoral diaphysis, being predominantly cortical bone, possesses a high elastic modulus and is designed to withstand axial, bending, and torsional loads. Comprehensive works on bone mechanics by Martin et al and Cowin describe bone as a load adaptive material whose mechanical properties are governed by both its microstructure and physiological loading environment [1]. Rho et al. further established that cortical bone exhibits anisotropic mechanical behaviour, with stiffness varying along longitudinal, radial, and circumferential directions [2].

One of the critical biomechanical challenges in orthopaedic implant design is stress shielding, which arises due to the stiffness mismatch between implants and surrounding bone. Huiskes et al. demonstrated that excessive implant stiffness leads to reduced mechanical loading on bone, resulting in bone resorption and implant loosening [3]. This problem has motivated the development of alternative structural designs that aim to more closely match the mechanical behaviour of bone.

Research into lattice and cellular solids provides a theoretical foundation for bone analogous structures. The work of Gibson and Ashby established relationships between relative density and effective mechanical properties in cellular materials [4]. Their studies demonstrated that by controlling geometry rather than material composition, stiffness, strength, and energy absorption of lattices can be effectively tailored. These concepts have directly influenced the adoption of lattice structures in biomedical engineering applications.

Despite extensive research on lattice structures, a significant research gap remains in the comparative evaluation of different lattice topologies under identical geometrical and loading conditions. Many studies focus on a single lattice configuration or use varying material systems, making performance comparison difficult. There is also limited literature focusing on structures such as the Fluorite lattice in orthopaedic applications. This highlights the need for a controlled comparative study evaluating different lattice geometries using consistent modelling and loading conditions.

The present work addresses this research gap by quantitatively comparing the stiffness behaviour of multiple lattice topologies within a unified computational framework. By evaluating the effective Young's modulus of BCC, FCC, Simple Cubic, and Fluorite lattices using deformation based homogenisation, this study contributes toward identifying lattice structures that approach femoral bone behaviour under axial loading. The findings form a foundation for future development of graded lattice designs that more closely mimic natural bone architecture.

3. Problem Definition (Motivation/objectives)

3.1. Problem Definition

The replacement of lost or damaged bone using artificial implants remains a persistent challenge in orthopaedic engineering due to the difficulty in achieving mechanical and biological compatibility with natural bone tissue. Conventional orthopaedic implants are typically manufactured from dense metallic materials such as stainless steel and titanium alloys, which possess significantly higher stiffness compared to human bone. While these materials provide adequate strength, their mismatch in elastic modulus relative to bone leads to an uneven distribution of load across the bone–implant system.

This stiffness mismatch results in a widely observed phenomenon known as stress shielding, wherein the implant bears the majority of the applied load while the surrounding bone experiences reduced stress. Since bone tissue remodels in response to mechanical stimuli, prolonged stress reduction leads to bone resorption, weakening the bone–implant interface and increasing the likelihood of loosening and implant failure. This remains a major clinical limitation in long-term orthopaedic success.

Furthermore, current scaffold designs often suffer from inadequate pore structure for biological integration. Effective bone scaffolds require interconnected porosity to facilitate nutrient exchange, vascularisation, and tissue growth. In many cases, pore geometry is not optimised for both mechanical integrity and biological performance, resulting in implants that either compromise strength or inhibit effective bone regeneration.

Hence, there is a clear need for improved design methodologies that enable the development of lattice scaffolds, which:

- More closely replicate the mechanical behaviour of natural bone,
- Reduce stress shielding,
- Provide adequate space for biological integration,
- And remain manufacturable using available techniques.

3.2. Objectives

The overall goal of this project is to develop a design and analysis workflow for lattice based scaffolds that can be extended to biomimetic bone applications, with a primary focus on the femoral diaphysis. The primary objectives of this phase of the project are:

a. To model lattice filled cylindrical specimens representing a simplified segment of the femoral diaphysis.

b. To implement and compare four lattice topologies — Simple Cubic (SC), Body-Centered Cubic (BCC), Face-Centered Cubic (FCC), and Fluorite.

c. To analyse the effect of strut thickness by evaluating two configurations (0.75 mm and 1.0 mm) for each lattice type.

d. To perform static structural analysis under a compressive load of 500 N with fixed support boundary conditions.

e. To compute the effective Young's modulus of each lattice structure using simulation derived deformation values.

f. To compare the stiffness behaviour of different lattice geometries using stress–strain equivalence.

4. Methodology

4.1. Geometric Model Creation

A simplified cylindrical model was used to represent a segment of the femoral diaphysis. The geometry was created with the following dimensions:

- Diameter: 20 mm
- Length: 20 mm

This cylindrical geometry was consistently used for all lattice configurations to ensure a fair comparison between different lattice topologies and strut thicknesses.

4.2. Lattice Structure Design

The cylindrical base geometry was populated with four lattice topologies:

- Simple Cubic (SC)
- Body-Centered Cubic (BCC)
- Face-Centered Cubic (FCC)
- Fluorite

For each lattice type, two strut thickness values were implemented:

- 0.75 mm
- 1.0 mm

All lattice structures were generated using the lattice design tools in nTop software. Unit cell parameters were kept constant wherever possible to isolate the effect of strut thickness and lattice topology.

In total, eight configurations were analysed:

- SC – 0.75 mm
- SC – 1.0 mm
- BCC – 0.75 mm
- BCC – 1.0 mm
- FCC – 0.75 mm
- FCC – 1.0 mm
- Fluorite – 0.75 mm
- Fluorite – 1.0 mm

4.3. Material Properties

For the purpose of simulation, all lattice structures were assigned the properties of structural steel. The material was assumed to behave as a linear elastic, isotropic and homogeneous material.

Typical properties assumed:

- Young's modulus, E_s = 200 GPa
- Poisson's ratio, ν = 0.3

As the main objective of the study is comparative analysis, the same material properties were used across all configurations.

4.4. Boundary Conditions

Static structural analysis was performed under uniaxial compression conditions.

Boundary conditions:

- The bottom face of the cylinder was fully constrained (fixed support).
- A compressive load of 500 N was applied uniformly to the top face of the specimen.

This simplified loading condition represents axial compression similar to what is applied during mechanical testing using a Universal Testing Machine (UTM).

4.5. Finite Element Analysis

All models were analysed using the simulation environment available within nTop.

For each configuration:

- Stress distribution
- Strain contours
- Total displacement fields

were obtained from the simulation solver.

The primary value extracted from each simulation was the axial displacement of the top face, which was later used to compute the effective Young's modulus.

4.6. Effective Young's Modulus Calculation

Each lattice filled cylinder was treated as an equivalent homogeneous solid specimen.

Using the simulation derived deformation values, the effective Young's modulus was calculated as:

$$E_{\text{eff}} = \frac{\sigma}{\varepsilon}$$

where:

- Effective stress:

$$\sigma_{eff} = \frac{F}{A}$$

- Effective strain:

$$\varepsilon_{eff} = \frac{\delta}{L}$$

with:

- $F = 500\ \text{N}$
- $A = \pi(10)^2 = 314.16\ mm^2$
- $L = 20\ mm$
- δ = displacement obtained from simulation

Thus:

$$E_{\text{eff}} = \frac{F}{A} \cdot \frac{L}{\delta}$$

This calculation was repeated for all lattice configurations to enable quantitative comparison.

4.7. Evaluation Criteria

Each lattice type was compared based on effective Young's modulus and lattice structures exhibiting stiffness values closer to human bone were considered more suitable for bone-analogous applications.

5. Mathematical Formulation

In this work, the lattice-filled specimens are treated as equivalent homogeneous cylindrical samples subjected to uniaxial compression. The mathematical formulation focuses on the geometric description, loading conditions, and the calculation of an effective Young's modulus for each lattice configuration.

5.1. Geometric Idealization

Each specimen is modelled as a right circular cylinder of:

Diameter, $D = 20\,\mathrm{mm}$

Length, $L = 20\,\mathrm{mm}$

Radius:

$$R = \frac{D}{2} = 10\,\mathrm{mm}$$

Cross-sectional area:

$$A = \pi R^2 = \pi(10\,\mathrm{mm})^2 = 314.16\,\mathrm{mm}^2$$

The internal volume of the cylinder is populated with one of four lattice topologies:

- Simple Cubic (SC)
- Body-Centered Cubic (BCC)
- Face-Centered Cubic (FCC)
- Fluorite

For each lattice type, two strut thickness values are used:

$$t \in \{0.75\,\mathrm{mm},\ 1.0\,\mathrm{mm}\}$$

5.2. Mechanical Model and Boundary Conditions

The lattice is assumed to be made of linear elastic, isotropic structural steel with Young's modulus E_s and Poisson's ratio ν. At the macroscopic scale, the specimen is analysed under quasi-static loading.

Boundary conditions:

- Bottom face ($z = 0$): fully fixed
- Top face ($z = L$): subjected to a compressive load

$$F = 500\,\mathrm{N}$$

applied uniformly over the circular area A.

The finite-element solver in nTop is used to obtain the displacement field and, from it, the stress, strain and deformation contours for each lattice configuration.

5.3. Effective Stress and Strain

To compare different lattice geometries using a single scalar quantity, each lattice filled cylinder is treated as an equivalent homogeneous bar under uniaxial compression.

5.3.1. Effective Stress

The nominal (average) axial stress is

$$\sigma_{\mathrm{eff}} = \frac{F}{A}$$

with $F = 500\ N$ and $A = 314.16 mm^2$, the same σ_{eff} is used for all configurations.

5.3.2. Effective Strain

From the simulation, the total axial deformation of the top surface, δ, is obtained for each lattice. The corresponding effective engineering strain is:

$$\varepsilon_{\mathrm{eff}} = \frac{\delta}{L}$$

where $L = 20$ mm is the original length of the specimen

5.4. Effective Young's Modulus

Using the homogenised one-dimensional stress–strain relation,

$$E_{\text{eff}} = \frac{\sigma_{\text{eff}}}{\varepsilon_{\text{eff}}}$$

Substituting $\sigma_{\text{eff}} = F/A$ and $\varepsilon_{\text{eff}} = \delta/L$

$$E_{\text{eff}} = \frac{F}{A} \cdot \frac{L}{\delta}$$

or

$$E_{\text{eff}} = \frac{FL}{A\,\delta}$$

For each lattice type (BCC, FCC, Simple Cubic, Fluorite) and strut thickness (0.75 mm, 1.0 mm), the corresponding displacement δ from simulation is substituted into the above expression to obtain the effective Young's modulus.

5.5. Use of Formulation

This mathematical framework enables:

- Direct quantitative comparison of stiffness between different lattice topologies and strut thicknesses.
- Identification of lattice structures whose effective Young's modulus lies closer to the desired bone-analogous range.
- A basis for future extension to graded lattices, where spatially varying stiffness can be imposed by locally modifying lattice geometry.

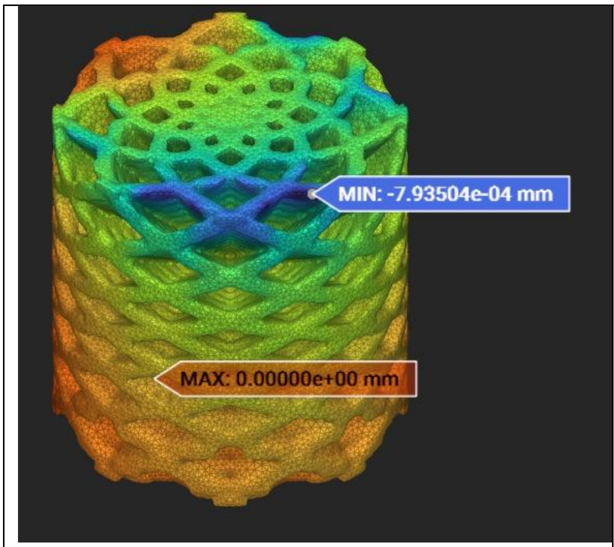
6. Results and Discussion

Static structural analysis was performed on cylindrical lattice specimens (20 mm diameter × 20 mm length) for four lattice topologies: Simple Cubic (SC), Body-Centred Cubic (BCC), Face-Centred Cubic (FCC), and Fluorite. Each lattice type was evaluated for two strut thicknesses (1.0 mm and 0.75 mm) under a compressive load of 500 N, while the bottom face was fully constrained.

The effective Young's modulus for each configuration was computed by treating the lattice-filled cylinder as an equivalent homogeneous solid and using the axial deformation obtained from simulation.

6.1. Comparison of Lattices

Lattice type	Strut thickness (mm)	Applied Load (N)	Section Length (m)	Diameter(m)	Cross-sectional area (m^2)	Deformation(m)	Equivalent Stress (Pa)	Equivalent strain	Effective Young's Modulus (Gpa)
BCC	1	500	2.00E-02	2.00E-02	0.000314159	7.94E-07	1591549.431	3.97E-05	40.1
	0.75	500	2.00E-02	2.00E-02	0.000314159	8.59E-07	1591549.431	4.30E-05	37
FCC	1	500	2.00E-02	2.00E-02	0.000314159	2.73E-07	1591549.431	1.36E-05	117
	0.75	500	2.00E-02	2.00E-02	0.000314159	1.67E-06	1591549.431	8.34E-05	19.1
Simple Cubic	1	500	2.00E-02	2.00E-02	0.000314159	1.36E-06	1591549.431	6.78E-05	23.5
	0.75	500	2.00E-02	2.00E-02	0.000314159	7.85E-06	1591549.431	3.93E-04	4.05
Fluorite	1	500	2.00E-02	2.00E-02	0.000314159	2.21E-07	1591549.431	1.10E-05	144
	0.75	500	2.00E-02	2.00E-02	0.000314159	3.74E-07	1591549.431	1.87E-05	85.1



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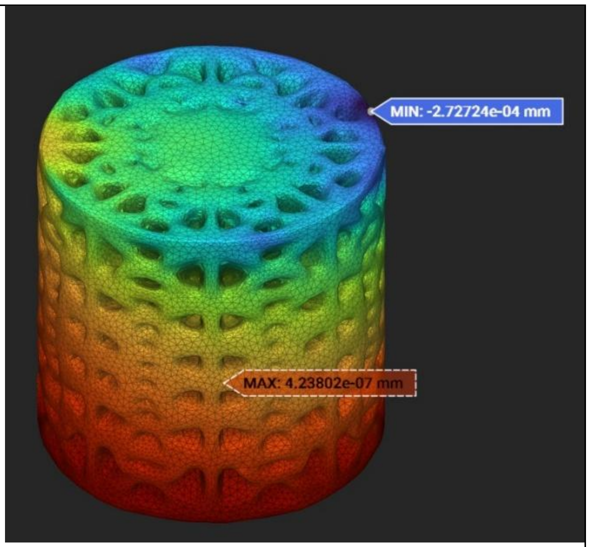

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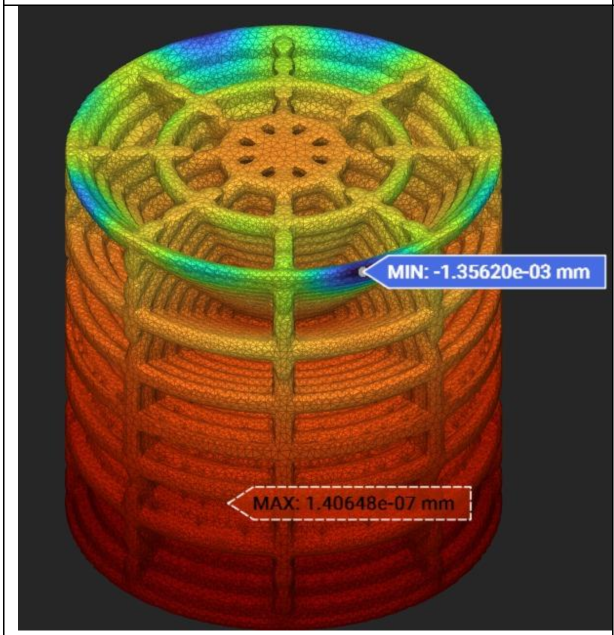

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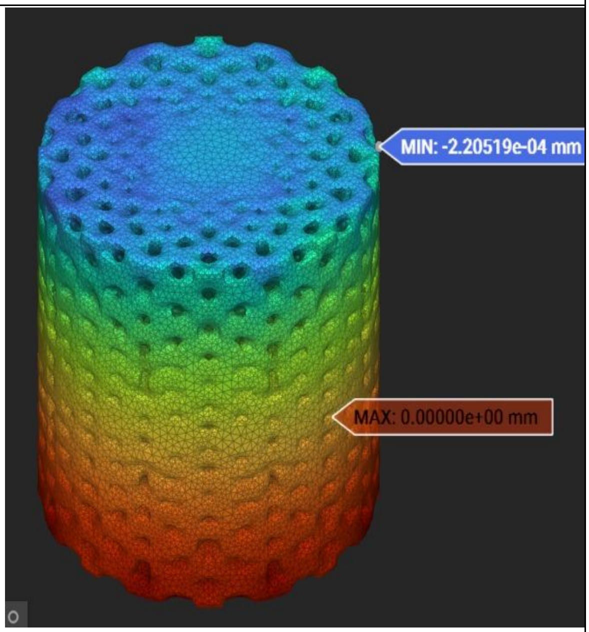

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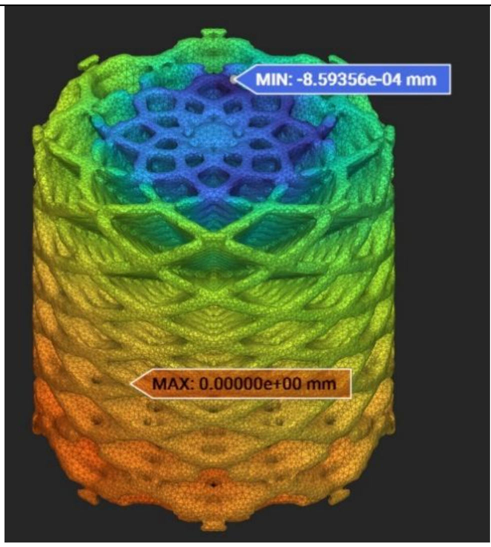
Table 1: Comparison of Deformations in (1) BCC, (2) FCC, (3) Simple Cubic and (4) Fluorite structures with 1mm thick struts



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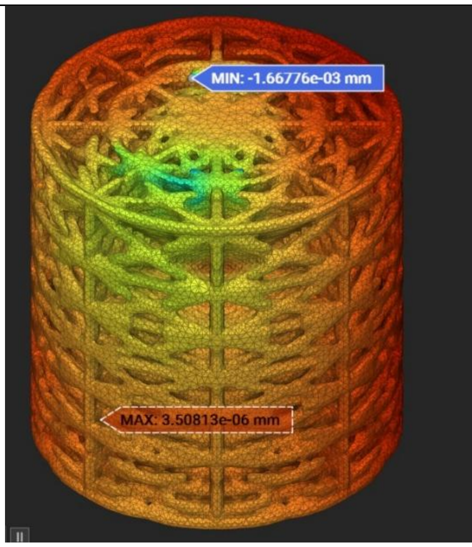

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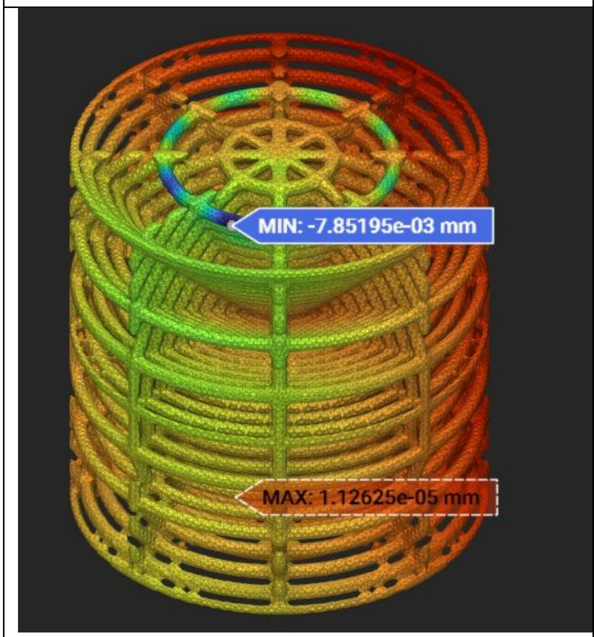

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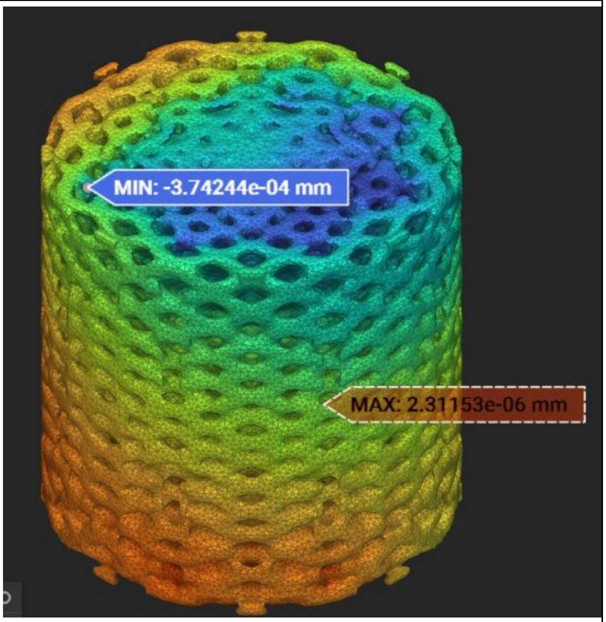

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Table 2: Comparison of Deformations in (1) BCC, (2) FCC, (3)Simple Cubic and (4)Fluorite structures with 0.75mm thick struts

6.2. Discussion

6.2.1. Effect of Lattice Topology

Among all lattice structures studied, the Fluorite lattice exhibited the highest stiffness for both strut thicknesses. At a strut thickness of 1.0 mm, Fluorite achieved an effective Young's modulus of 144 GPa, which is the highest of all configurations tested. This superior performance is attributed to the high connectivity of the Fluorite topology, which provides multiple load-transfer paths and greater structural redundancy.

The FCC lattice also demonstrated high mechanical stiffness, particularly at the 1.0 mm strut thickness, where it reached an effective Young's modulus of 117 GPa. This is due to its face-connected structure, which increases node coordination and improves load sharing across the lattice.

In contrast, the Simple Cubic lattice showed the lowest stiffness. For the 0.75 mm configuration, its effective modulus dropped to 4.05 GPa, making it nearly an order of magnitude lower than the FCC and Fluorite designs. This behaviour is expected because the Simple Cubic lattice has poor connectivity with fewer load paths, resulting in higher deformation under the same applied force.

The BCC lattice fell between FCC and Simple Cubic in terms of stiffness, reflecting intermediate connectivity and load-bearing capability.

6.2.2. Effect of Strut Thickness

For all lattices, increasing the strut thickness from 0.75 mm to 1.0 mm resulted in a reduced deformation and therefore an increase in effective Young's modulus. This clearly confirms that strut thickness is a dominant geometric parameter governing the global stiffness of lattice structures.

The change in thickness had a particularly strong effect for the FCC and Fluorite lattices, showing that highly connected structures respond more significantly to increases in strut size.

6.2.3. Comparison with Bone Behaviour

For the femoral diaphysis under axial loading, the shaft is mostly cortical bone, whose Young's modulus is roughly:

$$E_{\text{cortical}} \approx 17\text{–}20 \text{ GPa [1][2]}$$

Comparing this value with the results obtained from simulations, the most viable lattice structures for the femoral diaphysis are FCC with 0.75mm struts and Simple Cubic with 1mm struts, providing a balance between mechanical strength and mitigating stress shielding, which can weaken the bone.

7. Conclusion and Future Works

The present project focused on the development and evaluation of lattice-based scaffold structures for bone analogous applications, with specific emphasis on the mechanical response of different lattice topologies under axial loading. A simplified cylindrical model representing a segment of the femoral diaphysis was used to conduct a comparative study of four lattice configurations: Simple Cubic (SC), Body-Centred Cubic (BCC), Face-Centred Cubic (FCC), and Fluorite. Two different strut thicknesses, 0.75 mm and 1.0 mm, were implemented for each topology to analyse the influence of geometric variation on global stiffness.

Static structural analysis was performed by applying a compressive load of 500 N on each lattice-filled specimen using nTop software. The effective Young’s modulus for each configuration was computed using a homogenisation approach based on deformation-derived strain and nominal applied stress. This provided a consistent framework for comparing the macroscopic stiffness behaviour of different lattice structures.

The results demonstrated that lattice topology plays a critical role in determining the mechanical behaviour of scaffold structures. Among the evaluated configurations, the Fluorite lattice exhibited the highest effective Young’s modulus for both strut thicknesses, followed by the FCC lattice. The Simple Cubic lattice consistently showed the lowest stiffness, confirming the strong influence of connectivity and load path redundancy on stiffness. Increasing the strut thickness from 0.75 mm to 1.0 mm resulted in a consistent increase in stiffness across all lattice types, highlighting strut thickness as a dominant design parameter.

A comparison with femoral bone properties revealed that the obtained effective Young’s modulus values are comparable with the FCC lattice with 0.75 mm thick struts and the Simple Cubic lattice with 1 mm struts, which can be used for the design of femoral scaffolds.

Overall, this project successfully established a structured workflow for lattice modelling, simulation, and stiffness evaluation, serving as a foundation for further development towards graded, anatomically realistic bone scaffolds.

7.1.Future Works

While the current work provides valuable comparative insights, several areas remain for further investigation and improvement:

1. Functionally Graded Lattices
   Future studies will focus on developing graded lattice structures with spatially varying stiffness to better replicate the hierarchical architecture of natural bone.
2. Anatomically Accurate Geometry
   Instead of simplified cylindrical models, future work will involve implementing patient specific femur geometries derived from medical imaging data.
3. Material Selection
   The use of biologically relevant materials such as titanium alloys or polymer composites will be explored to improve biocompatibility and mechanical matching.
4. Experimental Validation
   Physical samples will be fabricated using additive manufacturing techniques and tested under compression using a Universal Testing Machine (UTM) to validate numerical predictions.
5. Advanced Mechanical Analysis
   Future simulations will include bending, torsion, and fatigue loading conditions to better reflect physiological environments.
6. Biological Integration Studies
   Analysis of pore size distribution and connectivity will be conducted to evaluate suitability for vascularisation and bone regeneration.
7. Design Optimization
   Geometry based optimization algorithms may be implemented to automatically tune lattice parameters for desired stiffness targets.

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