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Analysis of Porous Compression Plate having Different Lattice Structures with different Material Properties for Proximal Femoral Fractures

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Abstract: Proximal femoral fractures, which frequently affect the elderly, provide a significant problem in orthopaedic surgery that calls for creative treatments. This study focuses on the thorough examination of porous compression plates intended to treat these fractures that have different lattice structures of Gyroid, Schwarz D, Schwarz P and material properties. The research examines the mechanical behaviour of these implants using finite element analysis (FEA) simulations, as well as the impact of lattice parameters and material selections on deformation, stress distribution and strain. The results provide crucial information for selecting the best implants, which could alter the treatment of proximal femoral fractures by improving patient outcomes, lowering complications, and developing orthopaedic surgery. Schwarz P lattice structure was found to be best in case of Ti-6Al-4V while Schwarz D lattice structure was best for 316L SS.

I. INTRODUCTION

Biomechanical studies investigate how mechanical principles apply to living organisms, encompassing fields like human movement analysis, injury prevention, and the mechanics of biological systems. By simulating and analysing the mechanical behaviour of biological structures and systems, finite element analysis (FEA) helps to develop medical devices, understands musculoskeletal dynamics, and optimizes the biomechanics of movement. Finite Element Analysis (FEA) is a useful approach for investigating the biomechanical properties of the femur bone [1]. By developing elaborate computational models that simulate the complex geometry and material properties of the femur. It forecasts stress and strain distribution within the femur, providing insights into fracture risk, the effectiveness of orthopaedic implants [2], and bone health evaluation. With the use of this computational technique, scientists and engineers can learn more about how biological tissues and structures react to different pressures and environmental factors [3], advancing the fields of healthcare, orthopaedics, and sports science. The femur, the longest and strongest bone in the human body, is essential in daily activities [4-6]. It functions as a structural pillar of the thigh, supporting body weight and aiding upright posture during activities such as standing, walking, and running. Its rounded head articulates with the hip joint, allowing for a wide range of hip motion, which is essential for actions like bending, twisting, and turning. Furthermore, the lower end of the femur links to the knee joint, conveying forces during actions such as climbing stairs, sitting, and squatting [7]. Fundamental to our daily mobility and total functional independence is the femur's amazing strength and flexibility. Compression plates are crucial in the treatment of femoral fractures, particularly proximal femoral fractures [8]. They work as internal fixation devices, supporting and aligning shattered bone fragments, allowing structural integrity and patient movement to be restored. Porous compression plates are particularly important in this context due to their potential to improve osseointegration and so promote bone repair [9]. The porous structure promotes bone ingrowth while decreasing stress shielding effects and biomechanical incompatibility with neighbouring bone. This not only reduces the danger of implant loosening, but it also has the potential to speed up the healing process, minimizing complications and improving long-term outcomes, especially in complex fractures where optimum bone repair and maintained stability are critical. In orthopaedics, the usage of compression plates with Gyroid, Schwarz D and Schwarz P lattice structures constructed of Titanium alloy and Stainless Steel represents an exciting technique. These lattice structures provide a distinct combination of strength and low material density, making them potentially suitable for orthopaedic implants [10-11]. The geometric intricacy of the gyroid lattice allows for improved bone ingrowth and osseointegration, which is especially important for increasing long-term implant durability and patient recovery. Depending on specific clinical applications and patient needs, the option between titanium alloy and stainless steel allows for consideration of material biocompatibility, strength, and corrosion resistance. The study's findings could provide light on the performance and biocompatibility of these novel lattice architectures and materials used in compression plates for orthopaedic applications.

II. MATERIALS AND METHODS

A. Generating Geometric Model of Femur Bone

The data was collected utilizing CT (Computerized Tomography) equipment from a male volunteer aged 61 and weighing 72kg. These DICOM images were imported using MIMICS 21.0 (Altair Corp., Belgium) to partition the femoral skeletal information and build the femoral geometry model displayed in Fig.1. The model was then transferred using 3-matic software 21.0 (Altair Corp., Belgium) to smooth and polish the surface.

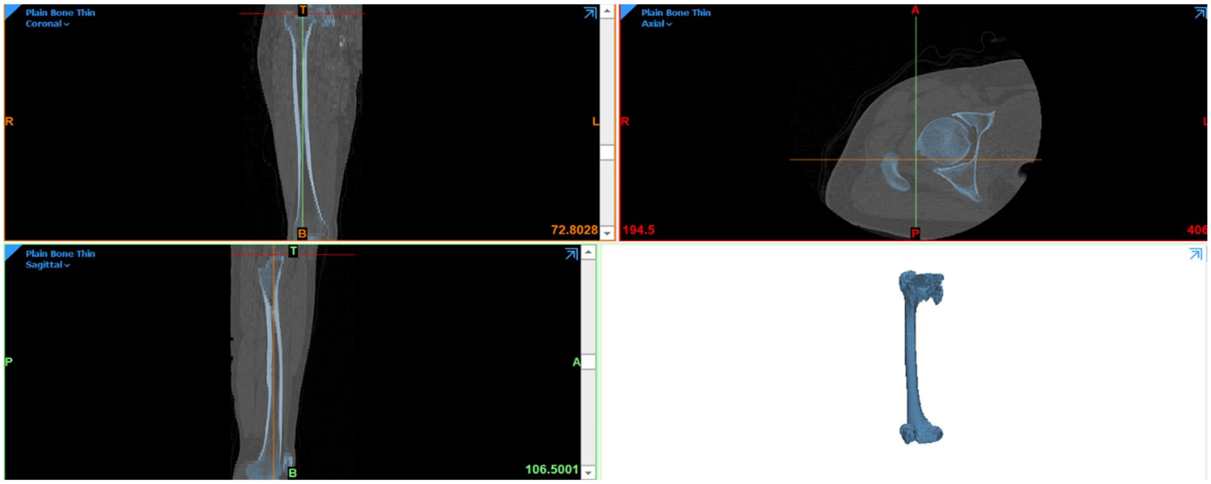
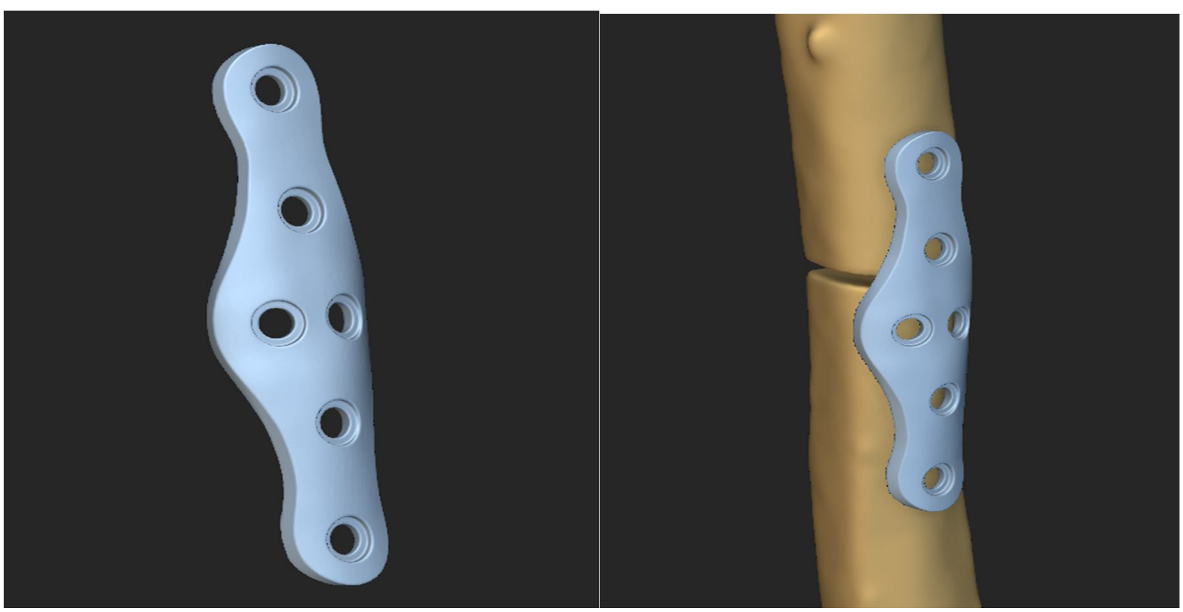


Fig. 1 The model of the Femur bone was built using DICOM files on MIMICS 21.0

The femoral bone's ultimate condition displayed a fracture within the cortical bone at its midpoint. Subsequently, we employed Solidworks 2020 (Dassault System SolidWorks Corp., Waltham, USA) to create a custom-fitted compression plate designed to match the contours of the fractured bone. The compression plate we devised featured a total of 6 screw placement apertures of which 2 situated at the centre and the remaining 4 positioned along the longitudinal axis. Its dimensions measured 35.41x10.41x5.24 mm, precisely tailored to cover and stabilize the fractured bone, as depicted in Figure 2.



(a) (b)

Fig. 2 (a) Design of Compression plate (b) Compression plate assembled to fractured bone

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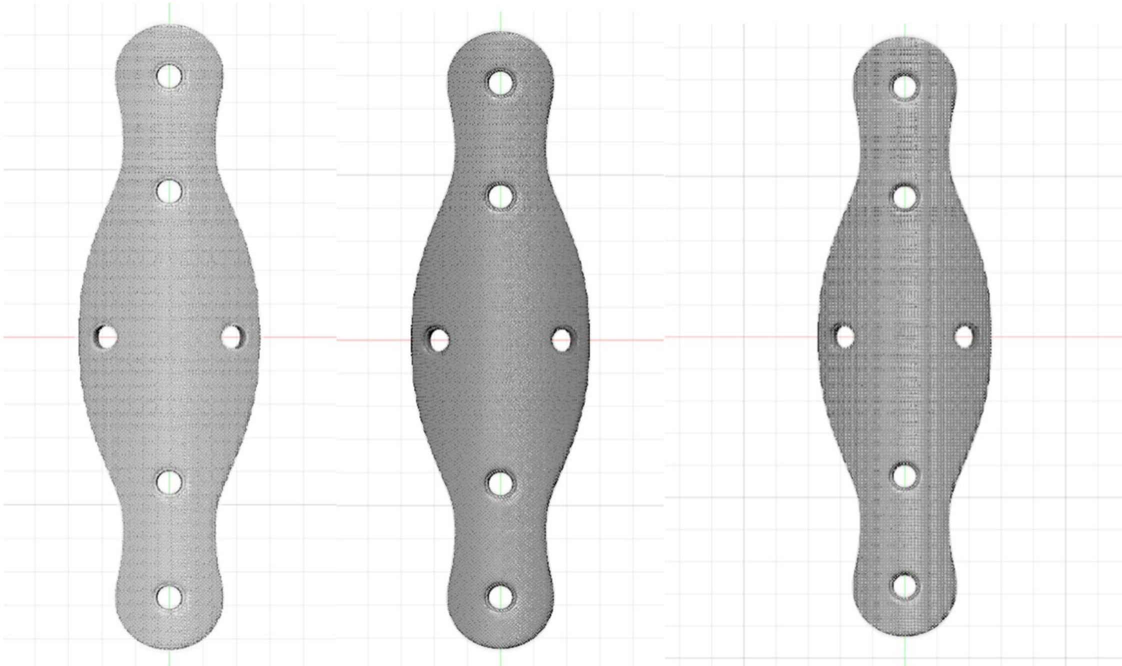
B. Creating Porous Model of Compression Plate

We generated a porous model of the compression plate using Fusion 360, taking into account three distinct lattice structures: Gyroid, Schwarz D, and Schwarz P of unit cell size 1mm as shown in Figure 3.



(a) (b) (c)

Fig. 3 Compression Plate of unit cell size 1mm of (a) Gyroid (b) Schwarz D (c) Schwarz P

C. Finite Element Model of Compression Plate

These compression plate model were transformed into a finite element model within Solidworks 2023 through meshing by Curvature-based solid mesh.

D. Material Allocations

We conducted simulations on the porous compression plate using a uniform, isotropic, linear material, which was made of Titanium Alloy (Ti-6Al-4V) having Elastic modulus of 1.048*e*+11 MPa and Poisson’s Ratio as 0.31 and Stainless Steel (316L SS) having Elastic modulus 2*e*+5 MPa and Poisson’s Ratio as 0.265.

E. Model Validation

To validate the results of the finite element analysis, we employed a comprehensive skeletal model. Load distribution was conducted in accordance with the methodologies outlined in the studies by Kumar et al. [12] and Anita et al. [13], encompassing walking condition.

F. Defining Constraint, Load and Boundary Conditions

A load of 750 N was applied to the upper surface of the knee head of the porous compression plate, while the femoral head was held in a fixed position. This load was equivalent to the patient's body weight, which measured 72 kilograms. In Solidworks 2023 software, we set up a static analysis step and introduced the necessary boundary and load conditions for this simulation.

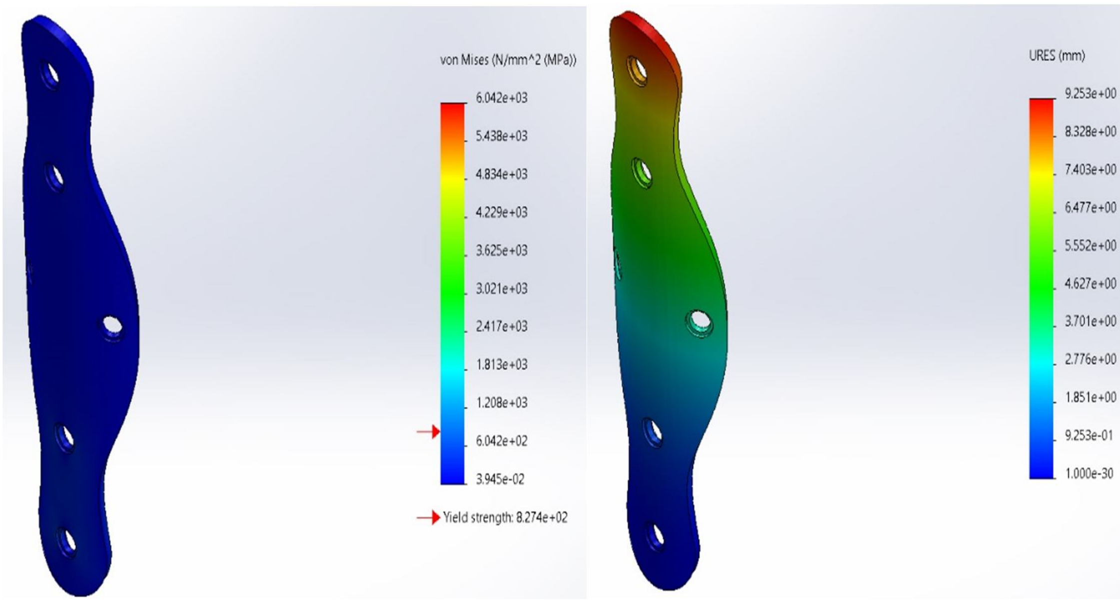
G. Outcome Measures

The stress, strain and deformation distributions of the porous compression plates were observed.

III. RESULTS AND DISCUSSIONS

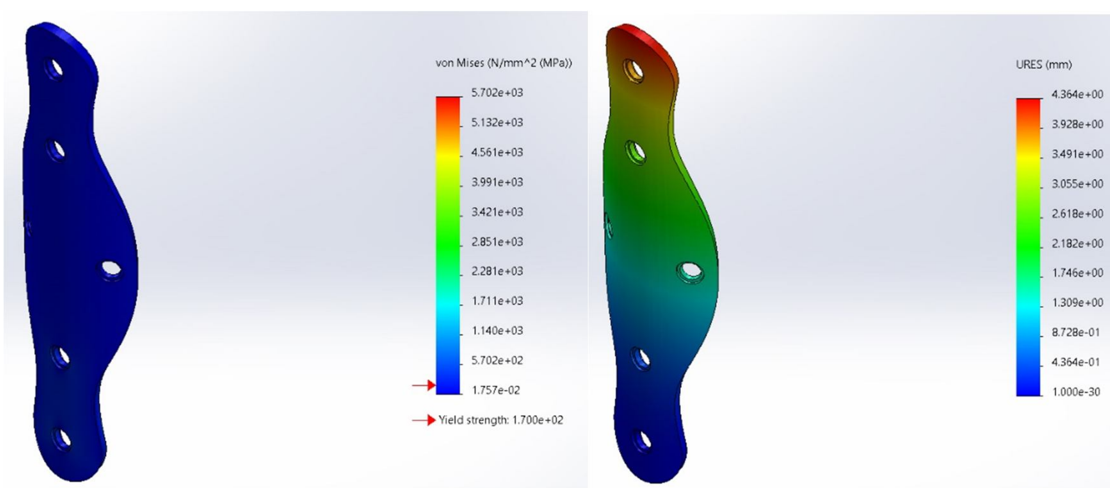
The results of our study, focusing on porous compression plates with Gyroid, Schwarz D, and Schwarz P lattice structures, incorporating two distinct material option Titanium Alloy (Ti-6Al-4V) and Stainless Steel (316L SS), subjected to loading during routine walking activities on the femur bone, are outlined below.

Initially, we assessed the stress, strain, and deformation in our conventional compression plate, illustrated in Figure 4-5, as a point of reference for comparing the outcomes with the porous compression plates, as detailed in Table 1.



(a) (b)

Fig. 4 Conventional Plate of Ti-6Al-4V (a) Stress (b) Displacement distribution

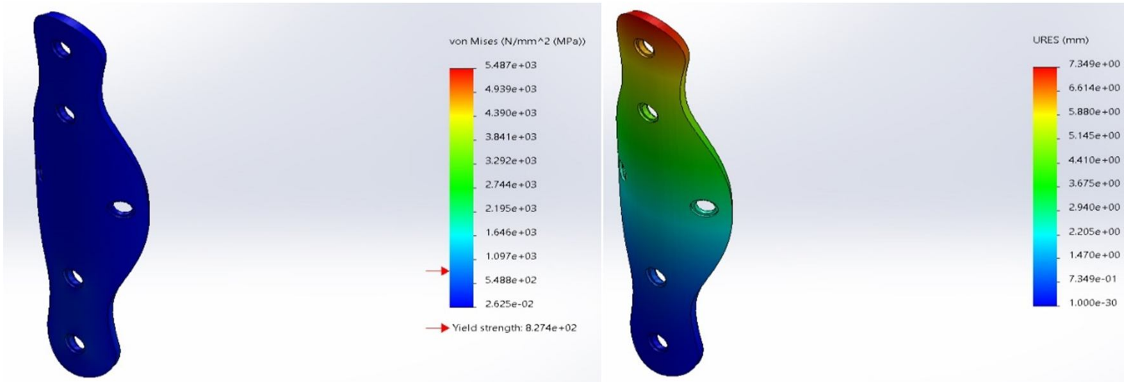


(a) (b)

Fig. 5 Conventional Plate of 316L Stainless Steel (a) Stress (b) Displacement distribution

A. In Gyroid Lattice Structured Compression Plate

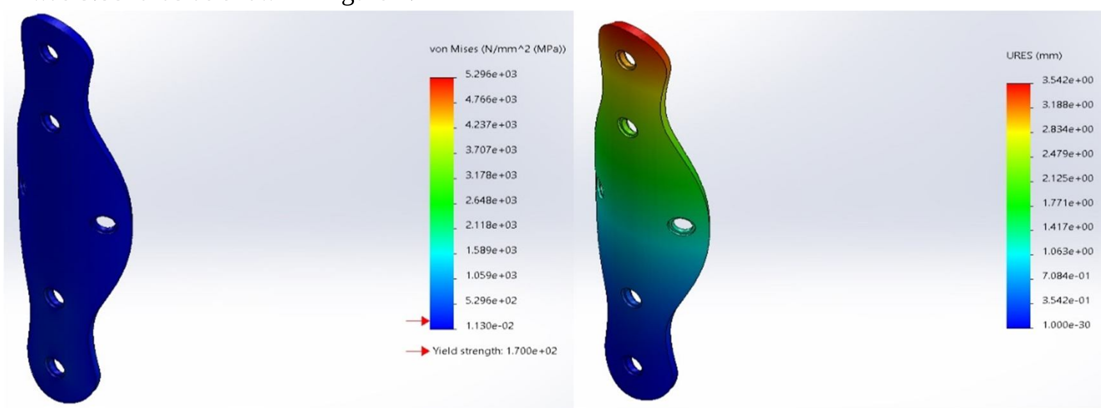
The analytical investigation demonstrated that in Gyroid lattice structured plate with 1mm unit cell size and having Ti-6Al-4V properties, the maximum stress was 5.487*e*+03 MPa and maximum deformation was 7.349*e*+00 mm and maximum strain was 7.392*e*-03 as shown in figure 6.



(a) (b)

Fig. 6 Gyroid compression plate of Ti-6Al-4V (a) Stress (b) Displacement distribution

While having 316L SS properties, the maximum stress was 5.296*e*+03 MPa and maximum deformation was 3.542*e*+00 mm and maximum strain was 3.582*e*-03 as shown in figure 7.

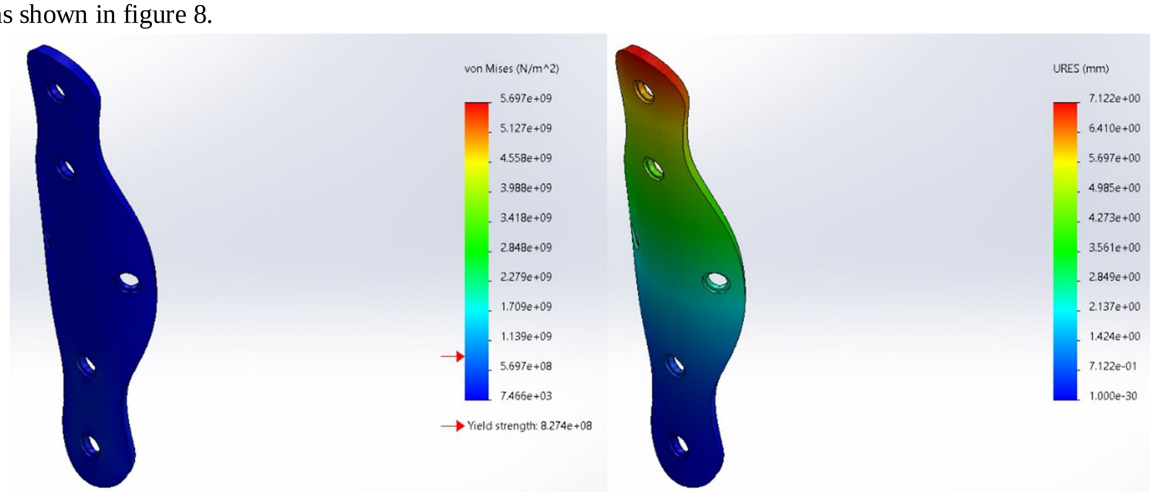


(a) (b)

Fig. 7 Gyroid compression plate of 316L SS (a) Stress (b) Displacement distribution

B. In Schwarz D lattice Structured Compression Plate

The analytical investigation demonstrated that in Schwarz D lattice structured plate with 1mm unit cell size and having Ti-6Al-4V properties, the maximum stress was 5.697*e*+03 MPa and maximum deformation was 7.122*e*+00 mm and maximum strain was 1.241*e*-02 as shown in figure 8.



(a) (b)

Fig. 8 Schwarz D compression plate of Ti-6Al-4V (a) Stress (b) Displacement distribution

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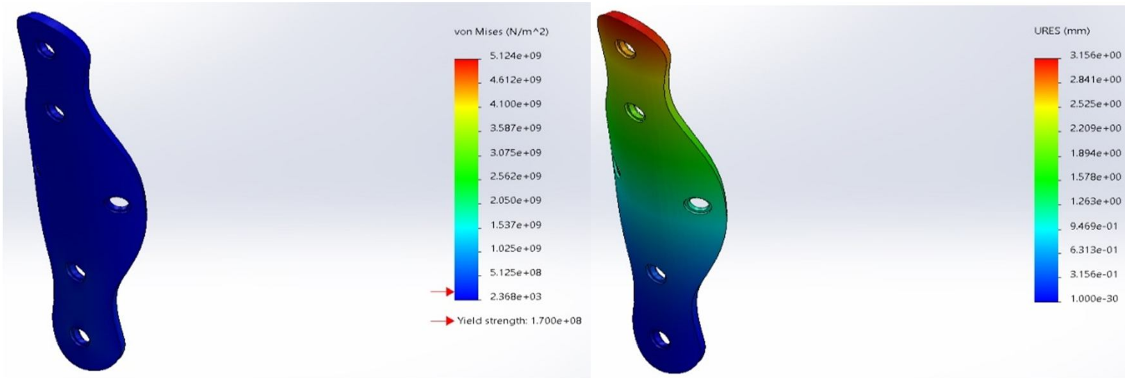
While having 316L SS properties, the maximum stress was 5.124*e*+03 MPa and maximum deformation was 3.156*e*+00 mm and maximum strain was 5.638*e*-03 as shown in figure 9.

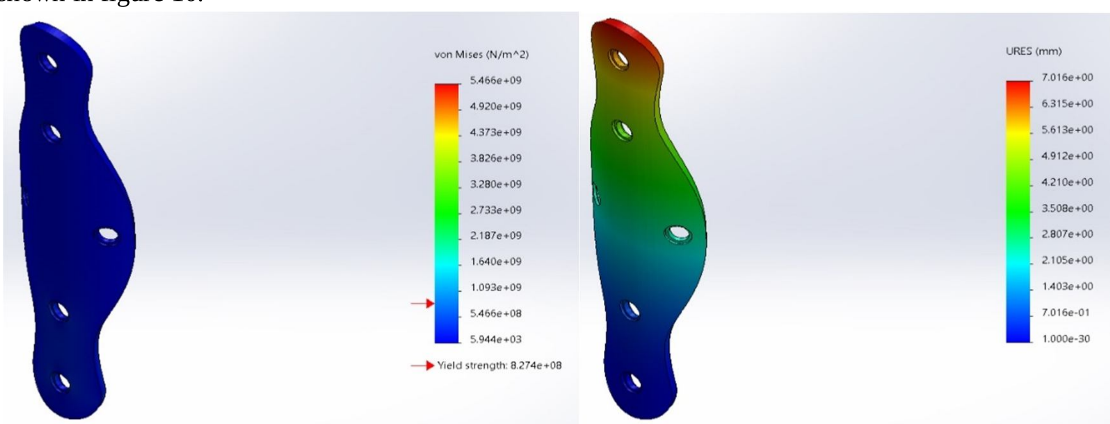


(a) (b)

Fig. 9 Schwarz D compression plate of 316L SS (a) Stress (b) Displacement distribution

C. In Schwarz P lattice Structured Compression Plate

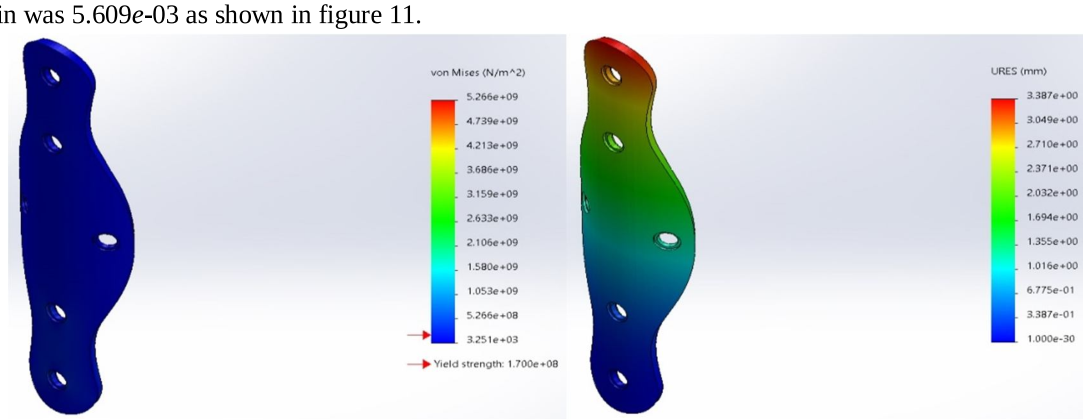
The analytical investigation demonstrated that in Schwarz P lattice structured plate with 1mm unit cell size and having Ti-6Al-4V properties, the maximum stress was 5.466*e*+03 MPa and maximum deformation was 7.016*e*+00 mm and maximum strain was 1.139*e*-02 as shown in figure 10.



(a) (b)

Fig. 10 Schwarz P compression plate of Ti-6Al-4V (a) Stress (b) Displacement distribution

While having 316L SS properties, the maximum stress was 5.266*e*+03 MPa and maximum deformation was 3.387*e*+00 mm and maximum strain was 5.609*e*-03 as shown in figure 11.



(a) (b)

Fig. 11 Schwarz P compression plate of 316L SS (a) Stress (b) Displacement distribution

Lattice Structure	None		Gyroid		Schwarz D		Schwarz P	
Material	Ti-6Al-6V	316L SS	Ti-6Al-4V	316L SS	Ti-6Al-4V	316L SS	Ti-6Al-4V	316L SS
Stress (MPa)	6.042*e*+03	5.702*e*+03	5.487*e*+03	5.296*e*+03	5.697*e*+03	5.124*e*+03	5.466*e*+03	5.266*e*+03
Deformation (mm)	9.253	4.364	7.349	3.542	7.122	3.156	7.016	3.387
Strain	1.161e-02	5.483*e*-03	7.392*e*-03	3.582*e*-03	1.241*e*-02	5.638*e*-03	1.139*e*-02	5.609*e*-03

Table 1 All Lattice Structured Plates Stress, Strain and Deformation

In this study compression plate of Ti-6Al-4V material properties, Schwarz P lattice structure had least stress with almost 10% less than conventional plate and also lowest deformation and strain, although values are somewhat consistent in all 3 lattice structure in terms of stress.

Compression plate of 316L SS material properties, Schwarz P lattice structure had least stress with almost 10% less than conventional plate and also lowest deformation while strain is lowest in Gyroid structure.

This research possesses several constraints primarily rooted in its reliance on finite element analysis. The study did not encompass torsional loading conditions, focusing solely on axial loading scenarios. To enhance the validity of our findings and promote potential alterations in compression plate design for diverse fracture types, future investigations could incorporate experimental testing as a complementary approach, providing empirical confirmation and insights.

IV. CONCLUSIONS

In the present research, we examine the performance of porous compression plates with varying material properties. The primary objective is to gain a comprehensive understanding of the behaviour of these porous compression plates. The outcomes of this study have practical applications in selecting the most suitable lattice structure for compression plates to ensure optimal stress distribution, in addition to determining the necessary plate thickness and material type for promoting the healing of fractured bones.

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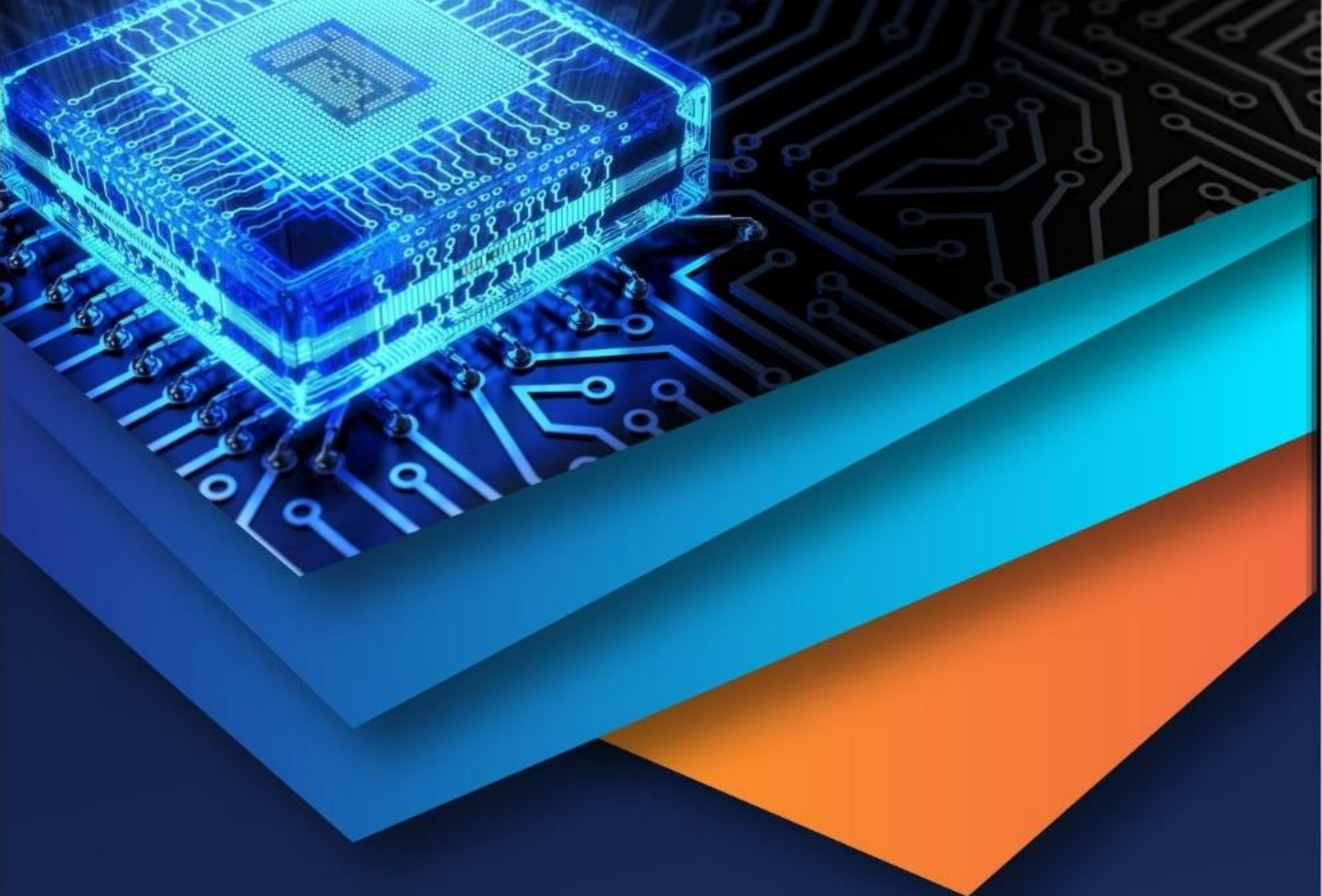

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