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Management of Ti-6Al-4V and SS316L Stress Shielding and Stability of Femoral Fracture Fixation Bone Plates by Finite Element Analysis in COMSOL Metaphysics

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Abstract:

The human femur is known as the longest bone in the human body. For compression, it is known as the most robust bone. The femur bears the majority of body weight and facilitates several essential functions, including ambulation and leaping from a height. Bone fractures typically result from an excessive stress that exceeds the maximum strain that a human bone can withstand. Due to the loss of the bone's capacity for self-healing, a bone fracture with a fragment larger than 5 mm needs extra support, such as a bone implant, for recovery. The repair process is accelerated with a bone implant that holds the parts in place, permits realignment, and limits excessive movement. The commercially available bone plates comprised of biocompatible metallic materials or metal alloys are used in the current fracture fixation technique. To aid in the healing process, these bone plates are often attached to one side of the fracture. Prosthetic bone bioimplants have been designed and developed using conventional metallic biomaterials like titanium alloy (Ti-6Al-4V) and stainless steel (SS 316L). Two typical internal fixation materials are relatively evaluated with Finite Element Method (FEM) in COMSOL Multiphysics and they comprise Titanium alloy (Ti-6Al-4V) and Stainless Steel (SS316L) in realistic conditions of loads in the fractures of the diaphyseal segment of the femur. The fixation of the fracture shall be stable and the issue of stress shielding is the issue due to the use of the relatively inelastic material that is SS316L (Young) which are the ones that bear the majority of the load and causes bone resorption A complex 3D model of the femur-plate-screw system with transverse fracture of 1 mm has been modeled with an intention of equaling the material with the same physiological biomechanical boundary loads. These results showed that theTi-6Al-4V plate system was in a superior state concerning the mechanical performance of an overall displacement of 3.887599mm, compared to the huge displacement of SS316L (25.1252). It proves that Ti-6Al-4V is better and provides greater structural stability and thus is even more suitable material which can be used as load-bearing orthopedic implants, where structural stability is of significant determinant of clinical success.

Keywords: *Femur fracture, Titanium alloy, Stainless Steel, Finite Element Method*

I. INTRODUCTION

The human femur, as the longest and most robust bone in the skeletal system, plays a critical role in supporting body weight, facilitating locomotion, and maintaining structural integrity during dynamic activities. The femur has a long, slender and nearly cylindrical structure of the body. The bottom (distal) part of the femur is bigger compared to the top. It is composed of two oblong eminences referred to as condyles (Das & Sarangi, 2014). The femur articulates with the socket at one end to create the hip joint, while at the opposite end, it articulates with the tibia and patella to form the knee joint. The most prevalent fracture that orthopedists deal with is the fracture of the femoral shaft (Gösling & Krettek, 2019). Its incidence is 0.01% (Weiss et al., 2009). It usually happens due to high energy traumas, and is linked to polytrauma, open fracture and multiple fracture (Li et al., 2016). The predominant causes of femur fractures are motor vehicle accidents, sports injuries, falls from significant heights, and pre-existing bone conditions are common causes of it in young patients, and in old osteoporotic patients (Gösling & Krettek, 2019; Weiss et al., 2009). That compromise bone integrity, such as Paget's disease and osteoporosis (Ahirwar et al., 2021). Despite the human femur's considerable resistance to fracture, it may sustain a break as a result of high-velocity traumatic traumas. The biomedical implants have bone plates and other materials that are applied to improve the physiological state of the victims of a road accident and the elderly to enjoy normal lives (Kurniawan et al., 2022)

The bone fracture normally takes place when the corresponding stress is beyond what human bone tissue can take. Once the bone no longer has the necessary capacity to heal correctly, especially when the fracture gap or fragment size is more than 5 mm, some mechanical assistance like a bone implant is necessary to help the bone heal correctly (Kurniawan et al., 2022). A number of treatment approaches are widely applied when working with the case of a broken femoral shaft, which includes skeletal traction, plate-and-screw fixation, intramedullary nailing, and external fixation (Crist & Wolinsky, 2009; Scannell et al., 2010; Zlowodzki et al., 2007). When intramedullary fixation is unable to be used effectively, plate fixation is usually suggested (Apivatthakakul et al. 2009; Köseoğlu et al., 2011). According to previous findings, material fatigue in the fixation device has been cited as one of the major causes of internal fixation failure (Birringer et al., 2016). Other studies have also examined the various plate-screw designs in order to enhance stability and performance of the fixation. Bone implants can be used to aid the healing process as they ensure that the fractured parts are stabilized so that the bone can heal properly, and they help in limiting excessive movement during the healing process (Cronier et al., 2010; Sheng et al., 2019; Wang et al., 2020).

Biomechanics is a scientific field that applies technical principles of mechanics of all forces acting on the human body and the impact of the forces on the bone to study the biological system. It is a science that involves the application of mechanical principles to an organism to gain insight behavior and mechanical behavior of biologic structures (Ganesh et al., 2005). Biomechanical systems can be modelled and tested by using the physics and engineering rules to investigate the performance of bones and other tissues in terms of structure. The biomechanical factors, which dictate the rate of healing efficacy of a fractured bone using plates and screw, are supplied to the fractured bone in the shape of (a) the degree of bone contact at the fracture interface and (b) stability offered to the fracture bone either locally at the fracture interface or distally away at the fracture interface (O'Rourke et al., 2023). Analyzed how to precisely forecast the likelihood and risk of fracture, in metastatic femurs using a finite element model. The material models, loading conditions and critical thresholds however vary in these models (Balasubramani et al., 2023). The orthopedic surgeons are struggling to treat bone fractures that occur as a result of accidents.

In order to solve this problem, external stabilization of fractured bones is done by the use of screws and locking compression plates. We modeled the bone of the femur, locking compression plate, and screws in this study. We proceeded to analyze the available materials to join plates with other materials (Naidu Manubolu et al. 2022). Bones are the structural support of the body that supports the body and safeguards the vital organs as well as providing us with a solid structure to move around. Learning about bone mechanics is relevant to learn about bone breakage and how and why it occurs. Fractures occur when the pressure or the weight on a bone surpasses its ability to support the weight (Kalaiyarasan et al., 2020). Bones are very important tissues composing calcium and phosphorus. They multiply rapidly during their young years and mend themselves satisfactorily. The human skeleton is vital as bones give support to the rest of the body which is usually soft. In case bones break, one of the most common ways of treating them is through bone joints that rejoin the broken parts (Fouad, 2011). In order to facilitate the stabilization of the bone structure, a number of internal fixation instruments such as bone plates are implanted (Innocenti et al., 2016). The femur skeleton is capable of supporting 25 percent of the body weight of the height of the person. It is capable of supporting 2500 N (4 times the body weight) without causing a noticeable reduction in the factor of safety (Ceddia et al., 2024).

The commercially available bone plates comprised of biocompatible metallic materials or metal alloys are used in the current fracture fixation technique. To aid in the healing process, these bone plates are often attached to one side of the fracture. Prosthesis geometry, material characteristics, and surface finishing are the most crucial aspects of femoral prosthesis design that impact a prosthetic bioimplant's long-term life. Furthermore, the dissimilarities between the rigidity of a native bone and a bioimplant are blamed for the prosthesis's failure. For prostheses to survive over time, the crucial biomechanical factors at the bone bioimplant interface must be carefully taken into account. High stiffness is known to lead to problems with stress shielding, which ultimately leads to the failure of a bioimplant. On the other hand, extremely low stiffness may result in micro dislocation and prosthesis migration. Prosthetic bone bioimplants have been designed and developed using conventional metallic biomaterials like titanium alloy (Ti-6Al-4V) and stainless steel (SS 316L) (Ahirwar et al., 2021). The most common type of implant fabrication material is the stainless steel (SS316L). The stainless steel (SS316L) is very rigid with high modulus (approximately 200Gpa) which makes it very likely to create strong shielding effect (Basirom et al., 2023). Despite these generalized impressions, the quantitative study in a direct and numerical manner of the effects of the two materials on the biomechanics of eccentric fracture of the femur at realistic conditions of multiload carries a strong clinical implication in the judgment (Zhang et al., 2021a).

Finite Element Method (FEM) is considered to be one of the most broadly embraced computational tools used to model biomechanical structures. FEM is a numerical method of solving complicated structural and mechanical problems that are not easy to solve numerically by other standard analytical methods. In biomechanical studies, solid modeling packages like SolidWorks have been popular in the creation of three dimensional models that are very similar to the structures of the human body. These models are then imported to simulation platforms to be analyzed in detail in the mechanical analysis.

The interactive method of Finite Element Analysis (FEA) is now a common tool of biomedical study in systematic exploration of biomechanical behavior. With the help of software programs like COMSOL Multiphysics, scientists are able to build more detailed three dimensional models which are able to depict the detailed cortical structure of bones like the femur. Using FEA, stress and strain distribution can be generated and visualized in the bone-implant system. Specifically, parameters of von Mises stress on the plate and bone surfaces could be assessed, which makes them a promising noninvasive and reliable means of estimating the implant performance and measuring the effect of stress shielding in the case of various loading conditions (Ronsivalle et al., 2025).

The goal of this research is to create a bone plate implant for the femur bone. COMSOL is used to design the implant to analyze and compare the mechanical behavior of titanium and stainless steel under identical loading and boundary conditions using finite element analysis. The study focuses on evaluating stress distribution and displacement responses to determine the effect of material selection and identify the more suitable material for load-bearing applications.

2. METHODOLOGY

A comparative biomechanical study of the Femur plate screw system was done using the Finite element method (FEM) in comsol Multiphysics in a stringent procedure to guarantee the reliability of the simulation. This was done by creating a 3D model of the femur, plate and screws with the correct anatomical dimensions and material properties. The materials were allocated depending on the nature of the bone (cortical and cancellous bone) and the implantation materials such as titanium or stainless steel. Previous conditions were used to model real-life constraints, including fixing the femur on the proximal end and leaving the end of the plate and screws, simulating their real-life connection. Compressive, shear, and bending forces were simulated to physiologically load the system in order to reproduce activities that humans typically perform during walking or standing. The model has been divided into smaller elements using a meshing strategy so that it can have more mesh density on the areas that are considered to be critical in calculating stress and strain. The findings helped in the understanding of the mechanical performance and possible points of failure of the system under different loading conditions.

2.1 Geometrical Model of a Bone Plate

The anatomy model of simulating a bone fracture is made in 3D that is comprised of two important structures; the outer solid cortical bone and the inner porous cancellous core. The outer layer of bone, the cortical bone is built to have a radius of 15mm and height of 200mm. This is a thick, compact layer of bones and serves the purpose of strength and protection, as does the same in the human body. This shell of the cortex is the cancellous bone, which is of spongy less dense structure; its radius measures 10mm and its height 200mm. The cancellous bone or the inner core is what makes the bone flexible and shock absorbing which aids in the distribution of forces within the bone.

The cancellous core is enclosed in the solid cortical bone in the model, which is a precise replica of the natural structure of the long bones, like the femur or the tibia.

To model a fracture, a transversal gap of 1mm is inserted at the mid-shaft which is an unstable bone fracture. This discontinuity means that the bone cannot carry the loads directly across the fractured bone. Rather, load-bearing across the fracture site should be carried all by an implant construct. The fracture is represented and has an elliptical cross-section along the long axis of the bone so that it is a true model of a fracture that can happen in practice. The elliptical form of this model helps in the structural integrity of the model and also makes the model suitable in biomechanical simulations.

The fractured bone is stabilized by the implant which is made of a plate of height 150mm, width 17mm and thickness 3mm which is the normal size of an orthopedic plate used to fix a fracture. This plate acts as the support as well as glue between the two parts of the broken bone. Seven screws are applied so that the plate can securely be in position. These screws have been designed as cylindrical designs with a radius of 3.5mm and a height of 22mm, which is the average size of screws in orthopedic surgeries. The screws are fit through pre-formed holes on the plate and it should be ensured to fit in the cortical bone in the right manner to transfer the actual weight, the screws were placed within the holes provided in the plate as indicated in Fig:1.

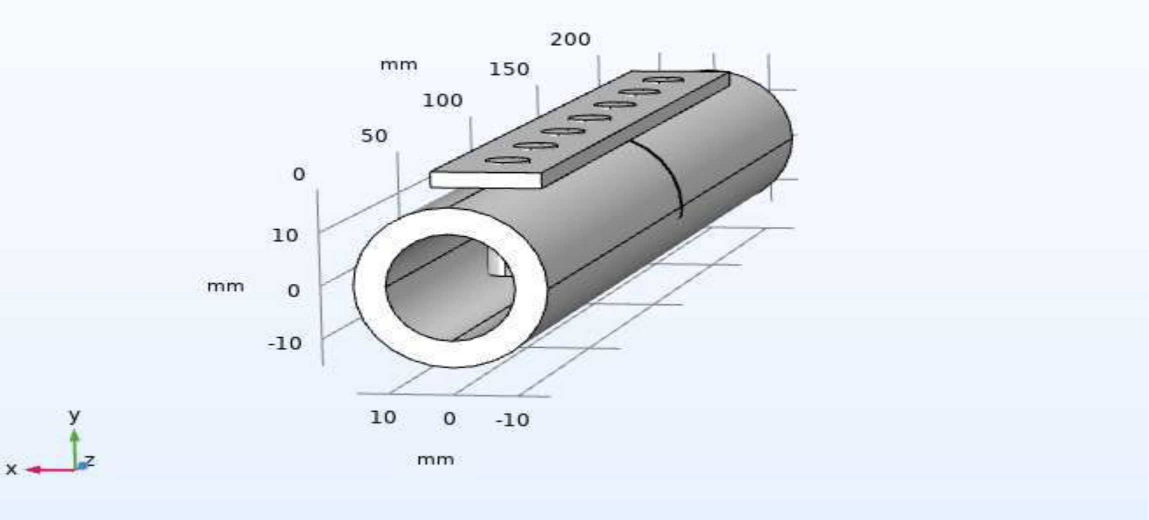


Figure 1: 3D Model of femoral bone with plate and screws

2.2 Materials and their characteristics

The two representative metal biomaterials that could represent the bone plate design were Ti-6Al-4V and SS 316L. Table 1 summarizes the metallic biomaterials including their physical and mechanical properties including their density, Young's modulus, Poisson ratio and tensile strength. The density of SS 316L is 7870kg/m3 and tensile strength of 600Mpa is better than Ti-6Al-4V (Ahirwar et al., 2021).

Table 1:Finite element model components used material properties

Component	**Material**	**Young's Modulus (Pa)**	**Poisson's Ratio (v)**	**Density**
Cortical Bone	Isotropic Elastic	17e9 Pa	0.3	1900 kg/m3
Plate+Screw	Titanium (Ti-Al-4V)	1.1e11 Pa	0.34	4430 kg/m3
Plate+Screw	Stainless steel (SS 316 L)	193e9 Pa	0.3	7870 r 3

2.3 FEM Boundary Condition

A load and a boundary condition are applied to the bone plate and solid mechanics analysis with COMSOL Multiphysics is applied.

2.3.1 Fixed Support

The distal end of the bone of the femur was given a fixed support as presented in the

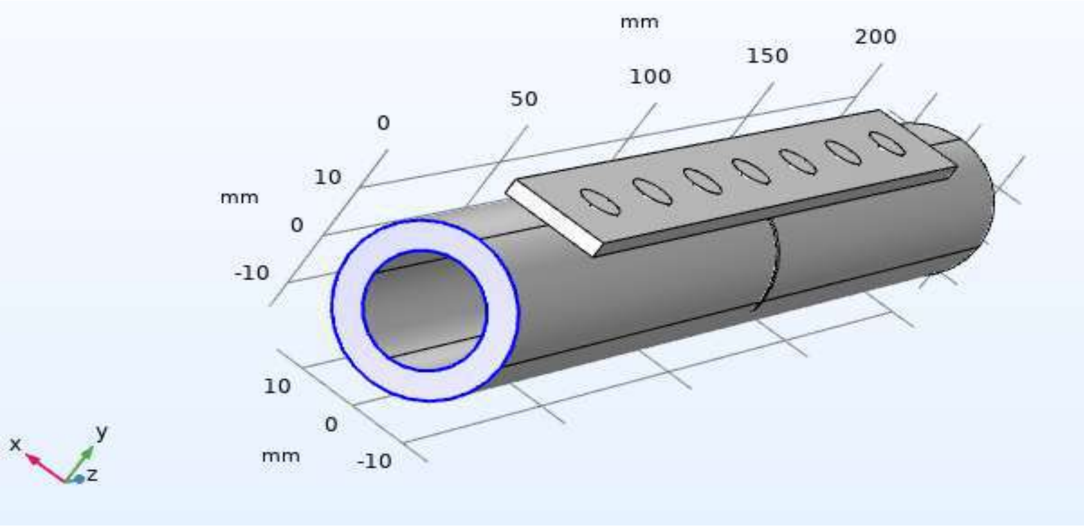


Fig:2.

Figure 2: distal end of the femur bone receives fixed support

2.3.2 Load

Figure 3 and 4 depict that a load of -1000 N was applied to the proximal end of the bone of the femur and a load of 1.1 MPa was applied to the surface of the bone that is opposite to the plate (Zhang et al., 2021b). This was done again with both plate

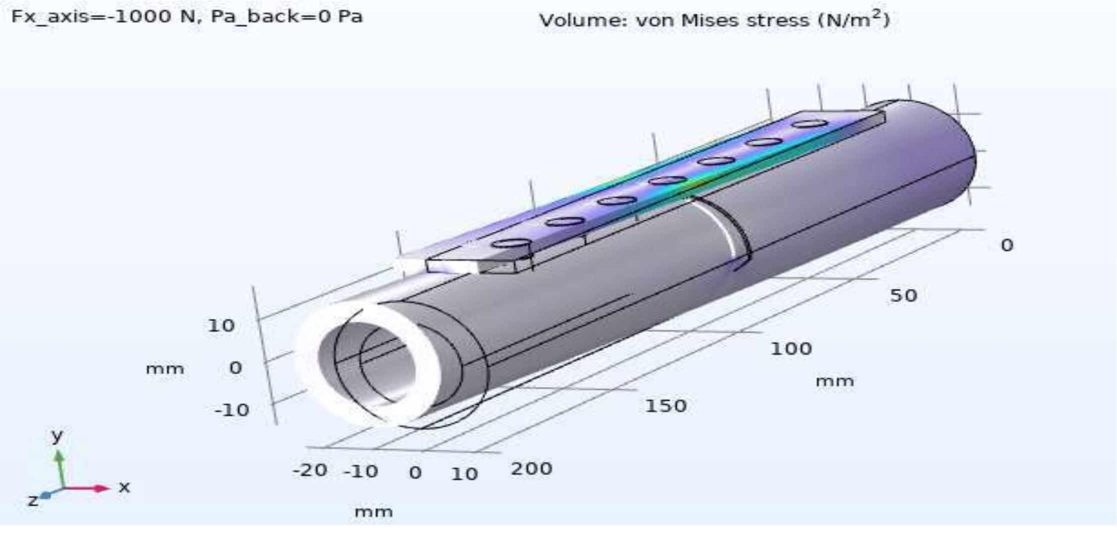


Figure 3: -1000N force is applied on the proximal end of femoral bone

materials to determine the biomechanical response of the system to these loading conditions.

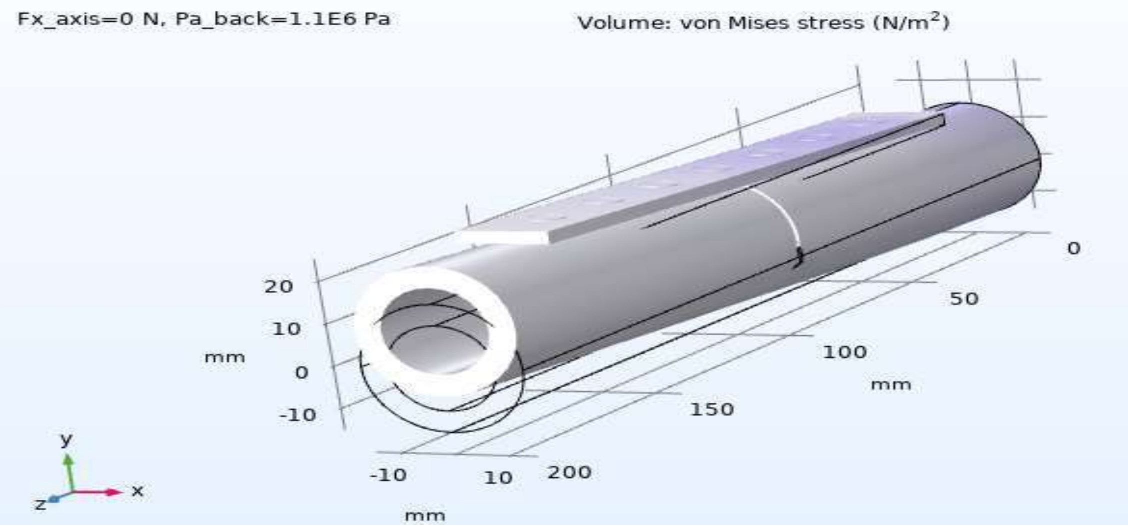


Figure 4: 1.1MPa pf load pressure is applied on the bone surface opposite to the plate

2.4 Mesh and Study

A sophisticated tetrahedric mesh of fine (0.2-0.5mm) elements in fracture regions and screws. Convergence affirmed <5% maximum variation in stress (Das & Sarangi, 2014). This reaction was aroused during the nonlinear geometry and contact stationary study to provide the correct analysis of stability.

3. RESULTS AND DISCUSSION

To compare the biomechanical performance of both Ti-6Al-4V (Titanium Alloy) and SS316L (Stainless Steel) bone plate systems, both alloys were tested in the same conditions of application and loading boundaries. Boundary loads which were 1000 N and proximal end of the femur and the pressure on the opposite surface of the plate which was 1.1 MPa was identical in both material systems. The greatest distinction between the two materials is the mechanical properties especially the stiffness, strength, and elasticity. Consequently, the behavior of the plate in deformation of the femur system was different based on the material in which the plate was made. Ti-6Al-4V is a titanium alloy that is known to be lightweight and its strength to weight ratio is much higher and therefore, tends to deform relatively less to the applied loads. Conversely, SS316L, austenitic stainless steel, is more rigid and flexible than titanium which means that it deforms differently in the same loading conditions. Such material behavior differences are observed in the deformation trajectories as the degree and distribution of stress and strain throughout the system are different in the two materials, which provide an insight into the behavior and the appropriateness of each material to the orthopedic uses.

3.1 Force is Applied on the Proximal End of Femoral Bone

For Ti-6Al-4V material, the displacement is between 0 to 4.867mm. and the max von Mises stress is 6.088E8 N/m² as shown in Fig:5. The 2D displacement contour on

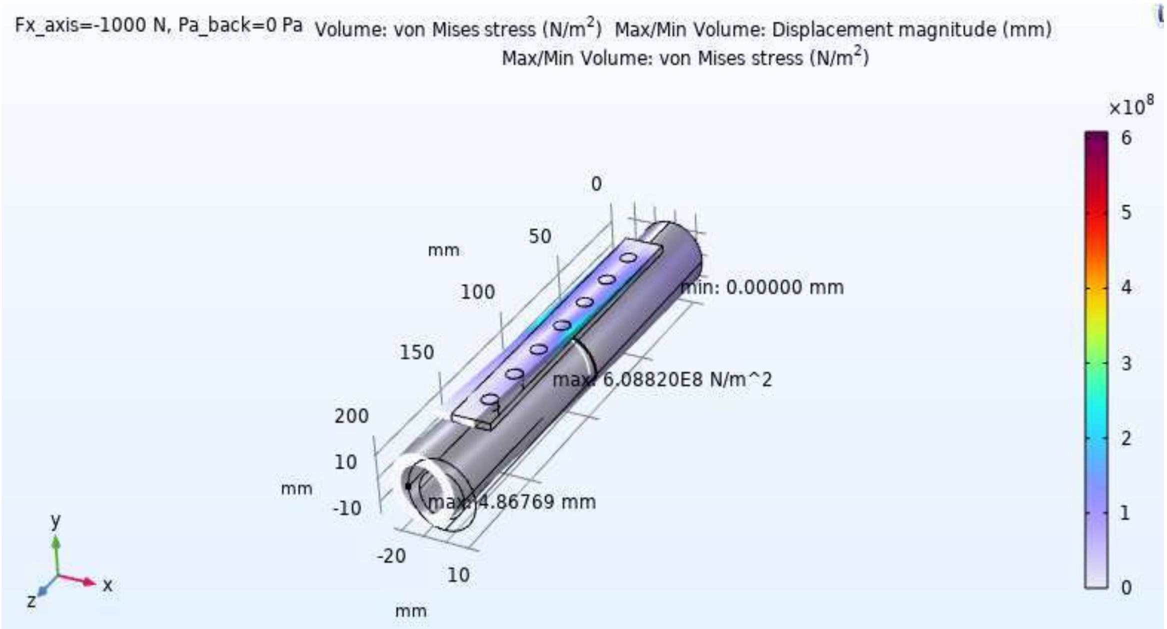


Figure 5: 3D displacement and von Mises stress in Ti-6Al-4V material

Fig:6 affirmed the displacement was greatest about the fracture gap than about the other parts of the bone. The point graph in 1D illustrates in fig. 7 the relationship between stress and displacement, showing how stress decreases as displacement increases. This graph is crucial for understanding the behavior of the material under different loading conditions.

For Stainless steel (SS 316L) material, the displacement is between 0 to 4.546 mm. and the max von Mises stress is 6.485E8 N/m² as shown in Fig:8. The 2D contour of the displacement as depicted in Fig:9 confirmed the fact that the deformation was highest around the fracture gap than the rest of the bone. The point graph in 1D illustrates in fig:10 the relationship between stress and displacement, showing how stress decreases as displacement increases. This graph is crucial for understanding the behavior of the material under different loading conditions.

Figure 7: 1D point graph of Ti material

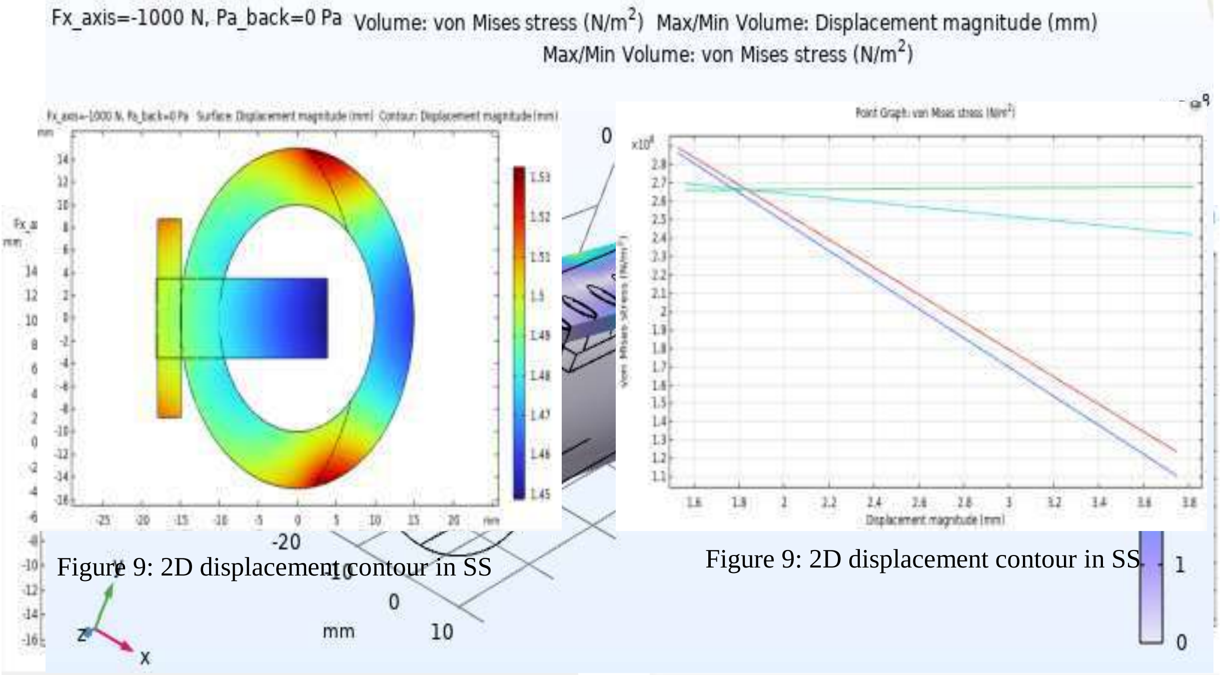


Figure 9: 2D displacement contour in SS

Figure 9: 2D displacement contour in SS

Figure 6: 2D displacement contour in Ti

Figure 8: 3D displacement and von Mises stress in SS 316L material

Figure 7: 1D point graph of Ti material

3.2 Pressure is Applied on the Bone Surface Opposite to the Plate

For Titanium alloy (Ti-6Al-4V) material, the displacement is between 0 to 9.283 mm. and the max von Mises stress is 3.019E9 N/m² as shown in Fig:11. The 2D contour of the displacement as shown in Fig:12 was useful in supporting how the greatest deformation was on the bone around the fracture gap than in other areas. The point graph in 1D illustrates in Fig:7 the relationship between stress and displacement, showing how stress decreases as displacement increases. This graph is crucial for understanding the behavior of the material under different loading conditions.

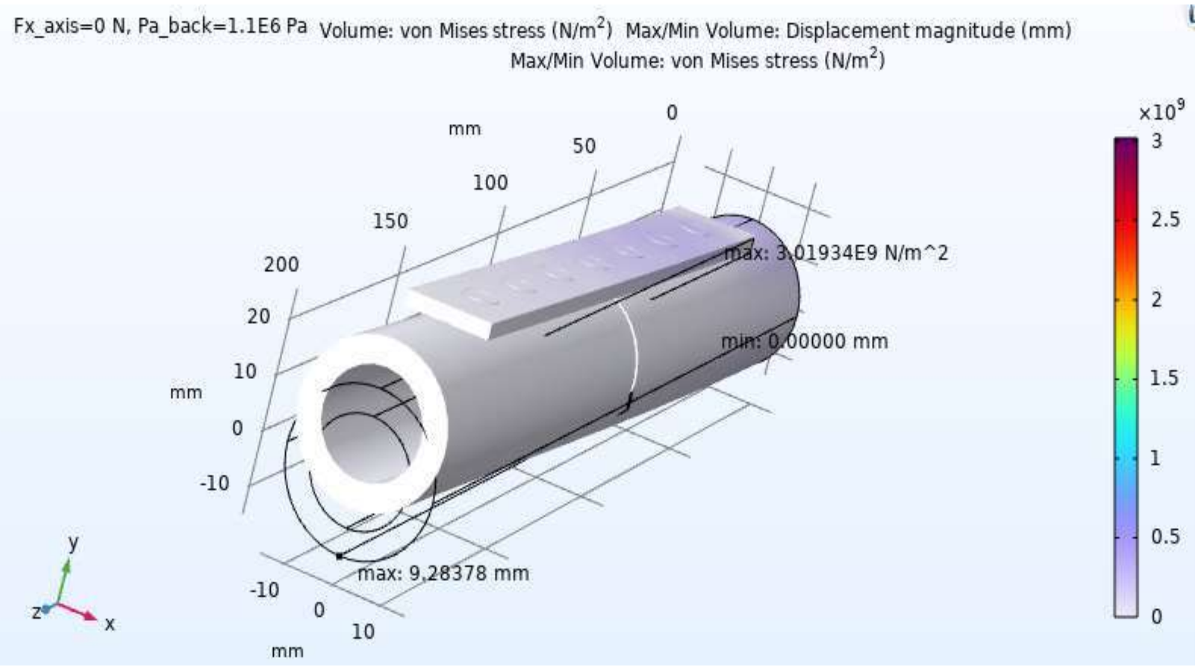
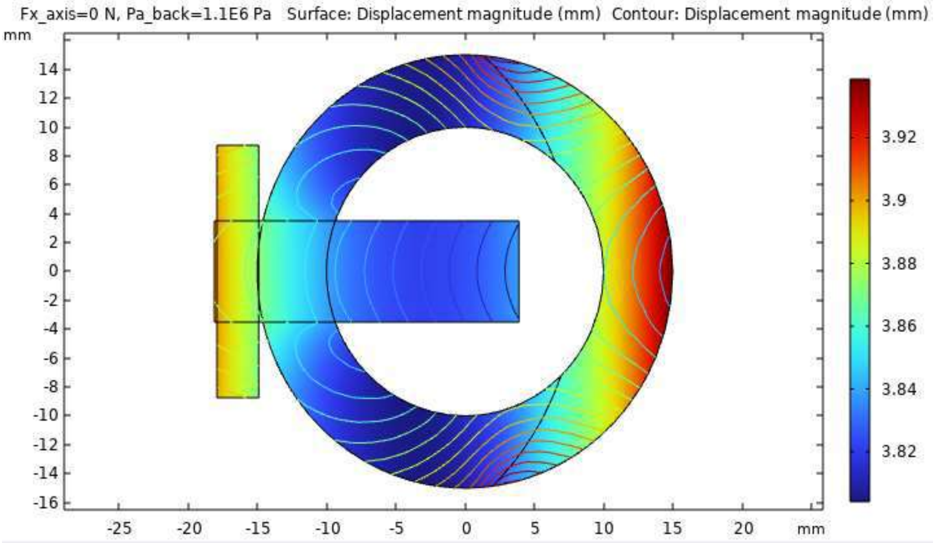


Figure 11: 3D displacement and von Mises stress in Ti-6Al-4V material

Figure 12: 2D displacement contour in Ti



For Stainless steel (SS 316L) material, the displacement is between 0 to 8.970 mm. and the max von Mises stress is 3.617E9 N/m^2 as shown in Fig:13. The 2D contour of the displacement as shown in Fig:14 was useful in supporting how the greatest deformation was on the bone around the fracture gap than in other areas. The point graph in 1D illustrates in fig:10 the relationship between stress and displacement, showing how stress decreases as displacement increases. This graph is crucial for understanding the behavior of the material under different loading conditions.

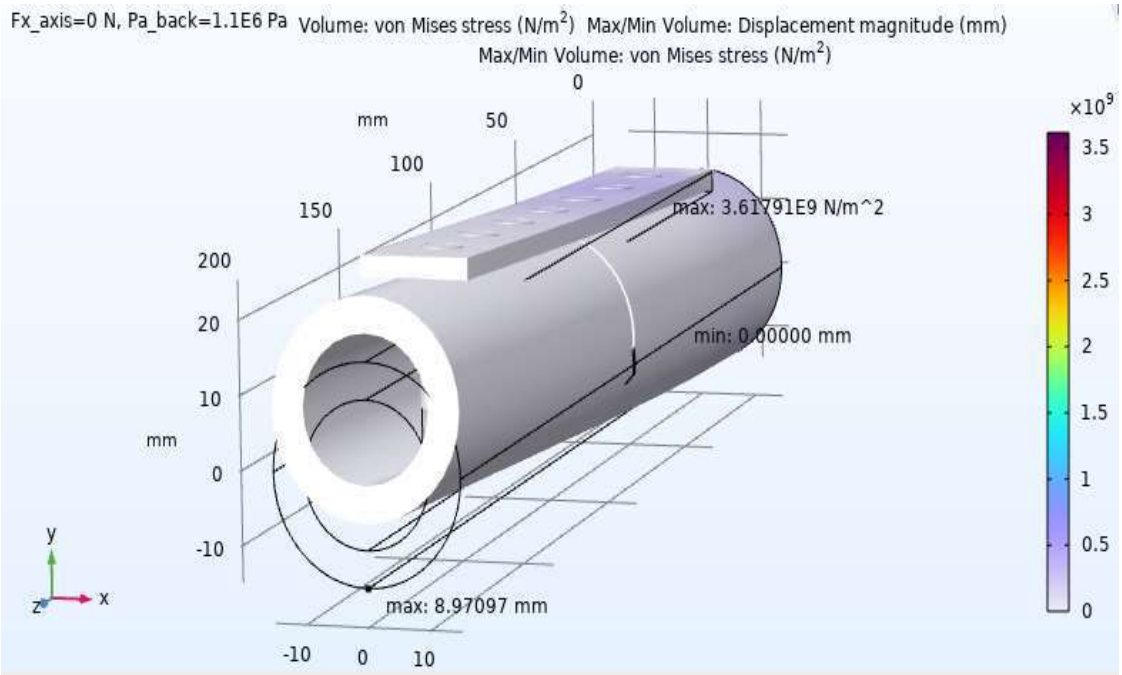


Figure 13: 3D displacement and von Mises stress in SS 316L material

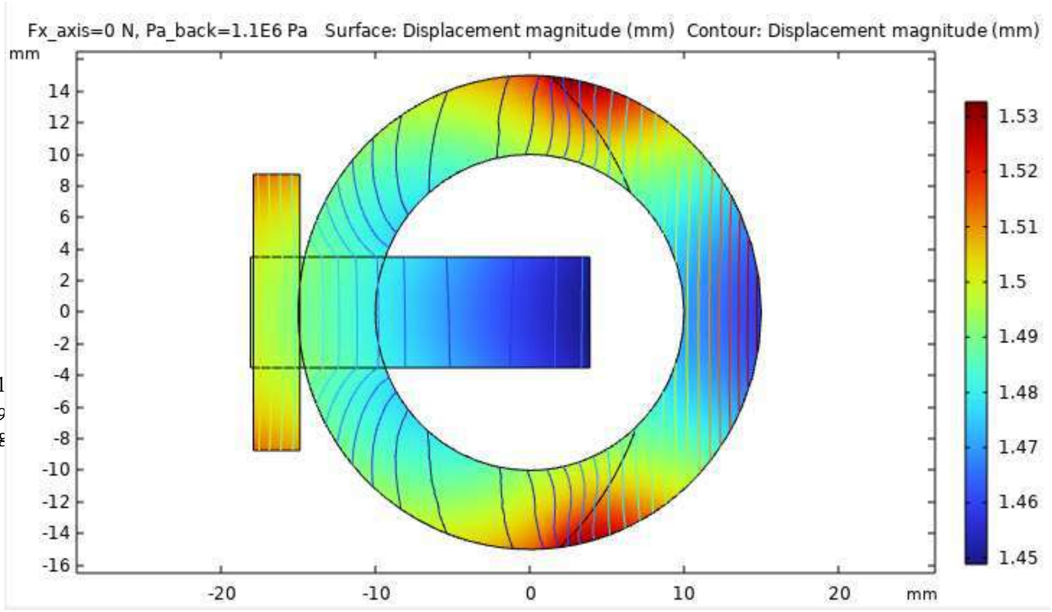


Figure 14: 2D displacement contour in SS

4. CONCLUSION & FUTURE WORK

The comparative analysis of the mechanical performance of two orthopedic materials that are commonly used in orthopedic implantation, including Titanium alloy (Ti-6Al-4 V) and Stainless Steel (SS316L), was made possible through the finite element analysis conducted in this study. The findings also showed that Ti-6Al-4V is more rigid and structurally stable during the physiological loading conditions. This could be seen in the lower values of deformation and displacement values recorded on the titanium alloy model than on SS316L. Reduced displacement also implies that the implant has a higher ability to maintain its structural integrity and withstand the bending or mechanical distortion when exposed to the external loads, which is critical in the assurance of stability of fixation constructs in fractured bones.

Conversely, SS316L demonstrated a higher displacement which implies that it is more flexible and less rigid when subjected to the same loading. Although a degree of deformation might be useful in some biomedical applications, too much deformation can adversely affect the ability of implants to stay in place, especially when the implant is required to support a load as with orthopedic implant items like bone plates and screws. High displacement may cause micro-movements at the fracture site that might influence fracture healing and extend the adverse consequences of fatigue or mechanical failure over time of implants. Thus, according to the findings obtained during the finite element analysis, Ti-6Al-4V could be regarded as a better choice of material to be used in orthopedic implantation with high mechanical stability and long-lasting performance, i.e., the fracture fixation plate and screw (Dudko, 2025).

The future step in work should be to perform tests on such materials under more complicated, dynamic loading conditions that can replicate real-life movements and investigate how surface treatments or coating can enhance biocompatibility and wear and corrosion resistance, as well as use patient-specific considerations to make the test more personalized. More so, the finite element models should be experimentally approved by in vitro and in vivo experiments to validate the results and optimize the design and materials selection of implants, in order to achieve improved clinical results.

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