

STRESS AND DEFORMATION ANALYSIS OF DISTAL FIBULA BONE-PLATE CONSTRUCTS USING COMSOL MULTIPHYSICS

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Abstract

Bone is a biologically active tissue that possesses the capability to repair on its own. However, to restore the anatomical alignment and functional integrity of unstable, displaced or load bearing fractures, surgical fixation is often required. Among ankle joint injuries, distal fibula fracture is the most common, which allows load to be distributed evenly and provide stability. The biomechanical performance of fixation devices, mainly bone plates, is strongly influenced by implant's material properties, geometry, and stress-transfer characteristics. Poor material selection may cause excessive stress concentration, implant failure, delayed union or stress shielding, thereby undermining the overall bone repair outcomes. In this study, "FEM (Finite element method) based computational framework" was developed to analyze and investigate the stress distribution and deformation behavior of a fractured distal fibula. COMSOL Multiphysics 5.5 is used to model a bone-Plate fixation system to stabilize distal fibula fracture, using bone plate and screws. The fibula was modeled as cortical bone while different materials, including Ti-6Al-4V alloy, stainless steel (SS316L) and polymethyl methacrylate (PMMA) were employed to design bone plate and screws to evaluate their biomechanical response. Physiologically relevant boundary conditions were simulated by fixing the proximal end of the fibula and applying a compressive load to the plate to mimic weight-bearing. The simulation outcomes identify the non-uniformity among stress and deformation along bone-plate construct, revealing maximum von Mises stress in distal region in parallel with total displacement. While areas of cortical bone away from fixation site possess significantly lower stress level. Metallic implants particularly Ti-6Al-4V revealed uniform stress deformation with reduced total deformation compared to PMMA. Hence indicating better load sharing characteristics and mechanical stability. The findings demonstrate the impact of implant stiffness on stress transfer and deformation behavior in distal fibula fixation. Overall, this FEM-based analysis adds meaningful biomechanical perspective into the performance of different bone plate materials for distal fibula fracture fixation. The results corroborate the metallic implants usage for improved mechanical stability and offer a computational basis for optimizing implant design, material selection, and clinical decision-making in orthopedic fracture management.

Introduction: The ankle joint, composed of three principal bones: the tibia, fibula, and talus, supported by an intricate network of ligaments, enable a wide range of movements, including dorsiflexion, plantarflexion and eversion, while preventing excessive motion in coronal and transverse planes. Despite the sophisticated architecture, the ankle remains vulnerable to traumatic injury when subjected to forces that exceed the load-bearing capacity of its bony and ligamentous components. Ankle fractures are one of the most prevalent musculoskeletal injuries accounting for approximately 9% of all fractures[1] and distal fibula fractures as the predominant fracture type, representing approximately 55% of all ankle fracture cases occurring due to falls from significant heights, motor vehicle accidents, sports-related collisions, or simply with compromised bone quality like osteoporosis.

The bone has the ability to heal by its own in four stages i.e. hematoma formation, soft callus formation, hard callus formation and remodeling [2] as shown in fig-1 However, in some cases this natural healing get restricted or slows down due to motion at fracture site, poor blood supply, infection, diabetes or large bone loss etc. These fractures and those exhibiting displacement require surgical intervention to restore anatomical alignment and functional ankle mechanics. In this regard, the appropriate selection between operative and nonoperative strategies directly influences functional outcomes and complication rates.

There are multiple approaches to classify ankle fracture particularly distal fibula as discussed below. The Pott classification system, among the earliest approaches, is based on number of malleoli involved, distinguishing unimalleolar, bimalleolar, and trimalleolar patterns. This approach, however, fails to differentiate between stable and unstable fracture patterns

and consequently provide limited guidance for treatment decision-making. The other approach, developed by Niel Lauge-Hansen, involves organizing fractures according to foot position and the direction of the deforming force at the moment of injury. It particularly, emphasize on rotational mechanisms and the sequential pattern of structural failure.

The more recent and anatomically focused aggrandizing classification is “Weber classification” that categorizes the distal fibula fractures according to the relationship between the fracture site and the ankle syndesmosis. This system is further categorized into three principal categories: Weber A (infrasyndesmotic) fractures with relative stability. In this fracture line is below the syndesmosis. Weber B (transsyndesmotic) fractures, with intermediate stability and last Weber C (suprasyndesmotic) fractures with greater biomechanical instability[3].

Amalgamated usage of both type of classification i.e Weber and Lauge-Hansen systems provides clinicians with fabulous results as in Weber classification, topographic anatomical description is focused, while Lauge-Hansen classification gives underlying trauma mechanism and sequential order of structural failure. This approach enhances the systematic identification of associated fractures, ligamentous injuries, and ankle instability on imaging. Hence, it helps in informing appropriate treatment strategies, whether conservative management with immobilization or operative intervention.

However, despite advances in classification systems and imaging modalities, the management of ankle fractures shows variability and occasional controversy. Determining the fracture stability, through radiographic parameters such as displacement of the fracture fragments and integrity of the syndesmosis, remains critical to treatment decisions.

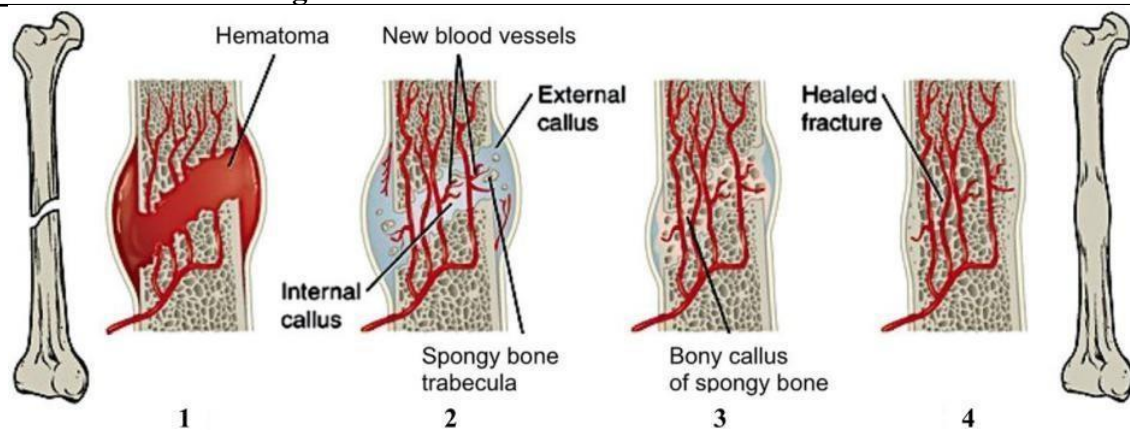


Figure 1: Four stages of natural bone healing: hematoma formation, soft callus formation, hard callus formation, and bone remodeling.

Methodology: The 3D model of the distal fibula bone plate was designed using COMSOL Multiphysics 5.5. Stress analysis of a fractured lateral malleolus (distal fibula) was performed by modeling a fibula bone with a length of 300 mm and a radius of 12 mm. The bone plate was designed with dimensions of 12 mm in width, 3 mm in thickness, and 100 mm in length. Two types of screws were modeled: small screws with a radius of 1.5 mm and a height of 14 mm, and

larger screws with a radius of 2.5 mm and the same height of 14 mm. To simulate the fracture, an elliptical shape was created on a work plane inclined at 30°, then extruded to form a 3D geometry. This elliptical portion was subtracted from the bone model using the difference operation to represent the fracture gap. Different materials were assigned to the bone, plate, and screws as summarized in Table 1 below.

Table 1: Mechanical Properties of different Materials

S. No.	Component Name	Material	Young's Modulus [MPa]	Poisson's Ratio	Density [Kg/m ³]
01.	Fibula Cortical Bone	Bone	7300	0.30	2000
02.	Bone Plate & Screws	[Ti-6Al4V]	110000	0.30	5410
03.	Bone Plate & Screws	Stainless Steel (S.S316L)	193000	0.3	1640
04.	Bone Plate and Screws	PMMA	4.2	0.28	1.2

The three-dimensional (3D) computational model of the fractured distal fibula with a bone-plate fixation system developed using COMSOL Multiphysics 5.5 is shown in figure 2. The model represents the distal fibula and the fixation assembly consisting of a bone plate and screws. The fibula was modeled with a length of 300 mm and a radius of 12 mm, while the bone plate was designed with a length of 100 mm, width of 12 mm, and thickness of 3 mm. The fracture was represented by creating an inclined elliptical fracture gap at an angle of 30° within the fibula. The Solid Mechanics module was used to define the physical behavior. A fixed

constraint was applied to the proximal end of the bone (boundary #03), while a load was applied on the bone-plate to assess stress distribution as shown in figure 3. A fixed constraint was applied at the proximal end of the fibula, while an external compressive load of -700 N was applied to the bone plate to simulate the mechanical loading experienced by the fractured fibula. This loading configuration was used to evaluate the resulting stress distribution and total deformation within the bone-plate-screw construct under steady-state conditions. A fine mesh and stationary study was conducted to analyse the stress distribution

in 3D model of fractured fibula.

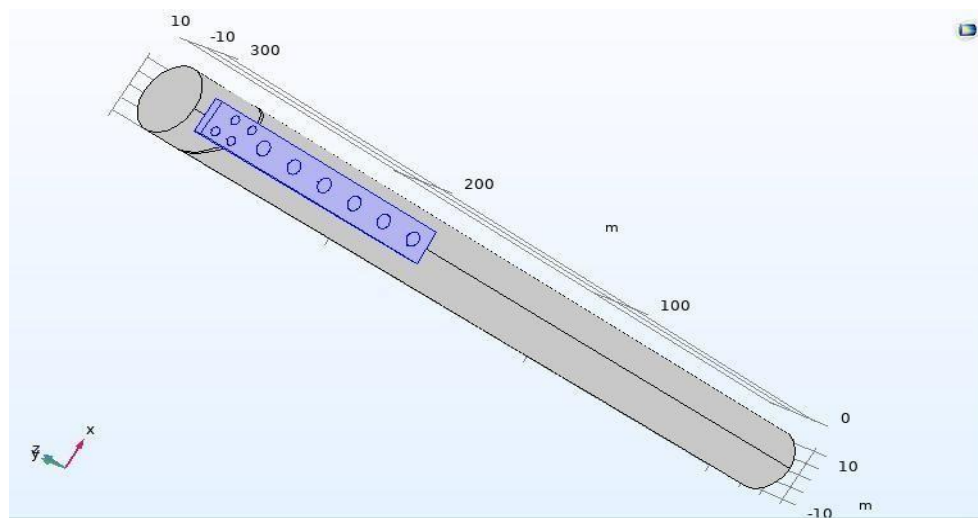


Figure 2: Three-dimensional model of the fractured distal fibula with bone-plate and screw fixation system

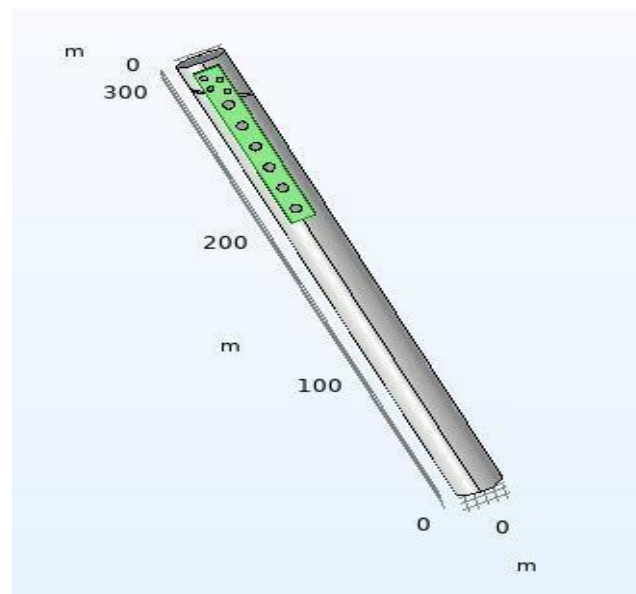


Figure 3: Application of compressive loading on the bone-plate fixation system with a fixed constraint at the proximal end of the fibula.

Results and Discussion

Finite element analysis were made to evaluate the mechanical response of fractured fibula with bone-plate fixation system under external compressive load of -700N. The analysis mainly focuses the total deformation of bone plate and screw assembly for different implant materials for fibula bone. All simulations converged successfully under steady-state conditions, demonstrating numerical stability and producing a trustworthy solution.

Total Deformation Analysis

The total deformation contours analysis of displacement pattern revealed non uniformity among bone- plate construct. Among the selected material configurations, The proximal end exhibited minimum deformation while the distal end where the bone plate is connected to the distal fractured segment of the fibula under fixed boundary conditions showed maximum

deformation. This deformation gradient shows the combined effect of load transfer through the bone plate and the geometric discontinuity introduced by the fracture gap.

The comparative evaluation of different materials selected for bone-plates analysis includes metal (Ti-6Al-4V, stainless steel) and PMMA. Metallic bone-plate were less prone to deformation and therefore exhibited higher

stiffness and improved structural support at the fracture site, in contrast to PMMA which has a significantly lower elastic modulus and consequently showed greater displacement, particularly near the distal fracture region, suggesting reduced mechanical stability under load-bearing conditions, as shown in figure 4 and 5

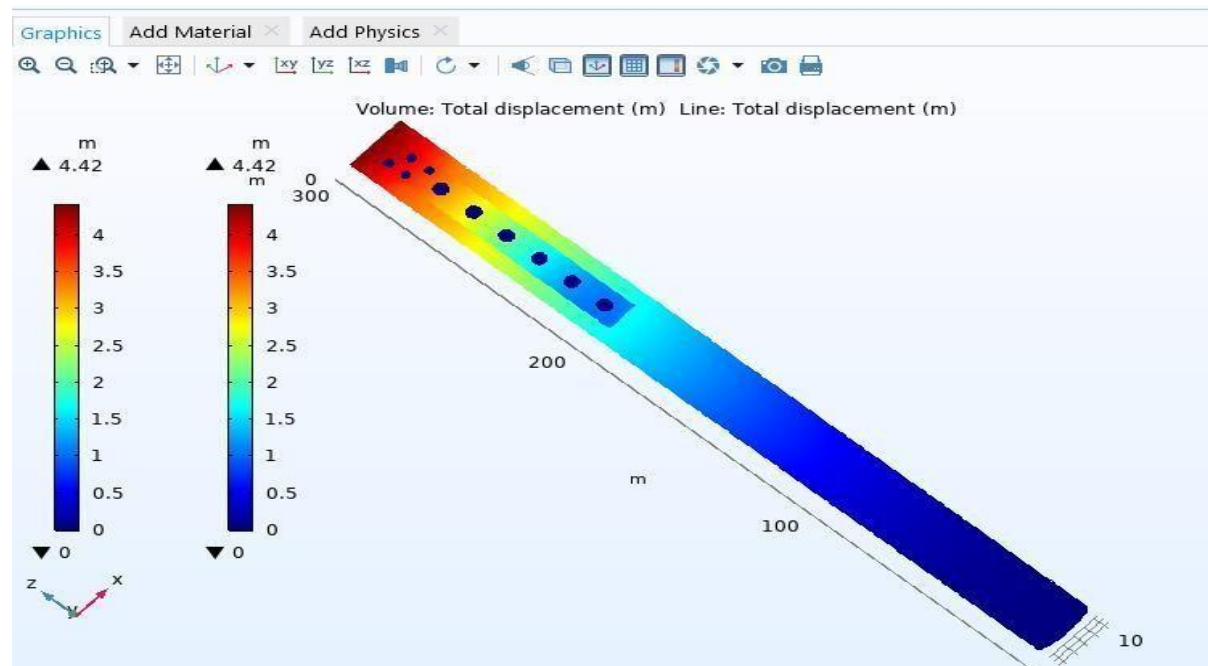


Figure 4: Total deformation of Bone and Bone-Plate[Ti-6Al-4V]

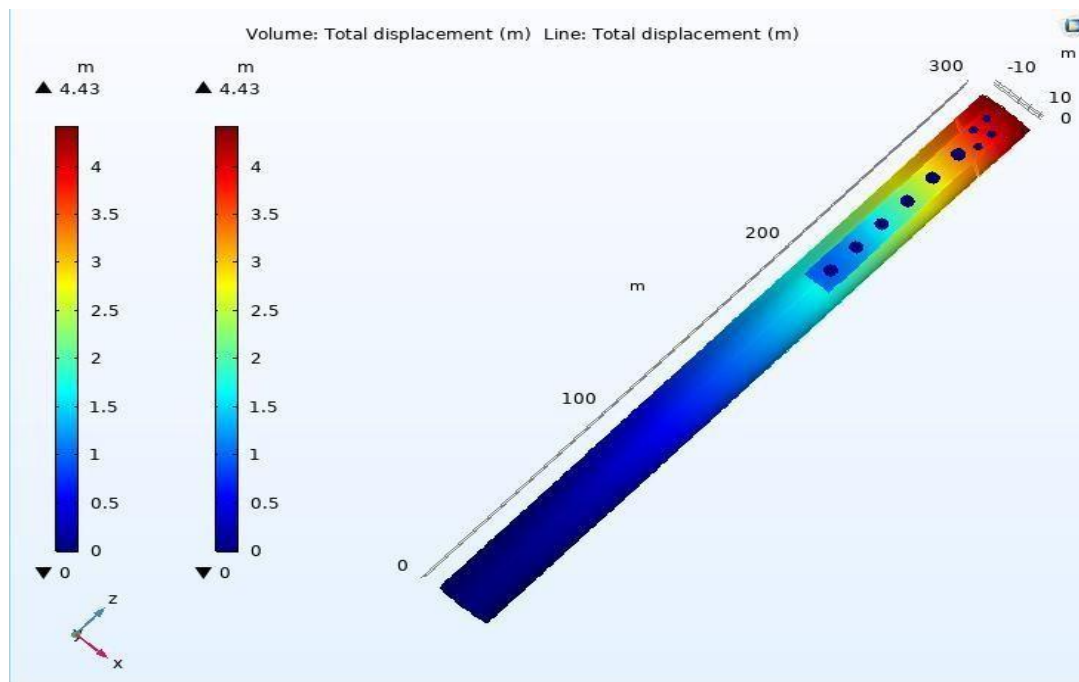


Figure 5: Total deformation over Bone and Bone-Plate[PMMA]

Stress Distribution Analysis

The von Mises stress distribution demonstrated a non-uniform stress pattern across the fractured distal fibula-plate construct. As illustrated in **Figure 6**, stress evaluation was performed at selected points (2, 4, 10, 22, 24, 26, and 28) to characterize the load transfer between the cortical bone and the fixation system. The points located within the plate-associated region (22, 24, 26, and 28) exhibited considerably higher stress levels than the points located in the cortical fibula away from the fixation region (2, 4, and 10). This distribution indicates that a substantial proportion of the applied compressive load was transferred through the bone plate and screw-bone interface rather than being distributed uniformly through the cortical bone.

The one-dimensional stress plots presented in Figures 7 and 8 further demonstrate the variation of von Mises stress along the bone-plate construct. Within the plate-associated region, comparatively higher stress levels were observed toward the distal portion of the plate, particularly at points 24 and 28. The elevated stress in these regions is consistent with the greater mechanical demand associated with load transfer near the distal fracture segment and the

transition between the fixed and fractured portions of the fibula. This localized stress concentration is important from a biomechanical perspective because regions experiencing higher stress may represent critical locations for implant loading and potential mechanical failure under repeated or excessive loading conditions.

In contrast, the stress levels measured at points 2, 4, and 10, which were located farther from the plate and screw fixation regions, were comparatively lower. This spatial variation suggests that the fixation system carried a greater proportion of the applied load, thereby reducing the mechanical load transmitted through the surrounding cortical bone. Such a reduction in bone stress is consistent with the load-shielding effect of a relatively stiff fixation plate. Overall, the results from Figures 6–8 confirm that stress was concentrated primarily around the plate-bone and screw fixation regions, with the highest localized stresses occurring toward the distal portion of the construct.

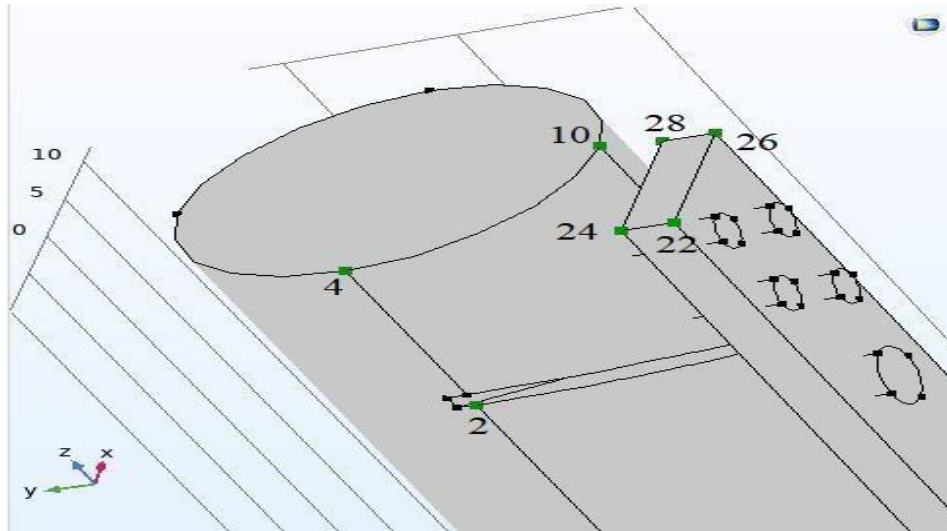


Figure 6: Points for Stress analysis of Load for Point Graph

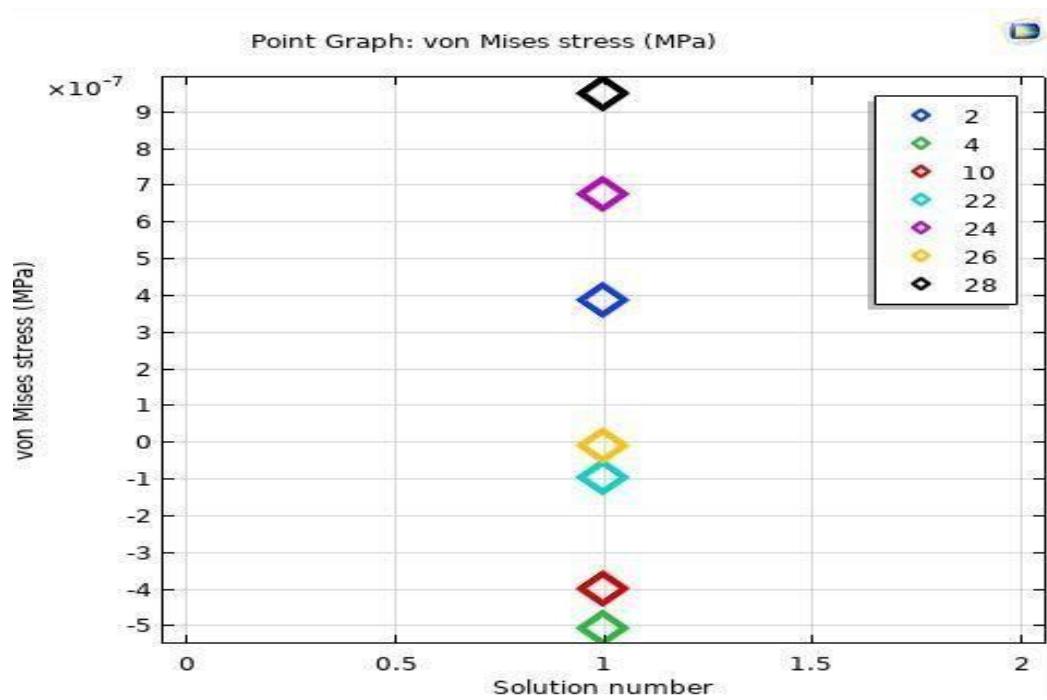


Figure 7: 1D plot for Stress Distribution Analysis

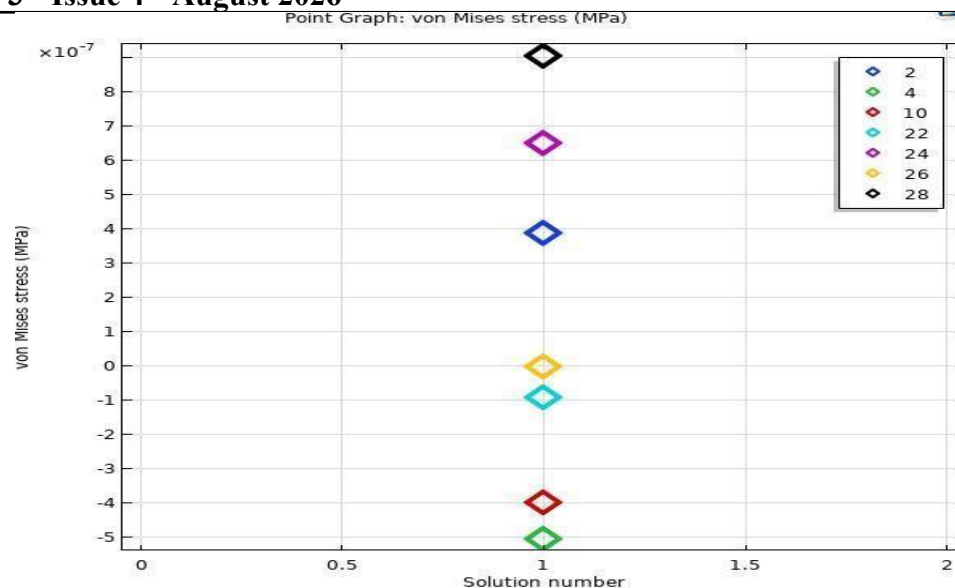


Figure 8: 1D plot for Stress Distribution Analysis

Two-Dimensional Stress Contour Evaluation

The two-dimensional von Mises stress contours presented in Figures 9 and 10 provide a spatial representation of stress distribution within the fractured fibula–bone plate construct for the Ti–6Al–4V and PMMA plate configurations, respectively. The contour plots demonstrate that the stress distribution is non-uniform and is strongly influenced by the location of the plate, screw fixation regions, and fracture interface. Higher stress concentrations are primarily observed in the vicinity of the bone–plate and screw–bone interfaces, whereas comparatively lower stress levels are evident in the cortical bone regions located farther from the fixation system.

In Figure 9, corresponding to the Ti–6Al–4V bone–plate configuration, the stress contours indicate relatively distributed load transfer along the plate and its adjacent bone region. The higher-stress zones are mainly associated with the plate–bone interface and screw fixation locations, while the surrounding cortical bone experiences comparatively lower stress. The relatively high stiffness of Ti–6Al–4V enables the plate to sustain a substantial portion of the applied load and provides effective mechanical support to the fractured segment. This behavior is also consistent with the lower deformation observed for the metallic plate configuration in the preceding analysis.

In comparison, Figure 10, representing the PMMA configuration, shows a more localized stress distribution, particularly around the fracture region and plate–bone interface. The considerably lower elastic modulus of PMMA results in greater deformation under the applied load and alters the load-sharing behavior between the plate and the cortical bone. Consequently, stress becomes more concentrated around mechanically critical regions of the construct rather than being distributed as effectively as in the Ti–6Al–4V configuration. The contour results therefore support the deformation findings, where the PMMA model exhibited greater displacement, particularly toward the distal fracture region.

Overall, the two-dimensional stress contours demonstrate that implant material stiffness has a significant influence on load transfer and stress distribution within the distal fibula fixation system. The Ti–6Al–4V configuration provides greater structural stiffness and comparatively more distributed load transfer, whereas the PMMA configuration exhibits greater deformation and more pronounced localized stress concentrations near the fracture and fixation regions. These findings indicate that implant material selection is an important factor in controlling stress concentration and maintaining mechanical stability in distal fibula fracture fixation.

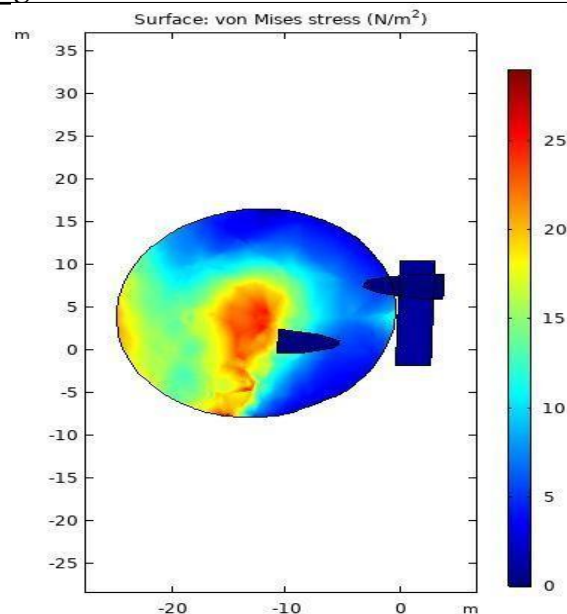


Figure 9: 2D-Stress plot of bone-plate complex (Ti-6Al-4V)

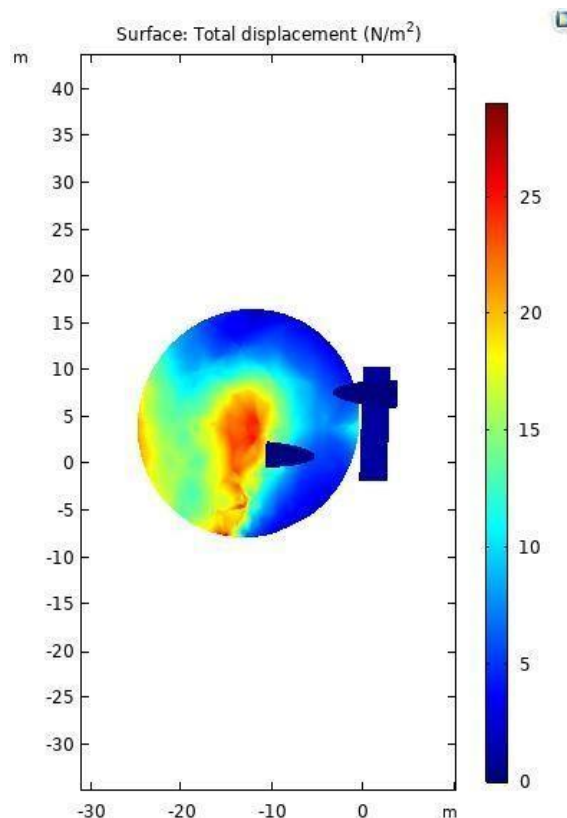


Figure 10: 2D Stress plot of bone-Plate complex[PMMA]

Summary of Mechanical Response

The deformation and stress analyses together confirmed that Implant's material properties play crucial role in biomechanical performance of distal fibula fixation. Metallic plates, particularly (Ti-6Al-

4V) shows more pronounced mechanical stability via minimum deformation and stress distribution across the construct. These combined characteristics are indispensable for preserving fracture alignment and promoting favorable healing conditions under

physiological loading

Conclusion

This paper revolves around the finite element based analysis of biomechanical behavior of fractured distal fibula secured by bone-plate fixation system. A 3D model was designed in COMSOL Multiphysics to study total deformation and stress distribution in response to physiologically relevant loading conditions. The study focuses the implications of material properties of implant on load transfer, stress concentration and structural stability at the fracture site.

The simulation results affirmed the non-uniform distribution of stress and deformation of bone-plate construct. The distal region of bone-plate interface gives maximum von Mises stress and total displacement. While region near proximal end which has fixed boundary constraints shows minimal deformation. The Contour and point based stress analysis reflects the maximum stress at the plate-screw region, which corroborate that implant was subjected to significant portion of the applied load.

The comparative analysis of Ti-6Al-4V and PMMA revealed that former biomaterial have more ability to resist overall deformation while facilitating uniform stress distribution. Hence, affirming that Ti-6Al-4V, under load bearing conditions possess good mechanical performance over PMMA. As the lower stiffness of PMMA causes amplified displacement with localized stress concentration near fracture site. Overall, the results undoubtedly conclude the importance of opting the implant material in order to repair distal fibula fracture. On the other hand, it emphasizes using high-stiffed metallic alloy for finer material support and balanced load handling. This research based work highlights the bio-mechanism of bone-plate design and material selection. This study can be extended to future studies like: patient-specific geometries, dynamic and cyclic loading scenarios, experimental validation, and study of long-term weary behavior as an advancement in clinical practice.

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