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The Impact of Plate Length and Material Variations on Tibial Bone Implants Analysis using Computational Biomechanics

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ABSTRACT

The aim of this research is to simulate the strength of the implant plate, as a method for healing tibia fractures by combining bone with a bone plate. Then model and analyze using ANSYS software to analyze loads such as deformation and the maximum distribution of von Mises stress values. The results of the Maximum Principal Stress analysis on the cobalt-chromium implant plate show a minimum value of -1.2527107 Pa (-12.527 MPa) and a maximum value of 7.57610 7Pa (75.76 MPa). Based on the research results, Co-Cr material has significant advantages compared to steel as an implant material. In addition, this material has excellent corrosion resistance and very good biocompatibility, making it safe for long-term use in the human body without significant risk of allergic reactions or irritation.

1. INTRODUCTION

Long bones in the body are divided into two, namely the long bones of the upper extremities and the lower extremities. As is known, the length of the lower limb plays a significant role in a person's height when standing. The most accurate equation for estimating height is based on the length of the tibia, femur, and fibula. The tibia is easily accessible for percutaneous estimation compared to other types of long bones. Furthermore, the tibia is the second largest bone in the body after the femur, making it more resistant to the process of decay (Lubis & Siregar, 2022).

Fracture is a term that refers to the loss of part or all of the bone cortex structure, with varying degrees of damage to the surrounding soft tissue, usually caused by trauma or physical force (Ramdhani dkk., 2024). Globally in 2019, there were 455 million fracture cases across all age groups, an increase of 70.1% since 1990, with the most common anatomical locations for fractures being the patella, tibia or fibula, or ankle. It was found that among the prevalence of fracture cases in Indonesia, the highest prevalence was fractures of the lower extremities due to accidents, accounting for 67.9% of 92,976 fracture cases. Patients with cruris fractures numbered 14,027. Meanwhile, the incidence of open fractures of long bones occurs at a rate of 13 cases per 100,000 people each year (Jorge-Mora dkk., 2018).

With the increasing rate of fracture cases, implants are needed to support the healing process of broken bones due to trauma or physical force. Implants are medical devices used to replace or support missing or damaged body structures. Implants can be made from various materials, including metals, ceramics, and polymers, and are designed to integrate with body tissues. implants are used to provide structural support to areas that have been damaged. Tibial implants used in orthopedic surgical procedures to repair or replace parts of the tibia (shinbone). Implants are usually used for total knee replacement surgery (total knee arthroplasty) and are designed to distribute loads in a manner similar to natural bone. The design and material of the tibial implant are crucial to ensure stability and good integration with the bone, as well as to navigate the risk of complications such as implant loosening (Mahyudin dkk., 2019) (Munford dkk., 2022).

The selection of materials for implants is very important because it affects biocompatibility, the healing process, complication risks, strength, and durability in the body. Cobalt alloys, particularly cobalt-chromium (Co-Cr) alloys, are one of the types of materials widely used in the manufacture of medical implants, especially in the field of orthopedics. Cobalt alloys are known for their good mechanical properties, corrosion resistance, and high biocompatibility. Cobalt material for implants is usually (Co-28Cr-6Mo) where the main composition of the materials is cobalt (Co), Chromium (Cr) 27-30%, and Molybdenum (Mo) 5-7%, with other mixtures such as manganese, silicon, and cadmium in very small proportions in the cobalt-chromium material (Marti, 2000). Cobalt as a material for implants has many advantages, such as corrosion resistance, where cobalt-chromium alloys form an oxide layer that protects the surface from corrosion, making cobalt-chromium safe for use in the human body environment. The next advantage is high mechanical strength, where cobalt-chromium has high tensile strength and wear resistance, making it capable of withstanding significant loads without experiencing damage. Biocompatibility, cobalt-chromium alloys generally do not cause allergic reactions or irritation in body tissues, making them suitable for long-term tibial implants. Cobalt-chromium alloy (Co-Cr), a material widely used for implants and easily obtainable in large quantities (Mani dkk., 2024). This is the basis of this research, which is to simulate the strength of the implant plate, as one of the methods for healing tibial bone fractures by combining the bone with a bone plate. Then, modeling and analyzing using ANSYS software to conduct load analysis such as deformation and distribution of maximum von Misses Stress values.

2. METHOD

The flow diagram in this study is shown in Figure 2.1.

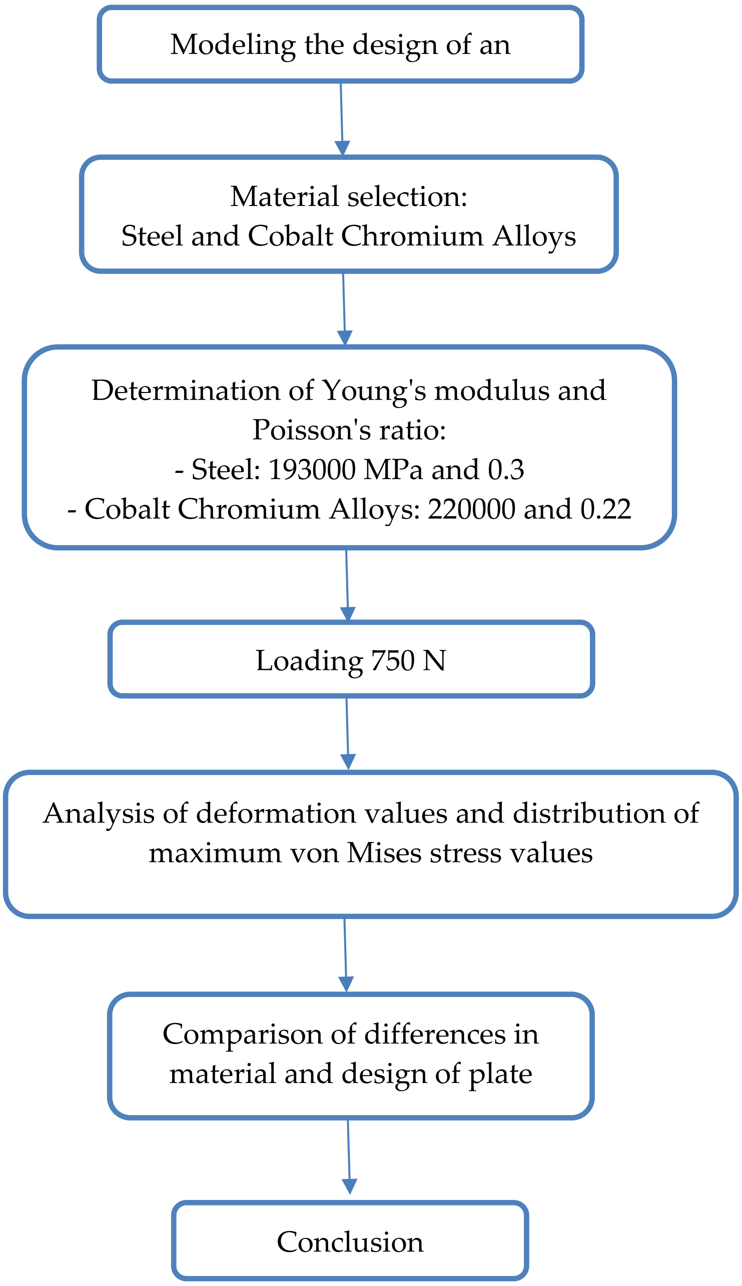

Figure 2.1 Flowchart of the research

The plate modeling uses two types of materials, namely steel with a Young's Modulus of 193000 MPa and a Poisson's ratio of 0.3, while the material made of Cobalt Chromium Alloys has a Young's Modulus of 220000 and a Poisson's ratio of 0.22. In addition to differentiating the types of materials, this study also varies the plate length as a variable, specifically 76 mm and 72 mm. After modeling using Solidworks, the design results were obtained as shown in Figure 2.2.

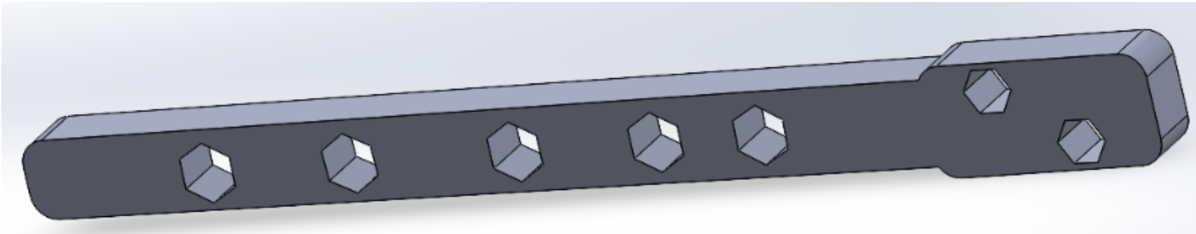

Figure 2.2 Implant plate design using Solidworks

After the design is completed using SolidWorks software, the next step is to convert the design file into the Parasolid file format. This conversion is important to ensure that the file can be properly imported into the ANSYS application, which is a widely used software analysis tool in engineering. By using ANSYS, we will conduct an analysis to compare two different types of materials, namely steel and cobalt-chromium. This process will involve testing various mechanical and thermal parameters of both materials, such as strength, resistance to increase, and behavior under certain loads. In this study, we used 2 different material inputs, the first material being Steel with a plate length of 76mm.

Table 2.1. Mechanical Properties Data of Steel

No	**Material Properties**	Value	**Scale**
1.	Modulus Young	1.93E+05	MPa
2.	Poisson Ratio	0.3	
3.	Bulk Modulus	1.6083E+11	Pa
4.	Shear Modulus	7.4231E+10	Pa

The second material is Cobalt Chromium Alloys with a plate length of 72mm.

Tabel 2.1 Mechanicaal Properties Data of Cobalt Chromium Alloys

No	**Material Properties**	**Value**	**Scale**
1.	Modulus Young	2.2E+05	MPa
2.	Poisson Ratio	0.22	
3.	Bulk Modulus	1.3095E+11	Pa
4.	Shear Modulus	9.0164+10	Pa

After the mechanical properties data of bone, Young's Modulus, and Poisson's ratio are entered into both materials in the Engineering data, the meshing method used on the plate model is the mesh method with a specific size. In the mesh method, a tetrahedron type and 1 part are used. Before conducting stress and total deformation simulations, static and dynamic simulations need to be performed on the design by applying a load on the x-axis with a compressive force of -750 N. Then, a directional deformation plot is created to measure the change in position of a point in the structural model when subjected to a load, providing information on how much and in which direction certain parts of the structure deform under the applied load. Equivalent stress is used to measure the Von Mises criterion, which describes the stress experienced by the material in response to the load. Additionally, it can assess the strength of the material used, determining whether it undergoes deformation or failure under the given load conditions. Maximum principal stress is used to measure the maximum stress occurring at a point in the material and to ensure that the structure does not exceed the material's strength limit.

3. RESULTS AND DISCUSSION

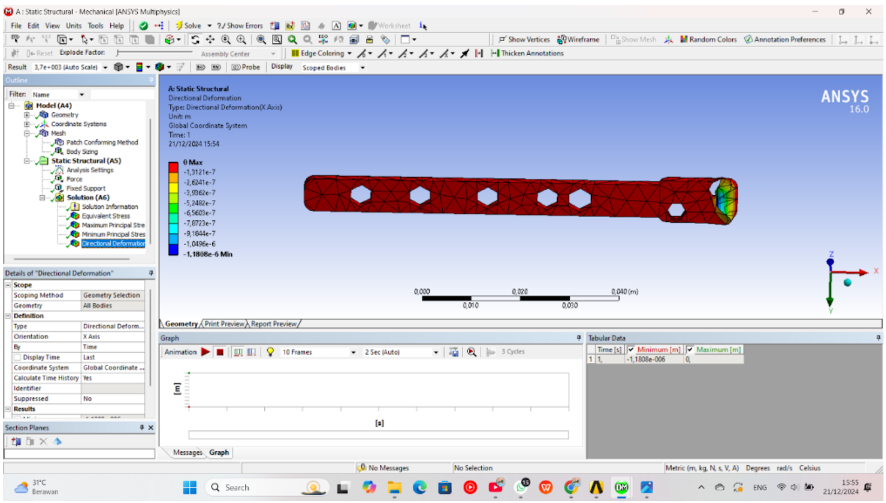

Figure 3.1 Directional Deformation material Co-Cr

$$E = \frac{\sigma}{\varepsilon}$$
$$\varepsilon = \frac{\delta}{L}$$

Notes:
$E: Modulus\ elastis\ (MPa)$
$\sigma: Tegangan\ tarik (MPa)$
$\varepsilon: Regangan$

$$\varepsilon = \frac{0}{0{,}088} = 0$$
$$\sigma = 2{,}2 \times 10^{11} \times 0 = 0\ MPa$$

In Figure 3.1, the results of the Finite Element Analysis using ANSYS software on cobalt-chromium material are shown. With the force in the image, the directional deformation is displayed in a color scale, with a maximum value of 0 (or 0 micrometers) and a minimum value of -1.1808 ×10−6 meters. This value can be seen in the bottom right corner of the image. and if on the color scale, the red color indicates areas with maximum deformation value and the dark blue color indicates areas with minimum deformation value or no significant shape change. From these results, it can be concluded that the material is small and prominent in certain areas, indicating the high strength of cobalt-chromium material. The elastic modulus is 214,000 MPa for Cobalt-Chromium Material.

According to the result of the analyis shown that the result is 0 MPa (from calculating analysis σ = 2.2×10^11 × 0 = 0 MPa) which is smaller than the elastic modulus of cobalt chromium, which is 214.000 MPa (210.000 MPa > 0 MPa), A zero stress value indicates that the load received by the material is very small, so it does not significantly affect the strength or safety of the material, thus stating that the deformation results for this cobalt-chromium material are safe. Cobalt chromium has the advantage of high fracture resistance and high elastic modulus, making it very suitable for use as an implant material. The obtained stress value affects the length of the plate because stress can influence the length of the plate through the resulting deformation value. Longer plates can produce higher deformation values compared to shorter plates under the same stress. Cobalt-chromium material has a density of about 8-9 g/cm3, which makes this material relatively very light, thus very ideal for implant applications that require strong yet lightweight materials.

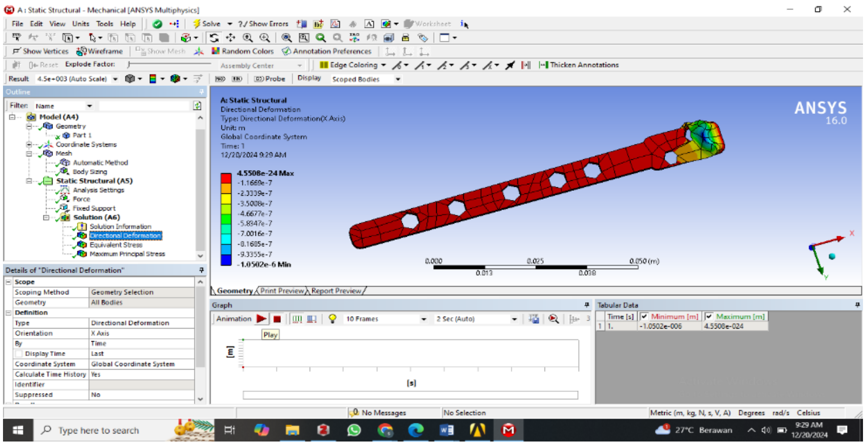

Figure 3.2 Directional Deformation of material Steel

Based on data from the analysis results using ANSYS with Steel material and a total plate length of 95 mm, the Directional Deformation value shows the deformation of the impact plate due to the applied load of -750 N in the x-axis direction. The minimum value of the deformation is -1.0502 $\times 10^{-6}$ m and the maximum value of deformation result is 4.5508 $\times 10^{-24}$ meter. These minimum and maximum values indicate the differences in deformation levels at various points on the implant plate due to the applied load. The part with the highest deformation value is shown on the plate in red, while the part with the lowest deformation value is in blue. The SK SNI T-15-1991-03 regulation states that the elastic modulus of steel is 200,000 MPa (Budi, 2011).

$$E = \frac{\sigma}{\varepsilon}$$

$$\varepsilon = \frac{\delta}{L}$$

Notes

E: $Modulus\ Elasticity\ (MPa)$

σ : $Stress (MPa)$

ε : $Strain$

$$\varepsilon = \frac{4{,}5508 \times 10^{-4}}{0{,}095} = 4{,}790 \times 10^{-3}$$

$$\sigma = 193 \times 10^{9}.4{,}790 \times 10^{-3} = 924\ MPa$$

Based on the stress results obtained, which is 924 MPa, it is smaller than the elastic modulus of steel, which is 200,000 MPa (200,000 MPa > 924 MPa). The stress value that is nearly zero indicates that the load received by the material is very small, so it does not significantly affect the strength or safety of the material, thus stating that the deformation results for this Steel material are safe. To ensure the safety of the Steel material, it is necessary to adjust the applied load, increase the thickness of the implant plate, and replace the type of steel material with a higher yield strength or modulus of elasticity. The obtained stress value affects the length of the plate because stress can influence the length of the plate through the resulting deformation value. Longer plates can produce higher deformation values compared to shorter plates under the same stress. Additionally, the type of material will also affect the deformation value, meaning that a high modulus of elasticity will result in smaller deformation compared to a low modulus of elasticity.

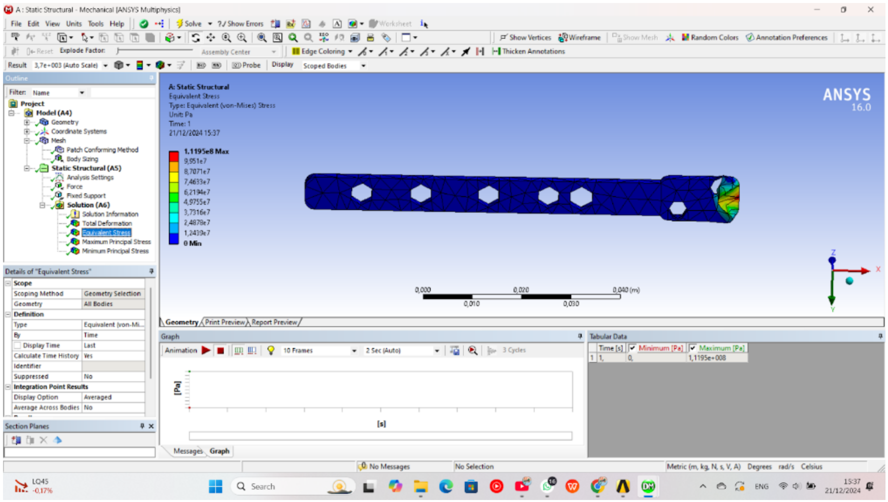

Figure 3.3 Equivalent stress material Co-Cr

The results of the stress analysis using the von Mises method (Equivalent Stress) on the cobalt chromium implant plate show a stress distribution with a minimum value of 0 MPa and a maximum value 1.1195×10^{8} Pa or equivalent with 111.95 MPa. Based on the strain calculations performed, the value obtained is $\varepsilon = 0$ and stress value is, $\sigma = 0$ MPa (from $\sigma = 2.2 \times 10^{11} \times 0$). These values indicate that the load received by the material is very minimal and still far below the yield strength limit of cobalt-chromium material, which ranges from 450-

1000 MPa. The stress distribution in the model shows that the highest stress concentration is at the ends of the plate, marked in red-yellow, while the middle part of the plate, colored blue, indicates very low stress. This stress distribution pattern shows that the implant plate design with the existing screw hole configuration has provided a good and safe stress distribution for medical applications. With the characteristics of cobalt-chromium material that has a high elastic modulus (214,000 MPa) as well as excellent corrosion and fatigue resistance, this design can be declared very safe and suitable for use as a medical implant. (214.000 MPa).

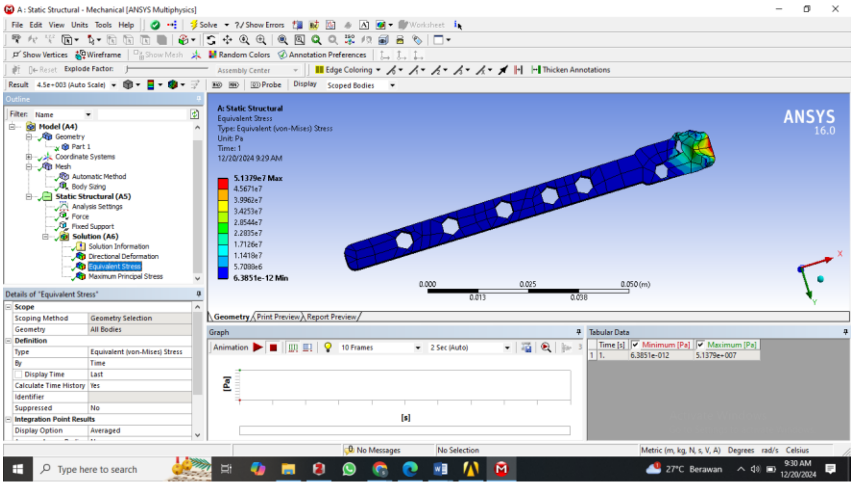

Figure 3.4 Equivalent stress material Steel

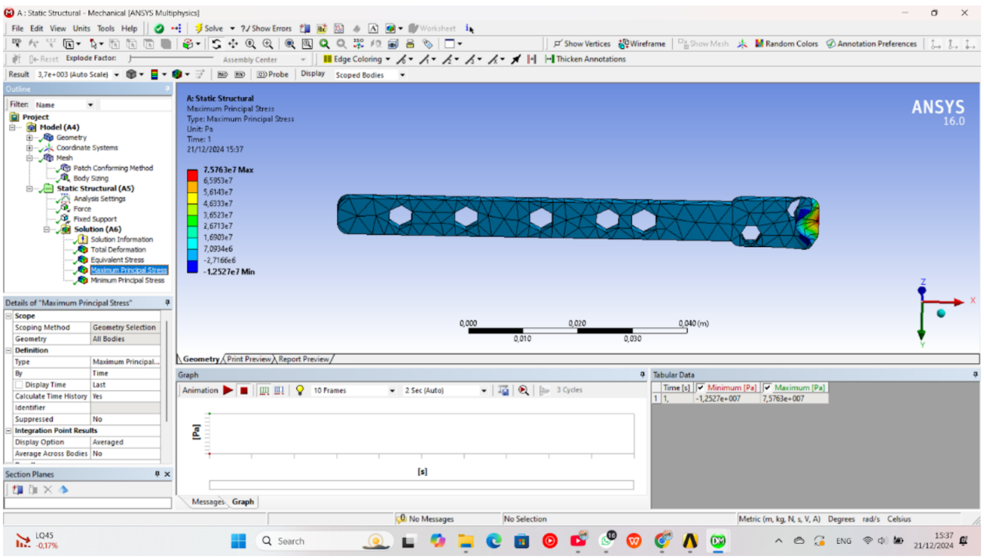

Figure 3.5 Maximum Principal Stress material Co-Cr

Based on Figure 3.4, the Equivalent Stress or von Mises Stress value is obtained to determine the material strength and ensure that the design condition is safe. The value of Equivalent stress for its minimum value is obtained 6.3851×10^{-12} dand for its maximum value of 5.137×10^{7}This indicates that the material used, namely Steel, is safe for use because the stress value that is almost zero shows that the load received by the material is very small and does not significantly impact the strength or safety of the material.

Based on the analysis results of Maximum Principal Stress on cobalt-chromium alloy implant plates, a minimum value was obtained -1.2527×10^7 Pa (-12.527 MPa) and 7.576×10^7Pa (75.76 MPa), respectively. The maximum stress value is still far below the yield strength limit of cobalt chromium, which ranges from 450-1000 MPa (75.76 MPa < 450 MPa). The maximum principal stress on the implant plate is still within the elastic limit of the cobalt-chromium material and is very safe to use. The stress distribution on the model shows that the highest stress concentration is at the ends of the plate, marked in red, while the middle part of the plate, colored blue, shows minimal stress. The material will return to its original shape after the load is removed because it is still within the elastic region. With the high elastic modulus of cobalt chromium (214,000 MPa) and relatively low maximum stress value, this implant plate has an excellent safety factor for medical applications. These characteristics are also supported by the superior biocompatibility and corrosion resistance of cobalt-chromium material, making it an excellent choice for long-term implant applications.

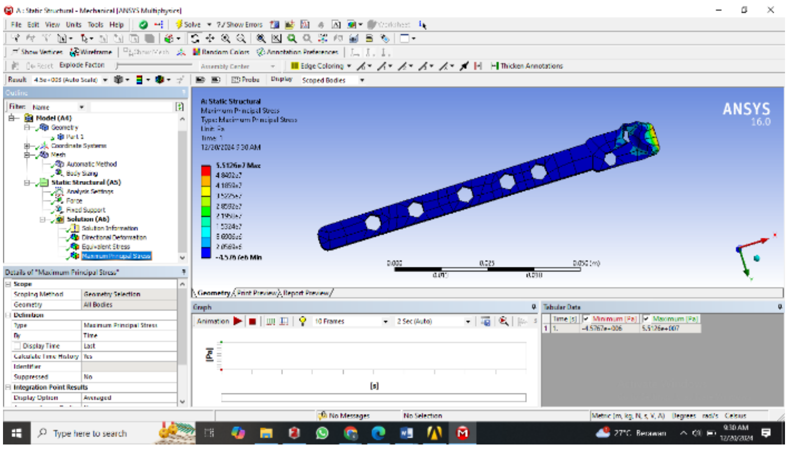

Figure 3.6 Maximum Principal Stress material Steel

Based on the research results, cobalt-chromium material shows very good performance for use as a tibial bone implant material. The analysis conducted using the von Mises Stress (Equivalent Stress) and Maximum Principal Stress methods shows that the maximum stress values occurring in this material, namely 111.95 MPa for Equivalent Stress and 75.76 MPa for Maximum Principal Stress, are still far below the yield strength of cobalt chromium, which ranges from 450-1000 MPa. This ensures that the material is within its elastic limit and will not experience permanent deformation. Moreover, the stress distribution in the model shows that the highest stress concentration is at the edge of the plate, while the middle part experiences very little stress, indicating that the plate design is effective in distributing the load. With a high elastic modulus of 214,000 MPa, this material also produces very small deformations, thereby providing optimal structural stability.

Based on the result on the Figure 3.6, the value of Maximum Principal Stress to know the failure the failure value of a material where for Steel material the minimum value is obtained -4.5767×10^6 and the maximum value is5.5126×10^7. This shows that 55.12 MPa

< 200 MPa. The maximum principal stress on the implant plate is still within the elastic limit of steel and is safe to use. The material will return to its original state after the pressure is removed and will not experience permanent damage.

Based on the research results, Steel material shows very good performance for use as a tibial bone implant material. The analysis conducted using the von Mises Stress (Equivalent Stress) and Maximum Principal Stress methods shows that the maximum stress value occurring in this material is 924 MPa for Equivalent Stress 5.137×10^7 and 5.5126×10^7 for Maximum Principal Stress, it is still far below the yield strength limit of steel, which ranges from 170-310 MPa. This ensures that the material is within its elastic limit and will not experience permanent deformation. Additionally, the stress distribution on the model shows that the highest stress concentration is at the edge of the plate, while the middle part experiences very little stress, indicating that the plate design is effective in distributing the load. With a high modulus of elasticity of 200,000 MPa, this material also produces very small deformations, thereby providing optimal structural stability.

4. CONCLUSION

Cobalt chromium (Co-Cr) material offers significant advantages over steel in tibial implant design. Its elastic modulus is 214,000 MPa, allowing for smaller deformation under the same load. Co-Cr plates have a maximum value of 111.95 MPa, below its yield strength limit. It also has excellent corrosion resistance and biocompatibility, making it safe for long-term use. Co-Cr plates with a length of 72 mm provide better mechanical performance compared to steel plates with a length of 76 mm. This shorter plate length allows for a more even stress distribution and minimal deformation in the implant structure, making it a superior material choice for orthopedic medical applications like tibial bone implants.

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