

Analysis of the Effect of Turbine Operational Load on the Strength of Coupling Bolt Structure Using the Finite Element Method

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Abstract - In transmitting kinetic energy from the turbine to the generator, the coupling will experience stress and deformation, especially on the bolts that support the coupling. Therefore, it is important to analyze how the operational load of the turbine affects the strength of its bolt structure. The author has conducted a literature study and numerical simulation to analyze the problem. In the simulation that has been done, it was found that the maximum von mises stress and strain values received by the bolt were 196.34 MPa and 0.0009687 mm/mm at maximum loading. The relationship between operational load and von mises stress value is that if the operational load is higher, the von mises stress received by the bolt will also be higher. Furthermore, there is also a relationship between operational load and von mises strain value, namely that if the operational load is higher, the von mises strain received by the bolt will also be higher. DBy using AISI Type S5 Tool Steel – Oil Quenched to 55 HRC, a relationship was obtained between operational load and safety factor value. The relationship between operational load and safety factor value is that if the operational load is higher, the safety factor value will be lower. From the simulation that the author has done, it is found that there is a difference in safety factor if the material used in the bolt is changed. It was found that AISI Type S5 Tool steel - Oil Quenched to 55 HRC has a higher safety factor value of 8.8111. Meanwhile, the AISI Type S5 Tool Steel material, Austenitized 855 – 870°C (1575 – 1600°F), Oil Quenched to 45 HRC has a lower safety factor value, namely 5.7552.

Keywords: Von Mises stress, Von Mises Strain, Coupling, Safety Facto.

I. INTRODUCTION

Coupling is a component used to transmit power from the turbine to the generator. In its transmission, the coupling often fails due to excessive stress and strain. Therefore, it is important to analyze how the operational load of the turbine

affects the strength of the coupling bolt structure, so that we can predict where the highest stress point experienced by the bolt is. The following are the objectives of the research that the author has conducted:

1. To determine the maximum von Mises stress experienced by the coupling bolt when operating at maximum conditions.
2. To determine the relationship between operating loads on Max Von Mises stress and strain received by coupling bolts and their effect on the Safety Factor.
3. To determine the effect of replacing coupling bolt material on the safety factor value at maximum operational load

Coupling is a connecting device that functions to transmit the rotating force from a rotating motor to the next mechanism. This coupling allows the transfer of rotational motion from one shaft to another. Couplings can be found in various machine applications, such as electric motors, pumps, compressors, and other drive systems [1]

Rigid coupling is a type of fixed coupling. It is used when two shafts must be connected with a straight axis. This means that the shafts connected with a rigid coupling must be perfectly parallel because this coupling cannot accommodate any misalignment or movement between the shafts [2]

Flexible coupling is a coupling that has an empty part along the body of the coupling and is helical or spiral in shape, making it flexible. Unlike rigid couplings that are stiff, flexible couplings can absorb and dampen vibrations and shifts, thus helping to protect mechanical components from damage due to dynamic loads [3]

Stress is defined as the force required by an object to return to its original shape or the force (F) applied to an object divided by the cross-sectional area (A) on which the force acts [4]

In addition to stress, there is also another quantity called strain. Strain is a change in size from the initial length as a result of a force that pulls or presses on the material. The elastic property limit of the stress-strain ratio will be linear and will end at the yield point. The stress-strain relationship is no longer linear when the material reaches the plastic property limit [5]

Normal stress is stress that works perpendicularly on the surface of an object (A) (Sutikno, 2011). Mathematically, stress due to normal force is formulated as follows:

$$\sigma = \frac{P}{A} \quad (1)$$

Normal stress represents the distribution of force per unit area in a material subjected to a load. It is a measure of the internal force produced by a load acting perpendicular to the plane of the material. Normal stress is often the primary focus in the stress and strength analysis of materials.

Shear stress is stress that occurs in an object or structure due to shear forces acting on it. Shear forces occur when two parts of an object move relative to each other in parallel but opposite directions. Shear stress is calculated based on the principle that shear force (V) is directly proportional to the stress (τ) produced and the area (A) where the shear force acts.

$$\tau = \frac{V}{A} \quad (2)$$

Shear stress can occur in various types of objects or structures, such as beams, plates, and other structural elements.

This is an important factor in material strength analysis, structural design, and material testing. Stress due to bending moment is stress that appears in a structure or object due to the bending moment acting on it [6]. The stress due to bending moment is calculated based on the principle that the bending moment (M) is directly proportional to the stress (σ) produced and the distance (y) from the center of bending, and inversely proportional to the moment of inertia (I) of the cross section:

$$\sigma = \frac{M y}{I} \quad (3)$$

Stresses due to bending moments can be calculated for various types of structures or objects, such as beams, I-beams, tubes, or other profiles, and are an important component in structural strength analysis, structural design, and material selection.

Normal strain is a measure of deformation of a material that occurs parallel to a force acting perpendicular to the surface of the material. Normal strain measures the change in length of a material relative to its original length and is expressed as the ratio of the change in length (ΔL) to the original length (L_0) of the material.

$$\varepsilon = \frac{\Delta L}{L_0} \quad (4)$$

Normal strain is a dimensionless quantity, because it is a comparison of two lengths. However, sometimes normal strain is expressed in terms of a comparison of units of length. If using the SI system, then the basic unit for length is the meter (m) [7]

Shear strain is a measure of the deformation of a material that occurs when layers of the material slide or slide past each other. Shear strain measures the change in angle between initially perpendicular lines in the material. In the context of shear stress, shear strain is a measure of the relative change in angle between two lines separated by a distance in the material [8]

$$\gamma = \frac{\pi}{2} - \theta \quad (5)$$

Shear strain is important in the analysis of structures involving shear forces, such as the design of mechanical connections, bolts, and steel structures. Understanding shear strain helps engineers predict how materials will behave under shear loads and design safe and efficient structures. Hubungan antara normal stress dan normal strain [9]

The relationship between stress and strain in a material is often described using Hooke's Law, which states that within the elastic limit of a material, stress is directly proportional to strain. This can be expressed by the following equation:

$$\sigma = E \cdot \varepsilon \quad (6)$$

An object if given a force will experience deformation, namely a change in size or shape. If the object can return to its original shape if the force is removed, then the object is said to be elastic. The measure of a material's ability to withstand changes in shape or bending that occur up to the proportional limit is called the Modulus of Elasticity (MoE). The modulus of elasticity is often called Young's Modulus which is the ratio between stress and axial strain in elastic deformation [10]

Relationship between shear stress and shear strain. For shear stress and strain, the relationship between shear stress

and shear strain can also be expressed in a form similar to Hooke's Law, using the shear modulus, formulated as follows:

$$\tau = G \cdot \gamma \quad (7)$$

The shear modulus of soil is one of the dynamic characteristics that is generally expressed with the notation (G). The maximum shear modulus (Gmax) is an important dynamic parameter in various soil dynamics problems. This parameter is mainly needed to calculate the resonance frequency and vibration amplitude of the foundation, so it is closely related to earthquakes. If an earthquake occurs, the soil factor as a vibration conductor has a very important role. Interaksitanah-strukturakibatbebandinamik, menentukan Soil-structure interaction due to dynamic loads, determining the stiffness coefficient of the soil under the foundation and wave propagation analysis [11]

Tensile testing is the basis of mechanical testing used on materials. Where the standardized test specimen is subjected to uniaxial loading so that the test specimen is stretched and lengthened until it finally breaks [12]

Principal stress is the maximum or minimum stress that occurs at a point in a rigid body or structure, where the normal or shear stress reaches an extreme value. The points where principal stress occurs are called principal points. Mathematically, principal stress is formulated as follows:

$$\sigma_{1,2} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2} \quad (8)$$

Von mises stress is a stress whose value is obtained from the theory of failure due to distortion energy. If the von mises stress value exceeds the yield stress of the material, the design will fail [13]

Mathematically, the Von Mises stress (σ_y) is calculated as the square root of half the sum of the squares of all stress components (normal stress and shear stress):

$$\sigma_y = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1 \sigma_2} \quad (9)$$

Von Mises stress is a scalar representation of multiaxial stress within a body. If the Von Mises stress generated at a point exceeds the material strength limit of the material, it can be indicated that the body is potentially subject to permanent deformation or even failure. *Safety Factor* [14]

Safety factor is the ratio of the maximum load capacity that a structure or component can withstand to the actual

applied load. It is a measure of the safety or reliability of a design or system.

$$SF = \frac{\sigma_{yield}}{\sigma_y} \quad (10)$$

A high safety factor indicates that a structure or component has a large excess capacity to withstand the loads imposed on it, while a low safety factor indicates that the structure or component is approaching the maximum load limit that it can withstand.

The Finite Element Method (FEM) is a numerical technique used to solve complex mathematical and physical problems in various fields of engineering and science. This method is often used to analyze and model the behavior of mechanical structures, thermal, fluids, electromagnetics, and various other physical phenomena.

II. METHODOLOGY

The research method that the author has done is by studying literature, then modeling it in a 3D model. After modeling in a 3D model, the next step is simulation using ansys static structural software. The following is a flow diagram of the research that the author has done.

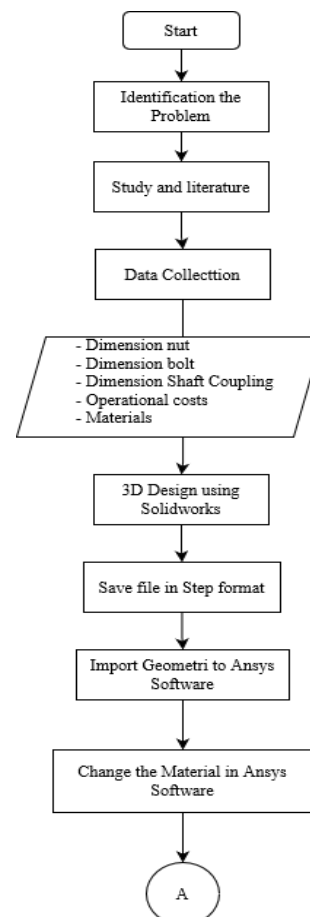


Figure 2.1: Schematic Diagram 1

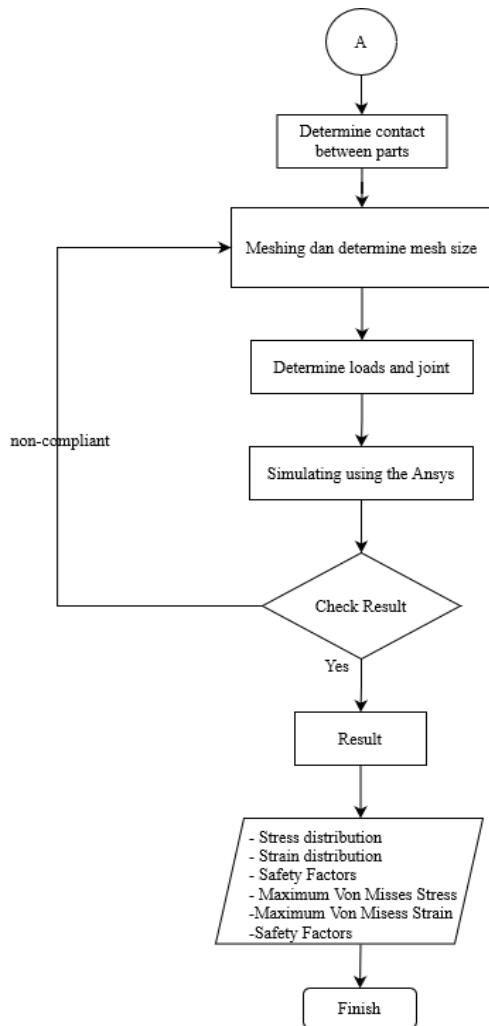


Figure 2.2: Schematic Diagram 2

2.1 Dimension dan Material

The following are the dimensions of the bolts, nuts, and shaft couplings that will be analyzed using the ANSYS static structural software.

2.1.1 Bolt Dimension

The following are the dimensions of the bolts that will be analyzed using the ANSYS static structural software, shown in Figure 2.3.

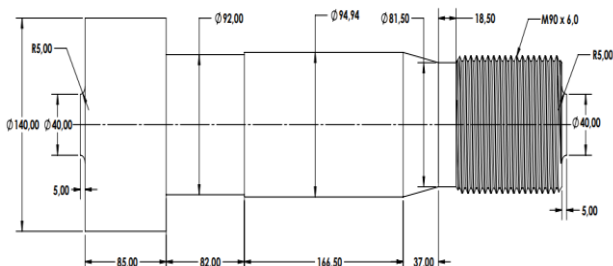


Figure 2.3: Coupling Bolt Dimension

2.1.2 Bolt Dimension

Following is the nut dimension, shown through Figure 2.4.

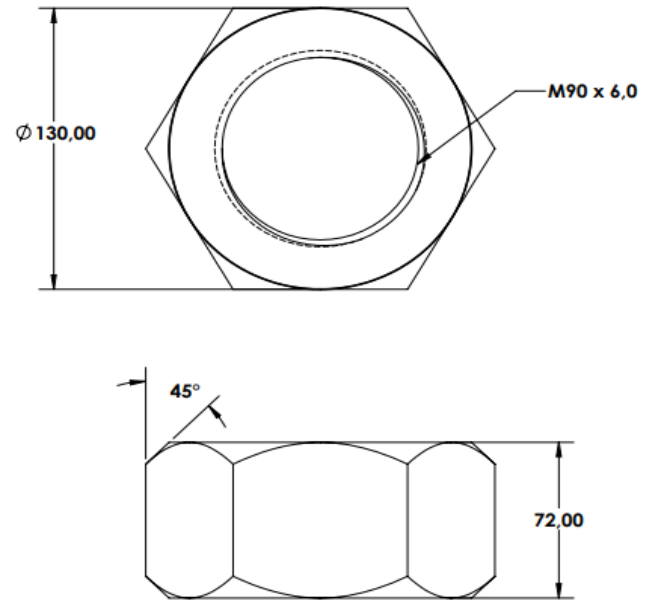


Figure 2.4: Bolt Dimension

2.1.3 Dimensi Shaft Coupling

The following is the dimensions of the shaft coupling, shown through Figure 2.5.

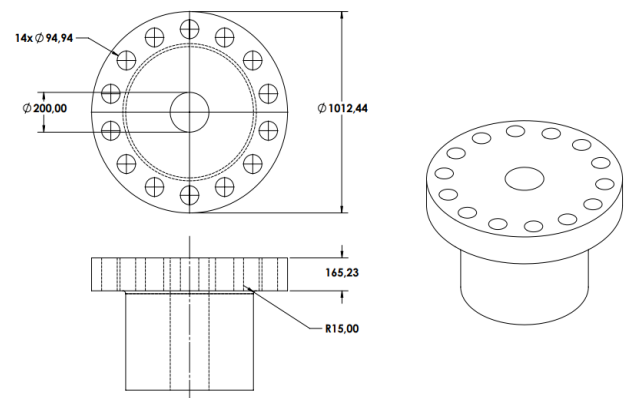


Figure 2.5: Dimensi Shaft Coupling

2.2 Bolt placement position

The following is the position of the bolt placement in the shaft coupling, shown through Figure 2.6.

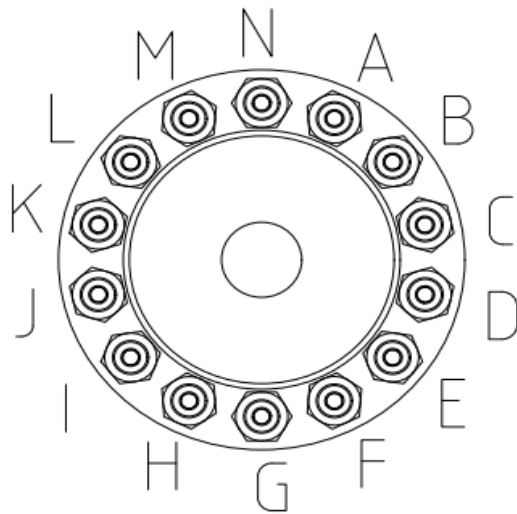


Figure 2.6: Bolt placement position

Hardness, Vickers	446
Tensile Strength Ultimate	1500 MPa
Tensile Strength, Yield	1130 MPa
Elongation at Break	15 %
Bulk Modulus	160 GPa
Shear Modulus	80 Pa

2.3 Material Baut

In the simulation that has been done by the author there are 2 types of materials that will be used for bolts, the materials are AISI Type S5 Tool Steel – Oil Quenched to 55 HRC and AISI Type S5 Tool Steel, Austenitized 855 – 870 ° C (1575 – 1600 ° F), Oil Quenched to 45 HRC. The following is a table of the mechanical properties of both materials shown through tables 2.1 and 2.2.

Table 2.1: Mechanical Properties AISI Type S5 Tool Steel – Oil Quenched to 55 HRC

Mechanical Properties	Nilai (Metric)
Density	7,83 g/cc
Hardness, Knoop	624
Hardness, Rockwell C	55
Hardness, Vickers	602
Tensile Strength, Ultimate	2230 MPa
Tensile Strength, Yield	1730 MPa
Elongation at Break	9,0 %
Bulk Modulus	160 GPa
Shear Modulus	80,0 GPa

Table 2.2: Mechanical Properties AISI Type S5 Tool Steel, Austenitized 855 – 870 ° C (1575 – 1600 ° F), Oil Quenched to 45 HRC

Mechanical Properties	Nilai (Metric)
Density	7,83 gr/cc
Hardness, Knoop	464
Hardness, Rockwell C	45

2.4 Simulation Set up

Simulation set up is done by giving torque load which is done on one end of shaft, while the other end is made as fix support. The following is a picture of simulation set up, shown in figure 2.7.

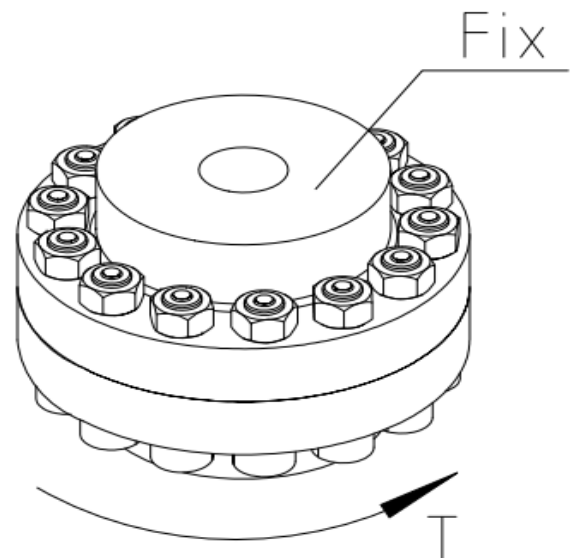


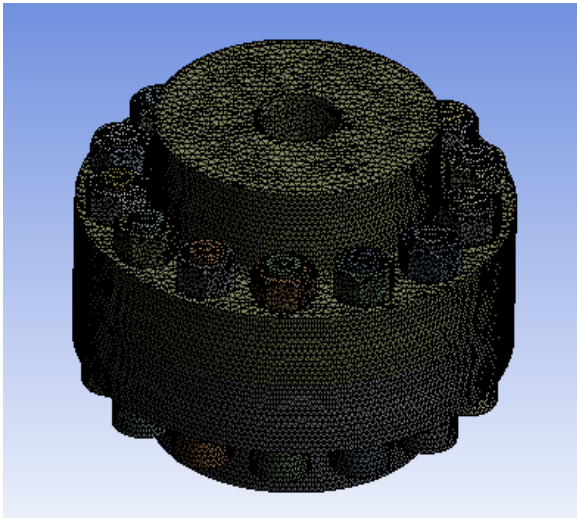
Figure 2.7: Set up Torque load on coupling

2.5 Contact Component

In the simulation that the author has conducted, the components between contacts are modeled as frictionless to simplify the model of the simulation that will be carried out. This modeling is done based on the effects of insignificant frictional forces.

2.6 Meshing

Simulation meshing is the process of dividing or forming complex geometric objects into smaller and simpler elements called "meshes" or "grids" for the purpose of numerical analysis and simulation. In this simulation, the mesh size used is 13.61 mm and the number of elements is 359620 as shown in Figure 2.8.



Statistics	
Nodes	592220
Elements	359620

Mesh Metric	Skewness
Min	1,8524e-004
Max	0,99454
Average	0,33556
Standard Devi...	0,18577

Figure 2.8: Meshing

Based on Figure 3.6 ABOVE, it is found that the average skewness value is 0.33556, Where Based on The Skewness Measure is classified as very good. The following are the skewness criteria in the finite element method shown in figure 2.9.

Skewness mesh metrics spectrum					
Excellent	Very good	Good	Acceptable	Bad	Unacceptable
0-0.25	0.25-0.50	0.50-0.80	0.80-0.94	0.95-0.97	0.98-1.00

Figure 2.9: Skewness Mesh Metrics Spectrums (Zhang, 2017)

III. ANALYSIS AND DISCUSSION

Normal force distribution, shear force, and flexible moment. If an object is subject to an external force, the object will form internal forces and bending moments. These inner forces consist of the normal force and shear force The following are free object diagrams and also the distribution of normal forces, shear forces, and flexible moments are shown through Figure 3.1, 3.2, 3.3, and 3.4.

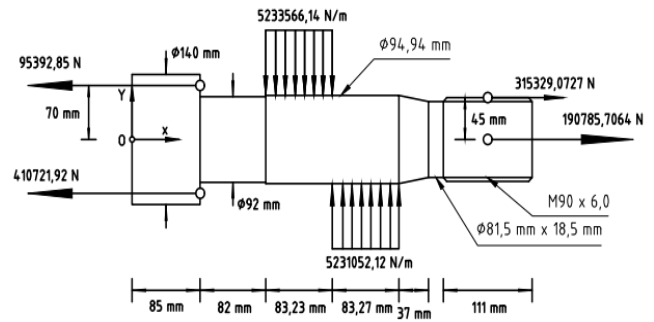


Figure 3.1: Bolts and external forces on them

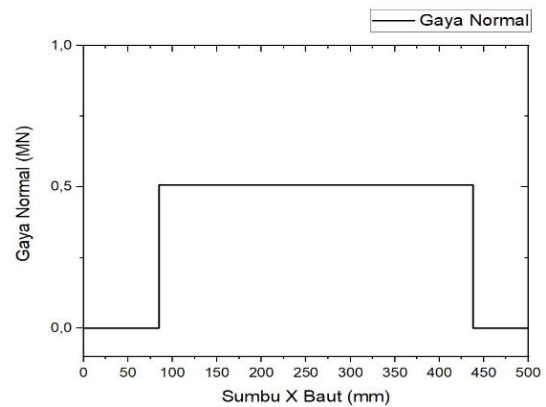


Figure 3.2: Normal force graph about the x-axis of the bolt

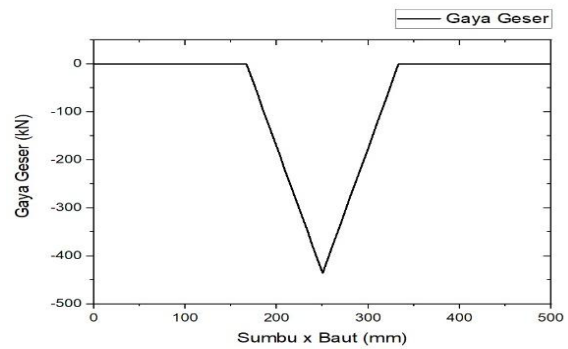


Figure 3.3: Normal force graph about the x-axis of the bolt

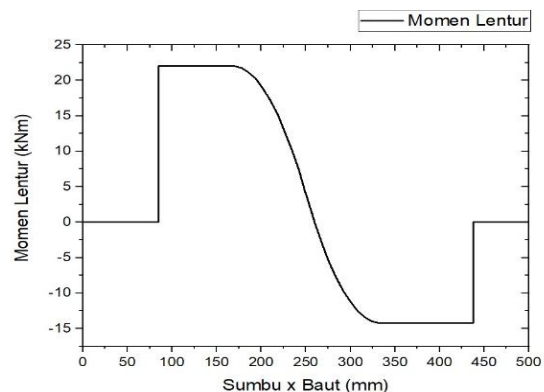


Figure 3.4: Bending Moment Graph about the x-axis of the bolt

3.1 Analytic Von Misses Calculation

From Figure 4.3 it is known that the maximum shear force received by the bolt is at 250.25 mm against the 0 axis. Because the dominant force works on the bolt is a shear force, we will only calculate the stress in this area. In accordance with the equation (1) obtained that stress due to the normal force is 71.53 MPa, while stress due to shear force and bending moments is not expressed in numbers but expressed in the form of equations to the bolt axis. Stress equation due to shear force and bending moment is $\tau_{xy} = -(36,42 \text{ GN} / \text{m}^2, 25.10 - 3m^2 - y^2)$ dan $\sigma_{My} = -990 \text{ MPay}$. Then based on equation (8), the principal stress at the maximum point is if $Y_{\text{max}} \approx -11.33 \text{ mm}$ from the zero point of the bolt coordinate axis. So that the principal stress obtained at this point is equal to $\Sigma_1 = 129.14 \text{ MPa}$ and $\sigma_2 = -46.39 \text{ MPa}$. And by entering the principal values of the stress into equation (9) obtained the Von Misses voltage value is 175.54 MPa. The following are illustrations and stress diagrams received by bolts are shown through Figure 3.5.

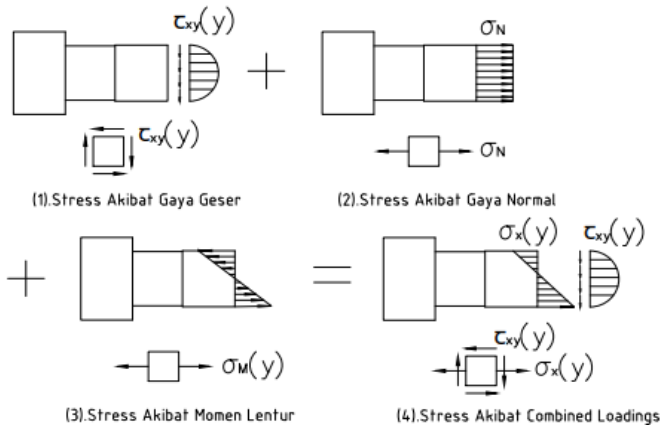


Figure 3.5: Stress received by the bolt analytically

3.2 Simulation Result

3.2.1 Results of Maximum Von Von Misses Stress

Max von Misses Strain, and Min Safety Factor on a maximum loading of 61.5 MW in the simulation that has been carried out it is found that the maximum von misses voltage value received by baut adalah sebesar 195,93 MPa. In addition, there is also a contour for von misses voltage at the maximum operational load of turbine, which is shown through Figure 3.6.

In addition, the simulation that the author has done is also found that the Von Misses strain value that occurs in the bolt is 0,00098188. In addition, in the simulation that the author has conducted, it was also found that the von Misses strain value that occurs in the bolt is 0.00098188 mm/mm. The following

is a contour image of the von Mises strain received by the bolt and its maximum value is shown in Figure 3.7.

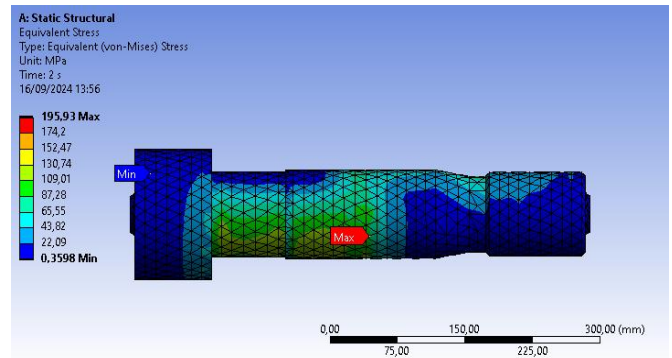


Figure 3.6: Von Mises stress contour on bolts

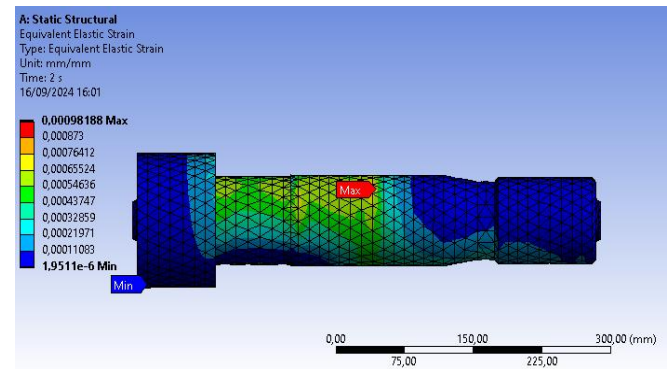


Figure 3.7: Von Mises strain contours on bolts

In addition, there are several variations in stress and strain received by the bolts based on their position on the shaft coupling, and the following is table 3.1 which shows the stress and strain values received by the bolts at a load of 61.5 MW.

Table 3.1: Simulation results of von mises stress and von mises strain received by bolts

No	Baut	Stress (MPa)	Strain (mm/mm)
1	A	194,96	0,00096102
2	B	196,97	0,00097147
3	C	195,96	0,00096599
4	D	197,99	0,00097812
5	E	195,65	0,00096504
6	F	194,96	0,00096132
7	G	198,08	0,0009789
8	H	194,68	0,00095961
9	I	196,35	0,0009683
10	J	195,93	0,00096578
11	K	198,15	0,00097906
12	L	195,64	0,00096504
13	M	194,76	0,0009603
14	N	198,72	0,00098188
Rata-rata		196,34	0,0009687

3.2.2 Graph of the relationship between loading and von mises stress

Based on the simulation results, there is a relationship between operational load and von mises stress value, namely if the operational load is higher, the von mises stress received by the bolt will also be higher. The relationship between operational load and stress is expressed in the linear equation $\sigma_y = (3.0614) P + 7.8419$ MPa which is based on graph 4.8. Grafik hubungan pembebanan terhadap von mises strain

In the simulation that the author has conducted, there is a relationship between operational load and the von mises strain value, namely that if the operational load is higher, the von mises strain received by the bolt will also be higher with the equation $\epsilon_y = (2 \times 10^{-5}) P + 2 \times 10^{-5}$ mm/mm base on grafik 4.9.

3.2.3 SF 2 Material Comparison

Based on the simulation simulation, it is obtained for AISI Type S5 Steel Tool - Oil Quented to 55 HRC has a higher safety factor value of 8.8111 while Aisi Type S5 Tool Steel material, Austenitized 855 - 870 ° C (1575 - 1600 ° F), Oil Quenched to 45 HRC has a lower safety factor value of 5,7552. Grafik Pembebanan terhadap Safety factor untuk material AISI Type Tool Steel – Oil Quenched to 55 HRC

In the simulation that the author has done for the Aisi type S5 Steel - oil quented to 55 HRC material, the relationship between operational loads and safety factor value is obtained. The relationship between operational loads and safety factor is shown through figure 4.10 with the recompanying equation is $SF = (427,51) P^{-0,942}$.

3.2.4 Validation of simulation results

Based on the simulation results, it was found that the maximum von mises stress value at a load of 61.5 MW was an average of 196.34 MPa, while using the von mises stress calculation according to Hibbler in his book entitled Mechanics of Materials, it was found that the von mises stress value received by the bolt was according to Hibbler in his book entitled Mechanics of Materials, it was found that the von mises stress value received by the bolt was 175.54 MPa. If the two von mises stress values are compared, with the comparison being the exact value based on the mechanics of material book, an error of 11.85% is obtained. The following is a comparison of the results of von mises stress theoretically according to the mechanics of material book with the numerical simulation that has been carried out shown in graphs 3.8, 3.9, and 3.10.

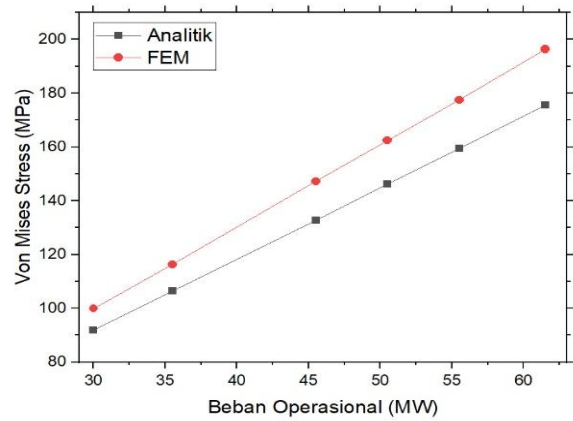


Figure 3.8: Loading graph against von mises stress

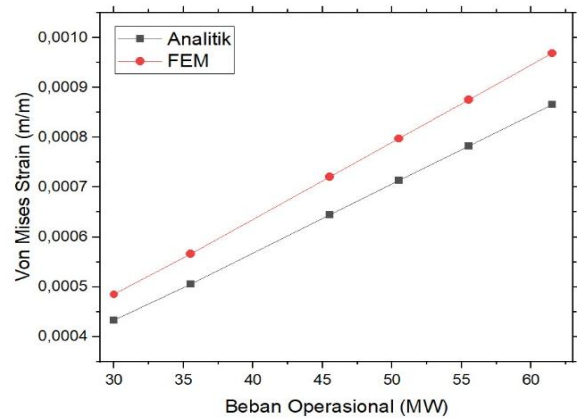


Figure 3.9: Graph of the effect of operational load on von mises strain

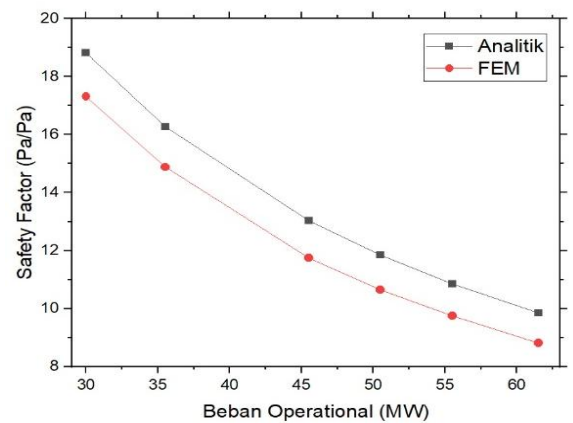


Figure 3.10: Graph of the influence of operational load on safety factor for AISI Type S5 Tool Steel material – Oil Quenched to 55 HRC

IV. SUMMARY

1. In the simulation that has been carried out, it was found that the maximum von misses stress value received by the bolt was 196.34 MPa.
2. The relationship between operational load and von misses stress value, namely if the operational load is higher, the von misses stress received by the bolt will also be higher.

Furthermore, there is also a relationship between operational load and von misses strain value, namely if the operational load is higher, the von misses strain received by the bolt will also be higher. In addition, with AISI Type Tool Steel material - Oil Quenched to 55 HRC, a relationship was obtained between operational load and safety factor value, namely if the operational load value is higher, the safety factor value will be lower.

- From the simulation that the author has done, it is found that there is a difference in safety factor if the material used in the bolt is changed. It is found that AISI Type S5 Tool steel - Oil Quenched to 55 HRC has a higher safety factor value of 8.8111 while the AISI Type S5 Tool Steel, Austenitized 855 - 870 ° C (1575 - 1600 ° F), Oil Quenched to 45 HRC has a lower safety factor value of 5.7552.

V. SUGGESTION

- It is recommended to use a smaller mesh size to increase the accuracy of the simulation if further research is carried out.
- It is recommended to use more diverse materials so that the simulation results can determine which materials have the potential to have better resistance.
- Based on the research that the researcher has conducted, it is recommended to use AISI Type S5 Tool Steel – Oil Quenched to 55 HRC because it has a greater safety factor than AISI Type S5 Tool Steel, Austenitized 855 – 870 ° C (1575 – 1600 ° F), Oil Quenched to 45 HRC.

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