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NUMERICAL AND ANALYTICAL ANALYSIS OF THE SHAFT DESIGN FOR A ROTATING DRUM BIOREACTOR USING STAINLESS STEEL 304 MATERIAL

Gladion Alim Putero
Faculty of Engineering & Science, Department of Mechanical Engineering
Universitas Pembangunan Nasional "Veteran" Jawa Timur, Surabaya, Indonesia
Email: 22036010004@student.upnjatim.ac.id

Rahmat Affandy
Faculty of Engineering & Science, Department of Mechanical Engineering
Universitas Pembangunan Nasional "Veteran" Jawa Timur, Surabaya, Indonesia
Email: 22036010011@student.upnjatim.ac.id

Mochamad Fauzi
Faculty of Engineering & Science, Department of Mechanical Engineering
Universitas Pembangunan Nasional "Veteran" Jawa Timur, Surabaya, Indonesia
Email: 22036010013@student.upnjatim.ac.id

Fikri Isya Zain
Faculty of Engineering & Science, Department of Mechanical Engineering
Universitas Pembangunan Nasional "Veteran" Jawa Timur, Surabaya, Indonesia
Email: 22036010018@student.upnjatim.ac.id

Moch. Nur Irsyad Prabawanto
Faculty of Engineering & Science, Department of Mechanical Engineering
Universitas Pembangunan Nasional "Veteran" Jawa Timur, Surabaya, Indonesia
Email: 22036010044@student.upnjatim.ac.id

Ahmad Khairul Faizin
Faculty of Engineering & Science, Department of Mechanical Engineering
Universitas Pembangunan Nasional "Veteran" Jawa Timur, Surabaya, Indonesia
Email: ahmad.khairul.tm@upnjatim.ac.id

ABSTRAK

Faktor keamanan dan tegangan Von Mises perlu dianalisis agar komponen tetap aman terhadap tegangan gabungan dan risiko kegagalan akibat beban dinamis serta kondisi tak terduga.Penelitian ini bertujuan untuk menganalisis faktor keamanan (*safety factor*) dan von mises perancangan poros pada *rotating drum bioreactor* yang menggunakan material *stainless steel* 304. Mesin ini dirancang untuk mendukung proses fermentasi terasi dengan metode *Solid State Fermentation* (SSF). Proses analisis dilakukan melalui simulasi menggunakan metode *finite element method* (FEM) untuk mengevaluasi distribusi tegangan dan nilai *safety factor* pada poros. Hasil simulasi menunjukkan bahwa nilai von mises atau tegangan maksimum pada poros adalah 10.98 N/mm², masih di *bawah yield strength* material *stainless steel* 304 sebesar 205 N/mm². *Safety factor* minimum yang diperoleh dari analisis adalah 19, menunjukkan bahwa desain ini aman untuk menahan beban selama proses operasi. Selain itu, hasil analisis numerik secara perhitungan manual didapatkan nilai tegangan maksimum poros sebesar 10.95 N/mm² dengan nilai *safety factor* minimum sebesar 18.7. Melalui perbandingan hasil analisis secara simulasi analitikal dan perhitungan numerik manual ini didapatkan perancangan mesin dengan tingkat keandalan dan keamanan struktur yang dinilai aman, serta meminimalkan risiko kegagalan mekanis.

Kata kunci: faktor keamanan, von mises, rotating drum bioreactor, stainless steel 304, FEM

ABSTRACT

The safety factor and Von Mises stress need to be analyzed so that the components remain safe against combined stress and the risk of failure due to dynamic loads and unexpected conditions. This study aims to analyze the safety factor and von mises of the shaft design on a rotating drum bioreactor using 304 stainless steel material. This machine is designed to support the shrimp paste fermentation process using the Solid State Fermentation (SSF) method. The analysis process is carried out through simulation using the finite element method (FEM) to evaluate the stress distribution and safety factor value on the shaft. The simulation results show that the von mises value or maximum stress on the shaft is 10.98 N/mm², still below the yield strength of 304 stainless steel material of 205 N/mm². The minimum safety factor obtained from the analysis is 19, indicating that this design is safe to withstand loads during the operation process. In addition, the results of the numerical analysis using manual *calculations obtained a maximum shaft stress value of 10.95 N/mm² with a minimum safety factor value of 18.7. Through a comparison of the results of the analytical simulation analysis and manual numerical calculations, a machine design with a level of reliability and structural safety that is considered safe, as well as minimizing the risk of mechanical failure.*

Keywords: *safety factor, von mises, rotating drum bioreactor, stainless steel 304, FEM*

1. INTRODUCTION

In the design of industrial machines, structural safety plays a crucial role in ensuring long-term reliability and operational durability. One of the essential components in the Rotating Drum Bioreactor (RDB) is the main shaft and frame, which must withstand the loads generated by the rotating drum and the fermentation materials inside. These loads include static and dynamic forces from the drum's rotation, material weight, and torque generated by the motor. Failure in these critical components could lead to operational disruption and significant maintenance costs [1].

A Rotating Drum Bioreactor is specifically designed to create a controlled environment for the fermentation process, which is essential in food processing industries, such as shrimp paste (terasi) production [2]. Unlike traditional open fermentation systems, the use of bioreactors provides better hygiene, reduces contamination risks, and improves the quality of the final product [3]. In this research, the fermentation process is based on Solid State Fermentation (SSF), where low moisture content substrates promote high product concentration and reduce processing time compared to conventional fermentation methods [4].

The Finite Element Method (FEM) is a reliable technique for evaluating the strength and safety of machine structures. This method simulates real-world loading conditions and predicts the stress and safety factor in machine components. With the help of SolidWorks, FEM allows engineers to validate designs and optimize structures before manufacturing, minimizing potential failures and production costs [5].

The main components evaluated in this study are the main shaft and frame made of stainless steel 304. This material is chosen for its high corrosion resistance, good mechanical properties, and suitability for food processing applications [6].

This research calculates the total torque of the Rotating Drum Bioreactor (RDB) shaft component obtained through calculations involving various factors, such as power requirements, system efficiency, and workload on the machine [7]. The main focus in this calculation is to determine the torque generated by the AC motor as the main driver. The torque of the AC motor is calculated by considering the electrical power supplied to the motor, motor efficiency, and rotational speed (RPM). The calculation can be done using the following formula

This study demonstrated that FEM is effective for determining stress distribution and identifying critical failure points. The safety factor of 2.5 indicated that the connecting rod design was within safe operational limits [8].

They successfully evaluated the vertical loading effects on a light steel bicycle frame. The results indicated a safety factor of 1.8, ensuring the frame's structural integrity [9].

Their study showed that the electric vehicle chassis maintained a safety factor of 3.2 under normal loading conditions, proving that the design was structurally sound and reliable [10].

The use of the Finite Element Method (FEM) to analyze shaft and frame structures has been thoroughly researched in order to guarantee mechanical reliability under a range of loading scenarios. A robust design of fatigue life prediction for machine shafts, which showed that a 30 mm diameter shaft under 72 Nm of torque achieved a safety factor of 10 [11]. The static behavior of shafts under various load variations was also examined using FEM, which revealed patterns of stress distribution [12].

Dynamic analysis of the rear axle shaft of a three-wheeler vehicle in the field of automotive engineering, using computational methods to forecast failure trends under varying loading conditions [13]. In their study of wind turbine main shafts, FEM used to pinpoint areas of stress concentration and suggested structural changes that greatly decreased stress levels and increased shaft dependability [14].

The optimization of shaft designs has been the subject of additional research after modeling and simulating a belt bucket elevator head shaft while taking geometric and fatigue stress concentration factors into account. This research concluded that the shaft would withstand loading stresses for the duration of its anticipated life cycle and the precision of FEM in predicting stress and deflection by contrasting its findings with analytical computations for a machine shaft [15].

This study examined the torsional stability of composite drive shafts in the context of composite materials, emphasizing the impact of fiber orientation and boundary conditions on mechanical behavior [16]. A tunnel shaft's strength was analyzed to suggest material and dimensional changes based on FEM findings to preserve structural integrity [17].

Using FEM simulations in this study examined the rear driveshaft failure of a truck, identifying critical stress areas and recommending design changes to stop similar failures in the future. The authors investigated the fracture and enhancement of the main shaft of a wind turbine, showing that structural changes based on FEM analyses could successfully lower stress concentrations and increase fatigue life [18].

This research analyzed the value of von mises stress and safety factor of a rotating drum bioreactor's shaft through analytical FEM (finite element method) through solidworks simulation and manual numerical calculations. Research methodology is based upon the previous studies along with literatures for the manual numerical calculations. The analytical and numerical results are compared to see the accuracy of the obtained result in assuring the reliability and structural safety of the shaft.

2. METHOD

In this experimental study of structural elements, the authors utilized the Finite Element Method to determine the value of stresses and the Factor of Safety of the shaft of a rotating drum bioreactor that was designed with 2 suspension bracket models for analytical analysis and manual calculations is used for the numerical analysis. In practice, Finite Element Analysis usually consists of three main steps, preprocessing, analysis, and post processing. In numerical methods, calculating the torque, shear force, moment force, and distortion energy are used to determine the results. Additionally, this section, consists discussion of the concept, materials, load distribution, and the dimensions and shape of the model used by the authors with a flowchart procedure that was followed in this study that is shown in Figure 1.

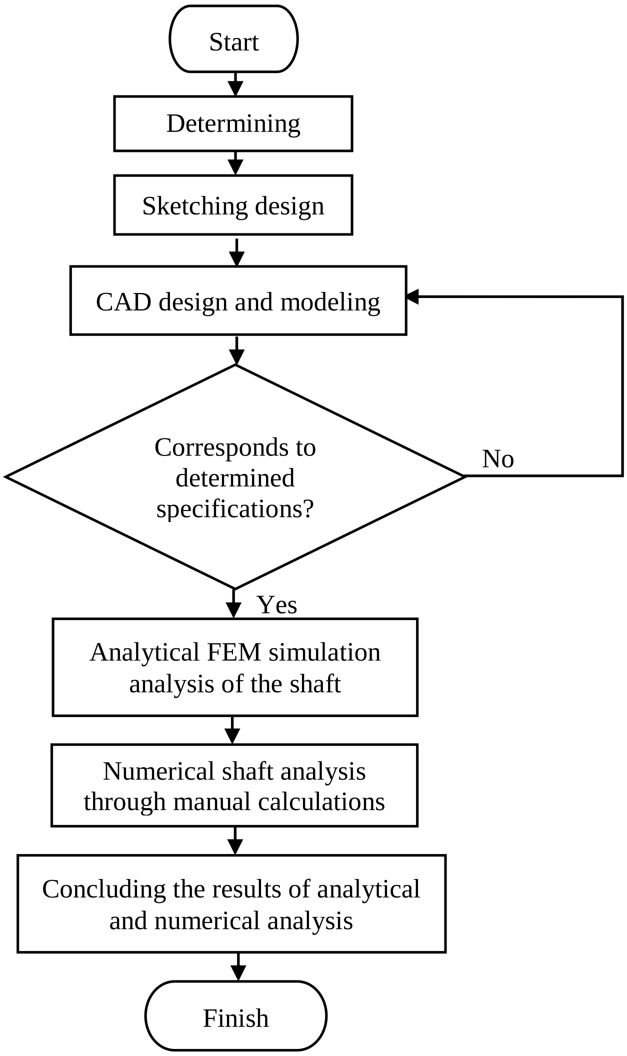

Figure 1. Flowchart

2.1 *Design*

Figure 3 shows the details and dimensions of the suspension bracket along with the supporting parts of the bioreactor main shaft which both are shown in the metric (millimeter) mm unit whilst Figure 2 is the rest of the components of the said bioreactors. The main shaft below is a part that is analyzed further in this research paper.

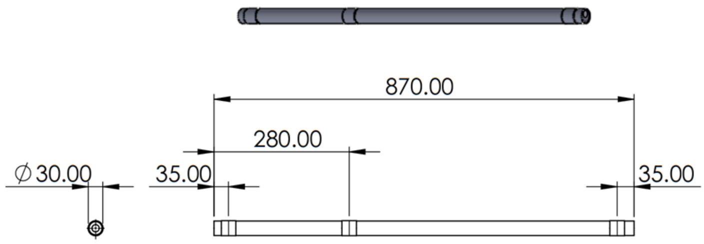

Figure 2. Shaft dimensions (in millimeters)

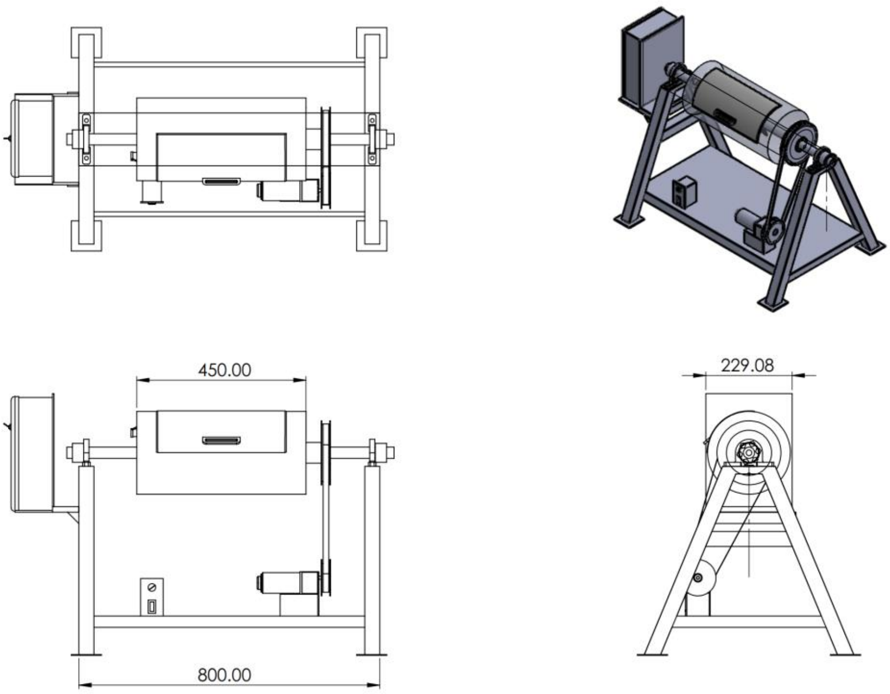

Figure 3. Bioreactor components assembly (in millimeters)

As highlighted in Figure 2 for the shaft dimensions and Figure 3 for the rest of components of the bioreactor in millimeters. The shaft is a critical component within the bioreactor rotating drum, it is to be analyzed by the actors with other contributing components taken into account for an accurate result in force distribution to determine the safety factor of the shaft.

2.2 *Material*

Shown in Table 1 below is the given specification of the SS304 material that the author uses for the shaft. The author's reasons for choosing this material is for its high corrosion resistance, good mechanical properties, and suitability for food processing applications.

Table 1. Specification of material SS304

No.	Parameter	Value
1.	Tensile strength	540-750 MPa
2.	Yield strength	205 MPa
3.	Thickness	1.5 mm

2.3 *Technical Specification*

Table 2 is the technical specification and the functionality of contributing components within the rotating drum bioreactor. These properties are also a contributing factor in further analyzing the machine elements specifically in calculating the von mises stress and factor of safety of the shaft.

Table 2. Machine specification

No.	Component	Specification	Function
1.	Vessel drum	Material : *stainless steel* 304 Mass : 8 kg Dimension : 450 x 220 mm	Fermentation vessel
2.	AC Motor	Type : AC analog Power : 9 watt 220 volt Dimension : 60 x 60 mm *Max.* output : 18 rpm	Mechanical component
3.	Motor gearbox	Ratio : 1:75	Torque and transmission control
4.	Motor pulley: drum	Ratio 1 : 2 = 6 mm :3 mm	Van belt connector
5.	V-belt	Adjusted accordingly with the pulleys positions	Mechanical connector

2.4 *Analytical Analysis*

2.4.1 *Mesh Quality*

In the Elemental Method simulation process, creating a net or breaking an object into smaller pieces, like a net, is another crucial step. Making a mesh that satisfies the requirements is an engineering simulation science acquisition because computers use mesh forms to solve problems based on formulas and various glass and mathematical equations. As a result, the more regular, uniform, and small the resulting mesh, the more data the computer can process, but the simulation process that is run also takes longer [19].

The type of mesh used is solid mesh, which is commonly preferred for structural analysis due to its high accuracy in representing the geometry and stress distribution of solid bodies. Solid mesh is particularly effective in capturing small geometric details and providing accurate results for mechanical components with complex loading conditions. Its ability to represent true 3D stress makes it superior to shell or beam mesh types in applications involving thick-walled components.

Table 3 displays the mesh specifications following a modified meshing procedure as opposed to using SolidWorks Simulation's default settings. According to mesh quality guidelines, the total number of elements obtained is 28032, which is within the "High" range and guarantees the possibility of accurate simulation results.

Table 3. Mesh specification

No.	Parameter	Specification
1.	Mesh type	Solid mesh
2.	Mesher used	Standard mesh
3.	Jacobian points	16 points
4.	Element size	3.81963 mm
5.	Tolerance	0.190982 mm
6.	Mesh quality	High
7.	Total nodes	60433
8.	Total elements	30468
9.	Maximum aspect ratio	8.8317
10.	Percentage of elements with aspect ratio	1.5 mm

Additionally, at least 90% of the mesh elements have an aspect ratio of less than 3, which is essential for maintaining high mesh quality and simulation accuracy. The author in this study utilizes a mesh density of 98.1%, ensuring that the simulation results are reliable and well within the acceptable range for engineering analysis.

2.5 *Numerical Analysis*

2.5.1 *Calculating Torque*

Determining torque and axial force of the main shaft to ensure an accurate result. Below is the formula for determining torque of the motor with a fixed RPM value that involves angle acceleration.

$$\omega = 2\pi \times \left(\frac{n}{60}\right) \tag{1}$$

where

ω = Angle acceleration (rad/s)
n = Speed of rotation (Rpm)

The calculation results do not include the weight of the front or rear shaft housing, because the test will only be applied to the main shaft torque, therefore, we can determine the value of the torque by considering the motor power and the angle acceleration with the following formula:

$$T = \frac{P}{\omega} \tag{2}$$

where

T = Torque (N.m)
P = Power (watt)

2.5.2 *Calculating Distortion Energy*

Bending, torsion, axial stresses are generally found in midrange and alternating components. Where it can be simplified by combining various types of stresses into midrange and alternating Von Mises stresses. Usually the axial stress that occurs at a critical point is small when compared to the bending and torsion stresses that are very dominant. Combining the distortion energy failure theory, with Von Mises for a rotating circular cross-sectional shape, the axial load is ignored. The utilized physical equations of the mathematical modelling can be written as [20].

$$\sigma_{DE} = (\sigma_x^2 + 3\tau_T^2)^{1/2} = [\left(k_t \frac{M.y}{I}\right)^2 + 3\left(k_{ts}\frac{Tr}{J}\right)^2]^{1/2} \tag{3}$$

where

σ_{DE}	= Distortion energy	y	= Distance from the neutral axis (mm)
τ	= Shear stress (MPa)	kts	= Shear stress concentration factor (dimensionless)
I	= Moment of inertia (kg·m²)	T	= Torque (N·mm)
σx	= Bending stress (MPa)	r	= Outer radius (mm)
kt	= Stress concentration factor (dimensionless)	J	= Polar moment of inertia (mm⁴)
M	= Bending moment (N·mm)		

Additionally, the value of inertia moment and polar inertia moment can be determined through the formula that considers the outer and inner diameter of the hollow shaft in which is shown in Figure 4.

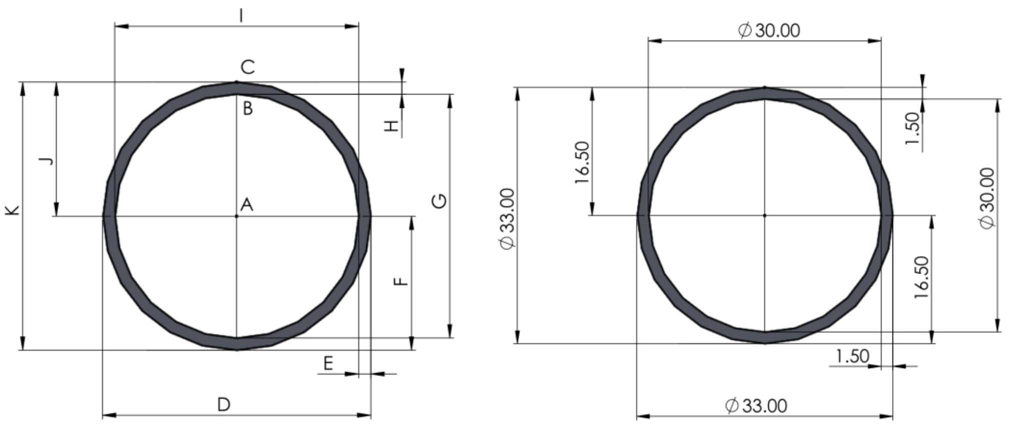

Figure 4. Cross section steel hollow

The formula used to determine the value of inertia moment (I) and polar inertia moment (J) based on the theory of axial moment and axial stress are as follows [20].

$$I = \frac{\pi}{4}(D^2 - d^2) \tag{4}$$

where

I = Moment of inertia (kg·m²)
D = Outer diameter (m)
d = Inner diameter (m)

As for the polar moment of inertia formula based on the theory of polar inertia moment are as follows [20].

$$J = \frac{\pi}{2}(D^4 - d^4) \quad (5)$$

where

J = Polar moment of inertia (mm⁴)
D = Outer diameter (mm)
d = Inner diameter (mm)

The design certainly considers many factors, one of which is the safety factor which plays an important role. According to Mott's theory for the design of structures that receive static loads with a high level of confidence, the safety factor value is 1.25 to 2.0 [21]. The calculation of the safety factor uses the following formula.

$$\eta = \frac{\sigma_{yield}}{\sigma_{max}} \quad (6)$$

where

η = Safety factor
σ_{yield} = yield strength
σ_{max} = distortion energy

3. RESULTS AND DISCUSSION

3.1 *Analytical Analysis*

Based on the stages in carrying out analytical structural analysis through Finite Element Method (FEM) Simulation, this section presents the results of the tests conducted. The analysis evaluates key parameters, including von mises stress, and the Factor of Safety (FOS), to determine the structural integrity of the design.

3.1.1 *Finite Element Method Simulation Results*

After The Finite Element Method (FEM) simulation results show that von Mises stress, and the Factor of Safety (FOS) remain within acceptable limits. The von Mises stress distribution confirms that stress concentrations do not exceed the material's yield strength. Additionally, the FOS values surpass the required safety threshold, ensuring the structure’s reliability. Overall, the analysis confirms that the design meets safety and performance standards, as shown in Figures 6 and 7.

The von Mises stress value from the simulation on the shaft of the Rotating Drum Bioreactor using stainless steel 304 material under a 100 N load and a torque of 14.33 N·m resulted in a maximum stress value of 10.98×10^6 N/mm². Since the yield strength of stainless steel 304 is 205 N/mm², it can be concluded that the von Mises stress analysis indicates the shaft is still within the safe range, as the maximum stress remains below the yield strength as seen in Figure 5.

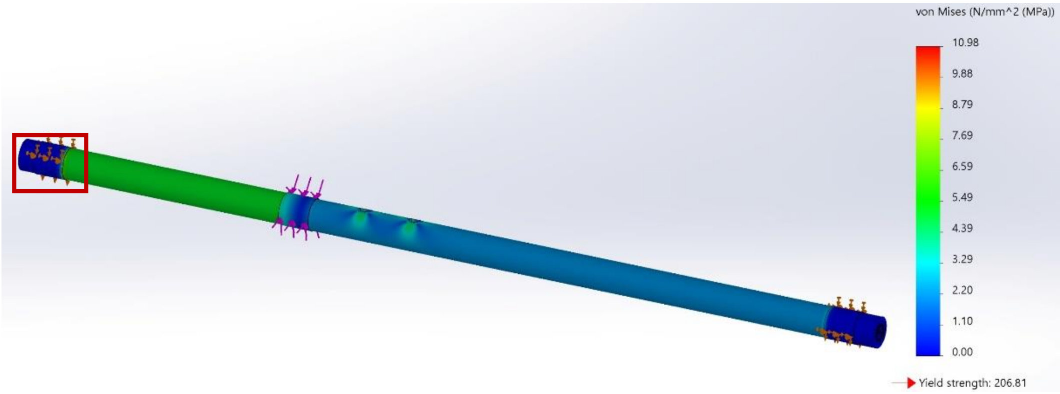

Figure 5. Von mises value

Additionally as marked in Figure 5, the critical areas are located around the edges of the suspension brackets at both ends that hold the shaft and the frame. As shown in Figure 6, a distributed stress analytical simulation ranging from 7.69 N/mm^2 to the maximum of 10.98 N/mm^2 are mainly allocated in this critical area.

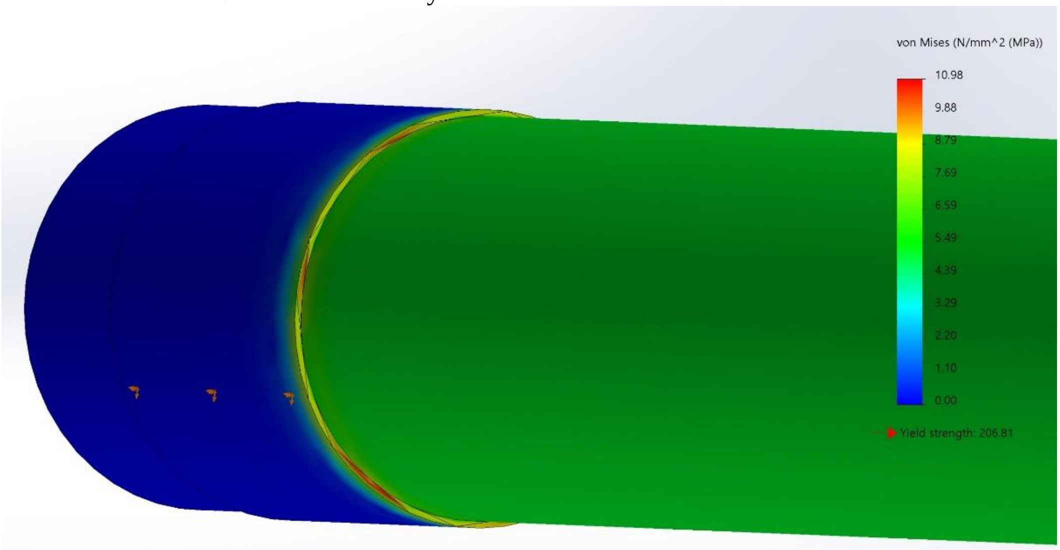

Figure 6. Critical area

Afterward, the result Factor of Safety (FoS). Using the Factor of Safety aims to ensure security against mechanical issues. Because of the release of a load under actual conditions in Figure 7, which displays the outcomes of Factor of Safety Simulation from this model, the safety factor is used.

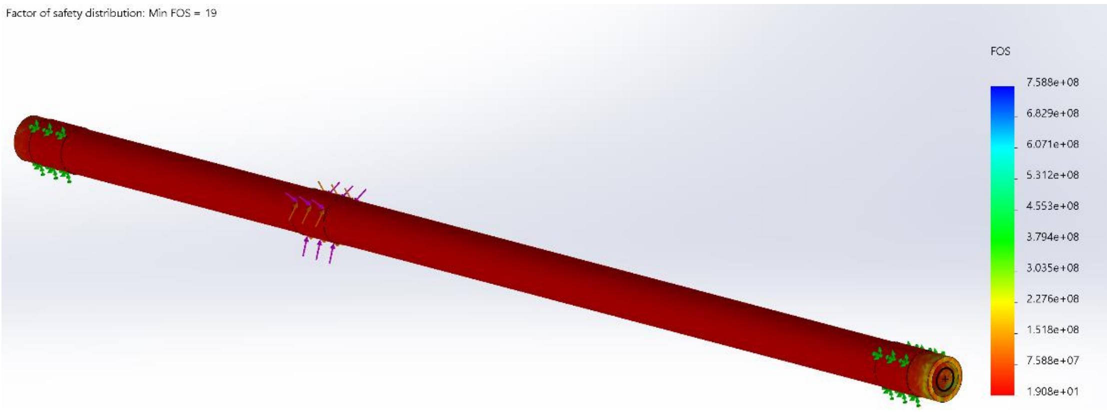

Figure 7. Safety factor value

The safety factor value from the simulation on the shaft of the Rotating Drum Bioreactor using stainless steel 304 material under a 100 N load and a torsional force of 14.33 N·m resulted in a minimum safety factor of 19. It can be concluded that the component's safety factor is within a safe range, as it exceeds the recommended value of 2.

Based on Figure 5 and 6, we can see the result of von mises magnitude and safety factor value in the design of the rotating drum bioreactor's shaft. The numbers in Table 4 are the results of simulations from solidworks 2020 software. In the simulation with a load of 100 N and torque of 14334 N.mm, as follows.

Table 4. Analytical simulation result

No.	Parameter	Value
1.	Von mises	10.98 MPa
2.	Safety factor	19

3.2 *Numerical Analysis*

To begin the calculations of numerical analysis it's important to determine the free body diagram of the analyzed component, in this case the shaft. Considering the gravity value axial force of 100 N and torque 14334 N.mm, the following is the loading value applied to determining the shear and moment force diagram but first we must determine the free body diagram shown in figure 8.

$$\Sigma M_A = 0\ (-\circlearrowleft)$$

$$0 = R_B \times (835 - 35)mm - (100N \times (280 - 35)mm) - 14334\ N.mm$$

$$0 = R_B \times (800mm) - \big(100N \times (245mm)\big) + 14334\ N.mm$$

$$\big(100N \times (245mm)\big) - 14334N.mm = R_B \times (800mm) \tag{7}$$

Thus, by substituting equation of point A (6) in determining the left side support reaction, we get the equations as follows

$$R_B = \frac{24500 - 14334}{800}$$

$$R_B = 12.7075\ N \tag{8}$$

Where the value of R_B is determined, the corresponding value can of point B can be determined by substituting the obtained as.

$$\Sigma F_y = 0\ (-\circlearrowleft)$$

$$R_A = 100 - 12.7075$$

$$R_A = 87.2925\ N \tag{9}$$

After the value of the left and right support reaction, we can now obtain the free body diagram of the shaft that is shown in Figure 8 to be used further in the numerical analysis with the length in millimeters (mm).

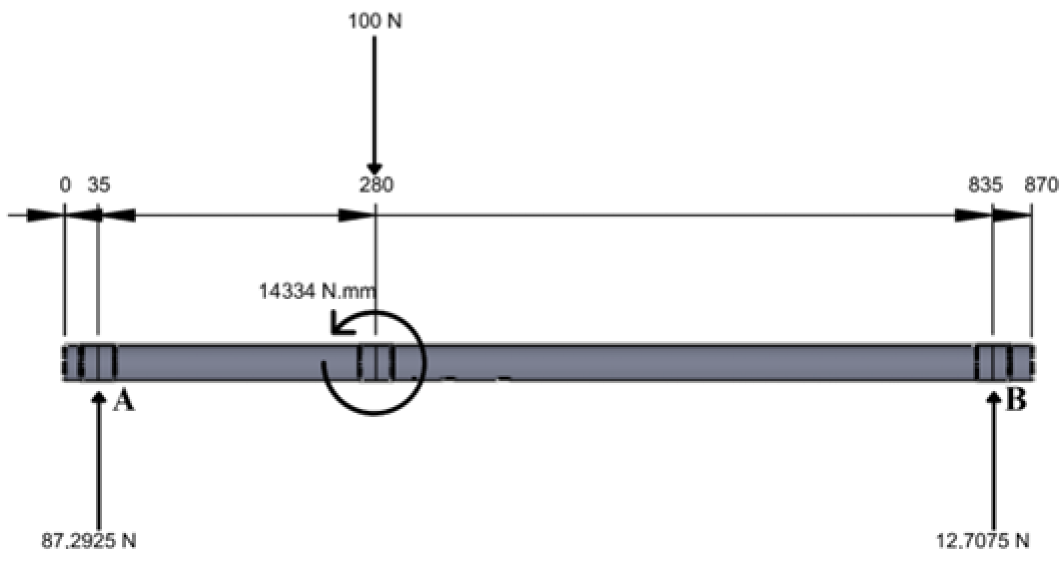

Figure 8. Free body diagram

Distribution of force from both axial and radial adds additional consideration in obtaining the von mises value of the numerical method. Figure 9 and 10 are respectively the distribution shear diagram and bending moment diagram that's obtained upon analyzing the free body diagram using SKYCIV software which was imported on an excel format to generate the graphs below with X axis representing the length dimension of the analyzed shaft.

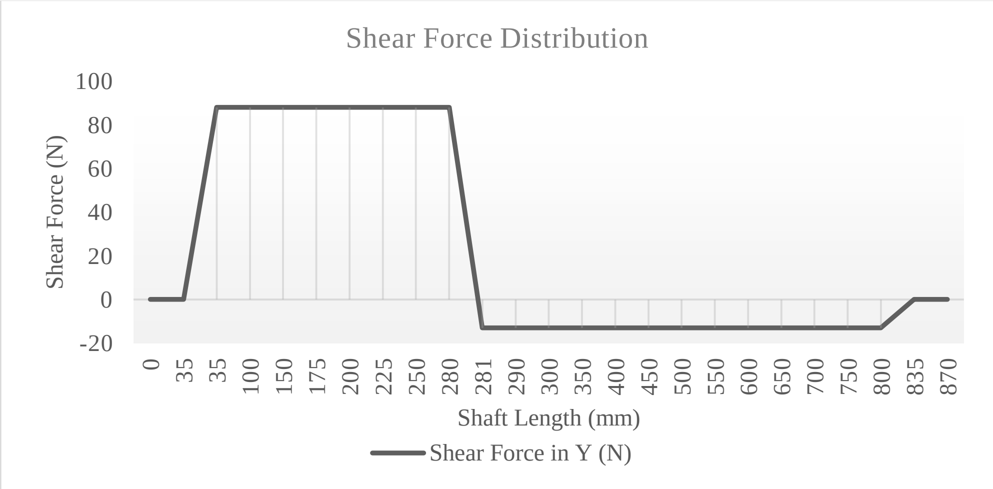

Figure 9. Shear force diagram

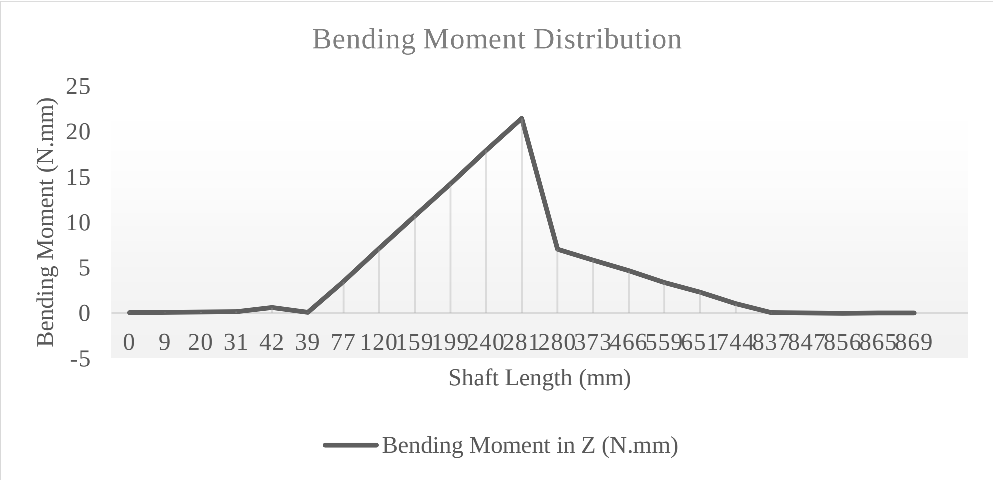

Figure 10. Moment force diagram

Using the equation of distortion energy or von mises stress (σ_{DE}) followed by the combined moment inertia and polar moment inertia from equation (4) and (5) respectively. Furthermore, determining the torque value using equation (2) is equally important in obtaining the distortion energy. To determine moment of inertia based on the theory of axial stress we obtain as follows.

$$I = \frac{\pi}{4}(33^4 - 30^4)$$

$$I = \frac{\pi}{4}(376921)$$

$$I = 2.952 \times 10^5 \ mm^4 \tag{10}$$

Substituting the value of inertia moment to normal stress in X axis formula from equation (3) we obtain as follows:

$$\sigma_x = 1.75 \frac{(21.387)(16.5)}{2.952 \times 10^5}$$

$$\sigma_x = 2.091 \ MPa \tag{11}$$

Using equation (4) in obtaining polar moment of inertia, we can obtain the value of shear stress by substituting polar moment of inertia to the shear stress formula (3).

$$J = \frac{\pi}{2}(33^4 - 30^4)$$

$$J = 5.904 \times 10^4 mm^4 \tag{12}$$

$$\tau = 1.55\frac{(14334)(16.5)}{5.904 \times 10^4}$$

$$\tau = 6.209 \text{ MPa} \tag{13}$$

Substituting equation (10), (11), (12), and (13) we can determine the value of distortion energy also known as von mises of the shaft numerically through the corresponding formulas as follows.

$$\sigma_{DE} = \sqrt{(2.091)^2 + 3(6.209)^2}$$

$$\sigma_{DE} = \sqrt{4.372 + 115.655}$$

$$\sigma_{DE} = \sqrt{120.027}$$

$$\sigma_{DE} = 10.95\ Mpa \tag{14}$$

We can now determine the safety factor of the shaft with the obtained value of distortion energy and yield strength of the shaft's material SS304 as follows

$$SF = \frac{205}{10.95}$$

$$SF = 18.7 \tag{15}$$

The results of numerical analysis is shown in Table 5 along with the result of safety factor calculation from equation (15).

Table 5. Numerical calculation result

No.	Parameter	Value
1.	Torque	14334 Nmm
2.	Moment inertia	$2.952 \times 10^5\ mm^4$
3.	Moment polar inertia	$5.904 \times 10^4 mm^4$
4.	Von mises	10.95 MPa
5.	Safety factor	18.7

3.3 *Analytical and Numerical analysis results comparison*

In order to know the validity of the results, each researcher can validate their research in various ways, such as testing the results by using theoretical calculations for numerical results. In this section, the authors are comparing the results of analytical calculations with the results from the Solidwork software. To determine the error difference in the validation method, obviously in Table 6.

Table 6. Result comparison

No.	Analysis Parameter	Analytical	Numerical	Error
1.	Yield strength (MPa)	205	206.81	0.88%
2.	Stress (MPa)	10.95	10.98	0.275%
3.	Safety Factor	18.7	19	1.58%

The analysis results reveal a strong correlation between the FEM simulations and theoretical calculations for yield strength, stress, and safety factor. The yield strength from SolidWorks is 206.81 MPa, closely matching the theoretical value of 205 MPa, resulting in a minor error of 0.88%. Similarly, stress values are nearly identical, with SolidWorks reporting 10.98 MPa compared to the theoretical 10.95 MPa, yielding a minimal error of 0.274%. The safety factor from SolidWorks is 19, while the theoretical calculation gives 18.7, leading to a 1.58% error. These low error rates indicate that the FEM provides reliable results that align closely with theoretical predictions, confirming its accuracy and effectiveness for design analysis in bioreactor applications.

4. CONCLUSION

The following is a description of some of the conclusion points that the writer got based on the research results regarding the shaft design when applied by force above:

1. The torque calculation indicates that the main shaft holds a torque of 14334 N·mm, ensuring the stability of the bioreactor's rotation during the fermentation process that weights 100 N.
2. The von Mises (distortion energy) analysis shows that the maximum stress on the shaft is 10.98 MPa through analytical simulation and 10.95 MPa though manual numerical calculation, which both significantly below the yield strength of stainless steel 304 at 205 MPa, confirming its structural safety with only 0.275% error.
3. The obtained safety factor from the analytical simulation is 19 while the manual numerical calculation is 18.7, demonstrating that the shaft design possesses excellent resistance to operational loads analyzed above 2 in value for both numerically and analytically with only 1.58% error.

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