

Influence of Fillet Radius on the Fatigue Life Behavior of an AISI 1040 Steel Transmission Shaft

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Abstract

Shafts are crucial components in mechanical transmission systems that transfer power between moving machine elements. In high-speed applications, shafts experience dynamic and cyclic loads that can trigger material failure due to fatigue, especially in cross-sectional areas such as stepped shafts. Stress concentrations that occur in diameter transition areas can be the starting point for cracking that leads to structural failure. One method to reduce these stress concentrations is by applying a radius fillet to the diameter change area. This study aims to analyze the effect of radius fillet on torsional and bending loads on a transmission shaft made of AISI 1040 steel. The method used is a numerical simulation based on Finite Element Analysis (FEA). It was found that the application of an 11 mm radius fillet on the stepped shaft provided better performance compared to a 1 mm radius fillet for a diameter transition from 190 mm to 150 mm. The use of an 11 mm radius fillet on the stepped shaft made of AISI 1040 material resulted in a reduction of total deformation by 1.8% and improvement of 74% in the safety factor was also observed for the 11 mm radius fillet configuration. In the previous design without a radius fillet, the shaft operated up to 9,066 loading cycles before failure occurred. With the implementation of an 11 mm radius fillet, a significant improvement in fatigue performance was observed, with the shaft sustaining up to 66,425 loading cycles.

Keywords : Shaft, radius fillet, fatigue cycles, AISI 1040, FEA.

1. INTRODUCTION

This study focuses on the design enhancement of a drive shaft made from AISI 1040 steel for the transfer carriage system. The transfer carriage functions as a transport mechanism that moves trolleys filled with fresh fruit bunches (FFB) from the loading ramp rail track to the sterilizer rail track. The system carries three trolleys, with a total load of approximately 7.5 tons, and operates with a transport cycle of 2–3 minutes per batch. The motion of the transfer carriage is driven by an electric motor and a hydraulic pump.

The transfer carriage serves as one of the critical supporting components in palm oil mill operations. Any malfunction in this mechanism can lead to production delays, consequently reducing the overall efficiency of the milling process. Field observations revealed that damage to the transfer carriage primarily occurs due to torsional and bending stresses acting on the drive shaft.

In mechanical power transmission systems, the shaft is a fundamental component responsible for transmitting power between rotating elements. Its role becomes particularly crucial in high-speed machinery, where the applied loads are dynamic and repetitive. Under such conditions, the shaft's reliability and service life are often challenged, as cyclic loading can induce stress concentrations at critical regions—especially in stepped shafts, where variations in diameter geometry occur.

Stress concentration is a localized phenomenon arising from geometric discontinuities such as holes, notches, or diameter transitions. These concentrated stresses can accelerate material failure due to fatigue, particularly in steels like AISI 1040. Although this material is widely used in engineering applications for its favorable mechanical properties, it remains susceptible to fatigue damage under fluctuating stress conditions.

The objective of this research is to improve the durability of the transfer carriage drive shaft under combined torsional and bending loads. One of the most effective approaches to minimize stress concentration is through geometric modification, specifically by introducing an appropriate radius fillet at the transition region of the shaft. The implementation of an

optimal radius fillet can smoothen the change in cross-sectional geometry and promote a more uniform stress distribution, thereby reducing of fatigue-induced failure. Therefore, it is essential to conduct a systematic analysis of how variations in radius fillet influence the stress distribution in stepped shafts made of AISI 1040 steel.

2. REVIEW OF LITERATURE

Several previous studies have demonstrated that increasing the radius fillet can significantly reduce stress concentration in stepped shafts. Suresh (1998) stated that enlarging the radius fillet in stepped shafts effectively decreases the stress concentration factor, thereby enhancing the fatigue life of the component. Similar findings were reported by Wahyudi et al. (2016) through a finite element analysis (FEA) approach, which revealed that a larger radius fillet leads to a notable reduction in maximum stress levels.

From a theoretical perspective, the influence of radius fillet on stress distribution was elaborated by Peterson (2000), who developed a series of charts and empirical equations for calculating the stress concentration factor (K_t) based on geometric parameters. In his model, an increase in the ratio of r/d (radius fillet to the smaller shaft diameter) has been shown to effectively lower the K_t value, thereby enabling more accurate and scientifically grounded design optimization. The following references served as the primary sources supporting the discussion and analysis in this study:

- a. Afif, Mokh. Makhrus (2020) Simulasi Pembebanan Gaya Berat Pada Shaft Crusher Machine di Pabrik PT. XXX dengan Metode Elemen Hingga. Undergraduate thesis, Universitas Muhammadiyah Surabaya. Universitas Muhammadiyah Surabaya.
- b. Baruqi, M. S., Sholihah, S. Z., Sugiharto, A., Martonio, B. C., Sulthoni, A., Supriyanto, D & Suryaningrum, W. (2009). Pengukuran Tensile Strength, Compressive Strength Dan Modulus Elastisitas Benda Padat. Universitas Airlangga. Surabaya.
- c. Chandra, H (2021). Investigasi Tegangan Pada Poros Bertingkat Menggunakan Metode Elemen Hingga Berbasis Computer Aided Engineering.
- d. D S Hoddinott (2004) Railway axle failure investigations and fatigue crack growth monitoring of an axle. HM Railway Inspectorate, Health and Safety Executive, Rose Court, 2 Southwark Bridge, London SE1 9HS, UK.
- e. Fadillah, R., Zakki, A. F., & Kiryanto, K. (2020). Analisa Fatigue Pada Kapal Tanker 6500 DWT Berdasarkan Common Structural Rules (CSR) berbasis Finite Element Analysis (FEA). Jurnal Teknik Perkapalan, 8(4), 588-599.
- f. Jead, Raymond Philander dan Andoko Andoko (2021) Failure analysis of railway freight car axle with finite method element. Mechanical Engineering Department, State University of Malang Semarang 5, Malang 65145, Indonesia.

3. METHOD

Modeling is the process of constructing an object using computational design systems. The overall modeling process includes part creation, assembly modeling, and the generation of two-dimensional engineering drawings (2D projections). In this study, the three-dimensional (3D) modeling stage was carried out based on the geometric reference of the transmission shaft under investigation.

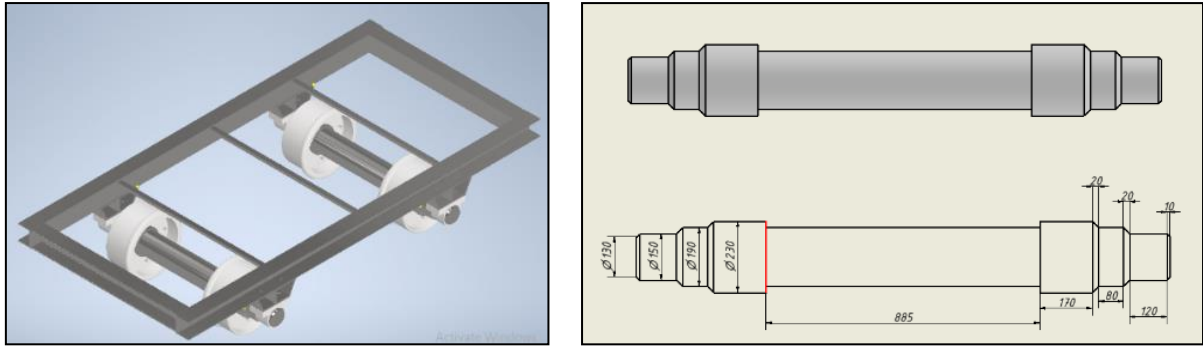


Fig. 1. Transfer carriage mechanism concept and dimention.

Berikut adalah data mechanical properties AISI 1040 yang digunakan penulis sebagai objek penelitian yang dilampirkan pada tabel berikut:

Table 1. Mechanical properties AISI 1040

Mechanical Properties	Symbol	Value
Young's modulus (GPa)	E	190-210
Poisson's ratio	ν	0,26
Density (kg/m ³)	P	7,860
Yield strength (MPa)	Sy	205-245
Tensile strength	St	400-510
Elongation		27-30
Hardness surface (HB)	Hb	160

Sumber: Mill certificate SeAH Besteel Corp

The schematic diagram of the simulation process for analyzing the implementation of radius fillet on the drive shaft is presented in the following figure:

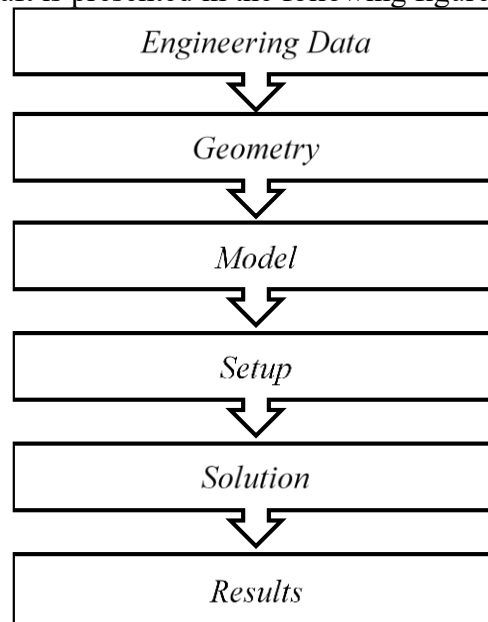


Fig. 2. FEA schematics for simulation.

The meshing process involves dividing the simulated component into smaller discrete regions, with the objective of obtaining a more detailed assessment of potential defects in each section. In this study, the model consists of 127,054 nodes and 75,160 elements, configured using a hexahedral element setup.

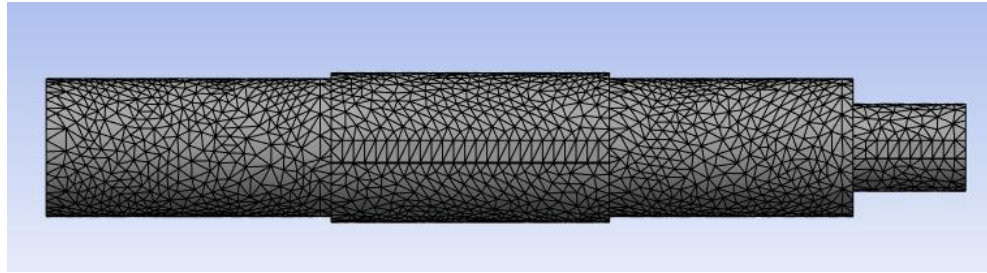


Fig. 3. Meshing setup in transfer carriage shaft.

According to Purnama Harry (2016), meshing is an integral process within finite element method (FEM) simulations. It significantly affects the accuracy, convergence, and computational efficiency in generating the solution representation of the finite element model.

A boundary condition refers to a set of constraints or requirements applied at the limits of a system (such as a structure, mechanical system, or differential equation) that define how the system interacts with its surrounding environment. In this context, boundary conditions describe how a structure responds to external forces or loading, which may result in deformation or displacement from its original position.

To ensure that a structural analysis problem can be solved, each location along the structural boundaries must have a defined boundary condition, either in terms of a known force or a known displacement. These specified forces or displacements may have a particular magnitude or be equal to zero. For instance, a section of the structure with no external load corresponds to a zero-force boundary condition, while a zero-displacement boundary condition indicates that the structure is fully constrained at that point.

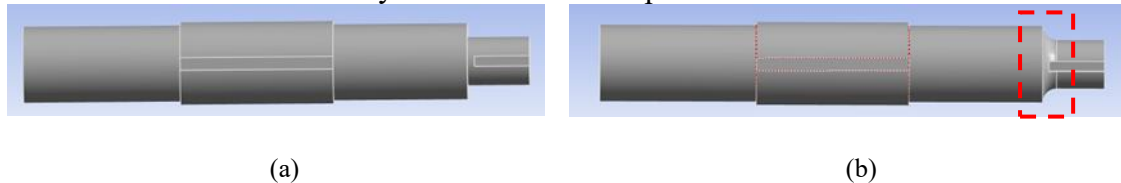


Fig. 4. Design Transfer Carriage shaft (a) without radius fillet, (b) with radius fillet.

4. RESULT & DISCUSSION

4.1 Total Deformation

The simulation aims to compare the behavior of the transfer carriage shaft under twelve variations of radius fillet. The simulation results provide insights into total deformation, equivalent elastic strain, and equivalent stress. These findings contribute to determining the optimal radius fillet to be implemented on the transfer carriage shaft.

Total deformation illustrates how the shaft changes shape when subjected to loading. The applied load affects the material and helps identify areas experiencing excessive stress concentration. Based on the simulation results presented in Figure 5, the highest total deformation occurs in the transfer carriage shaft with a 1 mm radius fillet, reaching a maximum deformation of 5.9514 mm under the applied load. Conversely, the lowest deformation is observed in the shaft with an 11 mm radius fillet, with a value of 5.8498 mm.

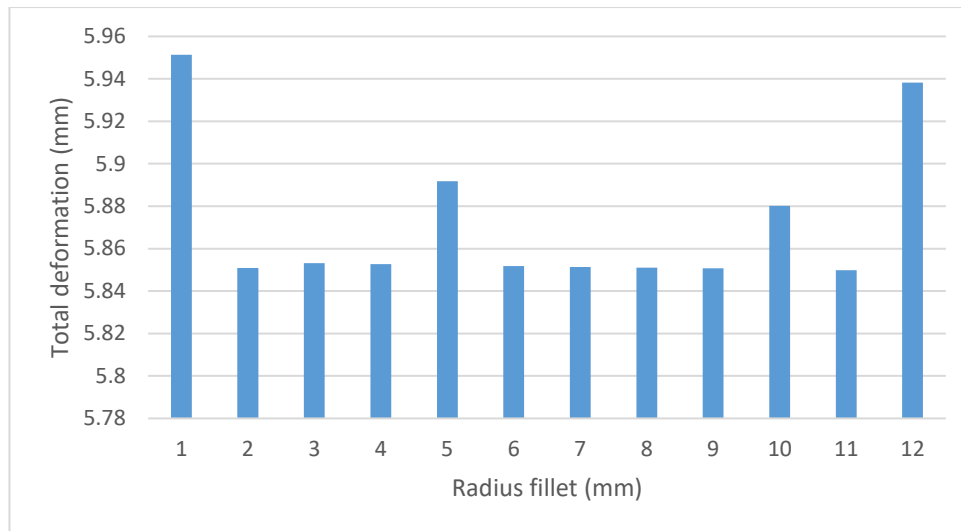


Fig. 5. Radius fillet effect to total deformation.

Figure 6 presents an illustration of the total deformation parameters under peak loading conditions. It can be observed that the deformation distribution exhibits both maximum and minimum zones as a result of the applied load.

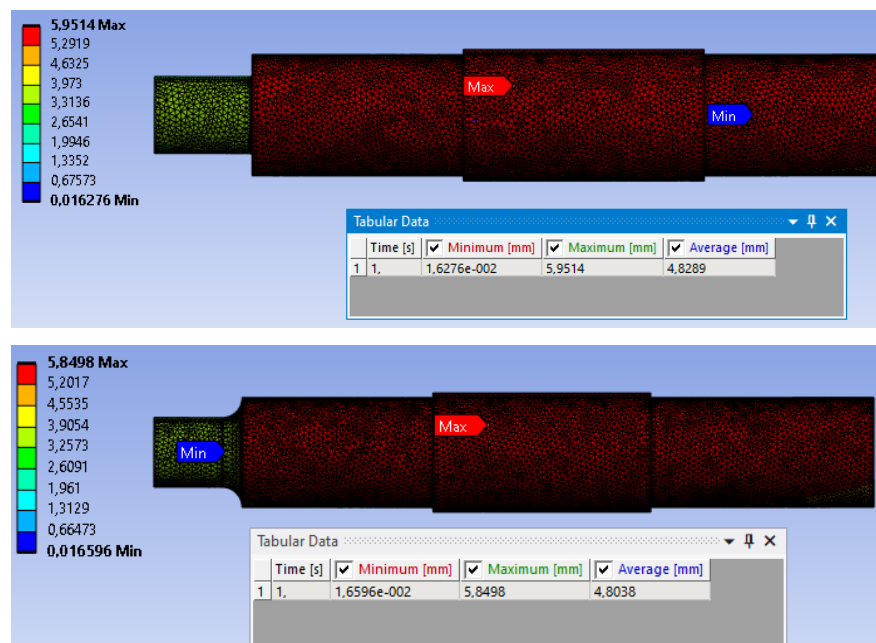


Fig. 6. Total Deformation effect radius fillet 1 mm and radius fillet 11 mm.

4.2 Fatigue Cycles

Fatigue life represents the total number of loading cycles a material or component can endure before fatigue failure occurs. In the context of the transfer carriage shaft, fatigue life indicates how long the shaft can perform its operational duties under cyclic loading conditions without experiencing structural damage or crack initiation. This analysis is essential in predicting the shaft's durability and reliability over its service period, particularly in applications involving repetitive stresses. The simulation results of fatigue life, as shown in the figure below, demonstrate the variation in lifespan corresponding to different radius fillet configurations. Shafts with a larger radius fillet tend to exhibit higher fatigue life values due to the reduction of stress concentration in the transition areas. Conversely, smaller fillet radii

produce higher localized stresses, which accelerate fatigue crack initiation and propagation, thereby shortening the component's life expectancy.

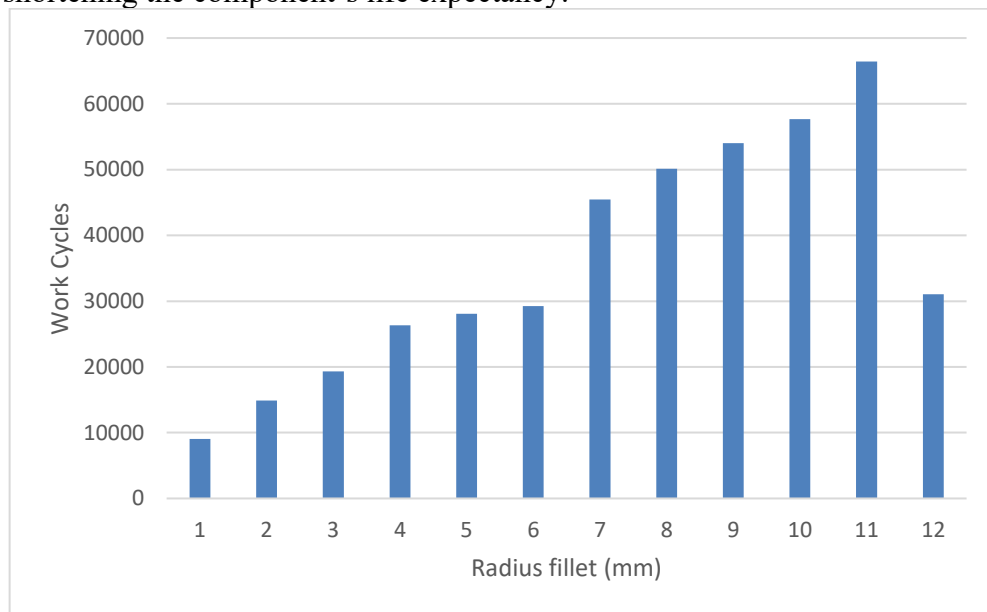


Fig. 6. Fatigue Life dari poros transmisi AISI 1040.

From the fatigue life diagram shown in Figure 6, it can be observed that the shaft with the lowest fatigue life corresponds to the 1 mm radius fillet, yielding a value of 9,066 cycles. In contrast, the highest fatigue life is obtained in the transfer carriage shaft with an 11 mm radius fillet, reaching 66,425 cycles. This significant difference indicates that increasing the radius fillet effectively enhances the component's resistance to cyclic loading by reducing stress concentration at the transition area, thereby extending the overall service life of the shaft.

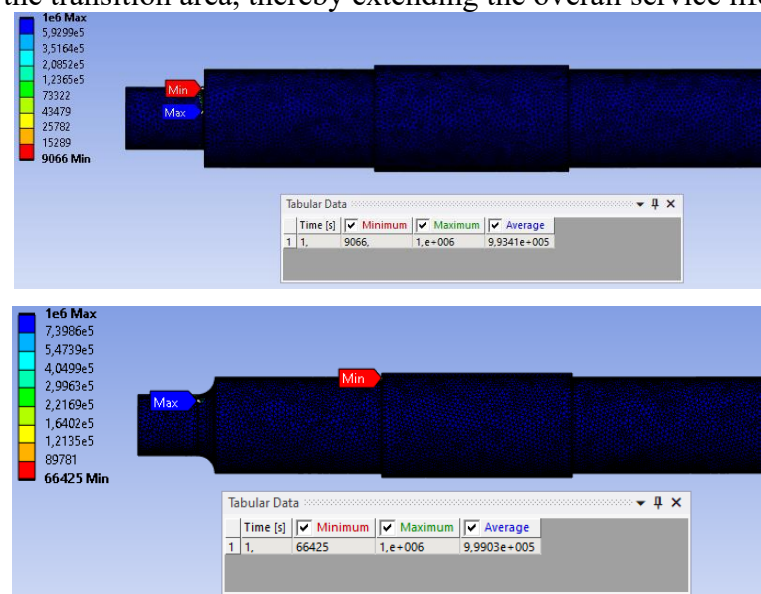


Fig. 7. Compared fatigue Life effect radius fillet 1 mm and radius fillet 11 mm shaft AISI 1040.

Understanding these relationships helps in selecting the optimal radius fillet that minimizes stress concentration while maintaining structural integrity. Consequently, the fatigue life analysis serves as a critical reference for improving design efficiency and ensuring the long-term performance of the transfer carriage shaft under operational loads.

4.3 Safety Factor

The safety factor is a critical parameter in mechanical design, as it ensures that a structure or component can sustain a specified load without undergoing failure or permanent deformation. An adequate safety factor indicates that the structure operates within acceptable safety margins and remains below the material's ultimate strength. In general, a structural design is considered safe when the safety factor value exceeds one, meaning that the applied load is lower than the component's maximum load capacity.

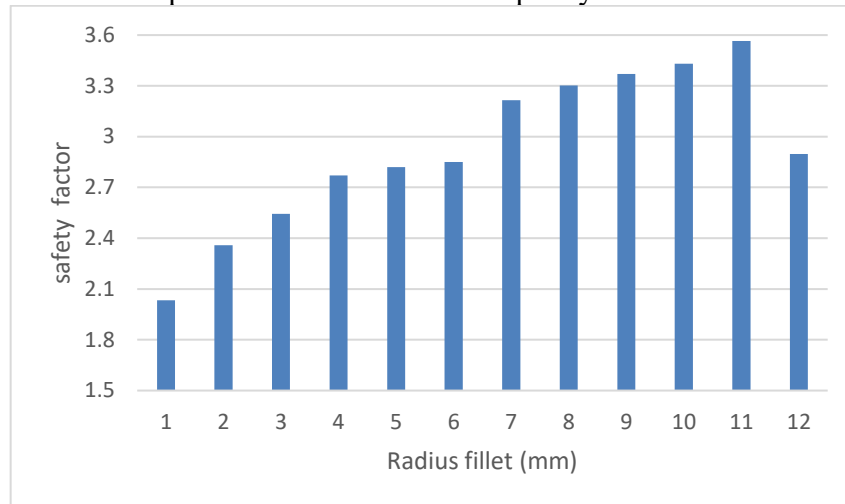


Fig. 6. Safety factor radius fillet AISI 1040.

From the results shown in the graph, it can be observed that the highest safety factor value is achieved by the transfer carriage shaft with an 11 mm radius fillet, recording a value of 3.5649. Conversely, the lowest safety factor value is found in the shaft with a 1 mm radius fillet, yielding 2.0337. This variation clearly demonstrates the influence of fillet geometry on structural performance under load. A larger radius fillet helps to distribute stress more evenly across the transition area, thereby reducing localized stress concentrations that typically act as initiation sites for failure.

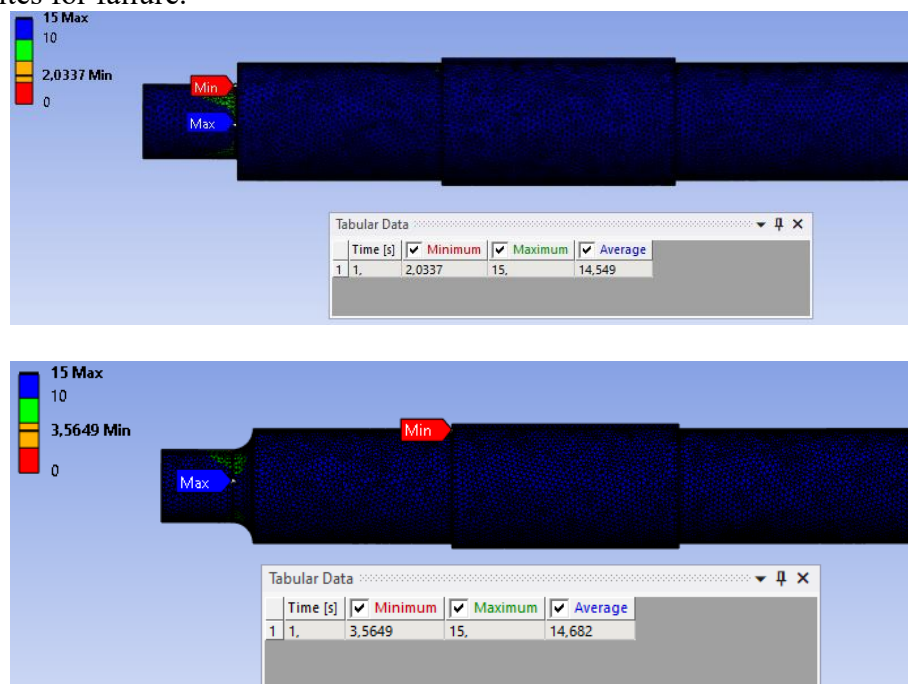


Fig. 8. Compared safety factor effect radius fillet 1 mm and radius fillet 11 mm shaft AISI 1040.

The increase in the safety factor with a larger radius fillet implies improved resistance to both static and cyclic loading conditions. Consequently, the application of a larger radius fillet not only enhances the shaft's mechanical reliability but also contributes to longer service life and improved operational safety. These findings underline the importance of optimizing geometric parameters in shaft design to achieve a balance between material efficiency and structural integrity.

5. CONCLUSION

The following are the conclusions that can be obtained from Implementation of Radius Fillet on AISI 1040 Transmission Shafts for Fatigue Behavior:

- a. The introduction of a fillet radius in the stepped region of the AISI 1040 transmission shaft effectively reduces stress concentration, resulting in improved deformation resistance and structural integrity under combined torsional and bending loads.
- b. Simulation results indicate that the 11 mm fillet radius configuration decreases total deformation by 1.8% and enhances the safety factor by 74% compared to the 1 mm fillet radius design.
- c. Fatigue life analysis shows a substantial improvement in durability, where the shaft with an 11 mm fillet radius can withstand up to 66,425 loading cycles, compared to only 9,066 cycles in the design without a fillet. This confirms that fillet optimization plays a crucial role in extending component lifespan and preventing premature mechanical failure.

6. REFERENCES

Books

- Suresh, S. (1998). *Fatigue of materials*. Cambridge university press.
- Kiyokatsu Suga. Sularso (1999) *Elemen Mesin*
- Hidayat, W. (2019). *Klasifikasi dan Sifat Material Teknik Serta Pengujian Material*.
- Nasmi Herlina Sari(2018) *Material Teknik*
- Jeffrey Erockho (2020) *Mechanics of Time-Dependent Materials*.

Journal Articles

- Alfif, Mokh. Makhrus (2020) *Simulasi Pembebanan Gaya Berat Pada Shaft Crusher Machine di Pabrik PT. XXX dengan Metode Elemen Hingga*. Undergraduate thesis, Universitas Muhammadiyah Surabaya. Universitas Muhammadiyah Surabaya. Universitas Muhammadiyah Surabaya.
- Alhaffis, F., & Fajrul, R. Pengaruh Konfigurasi Orientasi Serat 0⁰ dan 45⁰ Karbon/Epoksi (Woven) terhadap Karakterisasi Mekanik Drive Shaft. *Jurnal Elementer*, 7(2), 457162.
- Baruqi, M. S., Sholihah, S. Z., Sugiharto, A., Martonio, B. C., Sulthoni, A., Supriyanto, D., ... & Suryaningrum, W. (2009). *Pengukuran Tensile Strength, Compressive Strength Dan Modulus Elastisitas Benda Padat*. Universitas Airlangga. Surabaya.
- Chandra, H (2021). *INVESTIGASI TEGANGAN PADA POROS BERTINGKAT MENGGUNAKAN METODE ELEMEN HINGGA BERBASIS COMPUTER AIDED ENGINEERING*. Austenit
- D S Hoddinott (2004) *Railway axle failure investigations and fatigue crack growth monitoring of an axle*. HM Railway Inspectorate, Health and Safety Executive, Rose Court, 2 Southwark Bridge, London SE1 9HS, UK.

- Fadillah, R., Zakki, A. F., & Kiryanto, K. (2020). Analisa Fatigue Pada Kapal Tanker 6500 DWT Berdasarkan Common Structural Rules (CSR) berbasis Finite Element Analysis (FEA). *Jurnal Teknik Perkapalan*, 8(4), 588-599.
- Hidayat, W. (2019). Klasifikasi dan Sifat Material Teknik Serta Pengujian Material.
- Jead, Raymond Philander dan Andoko Andoko (2021) Failure analysis of railway freight car axle with finite method element. Mechanical Engineering Department, State University of Malang Semarang 5, Malang 65145, Indonesia.
- Rasyid, A. A., & Alhaffis, F. (2024). Implementasi Radius Fillet Pada Poros Penggerak Transfer Carriage. *Ranah Research: Journal of Multidisciplinary Research and Development*, 6(4), 493-497.