Stress and Deflection Analysis of Locomotive Structural Design: A Case Study on the Shaft of Locomotive CC 203

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Abstract

The increasing demand for railway transportation requires locomotive components to meet high safety and performance standards. One critical component is the shaft, which transmits power from the engine to the wheels and supports the locomotive's total load. This study analyzes the stress and deflection of the CC 203 locomotive shaft using empirical calculations. The shaft, made of ST52 steel with a ready load of 84 tons and dimensions of 2000 mm in length and 150 mm in diameter, was evaluated based on allowable limits. The results show a maximum stress of 112.27 MPa and a maximum deflection of 4.3 mm, both within the allowable limits of 260 MPa and 5 mm, respectively. These findings indicate that the shaft design meets structural safety and operational reliability requirements. Regular inspections are recommended to maintain optimal performance and prevent material degradation over time.

Keywords: Deflection, locomotive shaft, stress analysis, structural safety.

1. Introduction

The structural integrity of locomotive components plays a vital role in ensuring operational reliability and safety. The wheel shaft, a critical element in railway systems, must endure substantial mechanical stresses during service. Failure in shaft design or material selection can result in severe disruptions, leading to derailments or operational hazard that pose significant risks to transportation safety (Harshit Singh, Shivakant Yadav, Vicky Kumar Prabhakar, Ravi Jaiswal & Upadhyay, 2014). Therefore, material selection and structural analysis of the shaft are essential to ensure durability and mechanical efficiency.

The CC 203 locomotive is one of the widely used diesel-electric locomotives in Indonesia. Studies on its propulsion system indicate that wear, dynamic loads, and power fluctuations can affect operational efficiency(Hidayat & Sukmawan, 2020). However, specific studies focusing on the stress and deflection analysis of the CC 203 locomotive shaft are still limited.

ST52 steel is a low-carbon steel with manganese content, known for its high impact resistance and tensile strength. These properties make ST52 suitable for structural components such as shafts, which require a combination of strength and toughness. However, despite its excellent mechanical properties, this material must be thoroughly analyzed to ensure that the design complies with established safety standards (Nafidz et al., 2024).

Stress and deflection analysis can be conducted using empirical or numerical methods. In this study, an empirical approach is used to calculate critical parameters such as maximum stress and maximum deflection and compare them with the allowable stress and deflection values based on ST52 material specifications. The results of this study are expected to contribute to the design and maintenance of the CC 203 locomotive shaft. By understanding material limitations and the structural response of the shaft to operational loads, preventive measures can be taken to avoid component failures and ensure safer and more efficient railway operations.

2. Material and methods

2.1. Flowchart Diagram

Figure 1 below presents the research flowchart, outlining the process from the initial stages to data processing. It offers a structured summary of the methodology applied in this study.

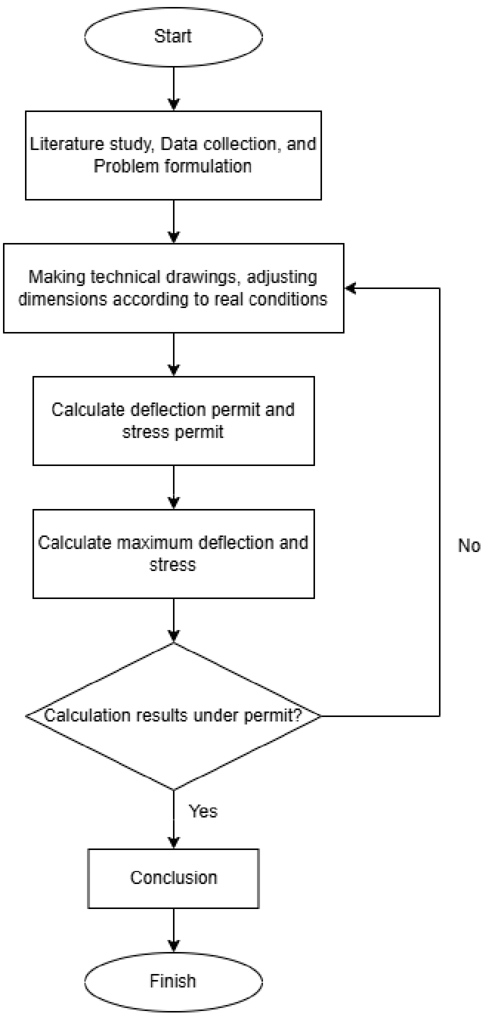

Figure 1. Flowchart Research

This flowchart illustrates the stress and deflection analysis of the CC 203 locomotive shaft, starting from literature review, data collection, technical drawing preparation, and calculation of permissible limits as well as maximum stress and deflection. If the calculation results are within the permissible limits, the data is processed for conclusions; otherwise, dimensional revisions are made. The shaft is made of ST52 steel with a load of 84 tons and is analyzed empirically using material mechanics for stress and the beam principle for deflection, ensuring the design meets safety and performance standards.

2.2. Design

This research is only based on secondary data obtained from literature studies by looking for theoretical references that are relevant to the problem or solution of the research being conducted. The materials used in this study primarily focus on the locomotive CC 203 shaft (Figure 2), which is constructed from high-strength carbon steel, specifically ST52. ST52 is a structural steel with low carbon content recognized for its remarkable strength, ease of welding, and suitability for machining, which makes it suitable for demanding engineering tasks. The usual chemical makeup consists of about 0,20 to 0,22% carbon and manganese levels reaching 1,6% (Table 1), leading to a high yield strength of about 355 MPa and tensile strength that varies from 470 to 630 MPa, depending on the thickness and processing conditions. ST52 is especially beneficial because of its capacity to handle both dynamic and static forces while in use (Okuroğullari et al., 2022). The material's strong resistance to impact guarantees that it can take on the pressures linked with the locomotive's motion and the heaviness of the loads it transports. Furthermore, ST52's outstanding capacity for welding makes it simple to create and put together parts, which is vital in producing locomotive shafts where accuracy and reliability are paramount.

Figure 2. Locomotive Shaft 3D Drawing

The figure 2 above is a 3D model of the CC 203 locomotive wheel shaft made of ST52 material with dimensions of 2000 mm in length and 150 mm in diameter.

Table 1. ST52 Chemical Composition

Standard	Grade	C	Si	Mn	P max	S max
DIN2391	ST52	≤0,22	≤0,55	≤1,6	0,025	0,025

Based on the data above, we could know the chemical composition of ST52 carbon steel.

Table 2 below presents the main dimensional specifications of the CC 203 locomotive, including wheelbase and overall body height. This information supports the structural context of the shaft analysis.

Table 2. CC 203 Locomotive Specification

Locomotive Dimensions	
1. Gauge	1067 mm
2. Body length	14135 mm
3. Body width	2642 mm
4. Maximum height	3637 mm
6. Wheelbase	3505 mm
7. Distance between connecting devices	15214 mm
8. Distance between pivots	7680 mm
9. Diameter of driver wheel	914 mm

Weight	
1. Empty weight	78 Ton
2. Ready weight	84 Ton
Motor Diesel	
1. Type	GE 7FDL8
2. Type	4 strokes, *turbocharger*
3. Machine power	2150 HP

4. Power generator	2000 HP

Table 3 below shows the dimensions and number of shafts analyzed in this study, which are critical for performing the stress and deflection calculations accurately.

Table 3. Shaft Dimension

Shaft Dimensions	
1. Length (L)	2000 mm
2. Diameter (D)	150 mm
3. Radius (R)	75 mm
3. Number of shafts on the locomotive	6 pieces
4. Shaft material	ST52

Based on the total load of 84 tons and the number of shafts on the locomotive 6 shafts so that the wheels are 12, the point load value on one wheel is 7 tons or 7000 kg.

2.3. Stress and Deflection Calculations

Before proceeding with the calculations, it is important to note that ST52 steel has an ultimate tensile strength of 520 MPa. In calculating the allowable stress, a safety factor of 2 is applied, resulting in an allowable stress of 260 MPa. This value is derived based on standard mechanical component design references (Shigley, J.E., Mischke, C.R., Budynas, 2011).

The following are the empirical calculations used to determine the maximum stress and maximum deflection on the shaft:

Stress

$$\sigma \max = \frac{M\,max}{W} \quad (1)$$

Where:
- σ max = Max bending stress (MPa)
- M max = Max bending moment (N/mm^2)
- W = Cross-sectional modulus (mm^3)
- w = Distributed load (kg)

Inertia Cross-sectional Calculation

$$\text{Inertia} = \frac{1}{64} \times \pi \times D^4 = 24837890{,}63\ mm^4 \quad (2)$$

Max. Stress Calculation

- Modulus

$$W = \frac{I}{R} = \frac{24837890{,}63\ mm^4}{75\ mm} = 331171{,}875\ mm^3 \quad (3)$$

- Moment

$$M\,max = \frac{P\,x\,L}{4} + \frac{w\,x\,L^2}{8} = \frac{7000\,kg\,x\,2000\,mm}{4} + \frac{0{,}58\,kg\,x\,(2000\,mm)^2}{8} = 3790000\ Kg/mm^2 \quad (4)$$

- Maximum Stress

$$\sigma \max = \frac{M\,max}{W} \quad (5)$$

$= \frac{379000\ kg/mm^2}{331171{,}875\ mm}$
= 11,45 Kg/mm × 9,81
= 112,27 MPa

Stress Allowance Calculation

$$\sigma \text{ allowance} = \frac{St}{Fs} \quad (6)$$

$= \frac{520}{2}$
= 260 MPa

So, the shaft stress still meets the clearance allowance.

- Deflection Calculation

$$\delta \max = \frac{P \times D^3}{48 \times E \times I} + \frac{5 \times w \times L^4}{384 \times E \times I} \quad (7)$$

Where:
- P = Total load (Kg or N)
- D = Shaft diameter (mm)
- L = Length of beam (mm)
- E = Material elasticity modulus (MPa)
- I = Moment of inertia of the beam (mm^4)
- w = Uniform load (Kg/mm)

$$\delta \max = \frac{7000\ kg \times (150\ mm)^3}{48 \times 210000\ MPa \times 24837890.63\ mm^4} + \frac{5 \times 0{,}58\ kg \times (2000\ mm)^4}{384 \times 210000\ MPa \times 24837890.63\ mm^4}$$

= 4,3 mm

Deflection Calculation Allowance

$$\delta \text{ allowance} = \frac{L}{K}$$

$= \frac{2000\ mm}{400}$
= 5 mm

So, the shaft deflection still meets the clearance allowance.

The stress and deflection calculations for the CC 203 locomotive shaft ensure that the structure meets safety and performance standards. The maximum bending stress is calculated using the bending moment and cross-sectional modulus, resulting in a value of 112,27 MPa. This is significantly below the allowable stress limits of 260 MPa, confirming that the shaft can withstand the applied loads without risk of failure. Similarly, the deflection analysis, which considers factors such as load, shaft diameter, beam length, material elasticity modulus, and moment of inertia, results in maximum deflection of 4,3 mm. This value is well within the allowable deflection limits of 5 mm, ensuring structural stability under operational conditions. Overall, these calculations demonstrate that the shaft design is safe, reliable, and capable of handling the required loads effectively.

3. Results and discussion

Table 6. Stress and Deflection

	Deflection (mm)	**Stress (MPa)**
Maximum Value	4,3	112,27
Allowable	5	260

Based on the empirical calculations of the CC 203 locomotive shaft using ST52 material, with a total operational load of 84 tons, the maximum deflection obtained is 4,3 mm and the maximum stress is 112,27 MPa. These values are compared to the established allowable limits—5mm for deflection and 260 MPa for stress. The comparison indicates that both stress and deflection remain within safe boundaries, confirming that the shaft design complies with structural safety standards and operational performance requirements. From a structural analysis perspective, the deflection value, which is lower than the allowable limit, demonstrates that the shaft maintains sufficient stiffness to withstand the load without excessive deformation. Similarly, the stress value, which is significantly below the allowable stress, indicates that ST52 material provides a high safety factor in this application. These findings are consistent with the study conducted by Armah, which used a design approach based on ASME B106.1M:1985 for power transmission shafts, where design safety is determined through a combination of static and fatigue stress analysis. Armah emphasized the importance of ensuring that stress caused by cyclic loading does not exceed the material's endurance limit or yield strength, with a minimum safety factor of 1,5 (Armah, 2018). A similar conclusion was also drawn by Asmara et al., who analyzed the structural behavior of a single girder overhead crane using ST52-3 steel. In their study, the maximum stress obtained for the redesigned girder using ST52-3 was 72,30 MPa, and the maximum deflection was 13,42 mm, both determined using finite element analysis. These values remained within the allowable limits of 177,5 MPa for stress and 23,33 mm for deflection. The structural redesign also reduced the overall girder weight from 3,18 tons to 2,55 tons and decreased the required motor power by approximately 1 kW (Asmara et al., 2020). Therefore, based on the analysis and comparison with previous studies, it can be concluded that the design of the CC 203 locomotive shaft using ST52 material satisfies the strength and stiffness criteria, both in terms of static loading and potential resistance to repeated (fatigue) loading, and aligns with structural performance expectations demonstrated in other applications.

4. Conclusion

Based on the empirical calculations of the CC 203 locomotive shaft using ST52 material, the maximum stress of 112,27 MPa and maximum deflection of 4,3 mm remain within the allowable limits of 260 MPa and 5 mm. This indicates that the shaft design, with dimensions of 2000 mm x 150 mm, meets safety and operational performance standards. Additionally, the shaft's stiffness and strength are sufficient to withstand the ready load of 84 tons without excessive deformation. Therefore, this shaft design can be reliably used in locomotive operations, while regular inspections should be conducted to ensure optimal material conditions throughout its service life.

Credit authorship contribution statement

Basith Baihaqi Amyanfama: Conceptualization, Writing – review & editing. **Ghagarin Diza Syahraihan**: Conceptualization, Writing – review & editing. **I Putu Sindhu Asmara**: Conceptualization, Supervision, Writing – review & editing. **Iklil Huril 'Ain**: Conceptualization, Writing – review & editing. **Indri Ika Widyastuti**: Conceptualization, Supervision, Writing – review & editing. **Safril Norman Ardiansyah**: Conceptualization, Writing – review & editing. **Salsabila Intan Nur Rizqi**: Conceptualization, Writing – review & editing

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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