Structural, Vibration and Damping Analysis of Railway Axle Using Different Materials

A N S. Surya Prakash[1], M. Shanmukh Kumar[2], D. Ujwal Vinayak[3],
Mutchu Sanjeev[4], P. Pavan Kumar[5], S. Jeevan Kumar[6]
[1]Assistant Professor, Avanthi Institute of Engineering &Technology
[2,3,4,5,6]Student, Avanthi Institute of Engineering &Technology

***Abstract*—This study analyzes a railway axle to evaluate its structural strength, vibration characteristics, and damping behavior. A 3D model was developed using CATIA, and Finite Element Analysis was performed in ANSYS to determine stress, deformation, and natural frequency. The results were validated using MATLAB through theoretical calculations. Damping analysis was carried out using impulse loading and the logarithmic decrement method. Seven materials 20MnCrTi Steel, CPM M4, AISI D2, AISI 4340, Brass, SS 303, and Structural Steel were analyzed and compared. Among these, AISI D2 steel showed superior performance with high stiffness and effective damping. The study concludes that AISI D2 is the most suitable material for railway axle applications.**

***Index Terms*—ANSYS, CATIA, Damping ratio, Finite Element Analysis (FEA), Material selection, Modal analysis, Railway axle, Vibration analysis.**

I. INTRODUCTION

The train axle is a critical component in railway vehicles, acting as the structural member that connects the wheels and supports the entire load of the train. It ensures proper load distribution and smooth movement of the vehicle along the track. During operation, the axle is subjected to various types of loads such as static loads due to weight and dynamic loads caused by braking, acceleration, and track irregularities. These loading conditions generate stresses, vibrations, and fatigue in the axle, which may affect its performance and safety.

Due to continuous cyclic loading, the axle is prone to fatigue failure, deformation, and excessive vibration. Failure of an axle can lead to serious consequences such as derailment and loss of safety. Therefore, it is necessary to analyze the structural strength, vibration characteristics, and damping behavior of the axle to ensure reliable performance and long service life.

Material selection plays an important role in determining the performance of the axle. The material must possess high strength, stiffness, and good damping capacity to withstand loads and reduce vibrations. In addition, the natural frequency of the axle should be carefully evaluated to avoid resonance conditions, which can increase vibration amplitude and cause damage. With the advancement of engineering tools, Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) techniques are widely used for analysis. CATIA is used to develop the 3D model of the axle, while ANSYS is used to perform structural and modal analysis. MATLAB is used for validation and damping analysis using numerical methods.

In this study, a railway axle is analyzed using seven different materials 20MnCrTi Steel, CPM M4, AISI D2, AISI 4340, Brass, SS 303, and Structural Steel. The objective is to compare their structural strength, vibration behavior, and damping characteristics to identify the most suitable material for railway axle applications.

Fig 1.1: Train Axle

II. LITERATURE REVIEW

Several researchers have studied the structural, vibration, and damping behavior of railway axles using analytical and simulation methods.

Samip Nikulbhai Shah (2018) compared conventional steel and composite materials for railway axles using Finite Element Analysis (FEA) in ANSYS. The study concluded that composite materials reduce stress and improve safety factors, highlighting the importance of material selection.

Antía López Galdo et al. (2022) developed a vibration-based fault detection system using convolutional neural networks (CNN). The results showed that vibration signals can effectively identify defects in train components and improve maintenance strategies.

S. W. Rienstra et al. (2020) analyzed the effect of train speed on axle-box failures. The study revealed that higher speeds can lead to resonance conditions, increasing the risk of cracks and structural damage.

Madhusudhan Raju et al. (2019) performed structural analysis of a train axle with disc brakes using ANSYS. The results identified critical stress regions and emphasized the importance of proper load analysis.

Y. L. Dong et al. (2020) investigated the influence of stiffness and damping on vibration control. The study concluded that proper damping improves ride quality and reduces vibration effects.

Rolek et al. (2025) conducted experimental modal analysis to detect axle damage using changes in natural frequency and damping ratio. The study highlighted the importance of modal parameters in identifying defects.

J. K. Singh and R. C. Gupta (2022) analyzed fatigue behavior of railway axles under cyclic loading conditions. The results showed that fatigue is a major factor affecting axle life and reliability.

Li et al. (2023) studied the effect of heat treatment on damping properties of materials. The study concluded that material processing significantly affects vibration and damping characteristics.

III. METHODOLOGY

The methodology adopted in this study includes CAD modeling, material selection, finite element analysis, and MATLAB-based validation to analyze the structural, vibration, and damping behavior of a railway axle.

Initially, the dimensions of the railway axle and wheel assembly are defined based on standard design specifications. These dimensions are used to create an accurate model for further analysis, as shown in Fig 3.1.

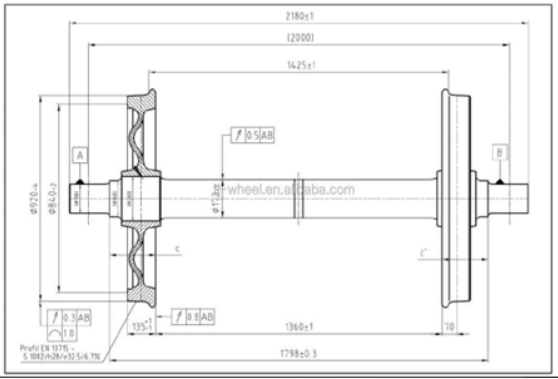


Fig 3.1: Detailed dimensions of axle and wheels

A 3D model of the railway axle is developed using CATIA software. The model is created by sketching the profile and revolving it using the shaft command to obtain a solid geometry. The developed model is shown in Fig 3.2.

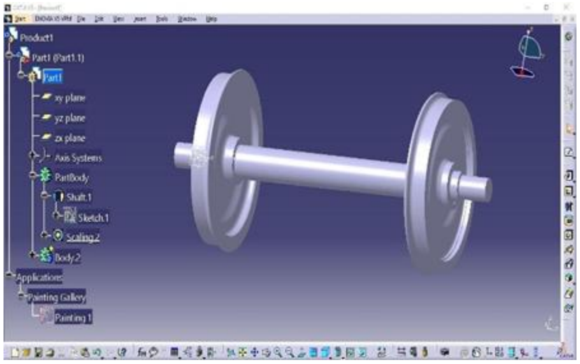
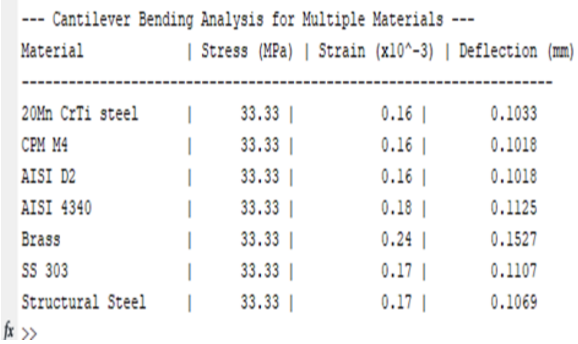


Fig 3.2: 3D model of axle and wheel

Seven different materials 20MnCrTi Steel, CPM M4, AISI D2, AISI 4340, Brass, SS 303, and Structural Steel are selected for analysis based on their mechanical properties such as strength, stiffness, and damping capacity. The developed CAD model is imported into ANSYS Workbench for finite element analysis. Initially, the model is meshed to discretize it into finite elements for accurate analysis. Appropriate boundary conditions and loads are applied to simulate real operating conditions of the railway axle. Structural analysis is carried out to evaluate parameters such as total deformation, equivalent (von

Mises) stress, and strain. Modal analysis is performed to determine the natural frequencies and vibration characteristics of the axle. MATLAB is used to analyze the dynamic response of the axle under impulse loading conditions. The displacement-time response is obtained to study vibration behavior and damping characteristics. The damping ratio is calculated using the logarithmic decrement method. The output results obtained from MATLAB are shown in Fig 3.5 and are used to validate the ANSYS results.



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--- Cantilever Bending Analysis for Multiple Materials ---
Material           | Stress (MPa) | Strain (x10^-3) | Deflection (mm)
-----------------------------------------------------------------
20Mn CrTi steel    |      33.33 |           0.16 |        0.1033
CPM M4             |      33.33 |           0.16 |        0.1018
AISI D2            |      33.33 |           0.16 |        0.1018
AISI 4340          |      33.33 |           0.18 |        0.1125
Brass              |      33.33 |           0.24 |        0.1527
SS 303             |      33.33 |           0.17 |        0.1107
Structural Steel   |      33.33 |           0.17 |        0.1069
fx >>
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Fig 3.3: MATLAB output results

IV. FINITE ELEMENT ANALYSIS

Finite Element Analysis (FEA) is carried out using ANSYS Workbench to evaluate the structural and dynamic behavior of the railway axle. The 3D CAD model developed in CATIA is imported into ANSYS for simulation. Initially, the geometry is discretized into smaller elements using meshing techniques to improve the accuracy of the analysis. The finite element model of the axle is shown in Fig 4.1.

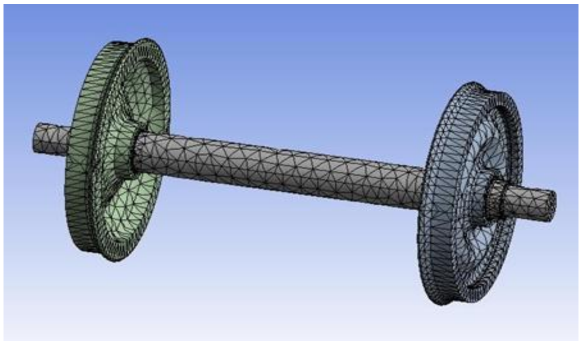


Fig 4.1: Finite element model of axle

Appropriate boundary conditions and loads are applied to simulate real operating conditions of the railway axle. Fixed supports and external loads are assigned at suitable locations, as shown in Fig 4.2.

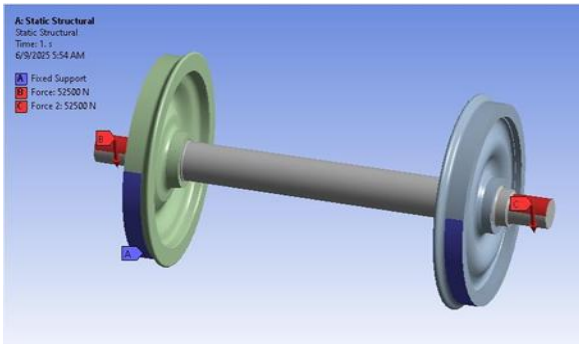
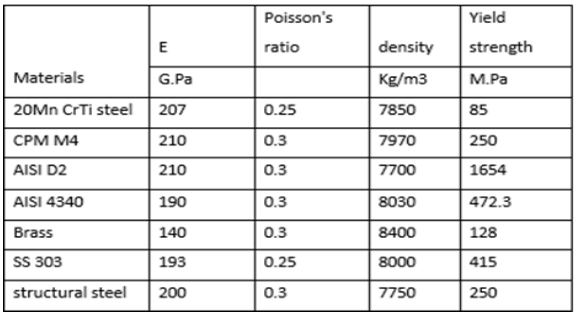


Fig 4.2: Boundary conditions of axle

The material properties play an important role in determining the structural and dynamic behavior of the railway axle. In this study, seven different materials are selected based on their mechanical properties such as Young’s modulus, density, and Poisson’s ratio. These properties are defined in ANSYS Workbench to perform accurate finite element analysis. The mechanical properties of all selected materials used in this study are listed in Table 4.1.



Materials	E G.Pa	Poisson's ratio	density Kg/m3	Yield strength M.Pa
20Mn CrTi steel	207	0.25	7850	85
CPM M4	210	0.3	7970	250
AISI D2	210	0.3	7700	1654
AISI 4340	190	0.3	8030	472.3
Brass	140	0.3	8400	128
SS 303	193	0.25	8000	415
structural steel	200	0.3	7750	250

Table 4.1: Mechanical properties of materials

Structural analysis is performed to evaluate parameters such as total deformation, equivalent (von Mises) stress, and strain developed in the axle under applied loading conditions. The deformation of the axle is shown in Fig 4.3.

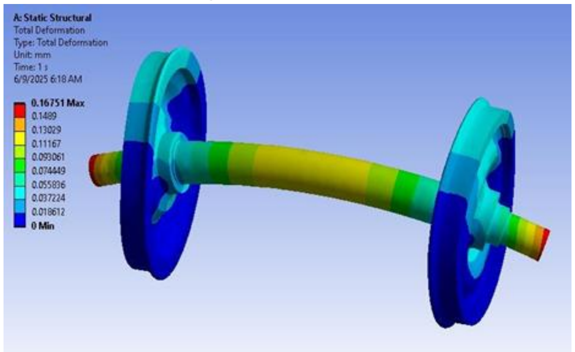


Fig 4.3: Deformation of axle

The stress distribution is analyzed to identify critical regions where maximum stress occurs, as shown in Fig 4.4.

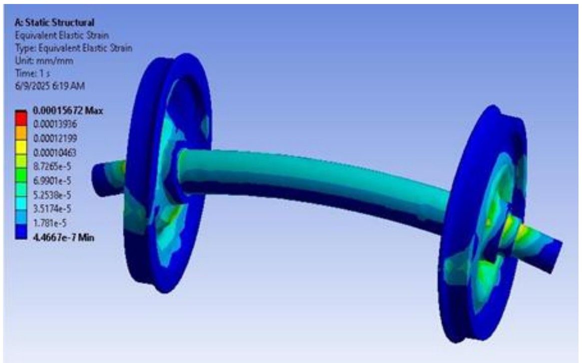


Fig 4.4: Stress distribution of axle

The strain developed in the axle is also evaluated to understand its deformation behavior under load, as shown in Fig 4.5.

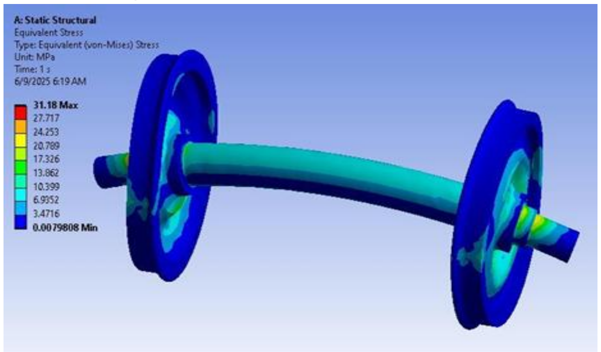


Fig 4.5: Strain of axle

V. VIBRATION ANALYSIS (MODAL)

Vibration analysis is carried out to study the dynamic behavior of the railway axle. Modal analysis is performed using ANSYS Workbench to determine the natural frequencies and corresponding mode shapes of the axle. Natural frequency is an important parameter, and resonance may occur if it matches the excitation frequency.

Therefore, it is necessary to evaluate the vibration characteristics of the axle. The first two mode shapes obtained from modal analysis are shown in Fig 5.1 and Fig 5.2. The corresponding mode shapes represent different deformation patterns of the axle during vibration.

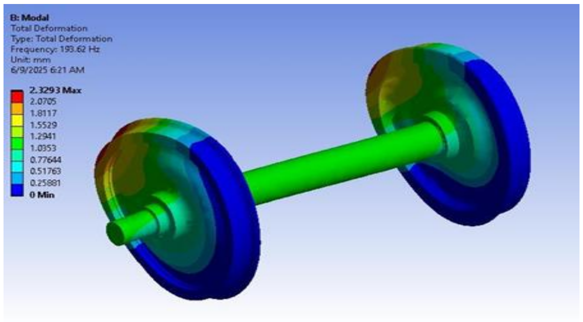


Fig 5.1: First mode shape of axle

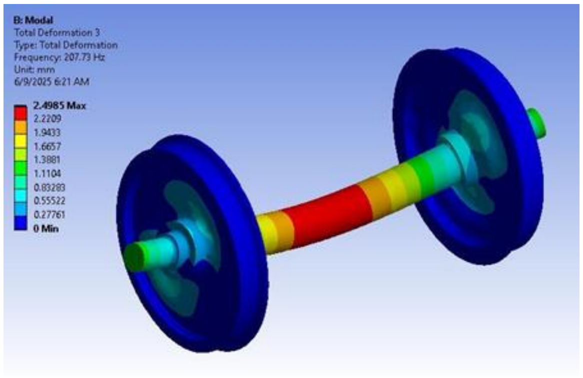


Fig 5.2: Second mode shape of axle

VI. DAMPING ANALYSIS

Damping analysis is carried out to evaluate the vibration characteristics of the railway axle. MATLAB is used to simulate impulse loading conditions, and the displacement-time response is obtained. The damping ratio is calculated using the logarithmic decrement method. The output response is shown in Fig 6.1.

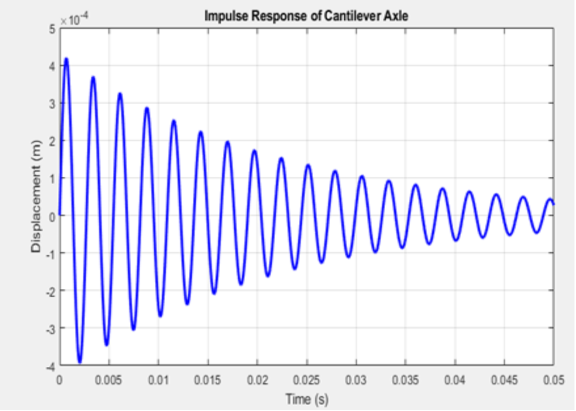
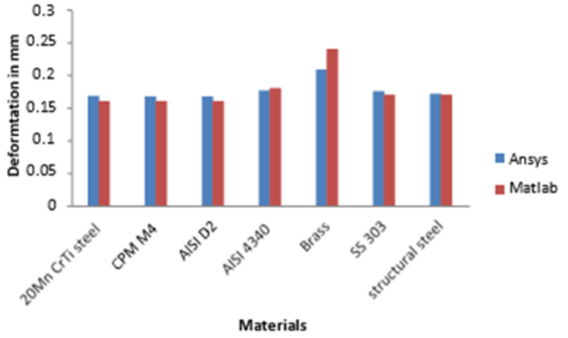


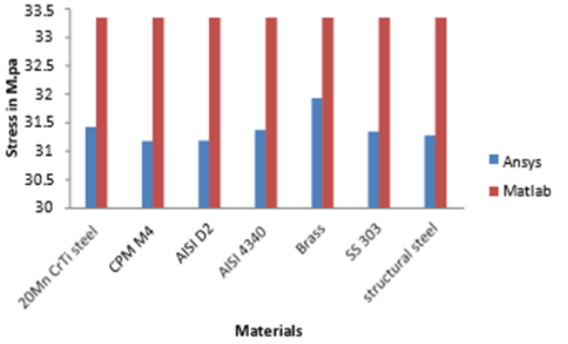
Fig 6.1: Impulse response of AISI D2.

VII. RESULTS AND DISCUSSION

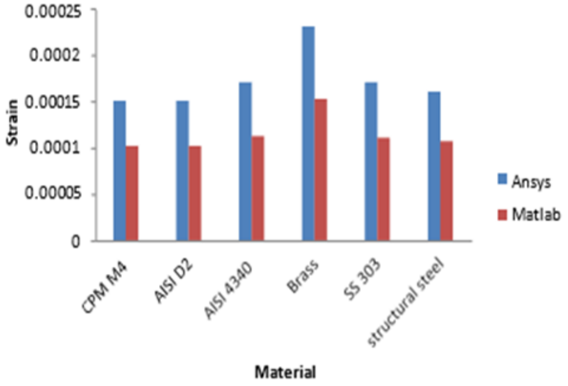
The results obtained from structural, modal, and damping analyses are compared for all selected materials. The deformation, stress, and strain results obtained from ANSYS are validated using MATLAB, as shown in Fig 7.1, Fig 7.2, and Fig 7.3.



Graph 7.1: Deformation results validation

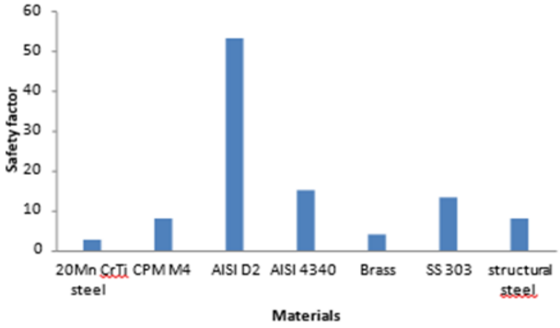


Graph 7.2: Stress results validation



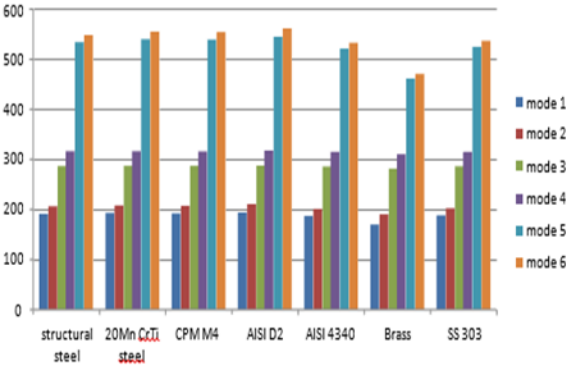
Graph 7.3: Strain results validation

The safety factor of the materials is evaluated to determine their reliability under applied loading conditions, as shown in Fig 7.4.



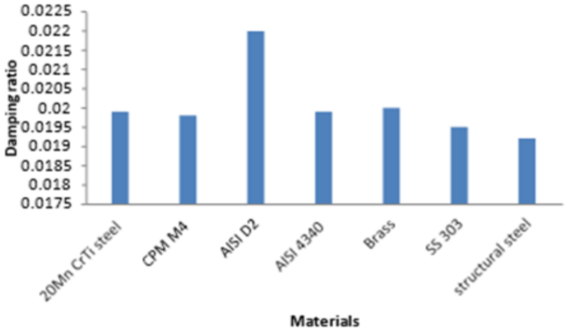
Graph 7.4: Safety factor

The natural frequency results indicate that materials with higher stiffness have higher natural frequencies, which helps in avoiding resonance, as shown in Fig 7.5.



Graph 7.5: Natural frequency results

The damping ratio results show that materials with better damping characteristics reduce vibration more effectively, as shown in Fig 7.6.



Graph 7.6: Damping ratio results

From the overall comparison, AISI D2 material shows better performance in terms of strength, stiffness, and damping characteristics, making it the most suitable material for railway axle applications.

VIII. CONCLUSION

In this study, the structural, vibration, and damping behavior of a railway axle is analyzed using CATIA, ANSYS, and MATLAB. A 3D model of the axle is developed and analyzed under various loading conditions to evaluate deformation, stress, and strain. Modal analysis is performed to determine the natural frequencies and vibration characteristics of the axle, while damping analysis is carried out using MATLAB to evaluate vibration decay behavior.

A comparative analysis is conducted for seven different materials 20MnCrTi Steel, CPM M4, AISI D2, AISI 4340, Brass, SS 303, and Structural Steel. Based on the results, AISI D2 material shows better performance in terms of strength, stiffness, and damping characteristics. It exhibits lower deformation, higher natural frequency, and effective vibration control, making it the most suitable material for railway axle applications. The study concludes that proper material selection plays a key role in improving the performance, safety, and durability of railway axle systems.

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