# Structural And Shape Optimization of a Commercial Vehicle Front Axle for Enhanced Performance

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***Abstract*—The front axle of a commercial vehicle is a critical load-bearing component that significantly influences vehicle stability, steering performance, and overall structural integrity. With increasing demand for lightweight and high-performance automotive components, there is a growing need to optimize axle design for improved efficiency and durability. This study focuses on the structural and shape optimization of a commercial vehicle front axle by evaluating different cross-sectional geometries under realistic loading conditions. A detailed 3D model is developed using computer-aided design (CAD) tools and analyzed through finite element analysis (FEA) to assess stress distribution, deformation, and structural behavior. Two geometrical configurations I-section and elliptical section are compared to understand the influence of shape on performance. The study also incorporates experimental validation through compression testing to support the numerical analysis. The research aims to identify an optimized axle design that achieves a better strength-to-weight ratio, improved load distribution, and enhanced durability while ensuring manufacturability. The findings contribute to the development of efficient and reliable front axle systems, aligning with modern automotive requirements for lightweight and sustainable design.**

***Index Terms*—Front axle; shape optimization; finite element analysis; I-section; elliptical section; commercial vehicle; lightweight design; Von Mises stress.**

## I. INTRODUCTION

The front axle is one of the most critical structural components in a commercial vehicle, responsible for supporting the vehicle load, maintaining wheel alignment, and transmitting forces generated during steering, braking, and road interactions. Its design directly influences vehicle stability, ride quality, and safety. In heavy-duty and commercial vehicles, the front axle is subjected to complex loading conditions, including bending, shear, and torsional stresses, making it essential to ensure adequate strength, stiffness, and durability throughout its service life.

Fig. 1. Front axle.

With the increasing demand for fuel efficiency, reduced emissions, and higher payload capacity, the automotive industry continuously strives to reduce the weight of structural components without compromising performance. Lightweight design has therefore become a key focus area, where optimizing material distribution and geometry plays a crucial role. Traditional axle designs are often conservative, leading to excess material usage and increased weight. Recent advancements in computational tools such as Computer-Aided Design (CAD) and Finite Element Analysis (FEA) have enabled engineers to accurately predict the structural behavior of components under realistic loading conditions. These tools facilitate the identification of critical stress regions, deformation patterns, and potential failure zones, thereby allowing for informed design improvements. In addition, shape optimization techniques provide opportunities to refine the geometry of structural components to enhance performance while minimizing material usage.

In this context, the cross-sectional geometry of the front axle plays a significant role in determining its structural efficiency. Different geometries, such as I-section and elliptical section, exhibit distinct characteristics in terms of stiffness, stress distribution, and load-carrying capacity. This study focuses on the structural analysis and shape optimization of a commercial vehicle front axle by comparing these cross-sectional configurations using FEA and experimental validation.

## II. LITERATURE REVIEW

A comprehensive review of prior work is presented to establish the context and motivation for this study.

Zheng et al. [1]

Zheng et al. combined topology and multi-objective optimization to design a lightweight drive axle housing. FEA under multiple loading conditions, alongside modal and fatigue analysis, established a performance baseline. Topology optimization removed non-load-bearing material, while DOE and NSGA-II methods balanced mass, stiffness, and fatigue life. The study provides a practical workflow for optimizing axle housings under realistic service conditions.

Liu et al. [2] Lightweight Axle Housing

Liu et al. focused on reducing the weight of electric vehicle axle housings while maintaining structural integrity. Using FEA, stress and deformation were analyzed under multiple load cases with targeted thickness optimization. The iterative approach achieved approximately 12% weight reduction without compromising performance, emphasizing practical and manufacturable lightweighting strategies.

Liu et al. [3] Steering Axle Optimization

This study investigated the optimization of steering axle structures for new energy vehicles using FEA. Stress, deformation, and dynamic behavior under steering and braking loads were analyzed. Optimization techniques reduced mass while maintaining stiffness and avoiding resonance, with fatigue analysis ensuring durability under cyclic loading.

Liu et al. [4] Multiphysics Frame Optimization

Liu et al. extended structural analysis to a multiphysics approach for electric SUV load-bearing frames. Static, modal, and material performance were evaluated, with integrated topology and parametric optimization considering manufacturability and assembly constraints.

Zhang [5]

Zhang investigated lightweight design of electric truck axle housings using topology optimization and FEA. Experimental validation of the parametric refinement demonstrated improved stress distribution and reduced mass with reliable fatigue life.

Ibhadode [6]

Ibhadode reviewed the integration of topology optimization with metal additive manufacturing, discussing SIMP and level-set approaches alongside manufacturing constraints such as overhangs and residual stresses. Challenges related to fatigue, cost, and certification were highlighted.

Amir [7]

Amir introduced a free-form shape optimization method for three-dimensional beam structures treating cross-sections as variable along the beam length. Using reduced-order models and sensitivity analysis, the method showed improved stiffness and reduced mass compared to traditional designs.

Qi et al. [8]

Qi et al. presented a comprehensive overview of topology optimization and shape-sensitivity methods, covering SIMP, level-set, and gradient-based optimization. Challenges including numerical stability, stress constraints, and manufacturability were discussed alongside automotive applications.

DOE + NSGA-II Approach [9]

This study demonstrated a combined FEA, DOE, and NSGA-II approach for axle housing optimization. Surrogate models reduced computational cost while generating a Pareto front balancing multiple objectives including stress, deformation, and mass.

Guoyong [10]

Guoyong focused on shape optimization of beam-type components using free-form surface modeling, demonstrating improved stiffness, fatigue life, and vibration characteristics through FEA-guided optimization with geometric manufacturability constraints.

Novelty of the Present Work: This study presents a comparative structural optimization of a commercial vehicle front axle using two distinct cross-sectional geometries under identical loading conditions. The work integrates both FEA-based analysis and experimental validation to ensure practical reliability. It highlights the trade-off between stiffness and stress distribution, providing a geometry-driven design selection framework for lightweight automotive structural design.

## III. PROBLEM STATEMENT

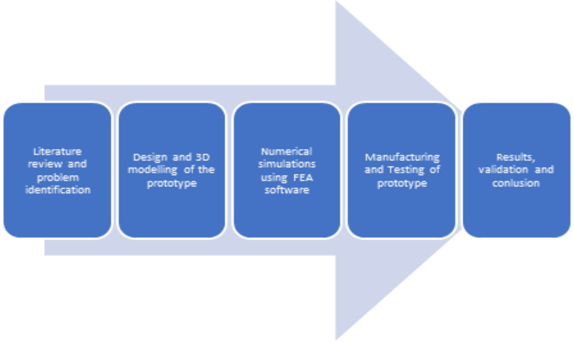
Commercial vehicles such as trucks and buses operate under demanding conditions requiring front axles that are robust, durable, and capable of withstanding significant static and dynamic loads. Traditional front axle designs, fabricated from conventional steel, tend to be excessively heavy. Therefore, there is a critical need to design, analyze, and shape-optimize a front axle that effectively balances structural integrity and durability with significant weight reduction, without compromising safety or introducing unnecessary manufacturing complexity.

## IV. OBJECTIVES

The specific objectives of this study are:

- To develop a robust 3D CAD model of a commercial vehicle front axle using SolidWorks, accurately representing its geometry and structural features.
- To perform static structural analysis of the front axle under various loading and boundary conditions using assumed material properties.
- To apply shape and material optimization to achieve weight reduction with concurrent stress minimization.
- To test the optimized front axle specimen using a Universal Testing Machine (UTM).
- To perform a comparative analysis between FEA simulation results and experimental data.

## IV. RESEARCH METHODOLOGY



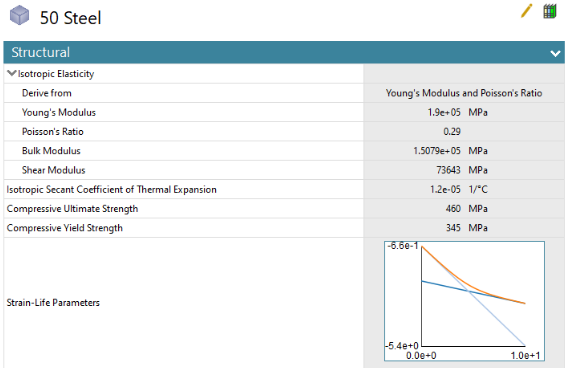
## V. FINITE ELEMENT ANALYSIS

Finite Element Analysis (FEA) is a numerical technique used to analyze structural behavior under various loading and boundary conditions. The method discretizes a continuous domain into a finite number of elements connected at nodes collectively forming a mesh. Each element approximates the displacement field using shape functions, enabling computation of strains and stresses via the strain-displacement and constitutive relations. For ductile materials, the Von-Mises stress criterion is used to evaluate yielding and structural safety.

In addition to static analysis, FEA supports modal, harmonic, and fatigue analyses for dynamic and long-term performance evaluation. Accuracy depends on mesh quality, boundary condition definition, and material model fidelity. In this study, FEA is employed to evaluate and compare the structural performance of two front axle geometries under identical realistic loading conditions.

### A. FEA of I-Section Front Axle

#### Material Properties



50 Steel

Structural

| | |
|---|---|
| Isotropic Elasticity | |
| Derive from | Young's Modulus and Poisson's Ratio |
| Young's Modulus | 1.9e+05 MPa |
| Poisson's Ratio | 0.29 |
| Bulk Modulus | 1.5079e+05 MPa |
| Shear Modulus | 73643 MPa |
| Isotropic Secant Coefficient of Thermal Expansion | 1.2e-05 1/°C |
| Compressive Ultimate Strength | 460 MPa |
| Compressive Yield Strength | 345 MPa |
| Strain-Life Parameters | |

Fig. 2. Material properties of structural steel.

#### Geometry

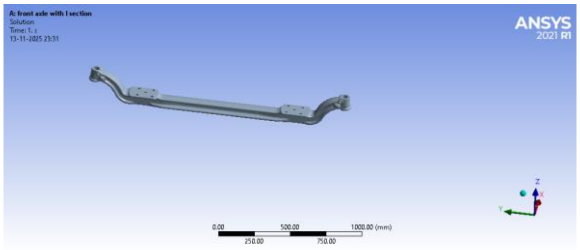
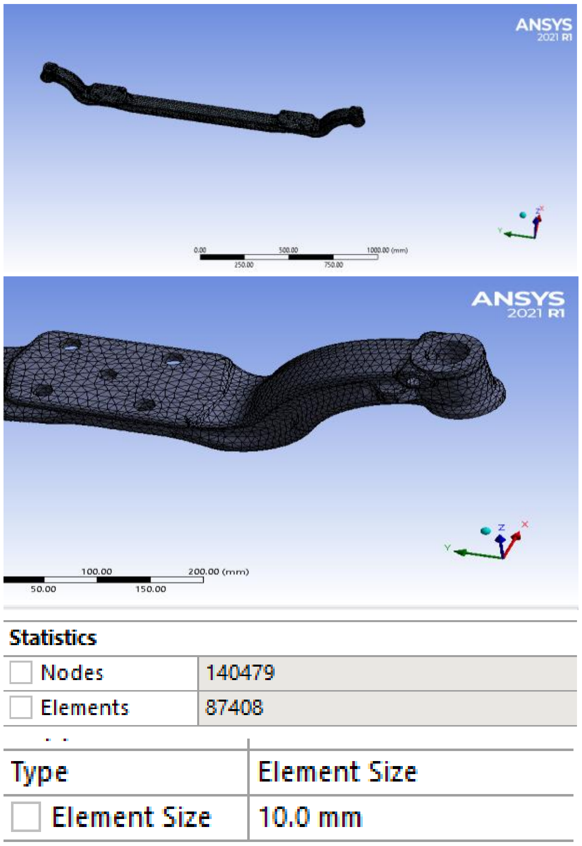


Fig. 3. CAD geometry I-section front axle.

#### Mesh



| Statistics | |
|---|---|
| ☐ Nodes | 140479 |
| ☐ Elements | 87408 |

| Type | Element Size |
|---|---|
| ☐ Element Size | 10.0 mm |

Fig. 4. Finite element mesh I-section front axle.

#### Boundary Conditions

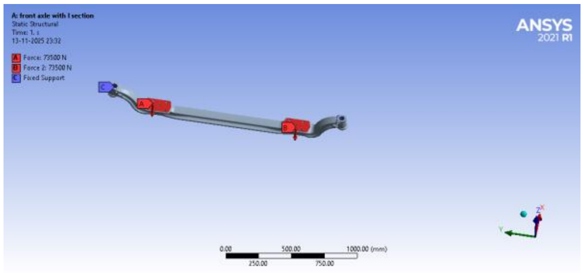


Fig. 5. Boundary conditions I-section front axle.

#### Results

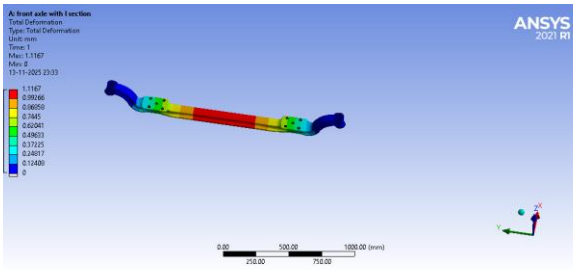


Fig. 6. Total deformation I-section front axle.

#### Equivalent stress

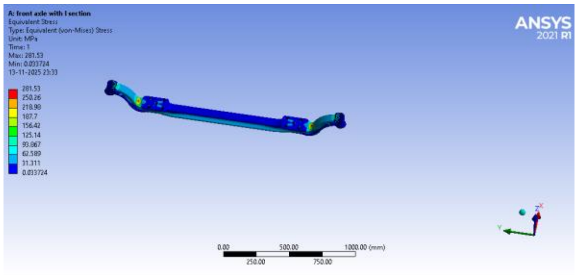


Fig. 7. Von-Mises equivalent stress I-section front axle.

#### Equivalent elastic strain

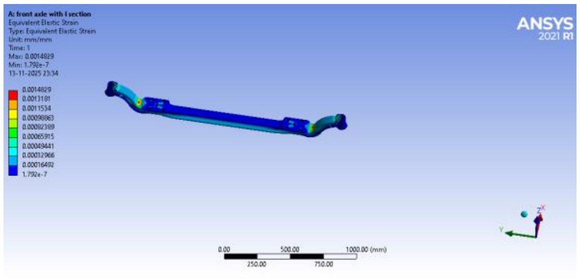


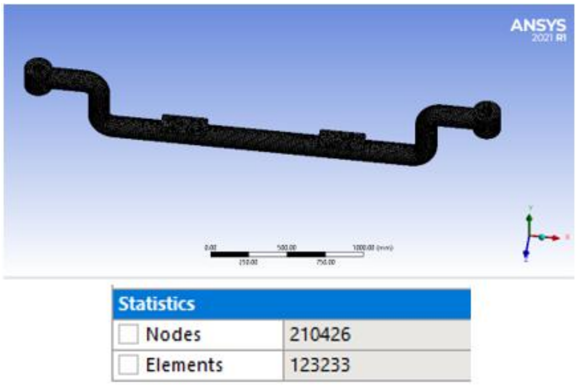
Fig. 8. Equivalent elastic strain I-section front axle.

### B. FEA of Elliptical Section Front Axle

#### Geometry

Fig. 9. CAD geometry elliptical section front axle.

#### Mesh



| Statistics | |
|---|---|
| ☐ Nodes | 210426 |
| ☐ Elements | 123233 |

Fig. 10. Finite element mesh elliptical section front axle.

Boundary Conditions

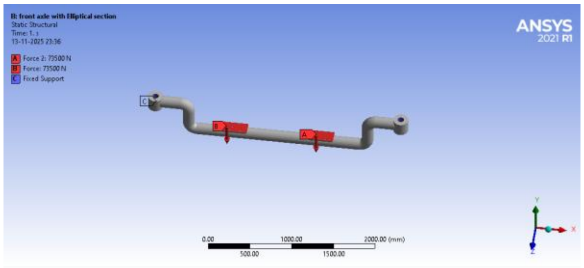


Fig. 11. Boundary conditions elliptical section front axle.

Results

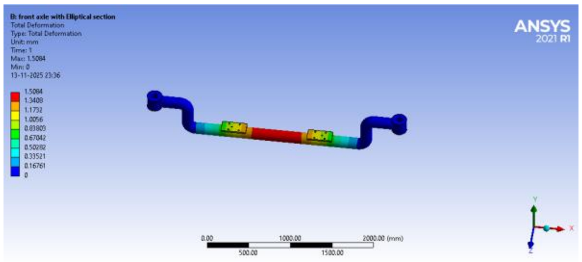


Fig. 12. Total deformation elliptical section front axle.

Equivalent stress

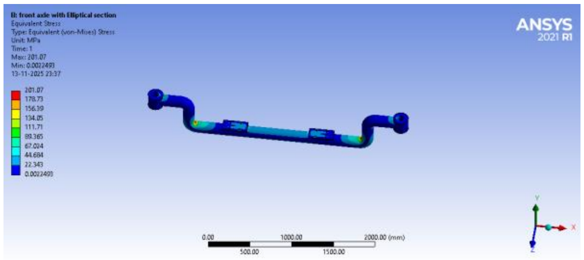


Fig. 13. Von-Mises equivalent stress elliptical section front axle.

Equivalent elastic strain

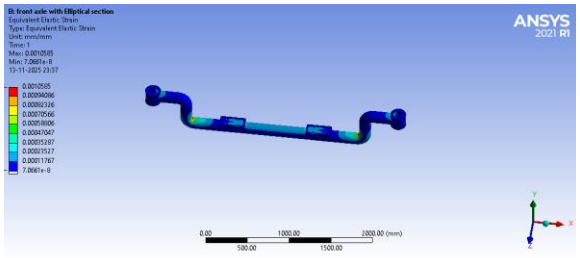


Fig. 14. Equivalent elastic strain elliptical section front axle.

C. FEA of Scaled-Down Model for Experimental Validation

To enable experimental validation using available laboratory equipment, a geometrically scaled-down model of the elliptical section axle was analyzed by FEA under equivalent loading conditions.

Geometry

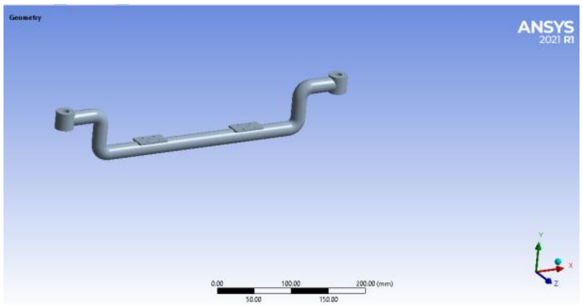
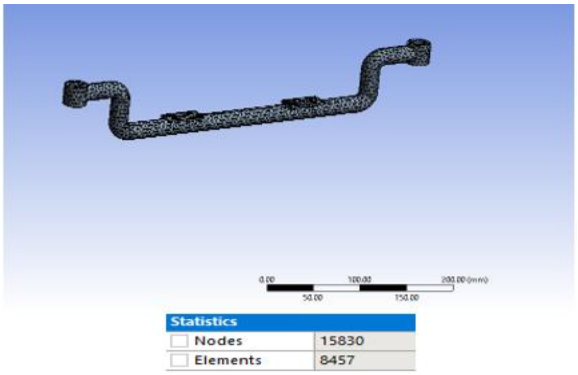


Fig. 15. CAD geometry scaled-down model.

Mesh



| Statistics | |
|---|---|
| Nodes | 15830 |
| Elements | 8457 |

Fig. 16. Finite element mesh scaled-down model.

Boundary Conditions

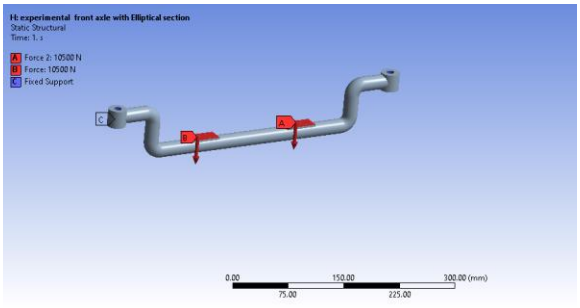


Fig. 17. Boundary conditions scaled-down model.

Results

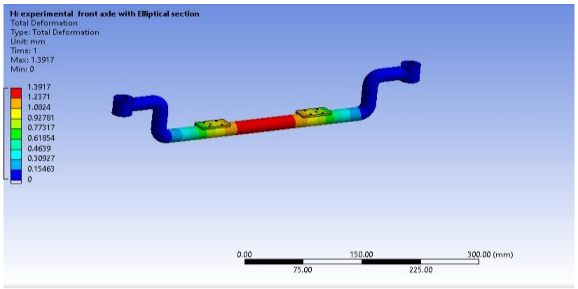


Fig. 18. Total deformation scaled-down model.

Equivalent Stress

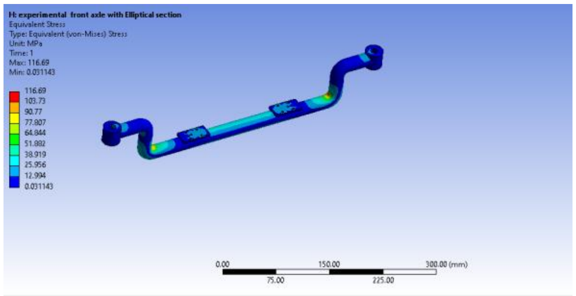


Fig. 19. Von-Mises equivalent stress scaled-down model.

Equivalent elastic strain

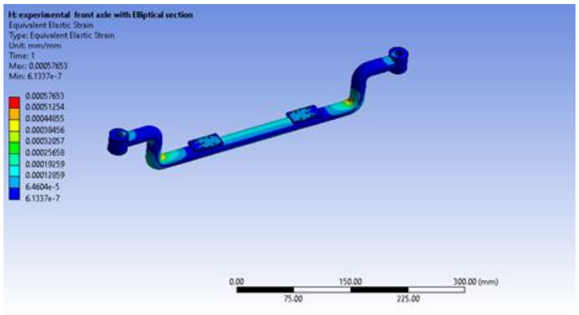


Fig. 20. Equivalent elastic strain scaled-down model.

The scaled-down FEA yielded a maximum total deformation of 1.3917 mm, a maximum equivalent stress of 116.69 MPa, and a maximum equivalent elastic strain of $5.77 \times 10^{-4}$.

## VI. FEA RESULTS AND DISCUSSION

Table I presents a comparative summary of FEA results for both cross-sectional geometries under identical loading conditions.

Table I, Comparative FEA Results I-Section vs. Elliptical Section

| Parameter | I-Section | Elliptical Section |
|---|---|---|
| Total Deformation (mm) | 1.1167 | 1.5084 |
| Equiv. Stress (MPa) | 281.53 | 201.07 |
| Equiv. Elastic Strain | $1.483 \times 10^{-3}$ | $1.059 \times 10^{-3}$ |

From the FEA comparison, the I-section axle exhibited higher stiffness, with a total deformation of 1.1167 mm compared to 1.5084 mm for the elliptical section indicating superior resistance to bending and deflection. However, in terms of stress, the elliptical section performed better, recording a lower Von-Mises stress of 201.07 MPa versus 281.53 MPa for the I-section. This indicates that the elliptical geometry provides more uniform stress distribution and reduced stress concentration.

The lower equivalent elastic strain of the elliptical section ($1.059 \times 10^{-3}$ vs. $1.483 \times 10^{-3}$) further confirms its advantages from a fatigue resistance and durability standpoint. The I-section, by contrast, is preferable where minimal deflection and rigidity are the dominant design requirements.

## VII. EXPERIMENTAL TESTING

Experimental testing validates numerical results by evaluating the actual mechanical behavior of the component under applied loads. A compression test was performed to determine the load-deformation characteristics and structural strength of the scaled-down axle specimen.

### A. Universal Testing Machine

A Universal Testing Machine (UTM) applies controlled loading to a specimen and measures the resulting deformation, enabling determination of strength, stiffness, and elasticity properties.

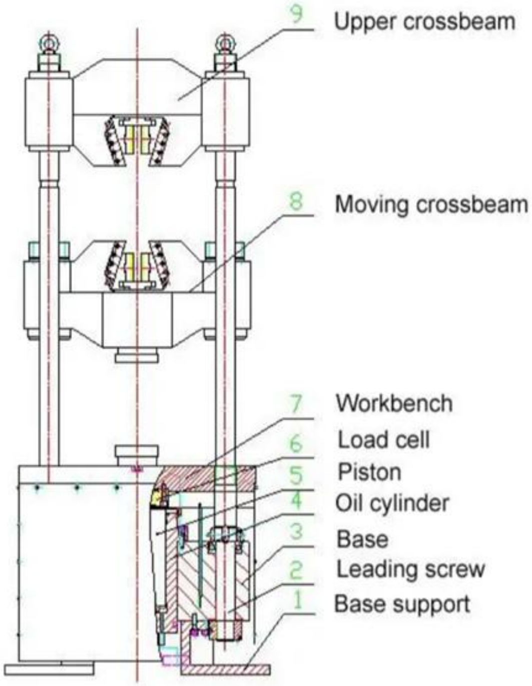


Fig. 21. Schematic diagram of a Universal Testing Machine (UTM).

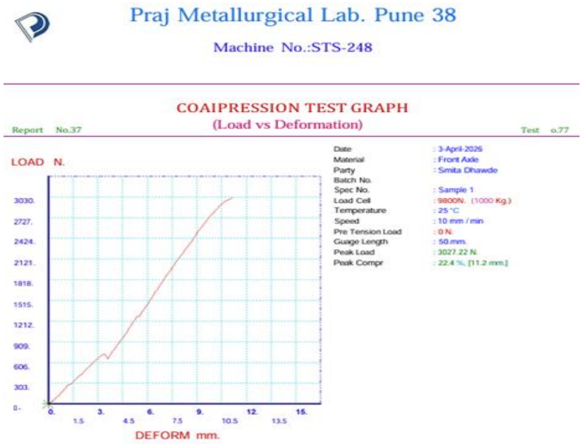
## VIII. EXPERIMENTAL PROCEDURE

1. Measure the width and thickness of the specimen.
2. Mark on the locations where the load will be applied.
3. Place the sample carefully on to the fixture of a universal testing machine.
4. Make sure that the loading point is placed on to the marked location.
5. Carry out the test.

Testing photograph

Fig 22. Specimen under compression test using a UTM

Testing graph



Praj Metallurgical Lab. Pune 38

Machine No.:STS-248

COAIPRESSION TEST GRAPH

(Load vs Deformation)

Report No.37

Test o.77

Date : 3-April-2026
Material : Front Axle
Party : Smita Dhawde
Batch No.
Spec No. : Sample 1
Load Cell : 9800N. (1000 Kg.)
Temperature : 25 °C
Speed : 10 mm / min
Pre Tension Load : 0 N.
Guage Length : 50.mm.
Peak Load : 3027.22 N.
Peak Compr : 22.4 %, [11.2 mm.]

Fig. 23. Load (N) vs. displacement (mm) compression test.

The load-deformation curve shows a nearly linear increase, indicating predominantly elastic behavior. The specimen reached a peak load of approximately 3,027 N at a deformation of ~1.4 mm, consistent with the FEA-predicted deformation of 1.3917 mm for the scaled-down model. The absence of abrupt load drops confirms stable structural behavior without sudden failure, validating the FEA predictions.

## IX. CONCLUSION

This study conducted a comparative structural and shape optimization analysis of a commercial vehicle front axle using I-section and elliptical cross-sectional geometries under identical loading conditions. The following conclusions are drawn:

- The I-section axle exhibits higher stiffness (total deformation: 1.1167 mm), making it preferable where minimal deflection is critical such as for maintaining wheel alignment and handling stability.
- The elliptical section axle demonstrates superior stress distribution (Von-Mise's stress: 201.07 MPa vs. 281.53 MPa), with lower strain, making it more suitable for applications demanding durability and fatigue resistance.
- Experimental compression testing validates FEA findings: the specimen sustained a peak compressive load of ~3,027 N at ~1.4 mm deformation, with no abrupt failure, confirming structural reliability and the accuracy of the simulation model.

Overall, the elliptical section offers a better balance between strength and safety, while the I-section provides superior rigidity. An optimized hybrid or modified design could further enhance both stiffness and strength for improved overall performance.

Future work should explore topology-optimized hybrid cross-sections, material substitution (e.g., high-strength steel alloys or composites), and fatigue life analysis under dynamic loading to further advance front axle design for next-generation commercial vehicles.

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