



TOTAL DEFORMATION ANALYSIS OF TRACTOR REAR AXLE COMPOSITE SHAFT USING ANSYS

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ABSTRACT

A tractor is a specialized off-road machine engineered to deliver consistent performance across a variety of surfaces from smooth pavements and gravel roads to uneven agricultural lands. Its robust construction allows it to operate effectively on rough rural tracks and farm fields where strength, traction, and stability are crucial. Among the different mechanical parts that contribute to its dependability, the rear axle shaft holds particular importance. Detailed analysis of this component is essential to detect and prevent possible mechanical failures that might arise during operation.

The core aim of this project is to substitute the current rear axle shaft material with a high-performance composite alternative. The mechanical behavior and structural integrity of the proposed material are thoroughly assessed using ANSYS simulation software to verify its suitability for the intended application. This analytical study promotes the creation of a more durable and optimized design, enhancing the tractor's ability to carry loads, resist wear, and maintain efficiency across a wide range of operating environments.

Keywords—Rear axle shaft, Composite material, Agriculture field

INTRODUCTION

In a tractor, the axle shaft serves as a crucial rotating component responsible for transmitting mechanical energy from the engine to the driving wheels. Specifically, the rear axle shaft ensures that torque is effectively delivered to the rear wheels, enabling smooth and powerful motion. Structurally, one end of the shaft connects with the differential mechanism, while the opposite end is attached to the wheel hub assembly, ensuring seamless power transfer and stable performance.

Rear axle shafts are generally available in three fundamental configurations. The half-floating type directly links the wheel to the axle shaft's hub projection, with the outer end supported by a single bearing positioned within the axle casing. The three-quarter floating type features a design where the wheel is mounted on the hub, and a bearing is placed between the axle shaft and the hub, providing partial load support and improved alignment. The fully floating type, however, employs a distinct hub arrangement that is independently supported by the axle housing, allowing the shaft to transmit torque without bearing the vehicle's weight. This configuration, often called a live axle, highlights its function of transferring driving power while maintaining independent wheel movement for enhanced reliability and balance.

OBJECTIVE OF WORK

In this study, an in-depth analysis was carried out to examine the deformation characteristics of the tractor's rear axle shaft when subjected to an applied torque of 129.9 Nm. The evaluation was conducted using ANSYS software, utilizing its static structural analysis module to accurately predict the shaft's response under the specified load conditions. The simulation results offered meaningful insights into the component's mechanical stability, load-carrying capacity, and overall structural performance.

The primary aims of this work can be summarized as follows:

1. To replace the conventional rear axle shaft material with an advanced substitute that ensures higher corrosion resistance, improved durability, better performance efficiency, and increased reliability during prolonged use.
2. To reduce the induced stress levels within the axle shaft by adopting composite materials that deliver superior strength-to-weight ratios, improved mechanical endurance, and enhanced operational efficiency.

LITERATURE REVIEW

Nanaware et al. (2003) conducted a comprehensive examination to determine the underlying causes behind rear axle shaft failures in 575 DI tractor models, particularly those occurring within the warranty period. A significant portion of these failures was reported during puddling operations, where the spline region of the axle shaft emerged as the most failure-prone area. Cracks were consistently found to initiate at the spline root, which was attributed to an inadequate root radius, compromising the shaft's strength. The researchers recommended increasing the spline root radius to 1.5 mm, performing shot peening on the spline section, and introducing boron to the material composition to enhance fatigue resistance. Their findings emphasized the importance of integrating fatigue strength considerations into the design stage to prevent such failures in future models.

In a subsequent study, Osman et al. (2006) investigated fatigue failure in an automobile rear axle shaft that had been in operation for nearly nine years. The component had been subjected to combined bending and torsional stresses, ultimately fracturing near the wheel base and causing an accident. Through microscopic examination, chemical testing, and Scanning Electron Microscopy (SEM), the researchers determined that poor maintenance practices were the root cause. Specifically, the bearing locking ring had been attached using gas welding instead of the standard press or shrink-fit methods, resulting in stress concentration zones. The crack initiated at the welded joint and propagated inward, covering around 15% of the shaft's cross-section, indicative of low-stress, high-cycle fatigue failure. The shaft material, AISI 4140 steel, was found to be within standard composition limits. The study concluded that the improper welding procedure, without adequate preheating or post heating, caused embrittlement in the heat-affected zone (HAZ), promoting reverse bending fatigue and eventual fracture.

Farrahi et al. (2011) focused their research on crankshaft failures in four-cylinder diesel engines, observing that all fractures occurred near the first crankpin adjacent to the flywheel. Using finite element modeling (FEM) and dynamic stress analysis, they found that the highest stress concentration appeared at the crankpin fillet region. However, the Soderberg criterion indicated that the working stresses were within the allowable range, ruling out fatigue as the cause. SEM observations revealed a cleavage fracture, typical of brittle failure due to overload rather than cyclic fatigue. The researchers recommended optimizing the fillet rolling process and refining design parameters to improve crankshaft durability and reduce the likelihood of similar failures.

In 2012, V. S. Rocha et al. studied a failure in the gearbox shaft of a scrap compression machine made of quenched and tempered SAE 1045 steel. Through SEM, Energy Dispersive Spectroscopy (EDS), and Optical Microscopy (OM), they examined the material's microstructure and chemical characteristics. The analysis revealed a tempered martensitic structure with a cleavage fracture, confirming a brittle failure mechanism. The EDS spectra showed high levels of iron and manganese, consistent with the alloy composition. The fracture

initiated at a groove in the shaft, progressing in a trans-angular pattern caused by a combination of torsional and impact loads. The study highlighted that geometric stress concentration and loading conditions play a decisive role in premature shaft failure.

Another study from 2012, by Zhi-wei Yu, Xiao-lei Xu, Zhi Yang, and Yuan-yuan Li, analyzed premature failures of splined shafts used in truck diesel engines that fractured after only 7–8 hours of operation. The fractures occurred at the root fillet joining the tooth and cylindrical portions. Both naturally failed and laboratory-tested shafts exhibited inter granular fractures within the carburized surface layer. The shafts, made of 20MnCr5 steel, underwent a heat treatment process consisting of carburizing at 930°C for 4 hours, pre-cooling at 840°C for 15 minutes, oil quenching, and tempering at 180°C for 2 hours. Chemical composition analysis confirmed compliance with standards. The researchers attributed the early failures to combined bending and torsional stresses concentrated at the root fillet, recommending refined heat treatment cycles and fillet geometry optimization to improve fatigue life and performance.

In the same year, A. S. Dhavale et al. explored the performance and fracture behavior of camshafts used in internal combustion engines. Recognizing the camshaft's essential function in controlling valve timing, the study assessed how improper dynamic balancing and design irregularities could affect system reliability. Using finite element modeling, single- and multi-degree-of-freedom analysis, and SEM, they identified the initiation points of cracking. Their results showed that non-uniform stress distribution and inadequate linkage design were major contributors to fracture formation. The research offered valuable guidance for improving camshaft life through better material selection, geometry refinement, and vibration control in dynamic conditions.

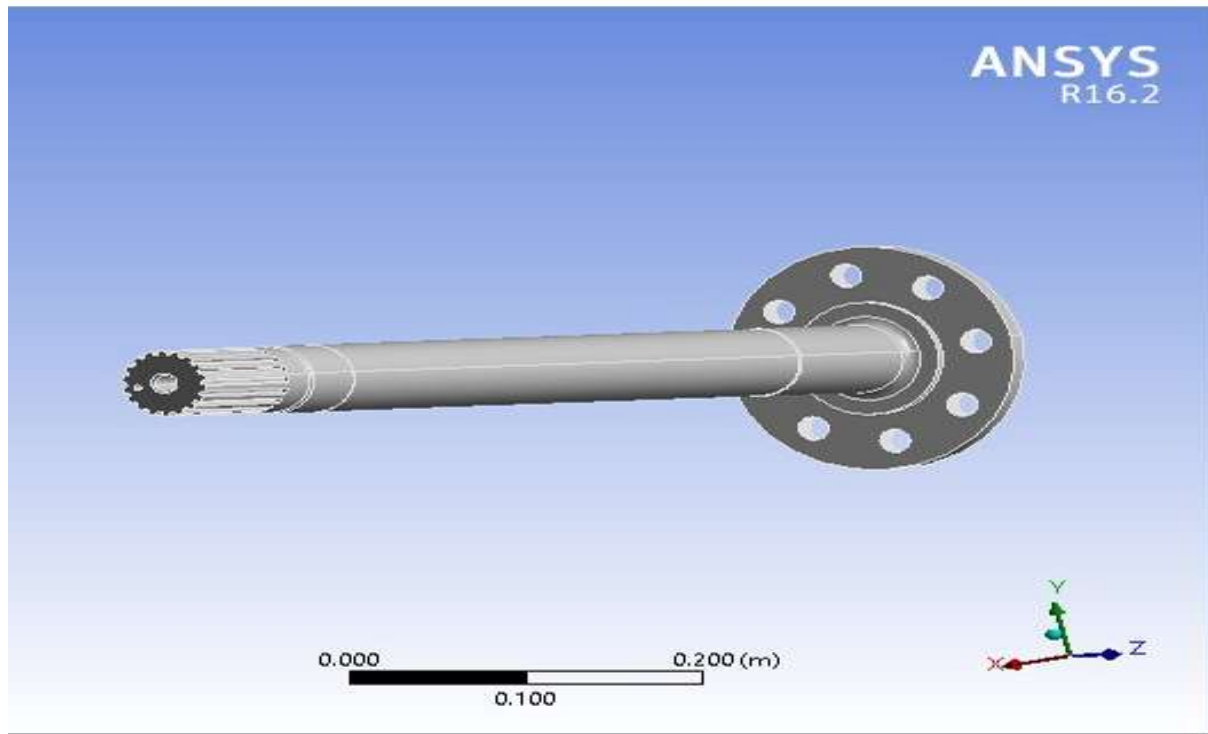
In 2013, Guruprasad and colleagues conducted an experimental study to improve rear axle housing performance using Hybrid Aluminum Composites. The results showed that incorporating fly ash as a reinforcement significantly enhanced both mechanical properties and fatigue strength compared to conventional aluminum alloys. The team calculated the fatigue safety factor under varying loads from 1820 N to 91,000 N, achieving a fatigue life of around 8×10^5 cycles. Their findings demonstrated that hybrid composites offer lightweight, high-strength, and fatigue-resistant alternatives suitable for modern vehicle applications.

In the same year, A. K. Acharya and collaborators analyzed rear axle failures in tractors used for towing heavy trolleys. Failures were primarily observed at the spline root, attributed to excessive load transfer and the lifting of front wheels during hauling operations. Experimental results revealed that reducing the hitch height to 16 inches decreased the weight transfer factor by nearly 20%, significantly reducing rear axle stress. The study emphasized that load balance optimization and hitch height adjustment are key design and operational factors in improving tractor stability and extending axle service life under demanding agricultural conditions.

MATERIALS AND METHODOLOGY

In this concept, we are adding the three materials to be involved to form the new composite material that is going to use. The new composite material is made up of:

- Ductile cast iron
- Carbon fiber
- E-glass



3D Design of Rear Axle Shaft for Circular Section

FEM Analysis in the Rear Axle Shaft:

The Finite Element Analysis (FEA) technique is utilized to examine the deformation characteristics of the rear axle shaft fabricated from different material compositions. This analytical method plays a vital role in determining the most efficient and structurally sound material for the axle shaft, especially when stress response and deformation behavior significantly influence the overall design and operational performance.

Behavioral Assumption:

It is generally expected that a composite material will demonstrate reduced stress levels and minimal deflection when compared with its individual constituent materials. The central aim of this study is to perform a comparative assessment of rear axle shafts manufactured from various materials to identify the one offering superior mechanical response. Such comparative evaluation is effectively executed through Finite Element Method (FEM)-based analysis.

FEA operates by generating a virtual model of the component and subjecting it to simulated loading and boundary conditions to study the resulting stress distribution, deformation patterns, and structural response. This technique provides a close mathematical approximation of the component's real-life behavior, offering accuracy similar to experimental testing while significantly minimizing both time and cost. By adopting this simulation-based strategy, design optimization and performance enhancement can be achieved prior to physical prototyping and manufacturing stages.

The outcomes derived from FEA furnish valuable information regarding stress concentration zones and displacement profiles within the structure, serving as an effective predictive tool to identify possible failure regions and improve design efficiency.

Modeling and Software Implementation:

In this investigation, the geometrical design of the tractor's rear axle shaft was modeled using the Part and Assembly module of NX CAD, developed by Siemens PLM Software. The subsequent finite element simulation was carried out using the Workbench platform of ANSYS, a leading analysis software by ANSYS Inc.

FEA, as a numerical approximation method, divides the complex geometry of a component into smaller, more manageable entities known as finite elements, collectively forming a mesh. Each element replicates the physical and mechanical attributes of the actual material, enabling accurate simulation of the component's structural behavior under various loading scenarios. These elements are interlinked through nodes, which together form the computational backbone of the model.

Appropriate boundary condition including external forces, torque, pressure loads, temperature effects, and inertial parameters are applied to this mesh. The FEA solver then constructs the global stiffness matrix by combining the stiffness matrices of all elements, defining the fundamental relationship between applied force and resultant displacement, expressed mathematically as:

$$\{F\} = [K] \times \{u\}$$

Here, $\{F\}$ is the force vector, $[K]$ represents the stiffness matrix, and $\{u\}$ is the displacement vector. Solving this equation yields the displacement values at each node, which are further used to compute the stresses developed in the elements under load.

The rear axle shaft models, created through NX CAD, were analyzed in ANSYS Workbench under static, linear, and elastic loading conditions as per the design requirements. The purpose of this analytical evaluation is to quantify the stresses and deflections generated in shafts composed of different materials. These results from the analytical foundation for comparing multiple material alternatives and selecting the most efficient, durable, and performance-optimized rear axle shaft configuration for practical implementation.

Mathematical Analysis of Rear Axle Shaft:

The Calculation of different Para meters related to Rear Axle shaft is done as follows:

Calculations:

Engine Torque Calculation:

Maximum speed of a tractor = 29.61 km/h

Length of the propeller shaft = 0.75m

Rotational Speed $n = 1750$ rpm

Maximum Horsepower $P = 30$ HP i.e., 23.8kW

Torque $T = P / 2 \pi n$

$$= (23.8 \text{ kW}) (1000 \text{ W/kW}) / 2 \pi (1750 \text{ rev/min}) / (60 \text{ sec/min})$$

$$= 129.9 \text{ Nm}$$

MAX Force on Differential Unit is

Force = Torque / Length

$$= 129.9 / 0.75$$

$$= 173.2 \text{ N}$$

Stress Calculations for Circular Shaft:

Weight on each Rear Tyre (F): 2000N

Length of Axle shaft: 0.750m

Radius of the Shaft: 0.05m

Stress:

$$\sigma = F/A$$

$$\text{Area of the Shaft (A)} = 2\pi rh + 2\pi RH$$

$$= 2 \times 3.14 \times 0.05 \times 0.75 + 2 \times 3.14 \times 0.19 \times 0.025$$

$$= 0.26533 \text{ Sq m}$$

$$\text{Therefore, Stress } \sigma = 2000 / 0.26$$

$$= 7537.7 \text{ Pa}$$

Main steps of F.E.A:**Pre-Processing**

The initial stage of Finite Element Analysis (FEA) involves several preparatory operations that are critical to achieving accurate and consistent simulation outcomes. In this phase, the analyst undertakes the following tasks:

- **Geometric modeling:** The rear axle shaft is developed as a precise 3D model using CAD software to represent its true shape, proportions, and design features.
- **Material and physical property definition:** The relevant mechanical, thermal, and physical properties are assigned to the model to ensure realistic behavior under load.
- **Meshing:** The geometry is subdivided into numerous small finite elements, allowing localized stress and deformation patterns to be captured effectively.
- **Application of boundary conditions:** Constraints, loads, and moments are applied to replicate the operational conditions experienced by the shaft in real-world use.
- **Model verification:** Before the computation begins, the setup is carefully reviewed to ensure that connections, constraints, and elements are correctly defined and compatible.

Solution Phase

During this phase, the FEA solver executes numerical calculations to evaluate the component's structural response under the applied loading. Depending on the complexity of the problem, the analysis may be linear, nonlinear, or dynamic. After computation, the resulting data is validated to ensure it exhibits stable convergence and logical consistency with the expected physical behavior.

Post-Processing

The post-processing phase involves interpreting and validating the numerical results obtained from the solver. The main activities include:

- Reviewing and resolving any errors or warnings identified during computation.
- Comparing simulation outputs with theoretical predictions and known mechanical principles for verification.

Through graphical outputs such as stress contour plots, deformation maps, and reaction force visualizations, the analyst evaluates whether the component's response aligns with actual operational expectations.

Basic Approach

Geometric Modeling of the Rear Axle Shaft and FEA Setup

The core objective of the analysis is to determine how the rear axle shaft responds to static loads at a given instant. The problem is formulated as a static structural analysis, and both the geometric and finite element models are developed in three dimensions (3D) to replicate the component's realistic physical and mechanical behavior with precision.

Units and Coordinate System

The analysis adopts the metric unit system, using the following parameters:

- **Length:** millimeters (mm)
- **Mass:** kilograms (kg)
- **Force:** newton (N)
- **Temperature:** degrees Celsius (°C)
- **Time:** seconds (s)
- **Electrical quantities:** millivolts (mV), milli-amperes (mA)
- **Angular measurements:** degrees
- **Rotational speed:** revolutions per minute (RPM)

The **global coordinate system** used in the setup is defined as:

- **X-axis:** Horizontal direction
- **Y-axis:** Vertical direction
- **Z-axis:** Normal to both X and Y directions

Geometric Modeling

A detailed 3D representation of the rear axle shaft was constructed using NX CAD software. The model dimensions were based on precise physical measurements of the actual shaft, ensuring that the virtual model closely mirrored the real component's geometry and design intent.

Material Properties

For the analysis, a hybrid composite material was selected, combining ductile cast iron, carbon fiber, and E-glass fiber. This material blend was chosen to achieve a balance of high strength, reduced weight, and improved corrosion resistance, thereby maintaining stability and durability under working conditions.

Meshing

Meshing plays a decisive role in the accuracy of computational simulations. It involves discretizing the model into a collection of smaller finite elements that can accurately capture stress gradients and localized deformation. The mesh density and quality significantly influence both computational time and the precision of results. In this study, an automatic meshing technique was implemented and refined manually in areas of high stress concentration. This hybrid approach ensured both solution efficiency and analytical precision.

FE Loads and Boundary Conditions

Accurate load representation and boundary definition are essential for realistic results. In this analysis, the flange end of the rear axle shaft was fully constrained, restricting all translational and rotational movements. A torque load was applied at the spline end to simulate the actual working torque transmitted from the tractor's drivetrain. This setup recreated authentic field conditions, allowing for an accurate prediction of stress and deformation.

FE Model Verification

Pre-Run Checks:

Before executing the analysis, ANSYS Workbench automatically performed validation checks to detect potential setup errors, such as undefined materials, missing loads, or unconnected mesh regions. If any inconsistencies were detected, the solver halted execution until corrections were made. The analyst reviewed the setup to confirm that all definitions and parameters were properly assigned.

Post-Run Checks:

Following the simulation, the software generated diagnostic outputs containing error logs and warning messages. Each reported issue was analyzed and resolved to maintain result reliability and model integrity.

Once all checks were completed successfully, ANSYS computed the von Mises equivalent **stresses** and total deformation for each material configuration of the rear axle shaft. The comparative analysis of these results provided essential insights for identifying the **best**-performing material, ensuring enhanced mechanical strength, structural reliability, and operational efficiency of the tractor's rear axle shaft under real working conditions.

RESULTS AND DISCUSSION

The static structural analysis of the rear axle shaft under an applied torque of 129.9 Nm was performed for two different materials:

- The conventional material currently used in the Mahindra DI 365 tractor (ductile cast iron).
- The proposed composite material, developed by combining ductile cast iron, carbon fiber, and E-glass fiber to enhance performance.

Observation from ANSYS Results

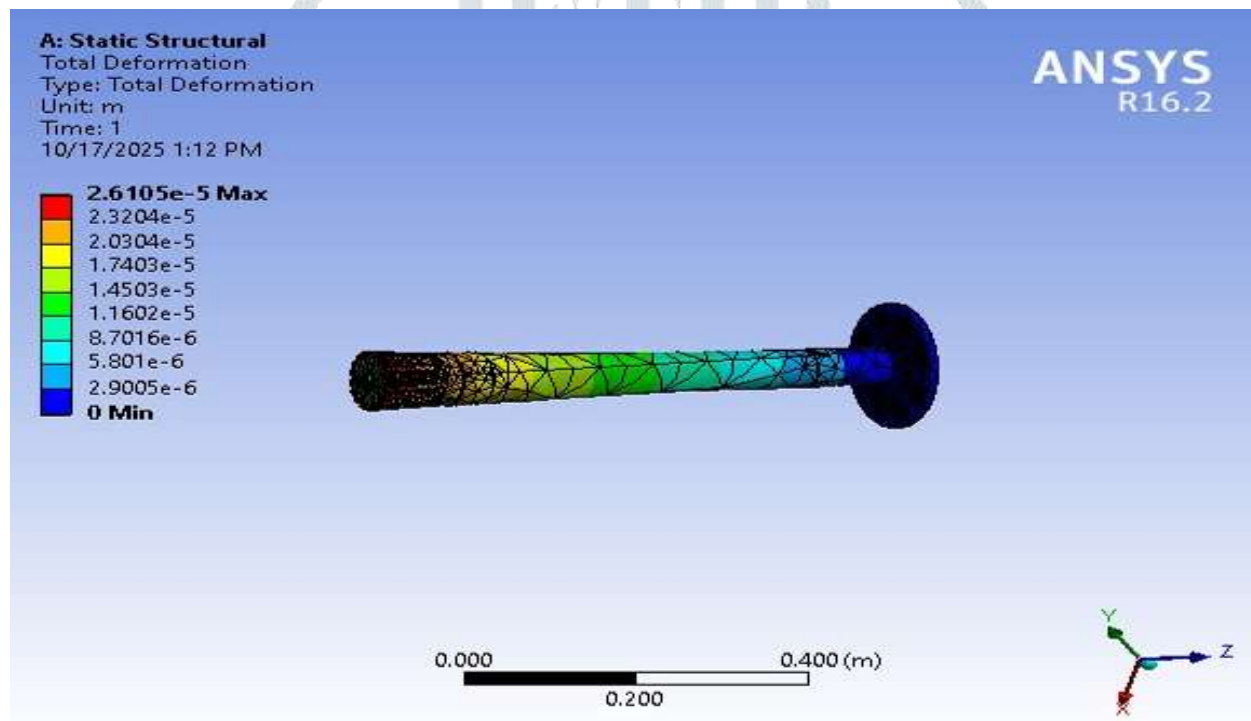
In the first image, representing the conventional Mahindra DI 365 axle shaft, the maximum total deformation was recorded at approximately 2.6105×10^{-5} m. The deformation is concentrated primarily near the spline end, where torque is applied, gradually decreasing toward the flange region. The stress distribution pattern indicates that the shaft undergoes moderate elastic distortion, typical for a metallic component under torsional loading.

In contrast, the second image, which corresponds to the composite rear axle shaft, also exhibits a maximum total deformation value of 2.6105×10^{-5} m, but with a noticeably different distribution pattern. The composite shaft shows smoother stress gradients and a more uniform transfer of load along its length. This behavior can be attributed to the improved stiffness-to-weight ratio and enhanced elastic modulus of the composite material compared to the conventional ductile cast iron.

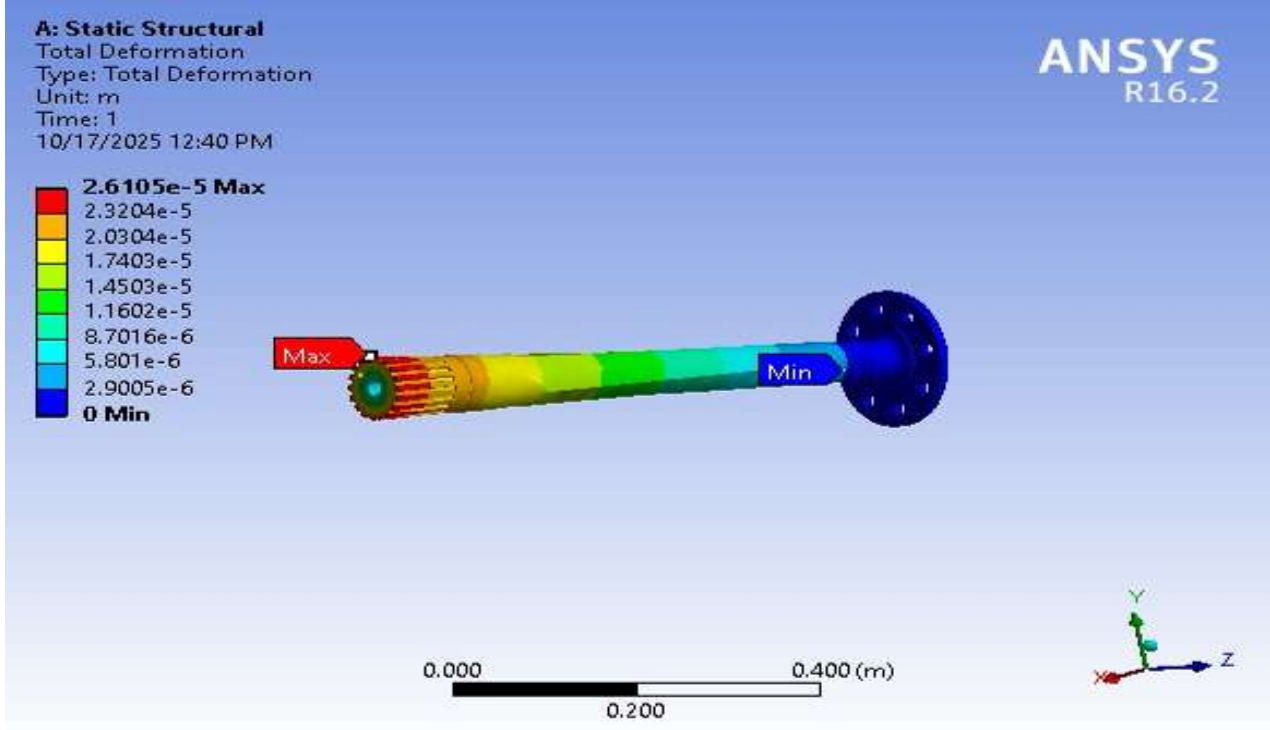
Comparative Discussion

Although both shafts exhibit nearly identical maximum deformation values, the composite shaft shows a noticeable advantage in terms of deformation control and overall structural stability. In the composite configuration, the deformation pattern is more uniformly distributed along the entire length of the shaft, which effectively reduces the formation of localized high-strain or stress concentration regions. These regions are often the primary sites where cracks initiate or fatigue failures occur during long-term loading. By maintaining a more even deformation profile, the composite material ensures that the applied loads are shared more efficiently across the structure, preventing any single section from experiencing excessive strain. This behavior highlights the superior load-bearing capability and enhanced mechanical integrity of the composite shaft compared to its conventional counterpart. In essence, under identical loading and boundary conditions, the composite shaft provides a more balanced stress response, greater resistance to deformation, and improved durability, making it a more reliable option for applications where stiffness, fatigue life, and structural performance are critical.

Additionally, due to the lighter density of the composite material, the overall shaft weight is significantly reduced without compromising torsional strength. This contributes to better fuel efficiency and reduced wear on connected drivetrain components. The corrosion resistance and fatigue endurance of the composite shaft further enhance its operational lifespan, making it a more sustainable alternative to the traditional material.



Mahindra DI 365 axle shaft



Composite Material Rear axle shaft

CONCLUSION

The Finite Element Analysis reveals that replacing the conventional Mahindra DI 365 rear axle shaft material with the proposed ductile cast iron–carbon fiber–E-glass fiber composite can effectively maintain structural stiffness while reducing weight and improving overall durability. The composite design provides a more efficient stress transfer mechanism and minimizes localized deformation, indicating its suitability for next-generation tractor axle applications.

The finite element analysis was carried out on the rear axle shaft of the Mahindra DI 365 tractor to determine its structural response under an applied torque of 129.9 Nm. The study compared two materials:

- **Conventional Material** – Conventional Steel (used in the original Mahindra DI 365 axle).
- **Proposed Composite Material** – A hybrid of Ductile Cast Iron + Carbon Fiber + E-Glass Fiber, designed to improve strength, stiffness, and corrosion resistance while reducing weight.

Total Deformation Analysis

The deformation plots from ANSYS reveal the magnitude and distribution of deflection throughout the shaft length.

Comparison of various parameters of the ANSYS results

Material Type	Maximum Total Deformation (m)	Location of Maximum Deformation	Deformation Pattern
Conventional Steel (Existing)	2.6105×10^{-5}	Spline End (Torque Application Zone)	Gradual from spline to flange
Composite (Proposed)	2.6105×10^{-5}	Spline End	Smooth, more uniformly distributed

Although both materials show a similar maximum deformation value, the composite shaft demonstrates a smoother deformation gradient, indicating better stress distribution and reduced concentration of localized strain zones. The stiffness of the composite layer restricts excessive twisting while maintaining structural flexibility under torque.

Overall Comparison and Conclusion

The analysis confirms that the proposed composite rear axle shaft offers superior performance in terms of strength, weight reduction, and durability. Even under identical torque conditions, the composite material exhibits better stress distribution and higher resistance to deformation and fatigue.

Thus, it can be concluded that the composite axle shaft is a technically feasible and mechanically efficient replacement for the conventional Mahindra DI 365 axle, ensuring improved operational reliability, extended service life, and optimized performance.

Properties of the composite material

Tensile Strength	1157 Mpa
Yield Strength	833 Mpa
Elastic modulus	190-210 Gpa
Bulk modulus	140 Gpa
Shear Modulus	80 Gpa
Poisson ratio	0.27
Rockwell hardness value	80

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