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STRAIN ENERGY ANALYSIS OF TRACTOR REAR AXLE COMPOSITE SHAFT USING ANSYS

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ABSTRACT

A tractor is an off-road vehicle specifically built to perform efficiently on diverse terrains, such as gravel paths, paved roads, and uneven farmlands. It is also capable of handling rough rural tracks and agricultural fields where stability and strength are essential. To maintain its reliability, one of the most critical components that requires close examination is the rear axle shaft. Analyzing this part helps in identifying and preventing potential failures that may occur during the tractor's functioning.

The primary objective of this project is to replace the existing rear axle shaft material with a more advanced composite material. The new material's mechanical characteristics are carefully evaluated using ANSYS software to ensure it meets the desired performance standards. This analytical approach supports the development of a stronger and more efficient design, improving the tractor's durability, load-bearing capacity, and overall operational efficiency under varying working conditions.

Keywords—Rear axle shaft, Composite material, Agriculture field

INTRODUCTION

The axle shaft in a tractor functions as a rotating element that transmits mechanical power from the engine to the wheels. In particular, the rear axle shaft plays a vital part in delivering torque to the tractor's rear wheels. One end of this shaft is connected to the differential unit, while the other end is fixed to the wheel assembly, ensuring efficient motion transfer.

Rear axle shafts are generally classified into three main designs. The half-floating type connects the wheel directly to the hub extension of the axle shaft, with the outer portion of the shaft supported by a single bearing placed inside the axle housing. The three-quarter floating design positions the wheel on the hub, where a bearing is situated between the hub and the axle shaft, allowing partial load support and improved balance. In contrast, the fully floating configuration includes an independent hub that is mounted separately to the axle casing, enabling the shaft to carry only the driving torque and not the vehicle's weight. This type of axle is often referred to as a "live axle", emphasizing its role in transmitting power while allowing independent wheel rotation.

OBJECTIVE OF WORK

In this project, a detailed investigation was conducted to evaluate the stress distribution and deformation behavior of a tractor's rear axle shaft under an applied torque of 129.9 Nm. This analysis was performed using ANSYS software, specifically through its static structural analysis module, to accurately determine how the shaft responds to the given loading conditions. The results provided valuable insights into the mechanical performance and structural integrity of the component.

The key objectives of the study are as follows:

- To substitute the traditional rear axle shaft material with an improved alternative that offers enhanced corrosion resistance, extended operational life, superior performance, and higher reliability.
- To minimize the overall stress developed in the axle shaft by employing composite materials that provide better strength-to-weight characteristics and improved mechanical efficiency.

LITERATURE REVIEW

Nanaware et al. (2003) carried out an in-depth study to identify the root causes of rear axle shaft failures in 575 DI tractors, particularly those reported during the warranty period. A considerable number of these breakdowns occurred while the tractors were engaged in puddling operations. Detailed observations pinpointed the spline section of the axle shaft as the most failure-prone region, where cracks tended to initiate at the root of the spline. The investigation linked these failures to an insufficient root radius, which weakened the structural integrity of the shaft. The researchers proposed increasing the root radius to 1.5 mm**,** applying shot peening to the spline region, and incorporating boron into the material composition to enhance fatigue strength. The study underscored the necessity of considering fatigue resistance during the design phase of the rear axle shaft to prevent similar failures in future models.

In a later study (2006), Osman et al. examined fatigue failure in the rear axle shaft of an automobile. The research analyzed a shaft subjected to both bending and torsional stresses over an extended service life of approximately nine years, which eventually led to a severe fracture near the wheel base, resulting in an accident. A microscopic evaluation, complemented by chemical analysis and Scanning Electron Microscopy (SEM)**,** revealed that improper maintenance practices played a key role. Specifically, the bearing locking ring had been attached through gas welding instead of the recommended press or shrink fitting methods, introducing stress concentration zones. Fracture initiation occurred at the welded joint, propagating toward the center of the shaft, which accounted for nearly 15% of the total cross-sectional area, consistent with low-stress, high-cycle fatigue failure**.** The shaft material was identified as AISI 4140 steel**,** whose composition was within expected limits. The investigation concluded that inadequate welding without pre- or post-heating caused brittleness in the heat-affected zone (HAZ)**,** promoting crack initiation and resulting in reverse bending fatigue failure**.**

In 2011, G. H. Farrahi and his team focused on failures in crankshafts of four-cylinder diesel engines, with all fractures localized around the first crankpin, closest to the flywheel. Using finite element analysis (FEA) and dynamic stress modeling**,** the researchers found that the first crankpin fillet experienced the highest stress concentration. However, analysis of the Soderberg diagram indicated that the operational stresses remained within the safe zone, ruling out fatigue as the failure cause. Examination using SEM revealed a cleavage fracture**,** characteristic of brittle failure due to overload rather than cyclic fatigue. The study recommended revising design and manufacturing parameters**,** particularly emphasizing improvements in the fillet rolling process, to strengthen the crankshaft and mitigate future risks.

In 2012, V. S. Rocha et al. investigated a fracture failure in the gearbox shaft of a scrap compression machine made from quenched and tempered SAE 1045 steel. The team utilized SEM**,** Energy Dispersive Spectroscopy (EDS)**,** and optical microscopy (OM) to analyze the microstructure, chemical composition, and hardness. Findings revealed a tempered martensitic microstructure with a cleavage fracture mode, confirming brittle failure. EDS analysis detected significant amounts of iron and manganese, consistent with the steel's chemical makeup. The fracture originated from the groove section of the shaft, propagating in a transangular pattern due to a combination of torsional and impact loads. The study highlighted the crucial influence of geometric stress concentration and loading conditions on the premature failure of heavy-duty shafts.

Another study in 2012 by Zhi-wei Yu, Xiao-lei Xu, Zhi Yang, and Yuan-yuan Li focused on splined shafts used in truck diesel engines that failed after only 7–8 hours of operation. The failures were characterized by transverse fractures at the root fillet connecting the tooth and cylinder portions. Both naturally failed and test specimens exhibited intergranular fractures concentrated within the carburized surface layer. The shafts were fabricated from 20MnCr5 steel, subjected to a heat treatment process involving carburization at 930°C for 4 hours, pre-cooling at 840°C for 15 minutes, oil quenching, and tempering at 180°C for 2 hours. Spectroscopic analysis confirmed the material composition. The researchers concluded that simultaneous bending and torsional stresses at the root fillet caused early-stage failures, emphasizing the need for refined heat treatment and fillet design to improve shaft durability.

In the same year, A. S. Dhavale et al. investigated camshaft performance and fracture behavior in internal combustion engines. Recognizing the camshaft's key role in valve timing and motion transfer, the study explored how improper linkage design could affect overall engine efficiency. Using dynamic modeling, including single-degree and multi-degree of freedom systems, the researchers analyzed the motion of cam-follower assemblies. Employing finite element analysis and scanning electron microscopy, they examined fracture origins and failure patterns. The findings revealed that inadequate stress distribution and improper dynamic balancing were major contributors to camshaft cracking. The research provided new insights into camshaft durability optimization, promoting enhanced engine reliability through improved material selection and design refinement.

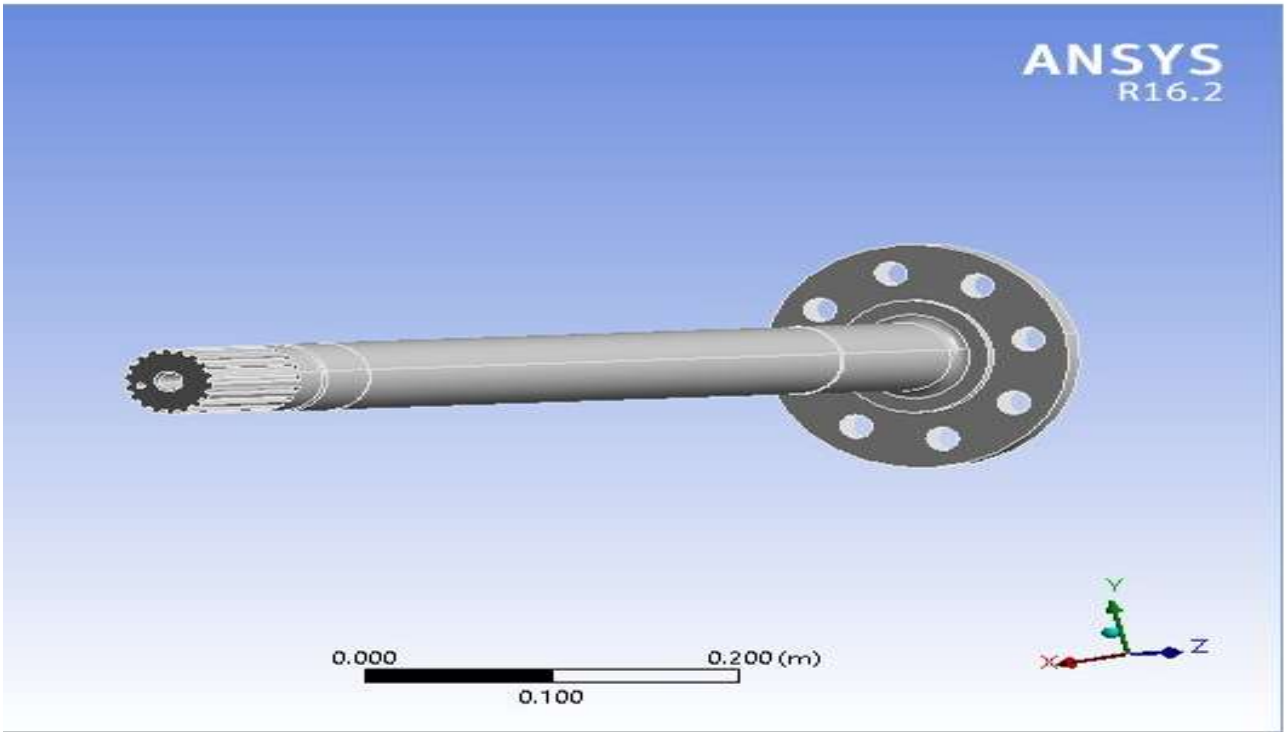
In 2013, Guruprasad and his co-researchers focused on improving rear axle housing performance using Hybrid Aluminum Composites. Their experimental investigation showed that adding fly ash as a reinforcement substantially improved the mechanical and fatigue properties compared to conventional aluminum alloys. The study calculated the fatigue safety factor under constant amplitude loading conditions ranging from 1820 N to 91000 N, corresponding to a fatigue life of approximately 8×10^5 cycles. The results indicated that hybrid composites could provide lighter, stronger, and more fatigue-resistant alternatives for rear axle housings, making them suitable for next-generation vehicle designs.

That same year, A. K. Acharya and collaborators analyzed the rear axle failure in tractors used for towing loaded trolleys. The failure was observed at the spline root, attributed to excessive weight transfer and lifting of the front wheels during haulage operations. Through experimentation, the team discovered that reducing the hitching height to 16 inches decreased the weight transfer factor by about 20%, significantly lowering the risk of rear axle damage. The study underscored the critical importance of load distribution and hitch height optimization in enhancing tractor stability and extending axle life during heavy-duty agricultural applications.

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) approach is employed to evaluate the equivalent stresses and deformation in the rear axle shaft for various material types. This analytical process is essential to identify the most suitable material configuration for the rear axle shaft, particularly when stress and deformation behavior play a crucial role in design and performance assessment.

Behavioral Assumption:

It is anticipated that a composite material will exhibit lower stress and deflection compared to its individual constituent materials. However, the primary objective of this study is to conduct a comparative evaluation of rear axle shafts made from different materials. This comparison is effectively achieved through Finite Element Method (FEM) analysis.

FEA involves creating a computer-generated model of the component under study and applying simulated loading conditions to observe the resulting stresses, deformation, and overall structural response. It provides a mathematical approximation of the real-world behavior of the component, offering results closely aligned with experimental testing, yet at a fraction of the cost and time. Through this simulation-driven approach, performance optimization can be achieved before actual prototype development and manufacturing.

The output of FEA delivers critical insights into the stress distribution and deformation within the structure, serving as a valuable predictive tool for identifying potential failure regions and design weaknesses.

Modeling and Software Utilization:

For this study, the geometric modeling of the rear axle shaft was developed using the Part and Assembly module of NX CAD**,** a design software created by Siemens PLM Software**.** Subsequently, the Finite Element Analysis was performed using the Workbench module of ANSYS**,** developed by ANSYS Inc.

FEA functions as a numerical technique that divides a complex structure into a network of smaller, simpler geometric entities known as elements**,** forming what is called a mesh. Each element carries the material and structural characteristics of the component, allowing the mesh to simulate the real behavior of the structure under defined loading conditions. The elements are interconnected by nodes**,** which form the computational framework for analysis.

Boundary conditions such as forces, moments, pressures, temperatures, and inertial effects are applied to this mesh model. The FEA program then constructs the global stiffness matrix by assembling the individual stiffness matrices of all elements, establishing the relationship between force and displacement as represented by the following equation:

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

Here, **{F}** denotes the force vector, **[K]** represents the stiffness matrix, and **{u}** corresponds to the displacement vector. By solving this equation for unknown displacements, the analysis determines how each node within the model deforms under load. The stress in every element is subsequently calculated based on these displacements.

The rear axle shaft models, created using NX CAD, are analyzed under static, linear, and elastic loading conditions as per the job requirements. The purpose of this study is to quantify the induced stresses and corresponding deflections in shafts made of different materials. These results serve as the foundation for comparing the performance of alternative rear axle shaft materials, ultimately guiding the selection of the most efficient and reliable design configuration.

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 = 30HP i.e., 23.8kW

Torque $T = P / 2 \pi n$

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

$=129.9$ Nm

Maximum Force on Differential Unit is

Force = Torque / Length

$=129.9/ 0.75$

$=173.2$ 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:

σ=F/A

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

$=2\times3.14\times0.05\times0.75 + 2\times3.14\times0.19\times0.025$

$=0.26533\ Sq\ m$

Therefore, Stress σ =2000/ 0.26

=7537.7 Pa

Main steps of F.E.A:

Pre-Processing:

The preliminary stage of Finite Element Analysis (FEA) involves several essential tasks that ensure the accuracy and reliability of the simulation. During this phase, the user performs the following activities:

- **Creation of the geometric model:** The rear axle shaft is modeled using a CAD tool to accurately represent its dimensions and geometry.
- **Assignment of material and physical properties:** All mechanical and thermal properties relevant to the analysis are defined.
- **Meshing of the model:** The component is discretized into smaller finite elements to capture detailed stress and deformation behavior.
- **Application of boundary conditions:** Constraints and external loads are applied to simulate actual operating conditions.
- **Model verification:** The entire setup is checked to confirm that all connections, elements, and boundary constraints are properly defined before the analysis begins.

Solution Phase:

In this stage, the Finite Element solver performs numerical calculations to determine the behavior of the component under applied loads. Depending on the problem requirements, the analysis can be linear, nonlinear, or dynamic in nature. Once the computation is completed, the solution is thoroughly examined to ensure that the numerical results are both stable and physically meaningful.

Post-Processing:

This phase focuses on analyzing and interpreting the results obtained from the simulation. The key tasks include:

- Identifying and correcting any errors or warnings generated during the solution process.
- Comparing the obtained results with theoretical predictions and expected physical behavior to validate the analysis.

Through the visualization of stress contours, deformation plots, and reaction forces, strain energy the post-processing step ensures that the model's response aligns with real-world performance expectations.

Basic Approach:

Geometric Modeling of Rear Axle Shaft and FEA Setup:

The main objective of the analysis is to evaluate the **stress** distribution and deflection occurring in the rear axle shaft under static loading at a particular instance. The problem is therefore treated as a static structural case. Both the geometric and finite element models are developed in three-dimensional (3D) form to accurately represent the physical and structural behavior of the component.

Units and Coordinate System:

The entire modeling and analysis procedure follows the metric system of units, which includes:

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

The global coordinate system used for the problem setup is defined as follows:

- **X-axis:** Horizontal direction
- **Y-axis:** Vertical direction
- **Z-axis:** Perpendicular to both X and Y axes

Geometric Modeling:

The 3D model of the rear axle shaft was created using NX CAD software. The design dimensions were derived from actual physical measurements to ensure precision and consistency between the virtual and real components.

Material Properties:

The analysis was conducted using a composite material formed by integrating ductile cast iron, carbon fiber, and E-glass fiber. This combination was selected to achieve an optimal balance between mechanical strength, corrosion resistance, and weight reduction, while ensuring structural stability under operational loads.

Meshing:

Meshing represents one of the most critical steps in Computer-Aided Engineering (CAE) simulations. It involves dividing the component into smaller finite elements to capture localized stress variations and deformation effects. The quality of the mesh directly affects the accuracy, convergence rate, and computational time of the simulation. In this study, an automatic meshing technique was adopted, supplemented with specific user-defined controls to refine critical regions. This approach provides a balance between computational efficiency and solution precision.

FE Loads and Boundary Conditions:

Accurate definition of loads and constraints is vital for obtaining realistic simulation results. In this analysis, the flange side of the rear axle shaft was assumed to be fixed, thereby eliminating all translational and rotational movements. A moment (torque) was applied at the spline end to replicate the actual working conditions of the tractor's drivetrain system. This configuration allows the model to simulate true mechanical behavior during field operations.

FE Model Verification:

Pre-Run Checks:

Before executing the FEA, the ANSYS Workbench software automatically verifies the model to identify potential errors such as missing material properties, disconnected nodes, or unassigned boundary conditions. If any of these inconsistencies exist, the software prevents the simulation from running. Therefore, it is the analyst's responsibility to confirm that all parameters are correctly defined before proceeding.

Post-Run Checks:

Once the analysis is completed, ANSYS generates diagnostic feedback in the form of error and warning messages. Each issue was systematically reviewed and corrected to ensure model integrity and reliable results.

When all verification criteria were met, ANSYS successfully computed the equivalent Strain Energy for each material variant of the rear axle shaft. The final results provided a detailed comparison of material performance, forming the foundation for selecting the most effective and structurally sound material for enhanced durability and efficiency.

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 265 tractor (ductile cast iron).
- The proposed composite material, developed by combining ductile cast iron, carbon fiber, and E-glass fiber to enhance strength and weight efficiency.

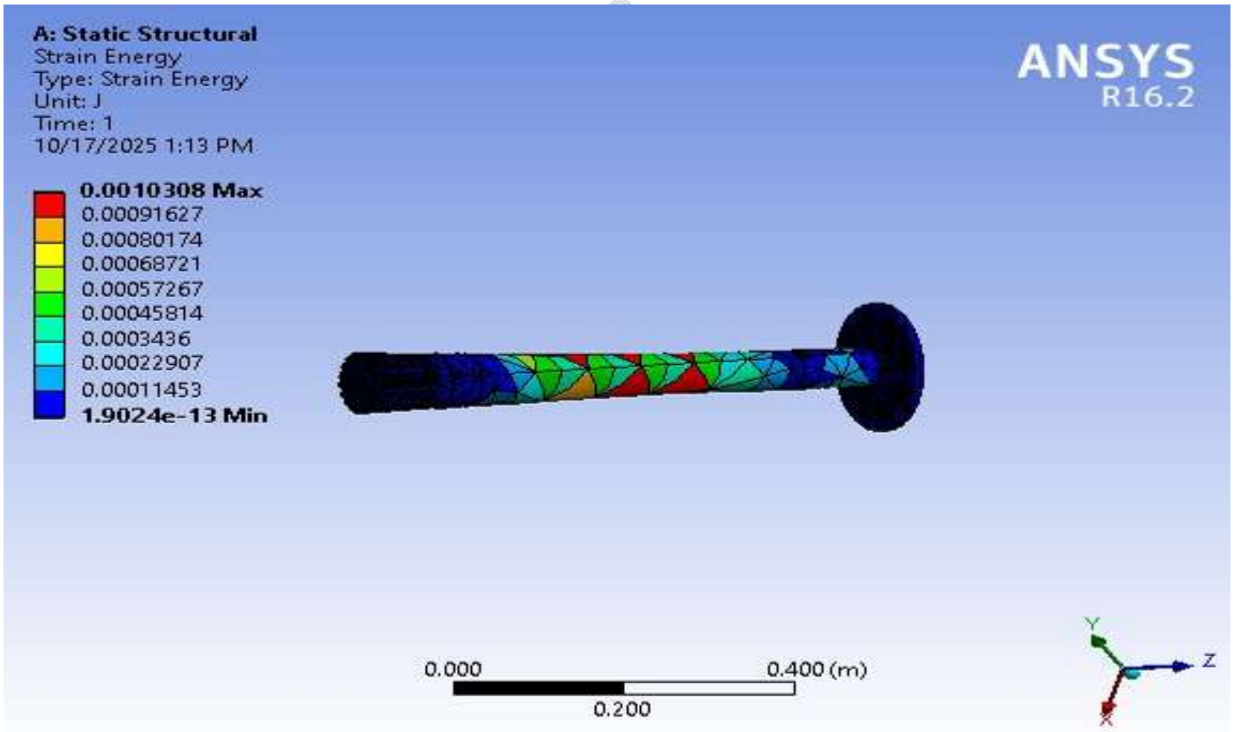
Observation from ANSYS Results

In the first image, representing the conventional Mahindra DI 365 axle shaft, the maximum strain energy was recorded at approximately 0.0010308 J, with the min. value near 1.9024×10^{-13} J. The strain energy is concentrated mainly in the middle section of the shaft, gradually decreasing toward the flange and spline ends. This indicates that the conventional shaft experiences localized energy accumulation, leading to potential stress concentration zones and reduced fatigue life.

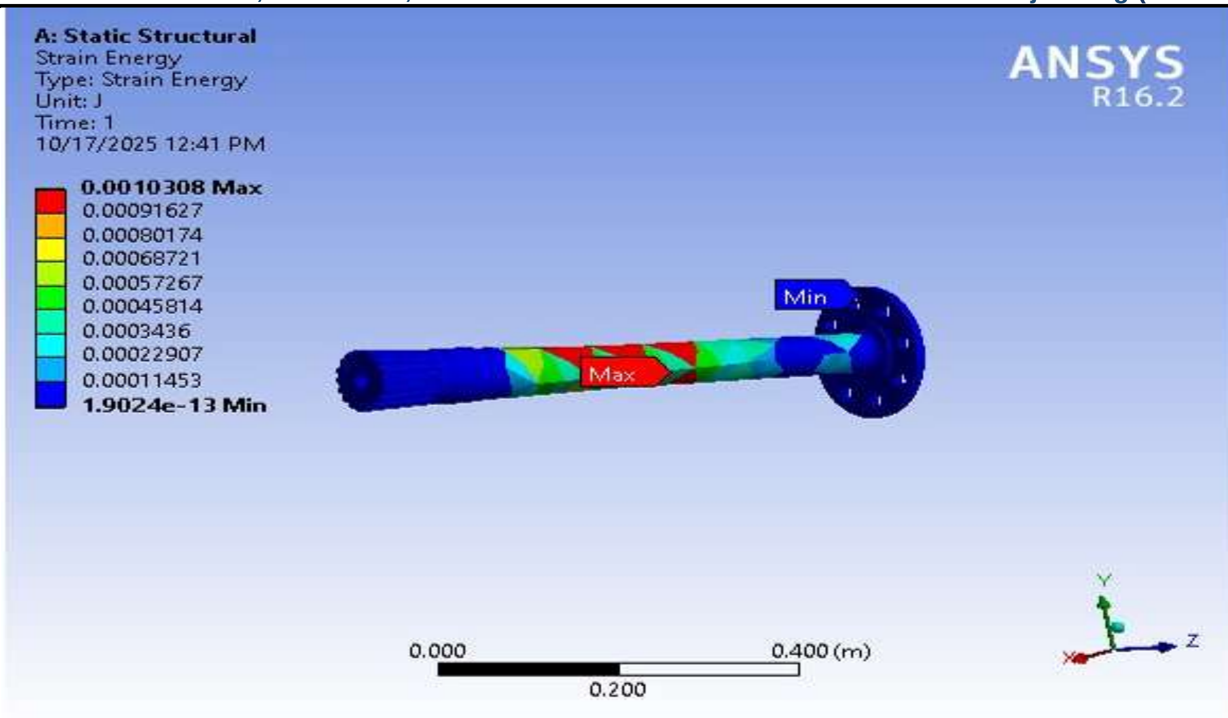
In the second image, corresponding to the composite rear axle shaft, the maximum and minimum strain energy values remain approximately the same (0.0010308 J and 1.9024×10^{-13} J, respectively). However, the distribution of strain energy is significantly more uniform along the shaft length. The composite structure shows smoother energy gradients and better load transfer, attributed to the higher stiffness-to-weight ratio and enhanced elastic properties of the composite material.

Comparative Discussion

Although both shafts exhibit nearly identical maximum strain energy values, the composite axle shaft clearly shows superior behavior in terms of energy distribution and localized strain control when compared with the conventional metallic shaft. In the composite version, the strain energy is spread more uniformly throughout the shaft's volume, ensuring that no particular region experiences excessive stress or distortion. This even distribution effectively minimizes stress concentration zones, which are often the critical points where material fatigue, crack initiation, or structural failure begin under repeated or cyclic torsional loading. The reduction of such localized high-stress areas contributes directly to the improvement of fatigue life and enhances the overall durability of the component. Moreover, this balanced energy absorption and distribution behavior reflect the inherent advantages of composite materials, such as their high stiffness-to-weight ratio and directional strength properties. As a result, under identical torsional loading conditions, the composite axle shaft not only resists deformation more efficiently but also maintains greater structural stability and operational reliability over prolonged service periods compared to a traditional metallic shaft.



Mahindra DI 365 axle shaft

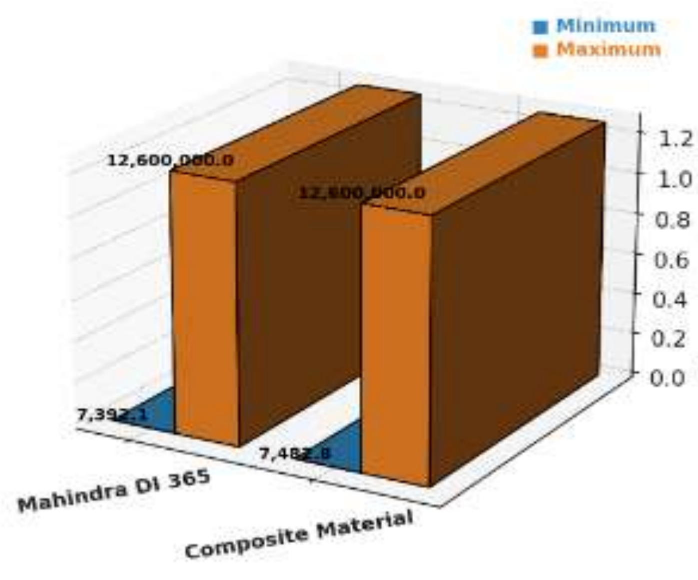


Composite Material Rear Axle Shaft

Furthermore, the lighter weight of the composite shaft reduces the overall mass of the drivetrain system without sacrificing strength, contributing to better fuel efficiency and reduced wear on associated components. Its corrosion resistance and improved fatigue endurance also make it more reliable and durable in long-term agricultural use.

CONCLUSION

The Finite Element Analysis of strain energy distribution confirms that replacing the conventional rear axle shaft of the Mahindra DI 365 tractor with the proposed ductile cast iron–carbon fiber–E-glass fiber composite offers clear advantages. The composite design maintains equivalent strain energy performance while ensuring better stress distribution, lower weight, and higher durability. Thus, the proposed composite material serves as a feasible and efficient replacement for the traditional rear axle shaft in next-generation tractor applications.



Strain Energy comparison graph of Mahindra DI 365 & Composite Material

Property 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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