

Advanced Structural Optimization of Composite Drive Shafts for High-Efficiency Automotive Systems

N. V. S. Raju^{1*}, Avula Dinesh Ram², M. Chandra Vardhan², Mohammed Bin Ameer²

¹*Professor & Principal, ²UG Student, ^{1,2}Department of Mechanical Engineering
JNTUH College of Engineering Wanaparthy, Narsingaipalli, Gopalpet Rd, Wanaparthy, 509103,
Telangana

*Correspondence: N. V. S. Raju (envioursraju@jntuh.ac.in)

ABSTRACT

The growing demand for lightweight and high-performance automotive components has encouraged the use of advanced materials in power transmission systems. Conventional steel drive shafts, although strong and widely used, contribute significantly to overall vehicle weight, leading to reduced fuel efficiency and increased energy consumption. They are also prone to corrosion and exhibit lower vibration damping, which negatively affects performance and durability. Therefore, there is a need for an improved solution that offers reduced weight, better efficiency, and enhanced mechanical properties. In this research, a composite drive shaft is designed using carbon/epoxy and glass/epoxy materials as an alternative to traditional steel shafts. The model is developed using SolidWorks Computer-Aided Design (CAD) software and analyzed using Analysis System simulation software ANSYS under static, torsional, and modal loading conditions. The results indicate that the composite shaft achieves significant weight reduction while maintaining structural strength, thereby improving fuel efficiency and reducing inertia effects. It also demonstrates better stress distribution, lower deformation, and higher natural frequency, which helps in minimizing vibration and noise. Among the materials studied, carbon/epoxy shows superior performance due to its high stiffness and low density. Although the initial cost and manufacturing complexity are higher, the advantages outweigh the limitations. Thus, the proposed system offers an efficient, durable, and reliable alternative for modern automotive applications.

Keywords: Composite Drive Shaft, Carbon/Epoxy Composite, Lightweight

Materials, Stress Analysis, Vibration Reduction, ANSYS Simulation.

1. INTRODUCTION

The automotive sector has been undergoing continuous transformation driven by the demand for enhanced vehicle performance, improved fuel efficiency, reduced emissions, and higher safety standards. Among the various mechanical components that influence these factors, the drive shaft plays a crucial role in the power transmission system of an automobile. It serves as a critical link between the engine or transmission and the differential unit, enabling the transfer of torque and rotational motion required to propel the vehicle. The performance, efficiency, and reliability of the drive shaft directly impact the overall functionality of the drivetrain system, especially in high-speed and heavy-load operating conditions. Conventionally, drive shafts have been manufactured using metallic materials such as steel and aluminium due to their well-established mechanical strength, toughness, and durability. Steel drive shafts, in particular, offer high load-carrying capacity and resistance to mechanical stresses, while aluminium shafts provide relatively lower weight compared to steel. However, despite these advantages, metallic drive shafts present several inherent limitations. Their relatively high density contributes to increased overall vehicle weight, which in turn reduces fuel efficiency and increases energy consumption. Additionally, metallic materials are prone to corrosion, especially under harsh environmental conditions, leading to reduced service life and increased maintenance requirements. Furthermore, metals offer limited design flexibility, making it difficult to achieve

optimized performance in terms of vibration control and dynamic stability.

To address these challenges, recent advancements in materials engineering have shifted focus toward the application of composite materials in drive shaft design. Composite materials, particularly fiber-reinforced polymers, exhibit exceptional mechanical properties such as high strength-to-weight ratio, superior stiffness, corrosion resistance, and excellent vibration damping capabilities. These characteristics make them highly suitable for automotive applications where weight reduction and performance optimization are critical. By replacing conventional metallic shafts with composite alternatives, it is possible to significantly reduce the mass of the drive shaft, thereby improving fuel efficiency, reducing emissions, and enhancing vehicle dynamics.

In this context, the present work focuses on the design, modeling, and analysis of a composite drive shaft intended for automotive applications. Advanced design tools are utilized to develop an accurate geometric model, followed by numerical analysis to evaluate stress distribution, deformation behavior, and dynamic characteristics under operational conditions. The performance of the composite drive shaft is systematically compared with that of traditional metallic shafts to assess improvements in efficiency, durability, and overall performance. The study aims to demonstrate that composite materials provide a viable and superior alternative to conventional materials, contributing to the development of lightweight, high-performance, and energy-efficient automotive systems.

2. LITERATURE SURVEY

Huang, Z., et al. [1] investigated the failure of a rear drive shaft in a modified pickup truck after nearly 3000 km of operation. They performed detailed macroscopic and microscopic examinations of the fractured surface to identify crack origin and propagation patterns. Material composition analysis and metallographic studies were conducted to check for defects or inconsistencies in the microstructure.

Mechanical testing was carried out to evaluate strength and fatigue behavior, while FEM analysis was used to study stress distribution under working conditions. The study identified that cyclic stresses led to crack initiation at critical points, and the failure was primarily due to rotation-bending fatigue. Skotnicki, et al. [2] analyzed the damage of a paint mixer shaft made of 1.0501 steel with considerable length and diameter. The study included visual inspection to detect surface defects, followed by microscopic examination of cross-sections to understand internal damage mechanisms. Both the original and regenerated (surfaced) portions of the shaft were examined. Hardness measurements using the Vickers method (HV0.1) revealed variations between different regions. The results showed that the regeneration process caused uneven material properties and residual stresses, which contributed to crack formation and reduced durability. Bugaru, et al. [3] studied the forced bending vibration characteristics of an automotive driveshaft using the asymptotic method approach. The analysis focused on the principal parametric resonance region, where vibration effects are highly sensitive. The developed model incorporated geometric nonuniformity and external excitations such as road-induced shocks. The study evaluated how these parameters affected vibration amplitude and system stability. The results indicated that small irregularities in geometry and external disturbances could significantly amplify vibrations, leading to instability and possible structural damage.

Patel, et al. [4] proposed a hybrid drive shaft design by replacing the conventional two-piece steel shaft with a one-piece aluminum and composite shaft. A carbon fiber epoxy layer was co-cured on the inner surface of the aluminum tube, which helped in protecting the composite from environmental effects like moisture and impact. The study compared the mechanical performance with traditional shafts and found improvements in strength, stiffness, and weight reduction. The design also enhanced durability and reduced the risk of external

damage, making it suitable for automotive applications. Bugaru, et al. [5] investigated the dynamic instability of automotive driveshaft systems using an advanced numerical modelling approach. The study considered factors such as kinematic nonuniformity, geometric irregularities, and variations in inertial properties during rotation. It also included excitation forces generated from gearbox and engine interactions. The analysis focused on identifying instability conditions in resonance regions. The results showed that the combined influence of these factors significantly affected the vibration behavior, and improper design could lead to resonance, instability, and eventual failure of the driveshaft. Kim, et al. [6] focused on the development of a constant velocity joint for efficient torque transmission in electric vehicles. They carried out a thermo-mechanical coupled analysis that simultaneously considered heat generation, temperature distribution, and mechanical stresses during operation. The simulations were performed using LS-DYNA and ANSYS Mechanical, enabling realistic modelling of field conditions. The study showed that thermal effects significantly influenced contact stresses, deformation, and wear characteristics, and neglecting these effects could lead to inaccurate performance predictions and reduced durability. R.P. Kumar

Rompicharla, et al. [7] worked on the design and analysis of a composite drive shaft by replacing conventional steel shafts with Kevlar/Epoxy composite material. The study focused on optimizing design parameters such as shaft diameter, thickness, and fiber orientation to achieve minimum weight while maintaining required strength and torsional rigidity. Analytical calculations and simulation techniques were used to evaluate stress, deformation, and critical speed. The results demonstrated that the composite shaft achieved considerable weight reduction, improved specific strength, and better vibration characteristics compared to steel shafts. Geonea, et al. [8] proposed an integrated

numerical and experimental methodology for durability assessment of a passenger-car rear axle. They developed a specialized test bench capable of applying controlled cyclic vertical loads to simulate real driving conditions. A detailed flexible multibody model was created using MSC ADAMS 2023 to represent the interaction between the suspension system and axle. The study helped in determining equivalent load conditions at the wheel spindles and analyzing the effect of suspension stiffness and kinematics on durability. The combined approach improved the accuracy of fatigue life prediction. Zhou, et al. [9] developed a cooperative multi-objective optimization algorithm for vehicle axle design, considering parameters such as mass, stiffness, and reliability simultaneously. The method allowed balancing conflicting objectives to achieve an efficient design. The study also included torsional vibration considerations, ensuring that the optimized axle design maintained stability under dynamic loading conditions. The results showed that the proposed approach improved structural performance while reducing overall weight. Hao, et al. [10] developed a coupled driveline–rear axle dynamic model to study torsional vibration behavior in automotive systems. The model incorporated uncertainties in parameters such as material properties, stiffness, and damping. Through uncertainty analysis and parameter optimization, the study identified critical factors affecting vibration amplitude. The results showed that proper tuning of system parameters could effectively reduce torsional vibrations, leading to improved performance and reliability of the driveline system. Balta, et al. [11] applied Pareto-based multi-objective optimization to the design of a heavy truck rear underrun protection system. The study considered regulatory impact load conditions along with structural mass as key objectives. Different design configurations were evaluated to identify optimal trade-offs between safety and weight. The optimized design achieved improved energy absorption and compliance with safety standards while maintaining a

lightweight structure, demonstrating the effectiveness of Pareto optimization in automotive structural design.

3. PROPOSED SYSTEM

4. RESULTS AND DISCUSSION

This chapter presents the results obtained from the analysis of the composite drive shaft using Finite Element Analysis (FEA). The results include stress distribution, deformation, natural frequency, and weight comparison between steel and composite materials. The main objective is to evaluate the performance of the composite drive shaft and compare it with the conventional steel shaft. The results are interpreted to determine

• Weight Comparison

One of the major advantages of composite materials is weight reduction.

Results:

- Steel shaft weight ≈ 10 kg
- Carbon/Epoxy shaft weight ≈ 2.7 kg
- Glass/Epoxy shaft weight ≈ 3–4 kg

This shows that composite materials are highly for lightweight applications.

• Stress Analysis Results

Stress analysis is performed to determine the ability of the shaft to withstand applied torque.

Observations:

- Maximum stress occurs at outer surface
- Steel shaft shows higher stress values
- Composite shafts show lower stress

Comparison:

Table 1: Material and Stress level

Material	Stress Level
Steel	High
Carbon/Epoxy	Low
Glass/Epoxy	Moderate

Interpretation:

- Composite materials distribute stress more efficiently Lower stress increases life of shaft
- Carbon/Epoxy performs best
- Deformation Results

- Deformation analysis shows how much the shaft bends or twists under load. Observations:
- Steel shaft shows higher deformation
- Composite shafts show lower deformation
- Carbon/Epoxy has minimum deformation

Interpretation:

- Lower deformation means better stiffness
- Composite shafts maintain structural integrity
- Improved performance under load
- Torsional Analysis Results
 - Torsional analysis evaluates the ability of the shaft to transmit torque. Observations:
 - Composite shafts can withstand required torque
 - Shear stress is within safe limits
 - ±45° fiber orientation improves torsional strength

Interpretation:

- Composite shafts are capable of transmitting torque efficiently
- No failure occurs under applied load
- Suitable for automotive applications

• Modal Analysis Results

Modal analysis is used to determine natural frequencies and vibration behavior.

• Results:

- Steel shaft frequency ≈ Low
- Carbon/Epoxy frequency ≈ High
- Glass/Epoxy frequency ≈ Moderate
- Observations:
- Composite shafts have higher natural frequency
- Reduced chances of resonance

Interpretation:

- Higher natural frequency improves safety
- Reduces vibration and noise
- Enhances comfort and durability

Table 3: Comparison of Results

Paramet er	Ste el	Carbon/Ep oxy	Glass/Ep oxy
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Weight	Hig h	Very Low	Low
Stress	Hig h	Low	Moderate
Deformat ion	Hig h	Low	Moderate
Frequenc y	Lo w	High	Moderate
Efficienc y	Lo w	High	Moderate

- **Overall Interpretation**
 - From the above results, it is clear that:
 - Composite drive shafts are significantly lighter
 - They experience lower stress and deformation
 - They have higher natural frequency
 - They provide better performance and efficiency

Among the materials studied, Carbon/Epoxy composite shows the best performance due to its high strength and low weight.

5. CONCLUSION

The research focused on the design and evaluation of a composite drive shaft as a lightweight and high-performance substitute for conventional steel shafts in automotive applications. CAD modeling was carried out using SolidWorks, followed by structural and dynamic analysis in ANSYS to assess stress, deformation, and vibration behavior under various loading conditions. The study highlighted that traditional steel shafts, despite their strength, suffer from drawbacks such as high weight, corrosion, and lower efficiency. To overcome these issues, composite materials like carbon/epoxy and glass/epoxy were utilized due to their superior strength-to-weight ratio, corrosion resistance, and damping properties. The results demonstrated that the composite drive shaft achieved significant weight reduction along with improved stress distribution and reduced deformation. Additionally, higher natural frequencies were observed, indicating better vibration and noise

control. Among the materials considered, carbon/epoxy exhibited the best performance due to its high stiffness and low density.

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