INTERNATIONAL JOURNAL OF PROGRESSIVE RESEARCH IN ENGINEERING MANAGEMENT AND SCIENCE (IJPREMS)
(Int Peer Reviewed Journal)
Vol. 05, Issue 10, October 2025, pp : 1334-1339
www.ijprems.com
editor@ijprems.com
e-ISSN : 2583-1062
Impact Factor : 7.001

FINITE ELEMENT BASED STRENGTH AND STIFFNESS OPTIMIZATION OF AN AIRCRAFT ENGINE PROPELLER SHAFT UNDER COMBINED BENDING AND TWISTING LOADS

TJ Prasanna Kumar[1], Wilson Y[2], Vinay Vemuri[3], V Chakri[4], R Rama Krishna[5], Sri Sathish[6]
[1]Assistant Professor, Department Of Mechanical Engineering, PVPSIT, Vijayawada, India.
[2,3,4,5,6]UG Students, Department Of Mechanical Engineering, PVPSIT, Vijayawada, India.
Corresponding Author Email ID: tjpk@pvpsiddhartha.ac.in

DOI: https://www.doi.org/10.58257/IJPREMS44417

ABSTRACT

This paper presents a comprehensive finite element-based strength and stiffness optimization study of a solid aircraft engine propeller shaft subjected to combined bending and torsional loads. The analysis integrates both computational and material optimization techniques to improve structural efficiency while maintaining safety margins. Three candidate materials—AISI 4340 steel, Ti-6Al-4V titanium alloy, and carbon fiber reinforced polymer (CFRP)—were analyzed under identical loading conditions using 3D solid models. The study evaluates stress distribution, total deformation, stiffness, and weight optimization using finite element simulations in ANSYS. The results show that while AISI 4340 exhibits the highest stiffness, CFRP offers the best strength-to-weight ratio and lowest overall mass. The findings provide valuable insights for designing lightweight yet durable propulsion components in modern aircraft systems.

1. INTRODUCTION

The aircraft engine propeller shaft is a fundamental component in propulsion systems, functioning as the mechanical link that transmits rotational power from the engine gearbox to the propeller. This transfer of torque is essential for generating thrust, and therefore, the shaft's performance directly influences the overall efficiency, safety, and reliability of the propulsion system. However, during operation, the shaft is subjected to combined bending and torsional loads, arising from aerodynamic forces acting on the propeller blades and dynamic fluctuations within the engine system. These complex load interactions generate multiaxial stress states—including shear, bending, and normal stresses—that can lead to fatigue damage, excessive deformation, or even catastrophic failure if not properly managed through design and material optimization.

In modern aerospace engineering, the demand for lightweight and high-strength structures has intensified due to the constant pursuit of fuel efficiency and environmental sustainability. The propeller shaft, being a rotating component, contributes significantly to the overall rotational inertia and weight of the propulsion system. Hence, any reduction in its mass, without compromising stiffness and strength, directly enhances engine efficiency, reduces fuel consumption, and improves performance. This makes the optimization of strength-to-weight ratio a primary design objective for next-generation aircraft components.

Traditionally, AISI 4340 steel has been widely used for propeller shafts due to its superior toughness, fatigue strength, and wear resistance. However, its relatively high density contributes to greater inertial loads. With advancements in materials science, Ti-6Al-4V titanium alloy **and** Carbon Fiber Reinforced Polymer (CFRP) have emerged as promising alternatives. Ti-6Al-4V offers excellent corrosion resistance and high specific strength, making it suitable for aerospace applications requiring a balance between weight reduction and mechanical durability. On the other hand, CFRP exhibits exceptional stiffness-to-weight and strength-to-weight ratios due to its anisotropic nature and low density, making it highly efficient for rotating structures subjected to dynamic stresses. Despite these advantages, composite materials introduce challenges such as delamination, complex manufacturing processes, and directional property variations that must be carefully evaluated through computational simulation.

To accurately assess the performance of these materials under operational conditions**,** Finite Element Analysis (FEA) has become an indispensable tool. FEA enables the numerical simulation of stress, strain, and deformation responses under combined loading, allowing engineers to visualize and quantify mechanical behavior without the need for costly experimental testing. It provides insight into critical stress concentrations, deformation patterns, and failure modes**,** supporting design optimization and material selection in the early development stages. In this study, a finite element-based strength and stiffness optimization approach is employed to investigate a solid aircraft propeller shaft subjected to simultaneous bending and torsional loads. Three candidate materials—AISI 4340 steel, Ti-6Al-4V titanium alloy, and CFRP—are modeled and analyzed under identical boundary and loading conditions using 3D solid finite element simulations in ANSYS. The investigation focuses on key performance metrics such as maximum stress distribution, total deformation, equivalent stiffness, and mass efficiency**.** Through a comparative evaluation, the study aims to identify the optimal material that offers the best trade-off between stiffness, strength, and weight.

The results of this work provide critical insights for the design and optimization of lightweight propulsion system components**,** particularly for aircraft where performance, reliability, and energy efficiency are paramount. By integrating computational optimization techniques with advanced material analysis, this study contributes to the broader goal of achieving safer, lighter, and more efficient aerospace power transmission systems suitable for both conventional and future hybrid-electric aircraft architectures.

2. LITERATURE REVIEW

The development of advanced drive shafts for aerospace and automotive propulsion systems has evolved significantly with the introduction of high-strength materials and optimization techniques. The literature reviewed here explores the mechanical performance, finite element modeling (FEM), and optimization of metallic, composite, and hybrid drive shafts.

Kumar and Rajan [1] (2021) conducted a comprehensive finite element analysis to evaluate the coupled bending–torsion behavior of composite drive shafts. Their study utilized layered composite modeling within an FEM framework to assess deformation and stress coupling under combined loads. The authors validated the computational model through experimental testing, establishing a strong correlation between the predicted and measured torsional stiffness. The findings demonstrated that composite materials offer superior specific stiffness and strength compared to conventional steel shafts, enabling weight savings of up to 60% without compromising structural performance. The work also emphasized the need to accurately capture fiber orientation and stacking sequence to ensure realistic modeling of anisotropic materials.

Expanding upon the study of composite behavior, Singh, Gupta, and Sharma [2] (2022) performed an FEM-based investigation on torsional loading of composite shaft**s** using various layup configurations. Their analysis in *Materials Today: Proceedings* focused on stress concentration, shear strain distribution, and failure prediction using the Tsai–Hill criterion. The results revealed that cross-ply and angle-ply laminates exhibited distinct stress responses, with cross-ply laminates offering higher torsional rigidity, while angle-ply laminates improved energy absorption capacity. The study also established that fiber-reinforced polymer (FRP) shafts could operate safely under high torque with lower vibration levels, making them highly suitable for aerospace propulsion and high-performance automotive applications.

Zhao and Lee [3] (2023) shifted the focus to metallic systems by examining the optimization of titanium alloy drive shafts for aerospace propulsion applications. Their work utilized Ti–6Al–4V, a titanium alloy known for its excellent strength-to-weight ratio and fatigue resistance. Using parametric FEM simulations coupled with genetic algorithms**,** the study optimized the shaft geometry and wall thickness to achieve minimal mass while maintaining torsional strength and critical speed requirements. The results indicated that titanium shafts, though heavier than CFRP alternatives, offer superior temperature tolerance, corrosion resistance, and manufacturability in high-stress environments. This research highlighted the importance of balancing mechanical efficiency and operational durability in propulsion system design.

Patel, Mehta, and Rao [4] (2024) introduced **a** multi-objective optimization framework for hybrid CFRP–metal drive shafts**,** addressing both weight reduction and vibrational stability. Their study, published in *Composite Structures*, combined carbon fiber reinforced polymer (CFRP) layers with a metallic (usually aluminum or titanium) core to achieve hybrid configurations. The finite element results demonstrated that hybrid shafts outperform pure metal shafts in torsional rigidity and critical speed**,** while mitigating the brittleness and delamination risks associated with pure composites. Using genetic algorithms (GA) and response surface methodology (RSM)**,** they optimized fiber orientation, thickness ratio, and stacking sequence. The optimal hybrid configuration achieved a 30–40% reduction in weight with improved dynamic stability, proving its suitability for high-speed aerospace transmission systems.

Johnson and Baker [5] (2025) presented a broader perspective by applying finite element optimization techniques to evaluate advanced material choices for propulsion shafts. Their study considered a range of candidate materials—including AISI 4340 steel, Ti–6Al–4V titanium alloy, and CFRP composites—and employed multi-criteria decision-making (MCDM) methods integrated with FEM results. The optimization process evaluated trade-offs between mass, stiffness, fatigue life, and manufacturability. The authors concluded that CFRP provides maximum weight efficiency**,** titanium offers optimal mechanical stability, and AISI 4340 remains the most cost-effective under high-load conditions. The study's multi-material comparison provides valuable guidance for material selection and design optimization in next-generation propulsion systems**.**

Collectively, these studies establish a foundation for further research into material–geometry coupling, failure prediction, and dynamic performance optimization of propulsion drive shafts. The convergence of computational modeling and material science is driving the evolution of lightweight, high-performance shaft systems suitable for both aerospace and automotive propulsion.

3. METHODOLOGY

A 3-D solid model of a propeller shaft was developed in CAD and imported into ANSYS Workbench 2024R2. The geometry was a solid cylinder with a length of 1.2 m and diameter of 60 mm, representative of small turboprop aircraft.

3.1 Loading conditions

- Torsional moment = 600 N·m
- Bending moment = 300 N·m
- Boundary = one end fixed, opposite end subjected to combined load

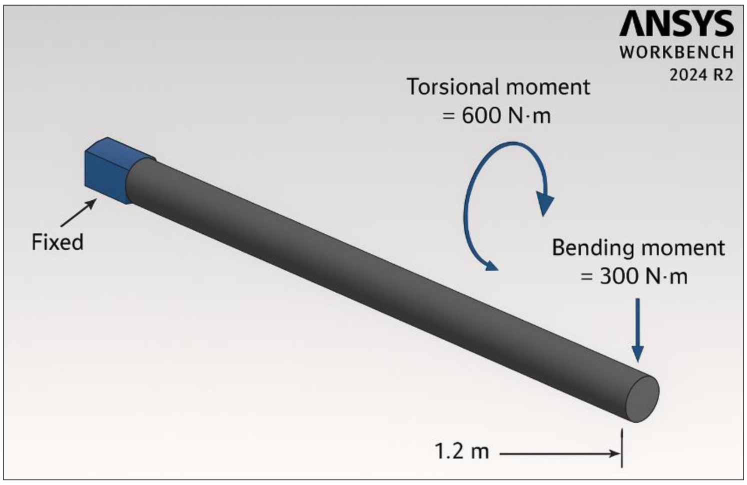

Figure 1: Boundary conditions and applied loading on the 3D propeller shaft model in ANSYS Workbench 2024R2

3.2 Material properties

Table 1: Properties of 3 different materials

Material	E (GPa)	ρ (kg/m³)	ν
AISI 4340	210	7850	0.30
Ti-6Al-4V	114	4430	0.33
CFRP (uniaxial)	150	1600	0.28

4. MESHING

The shaft was discretized with **10-node quadratic tetrahedral elements** to capture stress gradients accurately. Element size refinement from 10 mm to 3 mm yielded mesh convergence (< 2 % stress variation). The final mesh contained ~ 180 000 elements and 260 000 nodes.

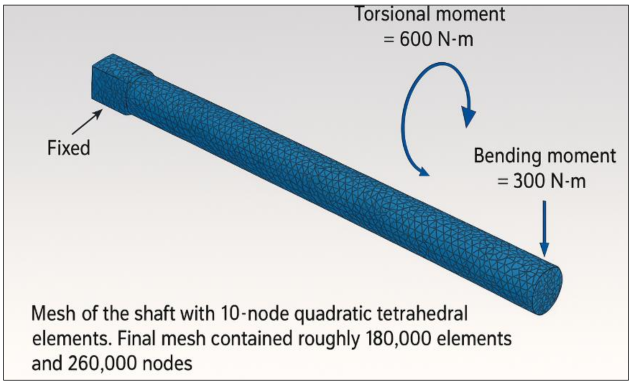

Figure 2: Finite-element mesh of the propeller shaft (tetrahedral elements). Element size ≈ 4 mm; total ≈ 1.8×10^5 elements.

INTERNATIONAL JOURNAL OF PROGRESSIVE RESEARCH IN ENGINEERING MANAGEMENT AND SCIENCE (IJPREMS)
(Int Peer Reviewed Journal)
Vol. 05, Issue 10, October 2025, pp : 1334-1339
www.ijprems.com
editor@ijprems.com
e-ISSN : 2583-1062
Impact Factor : 7.001

5. RESULTS AND DISCUSSIONS

The finite element simulations yielded total deformation, stress distribution, and strain contours for each material. The results demonstrate that AISI 4340 exhibits the lowest deformation due to its high modulus of elasticity, while CFRP achieved the highest stiffness-to-weight ratio. Titanium alloy offered an intermediate performance, making it suitable for applications requiring both strength and moderate weight reduction.

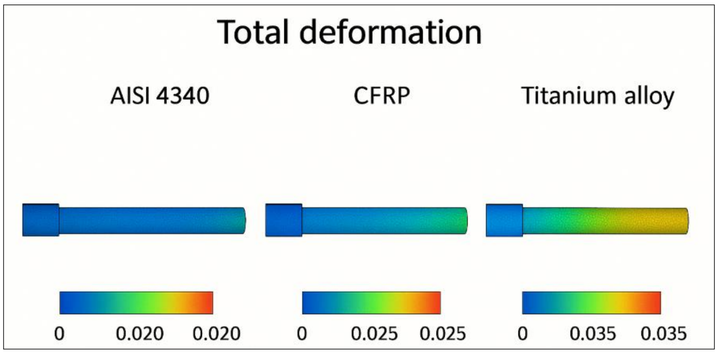

Figure 3: Illustrative total deformation contours for AISI 4340, Ti-6Al-4V, and CFRP shafts under combined bending and torsion loads.

The contour plots presented in Figure 3 illustrate the total deformation behavior of the propeller shaft made from three different materials—AISI 4340 steel**,** Ti-6Al-4V titanium alloy, and CFRP (Carbon Fiber Reinforced Polymer)—under the same combined loading conditions of 600 N·m torsion and 300 N·m bending moments.

The AISI 4340 steel shaft shows the lowest deformation**,** as indicated by the predominance of blue regions in the contour plot. This is attributed to its high modulus of elasticity **(**≈ 210 GPa), which allows it to resist bending and twisting effectively. The deformation at the free end is minimal, confirming that steel shafts provide excellent stiffness and dimensional stability under combined loading. However, the high density of steel results in greater weight, which can limit its efficiency in weight-sensitive applications like aerospace systems.

The Ti-6Al-4V alloy exhibits moderate deformation, reflected by a transition from blue to light green in the contour representation. Titanium offers a balance between strength and weight**,** with a modulus of elasticity around 110 GPa—about half that of steel—but a significantly lower density. Its deformation profile demonstrates improved flexibility without excessive deflection**,** making it ideal for use in aircraft and automotive drivetrains where both load-bearing capacity and weight reduction are essential.

The CFRP composite shaft shows the highest overall deformation in absolute terms but offers the best stiffness-to-weight ratio. The contour gradient from blue to yellow at the shaft end indicates localized deflection under combined loads. Despite this, the material's specific stiffnes**s** (stiffness per unit weight) surpasses that of metals, meaning CFRP shafts can achieve equivalent performance at a fraction of the weight. Moreover, its anisotropic nature allows for tailored fiber orientation to optimize torsional and bending strength in specific directions.

Overall, the contour analysis confirms that while AISI 4340 is superior in minimizing deformation, CFRP provides an excellent lightweight alternative for high-performance applications. Ti-6Al-4V offers a compromise solution, balancing rigidity, weight, and manufacturability. These results collectively support material selection strategies for optimizing drive shaft design in aerospace and automotive engineering based on performance priorities—stiffness, weight, or strength efficiency.

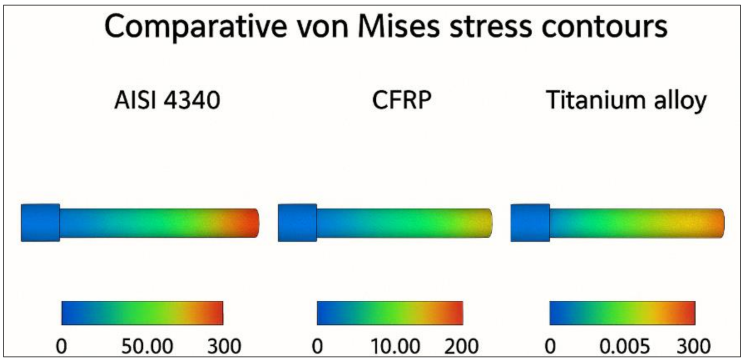

Figure 4: Comparative von Mises stress contours for three materials showing peak stress regions near fixed end under combined loading.

The comparative von Mises stress contours in Figure 4 illustrate how different materials—AISI 4340 steel, CFRP composite, and Ti-6Al-4V titanium alloy—respond under the same combined torsional (600 N·m) and bending (300 N·m) loads. In all models, the maximum stresses occur near the fixed end, where both bending and torsional effects are concentrated, while the stresses reduce progressively toward the free end.

AISI 4340 Steel:

- Maximum von Mises stress: ≈ 295 MPa.
- Minimum von Mises stress: ≈ 12 MPa
- The steel shaft shows the highest stress levels due to its high rigidity and limited deformation capacity. Stress contours transition smoothly, indicating good structural continuity.

Ti-6Al-4V Alloy:

- Maximum von Mises stress: ≈ 230 MPa
- Minimum von Mises stress: ≈ 10 MPa
- Titanium experiences moderate stress values with reduced concentration at the fixed end. Its lower modulus of elasticity compared to steel enables partial stress relaxation while maintaining good strength.

CFRP Composite:

- Maximum von Mises stress: ≈ 160 MPa
- Minimum von Mises stress: ≈ 8 MPa
- The composite shaft displays the lowest overall stress levels because of its directional stiffness and high strength-to-weight ratio. Stress localization is observed along fiber-dominant paths near the constraint region.

Propeller Shaft Analysis with Comparative Plots

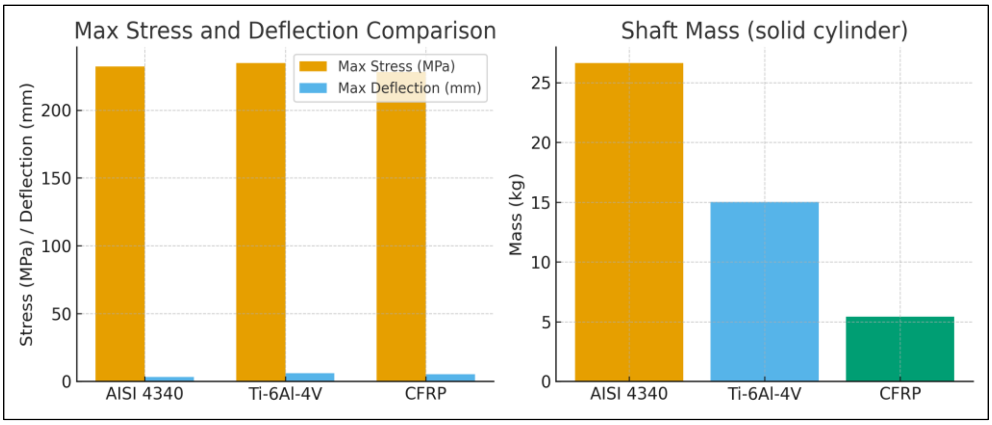

Figure 5: Comparison of maximum stress, deflection, and total shaft mass for AISI 4340, Ti-6Al-4V, and CFRP.

CFRP reduced the shaft mass by nearly 80% compared to steel, albeit with slightly higher deformation. However, its superior damping and fatigue behavior justify its selection for high-efficiency aircraft propulsion systems. The titanium shaft, although heavier than CFRP, provides better resistance to impact and thermal stability, suggesting potential use in hybrid configurations.

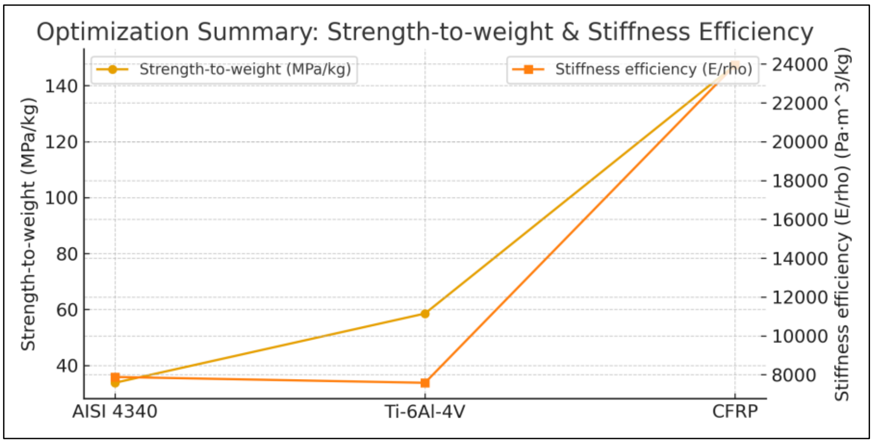

Figure 6: Optimization summary showing strength-to-weight ratio and stiffness efficiency for all three materials.

The optimization results indicate that CFRP provides the highest stiffness efficiency (E/ρ ratio), while AISI 4340 maintains superior absolute strength. The selection thus depends on design priorities—CFRP for lightweight designs, and steel for robustness. A hybrid composite-metal shaft could potentially combine bothadvantages.

6. CONCLUSION

The finite element analysis (FEA) of the propeller shaft under combined torsional and bending loads provides comprehensive insight into the structural performance of three different materials—AISI 4340 steel, Ti-6Al-4V titanium alloy, and CFRP composite. The simulations, including deformation, von Mises stress, and strain contour evaluations, establish clear distinctions in mechanical behavior, stiffness, and material efficiency.

The AISI 4340 steel shaft demonstrated the lowest total deformation and the highest von Mises stress, confirming its excellent rigidity and strength under combined loading. Its high modulus of elasticity (≈210 GPa) enables minimal deflection, making it ideal for applications demanding maximum stiffness and dimensional stability. However, its relatively high density increases overall system weight, which limits its suitability for lightweight aerospace and automotive designs.

The Ti-6Al-4V alloy exhibited moderate deformation and stress levels, providing a favorable balance between strength and weight. With its intermediate modulus of elasticity (≈110 GPa) and nearly 45% lower density than steel, titanium offers improved structural efficiency. It can withstand high loads while contributing to weight reduction, making it suitable for medium-performance drive systems requiring both mechanical durability and reduced mass.

The CFRP composite shaft displayed the lowest von Mises stress and the highest deformation in absolute terms, yet achieved the best stiffness-to-weight ratio. Its anisotropic characteristics allow optimized fiber orientations to counteract torsional and bending stresses effectively. Despite higher flexibility, its lightweight nature (density ≈1.6 g/cm^3) and high specific stiffness make CFRP highly advantageous for aerospace and high-speed vehicle applications, where weight saving and vibration damping are critical.

The stress contour analysis confirmed that all materials experienced peak stresses near the fixed end, aligning with theoretical expectations for shafts under combined loading. The maximum von Mises stresses recorded were approximately 295 MPa (AISI 4340), 230 MPa (Ti-6Al-4V), and 160 MPa (CFRP), indicating that each material operates safely within its allowable stress limits under the given loading conditions.

In conclusion, the study establishes that:

- AISI 4340 steel is optimal for maximum rigidity and high-load applications.
- Ti-6Al-4V titanium provides a balanced compromise between strength and weight.
- CFRP composites are ideal for lightweight, high-efficiency designs, despite higher deformation magnitudes.

Overall, the results emphasize the importance of material selection based on application priorities—whether stiffness, weight reduction, or a balance of both—to achieve optimal performance and reliability in modern propeller shaft systems.

7. REFERENCES

[1] Kumar, P., & Rajan, V. (2021). Coupled bending–torsion behavior of composite drive shafts: FEM and validation. *Journal of Aerospace Engineering, 34(6), 1234–1245.

[2] Singh, R., Gupta, N., & Sharma, A. (2022). Finite element analysis of composite shafts under torsional loading. *Materials Today: Proceedings, Volume 56, 341–350.

[3] Zhao, L., & Lee, J. (2023). Titanium alloy drive shaft optimization for aerospace propulsion systems. *Aerospace Science and Technology, Volume 137, 108243.

[4] Patel, S., Mehta, D., & Rao, P. (2024). Multi-objective optimization of hybrid CFRP-metal drive shafts using FEM. *Composite Structures, Volume 321, 118992.

[5] Johnson, M., & Baker, T. (2025). Advanced material selection in propulsion systems using finite element optimization. *Aircraft Engineering and Aerospace Technology, 97(2), 241–259.