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Study of Design and Analysis of S-glass Fiber Reinforced Epoxy Polymer Metal Laminate Composites in the Application of Propeller Shafts

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Abstract

The propeller shafts are utilized to transmit power from gear box to rear wheels in automobiles. It is found that the weight, cost, critical speed and buckling of shafts are the serious issues in conventional metallic propeller shafts. The propeller shafts made up of composite material are best suited for LMV due to single piece manufacturing. The fiber metal laminate propeller shafts are getting popular as the metal liner adds extra strength, rigidity and acts as a substrate and avoids leaking during manufacturing. The propeller shaft of light motor vehicle was selected for study. S-glass fibers, epoxy and a thin mild steel liner are the materials chosen. The design of the shaft was carried out according to ASME Standard code of design. The ply orientation and stacking sequence are selected as [±45°, 0°, 90°], to increase the torsional strength, enhance natural frequency and buckling strength respectively. The finite element analysis of the propeller shaft is carried out in Ansys APDL. It is found from the analysis that the weight, torsional strength, torsional stiffness and natural frequency of the S-glass fiber reinforced Epoxy Metal Laminate (FML) composites are superior than the conventional C-35 alloy steel material, and hence can be an alternative to the conventional alloy steel shaft.

Keywords: Ansys APDL, ASME, FML, LMV

1. Introduction

In modern engineering, the quest for lightweight yet robust materials has become a focal point, particularly in the domain of propulsion systems for various industries. Propeller shafts, critical components in marine, aerospace, and automotive applications, are subjected to demanding operational conditions, including high torque, cyclic loading, and exposure to harsh environments. Traditional materials such as steel and aluminium have been extensively used for these applications; However, advancements in composite materials have paved the way for innovative solutions that offer superior performance characteristics.

Among these composites, S-Glass Fiber Reinforced Epoxy Polymer Metal Laminate Composites (S-GFRP-MLCs) have emerged as a promising alternative due to their remarkable combination of strength, stiffness, and corrosion resistance. This study aims to explore the design and analysis of S-GFRP-MLCs specifically tailored for use in propeller shafts, assessing their mechanical properties, structural integrity, and overall performance in comparison to conventional metallic shafts.

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The use of advanced materials in propeller shafts offers several advantages over conventional materials. Firstly, the lightweight nature of composites significantly reduces the overall weight of the shaft, leading to reduced inertia and improved energy efficiency. This characteristic is of utmost importance in the automotive and aerospace sectors, where fuel consumption and emissions are primary concerns.

Secondly, S-GFRP-MLCs exhibit excellent fatigue resistance and durability, which are crucial factors considering the cyclic loading experienced by propeller shafts. The potential for extended service life and reduced maintenance requirements enhances the economic viability of adopting these composites in critical applications.

Moreover, S-GFRP-MLCs can be tailored through advanced design techniques to provide anisotropic material properties, allowing engineers to optimize the shaft's performance for specific loading conditions and operational requirements. This versatility opens new avenues for customization and innovation in propeller shaft design.

However, challenges persist in the integration of these composites into propeller shaft applications. Complexities related to composite manufacturing processes, the selection of appropriate layering sequences, and bonding with metallic components require careful consideration to ensure reliable and consistent performance. Moreover, while composite materials offer substantial benefits, understanding the limitations and addressing potential failure modes is essential to ensure safety and reliability in demanding environments.

This study endeavours to address these challenges by conducting a comprehensive investigation into the design and analysis of S-GFRP-MLCs for propeller shaft applications. Finite Element Analysis (FEA) is utilized to simulate various loading scenarios, and mechanical tests will be performed to validate the analytical predictions.

In conclusion, the successful implementation of S-GFRP-MLCs in propeller shafts has the potential to revolutionize propulsion systems, offering improved efficiency, durability, and customizability. By understanding the intricate interplay between material properties, design considerations, and operational demands, this research aims to contribute significantly to the advancement of composite materials in critical engineering applications.

F. Rubino *et al.*: This review provides an overview of fiber-reinforced polymer composites and their applications in the marine industry. It emphasizes the need for lightweight and corrosion-resistant materials for propeller shafts in marine vessels and highlights the potential benefits of using S-glass fiber reinforced epoxy polymer metal laminate composites[1].

M. Satya Prasad, S. Nagakalyan: The focus of this study is on the mechanical characterization of epoxy composites that have been reinforced with S-glass fibers, providing valuable insights into their strength, stiffness, and fracture behavior. The review of mechanical properties is essential for understanding the potential of S-glass fibers as the reinforcing phase in the proposed laminate composites[2].

E. Poodts *et al.*: This review examines the design and analysis of metal-polymer laminates and their applications in marine environments. It discusses the benefits of combining metals and polymers to enhance mechanical properties, which is relevant to the proposed epoxy polymer metal laminate composites for propeller shafts[3].

Ramli N. *et al.*: This paper focuses on aerospace applications, this study provides relevant information on S-glass fiber reinforced epoxy polymer composites. It discusses manufacturing techniques, mechanical properties, and the use of these composites in aerospace structures, offering useful parallels for marine applications[4].

B. Hamdi *et al.*: This research investigates the use of Finite Element Analysis (FEA) for composite structures in marine propulsion systems. It highlights the importance of FEA in predicting the mechanical behavior and structural integrity of composite components, which can be applied to the design and analysis of the proposed S-glass fiber reinforced epoxy polymer metal laminate composites[5].

D. Harsha Vardhan *et al.*: This study discusses the development and analysis of hybrid metal composite propeller shafts. Although not specific to S-glass fibers, the findings are relevant to the concept of epoxy polymer metal laminate composites in marine propulsion systems[6].

In conclusion, the literature review establishes the significance of the proposed study by highlighting the growing interest in fiber-reinforced polymer composites in marine applications and their potential advantages for propeller shafts. The review also emphasizes the importance of mechanical characterization, finite

element analysis, fatigue behavior, and corrosion resistance in evaluating and designing the S-glass fiber reinforced epoxy polymer metal laminate composites for optimal performance and reliability in marine environments.

2. Methodology

The methodology followed in the present work is as shown in the Figure 1. Literature review is the first step in which the previous works which have already been done in the area of the present work are studied and presented. After literature review, the selection of suitable dimensions of the shaft are done. This is followed by the selection of materials which is very crucial in the design of the propeller shafts. Selection of ply orientation and stacking sequence is important in composites and will decide the strength and stiffness of the material. Then the finite element analysis is carried out to determine the stresses and the natural frequency is determined through modal analysis.

In order to assess the material's suitability for the current application, the analytical and FEA results are compared. Finally, a suitable propeller shaft will be selected for the LMV's which has light weight, low stresses and better natural frequency.

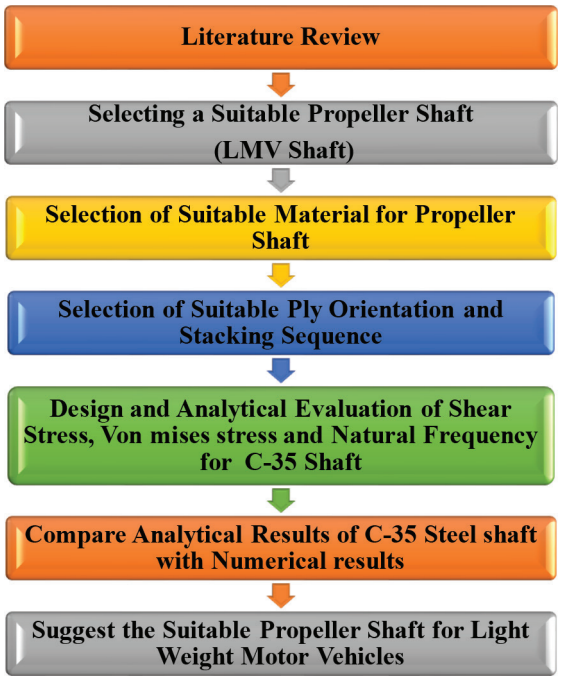


Figure 1. Methodology.

2.1 Design and Analysis of Conventional Steel c-35 Propeller Shaft

One of the most iconic vehicles sold by Maruti Suzuki, the largest carmaker in India, is the LMV van. The Maruti Omni is one of the few cars that can still be bought in India, despite its launch in 1984. The Omni minivan is in production for more than three decades and was the second vehicle introduced by Maruti in India after the 800. The Maruti Omni is capable of serving both the passenger car market and the commercial sector for cargo and ambulance usage.

In this project, Maruti Omni car propeller shaft is taken for study and understanding loading and boundary conditions. The dimensions of propeller shaft are shown in below Table 1.

2.2 Design of Conventional c-35 Steel Propeller Shaft

2.2.1 Determination of Torque on the Propeller Shaft (T_p)

T_{max} = 59.84 N-m (available on the engine in first gear)

The torque on the propeller shaft (T_p)

$$T_p = G_b \times G_r \times T_{\max} \tag{1.1}$$

On substitution one has $T_p = 963.87N - m.$

2.2.2 Design Based on ASME Standard

The shaft's design is mostly in accordance with the maximum shear stress theory.

Table 1: Specifications of Maruti omni propeller shaft

Sl. No.	Properties	Value
1.	Rear axle ratio (G_R)	4.333
2.	Bottom gear ratio (G_B)	3.721
3.	Rigidity modulus (G)	80GPa
4.	Poisson's ratio (μ)	0.35
5.	Yield stress (σ_{yt})	345MPa
6.	Ultimate stress (σ_{ut})	550MPa
7.	Speed (N)	5000rpm
8.	Material	C-35 steel
9.	Max torque at engine(T_{max})	59.84 N-m
10.	Young's modulus (E)	205GPa

$$\tau_{per} = 0.5\sigma_{yt} \quad (1.2)$$

Hence consider $\tau_{per} = 174.5Mpa.$

The shafts are usually subjected to gradual and sudden loads, so the equation below is adjusted in ASME code using appropriate load factors.

$$k_t \times T_p = \frac{\pi}{16} \times d_1^3 (1 - k^4) \tau_{per} \quad (1.3)$$

k_t= 1 to 1.5 for suddenly applied load

Let $k_t = \frac{d_2}{d_1} = 0.94$, let $k_t = 1.3$

$$1.3 \times 963.87 = \frac{\pi}{16} \times d_1^3 (1 - (0.94^4)) \times 99$$

$d_1 = 66.5mm$, $d_2 = 6.2cm$, $t = 2.25mm$

2.2.3 Calculation of Mass for C-35 Steel

The mass of s steel shaft is calculated by using the below equation.

For C-35 steel, $p = 7850 \frac{kg}{m^3}$

$$p = \frac{m}{v} \quad (1.4)$$

$$7850 \times A \times I = m$$

$$7850 \times \frac{\pi}{4}(d_1^2 - d_2^2) \times 1 = m$$

$$m = 2.69kg$$

$$J = \frac{\pi}{32}((0.066)^4 - (0.062)^4)$$

$$J = 1.9643 \times 10^{-7} m^4$$

2.3 Determination of Length

According to the empirical rule, the maximum angle of twist 1° for length of shaft = 20. The twist in the shaft is 7.5 to 3.5 for meter length assuming $\theta = 3^\circ$.

$$\frac{T_p}{J} = \frac{G\theta}{1}(1.5)$$

$$\frac{963.87 \times 1}{1.9643 \times 10^{-7}} = \frac{80 \times 10^9 \times \pi \times 3^\circ}{180}$$

$$1 = 853mm$$

2.4 Operating Frequency of Shaft

$$\omega = \frac{2\pi n}{60} \quad (1.6)$$

Where n = 5000 rpm (is the operating speed)

ω= 523.89 rad/s or f = 83.33 Hz is the operating frequency of the shaft.

2.5 Mass Calculation of Composite Propeller Shaft

$$m = \rho \frac{\pi}{4}(d_0^2 - d_i^2) \times L \quad (1.7)$$

$$m = 2139.5 \times \frac{\pi}{4} \times (0.050^2 - 0.032^2) \times 0.575$$

$$m = 1.42kg$$

$$\%\text{Saving of Mass} = \frac{\text{mass of steel shaft} - \text{mass of composite shaft}}{\text{mass of steel shaft}}$$

$$\%\text{ Saving of Mass} = \frac{2.69 - 1.42}{2.69}$$

Percentage Saving of Mass = 47%

2.6 Evaluation of Thickness (FRP + Aluminium Liner)

$$\tau_{all} = \frac{T_{max}}{2\pi r^2 t} \quad (1.8)$$

$$72 \times 10^6 = \frac{964}{2\pi(3.125 \times 10^{-2})^2 \times t}$$

$$t = 2mm$$

T_t= 2 +0.25 (liner) = 2.25 mm

3. Results and Discussions

The shaft's maximum shear stress and von mises stress are determined through finite element analysis. The results are presented in Figure 2 and Figure 3. The stresses are well within the limits.

In modal analysis, the first two modes are as shown in Figure 4 and Figure 5. It reveals that the First natural frequency and second natural frequency are 521.21Hz and 1354.5Hz respectively.

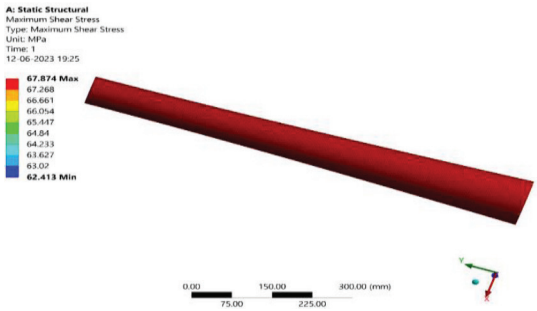


Figure 2. Maximum shear stress(Max stress=67.87MPa).

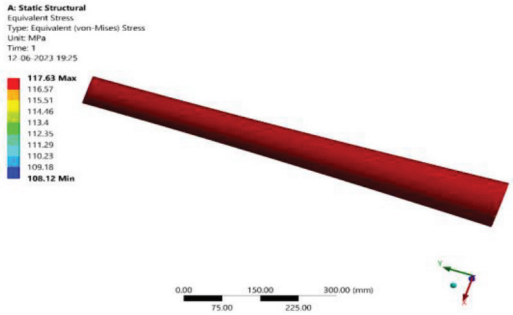


Figure 3. Von-mises stress (Max stress=117.63MPa).

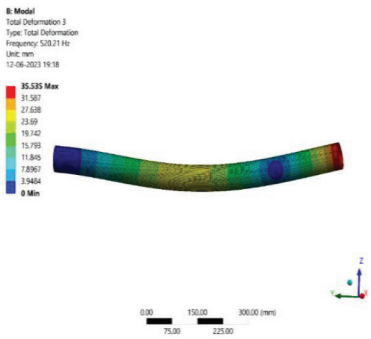


Figure 4. Mode shape-mode 1: 521.21Hz.

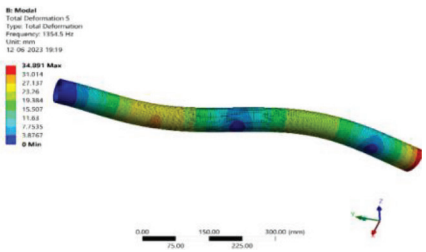


Figure 5. Mode shape-mode 2: 1354.5Hz.

3.1 Selection of Suitable Stacking Sequence and Ply Orientation

Using the afore mentioned factors, we have selected two sets of symmetrical laminates with a total of twelve layers.

$[\pm 45 / 0 / \pm 45]_s$ ----------1st type of composite shaft

[+45/-45/0/+45/-45/+45/-45/0/-45/+45] ----------1st type of Ply orientation

1. $[\pm 45/90_2/0_2]_s$----------2nd type of composite shaft

[+45/-45/90/90/0/0/0/0/90/90/-45/+45] ----------2nd type of Ply orientation

The angles of the ply's inclination measured in degrees are referred to in the numbers mentioned in the afore mentioned sets. The shaft of a Fiber Reinforced Plastic (FRP) composite made from twelve plies with thicknesses of 0.416mm for each ply is a typical example of how to make it.

3.2 Analysis of 1st Ply Orientation of Composite Shaft $[\pm 45 / 0 / \pm 45]_s$

For the composite shaft with ply orientation $[\pm 45 / 0 / \pm 45]_s$, linear static analysis is carried out to determine the value of stresses in the shaft. The von mises stresses and maximum shear stress are found to be 35.6MPa and 61.72MPa respectively as shown in Figure 6 and Figure 7.

In modal analysis, the natural frequencies were found to be 512.97Hz and 1318.2Hz respectively as evident from Figure 8 and Figure 9.

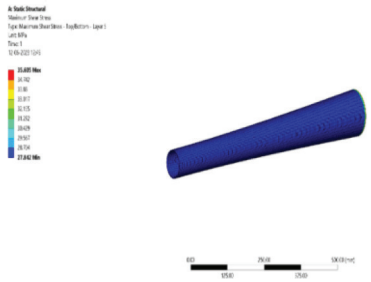


Figure 6. Maximum shear stress (Max stress=35.6MPa).

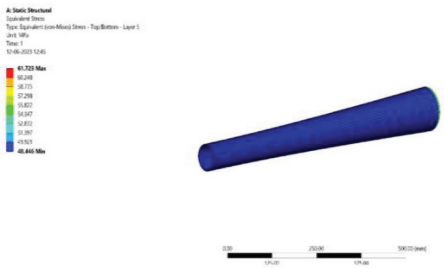


Figure 7. Von-mises stress (Max stress=61.72MPa).

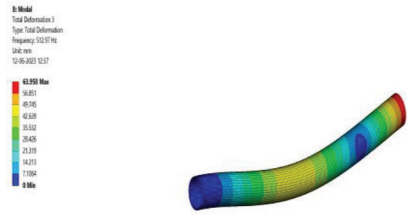


Figure 8. Mode shape-Mode 1: 512.97Hz.

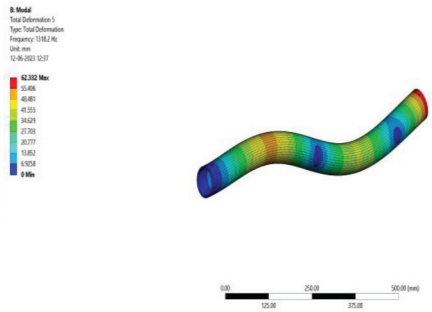


Figure 9. Mode shape-Mode 2: 1318.2Hz.

3.3 Analysis of 2nd Ply Orientation of Composite Shaft $[\pm 45 / 90_2 / 0_2]_s$

For the composite shaft with ply orientation $[\pm 45 / 90_2 / 0_2]_s$, linear static analysis is carried out to determine the value of stresses in the shaft. The von mises stresses and maximum shear stress are found to be 85.5MPa and 146.36MPa respectively as shown in Figure 10 and Figure 11.

In modal analysis, the natural frequencies were found to be 481.98Hz and 1275.5Hz respectively as evident from Figure 12 and Figure 13.

The comparison of the static structural analysis results is shown in Table 2. It is evident that S-glass epoxy with ply orientation $[\pm 45 / 0 / \pm 45]_S$ has lower stresses compared to the other materials.

The allowable shear stress for C-35 material which is half of yield strength is 175 MPa. Shear stress induced in the alloy steel shaft is 67.784 MPa compared to 35.68 MPa and 84.5 MPa of the fiber metal laminate shafts. Since the maximum torque occurs at the outer fiber at an orientation of 45^0, the increase in torsional strength can be achieved by orienting plies at this angle.

Since the shear stress induced on the composite shaft is also well behind the allowable shear stress, therefore both configurations of the FML shafts are suitable for carrying the torque.

The comparison of the modal analysis results is shown in Table 3. It is evident that S-glass epoxy with ply

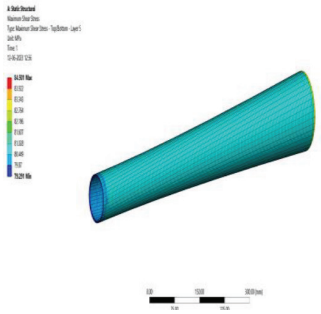


Figure 10. Maximum shear stress(Max stress=85.5MPa).

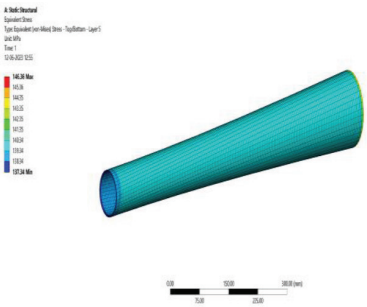


Figure 11. Von-mises stress (Max stress=146.36MPa).

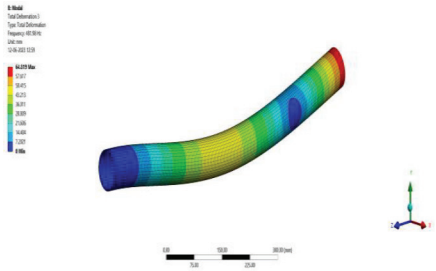


Figure 12. Mode shape-Mode 1: 481.98Hz.

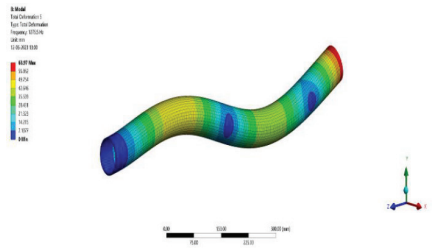


Figure 13. Mode shape-Mode 2: 1275.5Hz.

Table 2. Static structural analysis results

Stress/Material	Von Mises Stress in MPa	Maximum Shear Stress in MPa
Steel	117.63	67.874
S-Glass Epoxy$[\pm 45/0/\pm 45]_s$	61.723	35.68
S-Glass Epoxy$[\pm 45/902/02]_s$	146.36	84.50

Table 3: Modal analysis results

Sl. no	Natural Frequency for Steel shaft in Hz	S-Glass Epoxy $[\pm45/0/\pm45]_s$ Shaft Natural frequency in Hz	S-Glass Epoxy $[\pm45/90_2/0_2]_s$ Shaft Natural Frequency in Hz
1.	520.21	512.97	481.98
2.	1354.5	1318.2	1275.5

Table 4. Weight comparison of different shafts

Material	Mass in (kg)	% Saving in Weight
Steel	2.69	47%
S-Glass Epoxy $[\pm45/0/\pm45]_s$	1.42	
S-Glass Epoxy $[\pm45/90_2/0_2]_s$	1.42	

orientation $[\pm45\ /90_2/0_2]_s$ has lower stresses compared to the other materials.

The operating frequency of shaft is 83.33 Hz, it is evident that the natural frequency of both C-35 Shaft and FML composite shaft of 1st stacking sequence is higher than the operating frequency, but the 2nd configuration of FML Shafts natural frequency is below the operating frequency. Higher natural frequency can be achieved by having fibers oriented at 0^o.

It is evident from the Table 4 that there is a substantial decrease in weight of the composite shaft when compared to alloy steel shaft. Hence lesser the mass it is easy to accelerate and deaccelerate, and thus lesser the effect of inertia. The decrease in weight also decreases the sagging of the shaft, and lesser the vibrations due to damping effect of the epoxy reinforced composite material. It is also further desired to make the shaft as a single piece for light motor vehicle rather than two pieces, and thus further reducing the weight. The decrease in weight is due to the low density of the composite material and high stiffness modulus.

4. Conclusion

- The weight of the shaft can be considerably reduced without compromising the stiffness.
- The maximum shear stress induced in the S-Glass Fiber reinforced Epoxy Metal Laminate (FML) Composites shaft is less compared to allowable shear stress and thus can be an alternative for metallic shaft.
- The natural frequency for composite shaft of 1st stacking sequence is higher than the operating frequency and hence can be an ideal material to dampen the vibrations and avoid resonance. Whereas 2nd configuration of stacking sequence composite material will undergo resonance at operating frequency and may require plies at 0^0 orientations.
- Composite materials are non-corrosive and thus reduce maintenance costs and increase life of propeller shaft.
- Allows single piece manufacturing and thus reduce manufacturing cost.
- Since the parameters weight, vibration induced, torsional strength, torsional stiffness, ease of manufacture, cost *etc.*, are all comparable to metallic shaft and hence the S-Glass Fiber reinforced Epoxy Metal Laminate (FML) composite material can be an alternative to conventional alloy steel material shaft for the application in propeller shafts.

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