Design and Static Structural Analysis of Composite Propeller Shaft: A Comparative Study

Abstract

Advanced Fiber Reinforced Polymer (FRP) composites have emerged as an important class of engineering materials for load bearing applications with all round properties for many engineering and social applications. Composite materials are created by combining two or more dissimilar materials with a viewpoint to improve the properties or to create materials with desired properties. Substituting composite structures for conventional metallic structures has many advantages because of higher specific strength and low stiffness of composite materials. The role of composite material in weight reduction and fuel saving in automobiles is highly significant. Advanced composite seems ideally suited for long, power drive shaft applications. Their elastic properties can be tailored to increase the torque and the rotational speed at which they operate.

Composite driveshaft is designed based on filament winding technology for higher strength and torque applications. In the present work, a comparative study was carried out between carbon/epoxy, boron/epoxy, and e-glass/epoxy propeller shafts having high strength with reference to the conventionally used steel driveshaft. This study investigates the design of a composite propeller shaft for a lightweight passenger vehicle, engineered to withstand a maximum torque of 400 N-m. The design approach is based on strength criteria and utilizes the balanced symmetric laminate theory, employing composite macro-mechanics and classical lamination theory. Key performance constraints considered include torque transmission capability and angle of twist. Propeller shafts were designed and simulated using the material properties of steel (SM45C), carbon/epoxy, boron/epoxy, and E-glass/epoxy composites. The maximum stress obtained through numerical analysis for carbon/epoxy was found to be within permissible limits. Thus, an experimental test rig was developed to measure the angle of twist for the carbon/epoxy shaft, validating the simulation and theoretical results. This study highlights the significant impact of weight reduction in automotive components, contributing to increased payload capacity and reduced fuel consumption.

KEYWORDS – Composites, Carbon/epoxy, Boron/epoxy, E-glass/epoxy, Filament Winding technique

Introduction

Propeller shaft imparts power from the gearbox to the back centre with the help of far and wide joints. The power that is formed using the engine and power transmission must be moved to the rear tires to drive the vehicle. The driveshaft must give a smooth, relentless development of capacity to the axles. The driving shaft and differential are utilized to move this force and must give the power from transmission to the differential. During the power transmission from the gearbox and engine to the differential most of the bending and twisting moments occur on the propeller shaft. So, the material of propeller shaft plays a key role. In current study, an effort is made on interchanging the existing material to enhance the properties to withstand more twisting and bending loads. Also, the size the of the shaft was optimized to reduce the overall weight without affecting the strength of the shaft. Basically, interchanging the materials are composites like Carbon/Epoxy, E-glass/Epoxy, and Boron/Epoxy.

In the present work, a comparative study was carried out between carbon-epoxy, boron-epoxy, and e-glass-epoxy as a potential practical alternative material for the conventionally used steel propeller shaft to withstand a maximum torque of 400 N-m. Later, the proposed composite propeller shaft was manufactured using filament winding technique. The results computed were based on stress criteria, deformation criterion, angle of twist criterion, and mass criterion from theoretical, numerical, and experimental approaches. The obtained results show that carbon-epoxy outperforms other composites and the second choice within the composites would be e-glass/epoxy when cost is a constraint.

Several research works have taken place in the recent past on identifying a feasible alternative material for propeller shaft which can perform in a predetermined and acceptable way under various loading conditions and resist stresses acting in any form. In most of the research, design and simulation has been performed on a single material unlike the current study where a group of materials have been compared. [1] T. Rangaswamy et al. in their work on "Optimal Design and Analysis of Automotive Composite Propeller Shaft" designed and analyzed a composite driveshaft which was optimally designed using E-glass/epoxy and High modulus (HM) Carbon/epoxy composites. They have applied Genetic Algorithm (GA) to minimize the weight of the shaft subjected to different constraints and the results showed the stacking sequence of shaft which strongly affects buckling torque. [2] R. Jagadeesh Kumar et al. in their work on "Design and Analysis of Composite Propeller Shaft" have attempted to replace steel with composite materials (viz. Carbon/epoxy and E-glass/epoxy) to enhance the required properties and overcome the problems occurred in conventional steel shaft. Also have optimized the size of the shaft to reduce the overall weight without affecting the strength of the shaft and compared the results of steel shaft with composite shaft through manual calculations. [3] Priyanka Bhushan Bhargav et al. have worked on "Design and Analysis of Composite Propeller Shaft" to study the effect of carbon fiber on the properties of the composite formed by changing volume fraction and replacement of two-piece conventional steel shaft with the single piece composite shaft and have found that natural frequency and torsional buckling strength increases with increase in volume fraction of carbon fiber. [4] R. Vattipalli in their dissertation on "Design and Analysis of Automotive Composite Propeller Shaft" worked on replacing the conventional steel propeller shaft with

Kevlar and high modulus carbon/epoxy composite propeller shafts for an automotive application and later optimized the design parameters with the objective of minimizing the weight of composite propeller shaft. The design optimization also showed significant potential improvement in the performance of propeller shaft. [5] R. Srinivasa Moorthy et al. investigated about "Design of Automobile Driveshaft using Carbon/epoxy and Kevlar/epoxy Composites" and have found that use of Carbon/epoxy results in a mass saving of 89.756% when compared to the conventional SM45C steel driveshaft, whereas Kevlar/epoxy results in 72.53%. Moreover, the torsional buckling capacity and bending natural frequency are adequate enough to meet the design requirements in the case of Carbon/epoxy driveshaft. [6] Kumar V. Munde et al. carried out work on "FEA & Experimental Analysis of Glass Fiber Composite Propeller shaft" and presents the feasibility of composite shaft over conventional steel shaft of automobile. Results computed through FEA calculations show that the stresses induced on the composite shaft is less compared to the mild steel shaft. Also, the weight reduction of the composite driveshaft to that of conventional shaft is 67% lighter by numerical method and 72% lighter experimentally. Final results from FEA, Analytical and Experimental calculations show that the stresses and weight of composite driveshaft is less than conventional steel shaft. [7] Sarika Kishore Khare et al. in their work on "Design of Propeller Shaft Using Composite Materials" investigated the replacement of conventionally used steel (SM45C) driveshaft with lightweight composite materials. Software applications such as Creo 7.0 have been leveraged for modelling and simulation has been done on Abaqus software and later the theoretical calculations and analytical results are compared between steel, carbon/epoxy and e-glass/epoxy composites. Results show that carbon/epoxy composite is chosen as a viable alternative for SM45C steel shaft.

Objectives

This paper aims to conduct a comparative study between composite materials (viz. Carbon/epoxy, Boron/epoxy, E-glass/epoxy) to suggest a viable alternative material for conventionally used steel (SM45C) propeller shaft. The results computed are based on stress, deformation, angle of twist, and mass criteria from theoretical, numerical, and experimental approaches. Later, the recommended composite driveshaft was fabricated using filament winding technique and the experimental testing for angle of twist was carried to validate the simulation and theoretical values.

Methodology

The present disclosure relates, in general, to the propeller shaft or driveshaft and more specifically to the "Composite Propeller Shaft" wherein a benchmarking study was conducted/examined between Carbon/epoxy, Boron/epoxy, and E-glass/epoxy as a viable alternative for steel (SM45C) driveshaft.

Figure 1.1 depicts the step-by-step approach adopted to achieve the objectives.

According to the flowchart (as shown in Fig. 1.1), the materials for propeller shaft were selected based on their mechanical characteristics/properties for/to driveshaft applications such as strength-to-weight ratio, stiffness, fatigue. A comparative assessment was conducted between conventional steel (SM45C) and advanced composites such as carbon/epoxy, boron/epoxy, e-glass/epoxy to identify the material offering reduced weight without compromising on the structural performance. Based on the selected materials, shaft specifications were defined to meet the maximum torque requirement of 400 N-m and dimensional constraints suitable for a one-piece drive shaft. Design calculations were performed using classical lamination theory and strength criteria to determine critical parameters such as shaft diameter, wall thickness, and angle of twist. The three-dimensional model of the driveshaft assembly was designed in CATIA according to shaft specifications, later followed by ANSYS simulation. The simulation in ANSYS Workbench was performed on the propeller shafts with material properties of Steel (SM45C), Carbon/epoxy, Boron/epoxy, and E-glass/epoxy with **BALANCED SYMMETRIC PLY SEQUENCE** for a maximum torque of 400 N-m with the required boundary conditions. Later, the composite driveshaft was manufactured using Filament Winding technique and the experimental testing for angle of twist was conducted the composite driveshaft. Finally, the theoretical, numerical, and experimental values were compared and validated to arrive to a common consensus on the optimal composite material usage for propeller shaft application.

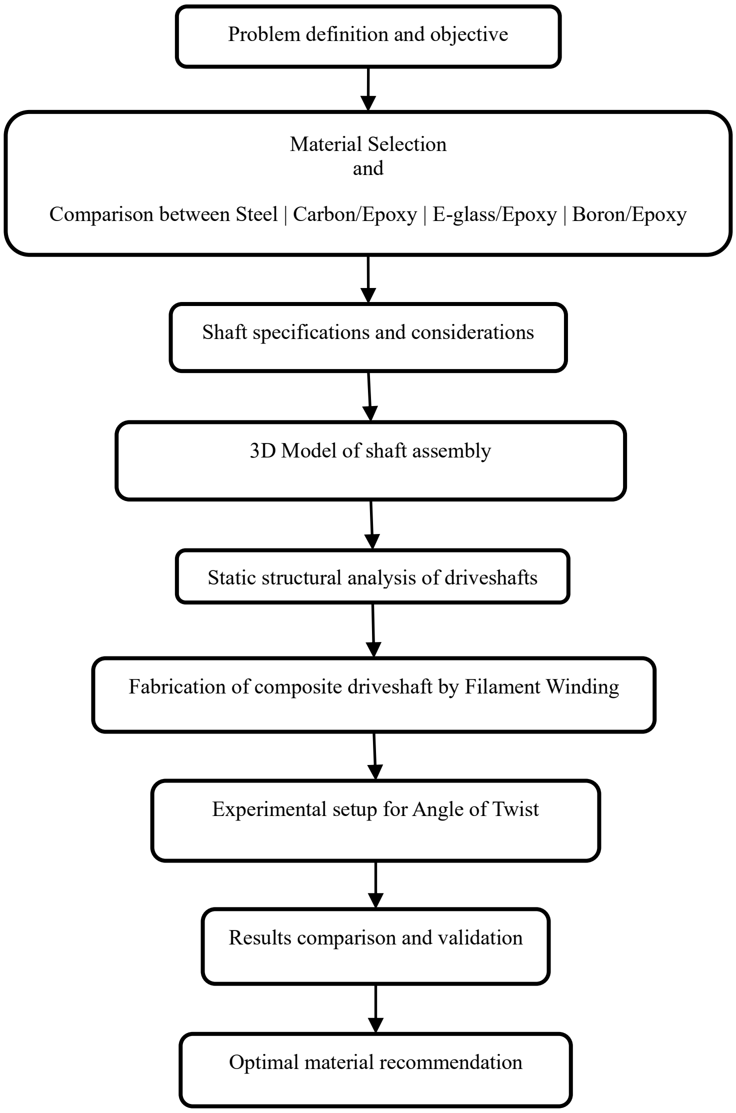

Figure 1.1: Chronological Order of Comparative Study

Firstly, the literature was reviewed to identify the methods to improve efficiency of automobiles. After thorough study, gaps and shortcomings were identified in the use of conventional steel propeller shaft indicating higher mass corresponding to reduced efficiency. As a result, efforts were made to replace the current steel shaft with composite shaft by taking carbon/epoxy, boron/epoxy, and e-glass/epoxy into consideration. Later, a 3D model of the composite shaft materials and steel (SM45C) shaft was made using CATIA. Static analysis was performed on all the four models and results were recorded. Parallelly, simulated and theoretical results were also compared and the shaft corresponding to the best results was fabricated and taken for experimental testing. Taking all the three results into consideration, deviations were measured and the shaft showcasing minimal deviations was chosen as a feasible alternative.

Material Specifications

The table (Table: 1.1) enlists various properties of the aforementioned materials. (**Refer APPENDIX**)

Among composite materials carbon/epoxy, boron/epoxy, and e-glass/epoxy are chosen as they are readily available and the material properties required for power transmission applications (propeller shaft driveshaft) closely aligns with selected materials for this study.

Shaft Specifications and Design Calculations

The composite driveshaft is designed for a lightweight motor vehicle (LMV) to sustain a maximum torque of 400 N-m made with the following materials - Carbon/Epoxy, Boron/Epoxy, E-glass/Epoxy.

Specifications of the composite driveshaft are as follows:

Specification	Value
Outer Diameter of Joint	76.2mm
Inner Diameter of Joint	63.5mm
Outer Diameter of Shaft	90.798mm
Inner Diameter of Shaft	76.2mm
Torque	400 N-m
Length	1160mm
Factor of Safety	5

Table 1.2: Shaft Specifications

The above table (Table: 1.2) shows the specifications of the composite driveshaft ascertained to carbon/epoxy, boron/epoxy, and e-glass/epoxy.

Three-Dimensional Modelling of Driveshaft Assembly

The CAD model of propeller shaft assembly (Fig 1.2) was designed in CATIA. One end of the shaft is attached to universal joint which allows transmission of rotational power between shafts that are not aligned, compensating for the angular misalignment/accommodating angular misalignment. The other end of the shaft is attached to slip joint which allows for absorbing changes/variation in length of the driveshaft while transmitting torque and as the vehicle's suspension moves.

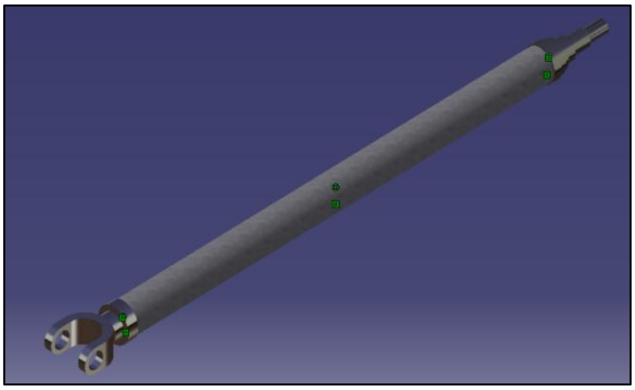

Figure 1.2: Propeller Shaft Assembly

The 3D model of the propeller shaft assembly is shown in figure 1.2. The bottom end of shaft is attached to the Universal/Hooke's joint, and the top end of the shaft is attached to the slip joint.

Static Structural Analysis of Propeller Shaft

The simulation tests for all the four shaft materials were carried out in ANSYS Workbench. The following are the boundary conditions given to the propeller shaft.

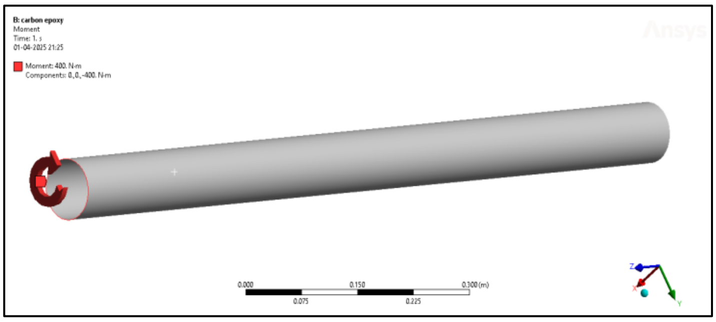

Figure 1.3: 400 N-m Torque Boundary Condition

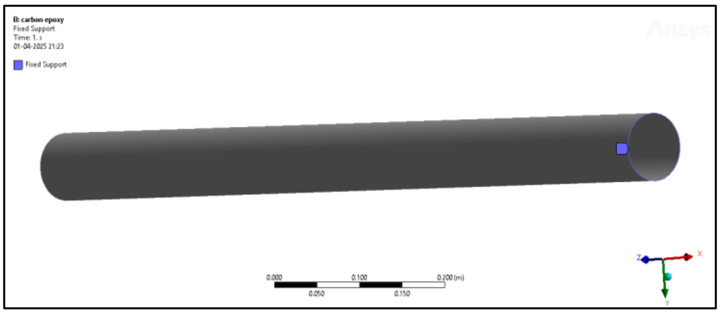

Figure 1.4: Fixed Boundary Condition

The above-mentioned figures (Fig. 1.3 and Fig. 1.4) are the two boundary conditions considered for the static structural analysis of composite propeller shaft. One end of the shaft is fixed in all degrees of freedom, and the free end of the shaft is given a torque of 400 N-m in Z axis.

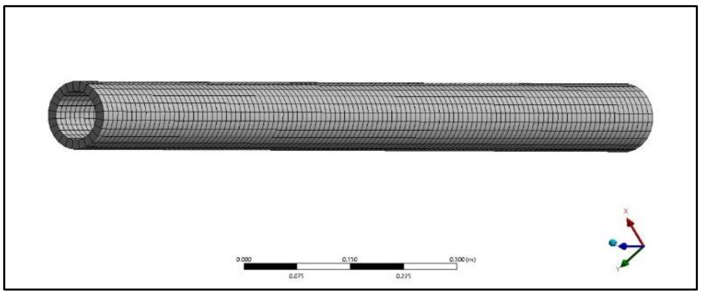

Figure 1.5: Mesh Model

The image shows (Fig 1.5 Mesh model of Propeller shaft) a meshed cylindrical shaft with hexahedral (brick) mesh. The geometry is meshed in a sweepable fashion. The mesh size is 10 mm.

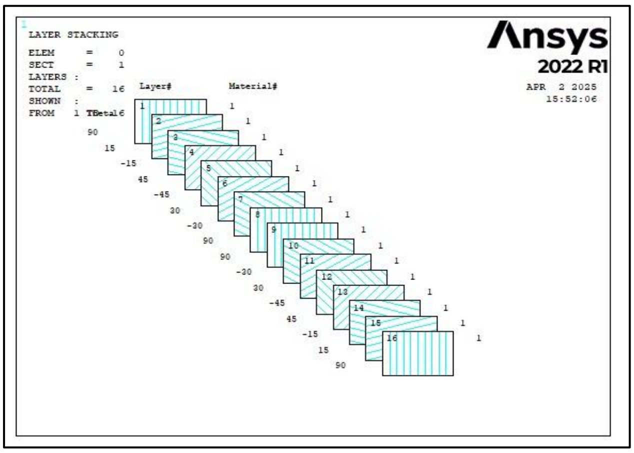

Figure 1.6: Lay-up Sequence in ANSYS APDL

Fig. 1.6 shows the “Balanced Symmetric Ply Sequence” developed for composite material for the Filament Winding process. (Refer **Balanced Symmetric Ply Sequence** subheading for the detailed ply sequence)

Note: As composites have different material properties in all directions, they are treated as “Anisotropic” in nature. In the current study, for simulation all the composite driveshafts are considered as Anisotropic.

Analysis of Steel (SM45C) Propeller Shaft

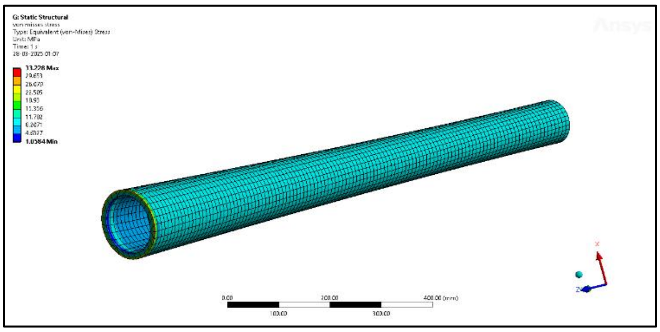

Figure 1.7: Von Mises Stress in Steel Shaft

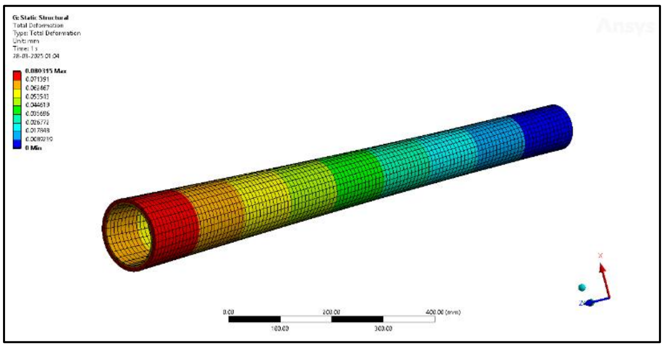

Figure 1.8: Total Deformation in Steel Shaft

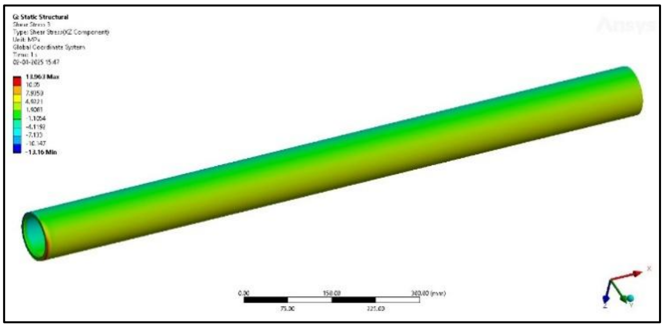

Figure 1.9: Maximum Shear Stress in Steel Shaft (XZ Plane)

The above-mentioned figures (Fig 1.7, Fig 1.8, and Fig. 1.9) show the various simulation tests conducted on the steel shaft. Refer “Results” section for detailed insights into the results recorded.

Analysis of Carbon/Epoxy Propeller Shaft

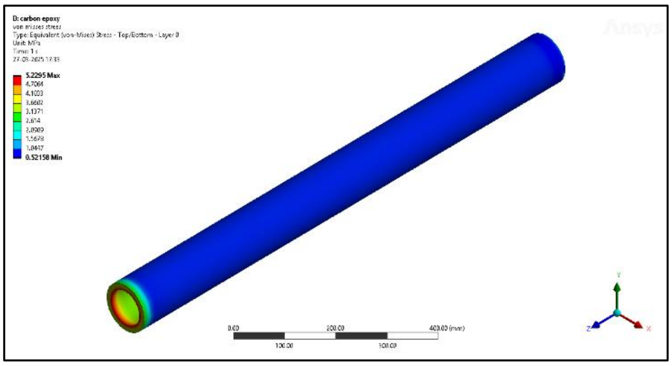

Figure 1.10: Von Mises in Carbon/Epoxy Propeller Shaft

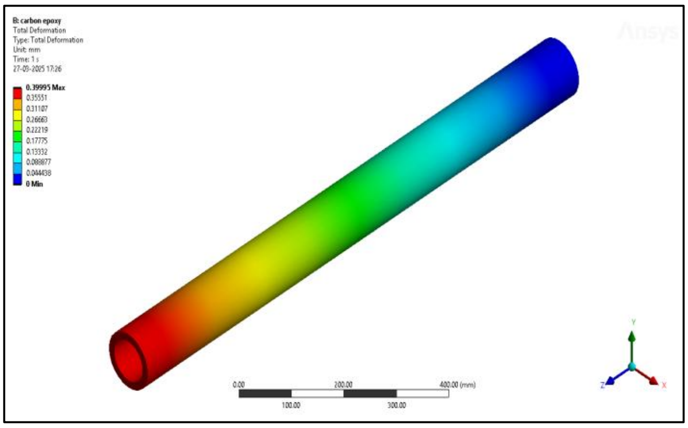

Figure 1.11: Total Deformation in Carbon/Epoxy Shaft

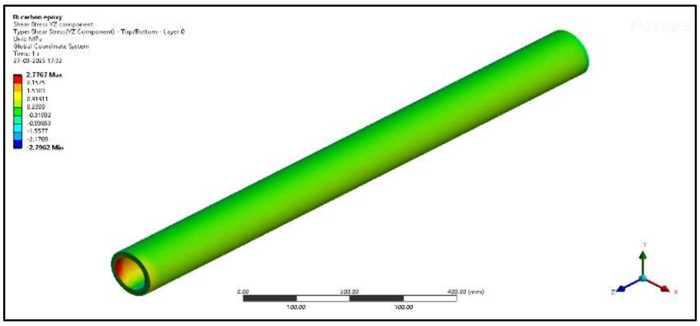

Figure 1.12: Maximum Shear Stress in Carbon/Epoxy Shaft (YZ Plane)

The above-mentioned figures (Fig 1.10, Fig 1.11, and Fig. 1.12) show the various simulation tests conducted on the steel shaft. Refer “Results” section for detailed insights into the simulation.

Analysis of Boron/Epoxy Propeller Shaft

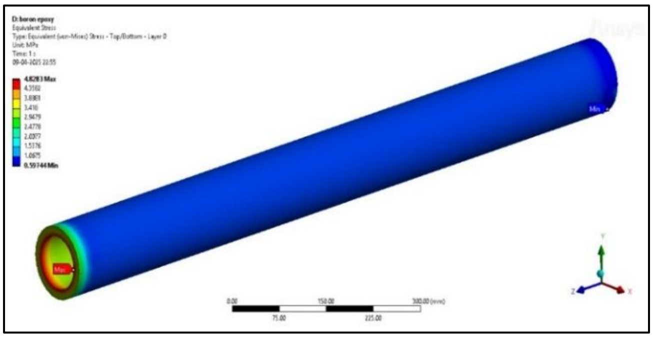

Figure 1.13: Von Mises in Boron/Epoxy Propeller Shaft

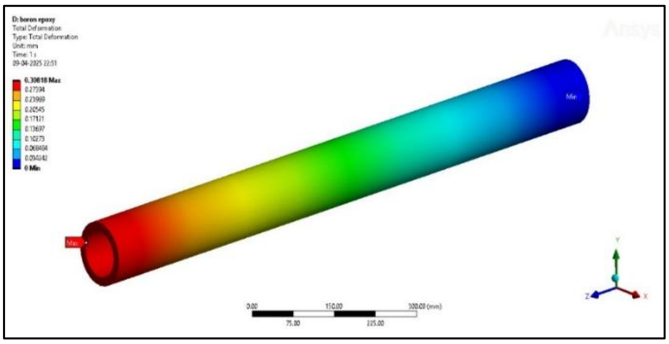

Figure 1.14: Total Deformation in Boron/Epoxy Shaft

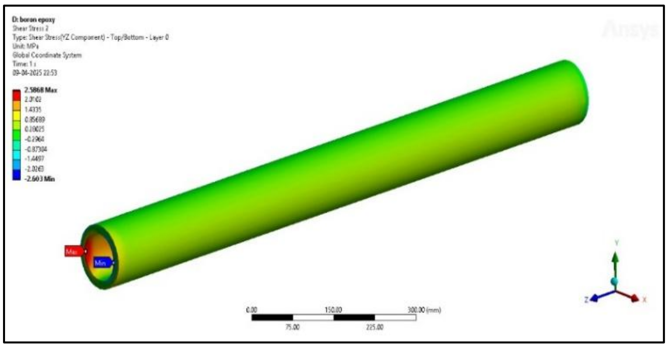

Figure 1.15: Maximum Shear Stress in Boron/Epoxy Shaft (YZ Plane)

The above-mentioned figures (Fig 1.13, Fig 1.14, and Fig. 1.15) show the various simulation tests conducted on the steel shaft. Refer “Results” section for detailed insights into the simulation.

Analysis of E-glass/Epoxy Propeller Shaft

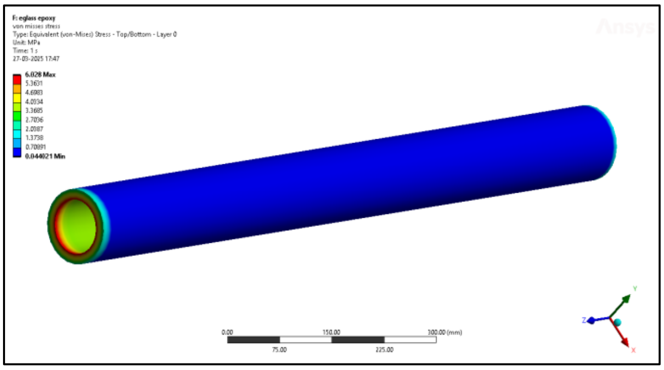

Figure 1.16: Von Mises Stress in E-glass/Epoxy Propeller Shaft

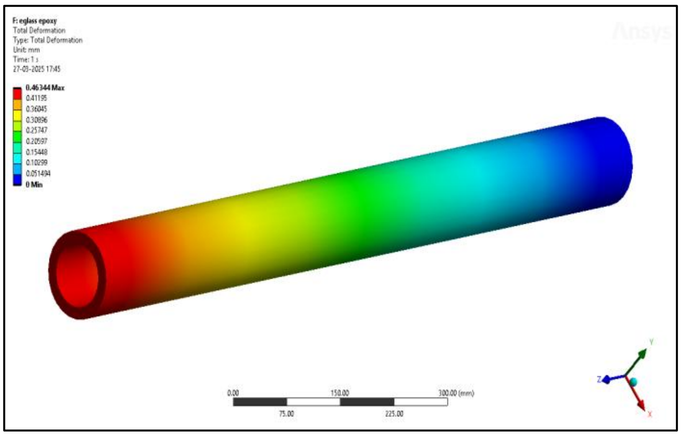

Figure 1.17: Total Deformation in E-glass/Epoxy Shaft

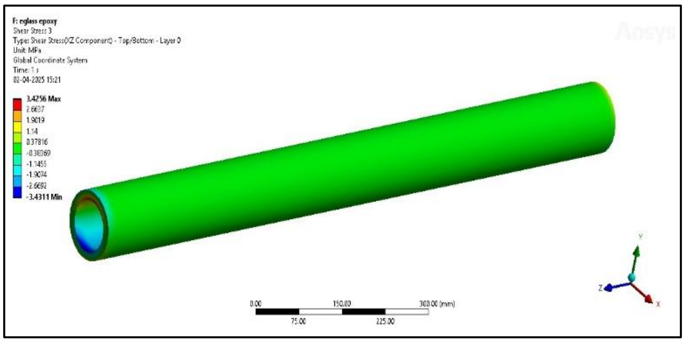

Figure 1.18: Maximum Shear Stress in E-glass/Epoxy Shaft (XZ Plane)

The above-mentioned figures (Fig 1.16, Fig 1.17, and Fig. 1.18) show the various simulation tests conducted on the steel shaft. Refer “Results” section for detailed insights into the simulation.

Fabrication of Composite Propeller Shaft by Filament Winding Process

In the current study, a composite propeller shaft is manufactured using **“Filament Winding Process”**.

Filament Winding is a continuous fiber reinforced composite production technique, in which resin impregnated band of continuous fibers are wound over a rotating mandrel. The “fiber” provides stiffness, strength, thermal stability, and other structural properties in the composites to carry the load and the “Resin/Matrix” binds the fibers together and transfers the load to the fibers and provides rigidity and shape to the structure. The winding of continuous fibers is performed either as adjacent bands or in the form of repeating bands to eventually cover the mandrel surface to produce one complete layer. The process continues with the winding of additional layers, until the design requirements are achieved. The production is completed by curing the filament-wound product in an oven and the removal of the mandrel.

The various steps involved in the filament winding procedure are – Mandrel Setup, Foam Disc Preparation, Foam Disc Stacking, Plaster of Paris (POP) Casting, POP Machining, Mixing and Fabrication, Filament Winding of Machine respectively.

Figure 1.19: Filament Winding Process

The above-mentioned figure (Fig 1.19 shows the Filament Winding Process setup.

Oven Curing Process

Post filament winding process follows oven curing process, where the hardening of the resin takes place which binds the fibers together creating a strong durable composite structure. Here, the composite shaft along with the mandrel is placed in the oven. In oven curing the variation in temperature and time depends on the number of heaters placed (as the number of heaters increases the time taken for curing decreases). In current oven for this study four ovens are placed. In oven curing process temperature variation during the curing cycle plays an important role for the overall hardening of the shaft.

Figure 1.20: Oven Curing Process

Temperature Variation during the Curing Cycle: The composite shaft along with the mandrel in the oven is initially set to room temperature. From room temperature to 120^0C it takes two hours and the next three hours is maintained at 120^0C. The temperature is varied between 120^0C to 150^0C for one hour and later, decreased from 150^0C to room temperature for four hours. Thus, the shaft is placed in the oven for a span of ten hours and then machine is turned off. Allow shaft to cool in the oven until it attains the room temperature. The process of curing increases the strength and hardness of the shaft. Table 1.3 is the tabular representation of temperature variation during oven curing process.

After the oven curing process the mandrel along with the composite shaft is taken out of the oven and kept in the lathe machine. The length of the composite shaft should be larger than required because after filament winding, the ends of the components do not have enough strength as required. By doing facing and turning operation, the composite shaft is brought to the exact dimensions i.e. length of the shaft is 1.16m. The partitioned shaft is taken and the foam POP inside the shaft is eased out to make it a hollow shaft.

TEMPERATURE (^{0}C)	**TIME (HOURS)**
Room temp. to 120^0C	2
120^0C	3
120^0C to 150^0C	4
150^0C to Room temp.	4
Total	10

Table 1.3: Temperature Variation during Oven Curing Process

Riveting Process: After completing manufacturing and oven curing of composite shaft, the next task is to assemble it with universal coupling and spline/slip joint. The joints are taken to make the holes with size M6 of 6 holes and similarly the holes must be done to the shaft also of same size of which was taken to the joints. Make sure that the holes of both shaft and joints match parallel to each other. (Fig 1.21 illustrates the riveting process done on the Carbon/epoxy filament wound shaft)

Figure 1.21: Riveting Process

Both ends of the hallow shaft and joints are cleaned with acetone so that there will be no scrap present on the holes. The joints surface is made roughness so that the aerolite can get grip enough to hold the joints inside the shaft. The riveted holes are cleaned thoroughly and then the screws of M6 are dipped in Loctite 242, so that the screws are tightly locked which makes the bonding with shaft so strong enough.

Figure 1.22: Rivets on the Shaft

The component with joints is mounted on to the mandrel for winding. First the glass fiber is winded on both ends of the joints to certain length up to the screws head are covered. Then the carbon fiber is done with 2 layers of hoop winding, and it is squeezed perfectly. Again, the component is taken to the oven curing which is done with a temperature of 110°c at 3 hours and 140°c at 3 hours. Finally, the required component with exact dimensions was brought.

Figure 1.23: Carbon/Epoxy Filament Wound Propeller Shaft

Balanced Symmetric Ply Sequence: The filament winding of carbon fibre follows a "Balanced Symmetric Laminate Sequence" for the fiber orientation on the winding setup. A layer of $+90^0$ degrees is wound onto the mandrel followed by $+15^0$ and -15^0 angles. The 90^0-degree layer is known as hoop. The spindle is maintained at 108rpm. The next layer is wound at an angle of $+45^0$ and -45^0 degrees and the spindle running at 127rpm followed by another layer of UD (Unidirectional fibers) at an angle $+30^0$ and -30^0 maintaining speed of spindle at 27 rotations per minute. (Fig 1.24 displays the detailed ply sequence designed for the composite structures)

S No.	Thickness (mm)	Angle (Degrees)	Orientation
1	0.9	90°	
2	0.9	+15°	
3	0.9	-15°	
4	0.9	+45°	
5	0.9	-45°	
6	0.9	+30°	
7	0.9	-30°	
8	0.9	90°	
9	0.9	90°	
10	0.9	-30°	
11	0.9	+30°	
12	0.9	-45°	
13	0.9	+45°	
14	0.9	-15°	
15	0.9	+15°	
16	0.9	90°	
MANDREL			

Figure 1.24: Balanced Symmetric Ply Sequence

The above-mentioned figure (Fig 1.24) follows a layup sequence of [90/+15/-15/+45/-45/+30/-30/90/90/-30/+30/-45/+45/-15/+15/90]. The notation code for the designed composite structure is [90/+15/-15/+45/-45/+30/-30/90]s ("s" indicates symmetry about the mid plane)

The mandrel is dismounted from the lathe and fitted on to the CNC machine for filament winding. The process of application of a relieving agent to the mandrel serves the purpose of mandrel removal after the process is completed. The mandrel rotates while a carriage moves horizontally, laying down fibers in the desired pattern. The filament used is carbon fiber and is coated with resin as it is wound.

The mandrel is completely covered to the desired thickness of 7.28mm. Filament winding is well suited for automation, where the tension on the filaments can be carefully controlled. Filaments that are applied with high tension results in a product that has high rigidity and strength, lower tension results in more flexibility. The orientation of the filaments can also be carefully controlled so that successive layers are piled up or oriented differently from the previous layer. The angles at which the fiber is laid down will determine the properties of the final product. A high angle of hoop will provide crush strength, while a lower angle pattern (known as a closed or helical) will provide greater tensile strength.

Experimental Setup to Determine Angle of Twist

Figure 1.25: Experimental Setup for Angle of Twist Calculation

The above Figure: 4.16 Experimental Setup for Angle of Twist Calculation shows the testing arrangement to ascertain the Angle of Twist for Carbon/Epoxy filament wound composite propeller shaft. One end of the shaft is fixed to the headstock of the lathe restricting the movement in all degrees of freedom, while on the other end (free end) of the shaft, a contraption was built in such a way that torsional load was applied to it. When the torsional load is applied to the shaft the fiber orientation of the carbon fiber changes temporarily which in turn causes a twisting deformation (temporary) or also called as "Angle of Twist". The pointer scale arrangement shows the twist in degrees where the pointer is mounted at a distance away from the free end of the shaft using hose clamp.

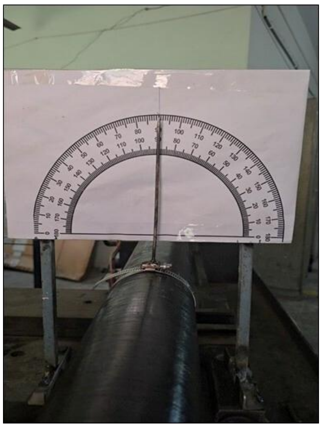

Figure 1.26: Pointer Arrangement to Determine Angle of Twist

Figure 1.27: Weighing Platform

Figure 1.26 and Figure 1.27 shows the pointer arrangement and weighing platform for the contraption built to determine experimental angle of twist. The pointer arrangement is a scaled model of a protractor, and a needle pointer set on shaft using hose clamp (angle of twist measured in degrees). The weighing platform is the area where the slotted weights are applied for the shaft to twist.

Results

Stress Criteria

MATERIAL	MAXIMUM STRESS (N/mm^2)	MINIMUM STRESS (N/mm^2)
STEEL (SM45C)	33.338	1.0584
CARBON/EPOXY	5.2295	0.52158
BORON/EPOXY	4.8283	0.59744
E-GLASS/EPOXY	6.028	0.044021

Table 1.4: Maximum & Minimum Von Mises Stress (MPa)

Table 1.4 shows the maximum and minimum values of von mises stress computed in all four materials in Ansys APDL to assess their performance under the same boundary conditions.

MATERIAL	Shear Stress in XY Component (MPa)	Shear Stress in YZ Component (MPa)	Shear stress in XZ Component (MPa)
STEEL (SM45C)	13.037	12.447	13.963
CARBON/EPOXY	0.030606	2.7767	2.7766
BORON/EPOXY	0.058786	2.5868	2.5866
E-GLASS/EPOXY	0.060295	3.4243	3.4256

Table 1.5: Shear Stress across various components

Table 1.5 presents shear stress values across three orthogonal components XY, YZ, XZ planes for all the four materials.

Deformation Criterion

Table 1.6: Deformation (Directional & Total) for various materials (**Refer APPENDIX**)

Table 1.6 displays directional and resultant deformations. The deformations are measured in X, Y, and Z directions along with resultant total deformations.

Carbon/Epoxy shows significantly higher deformation than steel but nearly identical values in X and Y directions indicating its predictable behaviour. Though boron/epoxy and e-glass/epoxy have less deformation values compared to carbon/epoxy, Carbon/epoxy is chosen according to the deformation criterion as it shows less deformation in Z direction and the deformation values for carbon/epoxy are within critical zone values.

Angle of Twist Criterion

Table 1.7: Theoretical and Simulation Angle of Twist (**Refer APPENDIX**)

The table 1.7 shows the theoretical and simulated values of angle of twist for all the four materials in the study.

The angle of twist is a critical design parameter for the design of driveshafts as it directly affects torque transmission ability, efficiency, withstanding of torsional loads. It also affects overall stiffness, structural integrity of the shaft. Excessive angle of twist may lead to torsional vibrations and fatigue failure due to cyclic stresses. By maintaining angle of twist within safer limits we can ensure that the shaft remains torsionally rigid, transmits power efficiently, and maintains long-term durability and safety.

The angle of twist was calculated using torsion equation:

$$\frac{T}{J} = \frac{\tau}{R} = \frac{G\theta}{l} \quad (1)$$

Experimental Angle of Twist

MATERIAL	ITERATIONS FOR THE EXPERIMENTAL ANGLE OF TWIST				AVERAGE (^{0}degrees)
CARBON/EPOXY	1	2	3	4	
	0.72	0.8	0.76	0.75	0.7575

Table 1.8: Mean Experimental Angle of Twist for Carbon/Epoxy

Table 1.8 shows the experimental angle of twist of carbon/epoxy driveshaft measured using the setup as shown in fig 1.24. From the Ansys tests conducted on various fiber-reinforced composites, it was observed that the carbon/epoxy propeller shaft exhibited an angle of twist value remarkably close to the theoretical and simulation results.

Mass Criterion

MATERIAL	DENSITY (ρ) Kg/m^3	MASS (M) Kg	WEIGHT (W) Newtons
STEEL (SM45C0	7850	17.1781	168.5171
CARBON/EPOXY	1800	3.9389	38.6406
BORON/EPOXY	2000	4.3765	42.9334
E-GLASS/EPOXY	1910	4.1796	40.9753

Table 1.9: Mass and Weight for various shaft materials

Table 1.9 shows the mass and weight for various shaft materials. The above-mentioned table reveals that composite materials offer a substantial reduction in mass – approximately 75% lighter than steel, while potentially enhancing performance characteristics. Among composites, carbon/epoxy stands out as the lightest option followed by e-glass/epoxy. The significant reduction in weight can lead to improved fuel efficiency, low inertial loads making composites highly compelling alternatives to traditional steel shafts.

Mass and weight were calculated using the following formulae:

$$\text{Density} = \frac{Mass}{Volume} \tag{2}$$

$$\text{Mass} = \text{Volume x Density} \tag{3}$$

$$\text{Volume} = \frac{\pi}{4}(D^2 - d^2) \times L \tag{4}$$

[OR]

$$\text{Volume} = \pi(R^2 - r^2) \times L \tag{5}$$

$$\text{Weight} = \text{Mass x } 9.81 \ (1\text{Kg} = 9.81\text{N}) \tag{6}$$

Discussions

As metal ores are getting depleted day by day and foundry technology is slowly getting extinct and produces high amount of radiation. So gradually, due to the latest advancements in Advanced manufacturing processes (additive manufacturing), the conventional manufacturing techniques like foundry is becoming obsolete and starting to fade out. Therefore, to minimize the usage of metallic structures namely steel in torque transmitting components and reduce the overall vehicular fuel consumption (increase fuel efficiency) and decrease/minimize the overall payload of a vehicle an effort was made to introduce advanced composites (fiber reinforced composites) as a propeller shaft material instead of conventionally used steel (SM45C) driveshaft.

The current study, aims to evaluate whether advanced fiber reinforced composites such as Carbon/epoxy, Boron/epoxy, and E-glass/epoxy could effectively replace the traditional steel (SM45C) propeller shaft in a lightweight motor vehicle for a maximum torque of 400 N-m. The study focused on key parameters like shear stress, deformation, angle of twist, and mass. The first part of the approach was benchmarking all the material properties of steel, carbon/epoxy, boron/epoxy, and e-glass/epoxy, followed by shaft specifications and dimensions were defined. This was followed by theoretical calculations, CAD modelling, and Ansys Workbench simulation tests on all the four driveshaft materials. Then after comparing the theoretical and simulation results, a viable alternative shaft material was proposed - carbon/epoxy. The chosen alternative material propeller shaft has been fabricated by filament winding technique, post that experimental testing has been run on the shaft to validate the theoretical and simulation results. And the results were verified using existing research literature.

Conclusions

The aim of the current study is to perform a comparative evaluation between conventionally used steel (SM45C) driveshaft and advanced composites (fiber-reinforced) such as carbon/epoxy, boron/epoxy, and e-glass/epoxy, and suggest a viable alternative to traditional steel propeller shaft. The propeller shaft was designed for a light motor vehicle to sustain a maximum torque of 400N-m. The propeller shaft was designed and analyzed for material properties of steel, carbon/epoxy, boron/epoxy, and e-glass/epoxy on Ansys Workbench. The results computed were based on the stresses induced, deformation, angle of twist, and mass of each propeller shaft.

From the experimental analysis, the results indicated carbon/epoxy as highly efficient, structurally sound, and a lightweight substitute for conventional steel as its deformations seemed controlled especially in the X and Y directions (0.39964mm and 0.39991mm respectively) and minimal in the Z direction (0.00023696mm)

Carbon/epoxy emerges as the most suitable composite as lower weight and reliable angle of twist response are desired in torsional applications. Theoretically carbon/epoxy exhibited an angle of twist of 0.7183^0 and also its simulated results indicated an angle of twist of 0.7275^0 showing a deviation of just 1.26%, whereas conventional steel, boron/epoxy, e-glass/epoxy showcased higher deviation. Carbon/epoxy can be emphasized as the better amongst the other materials considered in the study as its experimental angle of twist was indicated to be 0.7575^0, which is very close to the theoretical and simulated values.

However, through simulations, advanced composites showcased significant reduction in overall shear stress with reference to steel shaft since they indicated results of 80.1138% less stress in carbon/epoxy, 81.4738% less stress in boron/epoxy, and 75.4665% less stress in e-glass/epoxy.

As driveshaft applications include aerospace and automotive structures, significant weight savings result directly to improved vehicle fuel efficiency. Theoretically steel was the heaviest amongst the given materials with 17.18Kg mass and carbon/epoxy as the lightest of all with 3.94Kg mass indicating approximately 75% weight reduction. Carbon/epoxy composites exhibit a 90.25% higher strength of weight ratio compared to steel. Thus, proving to be efficient.

Carbon/epoxy emerges as the most suitable alternative to conventionally used steel (SM45C) for propeller or driveshaft applications followed by E-glass/epoxy. These results were determined by taking factors such as deformation, torsional rigidity, mass, shear stress and angle of twist into consideration.

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APPENDIX

Material Specifications

Properties	Young's Modulus (GPa)	Shear Modulus (GPa)	Poisson's Ratio (GPa)	Density (Kg/m^3)	Yield Strength (MPa)	Shear Strength (MPa)
Steel	207	80	0.3	7600	370	275
Carbon/Epoxy	190	5.6	0.36	1800	870	54
Glass/ Epoxy	50	5.59	0.3	1350	800	45
Boron/Epoxy	204	5.5	0.3	2000	870	47

Table 1.1: Material Specifications

Deformation Criterion

MATERIAL	Deformation in X direction (mm)	Deformation in Y direction (mm)	Deformation in Z direction (mm)	Resultant Deformation (mm)
STEEL (SM45C)	0.080299	0.080313	2.001×10^{-5}	0.080315
CARBON/EPOXY	0.39964	0.39991	0.00023696	0.39995
BORON /EPOXY	0.30795	0.30815	0.00015926	0.30818
E-GLASS/EPOXY	0.46305	0.4634	0.00015978	0.46344

Table 1.6: Deformation (Directional & Total) for various materials

Angle of Twist Criterion

MATERIAL	SHEAR MODULUS (G) (GPa)	THEORETICAL ANGLE OF TWIST ($\theta_{Theoretical}$) (Degrees)	SIMULATION ANGLE OF TWIST (θ_{Ansys}) (Degrees)
STEEL (SM45C)	80	0.05027768^0	0.2560773522^0
CARBON/EPOXY	5.6	0.7182526765^0	0.7274838439^0
BORON/EPOXY	5.59	0.719537565^0	0.6789432329^0
E-GLASS/EPOXY	5.5	0.7313118161^0	0.9138109969^0

Table 1.7: Theoretical & Simulation Angle of Twist