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Design, Analysis and Material Optimization of Propeller Shaft of 4 Wheeler Using Composite Material-A Case Study

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Abstract: *The Roadway vehicles like cars, buses, trucks and land movers having many mechanical parts in common like Engine parts, Propeller shafts, Gearbox, Brakes, Clutches, Wheels, etc., To make the vehicle fuel efficient which in result make the transportation economical, the weight of that vehicle should be reduced. Since the composite materials are light weight with more strength & stiffness, inclusion of composite materials to conventional steel materials used in auto parts will reduce the weight and improve the mechanical properties of those components. This Case study deals with designing the propeller shaft for its minimum dimensions to satisfy current problem specification and then replace conventional steel material with composite material..*

Keywords*:* Propeller Shaft, Composite Material, Carbon Epoxy, Glass Epoxy, SM45C, Abaqus, Solid work, Optimization, Analysis

I. INTRODUCTION

The objective of this chapter is to introduce the concepts and principles of shaft design. Specific attention is given to the arrangement of machine elements and features on a shaft, the connection of shafts, determining the deflection of shafts and critical speeds as well as specifying shaft dimensions for strength and fluctuating load integrity. An overall shaft design procedure is presented including consideration of bearing and component mounting and shaft dynamics for transmission shafting. The propeller shaft is an important component in the power transmission of any vehicle. Conventional steel drive shafts have weight and low critical speed limits. If the maximum efficiency of the power transmission is to be achieved, it is most important to reduce the weight of the drive shaft. The shaft in the front engine rear-drive vehicle will reduce the power according to the length of the vehicle. Natural bends occur when long shafts are used, to avoid this they are split using universal joints. When the number of universal joints increases its power transmitting capability decreases. The overall objective of this work is to control the power loss using composite material. Composite materials have high strength and stiffness and they can also withstand high temperatures. When the analysis is done by Abaqus & Solid Work software, properties like Deformation, Von-mises stress and Shear stress are analyzed. The composite materials such as Carbon Epoxy, Glass Epoxy and conventionally using SM45C steel shaft are analyzed as compared to these materials hybrid composite is formed when carbon fibers (high strength, high stiffness, but costly and brittle) are combined with glass fibers (good strength, impact resistance, lower cost).They are embedded in a polymer matrix (epoxy, polyester, vinyl ester, etc.), usually in layered or mixed orientations.

It will reduce the usage of universal joints. The traditional method uses two pieces of steel shaft with two universal joints. But in the case of composite materials the universal joint intermediate is not used. This is because the composite material has less deformation and bending than conventional shafts. High strength materials have been used to reduce weight and increase power transmission. The analyzed values have been compared using Abaqus software and the accuracy has been discovered.

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1.1 Background details

The term driveshaft first appeared in the mid-19th century. In Stower's 1861 patent reissue for planning and matching machines, the term is used to refer to the belt-driven shaft through which the machine was driven. The term is not used in its original patent. Another early use of the term occurs in the 1861 patent reissue for the Watkins and Bryson horse-drawn moving machine. Here, the term refers to the shaft transmitting power from the machine's wheels to the gear train that works the cutting mechanism.

1.2 Propeller shaft

A propeller shaft is used as a connection between different components of the driveline to transfer torque as shown in Figure 1.1, sometimes also called drive shaft. The advantages of using propeller shafts are that they allow the movement of components connected to each other. The area of application when the machine works on rough ground may be the connection between the wheel axles in construction equipment. A propeller shaft tolerates differences in length and angle. The function is enabled by an assembly of several parts. The fastening between the driveline components is possible due to the use of companion flanges.

Figure 1.1: Propeller shaft

1.3 Automotive Drive Shaft Vehicles

An automobile may use a longitudinal shaft to deliver power from an engine/transmission to the other end of the vehicle before it goes to the wheels. A pair of short drive shafts is commonly used to send power from a central differential, transmission, to the wheels.

1.4 Introduction to Composite Materials

Commercial material commonly has glass or carbon fiber in matrices based on thermosetting polymers, such as epoxy or polyester resins. Sometimes, thermoplastic polymers may be preferred, since they are moldable after initial production. There are further classes of composite in which the matrix is a metal or ceramic.

1.4.1 Composite Materials for Propeller Shaft

A **composite material** is a material made by **combining two or more different materials** in such a way that the final material has **better properties** than the individual ones.

One part is called the **matrix** → it holds everything together (usually resin, metal, or ceramic).

The other part is the **reinforcement** → it gives strength and stiffness (fibers, particles, or flakes).

The two materials remain **separate at the microscopic level**, but together they form a **new, improved material**.

Composites consist of two or more materials or material phases that are combined to produce a material that has superior properties to those of its individual constituents. The constituents are combined at a macroscopic level and or not soluble in each other. The main difference between composite and an alloy are constituent materials which are insoluble in each other and the individual constituents retain those properties in the case of composites, where as in alloys, constituent materials are soluble in each other and forms a new material which has different properties from their constituents.

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1.4.2 Classification of Composites

Composite materials can be classified as

- Polymer matrix composites
- Metal matrix composites
- Ceramic Matrix

Technologically, the most important composites are those in which the dispersed phase is in the form of a fiber. The design of fiber-reinforced composites is based on the high strength and stiffness on a weight basis. Specific strength is the ratio between strength and density. Specific modulus is the ratio between the modulus and density. Fiber length has a great influence on the mechanical characteristics of a material. The fibers can be either long or short. Long continuous fibers are easy to orient and process, while short fibers cannot be controlled fully for proper orientation. Long fibers provide many benefits over short fibers. These include impact resistance, low shrinkage, improved surface finish and dimensional stability. However short fibers provide low cost, are easy to work with, and have fast cycle time fabrication procedures.

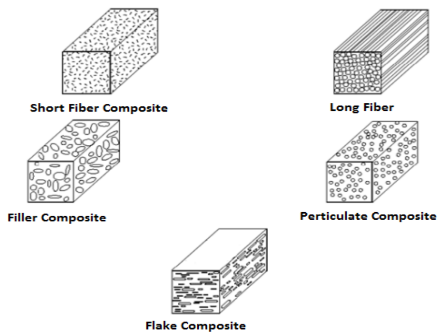

Figure 1.3: Composite's material

1.4.3 Mechanical Properties of Composite Material

The physical properties of composite materials are generally not isotropic (independent of direction of applied force) in nature, but rather are typically isotropic (different depending on the direction of the applied force or load). For instance, the stiffness of a composite panel will often depend upon the orientation of the applied forces and/or moments. The relationship between forces/moments and strains for an isotropic material can be described with the following material properties: Young's Modulus, the shear Modulus and the Poisson's ratio, in relatively simple mathematical relationships.

1.4.4 Merits of Composite Drive Shaft

1. They have high specific modulus and strength.
2. Reduced weights.
3. The fundamental natural frequency of the carbon fiber composite drive shaft can be twice as high as that of steel or aluminum because the carbon fiber composite material has more than 4 times the specific stiffness of steel or aluminum, which makes it possible to manufacture the drive shaft of passenger cars in one piece [7]. A one-piece composite shaft can be manufactured so as to satisfy the vibration requirements. This eliminates all the assembly, connecting the two-piece steel shafts and thus minimizes the overall weight, Vibrations and the total cost [9]-[10].
4. Due to the weight reduction, fuel consumption will be reduced
5. They have high damping capacity hence they produce less vibration and noise
6. They have good corrosion resistance
7. Greater torque capacities than steel or aluminum shaft
8. Longer fatigue life than steel or aluminum shaft
9. Lower rotating weight transmits more of available power

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1.4.5 Limitations of Composites

Mechanical characterization of a composite structure is more complex than that of a metallic structure
The design of fiber reinforced structure is difficult compared to a metallic
The fabrication cost of composites is high

1.4.6 Applications of Composites

The common applications of composites are extending day by day. Nowadays they are used in medical applications too. The other fields of applications are, Automotive: propeller shafts, clutch plates, engine blocks, push rods, frames, Valve guides, automotive racing brakes, filament-wound fuel tanks, fiberGlass/Epoxy leaf springs for heavy trucks and trailers, rocker arm covers, suspension arms and bearings for steering system, bumpers, body panels and doors.

1.5 Problem Statement

Stainless steel was mainly used because of its high strength. But this stainless steel shaft has less specific strength and less specific modulus. Stainless steel has less damping capacity. Because of its higher density of molecules of stainless steel, its weight is very high. Because of the increase in weight fuel consumption will increase, the effect of inertia will be more and increase in weight. The steel propeller shaft is replaced with the composite materials, which are very less weight when compared to that of stainless steel. The cost of composite materials is less when compared to that of stainless steel. The E-Glass/Epoxy and Carbon/Epoxy materials are selected for the composite drive shaft. Since, composites are highly orthotropic and their fractures were not fully studied.

1.6 Objectives of Project

The main objectives of this Case Study are
To investigate the existing design of automotive/automobile propeller shafts.
To check the design of the propeller shaft mathematically with a conventional material.
To check the design of the propeller shaft mathematically with composite material.
To perform FEM analysis with conventional as well as composite materials.
Finally optimize the design of the propeller shaft which should be compatible and cost effective.
Interprets the results of all conditions and analysis.

II. RESEARCH METHODOLOGY

A reliable experimental investigation is required for checking the design of composite structures. The goal of testing the driveshaft is the determination of torsional strength, natural frequency, and critical speed. Various techniques of experimentation were used for the above applications. Most of these are dealing with the deformation or strain measurement. The devices required for experimentation on the driveshaft are complex and require significant alterations. The experimental setups to fulfill these objectives are designed.

2.1 Proposed Methodology

The solution for the problem is performed in the following six stages –Defining dimensions, Material Selection, Theoretical Analysis, Creating a Solid Model, Finite Element Analysis and Comparative study. First task was to design the procedure of the propeller shaft according to the standard which is used. Next step was to create a model of the propeller shaft with the help of the design calculation of the propeller shaft which we had calculated in Abaqus. In the next step, we are taking the material which is used standard wise for propeller shaft i.e., Steel SM45 and we had developed an analysis report taking proper torque as per standard wise. Next step is to take the composite material i.e., Carbon Epoxy, Glass Epoxy and Carbon + Glass hybrid and take the required result of analysis. Final step is to take the comparative analysis in between Steel and Carbon Epoxy and glass Epoxy and Carbon + Glass hybrid composite results are shown.

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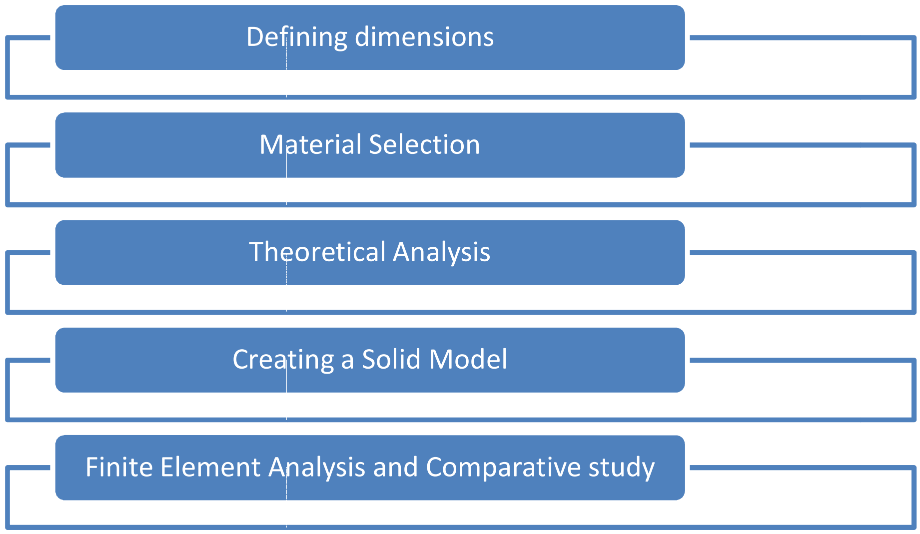

2.2 Finite Element Analysis

Finite element analysis process involves following steps.

- Preprocessing is carried out in Ansys 2023 Software.
- Geometry import & cleanup.
- Component collector creation.
- Material & property definition.
- 2D shell meshing of propeller tube & 3D meshing of solid parts.
- Joint's creation using 1D rigid RBE2 elements.
- Applying boundary conditions.
- Preparation of analysis Deck for Abaqus.

2.3 Post Processing

In this part results are analyzed, applied for visualization of the behavior of the component in the actual practice in all respects e.g., stresses, displacement.

2.4 Description of Composite Material

A composite material is a combination of two materials with different physical and chemical properties. When they are combined, they create a material which is specialized to do a certain job, for instance to become stronger, lighter or resistant to electricity. They can also improve strength and stiffness.

Carbon Epoxy

Carbon fiber reinforced composites have exceptional mechanical properties. These strong, stiff and lightweight materials are an ideal choice for applications where lightweight & superior performance are important, such as components for aircraft, automotive, rail and high-quality consumer products. The range offered is based upon composite sheets produced by stacking carbon fiber fabrics one upon another and then infusing the stack with resin under vacuum.

Constituents of carbon epoxy

Carbon fibers are produced from polymer fibers such as polyacrylonitrile and from pitch. The initial fiber material is drawn under tension whilst it is heated to around 1000°C causing 2-dimensional carbon-carbon crystals (graphite) to be

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formed when hydrogen is driven out. The carbon-carbon chain has extremely strong molecular bonds and this is what gives the fibers their high strength.

Glass epoxy

Laminated material in sheets, made from modified glass fabric as a reinforcement and epoxy resole resin. Besides good mechanical and electrical insulating properties, it has high climate resistance. It is used in production of components with good mechanical and electrical properties, for electrical equipment at higher temperatures or in humid environments, for stressed electrical insulating components, such as chassis, body equipment, housing parts of distribution boards, transformers, switchgears, electrical machines.

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It is characterized by excellent mechanical and electrical insulating properties, which keeps it even at higher temperatures. It is characterized by resistance to tracking. It is used in the production of components with good mechanical and electrical properties, for electrical equipment at higher temperatures or in humid environments, for stressed electrical insulating components, such as chassis, body equipment, housing parts of distribution boards, transformers, switchgears, electrical machines.

Constituents of Glass epoxy

Sheets are made of non-alkaline glass fabric and silicone resin. It is characterized by high temperature resistance (thermal class H) and by good dielectric properties.

2.5 Mechanical Properties of Materials used for propeller shaft

Mechanical Properties	Units	Steel (SM45C)	Carbon Epoxy	Glass Epoxy
Young's Modulus (E) or Modulus of Elasticity	GPa	207	175	45
Shear Modulus (G) or Modulus of Rigidity	GPa	80	5.5	5
Poisson's Ratio		0.3	0.281	0.275
Density	Kg/m3	7600	1550	1950
Shear Stress	MPa	350	90	65

Software used for Modeling and Analysis

CREO 7.0 Software

This software is used for modeling i.e., making CAD model of proposed multipurpose fiber extraction machine and for simulation purposes. Proper designing & modeling of fiber extraction machine using a CAD Modeling Software like CREO.

ANSYS 2023 is a suite of simulation software tools used for modelling and analysis in engineering – structural, fluid, thermal, electronics, etc. The **2023 release** refers to the versions released in that year (typically R1, R2) with updated features, performance improvements, and new workflows.

Key Updates in ANSYS 2023:

Faster solvers with **multi-GPU support** (especially in Fluent).
Better **integration of multiphysics** (structural + thermal + electrical).
Improved **ANSYS Discovery** for real-time simulation & topology optimization.
New automation tools (e.g., **PyMechanical**).
Enhanced **meshing, visualization, and user interface**.
Stronger tools for **semiconductor design, safety, and electronics**.

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III. DESIGN AND ANALYSIS

3.1 Design and Analysis The design procedure was carried out by considering the values stated in problem statement.

3.2 Theoretical Design

3.2.1 Mass of the shaft The mass m, of the hollow shaft is given by:

$m = \rho \times A \times L$ (3.1)

$m = \rho \times \pi\ 4\ (Do2 - Di2) \times L$

3.2.2 Torque transmission capacity of shaft Torque transmission capacity 'Tcr' of a steel drive shaft is given by:

$T = Ss\ \pi\ (Do4 - Di\ 4)\ /16Do$ (3.3)

Where, Ss is the shear strength,

Do and Di represent outside and inside diameter of the steel shaft.

3.2.3 Torsional Buckling capacity of shaft

If $(1\ *L^2t)\ /(\sqrt{(1-\mu^2)}\ *(2r)\ ^3) > 5.5$, it is called as long shaft otherwise it is called as short & medium shaft [6]. For a long shaft, the critical stress τcr is given by:

$\tau cr = (E\ (t/r)\ \hat{}\ (3/2))\ /(3\sqrt{2}(1-\mu 2)\ \hat{}\ (3/4))$ (3.4)

Where, E and µ represent steel properties. L, t and r are the length, thickness and mean radius of the shaft respectively.

The relation between the torsional buckling capacity τcr and critical stress is given by:

$Tcr = \tau cr 2\pi r\ 2t$ (3.5)

3.2.4 Fundamental bending natural frequency

The expression for the lowest natural frequency 'fn' is given as follows:

$fn = (\pi/\ 2)\ \sqrt{}\ (gEI\ /wL\ 4)$ (3.6)

Where, g, E, I, w and L are the gravitational acceleration, Young's modulus, polar moment of inertia, weight and length respectively.

3.2.5 Torsional Deflection of shaft The expression for the torsional deflection of the shaft 'θ' is given as follows:

$\theta = (L \times T)/\ (G \times J)$ (3.7) $\theta = 32 \times L \times T\ /\ (G\pi\ (Do\hat{}4 - Di\hat{}4))$

Where, T and G are the torque transmitted and shear modulus of rigidity respectively [5]

Then the design will be safe. As per our calculation the torque value of propeller shaft is less than Buckling Torque.

By using the theoretical design formula, all the dimensions were obtained which satisfies the given conditions in the problem statement. Further using data analysis, following dimensions were considered to obtain accurate results with minimum weight.

Dimensions for shaft are as follows:

- Length of the Shaft: 1200 mm
- Outer Diameter of the Shaft: 80 mm
- Inner Diameter of the Shaft: 75 mm
- Thickness: 2.5 mm

The design procedure was carried out by considering by the above values .

Table 3.1: Analytical Values of Propeller Shaft of Different Material

Properties	Units	Steel SM45C)	Carbon/Epoxy	Glass/Epoxy
Length (L)	m	1.2	1.2	1.2
Outer dia (d_o)	m	0.8	0.8	0.8
Inner dia (d_i)	m	0.075	0.075	0.075
Max. Shear Stress (τ_{max})	MPa	4.50	4.5	4.5
Von-Mises Stress	MPa	7.826	7.795	7.805
Critical Stress (τ_{cr})	MPa	1188.923	1414.89	363.335
Buckilng Torque (T_b)	N-mm	79.31 $x10^6$	66.74 $x10^6$	17.139 $x10^6$
Frequency	Hz	201.386	410.05	185.39

Mass (m)	**kg**	**5.551**	**1.132**	**1.424**
Weight in Mass Saving	**%**	**--**	**79.6**	**74.3**

3.3 Analysis

3.3.1 Solution Sequence

The complete finite-element analysis consists of 3 separate stages:

Preprocessing: In this stage you must define the model of the physical problem and create an Abaqus input file.

3.3.2 FEM analysis

The finite element analysis (finite element method) is a numerical technique for finding approximate solutions of partial differential equations as well as of integral equations. The solution approach is based on either eliminating the differential equation completely (steady state problems).

3.3.3 Post processing

In the earlier days of finite element analysis, the user would pore through reams of numbers generated by the code, listing displacements and stresses at discrete positions within the model.

3.3.4 Structural analysis

In this work propeller shaft is selected for structural analysis using Abaqus. The various composite materials like Carbon Epoxy, Glass Epoxy and conventional SM45C using finite element analysis software Abaqus.

3.4 Boundary Condition

We had applied torque of 110 Nm on one end of the shaft. Y and Z axis value was torque moment of 110 Nm.

3.5 Analysis is done on SM45C

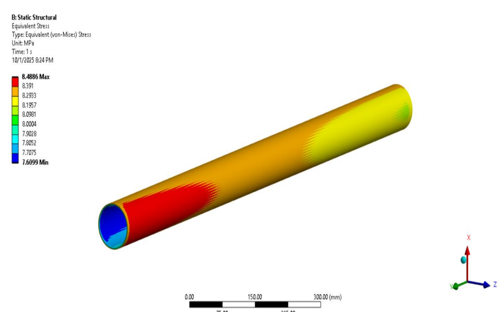

Figure 3.1: Von Mises Stresses of Propeller Shaft for SM45C
(Max Von Mises Stresses=8.4886, Min.Von Mises Stresses=7.6099)

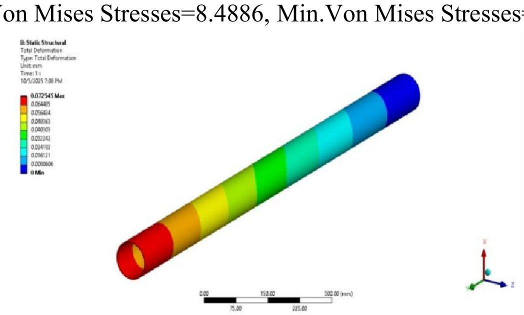

Figure 3.2: Displacement of Propeller Shaft for SM45C
(Max Displacement =0.07254, Min. Displacement = 0)

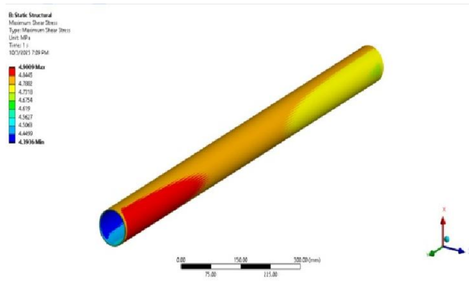

Figure 3.3: Maximum Shear Stress of Propeller Shaft for SM45C
(Max Shear Stress = 4.9009, Min. Shear Stress =4.3916)

3.6 Analysis is done on Carbon Epoxy

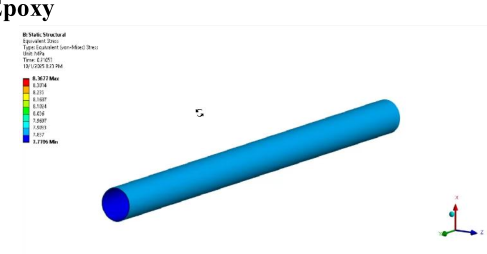

Figure 3.4: Von Mises Stresses of Propeller Shaft for carbon Epoxy
(Max Von Mises Stresses=8.3677, Min.Von Mises Stresses=7.7706)

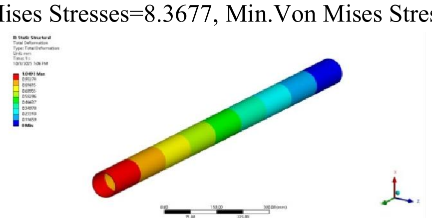

Figure 3.5: Displacement of Propeller Shaft for carbon Epoxy
(Max Displacement =1.0493, Min. Displacement = 0)

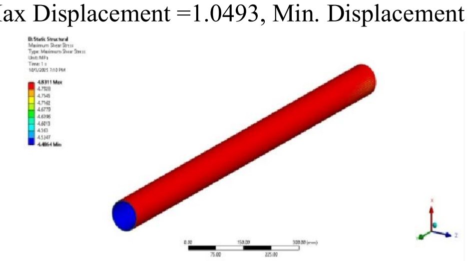

Figure 3.6: Maximum Shear Stress of Propeller Shaft for carbon Epoxy
(Max Shear Stress = 4.8311, Min. Shear Stress = 4.4864)

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3.7 Analysis is done on Glass Epoxy

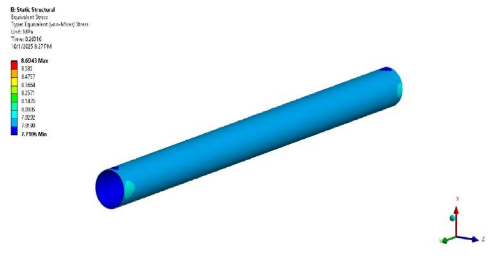

Figure 3.7: Von Mises Stresses of Propeller Shaft for Glass Epoxy
(Max Von Mises Stresses=8.6943, Min.Von Mises Stresses=7.7106)

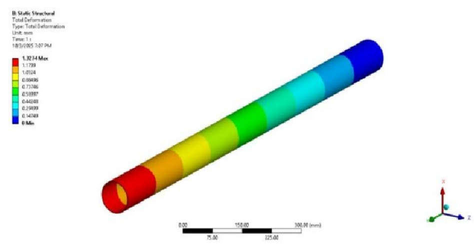

Figure 3.8: Displacement of Propeller Shaft for Glass Epoxy
(Max Displacement =1.3274, Min. Displacement = 0)

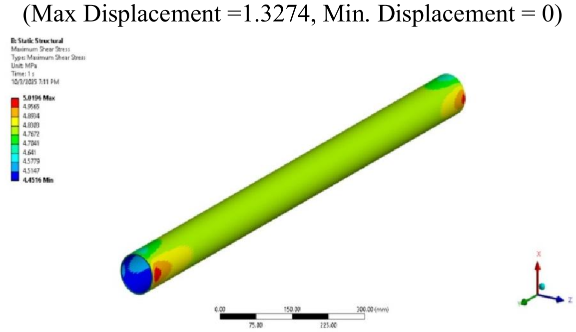

Figure 3.9: Maximum Shear Stress of Propeller Shaft for Glass Epoxy
(Max Shear Stress = 5.0196, Min. Shear Stress = 4.4516)

Validation and comparison of analytical and Ansys results

Result	SM45C		Carbon Epoxy		Glass Epoxy	
	Ansys 2023	Analytical	Ansys 2023	Analytical	Ansys 2023	Analytical
Von-Mises Stress (MPa)	8.4886	7.826	8.3677	7.795	8.6943	7.805
Max. Shear Stress (MPa)	4.909	4.50	4.831	4.50	5.019	4.50
Mass (Kg)	5.551	5.551	1.132	1.132	1.424	1.424

Table 3.2 : Validation and comparison of analytical and Ansys results

When comparing Carbon Epoxy and Glass Epoxy composite shaft to conventional steel shaft the Carbon Epoxy composite shaft provides 79.6% in mass savings and Glass Epoxy composite shaft provides 74.3% of mass savings than steel shaft. If the weight of shaft is low, then more performance and fuel efficiency shall be obtained by the vehicle, so composite shafts shall be preferred. Also, the Shear stress and Von-Mises stress of Carbon Epoxy composite shaft and Glass Epoxy composite shaft are well placed under their safe values. Hence these composite shafts shall be preferred as suitable material for propeller shafts.

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IV. CONCLUSION

The Carbon Epoxy and Glass Epoxy composite propeller shafts are designed to meet safe design requirements as the conventional steel shaft. From the torsional buckling and modal analysis, the deformation, Shear stress, Von-Mises stress, critical speed, bending natural frequency and weight are determined. Von mises stress of carbon epoxy and glass epoxy are under safe values so that fracture will not occur. Deflection is less in carbon epoxy. the usage of composite materials Propeller shaft has resulted in inconsiderable amt of weight saving in the range of 73-80% when compared to steel shaft. Apart from being lightweight, composites also ensure less vibrations and noise. Hence a Carbon Epoxy composite shaft will be used as a propeller shaft for automobile vehicles

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