

Design and Analysis of Propeller Shaft of an Automobile Using Composite Materials

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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 project deals with propeller shaft of MARUTHI OMNI to design the shaft for its minimum dimensions to satisfy current problem specification and then replace conventional steel material with composite material. The design of the propeller shaft is first theoretically designed for steel, Carbon/Epoxy and Glass/Epoxy composite material for its safe dimensions. Then they can be created as a part model for respective dimensions in NX 8.5 software. After modeling, Torsional buckling analysis and Modal analysis can be carried out in the propeller shafts using NX NASTRAN to check whether theoretical calculations and analytical results are similar. Then obtained results are compared among those three materials and Carbon/Epoxy composite material is selected as suitable replacement material for conventional steel material in terms of several mechanical properties.

KEYWORDS: Propeller shaft, Composite materials, NX NASTRAN, Torsional Buckling, Bending Natural Frequency,

I. INTRODUCTION

Nowadays transportation is very essential for mankind's day-to-day life. There are four ways of transportation in the world they are roadways, railways, seaways and airways. Among these roadways are economical and easiest transportation. To make this economical transportation into more economical, there are many research works going on every year. This project deals with improving the roadways into better transportation. It can be achieved commonly by tweaking the engine, alternative fuels, aerodynamics and inclusion of composite material to auto parts to reduce its weight, improve mechanical properties and fuel efficiency. The roadway vehicles having many similar mechanical parts such as engine parts, gearbox, propeller shaft, springs, clutch, wheels, etc., Out of these components a propeller shaft plays a major role in transmitting engine's power to wheels. This shaft connects the engine transmission output and rear axle differential unit.

Propeller shaft: The transmission of torque from engine to wheels is performed by a shaft for forward and reverse motion of vehicle. That shaft is known as Propeller shaft or Drive shaft. It consists of joints and couplings to connect engine and differential unit.

Composite materials: A new kind of material which is formed due to combination of two or more metals or non-metals is known as composite materials. Generally composite materials are lighter and stronger than conventional metals. The usages of composite materials were started from early 20th century itself. Concrete is one of the most

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famous composite material which is widely used in building bridges, houses, skyscrapers, etc., There are many types of composite materials like carbon epoxy, glass epoxy, Kevlar, etc.,

II. LITERATURE REVIEW

This work comprises of composite materials and propeller shafts hence there are many journals, books and websites were referred. These journals and books provide more knowledge about mechanical properties of composite materials and designing and analysis of propeller shaft in simulation software. The inclusions of composite materials in conventional steel materials were evolved in 1985 itself. The Spicer U-Joint Division of Dana Corporation for the Ford Econoline van models developed the first composite propeller shaft in 1985. The General Motors pickup trucks, which adopted the Spicer product, enjoyed a demand three times that of projected sales in its first year^[23]. The research works and other studies regarding composite materials and propeller shafts are discussed in following sections.

2.1 Propeller shaft analysis: There are many journals published regarding composite propeller shaft or propeller shaft. Pollard^[5] discussed about inclusion of composite materials in propeller shaft. Then he added few cars such as Renault Espace Quadra, Renault Safrane, Toyota Mark II and Audi Quattro using composite materials in few parts. The replacement of composite materials in conventional steel materials will reduce weight of those components and in terms it increases the fuel efficiency and performance of vehicle. There are few new kind of composites are used in Prajitsen G Damle et al^[4], research such as crowfoot satin woven glass fiber epoxy composite(GEP215). Then K. Rambabu et al^[18], analyses the propeller shaft with Kevlar/Epoxy composite which is widely used in industrial applications. They also concluded that composite shafts are having better mechanical properties with improved qualities.

2.3 Torsional Buckling and Modal analysis: There are many structural analysis takes place in a propeller shaft. The torsional strength, torsional bucking analysis and bending natural frequency are important analysis for a propeller shaft. A technical paper presented by Yonas Mitiku et al^[2], explained the design procedure for finding maximum deformation and maximum stresses present in both conventional steel shaft and composite shaft. They concluded that carbon/epoxy composite propeller shaft is way beyond better than steel shaft. The carbon/epoxy composite propeller shaft saves 89.75% of weight when compared to steel shaft. Then another journal describes about fundamental of natural frequency and torsional stress of E-Glass/Epoxy and CH-Kevlar/Epoxy composites in propeller shaft by Bhirud Pankaj Prakash et al^[17]. They resulted that Kevlar/Epoxy composite save 24-29% of weight when compared to conventional steel shaft. The static structural and modal analysis were again performed by D Dinesh et al^[19], presented that E-Glass/Epoxy, High Strength and High Modulus Carbon/Epoxy composites saves 48.36%, 86.9% and 86.9% of weight while comparing to steel propeller shaft. Another paper which describes about similar composite propeller shafts by Arun Ravi^[12] mentioned that HS Carbon composite save about 24% of weight and deflection of HS Carbon composite is very low than conventional steel propeller shaft. At last another technical paper from Sachin G Mahakalkar et al^[14] performed analysis for similar composite materials and concluded that these composite materials are suitable to replace conventional steel materials used in propeller shafts.

III. DESIGN PROCEDURE FOR PROPELLER SHAFT

3.1 Specification of the problem:

The following specifications were assumed suitably, based on the literature review and available standards of automobile propeller shafts especially Maruthi Omni.

The torque transmission capacity of the propeller shaft (T)	= 59Nm
The shaft needs to withstand torsional buckling (T_b) such that $T_b > T$	
The minimum bending natural frequency of the shaft ($f_{nb(min)}$)	= 80Hz
Outside radius of the propeller shaft (r_o)	= 25.5mm or 0.0255m
Length of the propeller shaft (l)	= 0.562m

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First, the conventional steel shaft was designed to facilitate comparison in terms of mass savings. Be it the conventional driveshaft or the composite one, the design should be based on the following criteria

- Torsional strength
- Torsional buckling
- Bending natural frequency

This work deals with propeller shaft of Maruthi Omni 8 seater vehicle. This propeller shaft is already using steel (SM45C) material. The mechanical properties of steel material are taken from reference [23] and Composite material properties are taken from reference [4] which is provided in the following tabulation.

Table 1 Mechanical Properties of Materials used for propeller shaft

Mechanical Properties	Units	Steel (SM45C)	Carbon epoxy	Glass epoxy
Young's Modulus (E)	GPa	207.0	131.6	43.3
Shear Modulus (G)	GPa	80.0	3.5	3.5
Poisson's ratio (ν)		0.3	0.281	0.3
Density (ρ)	kg/m ³	7600	1550	2100
Shear Stress(τ)	MPa	29.419	40	65

3.2 Torsional Strength

Since the primary load on a driveshaft is torsion, the maximum shear stress (τ_{max}) at the outer radius (r_o) of the shaft is given by

$$\frac{\tau_{max}}{F.S} = \frac{T r_o}{J} \dots\dots\dots (3.1)$$

where $J = \frac{\pi}{32} [d_o^4 - d_i^4]$

We know that

- T is max. torque applied in Nm
- J is the polar moment of inertia in m⁴
- d_o and d_i are outside and inner diameters of the shaft in m

Assuming Factor of safety as 3

Then internal diameter of hollow shaft is d_i

Thus wall thickness can be calculated by

$$t = (d_o - d_i)/2 \dots\dots\dots (3.2)$$

For composite shaft ply thickness $t_{ply} = 0.13\text{mm}$

Hence convert the obtained thickness of shaft to multiple of 0.13 in m

Maximum Shear stress of shaft,

$$\tau_{max} = \frac{2T r_o}{\frac{\pi}{32} [d_o^4 - d_i^4]} \dots\dots\dots (3.3)$$

3.3 Torsional Buckling

A shaft is considered as short shaft if the following condition satisfies; otherwise the shaft is considered as long shaft

$$\left(\frac{1}{\sqrt{1-\nu^2}} \right) \frac{L^2 t}{(2r)^3} > 5.5 \dots\dots\dots (3.4)$$

Where r is the mean radius, such that

$$r = \frac{(r_i + r_o)}{2} \dots\dots\dots (3.5)$$

Here the shaft is a short shaft, then the formula to calculate critical stress(τ_{cr}) is

$$\tau_{cr} = \frac{4.39 E}{(1-\nu^2)} \left(\frac{t}{r} \right)^2 \sqrt{1 + 0.0257(1 - \nu^2)^3} / 4 \frac{L^3}{(r t)^{1.5}} \dots\dots\dots (3.6)$$

The relationship between torsional buckling and critical stress is given by

$$T_b = \tau_{cr} 2 \pi r^2 t \dots\dots\dots (3.7)$$

If, $T_b > T$

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Then the design will be safe

3.4 Bending natural frequency

According to Bernoulli-Euler beam theory, by neglecting shear deformation and rotational inertia effects the bending natural frequency of a rotating shaft is given by

$$f_{nb} = \frac{\pi p^2}{2L^2} \sqrt{\frac{EI_x}{m}} \dots\dots\dots (3.8)$$

Where,

m_u is mass per unit length in kg/m

$$m_u = \rho \frac{\pi}{4} (d_o^2 - d_i^2) \dots\dots\dots (3.9)$$

Then I_x is area moment of inertia in x-direction in m^4

$$I_x = \frac{\pi}{64} (d_o^4 - d_i^4) \dots\dots\dots (3.10)$$

Thus obtaining all these values bending natural frequency should be

$$f_{nb} > f_{nb(min)}$$

Critical speed of the shaft is

$$N_{crb} = 60 f_{nb} \dots\dots\dots (3.11)$$

If $N_{crb} > N$

Then the designed propeller shaft meets all requirements.

The total mass of the shaft is

$$m = m_u L \dots\dots\dots (3.12)$$

Thus the design parameters for those shafts are calculated and mentioned below and outer diameter and length of the shaft cannot be changed due to space restriction in vehicle.

Table 2 Design parameters for steel, Carbon/Epoxy and Glass/Epoxy shafts

Properties	Units	Steel	Carbon/Epoxy	Glass/Epoxy
Length (L)	m	0.562	0.562	0.562
Outer dia (d_o)	m	0.051	0.051	0.051
Inner dia (d_i)	m	0.048434	0.04866	0.04944
Max. Shear Stress (τ_{max})	MPa	19.6104	13.2319	19.395
Critical Stress (τ_{cr})	GPa	522.69	228.32	44.634
Buckilng Torque (T_b)	Nm	3.2489x10 ⁶	1.0413x10 ⁶	1.3785x10 ⁵
Bending Natural Frequency (f_{nb})	Hz	458.94	807.39	400.81
Critical Speed (N_{cr})	rpm	27537.37	48443.55	24048.98
Mass (m)	kg	1.05914	0.159468	0.145163

IV. ANALYSIS AND RESULTS

The steel propeller shaft is imported to NX NASTRAN and is analysed for the maximum deflection, Maximum shear stress and the Von-Mises stress value. The resulting values are tabulated. The fixed constraint is given at the one edge of the shaft, where the shaft is connected to differential unit. The Torque T is given at the other edge of the shaft. The same procedure is repeated for E-Glass/Epoxy and Carbon/Epoxy leaf springs.

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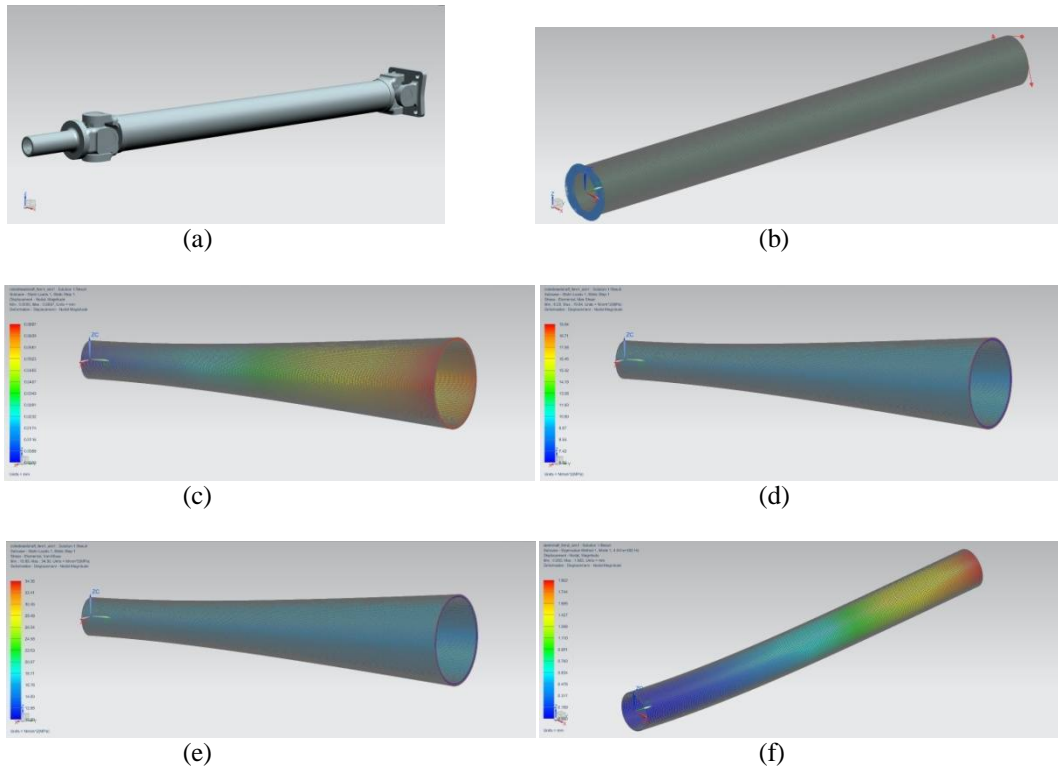


Fig 1 Part model and analysis result for Steel propeller shaft (a) Part model (b) Boundary conditions and meshing (c) Maximum deflection (d) Maximum shear stress (e) Von-Mises stress (f) Model1 in modal analysis

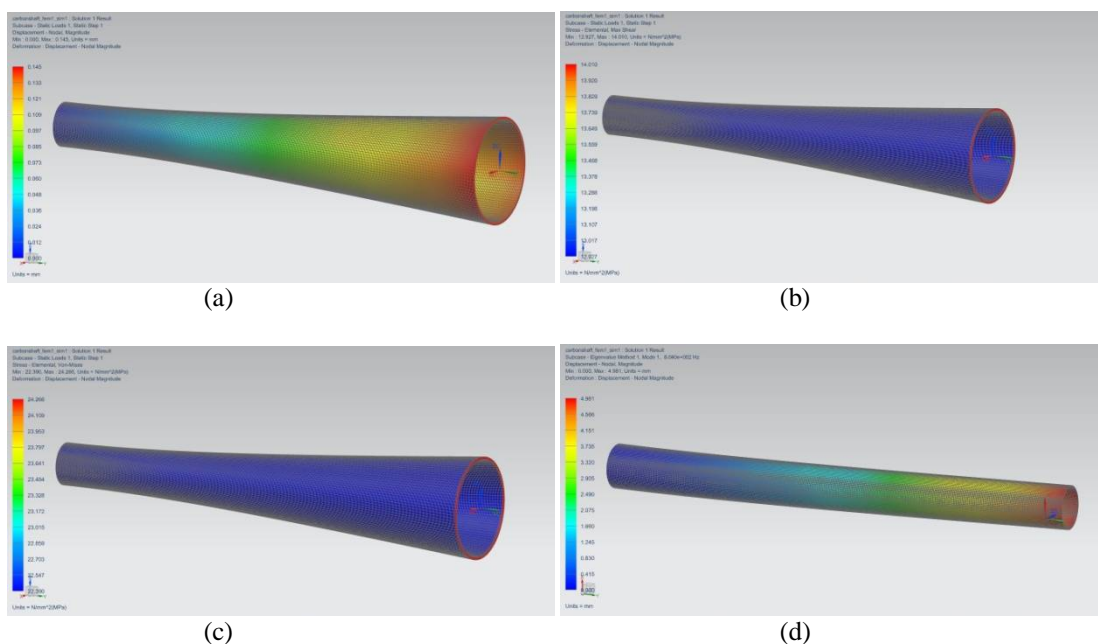


Fig 2 Analysis results of Carbon/Epoxy Composite propeller shaft (a) Maximum deflection (b) Maximum shear stress (c) Von-Mises stress (d) Model1 in Modal analysis

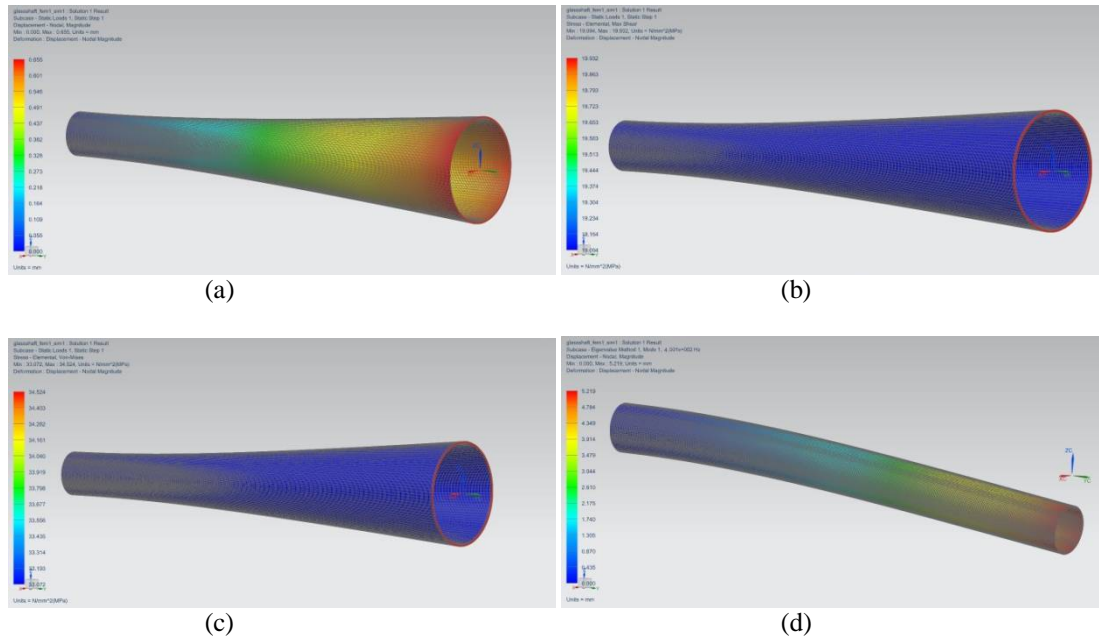


Fig 3 Analysis results of Glass/Epoxy Composite propeller shaft (a) Maximum deflection (b) Maximum shear stress (c) Von-Mises stress (d) Model 1 in Modal analysis

V. RESULT AND COMPARISON

5.1 Torsional Buckling Analysis

Material	Deflection	Shear stress	Von-Mises stress	Weight
Units	mm	MPa	MPa	kg
Steel	0.0697	19.84	34.36	1.05914
Carbon/Epoxy	0.145	14.010	24.266	0.15946
Glass/Epoxy	0.655	19.932	34.524	0.14516

Table 3 Torsional Buckling analysis result comparison

When comparing Carbon/Epoxy and Glass/Epoxy composite shaft to conventional steel shaft the Carbon/Epoxy composite shaft provides **84.94%** in mass savings and Glass/Epoxy composite shaft provides **86.29%** 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 shaft.

5.2 Modal Analysis

Material	Mode 1	Mode 2	Mode 3	Mode 4
Units	Hz	Hz	Hz	Hz
Steel	454.1	1842	4158	7304
Carbon/Epoxy	804.0	3229	7266	1286
Glass/Epoxy	400.1	1602	3808	6509

Table 4 Modal Analysis result comparison

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Then bending natural frequency of carbon/Epoxy composite shaft is **77.05%** greater and Glass/Epoxy composite shaft is **11.89%** lesser than the conventional steel shaft. When the bending natural frequency is high then critical speed is also high, so the shafts have more range of speed if the frequency is high. Hence carbon/Epoxy composite shaft is preferred.

VI. 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.

In overall comparison Glass/Epoxy composite shaft is better only in weight reduction and that too only **1.56%** lesser weight than Carbon/Epoxy composite shaft. Otherwise Carbon/Epoxy composite shaft is better in shear stress and von-mises stress with very small deformation and bending natural frequency of Carbon/Epoxy composite shaft is **100.9%** greater than Glass/Epoxy composite shaft. So it ticks all the boxes for a suitable material to replace conventional steel material in a automobile shaft. Hence a **Carbon/Epoxy composite shaft** will be used as a propeller shaft for Maruthi Omni vehicle.

Future work: Since this work relies on pure theoretical calculation and simulation in analysis software, the future work is to fabricate the propeller shaft in Carbon/Epoxy composite material and test it in real time environment.

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