DESIGN AND ANALYSIS OF SINGLE COMPOSITE DRIVE SHAFT FOR LIGHT MOTOR VEHICLE

[1]Taksande R. V., [2]Shende M. D.,
[1]PG Student, [2]Professor
[1,2] Mechanical Engineering Department,
[1,2] Shreeyash College of Engineering and Technology, Aurangabad, India

Abstract: The automotive like cars having various mechanical elements are built to create the vehicle fuel efficient that in result make the transportation economical, the weight of that vehicle ought to be reduced. The composite materials are lightweight with additional strength & stiffness, replacement of composite materials to traditional steel materials utilized in automotive vehicle components can scale back the weight and improve the mechanical properties of these parts. This project deals with drive shaft of MARUTI OMNI to design the shaft for its minimum dimensions and satisfy current drawback with specification then replace typical steel material with Carbon/Epoxy composite material. Then a part model created for individual dimensions in CATIA V5R19 software. Once modeling, Torsional buckling analysis and Modal analysis will be applied for propeller shafts using ANSYS R14.5 to validate the theoretical calculations and analytical results. The obtained results are compared and Carbon/Epoxy composite material is chosen as better replacement material for regular steel material in terms of many mechanical properties for light motor vehicle.

***Index Terms*- Drive shaft, Composite, Carbon/ Epoxy, CATIA V5R19, ANSYS R14.5.**

I. INTRODUCTION

This project deals with the rising roadways into better transportation. It is normally achieved by tweaking the engine, various fuels, aerodynamics and applications of composite material to automobile components to cut back its weight, enhance mechanical properties and fuel efficiency [1]. The roadway vehicles having several similar mechanical components such as engine elements, gearbox, drive shaft, springs, clutch, wheels, etc., Out of these the propeller shaft plays a significant role in transmission engines power to the wheels. This shaft connects the engine power output and rear shaft differential unit. The transmission of power from engine to wheels is performed by the shaft for forward and reverse motion of a car. That shaft is named as propeller shaft or Drive shaft. A replacement reasonably material which is made because of combination of two or number of metals or non-metals called as composite materials. This work deals with propeller shaft of Maruti Omni eight seater vehicle steel (SM45C) material [2]. The mechanical properties of steel and composite material are compared and discussed in this project.

II. LITERATURE REVIEW

This work includes the literature survey of different research work made by various researchers on composite driveshaft. Muhammad Zulfadhli Bin Md Zaki et al conferred a paper with design and Analysis of a Composite Drive Shaft by using specific winding angle of fibre with totally different stacking sequences [1]. Salaisivabalan T, Natarajan R et al performed design and analysis of one-piece automotive Carbon/Epoxy and Glass/Epoxy composite drive shafts to fulfil design necessities for Maruti Omni car and compare with conventional steel shaft [2]. Mohammad Reza Khoshravan et al presents the paper, design technique of composite drive shaft with some parameters such as critical speed, static torque and adhesive joints are studied and the analysis has performed using FEA [3]. A R Abu Talib et al present finite element analysis of the design variables of fiber orientation as well as stacking sequence give an insight to their effects of Carbon\Epoxy and Glass\Epoxy was studied [4]. Atul Kumar Raikwar et al accomplish FEA and optimize the design & weight with composite materials [5]. N Rajendar et al deals with the design and analysis for composite drive shaft and replacement of conventional steel shaft by minimizing the weight of composite drive shaft and analyze with the help of the FEA software ANSYS 14.5 [6].

III. DESIGN OF PRPELLER SHAFT

Transmission of power can be improved through the reduction of mass inertia and light weight. In the design of SM45C steel shaft, knowing the torque and the allowable shear stress for the steel material.

3.1 Problem Specification

The specifications were assumed appropriately, supported the literature review and standards offered for automobile propeller shaft particularly Maruti Omni [3].
The torque transmission capacity of the drive shaft (T) = 59 Nm
The shaft has to stand up to buckling torque (Tb) specified Tb > T
The minimum bending natural frequency of the shaft ($f_{nb\ min}$) = 80 Hz
Maximum diameter of the propeller shaft ($\mathbf{d_o}$) = 0.051 m
Length of the propeller shaft (l) = 0.562 m

First the traditional steel shaft was designed to facilitate comparison in terms of mass savings. Be it the traditional shaft or the composite one, the design ought to be supported the subsequent criteria

- Torsional strength

- Buckling torque
- Bending natural frequency

The mechanical properties of steel and composite material are taken from the literature available mentioned in the Table 1.

Table 1. Mechanical properties of materials for propeller shaft

Mechanical Properties	Units	Steel (SM45C)	Carbon epoxy
Young's Modulus (E)	GPa	207.0	131.6
Shear Modulus (G)	GPa	80.0	7.6
Poisson's ratio (ν)	-	0.3	0.281
Density (ρ)	Kg/m^3	7600	1550
Shear Stress(τ)	N/mm^2	29.419	40

3.2 Torsional Strength

The maximum torsional strength of the Steel shaft is calculated by using torsion equation [7]

$\frac{\tau}{r} = \frac{T}{J} = \frac{G\theta}{l}$

Where, T is torque transmitted in Nm.

Polar moment of inertia (J) = $\frac{\pi}{32}\left(d_o{}^4 - d_i{}^4\right) = 1.43019 \times 10^{-7}\ m^4$

Mean radius of shaft (r_m) = $\frac{r_o+r_i}{2}$ = 0.02475 m

r_o = is outside radius of hollow shaft in m

r_i = inside radius of hollow shaft in m

G = Shear Modulus = $80 \times 10^9\ N/m^2$

Assume angle of twist in radians(θ) = $5 \times \frac{\pi}{180}$ radian

Shear stress (τ) = $\frac{G\theta r_m}{l} = 307.45 \times 10^6\ N/m^2$

Now, $\frac{\tau}{r} = \frac{T}{J}$

T = 1776.61 Nm > 59 Nm. Therefore design is safe.

3.3 Bending Natural Frequency

Minimum bending natural frequency for Steel shaft (f_{nb} min) = 80 Hz

Natural frequency (f_{nb}) = $\frac{\pi}{2}\sqrt{\frac{E_x I_x}{m' L^4}}$

Where, $E_x = 207 \times 10^9\ N/m^2$

Moment of inertia in x direction(I_x) = $\frac{\pi}{64}\left(d_o{}^4 - d_i{}^4\right) = 7.1509 \times 10^{-8}\ m^4$

The mass per unit length of the shaft (m′) = $\rho\frac{\pi}{4}\left(d_o{}^2 - d_i{}^2\right)$ = 1.8311 Kg/ m

Where, density of steel (ρ) = $7850\ Kg/m^3$

d_o = 0.051 m, d_i = 0.048 m

Therefore bending natural frequency (f_{nb}) = 447.15 Hz > 80 Hz

3.4. Critical Speed

N is the maximum speed of the transmission system = 5000 rpm

Critical speed of the Steel shaft (Ncr) = 60 × f_{nb} = 51002.6 rpm > N

3.5. Weight of Steel Drive Shaft

Weight = Density ×Volume = 1.1478 Kg.

IV. DESIGN OF COMPOSITE SHAFT

4.1. Torsional Strength

The maximum torsional strength, $\frac{\tau}{r} = \frac{T}{J} = \frac{G\theta}{l}$

T is torque transmitted in Nm

Polar Moment of Inertia (J) = $\frac{\pi}{32}\left(d_o{}^4 - d_i{}^4\right) = 5.16848 \times 10^{-7}\ m^4$

Where, d_o = 0.051 m, d_i = 0.035 m

Mean radius of shaft (r_m) = $\frac{r_o+r_i}{2}$ = 0.0215 m

Shear Modulus (G) = $7.6 \times 10^9\ N/m^2$

Assume, angle of twist (θ) = $5 \times \frac{\pi}{180}$ radians

l = length of shaft = 0.562 m

Shear stress (τ) = $\frac{G\theta r_m}{l} = 25.37 \times 10^6\ N/m^2$

Hence, T = 609.94 Nm> 59Nm.

4.2. Bending Natural Frequency

Minimum bending natural frequency for composite shaft (f_{nb} min) = 80 Hz.

Natural frequency (f_{nb}) = $\frac{\pi}{2}\left(\frac{E_x I_x}{m' L^4}\right)^{1/2}$

$E_x = 177 \times 10^9\ N/m^2$

Moment of inertia in x direction$(I_x) = \frac{\pi}{64}\left({d_o}^4 - {d_i}^4\right) = 2.5842 \times 10^{-7}\ m^4$

The mass per unit length $(m') = \rho \frac{\pi}{4}(D^2 - d^2) = 1.67509$ Kg/ m

Where, density of composite material $(\rho) = 1550$ Kg/m^3

Bending natural frequency $(f_{nb}) = 821.82$ Hz > 80 Hz

4.3. Critical Speed of Shaft

N = 5000 rpm

Critical speed of the (Ncr) $= 60 \times f_{nb} = 49309.33$ rpm $>$ N

4.4. Weight of Steel Drive Shaft

Weight (W) = Density ×Volume $= \rho \times \frac{\pi}{4}(D^2 - d^2) \times L = 0.9414$ Kg

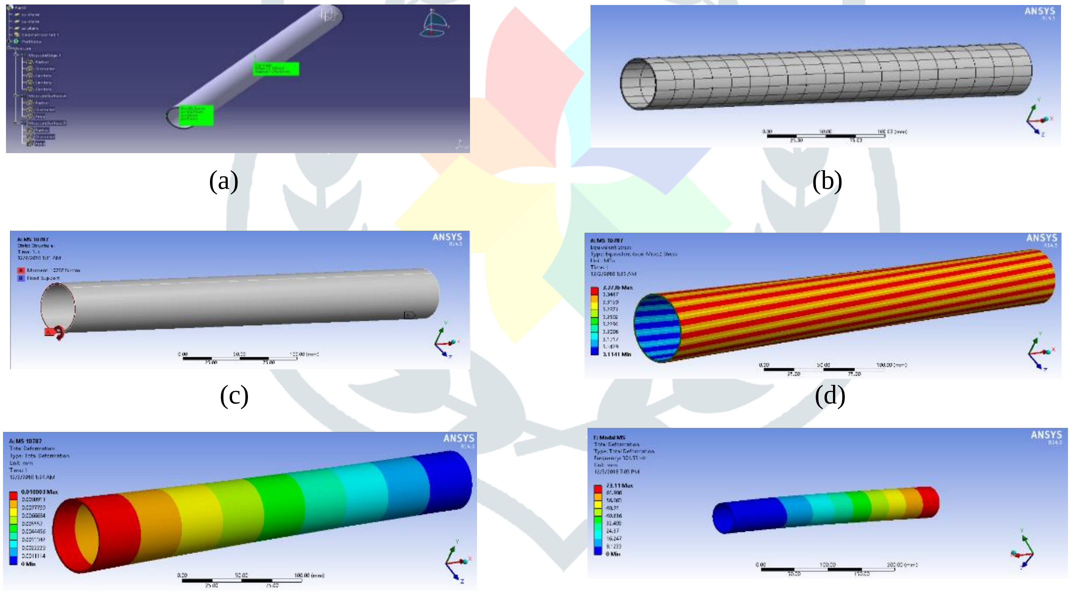
The design parameters for both the shafts are calculated and mentioned below in Table 2.

Table 2. Design parameters for Steel and Carbon/Epoxy propeller shaft

Properties	**Units**	**Steel**	**Carbon/ Epoxy**
Inner dia (d_i)	Mm	48.434	35
Max. Shear Stress	Mpa	307.45	25.37
Bending Natural	Hz	447.15	906.56
Critical speed (N_{cr})	N	26829.36	54939.6
Mass (m)	Kg	1.1478	0.9348

V. FINITE ELEMENT ANALYSIS

The steel shaft model is imported from CATIA V5R19 software to ANSYS R14.5 and analyzed for the maximum deflection, maximum shear stress as well as the Von-Mises stress values. The ensuing values are tabulated in Table 3. The fastened constraint is applied at the one end of the shaft.

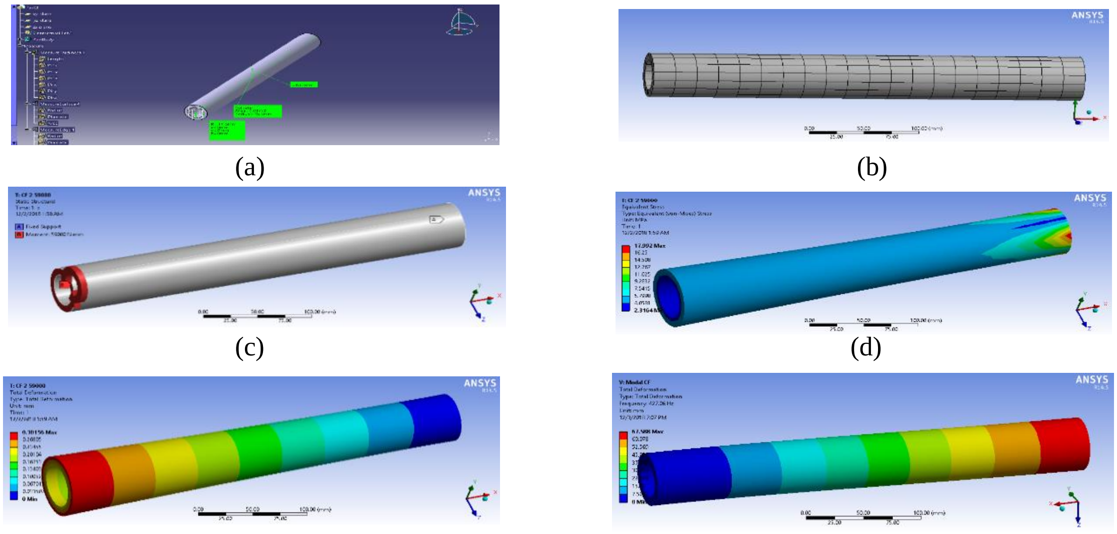


(a) (b)

(c) (d)

(e) (f)

Figure 1. Steel drive shaft analysis result (a) Part model (b) Meshing (c) Boundary conditions (d) Von-Mises stress (e) Total deflection. (f) Modal analysis.



(a) (b) (c) (d) (e) (f)

Figure 2. Composite drive shaft analysis result (a) Part model (b) Meshing (c) Boundary conditions (d) Von-Mises stress (e) Total deflection. (f) Modal analysis.

VI. RESULTS AND COMPARISON

6.1. Torsional Buckling

The steel shaft model has imported from CATIA V5R19 software to ANSYS R14.5 and analyzed for the maximum deflection, maximum shear stress as well as the Von-Mises stress value. The resulting values are tabulated as in Table 3. The fixed constraint is applied at the one edge of the shaft. The twisting moment is applied at the other edge of the shaft.

Table 3. Torsional Buckling analysis results and comparison

Material	**Deflection (mm)**	**Von Misses stress (MPa)**
Steel	0.05471	18.452
Carbon\ Epoxy	0.30156	17.992

6.2. Modal Analysis

When bending natural frequency is high then critical speed is also high. Therefore, the shafts have more range of speed if the natural frequency is high [3]. From comparison of natural frequency of both conventional Steel shaft and Carbon/ Epoxy composite shaft it is clear that composite shaft having higher values of natural frequency as shown in table 4. Result and Comparison of Modal Analysis which is more preferable for drive shaft in light motor vehicle.

Table 4. Result and Comparison of Modal Analysis

Material	Mode 1(Hz)	Mode 2(Hz)	Mode 3(Hz)	Mode 4(Hz)
Steel	301.53	301.53	1603.4	1660.2
Carbon/ Epoxy	427.06	476.13	984.08	1510.3

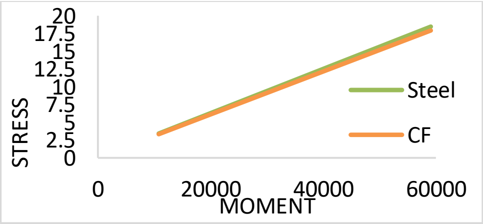


Figure 3. Moment Vs Stress

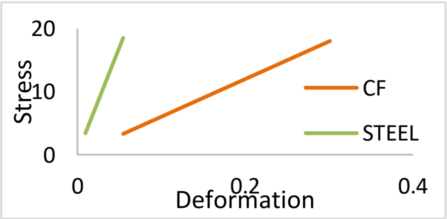


Figure 4. Deformation Vs Moment

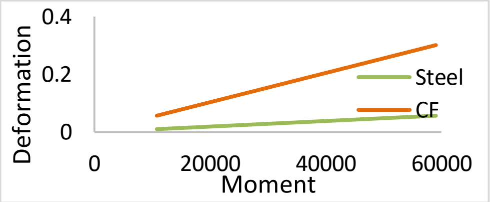


Figure 5. Moment Vs Deformation

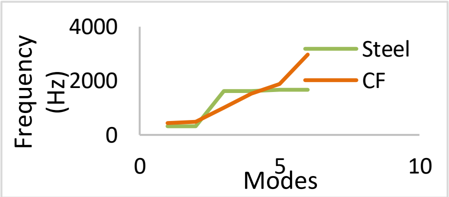


Figure 6. Modes Vs Frequency

6.3. Experimental Testing Results

Main factor to calculate the stress is the twisting angle by using torsion testing machine. Stress can be calculated by substituting this twisting angle in the formula to calculate the stress.

6.3.1 Experimental Calculation

To the stress is calculated for conventional steel shaft by using basic torsion equation given in Table 5 and 6. The table 5 which shows angular deflection for applied torque and corresponding stress values. It can observed that the stress with respect to the angular deformation induced in Carbon/Epoxy composite shaft is markedly lower as compared to the conventional Steel (SM45C) shaft which is validated by comparison of experimental and FEA results in Figures 8 and 9.

Table 5. Experimental results for stresses in Steel shaft and Composite shaft

Torque (Nmm)	Twisting angle (Degree)		Stress (N/mm^2)	
	Steel Shaft	Composite shaft	Steel Shaft	Composite shaft
10787	0.02	1	1.217	2.77
21575	0.04	2	2.435	5.542
34323	0.06	3	3.653	8.313
49033	0.1	4	6.089	11.084
59000	0.14	6	8.358	13.857

The experimental results are derived for conventional Steel and Carbon/ Epoxy composite shaft for same applied torque and then compared these results with the finite element analysis results.

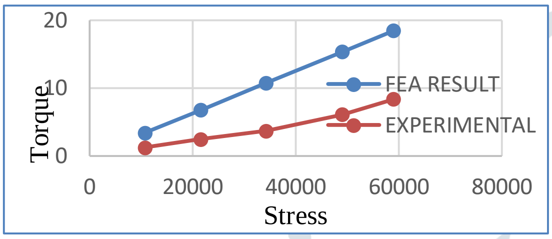


Figure 8. Results comparison for Steel shaft

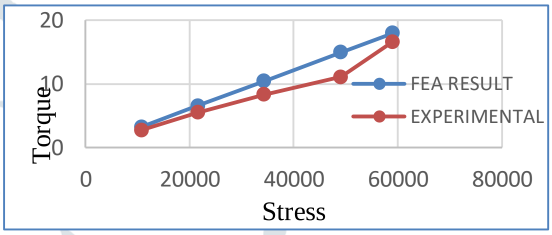


Figure 9. Results comparison for composite shaft

VI. CONCLUSION

From the torsional buckling and modal analysis the deformation, shear stress, Von-Mises stress, critical speed, bending natural frequency and weight are determined which gives better results as compare to Steel shaft. In comparison Carbon/Epoxy composite shaft is best solely in weight reduction which is 18.55% lesser than steel shaft. Carbon/Epoxy composite shaft is best in shear stress and Von-Mises stress is 41.63% larger and bending natural frequency of Carbon/Epoxy composite shaft is also larger than steel shaft. Therefore a Caron/Epoxy composite shaft can used as a propeller shaft for light motor vehicles like Maruti Omni.

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