International Journal of Engineering Technology and Management Sciences
Website: ijetms.in Issue: 1 Volume No.7 January - February – 2023
DOI:10.46647/ijetms.2023.v07i01.008 ISSN: 2581-4621

Design and Analysis of FRP Composite Drive Shaft for Light Motor Vehicle

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ABSTRACT
To make light vehicles such as cars fuel-efficient, which in turn cars make economical, the vehicle should have a lighter weight. The composite materials are lightweight with extra strength as well as stiffness; the replacement of FRP composite materials to conventional metal (SM45C) materials applied in automotive car components can cut back the weight and enhance the mechanical properties of those components. This task deals with the power shaft of MARUTI OMNI to design the shaft for its minimal dimensions and fulfil modern-day disadvantages with specification then replace traditional metallic material with Carbon/Epoxy FRP composite material. Then a component version created for individual dimensions in CATIA V5R19 software. As soon as modeling, Torsional buckling evaluation and Modal analysis could be carried out for propeller shafts the use of ANSYS R14.5 to validate the theoretical calculations and analytical outcomes. The received outcomes are compared and Carbon/Epoxy Fiber Reinforced Polymer composite material is selected as a better alternative material for normal steel material in terms of many mechanical properties for light motor cars.
Keywords—Cylinder block, V8 engine, design, analysis

1. Introduction
This task offers the growing roadways into better transportation. It's far typically achieved by way of tweaking the engine, numerous fuels, aerodynamics and applications of FRP composite material to vehicle components to scale back **its weight, enhance mechanical properties and gasoline efficiency [1].** The roadway cars have quite a few comparable mechanical elements such as engine elements, gearbox, power shaft, springs, clutch, wheels, etc., Out of these the propeller shaft performs a vast position in transmission engines energy to the wheels. This shaft connects the engine power output and rear shaft differential unit. The transmission of power from engine to wheels is carried out by using the shaft for forward and reverse action of a car. That shaft is named as the propeller shaft or Drive shaft. An alternative moderately fabric which is made due to the fact of mixture of two or a variety of metals or non-metals referred to as composite materials. This work involves propeller shafts of light vehicles like Maruti Omni car steel (SM45C) material [1]. The mechanical properties of metal and composite material are in contrast and mentioned in this project.

2. Literature Review
This work consists of the literature survey of special lookup work made through quite a number of researchers on composite driveshaft. Salaisivabalan T, Natarajan R et al carried out the design and analysis of single piece automobile Carbon/Epoxy and Glass/Epoxy composite drive shafts to fulfill design requirements for Maruti Omni vehicle and evaluate with traditional metal shaft [1]. Muhammad Zulfadhli Bin Md Zaki et al conferred a paper with design and Analysis of a Composite Drive Shaft by using the usage of particular winding angle of fiber with definitely exceptional stacking sequences [2]. A R Abu Talib et al current finite element analysis of the design variables of fiber orientation as properly as stacking sequence provide a perception to their outcomes of Carbon\Epoxy and Glass\Epoxy used to be studied [3]. Mohammad Reza Khoshravan et al offers the paper, design approach of composite power shaft with some parameters such as critical speed, static

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torque and adhesive joints are studied and the evaluation has carried out the use of Finite Element Analysis [4]. N Rajendar et al offers with the design and analysis for composite power shaft and substitute of traditional metal shaft by way of minimizing the weight of composite power shaft and analyze with the assist of the FEA software ANSYS 14.5 [5]. Atul Kumar Raikwar et al accomplish FEA and optimize the design & weight with composite materials [6].

3. Design of Propeller Shaft

Transmission of energy can be elevated thru the discount of mass inertia and decreased weight. In the design of SM45C metal shaft, understanding the torque and the allowable shear stress for the steel material

3.1 Problem Specification

The specifications have been assumed appropriately, supported the literature overview and requirements presented for vehicle propeller shaft specially Maruti Omni [4].
The torque transmission potential of the drive shaft (T) =59 Nm
The shaft has to stand up to buckling torque (Tb) distinctive Tb > T
The minimum bending natural frequency of the shaft (fnb min) = 80 Hz
Maximum diameter of the propeller shaft (**do**) = 0.051 m
Length of the propeller shaft (l) = 0.562 m

First the common SM45C shaft used to be designed to facilitate contrast in terms of mass savings. Be it the usual 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 SM45C and FRP Composite material are taken from the literature available mentioned in Table 1.

Table.1. Mechanical properties of propeller shaft materials

Mechanical Properties	Units	Steel (SM45C)	Carbon epoxy
Young's Modulus (E)	GPa	207.0	131.6
Modulus of rigidity (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 torque carrying capacity of the SM45C shaft [8]

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

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 × 10 -7 m4
τ is shear stress in N/m^2
Mean radius of shaft (r_m) = $\frac{r_o+r_i}{2}$ = 0.02475 m
r_o = is outer radius of hollow shaft in m
r_i = inner radius of hollow shaft in m
G = Modulus of rigidity = 80 × 109 N/m^2

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

$\tau = \frac{G\theta r_m}{l}$ = 307.45 × 10 6 N/m^2

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

T = 1776.61 Nm > 59 Nm. Hence design is looking safe.

3.3 Bending Natural Frequency

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

The drive shaft is considered as a simply supported beam subjected to transverse vibration.

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

Where, E_x = 207 × 10^9 N/m^2

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

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

Where, mass 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}

Ncr = 51002.6 rpm > N

3.5 Weight of Steel Drive Shaft

Weight = Mass density ×Volume

W = $\rho \times \frac{\pi}{4}\left({d_o}^4 - {d_i}^4\right) \times l$ = 1.1478 Kg.

The weight of the Steel drive shaft is 1.1478 Kg.

4. Design of FRP Composite Shaft

4.1 Torsional Strength

The maximum torsional strength of the Composite shaft is

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

T is torque transmitted in Nm

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

Where, d_o = 0.051 md_i = 0.035 m

Shear stress (τ) in N/m^2

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

Shear Modulus (G) = 7.6 × 109 N/m^2

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

l = length of shaft = 0.562 m

$\tau = \frac{G\theta r_m}{l}$ = 25.37 × 106 N/m^2

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

T = 609.94 Nm> 59 Nm. Hence design is safe.

4.2 Bending Natural Frequency

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

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Natural frequency (f_{nb}) = $\frac{\pi}{2}\left(\frac{E_x\,I_x}{m'\,L^4}\right)^{\frac{1}{2}}$
E_x = 177 × 10^9 N/m^2
Moment of inertia, $I_x = \frac{\pi}{64}\left({d_o}^4 - {d_i}^4\right)$ = 2.5842 × 10^{-7} m^4
The mass per unit length (m') = $\rho\frac{\pi}{4}(D^2 - d^2)$ = 1.67509 Kg/ m
Where, mass density of composite material (ρ) = 1550 Kg/m^3
d_o = 0.051 m, d_i = 0.035 m
Bending natural frequency (f_{nb}) = 821.82 Hz > 80 Hz

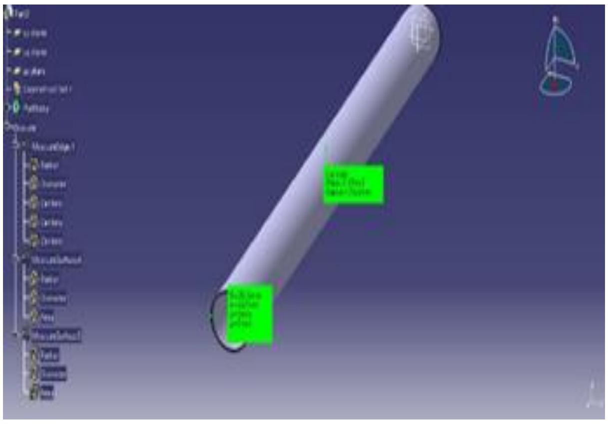
4.3 Critical Speed of Drive Shaft
N = 5000 rpm
Critical speed (Ncr) = 60 × f_{nb} = 49309.33 rpm > N

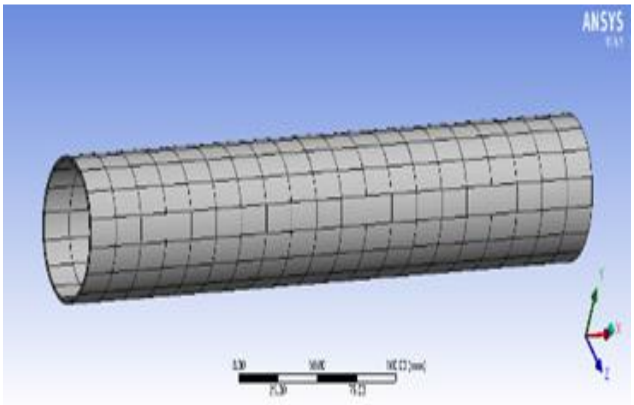
4.4 Weight of SM45C (Steel) Drive Shaft
Weight (W) = Mass density ×Volume
W = $\rho \times \frac{\pi}{4}(D^2 - d^2) \times L = 0.9414\,Kg$
The design parameters for each of the drive shafts are calculated and mentioned below in Table 2.

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

Properties	Units	Steel (SM45C)	Carbon/ Epoxy
Length	Mm	562	562
Outer dia (d_o)	Mm	51	51
Inner dia (d_i)	Mm	48.434	35
Max. Shear Stress (τ_{max})	Mpa	307.45	25.37
Bending Natural Frequency (f_{nb})	Hz	447.15	906.56
Critical speed (N_{cr})	N	26829.36	54939.6
Mass (m)	Kg	1.1478	0.9348

5. 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)

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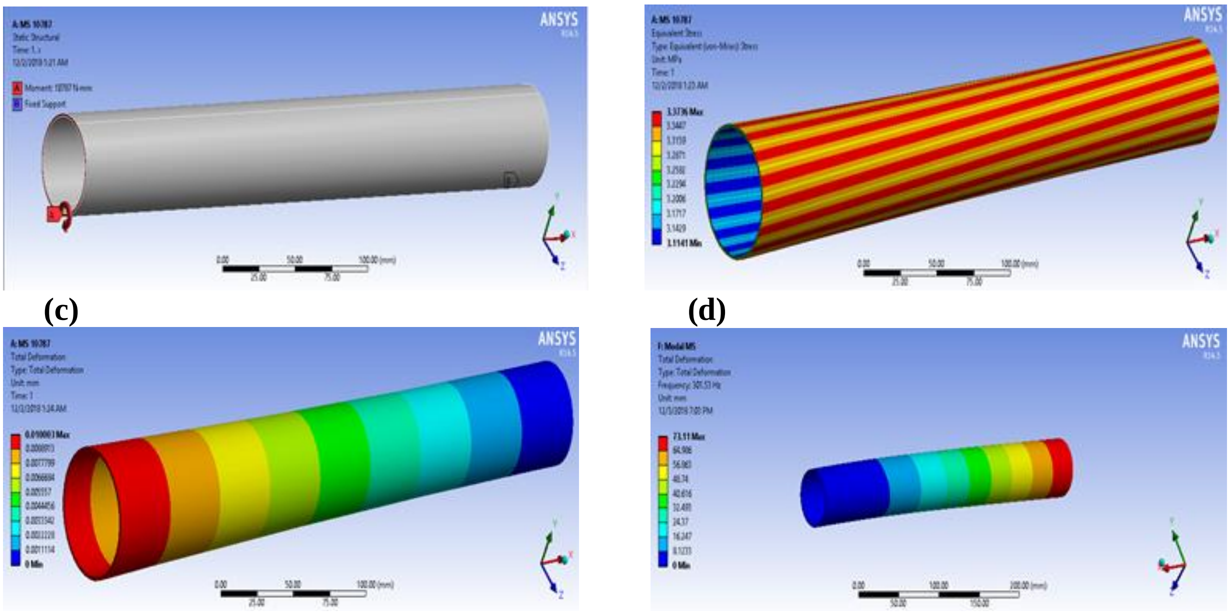
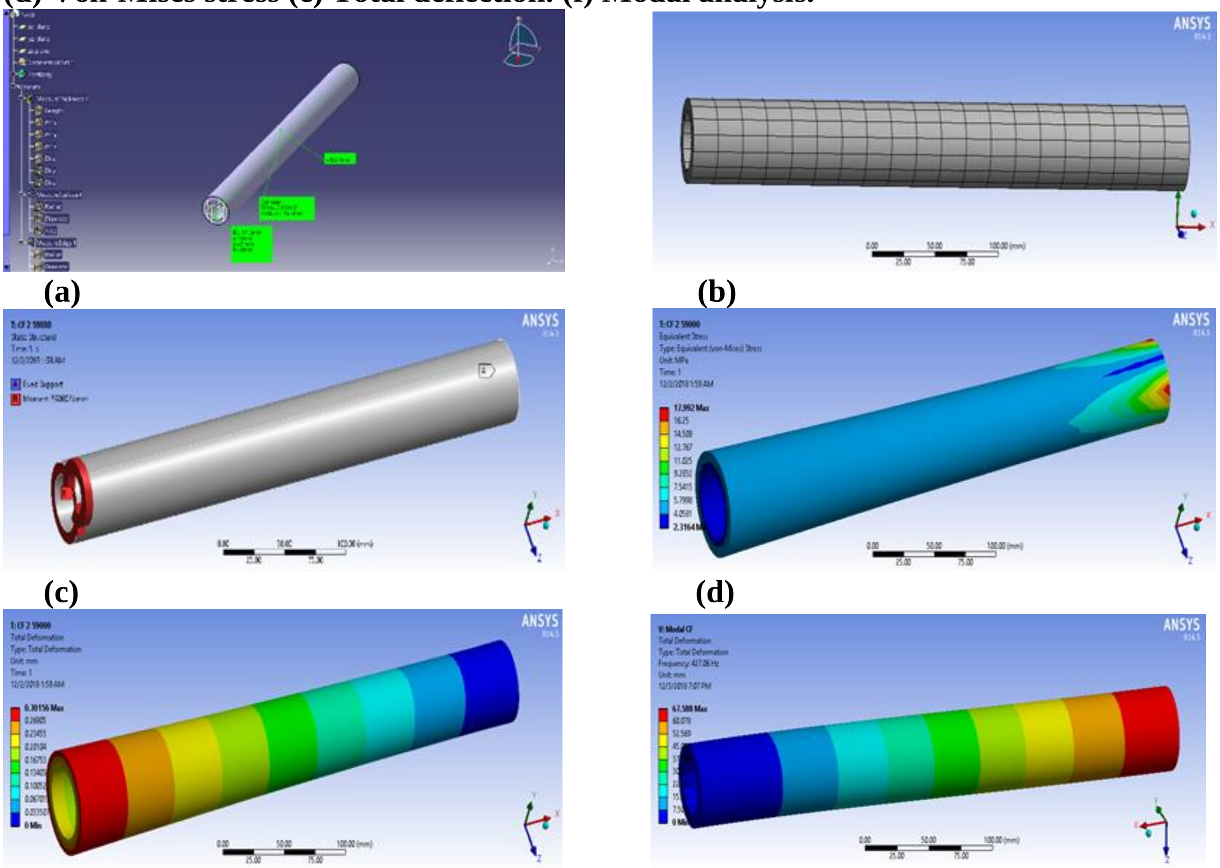


(c) (d)

(e) (f)

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



(a) (b)

(c) (d)

(e) (f)

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

The FRP Composite drive 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.

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6. Results and Comparison

6.1 Torsional Buckling

The metal shaft model has imported from CATIA V5R19 software to ANSYS R14.5 and analyzed for the maximum deflection, maximum shear stress as properly as the Von-Mises stress value. The ensuing values are tabulated as in Table 3. The constant constraint is utilized at the one area of the shaft, the place the shaft is connected to differential unit. The torque is applied at the other side of the shaft.

Table 3.Torsional Buckling Analysis Results and Comparison

Material	Deflection	Von Mises stress
Units	mm	MPa
Steel (SM45C)	0.05471	18.452
Carbon\ Epoxy	0.30156	17.992

6.2 Modal Analysis

The Model is used for Modal analysis and Buckling Analysis to achieve the outcomes as shown in figure 2. (f). this is observed that when bending natural frequency is excessive then critical speed is additionally high. Therefore, the drive shafts have greater range of velocity if the natural frequency is high [4]. The composite shaft having greater values of natural frequency as proven in Table 4. Result and Comparison of Modal Analysis which is greater preferable for drive shaft in light motor vehicle.

Table 4. Result and Comparison of Modal Analysis

Material	Mode 1	Mode 2	Mode 3	Mode 4
Units	Hz	Hz	Hz	Hz
Steel (SM45C)	301.53	301.53	1603.4	1660.2
FRP Carbon/ Epoxy	427.06	476.13	984.08	1510.3

Figure 3. Moment Vs Stress

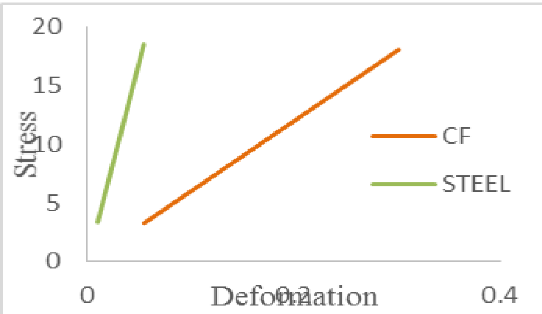

Figure 4. Deformation Vs Moment

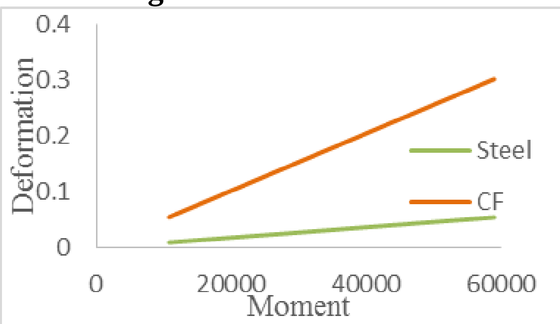

Figure 5. Moment Vs Deformation

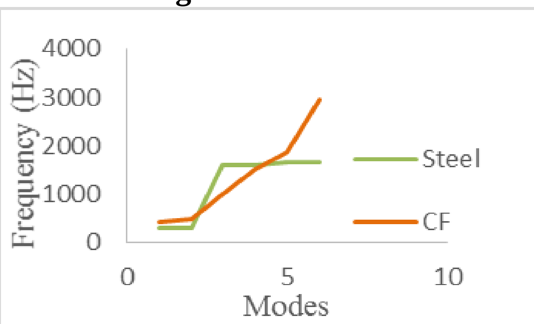

Figure 6. Modes Vs Frequency

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6.3 Experimental Testing Results

Fig. No. 7. Torsion testing machine

Main factor to calculate the stress is the twist angle by using a torsion testing machine as shown in Figure 7. Stress can be calculated by using this twist angle in the formula to calculate the stress. The stress calculated through this procedure has been practically calculated given in Table 5 and 6.

6.4 Experimental Calculation

Experimental data calculation for conventional Steel shaft is tabulated in table 5 which shows angular deflection for applied twisting moment and corresponding torsional shear stress values. The experimental results are derived for conventional Steel (SM45C) and FRP Carbon/ Epoxy composite drive shaft for the same twisting moment and then compared these results with the FEA. It can be observed that the stress with respect to the angular deformation induced in FRP Carbon/Epoxy composite shaft is remarkably lower as compared to the conventional Steel (SM45C) drive shaft which is validated by comparison of experimental and FEA results in Figure 8 and 9.

Table 5. Experimental results for stresses in Steel shaft

Torque (Nmm)	Twisting angle (Degree)	Stress (N/mm^2)
10787	0.02	1.217
21575	0.04	2.435
34323	0.06	3.653
49033	0.1	6.089
59000	0.14	8.358

The experimental results are obtained for conventional Steel (SM45C) and FRP Carbon/ Epoxy composite shaft for the same applied twisting moment and then compared these results with the FEA results.

Table 6. Experimental results for stresses in FRP Composite shaft

Torque (Nmm)	Twisting angle (Degree)	Stress (N/mm^2)
10787	1	2.77
21575	2	5.542
34323	3	8.313
49033	4	11.084
59000	6	13.857

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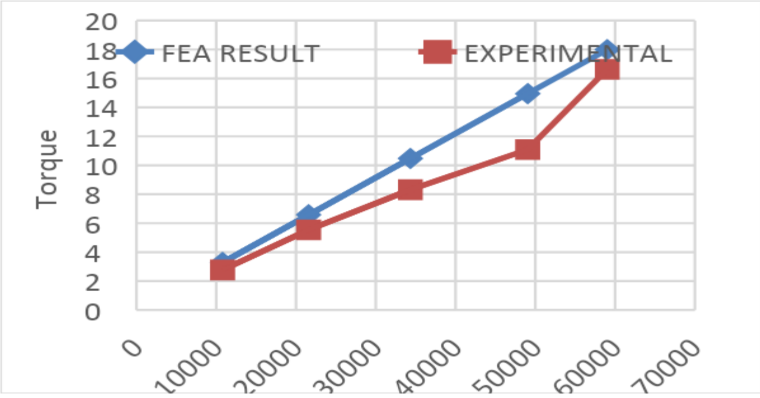

Fig 8. FEA and Experimental results comparison for FRP composite shaft

It can be observed that the torsional shear stress with respect to the angular deflection induced in FRP Carbon/Epoxy composite shaft is remarkably lower as compared to the conventional Steel (SM45C) shaft which is validated by comparison of experimental and FEA results.

7. Results and Comparison

From the torsional buckling and modal evaluation the angular deformation (Ɵ), torsional shear stress (τ), Von-Mises stress, critical speed (N_{cr}), bending natural frequency (f_{nb}) and weight are decided which offers better outcomes as compared to the conventional steel shaft. In usual evaluation FRP Carbon/Epoxy composite shaft is exceptional entirely in weight reduction which is 18.55% lesser than metal shaft. Carbon/Epoxy composite shaft is satisfactory in torsional shear stress and Von-Mises stress is 41.63% large and the bending natural frequency of FRP Carbon/Epoxy composite shaft is additionally large than metal shaft. Therefore a FRP Carbon/Epoxy composite shaft can used as a propeller shaft for cars like Maruti Omni. Results got through ANSYS are validated from analytical calculations and experimental testing.

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