Analysis of Carbon/Epoxy Composite Drive Shaft for Automotive Application

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Abstract — Composite material with higher specific stiffness, low weight, high damping capacity have greater torque capacity than conventional drive shaft. The advanced composite materials such as carbon and glass with epoxy resin are widely used because of their high specific strength and high specific modulus. The Automotive industry is exploring composite material technology for structural components in order to obtain reduction of weight without decreasing quality of vehicle and reliability. In this study, experimental and theoretical, torsional and vibration analysis is done on conventional SM45C steel drive shaft, carbon epoxy and glass epoxy composite drive shaft. The parameter like deflection, stresses, and natural frequencies under subjected loads using FEA will be studied. Modal analysis is carried to find out natural frequency, deflection, stresses under subjected loads.

Keywords— Composite drive shaft, Torsional analysis, Bending Natural Frequency, ANSYS Software.

I. INTRODUCTION

Numbers of methods are available for the design optimization of structural system and these methods are based on mathematical programming technique. In the present work an attempt is made to evaluate the suitability glass and carbon fiber/epoxy resin composite shaft. A single piece composite drive shaft for the rear wheel of drive automobile is optimally designed using ANSYS software.

M.A.K. Chowdhuri, R.A. Hossain,[2] They studied. The basic requirements considered here are torsional strength, Torsional Buckling and bending natural frequency. An optimum design of the draft shaft is done, which is cheapest and lightest but meets all of the above load requirements. Progressive failure analysis of the selected design is also done. Also, composite materials typically have a lower modulus of elasticity. As a result, when torque peaks occur in the driveline, the driveshaft can act as a shock absorber and decrease stress on part of the drive train extending life

Dinesh et al. [3] They Designed composite drive shaft for wheel drive automobile by using genetic algorithm technique for E-glass/epoxy, high strength carbon/epoxy and high modulus carbon/epoxy composite with objective of minimization of weight of the shaft which was subjected to torque transmission, torsional buckling and natural bending frequency.

Characteristics of composite materials can vary depending on the type of the applied material, quantity, fiber orientation angle, etc. (stiffness, resistance, thermal expansion, etc.) The choice of material depends on the service life needed, product shape complexity, computation of optimal characteristics of composite materials, etc. In some cases, the best results can be achieved using a combination of composite and traditional metal materials. This paper studies shafts obtained by a combination of aluminium and different composite materials – carbon fibers/epoxy resin, glass fibers/epoxy resin, and aramide fibers/epoxy resin.

For automotive applications, the first composite drive shaft was developed by the Spicer U-Joint division of Dana Corporation for Ford econoline van models in 1985 When the length of a steel drive shaft goes beyond 1500 mm, it is manufactured in two pieces to increase the fundamental natural frequency, which is inversely proportional to the square of the length and proportional to the square root of the specific modulus. The nature of composites, with their higher specific elastic modulus, which in carbon/epoxy exceeds four times that of aluminium, enables the replacement of the two-piece metal shaft with a single-component composite shaft which resonates at a higher rotational speed, and ultimately maintains a higher margin of safety.

A composite drive shaft offers excellent vibration damping, cabin comfort, reduction of wear on drive train components and increases tire traction. In addition, the use of single torque tubes reduces assembly time, inventory cost, maintenance, and part complexity. Figure 1 shows a photographic view of two-piece steel and a one-piece composite drive shaft.

(a)

Figure. 1 Photographic view of: a) two-piece steel;
b) one-piece composite drive shaft

II. Design of SM45C Steel Drive Shaft

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

i. Torsional Strength
ii. Torsional Buckling and
iii. Bending Natural Frequency

SM45C steel was selected, since it is widely being used for the design of conventional steel shaft. The properties of SM45C steel are:

Table 1 Mechanical properties of SM45C Steel

Sr. No	Mechanical Properties	Symbol	Unit	Value
1	Youngs Modulus	E	GPa	207
2	Shear Modulus	G	GPa	80
3	Poission's Ratio	v		0.3
4	Density		Kg/m^3	7600
5	Yield Strength	S_y	MPa	370
6	Shear Strength	S_x	MPa	275

i. *Torsional Strength*

Since the primary load on the drive shaft is torsion, the maximum shear stress (τ_{max}) at the outer radius (r_0) of the shaft is given by:

$$\frac{\tau_{max}}{F.S.} = \frac{T\, r_0}{J}$$

$$\frac{\tau_{max}}{F.S.} = \frac{32 T r_0}{\pi \left[d_0^4 - d_i^4 \right]}$$

Where,
J is the polar moment inertia in m^4, d_0 and d_i are outer and inner diameters of the shaft in meter.
T is Maximum torque applied in Nm

ii. Torsional Buckling

A shaft is considered as a long shaft, if

$$\frac{1}{\sqrt{1-v^2}} \frac{tL^2}{(2r)^3} > 5.5$$

Where, r is mean radius, such that:

$$r = \left(\frac{r_0 - r_i}{2} \right)$$

For a long shaft Torsional buckling capacity:

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

Where, the critical stress is given by,

$$\tau_{cr} = \left[\frac{E}{3\sqrt{2}(1-v^2)^{3/4}} \right] \left(\frac{t}{r} \right)^{3/2}$$

$$\tau_{cr} = 2.15 \times 10^9 \ N/m^2$$

$$T_b = 8932.7 \ N/m^2$$

Thus

$$T_b > T$$

iii. 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:

$$f_{nb} = \frac{\pi p^2}{2L^2} \sqrt{\frac{EI_x}{m'}}$$

Where,
m’ is mass per unit length in Kg/m
I_x is area moment of inertia in x-direction in m^4

$$I_x = \frac{\pi}{64}(d_0^4 - d_i^4)$$

$$I_x = 2.50188 \times 10^{-8} \ m^4$$

$$m' = p\frac{\pi}{4}(d_0^2 - d_i^2)$$

$$m' = 2.74 \ kg/m$$

$$f_{nb} = 157.4 \ Hz$$

Thus the designed SM45C steel drive shaft meets all requirements
Therefore, total mass of the shaft,

$$m = m' \times L$$
$$m = 1.09 \ kg$$

III. Design of Composite Drive Shaft

A. Specification of Problem

The torque transmission capacity of drive shaft is taken as 1200 Nm. The length and outer diameter is taken as 400mm and 28mm respectively. The drive shaft of transmission system was designed optimally to meet the specified design requirements.

B. Selection of fibers

Glass fibers:

Glass fibers are widely used in practice. The advantages of glass fibers over other materials are the easy and cheap production, possibility to produce very long fibers, high resistance to impact, good machinability, etc. The basic disadvantages of glass-fiber-reinforced composites lie in the fact that they have a low modulus of elasticity and that they lose resistance at elevated temperatures.

Carbon Fibers:

The need for stronger materials led to greater application of carbon fiber/epoxy resin composite. Carbon fibers have high strength, high modulus of elasticity, low density excellent machinability, resistance to elevated temperature, low thermal expansion coefficient, Inertness to most reagents etc. Their main advantages are low toughness and high anisotropy, which causes additional problems to constructors and high production compared to glass fibers.

C. Selection of Resin

The important consideration in selecting resin is cost, temperature capability, and elongation to failure and resistance to impact. The resins selected for most of the drive shafts are either epoxies or vinyl esters. For the manufacture of construction composites, the most widely used are the following: - matrices based on epoxy resins, matrices based on phenolic resins, matrices based on polyester resins, and metal based matrices.

The properties of composites mainly depend on: - the strength and chemical stability of the matrix, the strength and elasticity of the reinforcing fibers, the strength of the bond between the matrix and the resin forcing fibers.

Epoxy resins are polyether resins containing more than one epoxy group capable of being converted into the thermoset form. These resins, on curing, do not create volatile products in spite of the presence of a volatile solvent. The epoxies may be named as oxides, such as ethylene oxides (epoxy ethane), or 1,2-epoxide.

D. Assumptions:

i. The shaft rotates at constant speed about its longitudinal axis
ii. The shaft has uniform circular cross section.
iii. All damping and nonlinear effects are excluded
iv. The stress strain relationship for composite material is linear and elastic hence Hook's law is applicable for composite material.
v. Acoustical fluid interactions are neglected i.e. the shaft is assumed to be acting in a vacuum
vi. Since lamina is thin and no out of plane loads are applied. It is considered as under lane stress

E. Design Procedure:

The material properties of the drive shaft were analysed with classical lamination theory. The theory treats with the linear elastic response of laminated composite under plane stress, and it incorporates the Kirchhoff-Love assumption for bending and stretching of thin plates. From the properties of the composite materials at given fiber angles, the reduced stiffness matrix can be constructed. The expression for the reduced stiffness coefficients (Q_{ij}). In terms of standard material constants are as follows [1]

$$Q_{11} = \frac{E_1}{1 - v_{12}v_{21}}$$

$$Q_{22} = \frac{E_2}{1 - v_{12}v_{21}}$$

$$Q_{66} = G_{12}$$

$$Q_{12} = \frac{v_{12} v_{21}}{1 - v_{12} v_{21}}$$

$$v_{21} = \frac{E_2}{E_1} v_{12}$$

Where E is the modulus of elasticity, G is modulus of rigidity and v is poisson's ratio.

The next step is to construct the extensional stiffness matrix [A]. This matrix is the summation of the products of the transformed reduced stiffness matrix $[\bar{Q}]$ of each layer and the respective thickness, represented as

$$[A] = \sum_{k=1}^{n} [\bar{Q}]^k (z_k - z_{k-1})$$

The A matrix is used to calculate E_x and E_h, which are the average moduli in the axial and hoop direction respectively.

$$E_x = \frac{1}{t}\left[A_{11} - \frac{A_{12}^2}{A_{22}}\right]$$

$$E_h = \frac{1}{t}\left[A_{22} - \frac{A_{12}^2}{A_{11}}\right]$$

Table 2 Material properties of composite drive shaft:

Symbol	Unit	Carbon Fiber	E- Glass Epoxy
E_x	GPa	126 .9	40.3
E_y	GPa	11	6.21
E_z	Ga	126.9	40.3
v	-	0.2	0.2
G_{xy}	GPa	6.6	3.07
G_{xz}	GPa	4.23	2.39
G_{yz}	GPa	4.88	1.55
ρ	Kg/m^3	1610	1910

F. Carbon Fiber Composite *Drive Shaft*

In the design of composite shafts before applying the finite element technique, a closed form solution is useful. In order to have an order-of-magnitude solution for a design, a simple equation is needed to calculate the torsional buckling load of long thin-wall shafts. There are various existing equations for this purpose in the literature. These equations are empirical, obtained based on experimental studies. The buckling torque is given by

$$T_b = 2\pi r^2 t (0.272)\left(E_x E_y^3\right)^{1/4}\left(\frac{t}{r}\right)^{3/2}$$

$$T_b = 6565.14\ Nm$$

$$T_b > T$$

Torque Transmitted,

$$T = 2\pi r_m^2 t \tau_1$$

T = 1217 Nm

Bending Natural Frequency,

$$f_{nb} = \frac{\pi}{2L^2}\sqrt{\frac{E_x I_y}{m'}}$$

$$I_x = 2.50188 \times 10^{-8} \quad m^4$$

$$m' = 0.5816 \quad Kg/m$$

f_{nb} 255.3 Hz

Total mass of carbon fiber epoxy resin drive shaft,

$$m = m'L$$

$$m = 0.232 \, Kg$$

G. Glass Fiber Composite Drive Shaft

The buckling torque is given by

$$T_b = 2\pi r^2 t(0.272)\left(E_x E_y^3\right)^{1/4}\left(\frac{t}{r}\right)^{3/2}$$

$$T_b = 3209.95 \, Nm$$

$$T_b > T$$

Torque Transmitted,

$$T = 2\pi r_m^2 t \tau_1$$

T = 1190 Nm

Bending Natural Frequency

$$f_{nb} = \frac{\pi}{2L^2}\sqrt{\frac{E_x I_y}{m'}}$$

$$I_x = 2.50188 \times 10^{-8} \quad m^4$$

$$m' = 0.6900 \quad Kg/m$$

f_{nb} = 135.2 Hz

Total mass of carbon fiber epoxy resin drive shaft,

$$m = m'L$$

$$m = 0.276 \, Kg$$

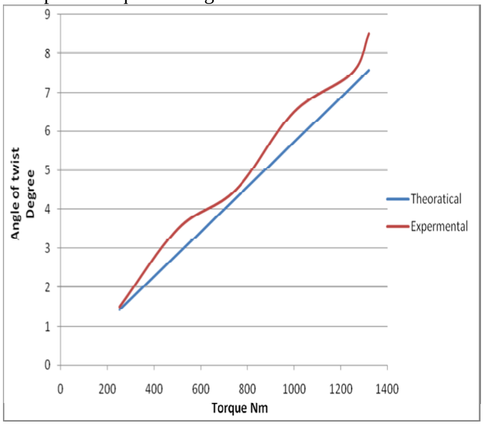
IV. EXPERIMENTAL WORK

Torsion test machine was used to perform the test. The testing machine with a specimen mounted on it, is shown in Figure 2 The torque was applied manually by a handle at a geared head. This torque is reacted by a transducer and displayed digitally. The angle of twist was measured over a specified gauge length. The maximum static torsion was obtained after the failure of the specimens and torque- angle of twist relations were obtained for different cases.

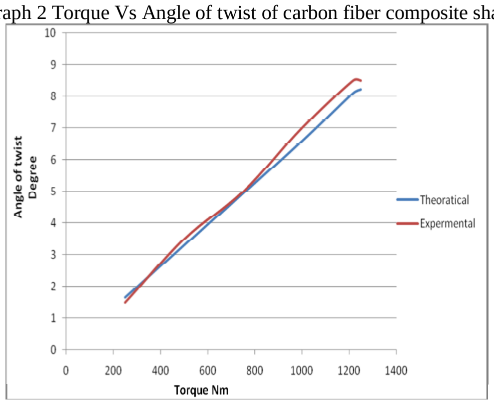
Figure 2. Torsional Testing of Carbon fiber composite shaft

Failure modes on drive shaft specimen during torsion testing. Here ductile failure occurred on torsion specimen due to the shear stresses applied. The ductile failure produces the fracture surface along the plane of the maximum shear stress and more frequently normal to the longitudinal axis of torsion specimen of drive shaft. The torsional failure of shaft occurred when the shearing stresses attain the yield stress of the shaft. The greatest shearing stresses in a hollow shaft occur in a cross-section and along the length of the shaft.

Graph 1 Torque Vs Angle of twist of SM45C steel shaft



Graph 2 Torque Vs Angle of twist of carbon fiber composite shaft



Graph 3 Torque Vs angle of twist of Glass fiber composite shaft

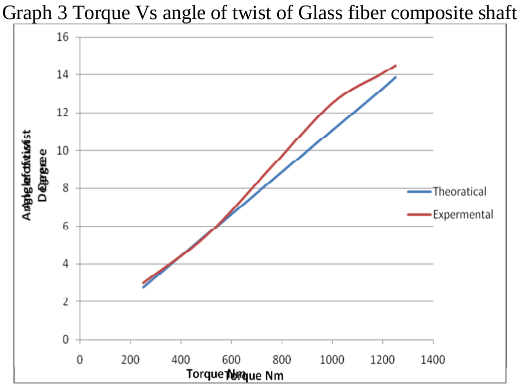


Table3 Torsion Specimen dimensions of drive shaft

Specimen	D_0	D_i	L	no of layers of composite	fiber orientation angle
SM45c steel shaft	28	18	400	-	-
carbon fiber	28	18	400	15	$\pm45^0$
glass fiber	28	18	400	14	$\pm45^0$

V. MODAL ANALYSIS

In this study, a finite element analysis was conducted using ANSYS commercial software. The 3-D model was developed and a typical meshing was generated by using Shell 99 element. The drive shaft was fixed at both ends and it was subjected to torque in the middle. The torque transmission capability of the drive shaft was taken as 1200 N.m, the length and the outer diameter here was considered as 400 mm and 28 mm, respectively. The shaft rotates at a constant speed about its longitudinal axis. The shaft has a uniform, circular cross section. The shaft was perfectly balanced, all damping and nonlinear effects were excluded. The stress-strain relationship for composite material is linear and elastic; hence, Hook's law is applicable for composite materials. Since lamina is thin and no out-of-plane loads were applied, it was considered as under the plane stress. Since the fiber volume of 60% is the standard fiber volume fraction for most industries, it was selected for composite drive shaft. Table 2 shows the mechanical properties of each layer of the laminate. Among the various laminate configurations, [±45] laminates possess the highest shear modulus and are the primary laminate type used in purely torsional applications.

Figure 2 illustrates the domain of a finite element mesh. Once the finite element mesh and the layers were created, the orientation of materials was defined for the shell element and the layer materials for each of these elements have been allocated. The other steps included placing the boundary conditions and selecting appropriate solvers. The drive shaft rotated at maximum speed so the design should include a critical frequency. If the drive shaft rotates at its natural frequency, it can be severely vibrated or even collapsed. The modal analysis was performed to find the natural frequencies in lateral directions. The mode shapes for all material combinations were obtained to their corresponding critical speeds. A number of fundamental modes, all of them critical frequencies, were obtained.

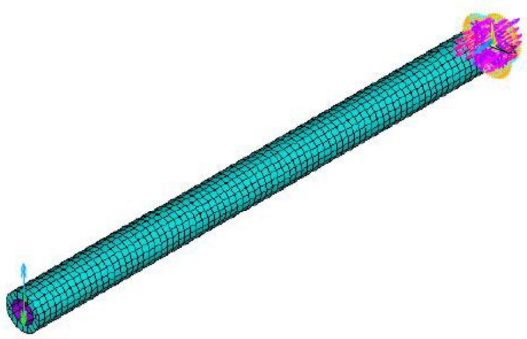


Figure 3. Meshing using Shell99 element

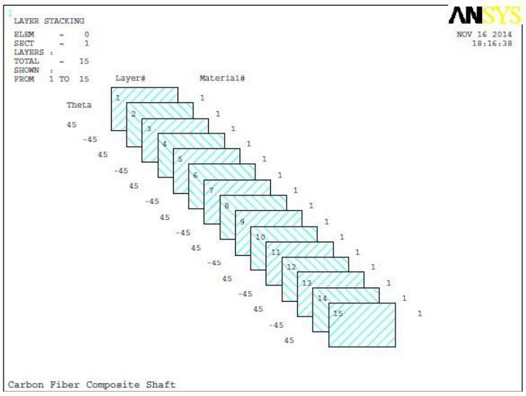


Figure 4 Arrangement of Layer for Carbon epoxy shaft

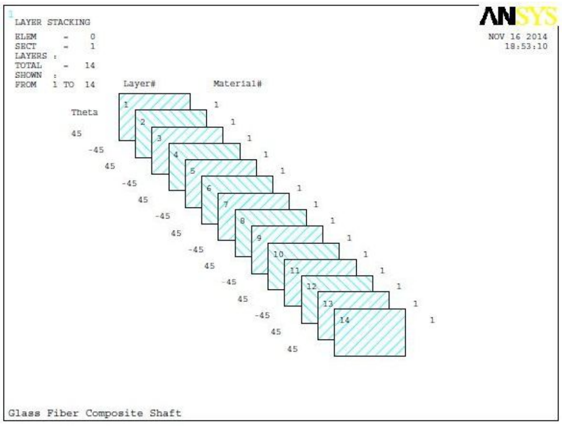


Figure 5 Arrangement of Layer for Glass epoxy shaft

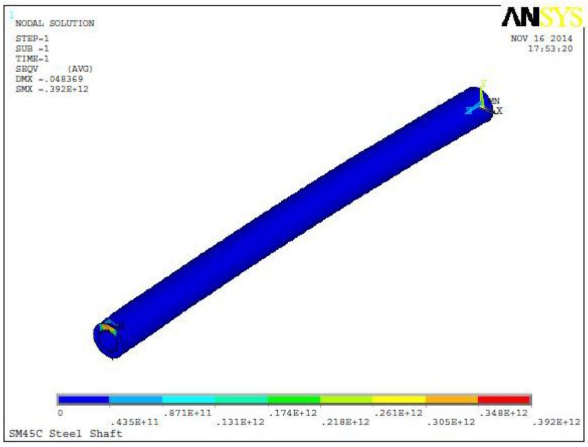


Figure 6. Vonmisess stresses of SM$5C steel drive shaft

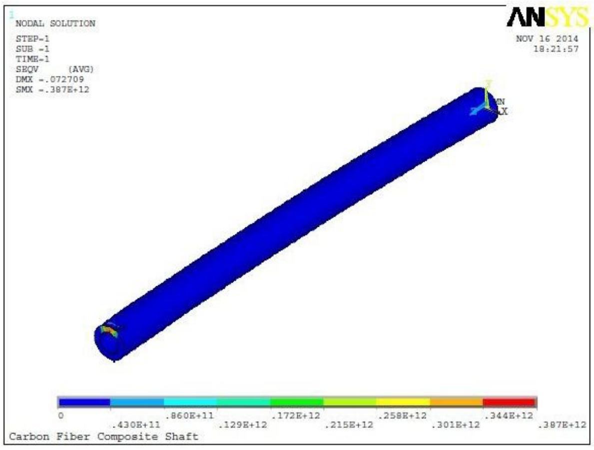


Figure 7: Vonmisess stresses of Carbon fiber composite drive shaft

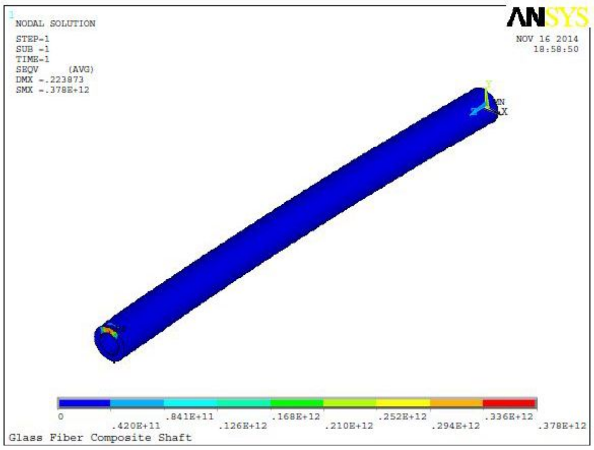


Figure 8: Vonmisess stresses of Glass fiber composite drive shaft

Table 3. Natural frequencies of Composite shaft

Specimen	Frequency, Hz (Theoretical)	Frequency, Hz (Ansys)	Weight, (Kg)
SM45C Steel	157.4	152.58	1.09
Carbon fiber	255.3	260.97	0.232
Glass Fiber	135.2	131.95	0.276

VI. CONCLUSIONS

An attempt has been made to design, fabricate and test hollow composite drive shaft to be used for automotive application, keeping in mind the benefits obtained in terms of reduction in weight and cost of manufacture.

Carbon/Epoxy and Glass/Epoxy composite drive shaft has been designed to replace conventional steel drive shaft of an automobile. A composite drive shaft is designed optimally with the objective of minimizing the weight of the shaft which is subjected to the constraints such as torque transmission capacity, torsional buckling capacity and natural bending frequency.

Considerable weight benefits have been obtained to the extent of a minimum of 40%.This study indicates that carbon fiber shafts can replace conventional steel drive shaft.

Natural bending frequency of composite drive shaft is much higher than the steel drive shaft which enhances the use of composite structures in higher mechanical operations involving severe vibration conditions.

Analysis of both drive shaft shows that the composite drive shaft has capability to transmit more torque, has more buckling torque transmission capability and has much higher fundamental natural bending frequency which provides better margin of safety than the conventional composite drive shaft.

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