Design of Composite Automotive Drive Shaft by using Classical Lamination Theory (CLT)

Mr. T.M Shaikh[1] Prof. M.N. Pradhan[2]
[1]P.G Student [2]Professor
[1,2]Maharashtra Institute of Technology, Pune

Abstract— The objective of this paper is to design a composite drive shaft by using classical lamination theory. Substituting composite structure for conventional metallic structures has many advantages because of higher specific stiffness and strength of composite materials. This work deals with the replacement of conventional two-piece steel drive shaft with single-piece carbon/epoxy. The substitution of composite drive shaft has resulted in considerable weight reduction about 64 % compared to conventional steel shaft.

Keywords: Composite drive shaft, Torque transmission capacity, Torsional buckling capacity, fundamental natural frequency, Bernoulli Euler theory, stacking sequence

I. INTRODUCTION

An automobile drive shaft transmits power from the engine to the differential gear of a wheel drive vehicle. The advanced composite material such as Carbon, Graphite, Kevlar and Glass with suitable resins is widely used because of their high specific strength (strength/density) and high specific modulus (modulus/density). The drive shafts are used in automotive, aircraft and the aerospace application. The weight reduction of the drive shaft can play an important role in the weight reduction of the vehicle and is a highly desirable goal, if it can be achieved without increase in cost and decrease in quality and reliability.The torque capability of the drive shaft for passenger cars should be larger than 3500 Nm and the fundamental bending natural frequency should be higher than 9200 rpm to avoid whirling vibration [2]. Since the fundamental bending natural frequency of a one-piece drive shafts made of steel or aluminum is normally lower than 5700 rpm when the length of the drive shaft is around 1.5 m [2], the steel drive shaft is usually manufactured in two pieces to increase the fundamental bending natural frequency because the bending natural frequency of a shaft is inversely proportional to the square of beam length and proportional to the square root of specific modulus. The weight reduction of the drive shaft can have a certain role in the general weight reduction of the vehicle and is highly desirable goal, if it can be achieved without increase in cost and decrease in quality and reliability. It is possible to achieve design of composite drive shaft with less weight to increase the first natural frequency of the shaft and to decrease the bending stresses using various stacking sequences. By doing the same, torque transmission and torsional buckling capabilities are also maximized.

II. DESIGN SPECIFICATION

The following specifications are assumed which are based on literature and available standards of automobile drive shaft.

1) The torque transmission capacity of the drive shaft(T) = 1472.45 N-m
2) Speed of drive shaft = 3050 rpm
3) Outside diameter of drive shaft = 68 mm
4) Length of drive shaft = 1.3 m

III. DESIGN OF CONVENTIONAL STEEL DRIVE SHAFT

The steel drive shaft should satisfy three design specifications such as torque transmission capability, buckling torque capability and bending natural frequency. Steel (SM45C) used for automotive drive shaft applications. The material properties of the steel (SM45C) are given in table-1

Mechanical properties	**Symbol**	**Units**	**Steel**
Young's Modulus	E	GPa	207
Shear modulus	G	GPa	80
Poisson's ratio	μ	-	0.3
Density	ρ	Kg/m^3	7800
Yield Strength	S_y	MPa	370

Table-1: Mechanical Properties of the Steel

A. *Design of Steel Based on Strength Basis:*

$$\tau = \frac{16M_t}{\Pi d_o^{\,3}(1-C^4)}$$

$$C = 0.92$$

We know,

$$C = \frac{d_i}{d_o}$$

$$d_i = 63.11\,mm$$

Thus the thickness of hollow steel shaft is,

$$t = r_o - r_i$$

$$t = 2.4\,\text{mm}$$

B. *Mass of Steel Drive Shaft:*

$$m = \rho AL$$

$$m = 5.10\,kg$$

Thus the mass of steel drive shaft is 7.01 kg.

C. *Torque Buckling Capacity of the Drive Shaft:*

$$T_b = (2\Pi r^2_{\,m}\,\text{t})(0.272)(\text{E})(\frac{t}{r_m})^{\frac{3}{2}}$$

$$T_b = 18332\,N-m$$

Thus the shaft need to withstand torsional buckling (T_b) capacity such that T_b>T. Hence the condition is satisfied.

D. *Bending Natural Frequency:*

It can be found by using two theories

1) Timoshenko beam theory
2) Bernoulli Euler theory

Bernoulli Euler theory neglects both transverse shear deformation as well as rotary inertia effects. Naturals frequency based on the Bernoulli Euler theory is given by [4]

$$f_{nt} = \frac{\pi P^2}{2L^2}\sqrt{\frac{EI_X}{m_1}}$$

Where,
$m_1$is mass per unit length in kg/m
I_x is area moment of inertia in x-direction in m^4

$$f_{nt} = \frac{\pi P^2}{2L^2}\sqrt{\frac{EI_X}{m_1}}$$

$$f_{nt} = 111.84\ Hz$$

This value is greater than the minimum desired natural frequency of 50 Hz. thus; the steel design of a hollow shaft of outer diameter 68 mm and thickness 2.4mm is an acceptable design.

IV. DESIGN OF COMPOSITE DRIVE SHAFT

A. *Specification of Problem:*

The specification of composite drive shaft for an automobile is same as of steel drive shaft except its outer and inner diameter. Because of the manufacturing constrained and availability of mandrel size the inner diameter of shaft is to be taken as 54mm and outer diameter is 66.8 and its thickness is 6.4 for an optimum design. Classical lamination theory was used for design of composite drive shaft

B. *Selection of Fibers:*

1) *Carbon Fiber (Panex 35):*

A carbon fiber is a long, thin strand of material about 0.0002-0.0004 in (0.005-0.010 mm) in diameter and composed mostly of carbon atoms. Carbon fibers have high strength, high modulus of elasticity, low density, excellent machinability, resistance to elevated temperature, low thermal expansion coefficient.Panex 35 continuous carbon fiber is manufactured from polyacrylonitrile (PAN) precursor. The consistency in yield and mechanical properties that are provided by large filament count strands gives the user the ability to design and manufacture composite materials with greater confidence and allows for efficient and fast buildup of carbon fiber reinforced composite structures.

Sr. No	Mechanical Property	Value	Units
1	Tensile Strength	4137	MPa
2	Tensile Modulus	242	GPa
3	Density	1.81	g/cc
4	Fiber Diameter	7.2	Microns
5	Carbon Content	95%	
6	Yield	270	m/kg
7	Poisson's ratio	0.3	
8	Shear Strength	36	MPa

Table 2: Mechanical Properties of Carbon Fiber (Panex 35, Zoltek)

C. *Selection of Resin:*

The important Parameters in selecting resin are cost, temperature capability, elongation to failure and impact resistance. The resins selected for most of the drive shaft are either vinyl esters or epoxies. For the manufacturing of composite shaft, the most widely used reins are based on following – matrices based on epoxy resins, matrices based on phenolic resins, matrices based on polyster resins.

Sr No.	Test Description	Unit	Typical Values
1	Tensile strength	MPa	70-74
2	Tensile elongation at break	%	4.6-5.0
3	Tensile modulus	MPa	2860-3000
4	Flexural strength	MPa	118-130
5	Flexural elongation at break	%	5.5-6.5
6	Flexural modulus	GPa	2900-3050
7	Shear strength	MPa	53-58

Table 3: Mechanical Properties Epoxy Resin (Ly 1564 Epoxy Resin)

D. *Mechanical Analysis of Lamina:*

1) Volume fraction of fiber– 0.7 (60%)
2) Volume fraction of matrix – 0.3 (40%)
3) Volume of composites – 1 (100%)

Using the formula of micromechanical analysis of lamina [3] following properties are calculated which is shown in Table-4

Sr. No	Composite Properties	Symbol	Value	Unit
1	Young's Modulus(Longitudinal direction)	E_1	170.27	GPa
2	Young's Modulus(Transverse direction direction)	E_2	9.71	GPa
3	Major Poison's ratio	μ_{12}	0.3	-
4	Minor Poisson's ratio	μ_{21}	0.3	-
5	Shear Modulus	G_{12}	3.72	GPa
6	Ultimate longitudinal strength	$(\sigma_1^T)_{ult}$	2910	MPa
7	Ultimate transverse strength	$(\sigma_2^T)_{ult}$	25.81	MPa
8	Ultimate longitudinal compressive strength	$(\sigma_1^C)_{ult}$	83.7	MPa
9	Ultimate transverse compressive strength	$(\sigma_2^C)_{ult}$	20.21	MPa
10	Minimum fiber volume fraction	$(V_f)_{min}$	0.327	%
11	Critical fiber volume fraction	$(V_f)_{cr}$	0.333	%
12	Shear strength	τ	12.85	MPa

Table 4: Properties of Composite Lamina (Carbon Fiber and Epoxy Resin)

E. *Composite Ply Orientation:*

Only 0^0, $\pm45^0$ and 90^0 were consider for the ply orientations, due to their higher advantages. Such as $\pm45^0$ plies increases the torsional strength/stiffness, 90^0 plies increase the critical torsional buckling load, and the 0^0 plies increase the natural frequency of the drive shaft.

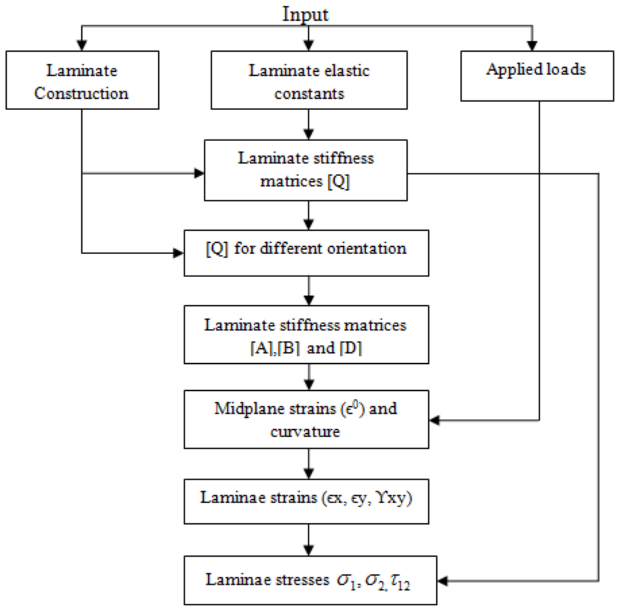

Fig. 1: Flow Chart for Laminate Stress Analysis

F. *Flow Chart for Laminate Stress Analysis:*

Once we decide the composite plies orientation $[90/45/-45/20]_s$ then follow the above flow chart [4], we get the values of the longitudinal young's moduli E_x and the transverse young's moduli E_y of the of the $[90/45/-45/20]_s$ carbon fiber/epoxy laminate.

G. *Torsional Strength:*

Assuming that the drive shaft is a thin, hollow cylinder, an element in the cylinder can be assumed to be a flat laminate. The only nonzero load on this element is the shear force; Nxy if the average shear stress (τxy) average the applied torque then it is [3]

$$T = (\tau_{xy})_{average}\,\Pi(r_0^2 - r_i^2)\,r_m$$

then

$$N_{xy} = (\tau_{xy})_{average}$$

$$N_{xy} = 256.94\times 10^3\, N/m$$

- Stacking Sequence of Laminate:

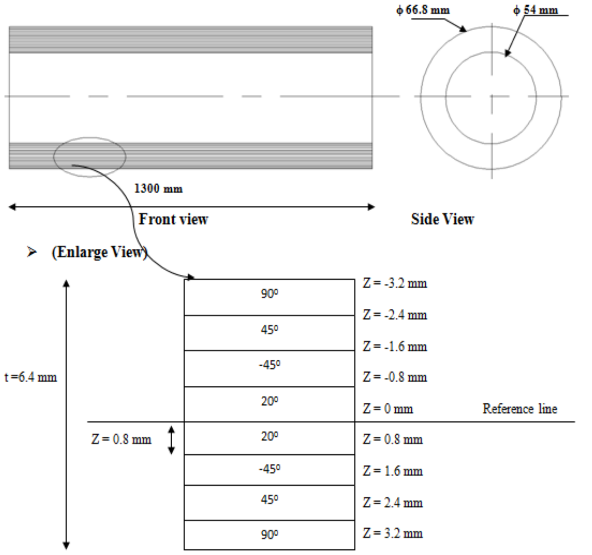

Fig. 2: Thickness and Coordinate Location of The Eight-Ply Laminates

H. *Torsional Buckling:*

An orthotropic thin hollow cylinder will buckle torsionally if the applied torque is greater than the critical torsional buckling load given by [3]

$$T_b = (2\Pi r^2_m\, t)(0.272)(E_x E^3_y)^{\frac{1}{4}}\left(\frac{t}{r_m}\right)^{\frac{3}{2}}$$

Using macro mechanical and micromechanical analysis of lamina, we get the longitudinal young's moduli E_x and the transverse young's moduli E_y of the $[90/45/-45/20]_s$ carbon fiber/epoxy laminate based on calculation,

$$E_x = 47.05\, GPa$$

$$E_y = 58.64\, GPa$$

Because lamina thickness is 0.8 mm, the thickness of nine ply $[90/45/-45/20]_s$ laminate t is,

$$t = 8\times 0.8$$

$$t = 6.4\ mm$$

Therefore,

$$T_b = (2\Pi r^2_m\, t)(0.272)(E_x E^3_y)^{\frac{1}{4}}\left(\frac{t}{r_m}\right)^{\frac{3}{2}}$$

$$T_b = 69933.58\, N-m$$

This value is greater than the applied torque of 2058.75 N-m, thus the composite drive shaft is safe in buckling.

I. *Natural Frequency:*

Let us find out the minimum natural frequency of the drive shaft, which is given by[3]

$$f_{nt} = \frac{\pi}{2}\sqrt{\frac{EI_x}{mL^4}}$$

$$f_{nt} = 110.03\ Hz$$

Because the minimum natural frequency is required to be 80 Hz, this requirement is also meet by the $[90/45/-45/20]_s$ laminate.

J. *Mass Saving:*

Mass of steel drive shaft = 5.10 kg

Mass of Composite drive shaft

$$m = 1.88\ kg$$

Percentage of mass saving over steel is

$$= \frac{5.10 - 1.88}{5.10}\times 100$$

$$= 63.13\ \%$$

V. RESULTS

Parameter	**Steel shaft**	**Composite shaft**
Applied Torque (T)	1472.45 N-m	1472.45N-m
Torsional Buckling (T_b)	18332.05 N-m	69933.88 N-m
Natural Frequency (f_{nb})	111.84 Hz	110.03 Hz
Critical speed (N_{cr})	6710.4 rpm	6601.8 rpm
Mass (m)	5.10 kg	1.88 kg
Percentage of mass saving	-	63.13 %

Table 5: Comparison between Steel and Composite Driveshaft

VI. CONCLUSION

1) The replacement of conventional drive shaft results in 64 % reduction in weight of automobile.
2) Composite shaft in comparison with the steel shaft with the same geometry have lower buckling torque.
3) The fiber orientation of composite shaft strongly changes the buckling torque.
4) Classical lamination theory was used in this work to find out torsional buckling strength, natural frequency of the shaft
5) Bernoulli-Euler theory was used to know the natural frequency of shaft.

REFERENCES

[1] M.A. Badie, E. Mahdi ,A.M.S. Hamouda An investigation into hybrid carbon/glass fiber reinforced epoxy composite automotive drive shaft, Materials and Design 32 (2011) 1485–1500
[2] Khalid YA, Mutasher SA, Sahari BB, Hamouda AMS. Bending fatigue behavior of hybrid aluminum/composite drive shafts. Mater Des 2007;28(1):329–34
[3] A.K. Kaw, Mechanics of Composite Materials, CRC Press, 1997.
[4] Jones R.M.,Mechanics of composite materials. McGraw-Hill, New york, 1975, pp. 72-75
[5] A.R. Abu Taliba, AidyAlib, Mohamed A. Badiea, NurAzidaCheLahb, A.F. Golestanehb Developing a hybrid, carbon/glass fiber-reinforced,epoxy composite automotive drive shaft, Materials and Design 31 (2010) 514–521
[6] O. Montagniera Ch. Hochard b Optimisation of hybrid high-modulus/high-strength carbon fibre reinforcedplasticcomposite drive shafts, Materials and Design 46 (2013) 88–100
[7] Dai Gil Lee, Hak Sung Kim, Jong Woon Kim, Jin Kook Kim Design and manufacture of an automotive hybrid aluminum/composite drive shaft, Composite Structures 63 (2004) 87–99
[8] Mutasher SA. Prediction of the torsional strength of the hybrid aluminum/composite drive shaft. Mater Des 2009;30(2):215–20.
[9] Rastogi N. Design of composite drive shafts for automotive applications. SAE, technical paper series, 2004-01-0485; 2004.
[10] Chen LW, Kung Peng W. The stability behavior of rotating composite shaftsunder axial compressive loads. Compos Struct 1998; 41:253–63.