# DESIGN & ANALYSIS OF COMPOSITE DRIVE SHAFT FOR AUTOMOBILE

**Ramchandra D Patil, Dr. D. M. Patel**
Assistant Professor, Professor
Mechanical Engineering Department
S.J.R.I.T. Dondaicha,Dhule,India

***Abstract*—Substituting composite structures for conventional metallic structures has many advantages because of higher specific stiffness and higher specific strength of composite materials. This work deals with the replacement of conventional two-piece steel drive shafts with one-piece automotive hybrid aluminum/composite drive shaft & was developed with a new manufacturing method, in which a carbon fiber epoxy composite layer was co-cured on the inner surface of an aluminum tube rather than wrapping on the outer surface to prevent the composite layer from being damaged by external impact and absorption of moisture. The optimal stacking sequence of the composite layer was determined considering the thermal residual stresses of interface between the aluminum tube and the composite layer calculated by finite element analysis. Press fitting method for the joining of the aluminum/composite tube and steel yokes was devised to improve reliability and to reduce manufacturing cost, compared to other joining methods such as adhesively bonded, bolted or riveted and welded joints. Protrusion shapes on the inner surface of steel yoke were created to increase the torque capability of the press fitted joint. The design parameters were optimized with the objective of minimizing the weight of hybrid aluminum/composite drive shaft &increase in torque capability compared with a conventional two-piece steel drive shaft.***

***Index Terms*—Drive shaft, Modeling, Composite, Weight reduction, ANSYS.**

## 1.INTRODUCTION

An automotive drive shaft transmits power from the engine to the differential gear of a rear wheel drive vehicle. 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. 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, 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 two-piece steel drive shaft consists of three universal joints, a center supporting bearing and a bracket, which increases the total weight of an automotive vehicle and decreases fuel efficiency. Since carbon fiber epoxy composite materials have more than four times specific stiffness (E= ρ) of steel or aluminum materials, it is possible to manufacture composite drive shafts in one-piece without whirling vibration over 9200 rpm. The composite drive shaft has many benefits such as reduced weight and less noise and vibration. However, because of the high material cost of carbon fiber epoxy composite materials, rather cheap aluminum materials may be used partly with composite materials such as in a hybrid type of aluminum/composite drive shaft, in which the aluminum has a role to transmit the required torque, while the carbon fiber epoxy composite increases the bending natural frequency above 9200 rpm.

## FUNCTIONS OF THE DRIVE SHAFT

1. First, it must transmit torque from the transmission to the differential gear box.
2. During the operation, it is necessary to transmit maximum low-gear torque developed by the engine.
3. The drive shafts must also be capable of rotating at the very fast speeds required by the vehicle.
4. The drive shaft must also operate through constantly changing angles between the transmission, the differential and the axles. As the rear wheels roll over bumps in the road, the differential and axles move up and down. This movement changes the angle between the transmission and the differential.
5. The length of the drive shaft must also be capable of changing while transmitting torque. Length changes are caused by axle movement due to torque reaction, road deflections, braking loads and so on. A slip joint is used to compensate for this motion. The slip joint is usually made of an internal and external spline. It is located on the front end of the drive shaft and is connected to the transmission.

## 2. LITERATURE REVIEW

### Composites

The theoretical details of composite materials and composite structures are extensively reviewed [6]. 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 [4, 5]. John. W. Weeton et al. [7] briefly described the application possibilities of composites in the field of automotive industry to manufacture composite elliptic springs, drive shafts and leaf springs. Beard more and Johnson [8] discussed the potential for composites in structural automotive applications from a structural point of view. Pollard [9] studied the possibility of the polymer Matrix composites usage in driveline applications. Faust et.al, [10] described the considerable interest on the part of both the helicopter and automobile industries in the development of lightweight driveshafts.Procedure for finding the elastic moduli of anisotropic laminated composites is explained by Azzi.V.D et.al, [11]. Azzi.V.D .et.al, discussed about anisotropic strength of composites[12].

### TorsionalBuckling

The problem of general instability under torsional load has been studied by many investigators. Greenhill [13] obtained a solution for the torsional stability of a long shaft. The first analysis of buckling of thin-walled tubes under torsion made by Schwerin [14], but his analysis did not agree with his experimental data. However, all these papers were limited to isotropic materials. As far as orthotropic materials are concerned, general theories of orthotropic shells were developed by Ambartsumyan [15] and Dong et al. [16]. Cheng and Ho [17] analyzed more generally, the buckling problems of non-homogeneous anisotropic cylindrical shells under combined axial, radial and torsional loads with all four boundary conditions at each end of the cylinder. Lien-Wen Chen et.al. [18] analyzed the stability behaviour of rotating composite shafts under axial compressive loads. A theoretical analysis was presented for determining the buckling torque of a cylindrical hollow shaft with layers of arbitrarily laminated composite materials by means of various thin-shell theories [19]. Bauchau et al., [20] measured the torsional buckling loads of graphite/epoxy shafts, which were in good agreement with theoretical predictions based on a general shell theory including elastic coupling effects and transverse shearing deformations.

### LateralVibrations

Bauchau [21] developed procedure for optimum design of high-speed composite drive shaft made of laminates to increase the first natural frequency of the shaft and to decrease the bending stress. Shell theory based on the critical speed analyses of drive shafts has been presented by Dos Reis et al. [22]. Patricia L.Hetherington [23] investigated the dynamic behaviour of supercritical composite drive shafts forhelicopter applications. Ganapathi.et.al [24] extensively studied the nonlinear free flexural vibrations of laminated circular cylindrical shells. A method of analysis involving Love’s first approximation theory and Ritz’s procedure is used to study the influence of boundary conditions and fiber orientation on the natural frequencies of thin orthotropic laminated cylindrical shells was presented [25].A first order theory was presented by Lee[26] to determine the natural frequencies of an orthotropic shell. Nowinski.J.L.[27] investigated the nonlinear transverse vibrations of elastic orthotropic shells using Von-Karman-Tsien equations.

### Optimization

The optimum design of laminated plates and shells subjected to constraints on strength, stiffness, buckling loads, and fundamental natural frequencies were examined [28]. Methods were proposed for the determination of the optimal ply angle variation through the thickness of symmetric angle-ply shells of uniform thickness [29]. The main features of GAs and several ways in which they can solve difficult design problems were discussed by Gabor Renner et.al.[30]. Raphael T.Haftka [31] discussed extensively about stacking-sequence optimization for buckling of laminated plates by integer programming. The use of a GA to optimize the stacking sequenceof composite laminates for buckling load maximization was studied. Various genetic parameters including the population size, the probability of mutation, and the probability of crossover were optimized by numerical experiments [32]. The use of GAs for the optimal design of symmetric composite laminates subject to various loading and boundary conditions were explained [33]. Kim, et.al. [34] minimized the weight of composite laminates with ply drop under a strength constraint. The working of Simple Genetic Algorithm was explained by Goldberg [35]. Rajeev and Krishnamoorthy [36] proposed a method for converting a constrained optimization problem into an unconstrained optimization problem.

## 3.DESIGN OF STEEL DRIVE SHAFT

### 3.1SPECIFICATION OF THE PROBLEM

The fundamental natural bending frequency for passenger cars, small trucks, and vans of the propeller shaft should be higher than 6,500 rpm to avoid whirling vibration and the torque transmission capability of the drive shaft should be larger than 3,500 Nm. The drive shaft outer diameter should not exceed 100 mm due to space limitations. Here outer diameter of the shaft taken is 51 mm which is of Maruti Omni. The drive shaft of transmission system is tobe designed optimally for following specified design requirements Thesteel/composite drive shaft should satisfy three design specifications such as static torque capability, buckling torque capability and bending natural frequency. The major role of the steel tube is to sustain an applied torque while the role of the carbon fiber epoxy composite is to increase bending natural frequency. The carbon fiber epoxy prepreg was USN150 manufactured by SK Chemicals (Korea), whose properties are similar to T300/5208. Tables4.1 and4.2 shows the mechanical properties of the carbon fiber epoxy composite and the steel tube (6061-T6), respectively.[5]

***Table 3.1 Design requirements and specifications***

| Sr. No. | Name | Notation | Unit | Value |
|---|---|---|---|---|
| 1. | Ultimate Torque | $T_{max}$ | Nm | 3500 |
| 2. | Max. Speed of shaft | $N_{max}$ | rpm | 6500 |

| | | | | |
|---|---|---|---|---|
| 3. | Outer Dia. Of Shaft | $d_0$ | mm | 51 |
| 4. | Length of shaft | L | mm | 660 |
| 5. | Thikness | T | mm | 2 |

The steel drive shaft should satisfy three design specifications such as

1. Torque Transmission Capability,
2. Buckling Torque Capability
3. Bending Natural Frequency.

**3.2. Torque Transmission Capacity of Drive shaft**

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

$$\boldsymbol{\tau = 259.15 * 10^6 N/m^2}$$

Therefore, putting this value in shear strength in above equation, we get,

$$T = \frac{259.15 * 10^6 * \frac{\pi}{32} * (0.051^4 - 0.047^4)}{0.0245}$$

$$\boldsymbol{T = 1956.88 Nm}$$

The torque transmitted by the steel shaft is 1956.88 Nm.

**3.2.3 Torsional Buckling Capacity of the Drive Shaft**

The critical stress is given by,

$$\tau_{cr} = \frac{E}{3\sqrt{2} * (1 - \mu^2)^{3/4}} * (t/r)^{3/2}$$

$$\boldsymbol{\tau_{cr} = 1221.37 * 10^6 N/m^2}$$

The relation between the torsional buckling capacity and critical stress is given by,

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

$$\boldsymbol{T_b = 9212.74\ Nm}$$

Here,

$$\boldsymbol{T_b} > T$$

Therefore, the Design is Safe.

**3.2.4 Bending Natural Frequency**

The shaft is considered as simply supported beam undergoing transverse vibration or can be idealized as a pinned-pinned beam. Natural frequency can be found using the following equation,

$$f_{nb} = \frac{\pi}{2} * \sqrt{\frac{EI}{ml^4}}$$

Here,

The moment of inertia of hollow shaft is given by,

$$I = \frac{\pi}{64} * (d_0^4 - d_i^4) = \boldsymbol{0.2064 * 10^{-6} m^2}$$

The mass per unit length of the shaft is given by,

$$\bar{m} = \rho * \frac{\pi}{4} * (d_o^2 - d_i^2) = \boldsymbol{2.4168\ \frac{Kg}{m}}$$

Therefore upon substitution of above values we get,

$$f_{nb} = \frac{\pi}{2} * \sqrt{\frac{EI}{ml^4}}$$

$$\boldsymbol{f_{nb} = 321.05\ Hz} > 80\ Hz$$

Here, the fundamental bending natural frequency of steel shaft is greater than the minimum natural frequency of the shaft assumed. Therefore, the designed Steel Shaft is Safe.

**3.2.5 Critical Speed of Shaft:-**

The critical speed of the shaft is given by,

$$N_{cr} = 60 * f_{nb}$$

$$\boldsymbol{N_{cr} = 19263 \text{ rpm}}$$

Therefore, the critical speed of the shaft is 19263 rpm which is more than the maximum speed of the transmission system.

**3.2.6 Weight of Steel Driveshaft:-**

Weight = Density ×Volume

$$W = \rho * V$$

$$W = \rho * \frac{\pi}{4} * (d_o^2 - d_i^2) * L$$

$$\boldsymbol{W = 1.595\ Kg}$$

The weight of the Steel Driveshaft is 1.595 Kg.

## 4. DESIGN OF COMPOSITE DRIVE SHAFT

The specifications of the composite drive shaft of an automotive transmission are same as that of the steel drive shaft for optimal design. The driveshaft is to be design for the following design requirements

**4.1 Assumptions**

1. About longitudinal axis, the shaft rotates at a constant speed.
2. The shaft has a circular and the uniform cross section along the length.
3. The shaft is such that at every cross section, the mass center coincides with the geometric center due to which the shaft is perfectly balanced.
4. All the nonlinear and the damping effects are excluded.
5. The shaft is be made of composite material and Hooke's law is applicable for composite material i.e. the stress strain relationship for composite material is linear and elastic.
6. The shaft is considered as it is under plane stress as the lamina is thin and out-of-plane loads are applied.

4.2 **Material selection and Mechanical Properties**

The carbon & glass fibre are selected as the best suitable material for the design of composite driveshaft as they are available in market as compared to other materials. Epoxy resin is selected due to its strength, good wetting of fibers and lower curing shrinkage. Following Cases for fiber volume fraction were considered here,

**CaseA.65%fibervolumefractionofE-Glass/Epoxyshaft ($V_{fg}$= 65% &$V_m$=35%).**

**CaseB.65%fibervolumefractionofCarbon/Epoxyshaft ($V_{fc}$ = 65% &$V_m$=35%).**

**Case C. 65% fiber volume fraction of Carbon and E-Glass/Epoxy shaft ($V_{fg}$= 35% & $V_{fc}$ = 30% & $V_m$=35%).**

Thematerialpropertiesoftheaboveconsideredshaftwere calculatedusingfibervolumefractiontheory.Considering the first case for unidirectional ply properties can be calculatedbyusingelastic properties of matrix and fiber materials for the calculations are taken from literature and are presented in Table 1 [41].

***Table 3.4 Elastic properties of matrix and fiber material [41]***

| Elastic properties | Matrix material (Epoxy resin) | Fiber material (E-Glass) | Fiber material (Carbon) |
|---|---|---|---|
| Young's modulus (E) in GPa | 3.45 | 73.1 | 228 |
| Poisson's ratio (v) | 0.35 | 0.22 | 0.3 |
| Shear modulus (G) in GPa | 1.28 | 29.95 | 12 |
| Density (□) in Kg/m$^3$ | 1200 | 2620 | 2000 |

The material properties of the composite material and its cases are given in Table 3.5. The composite drive shaft should satisfy three design specifications such as,

1.Torque Transmission Capability
2.Buckling Torque Capability
3.Bending Natural Frequency.

**4.2.1 Torque Transmission Capacity of Drive shaft**

Considering Case A the composite driveshaft is designed to meet the design requirements and specifications as mentioned above. The maximum torsional strength of the shaft is calculated by using the following equation,

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

$$\tau = \frac{G\theta r}{l} = \frac{3388 * 10^6 * \frac{5\pi}{180} * 0.0175}{0.660}$$

$$\mathbf{\tau = 7.83 * 10^6 N/m^2}$$

Therefore, putting this value in shear strength in above equation, we get,

$$T = \frac{7.83 * 10^6 * \frac{\pi}{32} * (0.042^4 - 0.028^4)}{0.0175}$$

$$\mathbf{T = 109.82\ Nm}$$

The torque transmitted by the composite shaft is 109.82Nm.

**4.2.2 Torsional Buckling Capacity of the Drive Shaft**

Since long thin hollow shafts are vulnerable to torsional buckling, the possibility of the torsional buckling of the composite shaft was checked by considering the hollow compositeshaftasanisotropiccylindricalshellthebuckling torque is givenby:

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

Where,
$E_x$=Young'smodulusin$x$direction.
$E_y$ = Young's modulus in $y$direction.
Here,weconsideredthecompositedriveshaftas orthotropic lamina.Therefore,

$$T_b = 2\pi * 0.0175^2 * 0.007 * 0.272 * (10000 * 10000^3)^{\frac{1}{4}} * \left(\frac{0.007}{0.0175}\right)^{\frac{3}{2}}$$

$$\mathbf{T_b = 9268Nm}$$

Here, Tb > T

Therefore, the design is safe.

From the above equation, we can see that the torsional buckling capability of composite shaft is strongly dependent on the thickness of composite shaftandtheaveragemodulus in the hoop direction.

.

**4.2.3 Bending Natural Frequency**

The shaft is considered as simply supported beam undergoing transverse vibration or can be idealized as a pinned-pinned beam. Natural frequency can be found using the following equation,

$$f_{nb} = \frac{\pi}{2} * \sqrt{\frac{E_x I}{m l^4}}$$

Here,

The moment of inertia of hollow shaft is given by,

$$I = \frac{\pi}{64} * (d_0^4 - d_i^4) = \mathbf{0.122 * 10^{-6} m^2}$$

The mass per unit length of the shaft is given by,

$$\bar{m} = \rho * \frac{\pi}{4} * (d_o^2 - d_i^2) = \mathbf{1.63\ \frac{Kg}{m}}$$

Therefore upon substitution of above values we get,

$$f_{nb} = \frac{\pi}{2} * \sqrt{\frac{E_x I}{m l^4}}$$

$$\boldsymbol{f_{nb} = 98.65\ Hz} > 80\ Hz$$

Here, the fundamental bending natural frequency of composite shaft is greater than the minimum natural frequency of the shaft assumed. Therefore, the designed composite Shaft is Safe.

**4.2.4 Critical Speed of Shaft:-**

The critical speed of the shaft is given by,

$$N_{cr} = 60 * f_{nb}$$

$\boldsymbol{N_{cr}}$**=5919 rpm**

Therefore, the critical speed of the shaft is 5919 rpm which is more than the maximum speed of the transmission system.

### 3.3.6 Weight of Steel Driveshaft:-

$$\text{Weight} = \text{Density} \times \text{Volume}$$
$$W = \rho * V$$

$$W = \rho * \frac{\pi}{4} * (d_o^2 - d_i^2) * L$$

$$\boldsymbol{W = 1.07Kg}$$

The weight of the Steel Driveshaft is 1.07 Kg.

***Table 3.5 Analytical results For Composite Drive Shaft of case A***

| Sr. No. | Parameter | Steel shaft |
|---|---|---|
| 1 | Outer Diameter | 42 |
| 2 | Thickness | 7 |
| 3 | Applied Torque (T) | 109.82 Nm |
| 4 | Torsional Buckling (Tb) | 9268 Nm |
| 5 | Natural Frequency (fnb) | 98.65 Hz |
| 6 | Critical speed (Ncr) | 5919 rpm |
| 7 | Mass (m) | 1.07 Kg |

***Table 3.5 Analytical results For Composite Drive Shaft of case A,B,C***

| Design Requirements | Steel (SM45C) | Glass Fiber | Carbon Fiber | Glass and Carbon Fiber |
|---|---|---|---|---|
| | | 65%-35% | 65%-35% | 35%-30%-35% |
| Shear Stress τ, (MPa) | 259.16 | 7.83 | 7.06 | 8.00 |
| Torsional Strength T, (Nm) | 1956.88 | 109.82 | 98.89 | 112.18 |
| Buckling Torque Tb, (Nm) | 9,212. 78 | 9268 | 8530.49 | 9339.48 |
| Natural Frequency fnb, (Hz) | 321.0 5 | 98.65 | 105.17 | 103.57 |
| Critical Speed Ncr, (rpm) | 19,263.54 | 5919 | 6310.40 | 6214.77 |
| Weight W, (Kg) | 1.595 | 1.07 | 0.87 | 0.98 |

## 5.FINITE ELEMENT ANALYSIS

Finite Element Analysis (FEA) is a computer-based numerical technique for calculating the strength and behavior of engineering structures. It can be used to calculate deflection, stress, vibration, buckling behavior and many other phenomena. It also can be used to analyze either small or large scale deflection under loading or applied displacement. In this project finite element analysis was carried out using the FEA software ANSYS. Static, Modal and Buckling analysis was carried out using the mentioned dimensions and material properties in the table given above for both steel and composite driveshaft.

Static Modal and Buckling analysis was carried out as follows

Model was created in ANSYS by taking 51mm as O.D. and 47mm as I.D. and 660mm length. The loading and boundary condition applied to shaft is shown in Fig

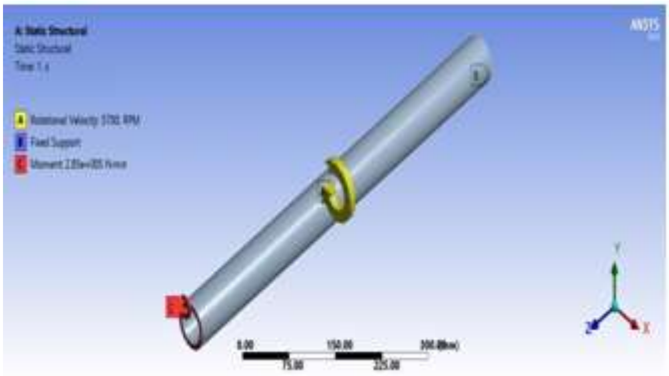

Fig. 5.1 Loading and Boundary Conditions applied to shaft

2.The Model was solved for Static, Modal and Buckling analysis to obtain results as shown in Fig- 5.2, Fig-5.3 and Fig-5.4.

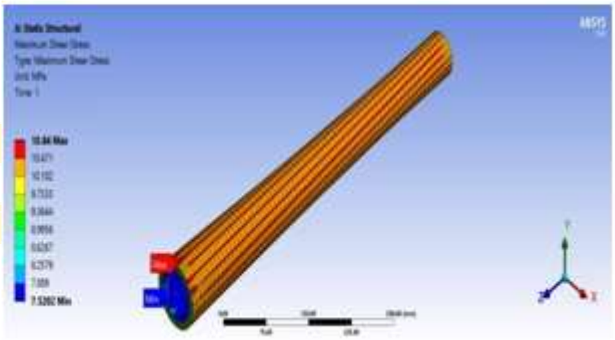

Fig-5.2: Maximum Shear Stress

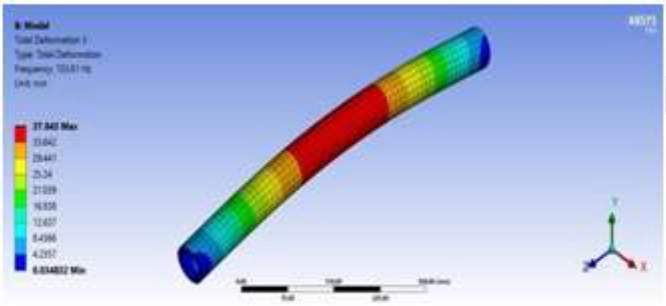

Fig-5.3: 1st Mode Natural Frequency

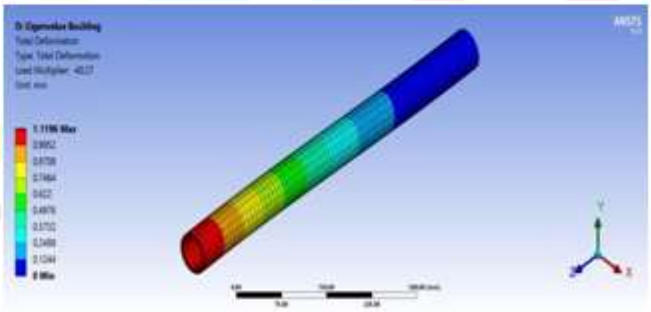

Fig-5.4: Eigenvalue Buckling Analysis

## 6. RESULTS AND DISCUSSION

The comparison is made between the analytical solutions of steel and composite propeller shaft for various parameters. The composite propeller shaft is having better results than the steel propeller shaft.

*Table 6.1 Comparison between steel and Composite propeller shaft*

| Cases | Material | Torque Applied (Nm) | Shear Stress (MPa) | Natural frequency (Hz) | Load Multiplier | Buckling torque (Nm) |
|---|---|---|---|---|---|---|
| 1. | Steel (SM45C) | 1900 | 251.12 | 309.77 | 4.7233 | 8,974.27 |
| A. | Glass Fiber with 65% Fiber Volume | 109 | 7.59 | 131.12 | 37.27 | 11,303.9 |
| B. | Carbon Fibre with 65% Fiber Volume | 98 | 7.02 | 131.47 | 30.056 | 9,224.46 |
| C. | Glass & Carbon Fibre with 65% Fiber Volume | 112 | 7.91 | 129.95 | 34.35 | 10,348.2 |

## 7.ACKNOWLEDGMENT

This work was carried out at the Department of Mechanical Engineering,D.N.Patel COE,Shahada under the supervision of Prof.Dr.D.M.Patel. This thesis work was initiated in August 2016.

We wish to express our sincere appreciations and gratitude to Prof.Dr.D.M.Patel for his wisdom, guidance, encouragement and many insight and valuable discussions during the development of ideas in this thesis.

## 8. REFERENCES

**[1]** Jones, R.M., 1990, Mechanics of Composite Materials, 2e, McGraw- Hill Book Company, NewYork.
**[2]** AurtarK.Kaw, 1997, Mechanics of Composite Materials, CRC Press, NewYork..
**[3]** Belingardi.G, Calderale.P.M. and Rosetto.M.,1990, “Design Of Composite Material Drive Shafts For Vehicular Applications”, Int.J.of Vehicle Design, Vol.11,No.6,pp.553-563.
**[4]** Rahul Reddy Nadikattu, 2014. Content analysis of American & Indian Comics on Instagram using Machine learning", International Journal of Creative Research Thoughts (IJCRT), ISSN:2320-2882, Volume.2, Issue 3, pp.86-103.
**[5]** Jin Kook Kim.DaiGilLee, and Durk Hyun Cho, 2001, “Investigation of Adhesively Bonded Joints for Composite Propeller shafts”, Journal of CompositeMaterials, Vol.35, No.11,pp.999-1021.
**[6]** Dai Gil Lee, et.al, 2004, “Design and Manufacture of an Automotive Hybrid Aluminum/Composite Drive Shaft, Journal of Composite Structures, Vol.63,pp87-89.
**[7]** Sikender Mohsienuddin Mohammad, "AN EXPLORATORY STUDY OF DEVOPS AND IT'S FUTURE IN THE UNITED STATES", International Journal of Creative Research Thoughts (IJCRT), ISSN:2320-2882, Volume.4, Issue 4, pp.114-117, November-2016, Available at :http://www.ijcrt.org/papers/IJCRT1133462.pdf
**[8]** Agarwal B. D. and Broutman L. J., 1990, "Analysis and performance of fiber composites", John Wiley and SonsInc.
**[9]** John W. Weetonet. al. 1986,"Engineers guide to composite materials, American Society for Metal, NewYork.
**[10]** H.Z. Shan and T.W. Chou, 1995, Transverse elastic moduli of unidirectional fiber composites with fiber/matrix interfacial debonding, Composites Science and Technology, 53, 383-391.