

# Investigation of Composite Torsion Shaft for Static Structural Analysis using Finite Element Analysis.

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## **Abstract**

The overall objective of this paper is to design and analyze a composite drive shaft for power transmission applications. A one-piece drive shaft for rear wheel drive automobile was designed optimally using E-Glass/Epoxy and High modulus (HM) Carbon/Epoxy composites. In this paper an Analytical and ANSYS Software has been successfully applied to minimize the weight of shaft which is subjected to the constraints such as torque transmission, Static Structural capacities. The results of Analytical Analysis are used to perform static analysis using ANSYS software. The results show the stacking sequence and fibre angle orientation of shaft strongly affects static strength of shaft.

## **1. Introduction**

A composite material or a compound is a mixture of two or more distinct constituents all of which are present in reasonable proportions and have different properties so that the composite properties exhibited are the combination of the best qualities of their constituents and also some qualities that neither of their constituents possesses. Plastic is not a composite because it is compound. An alloy is not composite because it is a homogeneous mixture. Following are some of the properties that can be improved by forming a composite material Strength, Stiffness, Corrosion resistance, Wear resistance, Weight, Fatigue failure. Naturally, not all of these properties are improved at the same time nor is there usually any requirement to do so. In fact, some of the properties are in conflict with one another, e.g., thermal insulation versus thermal conductivity.

## **2. Literature Review**

M.A. Badie et al. [1] examines the effect of fiber orientation angles and stacking sequence on the torsional stiffness, natural frequency, buckling strength, fatigue life and failure modes of composite tubes. Finite element analysis (FEA) has been used to predict

the fatigue life of composite drive shaft (CDS) using linear dynamic analysis for different stacking sequence. Experimental program on scaled woven fabric composite models was carried out to investigate the torsional stiffness. FEA results showed that the natural frequency increases with decreasing fiber orientation angles.

Mahmood M. Shokrieh et al. [2] has done Shear buckling of composite drive shaft under torsion was performed using FEM. The commercial finite element package ANSYS was used for the solution of the problem. In order to achieve model the composite shaft, the shell 99 element is used and the shaft is subjected to torsion. The shaft is fixed at one end in axial, radial and tangential directions and is subjected to torsion at the other end. After performing a static analysis of the shaft, the stresses are saved in a file to calculate the buckling load. The output of the buckling analysis is a load coefficient which is the ratio of the buckling load to the static load.

S.A. Mutasher [3] investigates the maximum torsion capacity of the composite shaft for different winding angle, number of layers and stacking sequences. The Composite shaft consists of aluminum tube wound outside by E-glass and carbon fibers/epoxy composite. The finite element method has been used to analyze the hybrid shaft under static torsion. ANSYS finite element software was used to perform the numerical analysis for the shaft. The specimen was analyzed. Elasto-plastic properties were used for aluminum tube and linear elastic for composite materials. The results show that the static torque capacity is significantly affected by changing the winding angle, stacking sequences and number of layers.

Y.A. Khalid et al [4] studied a bending fatigue analysis was carried out for composite drive shafts. The shafts used were fabricated using filament winding technique. Glass fiber with a matrix of epoxy resin and hardener were used to construct the external composite layers needed. Four cases were studied using aluminum tube wounded by different layers of composite materials and different stacking sequence or

fiber orientation angles. The failure mode for all the hybrid shafts was identified.

### 3. Analytical Analysis of Composite Shaft

$$\frac{1}{E_{11}} = \frac{\cos^4 \theta}{E_{xy}} + \frac{\sin^4 \theta}{E_{yy}} + \frac{1}{4} \left( \frac{1}{G_{xy}} - \frac{2\mu_{xy}}{E_{xx}} \right) \sin^2 2\theta$$

$$\frac{1}{E_{22}} = \frac{\sin^4 \theta}{E_{xx}} + \frac{\cos^4 \theta}{E_{yy}} + \frac{1}{4} \left( \frac{1}{G_{xy}} - \frac{2\mu_{xy}}{E_{xx}} \right) \sin^2 2\theta$$

$$\frac{1}{G_{12}} = \frac{1}{E_{xx}} + \frac{2\mu_{xy}}{E_{xx}} + \frac{1}{E_{yy}} - \left( \frac{1}{E_{xx}} + \frac{2\mu_{xy}}{E_{xx}} + \frac{1}{E_{yy}} - \frac{1}{G_{xy}} \right) \cos^2 2\theta$$

$$\mu_{12} = E_{11} \left( \frac{\mu_{xy}}{E_{xx}} (\sin^4 \theta + \cos^4 \theta) - \left[ \frac{1}{E_{11}} + \frac{1}{E_{22}} - \frac{1}{G_{12}} \right] \sin^2 \theta \cos^2 \theta \right)$$

$$\mu_{21} = \frac{E_{22}}{E_{11}} \mu_{12}$$

#### 3.1 Stiffness matrix:

$$Q = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{21} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix}$$

$$Q_{11} = \frac{E_{11}}{1 - \mu_{12}\mu_{21}}$$

$$Q_{22} = \frac{E_{22}}{1 - \mu_{12}\mu_{21}}$$

$$Q_{12} = Q_{21} = \frac{\mu_{12}E_{22}}{1 - \mu_{12}\mu_{21}} = \frac{\mu_{21}E_{11}}{1 - \mu_{12}\mu_{21}}$$

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

#### 3.2 $\bar{Q}$ Matrix

Using trigonometric identities, Tsai and Pagano have shown that the Elements in the  $\bar{Q}$  matrix can be written as,

$$\bar{Q} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{21} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{31} & \bar{Q}_{32} & \bar{Q}_{66} \end{bmatrix}$$

Where,

$$\bar{Q}_{11} = Q_{11} \cos^4 \theta + 2(Q_{12} + 2Q_{66}) \sin^2 \theta \cos^2 \theta + Q_{22} \sin^4 \theta$$

$$\bar{Q}_{12} = (Q_{11} + Q_{22} - 4Q_{66}) \sin^2 \theta \cos^2 \theta + Q_{12} (\sin^4 \theta + \cos^4 \theta)$$

$$\bar{Q}_{22} = Q_{11} \sin^4 \theta + 2(Q_{12} + 2Q_{66}) \sin^2 \theta \cos^2 \theta + Q_{22} \cos^4 \theta$$

$$\bar{Q}_{16} = (Q_{12} - Q_{12} - 2Q_{66}) \sin \theta \cos^3 \theta + (Q_{12} - Q_{22} + 2Q_{66}) \sin^3 \theta \cos \theta$$

$$\bar{Q}_{26} = (Q_{11} - Q_{12} - 2Q_{66}) \sin^3 \theta \cos \theta + (Q_{12} - Q_{22} + 2Q_{66}) \sin \theta \cos^3 \theta$$

$$\bar{Q}_{66} = (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66}) \sin^2 \theta \cos^2 \theta + Q_{66} (\sin^4 \theta + \cos^4 \theta)$$

#### 3.3 Lamina S/D/F-Strain Behavior

The S/D/F-strain relations in principal material coordinates for a lamina of an orthotropic material under plane S/D/F are:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{21} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \gamma_{12} \end{bmatrix}$$

In any other coordinate system in the plane of the lamina, the S/D/Fes are:

$$A_{11} = \bar{Q}_{11} t_1 + \bar{Q}_{11} t_2 + \bar{Q}_{11} t_3 + \bar{Q}_{11} t_4$$

$$\begin{bmatrix} \epsilon_{x^\circ} \\ \epsilon_{y^\circ} \\ \gamma_{xy^\circ} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{16} \\ a_{12} & A_{22} & a_{26} \\ a_{16} & a_{26} & a_{66} \end{bmatrix} \begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix}$$

$$\begin{bmatrix} \epsilon_{x^\circ} \\ \epsilon_{y^\circ} \\ \gamma_{xy^\circ} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{16} \\ a_{12} & A_{22} & a_{26} \\ a_{16} & a_{26} & a_{66} \end{bmatrix} \begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix}$$

$$\begin{bmatrix} a_{11} & a_{12} & a_{16} \\ a_{12} & A_{22} & a_{26} \\ a_{16} & a_{26} & a_{66} \end{bmatrix} =$$

$$\text{Inverse of } \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix}$$

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{21} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{31} & \bar{Q}_{32} & \bar{Q}_{66} \end{bmatrix} \begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{bmatrix}$$

### 4. Analytical Analysis of Steel and Aluminum Shaft

$$\text{Torque} = \frac{\pi}{16} \times \tau \times \left[ \frac{D_o^4 - D_i^4}{D_o} \right]$$

$$\gamma_{xy} = \frac{\text{shear stress}}{\text{modulus of rigidity}} = \frac{\tau_{xy}}{G}$$

## 5. Material Properties

Contain	Carbon Epoxy	Glass Epoxy	Steel	Al
E <sub>11</sub>	126.9 GPa	40.3 GPa	210 GPa	69 Gpa
E <sub>12</sub>	11 GPa	6.21 GPa	-	-
G <sub>12</sub>	6.6 GPa	3.07 GPa	80 GPa	26.5 GPa
μ <sub>12</sub>	0.2	0.2	0.3	0.3
Density Kg/m <sup>3</sup>	1610	1910	7810	2700

Table .1 Mechanical Properties for Composite and Metal Shaft

## 6. Finite Element Method

The finite element method is a numerical technique. In this method all the complexities of the problems, like varying shape, boundary conditions and loads are maintained as they are but the solutions obtained are approximate. Because of its diversity and flexibility as an analysis tool, it is receiving much attention in engineering. The fast improvements in computer hardware technology and slashing of cost of computers have boosted this method, since the computer is the basic need for the application of this method. A number of popular brand of finite element analysis packages are now available commercially. Some of the popular packages are STAAD-PRO, GT-STRUDEL, NASTRAN, NISA and ANSYS. Using these packages one can analyze several complex structures. The Finite Element Method (FEM) was developed more by engineers than mathematicians using abstract methods. The FE method is the way of getting a numerical solution to specified problem. The FE analysis does not produce formula as a solution, nor does it solve the class of problems. Also the solution is approximate unless the problem is so simple that convenient exact formula is available.

## 7. Finite Element Analysis

With different fibre angle orientation and Stacking sequence the analysis done in ANSYS 13.0 version for following dimension of hollow composite and steel shaft. For cost purpose we have selected one HM

Carbon Epoxy layer and remaining three layers are Glass epoxy. Length of the shaft is 1000 mm, Applied Torque is 350 N-m. Outer diameter is 104.032 mm, Inner diameter is 100 mm, thickness t<sub>1</sub>=0.1905 mm, t<sub>2</sub>=0.1905 mm, t<sub>3</sub>=0.635 mm, t<sub>4</sub>=1.016 mm.

### 7.1 SHELL 281 Element

For analysis purpose SHELL 281 Element is selected. An 8-node element with six degrees of freedom at each node. The element is suitable for analyzing thin to moderately-thick shell structures and is appropriate for linear, large rotation, and/or large strain nonlinear applications. The layer information is input using the section commands rather than real constants.

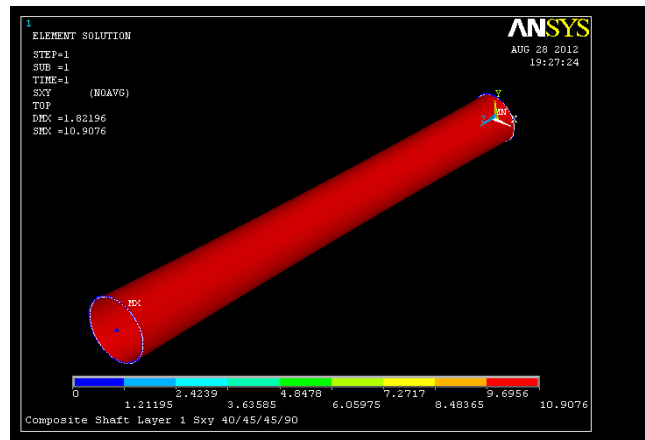


Fig. 1 ANSYS Result for Torsional Shear Stress for Composite Shaft

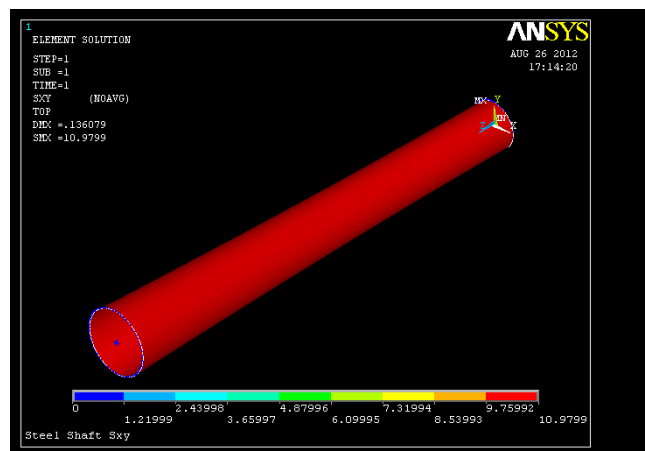


Fig. 2 ANSYS Result for Torsional Shear Strain for Composite Shaft

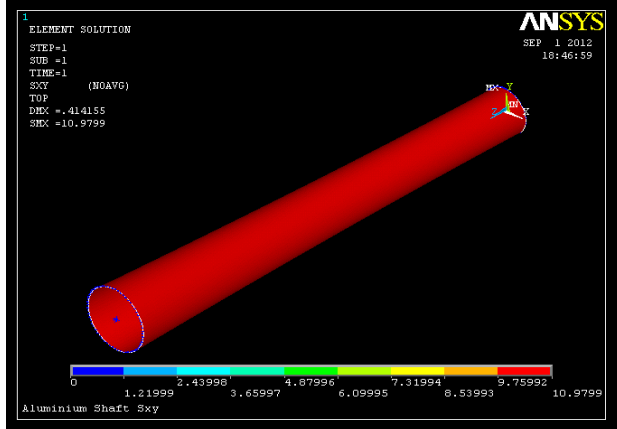


Fig. 3 ANSYS Result for Torsional Shear Strain for Aluminum Shaft

### 8. Result and Discussion

Metal Shafts. For Optimum Torsional Shear Stress the Stacking Sequence Carbon Epoxy/Glass Epoxy/ Glass Epoxy/ Glass Epoxy with Fibre Angle Orientation  $40^{\circ}/45^{\circ}/45^{\circ}/90^{\circ}$  gives the Torsional Shear Stress 10.9076 N/mm<sup>2</sup> which is less than 10.9799 N/mm<sup>2</sup> as compare to Steel Shaft and Aluminum Shaft.

Stacking Sequence	Fibre Angle Orientation	Torsional Shear Stress (N/mm <sup>2</sup> )	Torsional Shear Strain	Weight of Shaft (Kg)
C/G/G/G	$40^{\circ}/45^{\circ}/45^{\circ}/90^{\circ}$	10.9076	0.001952	1.226
C/G/G/G	$40^{\circ}/45^{\circ}/45^{\circ}/90^{\circ}$	10.9112	0.001906	1.226
C/G/G/G	$40^{\circ}/45^{\circ}/45^{\circ}/90^{\circ}$	10.9226	0.001436	0.9591
C/G/G/G	$40^{\circ}/45^{\circ}/45^{\circ}/90^{\circ}$	10.9691	0.001529	0.9563
Steel Shaft	--	10.9799	0.000136	5.087
Aluminum Shaft	--	10.9799	0.000414	1.759

Table 2: Static Structural Analysis with ANSYS 13.0 software

Stacking Sequence	Fibre Angle Orientation	Torsional Shear Stress (N/mm <sup>2</sup> )	Torsional Shear Strain	Weight of Shaft (Kg)
C/G/G/G	$40^{\circ}/45^{\circ}/45^{\circ}/90^{\circ}$	11.9176	0.002052	1.226
C/G/G/G	$40^{\circ}/45^{\circ}/45^{\circ}/90^{\circ}$	11.9222	0.001996	1.226
C/G/G/G	$40^{\circ}/45^{\circ}/45^{\circ}/90^{\circ}$	11.9200	0.001526	0.9591
C/G/G/G	$40^{\circ}/45^{\circ}/45^{\circ}/90^{\circ}$	11.9201	0.001626	0.9563
Steel Shaft	--	10.7384	0.000134	5.087
Aluminum Shaft	--	10.7384	0.000405	1.759

Table 3: Static Structural Analysis with Analytical Method

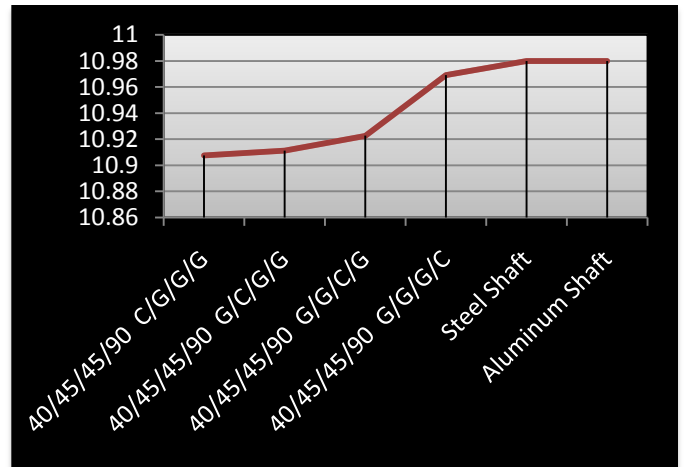


Chart No. 1 Torsion Shear Stress Comparison of Composite Shafts with Metal Shafts.

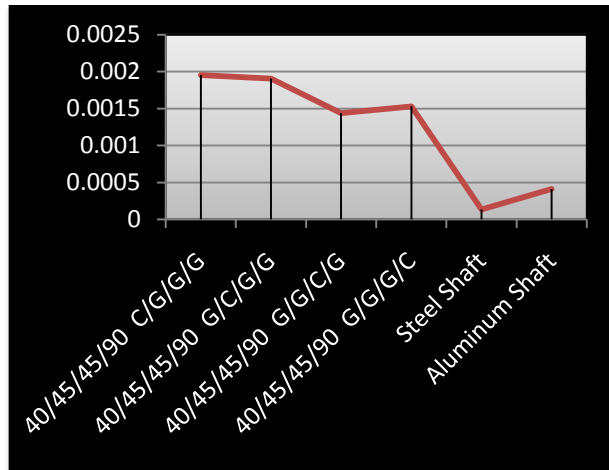


Chart No. 2 Torsion Shear Strain Comparison of Composite Shafts with Metal Shafts.

## 9. Conclusion

For Optimum Torsional Shear Stress the Stacking Sequence Carbon Epoxy/Glass Epoxy/ Glass Epoxy/ Glass Epoxy with Fiber Angle Orientation  $40^0/45^0/45^0/90^0$  gives the Torsional Shear Stress  $10.9076 \text{ N/mm}^2$  which is less than  $10.9799 \text{ N/mm}^2$  as compare to Steel Shaft and Aluminum Shaft. The weight is almost reduce 80% than the steel shaft and 43% than Aluminum shaft in composite shaft.

## 10. Future Scope

For Different thickness i.e. for Symmetric condition the Composite Shaft can be analysed for further investigation. For further investigation, the composite shaft can be analysed with negative fiber angle orientation. It is possible to investigate the Composite Shaft for more number of layers. It is possible to do the regression analysis for same work. For the same geometry modal analysis to find the natural frequency of composite shaft is possible.

## 10. References

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4. R. Sino, T.N. Baranger, E. Chatelet, G. Jacquet, "Dynamic analysis of a rotating composite shaft", *Composites Science and Technology* 68 (2008), pp 337–345.
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