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Investigation of Composite Torsion Shaft for Torsional Buckling 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 Torsional Buckling analysis using ANSYS software. The results show the stacking sequence and fiber angle orientation of shaft strongly affects Buckling strength of shaft.*

I. 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.

II. 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.

III. 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,

$$\overline{Q_{11}} = Q_{11}\,\mathrm{COS}^4\theta + 2(Q_{12}+2Q_{66})\sin^2\theta\,\mathrm{COS}^2\theta + Q_{22}\sin^4\theta$$

$$\overline{Q_{12}} = (Q_{11} + Q_{22} - 4Q_{66})\sin^2\theta\,\mathrm{COS}^2\theta + Q_{12}(\sin^4\theta + \cos^4\theta)$$

$$\overline{Q_{22}} = Q_{11}\sin^4\theta + 2(Q_{12}+2Q_{66})\sin^2\theta\,\mathrm{COS}^2\theta + Q_{22}\cos^4\theta$$

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

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

$$\overline{Q_{66}} = (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66})\sin^2\theta\,\mathrm{COS}^2\theta + Q_{66}(\sin^4\theta + \cos^4\theta)$$

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:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{21} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix}$$

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

$$A_{11} = \overline{Q_{11}}\,t_1 + \overline{Q_{11}}\,t_2 + \overline{Q_{11}}\,t_3 + \overline{Q_{11}}\,t_4$$

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

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

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

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

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

For Inner Layers of shaft Buckling Torque is

$$T_{cr} = \frac{2.289}{\sqrt{L}} \times (E_x)^{0.375} \times (E_y)^{0.625} \times (t)^{2.25} \times (D)^{1.25}$$

For outer layer of Shaft Buckling Torque is

$$T_{cr} = 2\pi r^2 t \times 0.272 \times [E_x \times E_y^3]^{0.25} \times [\frac{t}{r}]^{1.5}$$

IV. Analytical Analysis Of Steel And Aluminum Shaft

If $\frac{1}{\sqrt{1-\mu^2}} \times \frac{L^2 t}{(2r^2)} > 5.5$

Then, $\tau_{cr} = \frac{E}{3\sqrt{2}(1-\mu^2)^{3/4}} \times \left(\frac{t}{r}\right)^{3/2}$

V. Material Properties

Table .1 Mechanical Properties for Composite and Metal Shaft

Contain	Carbon Epoxy	Glass Epoxy	Steel	Al
E_{11}	126.9 GPa	40.3 GPa	210 GPa	69 Gpa
E_{12}	11 GPa	6.21 GPa	-	-
G_{12}	6.6 GPa	3.07 GPa	80 GPa	26.5 GPa
μ_{12}	0.2	0.2	0.3	0.3
Density Kg/m^3	1610	1910	7810	2700

VI. Finite Element Method

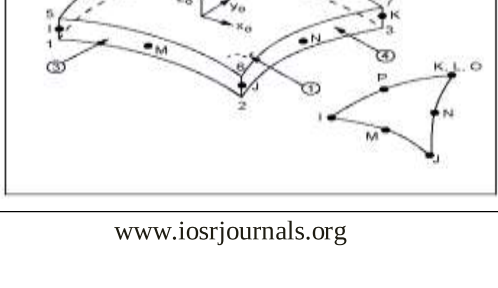
The finite element method is a numerical technique. In this method all the complexities of the problems, like varying shape, boundary conditions and loads are maintained as they are but the solutions obtained are approximate. Because of its diversity and flexibility as an analysis tool, it is receiving 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.

VII. Finite Element Analysis

With different fiber 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_1=0.1905 mm, t_2=0.1905 mm, t_3=0.635 mm, t_4=1.016 mm.

7.1 SHELL 181 Element

For analysis purpose SHELL 181 Element is selected. An 4-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.



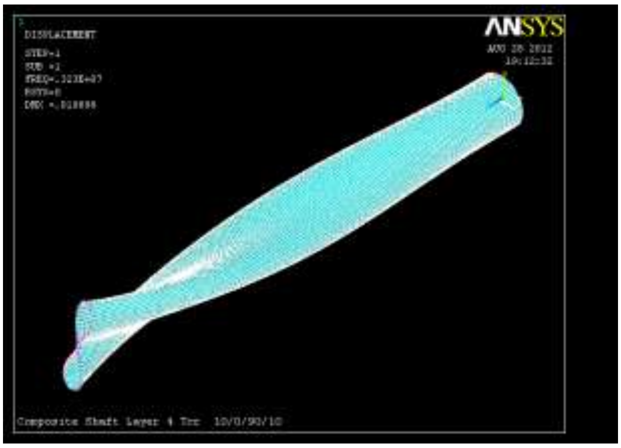


Fig. 1 ANSYS Result for Torsional Buckling Torque for Composite Shaft

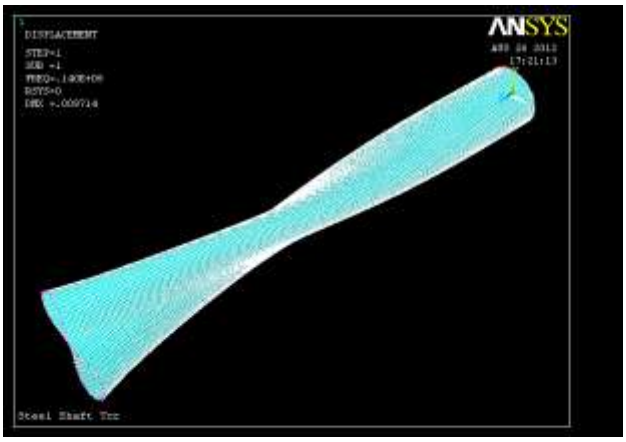


Fig. 2 ANSYS Result for Torsional Buckling Torque for Steel Shaft

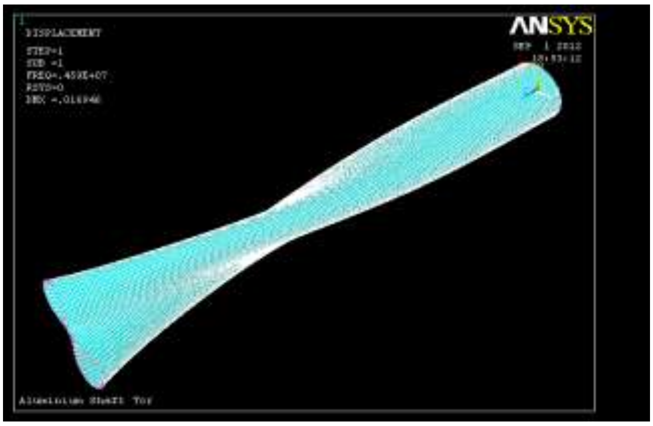


Fig. 3 ANSYS Result for Torsional Buckling Torque for Aluminum Shaft

VIII. Result And Discussion

1. It is found out that there is very minor error occurs in Analytical and in Ansys Method. To obtain optimum Torsional Buckling Torque we combine the fiber angle orientation and compare the Composite Shafts with Metal Shafts.

2. For Torsional Buckling Torque of Drive Shaft the maximum permissible limit is 2.5×10^6 N-mm. Hence the Stacking Sequence Glass Epoxy/Glass Epoxy/ Glass Epoxy/ Carbon Epoxy with Fiber Angle Orientation 100/00/900/100 give the Torsional Buckling Torque 3.23×10^6 N-mm which is beyond the permissible limit.

Table 2: Torsional Buckling Analysis with ANSYS 13.0 software

Stacking Sequence	**Fibre Angle Orientation**	**Torsional Buckling Torque (N-mm)**	**Weight of Shaft (Kg)**
C/G/G/G	$0^0/90^0/ 90^0/10^0$	2.39×10^6	1.226
C/G/G/G	$0^0/90^0/ 90^0/10^0$	1.76×10^6	1.226
C/G/G/G	$0^0/90^0/ 90^0/10^0$	2.01×10^6	0.9591
C/G/G/G	$10^0/0^0/ 90^0/10^0$	3.23×10^6	0.9563
Steel Shaft	--	14×10^6	5.087
Aluminum Shaft	--	4.59×10^6	1.759

Table 3: Torsional Buckling Analysis with Analytical Method.

Stacking Sequence	**Fibre Angle Orientation**	**Torsional Buckling Torque (N-mm)**	**Weight of Shaft (Kg)**
C/G/G/G	$0^0/90^0/ 90^0/10^0$	2.48×10^6	1.226
C/G/G/G	$0^0/90^0/ 90^0/10^0$	1.89×10^6	1.226
C/G/G/G	$0^0/90^0/ 90^0/10^0$	2.25×10^6	0.9591
C/G/G/G	$10^0/0^0/ 90^0/10^0$	3.39×10^6	0.9563
Steel Shaft	--	14.03×10^6	5.087
Aluminum Shaft	--	4.75×10^6	1.759

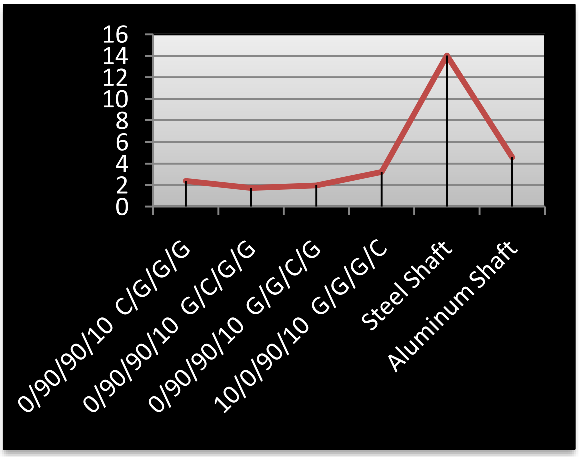


Chart 1: Comparison of Composite Shaft with Metal Shafts for Torsional Buckling Analysis

IX. Conclusion

It is found out that there is very minor error occurs in Analytical and in Ansys Method. To obtain optimum Torsional Buckling Torque we combine the fiber angle orientation and compare the Composite Shafts with Metal Shafts. For Torsional Buckling Torque of Drive Shaft the maximum permissible limit is 2.5×10^6 N-mm. Hence the Stacking Sequence Glass Epoxy/Glass Epoxy/ Glass Epoxy/ Carbon Epoxy with Fiber Angle Orientation $10^0/0^0/90^0/10^0$ give the Torsional Buckling Torque 3.23×10^6 N-mm which is beyond the permissible limit. The weight is almost reducing 80% than the steel shaft and 43% than Aluminum shaft in composite shaft.

X. 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.

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