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Effect of Fiber Angle Orientation on Stress, Deformation and Buckling Torque of the Composite Drive Shaft

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Strictly as per the compliance and regulations of :

Effect of Fiber Angle Orientation on Stress, Deformation and Buckling Torque of the Composite Drive Shaft

Miss. Priya Dongare [α] & Dr. Suhas Deshmukh [σ]

Abstract - The objective of this paper is to analyze a composite drive shaft for power transmission applications. Composite materials have many applications ranging from automotive to most of the industrial application and numerous advantages due to its high specific strength (strength / density) and high specific modulus (modulus / density), lighter weight and longer life. Analysis of composite drive shaft is carried out to understand the effect of fiber orientation on load carrying capacity (axial loadings, torque and buckling torque) of drive shaft. MODAL analysis is carried out to observe the effect of fiber angle on modal frequencies. Static and Modal analysis is carried out using FEM, results of FEM analysis is further used to develop a regression equation. These developed regression equation can be used for tuning of properties of shaft and understand the behavior with fiber orientation.

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I. Introduction

A composite is commonly defined as a combination of two or more distinct materials, each of which retains its own distinctive properties, to create a new material with properties that cannot be achieved by any of the components acting alone. Generally, a composite material is composed of reinforcement (fibres, particles, flakes, and/or fillers) embedded in a matrix (polymers, metals, or ceramics). The matrix holds the reinforcement to form the desired shape while the reinforcement improves the overall mechanical properties of the matrix.

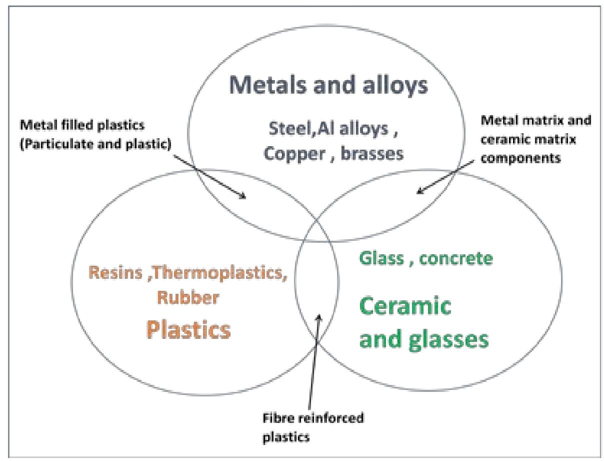

Figure 1 : Relationships between classes of engineering materials, showing evolution of composites

Composite materials have increased its utilization and its structural applications grown considerably in recent years. The major advantage is its higher strength to weight ratio. One of the major applications is to composite drive shafts, where strength to weight ratio is very important. To understand the effect of its fibre orientation various numerical techniques are evolved. Finite element method is one of the best methods adopted for analysing these composite structures (drive shaft). These numerical techniques evaluate, analyse the performance of drive shaft numerically. In present work FEM package ANSYS is used for analysing the composite drive shaft. Further results of FEM analysis is used for regression analysis so that we can easily design the drive shaft.

Section 2 explains detailed design specifi cations of composite drive shaft and its requirements along with suitable application. Section 3 of this paper explains static analysis of composite drive shaft. Here stacking sequence is varied to observe the behaviour of stress. Section 4 explains modal analysis, section 5 explains buckling analysis, section 6 explains about regression models established using FEA results and finally concluding remarks of work carried out.

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II. Composite Drive Shaft

Technologically the most important composite are those in which the dispersed phase is in the form of fibre. The design of fibre-reinforced composite is based on the high strength and stiffness on a weight basis, the principal basis. The principle fibres in commercial use are various types of glass, carbon, graphite and Kevlar. Here E-glass epoxy and carbon epoxy fibres are selected as potential material for the design of shaft.

The fibre orientation changes from layer to layer in a regular manner through the thickness of the laminate, e.g. a 0/90/0 stacking sequence results in a cross-ply composite. Hybrids are composites with mixed fibres and are becoming common place. The fibres may be mixed within a ply or layer by layer, and these composites are designed to benefit from the different properties of the fibres employed. For example, a mixture of glass and carbon fibres incorporated into a polymer matrix gives a relatively inexpensive composite, owing to the low cost of glass fibres, but with mechanical properties enhanced by the excellent stiffness of carbon [4].

In the present work the shaft is considered as simply supported beam with torque applied at the center.

Geometric and Material properties of composite drive shaft under analysis is listed in table below:

Table 1: Geometric Properties

Length	1 m
Inner Diameter	48.2×10^{-3}m
Outer Diameter	50×10^{-3}m
Thickness	0.2×10^{-3}m
Boundary Condition	Simply Supported

Table 2 : Orthotropic Material Properties of Composite Material

	E-Glass Epoxy	Carbon Epoxy
E_x	40.3×10^9 N/m^2	126.9×10^9 N/m^2
E_y	6.21×10^9 N/m^2	11×10^9 N/m^2
E_z	40.3×10^9 N/m^2	126.9×10^9 N/m^2
μ_{xy}	0.2	0.2
μ_{xz}	0.2	0.2
μ_{yz}	0.2	0.2
G_{xy}	3.07×10^9 N/m^2	6.6×10^9 N/m^2
G_{xz}	2.39×10^9 N/m^2	4.23×10^9 N/m^2
G_{yz}	1.55×10^9 N/m^2	4.88×10^9 N/m^2
Density	1910 Kg/m^3	1610 Kg/m^3

Table 1 shows the dimension of the shaft used for the static analysis. Table 2 is the geometric properties of the shaft. these properties are same at all points along the length of the shaft.

Next section explains the static structural analysis of shaft using FEM solver.

III. Static Structural Analysis (FEA)

Static analysis deals with the conditions of equilibrium of the bodies acted upon by forces. A static analysis can be either linear or non-linear. All types of non-linearity are allowed such as large deformations, plasticity, creep, stress stiffening, contact elements etc. A static analysis calculates the effects of steady loading conditions on a structure, while ignoring inertia and damping effects, such as those carried by time varying loads. A static analysis can however include steady inertia loads such as gravity, spinning and time varying loads. In static analysis loading and response conditions are assumed, that is the loads and the structure responses are assumed to vary slowly with respect to time. The kinds of loading that can be applied in static analysis includes, Externally applied forces, moments and pressures, Steady state inertial forces such as gravity and spinning, imposed non-zero displacements [4].

A static analysis result of structural displacements, stresses and strains and forces in structures for components caused by loads will give a clear idea about whether the structure or components will withstand for the applied maximum forces. If the stress values obtained in this analysis crosses the allowable values it will result in the failure of the structure in the static condition itself. To avoid such a failure, this analysis is necessary.

The composite shaft is considered as the simply supported beam with torque applied at the centre of the shaft as shown in the Figure 2.

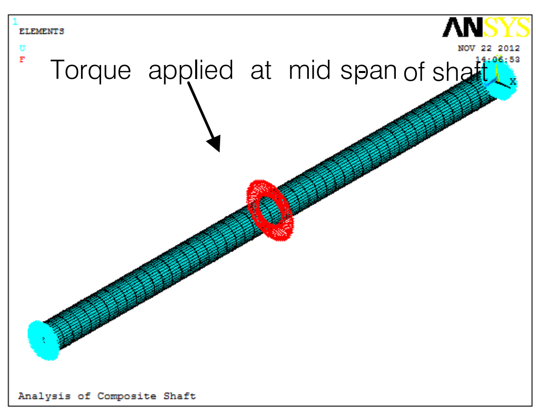

Figure 2 : Composite Shaft FEM Model with Boundary Conditions

The static analysis is done with help of FEM solver like ANSYS. Finite element models of the drive shaft were generated and analyzed. 3D model of hollow composite shaft is generated using APDL language available in ANSYS Multiphysics. Hollow shaft is meshed using layered element SHELL281. Thickness, material properties and fibre orientations of each layer is provided for element viacommandKEYOPT,1,8,1 SECTYPE,1,SHELL, secdata,T1,1,-90, secdata,T2,1,0, secdata,T3,2,0, secdata,T4,1,0. Four numbers of layers are taken into account for analysis. Appropriate simply supported boundary conditions are applied at both ends and torque is applied at mid-span of drive shaft. Application of torque is critical issue in FEA analysis, this is simplified by providing tangential force at exterior nodes of shaft and local co-ordinate system is rotated to provide a tangential directional force. This is possible by command csys, 1nrotat, all in ANSYS APDL. Static analysis is carried out to estimate maximum deformation and stress occurred in shaft.

The variation of the maximum stress along the length of the shaft is shown in figure3.static analysis is done for four layers of composite drive shaft. The comparison of stress variation for four layers is done in figure 4. It shows that the maximum stress is developed at fiber3.

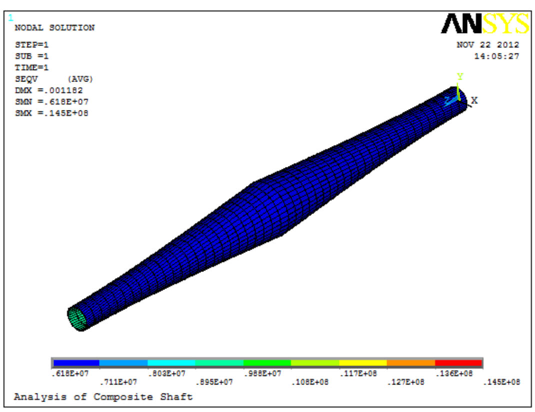

Figure 3 : Change in stress along the length of composite shaft

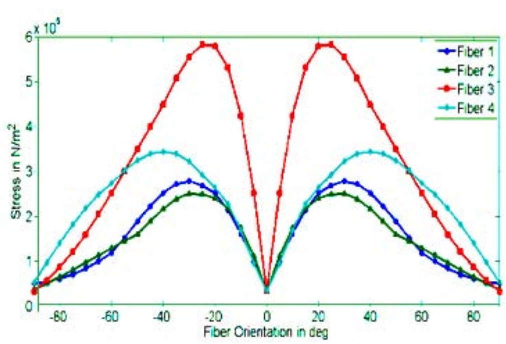

Figure 4 : Variation of the stress in layers composite shaft

Similar to stress analysis, the variation of deformation is also calculated at four layers of the shaft. (Shown in figure 5).

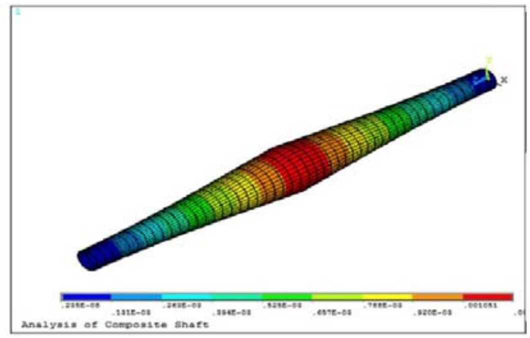

Figure 5 : Change in the deformation along the length of the composite shaft

Same as stress analysis the comparison for deformation variation along four layers of shaft is shown in figure 6.The deformation at third layer is low and shows maximum variation change in the fibre angle orientation.

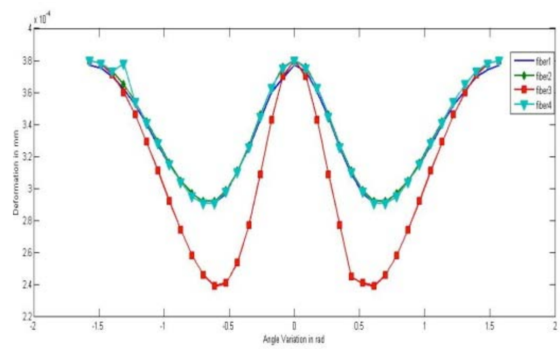

Figure 6 : Comparison of deformation in all layers of composite shaft

Below table summarize the statistical data for the static analysis.

Table 4 : Maximum and minimum stress values for four layers of shaft

	Angle (deg)	Maximum (N/mm^2)	Angle (deg)	Minimum (N/mm^2)
Layer 1	±30	278455	0	33058.5
Layer 2	±30	249726	0	33058.5
Layer 3	±25	582029	0	33058.5
Layer 4	±40	344292	0	33058.5

Table 5 : Maximum and minimum values for deformation for four layers of shaft

	Angle (deg)	Maximum (mm)	Angle (deg)	Minimum (mm)
Layer 1	±90/0	0.376	±40	0.291
Layer 2	±90/0	0.380	±40	0.292
Layer 3	±90/0	0.380	±35	0.239
Layer 4	±90/0	0.380	±35	0.291

Next section explains modal analysis for the shaft.

IV. Modal Analysis (FEA)

Modal analysis is used to determine the vibration characteristics such as natural frequencies and mode shapes of a structure or a machine component while it is being designed. It can be also a starting point for another more detailed analysis such as transient dynamic analysis, harmonic response analysis or spectrum analysis.

The main parameters considered in free vibration of shaft are natural frequency and vibration. The natural frequency and mode shape are important parameters in design of structure for dynamic loading condition.

In the research, the natural frequencies for each layer are obtained using ANSYS 13 by varying the orientation of fibre in layer 2 by 5^0 and keeping the orientation of other layers constant i.e.0^0.The variations for layers are as shown in figure 7

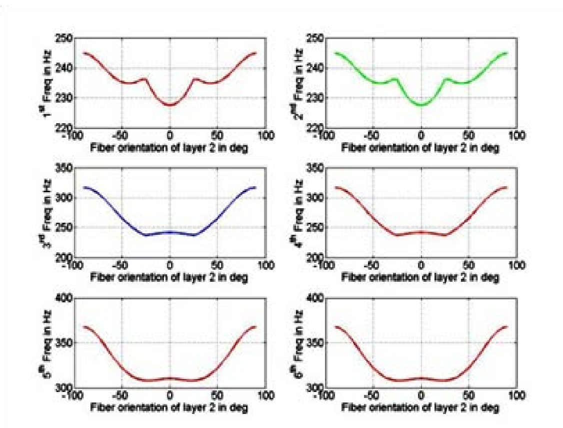

Figure 7 : Effect of the change in fibre orientation angle on natural frequency in second layer

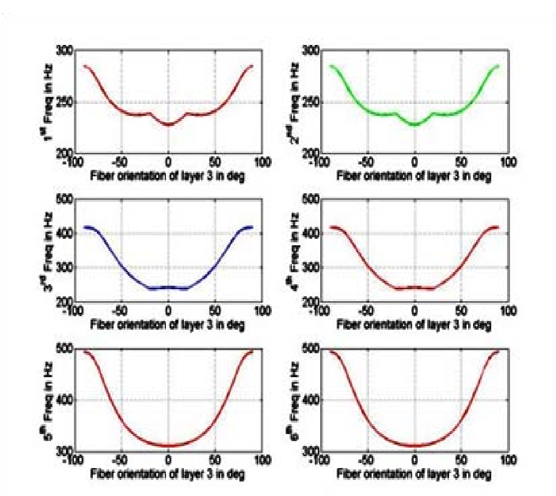

Figure 8 : Effect of the change in fibre orientation angle on natural frequency in third laer

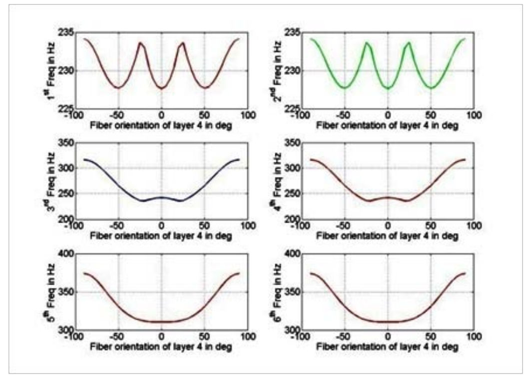

Figure 9 : Effect of the change in fibre orientation angle on natural frequency in forth layer

Figure 7, 8and 9 shows that the variation for the natural frequencies from fibre orientation of -90° to +90°.It gives the behaviour of mode shapes with respect to angle variation for six natural frequencies.

Next section explains about the buckling analysis for composite drive shaft.

V. Buckling Analysis (FEA)

Membranous filter with 37 mm in diameter and 0.8 micron powders.

Figure 10 shows the comparison of the buckling torque of four layers. It shows the variation in the second layer of the shaft.

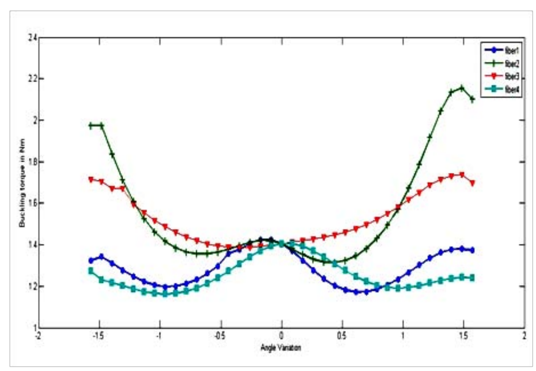

Figure 10 : Comparison for buckling torque of all layers of composite shaft

Table 6 : Result of buckling of each layer for composite shaft

	Angle (deg)	Maximum (Nm)	Angle (deg)	Minimum (Nm)
Layer 1	-10	1.4249	35	1.1719
Layer 2	85	2.1545	25	1.3134
Layer 3	85	1.7370	-20	1.3873
Layer 4	5	1.4046	-55	1.1623

Table.6 is the values obtained at the maximum and minimum values of the buckling torque

VI. Regression Modelling

Regression analysis is a statistical tool for the investigation of relationships between variables In general, there are two types of regression analyses:

Linear regression analysis-A linear regression analysis assumes that the regression model is a linear function with respect to the parameters of the regression model, i.e., the regression parameters are the coefficients of the regression terms.

Nonlinear regression analysis-For a nonlinear regression analysis, the regression model is a nonlinear function with respect to the parameters of the regression model. [7].

Multiple regressions are a statistical technique that allows us to predict someone's score on one variable on the basis of their scores on several other variables. E.g. the composite shaft has four layers.

The regression analysis is done to get the variation of the orientation of the fibre with respect to the stress and deformation. It will have one equation for each layer which will give the stress and deformation in terms of fibre angle orientation.

The regression equation for first layer is as below:

Deformation for θ1,

$$\Delta_{\theta 1} = 0.9911 + 0.0002 \times \sin\theta_1 + 1.0281 \times \cos\theta_1 + 0.0856 \times \sin(\theta_1^2) - 0.0001 \times \sin(\theta_1^3) + 0.3953 \times (\theta_1^2) - 0.0001 \times (\theta_1)$$

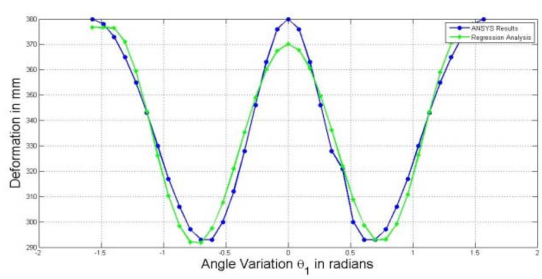

Figure 11 : Comparison of ANSYS result and regression result of first layer of composite shaft

Same as above the second layer fibre angle is varied keeping layer 1, 3, 4 constant (0^0) .the equation of the second layer is as below-

Deformation for θ2,

$$\Delta_{\theta 2} = -1.0032 + 1.0402 \times \cos\theta_2 + 1.0281 \times \cos\theta_1 + 0.0866 \times \sin(\theta_2^2) + 0.3999 \times (\theta_2^2)$$

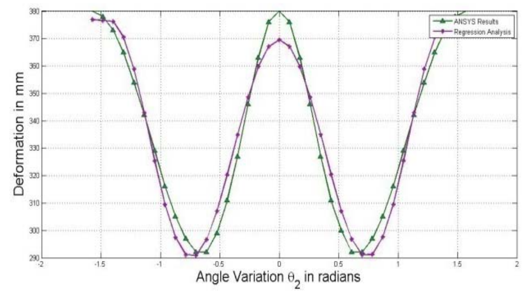

Figure 12: Comparison of ANSYS result for deformation and regression result of second layer of composite shaft

Similarly the equations are obtained for the third and forth layer as below.

Deformation for θ3

$$\Delta_{\theta 3} = -1.5493 + 1.5842 \times \cos\theta_3 + 0.1346 \times \sin(\theta_3^2) + 0.6089 \times (\theta_3^2)$$

-

Deformation for θ4,

$$\Delta_{\theta 4} = 1.5842 \times \sin\theta_4 + 0.1346 \times \cos\theta_4 + 0.6089 \times \sin\theta_4^3$$

II. Static and regression analysis for the stress in the composite shaft-

Same as deformation we can plot the results of variation in the stress values of the each layer.

Stress for θ1,

$$\sigma_{\theta_1} = 2.1927 - 2.1783 \times \cos\theta_1 - 0.1927 \times \sin\theta_1^2 - 0.8369 \times \theta_1^2$$

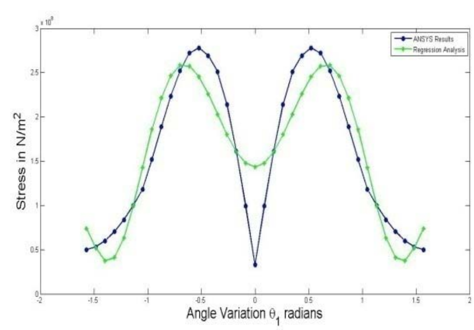

Figure 13 : The effect of fibre orientation angle on stress of First layer of composite shaft

Stress for θ2,

$$\sigma_{\theta_2} = 1.4391 - 1.4235 \times \cos\theta_2 - 0.1244 \times \sin\theta_2^2 - 0.5496 \times \theta_2^2$$

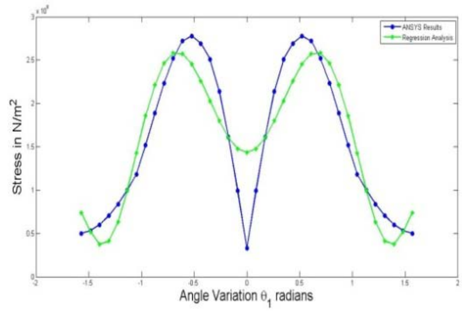

Figure 11 : The effect of fibre orientation angle on deformation of second layer of composite shaft

Stress for θ3,

$\sigma_{\theta_3} = 3.1961 - 3.1590 \times \cos\theta_3 - 0.2810 \times \sin(\theta_3^2) - 1.2214 \times (\theta_3^2)$Stressfor θ4,

$$\sigma_{\theta_4} = 3.1961 - 3.1590 \times \cos\theta_4 - 0.2810 \times \sin(\theta_4^2) - 1.2214 \times (\theta_4^2)$$

Regression analysis for buckling-

Below figures show the comparison of ANSYS result and regression result for respective layers.

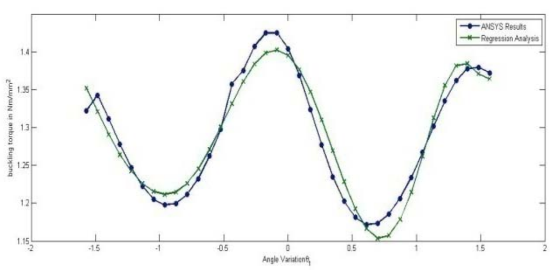

Figure 12 : The effect of fibre orientation angle on buckling torque of first layer of composite shaft

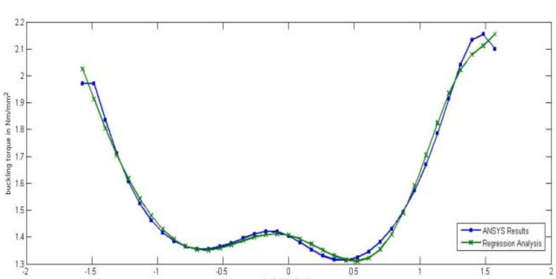

Figure 13 : The effect of fibre orientation angle on buckling torque of second layer of compositeshaft

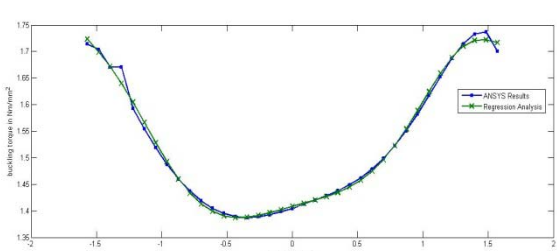

Figure 14 : The effect of fibre orientation angle

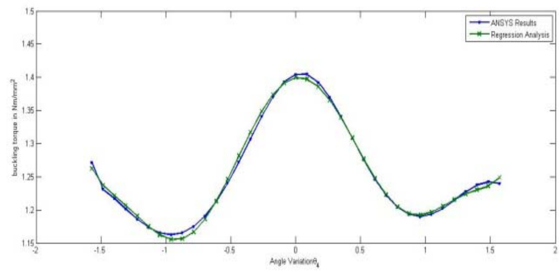

Figure 15 : The effect of fibre orientation angle on buckling torque of forth layer of composite shaft

Regression equation of each layer for buckling torque is as follows-

Layer1-

$$\tau_{\theta_1} = -2.0039 - 0.0153 \times \cos\theta_1 + 2.1434 \times \sin\theta_1^2 + 0.1717 \times \sin\theta_1^3 + 0.0098 \times \theta_1^2 + 0.0058 \times \theta_1^3$$

Layer2-

$$\tau_{\theta_2} = -2.2311 - 0.0108 \times \sin\ \theta_2 + 2.3717 \times \cos\theta_2 + 0.1961 \times \sin\theta_2^2 + 0.0140 \times \sin\theta_2^3 + 0.9393 \times \theta_2^2 + 0.0068 \times \theta_2^3$$

Layer3-

$$\tau_{\theta_3} = -4.8184 - 0.0695 \times \sin\theta_3 + 6.2265 \times \cos\theta_3 + 0.6136 \times \sin\theta_3^2 + 0.0085 \times \sin\theta_3^3 + 2.4946 \times \theta_3^2 - 0.0173 \times \theta_3^3$$

Layer4-

$$\tau_{\theta_4} = -1.3941 + 0.0034 \times \sin\theta_4 + 1.5340 \times \cos\theta_4 + 0.1137 \times \sin\theta_4^2 + 0.5871 \times \theta_4^2 - 0.0011 \times \theta_4^3$$

VII. Conclusion

If fibre angle orientation of any one layer is changed and it is kept constant in other layers-

Shear stress in that layer increases up to 45 degree orientation, then decreases till 90 degree and then again starts increasing; it shows sine nature of graph.

While shear stress in other layers decreases till 45 degree, then increases till 90 degree and again starts decreasing; it shows cosine nature of graph.

Deflection in each layer remains same for any angle of orientation; it decreases till 45 degree then increases for 90 degree and 0 degree.

2nd, 3rd, 4th and 5th natural frequencies increases with angle of orientation and then remains constant.

While 6th natural frequencies decreases with angle of orientation and then remains constant.

By doing regression analysis we have obtained relations between stress and fibre angle orientation, deflection and fibre angle orientation.

From fig.18, the buckling torque of second layer is maximum.

From fig.18, the buckling torque of second layer is maximum.

From buckling analysis it can be concluded that the fibre orientation angle has effect on the buckling torque.

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