MECHANICAL BEHAVIOR OF COMPOSITE AND FGM TRANSMISSION-BACK HUB AUTOMOTIVE DRIVE SHAFT USING FINITE ELEMENT METHOD

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ABSTRACT: *Recently, to improve vehicle energy conservation, composite materials are used but, these materials may be replaced one day with functionally graded materials (FGMs). FGM is also a composite of two components, characterized by a compositional gradient from one component to the other. This study modeled total deformation and natural frequency, under the subjected load of a car hollow drive shaft using steel, four layers' composite, and FGM drive shaft. The analysis is carried out using ANSYS and results were compared. The deformation values are shown in the results. It concludes that FGM material is comparatively better than the other two. It is noticed that; fiber angle orientation of the composite drive shaft has a great influence on both deformation and first frequency also, offers lower deformation than steel while FGM offers lower deformation than steel and composite. Also, in buckling and harmonic analysis, FGM material deformation is minimum.*

Keywords: FGM; Composite material; Steel; Driveshaft, Finite element.

1. INTRODUCTION

Some vehicle parts applications such as car body, driveshafts, fuel tank, brake pedal, and outside skin are manufactured from composite materials. When the propeller or Cardan shaft manufactured from steel, will be heavy, produces noise and vibrations [1], also, will be two pieces if the length is more than 1500 mm [2]. The composite materials have many advantages over the steel when, used in vehicle parts, due to their high specific elastic modulus which less noise, weight, and vibration [3] also, the first frequency of the Cardan shaft can be twice due to higher stiffness and manufactured one-piece [4]. Ch. Nagaraju and P. Satheesh Reddy [5] compared to steel and composite Cardan shaft based on strength/weight and tensional stiffness characteristics using FEM commercial software ANSYS. It is concluded that the weight reduction of the Cardan shaft can reach 97% than steel. Kaviprakash, G. *et al* [6] examined different vehicle composite Cardan shafts using ANSYS. Their conclusion was, using composite materials makes the drive shaft less stressed which reduces the shaft weight. Miss. Priya Dongare and Suhas Deshmukh [7] examined the effect of a power transmission composite drive shaft fiber orientation on modal frequencies and shaft load-carrying capacity such as axial load. Both modal analysis and static are carried out using FEM then, the results are used to develop a regression equation used to tune shaft properties and understand its behavior with fiber orientation. Yefa *Hu et al*. [8] calculated carbon-fiber-reinforced plastic driveshaft torsional stiffness. They used a technique based on the theory of classical lamination and mechanical analysis besides a torsion test platform. It is stated that; location of ±45° layers of the composite tube close to the inner surface is smaller than ones close to the outer also, the torsional stiffness stacking effect is lower in thin-walled than in thick-walled. Moreover, mechanical analysis can complement the theory of lamination which cannot reflect the stacking sequence effect. Functionally graded material is a mixture of two or more constituents whose, particles have nearly similar form and dimension, which can improve the efficiency of the systems. FGM increases industrial machines' performance due to their qualities such as lightness as a result of high strength characteristics and good corrosion resistance. It is associated with composite particles which, vary in one or more directions [9]. The use of FGMs is gradually increasing in different fields like automobiles due to their numerous advantages over conventional composite materials [10]. Justin Murin *et al.* [11] examined an asymmetric cross-section designed of an FGM with mass inertia terms and linearized stiffness matrix. They displayed the effectiveness and accuracy of FGM and stated that; the finite beam element can be used for static and buckling analysis of spatial beam and single beam structures. Fiorenzo A. Fazzolar [12] studied free vibration and elastic stability of three-dimensional functionally graded sandwich beams. Significant parameters effect such as boundary conditions and volume fraction on the circular frequency parameters and critical buckling loads were discussed. Mahmoud, M. A. [13] offered a general solution for the non-uniform, axially functionally graded cantilevers free transverse vibration, loaded at the tips with point masses. KyunghoYoon l. *et. al* [14] suggested a novelty method for analysis of functionally graded 3D beams employed continuum mechanics-based beam elements with the warping displacement to model complex modes of deformation. They stated that the warping function can be calculated for any beam with arbitrary cross-sections and material grading patterns. Ahmed Hassan Ahmed Hassan and İbrahim KELEŞ [15] used dummy thermal loads and ANSYS APDL to obtain FGM distributed properties. They stated that the main advantage of such a method is its simplicity and it does not require deep knowledge of mathematical models of FGM and delivers high accuracy.

2. Paper Objective

This work relates to the automotive shaft which, associates transmission with the back hub of the rear-wheel-drive and front engine installation, Figure 1. This study modeled total deformation and natural frequency, under the subjected load of a car hollow drive shaft using steel, four layers composite, and FGM drive shaft.

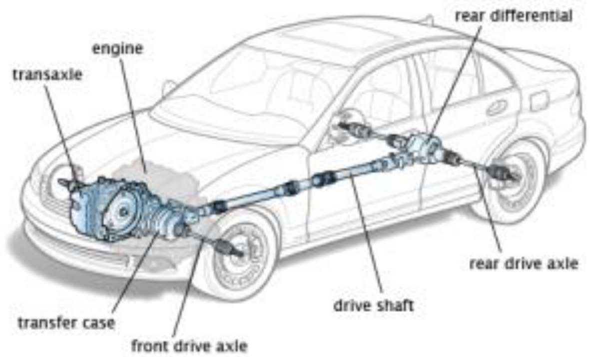


Figure 1 Car driveshaft

The finite element method (FEM) is a numerical method for solving integral equations and differential. This research includes the study of the driveshaft, which is a rotary shaft and transmit drive to car wheels. The Driveshaft needs to work through continually angles change in between the transmission and axle. A driveshaft is an association between the transmission and the back hub of the vehicle. The power generated by the vehicle engine is transferred to the transmission-like clutch assembly. The transmission is joined to the drive shaft by a universal joint and a yoke. The drive shaft transmits the power to the rear end. Then Power transferred by a pinion to the back wheels

3. Specifications of the Drive Shaft, Materials, and Methodology

The drive shaft of the transmission system is to be designed optimally for following specified design requirements.

Table 1: Design specifications of the hollow circular used drive shaft:

Geometric Properties		**Unit**
Driveshaft Length	1000	mm
Inner Diameter	48.2	mm
Outer Diameter	50	mm

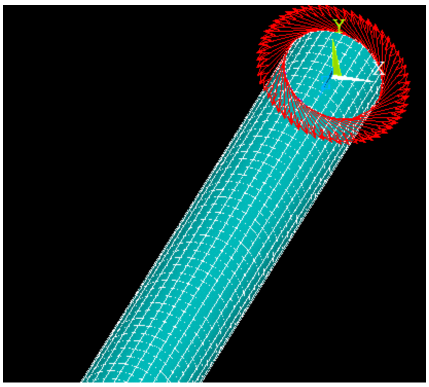


Figure 2 3D APDL model screen after applying the boundary condition

3. 1 Specifications of Used Drive Shaft

Hollow circular shafts are used because they are stronger in specific weight than solid circulars. It is shown from Table 1, the design specifications of the hollow circular used drive shaft either steel or composite or FGM.

3. 2 Materials:

The specification of three materials used to fabricate the drive shaft is shown in the following three tables. **Table** 2 shows the properties of the steel material used for the steel driveshaft.

Table 2: Properties of steel

Steel material	Properties
E (Young's Modulus)	$207\ x\ 10^9\ N/m^2$
$\boldsymbol{v}$ (Poisson's Ratio)	0.3
Density	$7600\ Kg/m^3$

Carbon fibers are used in the composite driveshaft due to their high specific strength and modulus, low thermal expansion, and high fatigue strength. Epoxy is used due to its high strength, good wetting of fibers, lower curing shrinkage, and better dimensional stability. **Table** 3 shows the properties of the Carbon/Epoxy materials used for composite drive shafts.

Table 3: Properties of Carbon/Epoxy

Carbon Epoxy	**Properties**
$\mathbf{E_x}$	$126.9\ x\ 10^9\ N/m^2$
$\mathbf{E_y}$	$11\ x\ 10^9\ N/m^2$
$\mathbf{E_z}$	$126.9\ x\ 10^9\ N/m^2$
$\boldsymbol{v}_{\mathbf{xy}}$	0.2
$\boldsymbol{v}_{\mathbf{xz}}$	0.2
$\boldsymbol{v}_{\mathbf{yz}}$	0.2
$\mathbf{G_{xy}}$	$6.6\ x\ 10^9\ N/m^2$
$\mathbf{G_{xz}}$	$4.23\ x\ 10^9\ N/m^2$
$\mathbf{G_{yz}}$	$4.88\ x\ 10^9\ N/m^2$
Density	$1600\ Kg/m^3$

Table 4: Properties of 4 layers of FGM metals and ceramics.

Layer	**E**	$\boldsymbol{v}$	**Density**
1	$213\ x\ 10^9\ N/m^2$	0.3	7247.5
2	$172.9\ x\ 10^9\ N/m^2$	0.3	6262.5
3	$101.6\ x\ 10^9\ N/m^2$	0.3	5277.5
4	$40.04\ x\ 10^9\ N/m^2$	0.3	4292.5

The most common FGMs are metal-ceramic composites where these materials are made from a mixture of ceramic and metal, the ceramic materials have good thermal resistance, anti-oxidant behavior. Metallic materials have excellent strength and superior fracture toughness.
Multiples different layers with different proprieties for each layer as shown in **Table** 4.

3. 3 Methodology

The main steps that have been followed are:

1. the first step is to go for “Preferences” and select “Structural”. After selecting the structural option from the tab, click ok to close it.
2. After closing the Preferences option, go to the “Preprocessor” option and click on “Element Type” to open the “ADD/EDIT/Delete” button. A new tab will open that would be used to define the type of element you want to use i.e. A beam, a link or plane. Click on the “Add” button.
3. After clicking on “Add” a new window will be opened, from which an element type would be selected. After clicking the “Beam” with subtype as “SOLIDSHELL”. Click “OK” and close the window.
4. When the element is defined, it needs a cross-section area and material properties to be fully defined. In the 3rd step, a cross-section would be defined. For this, the option “Sections” → “Shell” → “lay-up” would be clicked.
5. The last step in defining the prerequisites of modeling is to define the material model. For this step It is required to would go to “Material Props”→ “Material Models”→ “Structural “ → “Linear Elastic”.
6. The next step in the analysis is to model the point on the plotter and then connect the points to form a beam. For this step, “Modelling”→ “Create”→”Key points”→”Inactive CS”.
7. The next step in the analysis is to mesh the beam that has been designed and plotted. For this step, the options that would be selected are: “Preprocessor”→ “Mesh”→" Mesh tools".

After meshing analysis type would be selected as Modal and in properties, 3 would be entered in a number of frequencies. The solution would be solved using the Current LS and results would be viewed.

FGM drive shaft is designed by using ANSYS APDL by creating the following:

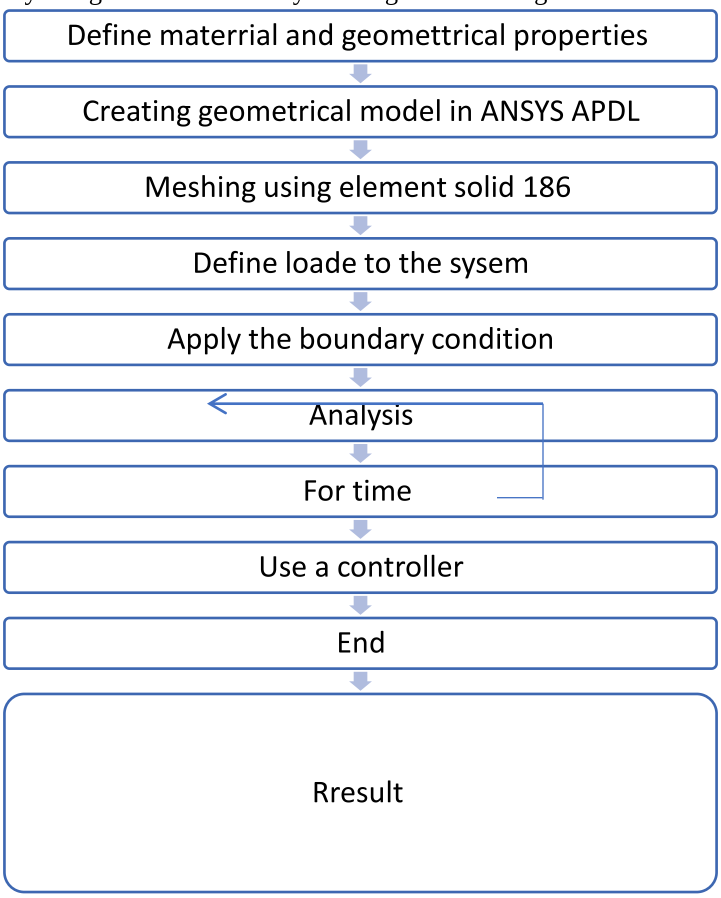


Figure 3 FGM Flowchart by ANSYS APDL

In macro loops in ANSYS programs, each loop will be calculated material properties values. The core philosophy is to use the cycle time variable as an index to the set time which will be a loop called macro. The loop going to closed when time end as following in the flowchart, **Figure** 2.

4. RESULT AND DISCUSSION

For the steel material used for steel driveshafts, the results of deformation and mode shape are shown in **Figure** 4.

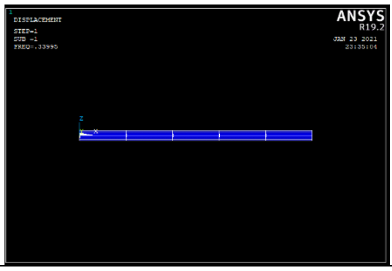
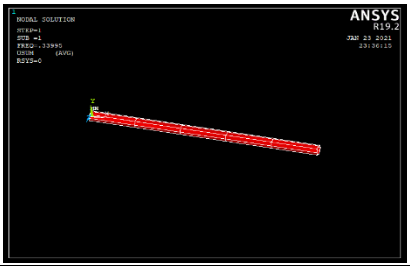
First frequency	Deformation (mm)
	
0.3305	0.6e-3

Figure 4 Steel material APDL results

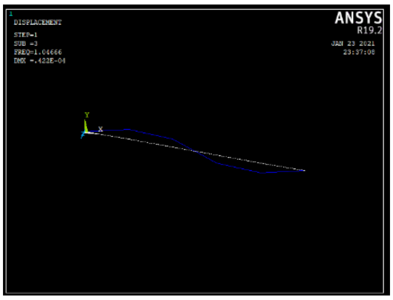
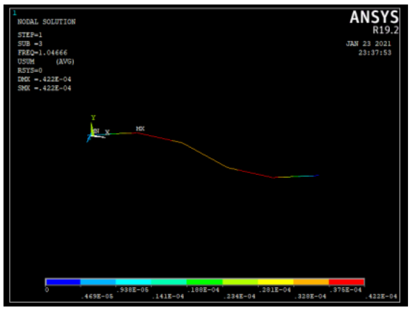
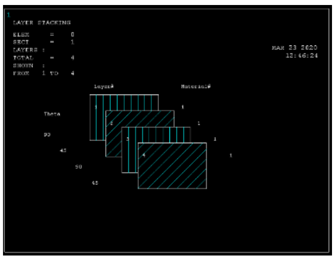
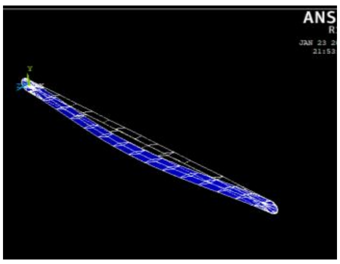
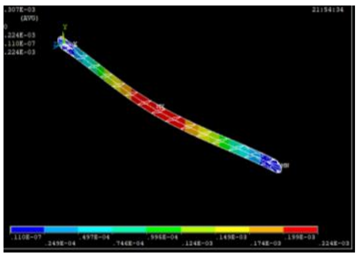
First frequency	Deformation (mm)
	
1.04666	0.375E-4

Figure 5 Steel material APDL results at 2nd frequency

After satisfying all requirements for Carbon/Epoxy composite driveshaft based on four layers of fiber orientation; $(90^{\circ}, 45^{\circ}, 90, 45^{\circ})$, $(70^{\circ}, 45^{\circ}, 70^{\circ}, 45^{\circ})$, $(45^{\circ}, 45^{\circ}, 45^{\circ}, 45^{\circ})$ and $(30^{\circ}, 45^{\circ}, 30^{\circ}, 45^{\circ})$. The fiber orientations angels $(45^{\circ}, 45^{\circ}, 45^{\circ}, 45^{\circ})$ are compared based on static analysis with others._ By changing the carbon fiber angle orientations, observations could be made on the natural frequency and dynamic characteristics of composite shafts

Orientations angel	First frequency	Deformation (mm)
		
$(90^{\circ}, 45^{\circ}, 90^{\circ}, 45^{\circ})$	0.001912	0.200e-03

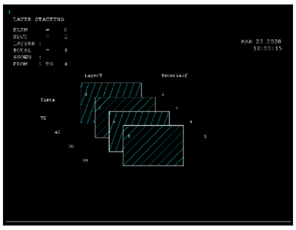
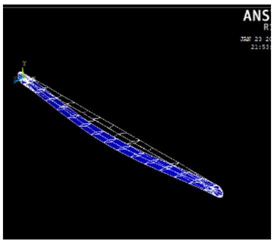
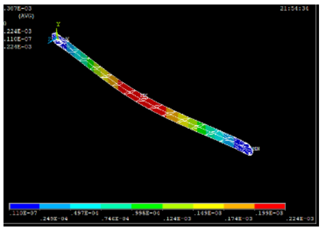
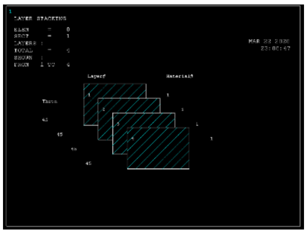
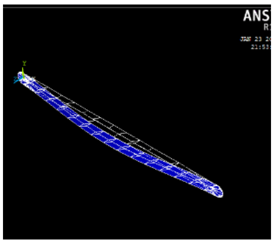
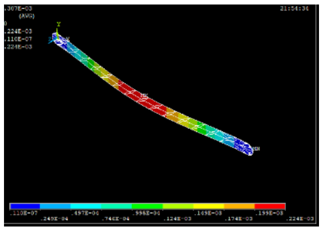
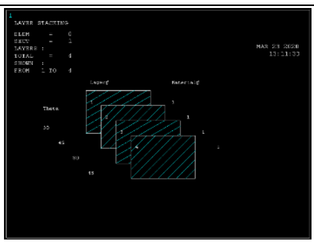
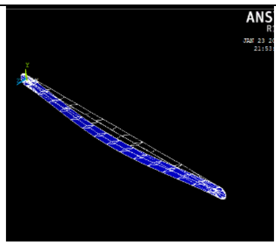
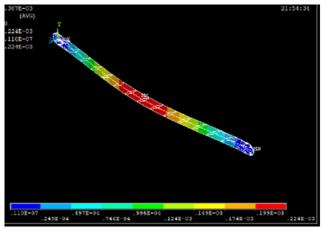
		
$(70^{\circ}, 45^{\circ}, 70^{\circ}, 45^{\circ})$	0.001903	0.199e-3
		
$(45^{\circ}, 45^{\circ}, 45^{\circ}, 45^{\circ})$	0.001864	0.197e-3
		
$(30^{\circ}, 45^{\circ}, 30^{\circ}, 45^{\circ})$	0.001823	0.199e-3

Figure 6 Composite material APDL result

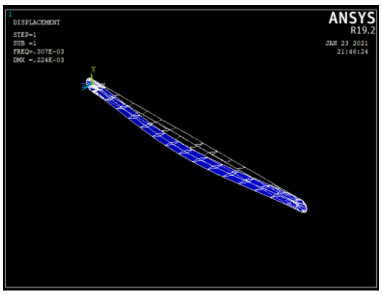
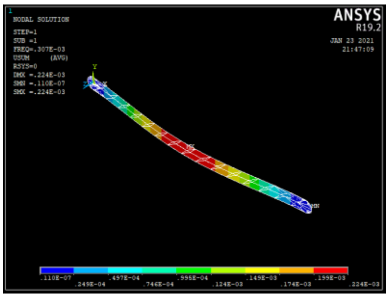
First frequency	Deformation (mm)
	
0.307	0.199E-3

Figure 7 FG material APDL result

For the FG material used for the driveshaft, the results of deformation and mode shape using FGM Ansys code is shown in **Figure** 7. The fiber angle orientation sequence to 45-45-45-45 composite driveshaft is compared with that of steel and FGM.

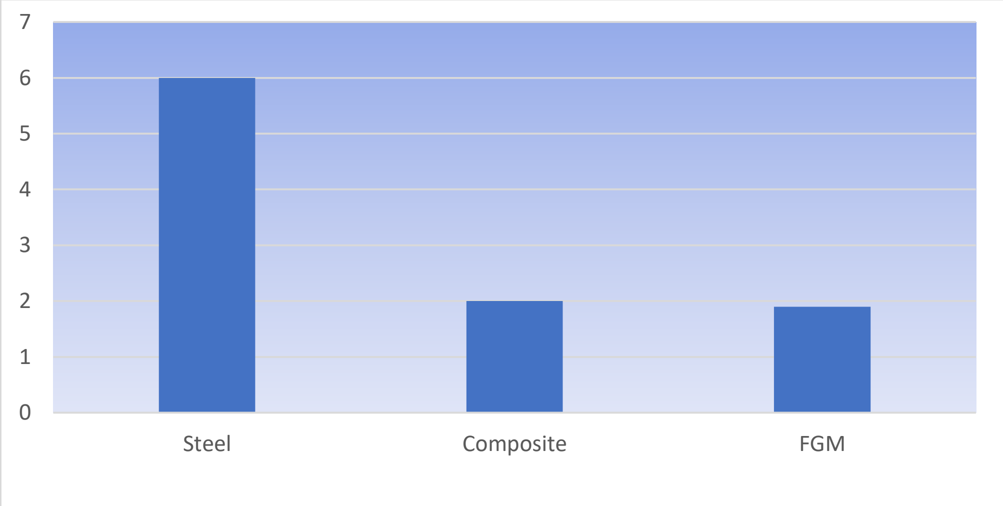


Figure 8 Deformation results of used materials

The study materials were steel, a composite material with different orientations fiber angel, and functionally graded material. it is clearly shown that; the deformation of FGM material is much better than others. FGM result shows deformation as $0.187\text{x}10^{-4}$ mm and the composite material with 45 orientations fiber angel shows deformation $0.527x10^{-4}$. The buckling and harmonic analysis on structural steel, composite material, and FGM is shown in **Figures** 9, 10**, and** 11 respectively.

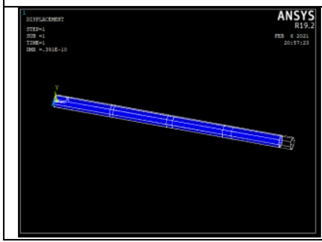
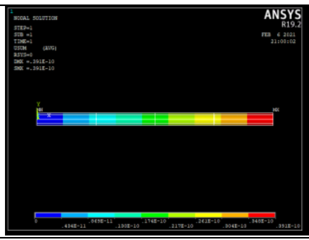
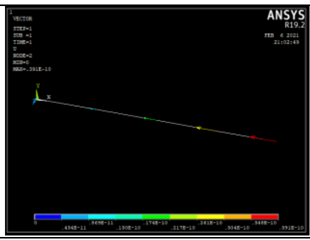
Buckling Analysis		Harmonic Analysis
Deformation	Nodal Solution	Deformation
		

Figure 9 Steel Material Buckling and Harmonic Analysis

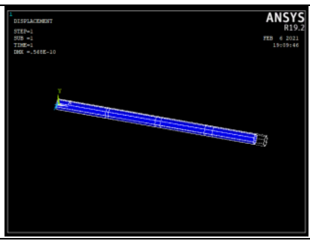
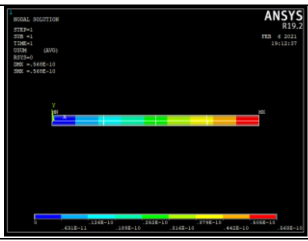
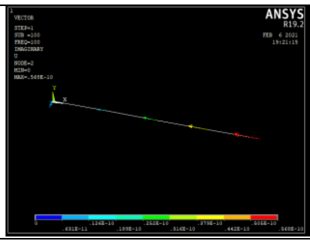
Buckling Analysis		Harmonic Analysis
Deformation	Nodal Solution	Deformation
		

Figure 10 Composite Material Buckling and Harmonic Analysis

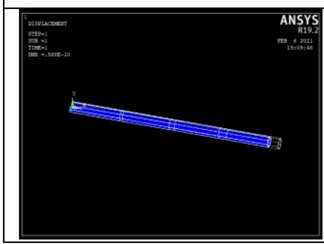
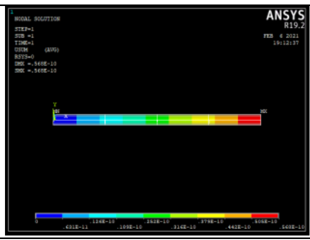
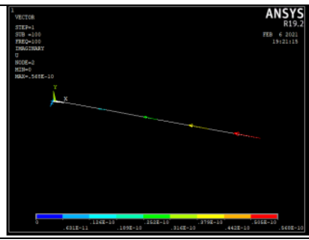
Buckling Analysis		Harmonic Analysis
Deformation	Nodal Solution	Deformation
		

Figure 11 FGM Buckling and Harmonic Analysis

In buckling analysis, the unit force was applied in the axial direction to see the buckling effect in steel, composite, and FGM. The static analysis was done for buckling effects while harmonic analysis was done in 100 steps. The value of deformation comes out to be 0.39e-10, 0.58e-10 and 0.568e-10 for steel, composite material and FGM respectively. It shows that results of structural steel are good, then comes FGM and for composite material where 4 layers are used the results are high for deformation of shaft.
As far as fatigue is concerned, there are various issues regarding this type of failure. Fretting fatigue may occur if the structural steel is selected, near the ends of the shaft. For other materials, may fail badly in fatigue if there is even a little bit of eccentricity in the shaft's rotational axis. Composites show a good response to fatigue under certain conditions. But the structural steel may fail in fatigue earlier than the composites. FGM material shows comparatively better results in this analysis.

5. CONCLUSIONS

Composite drive shaft material Carbon/epoxy and FGM deformation and first frequency were studied and compared with conventional steel drive shaft using ANSYS at the same condition. The shaft wall thickness is 0.9 mm and 1 meter long. It is noticed that the fiber angle orientation of the composite drive shaft has a great influence on deformation and first frequency. It is concluded concerning the weight of drive shaft that; composite drive shaft offers advantages as lower weight than steel and FGM drive shaft offers advantages as lower weight than both composite material and steel. Concerning the deformation of the drive shaft that; the composite drive shaft offers advantages as lower deformation than steel and the FGM drive shaft offers advantages as lower deformation than both composite material and steel. However, the buckling and harmonic analysis show that structural steel has less deformation while composite material shows high deformation. The FGM remains the second-best material. Therefore, the results of this study favor the FGM as it offers advantages of less weight and fewer deformation values, and also the buckling and harmonic analysis support the use of FGM.

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