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EVALUATION OF STRUCTURAL AND VIBRATIONAL CHARACTERISTIC OF COMPOSITE DRIVE SHAFT FOR AUTOMOBILE USING FEM

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ABSTRACT

In vehicle drive shaft is one of the most important component. It transmits torque from the engine to the differential gear of a rear wheel drive vehicle. Generally the drive shaft is made up of steel alloy but the use of conventional steel has disadvantages such as low specific stiffness and strength and high weight. Nowadays this steel drive shaft is replaced by composite material drive shaft. This advanced composite such as graphite, Kevlar, carbon, glass with suitable resin have advantage of higher specific strength, less weight, high damping capacity, longer life, high critical speed and greater torque carrying capacity and can results in considerable amount of weight reduction as compared to steel shaft. The main objective of this research work is to study the structural and vibrational behavior of composite material drive shaft assembly as compared to conventional steel drive shaft. Heavy duty vehicle transmission drive shaft has been used for the project. The conventional material steel SM45C and three composite materials HS carbon epoxy, E-glass epoxy, HM carbon epoxy have been used for drive shaft study so as to determine the suitable composite replacement in order to optimize the performance and design. The drive shaft was modelled using the CREO 3.0 cad software and finite element analysis were done using ansys 14.0 FEA as an analysis tool for numerical simulation to find the dynamic vibration response of composite material drive. The simulation result determines the total deformation, Equivalent Von misses stress, Maximum shear stress, natural frequencies and mode shapes under actual boundary conditions. The result concluded that HS carbon epoxy composite material is suited more for composite drive shaft application as compared to other composite materials.

KEYWORDS: Drive Shaft, Composites, Carbon Epoxy, Kevlar Epoxy, E-Glass Epoxy, PRO-E, ANSYS.

INTRODUCTION

A drive shaft is a mechanical component for transmitting torque and rotation. As torque carriers, drive shafts are subject to torsion and shear stress. An automotive drive shaft transmits power from the engine to the differential gear of a rear wheel drive vehicle is called a propeller shaft where the engine and axles are separated from each other. A prop-shaft assembly consists of a propeller shaft, a slip joint and one or more universal joints. Generally the drive shaft is made up of steel alloy SM45C, but the use of conventional steel has disadvantages such as low specific stiffness and strength and high weight and 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 which increases the total weight of an automotive vehicle and decreases fuel efficiency.

In this project an attempt has been made to replace two piece drive shaft with composite material single piece drive shaft. This composite material drive shaft have two universal joints and jaw coupling while the two piece drive shaft consists of three universal joint, a centre support bearing and a bracket. Substituting the composite structure for conventional metallic structure has many advantage. The simple design of single piece drive shaft reduces the weight and thus the design is optimized. The use of composite in not new in automobile industries they been using as early as 1930. In 1930 henry ford use the soya oil to produce a phenolic resins and thence to produce a wood filled composites material for car bodies

Many research work has been carried out to replace the conventional metallic material with the composites. Cho et al. [1] authors have studied the composite material single-piece drive shaft. The shaft was manufacture using fibre epoxy composite and aluminium tube for obtaining high natural bending frequency and torque transmission capability Nm. Sevkat et al. [2] authors have studied the problem of residual torsional properties of composite shafts. Shafts are subjected to impact loading condition. The research work concludes that the impact loading reduce the maximum torque, twisting angle and this reduction increases as increase in impact energy. Solanki et al. [3] author have studied the failure reason of AISI 304 stainless steel drive shaft. The main vibration reason for failure is low natural bending frequency. The failure of drive shaft hampers the function of vehicles. Aleyaasin et al. [4] have investigated the problem of flexural vibration for cantilevered marine propeller shaft. The frequency response method with inverse Fourier transform technique was used for identification of resonance and gyroscopic effects.

Dai Gil Lee, et.al [5] author develop a one-piece automotive hybrid aluminium/composite drive shaft by a carbon fibre epoxy composite layer co-cured on the inner surface of an aluminium tube rather than wrapping on the outer surface which resulted a hybrid aluminium/composite drive shaft with 75% mass reduction, 160% increase in torque capability compared with a conventional two-piece steel drive shaft. Baryrakceken [6] Author studied the failure analysis of pinion shaft mounted at the entrance. The pinion gear and shaft are manufactured in single part. The fatigue and fracture condition was monitored. The mechanical property of material was obtained and then chemical and microstructure properties were determined. Kim et al. [7] authors studied the problem of thermal residual stresses setup during bonding process of composite layer and aluminium tube for hybrid shaft. Thermal residual stresses are resultant of difference in coefficient of thermal expansion (CTE) for two materials. Mutasher [8] research work present's study of advanced composite, aluminium/ composite for hybrid shaft having high torque transmission, high natural bending frequency with less noise and vibration. The linear and nonlinear properties of materials were considered. The numerical result was verified with experimental results. Zhang et al. [9] authors studied the self-excited vibration of a propeller shaft. Caused due to friction induced instability. The shaft is supported on rubber bearing lubricated by water. The system was modelled in consideration with torsional vibration of continuous shaft and tangential vibration of rubber bearing.

DESIGN CONSIDERATION

Specification Of Problem

The designed drive shaft must satisfy three loading conditions. 1. The primary load carried by the drive shaft is torsion. The Shaft must be designed to have enough torsional strength to carry the torque without failure. 2. The Torsional buckling. This condition must be considered for a thin-walled tube. The third design condition is that the drive shaft has a Bending natural frequency which is sufficiently high. In this research work as Heavy duty vehicle transmission drive shaft is used for the project. For the heavy duty vehicle generally the torque transmission capability of the drive shaft should be larger than 8000 Nm (Tmax) and Fundamental natural bending frequency of the drive shaft should be higher than 4000 rpm that is its rotational speed to avoid whirling vibration.

Since the fundamental bending natural frequency of a one-piece drive shafts made of steel or aluminium is normally lower than 3800 rpm, 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. So in order to reduce vibration problem increase the length of the shaft but the length of the shaft is limited by the space restriction. So that there is only an option remains that is to manufacturers the shaft in two pieces. Physical dimensions of the shaft to be designed are assumed as were given in the table I. These were the values taken from the previously published papers [20] related to the composite drive shaft.

Table 1: Dimension for the drive shaft

Parameter of shaft	Symbol	Value	Unit
Outer diameter	do	90	mm

Inner diameter	di	83.36	mm
Length	L	1250	mm
Thickness	T	3.32	mm

Assumptions

1. The shaft rotates at a constant speed about it Longitudinal axis.
2. The shaft has a uniform, circular cross section.
3. The shaft is perfectly balanced
4. All damping and nonlinear effects are excluded.
5. The stress-strain relationship for composite material is linear & elastic hence Hooke’s law is applicable for the metallic Material.
6. Acoustical fluid interactions are neglected, i.e., the shaft is assumed to be acting in a vacuum.

Selection of Cross-Section

The drive shaft can be solid circular or hollow circular. Here hollow circular cross-section was chosen because:

1. The hollow circular shafts are stronger in per kg Weight than solid circular.
2. The stress distribution in case of solid shaft is zero at the centre and maximum at the outer surface While in hollow shaft stress variation is smaller In solid shafts the material close to the centre are not fully utilized

Design equation

1. Mass Of The Drive Shaft (M)

$M= \rho AL= \rho \times \Pi/4 \times (do2- di2) \times L$”……………….. (1)

2. Torque Capacity Of Drive Shaft(T)

“$T= Ss\times \Pi /16 \times [(do4- di4) \times do]$” ………..…. (2)

3. Fundamental Natural Frequency(F)

The fundamental natural frequency can be found by using the two theories:
1) Timoshenko Beam theory
2) Bernoulli Euler Theory

Timoshenko Beam Theory-Ncrt

“$Fnt= Ks (30 \Pi p2) / L2 X \sqrt{} (Er2 / 2\rho)$”……. (3)

“$Ncrt = 60 fnt$”…………………………….….... (4)

Where,

“$1 / Ks^{2} = 1 + (n2\Pi 2 r2) / 2L2 X [1 + fs E / G]$… (5)

Fnt= natural frequency base on Timoshenko beam theory, HZ Ks = Shear coefficient of lateral natural frequency
p = 1, first natural frequency
r = mean radius of shaft
Fs = Shape factor, 2 for hollow circular cross section
n = no of ply thickness, 1 for steel shafts

FEA BASED DESIGN ANALYSIS

Finite element analysis is a computer based analysis technique for calculating the strength and behaviour of structures during the given boundary condition. In the FEM the structure is represented as finite elements and are joined at particular points which are called as nodes. In our project FEM based analysis is carried out by using the ANSYS 14.0 analysis tool with help of which we determines quantities like the total deformation, Equivalent Von misses stress, Maximum shear stress, natural frequencies and mode shapes under actual boundary conditions. A solid modelled of Single-piece drive shaft was designed using the CREO 3.0 [15] software. The design model of heavy duty transmission drive shaft consists of a single-piece drive shaft assembly with universal joints at both the ends portion. Figure 1 shows the single-piece drive shaft Assembly with hook's joint at the ends. Figure 2 shows the meshed finite element model of transmission drive shaft assembly in Ansys 14.0 having high quality meshing facility with the total number of nodes and element given as:
(Nodes = 142747, Elements = 76625)

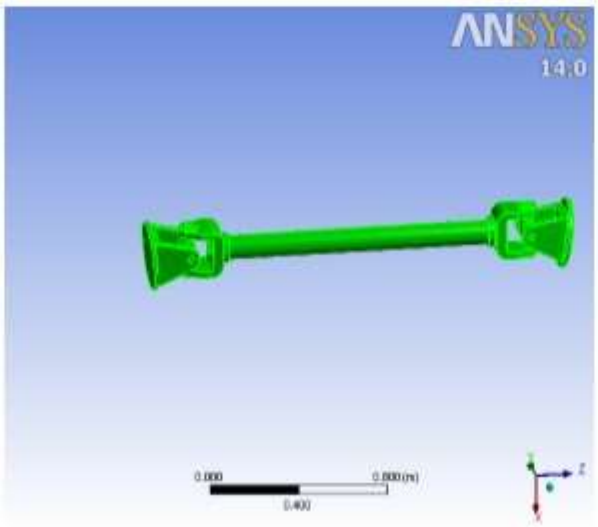


Figure 1 solid model of drive shaft assembly in ansys

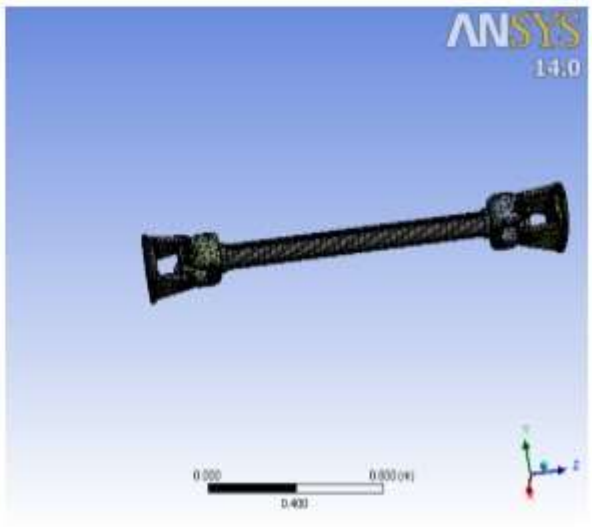


Figure 2 meshing of drive shaft assembly in ansys

MATERIAL PROPERTIES

The main objective of this research work is to study the structural and vibrational characteristic of composite material drive shaft as compared to conventional steel SM45C drive shaft assembly. The conventional material steel SM45C and three composite materials HS carbon epoxy, E-glass epoxy, HM carbon epoxy have been used for drive shaft study so as to determine the suitable composite replacement in order to optimize the performance and design The conventional steel alloy used for the drive shaft have disadvantages such as low specific stiffness and strength and high weight. It have the linear elastic properties and thus the hooks law is applicable. The steel alloy taken for analysis of drive shaft is steel SM45C whose properties is shown in table 2 below. Substituting the composite material for the drive shaft have advantage of higher specific strength, less weight, high damping capacity, longer life, high critical speed and greater torque carrying capacity and can results in considerable amount of weight reduction as compared to steel alloy drive shaft. Composite consist of two or more material phase that are combine to produce a material that has superior properties to these of its individual constituent The constituents are combined at a macroscopic level and or not soluble in each other. The composite material have the orthotropic elastic behaviour rather than linear elastic properties. The mechanical properties of the three composites HS carbon epoxy, HM carbon epoxy, E-glass epoxy are shown in the table 3 below. The specifications of the composite drive shaft of an automotive transmission are same as that of the steel drive shaft for optimal design. The properties were taken from the collected data from the books. [23-24]

Table 2: mechanical properties of steel(SM 45C)

Mechanical Properties	Symbol	Units	Steel
Young's Modulus	E	Gpa	207
Shear Modulus	G	Gpa	80
Poisson's ratio	ν	-	0.3
Density	ρ	Kg / M3	7600
Shear Strength	Ss	MPa	370

Table 3: Mechanical properties of composite material

Property	Units	E- Glass / Epoxy	HS Carbon / Epoxy	HM Carbon / Epoxy
E11	GPa	50	134	190
E22	GPa	12	7.0	707
G12	GPa	5.6	5.8	402
V12	-	0.3	0.3	0.3
St1=Sc1	MPa	800	880	870
St2=Sc2	MPa	40	60	54
S12	MPa	72	87	30
d	Kg/m3	2000	1600	1600

BOUNDARY CONDITIONS

To simulate the same working conditions real time boundary conditions, fixed support were applied on one side and rotational velocity and moment were applied on the other sides of the drive shaft assembly. Rotational velocity of 1500rpm (157.08 rad/sec) was applied for structural and vibration analysis. The rotational motion of drive shaft generates a torsional moment in whole body of drive shaft. This moment was applied on the opposite end of rotational velocity having magnitude equal to 245NM in the direction apposite to direction of rotational velocity [20]. The boundary condition were shown in the figure3 below.

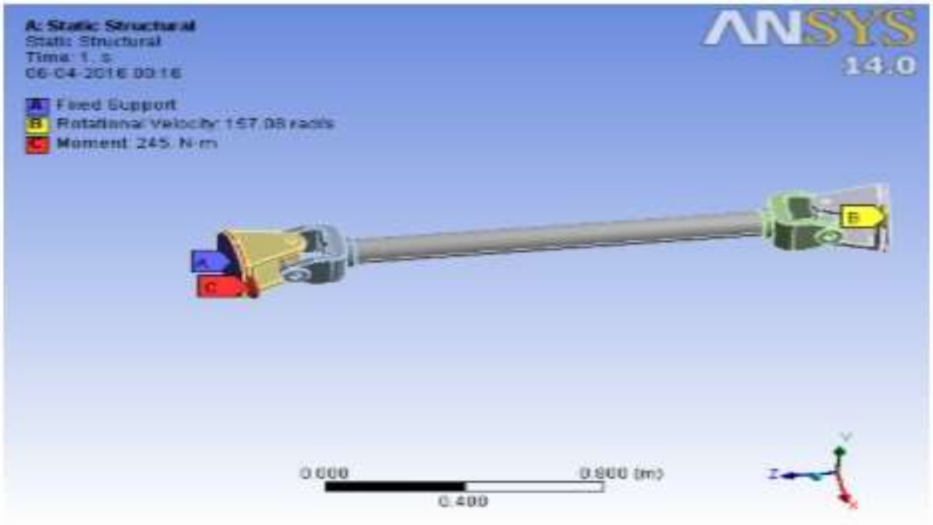


Figure3: boundary condition applied on drive shaft assembly

Figure3: boundary condition applied on drive shaft assembly

STATIC STRUCTURAL ANALYSIS

A static structural analysis were done to analyse the behaviour of the structure under the steady loading conditions, while ignoring inertia and damping effects, such as those carried by time varying loads. All types of non-linearity are allowed such as large deformations, plasticity, creep, stress stiffening, contact elements etc. this result will determined whether the structure will withstand for the applied external loads. 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. 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. In this project the FEA based ansys analysis tool were used to study the structural behaviour of the different composite material under the given boundary conditions by determining the totaldeformation, Equivalent Von misses stress, Maximum shear stress for each composite material and then the comparison were done to find out the most suitable composite under the given boundary conditions for the drive shaft assembly. In the Ansys the region with high stress were shown in red color while the region having less stress were shown in blue color.The FEM based structural analysis simulation results of Steel SM45C Single piece drive shaft are shown in figure (4, 5, and 6. The structural properties of HS carbon composites is shown in figure (7, 8 and 9). The structural properties of HM carbon composites is shown in figure (10, 11 and 12) .The structural properties of E-glass composites is shown in figure (13, 14 and 15) and Table 4 shows the structural properties result comparison with the other considered material

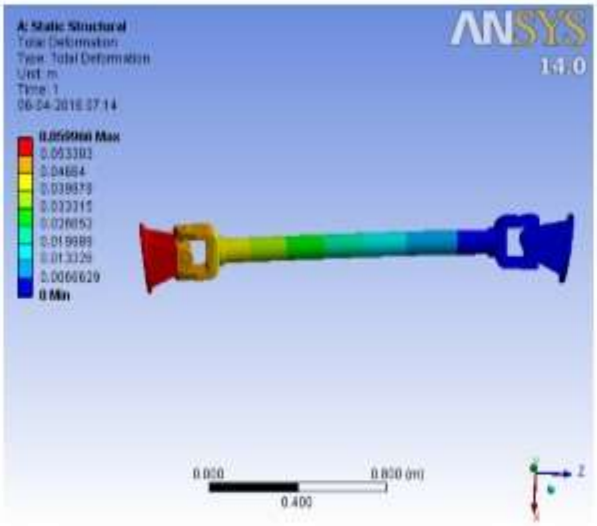


Figure 4 total deformation for steel shaft

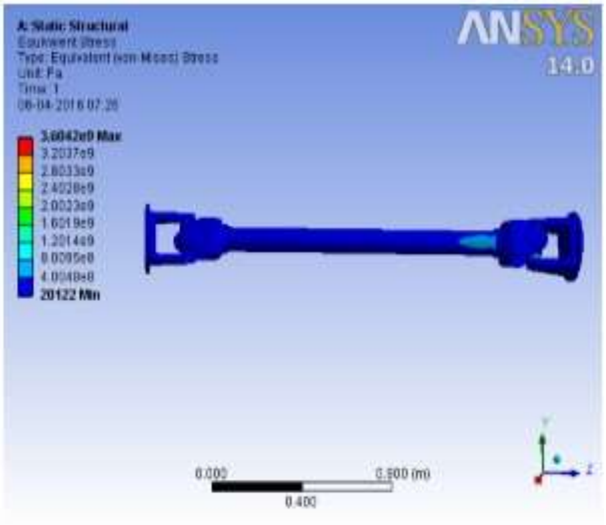


Figure 5 Equivalent stress distribution for steel shaft

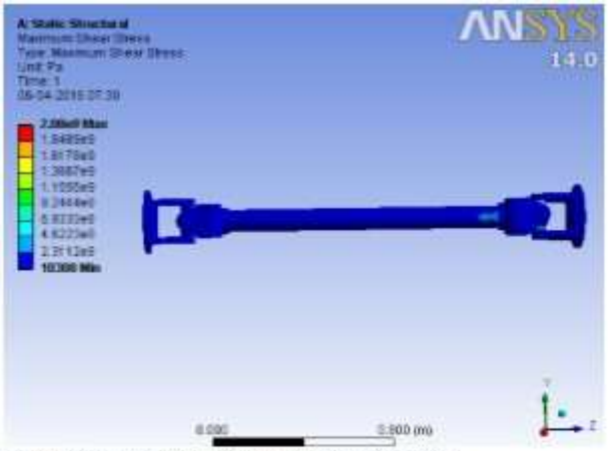


Figure 6 shear stress distribution for steel shaft

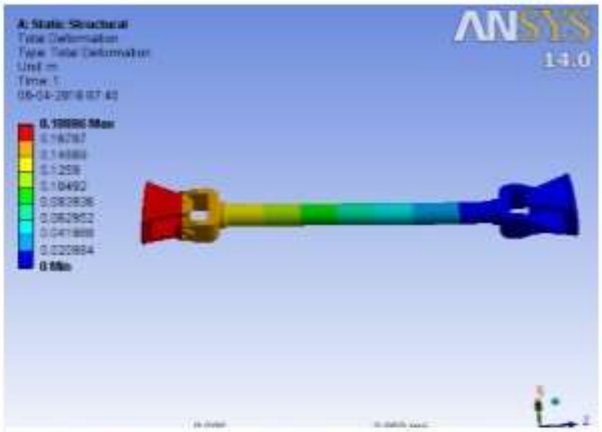


Figure 7 total deformation for HS carbon composite

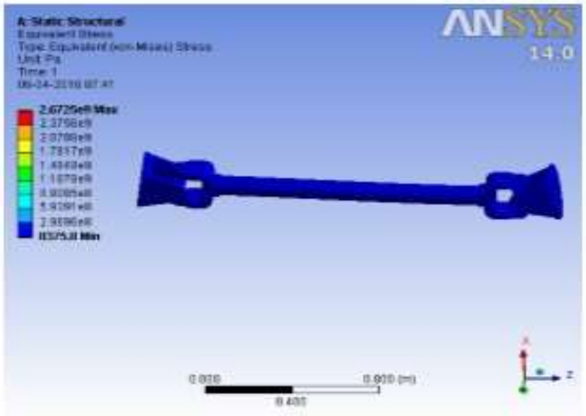


Figure 3 equivalent von misses stress for HS carbon composite

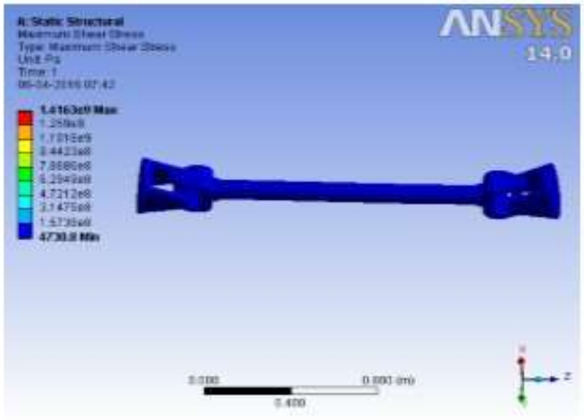


Figure 9 Shear stress distribution for HS carbon Shaft

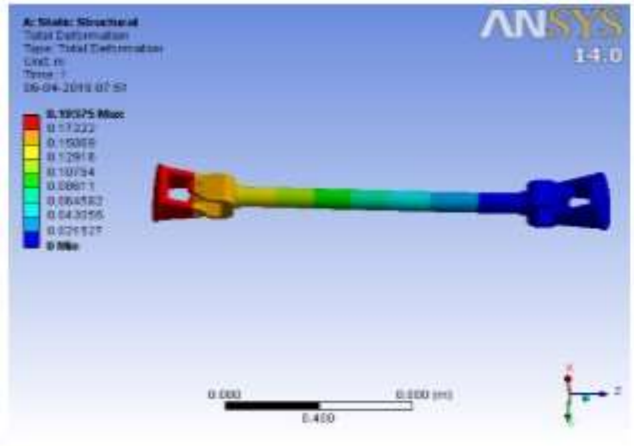


Figure 10 total deformation for HM carbon epoxy shaft

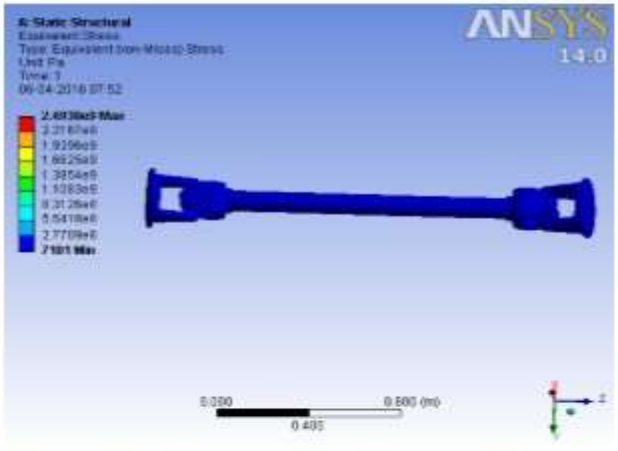


Figure 11 Equivalent stress for HM carbon epoxy shaft

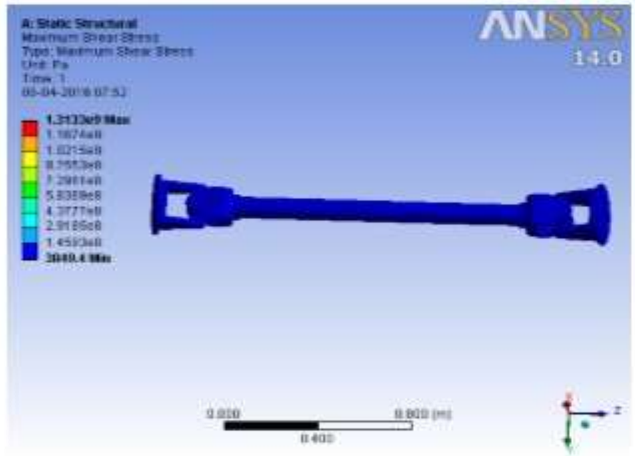


Figure 12 Shear stress distribution for HM carbon shaft

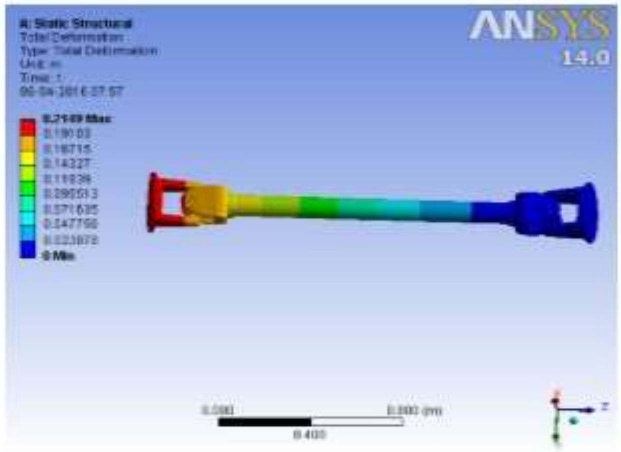


Figure 13 Total deformation for E-glass epoxy

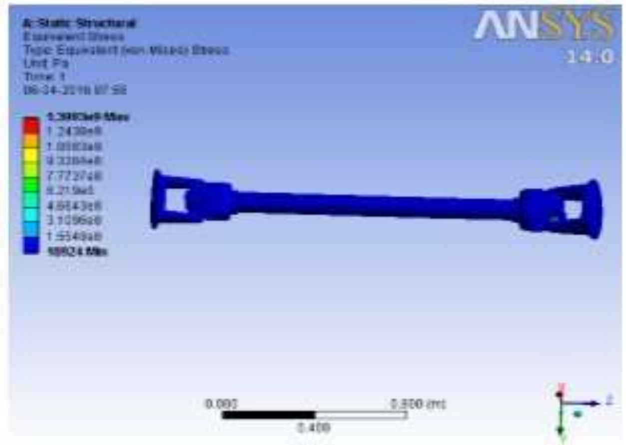


Figure 14 Equivalent Stress for E-glass epoxy

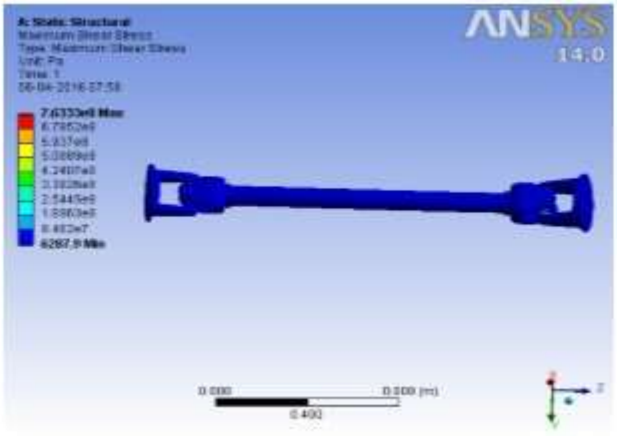


Figure 15 Shear Stress distribution for E-glass epoxy

Table 4: result of structural analysis

Material	Deformation (m)	Equivalent stress(Pa)	shear stress(Pa)
Steel SM45C	0.05996	3.60e9	2.08e9
HS carbon epoxy composite	0.1937	2.4938e9	1.313e9
HM carbon epoxy composite	0.18886	2.6725e9	1.4163e9
E-glass epoxy composite	0.2149	1.399e9	7.633e8

MODAL ANALYSIS

Modal analysis is used to analysis the behaviour of the structure during the dynamic loading condition. It determine the vibration characteristics such as natural frequencies and mode shapes of a structure as these parameters are most important for the design of structure during the dynamic loading conditions in order to avoid the resonance situation .When an system is free from external forces is disturbed from its equilibrium position it starts vibrating due to the inherent forces. It will vibrate at its natural frequency and its amplitude will gradually reduce with time due to energy decapitation due to the resistance force by motion. This type of system is known as free vibration system .The natural frequency of the drive shaft depends on the diameter of the shaft, thickness of the hollow shaft, specific stiffness and the length. The rotational speed of the body is limited by the lateral stability. The drive shaft designed should rotates at the speed lower than the first natural bending frequency of in order to avoid whirling vibration. In this work with the help of ansys analysis tool the natural bending frequency of drive shaft were determined up to 10 mode for all the material considered in order to determine the suitable material for heavy duty vehicle transmission.

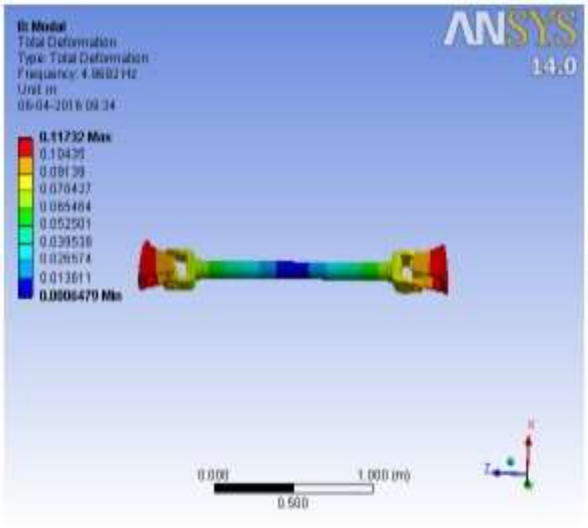


Figure 16 total deformation of steel shaft at 4th mode

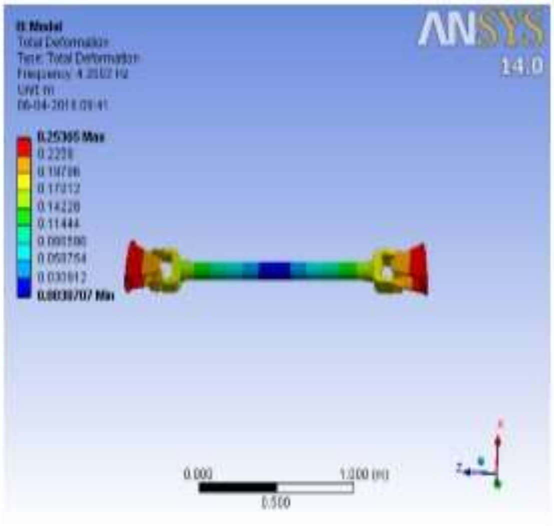


Figure 17 total deformation of HM carbon epoxy drive shaft at 4th mode shape

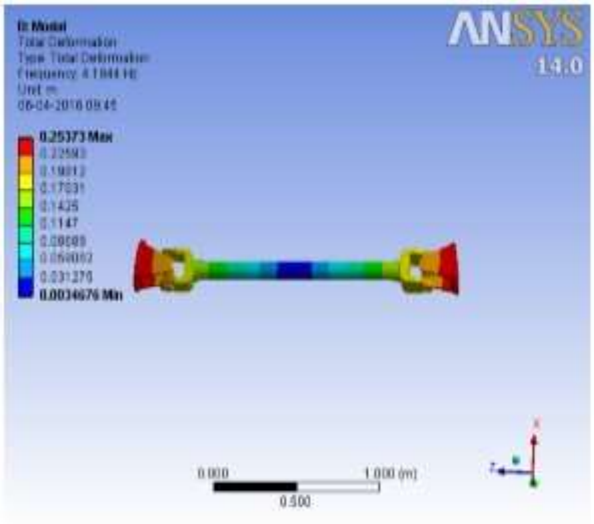


Figure 18 total deformation of HS carbon epoxy drive shaft at 4th mode shape

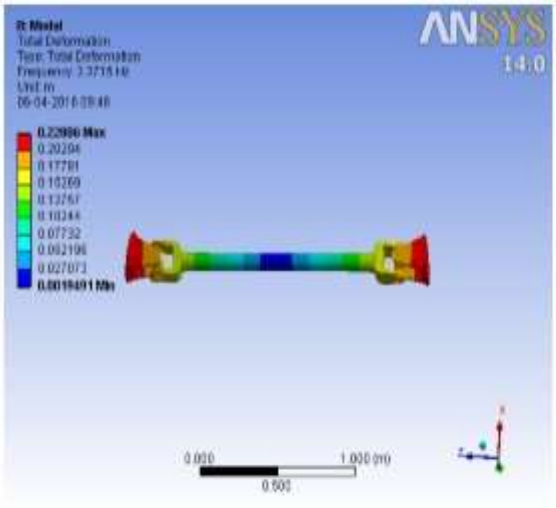


Figure 19 total deformation of E-glass drive shaft at 4th mode shape

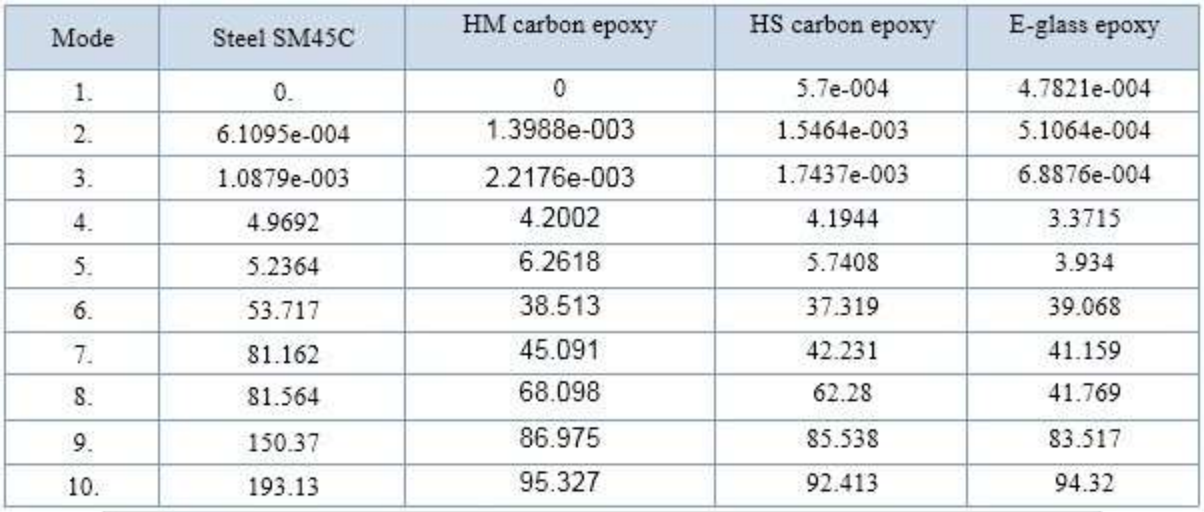
FEA SIMULATION RESULTS AND DISCUSSION

FEA based numerical simulations evaluate the results of structural and modal analysis for steel alloy and epoxy composite material. In analysis inertia and damping effects was not considered. Rotational and moments values are applied in form of loading. The automobile drive shaft is subjected to torque transmission, no direct load value act on it. The result of this analysis evaluates the static failure condition of drive shaft.

The structural analysis result shows that the shear stress distribution is maximum for the conventional steel alloy (2.08e9Pa) shown in figure 6 while it is minimum for the E-glass composite (7.633e8Pa) shown in figure 15 which shows that the E-glass epoxy have maximum torsional rigidity. The total deformation in single piece drive shaft under loading conditions is minimum (0.05996 m) for the steel alloy drive shaft while the maximum deformation (0.2149m) was shown by E-glass epoxy shown in figure 13. Equivalent (von-misses) stress have maximum value for conventional steel drive shaft (3.60e9Pa) shown in figure 5 while the minimum value is shown by E-glass epoxy composite (1.399e9Pa) shown in figure 14. This shows that the conventional steel drive shaft produces the maximum shear and von misses stress for the given transmission condition while the E-glass composite produces minimum stress for the given condition but have maximum deformation. The Fem analysis result shows that the HS carbon epoxy composite is the best suited composite material for the single piece drive shaft having minimum deformation with the average stress distribution.

Figure (16, 17, 18 & 19) shows the vibration mode shapes and corresponding natural frequency for steel alloy and the other composite material. The FEA analysis shows the first three mode have frequency nearly equal to zero and the first valid frequency occurs at mode 4. Mode 7 shows the deformation at the transmission end side. Mode 8 has deformation at centre portion due to axial bending vibration. Mode 10 shows torsional vibration the frequency variation for steel SM45C, carbon epoxy composite and E-glass epoxy composite. For trucks and vans bending frequency should be higher than (2400-4000) rpm. These technical requirements are fulfilled by the carbon epoxy composite material the relation between critical speed and natural frequency is given as (Ncr = 60 fnt). The table 5 shows the variation of fundamental natural frequencies to their corresponding mode shapes.

Table 5: Variation of natural frequency for different modes



Mode	Steel SM45C	HM carbon epoxy	HS carbon epoxy	E-glass epoxy
1.	0.	0	5.7e-004	4.7821e-004
2.	6.1095e-004	1.3988e-003	1.5464e-003	5.1064e-004
3.	1.0879e-003	2.2176e-003	1.7437e-003	6.8876e-004
4.	4.9692	4.2002	4.1944	3.3715
5.	5.2364	6.2618	5.7408	3.934
6.	53.717	38.513	37.319	39.068
7.	81.162	45.091	42.231	41.159
8.	81.564	68.098	62.28	41.769
9.	150.37	86.975	85.538	83.517
10.	193.13	95.327	92.413	94.32

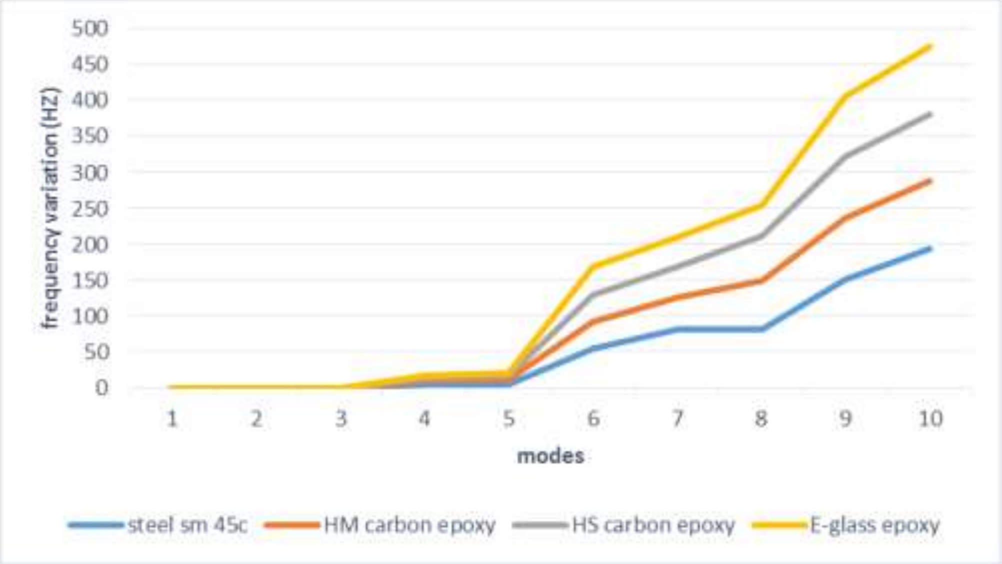


Figure 20: Natural frequency variation graph for different material.

Figure 20 shows the variation of natural frequencies for steel alloy and the epoxy composite materials. The graph shows that for all the material have natural bending frequency with some value starts with the 4th mode and as the mode increases the natural frequency increases correspondingly. With the analysis of the variation of the frequency with their modes it was concluded that the HS carbon epoxy composite material shows the excellent material properties for the design of single-piece composite drive shaft.

CONCLUSION

As the aim of the project is to replacing of conventional two piece drive shaft with the composite shaft. By using three different kind of composite materials HS carbon epoxy, HM carbon epoxy, E-glass epoxy the project has been carried and the Fem based numerical simulation of single piece drive shaft were carried out with the help of the Ansys 14.0 analysis tool and the structural and vibration response of driving shaft shows that HS carbon epoxy composite is suited for single-piece drive shaft. The research work concludes the following points-

1. The study successfully has investigated the use of composite materials for single-piece light weight drive shaft. HS carbon epoxy composite material is best suited on design and vibration criteria.

2. The structural analysis evaluates the shear stresses, maximum principal stress, total deformation, equivalent stress, and maximum shear stress for steel SM45C and the three epoxy composite material and conclude that the HS carbon epoxy composite material shows the high strength with less deformation.

3. Vibration analysis determines the natural frequencies for up to 10 mode (axial bending vibration, torsional vibration) for steel SM45C and epoxy composites material for the single-piece drive shaft to avoid the resonance situation.

4. Composite material HS carbon epoxy provides the suitable structural strength against shearing, torsional vibration and axial bending vibration.
5. Use of composites for the single piece drive shaft results in the significant decrease in mass and hence optimize the design.

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