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Abstract. Propeller shaft also called drive shaft is one of the foremost imperative components used to transmit power from the engine to the wheels and is usually made of steel. Reducing the weight of the automotive components, including the drive shaft, while preserving their functional characteristics has become an even more urgent task in the automobile industry. Therefore, many efforts have been made by the researchers to minimize the weight of the components. Despite all these endeavors, however, the matter still needs more investigation. The aim of this research is to reduce the weight of a drive shaft using different materials. Six different materials were used including a conventional material (steel) and five different composite materials such as carbon/epoxy, E-glass/epoxy, S-glass epoxy, Kevlar epoxy and thermoplastic polyimide with 30% carbon. A three-dimensional (3D) drive shaft was designed, modeled and simulated using ANSYS software. The results show that the unidirectional carbon/epoxy is the favorable fabric instead of structural steel, and the greatest stress is produced with the same dimensions and configuration load. Moreover, the amount of weight is decreasing compared with structural steel.

Keywords: Carbon/Epoxy, Composite material, Drive shaft, FEM, Weight reduction.

INTRODUCTION

A drive shaft, is sometimes referred to as a Cardan shaft or a propeller shaft, is a shaft that used to transmits engine power to the wheels. Also, it must work through continually angle changes between the axle and transmissions. It should give a smooth continuous flow of power to the axles. The common material which utilized for developing drive shaft is high-quality steel. Power transmission can be progressed through the decrease of light Hook's weight and inertial mass. In the design of shaft metallic, knowing the allowable shear stress and the torque for the material, the estimate cross-section of the shafts can be decided. Drive shafts for power transmission are used in a variety of applications, including cars, buildings, aviation, cooling towers and pumping systems [1–4]. In today's world, lightweight materials are in high demand in automotive applications. Composites have already shown to be good weight-saving materials; the current problem is to make them affordable. The conventional steel material can be replaced with advanced composite materials. Composite materials are widely used in manufacturing because of their excellent properties, such as specific or weight ratios of hardness and strength. Furthermore, composite materials often have the lowest modulus of elasticity [5, 6].

Composite materials are basically hybrid materials made up of a variety of materials arranged in a way that allows them to employ their different structural preferences in a single structural material. The components are macroscopically combined and are not dissolvable in one another. Dissimilar materials can be mixed on a microscopic scale, such as in metal alloying, yet the resulting substance is macroscopically homogenous, meaning the components cannot be distinguished by the naked eye and operate in concert. Composite materials have the benefit of displaying the best features of their constituents or components, as well as a few properties that neither ingredient has. Wear resistance, hardness, corrosion resistance, strength, stiffness, fatigue life, thermal insulation, temperature-dependent behavior, thermal conductivity, attractiveness, weight, and acoustical insulation are just a few of the characteristics that can be improved by forming a composite material. Naturally, not all of these

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properties are progressed at the same time, and there is no need to do so in most cases. In fact, a few of the properties are in strife with one another, the objective is simply to make a material that has only the characteristics required to perform the designed task. The structure of the composite material is made up of two building components. The first is known as the reinforcing phase, and the second is known as the matrix phase, in which it is implanted. Flakes, fibers and particles can be used as reinforcing stage materials. Materials in the matrix phase are usually continuous [7].

The progressed composite materials such as (fiberglass, aluminum, graphite, and carbon) driveshaft tube were created as a coordinate reaction to the industry request for efficiency and greater execution in light trucks, vans and high-performance automobiles. Important saving in weight for this was the most reason of a drive shaft. Because carbon fiber composite material has a higher specific stiffness than steel, the basic normal frequency of the carbon fiber composite drive shaft may be higher than steel, allowing the drive shaft of passenger cars to be constructed in one piece. In recent decades, the use of composite drive shafts in racing vehicles has gotten a lot of consideration. When a steel drive shaft fractures, the components are hurled in all directions like balls, and the drive shaft may also create a gap in the ground, launching the automobile into the air. A composite drive shaft, on the other hand, breaks into fine fibers that pose no danger to the driver. In order to accomplish weight reduction while preserving vehicle reliability and quality, the car industry is embracing composite material innovation for structural component development. One of the most significant objectives in weight reduction is energy saving, and vehicle design is one of the most appealing methods to achieve this aim. In fact, there's a near-coordinate proportionality between a vehicle's weight and its fuel consumption, particularly in city driving [1].

Mohan and Vinoth examined the possibility of replacing the two-piece steel drive shafts with a single composite drive shaft. FEA was used to analyze deflection stresses under simulated loads and characteristic frequencies, and the findings were compared to steel shafts to authorize the extension. When compared to a standard steel drive shaft, the results appear to show that using composite materials resulted in a significant weight savings of 70 to 63 percent [2].

Kumar, Manoj, and Reddy evaluated a vehicle propeller shaft in 2015 by substituting it with various materials such as Boron, Kevlar, and a mix of aluminum, carbon and glass. They came to the conclusion that Boron is an excellent steel substitute for constructing drive shafts. They also came to the conclusion that reducing weight has no impact on vehicle quality or reliability. Typically, a vehicle's reduced weight has a direct influence on its fuel usage [8].

Raikwar *et al*. proposed doing a FEM study and using composite materials to optimize the design and weight of a propeller shaft. They sought to identify the most acceptable composite material that might be used as a substitute for more traditional materials. For the same dimensions and boundary conditions, five materials were examined. These materials are SM45C alloy steel as customary material, Kevlar Epoxy, Epoxy E Glass, Thermoplastic polyimide with 30% carbon fiber and Epoxy carbon. They concluded that the best material to use as a substitute for traditional materials is the thermoplastic polyimide with 30% carbon fiber because the greatest stress is created in the same way as traditional propeller shaft materials, and the normal frequency of the thermoplastic polyimide with 30% carbon fiber is extremely close to that of traditional materials. The weight is produced maximum results up to the 82.04% as compared to conventional drive shaft material [9].

Karthikeyan *et al.* examined the modeling and analysis of drive shafts made of Kevlar/Epoxy and Glass/Epoxy resin composites to find the optimum replacement for regular steel drive shafts. Modeling was done with the CATIA computer software, and analysis was done with the ANSYS 10.0 program for easy comprehension. When compared to a conventional steel drive shaft, they found that the composite drive shaft reduces weight by 81.67 percent for Kevlar/Epoxy and 72.66 percent for Glass/Epoxy. It can be shown that Kevlar/Epoxy and Glass/Epoxy deform more under tensile load, resulting in the two pieces of steel drive shaft being replaced with a single shaft that transmits power more efficiently. Because of their elasticity, they reduce stress and serve as the greatest shock absorber when torque is high [10].

Ravi (2014) investigated the use of high-strength carbon drive shafts instead of steel drive shafts in an automotive application. High-strength (HS) carbon composites were used to create a one-piece composite drive shaft for a rear-wheel-drive car with the goal of reducing the shaft's weight while meeting constraints like tensional buckling capacities, characteristic bending frequency and torque transmission. When compared to a steel shaft with the same dimensions, the HS carbon saves 24 percent in weight [4].

Ganapathi, Omprakash and Kumar, (2017) investigated the modeling and analysis of a drive shaft made of composite materials instead of stainless steel. The standard drive shaft is made of steel and consists of two-piece, but they used composite materials to make it into a single long persistent shaft. They employed different composite materials including high modulus carbon epoxy, high strength carbon epoxy and E-glass epoxy. ANSYS was used to perform model, static and buckling analysis on these materials. They came to the conclusion that using composite materials reduced the weight of the drive shaft significantly [11].

In 2015, Rothe and Bombatkar endeavored to design a light drive shaft for a car by using different materials instead of steel. To manufacture a one-piece composite Cardan shaft for a raise wheel drive vehicle, they utilized high modulus carbon/epoxy and high strength carbon/epoxy materials. The weight reductions of the high strength carbon/epoxy and high modulus carbon/epoxy shafts were 85.20 percent and 82.26 percent, respectively, of the weight of steel shafts [12].

Therefore, the aim of this study is to design and analysis a drive shaft using a conventional material (steel) and different composite materials by employing ANSYS software.

MATHEMATICAL MODULE

1. Design of Steel Cardan shaft

Fundamentally, the bending frequency characteristic of the capability torque transmission of the drive shaft for vans, small trucks and traveler cars should be more than (3500) *N.m*. The drive shaft outside distance across is (90) *mm*. Here outside diameter over of the shaft is taken as (84) *mm*. The transmission drive shaft system is to be sketched out ideally for taking after shown plan necessities as showed up in Table (1).

TABLE 1. Parameters of steel drive shaft and design requirements

Property	Value	Unit
Ultimate Torque (T_{max})	3500	N.m
Maximum shaft speed (N_{max})	6500	RPM
Shaft length	1200	mm
Outer diameter (d_o)	90	mm
Inner diameter (d_i)	84	mm
Shaft thickness (T)	3	mm

The mechanical characteristics of the structural steel utilized in this investigation are shown in Table (2).

TABLE 2. Mechanical characteristics of structural steel

Mechanical properties	value	unit
Density (ρ)	7600	Kg/m^3
Young's Modulus (E)	207	GPa
Poisson's Ratio (υ)	0.3	-
Shear Modulus (G)	80	GPa
Shear Strength (S_s)	370	MPa

The steel driving shaft's mass,

$$m = \rho AL = \rho \times \Pi/4 \times (d_o^2 - d_i^2) \times L \quad 1$$

$$m = \frac{7600x3.14}{4}x(90^2 - 84^2)x1200$$

$$m = 7.47 \text{ Kg}$$

The drive shaft torque transmission capacity

$$T = S_S \frac{\pi(d_o^4 - d_i^4)}{16d_o} \quad 2$$

The drive shaft torsion buckling capacity.

If $\frac{1}{\sqrt[3]{1-v^2}} \frac{L^2 t}{(2r)^3} (\frac{t}{r})^{3/2}$

It is called as the long shaft; the critical stress comes from,

$$\tau_{cr} = \frac{E}{\sqrt[3]{2(1-v^2)^{3/4}}} (\frac{t}{r})^{3/2} \quad 3$$

While the critical stress for short and medium shaft is given by,

$$\tau_{cr} = \frac{4.39\ E}{(1-v^2)} (\frac{t}{r^2}) \sqrt{1 + 0.0257(1-v^2)^{3/4} \frac{L^3}{(rt)^{1.5}}} \quad 4$$

The relationship between the torsional buckling capacity and critical stress is seen in Equation 5,

$$T_{cr} = \tau_{cr}\, 2\pi r^2 t \quad 5$$

The shaft can be modeled as a pinned-pinned beam or as a simply supported beam subjected to transverse vibration. The common frequency may be determined by using the following two theories:

1- Theory of Bernoulli-Euler Beams

Both transverse shear deformation and rotational inertia are not taken into account. The Bernoulli-Euler beam theory gives the natural frequency as follows:

$$f_{nbe} = \frac{\pi\, p^2}{2\, L^2} \sqrt{\frac{E\, I_X}{m_1}} \quad 6$$

where p=1, 2

$$N_{crbe} = 60 f_{nbe} \quad 7$$

2- Theory of Timoshenko Beam

It takes into account both transverse shear deformation and rotational inertia. According to this theory, the natural frequency is calculated as follows:

$$f_{nt} = K_s \frac{30\pi\, p^2}{L^2} \sqrt{\frac{E\, r^2}{2\rho}} \quad 8$$

$$N_{crbe} = 60 f_{nbe} \quad 9$$

$$\frac{1}{K_s^2} = 1 + \frac{n^2 \pi^2 r^2}{2L^2} \left[1 + \frac{f_s E}{G}\right] \quad 10$$

For hollow circular cross-sections, f_s= 2

Bernoulli-Euler and Timoshenko Beam Theories are related by:

$$f_{nt} = K_s f_{nbe} \quad 11$$

Where:

m = Weight of the shaft, *Kg*
ν = Poisson's ratio
ρ = Material density, *kg/m³*
r = Mean radius of the shaft, *mm*
L= Shaft length, *mm*
T = Shaft thickness, *mm*
d_i = Inner diameter of the shaft, *mm*
τ_{cr} = Critical shear stress, *MPa*
d_0 = Outer diameter of the shaft, *mm*
E = Young's Modulus, *GPa*
T= Shaft's torque transmission capability, in *N.m*
S_s= Shear Strength, *MPa*
G = Shear Modulus, *GPa*
I_x = Moment of inertia of cross-section of the shaft, m^4
N_{crbe}= Critical Speed, *RPM*
K_s = Shear coefficient of the lateral natural frequency
f_{nbe} =Natural Frequency, *Hz*; based on Bernoulli-Euler beam
f_{nt} = Natural Frequency, *Hz*; based on Timoshenko beam
n = Total Number of plies

2. Design of a Composite Cardan Shaft

For the optimum design, the details of the composite propeller shaft in an automotive transmission are identical to those of a steel drive shaft. The drive shaft's cross-section might be hollow or solid circular. In this study, a hollow circular cross-section was chosen since; the stress dispersion in case of a solid shaft is maximum at the external surface and zero at the center while in a hollow shaft stress variation is littler and the hollow circular shafts are stronger per *kg* weight than solid circular [12].
The following points have been assumed for design the drive shaft.

- The shaft is fully adjustable, spins at a constant speed along its longitudinal axis, and has a circular cross-section.
- Nonlinear damping is not taken into account.
- Hook's law applies because the relationship between strain and push for the composite material is linear and elastic.
- It is assumed that the shaft rotates in a vacuum.

MATERIAL SELECTION

Five different composite materials are employed in this investigation, based on the advantages mentioned before. The materials are the high strength carbon epoxy UD 230 *GPa*, E-glass epoxy UD, Kevlar epoxy, S-glass epoxy UD and thermoplastic polyimide 30% carbon fiber. Table (3) shows the properties of these composite materials.

TABLE 3. Mechanical characteristics of composite materials

Mechanical properties	Epoxy carbon 230 GPa	Epoxy E Glass	Epoxy S Glass	Kevlar epoxy	Thermoplastic polyimide 30% carbon fiber
Density, *Kg/m*^{3}	1540	2000	2490	1384	1410
Young Modulus, *GPa*	89	80	89	80	190
Poisson's Ratio	0.27	0.3	0.21	0.34	0.3
Shear Modulus, *GPa*	5.5	5.6	35	2.2	7.3
Shear Strength, *MPa*	100	72	-	-	215

The characteristics of a steel Cardan shaft are the same for a composite Cardan shaft. A carbon epoxy Cardan shaft, for instance, has a mass of:

$$\mathrm{m} = \rho \mathrm{AL} = \rho \times \Pi/4 \times (d_o^2 - \mathrm{d}_i^2) \times \mathrm{L} \qquad 12$$

$$\mathrm{m} = \frac{1540x3.14}{4} x(0.090^2 - 0.084^2)x1.200$$

$$\mathrm{m} = 1.50\ Kg$$

Torsional buckling capacity (T_{cr}): Because long thin hollow shafts are prone to torsional buckling, the plausibility of the composite shaft's torsional buckling was verified using the following formula for the torsional buckling load T_{cr} of a thin-walled orthotropic tube.

$$T_{cr} = (2\pi r^2\ t)\ (0.272)\ (E_x\ E_y^3)^{0.25}\ (t / r)^{1.5} \qquad 13$$

This equation was derived from the isotropic cylindrical shell equation and is used in the design of the propeller shaft. The ability of a composite shaft to withstand torsional buckling is largely influenced by its thickness and average modulus in the circular direction.

DESIGN ANALYSIS

Finite element analysis (FEA) is a computer-based analytical method for evaluating the strength and behavior of structures. The structure is represented as finite elements in the FEM. These elements are connected at nodes, which are defined as particular positions. The FEA is applied to evaluate the stresses, strains, deflection, temperature and buckling behavior of the part. FEA is carried out in this study with the help of ANSYS 14.0. The stresses, strains, forces, and displacements in structures or components induced by loads that do not actuate damping impacts and critical inertia are determined using static analysis. Externally applied forces, pressures, and moments, as well as steady state inertial forces like gravity and spinning forced non-zero displacements, can all be included in the static analysis. The structure will fail in the static state if the stress values determined in this investigation surpass the permitted limits. To avoid such a failure, this investigation is necessary. The maximum load condition for a shaft occurs when the differential (Wheel) development is recorded and the gearbox is active. Therefore, the researcher is applying three boundary conditions, a moment of 3500 *N.m* was applied at one end while the other end was fixed [3].

1. Engineering data

ANSYS workbench 14.0 was used for modeling the 3D propeller shaft based on the specifications presented in Table (1). The drive shaft's mechanical characteristics are considered as isotropic, homogenous and linearly elastic in this study. As previously stated, five different composite materials were chosen and compared against structural steel.
The 3D drive shaft is meshed by a tetrahedral element type as appeared in Fig. 1.

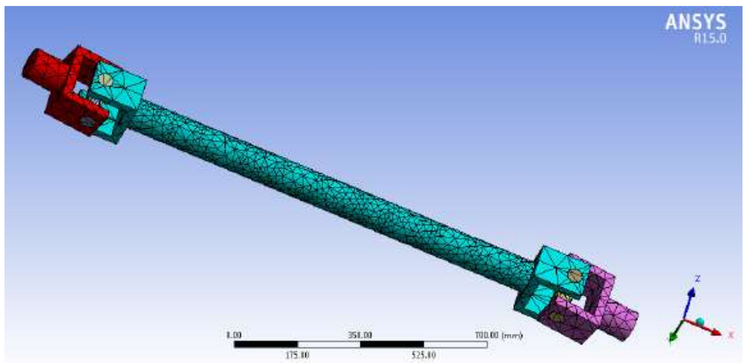

FIGURE 1. Meshing of the Original Driveshaft

2. Boundary conditions

Fig. 2 shows a finite element model of a structural steel drive shaft. One end is stationary, while the other is subjected to a moment of (3500) *N.m.*

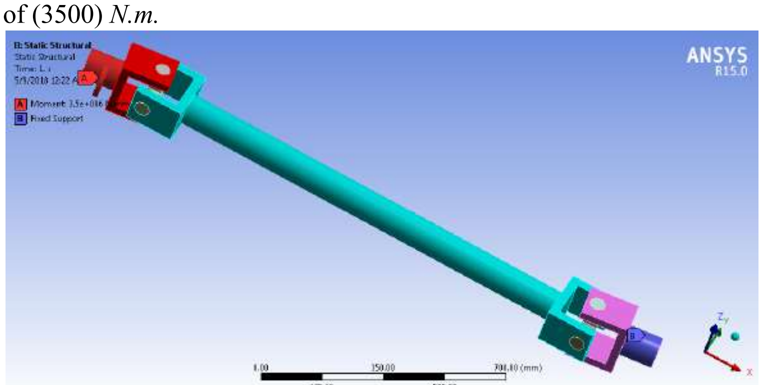

FIGURE 2. Boundary condition of Driveshaft

RESULT AND DISCUSSION

Equivalent stress, maximum shear stress, equivalent elastic strain and total deformation are used to evaluate the outcomes in this study. The comparison between structural steel and Epoxy E-glass (UD) show that the total deformation of the structural steel is calculated, and the values obtained (8.1037) *mm* as the maximum deformation, and the minimum deformation is (0) as shown in Fig. 3, and the total deformation of the Epoxy E-glass (UD) is calculated and the values obtained is (93.209) *mm* as the maximum deformation and the minimum deformation is (0) as shown in Fig. 4.

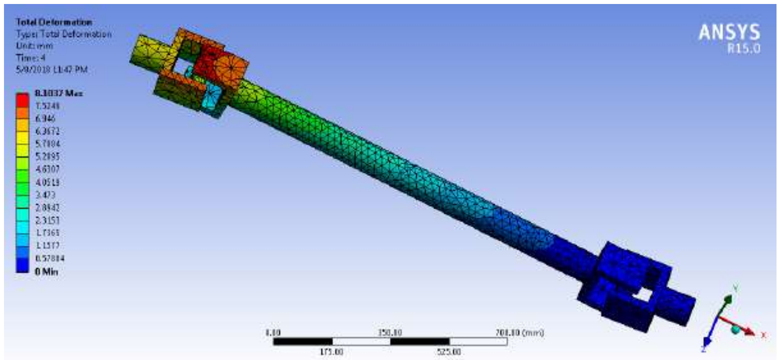

FIGURE 3. Total deformation (structural steel)

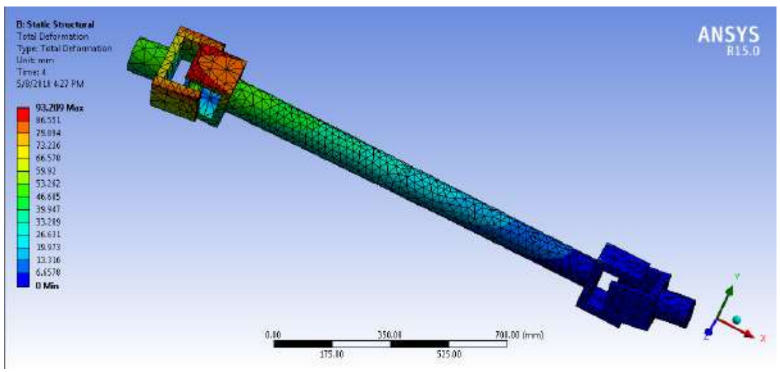

FIGURE 4. Total deformation (Epoxy E-glass UD)

The equivalent stress of the structural steel is calculated; and the values obtained like maximum stress which is (217.92) *MPa* and the minimum stress is (0.00042327) *MPa* as shown in Fig. 5. The equivalent stress of the Epoxy E-glass (UD) is calculated, and the values obtained are: the maximum stress is (240.87) *MPa* and the minimum stress is (0.0019) *MPa* as shown in Fig. 6.

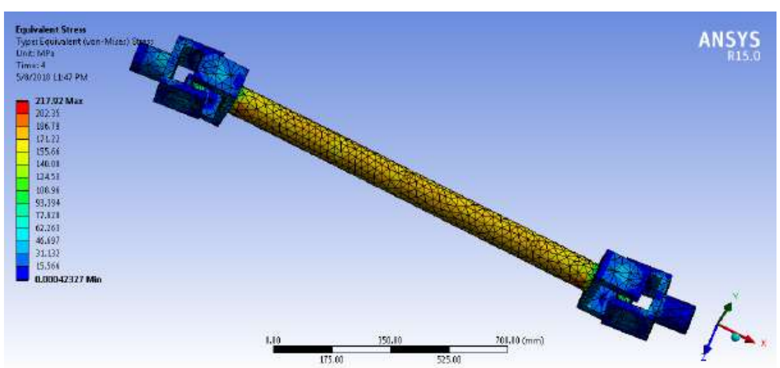

FIGURE 5. Equivalent stress (structural steel)

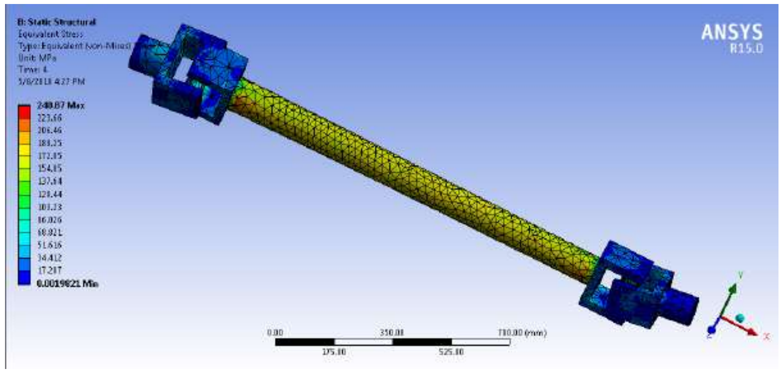

FIGURE 6. Equivalent stress (Epoxy E-glass UD)

Fig. 7 shows the equivalent elastic strain of the structural steel propeller shaft. Where the maximum and minimum values of strain are 0.0011 and 3.8831 e^{-9}, respectively. While Fig. 8 shows the equivalent elastic strain of the Epoxy E-glass propeller shaft and the maximum and minimum values of strain are 0.02212 and 2.6 e^{-7} , respectively.

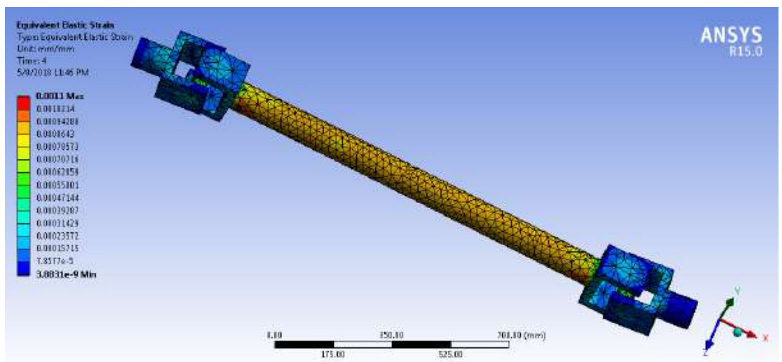

FIGURE 7. Equivalent elastic strain (structural steel)

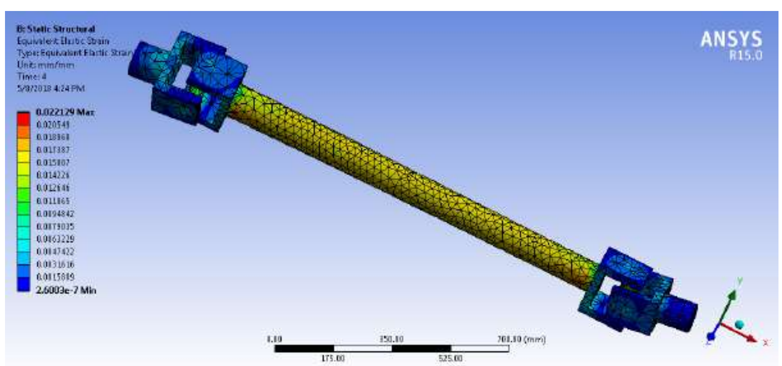

FIGURE 8. Equivalent elastic strain (Epoxy E-glass UD)

The results of the shear stress for both structural steel and Epoxy E-glass drive shafts are shown in Fig. 9 and Fig. 10. As can be seen from the Fig. 9, the maximum and minimum values of the shear stress in the steel drive shaft are 124.45 *MPa* and 0.000242 *MPa*, respectively. While the maximum and minimum values of the shear stress in the Epoxy E-glass drive shaft are 138.65 *MPa* and 0.001 *MPa*, respectively as shown in Fig. 10.

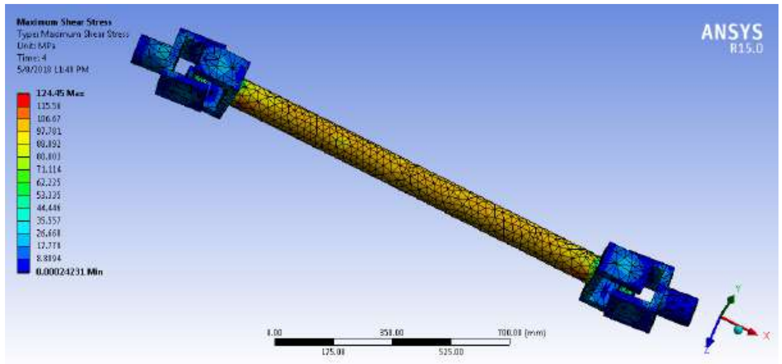

FIGURE 9. Shear stress (structural steel)

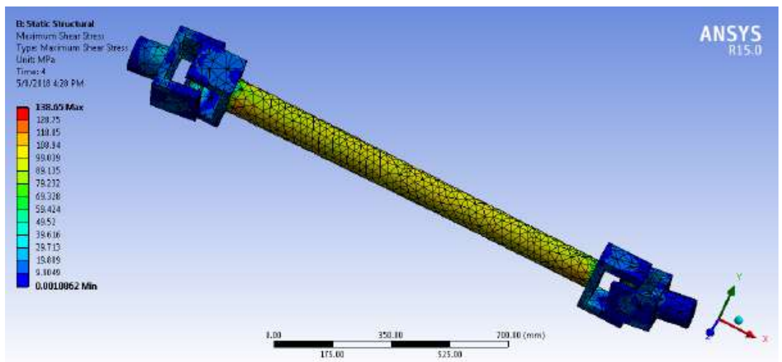

FIGURE 10. Shear stress (Epoxy E-glass UD)

Table (4) shows the whole results of this study in terms of maximum including total deformation, equivalent stress, equivalent strain and shear strain.

TABLE 4. The whole results

Materials	Total deformation (mm)	Equivalent stress (MPa)	Equivalent Strain	Shear stress (MPa)
Structural steel	8.1037	217.92	0.0011	124.45
Epoxy carbon UD 230 GPa prepreg	87.913	444.94	0.0232	236.42
Epoxy E-glass UD	93.209	240.87	0.022129	138.65
Epoxy S-glass UD	93.09	266.7	0.024638	153.46
Thermoplastic polyimide 30% carbon fiber	85.314	217.92	0.011579	124.45
Kevlar/epoxy	144.43	218.53	0.019362	124.75

CONCLUSION

The aim of the present research was to examine different materials for a drive shaft in order to reduce weight while maintaining strength. In this study, six different materials were used including one conventional material (steel), and five composite materials (carbon/epoxy, E-glass/epoxy, S-glass epoxy, Kevlar epoxy and thermoplastic polyimide with 30% carbon). The comparison of the drive shaft was carried out based on total deformation, stress, strain, and maximum shear stress actuated within the shaft. The results demonstrate that the utilize of fibers has an extraordinary impact on the static characteristics of the composite shafts.

- When compared to a traditional steel drive shaft, the use of composite material has resulted in significant weight savings and weight reduction.
- The procedure was designed to reduce the automobile's fuel consumption within the specific machine or any other machine that uses propeller shafts.

By considering weight savings, shear stress initiation, deformation and resonance frequencies, it is obvious that a crossover of high strength carbon, high modulus carbon, and carbon epoxy composite has the most powerful qualities to operate as a structural steel replacement.

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