Design and Analysis of Different Characteristics of Hollow and Solid Propeller Shaft by Varying Different Materials.

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Abstract - *In automobiles, the propeller shaft is used for the transmission of motion from the engine to the differential. An automotive propeller shaft transfers power from the engine to differential gears of rear wheel-driving vehicle. Torque transmission capacity of hollow propeller shaft is much better than solid propeller shaft however diameter of hollow propeller shaft is more than solid propeller shaft so applications in which space constraint is present hollow propeller shaft can't be used. In the present work, an attempt has been made to design hollow and solid propeller shaft for heavy duty truck "TATA LPT-1613-TC" for different materials like carbon steel and aluminum. Theoretical design has been done on the basis of maximum torque transmitting capacity, maximum shear stress produced, shear strain produced, equivalent stress, critical speed requirement. A comparative analysis is also done for the mentioned materials.*

Key Words: ANsys, CATIA, Meshing, Calculation Comparison Tables.

1. INTRODUCTION

A propeller shaft also called as driving shaft is associated with a mechanical component which is used for rotational purpose, transmitting torque and rotation and subjected to torsional or shear stress. The propeller shafts must be strong enough, low notch sensitivity factor, having heat treated and high wear resistant property so that it can sustain high bending and torsional load. To manufacture propeller shaft carbon steel is used due to their high torsional rigidity as compare to other material also due to their good shear strength to transmit torque. Whereas, aluminum is used, due to their less weight compare to carbon steel. Vehicle weight reduction saves energy, minimizes brake and tire wear and cuts down emissions. Weight reduction of vehicles is directly linked to lower CO_2 emissions and improved fuel economy. The benefits of even modest vehicle weight reduction are significant. The vehicle for which we are designing the propeller shaft is "TATA LPT-1613-TC".

1.1 OBJECTIVE OF PRESENT WORK

The main objectives of this present research are listed as follows:

1. To check the design of propeller shaft mathematically with a conventional material.

2. To check also design of propeller shaft mathematically with composite material.

3. To perform FEM analysis with conventional as well as composite materials.

4. To compare the result with mathematical and FEM analysis.

5. Finally optimize the design of propeller shaft which should be compatible and cost effective.

6. Interprets the results of all conditions and analysis.

2. Materials Use for Propeller Shaft

2.1 Carbon steel: Automotive shafts are manufactured by forging process. This means that the propeller shaft meets its rated strength and has required ductility and fatigue properties. The reliability and consistency in the properties of the shaft is required because of the nature of the application. Propeller shafts are designed on the basis of torsional loading. The commonly used materials for manufacturing the propeller shaft is low carbon steel with 10-18 % Chromium and 5-8 % Nickel. The strength of the material used for manufacturing propeller shaft is: Yield Strength (Syt) = 370 N/mm^2.

Table 1: Mechanical properties of carbon steel

Sr. no.	Parameter	Value	Unit
1	Young's modulus	210	GPa
2	Shear Modulus	80	GPa
3	Poisson's ratio	0.3	-
4	Density	7860	Kg/m^3
5	Yield strength	370	MPa

2.2 Aluminum:

Aluminum has a density around one third that of steel or copper making it one of the lightest commercially available metals. The resultant high strength to weight ratio makes it an important structural material allowing increased payloads or fuel savings for transport industries. Pure aluminum doesn't have a high tensile strength. However, the addition of alloying elements like manganese, silicon, copper and magnesium can increase the strength properties of aluminum and produce an alloy with properties tailored to particular applications. When exposed to air, a layer of aluminum oxide forms almost instantaneously on the surface of aluminum. This layer has excellent resistance to corrosion. It is fairly resistant to most acids but less resistant to alkalis.

Table 2: Mechanical properties of aluminum

Sr. no.	Parameter	Value	Unit
1	Young's modulus	72	GPa
2	Shear modulus	27	GPa
3	Poisson's ratio	0.33	-
4	Density	2700	Kg/m^3
5	Yield strength	270	MPa

2.3 Kevlar Epoxy Composite Material: When Kevlar is spun, the resulting fiber has a tensile strength of about 3,620 MPa, and a relative density of 1.44. The polymer owes its high strength to the many inter-chain bonds. These inter-molecular hydrogen bonds form between the carbonyl groups and NH centers. Additional strength is derived from aromatic stacking interactions between adjacent strands. These interactions have a greater influence on Kevlar than the van der Waals interactions and chain length that typically influence the properties of other synthetic polymers and fibers such as Dyneema. The presence of salts and certain other impurities, especially calcium, could interfere with the strand interactions and care is taken to avoid inclusion in its production.

E(X) = 95.71 GPa

E(Y) = 10.45 GPa
E(Z) = 10.45 GPa
Shear modulus in all directions (G) = 80GPa
μ(XY) = 0.34
μ(YZ) = 0.37
μ(XZ) = 0.34
Density = 1042 Kg/m^3

2.4 Glass Epoxy Composite Material:

Density= 2000 Kg/m^3

Young Modulus (X- direction)= 45000 MPa

Young Modulus (Y- direction)= 10000 MPa

Young Modulus (Z- direction)= 10000 MPa

Poisson's Ratio(XY)= 0.3

Poisson's Ratio(YZ)= 0.61

Poisson's Ratio (XZ) = 0.3

Shear Modulus (XY) = 5200 MPa

Shear Modulus (YZ) =3846.2 MPa

Shear Modulus (XZ) = 5000 MPa

2.5 Epoxy Carbon Composite Material:

Density= 1540 Kg/m^3

Young's modulus X direction =2.09E+03 Mpa

Young's modulus Y direction =9450 Mpa

Young's modulus Z direction= 9450 Mpa

Poisson's Ratio (XY) = 0.27

Poisson's Ratio (YZ) = 0.4

Poisson's Ratio (XZ) = 0.27

Shear modulus (XY) = 5500 Mpa

Shear modulus (YZ) =3900 Mpa

Shear modulus (XZ) = 5500 Mpa

3. Technical specification of vehicle:

Model name: TATA LPT-1613-TC

Wheel base: 4225 mm

Power: 100KW at 2400 RPM

Max Torque: 490Nm at 1400 RPM

Weight: 16250 Kg

Length of Propeller shaft (approx.): 2550 mm

4. Design on strength basis.

a. Solid propeller shaft:

When shaft is subjected to axial tensile force the tensile stress is given by,

Tensile stress= $\frac{P}{\pi r^2}$ **(1)**

When shaft is subjected to pure bending moment, the bending stress is given by,

Bending stress= $\frac{32M}{\pi d^3}$ **(2)**

When the shaft is subjected to pure torsional moment, the torsional shear stress is given by

$$\tau = \frac{16M_t}{\pi d^3} \quad \textbf{(3)}$$

When shaft is subjected to combination of loads the principal stress and shear stress are obtained by constructing Mohr's circle.

But as in propeller shaft only torsional shear stresses are acts significantly so we have to design shaft by using eq^n 3 only.

b. Hollow propeller shaft:

The design of hollow shaft consists of determination of correct inner and outer diameters from strength and rigidity basis. Let

$$\frac{D_i}{D_o} = C \tag{4}$$

Where

D_i=inner dia. of hollow shaft.

D_o=outer dia. of hollow shaft.

C=ratio of inner diameter to outer diameter.

When shaft is subjected to pure torsional moment, the torsional shear stress is given by

$$J = \frac{\pi\left(D_o^4 - D_i^4\right)}{32} \tag{5}$$

$$J = \frac{\pi D_o^4\left(1-C^4\right)}{32} \tag{6}$$

$$\tau = \frac{16T}{\pi D_o^3\left(1-C^4\right)} \tag{7}$$

4.1 Calculations for solid propeller shaft

4.1.1 Aluminium

Shear stress

Outside diameter = 95mm

Inside diameter = 57mm

Torque = 490Nm

σyield = 270Mpa

τ = 270/2 = 135 Mpa

According to Torsional formula

T = π/16*τ*D^3

Where,

T=torque

τ=shear stress

D=outside diameter

490*10^3 = π/16*τ*95^3

490*10^3*16/π*95^3=τ

τ = 2.9106 N/mm^2

The actual shear stress of a shaft is less than theoretical shear stress so design is safe.

Shear strain

Shear modulus= shear stress/shear strain

G = τ/e

27*10^3 = 2.9106/e

e = 2.9106/27*10^3

e = 0.0001078

Factor of Safety

$$\text{FOS} = \frac{\text{Maximum stress}}{\text{Working stress}}$$

Mass of aluminium propeller shaft

Density of aluminium rods = 2700 kg/m^3

Density= mass/volume

ρ = m/v

m = ρ*v =ρ*π/4*d^2*L

= π/4*0.95^2*2.550*2700

m = 48.8 kg

Deflection

δ = 5*wl^4/384EI

Where, δ = deflection (mm)

E = Young's modulus (72GPa)

I = Moment of inertia (mm^4)

W = weight (N)

L = length (mm)

δ = (5*48.8*9.81*2.550^4)/(384*72*10^9*(π/64*0.095)^4)

$\delta = 9.155*10^{-4}$ m

Critical Speed

Critical speed = $\sqrt{\text{Acceleration due to gravity} / \text{deflecction}}$

$\omega = \sqrt{g/\delta}$

$\omega = \sqrt{9.81/0.0009155}$

ω =103.515 rad/sec

$Nc = \frac{\omega}{2\pi}$

$N\,c = \frac{103.515}{2\pi}$

Nc = 988.50 rpm

4.1.2 Carbon Steel

Shear stress

Outside diameter = 95mm

Inside diameter = 57mm

Shear Modulus = 80 Gpa

σ_{yield} = 370Mpa

σ= 185Mpa

Torsional Formula

$T = \pi/16*\tau*d_0^3$

T = torque

τ = shear stress

D =outside diameter

$490*10^3 = \pi/16*\tau*95^3$

$\tau = (490*10^3*16) / (\pi*95^3)$

τ = 2.9106 N/mm^2

The actual shear stress of a shaft is less than theoretical shear stress so design is safe.

Shear strain

Shear modulus = $\frac{\text{shear stress}}{\text{shear strain}}$

$G = \tau/e$

$80*10^3 = 2.9106/e$

e = 2.9109 / 80000

$e = 3.63825*10^{-5} = 3.64*10^{-5}$

Mass of carbon steel

Density = $\frac{\text{mass}}{\text{volume}}$

Where, ρ = density

m = mass

v = volume

Density of Carbon Steel = 7860 kg/m^3

$\rho = m/v$

$m = \rho*v$

$m = 7860*(\pi/4*0.095^2)*2.550$

m = 142.069 kg = 142.07kg

Deflection

E = 210Gpa

$\delta = 5*wl^4/384EI$

Where, δ = deflection (mm)

E = Young's modulus (72GPa)

I = Moment of inertia (mm^4)

W = weight (N)

L = length (mm)

$\delta = (5*48.8*9.81*2.550^4) / (384*210*10^9*(\pi/64*0.095)^4)$

$\delta = 9.3157*10^{-5}$ mm

Critical speed of Carbon Steel propeller shaft

$\omega = \sqrt{\text{acceleration due to gravity/deflection}}$

Where,

Nc = critical speed

g = acceleration due to gravity

δ = deflection

$\omega = (9.81)/(9.315*10^{-5})$

ω = 324.52m/s

Nc = $(\omega)/(2*\pi)$

Nc = $(324.52)/(2*\pi)$

Nc = 3098.94 rpm

4.2 Calculations for hollow propeller shaft

4.2.1 Aluminium

Shear stress

Outside diameter = 95mm

Inside diameter = 57mm

Torque = 490Nm

Torsion formula Hollow Shaft

$T = \pi/16*\tau*d0^3*(1-k^4)$

Where, T=torque (N*mm)

τ=shear stress (N/mm^2)

D =outside diameter (mm)

d = inside diameter (mm)

K = diameter ratio (D/d) = 0.6

$490*10^3 = \pi/16*\tau*95^3*(1-0.6^4)$

$\tau = (490*10^3 *16) / (\pi *95^3(1-0.6^4))$

τ = 3.34 Mpa

The actual shear stress of a shaft is less than theoretical shear stress so design is safe.

Shear strain

Shear modulus= shear stress/shear strain

$G = \tau/e$

$27*10^3 = 3.34/e$

$e = 3.34/27*10^3$

e = 0.0001237

Factor of Safety

$$FOS = \frac{Maximum\ stress}{working\ stress}$$

Mass of aluminium

Density of aluminium rods = 2700 kg/m^3

Density = mass/volume

$\rho = m/v$

$m = \rho*v = \rho*(\pi/4*(D-d)^2)*L$

$= (\pi/4*(0.095-0.057)^2)*2.550*2700$

m = 31.2335 kg

Deflection of Aluminium rods

$\delta = 5*wl^4/384EI$

Where, δ = deflection

E = Young's modulus (72GPa)

I = Moment of inertia (mm^4)

W = weight

L = length

D =outside diameter (mm)

d = inside diameter (mm)

$\delta = (5*48.8*9.81*2.550^4) / (384*72*10^9*(\pi/64*(0.095-0.057)^4))$

$\delta = 6.7325*10^{-4}$

Critical Speed =

$$\sqrt{Acceleration\ due\ to\ gravity\ /deflecction}$$

$\omega = \sqrt{g/\delta}$

$\omega = \sqrt{9.81/0.00067325}$

ω =120.711rad/sec

$$Nc = \frac{\omega}{2\pi}$$

$$N\ c = \frac{120.711}{2\pi}$$

Nc = 1152.70 rpm

4.2.2 Carbon Steel

Shear stress

Outside diameter = 95mm

Inside diameter = 57mm

Shear Modulus = 80 Gpa

σ_{yield} = 370Mpa

σ= 185Mpa

Torsional Formula

$T = \pi/16*\tau*d0^3*(1-k^4)$

Where, T = torque (N*mm)

τ = shear stress (N/mm²)

D =outside diameter (mm)

d = inside diameter (mm)

$490*10^3 = \pi/16*\tau*95^3*(1-0.6^4)$

$\tau = (490*10^3 *16) / (\pi *95^3(1-0.6^4))$

τ = 3.34 Mpa

The actual shear stress of a shaft is less than theoretical shear stress so design is safe.

Shear strain

$$\text{Shear modulus} = \frac{\text{shear stress}}{\text{shear strain}}$$

G = τ/e

$80*10^3 = 3.34/e$

e = 2.9109 / 80000

$e = 3.63825*10^{-5} = 3.64*10^{-5}$

Mass of carbon steel

$$\text{Density} = \frac{\text{mass}}{\text{volume}}$$

Where, ρ = density

m = mass

v = volume

Density of Carbon Steel = 7860 kg/m³

ρ = m/v

m = ρ*v

$m = 7860*(\pi/4*(0.095-0.057)^2)*2.550$

m = 90.924 kg

Deflection of Carbon Steel Propeller Shaft

E = 210Gpa

$\delta = 5*wl^4/384EI$

Where, δ = deflection (mm)

E = Young's modulus (72GPa)

I = Moment of inertia (mm⁴)

W = weight (N)

L = length (mm)

$\delta=(5*48.8*9.81*2.550^4)/ (384*210*10^9*(\pi/64*(0.095-0.057)^4)$

$\delta = 4.052*10^{-5}$ mm

Critical speed of Carbon Steel propeller shaft

$$\omega = \sqrt{\text{acceleration due to gravity/deflection}}$$

Where, Nc = critical speed

g = acceleration due to gravity

δ = deflection

$\omega = (9.81) / (4.052*10^{-5})$

ω = 492.008m/s

Nc = (ω) / (2*π)

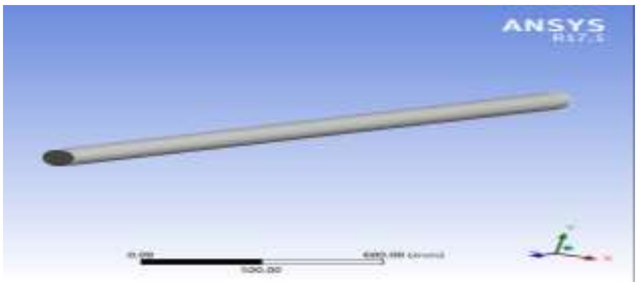
Nc = (492.008) / (2*π)

Nc = 4698.33 rpm

5. Static analysis of solid and hollow propeller shaft:

Simple Structure of solid propeller shaft On ANSYS

- Outside diameter of shaft -95mm
- Inside diameter of shaft-57mm
- Length of shaft -2550mm



Boundary condition applied on solid propeller shaft

- Maximum torque applied -490 N-m
- Speed at which torque is applied -1400 RPM

Analysis based on maximum shear strain:

5.1. Solid shaft

5.1.1 Carbon Steel Fig. shows the maximum shear strain across the length of the propeller shaft for carbon steel, the max. and the min. value of shear strain are (0.000025096-0.0000030119)

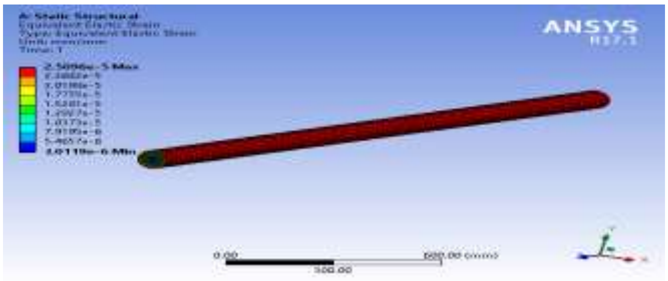


Fig. 5.1.1 Carbon Steel (Maximum Shear Strain)

5.1.2 Aluminium Fig. shows the maximum shear strain across the length of the propeller shaft for aluminium, the max. and the min. value of shear strain(0.00011148-0.000010204)

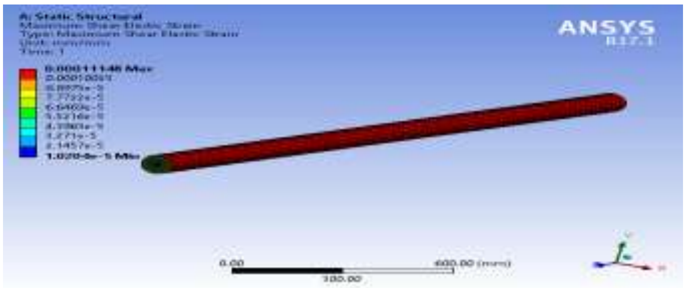


Fig.5.1.2 Aluminium (Maximum Shear Strain)

5.1.3. Carbon Epoxy Fig. shows the maximum shear strain across the length of the propeller shaft for epoxy carbon, the max. and the min. value of shear strain are (0.00044968-0.0000362)

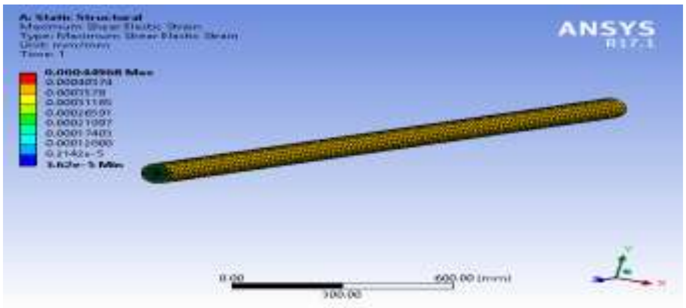


Fig.5.1.3 Epoxy Carbon (Maximum Shear Strain)

5.1.4 Epoxy Glass Fig. shows the maximum shear strain across the length of the propeller shaft for epoxy carbon, the maximum and the min. value of shear are (0.00076890.000066352)

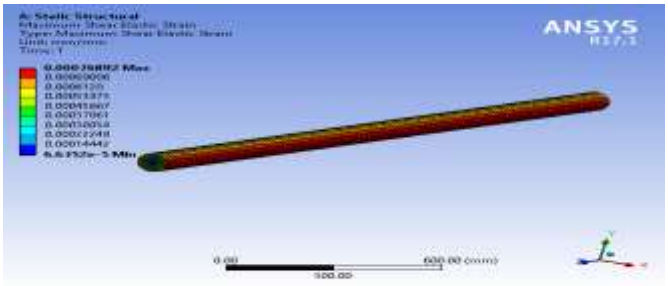


Fig.5.13 Glass Epoxy (Maximum Shear Strain)

5.1.5 Kevlar Epoxy Fig. shows the max. shear strain across the length of the propeller shaft for Kevlar epoxy, the max. and the min. value of shear strain are0.00075838-0.000064433)

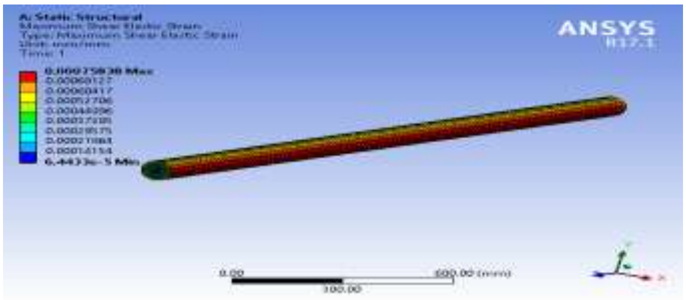


Fig.5.1.5 Kevlar epoxy (Maximum shear strain)

For Hollow shaft:

5.2.1 Carbon Steel Fig. shows the max. shear strain across the length of the propeller shaft for carbon steel, the max. and the min. value of shear strain are (0.0000542020.00002219)

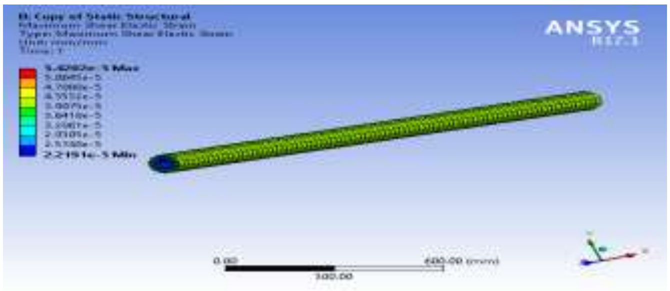


Fig.5.2.1 Carbon Steel (Maximum Shear Strain)

5.2.2 Aluminium Fig. shows the max. shear strain across the length of the propeller shaft for aluminium, the max. and the min. value of shear strain are (0.000160940.00006602)

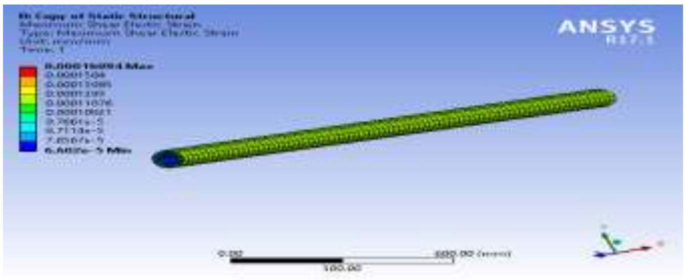


Fig.5.2.2 Aluminium (Maximum Shear Strain)

5.2.3 Carbon Epoxy Fig. shows the max. shear strain across the length of the propeller shaft for carbon epoxy, the max. and the min. value of shear strain are (0.0017621-0.00022273)

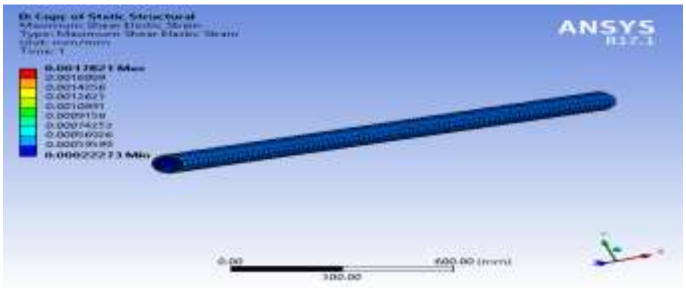


Fig.5.2.3 Carbon Epoxy (Maximum Shear Strain)

5.2.4 Epoxy Glass Fig. shows the max. shear strain across the length of the propeller shaft for epoxy glass, the max. and the min. value of shear strain are (0.00092994-0.00035855)

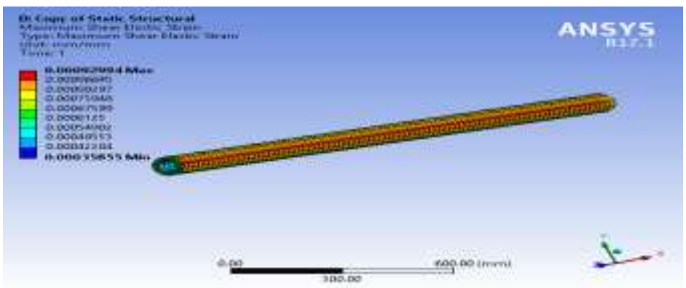


Fig. 5.2.4 Epoxy Glass (Maximum Shear Strain)

5.2.5 Kevlar Epoxy Fig. shows the max. shear strain across the length of the propeller shaft for Kevlar epoxy carbon steel, the max. and the min. value of shear strain are (0.00092994-0.00035855)

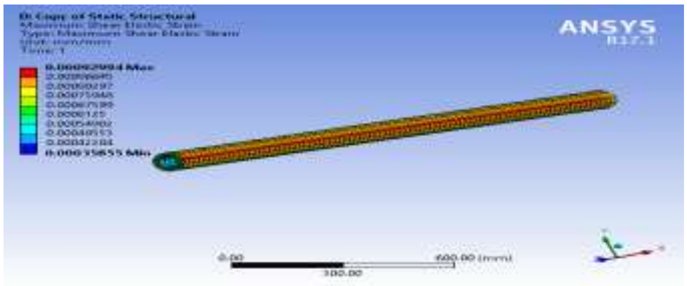


Fig.5.2.5 Kevlar Epoxy (Maximum Shear Strain)

6. Comparison of Different Material of Propeller Shaft According to maximum elastic shear strain

Solid Propeller Shaft

Table 6.1 comparison of maximum elastic strain of solid shaft

Sr. no	Type of materials	Maximum elastic shear strain
1	Carbon steel	0.000111
2	Aluminum	0.0000347
3	Carbon epoxy	0.00044
4	Epoxy glass	0.000768
5	Kevlar epoxy	0.000758

From above observation we can easily conclude that maximum elastic strain in aluminium is smaller than other materials so according to maximum elastic strain aluminium is best suited material.

Hollow Propeller Shaft

Table 6.2 comparison of maximum elastic strain of hollow shaft

Sr. no	Type of materials	Maximum elastic shear strain
1	Carbon steel	0.000160
2	Aluminum	0.0000544
3	Carbon epoxy	0.000178
4	Epoxy glass	0.000929
5	Kevlar epoxy	0.000914

From above observation we can easily conclude that maximum elastic strain in aluminium is smaller than other materials so according to maximum elastic strain aluminium is best suited material.

7. Conclusions

- The usage of composite materials has resulted in considerable amount of weight saving in the range of 81% to 72% when compared to conventional steel drive shaft.

- Taking into account the weight saving, deformation, shear stress induced and resultant frequency it is evident that composite has the most encouraging properties to act as replacement to steel
- The present work was aimed at reducing the fuel consumption of the automobiles in particular or any machine, which employs drive shaft, in general. This was achieved by reducing the weight of the drive shaft with the use of composite materials. This also allows the use of a single drive shaft (instead of a two piece drive shaft) for transmission of power to the differential parts of the assembly.
- Apart from being lightweight, the use of composites also ensures less noise and vibration.
- If we consider cost of glass/epoxy composite, it is slightly higher than steel but lesser than carbon/epoxy.
- The composite drive are safer and reliable than steel as design parameter are higher in case of composite.

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