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Structural Analysis of Steel and Composite Drive Shaft

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***Abstract* - The main objective of this research is to design automotive drive shaft of reduced weight and more strength through parametric analysis. The weight reduction of the drive shaft plays an important role in overall performance of the vehicle. Failure of drive shaft, subjected mainly occurs due to bending natural frequency and bending stresses which are directly related to weight of the drive shaft. Components for automobiles are made of composite materials for being corrosion-free, high stiffness, produce complex geometries, light in weight, and absorb more impact energy. The current research includes structural analysis on drive shaft of Truck model-6DT120, H-Series Ashok Leyland Engine. Drive shafts with different materials and internal geometries are investigated and compared. The results show that internal geometries have significant effect on the resultant stresses. In addition, use of composite material with appropriate internal geometry significantly reduces the induced stresses and the drive shaft's overall weight.**

Keywords: Internal geometry, Drive shaft, Structural analysis, composite material.

I. INTRODUCTION

Drive shaft is a component that is utilized to transmit torque from the gearbox to the differential or rear axle. Torque is carried through drive shafts, they experience shear stress and torsion, which is equal to the variance between the input torque and the load. They must consequently be capable of withstanding the load without adding excessive weight, which lead to increasing its inertia [11]. In 1899the term "drive shaft" was used to describe transmission of power from wheels to driven machinery utilizing universal joints [23]. The propeller is another name for the vehicle's driving shaft because, apart from transferring rotating motion from front to rear of a vehicle, these shafts also move vehicle ahead [18]. Many applications, such as cooling towers, pumping sets, aircraft, Ships, trucks, and cars, utilize drive shafts as power transmission tubing [10]. Material Construction for the shaft normally uses high-quality steel of grade SM45C [8].Steel drive shafts longer than 2000 mm are produced in two sections, in order to raise the basic natural frequency, which has an inverse relationship with length squared and proportionate to the specific modulus's square root [17]. Composite material refers to material made up of two or more entities. The major distinction between a composite and an alloy is that a composite's component elements are insoluble in one another while yet sustaining their original properties [1], It's possible that advancements in composite material properties, as well as new production technologies, have broadened its application rang [5].It has capacity to create complex geometries, light in weight, high specific stiffness, and zero corrosion [22].

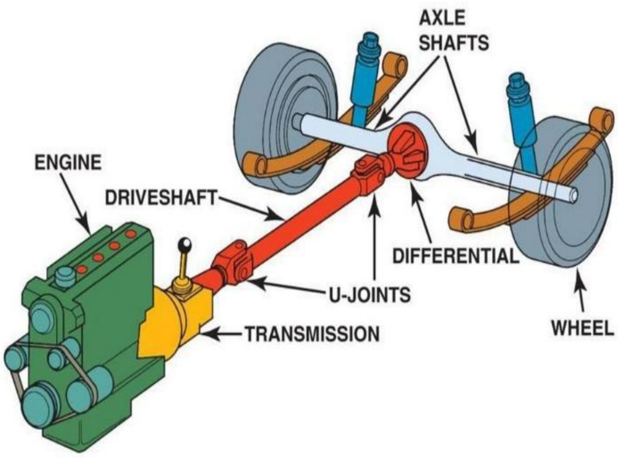

Figure 1: Typical rear-wheel-drive power train arrangement

II. LITERATURE REVIEW

In literature journals and researches different approaches have been employed to decrease weight as well as strengthen the drive shaft, some of them are discussed as follows.

CH.Mani deep and E. Raja (2022) developed a single piece steel (Cr–Mo SCM440) drive shaft using CAD tool. FEM was used for static analysis and free vibration. Results were compared with the propeller shaft made of carbon and glass epoxy composites. Concluded that using carbon epoxy offered better results from steel and glass epoxy [5].

Akash Devendra Rathod (2021) compared the results of conventional steel and other composite materials for drive shaft. The weight of composite material was 82.3% less than steel shaft, the deformations due to stress induced were much less in composite material compared to steel, he concluded that out of all the selected composite material, carbon/epoxy is the best material for the application of propeller shaft [15].

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An, K., Jeong, H., Lee & S.K (2021) compared the vibration reduction performance of the DMDD with that of the SMDD. Finally, the DMDD is applied to the drive shaft of a passenger car, and its effect on vibration reduction is confirmed in a vehicle test [4].

Reportlinker.com (2022) announces the release of the report that the global automotive drive shaft market is expected to grow from $15.12 billion in 2021 to $15.97 billion in 2022 at a compound annual growth rate (CAGR) of 5.6%. The automotive drive shaft market is expected to grow to $19.99 billion in 2026 at a compound annual growth rate (CAGR) of 5.8% [3].

Mohan raj K S (2019) utilized composite materials with the optimum laminate bonding angles for the identical boundary conditions, a single piece shaft was analyzed. In this study, the genetic algorithm was utilized to reduce the time required for choosing the composite material and layer wrapping techniques [23].

Balakumaran1, K. Nithieskumar2 (2019) designed and analyzed hexagonal half drive shaft instead of conventional telescopic half shaft made of splined plungers. This shaft employed in an (ATV) was found to be strong, durable, and effective [7].

Ramchandra D Patil, Dr. D. M. Patel (2019) carbon fiber epoxy composite layer was co-cured on the inner surface of an aluminum tube rather than wrapping on the outer. The hybrid aluminum/composite drive shaft's design characteristics were optimized to reduce weight and boost torque capacity compared to a traditional two-piece steel drive shaft [5].

S. Mohan and M. Vinoth (2016) a one-piece composite drive shaft for a rear-wheel drive car was constructed using High Strength Carbon fiber composites with the goal of minimizing shaft weight while meeting constraints and limitations. Utilizing composite materials has brought forth remarkable weight reduction ranging about 70% to 63% [1].

V. S. Bhajantri1, S. C. Bajantri2, and others (2014) regression analysis was used in order to find relationships between factors such stresses created in each layer, layer deflection, and the natural frequencies of the composite shaft [11].

Arun Ravi (2014) Diameters of different sizes made of steel and composite materials were chosen for investigation, and recommended the optimal diameter to be in between 100mm and 50mm for a hollow shaft. The propeller shaft's mechanical characteristics were treated as linear elastic, isotropic, homogeneous [19].

Nimaish A. Patel1, M. Patel2, Prof A. B. Patel3 (2013) compared several composite materials using ANSYS, such as E-glass, Boron and Kevlar epoxies, for use in shafts [18].

Parshuram D1, Sunil 2 (2013),utilized FEA to calculate deflection, stresses under applied loads, and natural frequencies of drive shaft modeled in CATIA using composite materials for drive shaft as it has been employed in auto-mobile other components [22].

Harshal Bankar1, Viraj Shinde2, P. Baskar3 (2013) the study was performed for three distinct ply orientations of the composites in order to recommend the most appropriate ply orientation provided the greatest weight reduction and better strength of drive shaft [2].

Asmamaw Gebresilassie (2012) torsion load was studied theoretically and numerically on the test specimens. Torsional deflections are derived for each torque value after applying torque and boundary conditions. The results reveal that there is a linear correlation between torque with deflection, torque with stress, and torque with strain [8].

M.A.K. Chowdhuri1, R.A. Hossain 2(2010) the suggested design was subjected to a progressive failure analysis utilizing the program "PROMAL." Among many designs, a drive shaft made of glass-epoxy laminate with a stacking sequence of (0° /90° /0° /45° /90° /-45°) is chosen. Because it meets all of the specifications for a drive shaft and will catastrophically don’t fail [6].

In the literature, it is found that researchers have focused on material selection and conversion of two-piece drive shaft to single piece drive shaft in order to increase bending natural frequency, lighten and strengthen the drive shaft. However, they have not analyzed the different internal geometries of drive shafts with steel and the composite material for further improvements which is a scope of this research.

III. PROBLEM STATEMENT AND OBJECTIVE

Drive shaft is among the most essential components of a vehicle. A drive shaft must be both durable enough to withstand the engine's torque and light enough to lower the vehicle's total weight which is greatly desired objective. Increased weight of drive shaft may cause bending natural frequency and bending stresses that leads the drive shaft toward failure. Based on their geometrical construction, drive shafts may be classified into three groups: single piece, two-piece, and three-piece drive shafts. Drive shafts made of conventional material are typically split into two pieces to increase the fundamental bending natural frequency because the basic natural frequency has an inverse relationship with length squared and proportionate to the specific modulus’s

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square root. Three universal joints, a bearing in the middle and the two-piece steel drive shaft is comprised up by a bracket, which increases the weight of the vehicle as shown in Figure 2. Drive shafts are carriers of torque and subject to torsion and shear stress, equivalent to the difference between the input torque and the load. They must therefore be strong enough to bear the stress, whilst avoiding too much additional weight as that would in turn increase their inertia. Hence, the Drive Shaft must be strong enough and light weight to absorb torsional forces and increase bending natural frequency. The objective of this research is "To investigate the Structural analysis of Steel and Different Composite Drive Shaft By changing internal diametric Geometry of Drive Shaft".

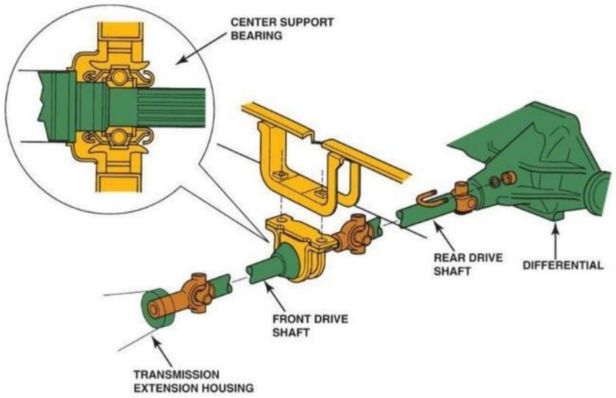

Figure 2: Two-piece steel drive shaft

IV. RESEARCH METHODOLOGY

Design calculation for 3D drive shaft Dimensions modeling taken from report [1] and modelled accordingly using Solid Works for steel and composite materials. Boundary conditions, meshing and Structural analysis are performed using Solid Works 2022 by selecting different types of material taken from references [1, 2, 5 & 15]. Model is validated with the results in a report of Middle-East Journal of Scientific Research [1].After making models of different internal geometry for driveshaft of the same dimensions and Structural analysis are applied on the drive shafts. Results are compared and the near optimal design with reference to material and geometry is presented.

V. STRUCTURAL ANALYSIS

Material selection and Modelling of Driveshaft will be carried out in this Section on which we will use Solid Works 2022 to carry out static structure analysis. We shall adhere to the process of methodology as described step by step in the previous section.

Material Selection and its Mechanical Properties

Material Selection

Material commonly used for construction of Drive shaft is high quality steel of grade SM45C. In Composite Materials; Carbon Fiber-Epoxy, is chosen as the optimal material for the development of composite drive shafts [1].

Mechanical Properties

Table 1: HS Carbon/Epoxy

S.No	Mechanical properties	Units	Symbols	Value
1	Density	Kg/m	ρ	1600
2	Shear modulus	Gpa	G	70
3	Poisson's ratio		υ	0.3
4	Young's modulus	Gpa	E	210
5	Shear strength	Mpa	Ss	420

Table 2: Steel SM45C

S.No	Mechanical properties	Units	Symbols	Value
1	Density	Kg/m	ρ	7600
2	Poisson's ratio		υ	0.3
3	Yield strength	MPa	Sy	370
4	Young's modulus	GPa	E	207
5	Shear modulus	GPa	G	80
6	Shear strength	MPa	Sx	275

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Design Calculation of Drive Shaft

The engine Specification of Truck model 6DT120, H Series Ashok Leyland Engine is shown in Table 3 [1].

Table 3: Specifications of Engine

Truck model 6DT120, H Series Ashok Leyland Engine:			
Max. Power *(P)*	Speed *(N)*	Max Torque *(T)*	Length *(L)*
132kW	1200-1600rpm	660Nm	1800mm

Following values have been calculated in order to fulfill the basic design criteria of hollow drive shaft shown in Table 4.Torsional Bucking and Natural Bending frequency both are in safer side of engine's maximum torque (T) and Speed (N) respectively.

Table 4: Basic design criteria

Steel	
Torsional Buckling *(Tb)*	Natural bending frequency *(fnb)*
239.27KN-m	56.70Hz
Carbon fiber (Composite)	
Torsional Buckling *(Tb)*	Natural bending frequency *(fnb)*
242.79KN-m	124.49Hz

The inner diameter *(Di)* and outer diameter *(Do)* have been calculated by using the PSG data book of design, so the diameters satisfy both stiffness and strength of the material of the drive shaft.

Table 5: Dimensions of Drive Shaft

Outer dia *(Do)*	Inner dia *(Di)*	Shaft Thickness *(t)*	Shaft's Length *(L)*	Shaft Radius *(r)*
70mm	56mm	7mm	1800mm	31.5mm

CAD Modeling of Drive Shaft

All the CAD modelling and Simulation is done using SolidWorks 2022. Dimension of Hollow drive shaft is mentioned in the previous section. Following are the 3d CAD modelling of propeller or drive shaft according to material as shown in Figure 3.

Figure 3: CAD modeling of drive shaft of different material

Following are the CAD modelling of drive shaft according to internal diametric geometry as shown in Figure 4. The edges of Hexagonal and Octagonal geometry are filleted in order to avoid the stress concentration that may lead to the failure of shaft.

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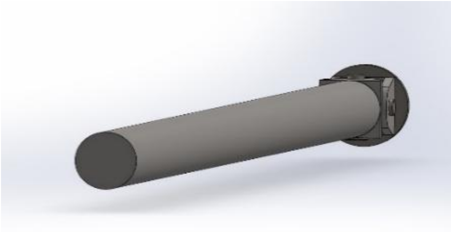

Figure 4(a): Solid Drive Shaft

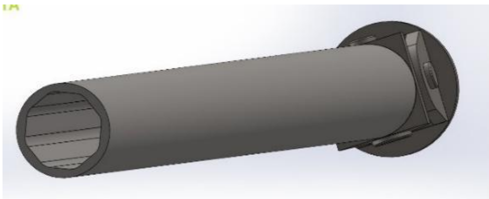

Figure 4(b): OCTID Drive Shaft

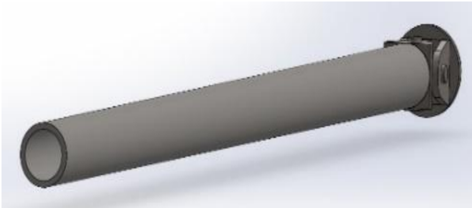

Figure 4(c): Hollow Drive Shaft

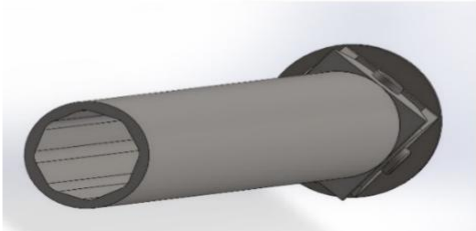

Figure 4(d): Hollow Drive Shaft

Figure 4: Cross section views of drive shafts according to internal diametric geometry

Boundary Conditions and Meshing

Drive shaft is fixed at one end and torque of 660Nm is applied at the other end as shown in Figure 5.

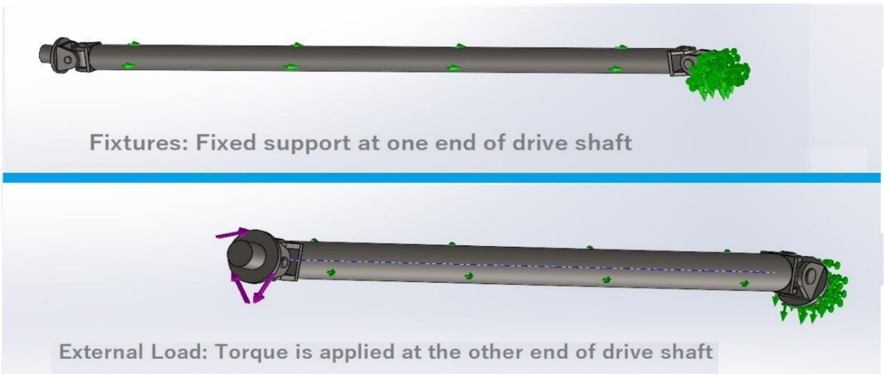

Figure 4: Boundary conditions applied on drive shaft

After boundary conditions, mesh is been generated as shown in Figure 6. Mesh details including: mesh quality: high, total nodes: 23938, total elements: 11893, maximum element size: 38.5191mm, and minimum element size: 3.82683mm.

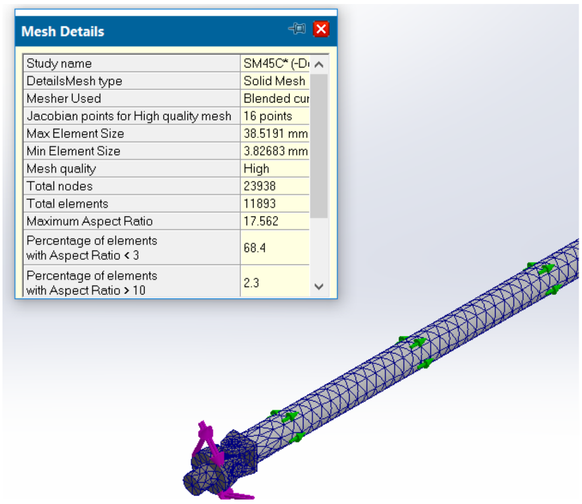

Figure 6: Mesh Details

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VI. RESULTS AND DISCUSSION

Initially the results of the selected materials are carried out with analyzing hollow drive shaft, solid shaft, hexagonal internal diametric (HEXID) drive shaft and octagonal internal diametric (OCTID) drive shaft. Then, the results are compared in order to find out the better results.

Von-mises Stresses in drive shafts

Von-mises Stresses induced under the subject load in Hollow, Solid, HEXID and OCTID drive shafts are being discussed. Von-mises Stresses induced under the subject load in Hollow drive shaft with selected material is shown in the Figure 7(a). The Maximum and Minimum Von-Mises stresses induced in SM45C steel comes out to be 337.826MPa and 0.0016MPa respectively as shown in Table6.Von-mises Stresses induced under the subject load in Solid drive shaft in the selected material are shown in the Figure7(b). The Maximum and Minimum Von-Mises stresses induced in SM45C steel comes out to be 333.295MPa and 0.0017MPa respectively as shown in Table 6.

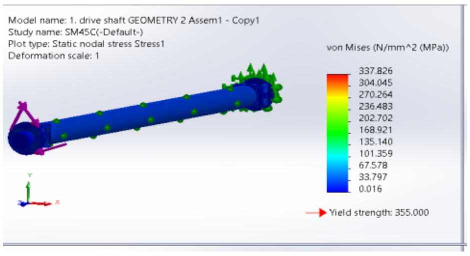

Figure 7(a): Hollow Drive Shaft

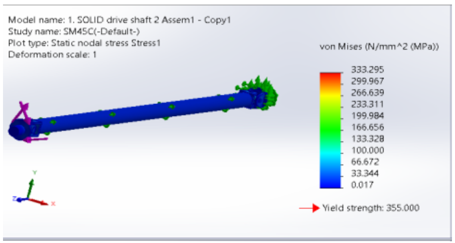

Figure 7(b): Solid Drives Shaft

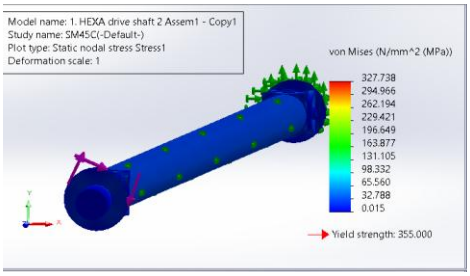

Figure 7(c): HEXID Drive Shaft

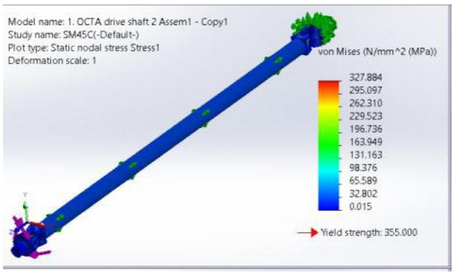

Figure 7(d): OCTID Drive Shaft

Figure 7: Von-Mises Stresses induced in (a), (b), (c) and (d)

Von-mises Stresses induced under the subject load in HEXID drive shaft in the selected materials are shown in the Figure 7(c).The Maximum and Minimum Von-Mises stresses induced in SM45C steel comes out to be 327.74MPa and 0.015MPa respectively as shown in Table 6.Von-mises Stresses induced under the subject load in OCTID drive shaft in the selected materials are shown in the Figure 7(d). The Maximum and Minimum Von-Mises stresses induced in SM45C steel comes out to be 327.88MPa and 0.015MPa respectively as shown in Table 6.

In the comparison of stresses induced in Hollow shaft, Solid shaft, HEXID and OCTID shafts Shown in Table 6, it is observed that the HEXID and OCTID drive shafts giving comparatively better results in reduction of induced Von-Mises stresses. SM45C steel and Carbon fiber Epoxy are nearly similar in strength, Carbon fiber Epoxy helps to produce complex shapes and lighter in weight.

Table 6: Von-Mises Stress Comparison for Different Shafts

Maximum Von-mises stress (MPa)				
Material	Hollow Drive Shaft	Solid Drive Shaft	HEXID Drive Shaft	OCTID Drive Shaft
SM45C Steel	337.83	333.30	327.74	327.88
Minimum Von-mises stress (MPa)				
Material	Hollow Drive Shaft	Solid Drive Shaft	HEXID Drive Shaft	OCTID Drive Shaft
SM45C Steel	0.0016	0.0017	0.015	0.015

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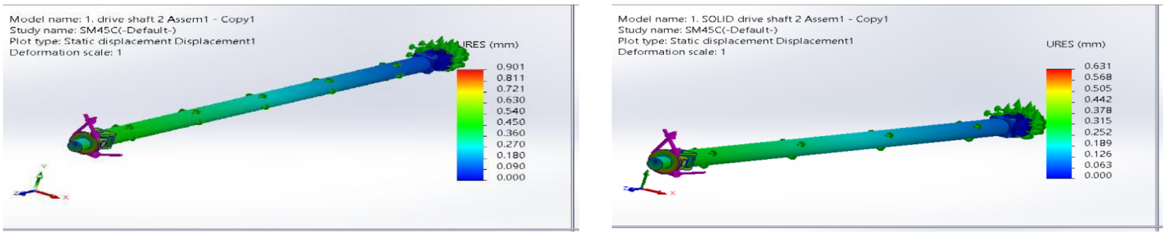
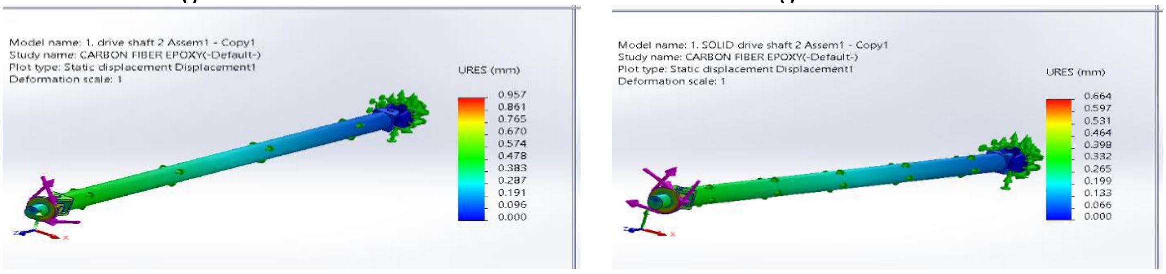
Deflection in drive shafts

Deflection due to the subject load in Hollow, Solid, HEXID and OCTID drive shafts are being discussed. Deflection in Hollow drive shaft of the selected materials is shown in the Figure 8. The maximum deflection in SM45Csteel and Carbon Fiber Epoxy comes out to be 0.901mm and 0.957mm respectively as shown in Table 7. Deflection due to the subject external load in Solid drive shaft of the selected materials is shown in the Figure 8. The maximum deflection in SM45C steel and Carbon Fiber Epoxy comes out to be 0.631mm and 0.664mm respectively as shown in Table 7.



(i)Material: SM45C Steel (i)Material: SM45C Steel

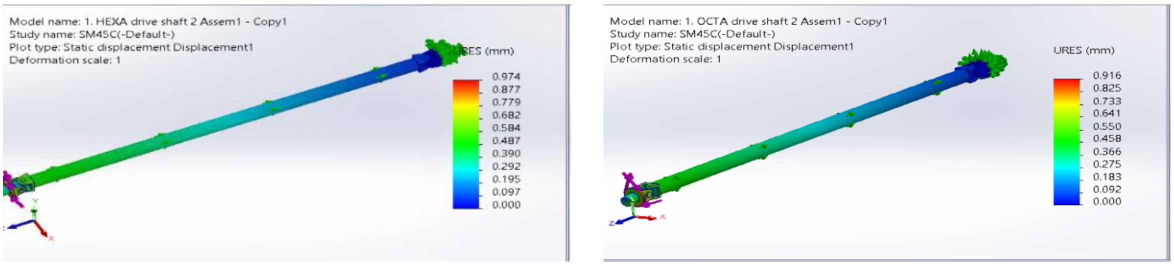


(ii) Material: Carbon Fiber Composite (ii) Material: Carbon Fiber Composite

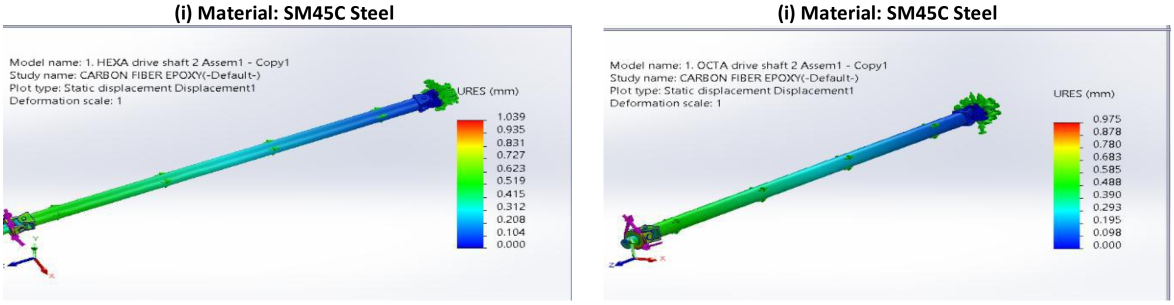
Figure 8(a): Hollow Drive Shafts Figure 8(b): Solid Drive Shaft

Figure 8: Deflection in (a) Hollow Drive Shafts and (b) Solid Drive Shaft w.r.t material (i) & (ii) respectively

Deflection due to the subject external load in HEXID drive shaft in the selected materials are shown in the Figure 9. The Maximum deflection in SM45C steel and Carbon Fiber Epoxy comes out to be0.974mm and 1.039mm respectively as shown in Table 7. Deflection due to the subject external load in OCTID drive shaft of the selected materials is shown in the Figure 9. Values of the maximum deflection in SM45C steel and Carbon Fiber Epoxy are shown in Table 7.



(i) Material: SM45C Steel (i) Material: SM45C Steel



(ii) Material: Carbon Fiber Composite (ii) Material: Carbon Fiber Composite

Figure 9(a): HEXID Drive Shafts Figure 9(b): OCTID Drive Shaft

Figure 9: Deflection in (a) HEXID Drive Shaft and (b) OCTID Drive Shaft w.r.t Material (i) & (ii) respectively

Deflection in SM45C steel and Carbon Fiber Epoxy having closer values however the Solid shaft has lowest deflection but it increases both the cost, material as well as its higher mass may results in bending natural frequency and fuel efficiency will decrease. By studying the Von-mises stresses and Deflection comparison Tables. It is observed that in Von-Mises Stresses there is

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minor trifling lower value difference between HEXID and OCTID drive shafts but rise in deflection can be seen in HEXID drive shaft compared to OCTID drive shaft.

Table 7: Comparison of deflection in Different shaft geometry and materials

Deflection (mm)		
Material	**SM45-C Steel**	**Carbon Fiber- Epoxy**
Hollow Drive Shaft	0.90	0.96
Solid Drive Shaft	0.63	0.66
HEXID Drive Shaft	0.97	1.04
OCTID Drive Shaft	0.92	0.98

Increased mass of drive shaft decreases bending natural frequency of the drive shaft and increase in bending stresses, Carbon fiber Epoxy has higher Modulus of Elasticity and rigidity as well as lesser density than SM45C steel which makes it higher in strength and lighter in weight also has the ability to produce complex shapes. HEXID and OCTID drive shafts are comparatively lighter in weight than Hollow drive shaft. HEXID drive shaft is lighter in weight but OCTID drive shaft possess higher strength as shown in the Comparison of Mass for Different Geometries of shaft with the selected Materials in the below Table 8.Light weight of drive shaft also helps to lower the vehicle's total weight as well as improves vehicle's fuel efficiency.

Table 8: Comparison of Mass with Different Geometries

Mass (Kg)				
Material	Hollow Drive Shaft	Solid Drive Shaft	HEXID Drive Shaft	OCTID Drive Shaft
SM45C Steel	26.28	59.97	23.26	24.67
Carbon Fiber Epoxy	11.32	18.41	10.68	10.98

It also can be noticed that a Solid Carbon fiber shaft can be used instead of hollow SM45C steel Shaft because mass of Carbon Fiber Solid Shaft is 18.41Kg and Hollow steel shaft is 26.28Kg which is comparatively 7.87Kg heavier but final decision cannot be taken only on mass-based observation until all the other Results and parameters are compared. Hence, the structural analysis comparison Table9 can be seen as below.

Table 9: Structural Analysis Results

<table>
<tr><td rowspan="2">Material</td><td rowspan="2">Max Von-mises stress (MPa)</td><td>Hollow Drive Shaft</td><td>Solid Drive Shaft</td><td>HEXID Drive Shaft</td><td>OCTID Drive Shaft</td></tr>
<tr><td>337.83</td><td>333.30</td><td>327.74</td><td>327.88</td></tr>
<tr><td rowspan="4">SM45C Steel</td><td>Deformation (mm)</td><td>0.90</td><td>0.63</td><td>0.97</td><td>0.92</td></tr>
<tr><td>Max Shear Stress (MPa)</td><td>109.70</td><td>109.30</td><td>109.00</td><td>108.80</td></tr>
<tr><td rowspan="2">Mass (kg)</td><td>26.28</td><td>59.97</td><td>23.26</td><td>24.67</td></tr>
<tr><td>100%</td><td>228.2%</td><td>88.5%</td><td>93.9%</td></tr>
<tr><td rowspan="4">Carbon Fiber Epoxy</td><td>Deformation (mm)</td><td>0.96</td><td>0.66</td><td>1.04</td><td>0.98</td></tr>
<tr><td>Max Shear Stress (MPa)</td><td>109.09</td><td>108.69</td><td>108.35</td><td>108.22</td></tr>
<tr><td rowspan="2">Mass (kg)</td><td>11.32</td><td>18.41</td><td>10.68</td><td>10.98</td></tr>
<tr><td>100%</td><td>162.7%</td><td>94.4%</td><td>97.0%</td></tr>
</table>

After study and investigation of analysis and results it has been observed that Solid drive shaft Carbon fiber composite material gives better results compared to Hollow drive shaft with SM45C Steel as shown in Table 9, but basic purpose of selecting composite drive shaft is to compared with hollow drive shaft with SM45C steel, having nearly same strength with a significantly light weight. It has been observed that HEXID and OCTID drive shafts give better results compared to other geometries. Moreover, the OCTID drive shaft with Carbon fiber Composite material has better results when compared to HEXID drive shaft as shown in Table 9.

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VII. CONCLUSION

The best materials for high stiffness and light weight were chosen from the citation study, and different internal diametric geometries were modelled in SolidWorks 2022 and investigated in order to find the best internal diametric geometry with the best material. Hence, after performing and studying the structural analysis of materials along with geometries the results were compared. The selected Materials are: SM45C steel, Carbon fiber Epoxy, while the geometries are: Hollow, Solid, HEXID and OCTID. After the comparison it is concluded that changing the internal diametric geometry can cause a significant impact on stresses and weight of drive shaft. Utilizing composite materials would make the drive shaft lighter in weight and higher in strength. OCTID drive shaft of Carbon Fiber Epoxy Composite material has comparatively better results in Von-mises stresses, Deflection and weight of drive shaft shown in Solid Works Simulation. Therefore, OCTID (Octagonal Internal Diametric) Geometry with Carbon fiber Epoxy Composite Material is suggested for Drive Shaft Design.

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