Material optimization and analysis of Composite propeller shaft and its behavior under Torsional and Bending Loading: A Research

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Abstract – Automobiles which correspond to design with rear wheel drive and front engine installation has transmission shafts. The weight reduction of the drive shaft can be achieved without increase in cost and decrease in quality and reliability. To achieve such criteria, we need to design composite drive shaft with less weight to increase the first natural frequency of the shaft. This work deals with the replacement of a conventional steel drive shaft with High Strength light weight Composite shafts for an automobile application. In this Study, the drive shaft of a vehicle will be considered for testing and analysis. The modeling and analysis will be performed using CREO and ANSYS software respectively. The analysis will be done for both the materials.

***Key Words*: Torsional Strength, Drive Shaft, Optimization, FEA, Matrix Composites.**

1. INTRODUCTION

1.1 Drive Shafts: Drive shafts are mechanical components that are widely used in vehicle powertrain systems to transmit torque and rotation between different components which are not in line or cannot be connected directly. Drive shafts must have elements, such as splines, gears, grooves and oil galleries, mounted or manufactured on to transmit power or deliver lubricant. The shaft must be strong enough to bear the stress for short term loading, the stress state is quasi static and the drive shaft should be designed to prevent plastic deformation; for long term loading, the stress state is dynamic therefore the shaft must be designed for millions of stress cycles. It is a driveshaft that is designed for applications that call for increased horsepower, so you can hit the road with confidence. Reduced overall weight and rotating mass, delivers improved driving performance and Provides quicker acceleration.

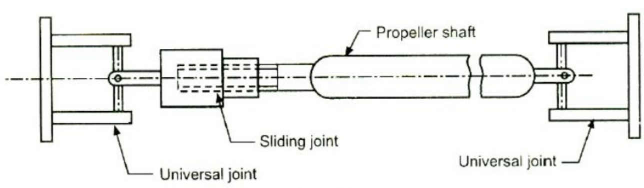


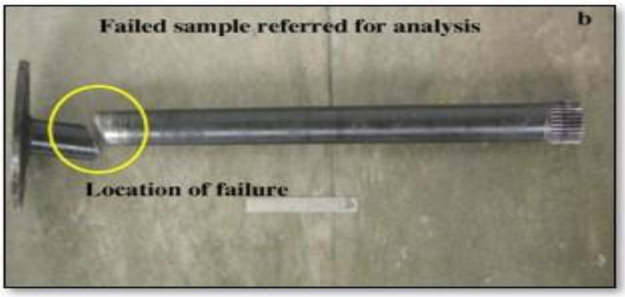
Fig -1: Propeller shaft

1.2 Failure modes of Shaft

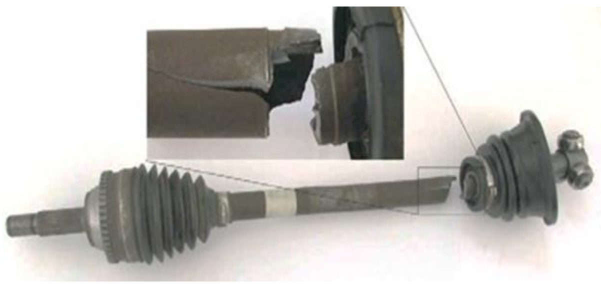
The main purpose of shaft is that it must transmit the torque from transmission of Differential Gear Box. As its aim to transfer speed, it should be capable of rotating at fast speed as required by the vehicle. It must operate through constantly changing angles between the transmission, differential and axels. Due to its functional conditions, the shaft is subject to torsional and bending forces under operating conditions.

1.3 Causes of failures of Drive Shafts:

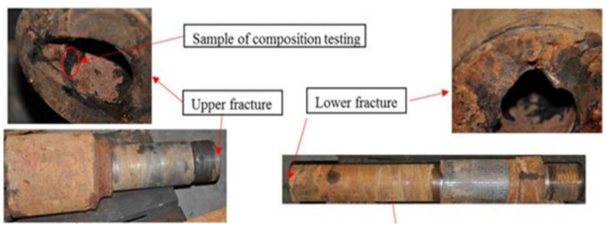
1.3.1 Shear Failure:



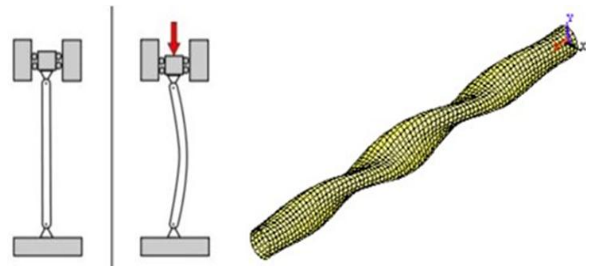
1.3.2 Rupture Failure



1.3.3 Fracture Failure



1.3.4 Buckling Failure



1.4 Problem Definition

"To design and analyze the automobile drive shaft by using matrix composite material so as to increase the torsional strength." The Drive shaft is made of heavy-duty steel due to its tremendous amount of strength and applicability. But to overcome this strength, the material quantity is increased which affects the torsional stability of the component, thereby affecting the power transmission capacity. Hence, in this case, an attempt is made to design analysis and optimize the drive shaft which is made of steel. The objectives of this research are,

-Finite Element Stress and Deformation analysis to obtain the torsional strength of material.
-To select the Best possible material so as to replace it with the Steel.
-To determine the torsional strength of composite materials.
-To reduce the weight of Shaft.
-To increase the Strength of Shaft.

2. Literature review

[1] The shaft made of steel and fabric reinforcement added to the shaft made the shaft advantageous in weight reduction.

[2] The forged steel shafts have its own advantages and disadvantages in implementation and use. The paper describes the chemical composition and material properties of forged steel.

[3] The shaft meets with the fracture due to bumping nature of road condition. The material discuss in the paper is 42CrMo4 grade of steel.

[4] The parameters of impact are discussed along with the experimental test of Izod Test.

[5] [6] The shaft is designed using carbon fibre and various failure criteria's which help in designing of shaft.

[7] Shaft of Maruti Suzuki Omni and various Design Considerations of Shaft subjected to different moments.

[8] Conducts the buckling analysis of composite drive shaft for automotive applications.

[9] The work carried out on the composite drive shafts which are used in the automotive applications; fabrication techniques and materials used in the fabrication of composite shafts, finite element analysis on composite shaft and steel shaft.

[10]. An attempt is made to evaluate the suitability of composite material such as E-Glass/Epoxy and Carbon/Epoxy for the purpose of automotive transmission applications.

[11]. The research work is to replace conventional steel material two-piece three universal joints drive shaft with composite material single-piece drive shaft. Single-piece drive shaft is designed in Solid Edge and Pro-E software.

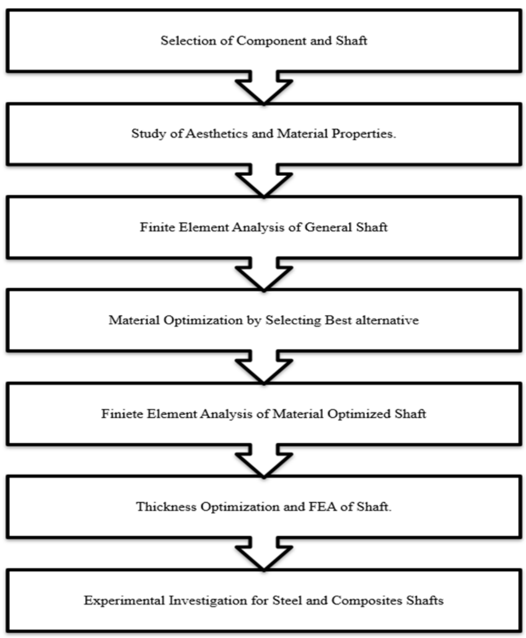
[12] The modeling of composite drive shafts is made in analysis software ANSYS.

[13] In the process of damage accumulation, the damage first appears at the stress concentration of fibre matrix.

[14] In the present work, Composite propeller shaft of E Glass/Epoxy is made identical as steel propeller shaft of same torque carrying capacity. The propeller shaft is designed for 2 Ton truck with torque capability of 1500 Nm.

[15] The tensile and torsion experiments were carried out on 3D braiding composite shafts with different braiding angles, and AE was used to monitor the damage evolution during the experiments.

3. Methodology



4. Component Specifications

In this case study, the design and analysis of propeller shaft is considered. The shaft considered for case study is selected from Maruti Omni. Maruti Suzuki Omni is 5 seating Capacity vehicles depending on the seating arranged. Specifications of car are given in *Table 1*. In this study Maruti Omni car drive shaft is taken for study. For the understanding loading and boundary conditions. The Current Shaft is made of Steel SM45C. SM45C is quenched and tempered steel; it belongs to low carbon, low carbon chromium, molybdenum and nickel. The chemical composition and material properties are shown in *Table 2*. And *Table 3*.

Parameter	Value
Max Power	8.04 bhp @ 3400 rpm
Max Torque	6.1 kgm @ 3000 rpm
Overall Length (mm)	3310
Overall Width (mm)	1410
Overall Height (mm)	1640
Kerb Weight (Kgs)	785 Kg
Gross Vehicle Weight (GVW)	1385 Kg
Body Option	Multi-Purpose Vehicle
Mileage (Diesel Fuel)	19 kmpl

Table 1. Specifications of Maruti Omni

Material	C	S	Si	Cr	Mn	Ni	P	Cu
%	0.48	0.035	0.35	0.2	0.9	0.2	0.03	0.25

Table 2. Chemical Composition of SM45C

Parameter	Value
Ultimate Tensile Strength	420 MPa.
Yield Strength	370 MPa.
Young's Modulus	207 GPa.
Shear Modulus	80 GPa.
Poisson Ratio	0.3
Density	7600 Kg/m3

Table 3. Material Properties of SM45C

5. Loading Constraints

5.1 Torsional Moment

As the maximum engine speed is 3400 rpm, hence, the maximum power transmitted by the engine is 6KW, the torque transmitting capacity of the engine is 59.82N.m, hence the same is considering as applied torque as shown in *Figure 1*.

Figure 1. Drive Shaft for Case Study

5.2 Torsional Force

The torsional force is the force which is required to produce the estimated torque. Hence Torsional Force (F1) generated by engine during running is 2790N to a margin considered as 3000N (Safety) as shown in *Figure 2*.

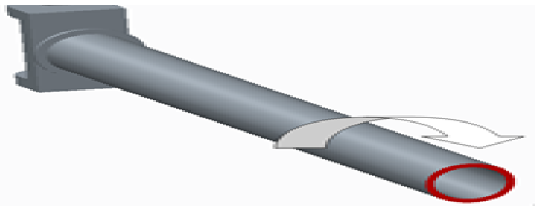


Figure 2. Application of Torque

5.3 Rotational Velocity

It is the speed of the shaft which is running to transmit the speed. As the engine speed is 3400 rpm, the rotational velocity is considered the same. The Angular Velocity (ω) is 356.04 Rad/Sec. as shown in *Figure 3*

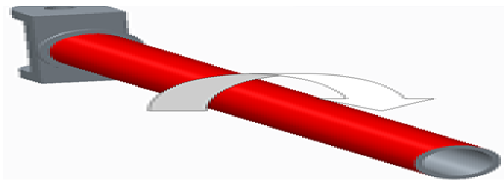


Figure 3. Rotational Velocity

5.4 Shaft Subjected to Bending Moment

Considering the shaft subjected to its self-weight of 4 Kg which is equivalent to 40 N. Hence Bending Moment, (M) is considered as 5 x 105 N.mm. as shown in *Figure 4*.

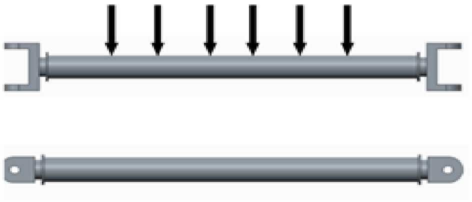


Figure 4. Rotational Velocity

5.5 Torsional Buckling

Torsional buckling (Ø) capacity of shaft Torsional buckling (Ø) capacity of shaft as 433 N.mm

6. Application of Finite Element Analysis

The Shaft model is first modeled in the Creo software of Version 3.0. The Creo file is further saved in IGES to call in Ansys. ANSYS meshing is automated high-performance meshing as shown in *Figure 5.* It produces the most appropriate mesh for accurate, efficient multiphasic solutions. Accuracy obtained from any FEA model is related to the finite element mesh.

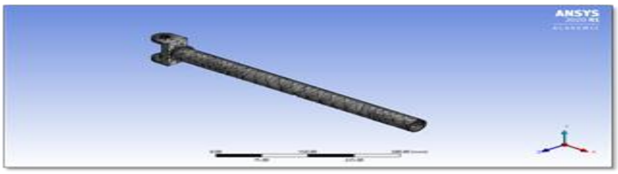


Figure 5.

6.1 ANSYS Setting for Torsional Loading

The Component is subjected to Static, Sudden, and Torsional loading on various sections as explained in detail in Table 4. The Values are substituted on their respective Section as shown in the *Figure 6*.

Properties	Value
Ultimate Tensile Strength	469 MPa
Tensile Yield Strength	324 MPa
Modulus of Elasticity	73.1 GPa
Shearing Strength	283 MPa.
Density	2780 Kg/m³
Poison's Ratio	0.33
Fatigue Strength	138 MPa

Table 4. Mechanical Properties of AL2024

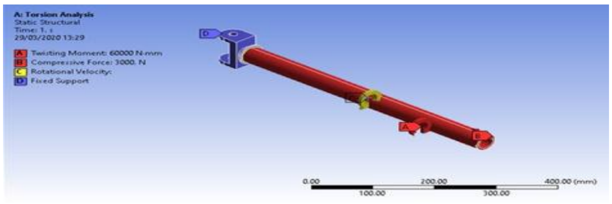


Figure 6. Analysis setting for Conditions for Torsional Loading

6.2 Ansys Setting for Buckling Load

The bending buckling is produced due to the weight occurring on the shaft. In the current case study, the weight of shaft is 40N, hence this is considered as the buckling weight. The buckling is produced due to the couple acting of 40N. The application of buckling force is described in *Figure 7.*

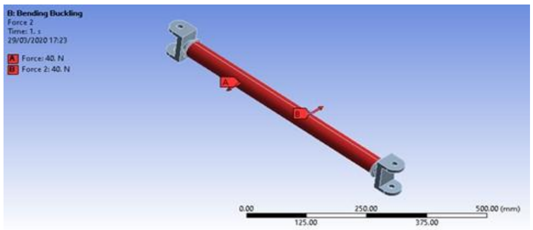


Figure 7. Analysis setting for Conditions for Buckling Loading

6.3 Ansys Setting for Fatigue Analysis

Twisting moment is applied of 60000 N mm. Compressive force of 3000N and bending force by self-weight of 40N. Shown in *Figure 8.*

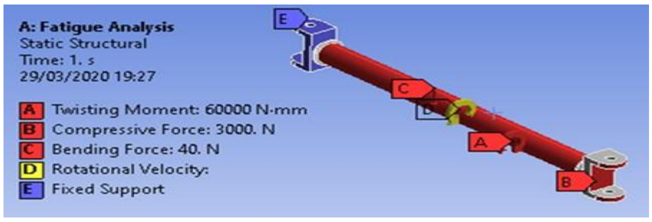


Figure 8. Analysis setting for Conditions for Fatigue Analysis

7. Finite Element Analysis of SM45C Steel

7.1 FEA for Torsional Loading subjected to SM45C

The FEA is done all of the above loading constraints on SM45C to determine the Equivalent Stress of 31.122 MPa shown in *Figure 9.*, Deformation of 0.3907 mm shown in *Figure 10.* and Shear Stress of 16.102 MPa shown in *Figure 11.* was produced.

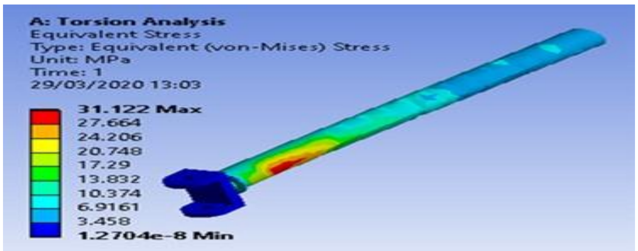


Figure 9. Equivalent Stress Produced after Torsional Loading for SMC45

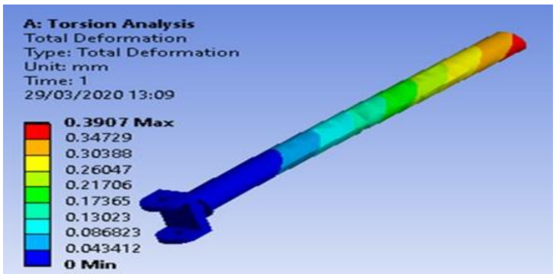


Figure 10. Deformation Produced after Torsional Loading for SMC45

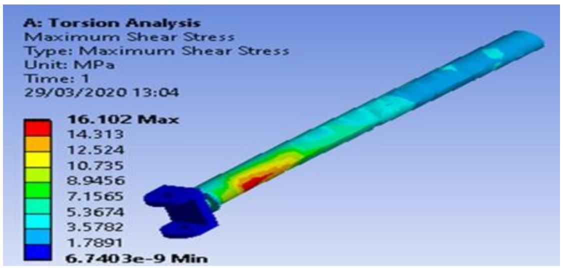


Figure 11. Shear Stress Produced after Torsional Loading for SMC45

7.2 FEA for Buckling Loading subjected to SM45C

The Maximum Equivalent Stress produced after buckling loading for SM45C was 53.264 MPa shown in *Figure 12*. and Deformation of 0.053025 mm shown in *Figure 13.*

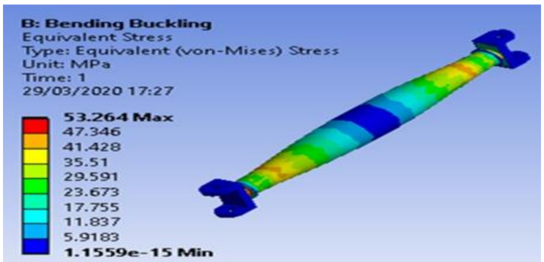


Figure 12. Equivalent Stress Produced after Buckling Loading for SMC45

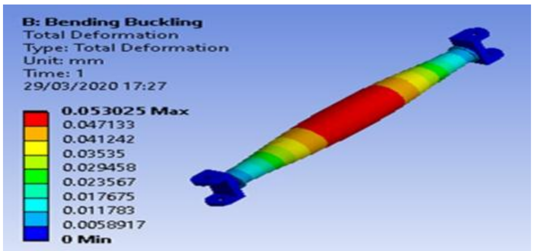


Figure 13. Deformation Produced after Buckling Loading for SMC45

8. Finite Element Analysis of AL2024

Various types of materials can be used for the shaft which are made of Aluminum matrix composites components due to its high yield strength but the and low weight. These materials are light in weight, hence can be implemented for Reduction in overall weight of the assembly and Reduction in material cost. Hence in the current study, the metal matrix of Aluminum 2024 (AL2024) is been used as replacement material. Mechanical properties of AL2024 are given in *Table 4.*

Properties	Value
Ultimate Tensile Strength	469 MPa
Tensile Yield Strength	324 MPa
Modulus of Elasticity	73.1 GPa
Shearing Strength	283 MPa.
Density	2780 Kg/m^3
Poison's Ratio	0.33
Fatigue Strength	138 MPa

Table 4. Mechanical Properties of AL2024

8.1 FEA for Torsional Loading subjected to Al2024

The FEA is done all of the above loading constraints on AL2024 to determine the Equivalent Stress of 14.46 MPa shown in *Figure 14*., Deformation of 0.10744 mm shown in *Figure 15.* and Shear Stress of 8.4402 MPa shown in *Figure 16.* was produced.

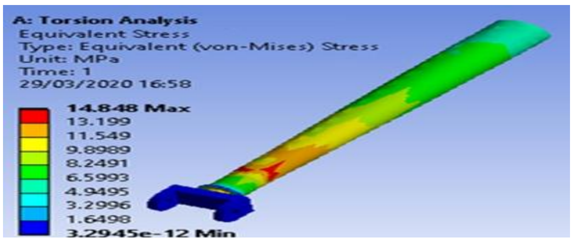


Figure 14. Equivalent Stress Produced after Torsional Loading for Al2024

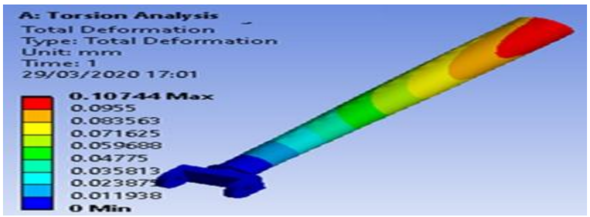


Figure 15. Deformation Produced after Torsional Loading for Al2024

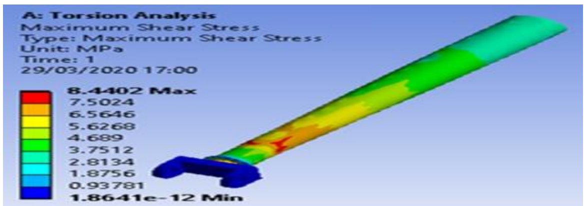


Figure 16. Shear Stress Produced after Torsional Loading for Al2024

8.2 FEA for Buckling Loading subjected to Al2024

The Maximum Equivalent Stress produced after buckling loading for AL2024 was 53.211 MPa shown in *Figure 17.* and Deformation of 0.15358 mm. shown in *Figure 18*.

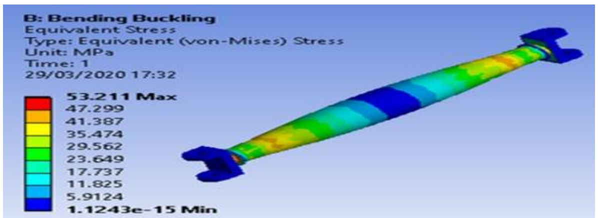


Figure 17. Equivalent Stress Produced after Buckling Loading for Al2024

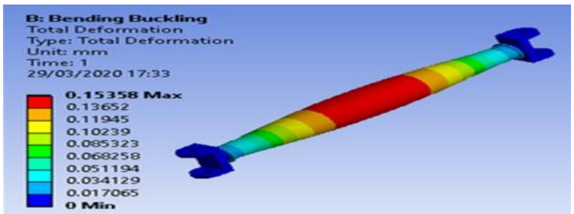


Figure 18. Deformation Produced after Buckling Loading for Al2024

9. Finite Element Analysis of Carbon Fiber

Polymer matrix composites are widely used in the aerospace and automobile industries due to its light weight. These materials possess high yielding strength and less fracture damage. Due to its strength and weight, this material is found to be implemented. Carbon fiber is strong composite polymer material that is used for case study of the shaft in this paper. Mechanical properties of Carbon fiber are stated in *Table 5.*

Material and Properties	Carbon Fibre
Tensile Strength (MPa)	1100
Yield Strength (MPa)	900
Young's Modulus (MPa)	$0.5e^3$
Poisson's Ratio	0.25
Density (kg/m³)	1600
Energy Absorption (J/Kg)	99

Table 5. Mechanical Properties of Carbon Fiber

9.1 FEA for Torsional Loading subjected to Carbon Fibre

The FEA is done all of the above loading constraints on Carbon Fibre to determine the Equivalent Stress of 14.848 MPa shown in *Figure 19.*, Deformation of 0.23201 mm shown in *Figure 20.* and Shear Stress of 8.3639 MPa shown in *Figure 21.*was produced.

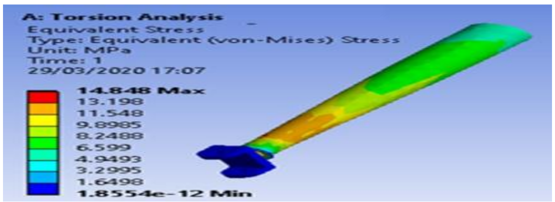


Figure 19. Equivalent Stress Produced after Torsional Loading for Carbon

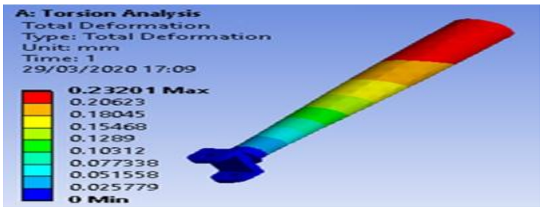


Figure 20. Deformation Produced after Torsional Loading for Carbon Fibre

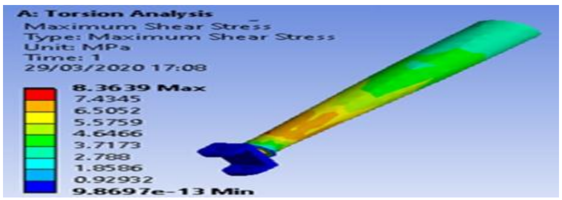


Figure 21. Shear Stress Produced after Torsional Loading for Carbon Fibre

9.2 FEA for Buckling Loading subjected to Carbon Fibre

The Maximum Equivalent Stress produced after buckling loading for Carbon Fibre was 53.295 MPa shown in *Figure 22.* and Deformation of 0.47069 mm shown in *Figure 23.*

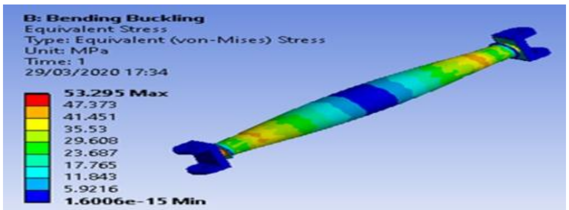


Figure 22. Equivalent Stress Produced after Buckling Loading for Carbon Fibre

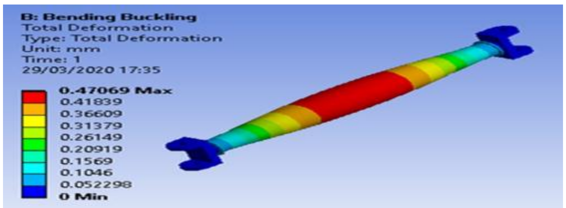


Figure 23. Deformation Produced after Buckling Loading for Carbon Fibre

10. Result and Discussions

10.1 Comparison of Results for Torsional Loading

The resultant stress produced is lesser for all Aluminum Matrix and Polymer Matrix materials as shown in *Table 6.* Hence, in strength criteria for equivalent stress, the optimized materials of Al2024 and Carbon Fibre satisfy the condition. The Shear stress produced is lesser for Al2024 and Carbon Fibre. Hence, in shear strength criteria the optimized materials of Al2024 and Carbon Fibre satisfy the condition. The deformation produced is lowest in case of Al2024 and moderate in case of carbon fibre. The deformation is found highest in Steel material. Strain is the change in shape of object. With respect to the above graph, the strain is maximum in Polymer material, but as the deformation is low here, hence we can consider that the change is shape will also be moderate. Shown in *Figure 24*.

Criteria	SM45C	Al-2024	Carbon Fibre
Stress (MPa)	31.22	14.84	14.74
Shear (MPa)	16.1	8.44	8.36
Strain	1.5	2.1	7.9
Deformation (mm)	3.9	1.7	2.32

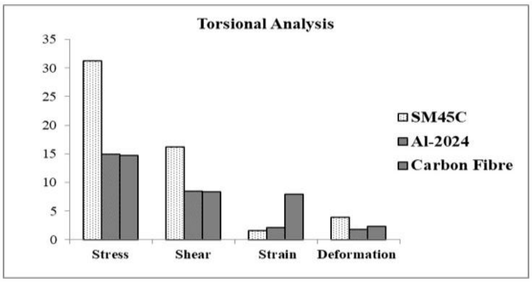


Figure 24. Result Analysis for Torsional Analysis

10.2 Comparison of Results for Bending Buckling

As we can see from the *Figure 25*, for all the loading conditions, the stress produced for steel, Al2024 and Carbon Fibre is similar. Hence, we can say that, with respect to bending load, the strength of shaft will be same for all the material. Referring to *Table 7*, the deformation is lowest in steel due to elasticity property of steel. The deformation in other two materials of Al2024 and Carbon Fibre, even though, more than the steel, but it is less than the magnitude of 1. Hence with respect to bending, the material satisfies the deformation criteria.

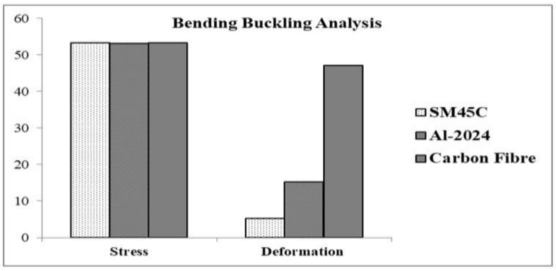


Figure 25. Result Analysis for Bending Buckling Conditions

Criteria	SM45C	Al-2024	Carbon Fibre
Stress (MPa)	53.26	53.21	53.29
Deformation mm	0.053	0.15	0.47

Table 7. Result Analysis for Bending Buckling

10.3 Comparison of Results for Fatigue Life Analysis

With respect to the working hour's life, the life of carbon fibre and Al-2024 is more than that of steel. As represented in *Table 8.* Hence use of matrix components will increase the life of shaft. Fatigue damage is the design life divided by available life of component. This result may be scoped. The default design life is set by control panel. For Fatigue, values greater than 1 indicates failure before designed life. Hence, according to damage criteria, all the three materials are safe.

Biaxiality indication is said to be the principal stress smaller in magnitude divided by larger principal stress with the principal stress nearest to zero. Hence, with the more ratio the more effective material. Hence all the three materials are safe under working.

Criteria	SM45C	Al-2024	Carbon Fibre
Life in Hours	2.77E+11	2.77E+13	2.77E+14
Biaxiality Indication	0.99	0.98	0.97
Damage Factor	0.036	0.042	0.051

11. Conclusion

In this paper, the material optimization of shaft made SMC45 Steel is done with the replacement of aluminum and polymer matrix components. All the loading constraints have been studied and applied to determine the loading conditions that can be used for FEA. For finite element analysis, the ultimate loading condition of 1.2 Factor of safety has been considered. FEA is done in Ansys software for determination of Equivalent Stress, deformation and strain produced in the material for all the loading conditions. The optimized material of Aluminum and Polymer matrix satisfies the strength criteria of Stress and shear, hence can according to this condition the experiment is successful. Use of Al-Matrix and Polymer matrix material is also optimal as it reduced the cumulative weight as reduction of 40% with improvement in strength. This reduction in weight of vehicle can lead to economic value of product as the raw material and manufacturing cost can be reduced.

12. Acknowledgments

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