COMPARATIVE COMPOSITE AND CONVENTIONAL DRIVE SHAFT ANALYSIS

Marko Denić [1]*, Zorica Đorđević* [2]*, Vesna Marjanović* [3]*, Nenad Petrović* [4]*, Nenad Kostić* [5]

UDC:621,824

1. INTRODUCTION

The automobile industry has seen a growth in implementation of composite materials in the past years, however it is still a slow process, as the material properties for various load cases is still being researched. Following this trend of using lightweight materials to replace steel components more and more parts are being produced using composites. However composites are still most frequently found in static and cosmetic elements. Drive shafts made of composites have most recently been featured in some BMW M series models. Use of composite materials for propulsion components is still a developing field of study. Drive shafts (cardan shafts) are main driving components for transferring torque in vehicles. The use of composite materials for making drive shafts implies decreasing the mass compared to conventional material shafts. In the use of composite materials the orientation of fibers plays an important role in load distribution and stress characteristics. Depending on the load case, fibers need to be placed at optimal angles to minimize deformation of the shaft. The base of this research is to analyze and compare drive shaft numerical calculations for steel and composite drive shafts in the same loading scenarios.

Kaviprakash et al. [3] conducted research on fiber orientation in laminar composites, as well as the order of layering. Their optimization was done in ANSYS for hybrid shafts made from high strength carbon fibers, high module carbon fibers, Kevlar, and epoxy resins. The results were compared to conventional shafts and showed improvements in decreasing mass of approximately 79%, lowering stress as well as improving fuel economy. Hatwar and Dalu [2] analyzed E Glass and carbon fiber shafts in combination with epoxy resins. Static analyses conducted in ANSYS were compared to analytical results for maximum shear strain, shear stress, equivalent stress, natural frequency, and mass, for steel shafts, carbon, and glass shafts. The results showed a decrease of mass by over 72% for composite shafts with similar deformation and stress characteristics. Rothe and Bombatkar [5] tested a composite shaft made from high strength carbon fibers using static, modal, and buckling analyses. Bhajantri et al. [1] replaced a two-part steel shaft for a single-part composite shaft decreasing the mass by up to 50% and concluding optimal parameters for the orientation of fibers in layering using regression analyses. Ravi [4] analyzed composite

---

[1] *Marko Denić, Ph. D. student, University of Kragujevac, Faculty of Engineering, Sestre Janjić 6, 34000 Kragujevac, mdenic@kg.ac.rs*

[2] *Zorica Đorđević, Prof., University of Kragujevac, Faculty of Engineering, Sestre Janjić 6, 34000 Kragujevac, zoricadj@kg.ac.rs*

[3] *Vesna Marjanović, Prof., University of Kragujevac, Faculty of Engineering, Sestre Janjić 6, 34000 Kragujevac, vmarjanovic@kg.ac.rs*

4 Nenad Petrović, Assist., University of Kragujevac, Faculty of Engineering, Sestre Janjić 6, 34000 Kragujevac, npetrovic@kg.ac.rs

[5] *Nenad Kostić, Research assoc., University of Kragujevac, Faculty of Engineering, Sestre Janjić 6, 34000 Kragujevac, nkostić@kg.ac.rs*

shafts made from carbon fibers using a combination of tetrahedral and hexagonal finite elements. The results were compared to conventional shafts and showed a decrease in mass by 24%. The analysis covered hollow and full shafts concluding favourable dimension ratios for hollow shafts. Sivakandhan and Prabhu [6] optimized fiber angles in symmetrical layers of equal thicknesses for composite shafts. They optimized composite drive shafts achieving decreases in mass of 15% and 72% respectively compared to conventional shafts.

This paper analyses single-part laminar composite drive shafts, for possible use in heavy duty trucks, and gives a comparison of numerical calculations for both the composite shaft and its steel and aluminium counterparts. Three of the most frequently used composite materials are used in this research, as determined by literature review. Results are shown for all parameters for both composite and metal shafts. Analysed properties are twist angle, deflection, eigenfrequencies, and mass. Additionally variations of the number of layers, their direction and possible combination with conventional materials are also explored.

Test example drive shafts were tested in Autodesk Helius Composites 2016. This new software is easy to use and it is accurate in simple load cases in comparison to other software, which use FEA method, such as ANSYS, Abaqus, and DS CATIA.

2. SELECTION OF MATERIALS

The comparative analyses conducted in this paper aim to show the difference in performance and mass of conventional, metal, shafts and various frequently used composite shafts. Calculations were performed in ANSYS and verified in Helius Composites for both metal and composite shafts.

The conventional materials used for the purposes of this research are S275JR, as it has widespread use in the automobile industry, and 6061-T6 Aluminium. Material characteristics are taken from the standard material library in ANSYS and are given in table 1. A survey of available literature on the subject shows that the most frequently used composite materials for drive shafts are E Glass Epoxy, High Strength Carbon, and Kevlar (Kevlar-49). Material characteristics for E Glass and Kevlar-49 are taken from the material library in Helius Composite and are given in table 1. HSC characteristics were used from [3] and a material with those properties was created in the software manually.

Table 1 Characteristic of steel, aluminum and composite materials

Material	E11, [MPa]	E22, [MPa]	E33, [MPa]	G12, [MPa]	G13, [MPa]	G23, [MPa]	ν12, [/]	ν13, [/]	ν23, [/]	ρ, [kg/m3]
Steel	$2.1\cdot 10^5$	$2.1\cdot 10^5$	$2.1\cdot 10^5$	$8\cdot 10^4$	$7.6\cdot 10^4$	$7.6\cdot 10^4$	0.3	0.3	0.3	7860
Aluminum	$6.83\cdot 10^4$	$6.83\cdot 10^4$	$6.83\cdot 10^4$	$2.62\cdot 10^4$	$2.62\cdot 10^4$	$2.62\cdot 10^4$	0.33	0.33	0.33	2710
E Glass	$4.48\cdot 10^4$	$1.24\cdot 10^4$	$1.24\cdot 10^4$	$5.52\cdot 10^3$	$5.52\cdot 10^3$	$3.60\cdot 10^3$	0.28	0.28	0.36	2080
HSC	$1.35\cdot 10^5$	$7\cdot 10^3$	$9.26\cdot 10^3$	$5.8\cdot 10^3$	$6.15\cdot 10^3$	$3.08\cdot 10^3$	0.31	0.31	0.50	1580
Kevlar-49	$7.58\cdot 10^4$	$5.52\cdot 10^3$	$5.52\cdot 10^3$	$2.07\cdot 10^3$	$2.07\cdot 10^3$	$1.54\cdot 10^3$	0.34	0.34	0.47	1380

3. EXPERIMENT

Literature suggests general dimensions of shafts in the automobile industry as well as their loads. This research will be conducted on a modified version of the example from [2]. The hallow drive shaft is 1000 mm long, 100 mm in diameter, while the wall thickness is 3.32 mm. The shaft is loaded with 3000 Nm of torque on one end, while the other end is fixed. In order to analyze bending of the shaft (deflection) the standard procedure for simulating bending loads was used in three points with a force of 1000 N**.**

The steel drive shaft was first calculated for maximal shear stresses, twist angle and deflection of the shaft on bending analytically. In order to verify the analytical method, a numerical analysis was conducted under the same loading and constraint conditions in ANSYS. The finite element mesh consists of 15876 tetrahedral elements with 5 mm sides and 108415 nodes. Calculated values as well as the mass of the steel shaft are given in table 2.

Table 2 Analytical and Numerical results comparison for steel shaft

	Analytical	Numerical	Difference [%]
Shear Stress [*MPa*]	63.58	63.917	0.527
Twist angle [°]	0.911	0.947	3.801
Deflection [*mm*]	0.076	0.084	9.524
Mass [*kg*]	7.916	7.916	0

Comparing the calculated values, it can be concluded that the differences in results are less than 10%, and given the magnitude of the values, the numerical results are adopted as valid.

Further calculations of the composite and aluminium shafts, conducted in Autodesk Helius Composites 2016, will be compared to the numerical results from ANSYS for the steel shaft.

4. RESULTS

Numerical calculation resaults are shown and compared graphically to best illustrate the difference in characteristics of the examined materials of shafts. Results attained are mass, twist angle, deflection, and eigenfrequency values for steel, aluminum, E Glass, HSC and Kevlar-49 shafts.

The greatest benefit of using composite shafts in the automobile industry is decreasing the mass of the vehicle. The masses of the examined shafts are given in figure 1.

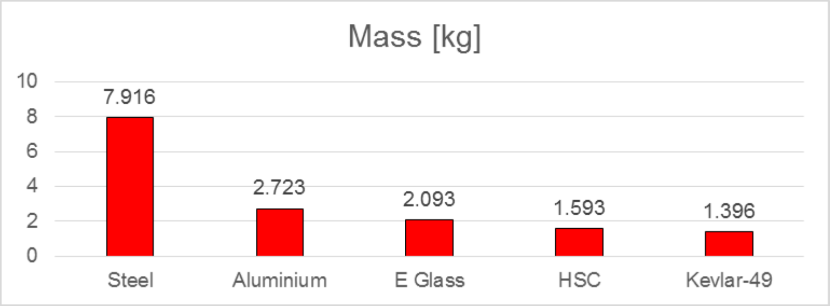

Figure 1 Masses of drive shafts

The twist angle is the other important parameter calculated for the shafts. Figure 2 shows the twist angle values in degrees for all calculated drive shafts.

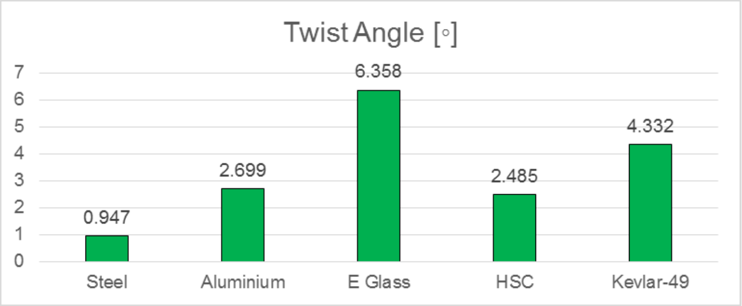

Figure 2 Twist angles of drive shafts

Even though drive shafts in automobiles are most frequently just subjected to torsion, they are also calculated for the case of bending, usually by subjecting them to forces in three points. The maximal deflection is calculated in the middle of the shaft. There are no suggestions stipulated for deflection, however it is best to keep deflection under a few millimetres per meter of length. As the drive shaft has enough clearance to withstand such deformations due to stochastic changes in terrain over which the vehicle is moving these small deflections are acceptable. Figure 3 shows maximal deflection values in the middle of the shaft.

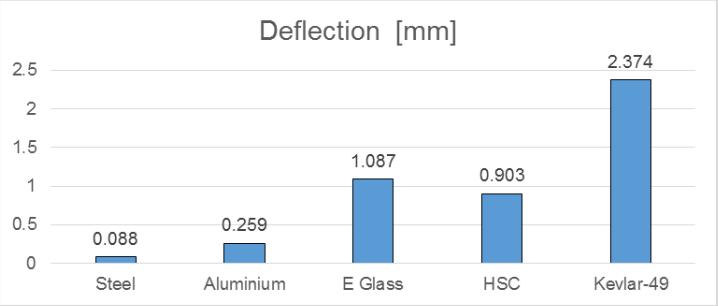

Figure 3 Deflection of drive shafts

Figure 4 graphically shows values of eigenfrequencies (for the 1st mod) for each shaft. One of the main reason for practical implementation of two-part steel drive shafts is that the single-part drive shaft exhibited unfavourable eigenfrequencies due to the length of the shaft. Due to a drastic difference in eigenfrequencies of composite material shafts, two-part metal shafts can be exchanged for single-part composite shafts.

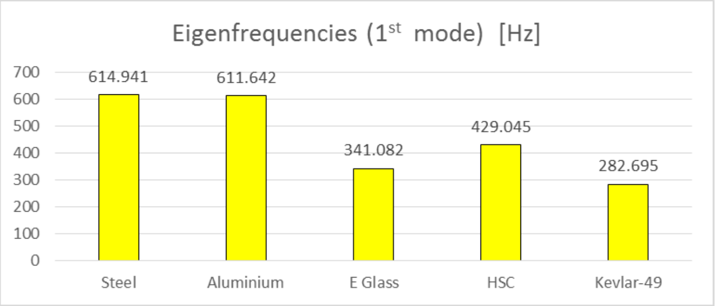

Figure 4 Eigenfrequencies of drive shafts (1st mode)

All fibers for the calculated composite shafts are set at an angle of ±45° in for layers as suggested by literature as being optimal positioning of fibers in the layers of the composite for more than one loading scenarios.

5. COMPOSITE VARIATIONS

Further analysis is directed towards determining the best variation of the composite drive shafts. The variation of the number of layers by doubling the number in every sequential iteration is conducted to determine the influence of the change in the number of layers on the previously calculated parameters. The overall thickness of the layers is 3.32 mm and is constant. All the same calculations were conducted as in the previous section, except that the experiment of the change in the number of layers is only conducted on the E Glass shaft, as it is most frequently used in literature. The results of the varied number of layers are shown in table 3.

Table 3 Influence of the change in the number of layers on deflection, torsion and eigenfrequency for E Glass drive shafts

Number of layers	4	8	16	32
Deflection [mm]	1.0872	1.0739	0.0708	1.07
Angle of Twist [^{0}]	6.039	5.759	5.693	5.676
Eigenfrequency(1st mode) [Hz]	341.082	341.191	343.694	343.819

As the change in the number of layers has been found to not have a big influence on shaft characteristics, the next variation in this experiment is directed towards determining the influence of the layer order. Various orientation of the angle of fibers when the fibers in the layers are oriented from 0^0 to 90^0 is tested for the four layer E Glass shaft. Two variations are tested with layer combinations of -45^0, 0^0, 45^0, and 90^0 in variations and the resulting characteristics presented in table 4, with the first combination being the same as in the first comparison.

Table 4 Influence of fiber direction changes in layers

Directions of fibers combinations in layers	$45^0/-45^0/45^0/-45^0$	$0^0/-45^0/45^0/90^0$	$45^0/0^0/90^0/-45^0$
Deflection [mm]	1.0872	0.926	0.822
Angle of Twist [^{0}]	6.039	8.152	9.873
Vibration (1st mode) [Hz]	341.082	369.584	392.366

Due to the high costs of composite materials, there is a tendency to combine conventional with composite materials in drive shaft design to form hybrid drive shafts. This way the best of both materials characteristics can be exploited. The idea is to start off with a steel or aluminium base and layer over them with composites. The distribution of stress in the layers needs to be accounted for in order to avoid having the metal base from transmitting the greater part of the load, thereby not using the potential of the composite layers. This research tested steel and aluminium base shafts in combination with E Glass composite in four layers 1.66 mm thick oriented in the setup of 45/-45/45/-45. The steel and aluminium bases have thicknesses of 1.66 in both cases. Table 5 gives the characteristics of two hybrid shafts and compares the values to their base metal and purely E Glass shafts.

Table 5 Comparison of hybrid steel/E Glass and Aluminum/E Glass shaft to the metal and E Glass composite drive shaft characteristics

Material	Steel/ E Glass	Steel	Aluminum /E Glass	Aluminum	E Glass
Deflection [mm]	0.342	0.088	0.577	**0.259**	1.087
Angle of Twist [^{0}]	2.594	**0.947**	4.11	2.699	6.358
Mass [kg]	5.01	7.916	2.414	2.723	**2.093**
Eigenfrequency (1st mode) [Hz]	393.018	614.941	436.039	611.642	**341.082**

6. CONCLUSIONS

This paper analysed the use of composite materials and their variations and compared their characteristics (deflection, torsion, eigenfrequency and mass) with those of conventional shafts.

The use of composite materials for creating drive shafts can significantly decrease the mass of this component. The difference in weight among the composite shafts is around 10%, and the composite with the smallest mass is Kevlar-49 with a decrease in mass of 82.36%. Other tested characteristics for composite shafts do not show such drastic differences.

High strength carbon (HSC) showed itself as the least susceptible to torsion, with a twist angle of 2.485^0, which is less than that of its aluminium counterpart, but over 2.6 times greater than that of the corresponding steel shaft. E Glass has performed the worst under these circumstances with a twist angle of 6.358^0 which is still acceptable.

Deflection has the greatest variance in results between the materials. Of the composite shafts HSC performed the best, while Kevlar-49 had the greatest deflection, however all deflection values can be considered acceptable due to their minuscule values. Eigenfrequencies are significantly lower for composite materials than for conventional steel and aluminum shafts, as was expected.

Further variations of the E Glass composite by changing the number of layers made small decreases the twist angle with the increase of the number of layers, and had an overall insignificant influence on the characteristics of the shaft in comparison to the increased complexity of production. The changes in fiber orientation in the layers only slightly improved deflection from the initial setup, while worsening other characteristics. Therefore it can be concluded that the initially calculated setup of composites with 4 layers with angles of fibers changing from +45^0 to -45^0 in each layer to be optimal.

Due to the costliness of composite materials a compromise in the design solution can give favourable results compared to conventional design solutions. The combination of E Glass with steel, and E Glass with aluminium was tested and demonstrated improvements in deflection (around 31% increase for Glass/steel), and twist angle (around 40% decrease for E Glass/steel), while having a greater mass and eigenfrequency compared to a purely E

Glass composite shaft, but a significantly lower mass than their corresponding metal counterparts.

Any decrease of mass in automobiles is in direct correlation with the decrease of fuel consumption. An improvement of fuel economy through further research into, and implementation of composite materials inevitably leads to a decrease of automobiles negative effects on the environment.

REFERENCES

[1] Bhajantri S. V., Bajantri C. S., Shindolkar M. A., Amarapure S. S., „Design and Analysis of Composite Drive Shaft“, International Journal of Engineering Research & Technology (IJERT), ISSN:2321-7308, Vol. 3 Special Issue 3, May 2014.

[2] Hatwar K. P., Dalu S. R., „Design and Analysis of Composite Drive Shaft“, International Journal of Science and Research (IJSR), ISSN (Online):2319-7064, Vol. 4 Issue 4, April 2015.

[3] Kaviprakash G., Lawrence I. D., Kannan C. R., Regan A. P., „Design and Analysis of Composite Drive Shaft for Automotive Application“, International Journal of Engineering Research & Technology (IJERT), ISSN:2278-0181, Vol. 3 Issue 11, November 2014.

[4] Ravi A., „Design, Comparison and Analysis of a Composite Drive Shaft for an Automobile“, International Review of Applied Engineering Research, ISSN:2248-9967, Vol. 4, Number 1 (2014), pp. 21-28.

[5] Rothe G. C., Bombatkar S. A., „Design and Analysis of Composite Material Drive Shaft“, International Journal of Inovative and Emerging Research in Engingeering (IJERT), ISSN:2394-5494, Vol. 2 Special Issue 1, 2015.

[6] Sivakandhan C., Prabhu P. S., „Optimum Design and Analysis of the Drive Shaft in Compostie Material“, Material Science Research India, Vol. 8(2), 125-130 (2011).