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# ANALYSIS OF INFLUENTIAL PARAMETERS ON THE STATIC CHARACTERISTICS OF A COMPOSITE SHAFT

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*Abstract: For the automotive industry, the use of new materials that could lead to a reduction in vehicle mass and an improvement in its performance is of great importance. The aim of this paper is to investigate the possibility of replacing the steel drive shaft of the Toyota Qualis with a shaft made of composite materials. The paper also analyzes the influence of fiber orientation angle and layer stacking sequence on the static characteristics of the shaft, such as stress and the angle of twist. The analysis was carried out using the Finite Element Method (FEM) in the FEMAP 2021.2 software.*

*Key words*: *composite materials, composite shaft, fiber orientation, stress, angle of twist*

## 1 INTRODUCTION

The use of composite materials for the manufacture of drive shafts, i.e. propeller shafts, represents one approach to reducing vehicle mass while maintaining adequate load-carrying capacity and structural stiffness. Carbon-fiber-reinforced composites are of particular importance because they provide a favorable ratio of specific strength to specific stiffness, while the mechanical characteristics of the shaft can be tailored by changing the fiber orientation, the number of layers, and their stacking sequence.

Okutan and Genel [1] investigated the torsional behavior of a carbon-fiber composite drive shaft for different stacking sequences and fiber orientation angles. Twenty-five different configurations of a ten-layer laminate with fiber orientations of 0°,

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45°, and 90° were analyzed. Stiffness, bending natural frequency, and critical buckling torque were determined both by the finite element method and analytically [1].

Georgantzinos et al. [2] analyzed a laminated composite drive shaft reinforced with multi-walled carbon nanotubes using an analytical approach and the finite element method. Particular attention was paid to the effects of fiber orientation angle and nanotube content on the natural frequency and critical torsional buckling torque. The results showed that the addition of nanotubes can significantly improve the characteristics of the composite drive shaft [2].

Altın et al. [3] investigated the determination of design criteria for a composite drive shaft intended for automotive applications, using carbon fibers and an epoxy matrix. The analysis of different winding angles and numbers of layers showed that a ten-layer configuration with a ±45° orientation is favorable in terms of strength and cost. The manufactured composite drive shaft was approximately 80% lighter than the corresponding steel shaft, which was additionally confirmed by experimental testing [3].

Jarrett et al. [4] provided a comprehensive review of the development of hybrid composite drive shafts and methods for joining them to metallic components, with particular emphasis on aerospace applications. The authors point out that the stacking sequence, fiber orientation, and laminate thickness directly affect shaft performance. However, in practical applications, particular challenges include the composite-to-metal joint, damage, corrosion, moisture absorption, and differences in coefficients of thermal expansion [4].

Zhang et al. [5] developed a multiscale optimization approach for a CFRP drive shaft that links the microscopic and macroscopic parameters of the composite material. Unlike approaches mainly based on optimizing the number and orientation of layers, this study also considered microstructural parameters, constraints of the stacking process, and structural reliability. The optimization achieved a significant reduction in mass while satisfying the specified reliability requirements [5].

In a more recent study, Zhang et al. [6] proposed an integrated composite drive shaft with a variable-thickness membrane disk, using a combination of numerical optimization, finite element analysis, and experimental verification. The analysis included strength, stiffness, and dynamic behavior, demonstrating that optimization of the geometry and layer arrangement can further improve the performance of the composite drive shaft [6].

Djordjević et al. [7] analyzed the influence of carbon-fiber orientation angle on the stability of a laminated composite drive shaft using the finite element method. The results showed that changing the fiber orientation angle from 0° to 90° can lead to a significant decrease in natural frequencies, by as much as 73.2%, as well as a change in the critical buckling torque, confirming the importance of selecting the fiber orientation when designing a composite drive shaft [7].

## 2 CHARACTERISTICS OF COMPOSITE DRIVE SHAFT

The aim of this paper is to analyze the possibility of replacing the steel drive shaft of a 2001 Toyota Qualis with a composite-material shaft without compromising the strength and reliability of the component. The dimensions of the analyzed shaft are as follows: shaft length 1500 mm, outer diameter 72 mm, and wall thickness 4 mm. The calculation was performed numerically in Femap 2021.2 for a maximum torque of 3000 Nm.

The mechanical properties of the analyzed shaft materials (steel and the composite materials HM carbon/epoxy, HS carbon/epoxy, E-glass/epoxy, and E-glass/polyester) are presented in Table 1.

Table 1. *Mechanical properties of the shaft materials* [8]

| *Material* | *Steel* | *HM carbon / epoxi* | *HS carbon / epoxi* | *Eglass / epoxi* | *Eglass / polyester* |
|---|---|---|---|---|---|
| $E_1$, *MPa* | *210000* | *190000* | *134000* | *50000* | *34000* |
| $E_2$, *MPa* | *210000* | *7700* | *7000* | *12000* | *6530* |
| $G_{12}$,, *MPa* | *83000* | *4200* | *5800* | *5600* | *2433* |
| $G_{23}$, *MPa* | *83000* | *4200* | *5800* | *5600* | *1698* |
| $\nu$ | *0,3* | *0,3* | *0,3* | *0,3* | *0,22* |
| $\rho$, *kg/m*$^3$ | *7830* | *1600* | *1600* | *2000* | *2100* |

In Table 1, the following notation is used: $E_1$ – longitudinal modulus, $E_2$ – transverse modulus, $G_{12}$, $G_{23}$ – shear modulus, $\nu$ - Poisson's ratio, $\rho$ - density.

The shaft model with the generated finite element mesh is shown in Figure 1.




Figure 1. *Model of the analyzed shaft*

## 3 ANALYSIS OF THE STRESS-STRAIN STATE OF THE SHAFT

The values of torsional stress and shaft twist angle were determined numerically for both the steel and composite shafts.

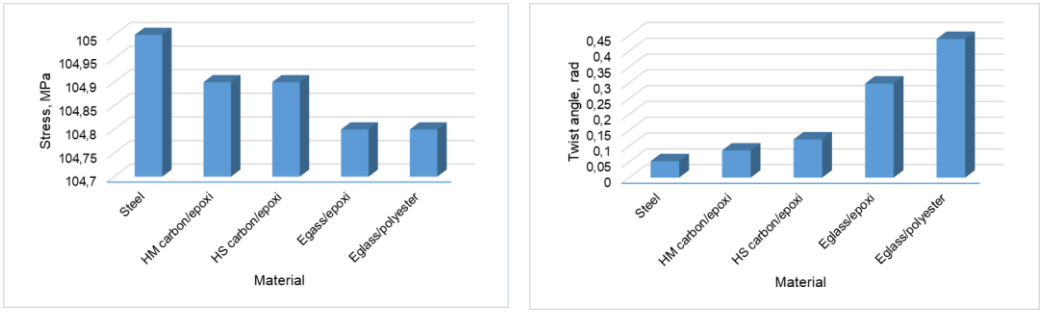


Figure 2. *Stress values (left) and shaft twist angle (right)*

Analysis of the obtained maximum stress values shows that they are approximately the same for all analyzed materials. Regarding the shaft twist angle, the lowest value is obtained for the steel shaft. Among the composite materials, HM carbon/epoxy exhibits the best characteristics, whereas E-glass/polyester shows the least favorable behavior. The analysis also showed that the composite materials can withstand these stresses and deformations without the risk of failure. The analyzed

composite shafts are laminated structures with a fiber orientation of $[\pm 45°]_{4S}$. It should also be emphasized that the mass of the steel shaft is more than 4,5 times greater than that of the carbon-fiber composite shafts and more than 3,5 times greater than that of the glass-fiber shafts, confirming that this replacement would lead to a significant reduction in vehicle mass.

## 4 EFFECT OF FIBER ORIENTATION ANGLE ON THE SHAFT TWIST ANGLE

For laminated materials, the fiber orientation angle has a major influence on both the static and dynamic characteristics of the shaft. Figure 3 presents the obtained shaft twist angles for all analyzed materials and fiber orientation angles ranging from 0° to 90°, with each layer having the same fiber orientation angle. The analysis showed that the lowest twist angles occur at a fiber orientation angle of 45°, and this applies to all analyzed composite materials.

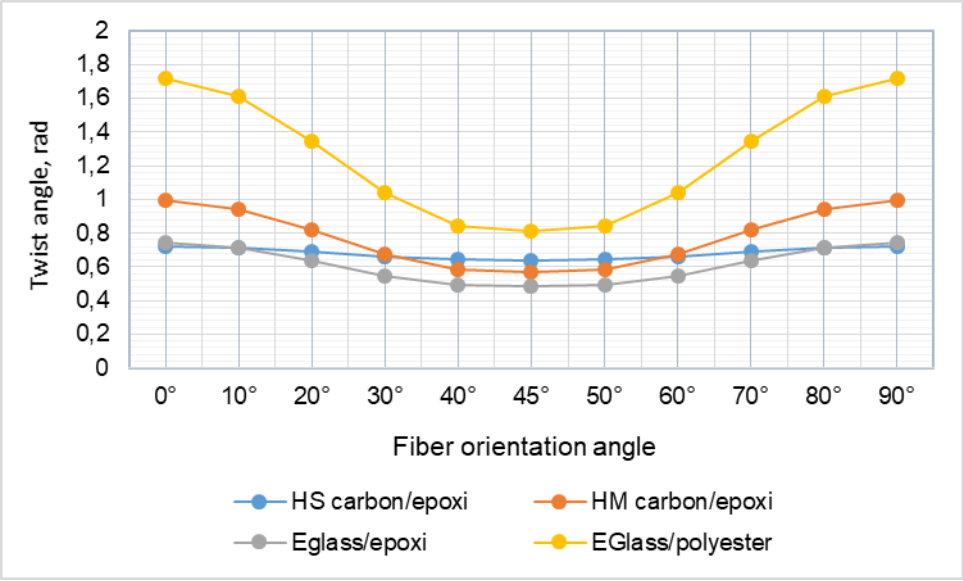


Figure 3. *Effect of unidirectional fiber orientation on the shaft twist angle*

If the layers are arranged in a cross-ply ± configuration (the same absolute fiber orientation angle but with opposite signs in adjacent layers), lower shaft twist angles are obtained than with unidirectional fiber orientation, as shown in the diagram in Figure 4. In this case as well, the lowest shaft twist angles are obtained for the $[\pm 45°]_{4S}$ orientation. With regard to the material, HM carbon/epoxy showed the best characteristics, while E-glass/polyester exhibited the least favorable torsional resistance, particularly for unidirectional fiber orientation. Therefore, a composite shaft made of HM carbon/epoxy with a $[\pm 45°]_{4S}$ fiber orientation emerges as the most suitable replacement for the steel shaft.

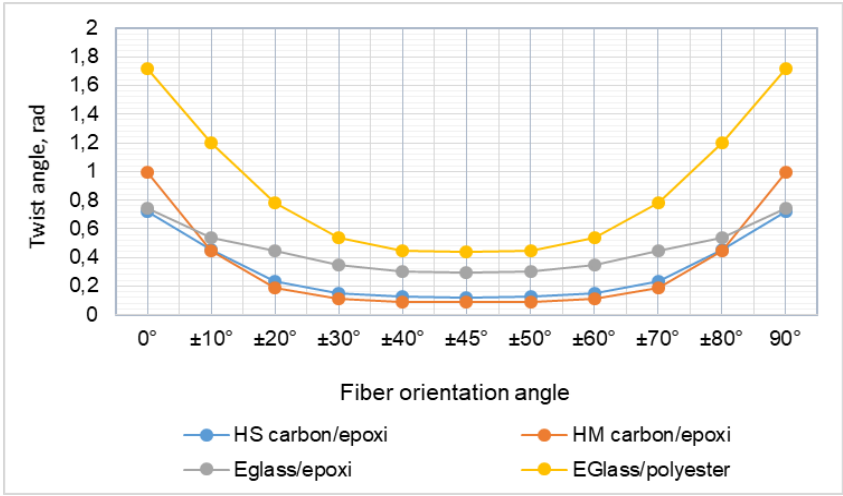


Figure 4. *Effect of alternating fiber orientation on the shaft twist angle*

## 5 EFFECT OF LAYER STACKING SEQUENCE ON THE SHAFT TWIST ANGLE

The previous analysis showed that fiber orientation angles have a significant influence on the torsional resistance of the shaft. It is therefore of interest to further analyze how combinations of 0°, ±45°, and 90° orientations, as well as different layer stacking sequences, affect shaft deformation due to torsion, i.e. the shaft twist angle. Analysis of the diagram in Figure 5 shows that increasing the number of layers with fibers oriented at 45° reduces the shaft twist angle.

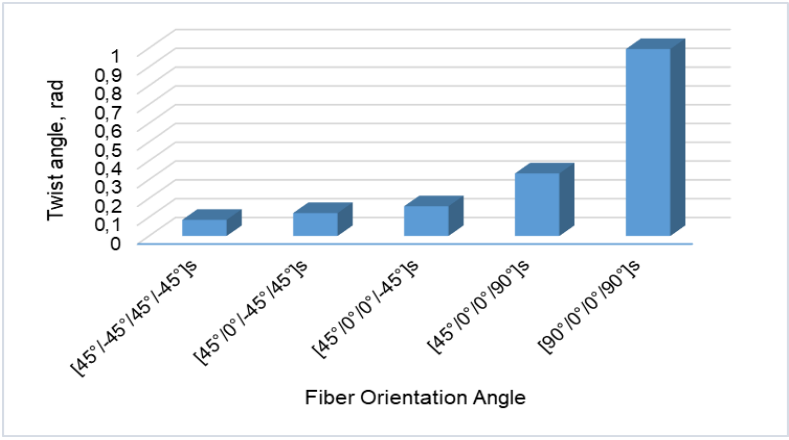


Figure 5. *The influence of layers stacking sequence on the shaft twist angle*

## 6 CONCLUSION

The continuous development of mechanical systems and materials in the automotive industry is aimed at producing vehicle drive shafts with lower mass, increased load-carrying capacity, improved static and dynamic characteristics, and greater operational reliability. One way to achieve this is through the use of laminated

composite materials, which allow the mechanical characteristics of the shaft to be tailored to a specific application and loading conditions.

One of the most important parameters considered in this paper is the selection of the fiber orientation in the laminate layers that provides the greatest resistance of the shaft to torsion. The results indicate that a ±45° orientation is the most favorable for all analyzed composite materials. A higher proportion of layers with this fiber orientation leads to a substantial reduction in the shaft twist angle. With regard to the material, HM carbon/epoxy exhibited the best characteristics and can represent an adequate substitute for steel in the manufacture of the drive shaft of a 2001 Toyota Qualis.

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