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OPTIMIZATION OF FIBER ORIENTATION ANGLE OF A HYBRID Al / COMPOSITE CARDAN SHAFT

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***Summary**: One important property of composite materials is the possibility to change their characteristics by changing the fiber orientation angle. By determining the optimal fiber orientation, the resistance to the torque effect, as well as the value of the critical rotational speed, can significantly be increased. In this paper, using the finite element method, we have examined the effects of fiber orientation angle on the basic static and dynamic characteristics of the shaft (twist angles, natural frequency). The shaft is composed of a combination of aluminum and composite layers of carbon and aramid fibers. In the conclusion section of the paper, optimal variants of the shaft have been identified.*

Key words: shaft, twist angles, natural frequency, aramid fiber, carbon fiber

1. INTRODUCTION

The modern development of technology and industry calls for more rigid requirements in terms of characteristics of materials used for manufacturing of various mechanical elements and constructions. For the purpose of getting better mechanical characteristics of certain products, over the last decades, there has been a growing tendency for using artificial materials. The advantage of composites as artificial materials over convential materials is in the fact that in their case the best characteristics of materials they are made of are used. Composite materials are the ones in which it is possible to optimize the mechanical features, machining and forming abilities, environmental effect, material and production costs, since they are made by combining two or more materials with complementary characteristics.

Resistant and fiber-reinforced composite materials of high rigidity and relatively low specific weight are convenient for manufacturing of shafts. Composite shafts, when compared to steel shafts, are attibuted with less mass, less value of tension and deformation, extremely harmonic absoption of vibrations and higher values of its own frequencies.

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Numerous studies have dealth with optimal design of cardan shafts as well as with types of materials shafts are made of and of course with fiber orientation. The paper [1] presents an experimental and simulation studies to investigate the behaviour of composite hollow shafts, with a specific focus on the maximum torsion capacity of the composite hollow shaft for different winding angles. The maximum static torsion capacity of kenaf yarn fibre reinforces unsaturated polyester composite shaft at a winding angle of 45° was higher strength than 90° orientation.

In paper [2] examines the effect of fiber orientation angles and stacking sequence on the torsional stiffness, natural frequency, buckling strength, fatigue life and failure modes of composite tubes. FEA results showed that the natural frequency increases with decreasing fiber orientation angles. On the other hand, the critical buckling torque has a peak value at 90° and lowest at a range of 20–40° when the angle of one or two layers in a hybrid or all layers in non-hybrid changed similarly.

In this study [3], a finite element analysis was used to design composite drive shafts incorporating carbon and glass fibers within an epoxy matrix. The results show that, in changing carbon fibers winding angle from 0° to 90°, the loss in the natural frequency of the shaft is 44.5%, while, shifting from the best to the worst stacking sequence, the drive shaft causes a loss of 46.07% in its buckling strength, which represents the major concern over shear strength in drive shaft design.

A hybrid aluminum/composite is an advanced composite material that consists of aluminum tube wound onto outside by layers of composite material. This paper [4] investigates the maximum torsion capacity of the hybrid aluminum/composite shaft for different winding angle, number of layers and stacking sequences. The hybrid shaft consists of aluminum tube wound outside by E-glass and carbon fibers/epoxy composite. The results show that the static torque capacity is significantly affected by changing the winding angle, stacking sequences and number of layers.

2. DESIGN PROCEDURE

The lamina is thin it is considered as the plane stress problem. Hence, it is possible to reduce the 3-D problem into 2-D problem. For unidirectional 2-D lamina, the stress-strain relationship in terms of physical material direction is given by [3]:

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix}. \tag{1}$$

The matrix [Q] is referred as the reduced stiffness matrix for the layer and its terms are given by:

$$\begin{aligned} Q_{11} &= \frac{E_{11}}{1-\nu_{12}\nu_{21}}; \qquad Q_{12} = \frac{\nu_{12}E_{22}}{1-\nu_{12}\nu_{21}} \\ Q_{22} &= \frac{E_{22}}{1-\nu_{12}\nu_{21}}; \qquad Q_{66} = G_{12} \end{aligned} \tag{2}$$

where E is modulus of elasticity, G is modulusof rigidity and ν is Poisson's ratio.

In Descartes rectangular coordinate system x-y-z (x-axis is the axial shaft axis), whereas the angle of fibers is measured in reference to the positive direction of x-axis, the relation between tension and deformation may be presented as follows:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix}. \tag{3}$$

The lowest natural frequency expression is given as:

$$f_n = \frac{\pi}{2}\sqrt{\frac{gE_x I}{WL^4}}\,. \tag{4}$$

where g is the acceleration due to gravity, W is the weight per unit length, L is the shaft length and I is the second moment of inertia given, for a thin-walled tube, as:

$$I = \frac{\pi}{4}\left(r_0^4 - r_i^4\right) \approx \pi r^3 t\,. \tag{5}$$

here, r_0 is an outer radius, and r_i is an inner radius.

3. FINITE ELEMENT ANALYSIS COMPOSITE CARDAN SHAFT

This paper analyses a real shaft of the truck TURBO ZETA 85.14B, which is not made of steel, but of aluminium/composite material [5]. Two different types of composite materials were used: carbon fibre/epoxy resin and aramid fibre/epoxy resin. Table 1 shows the basic properties of these composite materials.

Table 1 *Basic properties of composite materials*

Material	E_1, GPa	E_2, GPa	G_{23}, GPa	G_{12}, GPa	ν	ρ, kg/m^3	t_{ply}, mm
Carbon fibres/epoxy composite	131,6	8,20	3,5	4,5	0,281	1550	0,125
Aramid fibres/epoxy composite	81,8	5,10	1,82	1,51	0,31	1380	0,125

In Table 1, the following notation is used: E_1- longitudinal modulus; E_2 – transverse modulus; G_{12}, G_{23} – shear modulus; ν – Poisson's ratio; ρ – density; t_{ply} – composite layer thickness.

The basic dimensions of the analysed shaft [5] are: shaft length 1,35 m, mean radius of the shaft 0.041 m, wall thickness of the ring shaped cross section of the shaft 0,003 m. The shaft was tested under the action of maximum value of the static torsion moment of 5000 Nm.

The analyzed shaft was modelled by linear isoparametric square shell finite elements. The model of the analysed shaft can be seen in Figure 1. In the numerical analysis, the shaft is fixed at one end while the other is free and under the effect of the torque. The NX Nastran software was used for the analysis. The composite part of the shaft consists of 8 layers (carbon fibres/epoxy resin and aramid fibres/epoxy resin).

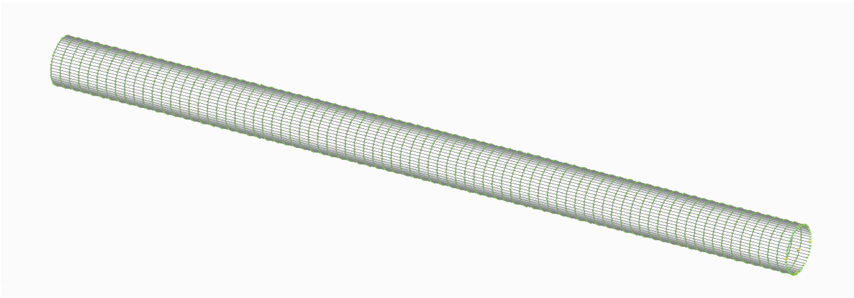

Fig. 1 *Finite element model of the aluminium/composite shaft*

Values of shaft torsion angles resulting from numerical calculation for both analyzed composite materials (carbon and aramide), at different values of fiber orientation angles, are indicated in Fig. 2.

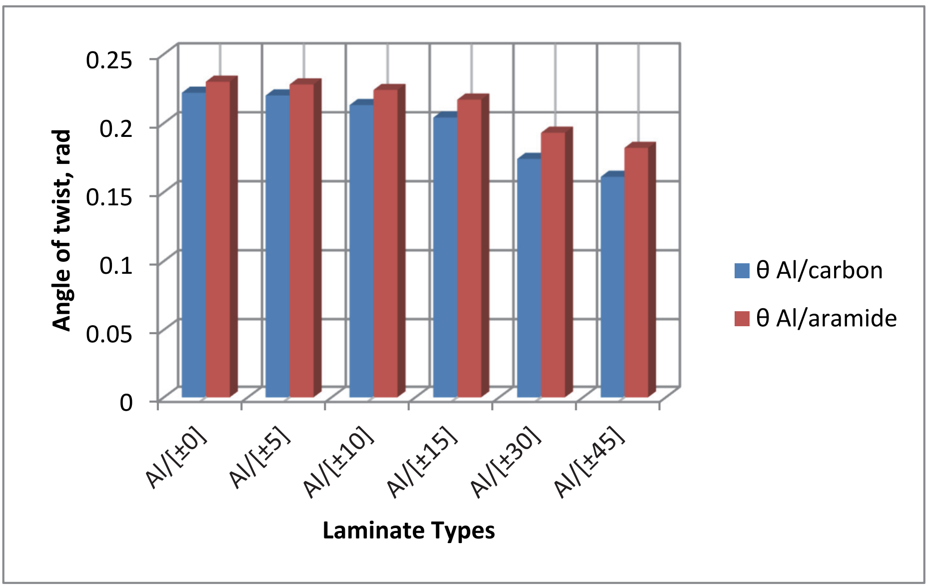

Fig. 2 *Influence of fiber angle orientation to torsion angle value forhybrid Al/carbon and Al/aramide shafts*

As indicated in Figure no. 2 the values of torsion angles are somewhat lower in case of carbon versus aramide fibres. Also, one may see that in case of both materials, the highest values of shaft torsion angles are at fibre orientation angle of 0°, and the lowest with fiber orientation of ±45°.

By using NX Nastran software, the numerical values of natural frequencies of hybrid Al/carbon and Al/aramide shafts have been determined. On grounds of acquired values of natural frequencies f_s , in the first oscillation critical numbers of rotations of analyzed shafts may be set applying the following expression:

$$n_{kr} = 60 \cdot f_s . \quad (6)$$

It is well known that the values of natural frequencies depend on ratio E_1/ρ. In case of composite materials, that ratio varies and depends on fiber orientation. The ratio has the maximum value for the fiber angle of 0°, and it decreases as the orientation angles of fibers increase. In reference to that, Figure no. 3 shows that in case of carbon and aramide fibers of natural frequency, the critical number of shaft rotations have the highest value at angle of 0°, whereas the value drops down with fiber orientation angle getting closer to ±45°. Also, Figure 3 indicates that carbon fibers show significantly better results (higher values of critical number of rotations) than aramide fibers.

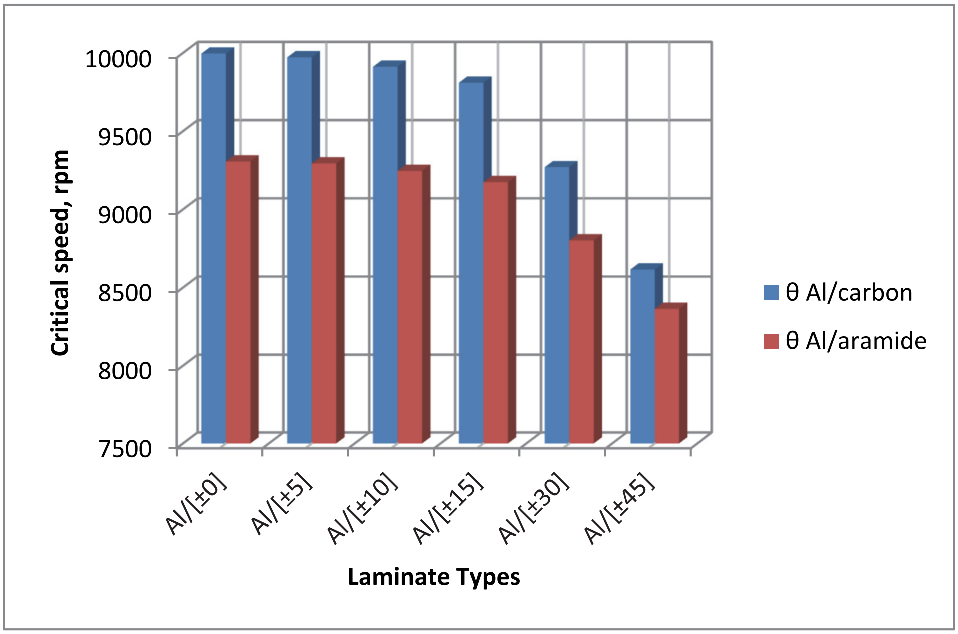

Fig. 3 *Influence of fiber orientation angle upon values of critical number of rotations for hybrid Al/carbon and Al/aramide shafts*

4. CONCLUSION

In this paper we have analyzed the relation between types of fiber and fiber orientation angles on one side and parameters such as shaft torsion angle and critical number of rotations on the other. The results show that orientation of fibers has a significant influence upon statistical and dynamic shaft characteristics.

By way of analyzing shaft torsion angles, we got the best results for hybrid

Al/carbon shafts with fiber orientation angle of ±45 ^{o}. For getting the highest possible values of critical number of rotations, carbon fibers with the least possible angles of fiber orientation should be used.

Finding the optimal orientation of fibers helps in discovering the optimal design of composite shaft which would result also in reduction of production costs.

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