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Analysis of the Influence of the Fibre Type on Static and Dynamic Characteristics of Composite Shafts

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Characteristics of composite materials (stiffness, resistance, thermal expansion, etc.) can vary depending on the type of the applied material, quantity, fibre orientation angle, etc. The choice of material depends on the service life needed, product shape complexity, computation of optimal characteristics of composite materials, etc. In some cases, the best results can be achieved using a combination of composite and traditional metal materials. This paper studies shafts obtained by a combination of aluminium and different composite materials – carbon fibres/epoxy resin, glass fibres/epoxy resin, and aramide fibres/epoxy resin

Key words: **composite materials, aluminium, carbon fibre, glass fibre, aramide fibre, shaft, dynamic characteristics, static characteristics.**

Introdustion

IN recent years, composite materials have been increasingly used in various engineering constructions in the field of mechanical engineering, plane engineering, navy, etc. These materials have excellent mechanical characteristics and a good stiffness to weight ratio, which can be additionally improved by the right selection of a fibre type or by a proper fibre orientation in different layers.

The finite element method (FEM) is the most frequently used method for the analysis of static and dynamic characteristics of composite shafts. It has a special place among other numerical methods because of its simple mathematical and physical formulation and because there are numerous computer programmes for it. The underlining principle of this method is physical discretisation of the continuum.

The finite element method is characterised by a wide range of applications, simple analysis of the environmental influence on the construction (mechanical and thermal loads, boundary conditions, etc.) and a possible automatisation of all computational stages. The popularity of this method is partly due to the simplicity of its physical interpretation.

When studying a deformable body, the principal task is to choose a discrete model that gives the best approximation of the stress state, deformation state and the boundary conditions. Either one type or a combination of several types of finite elements can be used for the discretisation of the continuum. There are no explicit criteria how to select a discrete model that would ensure accuracy of the solution. In addition to the knowledge of the finite element theory, it takes a huge experience in engineering to choose the right type of elements that would approximate a construction shape best.

For the analysis of hollow shafts of small wall thickness, like composite shafts, shell-shaped and beam-shaped elements are most frequently used.

The equivalent modulus beam theory (EMBT), which is widely used for the dynamic analysis of composite shafts, was firstly introduced by Tsai [1]. With this approach, equivalent longitudinal Young and in-plane shear moduli are identified by using the laminate theory for symmetrical stacking. Then, the classical beam theory can be used to model the shaft, see Pereira [2] and Singh and Gupta [3]. This approach has many limitations summarized by Singh and Gupta in [4]. They studied the natural frequencies and damping ratios in flexural modes of cylindrical laminate tubes and compared shell and EMBT models for symmetric laminate stacking, concluding that in the case of the tube configurations usually used in composite shaft applications, the differences in flexural frequencies between the two models are negligibly small. Using the shell theory in [5], the same authors showed that the modal loss factors are more sensitive to parametric (laminate stacking, angle orientations, etc.) changes than frequency values. They also presented a comparison between the EMBT theory and the layerwise beam theory (LBT) for symmetric and asymmetric stacking in [6].

Recently, Gubran and Gupta have presented in [7] a modified EMBT method which takes into account the effects of a stacking sequence and different coupling mechanisms. They considered a graphite/epoxy shaft simply supported on rigid bearings and compared the first three frequencies with those obtained by using the LBT method. In spite of its simplicity, the natural frequencies obtained using a modified EMBT method excluding

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different coupling effects agree well with those obtained using the LBT and those reported in the literature. In these cited works, the internal damping is not often taken into account, except in [4] where viscoelastic material damping is assumed.

Types of composite fibres for shaft construction

Composite materials belong to the group of isotropic materials, so their mechanical properties depend a great deal on the angle of measurement of their characteristics. Their strength depends on the orientation of reinforcing fibres, while the longitudinal tensile strength greatly exceeds the transversal strength.

The basic requirements that fibres should meet are:

- high fibre strength,
- high modulus of elasticity,
- appropriate dimensions and shape of the fibres,
- stability of the properties,
- simple manufacturing,
- good adhesion to the matrix, etc.

Glass, carbon, organic (kevlar-aramid etc.) and boron fibres are the ones that are most often used for construction composites.

Glass fibre/polyester or glass fibre/epoxy resin composites are widely used in practice. The advantages of glass fibres over other materials are the following: easy and cheap production, possibility to produce very long fibres, high resistance to impact, good machinability, etc. The basic disadvantages of glass-fibre-reinforced composites lie in the fact that they have a low modulus of elasticity and that they lose resistance at elevated temperatures.

Figure 1. Glass fibre

The need for stronger materials led to a greater application of carbon fibre/epoxy resin composites. Carbon fibres have high strength, high modulus of elasticity, low density, excellent machinability, resistance to elevated temperatures, low thermal expansion coefficient, inertness to most reagents, etc. Their main disadvantages are low toughness and high anisotropy, which causes additional problems to constructors, and a high production cost compared to glass fibres.

Figure 2. Carbon fibre

The best-known organic fibres are aramide fibres such as Kevlar. Aramide fibres have extremely high tensile strength, low density, excellent impact resistance, excellent isolating and heat properties, they are stable at a wide temperature range, they neither melt nor shrink, they are easy to machine and they can be produced in the form of weave. Their disadvantages are low compression, a rather low modulus of elasticity, they are difficult to obtain, and they have a high production cost. For these reasons, these fibres are often combined with carbon or boron fibres to form the so-called hybrid composites.

Figure 3. Aramid fibre

Boron fibres are characterised by high compression strength and torsion resistance. They have a positive coefficient of linear expansion. Their disadvantages are difficulty to machine and shape due to their high hardness, and a high production cost.

The physical and mechanical properties of the most frequently used reinforcing fibres for the construction composites are given in Table 1.

Table 1. Physical and mechanical properties of fibres

Fibre	Density ρ, kg/m^3	Yield strength R_m, MPa	Tensile modulus E, GPa	Specific strength R_m/ρ x10^6 m	Specific stiffness E/ρ x10^9 m
Glass	2400-2500	2100-4600	72-86	0.83-1.85	28.5-34.5
Carbon	1700-2000	2800-4500	260-385	1,1-1,91	126-205
Boron	2600	2800	385-430	1.18	148
Aramide	1440	2800	135	1.87	77

Matrices for composite material production can be polymer, metal, ceramic, carbon, and poly-matrices. The matrix is the basis of the composite material and it serves to:

- bind fibres together,
- transfer loads from fibre to fibre,
- protect the fibre surface and thus prevent the effects of abrasion,
- ensure the machinability of composites,
- prevent fibre-to-fibre contact, thus preventing the fibre damage,
- prevent crack widening, i.e., fibre breaking.

For the manufacture of construction composites, the most widely used are the following:

- matrices based on epoxy resins,
- matrices based on phenolic resins,
- matrices based on polyester resins, and
- metal- based matrices.

The properties of composites mainly depend on:

- the strength and chemical stability of the matrix,
- the strength and elasticity of the reinforcing fibres,
- the strength of the bond between the matrix and the reinforcing fibres.

Computation of composite shafts

This paper analyses a real shaft of the truck TURBO ZETA 85.14B, which is not made of steel, but of aluminium/composite material [8]. Three different types of composite materials were used: carbon fibre/epoxy resin, glass fibre/epoxy resin and aramide fibre/epoxy resin.

The basic dimensions of the analyzed shaft [8] are: shaft length 1.35 m, the 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 the maximum value of the static torsion moment of 5000 Nm.

The analyzed shaft was modelled by isoparametric square shell finite elements. It was divided into 20 elements in the axial and 12 elements in the circular direction. The total of 252 elements was used for modelling. The model of the analysed shaft can be seen in Fig.4.

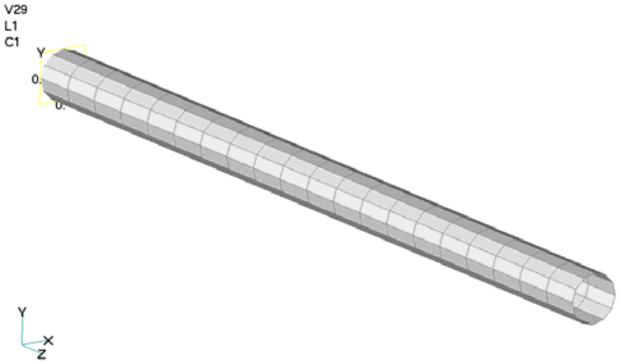


Figure 4. Finite element model of the aluminium/composite shaft

Figs.5, 6 and 7 show the obtained values of the shaft twisting angles for all three types of composite materials under the same conditions (the same shaft dimensions, loads and fibre orientation angles). All these figures (Fig.8 in particular) show that the lowest values of the twisting angles are obtained when the shaft is made of aluminium/carbon fibre/epoxy composite (Al/USN). The combination of aluminium/glass fibre/epoxy composite (Al/UGN) and aluminium/aramide/epoxy composite (Al/UKN) gives similar shaft twisting angles, but their values are significantly higher than in the case of carbon fibres.

Al/[±30$_{USN,4}$]

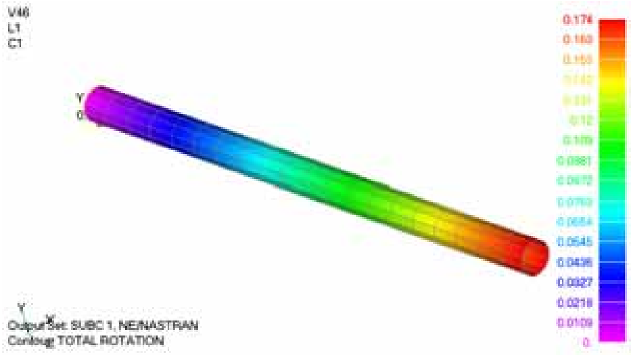


Figure 5. Angle-twisting for the hybrid Al/carbon fibre/epoxy composite shaft

Al/[±30UGN,4]

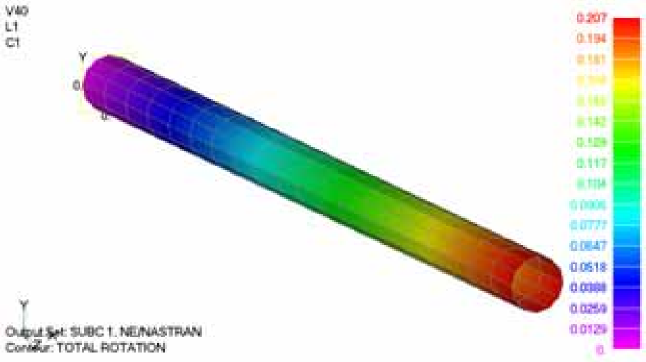


Figure 6. Angle-twisting for the hybrid Al/glass fibre/epoxy composite shaft

Al/[±30UKN,4]

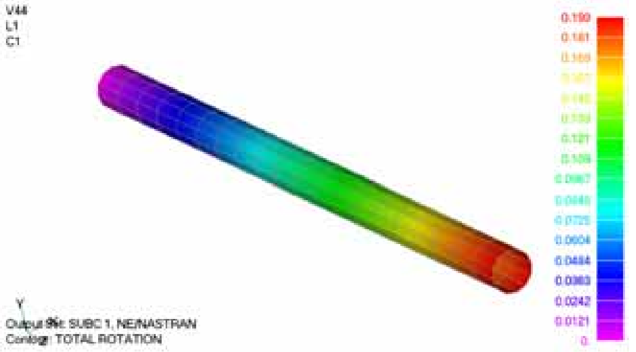


Figure 7. Angle-twisting for the hybrid Al/aramide fibre/epoxy composite shaft

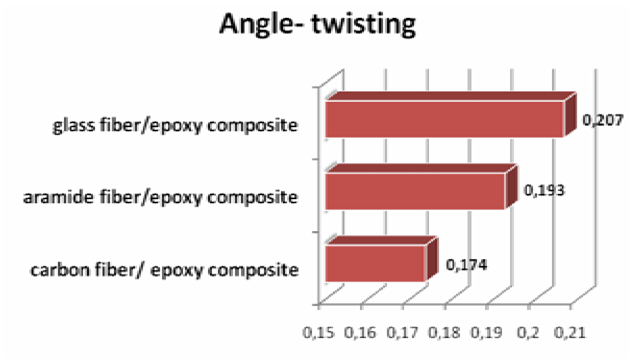
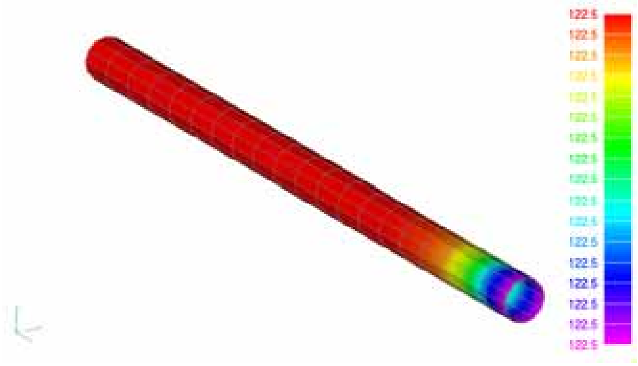


Figure 8. The bar chart of the influence of the shaft material type on the values of twisting angles

The stress values in the aluminium and composite layers for all three composite fibre types have also been analysed.

Stresses in aluminium layer

Al/[±30$_{USN,4}$]



Stresses in the highest-load composite layer

Al/[±30USN,4]

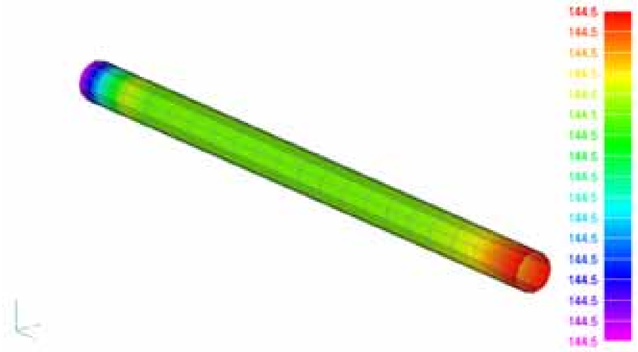
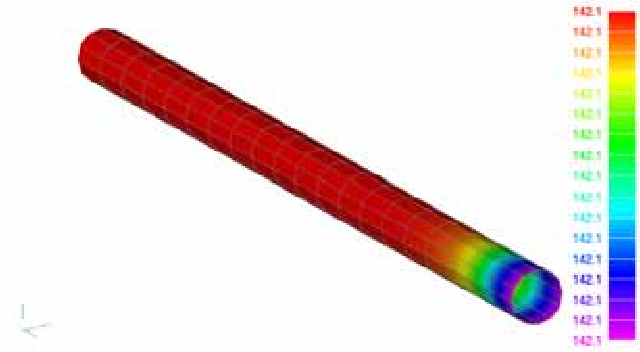


Figure 9. Stresses due to torsion in aluminium and the highest-load composite layer of hybrid Al/USN shafts

Stresses in the aluminium layer

Al/[±30UGN,4]



Stresses in the highest-load composite layer

Al/[±30UGN,4]

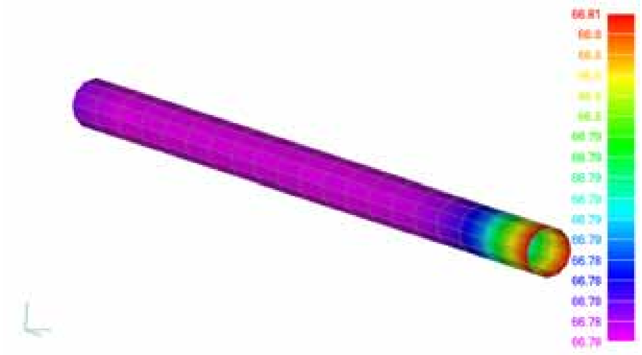
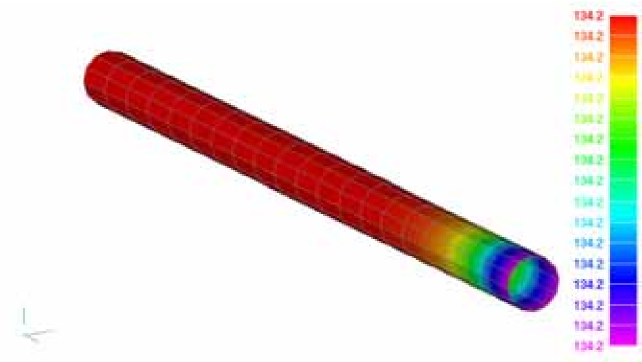


Figure 10. Stresses due to torsion in aluminium and the highest-load composite layer of hybrid Al/UGN shafts

Stresses in the aluminium layer

Al/[±30UKN,4]



Stresses in the highest-load composite layer

Al/[±30UKN,4]

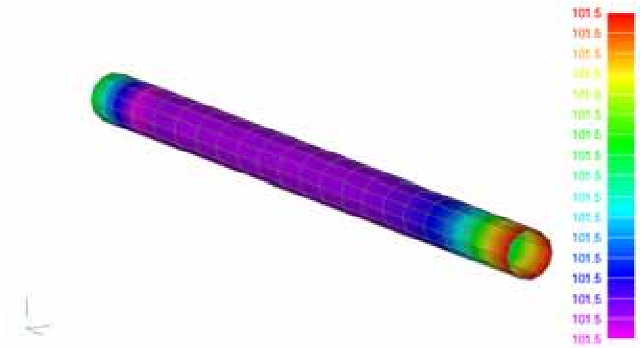


Figure 11. Stresses due to torsion in aluminium and the highest-load composite layer of hybrid Al/UKN shafts

The best results are obtained in the case when carbon fibres are used and when the carrying capacity is the capacity of the composite layer (Fig. 9). In the case of glass fibre (Fig. 10), and particularly in the case of aramide fibres (Fig. 11), the carrying capacity mainly comes down to the capacity of the aluminium layer.

Analysis of shaft stability

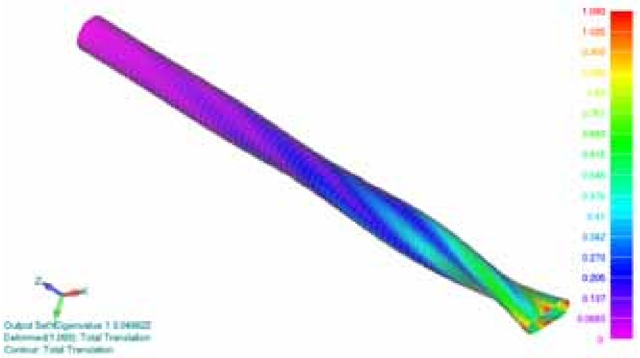
The critical buckling torque values that lead to the instability of a shaft exposed to torsion can be determined numerically by the buckling analysis. In fact, the value of the coefficient λ for the first buckling mode can be determined numerically, while the critical torque can be determined using the following expression:

$$T_{tcr} = T_t \cdot \lambda \qquad (1)$$

where T_t is the value of the maximum torque the shaft is exposed to (in this case 5000 Nm).

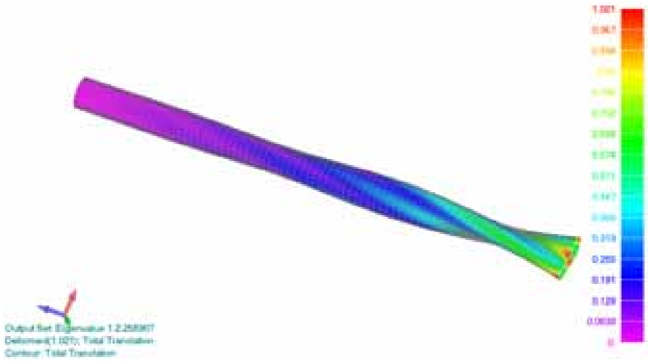
The obtained values of the coefficient λ for the first buckling mode for all three types of the analysed hybrid shafts are given in Fig. 12.

Al/[±30USN,4]



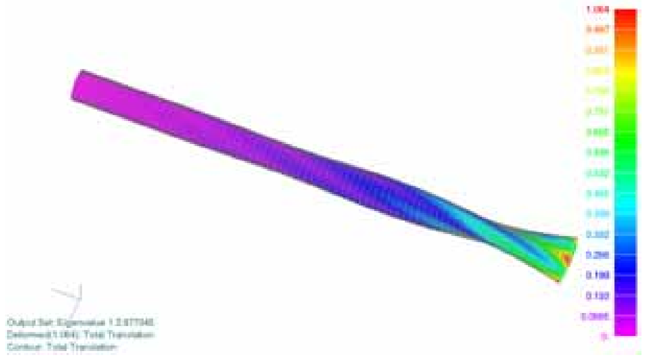
The coefficient λ in the case of hybrid Al/ USN carbon/epoxy composite shafts

Al/[±30UGN,4]



The coefficient λ in the case of hybrid Al/ UGN glass/epoxy composite shafts

Al/[±30UKN,4]



The coefficient λ in the case of hybrid Al/ UKN aramide/epoxy composite shafts

Figure 12. Values of the coefficient λ for all types of hybrid shafts

The obtained values of the critical buckling torques for the analysed hybrid shafts are given in Table 2.

Table 2. Critical buckling torque T_{tcr}

Material	Buckling load factor λ	Critical buckling torque (Nm)
Al/[$\pm 30_{\mathrm{USN},8}$] carbon fibre epoxy composite	3.05	15249
Al/[$\pm 30_{\mathrm{UGN},8}$] glass fibre epoxy composite	2.26	11279
Al/[$\pm 30_{\mathrm{UKN},8}$] aramide fibre epoxy composite	2.98	14886

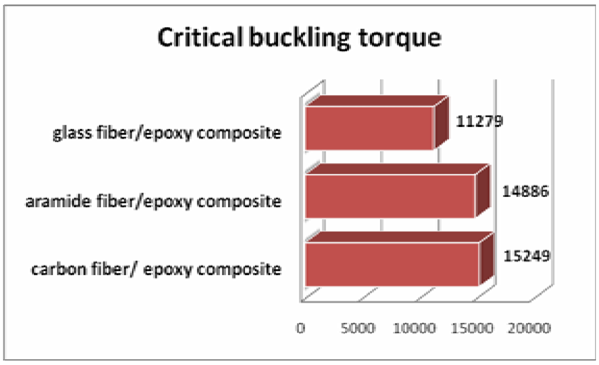


Figure 13. The bar chart of the influence of the material type on the critical buckling torque values

Therefore, based on Table 2, and especially on the bar chart given in Fig. 13, it can be concluded that the critical buckling torque has the highest values for the hybrid Al/ USN carbon/epoxy composite shafts, slightly lower values for the hybrid Al/UKN aramide/epoxy composite shafts, and the lowest values for Al/UGN glass/epoxy composite shafts.

Conclusion

Since there is a worldwide tendency to manufacture shafts using a combination of aluminium and composite materials, these materials occupy a central place in our study. This paper studies application of carbon, glass and aramide fibres in an epoxy resin matrix. The obtained results show that carbon fibres have the best characteristics concerning resistance and stability; therefore, they are recommended for practical application.

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Analiza uticaja vrste vlakana na statičke i dinamičke karakteristike kompozitnog vratila

Karakteristike kompozita (tj. krutost, otpornost, termičko širenje i dr.) mogu da variraju zavisno od vrste primenjenog materijala, količine, ugla orijentacije vlakana i dr. Izbor materijala zavisi od zahtevanog radnog veka, složenosti oblika proizvoda, veštine proračuna optimalnih karakteristika kompozita i dr. U nekim slučajevima najbolji rezultati mogu biti postignuti korišćenjem kombinacije kompozita i tradicionalnih metalnih materijala. U radu su analizirana vratila dobijena kombinacijom aluminijuma sa različitim kompozitnim materijalima – karbonska vlakna/epoksi smola, staklena vlakna/epoksi smola, aramidna vlaka/epoksi smola.

Ključne reči: **kompozitni materijali, aluminijum, grafitno vlakno, stakleno vlakno, aramidno vlakno, vratilo, dinamičke karakteristike, statičke karakteristike.**

Анализ влияния типа волокон на статические и динамические характеристики композитных валов

Характеристики композитных материалов (то есть, жёсткость, устойчивость, тепловое расширение и.т.д.) могут различаться в зависимости от типа используемых материалов, количества, угла ориентации волокон и другого. Выбор материала зависит от требуемого срока службы, сложности формы товаров, способа расчёта оптимальных характеристик композитных материалов и другого. В некоторых случаях наилучшего результата можно добиться используя сочетание традиционных металлических и композитных материалов. В настоящей работе анализированы валы полученные сочетанием алюминия с различными композитными материалами – карбоные волокна / эпоксидная смола, стекловолокно / эпоксидная смола, арамидные волокна / эпоксидная смола.

Ключевые слова: **композитные материалы, алюминий, углеродное волокно, стекловолокно, кевлар, вал, динамические характеристики, статические характеристики.**

Analyse de l’influence du type du fibre sur les caractéristiques statiques et dynamiques chez l’arbre composite

Les caractéristiques des composites (rigidité, résistance, propagation thermique etc.) peuvent varier en fonction des matériaux employés, de la quantité, de l’angle de l’orientation des fibres etc. Le choix des matériaux dépend de la durée de vie exigée, de la complexité de la forme du produit, de la computation des caractéristiques optimales des composites etc. Dans certains cas les meilleurs résultats peuvent être obtenus par l’utilisation de la combinaison des composites et des matériaux traditionnels de métal .Dans ce travail on a analysé les arbres réalisés en combinant aluminium avec des différents matériaux composites : les fibres du carbone/résine époxy, fibres de verre/résine époxy, fibres aramide / résine époxy.

Mots clés: **matériaux composites, aluminium, fibre, fibre de verre, fibre aramide, arbre, caractéristiques dynamiques, caractéristiques statiques.**