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## Original Article

# Hybrid fiber and nanopowder reinforced composites for wind turbine blades<sup>☆</sup>



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### ABSTRACT

The results of an investigation into the production of wind turbine blades manufactured using polymer composites reinforced by hybrid (carbon, basalt, glass) fibers and strengthened by various nanopowders (oxides, carbides, borides) are presented. The hybrid fiber-reinforced composites (HFRC) were manufactured with prepreg technology by molding pre-saturated epoxy-strengthened matrix-reinforced fabric. Performance of the manufactured composites was estimated with values of the coefficient of operating condition (COC) at a moderate and elevated temperature.

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## 1. Introduction

At present, a major problem in the power industry is to increase the amount of electricity manufactured from wind in the world energy balance to 12% by 2020, on the basis of a gain of 25–30% in the rated capacity per year. Small-scale power developed in microgrid systems plays a significant role in the power supply of developing countries, as well as in the rural and remote regions of any country. Development of environmentally friendly small-scale power, focused on the private consumer, requires an increase in the efficiency of wind turbines and the reduction of their cost, as well as stable provision of energy at moderate wind speed. The power efficiency and the cost of a wind turbine vary considerably and are primarily defined by its main elements – blades and a wind rotor.

The need to increase the efficiency of wind turbines at low wind speeds has led to the development of a number of special programs in various countries. One example of this type of program is the US Small Wind Turbine Industry Roadmap, a 20-year industry plan for small wind turbine technology.

In 2006–2008, the Science and Technology Center in Ukraine financed the project “The small wind turbine of the raised efficiency at moderate winds with adaptive aero elastic blades from composite high-modular materials” (Project Manager Dr. N.P. Ushkin, State Design Office, National Space Agency of Ukraine).

The main objective of the project was the development of a small wind turbine, energetically more effective than current models (by 30–50%) at prevailing moderate wind speed (4.0–6.0 m/s) and with a reduced specific cost (by 30–50%). This was based on the use of a new design for the blade, a decrease

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in the threshold of activation of the turbine (from 2.5 to 3.5 m/s to 2 m/s), and a decrease in magnitude of anticipated wind speed (from 12 to 14 m/s to 9–10 m/s), as well as the application of a new hybrid composite for the turbine blade. To perform the material testing needed for the project, i.e., the development of a new composite for the turbine blade, the Frantsevich Institute for the Problem of Materials, part of the National Academy of Sciences of Ukraine (Project Manager, Dr. L. R. Vishnyakov) and the Mining Institute of the Academy of Sciences of Georgia (Project Manager, Dr. N.M. Chikhradze) were engaged. In the present paper, the main results were obtained at the Mining Institute. To perform the objectives of the project, the authors were guided by the current belief that the application of blades rigidly fixed in a nave is the modern technical solution allowing for simplification of the design and increasing the reliability of the system. However, the adaptive blades demand the use of very expensive carbon fibers to ensure the required rigidity and elasticity of the blade. In the material testing performed, a novel choice was made to use a new material for the adaptive blades, partially replacing the expensive carbon fiber, which will considerably reduce (30–35%) the blade cost.

Currently for the production of hybrid blades, carbon and glass fibers are mainly used as the basic materials [1]. Additionally, studies on reinforcing the epoxy matrixes using basalt and other fibers [2] have been performed. The present authors attempted to achieve the aforementioned purpose using composites of hybrid reinforcing fibers (carbon-basalt, carbon-basalt-glass) and polymeric matrixes with high-modular fillers (fibers, powders). The results from these investigations have recently been published [3–6].

## 2. Experimental

### 2.1. Experiments on composite matrix strengthening

The current investigation utilized epoxy-diane resin with passive diluents – using dibutyl phthalate at 15 m.f. per 100 m.f. of resin. The resin has a density of  $1.168 \text{ g cm}^{-3}$ , and its viscosity at  $20^\circ\text{C}$  is 120 P. The resin's components were epoxy groups at 17 mass%, total chlorine at 0.85 mass%, chlorine ions at 0.007 mass%, volatiles at 0.85 mass% and the time of gelation of the resin at  $100^\circ\text{C}$  was 3.0 h.

To reinforce the epoxy resin, powders of boron carbide ( $100 \mu\text{m}$ ), silicon carbide ( $80 \mu\text{m}$ ) and zirconium diboride ( $100 \mu\text{m}$ ), as well as mullite-like oxide crystals  $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$  (diameter 2–8  $\mu\text{m}$ , length 80–200  $\mu\text{m}$ ), basalt powder ( $100 \mu\text{m}$ ) and diluvium powder ( $60 \mu\text{m}$ ) were used. The diluvium powder had the following chemical composition:  $\text{SiO}_2$  – 57.5;  $\text{Al}_2\text{O}_3$  – 19;  $\text{Fe}_2\text{O}_3$  – 7.4;  $\text{CaO}$  – 1.1;  $\text{MgO}$  – 3.0;  $\text{R}_2\text{O}$  – 5.2. For production of boron carbide, amorphous boron and technical carbon were used as ingredients. The prepared mixture was briquetted in a graphite mold. Boron carbide was synthesized in a vacuum electric furnace. Synthesis was performed at  $1850 \pm 25^\circ\text{C}$  for 2.5 h. Cooling was performed under vacuum over 10 h. Zirconium diboride was produced using the method of boron carbide reduction. Zirconium dioxide and carbide were preliminary processed under vacuum for charge production. Mullite-like crystals were prepared using the method

of oxide solution crystallization in a melt bed. Basalt powder preparation included the following operations: crushing of basalt stones at the hydraulic press; melting; crushing and grinding of ingots; fractionation of the ground powder in a high energetic “Fritsch” planetary premium line ball mill. The used diluvium powder was dispersive, loose, anthropogenic raw material.

The amount of powders added to the epoxy resin was 7% of the resin mass. The hardener used for the compositions was polyethylene polyimine (12% of the resin mass).

The following samples were prepared: “a” – pure epoxy resin, “b” – with diluvium, “c” – with boron carbide, “d” – with silicon carbide, “e” – with  $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ , “f” – with  $\text{ZrB}_2$  and “g” – with basalt. The samples were molded under tension in the form of mortar briquettes of  $50 \text{ mm} \times 4 \text{ mm} \times 2 \text{ mm}$  dimensions. Strips of  $170 \text{ mm} \times 15 \text{ mm} \times 3 \text{ mm}$  for fatigue testing were prepared as well.

Short-term mechanical tensile tests were conducted using an FPZ-100 machine with automatic recording of strength-deformation. The tensile machine's maximum load was 1.0 T using a test velocity of 15 mm/min. The reinforcement coefficient of the composites was evaluated by comparison with the strength and deformation results of the pure epoxy resin.

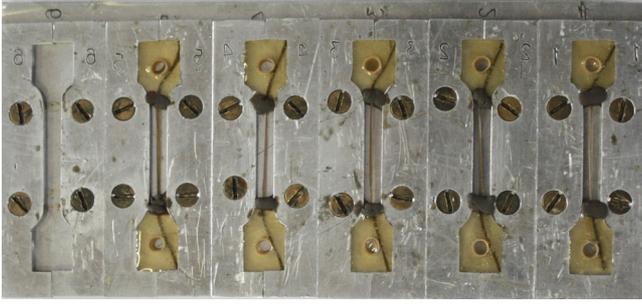
For material testing on fatigue bending, the device shown in Fig. 1 has been used. The main parameters of the device are: the simultaneous testing of three sheets or samples; a bending angle from  $20^\circ$  to  $180^\circ$ ; clamp width of samples up to 30 mm; weights for preliminary load from 0.2 to 5 kgf; number of bends per minute – 100; three individual counters with an automatic shut-off at sample breakage.

As shown in Fig. 1, each specimen was fixed in a special grip that swings about its axis of rotation. The grip is designed so that the band axis coincides with the rotation axis, and the specimen is repeatedly subjected to a load imposed by hanging weights. This is associated with a definite preliminary tension. For this study, the bending angle was selected as  $20^\circ$ , the load was 2 kgf, and the number of the bends per minute was 100.

An endurance coefficient was determined from appropriate compositions (series “d”, “g”), with regards to reinforcement. The endurance coefficient signified a ratio between the residual strength of the composition after cyclic testing and its short-term static strength. The magnitude of this ratio, which reduces slightly regardless of number of cycles ( $N$ ), was used as the endurance coefficient.



Fig. 1 – Device for testing on fatigue.



**Fig. 2 – Metallic knock-down mold for preparation of the samples.**

## 2.2. Experiments on reinforced basalt fiber

The short-term strength of produced elementary fibers was studied. The fiber diameter was measured by microscope at magnification of  $\times 750$  with a 10 mm working sample length. The long-term strength of the fibers was also studied. The fibers with a linear density of 110–130 tex were chosen to be the research subject representative of elementary fiber composition, obtained from the most uniform melt of the deposit. The sample for testing the fibers had an overall length of 40 mm (working length of 25 mm), the ends of which were embedded for 10 mm in the plates of epoxy resin. The samples placed in the grips with the knurled surface were fixed through the sample plates using bolts. The samples were prepared in metallic knock-down molds using a separating layer for ease of sample removal from the mold (Fig. 2).

For testing of long-term strength, lever plants were used, as shown in Fig. 3.

The capabilities of the lever plants are significant: in addition to material strength, they measure the creep of the material in normal conditions as well as at elevated temperatures and in aggressive media. The advantage of the lever plants in comparison with other apparatus lies in the fact that they provide a constant stress on the sample. The application

of constant stress is of high importance in conducting a practical investigation.

The determination of the long-term strength of the composite fibers consisted of the following:

1. Short-term breaking force (load) was determined for the samples ( $F_0$ , kgf).
2. The levels of constant loads on the samples were assigned –  $F$ , kgf (for example, 0.9; 0.8; 0.7; 0.6; 0.5 from  $F_0$ ), and the time elapsed from loading to breaking of the samples was fixed ( $\tau$ , s).
3. The dependence graph between the coefficient of the long-term strength and logarithm of time was constructed.

## 2.3. Experiments on hybrid fiber-reinforced composites (HFRC)

### 2.3.1. Coefficient of operating condition (COC) at elevated temperature

The aim of the work is to determine the COC of a composite for a predetermined service life and temperature ( $K_t^T$ ). The COC represents a ratio between long-term breaking stress after a defined interval corresponding to service life of wind turbine blades ( $\sigma_{l-t}$ ) and breaking stress obtained by standard short-term testing of the material at room temperature ( $\sigma_{sh-t}$ ):

$$K_t = \frac{\sigma_{l-t}}{\sigma_{sh-t}} \quad (1)$$

The direct experimental determination of the COC is associated with several difficulties, particularly the necessity to maintain constant outer conditions and the predetermined stress over an extended duration. Extrapolation of experimental data and selected time under stress was carried out using S.N. Zhurkov's equation based on the kinetic nature of the strength of solids:

$$\tau = \tau_0 \exp\left(\frac{U_0 - \gamma\sigma}{kT}\right) \quad (2)$$



**Fig. 3 – Plants for the long-term testing.**

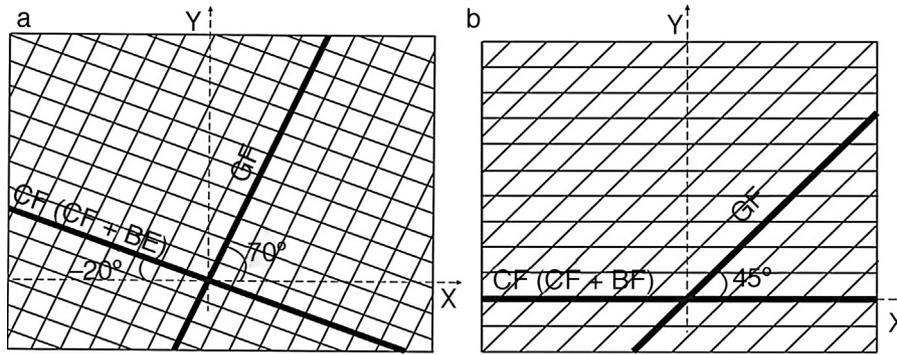


Fig. 4 – Arrangement of reinforcing elements in composite destined for (a) shell and (b) spar.

where  $\tau$  is the time before material destruction,  $\tau_0$  is a constant, approximately equal to  $10^{-13}$  s, which in order of a value is near to the period of thermal oscillations of atoms,  $U_0$  is the initial activation energy of the process of material destruction,  $\gamma$  is the average coefficient of overstresses,  $T$  is the absolute temperature,  $k$  is Boltzmann's constant, and  $\sigma$  is the stress applied on a material.

In this case, we have tried to account for joint effects of stress, time and temperature using the accelerated method for determination of  $\sigma_{1-t}$  as in the well-known parametric method of S. Goldfein. This method is based on a combination of temperature ( $T_i$ ) and time to material failure ( $\tau_f$ ) in one parameter whereby a long-term strength is determined:

$$P = \frac{T_0 T_i}{T_0 - T_i} (c + \lg \tau_f) \quad (3)$$

where  $T_0$  is the temperature at which an infinitely small stress causes the materials failure, and  $c=20$  for solid materials, including our research object because the sample is bound in a glassy state.

It is possible to use Eq. (3) to construct the dependence  $\sigma = f(P)$  using short-term testing at elevated temperatures and by varying  $T$  and  $\tau_f$  to calculate long-term strength at various temperatures. According to previous studies [7], it was shown that from Eq. (2) a linear relationship between the parameter  $P$  and the long-term strength is evident:

$$\sigma_{1-t} = a - bP \quad (4)$$

where  $a = U_0/\gamma$ , and  $b = 2.3k/\gamma$ .

According to the recommendations of previous wind turbine studies, when manufacturing turbine blade shells the carbon fibers should be arranged at  $-20^\circ$  relative to the blade axis (i.e., X axis), and the glass on fibers should be perpendicular to the carbon fibers [8–10]. When manufacturing spar reinforcing, the fibers were arranged parallel and at a  $+45^\circ$  angle to X-axis. The structure of composites destined accordingly for shell and spar of blade is shown in Fig. 4.

Six types of composite were selected as research objects representing monolithic layered reinforced materials. In composites 1, 2 and 3, which were destined for the shells, carbon fibers (CF) and glass fibers (GF) were used in a mass ratio of GF:CF = 0.3:0.7. In a midpoint of the cross-section of composite

1, CF were interchanged with GF and the total number of layers was CF-7, GF-4. In composite 2, CF was replaced by basalt fibers (BF) for up to 20% of the mass of CF. In composite 3, the amount of CF replaced by BF is 30%. Composites 4–6 are intended for spars. Composite 4 is made of used CF by way of roving. In composites 5 and 6, CF is replaced by BF correspondingly, by 20% and 30% by weight, again by way of rovings. In all cases, the fabrics were manufactured from non-twisted rovings.

Fabric from polyacrylonitrile carbon roving has a thickness of 0.7 mm, a surface density of 200–800 g/m<sup>2</sup>, a density in warp of 2.1–3.8 thread/cm, and a density in weft of 3.2–4.0 thread/cm. The fabric using basalt roving has a thickness of 0.4–0.9 mm, with a surface density of 300–700 g/m<sup>2</sup>, a density in warp of 1.7–3.5 thread/cm, and a density in weft of 2.9–4.0 thread/cm.

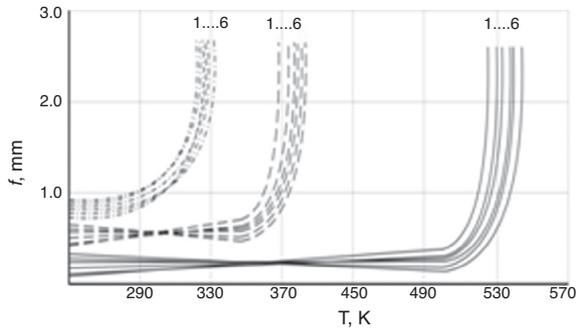
The mode of preparation of composite was prepreg technology (PrT), using layer-by-layer lining and forming the preregs in a thermal chamber. The thickness of the manufactured composite sheet was 6, 7 and 8 mm, with a density of 1.5 g/cm<sup>3</sup>.

Short- and long-term bending tests of monolithic samples cut out from sheets were conducted. Samples were of the dimensions 150 mm × 55 mm × 2 mm. The speed of movement of the machine's head was 30 mm/min.

The procedure to determine the values of the COC for the composites involved the following:

- Determination of the values of breaking stress using standard short-term static testing at room temperature ( $\sigma_{sh-t}$ ).
- Determination of the values of breaking stress at the temperatures of 310, 330 and 360 K.
- Selection of  $T_0$  for Eq. (3).
- Calculation of the values of parameter  $P$  for temperature testing.
- Construction of the dependence “strength-parameter  $P$ ” using coefficients  $a$  and  $b$  in Eq. (4).
- Calculation of the predetermined service life at temperature 330 K.
- Determination of  $K_t^T = \sigma_{1-t}/\sigma_{sh-t}$ .

To select the values of  $T_0$ , the indexes of sharp increase in composites deformation were used. This approach to



**Fig. 5 – Thermo-mechanical curves of the composites at various stresses: ..... 1 MPa; - - - 60 MPa; - . - 120 MPa; 1...6 – composites**

determine  $T_0$  in relation to glass plastics has been previously used [11].

Thermo-mechanical curves at various stresses were constructed and the temperature at which a sharp increase of deformation takes place was determined by applying stress to the material. As seen in Fig. 5, 510 K is value for  $T_0$ .

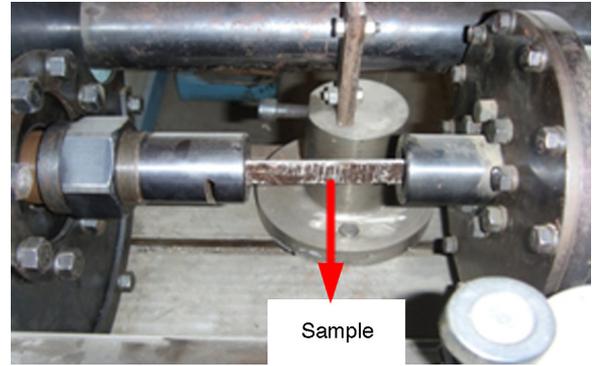
### 2.3.2. Testing of hybrid fiber-reinforced composites (HFRC) with dynamic loads

At PrT the layers of preliminary impregnated belts prepared from the fibers of given orientation were collected into packages and pressed in the thermal chamber.

In the composites in series A, only high-strength and high-modulus carbon fibers are located in parallel and at an angle of  $45^\circ$  to X axis (Fig. 4). In the composites in series B, the carbon fiber is in the same location, but 20% is replaced by high-strength basalt fiber. In the composites of series C, similar to series B the content of basalt fiber is increased to 40%. Reinforcing components are characterized by the following data: the linear density of carbon filament is 390 tex, and basalt filament is 330 tex.

Composites have the following characteristics: density of  $1.49\text{--}1.55\text{ g/cm}^3$ , porosity of  $9.2\text{--}9.7\%$ , and phase concentrations of matrix  $61.1\text{--}67.0\%$ , and of fibers  $38.9\text{--}43.0\%$ . The samples dedicated for testing on cyclic torsion followed by their testing on tension were right-angled strips of  $160\text{ mm} \times 15\text{ mm} \times 2\text{ mm}$ , cut from the composite plates in parallel to the X axis.

For composite testing on torsion, the machine was equipped with an exciter of cyclic displacements (Fig. 6). The range of amplitude variation for the displacement was



**Fig. 6 – The machine for testing torsion.**

0–16 mm, with the limit of permissible error  $\pm 0.02\text{ mm}$  at maximum amplitude of the displacements. The excitation frequency in this case was  $90\text{ min}^{-1}$ . The sample was tested by twisting  $20^\circ$  in alternate directions.

In essence, the method involves the determination of the endurance factor of the material under alternating twisting. To determine the endurance factor, the ratio between composite residual strength after cyclic testing and its short-term static strength is calculated. The level of this ratio, which is slightly reduced regardless of the number of cycles, is taken as the endurance factor.

## 3. Results and discussion

### 3.1. Matrix

The results of composition samples testing on strength ( $\sigma$ ) and deformability ( $E$ ) are given in Table 1. The amount of tested samples in each series was  $n=6$ , and the coefficient of variation of obtained data is variable from 5% to 8%.

The effect of resin reinforcement was a result of the addition of silicon carbide as well as basalt powder. Increase in the value of the elasticity modulus was also noted for compositions containing those ingredients. The addition of zirconium carbide to resin gave an insignificant increase of in the conventional coefficient of rigidity. It is noted that basalt powder of a given fineness of grind is comparable to boron and silicon carbides and zirconium diboride and in some cases outperforms them. A considerable increase in longitudinal strain was noted for compositions containing diluvium, which has a layered structure. By its characteristics, this composition is close to an elastomer.

**Table 1 – Results of short-term testing of composition sample.**

Series of composition	$\sigma$ (MPa)	Reinforcement coefficient	$E \times 10^{-3}$ (MPa)	Coefficient of rigidity's elevation
a	56.6	–	25.0	–
b	21.8	No reinforcement	11.2	No elevation
c	37.6	No reinforcement	24.4	No elevation
d	62.7	1.11	31.0	1.24
e	33.0	No reinforcement	21.1	No elevation
f	53.1	No reinforcement	26.1	1.04
g	64.9	1.15	32.2	1.29

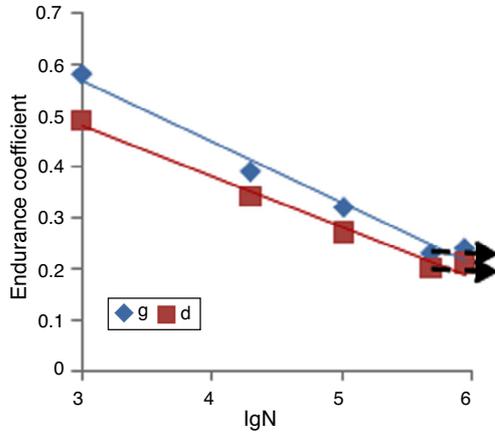


Fig. 7 – Diagram of fatigue strength of compositions “d” and “g”.

A diagram of fatigue strength of compositions is presented in Fig. 7. It was shown at the threshold of  $10^6$  cycles that no considerable drop in strength occurs for compositions containing silicon carbide and basalt powder. The endurance coefficient of compositions “d” and “g” comprised 0.21 and 0.24, respectively.

### 3.2. Basalt fibers

A short-term strength index of elementary fiber is 2000 MPa. In all long-term strength testing, the samples of the roving were broken in the middle of the working part (Fig. 8). There was no slippage or pulling of the ends from the epoxy plates. The main result the long-term strength testing is proof of the linear character of the temporal strength dependence (Fig. 9). If we assume that there is now deviation from above-mentioned dependence in time, then on the basis of proposed time of exposition of the material under load, by prolongation of the dependence curve, arbitrarily the value of the coefficient of long-term strength of basalt roving may be predicted. As the figure shows, the coefficient of long-term strength of the roving on the basis of nearly 30 years is equal to 0.25.

### 3.3. Hybrid fibers reinforced composites

#### 3.3.1. The COC of HRFC

Table 2 shows the values of short-term strength (MPa) and logarithm of time before fracture (s) of samples of composites 1-6 at temperatures of 293, 310, 330 and 360 K. At each



Fig. 8 – The roving after testing on long-term strength.

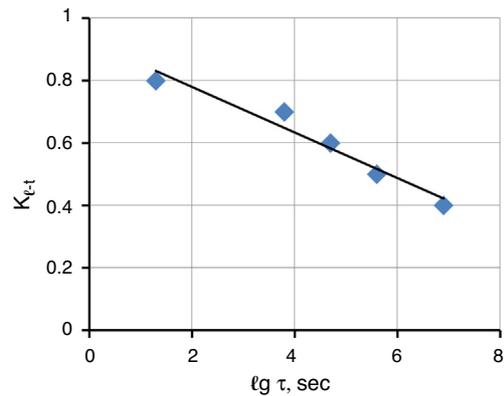


Fig. 9 – Dependence of long-term strength of the roving on time before fracture.

temperature, at least 10 samples have been tested. The coefficient of experimental data variation is in the range of 9-16%.

Based on these data and using the value of  $T_0$ , parametric curves were built and are shown in Fig. 10. Table 3 shows the values of coefficients  $a$  and  $b$  expressed by Eq. (4) calculated from statistical treatment of the experimental data. Coefficients of correlation characterizing the level of linear connections  $\sigma_{l-t}$  and  $P$  for composites 1-6 are, respectively, as follows: 0.980, 0.828, 0.933, 0.980, 0.989 and 0.910.

At the presumptive time of use of turbine blades of  $3 \times 10^5$  h, at a temperature of 330 K calculated by formula (3),  $P$  is  $23.8 \times 10^3$  and the required COC of a blade as identified by formula (1) are shown in Table 4.

Table 2 – The values of short-term strength and logarithm of time before fracture of composites.

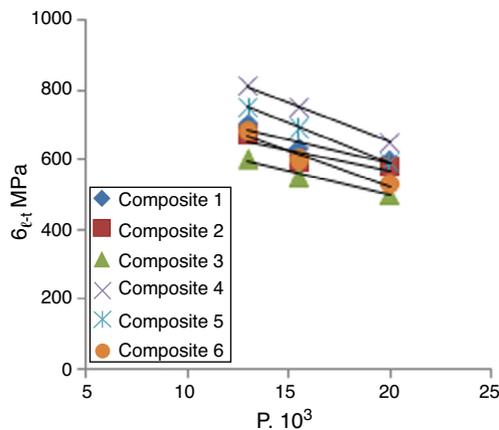
T (K)	Composites											
	1		2		3		4		5		6	
	$\sigma_{sh-t}$	$lg \tau_f$										
293	770	2.11	700	1.82	660	1.76	911	1.86	801	1.76	755	1.66
310	690	1.86	660	1.79	600	1.71	818	1.34	750	1.05	665	1.11
330	620	1.33	580	1.26	555	1.20	746	1.00	680	1.07	601	0.99
360	590	0.91	565	0.85	503	0.76	650	0.96	580	0.85	532	0.76

**Table 3 – The values of coefficients  $a$  and  $b$ .**

Coefficients	Composites					
	1	2	3	4	5	6
$a$	981.4	936.0	936.6	1115.0	1132.0	1111.0
$b$	-0.014	-0.018	-0.021	-0.018	-0.024	-0.025

**Table 4 – COC of composites 1–6.**

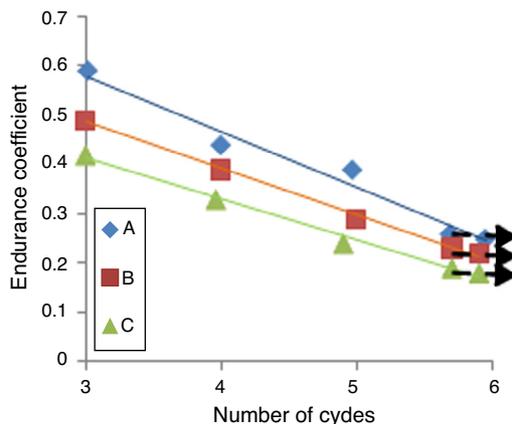
COC	Composites					
	1	2	3	4	5	6
$K_t^T$	0.80	0.68	0.62	0.75	0.66	0.62

**Fig. 10 – Parametric straight line for composites 1–6.**

Thus, according to these calculations, sufficiently long-term time of use of a wind turbine's blade at possible elevated temperature can reduce the COC; however, such reduction is not significant enough to reduce the operating capacity of the blades due to bending.

### 3.3.2. Endurance of HFRC

The results of the testing of composites 1–3 on endurance of torsion are presented in Fig. 11. Experimental points are

**Fig. 11 – Endurance of composites 1–3.**

obtained as the samples pass the defined number of torsion cycles ( $10^3$ ,  $10^4$ ,  $10^5$ , etc.) and after the determination of residual strength of these samples at short-term tension.

From the data in Fig. 11 it should be concluded that after approximately  $5 \times 10^5$  cycles the observed strength does not decrease significantly with further twisting. The measured endurance coefficients for composites 1, 2, 3 are 0.25, 0.22 and 0.18, respectively. Hence, it can be concluded that the endurance of a composite of a selected composition and structure may vary moderately, along with a reasonable decrease in the short-term strength index of the composite and in the endurance coefficient of the epoxy matrix.

## 4. Conclusions

From the present study, the following conclusions are drawn:

1. Currently, we have significant knowledge on the development of composite materials with reinforcing hybrid fibers. However, the data on physical-mechanical properties with hybrid basalt fibers as well as the variation of these properties under expected operating conditions are extremely limited, which delays their application as structural materials.
2. With the addition of 7% mass of silicon carbide to the epoxy resin, an 11% increase in static strength and a 24% increase in elastic modulus were obtained. An addition of basalt powder to the resin in same amount leads to increases of 15% and 25%, respectively. From these data, the effect of the reinforcement of epoxy resin by basalt powders deserves attention because basalt is a highly available and cheap reinforcement for a wide range of resins.
3. The endurance coefficient of samples containing silicon carbide and basalt powders under cyclic alternating loads at a frequency of  $100 \text{ min}^{-1}$  is in the range of 0.21–0.24.
4. The short-term strength of elementary basalt fiber is 2000 MPa. The coefficient of long-term strength of the roving with linear density of 110–130 tex is equal to 0.25–0.30.
5. The coefficient of endurance of the composite fabricated with epoxy matrix and high-strength, high-modulus carbon fiber is 0.25. In the hybrid composite, with partial replacement of carbon fiber by high-strength basalt fiber (at 20% or at 40%), the endurance coefficient is 0.22 and 0.18, respectively. Thus by replacing carbon fibers with the

more inexpensive basalt fibers, the material may maintain its work capacity under torsion.

6. The proposed time extrapolation of a wind turbine at elevated temperature (up to 330K) estimated for 35 years, causes the reduction of the COC on bending of composites based on epoxy matrix, carbon and glass fibers being considered in present work up to 0.75–0.80.
7. Under the same conditions, the reduction of COC of composites with hybrid reinforcement (carbon, glass, basalt) is also observed but does not go below 0.62, which is acceptable.
8. Thus, in the manufacture of wind turbine blades, a partial substitution (up to 20–30%) with basalt fibers is recommended in place of the expensive high-strength high-module carbon fibers.

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### Conflicts of interest

The authors declare no conflicts of interest.

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