Chapter 11

Investigation of Polymer Composites for Wind Turbines Blades

N. Chikhradze*, G. Abashidze

Mining Institute
7, Mindeli str., Tbilisi, Georgia
*g.pkhaladze@mail.ru

I. INTRODUCTION

For the recent years, considerable attention has been dedicated to renewal power sources, such as wind power. This work was carried out in order to develop a small wind turbine of 1-10kW power generation capacity. This wind turbine is designed to be energetically more efficient by 30-50% having a lower specific cost (by 25-30%). In this chapter, an issue concerns the development of a new type of composite materials for potential application within the wind turbine blades structural design. We present the results of research work undertaken on the development of flexible technology for fabrication of hybrid composites reinforced with carbon, basalt and glass fibers. The new composites were fabricated using strengthened epoxy matrices. Basalt fibers for composite were produced from raw materials with chemical composition: SiO_2 – 49%; Al_2O_3 – 16%; CaO – 9%; FeO – 6.5%; MgO – 6%; Fe_2O_3 – 5%; Na_2O – 3%, K_2O – 1.5%; TiO_2 – 1.3%; H_2O – 1.6%.

The wind-power engineering is a priority area of energy generation due to its resource-saving and ecological safety. The power cost primary is determined substantially by basic power element-blades. At present, hybrid fibers (carbon and glass) are mainly used for fabrication of the blades [1], however, there are some works dedicated to reinforce epoxy matrices with basalt and other fibers [2]. The task of cost reduction may be solved through application of the less expensive materials in comparison with carbon fibers. For blade development, an application of new composite hybrid material is suggested on combinations of high-strength and high-modulus carbon and basalt fibers. Basalt reinforcing element of composite was prepared on basis of Georgian raw materials. The problem consists in partial substitution of expensive carbon fiber in the material.

Basalt fibers are practically highly competitive with glass ones by main mechanical characteristics and surpasses them by some of them, in particular, by water-resistance and chemical stability. But in the form of twisted and non-twisted threads, roving, roving cloth and discrete fibers, basalt fibers represent an alternative and promising reinforcing element for composites. In addition, at solving of a series of specific problems, for example, for preparation of materials with predetermined strength and deformation characteristics in different directions of load application, the combination of glass, high-strength basalt, high-strength and high-modulus carbon fibers were used, that is to say, the production of composites, reinforced by hybrid fibers (HFRC) was organized.

In parallel with the advantages, HFRC, undoubtedly, are characterized by some disadvantages, which must be taken into account at the preparation and operation of blades with the use of HFRC. These disadvantages involve:

- Structural non-uniformity and inadequate stability of the technology of preparation, which leads to considerable dissipation of mechanical and other indices that may attain to 15-20% in relation to average values even at standard short-term testing. At long-term, testing the dissipation increased.
- Polymeric nature of a matrix determines an enhanced sensitivity of materials to the prehistory of preparation and to temperature-time regime of further operation, which is responsible for determining strength and deformation properties of HFRC. At moderate temperatures, for traditional structural materials, a temperature-time dependence of mechanical and other properties appears only slightly, whereas the presence of polymeric matrix in the considered materials predetermines an impossibility to evaluate strength or deformability even at room temperature without time indication in the course of which the materials are in the stressed state.
- Directional locating of reinforcing fibers in the plane of reinforcement as well as a lamination of the structure in the direction perpendicular to the mentioned plane, causes an anisotropy of mechanical and other properties. As a rule, a number of characteristics, necessary for the determination of one or other properties of reinforced plastics, is considerably more important than for isotropic materials. Moreover, the regularities of the behavior of reinforced plastics at mechanical testing depend on the direction of load application. In instance for oriented composites, a tension diagram in the direction of

reinforcement is governed by Hooke's law. At loading at an angle to the direction of reinforcement, this diagram is getting considerably nonlinear.

- A lamination of the structure of polymeric composites predetermines their low resistance to interlayer shear and to transverse breaking off. Therefore, at bending, these materials may be destroyed because of the fact that tangential stresses will be higher than material's resistance to interlayer shear instead of the fact that normal stresses (extending or compressing) may attain the limiting values.

- Deformations, generated perpendicularly to reinforcing fibers, are mainly realized in matrix interlayers because of low rigidity of the latter in comparison with glass, basalt or carbon fibers; this leads in fact to the formation of the cracks in the interlayers of a binder between the fibers or at phase boundaries. Low crack resistance is particularly characteristic of oriented plastics. The cracks have little or no effect on the values of characteristics, obtained as a result of short-term testing. However, such characteristics of a material as hermeticity, resistance to corrosive media, mechanical and electrotechnical properties in the conditions of long-term operation at the appearance and intergrowth of the track are significantly impaired.

- Relatively low value of modulus of elasticity of reinforced plastics and composites leads to the fact that load-carrying ability of thin-wall structures is limited by deformability and stability instead of the strength. For complete use of high strength characteristics of the composites, it is profitable to design the item and structure as three-layered or to provide the stiffening ribs. Designing must be carried out in such a way that the material will operate in tension instead of compression, whenever possible.

Considered peculiarities of reinforced polymers, in general, and of HFRC, in particular, must be taken into account the considered peculiarities of reinforced polymers, in general and HFRC, in particular, must be taken into account at designing of blades of the wind turbine.

Appearance of new generation of reinforced polymers (i.e., HFRC) is due to the quest for preparation of the materials, characterized by higher initial mechanical and other indices and by higher stability of these indices at the action of various operating factors.

At the present time, the volumes of the production and the use of composites reinforced by high-strength and high-modulus fibers are not big. The main barrier to the extension of fields of use of such materials, in wind power engineering, is their high cost.

In regard to the cost of HFRC, it should be noted that the ways for their cost reduction, probably, are linked not with increase of output rate, but with reduction in price of raw materials and mechanization of the production. In this regard, a problem of the cost reduction for composites seems to be very topical through even partial replacement of expense and deficit carbon fiber by incomparably cheap basalt fiber without considerable loss of main operating properties of the material. Moreover, the share of reinforcing fibers as well as of a binder in the expenses of raw materials is distinct for the composites of various types. For the composites, in which the nonwoven reinforcing elements are used in the form of threads and mats, the expenses of reinforcing materials attain 30-35% of all material expenses. At the same time, the expenses of reinforcing materials in the form of cloths may attain 50-70% at the preparation of basalt plastics. Therefore, an essential method in the reduction of composite's cost may be achieved by replacing the cloths from twisted threads by nonwoven reinforcing materials and roving cloths.

Price cost reduction for HFRC is also possible at the expense of introducing efficient fillers-reinforcers into the matrix composition. This method allows a considerable decrease of fiber content without an essential reduction of characteristics of the resulting material.

One more way to enhance the efficiency of HFRC use in practice, is a rational design and application of products with regard to the influence of real environment on the material. Below the primary attention is given to more or less detailed consideration of these problems.

II. APPROACH TO THE ESTIMATION OF DURABILITY OF COMPOSITES FOR WIND TURBINE BLADES

In the design of wind turbine blades from composite materials, primarily the values of their calculated resistances are necessary. The long-term resistance (R_{cl}) of the material in normal conditions is calculated by the product of (i) the normative resistance of the material, (ii) the coefficient of long-term resistance and (iii) the coefficient of the uniformity of its mechanical characteristics. In other words, this may be given by the following relation: $R_{cl}=R_{nor}K_{\ell\text{-}t}\,K_u$

The normative resistance (R_{nor}) was determined from a strength limit of the materials under study by the results of short-term testing of small samples, carried out in accordance with acting standards. The coefficient of long-term resistance ($K_{\ell\text{-}t}$) was determined by testing to failure of the series of the samples of the materials at long-term loading at the stresses comprising a definite part from a strength limit of the material. Uniformity coefficient (K_u) was determined by well-known three sigma rule by calculation of arithmetic mean and by root-mean-square deviation of the strength, which are defined on the basis of statistical analysis of the results of mass testing of strength properties of HFRC.

Calculated resistances of the materials, operating at the joint action of static load and regimes, different from normal ones (elevated temperature, high humidity, corrosive medium and etc.) were determined by multiplying the long-term calculated resistances into corresponding coefficients of operating conditions:

$$R^{T}_{c\ell} = R_{c\ell} \cdot K_{T}, \qquad R^{w}_{c\ell} = R_{c\ell} \cdot K_{w}, \qquad R^{cor}_{c\ell} = R_{c\ell} \cdot K_{cor}, \qquad R^{atm}_{c\ell} = R_{c\ell} \cdot K_{atm}$$

where: K_T, K_w, K_{cor}, K_{atm} are coefficients of operating conditions of composites, service of which is provided, respectively, at elevated temperature, in water or at high humidity at the action of corrosive media, in atmospheric conditions, as well as at synchronous long-term action of load as well as of external factors. In some cases the coefficients of operating conditions can be determined at the joint action of various factors, for example, of temperature, water /humidity ($K_{T,w}$).

The results of determination of normative resistances at various types of stressed state (tension, bending, compression, shear: R^{t}_{nor}, R^{b}_{nor}, R^{c}_{nor}, R^{sh}_{nor} , respectively) as well as of short-term modulus of elasticity in tension, bending and compression (e.g., E^{t}_{s-t}, E^{b}_{s-t}, E^{c}_{s-t} , respectively) and coefficients of uniformity of strength properties of the materials under study, are all given in Table 1.

Concerning the problem on uniformity coefficient of material, it should be noted that tests carried out for its determination were performed at room temperature – humid conditions. Incidentally, in the course of operating of the structures by the use of plastic materials, they may undergo various temperature- humid effects and it may be suggested that these effects may exert some influence not only to the variation of absolute values of mechanical properties of HFRC, but, to some extent, they may reflect on the indices of uniformity of strength properties of the materials. To check this suggestion, the investigations were carried out in order to reveal the influence of preliminary action on the indices of uniformity of strength properties of HFRC-2 and HFRC-4 at tension. The results of these testings are given in Table 2. They involve the data necessary to calculate the uniformity coefficient (number of testing – n, arithmetic – mean value for strength - σ_{av}, mean square deviation - σ′ as well as variation coefficient – V). The regimes of preliminary action on the samples of the material were: №1 – holding in laboratory room; №2 – heating at 353K over 10 days; №3 – steeping over 1 day; №4 – steeping over 10 days; №5 – steeping over 10 days by further drying over 10 days; №6 – steeping over 10 days at 353K.

TABLE 1 NORMAL RESISTANCE, SHORT-TERM MODULUS OF ELASTICITY AND UNIFORMITY COEFFICIENTS FOR HFRC

Material	R^{t}_{nor} (MPa)	R^{b}_{nor} (MPa)	R^{c}_{nor} (MPa)	R^{sh}_{nor} (MPa)	E^{t}_{s-t} (GPa)	E^{b}_{s-t} (GPa)	E^{c}_{s-t} (GPa)	K_u
HFRC-1	195.6 / 163.1	480.2 / 270.3	261.1 / 219.1	10.2 / 8.1	9.4 / 3.9	14.5 / 3.4	10.6 / 4.2	0.72
HFRC-2	292.5 / 228.2	567.2 / 351.4	410.2 / 319.9	12.2 / 10.2	15.0 / 5.4	23.4 / 5.4	14.6 / 5.8	0.68
HFRC-3	455.4 / 6.9	718.1 / 19.9	420.8 / 8.0	24.8 / 1.2	96.9 / 5.8	78.6 / 5.2	78.1 / 4.1	0.74
HFRC-4	132.2 / 85.6	415.7 / 95.9	160.2 / 107.7	8.8 / 2.4	49.7 / 19.8	58.8 / 16.4	51.0 / 16.7	0.70

Remark: HFRC-1, HFRC-2, HFRC-3, HFRC-4 – composites of different composition and fiber orientation.
The values given in numerator and denominator are along and transversely to X axis (Figs. 3, 6).

TABLE 2 STATISTICAL PROCESSING OF THE RESULT OF TESTING TO REVEAL THE INFLUENCE OF PRELIMINARY ACTION OF VARIOUS FACTORS ON UNIFORMITY INDICES

Material	Act. reg.	n	σ_{av}, (MPa)	σ′ (MPa)	V (%)	K_u
HFRC-2 (δ=1.5mm)	№1	92	292	29	9.9	0.70
	№2	95	262	25	9.5	0.71
	№3	99	277	29	10.5	0.69
	№4	100	295	30	10.2	0.69
	№5	93	290	31	10.7	0.68
	№6	95	277	30	10.8	0.68
HFRC-4 (δ=0.8mm)	№1	100	155	10	6.5	0.80
	№2	100	166	18	10.8	0.67
	№3	95	125	12	9.6	0.71
	№4	96	115	12	10.4	0.69
	№5	99	140	14	10.0	0.70
	№6	91	111	12	10.8	0.68

As it can be seen from Table 2 that the variation of K_u is relatively small and the maximum reduction of K_u comprises 6 % for HFRC. Hence, the value of K_u, obtained by testing in normal temperature- humid conditions, may be used by confidence at practical calculations.

Under prolonged (long-term) strength of the solid the dependence of time duration up to its failure on the stress and temperature is meant. The coefficient of long-term resistance is a value, determined by testing of a series of the materials samples under prolonged loading to failure at the stresses, constituent a definite part from material strength limit. Thus, in the terms "long-term resistance" and "durability" an equal meaning is assigned.

III. EXPERIMENTS ON COMPOSITE MATRIX STRENGTHENING

Investigation was concerned with epoxy Diane resin with passive diluents – didutylphtalate (15m.f. per 100m.f. of resin). Resin had a density of 1.168 g.cm^{-3}, viscosity at 20^{o}C – 120 P, involved epoxy groups – 17 mass %, total chlorine – 0.85 mass %, chlorine ions – 0.007 mass %, volatiles – 0.85 mass %, time of gelation of resin at 100^{o}C comprised 3.0 hours.

As ingredients, reinforcing a resin, were used: powders of boron carbide (100 μm) and silicon carbide (80 μm), of zirconium diboride (100 μm), as well as mullitelike oxide crystals $3Al_2O_3 \cdot 2SiO_2$ (diameter 2-8 μm, length 80-200 μm), basalt powder (100 μm) and diluvium powder (60 μm). Diluvium had the following chemical composition, respectively: SiO_2 – 57.5; Al_2O_3 – 19; Fe_2O_3 – 7.4; CaO – 1.1; MgO – 3.0; R_2O – 5.2. Above are listed powders that were prepared by technology elaborated by the authors. For the production of boron carbide, amorphous boron and technical carbon were used as ingredients. Prepared mixture was briquetted in graphite mould. Boron carbide was synthesized in vacuum electric furnace. Synthesis was performed at the temperature of 1850±25^{o}C, endurance – 2.5 hours. Cooling proceeds was performed in vacuum over 10 hours. Zirconium diboride was produced by method of boron carbide reduction. Zirconium dioxide and carbide were preliminary processed in vacuum for charge production. Mullites like crystals were prepared using the method of oxide solution crystallization in melt bed. Basalt powder preparation includes the following operations: crushing of basalt stones at the hydraulic press; melting; crushing and grinding of ingot; fractionation of the grinded powder at horizontal screen.

An amount powders, added to epoxy resin, was 7% from resin mass. Hardener of the compositions was polyethylene polymine (12% from resin mass), containing 36% of total nitrogen (in terms of dry substance).

The following series were prepared: "a" – pure epoxy resin; compositions: "b" – with diluvium, "c" – with boron carbide; "d" – with silicon carbide; "e" – with $3Al_2O \cdot 2SiO_2$; "f" – with ZrB_2; "g" – with basalt. Moulding of samples on tension in the form of mortar briquettes of (50X4X2) mm size were prepared in the castings. Samples – strips, dedicated from fatigue test, were prepared, too and measured: (170x15x3) mm.

Short-term mechanical testing's of the mouldings with an automatic recording of deformation were carried out on the machine FPZ-100 of German production. Strength and deformation characteristics of compositions were determined and based on a comparison of these data with characteristics of pure epoxy, degree of resin reinforcement was concluded.

For material testing on fatigue bending the device shown in Fig. 1 has been used. The main parameters of the device: simultaneous testing of 3 sheets or samples; bending angle from 20° to 180°; samples clamp width up to 30 mm; weights for preliminary load from 0.2 to 5 kgf; number of bends per minute – 100; counters (3 pieces) with an automatic turn-off at sample breakage.

The sample was fixed in the clamp, which is swung about its axis of rotation. The clamp is designed so that the bend axis is coincident with the axis of rotation at the swinging the clamped sample is repeatedly bended by weights, which impart to the sample the definite preliminary tension. Bending angle was selected as 20°, load – 2 kgf, number of the bends per minute – 100.

An endurance coefficient was determined from appropriate compositions (series "d'', "g''), from the viewpoint of reinforcement. Under an endurance coefficient a ratio between residual strength of composition after cyclic testing and its short-term statically strength is meant. The level of this ratio, whereby it reduces slightly regardless of a number of cycles, was taken as an endurance coefficient.

Fig. 1 Device for testing bending fatigue

The results of testing of composition samples (σ) and deformability (E) are given in Table 3. The amount of tested samples in each series is n=6; and the coefficient of variation of obtained data is variable from 5 to 8%.

TABLE 3 RESULTS OF SHORT-TERM STATICALLY TESTING OF COMPOSITION SAMPLES

Series of composition	σ (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	The same	24.4	The same
"d"	62.7	1.11	31.0	1.24
"e"	33.0	No reinforcement	21.1	No elevation
"f"	53.1	The same	26.1	1.04
"g"	64.9	1.15	32.2	1.29

Effect of resin reinforcement has been obtained as a result of the addition of silicon carbide to it as well as of basalt powder. Increase of the value of the modulus of elasticity was also noted for compositions containing these ingredients. An addition of zirconium carbide to resin gives an insignificant increase of its conventional coefficient of rigidity. An attention must be given to the fact that basalt powder of a given fraction of grinding, by its efficiency, is just as good as such reinforcers as boron and silicon carbides and zirconium diboride and in some cases outperform them. Considerable increase of longitudinal strains was noted for composition containing diluvium, which has a layered structure. This composition is close to elastomer by its characteristics.

Diagram of fatigue strength for compositions "g" and "d" is presented in Fig. 2. It was shown that a considerable drop of strength of composition, containing silicon carbide and basalt powder, practically does not take place at the threshold of 10^6 cycles. Endurance coefficient of compositions "d" and "g" comprises 0.21 and 0.24, respectively.

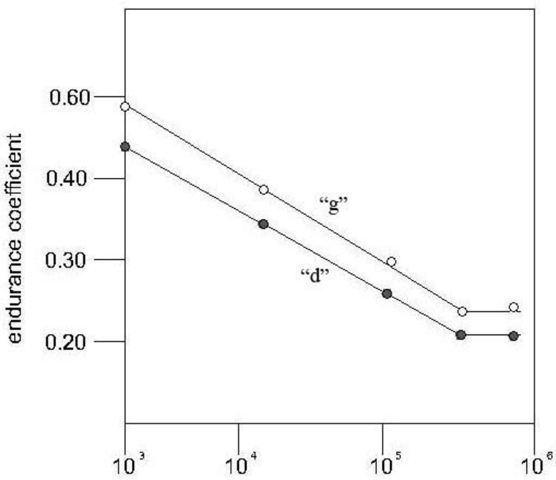


Fig. 2 Diagram of fatigue strength for compositions "d" and "g"

IV. COEFFICIENT OF OPERATING CONDITION OF HFRC AT ELEVATED TEMPERATURE

The aim of the work involves determination of the coefficients of operating conditions (COC) of a composite for predetermined service life and temperature (K_τ^T). The COC represents a ratio between a breaking stress after an interval, corresponding to service life of wind turbine blades that is long-term breaking stress and a breaking stress obtained by standard short-term testing of the material at room temperature (σ_{sh-t}):

$$K_\tau = \frac{\sigma_{l-t}}{\sigma_{sh-t}} \tag{1}$$

Direct experimental determination of σ_{l-t} is connected with difficulties, namely, with necessity for the maintenance of constant outer conditions and predetermined stress over a long time. Extrapolation of experimental date and predetermined time of stress action is carried out by use of S. N. Zhurkov' s equation based on the kinetic nature of the strength of solids:

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

where, τ is the time before material destruction; τ_0 is a constant, approximately equal to 10^{-13} sec, 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; γ is the average coefficient of overstresses; T is the absolute temperature; k is the Boltzmann's constant; σ is the stress applied on a material.

In this case, we have tried to realize a possibility of the account of joint effect of stress, time and temperature by accelerated method for the determination of $\sigma_{l\text{-}t}$ by use of the well-known parametric method of S. Goldfein. The method is based on a combination of temperature (T_i) and time to material failure (τ_f) in one parameter whereby a long-term strength is determined using the following equation:

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

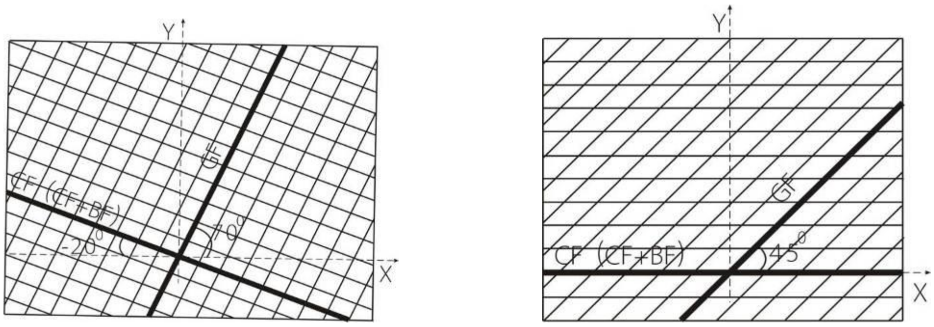
where, T_0 is a temperature at which an infinitely small stress causes the materials failure; c =20 for solid materials, including the present research, since a binder is in glass state.

The sense of Eq. (3) includes possibility to construct dependence $\sigma = f$ (p) by short-term testing at elevated temperatures and by varying T and τ_f and to calculate a long-term strength at various temperatures. According to the work undertaken in [3], it was shown that from Eq. (2) a linear relationship between the parameter P and the long-term strength ($\sigma_{l\text{-}t}$) is evident:

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

Where, $a = \frac{U_0}{\gamma}$ and $b = \frac{2.3k}{\gamma}$

According to the recommendations of investigators of wind turbines, at manufacturing of blade shells, the carbon fibers should be arranged at an angle of -20^o relative to the blade axis (i.e., X-axis) and the glass fibers should be perpendicular to the carbon fibers [4-6]. At manufacturing of spar reinforcing, fibers were arranged parallel and at +45^o angle to X-axis. The structure of composites destined accordingly for shell and spar of blade is shown in Fig. 3.



(a) (b)

Fig. 3 Scheme of arrangement of reinforcing elements in composite destined for (a) shell and (b) spar

Six types of composites were selected as research objects representing monolithic layered reinforced materials. In the composites 1, 2 and 3 destined for a shell, carbon fibers (CF) and glass fibers (GF) are used. The relation between these two types of fibers is GF: CF=0.3:0.7 (according to mass). In a midpoint of cross-section of composite 1, CF were interchanged with GF. The number of layers is 7 for CF and 4 for GF. In composite 2, CF partially (up to 20% of their mass) are replaced by basalt fibers (BF) by way of fabric. In composite 3, number of replaced BF is 30%. Composites 4, 5 and 6 are intended for spar. Composite 4 is made of used CF by way of roving. In composites 5 and 6, CF partially (accordingly, by 20 and 30%) are replaced by BF, again by way of rovings. In all cases, the fabrics manufactured from non-twisted rovings were used.

Fabric from polyacrylonitrile carbon roving has thickness of 0.7 mm; surface density 200-800 g.m^{-2}; density in warp 2.1-3.8 th/cm; density in weft 3.2-4.0 th/cm. The fabric from basalt roving of a thickness of 0.4-0.9 mm has surface density 300-700 g.m^{-2}; density in warp 1.7-3.5 th/cm; density in weft 2.9-4.0 th/cm.

The mode of preparation of composite - prepreg technology (PrT): layer-by-layer lining and forming of prepregs in thermal chamber. The thickness of the composite sheet was 6-8 mm with a density of 1.5g.cm^{-3}.

Short- and long term tests of monolithic samples cut-out from sheets were carried out on bending. Size of samples-scantlings was (150x55x2) mm. Speed of movement of machine's head was 30mm/min. Heating regime of samples was 50 ℃ per hour.

The procedure for determination of the values of the COC for the investigated composites involves the following:

- Determination of the values of breaking stress by standard short-term static testing at room temperature ($\sigma_{sh\text{-}t}$).
- Determination of the values breaking stress at the temperature 293, 310, 330, 360 K.
- Justification of selection of T_0, involving in Eq. (3).

- Calculation of the values of a parameter *P* for testing temperatures.
- Construction of dependence: "strength-parameter *P*" with coefficients ***a*** and *b* as illustrated in Eq. (4).
- Calculation of σ_{l-t} for predetermined service life and temperature 330 K.
- Determination of $K_\tau = \sigma_{l-t} / \sigma_{sh-t}$.

To select the values of T_0, that is to say zero strength, the indexes of sharp increase of composites deformation were used. Such approach to determine T_0, in relation to glass plastics, has been previously used in the work published in [7].

Thermo-mechanical curves at various stresses were constructed and the temperature was determined at which a sharp increase of deformation takes place by application to the material the stress tending to zero. As it can be evidently seen from Fig. 4, 510 K can be admitted for T_0.

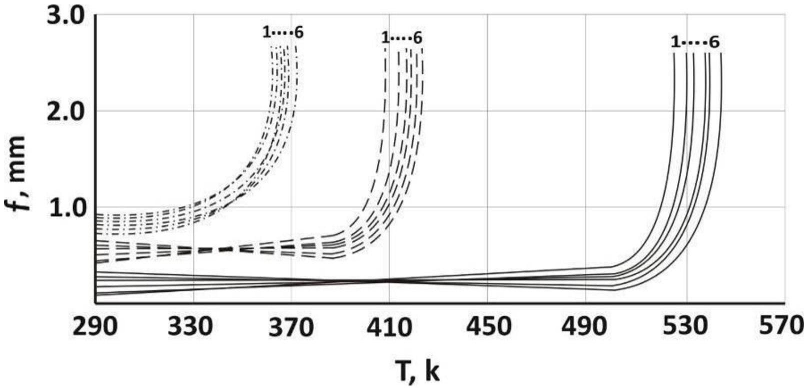


Fig. 4 Thermo-mechanical curves of 1-6 composites at various stresses:_____1 MPa; - - - 60 MPa; _ . _ . 120 MPa

Table 4 shows the values of short term strength (MPa) and logarithm of time before fracture (sec) of samples of the composites 1-6 at temperatures 293, 310, 330, 360 K. At each temperature, at least 10 samples have been tested. The coefficient of experimental data variation has been changed over the range 9-16%.

TABLE 4 VALUES OF SHORT TERM STRENGTH AND LOGARITHM OF TIME BEFORE FRACTURE OF COMPOSITES

T, k	Composites											
	1		2		3		4		5		6	
	σ_{sh-t}	$\lg\tau_f$	σ_{sh-t}	$\lg\tau_f$	σ_{sh-t}	$\lg\tau_f$	σ_{sh-t}	$\lg\tau_f$	σ_{sh-t}	$\lg\tau_f$	σ_{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

Based on these data, by using of found value of T_0, parametric curves are built and shown in Fig. 5.

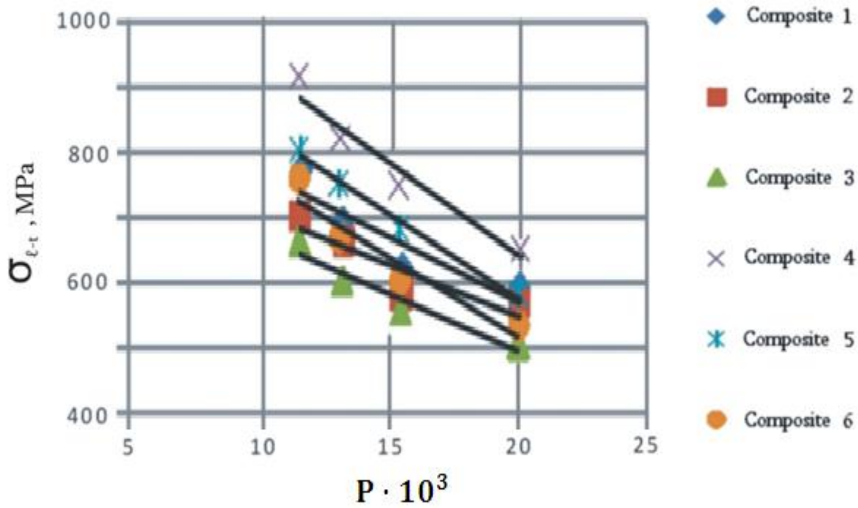


Fig. 5 Parametric straight line for composites 1-6

Table 5 shows the values of coefficients *a* and *b* expressed by Eq. (4) resulted from statistical treatment of experimental data.

TABLE 5 VALUES OF COEFFICIENT 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

Coefficients of correlation characterizing level of linear connections $\sigma_{\varepsilon-t}$ and *P* for the composites 1-6, accordingly are as follows: 0.980; 0.828; 0.933; 0.980; 0.989 and 0.910.

At expected operation life of turbine blades 300 000 hours, in conditions of temperature influence 330K, calculated acc. to Eq (3) P=23800. Required blades of COC materials, identified acc. to Eq. (1) are recapitulated in Table 6:

TABLE 6 THE COC OF COMPOSITES 1-6

COC	Composites					
	1	**2**	**3**	**4**	**5**	**6**
K_{τ}^{T}	0.80	0.68	0.62	0.75	0.66	0.62

Thus, according to these calculations, sufficiently long-term time of exploitation of a wind turbine's blade at possible elevated temperature, can reduce COC up to certain level, however, such reduction is not significantly enough to lose operating capacity of the blades working on bending.

V. TESTING OF COMPOSITES UNDER DYNAMIC LOADS

At Prepreg Technology (PrT), the layers of preliminary impregnated belts prepared from the fibers of given orientation were collected into package and pressed in thermal chamber.

In the composite of series 1, only high-strength and high-modulus carbon fibers are located in parallel and at an angle of 45^0 to X-axis (Fig. 6). In the composite of series 2, the carbon fiber of the same location of the fibers – 20% is replaced by high-strength basalt fiber. In the composite of series 3, the content of basalt fiber is increased to 40%.

Composites have the following characteristics: density 1.49-1.55 g.cm^{-2}; porosity 9.2-9.7%; phase concentrations: of matrix 61.1-67.0%, of fibers 38.9-43.0%. The samples dedicated for testing on cyclic twisting followed by their testing on tension represent the right-angled strips of (160x15x2) mm size, cut from the composite plates in parallel to X-axis.

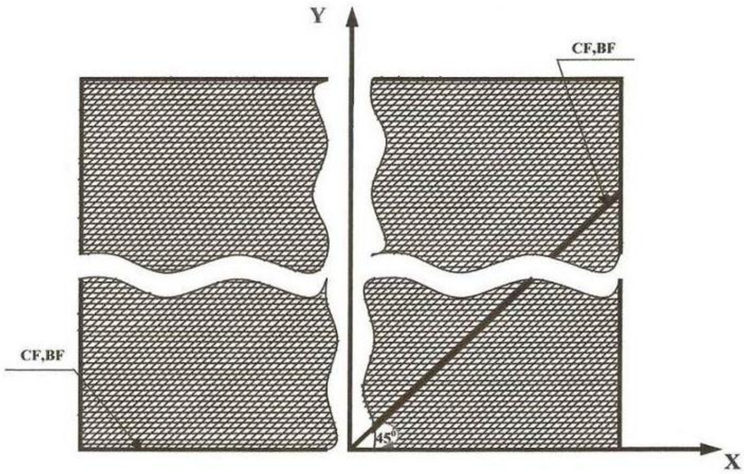


Fig. 6 Scheme of arrangement of reinforcing elements in composite

For composite testing on twisting, the machine equipped by exciter of cyclic displacements was used (Fig. 7). Range of amplitude variation of the displacements: 0-16 mm, the limit of permissible error ± 0.02 mm at maximum amplitude of the displacements. Excitation frequency in this case comprised 90 min^{-1}. The angle of alternating twisting of the samples comprised 20 °at the testing.

Essence of the method involves the determination of the endurance factor of the material operating alternately on twisting. Under the endurance factor, the ratio between composite residual strength after cyclic testing and its short-term static strength is meant. The level of this ratio, at which it slightly reduces regardless of the number of cycles, is taken as the endurance factor.

The results of the testing of the composites on endurance at twisting are presented in Fig. 8. Experimental points are obtained as the samples pass the definite number of the cycles on twisting (10^3, 10^4, 10^5 and etc.) and after the determination of residual strength of these samples at short-term tension.

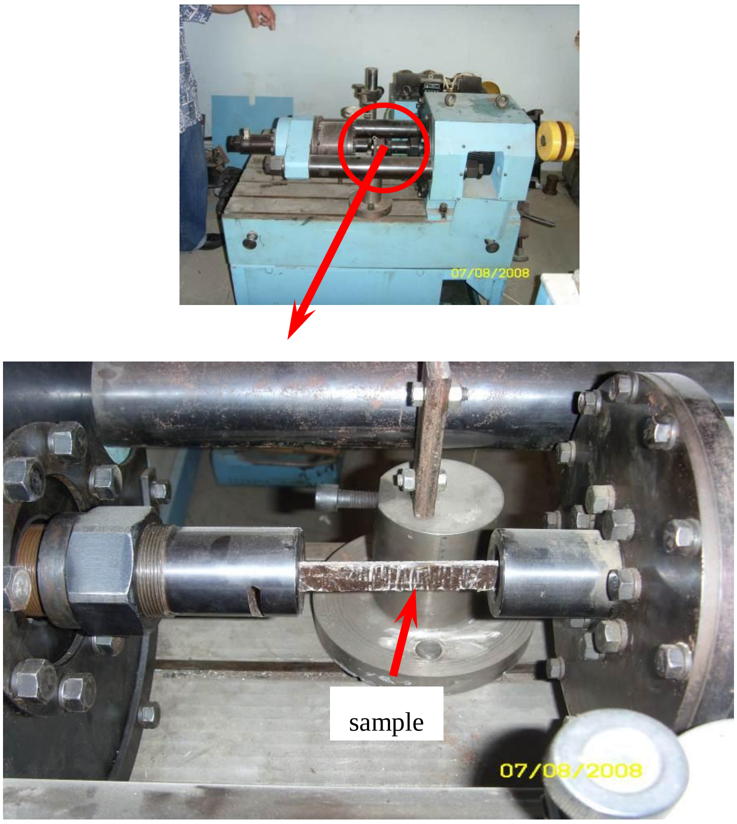


Fig. 7 The Machine for testing on twisting

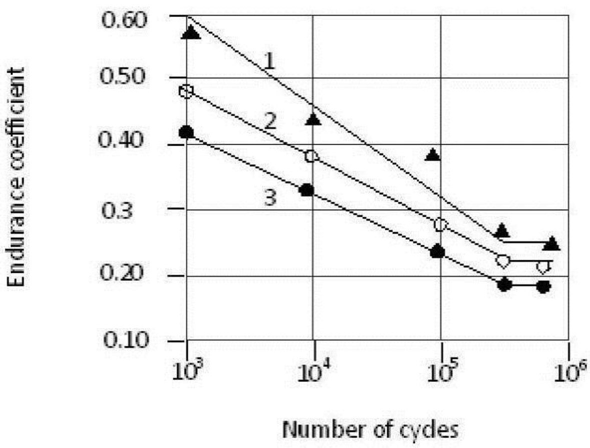


Fig. 8 Endurance of composites 1, 2 and 3

From the plot illustrated by Fig. 8, it should be concluded that after about 5.10^5 cycles twisting the further decrease of material strength is not observed. Endurance coefficients for the composites 1, 2, 3 are 0.25; 0.22; 0.18, respectively. It should be added that endurance coefficient of the composites depends on a type of matrix and technological regimes of their production. Under PrT, maximum values of endurance coefficient are observed in the composites on more plastic matrix.

VI. CONCLUSIONS

1. At present a sufficient experience is accumulated in world practice in the field of the technology of preparation of basalt plastics and composite materials with reinforcing structures from hybrid fibers. In parallel with it, it should be noted that at present the data for physical-mechanical properties of basalt plastics and composites on the basis of hybrid fibers as well as for variation of these properties in expected operating conditions are extremely limited, which retards their use as structural materials.

2. By addition of silicon carbide to epoxy resin in amount of 7% from a resin mass, an increase of static strength and modulus of elasticity may be attained by 11 and 24%, respectively. An addition of basalt powder to a resin in same amount leads to the increase of a strength and modulus of elasticity by 15 and 25%, respectively. From these data, an effect of the

reinforcement of epoxy resin by basalt powder deserves an attention, since basalt is a most non-scarce and cheap reinforcer for resin.

As a result of cyclic alternating loading (by frequency 100 min^{-1}) of composition samples, containing silicon carbide and basalt powder, on bending at an angles of 20^o, their endurance coefficient is in the range of 0.21 - 0.24.

3. Endurance coefficient on twisting of composites based on epoxy matrix and high-strength, high-modulus carbon fiber is 0.25. In the composite, partial substitution of basalt fiber (20%, 30%) for carbon fiber causes reduction of endurance coefficient up to 0.22 and 0.18, accordingly. Thus, at partial substitution of basalt fiber for carbon fiber, the composites retain operability at alternating cyclic twisting.

4. The proposed exploitation time of a wind turbine at elevated temperature (up to 330 K) estimated of for 35 years, causes reduction of COC on bending of composites based on epoxy matrix, carbon and glass fibers being considered in present work of structures up to 0.75......0.80.

At the same conditions, it is expected reduction of COC of composites with hybrid reinforcement (carbon, glass, basalt). However, at the above mentioned significant duration of materials' exploitation, such reduction of COC is quite acceptable. It can be recommended partial substitution (up to 20-30%) of basalt fibers for expensive and deficit high-strength and high-module carbon fiber at manufacturing of wind turbine blades. Herewith, COC of material is not decreased below 0.62.

The obtained values of COC of composites based on epoxy matrix and hybrid fibers can be recommended for estimation on strength of constructions of wind turbine blades, as well as constructions with other functions working at the same conditions.

REFERENCES

[1] P. Bronds, H. Lilhopt, A. Lystrup: *Annual Review of Materials Research*, vol. 35, pp.505-538, 2005.

[2] J. M. Park, W. G. Shin, D. J. Yoon: *Composites Science and Technology*, v. 59, 1.3, pp. 355-370, Feb. 1999.

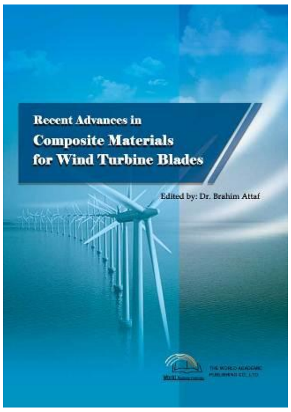
[3] Yu. M. Tarnopolski, A. M. Skudra. Structural strength and deformability of glass reinforced plastics. Zinatne, Riga, 1966 (Конструкционная прочность и деформативность стеклопластиков, Зинатне, Рига, 1966).

[4] D. A. Griffin: SAND 2002-1879, vol. I, Albuquerque, NM: Sandia National Laboratories, 2002.

[5] D. A. Griffin, T. D. Aswill: *Proceedings of the 48 International SAMPE Symposium and Exhibition*. Long Beach, CA, 2003.

[6] D. A. Griffin: SAND 2004-0073, vol. II, Sandia National Laboratories, 2004.

[7] V. I. Alperin. Constructional glass reinforced plastics. Publisher "Khimia", M, 1979 (Конструкционные стеклопластики. Изд-во «Химия», М. 1979).



Recent Advances in Composite Materials for Wind Turbine Blades
Edited by Dr. Brahim Attaf

ISBN 978-0-9889190-0-6

Hard cover, 232 pages

Publisher: The World Academic Publishing Co. Ltd.

Published in printed edition: 20, December 2013

Published online: 20, December 2013

This book of science and technology provides an overview of recent research activities on the application of fibre-reinforced composite materials used in wind turbine blades. Great emphasis was given to the work of scientists, researchers and industrialists who are active in the field and to the latest developments achieved in new materials, manufacturing processes, architectures, aerodynamics, optimum design, testing techniques, etc.. These innovative topics will open up great perspectives for the development of large scale blades for on- and off-shore applications. In addition, the variety of the presented chapters will offer readers access to global studies of research & innovation, technology transfer and dissemination of results and will respond effectively to issues related to improving the energy efficiency strategy for 2020 and the longer term.

How to cite this book chapter

Chikhradze N. and Abashidze G. (2013). Investigation of Polymer Composites for Wind Turbine Blades, *Recent Advances in Composite Materials for Wind Turbines Blades*, Dr. Brahim Attaf (Ed.), ISBN 978-0-9889190-0-6, WAP-AMSA, Available from: http://www.academicpub.org/amsa/chapterInfo.aspx

World Academic Publishing - Advances in Materials Science and Applications