Considerations Concerning the Mechanical Strength of Wind Turbine Blades Made of Fiberglass Reinforced Polyester

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The paper shows and analyzes the results of some researches on a plastic composite material as fiberglass reinforced polyester (FGRP) that is considered for being used for manufacturing the blades of small power wind turbines, such is the 5 kW wind turbine from Ciugud site in Alba County, Romania. During their operation the wind turbine blades are continuously subject to variable loadings developed by the stochastic and uncontrollable wind flow. Consequently has been performed mechanical strength researches done on a real blade, as well as, by lab testing on test specimens sampled from the original material of one blade tested at SC CLAGI Srl Company. The results of this research work came to confirm the quality of the FGRP used for blade fabrication, as well as, its capacity to bear well the loads and implicitly the structural stresses produced by the wind upon the wind turbine blades, although a metallic reinforcement included within the inner part enhances the whole mechanical strength of the blade structure.

Keywords: fiberglass reinforced polyester (FGRP), wind turbine, aerodynamic forces, loads, stresses, mechanical strength.

Nowadays the demand for small power wind turbines is growing more and more being driven by environmental motivations, but also by the willingness of the users in getting their own energy independence.

The small wind turbine (0.1 - 10 kW) is one of the most used mean to generate electricity either for supplying local residential and commercial applications in certain remote areas without access to the power grid, or for householder energy independence, in those areas where the annual average wind speed at the wind turbine hub height is at least 4-5m/s.

Large scale manufacturing and the use of small wind turbines is imposed by the advantage of being easyly handled and installed, even by the users without any high professional training, but having basic mechanical and electrical skills.

Due to a large variety of possible sites, as wind conditions, the small wind turbines are made in very diversified constructive variants with horizontal or vertical axis, upwind or downwind rotor, having 2, 3 or more blades, with passive or active yaw system, mechanical or electronic control and protection systems against rotor overspeeding or high loading due to strong wind gusts [1], etc.

The main wind turbine component, that determines the energy efficiency, is the rotor comprising the hub and the blades (blade set). The blade is the component that achieves the conversion of the air flow kinetic energy into the stereo-mechanical energy of a rotating shaft. The blade is permanently subject to mechanical loads (forces and moments) caused by the aerodynamic and mass forces. Its geometrical shape and constructive concept must satisfy both optimal energy conversion and structural strength requirements. In this context, the blade shall be made of such materials which enable easily to achieve the 3D twisted shape, light weight, and high mechanical strength to aerodynamic and mass generated loads during wind turbine operation. Consequently the scientists and engineers have tested and used various materials for manufacturing wind turbine blade such are wood, steel, aluminum, and composite materials [2, 3].

Blade safe operation and its life span rely and depend on the quality of these materials.

Such a small wind turbine (5kW) was been developed by “Politehnica” University of Timisoara, being installed and operated in site at Ciugud in Alba County. The wind turbine conversion system serves the village public lighting. The blades of this wind turbine have been manufactured of fiberglass reinforced polyester by SC. CLAGI Srl in Biled, Timis County.

The paper shows the researches performed upon this composite material, which consequently has led to be used for manufacturing the wind turbine blade set.

The blade of wind turbine sited at Giugud-Alba county

Within the partnership between Politehnica” University of Timisoara and SC. CLAGI SRL- Biled a research project has been developed, its results being used lately in manufacturing a wind turbine blade with a total span/length (up to the hub) of 2170 mm. The blade has a 3D geometrical shape with a variable cross section and twisted along its longitudinal axis. At its tip is progressively extended with a 90^0 winglet meant to avoid, at least partially, the tip looses due to blade finite span effect involving turbulence occurrence and lift force depreciation.

The geometrical shape of the blade resulted through aerodynamic and mechanical design was set by a CAD software into a virtual 3D model (fig. 1). This model was used on a 5 axis CNC cutting machine at SC. CLAGI Srl in order to get the blade mold block that has been utilized to generate the two half part molds of the blade.

The 5 kW wind turbine rotor was originally equipped with a set of 5 blades.

Loads upon wind turbine blade

The main loads subjecting a wind turbine blade are caused mainly by the aerodynamic, inertial and weight forces. These forces produce into the blade material

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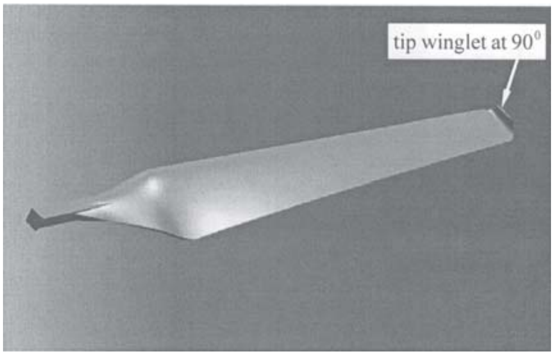


Fig. 1. 3D model of a blade used on the 5 kW wind turbine from Ciugud site in Alba County

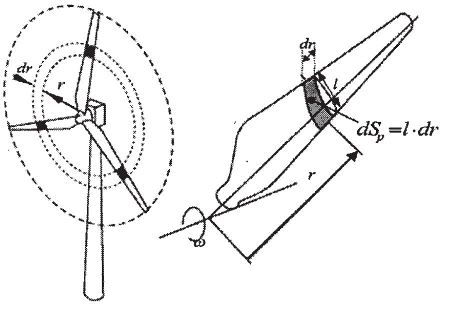
structure mechanical tension-compression stress, bending stress and torsion stress.

Some of the loads have a steady/permanent pattern (i.e. static loading), while others are cyclically or/and randomly variable (i.e. dynamic loading) determined by the turbine operation parameters (e.g. operating rotational speed) and the wind regime features (e.g. wind speed, atmospheric turbulence, etc.). The variable loads develop the fatigue phenomenon upon the blade material, which usually might have more severe effect.

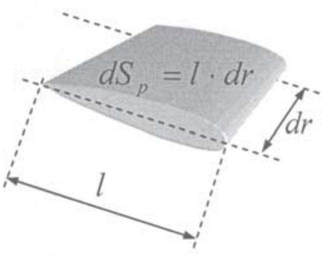
In this context, the dimensioning/checking calculation of the blade structural design is performed for an extreme static load related to an exceptional/rare case, as well as, for a dynamic load involving fatigue and associated with normal operation conditions.

The aerodynamic loads either static or dynamic are caused by the air flow interaction with the rotor blade. For a wind turbine in operation they depend on the operation rotational speed, wind velocity component normal to the rotor plane, turbulence, air density, and also on the blade design.

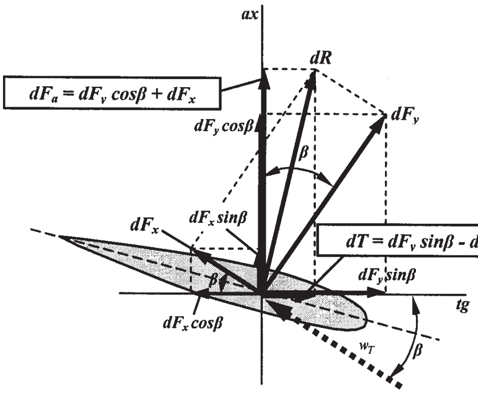
Figure 2 gives generically the forces resulted through the interaction of the air flow with a rotor blade. The aerodynamic lift force (F_y) and the drag force (F_x), occurring from flow air interaction with the blade contour, have projections into the normal and tangential direction to the rotor plane represented by an axial force (F_a), and a tangential force (T). Figure 2a shows these forces given for a blade element dr (fig. 2a,b) associated to an infinitesimal annular section of rotor swept area (fig.2a).



a) Wind turbine rotor and blade element



b) Blade element used for computing the aerodynamic forces



c) Aerodynamic forces upon a generic blade cross section airfoil

Fig. 2 Aerodynamic forces upon the blade element (dF_y - lift force; dF_x - drag force; dF_a - axial force (with respect to the rotor axis-'*ax*'), **dT** - tangential force (in the rotor plane- 'tg'), *dr* - blade element)

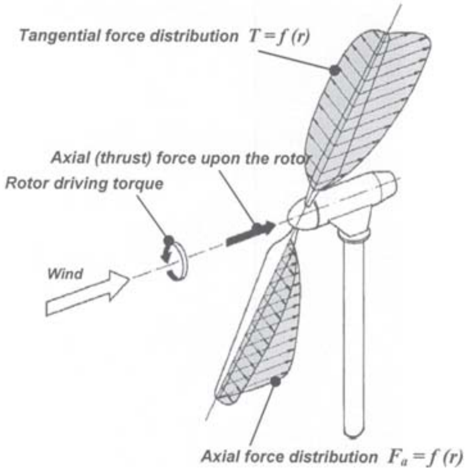


Fig. 3. Loads acting upon the wind turbine rotor

The load distributions along the blade length coming from aerodynamic forces (fig.3) are variable, depending both on wind turbine operational regime (i.e. rotational speed and wind speed) and blade aerodynamic design.

The elementary axial force and the tangential force figure 2c associated to a blade element of length dr, have the following expressions [4]:

$$dF_a = dF_y \cdot cos\,\beta + dF_x \cdot sin\,\beta = \\ = \rho \cdot \frac{w_T^2}{2}\left(C_y \cdot cos\,\beta + C_x \cdot sin\,\beta\right) \cdot l \cdot dr \qquad (1)$$

$$dT = dF_y \cdot sin\,\beta - dF_x \cdot cos\,\beta = \\ = \rho \cdot \frac{w_T^2}{2}\left(C_y \cdot sin\,\beta - C_x \cdot cos\,\beta\right) \cdot l \cdot dr \qquad (2)$$

Consequently, the bending moments associated to a current radial position r are [4]:

$$dM_{F_a} = \rho \cdot \frac{w_T^2}{2}\left(C_y \cdot cos\,\beta + C_x \cdot sin\,\beta\right) \cdot l \cdot (R - r) \cdot dr \qquad (3)$$

$$dM_T = \rho \cdot \frac{w_T^2}{2}\left(C_y \cdot sin\,\beta - C_x \cdot cos\,\beta\right) \cdot l \cdot (R - r) \cdot dr \qquad (4)$$

where :

ρ - air density;

w_T - relative velocity of air flow through the rotor;

β - angle of relative velocity;

C_y - lift coefficient of the blade cross section airfoil associated to a current radius r;

C_x: drag coefficient of the blade cross section airfoil associated to a current radius r;

R - rotor radius (radial position of the blade tip).

The total value of the forces and moments upon the whole blade can be computed by integrating relation (3) and (4) along the blade, starting from the tip and going up to the blade root.

Within the normal operation range, up to the cutout wind speed, the prevailing loadings are given by the aerodynamic forces beside which come those introduced by the centrifugal forces (mass forces), too.

During an accidental overspeeding regime (unloaded runaway) the prevailing loadings are those of the centrifugal forces, while the aerodynamic forces have just a minimal effect.

The centrifugal forces, loading the blade material with tension stresses, can be computed using the formula:

$$F_{cf} = m_p \cdot r_{CG} \cdot \omega^2 \equiv m_p \cdot r_{CG} \cdot \left(\frac{\pi \cdot n}{30}\right)^2 \qquad (5)$$

where :

m_p: blade mass

r_{CG}: blade mass center with respect to rotor axis

w: operational angular speed

n: operational rotational speed

A particular extreme case, a wind turbine might face with, is represented by an extreme wind gust regime having a short duration of just a few minutes and high wind speeds exceeding much more the normal operating wind speeds.

For such extreme cases, the static load upon the blade is computed assuming the rotor parked and having the blades exposed (quasi)perpendicular to the wind.

The bending moment has the maximum value in the blade root cross section, being given by expression:

$$M_{incov}^{catastrof.} = C_x \cdot \rho \cdot \frac{v_{EXT.}^2}{2} \cdot S_p \cdot \frac{R - r_b}{2} \qquad (6)$$

where :

C_x - aerodynamic drag coefficient - can be assumed as $C_x \approx 1.5$

S_p - planform area of the blade : $(Sp = l_{med} \times (R - r_b))$

l_{med} - average blade width

v_{EXT} - extreme wind gust, is correlated with the annual average wind speed at hub height v_{mz}, and can be calculated for a 1 year or /and 50 years occurrence period [5] as:

$$v_{EXT\,1year} = 5.25 \cdot v_{m_Z} \qquad (7)$$

$$v_{EXT\,50\,years} = 7.00 \cdot v_{m_Z} \qquad (8)$$

In case of a direct electrical short at the output of the electrical generator (or internal short in the generator) due to inertial forces, the blade is subject to bending load The maximum value of the bending moment for most loaded section can be computed using the expression [5]:

$$M_{(ES)} = \frac{k \cdot M_T}{z} + m_b \cdot g \cdot r_{bmc} \qquad (9)$$

where:

$k \cong 2$;

z - number of the blades;

M_T - rotor torque; $g \cong 9.81$ m/s^2.

Material used for wind turbine blade manufacturing

Nowadays, for wind turbine blade fabrication there are widely used plastic composite materials as FGRPs , comprising mainly two basic components:

- a resin (polymer) as matrix (e.g. polyester, epoxy, vinylester)
- glass fiber as reinforcement (e.g. E-glass , S-glass).

The physical and mechanical characteristics of these materials are highly dependent mainly on the type and content of the resin (matrix) and fiberglass reinforcement structure.

According to reference [2] such of a plastic composite material, comprising 40% (vol.) polyester and 60% fiberglass, shows the following characteristics:$\rho \cong 1700$kg/m^3;$E_{tensile} = 15$GPa, $\sigma_{ultimate}^{(tensile)} = 420MPa$, $\sigma_{fatigue(10^7,R=-1)}^{(tensile)} = 35MPa$

For composite plastic materials fatigue strength is commonly expressed as [3]: $\sigma_{fatigue} = \sigma_{ultimate}$. (1-B . log N) where: N= number of cycles, B= coefficient depending on stress alternation (e.g. $B = 0.1$ for a stress ratio of R= 0.1. Consequently, for a common FGRP a relation of $\sigma_{fatigue(10^7\,cycles)} \approx 0{,}25 \cdot \sigma_{ultimate}^{tensile}$ might be coarsely admitted.

Reference [6] gives also for different FGRPs, depending on the type and content of the resin and fiberglass reinforcement structure the following features: $\rho \cong$ 1280...1900 kg / m^3, $\sigma_{ultimate}^{(tensile)} = 100...800MPa$, $\sigma_{ultimate}^{(compression)} = 140...250$ MPa.

In reference [7] physical and mechanical characteristics of some FGRPs made by different resins and 25-40% glass fibers show the following range of values: $\sigma_{ultimate}^{(tensile)} = 80...190MPa$, $\sigma_{ultimate}^{(compression)} = 120...230MPa$, $\sigma_{ultimate}^{(flexural)} = 110...260MPa$, $E_{tensile} = 4{,}8...11{,}7GPa$, $E_{flexuaral} = 5{,}1...9{,}65GPa$.

For manufacturing the blades of the 5 kW small wind turbine, SC CLAGI SRL have used a GFRP material comprising the following basic components:

- CSM 225 - (fiberglass) chopped strand mat of 225 g/m^2
- Diolen 540 - Diolen® polyester woven fabric of 540 g/m^2
- VR 37 - 37 vinylester resin

The blade shell was designed and fabricated for a 5 mm thickness allover the blade contour excepting the blade root zone where thickness was increased to 10 mm.

The layering used for molding the two half shells of the blade is:

- for 5mm shell thickness : CSM 225, VR 37, CSM 225, Diolen 540, CSM 225
- for 10mm shell thickness: CSM 225, VR 37, CSM 225, Diolen 540, CSM 225, CSM 225, Diolen 540, CSM 225, Diolen 540, CSM 225, VR 37, CSM 225.

The reinforcement has a total mass ratio of 30%.

Our option of using a FGRP material for manufacturing the blades for our 5 kW wind turbine was motivated firstly by its superior qualities comparing with traditional materials, such as resistance to corrosion (achieved by a proper choice of the resin type); specific physical and mechanical properties comparable with metals; handling and facile mounting; low density comparing with metals. Secondly, was the previous experience of SC CALGI SRL in using and handling FGRP fabrication technology in manufacturing equipment for chemical industry (e.g. pumps and pipelines); fan blades for cooling towers up to 13m diameter; skis, toboggans, boats, components which are subject during their operation to mechanical loadings comparable with those of the wind turbine blade.

At the same time it was considered that the parts and components made by FGRP can be manufactured by hand lay-up or compression methods by building up layers of fiberglass successively impregnated with catalyzed resin around a suitable mold. At the end of polymerization reaction the stratification copy the mold shape, which is essential for the spatial twisted shape of wind turbine blade.

The mechanical strength characteristics of FGRP material used for fabricating the wind turbine blade was initially assumed by the blade manufactures, i.e. SC CALGI SRL, as reaching values of 156 MPa for ultimate strength, and 60 – 70 MPa for yield strength.

Researches on FGRP material strenght

Preliminary assessments

In order to check out and to confirm the mechanical strength capacity/features of the FGRP used for the blade fabrication, within the Strength of Materials Laboratory of "Politehnica" University of Timisoara, have been performed strength tests on the blade material. Tests were performed on test specimens taken from a real blade, as well as, on test specimens cut from panels specifically made for this purpose. Additionally, and prior to the laboratory strength tests, at SC CALGI SRL facility, have been performed an in-house static load test with sand bags upon a blade that was identically manufactured as the 5 blades mounted on the 5 kW wind turbine. The goal was to find out experimentally the normal stress - σ^{TEST} - produced by the static loads in order to compare it with theoretical values computed in the blade design - $\sigma^{COMPUTED}$- (corresponding to equations given in chapter 3) depending on the operation regime.

The stress calculation was done for the critical cross section of the blade, for the following input parameters:

- radial position: $r_{crit} \cong 0.6$ m
- cross section area of the FGRP shell : $A \cong 15$- 32 cm^2
- cross section strength modulus: $W = 28 - 64$ cm^3
- blade mass : $m_b = 10 - 10.5$ kg
- blade mass center with respect to rotor axis: $r_{bmc} \cong 1$ m.

The results concerning the stress into the blade material computed for certain relevant operational regimes are as follow:

- Normal operation around the rated point

In this case the prevailing loads are represented by centrifugal and aerodynamic forces

The input parameters assumed for calculation are:

- wind speed: $v = 10 - 11$ m/s
- tangential speed of the blade tip: $u_R = 40 - 44$ m/s (optimum tip speed ratio: $\lambda_0 = 4$)
- wind turbine rotor power (at the rotor shaft): $P_T = 3750 - 5500$ W
- rotational speed: $n = 153 - 168$ rot/min
- rotor torque: $M_T = 234 - 312.5$ N×m

The computed values of normal stress resulted for the blade critical section is given in table 1.

- Maximum rotational speed (overspeeding)

In this case the aerodynamic forces have just a neglecting effect while centrifugal forces are dominant (table 2).

- Parked wind turbine under extreme wind

In this case, the blade is subject to bending moment due to aerodynamic loading.

The values of the normal stress computed for this extreme loading are given in table 3.

- Maximum thrust (axial force) in operation

The stress in the critical section of the blade, produced by the aerodynamic loads, is usually assessed for a characteristic operational wind speed $v_{MT} = 2.5 \cdot v_{mz}$[5] . Assuming $v_{mz} = 6$ m/s, as well as, $v_{mz} = 3.2$ m/s, the results obtained by calculation are those shown in table 4.

- Short circuit at load connection

The computed values of the normal stress caused by blade inertia and its weight are centralized in table 5.

Table 1
NORMAL STRESS COMPUTED
FOR RATED OPERATION REGIME

$W[cm^3]$	28	64
$A[cm^2]$	15	32
$M[daNcm]$	1872 - 2500	
$F_{cf}[daN]$	257 - 310	
$\sigma_{flexural} = \frac{M}{W}[daN/cm^2]$	67 - 87	29 - 39
$\sigma_{tensile} = \frac{F_{cf}}{A}[daN/cm^2]$	17 - 21	8 - 10
$\sigma_{combined} = \sigma_{flexural} + \sigma_{tensile}[daN/cm^2]$	84 - **108**	37 - 49

Table 2
COMPUTED VALUES OF THE NORMAL STRESS AT DIFFERENT ROTATIONAL SPEEDS

$n[rot/min]$		150	200	250	300	500	650*)
$F_{cf}[daN]$		247	439	685	987	2742	4633
$\sigma_{tensile} = \frac{F_{cf}}{A}[daN/cm^2]$	A = 15 cm^2	16.5	29.3	45.7	65.8	182.8	**309**
	A = 32 cm^2	7,7	13,7	21,4	30,8	85,7	145

*) the value represents the runaway speed that wind turbine reaches for the cutout wind speed $v_{cutout} = 25 m/s$.

Table 3
NORMAL STRESS COMPUTED FOR EXTREME WIND LOADING

$v_{EXT}[m/s]$		15	25	35	45*)
$M_{(EXT)}[daNcm]$		984	2735	5360	8860
$\sigma_{flexuaral} = \frac{M_{(EXT)}}{W}[daN/cm^2]$	W = 28 cm^3	35.1	96.7	191.4	**316.4**
	W = 64 cm^3	15.4	42.7	83.8	138.4

*) the value is associated to a 50 years occurrence extreme wind gust for a location having (at the hub height) an annual average wind speed $v_{m_z} = 6 m/s$ (much higher than Ciugud site has, e.g. $v_{m_z} = 3.2 m/s$)

Table 4
NORMAL STRESS INTO THE BLADE MATERIAL FOR MAXIMUM TRUST LOADING

$v_{m_z}[m/s]$		6	3,2
$\sigma_{flexural} = \frac{F_a \cdot \frac{R}{2}}{W}[daN/cm^2]$	W = 28 cm^3	**121**	34
	W = 64 cm^3	53	15

$R = D/2 = 2.5 m$

Tabel 5

COMPUTED VALUES OF NORMAL STRESS IN THE CASE OF ELECTRICAL SHORT CIRCUIT AT LOAD CONNECTION

$M_{(ES)}[daN \cdot cm]$		1966	2280
$\sigma_{flexural} = \frac{M_{(ES)}}{W}[daN/cm^2]$	W = 28 cm^3	70.2	**81.4**
	W = 64 cm^3	30.7	35.6

Table 6

CROSS SECTION EFFECTIVE SIZE OF TESTED SPECIMENS

Tensile			Flexural		
Specimen	h [mm]	b [mm]	Specimen	h [mm]	b [mm]
A	5.18	4.26	**A**	4.55	20.65
B	Did not test		**B**	3.33	20.80
C	4.91	4.27	**C**	3.33	20.28
D	5.16	4.63	**D**	4.30	21.20
E	5.24	4.39	**E**	4.94	20.72
1	4.97	10.07	**1**	10.14	20.06
2	4.88	10.22	**2**	10.17	20.02
3	5.14	10.21	**3**	10.19	20.01
4	5.15	10.20	**4**	10.18	19.98

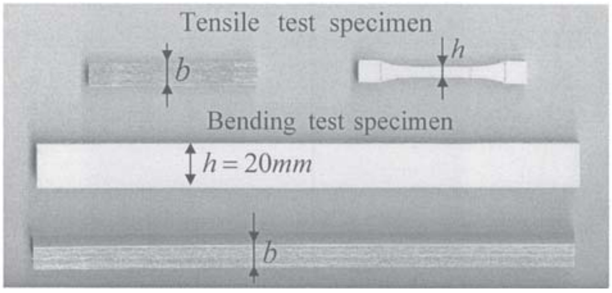
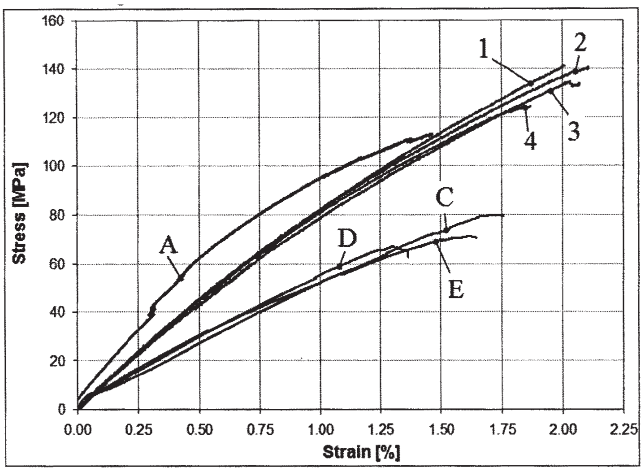
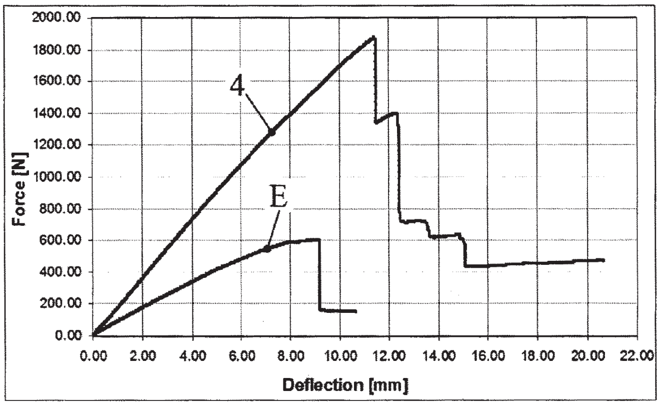


Fig. 4. Shape and size of test specimens used for lab testing



a) tensile test



b) Flexural test

Fig. 5. Mechanical strength characteristic curves

- Laboratory strength tests on blade material

Mechanical strength tests were performed within the Strength of Materials Laboratory of “Politehnica” University of Timisoara being used two types of test specimens:

- specimens made from the 5mm thick shell of a blade originally tested in-house at SC Clagi SRL - marked with letters: **A**, **B**, **C**, **D**, **E**.
- specimens made from FGRP panels of 10mm thickness, prepared separately from the blades, but through the same technological process as used for manufacturing all the blades (layering structure: CSM 225, VR 37, CSM 225, Diolen 540, CSM 225, CSM 225, Diolen 540, CSM 225, Diolen 540, CSM 225, VR 37, CSM 225; multiaxial reinforcement with orthogonal fibers at +/-45^0 ; 30% reinforcement ratio) - marked with numbers: **1**, **2**, **3**, **4**.

Test specimens were used for tensile (traction) testing and flexural (bending) testing, too (fig. 4). The accurate sizes of these specimens are given in table 6.

The results of the laboratory tests performed on specimens are exemplified through characteristic curves in figure 5.

Figure 5 reveals both, for the 3 specimens sampled from blade material (e.g. **C**, **D** and **E**), and for the 4 specimens of the 10mm FGRP panels also, that they have practically an identical tensile behavior (e.g. mechanical strength). This behavior shows the homogeneity of both type of materials of 5mm and 10mm thickness. Higher strength shown by specimen **A** is due to a special clamping device added to specimen for a better stiffness, the assembly being tested and behaving mostly as a unified body.

Data from fig.5.b indicates that by increasing the number of reinforcement layers, the necessary load required to produce the same deformation (i.e. deflection) increases, in some cases, even by 7 - 8 times, that consequently means a higher material stiffness.

Analyzing the results shown in figure 5 a, b, results the following average values of tensile and flexural strength of tested FGRP can be concluded:

- for tensile testing:

- specimens sampled from blade material: $\sigma_{tensile}^{TEST} \cong$ 72MPa (considering specimen **C**, **D** and **E**), and $\sigma_{tensile}^{TEST} \cong$ 83 MPa (considering specimen **C**, **D**, **E**, and **A**)
- specimens made from 10mm FGRP panels: $\sigma_{tensile}^{TEST} \cong$ 135 MPa (considering specimen **1**, **2**, **3**, **4**)

- for flexural testing:

- specimens sampled from blade material: $\sigma_{tensile}^{TEST} \cong$ 135 MPa (considering specimen **A**, **C**, **D** and **E**)
- specimens made from 10mm FGRP panels: $\sigma_{tensile}^{TEST} \cong$ 205 MPa (considering specimen **1**, **2**, **3**, **4**)

Static load test- the blade

Complementary with the laboratory strength testing it was also performed an in-house checking test on a real

Fig. 6. Blade loaded with sandbags; measurement on blade tip deflection

Table 7

COMPARISON BETWEEN COMPUTED AND MEASURED DATA

COMPUTED			EXPERIMENTAL (TEST)			$c = \frac{\sigma^{TEST}}{\sigma^{COMPUTED}}$
OPERATION CASE			FGRP thickness b [mm]	$\sigma^{TEST}_{tensile}$ [daN/cm^2]	$\sigma^{TEST}_{flexural}$ [daN/cm^2]	
NOMINAL v=10 -11 m/s n=153 - 168 rpm P_T = 3,75 - 5,5 kW	$\sigma^{COMP.}_{combined} = \sigma^{COMP.}_{flexural} + \sigma^{COMP.}_{tensile}$ [daN/cm^2]		5	724 $\sigma^{TEST}_{combined}$ *)=	1345 1221	14.5 - **11.1** 33,0 - 24,9 22.7 - 17.3 51.5 - 38.9
	A=15cm^2 W=28 cm^3	84 - 110				
	A=32cm^2 W=64 cm^3	37 - 49				
OVERSPEED v= 25 m/s $n_{runaway}$ = 650 rot/min	σ^{CALC}_{incov}	[daN/cm^2]				4.3 - 9.2 6.6 - 14.1
	A=15cm^2 W=28 cm^3	309				
	A=32cm^2 W=64 cm^3	145				
EXTREME WIND V_{EXT} = 45m/s	σ^{CALC}_{incov}	[daN/cm^2]				**4.2** - 9.7 6.5 - 14.8
	A=15cm^2 W=28 cm^3	316	10	1350 $\sigma^{TEST}_{combined}$ =	2046 1907	
	A=32cm^2 W=64 cm^3	138				
MAXIMUM THRUST v_m = 6 m/s	σ^{CALC}_{incov}	[daN/cm^2]				11.1 - 25.4 16,9 - 38,6
	A=15cm^2 W=28 cm^3	121				
	A=32cm^2 W=64 cm^3	53				
SCURT CIRCUIT BORNE GENERATOR	σ^{CALC}_{incov}	[daN/cm^2]				16.6 - 37.4 25.3 - 56.8
	A=15cm^2 W=28 cm^3	81				
	A=32cm^2 W=64 cm^3	36				

*) $\sigma^{TEST}_{combined} = 0,8 \cdot \sigma^{TEST}_{flexural} + 0,2 \cdot \sigma^{TEST}_{tensile}$

blade, at SC CLAGI Srl. The blade was progressively loaded by placing uniformly sandbags (each of 25 kg) along the blade length in a few layers (fig. 6) ultimately up to the breaking point. For this testing the blade was installed in horizontal position being fixed on a supporting frame similarly as it is fastened on the rotor hub. Prior to achieve the ultimate breaking test, the blade was for a couple of times successively loaded and unloaded into the range of elastic deformation. For each loading/unloading step blade tip deflection was monitored and recorded, as well as the blade twisting, too.

The test aimed to verify the elastic strength of the blade structure and also to verify the mechanical strength limit of minimum 60 MPa guaranteed by blade manufacturer.

Based on the reference literature [8, 9] it was generically assumed, for common FGRPs, a ratio of approx. 1/2 between the elastic strength and yield strength, which gives in our case $\sigma_{elasticity} \cong 0.5 \,.\, 60$ MPa = 30 MPa.

The static load testing performed at SC CLAGI Srl confirmed the result obtained by lab testing on test specimen. The ultimate braking test have revealed for yield strength a value of $\sigma_{yield} \cong 60$ MPa, that is positioned in the range of strength characteristics of similar FGRPs.

Results and discussions

In order to facilitate a comparative analysis concerning the strength features of the FGRP used for fabricating the blade set of a small wind turbine, both the computed and experimental data were synthetically centralized in table 7.

The comparative analysis of results shown in table 7 reveals that even for the most unfavorable cases (e.g. 15mm^{2}cross section; 5mm thick shell) safety coefficients of following order are assured:

- for normal operational regime (fatigue loading): 11.1
- for extreme wind gusts (ultimate loading to v_{EXT} = 45 m/s): 4.2

Obviously, in the case of 10mm thick FGRP, the values of available safety coefficients with respect to ultimate strength are much bigger.

The International Electrotechnical Commission standard IEC61400-2/2006 "Design requirements for small wind turbine" recommends as being assumed a partial safety factor of material of **10** for fatigue strength analysis (assuming a minimal characterization of the material), and **3** for ultimate strength analysis [5].

In this context, the results obtained by laboratory tests confirm that strength characteristics of FGRP material comply with these requirements, justifying so the option of being used for blade fabrication.

Conclusions

The plastic composite material (e.g. FGRP) used for the blade set fabrication of a 5 kW small wind turbine currently operated on Ciugud site of Alba County, has physical and mechanical strength features placed into the range of recommended values given by the reference literature.

The results presented into the paper show that fiberglass reinforced polyester has mechanical strength qualities that makes it suitable for being used for wind turbine blade fabrication (particularly for the small wind turbine developed for Ciugud site), components which are subject to fatigue loadings and extreme loadings given even by strong wind gusts or catastrophic winds.

The strength tests performed both in laboratory on specimens and in-house by the blade manufacturer show for whatever wind turbine operational conditions, that the values of the safety coefficients as requested by IEC61400-2 international standard are exceed.

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