Wind turbine blades structure based on palm cellulose fibers composite material

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Abstract

The uses of the cellulosic fibers in the natural fiber reinforced polymer composites (NFC) for constructing a wind turbine blade structure will be evaluated in the present work through experimental study. The blade shape designed according to the local wind characteristics on the Tabuk city in Saudi Arabia. The blade mechanical resistance identifies, according to the different forces applied to wind turbine blades. The palm cellulosic fibers were used as reinforcement. Those fibers were prepared through mechanical and chemical extraction process. The extraction was through mechanical decomposition in thin fibers and chemical extraction method by chloride and alkaline. To evaluate the reinforcement effect on wind turbine blades a horizontal wind turbine was constructed. The palm natural fibers used as reinforcement of blades with resin-epoxy gives an encouraging result in the sense of robustness and efficiency. The uses of NFC based on cellulosic fibers for constructing wind turbine blades can be considered as a potential candidate for the manufacturing of total recycling wind turbine blades from natural fibers.

Keywords: wind energy, wind turbine blades, palm cellulosic fibers, natural fiber composites (NFC)

Kulcsszavak: szélenergia, szélturbina lapátok, pálma cellulózrostok, természetes rost kompozitok (NFC)

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1. Introduction

Several countries resort to the use of the renewable energies. The renewable energy power systems, such as solar panels and wind turbines produces fewer emissions than other power sources over their lifetime. In particularly wind turbines, which gives high efficiency in the presence of high wind flow and minimize the uses of fossil fuel and ameliorate the environment protection.

The installation and use of large numbers of wind turbines are one of the keys to increase the production of clean energy in the near future. Then the performances of such a wind turbine can be fulfilled only by using innovative, lightweight and highly durable composite materials such as glass, carbon and Kevlar fibers [1, 2].

The most important part of the wind turbine system, produced from composite material, is the wind turbine blade (WTB). The WTB is subjected to complex solicitations included combined impact, static and random cyclic loading. In order to reduce the different types of forces on WTB, it is recommended to build the wind blades from fiber reinforced polymer composites.

It is apparent that the currently most available solution for fiber reinforced composite is the use of E-glass/epoxy or carbon fiber composite [3]. But in the end life of WTB a recycling problematic will be created [4, 5]. Then the solution for the recycling issue could be fulfilled by the use of recycled composite material. But it is required that this composite has a reinforcement can reach higher fracture and toughness resistance [6]. One of the existing solutions, is to use natural fiber composite (NFC) instead of carbon, Kevlar or glass fibers. The uses of NFC give important resistance to complex wind loading and are environmentally friendly and recyclable.

Blades are the most important composite part and the highest cost component of the wind turbines [7]. A wind turbine blades consists of two faces joined together and stiffened both by one or several integral webs linking the upper and lower parts of the blade shell or by a box spar with shell fairings [8]. For that reason, in this work to evaluate the blade structure made from NFC it is necessary, first, to identify the blade optimum structure and composite laying to withstand the wind solicitations. Secondly extract the cellulose palm fibers and then, construct the blades

by hand lay-up molding. And finally, the experimental test was proposed to be conducted on horizontal wind turbine prototype constructed from three blades made from NFC.

2. Materials and procedures

In order to construct the blades (Fig. 1) and test the performance of NFC on horizontal axis wind turbine (HAWT) the blade structure was analyzed numerically and experimentally, see Fig. 2.

Fig. 1 The two aero-shells and the two shear webs of wind turbine blade [9]
1. ábra A szélturbina lapátjának két burkolata és nyírőve [9]

Fig. 2 Construction and evaluation of WTB made from NFC
2. ábra Az NFC-ből készült WTB felépítése és értékelése

3. Characterization of the palm fibers (PF)

The tensile test on palm fibers were conducted in Gant Universal Test Machine WP3, the average curve of the conducted tests is presented in Fig. 3 [9].

Fig. 3 Tensile test result of the palm fibers (PF) [9]
3. ábra A pálmrostok (PF) szakítóvizsgálati eredménye [9]

According to the Fig. 1 the ultimate tensile resistance of the PF is about 27 MPa, the maximum tensile strain at break is about 3.44% and the elastic modulus is about 8.96 GPa.

The present mechanical behavior is relatively weak compared with ordinary synthesized fibers usually uses in blade

construction such as glass, kevlar and carbon fibers. Then it was necessary to stratify the composite in multi-layers with several fiber directions in order to bring an additional strength resistance to the blades.

4. Principal solicitations in wind turbine blade

The wind turbine blades consist of two faces joined together and stiffened both by one or several integral webs linking the upper and lower parts of the blade shell or by a box spar with shell fairings [7]. The flap wise load on wind turbines is caused by the wind pressure, and the edgewise load is caused by gravitational forces and torque load. Table 1 gather the solicitation needed to be overcome during the construction of the blades.

Blade part	Solicitation needed to overcome
The two external faces: The upper part of the blade shell The lower part of the blade shell	Edgewise bending. Cyclic tension-tension loads. Cyclic compression-compression loads
The shear webs	Flap-wise bending
The spar caps	Flap-wise bending
The aero-shells	Elastic buckling
The leading and trailing edge panels	Bending moments associated with the Gravitation loads

Table 1 Common solicitation in wind turbine blades
1. táblázat Gyakori terhelések a szélturbina lapátjaiban

Wind direction

Fig. 4 Representation of the zones of the blade solicitation and the blade induced velocity and forces [10]

4. ábra A penge terhelési zónáinak ábrázolása és a penge által kiváltott sebesség és erők [10]

The modelling of the wind turbine blades structure, starts by the identification of the applicable load case. For this study it was considered two cases of load at normal operation and at extreme wind loading, see Fig. 4.

The vortex system induces on a wind turbine composed by an induced axial velocity and an induced tangential velocity component, see Fig. 4.

The induced axial velocity is specified as:

$$V_{ia} = a \times V_0 \quad (1)$$

Where:

V_0 : is the undisturbed wind speed.

a : the axial induction factor

The induced tangential velocity is in the rotor wake is specified through as

$$V_{it} = 2a'\omega r \quad (2)$$

Where:

a' the tangential induction factor

ω denotes the angular velocity of the rotor

and r is the radial distance from the rotational axis.

Since the wind flow does not rotate upstream of the rotor, the tangential induced velocity in the rotor plane is thus approximately $a'\omega r$.

If a and a' are known, a 2-D equivalent angle of attack could be found based to the work of Martin O. L. Hansen [6] as follows:

The axial velocity specified as shown in Eq. (3)

$$V_a = (1-a)V_0 \quad (3)$$

The rotor velocity specified as shown in Eq. (4)

$$V_{rot} = (1+a')\omega r \quad (4)$$

The relative wind speed V_{rel} has a flow angle direction ϕ :

$$\phi = \alpha + \theta \quad (5)$$

Where:

θ : The local twist angle of blade

α : The local angle of attack

Based to the Fig.4, the angle between wind speed and axial velocity, is the flow angle ϕ determined as shown in Eq. (6):

$$\tan \phi = \frac{(1-a)V_0}{(1+a')\omega r} \quad (6)$$

The lift and drag normal F_N and tangential forces F_T are determined as shown in Eq. (7) and Eq. (8) respectively:

$$F_N = F_L \cos \phi + F_D \sin \phi \quad (7)$$

$$F_T = F_L \sin \phi - F_D \cos \phi \quad (8)$$

Where:

F_L : The lift force

F_D : The drag force

The normal force coefficient C_N and tangential force coefficient C_T are shown in Eq. (9) and Eq. (10) respectively:

$$C_N = C_L \cos \phi + C_D \sin \phi \quad (9)$$

$$C_T = C_L \sin \phi - C_D \cos \phi \quad (10)$$

Where:

C_L : The lift coefficient

C_D : The drag coefficient

If the rotor solidity is introduced as σ (see Eq. (11)):

$$\sigma(r) = \frac{c(r)B}{2\pi r} \quad (11)$$

Where:

B : Number of blades

$C(r)$: is the local chord

and r : is the radial position of the control volume

The uses of the momentum theory to connect the momentum changes in the air flowing through the turbine with the forces acting upon the blades, gives for normal forces as shown in Eq. (12):

$$4\pi r a = \frac{1}{2} B \frac{(1-a)}{\sin^2 \phi} c C_N \quad (12)$$

$$\text{Hence: } \frac{4 \sin^2 \phi}{\sigma C_N} a = 1 - a \quad (13)$$

the momentum theory for Tangential forces gives:

$$4\pi r a' = \frac{1}{2} B \frac{(1+a')}{\sin \phi \cos \phi} c C_T \quad (14)$$

Where:

B : the number of blades

c : the local chord

r : the radial position of the control volume

C_N : the normal force coefficient

C_T : the tangential force coefficient

$$\text{Hence: } \frac{4 \sin \phi \cos \phi}{\sigma C_T} a' = 1 + a' \quad (15)$$

These equations can be rearranged to give the axial and angular induction factors as a function of the flow angle (Eq. (16) and Eq. (17)).

$$\text{Axial induction factor: } a = \frac{1}{\frac{4 \sin^2 \phi}{\sigma C_N} + 1} \quad (16)$$

$$\text{Angular induction factor: } a' = \frac{1}{\frac{4 \sin \phi \cos \phi}{\sigma C_T} - 1} \quad (17)$$

The normal force F_N causes a "flapwise" bending moment at the root of the blade as shown in Eq. (18):

$$M_N = \int_{r_{\min}}^R F_N (r - r_{\min}) dr \quad (18)$$

Where:

r : the local radius

$r_{\min}$: the local minimum radius

R : the total radius of the rotor

dr : the incremental part of the blade

The tangential force F_T causes a tangential bending moment M_T at the root of the blade shown in Eq. (19):

$$M_T = \int_{r_{\min}}^R F_T (r - r_{\min}) dr \quad (19)$$

If neglect the relatively small twist of the blade cross section and assume that these bending moments are aligned with the principal axes of the blade structural cross section.

The maximum tensile stress due to aerodynamic loading is therefore given by Eq. (20):

$$\sigma_{\max, \text{aero}} = \frac{M_N}{I_{TT}} \frac{d_o}{2} + \frac{M_T}{I_{NN}} \frac{b}{2} \quad (20)$$

Where:

M_N : flapwise bending moment

M_T : tangential bending moment

I_{TT} : tangential moment of inertia

I_{NN} : moment of inertia about the flapwise

d_o : length of the blade

b : the flapwise length

Consider equilibrium of element of blade, see Fig. 5 then:

$$\frac{dF_c}{dr} = -m(r)\omega^2 r \quad (21)$$

Where:

$m(r)$ is the mass of the blade per unit length

dF_c is the incremental centrifugal force

ω is the angular velocity

Fig. 5 Element of blade
5. ábra A penge egy eleme

Then, the rotor solidity can be written as:

$$\sigma_c = \frac{F_c(r)}{A(r)} \quad (22)$$

Where, $A(r)$ is the local area at the blade element

In the other hand, the bending moment at the blade root due to self-weight loading can dominate the stresses at the blade root. The bending moment is a cyclic load with a frequency of $f = \omega / 2\pi$. The maximum self-weight bending moment occurs when a blade is horizontal, see Fig. 6.

Fig. 6 Blade self-weight
6. ábra Penge önsúlyának figyelembe vétele

The maximum self-weight bending moment could be written as shown in Eq. (23), and this is a tangential (edge-wise) bending moment.

$$M_{sw} = \int_{r_{min}}^R m(r)g(r-r_{min})dr \quad (23)$$

Therefore, the maximum bending stress due to self-weight is given by Eq. (24):

$$\sigma_{max,sw} = \frac{M_{sw}}{I_{NN}} \frac{b}{2} \quad (24)$$

Finally, the whole Combined Loading could be written as shown in Eq. (25):

$$\sigma_{max} = \sigma_{max,aero} + \sigma_c + \sigma_{max,sw} \quad (25)$$

According to the Eq. (25), it is necessary to conduct a calculation on the combined load of the whole blade structure, in order to fix the dimensions and select the composite structure that could withstand the combined load. For that reason, a FE modelling it was conducted in previous work [8].

5. Construction of the blades and test of the wind turbine

The composite should withstand essentially to the complex loading of the wind. The natural fibers were selected, extracted and treated to prevent any rapid degradation due to existing of water or any other non-desired constituent. A stratified multi-layer layup composite was choosing to withstand combined load, see Fig. 7.

Fig. 7 (a) The extracted Long Palm fibers (b) the construction of the blades from palm natural fibers and resin epoxy
7. ábra (a) A kivont hosszú pálma szálak (b) a pengék felépítése természetes pálma szálakból és epoxy gyantából

The wind blade prototype was constructed as shown in Fig. 8, with a total length 4400 mm a maximum width 400 mm, the shape was selected with zero airfoil twist angle to prevent any additional vortex and fatigue to the blade structure, see Fig. 8.

Fig. 8 The blade's dimensions (all dimensions in millimeter)
8. ábra A penge méretei (milliméterben)

6. Results and discussion

All experimental tests were obtained at the month of April 2020, the test were conducted on the wind turbine prototype shown in Fig. 9. The test of the wind turbine performance was executed at several wind conditions as shown in the Table 2. The maximum wind speed is about 25 km/h and the minimum speed about 5 km/h.

The optimum pitch angle was identifying through the determination of the wind direction and the maximum experimental rotational speed of the rotor. The actual measured power was calculated as an input mechanical power without generation of electricity.

Fig. 9 The wind turbine prototype
9. ábra A szélburbina prototípusa

Date	Wind Speed [km/h]	N [rpm]	Torque [N.m]	Input Power [Watt]	Optimum Pitch Angle [Degree]
7-Apr	14	10	9.8	10	15
8-Apr	7	5	9.8	5.1	5
9-Apr	22	14	9.8	14	22
10-Apr	14	10	9.8	10	15
11-Apr	18	12	9.8	12	20
12-Apr	15	10	9.8	10	15
13-Apr	25	18	9.8	18	24

Table 2 Test of the wind turbine at several wind conditions
2. táblázat A szélburbina vizsgálata többféle szélviszony mellett

The change in power versus the rotation speed of the wind turbine is shown in the Fig. 10.

Fig. 10 The change of power according to the rotation speed of the wind turbine.
10. ábra A teljesítményváltozás a szélburbina forgási sebessége szerint.

The change in power versus the wind speed is shown in the Fig. 11.

Fig. 11 The change of power versus the wind speed
11. ábra A teljesítményváltozás a szélesség függvényében

The influence of wind speed vs the rotation speed of the wind turbine is shown in the Fig. 12.

Fig. 12 The change in wind turbine rotation speed versus the wind speed
12. ábra A szélburbina forgási sebességének változása a szélességhez viszonyítva

Fig.13 The change in power according to the blade pitch angle
13. ábra A teljesítményváltozás a penge dőlősszöge szerint

The variation of pitch angle could increase the input power of the wind turbine, see Fig. 13.

The observed tests and results shows that the power increases linearly with the rotation speed and wind speed, the power could reach 18 Watt. As well as, the change of the blade pitch angle influence positively the input power of the wind turbine.

Also it was observed that, at slow wind speed $v = 7$ km/h the wind turbine gives a power about 5 Watt, due to light weight of wind blades. The blade structure was tests at several wind conditions and the structure is remaining stable and the composite withstand climatic severe conditions without any damage.

7. Conclusions

Small wind turbine applications are now becoming a solution for producing alternative energy. Actually, as the cost of small wind turbines drops through mass production and technical developments, and as the fee of electrical energy rises, mounting small wind turbines in windy sites will become progressively sustainable. However, the end life of wind turbine and wind turbine blades will challenge the society to a huge waste volume of no recycling material. Then, in the present investigation, the solution was to use natural palm fibers (PF) instead of glass fiber, Kevlar and carbon fiber.

The experimental tests and results on wind turbine made from PF, indicates that the power increases linearly with the rotation speed and wind speed, the power could reach 18 Watt. As well as, the change of the blade pitch angle influence positively the input power of the wind turbine.

Also, it was observed that, at slow wind speed $v = 7$ km/h the wind turbine gives power about 5 Watt, due to the light weight of wind blades, which represent a great advantage compared with the heavy classic wind turbines. The blade structure was tested at several wind conditions and the structure is remaining stable and the composite withstand climatic severe conditions without any damage. The palm natural fibers used as reinforcement of blades with resin, epoxy gives an encouraging result in the sense of robustness and efficiency.

The palm fibers have proved an excellent mechanical properties and are available free of charge in the Tabuk region in Saudi Arabia. Also near to Tabuk city a significant high continues wind speed, especially in the Neom region, where the wind speed could provide high input power to the wind turbines. The uses of NFC based on cellulosic fibers for constructing wind turbine blades can be considered as a potential candidate for the manufacturing of total recycling wind turbine blades from natural fibers.

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Conflicts of Interest

The authors declare no conflict of interest.

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