Journal of Engineering Science and Technology
Special Issue on Development of Sustainability Systems - I, 1 - 17

NUMERICAL ANALYSIS OF WIND TURBINE BLADES MANUFACTURED FROM COMPOSITE MATERIALS AT DIFFERENT VELOCITIES AND ARRANGEMENTS

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Abstract

Since wind turbines are found all over the world, technology for acquiring renewable energies must be developed. The work of wind turbines depends mainly on generating wind energy and converting it into electrical energy. And the materials manufactured for wind turbines can withstand the pressures and forces coming from the wind. The problem lies in resolving the fatigue phenomenon in wind turbines because of changes in air pressure. To solve this problem, it is necessary to use composite materials, which have become a major part of industrial applications due to their ability to withstand various mechanical conditions. An air turbine was designed and simulated the amount of pressure generated from the air. Thus, the best arrangement of composite materials was made to obtain the strongest bearing capacity for the turbine. The model was designed based on the main dimensions of the FFA-W3, NACA-63-xxx, MIX turbine. The result shows the ideal situation is achieved by arranging the angles, which is the stress value of a turbine blade when it moves at a speed of 15 m/s and possesses 358650 Pa. The fundamental working mechanism of composite materials is the strategy of arranging composite materials with the necessary angles to achieve the best configuration that can withstand large loads and not fail under them. Compared to other examples, the arrangement of the angles (0,0,0) prefers bearing deformations and stresses, and it can withstand the phenomenon of fatigue.

Keywords: Carbone fibre, CFD, Composite material, Fatigue life, FSI, Wind turbine.

1. Introduction

Wind turbines are essential for acquiring renewable energy and converting wind energy into electrical energy. The materials used in wind turbines must be strong enough to withstand pressure and forces. To combat tiredness caused by air pressure fluctuations, composite materials, which can tolerate various mechanical conditions, are needed. These materials are essential for industrial applications and are essential for overcoming tiredness issues. A stochastic technique creates computer code that simulates wind flow on the blade. Each load scenario is weighed by its frequency of occurrence using a Weibull wind speed distribution. Accumulated fatigue damage modelling is used as a damage estimate rule [1]. Experimentally, structural deterioration in a composite wind turbine blade subjected to fatigue stress is seen. They look at and talk about how fatigue affects bending stiffness, natural frequencies, and damping ratios. The work offers the first observation of this sort in the literature on full-scale composite rotor blades [2]. The most significant models pertinent to assessing the fatigue response of composite wind turbine blades are reviewed. Progressive damage models are the most effective tool among the fatigue modelling strategies discussed. They adequately measure and characterize the progression of physical damage during exhaustion.

There is extensive discussion of the literature's faults and lack of agreement [3]. An exhaustive weakness investigation system has been made for composite breeze turbines with sharp edges. It includes pressure forecast by limited component investigation, evaluation of weariness harm in view of the gathered weakness information, and variable breeze loads through wind field reproduction and streamlined examination. A high-constancy, limited component, sharp-edge model has been defined for intensive pressure examination. This model considers simple customization of the plan of composite materials [4]. Cut-edge computational techniques and how they may be coupled to forecast fatigue damage progression in full-scale composite wind turbine blades are presented. The blades' initial damage, development, and final failure are all documented.

The Micon 13M wind turbine with Sandia CX-100 blades uses the linked FSI and fatigue-damage formulas [5]. The structural safety of composite wind turbine blades is becoming more crucial as the number of blade failures at wind farms has grown. The blade root failure is one of the critical failure modes, and it may cause the blade to come loose from the wind turbine while it is in use. A more thorough FE study of the blade root is required at the design stage to improve structural safety [6]. The examination of several of the 300 kW wind turbine blades that had damage found that it was likely the result of a fatigue mechanism. The failure's causes (superficial cracks, geometric concentrators, abrupt changes in thickness) have been investigated, and it has been confirmed using the Germanischer Lloyd (GL) standard's streamlined fatigue life evaluation procedure that these causes can account for the failure observed during the time that it occurred [7]. Wind turbine cutting edges are a principal part of the breeze turbine framework and should achieve an extremely lengthy functional existence of 20-30 years. The notable S-N harm condition, the heap range, and Spera's experimental formulae were utilized in this review to gauge the weariness life of a medium-scale (750 kW) hub wind turbine. Because of satisfactory security edges from the exhaustion prerequisite, it was demonstrated that the composite breeze turbine edge satisfies the plan boundaries for the 20-year weakness life [8].

A structural design for a 750-kW horizontal axis wind turbine system's composite medium-scale blade built of E-glass or epoxy is proposed. Different load situations listed in the IEC61400-1 international standard and the GL guidelines for the wind energy conversion system were used to estimate the design loads. It was suggested to design a specialized composite construction that can withstand various loads [9]. Turbines that harness the wind's kinetic energy to generate electricity play a crucial role in structural behaviour. For design and maintenance purposes, it is essential to have an accurate estimate of a wind turbine's life duration. Turbines should last longer with fewer interruptions from outside sources and fewer chances of breakdown [10].

Carbon nanotubes are allotropes of carbon with a nanostructure that might have a viewpoint proportion greater than a million. These carbon atoms, which are round and hollow in shape, have extraordinary elements that could make them accommodate wind turbines with sharp edges [11]. Investigations by Kulkarni et al. [12] intended to assist with the primary and exhaustion investigations of a minuscule flat pivot wind turbine with a sharp edge made of composite material. The edge has a helpful existence of close to 20 years, and its skin close to the sharp edge's root is where weariness initially starts to show. It incorporates high loyalty, displaying the sharp edge, wind conjectures, and static and weakness investigations.

Kulkarni et al. [13] evaluated the precision of long-haul wind turbine conjectures utilizing cutting-edge profound brain networks like the nonlinear autoregressive organization with outside inputs and a repetitive brain network called long momentary memory. After testing, it was resolved that the cutting-edge had a valuable existence of 23.6 years. Hu et al. [14] examined dependability-based plan streamlining (RBDO) utilizing a 5-MW wind turbine's sharp edge. The RBDO method gauges the probability of exhaustion and disappointment during a 20-year administration. Exhaustion areas of interest are situated in the overlay piece of the edge at different stages through the cycle. Deterministic plan streamlining uses the mean breeze load from the breeze load vulnerability model.

Wind turbine blades for wind turbines were analysed using computed tomography to determine their fatigue processes. This study quantifies and maps almost 10,000 voids within the gauge length of each specimen. The area around the crack's transition from sub-critical to critical damage was also the region with the longest fatigue life [15]. The 3D angle interlock T-joint performed the best in tests with static and fatigue loads. When subjected to a static load, the interlaminar veil dramatically improves the material's ultimate strength. The through-thickness reinforcement greatly improves fatigue performance when applied to the flange-skin areas [16]. Some tests carried out by Mandell et al. [17] at a dedicated high-frequency small-strand testing facility have reached 1010 cycles of tensile fatigue. A more nuanced Goodman diagram with improved R-values has been created. Epoxy resin laminates reinforced with carbon fibres have somewhat better compressive strength and fatigue resistance. The fundamentals of wind turbines and rotor blades are discussed, along with the role that wind, and gravity have on the fatigue performance of the materials. High stiffness, low density, and exceptional fatigue performance are highlighted as defining characteristics of composites.

Technologies for processing and analysing huge volumes of test data are covered [18]. The average diameter of a wind turbine rotor blade has expanded from 40 meters to more than 120 meters. Turbines have a 20-year expected lifespan; they will see more than 108 load cycles. A thorough understanding of the fatigue behaviour of the material and structural features is required [19]. Composite constructions are widely used in wind turbine equipment due to their high stiffness-to-mass ratio and strength. However, their vulnerability to microdamage, such as fibre breakage and matrix cracks, poses a significant problem. A multi-scale modelling technique was proposed to examine failure processes and the damage evolution of composite blades [20]. The technique uses isoperimetric micromechanical models, traditional laminate theory, reverse modelling techniques, and a macroscopic 3D model integrated into the ANSYS/LS-DYNA program. Multi-objective structural optimization was used to design a composite wind turbine blade with exterior geometry using the NREL 5 MW model [21]. It addresses optimization problems like blade tip displacement, vibration frequencies, critical load factor, and four other factors. Performance metrics and the maker's multi-criteria decision-making are used to assess non-dominated solutions.

The originality of this study is to numerically investigate the deformation, stress, and strain characteristics of turbine blades manufactured from composite materials with multiple arrangements under different velocities. The goal is to understand these blades' structural behaviour and performance to optimize their design and ensure their reliability and durability in operating conditions. The current work aims to numerically investigate fatigue and buckling with vibration for turbine blades made of composite materials. To achieve this aim, the effect of wind speed on the pressure generated by the turbine blade, the effect of the arrangement of composite materials, and the effect of the fatigue phenomenon on composite materials in turbine blades have been addressed.

2. Materials and Methods

The investigations have been performed numerically by computational simulation. A computational model of a turbine blade has been created. Two different types of manufacturing materials have been selected, and the results of the generated stresses are compared.

2.1. Simulation procedure

A control volume-based technology consisting of accompanying developments, which can be used to arrange:

- A mesh is produced on the field.
- Sets of conditions like speed, pressure, and preserved scalars, logarithmic is built by the mix on each control volume of the overseeing conditions.
- The Discretized Equations are linearized and addressed iteratively.

ANSYS is the arrangement calculation utilized by FLUENT and is embraced in the current work. The overseeing conditions are addressed consecutively (i.e., isolated from each other). Since the overseeing conditions are non-direct and coupled, numerous cycles might be finished before a united arrangement is gotten. In the current study, the air is considered the system's running fluid. The characteristics of flow are assumed to be static flow, 3D, Newtonian incompressible, and turbulent.

2.2. Computational modelling

The model was designed based on the main dimensions of the FFA-W3, NACA-63-xxx as Tab. 1, MIX turbine, which are according to the dimensions taken from the source [1], where the SolidWorks program converted these dimensions into an adjustable three-dimensional model. The surface was divided into three layers with a thickness of 1 cm for each layer because the size of the turbine in full measurements is relatively large, as shown in Fig. 1. The general specifications of the investigated blade are shown in Table 1.

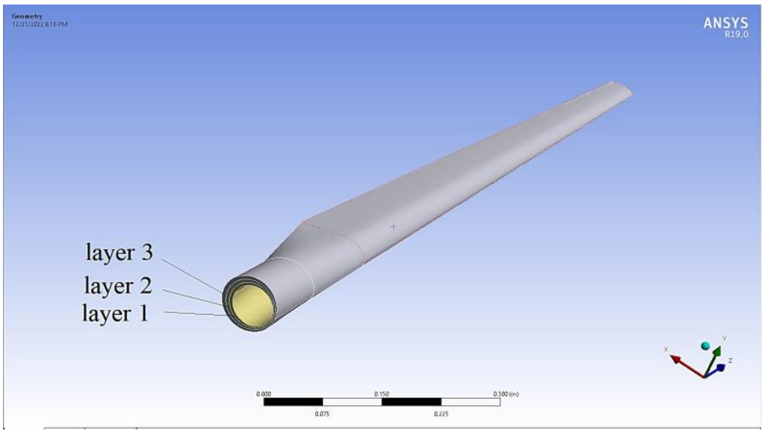


Fig. 1. Geometry of turbine blade layers.

Table 1. General specifications of the investigated blade.

Length	22,900 mm
Maximum chord	2087 mm
Station of maximum chord	R4500
Minimum chord	282.5 mm
Twist	15.17^{o}
Station of CG	R8100
Weight of blade	1250 kg
Tip to tower distance	4.5 m
Surface area	28 m^2
Aerofoil cross-section types	FFA-W3, NACA-63-xxx, MIX

2.3. Mesh generation and independency check

After completing the model design, it is necessary to check the accuracy of the mesh. This is done by reducing the size of the element and displaying the results until a good convergence is reached in the variables of the results, which is called mesh reliability, as shown in Table 2.

Table 2. Mesh independency check.

Case	Element	Node	Max. stress Pa
1	4835423	6825423	44127
2	5513298	8345232	44065
3	6104343	9363220	44030
4	6451112	10300704	44028

The element count reached 6451112 at stress 44028 Pa, in element sizing 0.05 m, and the type of element was tetrahedron, which is sufficient to simulate the situation and reach results close to reality, as shown in Fig. 2.

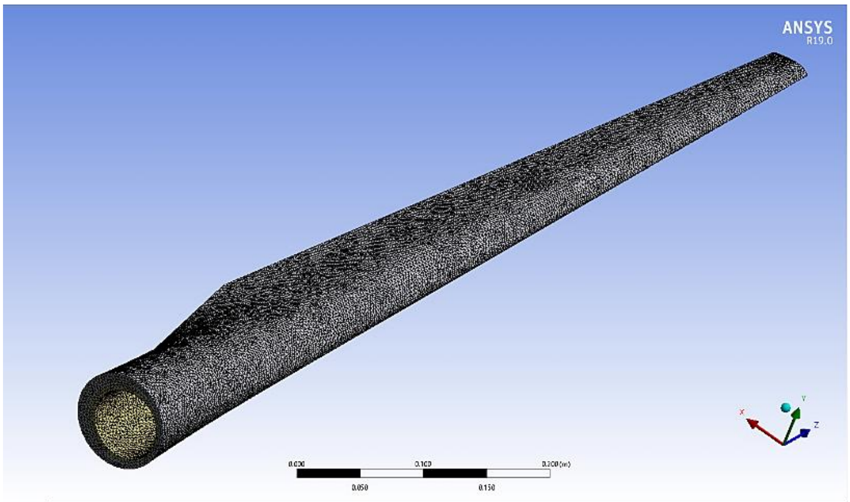


Fig. 2. Mesh geometry.

Composite materials play an important role in the design of wind turbine bearings, as the arrangement of angles helps to understand the shedding of loads. Therefore, it is studied which of these arrangements is better. The angles were arranged based on the layers used, which are 5 in our case, to understand any appropriate arrangement that can increase the fatigue phenomenon, as in Fig. 3.

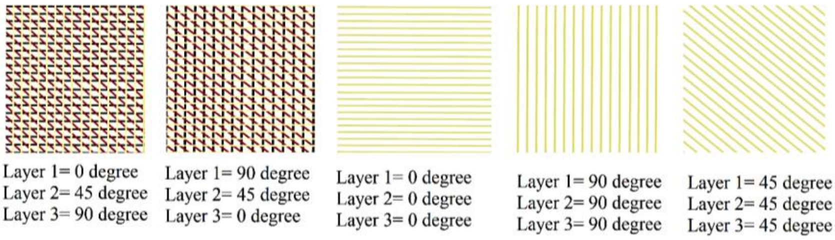


Fig. 3. Composite materials arrangement.

2.4. Governing equations

For a linear structure static analysis, the general equilibrium equations are as follows:

$$[K]\{u\} = \{F\} \tag{1}$$

or

$$[K]\{u\} = \{F^a\} + \{F^r\} \tag{2}$$

where:

[K] = $\sum_{m=1}^{N}[K_e]$ = integrated matrix of stiffness (N/m)

$\{u\}$ = displacement vector at a node (m)

N = number of elements

$[K_e]$ = Stiffness matrix of elements (described in Element Library) (may include the stress stiffness matrix of the element, as detailed in Stress Stiffening) (N/m)

$\{F^r\}$ = reaction load vector (N)

$\{F^a\}$ = the vector sum of all external forces applied, is defined as: (N)

$$\{F^a\} = \{F^{nd}\} + \{F^{ac}\} + \sum_{m=1}^{N} \left(\{F_e^{th}\} + \{F_e^{pr}\}\right) \quad (3)$$

where:

$\{F^{nd}\}$ = vector of force exerted on a node (N)

$\{F^{ac}\} = -[M]\{a_c\}$ = load vector acceleration (m^2/s)

$[M] = \sum_{m=1}^{N}[M_e]$ = the whole mass matrix (kg)

$[M_e]$ = distribution of elemental masses matrix (described in Derivation of Structural Matrices) (kg)

$\{a_c\}$ = whole acceleration vector (defined in Acceleration Effect) (m^2/s)

$\{F_e^{th}\}$ = thermal load vector elements (described in Derivation of Structural Matrices) (N)

$\{F_e^{pr}\}$ = pressure load vector element (described in Derivation of Structural Matrices) (N), [22].

2.5. Boundary conditions

The simulation process requires an installation area, which is the base of the turbine. The other area is distributed pressure along the blade of the turbine. This pressure was obtained by simulating the airway of the turbine blade and using different speeds of 5, 10, and 15 m/s to see the pressure change during the fatigue process. The details of the momentum boundary conditions are shown in Table 3. The initial conditions for the gauge pressure and velocities along the *x*, *y*, and *z* axes are all set to zero.

Table 3. Momentum boundary conditions.

Part	**Type**	**Momentum Conditions**	
		State	**Shear Condition**
Inlet	Velocity inlet	5, 10, and 15 m/s	-
Outlet	Pressure outlet	0 Pa	-
Wall turbine	Wall	Stationary	No Slipping

2.6. Materials

Two composite materials were used which are carbon fibre and fiberglass. It is arranged according to the layers: the first and third layers carry the carbon fibre material, and the second layer carries the glass fibre material, as Tables 4 and 5 show the properties of these materials.

Table 4. Carbon fibre properties [22].

Property	Value	Unit
Density	1.75-2.00	g/cm^3
Young's Modulus X direction	2.09E+05	MPa
Young's Modulus Y direction	9450	MPa
Young's Modulus Z direction	9450	MPa
Poisson's Ratio XY	0.27	
Poisson's Ratio YZ	0.4	
Poisson's Ratio XZ	0.27	
Shear Modulus XY	5500	MPa
Shear Modulus YZ	3900	MPa
Shear Modulus XZ	5500	MPa

Table 5. Glass fibre properties [22].

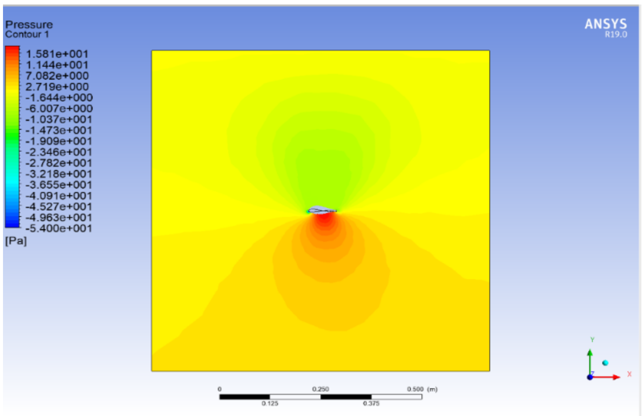
Property	Value	Unit
Density	2.54	g/cm^3
Young's Modulus X direction	45000	MPa
Young's Modulus Y direction	10000	MPa
Young's Modulus Z direction	10000	MPa
Poisson's Ratio XY	0.3	
Poisson's Ratio YZ	0.4	
Poisson's Ratio XZ	0.3	
Shear Modulus XY	5000	MPa
Shear Modulus YZ	3846.2	MPa
Shear Modulus XZ	5000	MPa

3. Results and Discussion

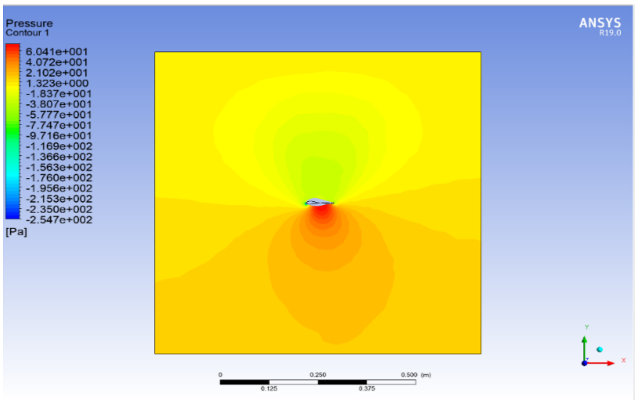
3.1. The effect of wind speed on the generated pressure

The stress generated in the blade of the turbine is produced by the passage of the air current in it, so it works as a phenomenon of fatigue, which is bad in some cases and leads to failure. The pressure contours of Fig. 4 show that the value of the pressure at the air velocity of 5 m/s was 15 Pa, which is relatively low, but at the velocity of 10 m/s, the value of the pressure generated on the turbine blade was 60 Pa. The highest value of the generated pressure was when the air velocity was 15 m/s; when the pressure value reached 135 Pa, the air velocity at which the pressure rose to its greatest level, 135 Pa, was at a speed of 15 m/s.

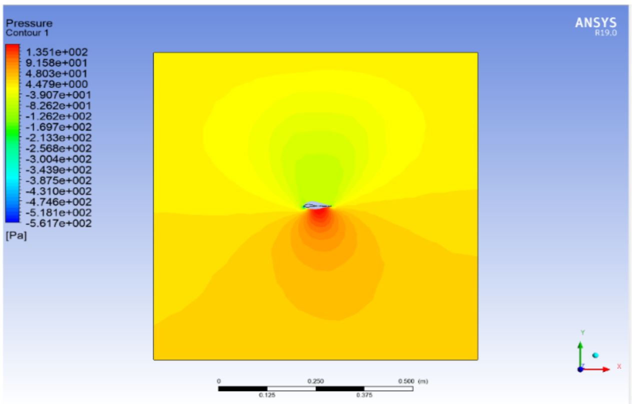
Figure 5 depicts the velocity streamlines. The two vortices behind the blade and its intensity increase with the increase in air velocity. Wind velocity significantly affects the pressure generated by wind turbine blades. Higher wind speeds result in greater pressure differences, leading to increased power generation up to a certain point. Wind turbine operators need to understand the relationship between wind speed and pressure to maximize energy production while ensuring the safety and longevity of the equipment. The two vortices behind the blade are clearly visible, and their intensity rises as air velocity rises.



(a) 5 m/s

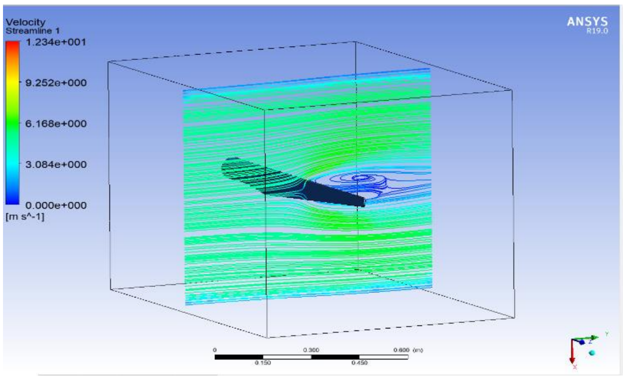


(b) 10 m/s

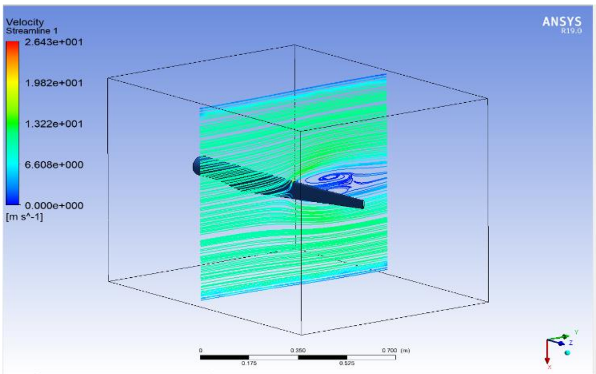


(c) 15 m/s

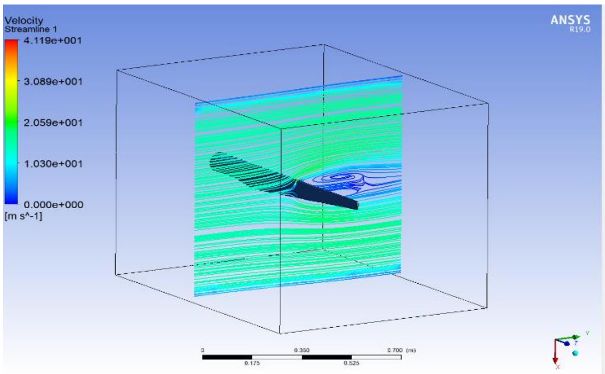
Fig. 4. Pressure contour at different velocities.



(a) 5 m/s



(b) 10 m/s



(c) 15 m/s

Fig. 5. Velocity streamlines at different velocities.

3.2. The effect of the composite materials arrangement on the blade

The basic working mechanism of composite materials is the method of arranging them with the required angles to obtain the most arrangement that can resist high stresses and not fail. Where it was shown in Fig. 6 and according to the difference in the entry speed of the air that works high pressure on the turbine blade, the best case that was reached as the least resulting distortion is the case in which the arrangement of angles is (0,0,0), where the value of the deformation was 0.00001483 m at the speed of 15 m/s.

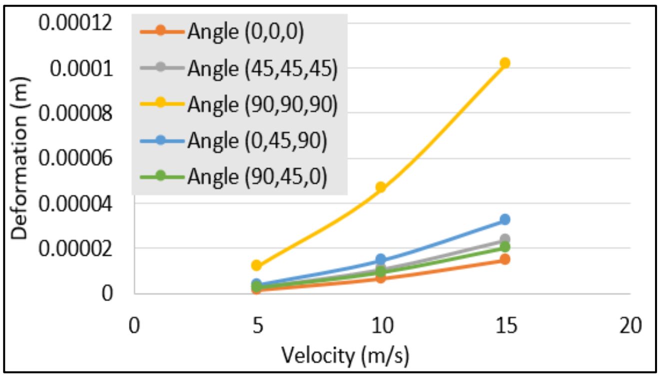


Fig. 6. Deformation with different velocities at all arrangements.

The fundamental working mechanism of composite materials is the strategy of arranging composite materials with the necessary angles to achieve the most configuration that can withstand large loads and not fail in them. The best case that was reached as the least resulting distortion is the case in which the arrangement of angles is (0,0,0), where the value of the deformation was 0.00001483 m at the speed of 15 m/s, as shown in Fig. 6 and according to the difference in the entry speed of the air that works high pressure on the turbine blade. Following the degree of deformation is the strain measurement.

The value of strain follows the state of deformation. The best case that has little strain may be the case of the arrangement of angles (0,0,0), in which the strain value reached 0.00002592 m/m at a velocity of 15 m/s, as in Fig. 7.

The case of the angles (0,0,0), where the strain value reached 0.00002592 m/m at a velocity of 15 m/s, as shown in Fig. 7, may be the best example with the least strain. Studying the value of the effective stresses, which comprise a significant portion of the turbine blade bearing the external loads of air pressure, is important to arrive at the optimum scenario in the arrangement of angles for composite materials.

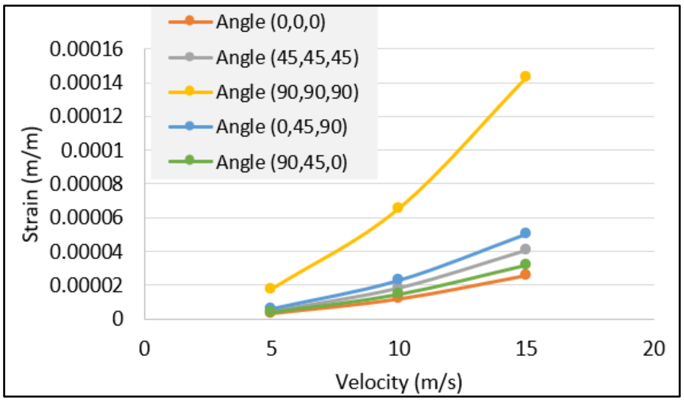


Fig. 7. Strain with deferent velocities at all arrangements.

However, the ideal situation is achieved by arranging the angles (0,0,0), which is the stress value. In Fig. 8, it moves at a speed of 15 m/s and possesses 358,650 Pa.

To reach the best case in the arrangement of angles for composite materials, it is necessary to study the value of the effective stresses, which are a major part of the turbine blade bearing the external stresses of air pressure. The best condition reached is when arranging the angles (0,0,0), which is the value of the stresses. It has 358,650 Pa at a speed of 15 m/s in Fig. 8.

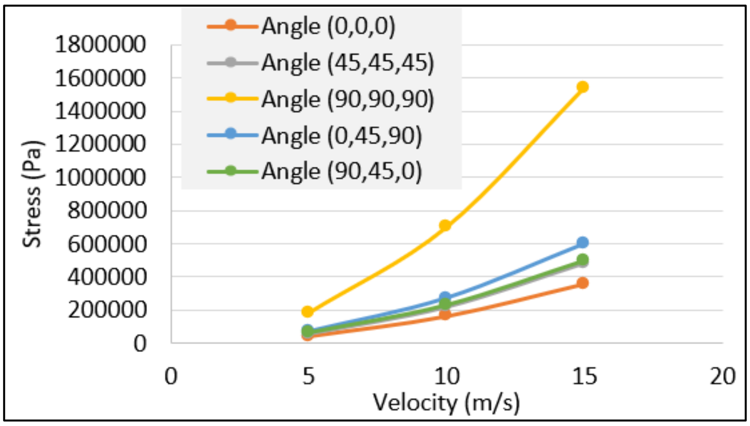
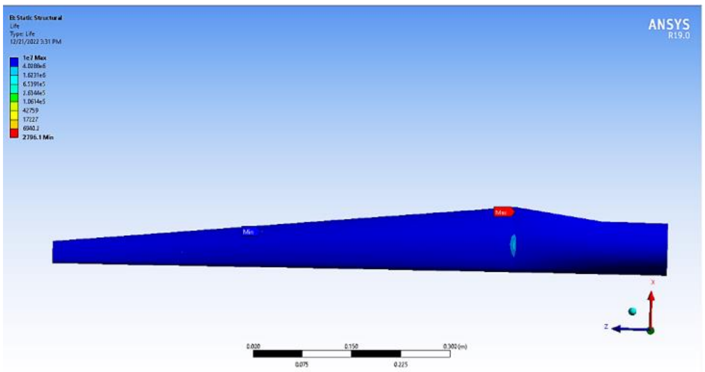


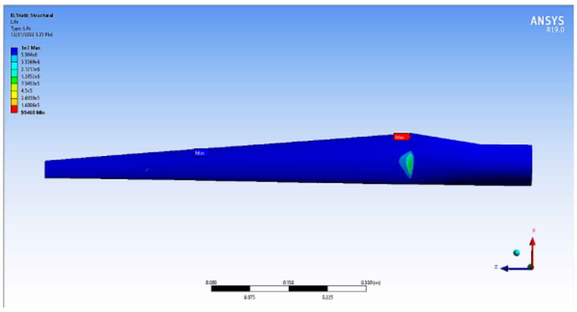
Fig. 8. Stress with deferent velocities at all arrangements.

3.3. Fatigue phenomenon effect on the blades composite materials

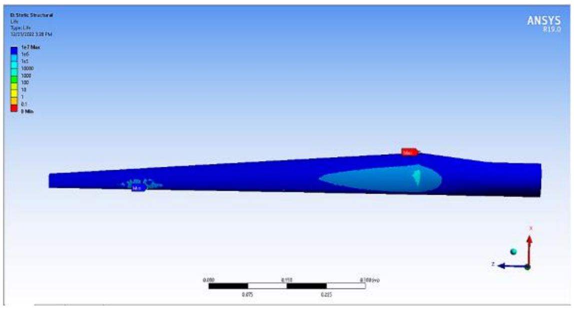
The phenomenon of fatigue gives a clear understanding of the deformation of the material during repeated load cycles. It can be seen from Fig. 9 that the method of arranging the angles of the composite materials on the turbine blade has a clear effect on the phenomenon of fatigue.



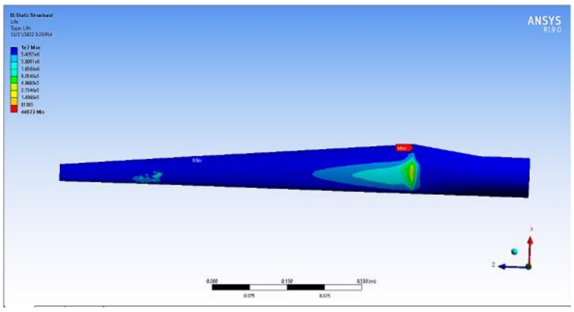
(a) 0,0,0 arrangement



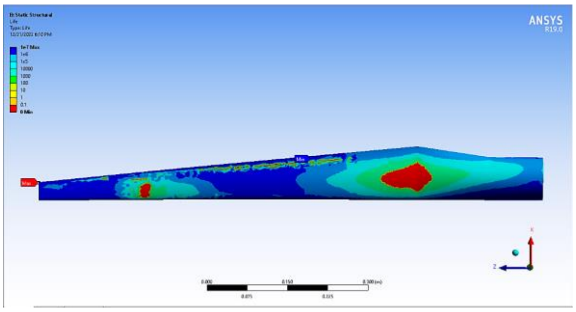
(b) 90,45,0 arrangement



(c) 45,45,45 arrangement



(d) 0,45,90 arrangement



(e) 90,90,90 arrangement

Fig. 9. Life contour of fatigue at different arrangements.

The arrangement of the angles (0,0,0) has a preference in terms of bearing deformations and stresses, and it is certainly able to bear the phenomenon of fatigue, so it takes a greater number of cycles to reach the preferred state compared to other cases.

The deformation of the material over repeated load cycles is well understood via the phenomenon of fatigue. Figure 9 illustrates how the composite materials' angles are arranged on the blade and the effects on the fatigue. Compared to other examples, the arrangement of the angles (0,0,0) prefers bearing deformations and stresses, and it can withstand the phenomenon of fatigue. As a result, it requires more cycles to achieve the optimum condition.

3.4. Validation with previous work

To ensure the correctness of the solution in the submitted research paper, it must be compared with previous research on the work done. The dimensions and details required to make a simulation were obtained, and close results with an error rate not exceeding 5% were obtained. Figure 10 shows the stress-to-strain ratio compared to the number of cycles in the case when the influence of the angles of the composite materials is zero, and the force is applied longitudinally.

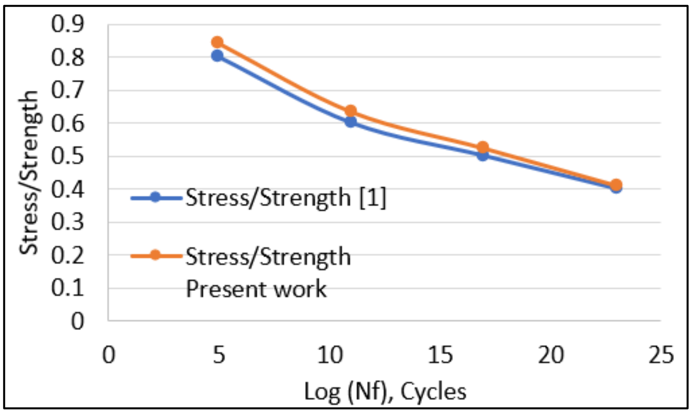


Fig. 10. Stress/strength with cycles.

The submitted research paper's answer must be compared against earlier studies on the work done to confirm its accuracy. The dimensions and information needed to create a simulation were gathered, and accurate results were achieved with an error rate under 5%. Figure 10 shows the stress-to-strain ratio for a situation in which the angles of the composite materials have no effect, and a force is applied along the length of the material. The number of cycles is also shown.

4. Conclusions

Derived from the results obtained and the conducted analysis in this research, the primary findings are outlined as follows:

- The pressure value at the air speed of 5 m/s was 15 Pa, which is relatively low, and the pressure created on a turbine blade at the speed of 10 m/s is 60 Pa. And that the air velocity at which the pressure rose to its greatest level, 135 Pa, is at a speed of 15 m/s.

- The fundamental working mechanism of composite materials is the strategy of arranging composite materials with the necessary angles to achieve the best configuration that can withstand large loads and not fail under them. Studying the value of the effective stresses, which comprise a significant portion of the turbine blade bearing the external loads of air pressure, is important to arrive at the optimum scenario. The ideal situation is achieved by arranging the angles, which is the stress value. It moves at a speed of 15 m/s and possesses 358650 Pa.
- The deformation of the material over repeated load cycles is well understood via the phenomenon of fatigue. The angles of the composite materials are arranged on the turbine blades, and their arrangement has a preference for bearing deformations and stresses. As a result, it requires more cycles to achieve the optimum condition.
- The stress-to-strain ratio in the scenario when the impact of the angles of the composite materials is 0, and the force is applied longitudinally in relation to the number of cycles. The submitted research paper's answer must be compared against earlier studies on the work done to confirm its accuracy.

Acknowledgment

The authors would like to thank Al-Mustaqbal University College, 51001 Hillah, Babylon, Iraq, for their assistance in completing this work.

Nomenclatures

$\{a_c\}$	Whole acceleration vector (defined in Acceleration Effect), m^2/s
$\{F^a\}$	The vector sum of all external forces applied is defined as N
$\{F^{ac}\} = -[M]\{a_c\}$	Load vector acceleration, m^2/s
$\{F^{nd}\}$	Vector of force exerted on a node N
$\{F_e^{pr}\}$	Pressure load vector element (described in Derivation of Structural Matrices) [22], N
$\{F^r\}$	Reaction load vector, N
$\{F_e^{th}\}$	Thermal load vector elements (described in Derivation of Structural Matrices) , N
$[K] = \sum_{m=1}^{N}[K_e]$	Integrated matrix of stiffness, N/m
$[K_e]$	Stiffness matrix of elements (described in Element Library) (may include the stress stiffness matrix of the element, as detailed in Stress Stiffening), N/m
$[M] = \sum_{m=1}^{N}[M_e]$	The whole mass matrix, kg
$[M_e]$	Distribution of elemental masses matrix (described in Derivation of Structural Matrices), kg
N	Number of elements
$\{u\}$	Displacement vector at a node, m

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