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Modeling and Finite Element Evaluation of a Composite Blade for a Small-Scale Horizontal Axis Wind Turbine

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ABSTRACT

Growing environmental concerns such as global warming and ozone layer depletion have accelerated the global shift toward renewable energy sources, with wind energy being a significant contributor. A wind turbine functions by converting the kinetic energy of wind into mechanical energy, and subsequently into electrical energy. The primary components of a wind turbine include the tower, rotor blades, hub, gear assembly, generator, braking system, pitch, and yaw control mechanisms.

Among these, the rotor blade is a critical element as it endures dynamic loads during operation. Hence, its design, manufacturing, and maintenance demand careful attention. Traditionally, mechanical systems are tested before deployment; however, the advancement of computer-aided engineering tools has enabled efficient virtual testing, reducing the need for physical prototypes. This approach saves both development time and cost.

In the present study, a small-scale horizontal axis wind turbine blade is modeled using Pro/ENGINEER (Pro-E) 5.0, and a finite element stress analysis is conducted using ANSYS Workbench 14.5. The analysis aims to evaluate the structural integrity of the blade under operational loads and to identify regions vulnerable to stress concentration or failure. Results indicate that the blade tip experiences maximum stress and directional deformation, highlighting the need to maintain an adequate clearance between the blade and the tower.

Keywords: *Wind Energy, Rotor Blade, Finite Element Analysis, Pro-E, ANSYS Workbench, Structural Integrity, Renewable Energy*

1. INTRODUCTION

Wind energy is a renewable energy source that transforms the kinetic energy of moving air into practical forms such as electrical energy, mechanical power, or propulsion, depending on its intended use. For instance, wind turbines are employed to generate electricity, windmills perform mechanical tasks, wind pumps aid in water lifting or drainage, and sails utilize wind to propel marine vessels.

The primary technology used for harnessing this form of energy is the wind turbine. A conventional wind turbine comprises a foundation, a tower, and a nacelle or hub connected to multiple rotor blades (as shown in Figure 1). In the widely used three-bladed horizontal-axis wind turbine (HAWT) configuration, the blades are spaced evenly at 120 degrees and rotate around a horizontal axis.

Wind turbines are broadly divided into lift-type and drag-type categories based on the aerodynamic principle they utilize. Lift-type turbines, which rely on the lift generated by blade profiles, are significantly more efficient than their drag-based counterparts and are therefore more prevalent in commercial installations. Among these, HAWTs are favored due to their superior performance and efficiency, making them a central subject in research and development efforts.

A critical factor in wind turbine performance is the airfoil, which represents the blade's cross-sectional shape (refer to Figure 2). The camber line—located midway between the blade's upper and lower surfaces—defines the curvature and form of the airfoil. The airfoil design process begins with sketching the camber line, after which thickness is symmetrically applied perpendicular to this line to complete the shape. The chord line, which connects the leading edge and trailing edge, determines the length of the airfoil.

The leading edge is the rounded front portion of the blade that first interacts with incoming air and usually has the highest curvature. The trailing edge is the sharp end where airflow separates (as shown in Figure 3). In practice, wind turbine blades use a series of airfoils along their span to optimize aerodynamic efficiency. The pitch angle adjusts the entire blade's orientation to control the angle of attack, while the twist refers to the gradual variation in blade angle along its length, allowing for optimal performance under different flow conditions

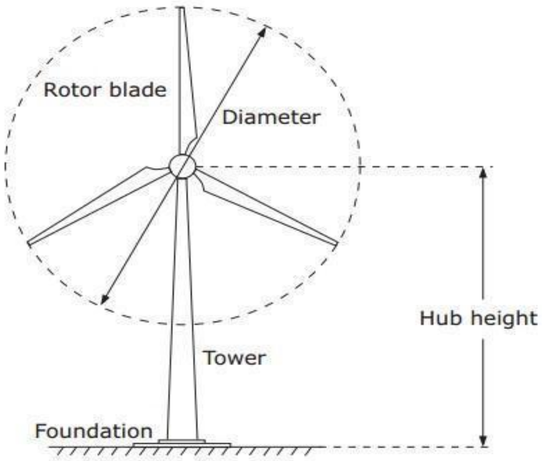

Fig.1. Wind turbine nomenclature [6]

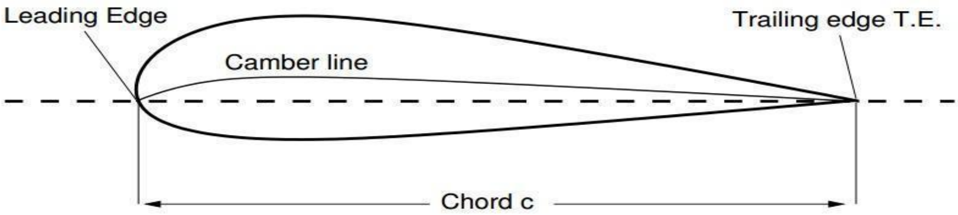

Fig.2 Air foil Nomenclature [3]

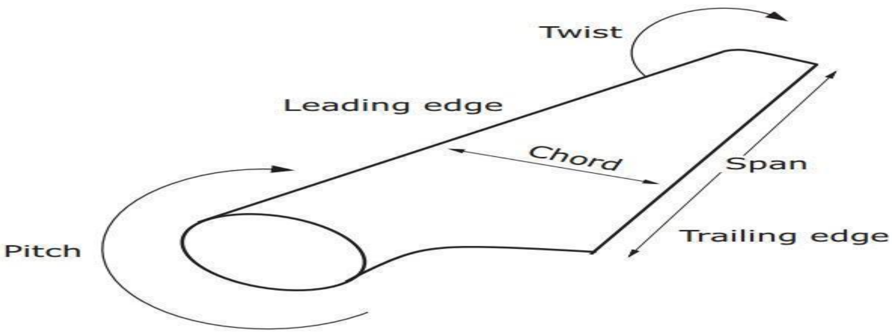

Fig.3 Blade nomenclature [6]

2. METHOD & MATERIALS

In this study, the tangential force acting on the wind turbine blade was initially computed using the Blade Element Momentum (BEM) theory. Following the force analysis, a 3D blade model was developed in Pro/ENGINEER (Pro-E) utilizing the coordinates of the NACA 2412 airfoil profile.

2.1 Estimation of Thrust Force Using Blade Element Momentum (BEM) Theory

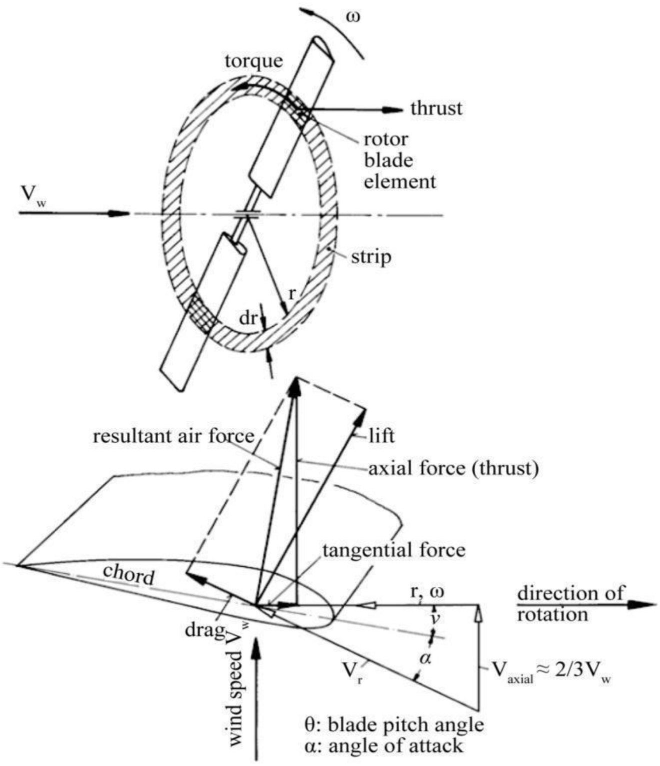

Figure 4: Representation of Aerodynamic Forces Acting on a Wind Turbine Blade [5]

As outlined by Kulunk E. [1], the expressions for moment and tangential forces are applied to determine the aerodynamic loading on wind turbine blades. The equations are as follows:

Moment Force:

$dF_m = dL\cdot\sin(\alpha + \theta) - dD\cdot\cos(\alpha + \theta)$Tangential Force:

$dF_x = dL\cdot\cos(\alpha + \theta) + dD\cdot\sin(\alpha + \theta)$

Where:

dL is the differential lift force and is given by:

dL = (C_L·ρ·W²·dA)/2

dD is the differential drag force and is given by:

dD = (C_D·ρ·W²·dA)/2

(α + θ) is the inflow angle (*i*)

tan(i) = V_{axial} / *u*, where *u* = ω·r (tangential velocity)

Using the above expressions, the tangential force was calculated individually for 16 discrete blade elements and summed to obtain the total force. The resultant tangential force was found to be approximately 390 N, which significantly contributes to the stress distribution within the rotor blade.

2.2 Solid Modelling

The 3D virtual model of the wind turbine rotor blade was created using Pro/ENGINEER (Pro-E) 5.0, as illustrated in Figure 5. The essential geometric and material parameters used for the design are listed below:

Blade Length**:** 2500 mm

To ensure low inertia and high durability, the blade must be both lightweight and structurally robust. E-glass fibre-reinforced composite material is selected to meet these requirements due to its favorable mechanical properties, which are detailed in Table 1.

Properties	Value	Unit
Compressive strength	4000-5000	MPa
Tensile strength	1950-2050	MPa
Young’s modulus	72-85	GPa
Bulk modulus	43-50	GPa
Shear modulus	30-36	GPa
Poisson ratio	0.2	(unitless)
Density	2.58	g/cm3
Hardness	3000-6000	MPa

Table 1. The mechanical properties of E-glass fibre [11]

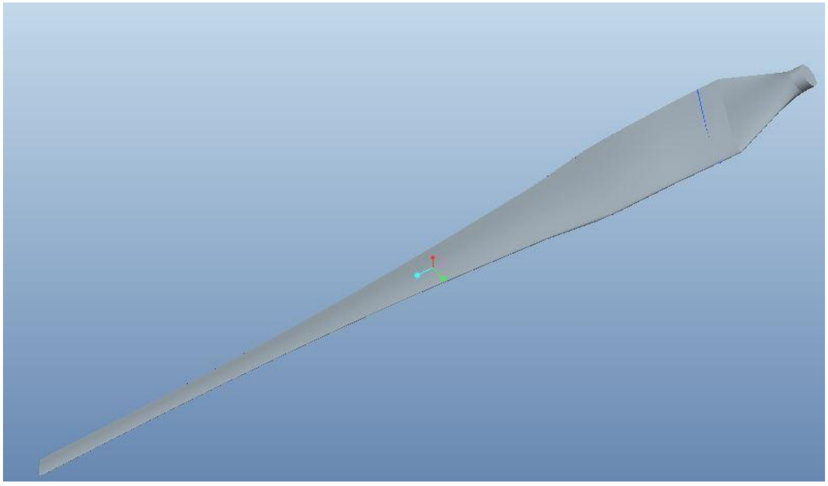

Fig.5 modelling of wind turbine blade

2.3 Stress Analysis:

The wind turbine rotor blade was analyzed and simulated using ANSYS software to evaluate the stress distribution across its structure. The blade was modeled as a cantilever beam, with one end fixed and the tip left free. The previously calculated tangential load was applied to the lower surface of the blade to assess its structural response under operating conditions.

As shown in **Figure 6**, the maximum stress experienced by the wind blade remains well below the material’s elastic limit, indicating that the blade can safely withstand operational loads.

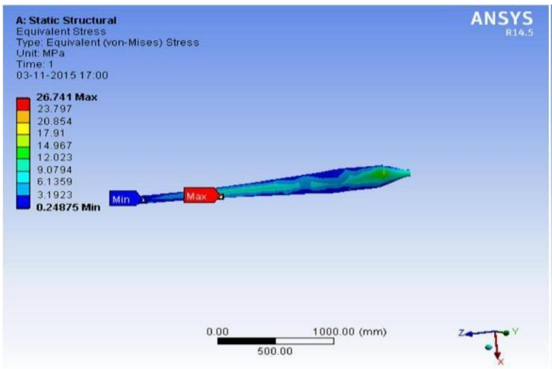

Fig.6 Distribution of Equivalent

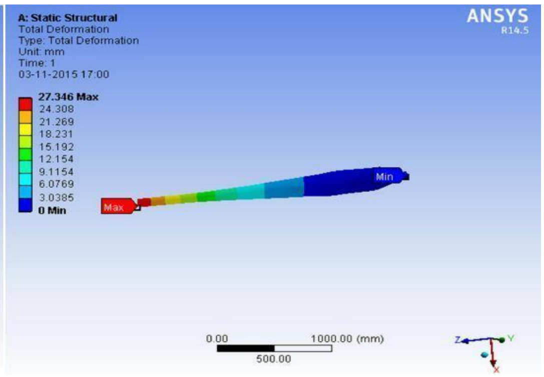

Fig.7 Total deformation

(Von-Misses) stress

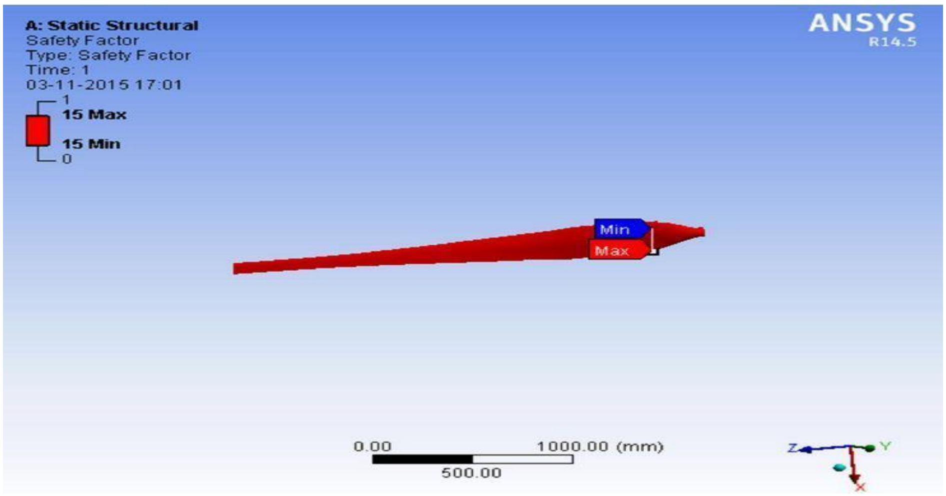

Fig.8 Safety factor

The wind turbine blade was designed and analyzed to verify its durability during operation. Finite Element Analysis performed using ANSYS Workbench 14.5 showed that the greatest deflection occurs at the blade tip, measuring 27.346 mm (refer to Figure 7). This displacement is significantly less than the available clearance between the blade tip and the tower, ensuring no risk of collision during use. Furthermore, Figure 8 illustrates that the blade has a factor of safety of 15, meaning it can safely endure loads fifteen times higher than the expected operational loads without failure.

3. CONCLUSION

Based on the results, the choice of blade material should consider factors such as weight, stress resistance, and tip deflection. Epoxy carbon fiber emerges as the most suitable material due to its combination of low deflection and light weight. Additionally, composites like epoxy carbon and epoxy-s-glass offer excellent resistance to harsh weather conditions, making them particularly advantageous for offshore wind turbines that operate in highly humid and corrosive environments. This durability reduces maintenance requirements and lowers associated costs. Although epoxy carbon is more expensive than epoxy-s-glass, its superior stiffness helps minimize tip deflection. On the other hand, aluminum alloy provides good stress resistance but is heavier than the composites, necessitating stronger bearings, hubs, and towers, along with additional protection against environmental corrosion. Overall, composite materials are becoming the preferred choice for wind turbine blades and pose strong competition to traditional metals and alloys.

Nomenclature

W= Relative wind speed (m/s)

ρ = Air density (taken as 1.21 kg/m^3)

α = Angle of attack (degree)

θ = Pitch angle (degree)

C_L = Coefficient of Lift

C_D = Coefficient of Drag

dA = Lower surface area of strip

u = Linear velocity of blade element (m/s)

ω = Angular velocity (rad/sec)

r = Radius (m) of the rotor

V_{axial} = (2/3) of Free wind velocity

V = Free wind velocity (taken as 15 m/s

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