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Fabrication And Modal Analysis Of Wind Turbine Rotor Blade

C.Suresh[1], Dr.L.Balasubramanyam[2],G. Shoukath Vali[3], C. Vamsi[4], C .Manoj Kumar[5],

[1]Assistant Professor, [2]Professor & Head of Department of Mechanical Engineering, PVKK Institute of Technology, Anantapur, India-51001

[3,4,5,] Student, Department of Mechanical Engineering, PVKK Institute of Technology, Anantapur, India-51001

ABSTRACT

Wind energy has emerged as one of the most promising sources of renewable energy, with wind turbine rotor blades serving as a critical component in converting wind into mechanical power. The performance, durability, and efficiency of these blades significantly influence the overall output of the turbine. This project focuses on the fabrication and modal analysis of a wind turbine rotor blade to evaluate its dynamic behaviour under operational conditions. The fabrication process involves the use of lightweight, high-strength composite materials such as, GFRP, CFRP, epoxy, polyester, graphene, and MWCNT. These materials are selected for their excellent mechanical properties, including high stiffness-to-weight ratios and resistance to environmental degradation. Fabrication is carried out using techniques like hand lay-up and vacuum bagging, ensuring precise layering and proper curing to achieve the desired blade shape and structural integrity. Following fabrication, modal analysis is performed to study the blade's vibrational characteristics. This analysis identifies the natural frequencies and mode shapes of the rotor blade, which are essential for understanding its dynamic response to external excitations like wind gusts and mechanical vibrations. Finite Element Analysis (FEA) tools are used to create a detailed model of the blade, and boundary conditions are applied to simulate real-world mounting scenarios. Understanding the modal behaviour is crucial to prevent resonance, which can lead to structural failure or reduced operational life. The results from the modal analysis provide valuable insights for optimizing blade design, enhancing reliability, and ensuring safe and efficient turbine operation. This project demonstrates the integration of advanced manufacturing and analytical techniques to improve the design and functionality of wind turbine rotor blades, supporting the continued growth of clean energy technologies.

KEY WORDS : Wind Turbine Blade,NACA 63415, Modal Analysis, Deformation , Solid Works .

1. Introduction

Composite materials are engineered materials composed of two or more constituent materials with significantly different physical or chemical properties. They are widely used in various industries, including aerospace, automotive, and renewable energy, due to their superior strength-to-weight ratio, durability, and resistance to environmental degradation. Composite materials are engineered materials made by combining two or more distinct components to achieve superior properties [1]. Unlike traditional materials such as metals or plastics, composites offer high strength, low weight, corrosion resistance, and design flexibility, making them ideal for structural applications in aerospace, wind energy, automotive, and marine industries [4,6,2].

Composite materials have been used for thousands of years, evolving from natural materials to advanced engineered composites used in modern industries. The development of composites has been driven by the need for stronger, lighter, and more durable materials for construction, transportation, aerospace, and energy applications.

Composite materials can be categorized based on their matrix phase into several types. Polymer matrix composites (PMCs) are the most commonly used and include fiber-reinforced polymers (FRPs) such as glass fiber-reinforced polymer (GFRP) and carbon fiber-reinforced polymer (CFRP). These materials offer a good balance of strength, weight, and cost-effectiveness. Metal matrix composites (MMCs) consist of metal matrices reinforced with ceramic or metal fibers, providing improved strength and high-temperature performance. Ceramic matrix composites (CMCs), on the other hand, feature ceramic matrices combined with ceramic fiber reinforcements, which significantly enhance their thermal resistance and structural integrity under extreme conditions. A specialized class of PMCs, hybrid composites incorporate multiple types of fibers, such as a combination of carbon and glass fibers, to optimize and balance various mechanical properties for specific engineering applications. Figure 1.1 shows the classification of the composite materials.

Wind turbine blades require materials that provide high strength-to-weight ratios, resistance to environmental degradation, and improved fatigue life. Traditional materials such as pure glass fiber-reinforced composites are commonly used, but hybrid composites can offer superior mechanical properties. Studies have shown that combining carbon and glass fibers in a polymer matrix can enhance the overall mechanical performance of wind turbine blades, reducing weight while maintaining or improving structural integrity [4,2,3,5,6].

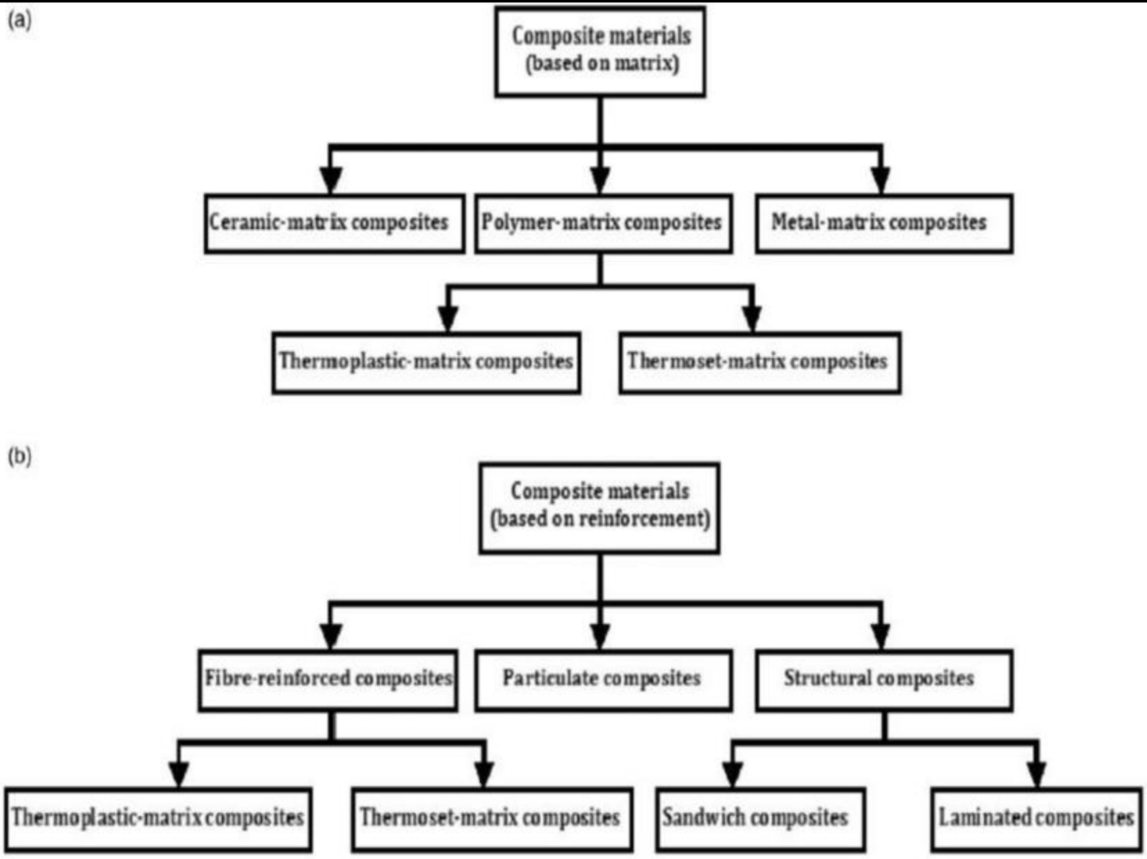


Fig.1.1: Classification of Composite materials

2. Literature review

Research and development in renewable energy, particularly wind and solar, has increased significantly due to the global energy crisis and environmental concerns [G.B.M. VijayBabu, CH Hemanth, K Ramakrishna, P Rakesh Kumar, M. MouliKumar (2023) [1], Sudarshan T, Bhavya , Manjesh B, Kavithanjan K , Akash Krishna R (2022) [4]]. A key focus is the development of hybrid systems that combine wind and solar power to generate energy efficiently for various applications [G.B.M. VijayBabu, CH Hemanth, K Ramakrishna, P Rakesh Kumar, M. MouliKumar (2023) [1], Sudarshan T, Bhavya , Manjesh B, Kavithanjan K , Akash Krishna R (2022) [4]]. The design and materials of wind turbine blades are a major area of study, with research exploring advanced materials like composites reinforced with nanomaterials and carbon nanotubes to achieve low weight, high strength, fatigue resistance, and stiffness [Lijin Thomas ,M. Ramachandra (2023) [2], Sri Sai P. Reddy , Rohan. Suresh (2021) [7]]. Aerodynamic design and structural analysis using CFD and FEM are crucial for optimizing blade profiles [Snehil Kumar M (2023) [3]]. Cost-effectiveness is also a priority, with investigations into materials like bamboo fiber reinforced with recycled plastic, which offer both economic and environmental advantages [Sudarshan T, Bhavya , Manjesh B, Kavithanjan K , Akash Krishna R (2022) [4], P. Y. Andoh,C. K. K. Sekyere, G. K. K. Ayetor, M. N. Sackey(2021) [8]]. Different turbine configurations are being examined, including VAWTs for urban settings [G.B.M. VijayBabu, CH Hemanth, K Ramakrishna, P Rakesh Kumar, M. MouliKumar (2023) [1], Manoj Kumar Shanmugam, B. Melvin, D. Anish, A. Rajiv (2022) [5]], multirotor windmills for increased efficiency [Vanitha V, Sabarish D, Sudhan G, Tharani N, Varunya V (2020) [9]], and bladeless wind turbines as a novel approach [N. Sai Charan, A. Sai Vasudev (2022) [6]]. Overall, current research endeavors to advance wind turbine technology through material innovation, design optimization, and configuration diversification to meet the growing global demand for renewable energy. Overall, current research endeavors to advance wind turbine technology through material innovation, design optimization, and configuration diversification to meet the growing global demand for renewable energy K. P.M.Y.V.Dathu, R. Hariharan (2020) [10] .

3. Composite Fabrication Process

3.1 Introduction

Many a times the fabrication is being misunderstood. Fabrication is the one of the Manufacturing process in which an item is made (fabricated) from raw or semi- finished materials instead of being assembled from ready-made components or parts. In electronics it carries a different meaning, which states that different electronic components are assembled to make a device.

3.2 Composite Fabrication process

There is different fabrication process available for the fabrication of composite materials. Among them the best feasible ones are selected according to its applications. Some of the fabrication process is discussed briefly below.

3.2.1 Wet/Hand Lay-Up

The fibers are first put in place in the mould. The fibers can be in the form of woven, knitted, stitched or bonded fabrics. Then the resin is impregnated. The impregnation of resin is done by using rollers, brushes or a nip-roller type impregnator. The impregnation helps in forcing the resin inside the fabric. The laminates fabricated by this process are then cured under standard atmospheric conditions.

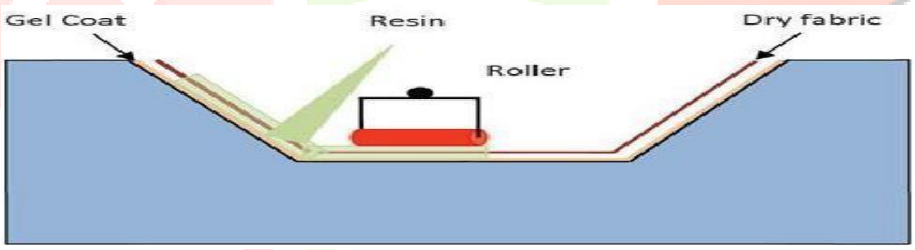


Fig 3.1: wet layup process

The materials that can be used have, in general, no restrictions. One can use combination of resins like epoxy, polyester, vinylester, phenolic and any fiber material.

- It discusses how fabrication is a manufacturing process where items are made from raw or semi-finished materials, rather than being assembled from ready-made parts.
- The chapter outlines several composite fabrication processes, with a focus on the wet/hand lay-up method.
- The wet/hand lay-up process involves placing fibers in a mold and impregnating them with resin using tools like rollers or brushes.

The document further details the materials used in the fabrication process, including:

- Resins (like Polymer 31-441)
- Fiberglass
- Various other components like styrene monomer, hardener, cobalt accelerator, toner, lowilite, and durawax.

The steps involved in the fabrication of a wind turbine blade are also explained, starting from mold preparation to the final finishing processes.

4. MODELLING

Computational Details

The global focus on clean and renewable energy has intensified the need for efficient wind turbine systems. Rotor blade design is a critical aspect of wind turbine performance. The blade must offer optimal aerodynamic characteristics while maintaining structural integrity under dynamic loading. Computer-aided design (CAD) tools, particularly SolidWorks, have transformed the design process by enabling precise and parametric 3D modelling. This paper details the complete modelling workflow of a rotor blade using the NACA 63415 air foil and SolidWorks software.

4.1 Software Tool: SolidWorks

SolidWorks, developed by Dassault Systems, is an advanced CAD and CAE software used across industries for design and simulation. Its capabilities relevant to this study include:

- 3D Modelling: Precision modelling of complex shapes.
- Parametric Design: Easy modification of geometry using constraints.
- Simulation Integration: Compatibility with FEA tools.
- Lofting & Surfacing: Ideal for aerodynamic designs.
- File Interoperability: Supports various formats (.IGES, .STEP, .DXF).

4.2 Methodology: Rotor Blade Design Steps

4.2.1 Reference Plane Creation*

To represent the changing cross-sections of the blade, reference planes were created at designated distances from the root (e.g., 0, 100, 175, 237 mm, etc.) using the *Features → Reference Geometry → Plane* function in SolidWorks.

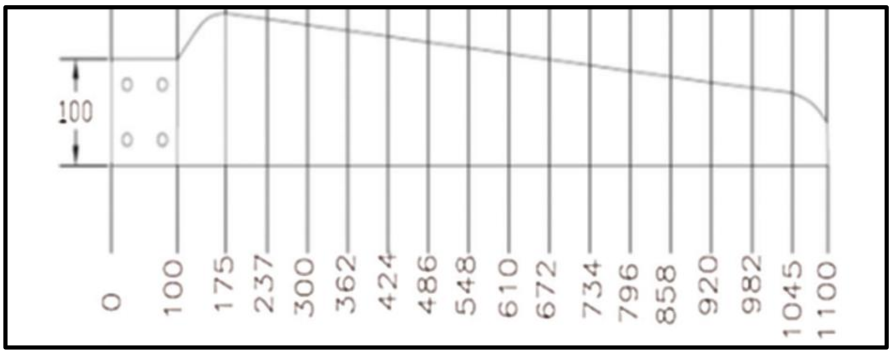


Fig : 4.1 Reference balde

4.2.3 Lofted Blade Generation

Multiple air foil profiles were aligned across the reference planes and lofted using the Lofted Boss/Base feature to create the blade geometry. Scaling and positioning ensured aerodynamic accuracy.

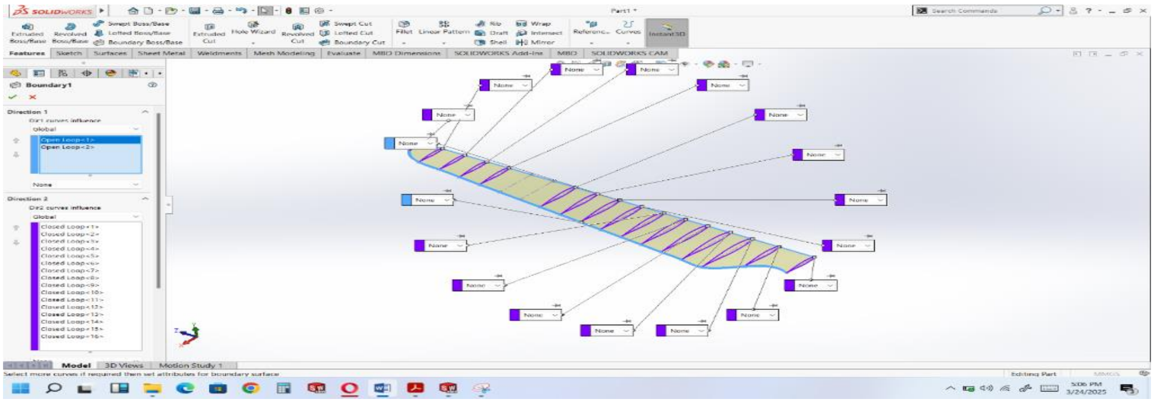


Fig 4.2: Section of Air Foil

4.2.4 Structural Detailing

- The blade body was hollowed to reduce weight using *Shell* features.
- UV hard foam bars were embedded between the internal walls for additional reinforcement.
- Cut-Extrude was used to simulate drilling and other machining operations.
- Fillets and Chamfers were added to smoothen edges and reduce stress concentrations.

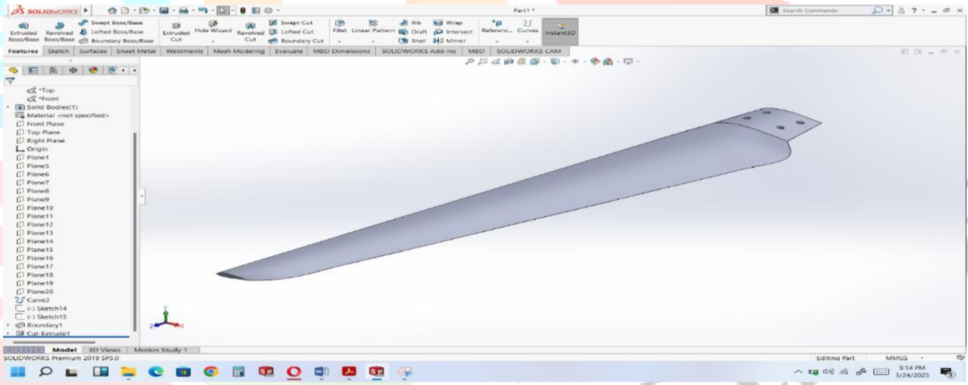


Fig 4.3: View of the Blade

5. ANSYS MODELLING

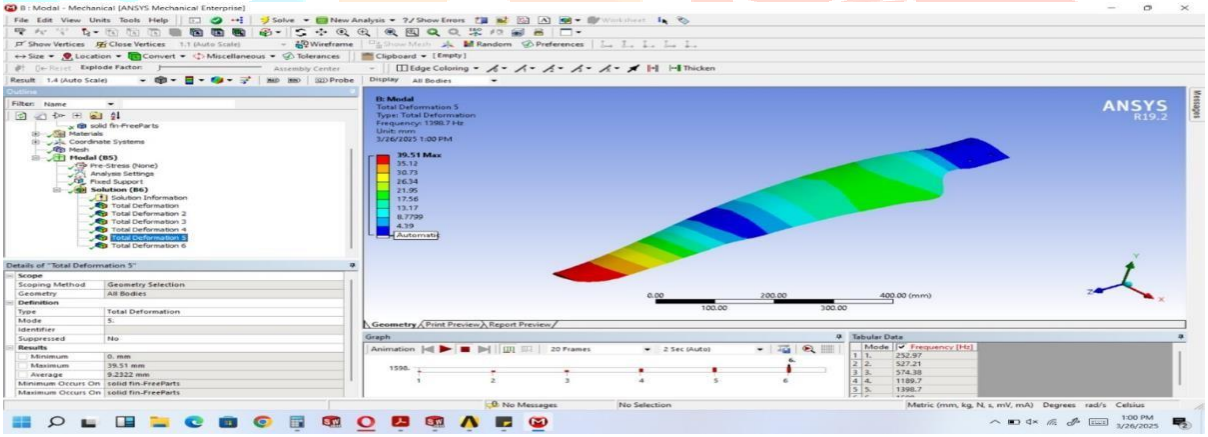
ANSYS Modelling," provides details on using ANSYS software to model and analyze wind turbine rotor blades. Here are the important points covered in this chapter:

- Introduction to ANSYS Software Modelling: The chapter starts with an overview of ANSYS software and its application in modeling wind turbine rotor blades.
- Modal Analysis of Composite Materials: A significant focus is on the modal analysis of different composite materials used for the blades. This analysis helps in understanding the vibrational characteristics of the blades.
- Material Combinations: The chapter details the modeling process for various material combinations, including:

- GFRP with polyester and graphene fillers
- GFRP with epoxy and graphene fillers
- GFRP with epoxy and MWCNT
- GFRP with polyester and CFRP
- GFRP with polyester and MWCNT
- UV hard foam

- Modeling Process: For each material combination, the chapter explains the steps involved in the modeling process:
    - Mesh generation
    - Applying boundary conditions
    - Interpreting the results of the modal analysis

In summary, Chapter 5 provides a comprehensive guide on how to use ANSYS to model wind turbine



rotor blades made of different composite materials and how to perform modal analysis to understand their dynamic behavior.

Fig 5.1 : Deformation of blade

RESULT AND CONCULSION :

RESULT:

Table 6.1 : : Deformation Response of Materials at Specific Frequencies

S.no	Material Names	Frequency (HZ)	Total Deformation (mm)

1	GFRP+ Polyester + Graphene Fillers	1459.8	67.417
2	UV Hard form	1290.8	198.75
3	GFRP+ Epoxy + Graphene Fillers	1524.7	69.467
4	GFRP+ Polyester + CFRP	1611.4	69.518
5	GFRP+ Epoxy + CFRP	1538.1	67.88
6	GFRP+ Polyester + MWCNT	1538.1	67.88
7	GFRP+ Epoxy + MWCNT	1557.2	68.724

CONCULSION :

The project Fabrication and Analysis of Wind Turbine Rotor Blade has successfully demonstrated and simulated to enhance the performance of wind turbine blades. The fabrication process involved the use of hybrid composite materials such as GFRP, CFRP, epoxy, polyester, and nano-fillers like graphene and MWCNTs, which significantly improved the mechanical properties and reduced the overall weight of the blade. Advanced fabrication techniques including hand lay-up and proper mold preparation ensured structural accuracy and durability. The fabricated blade was then analyzed using ANSYS 19.2 through modal analysis to study its vibrational characteristics under operational conditions. Different material configurations were evaluated, and the combination of GFRP + Epoxy + MWCNT yielded the highest natural frequency and lowest deformation, indicating better dynamic stability. The deformation pattern confirmed expected cantilever behavior, with the root fixed and the tip experiencing maximum displacement. The results validate the effectiveness of hybrid composites in wind energy applications, combining structural strength with lightweight construction. This study concludes that hybrid polymer composites, when fabricated and analyzed systematically, can significantly enhance blade performance. Future efforts will focus on experimentation of fabricated blades and has compared with the simulation results.

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