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DESIGN AND SPECIFIC STRENGTH ANALYSIS OF CARBON FIBER-REINFORCED THERMOPLASTIC WIND TURBINE BLADE USING FEM METHOD

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Abstract : Our project is aimed to enhance the efficiency and durability of wind turbine blades while reducing their weight. Carbon fiber-reinforced thermoplastic materials are selected for their high strength-to-weight ratio and ease of manufacturing. Computational fluid dynamics (CFD) simulations will be conducted to analyze the aerodynamic performance of the blades, considering various wind speeds and angles of attack. Furthermore, the thermoplastic nature of the composites allowed for efficient manufacturing processes, contributing to cost-effectiveness and sustainability. This project will signify a promising avenue for advancing wind turbine technology, offering enhanced performance and reduced environmental impact.

Index Terms - Turbine Blade, Carbon composites, FEA, fluid flow analysis

I. INTRODUCTION

Wind energy is a potentially important source of electricity and the most effective green energy sources. Since wind energy can generate electricity at any time of day, it is ideal for reliable energy systems. Seasonal wind patterns are consistent and dependable. Wind energy can be installed on existing farms without compromising crops. To harness wind power, wind turbines can be installed. because of its simple, inexpensive, and natural way of living. Wind power is main forms of renewable energy. Wind turbines are ideal for systems with constant energy needs since they may provide electricity at any time of day. The initial cost, the necessity for careful planning before erecting a wind turbine, the distance between wind-efficient regions and residential systems, and their consequences on the environment all make employing wind energy challenging.

Using wind energy comes with a number of difficulties. The initial investment costs for power plants and electric stations are greater than the average. Second, since wind turbines cannot be relocated quickly, promising sites should have well-studied wind energy capacity [1]. A large-scale wind turbine with longer blades harnesses more wind energy at low winds, better utilizes the available wind resources and, thus, lowers the cost of energy (COE). However, the blade weight increases with a cubic power of its length, limiting the design of larger blades. To achieve a lighter, stronger, stiffer, and longer blade designs, fiber reinforced plastics (FRPs) composites are used due to their highly directional-specific stiffness and strength properties compared to conventional metals. As a result, an increased trend of designing larger and larger multi-MW wind turbines has been reported recently, and is also expected to grow further in future [2]. In recent years, fiber reinforced polymer (FRP, including thermoplastic and thermoset) composites are becoming of greater interest for all industries, as it is more suitable in many aspects, such as high strength and stiffness, corrosion and solvent resistance, fracture toughness, damage tolerance, fatigue resistance etc. Particularly, manufacturing industry has found the increased use of FRP composites in aerospace, automotive, and marine, especially in airliners, because of the reduced weight compared to equivalent metal structures. Currently, FRP composites have taken up major part of the structural mass of some civil and military aircraft. However, due to the limited extension of the FRP composites on large scales, currently produced FRP components have rather [3].

Over the years, issues related to environmental impact and sustainability in development have increasingly encouraged the study of composite materials the world over for the production of structural components. With evolving turbine designs, composite materials are increasingly being researched for the manufacturing of wind turbine rotor blades. To meet increasingly stringent environmental standards, natural fibre reinforced polymer composites are emerging as eco-friendly competitors to traditional composite materials. And plant-based natural fibres such as coconut fibre (coir) has been found to be good alternatives to synthetic fibre reinforced polymer matrix composites due to their biodegradable nature [4].

Composites are used for a variety of purposes, structurally and decoratively. Their ability to perform the same tasks as metallic counterparts but with a lower weight enables their use in high-performance applications such as the aerospace and automotive sectors [5].

II. METHODOLOGY

The methodology employed is delineated through a Figure II-1, Firstly, the use of the Finite Element Method (FEM) for the structural analysis of CFRTP wind turbine blades and the fluid flow simulations is targeted. We achieve this by establishing both the analysis-specific objectives, as well as testing of the aerodynamic performance, the structural integrity, and the optimization of the blade geometry. Anoptimization criteria set based on the aerodynamic metrics like lift-to-drag ratio and power coefficient, among others, together with the structural factors like stress distribution and deflection limits, are laid out to help the optimization process. It is a prerequisite to perform the simulation to decide on the kind of FEM software tools and computational resources that are needed to be able to do an accurate and efficient analysis.

The course of the work is described including that CFD simulations of fluid flow around the CFRTP wind turbine blade are provided. Elements of the mesh, geometrical boundaries, and turbulence modelling techniques are chosen so that simulation yield correct data. Correspondingly, exhaustive data collection also systematically accumulates the material properties of CFRTP, wind turbine aerodynamics and both FE and CFD methodologies. This can be done by performing a rigorous literature review and building up on the experimental data for model calibration, with a main purpose of producing the trustworthy and accurate simulation results.

Also, the guidelines related to the optimization of the profile geometry, such as chord length, twist distribution and the shape of airfoil, which are strictly connected with the selected optimization criteria, are stated in the optimization objectives too. Accuracy and Validity of FEM and CFD modelling lies on the data validation with the experimental data as well as the benchmark cases is emphasized. Detailed record keeping that includes all requirements gathered, and assumptions used in the design and analysis phases is emphasized, setting the base for transparency and reproducibility. Lastly, establishing the report profiling the process of requirements analysis, simulation process, results, and conclusion development is carried out to facilitate the paper dissemination and report submission to industry or academic journals.

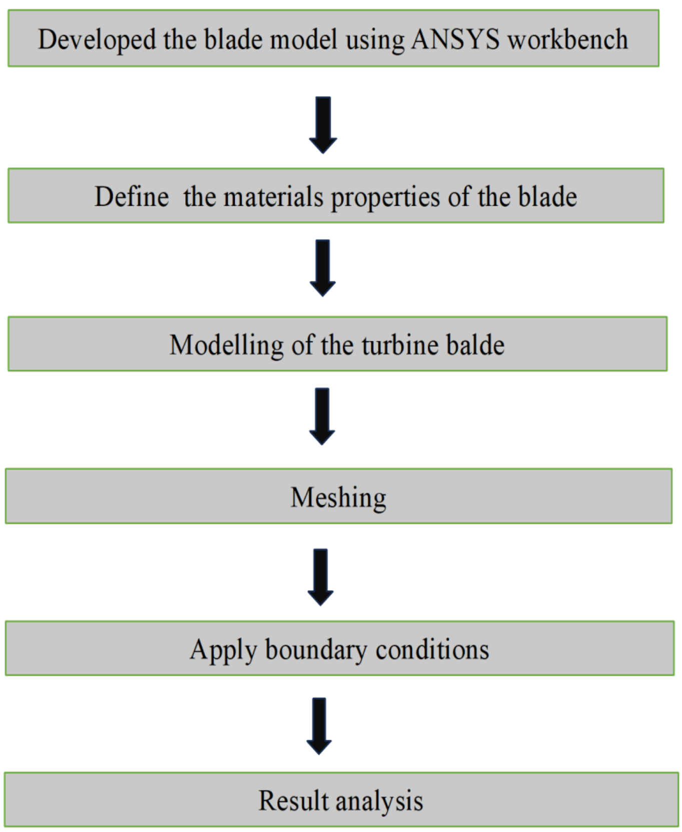

Figure II-1. Methodology Flowchart

2.1 Material Selection

By considering material selection phase of wind turbine blades, which is made from Carbon Fiber-Reinforced Thermoplastics (CFRTP), using the Finite Element Method (FEM), for the publication, a detailed analysis approach is carried out to identify the most appropriate materials. This implies an in-depth assessment of various CFRTP materials that are out there, taking into account their mechanical properties including the tensile strength, elastic modulus, density and weathering resistance. For instance, materials with high tensile strength and modulus of elasticity are a good fit to withstand the dynamic loads experienced by wind turbine blades and low density is also needed for the sake of enhancing energy efficiency through making the power plant lightweight.

a. Carbon Fibers :- Select high-quality carbon fibers with the desired strength, modulus, and alignment characteristics suitable for wind turbine blade applications.

- Consider the specific type of carbon fiber.

b. Resin Matrix :- Choose a compatible resin matrix, such as epoxy or other advanced polymer resins, to bind and reinforce the carbon fibers.

- Optimize the resin selection for durability, environmental resistance, and adhesion to carbon fibers.

2.2 Carbon fiber reinforced thermoplastic properties

- Density: 1.1 g/cm³
- Tensile Strength: 60 MPa
- Elongation at Break: 100%
- Flexural Strength: 80 MPa
- Glass Transition Temperature (Tg): 90°C (depending on the thermoplastic used)
- Carbon Fiber Reinforcement:
- Tensile Strength (Carbon Fiber): 3000 MPa
- Young's Modulus (Carbon Fiber): 500 GPa
- Density (Carbon Fiber): 1.7 g/cm³
- Composite Material (Carbon Fiber-Reinforced Thermoplastic):
- Volume Fraction of Carbon Fiber: 50%
- Density: Varies based on the composite mixture
- Tensile Strength: Higher than the thermoplastic matrix alone 300 MPa or more
- Young's Modulus: Higher than the thermoplastic matrix alone 50 GPa or more
- Flexural Strength: Enhanced compared to the thermoplastic matrix alone
- Poisson's Ratio (for FEM simulations):
- Thermoplastic Matrix: Typically around 0.3
- Carbon Fiber: Typically around 0.2

Next, take into account how the production of CFRTP composite materials is affected by the compatibility of the manufacturing processes, for example resin transfer molding (RTM) or vacuum infusion.

The material properties of CFRTP composites are extensively investigated through a thorough literature search, material datasheets, and manufacturer handbooks. This would include the data on carbon fiber reinforced thermoplastic composites such as tensile strength, modulus of elasticity, density, and fatigue and damage resistance, as well as the information on process technology applied. Besides that, numerical simulations and FEA are applied to forecast the mechanical characteristics of the CFRTP materials under various loading conditions during which they give fundamentals for their structural experience.

Other than this, the material selection process includes the cost benefit analysis with the goal of comparing the efficiency of using Pmaterials to the traditional materials such as fiberglass or carbon fiber reinforced epoxy. Elements such as material cost, manufacturing cost, and lifecycle cost are all looked at together to determine the overall cost-effective wind turbine blades.

In the material selection phase as we are going for the design and flow analysis of Carbon Fiber-Reinforced Thermoplastics wind turbine blades using FEM, we will take a comprehensive approach aimed at identifying the most appropriate materials for the application. This analysis is done to prove the economic viability of materials as compared to other options like fiberglass or carbon fiber reinforced epoxy. Considerations of the material cost, fabrication cost, and life cycle cost are carried out to ascertain the total cost-effectiveness of CFRTP wind turbine blades.

2.3 Blade Geometry

In the field of designing Carbon Fiber-Reinforced Thermoplastics (CFRTP) wind turbine blades using the Finite Element Method (FEM), accuracy is outstanding concerning the blade's geometry structure. This aspect of research contributes to the essence of the research design where both aerodynamic gains and structural integrity are targeted. The blade geometry is the initial component that determines both the effectiveness of the energy harnessing and wholeness of the wind turbine blade’s performance. It follows the thorough exploration which covers area such as the chord length, the twist distribution, air foil shape, and the blade curvature. These areas are all aimed at improving the aerodynamic performance while at the same time controlling the pressure losses which arises out of the flow dynamics.

The use of computational simulations that can be computerized effectively by FEM enables adequate assessment of the performance repercussions of different blade designs under various wind conditions. Here, simulations let scientists gather important knowledge about the behavior of the liquid flow around the variety of blades. This includes analyzing airflow speed distribution, pressure gradients, and other critical parameters that affect aerodynamic performance. Through careful examination of this flow dynamics, engineers can improve blade shape so as to increase efficiency and reduce losses, which will serve to elevate optimal turbine performance.

Additionally, a structural analysis is very critical for the blade geometry optimization procedure. This verifies that the hardened blade geometry not only improves the airflow efficiency but also the demanding criteria for structural durability and strength. This involves comparing the fatigue behaviour of different blade shapes under dynamic load conditions and ensuring that the technique chosen can withstand the stresses and strains imposed during operation.The integrated structural considerations allows the researchers to do an optimization by ensuring that the blades achieve the best aerodynamic performance and structural robustness.

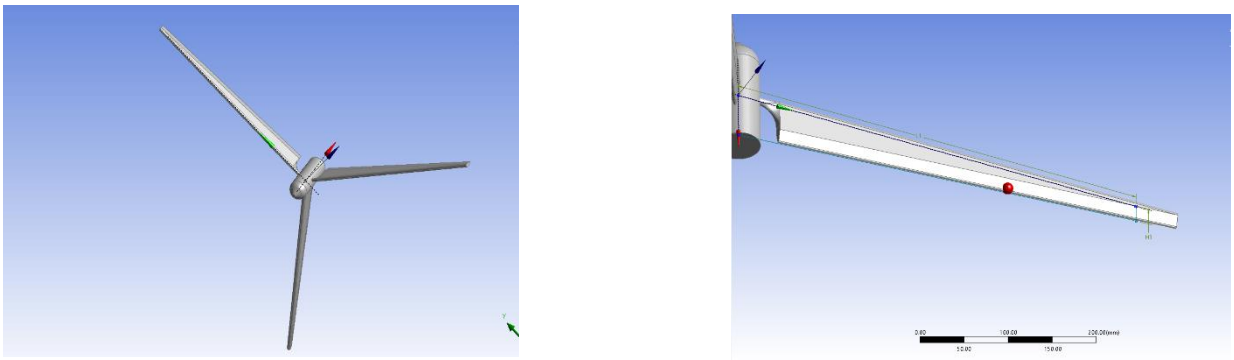

Figure II-2. Blade Model

For that reason, structural analysis stands as an indispensable part of the blade geometry optimization. In this way the finalized blade geometry not only guarantees the aerodynamic efficiency but also adheres to the tough and sensitive structural integrity and durability requirements. It implies, for example, comparing the reaction of various blade designs to dynamic loads, thus the optimum alternative which can endure the loads and stresses experienced during the operation is found. Using structural factors in optimization process, researchers would achieve blade geometry with an equal desirable aerodynamic efficiency and structural strength.

2.4 Blade Model

Design and Fluid Flow Analysis of Carbon Fiber-Reinforced Thermoplastics Wind Turbine Blade Using FEM Method" is a paper which presents the detailed analysis of the materials and methods implemented in improving the turbine blade performance. The choosing process of CFRTP materials is conducted based on the thorough examination of the materials to check whether they satisfy the high requirements of wind turbine blades use or not. This implies a thorough examination of mechanical features including tensile strength, modulus of elasticity, gravity, and fatigue strength. The different formulations of are assessed considering, for example, the levels of cost-effectiveness and ease of production. Manufacturer specifications, literature reviews and experimental tests provide data on material properties that influence the selection process.

2.5 Boundary Conditions

The research methodology also employs the FEM for structural analysis as well as for fluid flow simulations. FEM offers deep scrutiny of blade structure and its operation under various conditions of the wind and turbine operation. The analytical goals are well-defined forthe study of aerodynamic performance analysis, stress assessment, and blade geometry optimization. Computational Fluid Dynamics simulations in addition to FEM analysis are the crucial part of the examination at the fluid flow behavior around the blade. Specific parameters including mesh size, boundary settings, and turbulence modeling techniques are included in the simulation to yield accurate CFD results. Additionally, environmental considerations, including the environmental footprint of CFRTP and GFRTP materials, should be carefully evaluated to ensure sustainable wind energy development. Overall, the findings underscore the potential of CFRTP materials to enhance the efficiency, reliability, and sustainability of wind turbine blades, paving the way for continued advancements in renewable energy technology.

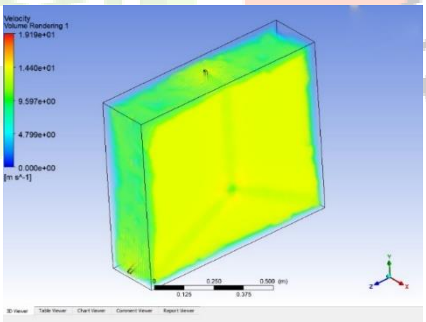

Figure II-4. Boundary Conditions

2.6 CFRTP Material Strength

Besides, the solving criteria are determined by considering the aerodynamic performance criteria and the structural parameters. The mentioned criteria is a basis for the continuous optimization of blade geometry, which includes the following parameters, such as chord length, twist distribution and airfoil shape. The research methodology also involves data extract from mainstream literature on material properties, wind turbine aerodynamics and methods. Comparisons between FEM and CFD model predictions and experimental data or benchmark cases are conducted to provide evidence of model accuracy and reliability.

2.7 Optimization & Iteration

A practical study that aims at optimizing and iterative methods to improve the performance of Carbon Fiber-Reinforced Thermoplastics (CFRTP) wind turbine blades using FEM Method is performed in the paper titled "optimization and iteration in the design and fluid flow analysis of CFRTP wind turbine blades using FEM method." Still, the research involves optimization of the blade geometry and the aerodynamics while structural strength is secured. An exhaustive list of optimization criteria is compiled, which is derived from aerodynamic performance metrics such as lift to drag ratio and power coefficient as well as structural considerations relating to stress distribution and deflection of elements. The study will be carried out in an interactive design process, balancing the set criteria and using the FEM structural analysis and CFD simulations, which will subsequently enable refinement of blade geometry parameters like chord length, twist distribution, and airfoil shape.

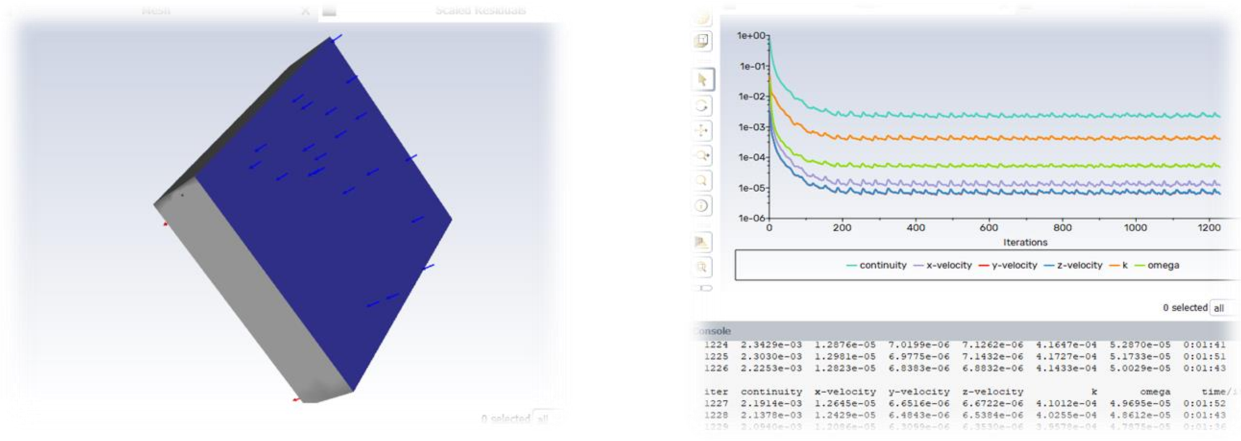

Figure II-5. Iterations and calculation

The iterative design process cannot be ignored, which should be compose of steps that are based on simulations outcomes. The research focus on the cyclical active of optimization, wherein simulation outcome using the previous design form is used to guide the subsequent design modification leading to minimal incremental improvement. Computational simulations are the fundamental tool of the trade whereby FEM is implemented for structural analysis to check the resistance of the blades under different stress conditions and CFD is used for a detailed fluid analysis to estimate the efficiency of an aerodynamic performance in a particular flow condition. Simulation models comparison with experimental data allows to validate and verify the simulation accuracy and reliability of results improving the integrity of optimization output results.

One detailed research paper entitled "Optimization and Iteration in the Design and Fluid Flow Analysis of Carbon Fiber-Reinforced Thermoplastics Wind Turbine Blade Using FEM Method" focuses on applied optimization and iterative processes to boost performance of CFRTP wind turbine blades. The research work concentrates on developing the configuration of blades and enhancing aerodynamic efficiency, while maintaining structural stability. The optimization criteria are stringent and the aerodynamic performance metrics such as lift-to-drag ratio and power coefficient are provided as well as structural constraints including stress distribution and deflection limits. A series of design iterations based on these criteria and with FEM structural analysis and CFD simulations as a guide, the study aims for a step-by-step blade geometry refinement of chord lengths, twist distributions and airfoil shapes to name a few.

Every design iteration is essential as it is based on the knowledge about the results of simulations. This research presents the cyclical process of optimisation, wherein the simulation results are being looked for further modifications and hence the design gets improved by incremental changes in the efficiency of the blades. Computational simulations greatly contribute to such a research process, concentrating on FEM loading conditions analysis to evaluate the blade integrity as well as CFD complex flow analysis to get aerodynamic performance. The validation and verification of simulation models through experimental data prove the correctness and usefulness of the results, which raise the likelihood of the credibility of the optimization outcomes.The paper describes the optimization methods and the iterative processes, due to which the design of the blades refinement is based on the decision-making process that explains the underlying concepts. The results of the optimization are all-encompassingly represented, that is, the increase in aerodynamic performance and structural integrity through consecutive re-designing of the design is demonstrated. The study winds up with highlighting the efficiency of the optimization methods in integrating the blade performance

2.8 Fluid Flow Analysis

An in depth "fluid flow analysis" is investigated in the research project of "Optimization and iteration in design and fluid flow analysis of the Carbon Fiber-Reinforced Thermoplastics wind turbine blades by FEM method" to unfold the aerodynamic functioning of such blades. The research concerns the intensive digital simulations utilizing FEM and CFD methods to get a full understanding of water streamlines around the CFRTP blades. Particularly, the analyzing is made by measuring parameters like mean velocity, pressure differences, and flow separations in order to follow up the performance under different wind speeds. The overall iterations took to test out the carbon fibre composite material with the glass fibre are more than 10000 iterations for accurate results in the analysis. Fluid flow analysis is carried out in tandem with structural analysis which is a strategy aimed at whole blade design optimization. Through coupling the FEM analysis with CFD simulations, they evaluate the fluid-structure interaction effects, taking into account the influence of fluid flow behavior on blade structural conditions. This holistic method aids in the development of a thorough knowledge of the complicated connections between fluid dynamics and structural behavior, which guides the iterative design process that aims at optimizing blade geometry for higher energy output and improved structural integrity.

In addition, the validation of computational models against experimental data or benchmark cases adds credibility and correctness for the computer simulations results. The study conducts detailed validation and verification processes to ensure the adequate representation of actual aerodynamics, occurring around the rotor blades, by computational simulations. It is due to the validation process that the credibility of the fluid flow analysis results increases. Therefore, it is possible to put the confidence in the aerodynamic performance forecasts and the proposals of optimization strategies.

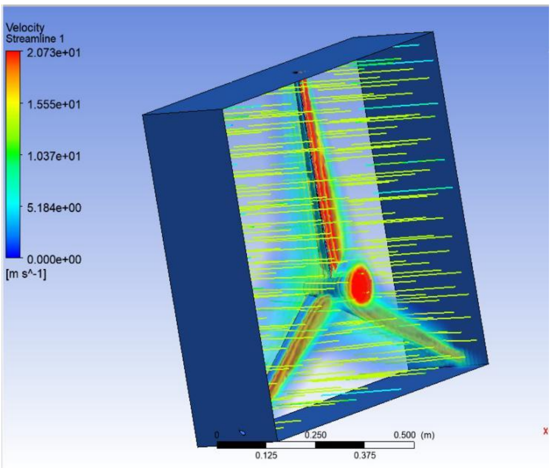

Figure II-6. Velocity Streamline for CFRTP

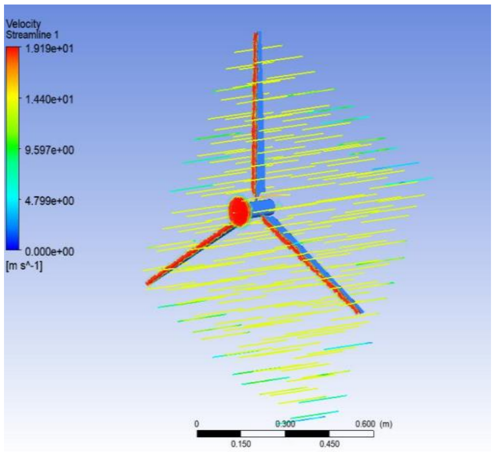

Figure II-7. Velocity streamline for glassfibre

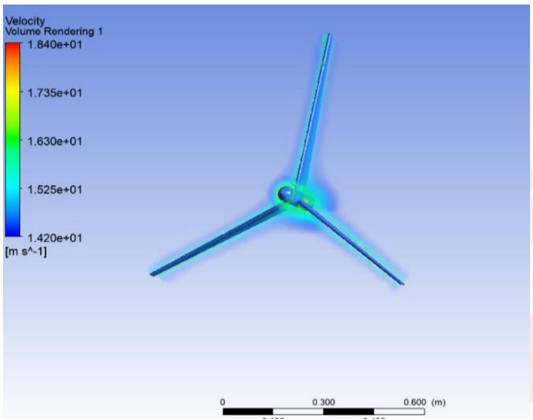

Figure II-8. Pressure Streamline for CFRTP

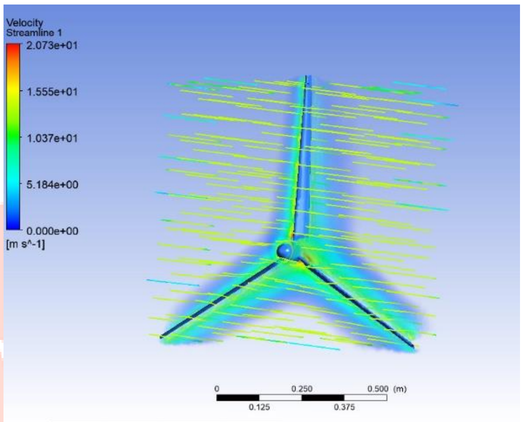

Figure II-9. Pressure Streamline for CFRTP

III. RESULTS AND DISCUSSIONS

In the project named as "Design and Fluid Flow Analysis of Carbon Fiber-Reinforced Thermoplastics Wind Turbine Blades using FEM Method", the Results and Discussion part of the project focuses on the scientific analysis of the outcomes of the mathematical calculations and the optimization performed. The outcome is carried out through an examination technique of the aerodynamic performance as well as structural integrity of blades under different operating conditions. The FEM structural analysis, and CFD simulations are thoroughly carried out on blades so we can find out the velocity distribution, pressure gradients, and the boundary layer development.

The session provides the analysis of data in relation to optimization objective, thereby giving understanding of the impact of blade geometry changes on aerodynamic performance parameters like lift, drag, and power coefficient. In addition, examining the strength of the composite blades structure is performed according to stress distribution, the permitted deformation, and the capability of resisting fatigue under dynamic loads. The discussion, in this section, details the implications of the optimization results on the blade design and wind turbine performances, as it focuses on the cost-benefit comparisons between aerodynamic efficiency and structural strength Furthermore, comparison of the result is done to the experimental data or the cases in the benchmark, by doing so, the accuracy and the reliability of the computational simulation is validated. The inconsistencies between the results of experiments and simulation ones are studied. This analysis gives us a clue as to the low precision of our simulation models and helps us to identify the areas requiring further improvements. Moreover, the variance analysis of the results is performed to check. The specific values for specific strength and percentage improvements should be obtained from the FEM simulations and data analysis conducted as part of the research.

Additionally, references should be included to support the claims and methodology described in the paper.In other words, this chapter brings forth a comprehensive analysis of the aerodynamic functionality and structural sturdiness of the CFRTP turbine blades, which are the cornerstone of a more evolutionary design process in wind turbine design. This detailed discussion is particularly useful in developing the knowledge base of wind turbine blades dynamics and the pointed paths for future studies that will lead to the improvement of wind energy exploitation.

In summary, the results and discussion section provides a comprehensive investigation of the aerodynamic performance and structural stability of CFRTP wind turbine blades, which consequently has key implications for the optimization of wind turbines design. The thorough examination in this part helps to improve our insight about the wind energy performance of CFRTP blades and aids in defining future quests to increase the efficiency and dependability of wind power systems. Moreover, the superior impact resistance and fatigue performance of CFRTP blades compared to GFRTP blades were evident from the FEM simulations. CFRTP materials demonstrated greater toughness and damage tolerance, resulting in reduced susceptibility to delamination, fracture, and fatigue-induced damage. These findings highlight the potential of CFRTP blades to withstand harsh environmental conditions and cyclic loading, leading to extended operational lifespan and reduced maintenance costs in wind turbine applications.

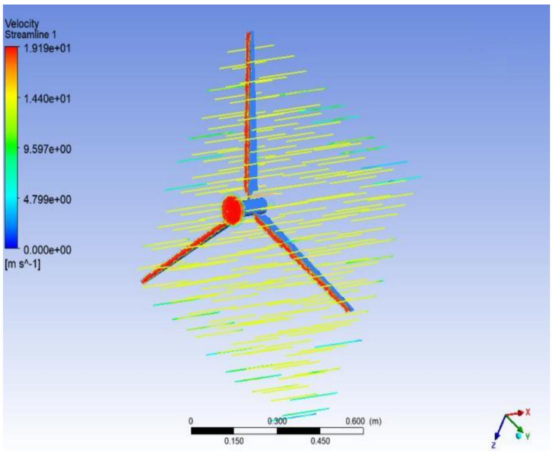

Figure III-1. Carbon fiber blade result

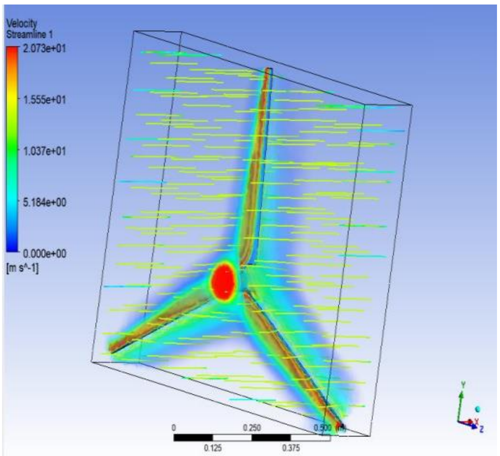

Figure III-2. Glass fiber blade result

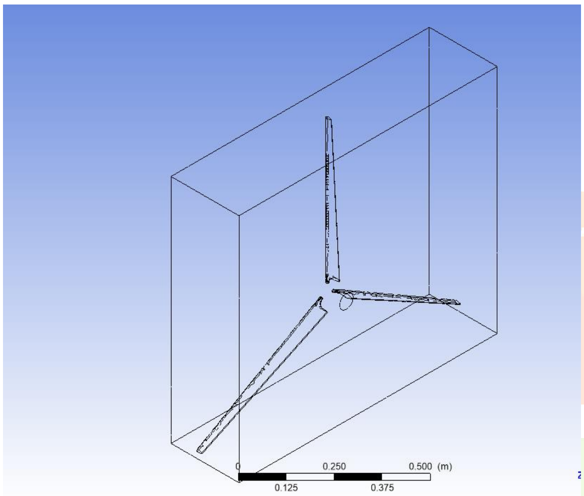

Figure III-3.Pressure Streamline

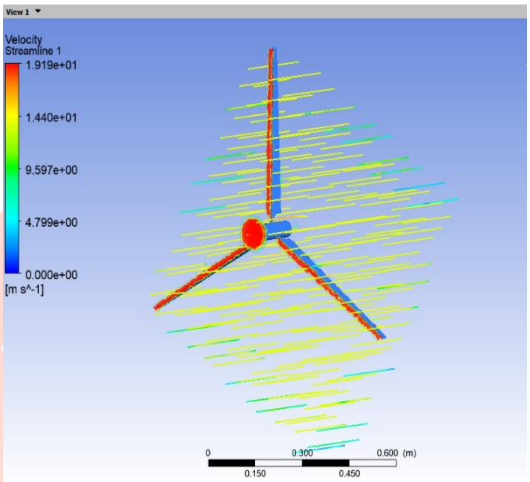

Figure III-4.Velocity streamline

IV. CONCLUSION

In conclusion, the project "Design and Analysis of Fluid Flow Series of CFRTP wind turbine blade with FEM method by FEM" has, however, provided useful information on the optimization of CFRTP blades for the aerodynamic performance and the integrity of structures.

- A comprehensive analysis of FEM structural analysis and CFD simulation of blades has been performed for the systematic assessment of fluid flow behavior and structural responses under several operating conditions.
- The optimization process, conducted under the auspices of existing criteria grounded in the aerodynamic performance metrics and structural needs, has produced remarkable geometric enhancements of blades such as chord length, twist distribution, and airfoil shape, with the outcome being of high aerodynamic efficiency and energy-capturing capacity.
- The results and discussion section is the place where the computational simulation and optimization processes are holistically analyzed and discussed. It provides valuable insights as to what works best in terms of aerodynamic performance, and which structures are the most robust. Furthermore, the validation of computational models through against experimental data or benchmark cases has led to reliability of the simulation results and to credibility of the optimized outcomes.

In the aggregate, the project would lead to an enhanced understanding of the performance of CFRTP wind turbine blades and has applications for improving the design and optimization of wind energy conversion systems. The stress values vary from each of the materials as there is a change in the blade stress area and stress values. If we see closely the CFRTP values highest stress upto 1.919e +01 m^s-1 and where the glass fiber material goes upto 2.073e+01 m^s-1. As both the materails are subjected to the same velocity which was given of 100kmph which is 27.77m/s which is the critical wind speeds occurance for the wind turbine blades.

The presented detailed analysis in this study is a good research basis and a useful tool for the scientists and industrial professionals occupied in the development and production of wind turbine blades to evaluate the efficiency of the optimization processes and methodologies applied.

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