Dandao Xuebao/Journal of Ballistics
ISSN: 1004-499X
Vol. 37 No. 1 (2025)

Improved Aero Blade Design for Multi-Disciplinary Integration in Wind Turbines

Shubham Bhimrao Bangar[1], Dr. Kuldip. A. Patil[2], Dr. Vaishali S. Phalake[3], Rutuja Rajendra Manukar[4]
[1] MTech Student, Bharati Vidyapeeth Deemed University College of Engineering, Pune
[2]Associate professor, Bharati Vidyapeeth Deemed University College of Engineering, Pune
[3]Bharati Vidyapeeth Jawaharlal Nehru, Institute of technology
[4]JSPM's Rajarshi Shahu college of engineering Pune

Abstract

The increasing demand for renewable energy has placed wind power at the forefront of global efforts to reduce carbon emissions. This study investigates the integration of aerodynamic and structural analysis in the design of wind turbine blades, emphasizing the optimization of both aspects to improve performance and reduce costs. Using CATIA for design and ANSYS for simulation, the research follows a multi-step approach, starting from initial blade geometry creation and progressing through aerodynamic and structural simulations. The results indicate significant improvements in both aerodynamic efficiency and structural integrity. CFD analysis enhances airflow performance, while structural simulations ensure the blade's resilience under operational loads. The final optimization step successfully balances aerodynamic efficiency, structural integrity, and weight reduction. The study highlights the importance of multi-disciplinary design, where high-fidelity modeling and optimization lead to more efficient and durable wind turbine blades. The findings demonstrate that an integrated design approach can improve torque, reduce mass, and ensure the longevity of wind turbine blades, supporting the growing need for sustainable and cost-effective wind energy solutions.

Keywords: *Wind turbine blades, aerodynamic optimization, structural analysis, multi-disciplinary design, CFD simulation.*

I. INTRODUCTION

Climate change and the need to cut greenhouse gas emissions have made wind energy a more important clean, renewable energy source in the global energy mix. Wind turbines transform wind energy into electricity, minimizing fossil fuel use. Countries throughout the globe have invested extensively in large-scale onshore and offshore wind farms, making wind power one of the fastest-growing energy sources [1]. The worldwide wind energy industry has grown significantly due to technology advances, government incentives, and environmental consciousness. Wind energy generates a large share of power in many nations, especially in windy locations. Wind power contributed for 9% of worldwide electricity generation in 2020, with Denmark, Spain, and Germany producing most of their energy from wind. Meeting climate goals and decreasing carbon emissions requires this wind energy revolution. Wind power relies on wind turbines, and its efficiency determines its practicality and usefulness [2] [1]. Optimizing wind turbine performance involves maximizing energy extraction, minimizing expenses, and assuring long-term dependability and durability. Wind turbines are complex equipment that transform wind energy into electricity [3]. Wind turbines have rotor blades, hubs, nacelles, gearboxes, and generators. Rotor blades spin around a hub due to wind energy. From the gearbox, the generator converts this rotating motion into energy. Atop a tall tower, the nacelle holds the gearbox, generator, and turbine control center [4]. Modern wind turbines absorb more wind energy due to material and design advances that allow for bigger rotor diameters and hub heights. Wind turbines are essential to clean, sustainable power production as renewable energy sources grow more relevant in the low-carbon transition [5].

Figure 1. Wind Turbines

1.1 Basic components and working principles.

Wind turbines are complex structures designed to convert kinetic energy from the wind into electrical power, and their efficiency and reliability depend heavily on their foundational stability [6]. The basic components of a wind turbine include the rotor blades, nacelle, tower, and foundation. The rotor blades capture wind energy and convert it into rotational motion. This motion is transferred to the nacelle, which houses the generator and gearbox, converting the mechanical energy into electrical energy [7]. The tower elevates the nacelle and blades to optimal heights where wind speeds are higher and more consistent. The foundation anchors the turbine to the ground, ensuring stability and safety, especially under dynamic wind loads [8].

1.2 Advancements in wind turbine technology.

Advancements in wind turbine technology have significantly improved their efficiency and durability. Modern turbines feature larger blades and taller towers, which capture more wind energy and generate higher outputs [9]. Innovations such as variable-speed generators, advanced control systems, and improved materials have enhanced performance and reliability. Additionally, floating foundations and new anchoring techniques have expanded the potential for offshore wind farms, where wind conditions are often more favorable. These advancements necessitate rigorous investigation into how dynamic wind loads affect turbine foundations, as the increased size and offshore deployment introduce new stresses and challenges [10]. Ensuring the integrity of these foundations is crucial for the continued growth and success of wind energy technology [11].

II. LITERATURE REVIEW

This chapter reviews research on wind turbine blade design, focusing on integrating aerodynamic and structural analysis. It discusses optimization methods, challenges in multi-disciplinary design, and the importance of high-fidelity modeling to improve performance, reduce costs, and enhance efficiency. Ali Akbar Firoozi (2024) This study explores advancements in wind turbine blade technology, focusing on innovative materials, aerodynamic designs, and sustainable practices. It highlights the impact of composite materials, case studies of major projects, and the importance of regulatory frameworks in driving technological advancements. McGugan, Malcolm et.al (2025) This research presents the MARE-WINT program, focusing on reliability, maintenance, and multi-body fluid-structure interaction models for wind turbine blade design. It explores trends, issues, and the development of “smarter” blades that address these challenges. Marco Mangano et.al (2023) This study presents an aero structural framework integrating CFD and CSM for wind turbine optimization. A gradient-based optimization approach is used, achieving significant improvements in torque (up to 14%) and mass reduction (up to 27%) for optimized rotor designs.

Sagidolla Batay et.al (2023) This research focuses on aero-structural optimization to improve wind turbine blade performance. The optimization increases torque by 6.78% and reduces mass by 4.22%, showing the effectiveness of the method in enhancing performance while maintaining structural integrity. Marco Mangano et.al (2023) This study explores high-fidelity optimization of wind turbine rotors using a coupled aero structural model. The results demonstrate up to 14% increase in torque and up to 27% reduction in mass, showcasing the benefits of tightly-coupled optimization. Lei Xi, Lihua Zhao et.al (2022) This paper investigates wind turbine blade design, using NACA airfoil elements and Qblade software to optimize wind energy utilization. It highlights how blade optimization improves energy efficiency and ensures root strength, particularly for larger-capacity turbines. S. Selvan Nambi et.al (2018) This study explores wind turbine design, focusing on the dynamic conditions and power generation at various wind speeds. It addresses structural sensitivity to centrifugal force and provides solutions for managing torque at high wind speeds.

Pietro Bortolotti et.al (2015) This paper presents a holistic optimization approach for wind turbines, integrating rotor diameter, tower height, and component sizing. It reduces the cost of energy by considering aerodynamic and structural interdependencies, with applications in both onshore and offshore turbines. Peter J. Schubel et.al (2012) This study reviews wind turbine blade design, focusing on efficiency, aerodynamic principles, and blade load analysis. It emphasizes horizontal axis rotors, detailing aerodynamic design principles, including plan shape, airfoil selection, and optimal attack angles. F. Campagnolo et.al (2012) This paper discusses multi-disciplinary design optimization for wind turbines using high-fidelity aeroservo-elastic models. The procedure alternates between aerodynamic and structural optimization to reduce computational costs, demonstrated on multi-MW wind turbines and scaled wind tunnel models. C.L. Bottasso et.al (2009) This study presents multi-disciplinary optimization techniques for wind turbines, using high-fidelity aero-servo-elastic models. The optimization is based on global-local techniques to maximize/minimize performance indexes, implemented in a program used for industry wind turbine optimization.

III RESEARCH METHODOLOGY

This paper describes the approach used to examine and enhance wind turbine aerodynamic blade design. A systematic strategy was used to optimize wind turbine blades via multi-disciplinary integration. The chapter describes the tools and methods used from original design to simulation and optimization. CATIA, a CAD application, was used to create an early blade design for wind turbine blade geometric modelling. The design was subsequently analyses using ANSYS, a sophisticated finite element analysis and computational fluid dynamics software package, for aerodynamic and structural simulations. These simulations examined the blade's aerodynamic performance and structural integrity under different operating situations. Design optimization to balance aerodynamic efficiency, material strength, and fatigue resistance followed. The chapter also outlines the study flowchart, showing task relationships and sequencing. The research used this strategy to solve wind turbine blade design difficulties to ensure efficiency, structural safety, and durability. Aerodynamics, structural mechanics, and material science were used to produce a complete wind turbine blade performance solution. This chapter details the approaches and tools utilized to attain these aims.

This study used a flowchart to organize its steps. From conceptual wind turbine blade design to simulations to analysis and optimisation, the flowchart covered the essential steps. The flowchart was designed to enable a methodical approach to each activity and obvious multi-disciplinary design process links. Key stages in the approach were:

- Initial Concept Design
- CAD Modeling (using CATIA)
- Aerodynamic and Structural Simulation (using ANSYS)
- Data Analysis and Optimization
- Validation and Final Assessment

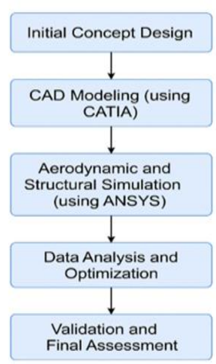

Figure 2. Flowchart

Objective:

To analyze and optimize the aerostructural performance of an improved wind turbine blade using Computational Fluid Dynamics (CFD) and Computational Structural Mechanics (CSM) in ANSYS. The goal is to balance aerodynamic efficiency, structural integrity, and weight reduction.

3.1 Material Properties

The structural analysis will be performed assuming composite materials commonly used in wind turbine blades, such as fiberglass and carbon fiber reinforced polymers (CFRP).

Property	Fiberglass (E-Glass/Epoxy)	Carbon Fiber (CFRP)

Density (kg/m³)	2000	1600
Young's Modulus (GPa)	35-50	100-120
Poisson's Ratio	0.3	0.28
Tensile Strength (MPa)	900	1500
Compressive Strength (MPa)	500	1200

The spar caps will be designed using carbon fiber for stiffness enhancement. The shear webs and skins will use fiberglass to balance cost and weight.

3.2 Blade Dimensions

The improved blade is based on the DTU 10MW turbine blade with modifications for performance enhancement.

Parameter	**Value**
Blade Length	89.15 m
Chord Length (Max)	4.7 m
Twist Distribution	Variable from 15° at root to 2° at tip
Airfoil Sections	DU, FFA-W3 Series
Tip Speed Ratio (TSR)	7.8
Rotor Diameter	178.3 m

3.3 Boundary Conditions for ANSYS

- Fixed Support: The root of the blade is completely fixed at the hub interface.
- Aerodynamic Load: Wind loads are applied as distributed pressure loads along the blade span based on CFD results.
- Gravitational Load: Consider gravity effects acting downward (9.81 m/s²).
- Rotational Speed: 9.6 RPM (from DTU 10MW wind turbine).
- Pre-bend and Pre-cone Effects: Included in geometry to improve load distribution.
- Aerodynamic Forces: Computed from CFD analysis using ANSYS Fluent or CFX.

3.4 Loading Conditions

- Steady Wind Speed: 8 m/s (below-rated condition, reference from DTU 10MW).
- Extreme Wind Load: 50-year gust wind speed at 50 m/s (IEC 61400).
- Operational RPM: Nominal 9.6 RPM.
- Tip Deflection Limit: Below 5% of rotor radius.
- Torque Constraint: The optimized blade should achieve at least 5% higher torque
- than the baseline.
- Thrust Limitation: Total thrust should not exceed a 14% increase over the baseline.

3.5 ANSYS Setup

Structural Analysis:

- Solver: Static Structural (ANSYS Mechanical)
- Mesh: Hexahedral dominant, fine mesh at spar caps and leading edge.
- Element Type: Shell elements for skins, solid elements for spars.
- Optimization: Size and topology optimization for mass reduction.

Aerodynamic Analysis (CFD):

- Solver: ANSYS Fluent (RANS-based CFD)
- Turbulence Model: Spalart-Allmaras / k-ω SST
- Mesh Type: Unstructured with finer mesh at leading and trailing edges.
- Boundary Conditions:
  - Inlet: Wind velocity at 8 m/s.
  - Outlet: Pressure outlet at 0 Pa gauge pressure.
  - Wall: No-slip condition on blade surface.
  - Tip Treatment: Slip wall or periodic boundary conditions for efficiency.

Optimization Goals:

- Minimize blade mass by up to 27% while maintaining or increasing torque.
- Increase aerodynamic efficiency by 14-15% through optimized twist-chord distributions.
- Improve structural integrity by ensuring maximum von Mises stress < allowable limits.
- Ensure tip deflection remains below the threshold to prevent tower strikes.

3.6 CATIA and ANSYS Modeling Tool

In this research, CATIA and ANSYS were selected as the primary tools for the design and simulation phases. CATIA was used for the computer-Aided Design (CAD) modeling of the wind turbine blades. The blade geometry was created with careful attention to aerodynamic considerations, material properties, and structural integrity. Once the design was finalized, the model was exported to ANSYS for simulation. ANSYS was used for both the aerodynamic and structural simulations. The aerodynamics of the wind turbine blade were analyzed using Computational Fluid Dynamics (CFD) simulations, while the structural analysis was carried out to assess the blade's strength under various operational conditions. Both tools were integrated for multi-disciplinary analysis, ensuring that the aerodynamic and structural designs complemented each other effectively.

3.7 Steps of Simulation

Step 1: Pre-processing and Geometry Creation

The blade geometry was designed in CATIA, including airfoil profiles, taper, twist, and variations from root to tip. It aimed to optimize aerodynamic performance while maintaining structural integrity. The geometry was then imported into ANSYS for simulation.

Step 2: Aerodynamic Analysis

A CFD analysis was conducted in ANSYS to assess airflow over the blade. This simulation considered different wind speeds, angles, and environmental conditions to determine aerodynamic forces, identifying areas for performance improvement.

Step 3: Structural Analysis

After aerodynamic simulations, the blade model underwent a structural analysis in ANSYS, examining stress distribution, deformation, and fatigue life under operational loads like wind, rotational speed, and gravity. It ensured the blade could endure long-term use without failure.

Step 4: Optimization

Optimization algorithms were applied to refine the blade design, maximizing aerodynamic efficiency, minimizing material usage, and ensuring structural integrity based on the results from aerodynamic and structural simulations.

Step 5: Post-processing and Data Analysis

Simulation results were analyzed to evaluate performance metrics such as lift-to-drag ratio, power output, and fatigue resistance. The analysis helped assess the design's effectiveness and identify further areas for improvement.

IV.RESULT AND DISCUSSION

4.1 CFD analysis of wind turbine

Step 1: 3D Modeling of the Wind Turbine Blade in CATIA V5

CATIA V5 is used to create a parametric 3D model of the wind turbine blade based on the given parameters.

1.1. Create Airfoil Sections

1. Open CATIA V5 and start a new Part Design.
2. Use Generative Shape Design to import the airfoil sections (DU, FFA-W3 series) for different sections of the blade.
    - Airfoil sections can be imported as DXF files or manually sketched using coordinate points.
    - Ensure smooth curves using Spline Tool.
3. Align airfoil sections along the span-wise direction from root to tip.

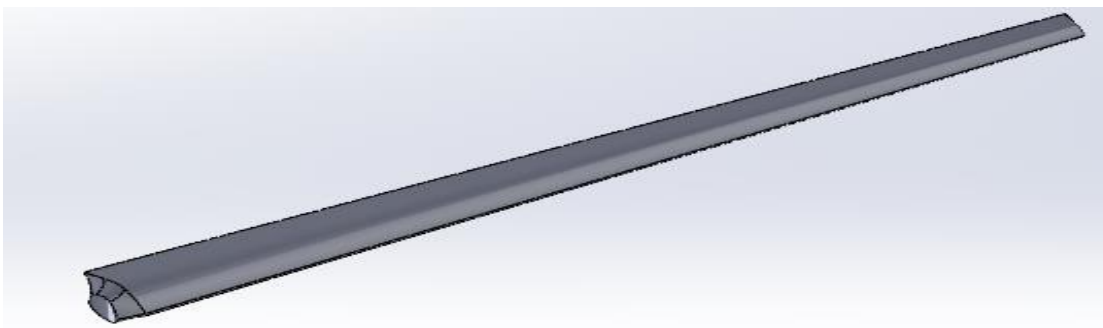

Figure 3. Single blade Cad Design

FEA analysis method

Once the 3D model is ready, import it into ANSYS Fluent, OpenFOAM, or Star-CCM+.

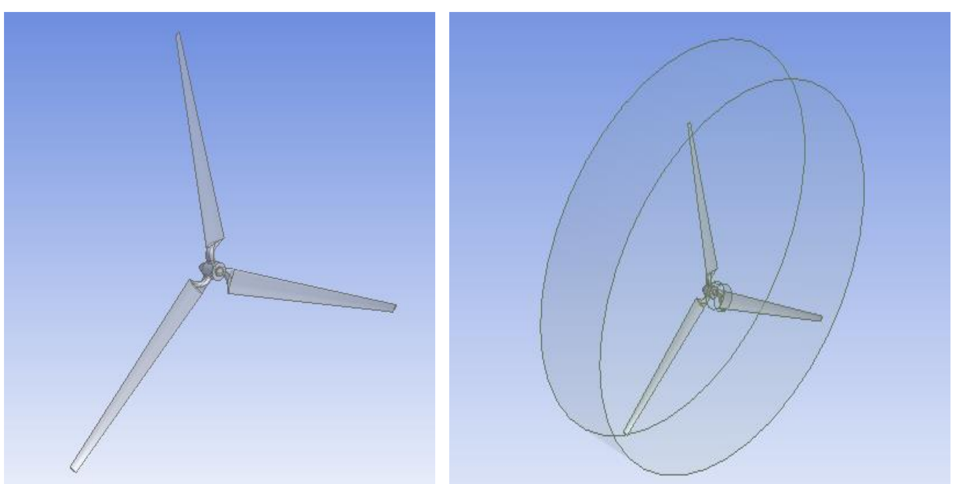

Figure 4. a) Importation of geometry into the design modeler of Ansys CFD module b) Creation of enclosure around the blade for environment preparation

Dandao Xuebao/Journal of Ballistics
ISSN: 1004-499X
Vol. 37 No. 1 (2025)

2.1. Domain Creation

1. Create a **cylindrical domain** (wind tunnel) for airflow simulation:

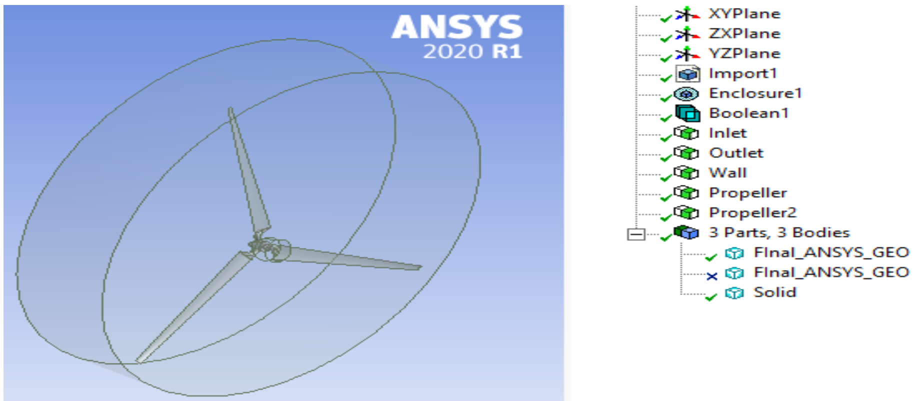

Figure 5. Create Named selection for applying and plotting boundaries and results

Solver Settings

4. Use **RANS (Reynolds-Averaged Navier-Stokes)** or **LES (Large Eddy Simulation)** for turbulence modeling.

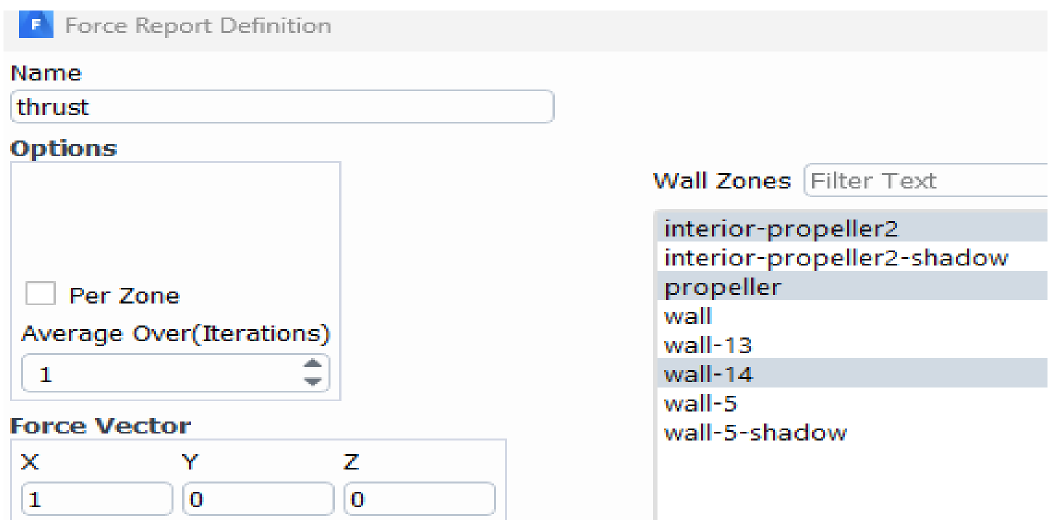

Figure 6. force report definition for power and torque and force

5. Apply **k-ω SST turbulence model** (accurate for rotating flows).

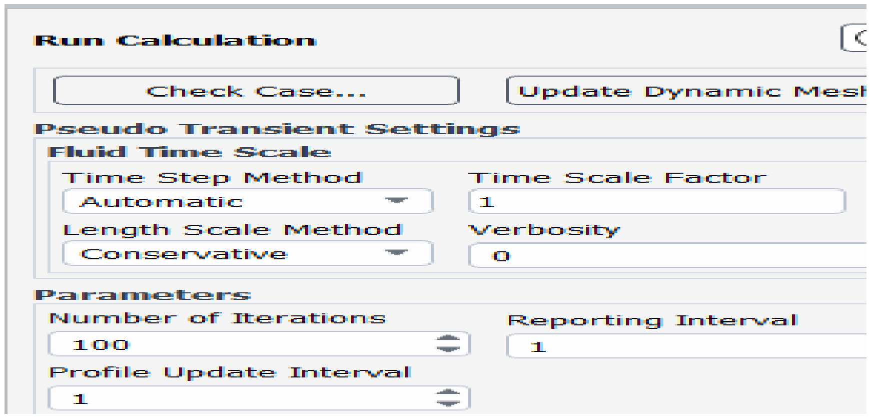

Figure 7. Number of iterations performed during solution

6. Define **Tip Speed Ratio (TSR)** = for rotor rotation.

2.5. Post-Processing

7. Analyze:

   - **Pressure distribution** on the blade.

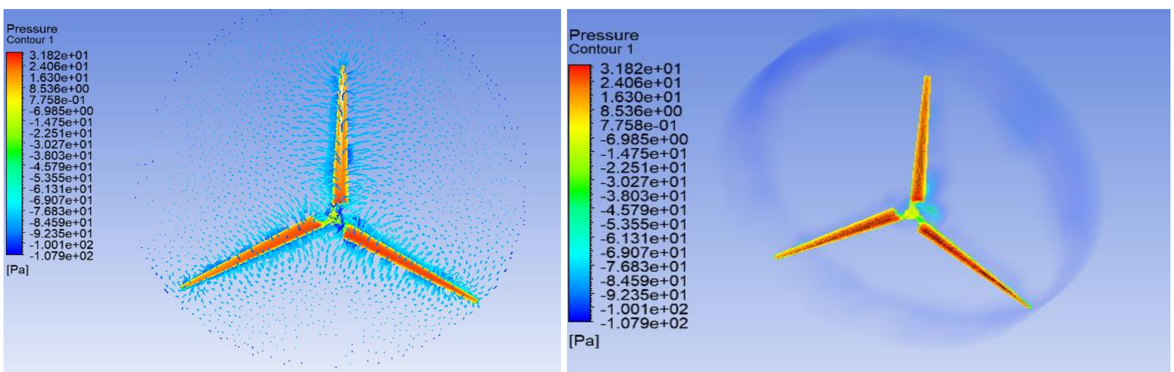

Figure 8. pressure results at 5m/sec air velocity

   - **Velocity streamlines** and vortex formation.

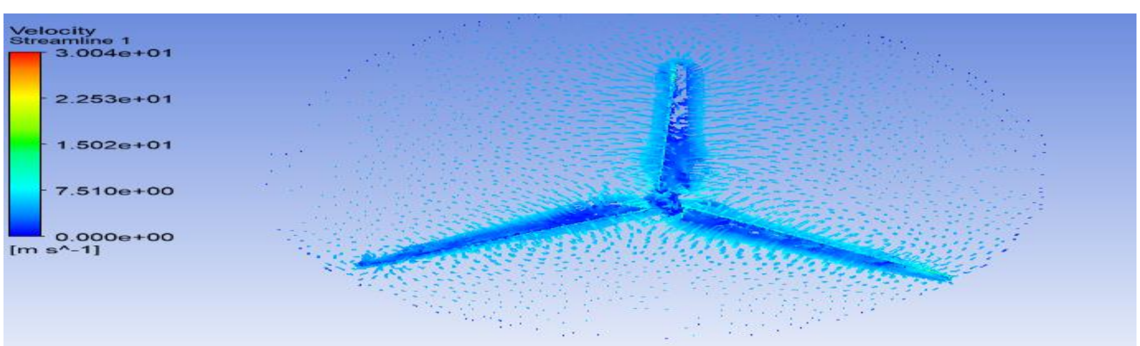

Figure 9. velocity profile around the turbine blades and air flow pattern

- **Torque and power output calculation**.

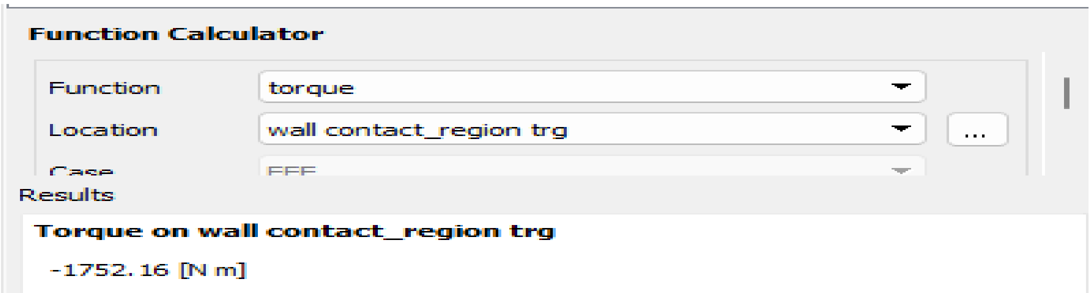

Figure 10. torque results at 5 m//sec air velocity and standard air blade design

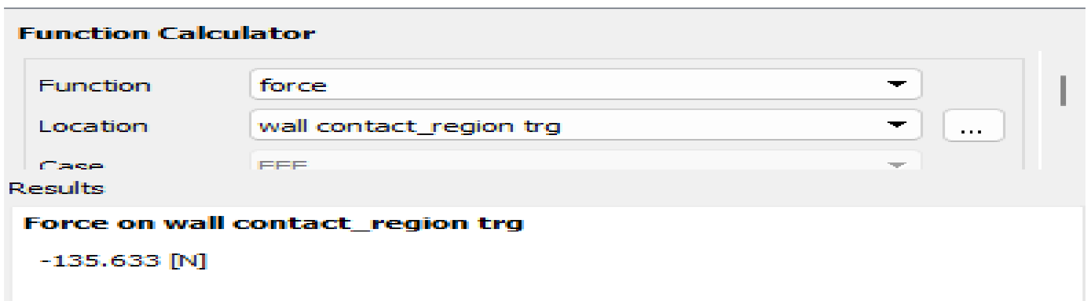

Figure 11. 135.633 N force at each blade

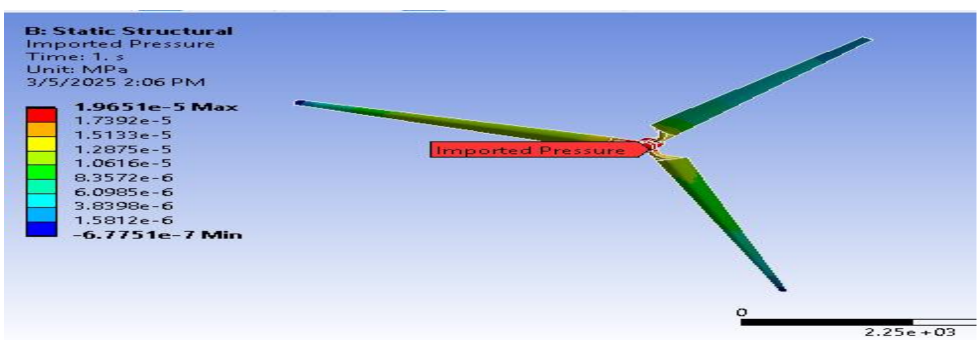

Figure 12. imported pressure

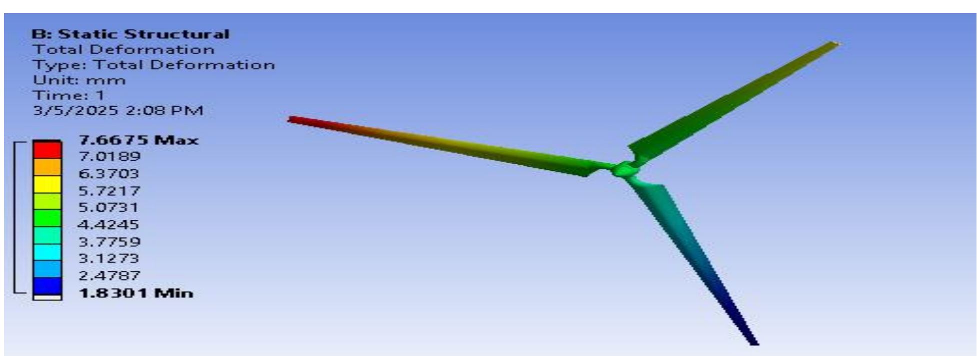

Figure 13. total deformation on applied boundary conditions

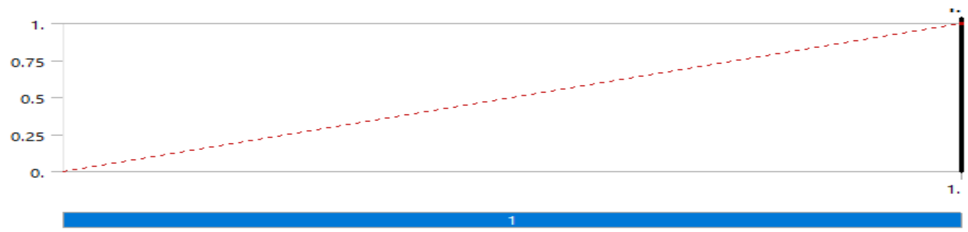

Figure 14. imported pressure on blade profile from CFD post process

Comparison of FRP & CFRP Properties

Property	**Fiberglass-Reinforced Polymer (FRP)**	**Carbon Fiber-Reinforced Polymer (CFRP)**
Density (g/cm³)	1.8 – 2.0	1.6 – 1.8
Tensile Strength (MPa)	300 – 900	600 – 3000
Young's Modulus (GPa)	20 – 50	125 – 300
Flexural Strength (MPa)	500 – 1500	800 – 2000
Fatigue Resistance	Good	Excellent
Weight	Moderate	Very Lightweight (30-40% lighter than FRP)
Cost	Low to Medium	High
Durability	High	Very High
Thermal Expansion (10^{-6}/°C)	10 – 20	0 – 1 (Minimal Expansion

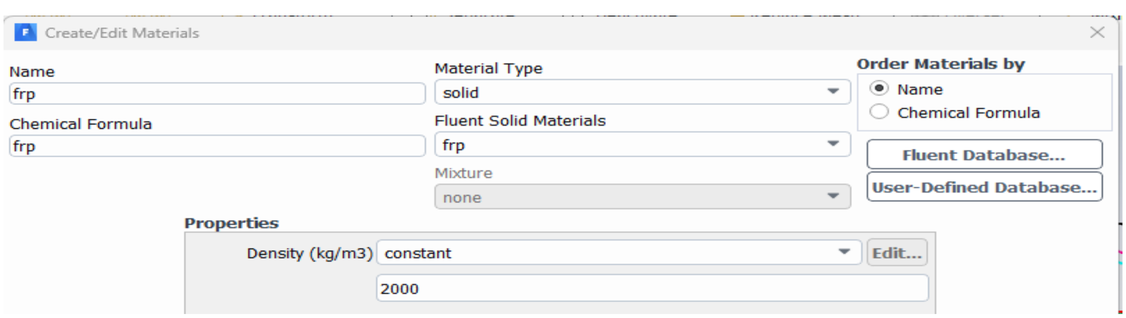

Figure 12. Material

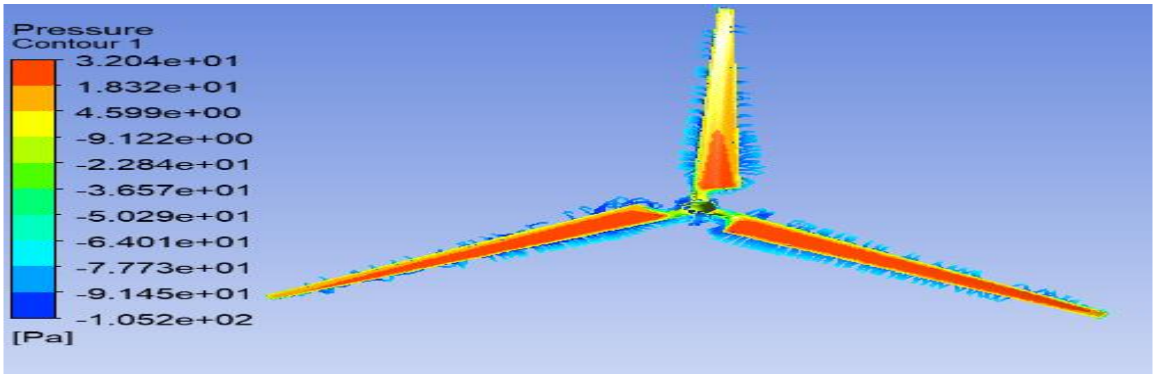

Figure 15. Pressure on FRP Windmill turbine

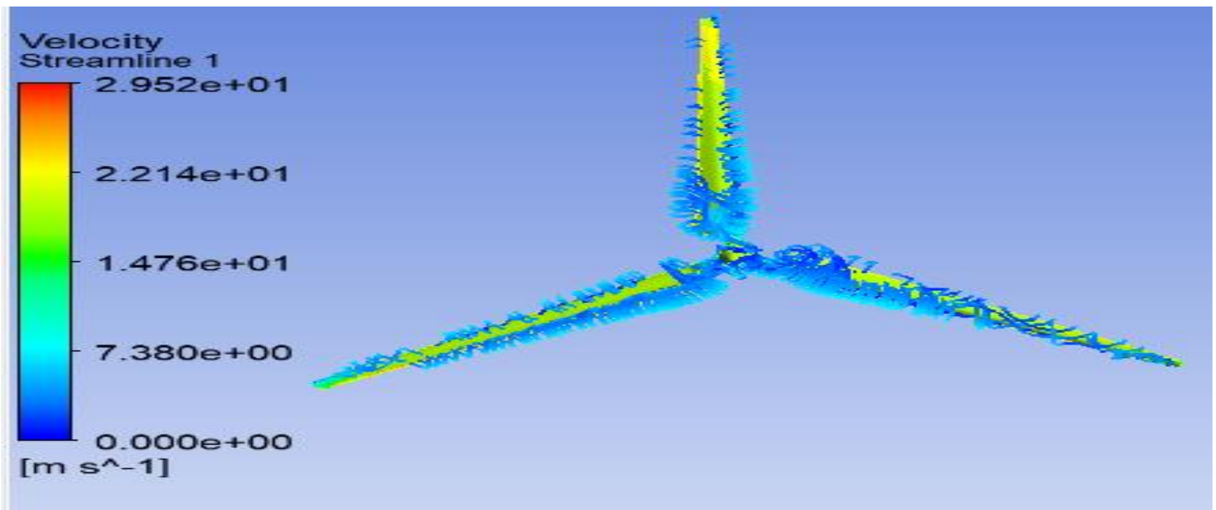

Figure 16. velocity probe

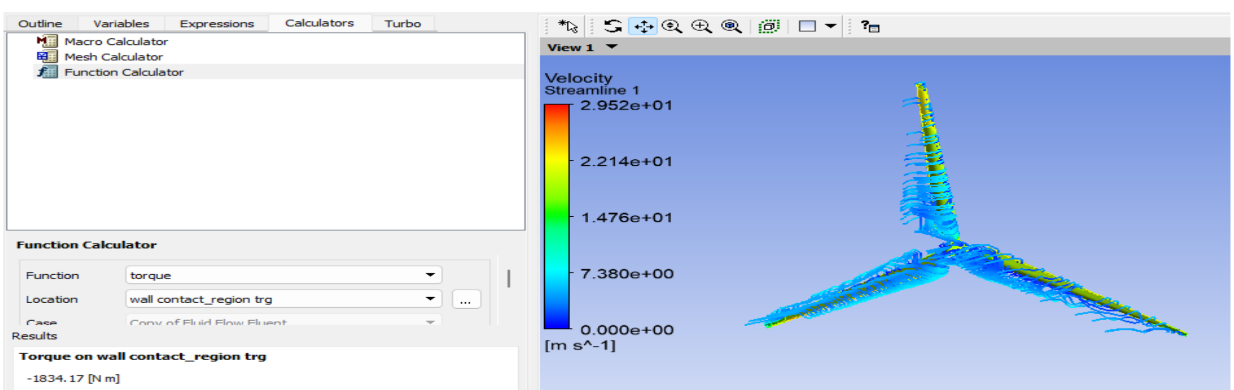

Figure 17. torque results in N-m

Iteration 3 CFRP Material for blade

Generate Blade Twist and Chord Distribution

4. Apply **twist distribution**:
   - Rotate airfoil sections along the blade axis.
   - Root section: **15° twist from to 20°**
   - Tip section: **2° twist**
5. Define **chord length variation**:
   - Root (near hub) has a **maximum chord length of 4.7 m**.
   - Gradually decrease the chord length towards the tip.

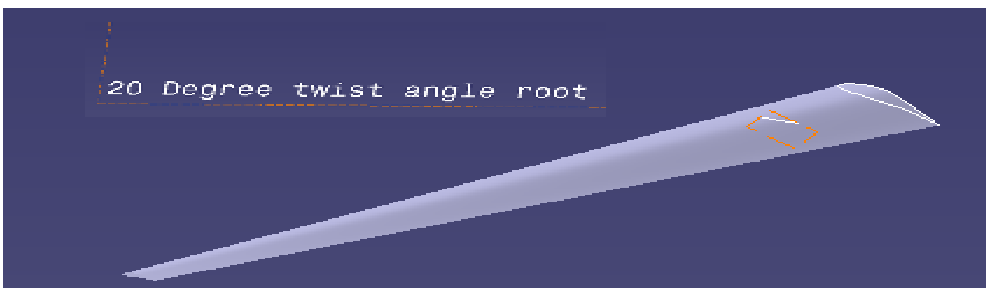

Figure 18. Catia v5 3D cad Modal with single blade 20° twist angle at root

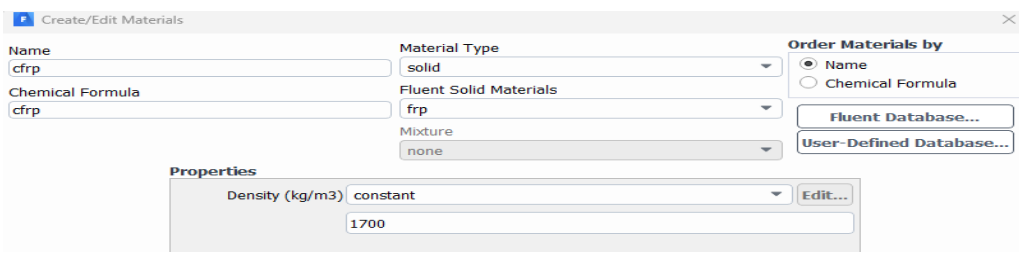

Figure 19. Material properties

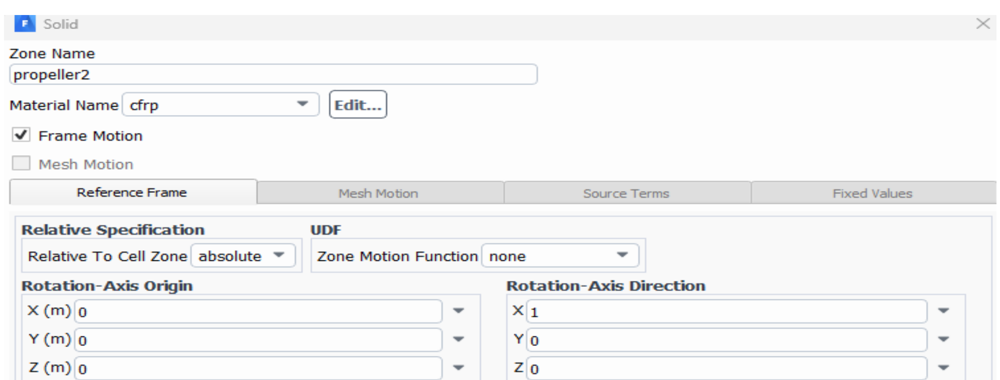

Figure 20. Zones

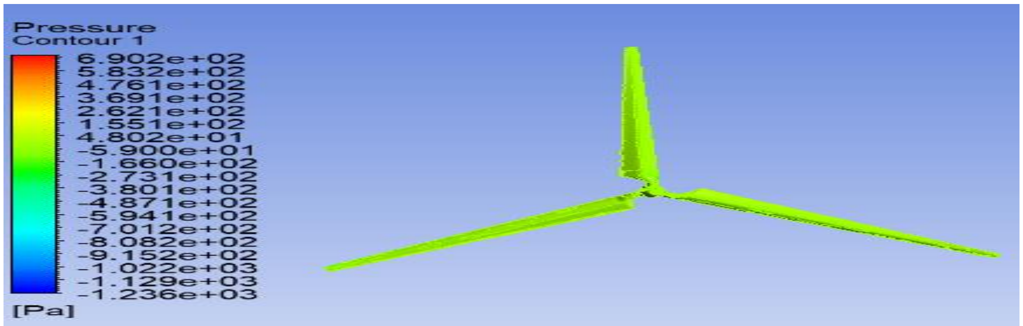

Figure 21. Pressure flow on blade on CFRP With optimized design

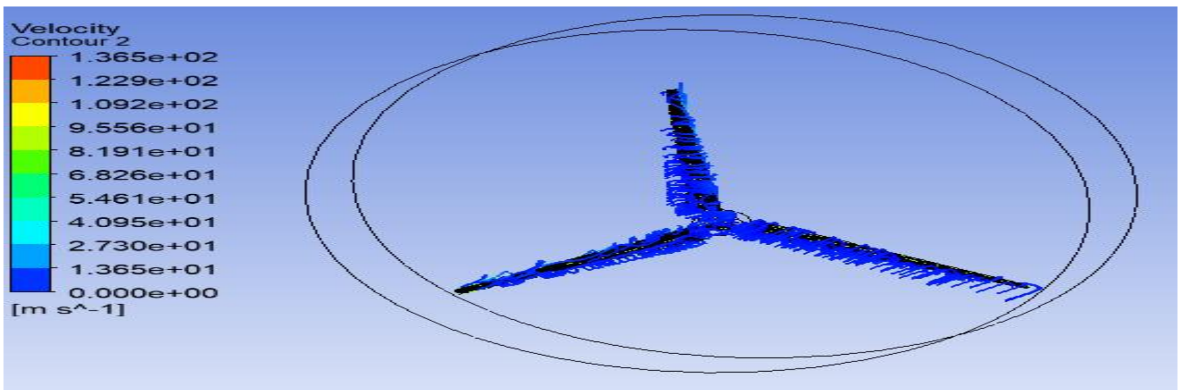

Figure 22. Velocity ratio in m/sec

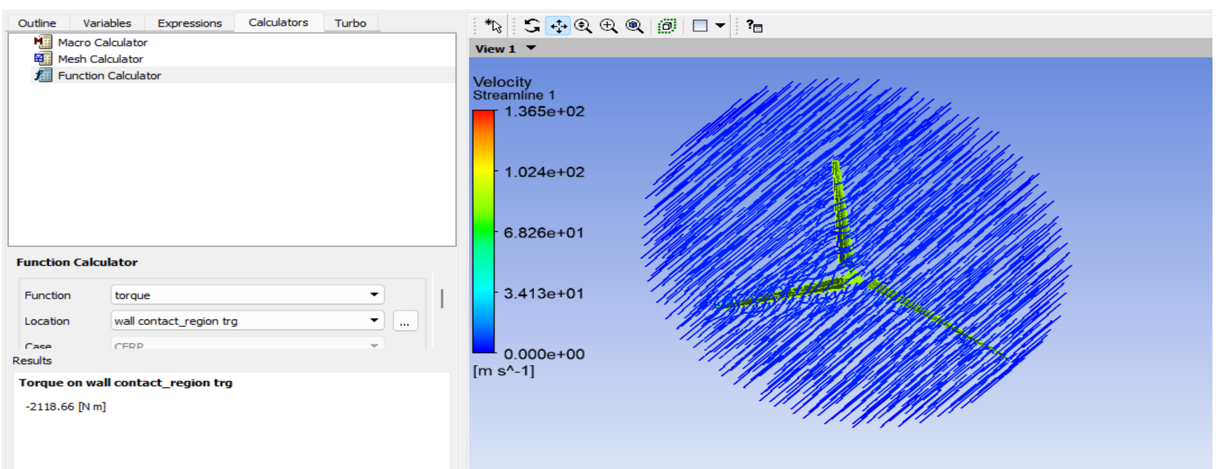

Figure 23. Torque results for optimized design with CFRP

Conclusion

The integration of aerodynamic and structural analysis for wind turbine blade design plays a critical role in enhancing turbine performance and reliability. This research demonstrates that multi-disciplinary optimization, involving both CFD and FEA simulations, results in significant improvements in aerodynamic efficiency and structural integrity. By using high-fidelity models in ANSYS and CATIA, the study successfully optimized the wind turbine blade design to reduce mass by up to 27% while maintaining or even increasing torque output. Furthermore, the optimization approach ensured that the blades could withstand long-term operational loads without failure, offering valuable insights into balancing performance and durability. The research also emphasizes the importance of considering material properties, such as using composite materials like CFRP for improved strength-to-weight ratios, which contribute to the overall efficiency of wind turbines. This study lays the groundwork for future developments in wind turbine blade design, underlining the necessity of continuous innovation in materials, optimization techniques, and multi-disciplinary integration to meet the increasing global demand for renewable energy and sustainable development.

Statements and Declarations

Ethical Approval

"The submitted work is original and not have been published elsewhere in any form or language (partially or in full), unless the new work concerns an expansion of previous work."

Consent to Participate

"Informed consent was obtained from all individual participants included in the study."

Consent to Publish

"The authors affirm that human research participants provided informed consent for publication of the research study to the journal."

Funding

"The authors declare that no funds, grants, or other support were received during the preparation of this manuscript."

Competing Interests

"The authors have no relevant financial or non-financial interests to disclose."

Availability of data and materials

"The authors confirm that the data supporting the findings of this study are available within the article."

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

1. Schubel, P. J., & Crossley, R. J. (2012). Wind turbine blade design. Energies, 5(9), 3425–3449. https://doi.org/10.3390/en5093425
2. Olofsson, A. (2007). MASTER ' S THESIS Improved Aero Blade Design for Multi-Disciplinary Integration.
3. Mangano, M., He, S., Liao, Y., Caprace, D., Ning, A., & Martins, J. R. R. A. (2023). Aeroelastic Tailoring of Wind Turbine Rotors Using High-Fidelity Multidisciplinary Design Optimization. February, 1–33.
4. Batay, S., Baidullayeva, A., Zhao, Y., Wei, D., Baigarina, A., Sarsenov, E., & Shabdan, Y. (2024). Aerostructural Design Optimization of Wind Turbine Blades. Processes, 12(1). https://doi.org/10.3390/pr12010022

5. Firoozi, A. A., Firoozi, A. A., & Hejazi, F. (2024). Innovations in Wind Turbine Blade Engineering: Exploring Materials, Sustainability, and Market Dynamics. Sustainability (Switzerland), 16(19). https://doi.org/10.3390/su16198564
6. Ostachowicz, W., McGugan, M., Schröder-Hinrichs, J. U., & Luczak, M. (2016). MARE-WINT: New materials and reliability in offshore wind turbine technology. MARE-WINT: New Materials and Reliability in Offshore Wind Turbine Technology, 1–432. https://doi.org/10.1007/978-3-319-39095-6
7. Xi, L., & Zhao, L. (2022). Optimal Design of Wind Turbine Blades by Combination of Multi-airfoil Leaf Elements. Journal of Physics: Conference Series, 2235(1). https://doi.org/10.1088/1742-6596/2235/1/012008
8. Bottasso, C. L., Campagnolo, F., Croce, A., & Giuliani, M. (2009). Multi-disciplinary optimization of wind turbines using comprehensive aero-servo-elastic models. 5th European and African Conference on Wind Engineering, EACWE 5, Proceedings, July.
9. Shasha Vali, S., & Sathees Kumar, S. (2023). Design and analysis of wind turbine blade. AIP Conference Proceedings, 2548(1). https://doi.org/10.1063/5.0118663
10. Bottasso, C. L., Campagnolo, F., & Croce, A. (2012). Multi-disciplinary constrained optimization of wind turbines. Multibody System Dynamics, 27(1), 21–53. https://doi.org/10.1007/s11044-011-9271-x
11. Pietro Bortolotti, Carlo L. Bottasso, & Alessandro Croce. (2016). Detailed design of wind turbines. Wind Energy Science Discussion, 1(January), 71–88. https://doi.org/10.5194/wes-2015-2