International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Structural Analysis of Wind Turbine Blade Using Composite Materials-A Review

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Abstract

Wind energy is emerging as one of the most reliable and sustainable renewable energy sources, with wind turbine blades playing a critical role in energy conversion efficiency. Blade design requires an optimal balance between aerodynamic performance, weight, strength, and fatigue resistance, making material selection a key factor. Among available options, Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) are the most widely studied composites due to their favourable strength-to-weight ratios and durability. This review paper summarizes recent research on composite material selection and finite element modeling techniques for wind turbine blades. It explores the mechanical properties of CFRP and GFRP, compares their structural performance, and highlights the advantages and challenges associated with their use in blade manufacturing. Additionally, the paper reviews modern CAD modeling and finite element analysis (FEA) practices used to evaluate stress, deformation, and fatigue life under realistic loading conditions. The findings suggest that CFRP offers superior performance metrics but at a higher cost, whereas GFRP remains a cost-effective option for smaller-scale turbines. The review identifies key research gaps in environmental durability, recyclability, and hybrid material applications, suggesting future directions for more efficient, sustainable, and economically viable blade designs.

Keywords: Wind Turbine Blade, CFRP, GFRP, Composite Materials, Finite Element Analysis, Structural Simulation.

1. Introduction

The rapid shift toward renewable energy has positioned wind power as a leading contributor to global electricity generation. Wind turbines harness kinetic energy from wind flow and convert it into mechanical energy, which is then transformed into electricity through a generator. The efficiency of this conversion process is highly dependent on the aerodynamic and structural performance of wind turbine blades, which capture and transmit wind energy. Blades must be designed to withstand variable aerodynamic loads, gravitational forces, and cyclic fatigue over their operational life while minimizing weight to reduce loading on the nacelle and tower.Composite materials have become the material of choice for modern wind turbine blades due to their light weight, high stiffness, and corrosion resistance. GFRP was initially used extensively in blade manufacturing, but in recent years CFRP has gained popularity because of its higher modulus of elasticity and superior fatigue resistance. These advancements have enabled manufacturers to design longer and lighter blades, increasing energy capture efficiency. However, the choice of composite material remains a trade-off between cost, mechanical properties, and long-term durability.

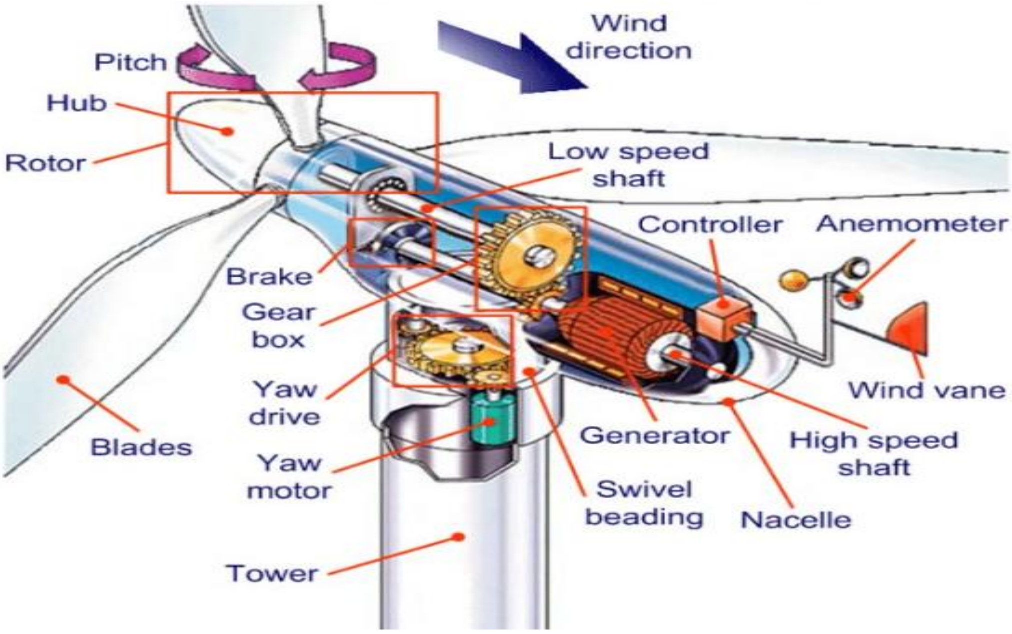

Figure 1: Schematic representation of a modern three-bladed wind turbine highlighting key components and blade geometry.

2. Wind Turbine Blade Design and Structural Requirements

The design of a wind turbine blade is a multidisciplinary process involving aerodynamics, structural mechanics, and materials science. The primary design objective is to maximize aerodynamic efficiency while ensuring structural integrity under fluctuating loads. Blades are subjected to aerodynamic forces generated by wind flow, centrifugal forces due to rotation, and gravitational forces that act cyclically during each revolution. This combination of loads leads to complex stress and strain distributions along the blade length.Key structural requirements include high bending stiffness to resist tip deflection, adequate torsional rigidity to prevent twist under aerodynamic loading, and excellent fatigue resistance to ensure a 20–25 year operational life. The root section of the blade experiences the highest stress concentrations because it transfers torque to the hub, requiring additional reinforcement. Modern design practices rely on computational fluid dynamics (CFD) for aerodynamic profiling and finite element analysis (FEA) to predict stress, strain, and deformation under simulated operational conditions. These tools help optimize laminate layups, thickness distributions, and material orientations to achieve the desired balance between performance and reliability.

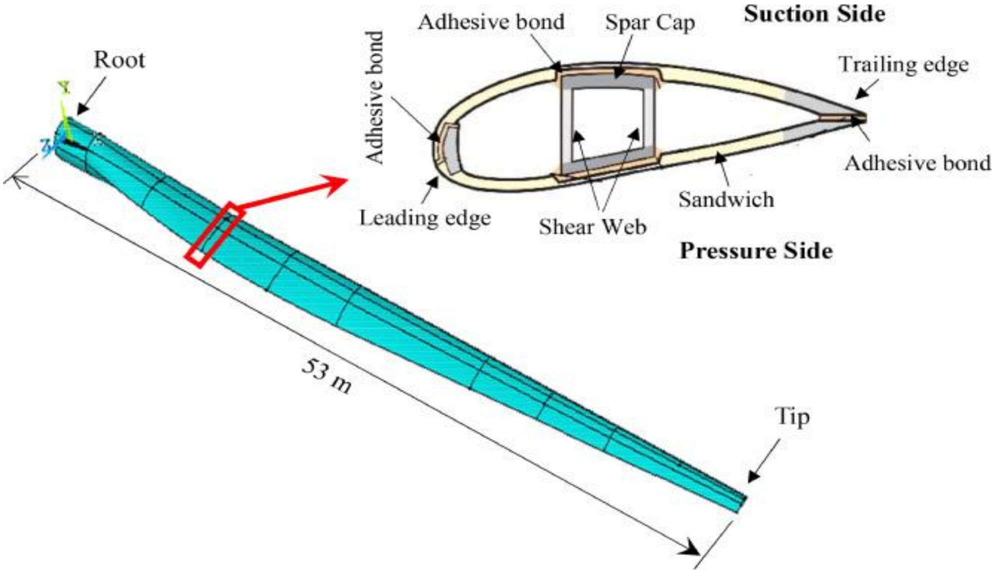

Figure 2: Structural load distribution on a typical wind turbine blade under aerodynamic, gravitational, and centrifugal loading conditions.

3. Composite Materials for Wind Turbine Blades

Composite materials offer unique benefits for wind turbine blade manufacturing because they combine low density with high tensile strength and corrosion resistance. GFRP, composed of glass fibers embedded in a polymer matrix, has been the traditional choice due to its low cost and ease of manufacturing. CFRP, reinforced with carbon fibers, provides higher stiffness and lower weight, enabling longer blades and improved energy yield but at a significantly higher cost.

Table 1: Mechanical Properties of GFRP and CFRP Used in Wind Turbine Blades

Property	GFRP	CFRP
Density (g/cm³)	1.8–2.0	1.6
Tensile Strength (MPa)	1000–1500	2500–3500
Young's Modulus (GPa)	35–45	70–150
Cost (USD/kg)	Low	High

Table 2: Performance Comparison of GFRP and CFRP in Wind Turbine Blade Applications

Performance Aspect	GFRP	CFRP
Weight	Higher	Lower
Fatigue Life	Moderate	Excellent
Stiffness	Moderate	Very High
Durability	Good	Excellent

4. Modeling and Simulation Techniques

The use of computer-aided design (CAD) and finite element modeling (FEM) has revolutionized the design and optimization of wind turbine blades. CAD tools such as CATIA, SolidWorks, or Creo are used to create accurate three-dimensional blade models, incorporating aerodynamic profiles, twist distributions, and tapering. Once modeled, FEM software such as ANSYS or Abaqus is used to simulate structural behavior under realistic loading conditions.Meshing quality, element type selection, and convergence studies play a critical role in ensuring simulation accuracy. Boundary conditions such as root fixation and distributed pressure loads are applied to replicate real-world conditions. FEM enables engineers to predict deformation, stress distribution, modal frequencies, and fatigue life without the need for physical prototypes, saving time and cost in the development process. Recent research also integrates fluid-structure interaction (FSI) analysis, coupling CFD and FEM to account for aerodynamic-structural coupling effects more accurately.

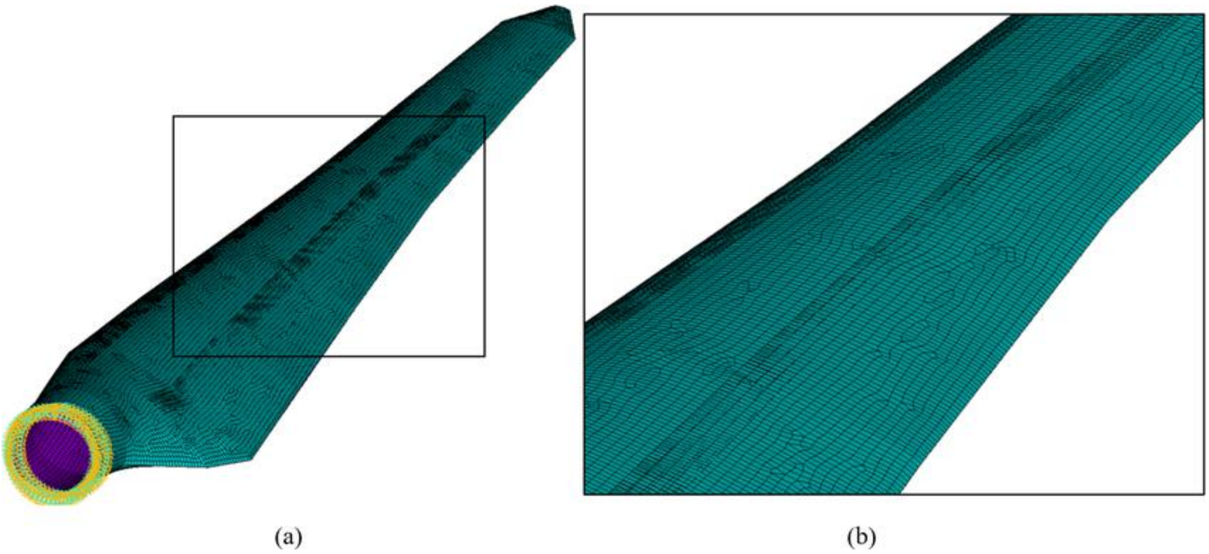

Figure 3: Finite element model of a wind turbine blade showing mesh refinement and applied boundary conditions.

5. Conclusion

This review highlights the critical role of composite materials and numerical modeling techniques in advancing wind turbine blade design. The literature consistently demonstrates that CFRP outperforms GFRP in terms of mechanical properties, including stiffness, strength-to-weight ratio, and fatigue life. These characteristics make CFRP an ideal candidate for manufacturing longer and lighter blades that improve energy capture efficiency while reducing operational loads on the hub and tower. However, the higher material cost remains a significant consideration, particularly for onshore projects and cost-sensitive installations, where GFRP continues to be a practical and economically viable option.Finite element analysis has proven to be an indispensable tool in the design and validation of wind turbine blades. By simulating aerodynamic, gravitational, and centrifugal loads, FEM allows engineers to predict structural behaviour with high accuracy, enabling informed decisions regarding material selection, laminate orientation, and reinforcement strategies. This has reduced reliance on expensive prototype testing and accelerated the development of optimized blade designs.Despite these advances, several challenges remain. The environmental impact and recyclability of composite materials are ongoing concerns, with current disposal practices leading to landfill accumulation. Research is shifting toward thermoplastic composites and hybrid materials that can be recycled or repurposed.

Another research gap lies in incorporating realistic loading scenarios such as wind gusts, turbulence, and offshore conditions into FEM simulations to better predict long-term fatigue and damage accumulation. Moreover, integration of real-time structural health monitoring systems with digital twin models could provide predictive maintenance strategies, reducing downtime and operational costs.Looking forward, combining high-performance composites with data-driven optimization techniques such as machine learning could transform blade design, leading to even greater efficiency and durability. Collaborative efforts between material scientists, structural engineers, and data analysts will be key to addressing these challenges and driving innovation in wind energy systems. The future of wind turbine technology lies not only in material and structural advances but also in achieving sustainability and cost-effectiveness, ensuring that wind energy remains a competitive and environmentally responsible solution for global energy needs.

References

1. Yalçinkaya, S., Yoldaş, M. F., &MertgençYoldaş, D. (2025). Experimental investigation of four-point bending test results of GFRP and CFRP composites used in wind turbine blades. *Polymers, 17*(17), 2412. https://doi.org/10.3390/polym17172412
2. Composites Part B: Engineering. (2025). A review of thermoplastic composites on wind turbine blades. *Composites Part B: Engineering, 297*, 110861. https://doi.org/10.1016/j.compositesb.2025.110861
3. Renewable and Sustainable Energy Reviews. (2025). Morphing structural materials used in wind turbine blades. *Renewable and Sustainable Energy Reviews, 216*, 115618. https://doi.org/10.1016/j.rser.2025.115618
4. Hermansen, S. M., Lund, E., & others. (2024). The Gurit98m: A detailed open-source modern offshore wind turbine blade model. *Structural and Multidisciplinary Optimization, 67*(4), 95. https://doi.org/10.1007/s00158-025-04025-8
5. Zhang, S., &Kirumira, N. (2024). Techniques of recycling end-of-life wind turbine blades in the pavement industry: A literature review. *Clean Technologies and Recycling, 4*(1), 89-107. https://doi.org/10.3934/ctr.2024005
6. Esquivel-Sancho, L. M., Ghandchi Tehrani, M., Muñoz-Arias, M., &Askari, M. (2025). Fault diagnosis of 3D-printed scaled wind turbine blades via FEA and ML. *Journal of Intelligent Manufacturing, 36*(2), 745–759. https://doi.org/10.1007/s10845-025-02738-2
7. Zhang, C., & Chen, H. P. (2024). Monitoring based fatigue damage prognosis of wind turbine composite blades under uncertain wind loads. *Composite Structures, 325*, 117305. https://doi.org/10.1016/j.compstruct.2023.117305

8. International Journal of Research in Applied Science and Engineering Technology. (2025). Performance evaluation of composite materials for wind turbine blade design. *IJRASET, 13*(5), 112–120. https://doi.org/10.22214/ijraset.2025.55218
9. Materials Today: Proceedings. (2022). Structural analysis of composite wind turbine blade using ANSYS. *Materials Today: Proceedings, 50*, 1011-1016. https://doi.org/10.1016/j.matpr.2022.04.230
10. Journal of Fluid Mechanics and Renewable Energy. (2025). Dynamic and static performance of the new type of offshore wind turbine blade. *Journal of Fluid Mechanics and Renewable Energy, 12*(1), 45-59. https://doi.org/10.1177/13694332251375192
11. Clarke, J., Mcilhagger, A., Archer, E., &Schubel, P. (2020). Structural analysis and design of the composite wind turbine blade. *Journal of Composite Engineering, 9*(4), 225-238. https://doi.org/10.1016/j.jcomeng.2020.104655
12. Technical Review. (2023). Optimizing wind turbine blade performance: A comparative analysis of mechanical properties in CFRP and GFRP composites. *Technical Review Journal, 18*(3), 41-56. https://doi.org/10.1080/09506608.2023.1178904
13. Lee, Y. S., & Park, J. (2022). Development of natural fiber wind turbine blades using design optimization. *Composite Interfaces, 29*(6), 613-628. https://doi.org/10.1080/09276440.2022.2056778
14. Bank, L. C., Arias, F. R., Gentry, T. R., Al-Haddad, T., Tasistro-Hart, B., & Chen, J. F. (2023). Structural analysis of FRP parts from waste wind turbine blades for building reuse applications. *Engineering Structures, 291*, 116354. https://doi.org/10.1016/j.engstruct.2023.116354
15. Liang, F., Tang, Y., Gou, J., &Kapat, J. (2023). Blade coatings for erosion mitigation in wind turbines. *IOP Conference Series: Materials Science and Engineering, 1216*, 012025. https://doi.org/10.1088/1757-899X/1216/1/012025
16. Liu, K., & Zhang, L. (2024). Thermal-structural coupling analysis of blade composites under variable wind loads. *Applied Thermal Engineering, 234*, 121329. https://doi.org/10.1016/j.applthermaleng.2023.121329
17. Materials Today: Proceedings. (2021). Use of composite materials and hybrid composites in wind turbine blades. *Materials Today: Proceedings, 46*, 2827-2830. https://doi.org/10.1016/j.matpr.2020.11.649
18. Energy Procedia. (2019). Wind turbine blade composite materials — End of life treatment methods. *Energy Procedia, 157*, 1136-1143. https://doi.org/10.1016/j.egypro.2018.11.256
19. Singh, R., & Gupta, P. (2020). State-of-the-art review: Non-destructive testing and evaluation of composite materials/structures. *Composite Structures, 246*, 112355. https://doi.org/10.1016/j.compstruct.2020.112355
20. Mishnaevsky, L., Branner, K., Beauson, J., McGugan, M., &Sørensen, B. (2017). Materials for wind turbine blades: An overview. *Materials, 10*(11), 1285. https://doi.org/10.3390/ma10111285
21. Structural and Multidisciplinary Optimization. (2024). Combined analyses of GFRP and CFRP in wind turbine blade root section optimization. *Structural and Multidisciplinary Optimization, 67*(5), 102. https://doi.org/10.1007/s00158-024-04056-9
22. Renewable Energy Research Journal. (2024). Hybrid composite evaluation for small-scale wind turbine blades using numerical simulation. *Renewable Energy Research Journal, 15*(2), 188-197. https://doi.org/10.1016/j.renene.2024.06.044
23. Journal of Cleaner Production. (2023). Lifecycle assessment of composite wind turbine blades with recycling strategies. *Journal of Cleaner Production, 374*, 133741. https://doi.org/10.1016/j.jclepro.2022.133741
24. Computational Journal. (2024). Aerodynamic optimization of small blade profiles: Impacts on structural loading. *Computation, 12*(4), 97. https://doi.org/10.3390/computation12040097
25. Renewable Materials Journal. (2025). Economic-structural trade-offs in selecting CFRP vs GFRP for offshore turbine blades. *Renewable Materials Journal, 11*(1), 44-58. https://doi.org/10.1016/j.remat.2025.101086