

A STUDY ON EXPERIMENTAL INVESTIGATION OF ARAMID AND BASALT FIBRE REINFORCEMENTS FOR WIND TURBINE BLADE OPTIMIZATION: A REVIEW

Sreevidya N

Department of Mechanical Engineering
C.Byregowda Institute of Technology
Kolar 563101

nsreevidya88@gmail.com

Madhusudhana SV

Department of Aerospace Engineering
Sri Jagadguru Chandrashekaranaatha Swamiji Institute of Technology
Chikkaballapur 562101

hodas@sicit.ac.in

Manjunatha Babu NS

Department of Mechanical Engineering
Dr.T.Thimmaiah Institute of Technology
KGF 563120

hod.mech@drttit.edu.in

Abstract: Wind energy is considered a major renewable power source, and the performance of a wind turbine largely depends on the structural efficiency of its blades. Most modern blades are manufactured using fiber reinforced polymer composites because they offer low weight, corrosion resistance, and good mechanical strength. However, conventional glass fiber composites face limitations when blades become larger, particularly in terms of stiffness, fatigue endurance, and resistance to impact damage. To address these challenges, aramid and basalt fibers are being explored as alternative reinforcements. Aramid fibers are well known for high toughness, excellent energy absorption, and superior impact resistance, whereas basalt fibers provide improved stiffness, thermal stability, and chemical resistance with moderate cost. This review summarizes the characteristics of aramid- and basalt-based composite laminates, key manufacturing techniques, mechanical performance trends, and typical damage mechanisms. The potential of hybrid aramid-basalt laminates for enhancing strength-to-weight ratio, fatigue life, and damage tolerance in wind turbine blades is also discussed. Finally, major research gaps and future development directions are highlighted for practical large-scale implementation.

Keywords: Wind turbine blade, aramid fiber, basalt fiber, fiber reinforced polymer, hybrid composite, fatigue performance, blade design optimization.

I. INTRODUCTION

Wind power generation has expanded rapidly due to increasing electricity demand and the need to reduce dependence on fossil fuels. A wind turbine converts aerodynamic wind energy into electrical power, and the blade is the most critical component influencing energy capture efficiency.

To maximize power generation, modern wind turbines are designed with longer blades. Although longer blades increase swept area, they also increase bending moments and cyclic fatigue stresses. Glass fiber reinforced polymer composites are widely used because of low cost and acceptable strength. Nevertheless, glass fiber composites may not provide sufficient stiffness and fatigue resistance for large blades. Carbon fibre offers high stiffness but is expensive. As a result, aramid and basalt fibres have attracted interest as reinforcements that can potentially improve blade mechanical behavior while remaining cost effective.

II. COMPOSITE MATERIALS IN WIND TURBINE BLADES

Wind turbine blades are typically manufactured using polymer matrix composites, where epoxy resin is commonly used as the matrix and continuous fibres are used as reinforcement. The material used in these regions must satisfy requirements such as high tensile and flexural strength, sufficient stiffness, low density, high fatigue endurance, and resistance to corrosion and weathering. The selection of fibre reinforcement directly controls these properties, and hence research is focused on alternative fibres such as aramid and basalt.

III. ARAMID FIBRE REINFORCED COMPOSITES

Aramid fibres, commonly known through commercial variants such as Kevlar, are synthetic fibres recognized for high tensile strength, low density, and excellent impact resistance. These fibres are capable of absorbing high energy and delaying crack growth, making them suitable for structural components where toughness is required. In wind turbine blades, aramid fibres are often considered for regions vulnerable to impact damage such as leading edges. Despite their advantages, aramid fibres show comparatively lower compressive strength and may absorb moisture. In addition, poor bonding with polymer matrices can occur unless suitable surface treatments are applied, which limits their use as a standalone reinforcement in primary load-carrying zones.

IV. BASALT FIBRE REINFORCED COMPOSITES

Basalt fibres are produced by melting natural basalt rock and drawing it into filaments. Since the raw material is naturally available, basalt fibres are considered environmentally friendly compared to many synthetic fibres.

Basalt fibre composites generally provide higher stiffness and better thermal and chemical resistance than conventional glass fibre composites. These characteristics make basalt fibres suitable for wind blade structures where rigidity and environmental stability are required. However, basalt fibres are denser than aramid fibres and may exhibit brittle failure under sudden impact loading, which can reduce their damage tolerance.

V. MANUFACTURING METHODS FOR ARAMID AND BASALT COMPOSITES

The final performance of a composite structure depends strongly on the manufacturing method, fibre orientation, and void.

Hand lay-up is a simple technique but may result in trapped air and inconsistent quality. Vacuum bagging reduces void formation and improves consolidation. Vacuum Assisted Resin Transfer Molding (VARTM) is widely adopted in wind blade manufacturing because it produces high-quality laminates with controlled resin flow. Resin Transfer Molding (RTM) provides good repeatability but requires higher tooling cost and is generally used for smaller components.

VI. MECHANICAL PERFORMANCE COMPARISON

Wind turbine blades are subjected to combined tensile, compressive, bending, and shear loading along with long-term cyclic fatigue. Mechanical properties are evaluated using standardized tests such as tensile testing (ASTM D3039), flexural testing (ASTM D790), and impact testing.

Aramid fibre composites usually show superior tensile strength and very good resistance to impact damage due to their high toughness. Basalt fibre composites offer improved stiffness and flexural modulus, which can enhance blade rigidity. From a fatigue perspective, aramid fibres can slow

crack growth while basalt fibres contribute to better load carrying capability compared to glass fibre composites. Therefore, both materials provide useful improvements depending on the required blade performance objective.

VII. FAILURE MECHANISMS IN COMPOSITE BLADES.

Composite wind turbine blades fail through different mechanisms depending on load type and laminate design. Common damage modes include matrix cracking, fibre breakage, and delamination between layers, fibre pull-out, interfacial debonding, and fatigue-induced fracture.

Aramid-based laminates may show fibre pull-out because of weak fibre-matrix adhesion, but their toughness delays rapid crack propagation. Basalt composites often demonstrate matrix cracking and brittle fracture behavior. Delamination is also a major issue, especially under cyclic bending loads. Microscopic techniques such as Scanning Electron Microscopy (SEM) are frequently used to identify damage characteristics and understand failure progression.

VIII. WIND TURBINE BLADE OPTIMIZATION USING HYBRID ARAMID-BASALT SYSTEMS

Blade optimization aims to reduce weight while ensuring sufficient stiffness, strength, and long-term fatigue durability. Hybrid laminates combining basalt and aramid fibres can provide a balanced combination of properties.

Basalt fibre layers contribute higher stiffness and improve bending resistance, while aramid fibre layers enhance toughness and impact resistance. The stacking sequence and fibre orientation strongly influence performance. Typically, 0° layers resist bending loads, $\pm 45^\circ$ layers support shear loads, and 90° layers improve transverse stability. Proper hybrid design can increase the strength-to-weight ratio and extend fatigue life, making hybrid composites promising for next-generation wind turbine blades.

IX. ENVIRONMENTAL AND ECONOMIC CONSIDERATION.

Sustainability and cost are major factors in selecting blade materials. Basalt fibres are produced from natural rock with limited chemical processing, making them relatively eco-friendly.

In terms of cost, carbon fibre remains the most expensive option. Aramid fibre is also costly, while basalt fibre is moderately priced and generally more affordable than carbon fibre. Glass fibre remains the cheapest but has limitations in stiffness and fatigue performance. Hence, basalt fibre offers a practical balance between cost and mechanical improvement for wind turbine blade applications.

X. RESEARCH GAPS AND FUTURE SCOPE

Although aramid and basalt fibres show potential for wind turbine blade reinforcement, several research challenges remain. Long-term fatigue studies on basalt composites are still limited. Similarly, the influence of moisture absorption and ultraviolet aging on aramid composites requires further investigation.

Future work should focus on optimizing hybrid laminate design, improving fibre-matrix bonding through surface treatments, performing numerical simulations using finite element analysis, and conducting full-scale blade testing to validate laboratory results under realistic operating conditions.

XI. CONCLUSION

Aramid and basalt fibres are promising reinforcements for improving wind turbine blade composites. Aramid fibres provide excellent toughness and impact resistance, while basalt fibres deliver higher stiffness, good corrosion resistance, and moderate cost benefits. Hybrid aramid-basalt laminates offer an effective approach to enhance strength-to-weight ratio, fatigue life, and damage tolerance. However, further experimental validation and numerical optimization are necessary before these materials can be widely adopted in large-scale commercial wind turbine blades.

REFERENCES

- [1] T. Burton, D. Sharpe, N. Jenkins, and E. Bossanyi, *Wind Energy Handbook*, 2nd ed. Wiley, 2011.
- [2] J. F. Mandell and D. D. Samborsky, "Fatigue of composite materials and substructures for wind turbine blades," Sandia National Laboratories Report, 2002.
- [3] P. Brøndsted, H. Lilholt, and A. Lystrup, "Composite materials for wind power turbine blades," *Annual Review of Materials Research*, vol. 35, pp. 505–538, 2005.
- [4] A. Fiore, T. Scalici, and G. Di Bella, "A review on basalt fibre and its composites," *Composites Part B: Engineering*, vol. 74, pp. 74–94, 2015.
- [5] M. R. Piggott, *Load Bearing Fibre Composites*, 2nd ed. Springer, 2002.
- [6] ASTM D3039, *Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*, ASTM International, 2017.