

Application of Composite Materials in the Lightweight Design of Wind Turbine Blades

Haowen Wang

School of Physics and Materials Science, Nanchang University, Nanchang, 330031, China

Abstract: In the process of global transition towards sustainable energy infrastructures, continuous optimization of mechanical design parameters of wind energy harvesting is required. The blades of wind turbines are aerodynamic parts that are related to efficiency, structural stability and mass of the material. This is a narrative review to examine the development of composite materials in lightweight blade architectures. Standard Glass Fiber Reinforced Polymers (GFRP), advanced Carbon Fiber Reinforced Polymers (CFRP) and emerging Carbon Glass Hybrid configurations are evaluated by engineers. Structural optimization is done based on multi objective criteria. The objectives of this study are fatigue resistance, tensile strength and weight reduction. This paper summarizes the present research needs in weight reduction strategies, including material evolution, advanced manufacturing paradigms like Vacuum Assisted Resin Transfer Molding (VARTM) and end of life recycling challenges. The review identifies emerging wind energy trends including full digital simulation, and the shift to recyclable thermoplastic resins as part of a circular economy.

Keywords: Wind Energy, Composite Materials, Carbon Fiber Reinforced Polymers (CFRP), Glass Fiber Reinforced Polymers (GFRP), Structural Optimization.

1. Introduction

For optimal energy harvesting in wind power generation, mechanical system components need to be continually improved [1]. The aerodynamic performance of the entire system is determined by the turbine blades, which are also responsible for the structural loading that is transferred to the nacelle, tower and foundation [2]. In the last 30 years, the industry worked towards increasing the swept area of the rotor to the maximum possible extent. Blade spans of over 100 m [3, 4] are often used in modern offshore installations. Such a growth in size also means that the gravitational and aerodynamic stresses are enormous. The power which can be captured by the turbine is proportional to the square of the length of the blades and the mass of the blades is proportional to the cube of the length of the blades [5]. The square cube paradox is that the longer the blades get with conventional isotropic materials, the heavier they get, exponentially. The heavier the rotor, the greater the inertia, and the slower the turbine's response to wind changes and increased fatigue at the blade root [6]. Advanced composite materials offer a promising path towards meeting lightweight design requirements while maintaining mechanical integrity [7]. Designers can decrease the mass of the structure by using high strength fibers in special polymer matrices that will provide the necessary stiffness to prevent aerodynamic stall and tower strike.

This paper adopts a narrative review, which will bring together the historical development, mechanical constraints and end-of-life issues of composite materials used in wind turbine blades. The authors searched the main engineering databases for literature. These are Scopus, IEEE Xplore and Web of Science. The search was done on the material mechanics, structural optimization and composite recycling technologies mainly in the period of 2000–2025. The synthesis is based on basic aerodynamic scaling laws [4, 5] and experimental analyses of hybrid laminate performance [8, 9] to give a common thread from traditional production

methods to new circular economy approaches.

2. The Scaling Challenge and Material Evolution

2.1. Fundamental Concepts: The Scaling Challenge in Wind Energy

The necessity of weight reduction with composites can be understood by considering the relevant fluid dynamics and solid mechanics. The basic measure of aerodynamic performance of a horizontal axis wind turbine is the power extracted [4]:

$$P = 0.5\rho\pi R^2 v^3 C_p$$

The variable R (blade length) is the primary driver of current structural scaling challenges. Maximizing the energy yield demands an increase in R . The maximum bending moment M acting at the root of the blade increases exponentially as the length extends [5]:

$$M \approx \int_0^R r q(r) dr$$

This study states that we have to increase the area moment of inertia at the root section so that the structure will not fail under these loads. A blade made of regular heavy materials such as steel is too heavy to spin effectively in normal wind conditions. This translates to smart application of lightweight composites [2].

2.2. Material mechanics GFRP vs CFRP synthesis

Manufacturers use Glass Fiber Reinforced Polymers (GFRP) and Carbon Fiber Reinforced Polymers (CFRP) for utility scale blades [8, 9]. The basic E glass and advanced S glass variants are very environmentally friendly with well-defined failure curves [2]. One of the drawbacks of using glass composites for offshore structures is the relatively low

elastic modulus of the material [10]. In the case of longer blades, the lower stiffness of the glass fibers causes too much tip deflection [10]. This means that designers must make the laminate thicker and heavier [11]. Carbon fibers have high specific modulus and high ultimate tensile strength [9] which overcomes the stiffness and weight limitations. The main load bearing spar caps can be made of carbon fibers to minimize the deflection of the tip and to decrease the weight of the structure [12]. GFRP is still the economic benchmark for onshore turbines below 60m. CFRP is a structural requirement to reduce critical gravitational fatigue, even though it is more expensive for offshore architectures that are more than 100 meters [9, 10]. Comparative mechanical properties are given in table 1 [13].

Table 1. Comparative Mechanical Properties of Cured Composite Laminates

Property Metric	Standard E-Glass Epoxy	Standard Carbon Epoxy	High Modulus Carbon Epoxy
Density (g/cm ³)	1.95	1.55	1.52
Tensile Strength (MPa)	900	2200	1800
Tensile Modulus (GPa)	45	140	200

3. Structural Optimization and Failure Mechanisms

3.1. Multi Objective Structural Optimization

The mechanical behavior of the composite laminate needs to be predicted for the design of a modern wind turbine blade. The Rule of Mixtures is used to estimate the baseline mechanical properties [14]. The longitudinal elastic modulus of a unidirectional composite lamina E_c is given by this equation:

$$E_c = E_f V_f + E_m (1 - V_f)$$

Applying this mathematical model reveals maximizing the fiber volume fraction V_f directly increases structural stiffness [14]. Physical manufacturing constraints limit V_f to prevent dry spots and void formations [15]. Optimization algorithms must balance the theoretical stiffness aerodynamic models require against the physical permeability limits of the manufacturing process.

3.2. Failure Mechanisms of Composite Matrices

The blades of wind turbines are subjected to very

complicated cyclic loading conditions. Gravitational forces and turbulent wind shear are acting at the same time, which results in large flap wise and edgewise bending moments [11]. These alternate loads result in micro damage which leads to macro damage of the structure. Microcracks in the matrix are the first sign of a possible fatigue failure. The environmental sealing breaks when the resin matrix cracks [16]. Following this initiation, all of the internal loads are borne by the continuous fiber network, and interlaminar delamination takes place in thick laminates.

4. Advanced Material Architectures

4.1. Carbon Glass Hybrid Composites and Nano Reinforced Matrices

The pure CFRP and pure GFRP were economically limited by the growing structural requirements of long blades and physically limited by the length of the blades [12]. One of the main methods of optimizing the cost, weight and structural performance is hybridization [17]. The mechanical response of the blade spar caps [18] is customized by mixing high modulus carbon fibers and high ductility glass fibers. The total stress a hybrid laminate σ_h can carry up to the first failure point for the fibers is given by this expression:

$$\sigma_h = \sigma_{f1} V_{f1} + \sigma_{f2} V_{f2} + \sigma_m V_m$$

Where σ_h is the total longitudinal tensile stress capacity of the hybrid composite, σ_{f1} and σ_{f2} are the stresses the primary and secondary reinforcing fibers carry, V_{f1} and V_{f2} are the absolute volume fractions of those fibers, σ_m and V_m represent the stress and volume fraction of the underlying polymer resin matrix. To mathematically model porosity degradation, engineers apply an overall empirical knockdown factor to the continuous matrix.

4.2. Sandwich Structures and Advanced Core Configurations

To prevent buckling and to minimize mass, sandwich construction is used in the structural sub panels by the designers [19]. This geometric configuration provides a large area moment of inertia with little weight additions. In the past, end grain balsa wood was the main product in the core market. One of the reasons for the use of synthetic foams is the rot susceptibility [20, 21]. The engineering properties of these high-performance materials are given in Table 2 [20].

Table 2. Engineering Characteristics of High Performance Structural Core Materials

Core Material Category	Density (kg/m ³)	Shear Modulus (MPa)	Shear Strength (MPa)	Compressive Modulus (MPa)	Moisture Absorption Resistance
End-Grain Balsa Wood	150	160	3.0	4000	Very Poor
Cross-Linked PVC Foam	80	30	1.2	90	Excellent
Linear PET Foam	100	38	1.1	115	Outstanding

5. Manufacturing Technologies, Defects, and Research Gaps

5.1. Advanced Manufacturing VARTM vs. AFP

The industry standard methodology for producing blades is Vacuum Assisted Resin Transfer Molding (VARTM) [15]. This process relies on pressure to drive liquid polymer resin through dry reinforcing fibers, governed mathematically by Darcy's Law:

$$q = -\frac{K}{\mu} \nabla P$$

Where q is the superficial volumetric flow rate of the liquid resin, K is the permeability tensor of the dry fiber preform, μ is the dynamic viscosity of the liquid polymer matrix, and ∇P is the pressure gradient driving the infusion process. To maximize the flow rate and minimize processing time, engineers manipulate the permeability variable by introducing specialized flow meshes. Heating the resin to lower the dynamic viscosity is common but requires precise thermal management to prevent premature curing before the infusion completes. Ensuring complete saturation is critical. Incomplete wetting leaves porosity, degrading interlaminar shear strength.

To address VARTM limitations, the industry explores Automated Fiber Placement (AFP) [22, 23]. AFP uses multi axis robotic heads to deposit continuous pre impregnated

tapes. VARTM remains the most economically scalable method for whole blade molding. Advancements in AFP technologies actively mitigate the microstructural defects historically associated with manual resin infusion processes [24]. AFP provides excellent defect predictability but carries exceptionally high capital equipment costs.

5.2. Characterization of Defects and Structural Integrity

Despite all the precautions taken in quality control, manufacturing defects are likely to be produced because of the size of the blades of wind turbines. The defects are localized and disrupt the load path of the continuous fibers and have a significant impact on the ultimate tensile strength of the structure. The most important manufacturing faults that are created during the infusion process are macro porosity and fiber waviness. These are manufacturing defects in the microstructures and are depicted in Figure 1.

The liquid resin contains microscopic air pockets during the curing process, which is known as porosity. These voids serve as stress concentrators in dynamic loading. The dry fabric layers are pushed out of alignment by heavy vacuum pressure, causing the fabric to be wavy. The fibers are not straight but in the form of sinusoidal waves, which significantly decrease the compressive buckling resistance of the spar cap. These common defects are classified, and manufacturing mitigation strategies are outlined in Table 3.

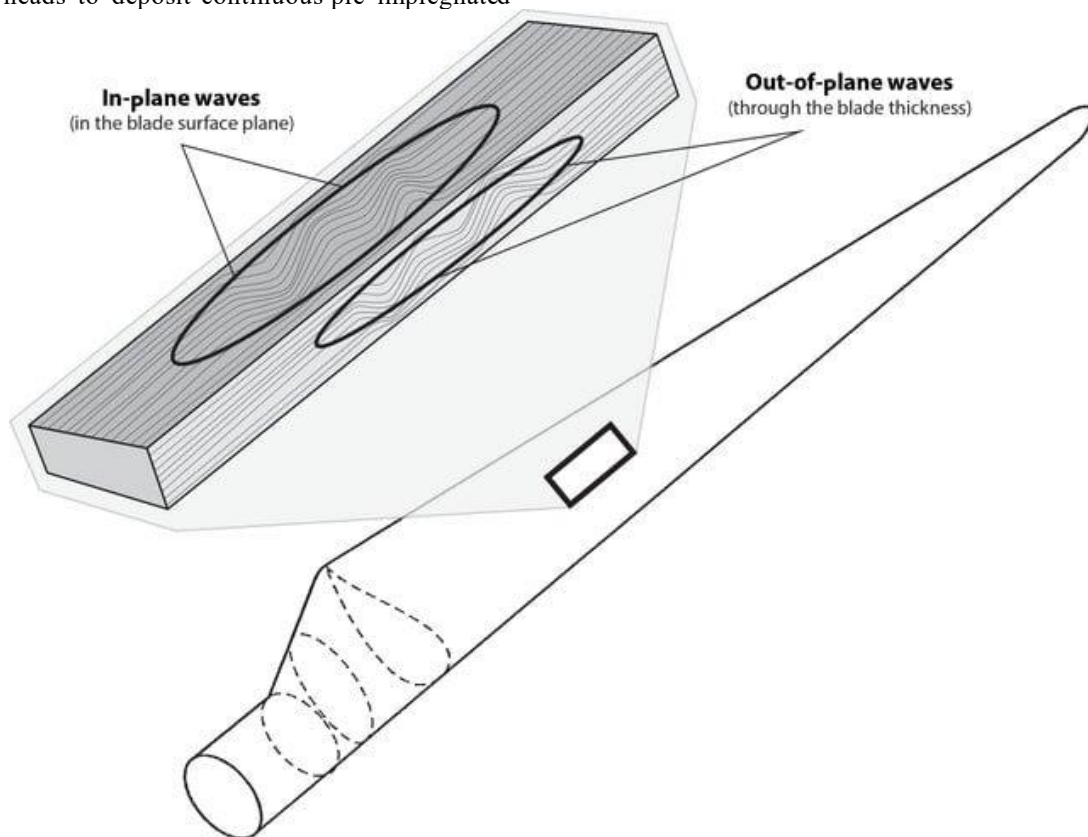


Figure 1. Schematic illustration of in-plane and out-of-plane fiber waviness defects in wind turbine blade composite laminates [10].

Table 3. Defect Classification and Structural Impact Mitigation

Defect Classification	Primary Cause	Structural Consequence	Detection Methodology	Manufacturing Mitigation Strategy
Entrapped Porosity (Micro Voids)	Inadequate resin degassing prior to infusion	Reduction in interlaminar shear strength	Ultrasonic C Scan	Controlled temperature ramping and extended vacuum hold
In Plane Fiber Waviness	Uncontrolled resin surge displacing dry tows	Massive drop in compressive modulus	Thermal Imaging	Staged vacuum application and rigid fiber tacking
Dry Spots (Unwetted Regions)	Insufficient flow paths or premature resin gelation	Immediate delamination under primary loading	Visual Inspection	Implementation of highly engineered flow media networks
Resin Rich Pockets	Bridging of the vacuum bag over sharp geometric corners	Localized embrittlement and thermal cracking	X Ray Computed Tomography	Precision tailored consumable bagging materials

5.3. Automated Manufacturing Technologies: The Precision Shift

The natural variability of manual lay-up processes motivated the wind energy industry to come up with very sophisticated automation strategies. The next stage of development of the utility scale composite manufacturing is Automated Fiber Placement (AFP) and Automated Tape Laying. These robotic systems are equipped with multi axis articulation heads, which deposit continuous pre impregnated

composite tapes directly onto the mold surface, with extreme precision. The precision is achieved by resin infusion with Automated Fiber Placement without any liquid substrate. The raw material is narrow carbon or glass tows which have already been impregnated with the right amount of resin. The robotic head applies heat and consolidation pressure at the same time while the head is laying down the material. This in situ consolidation significantly decreases the void content and completely prevents the occurrence of massive dry spots. These manufacturing paradigms are compared in Table 4.

Table 4. Comparative Analysis of Manufacturing Paradigms

Manufacturing Metric	Vacuum Assisted Resin Transfer Molding	Automated Fiber Placement	Automated Tape Laying
Capital Equipment Cost	Low to Moderate	Exceptionally High	High
Material Deposition Rate	Extremely Fast (Bulk Infusion)	Slow (Precision Placement)	Fast (Wide Coverage)
Geometric Complexity Limit	Very High	High	Moderate (Restricted to flat or gentle curves)
Fiber Volume Fraction Yield	50% to 55%	60% to 65%	60% to 65%
Defect Predictability	Poor (Highly dependent on manual skill)	Excellent (Machine controlled parameters)	Excellent

5.4. Research Gaps in Blade Manufacturing

A detailed analysis of the existing manufacturing processes reveals that there are some serious differences between the theory and practice of material science in industry. In the

laboratory scale studies, often nano reinforced matrices and highly tailored hybrid layups are demonstrated to be superior. These technologies are still highly problematic to be scaled up to 100 m class blades. The research gaps in lightweight design are identified in Table 5.

Table 5. Identified Research Gaps in Lightweight Design and Manufacturing

Specific Research Gap	Current Technical Limitation	Future Opportunity and Required Direction
Exothermal Scalability	Nano resins cure too quickly in ultra thick spar caps resulting in thermal degradation	Development of latent curing agents specifically tuned for massive scale infusion
Automated Inspection	Current ultrasonic scanning is too slow for production line integration on monolithic structures	Integration of Artificial Intelligence driven thermography for real time defect recognition
Out of Plane Defect Modeling	Finite element models struggle to accurately predict compressive failure initiated by complex 3D fiber waves	Machine learning algorithms trained on physical destruction data to replace conservative knockdown factors
In Situ Hybrid Consolidation	AFP systems cannot efficiently alternate between differing melt temperatures required for Carbon Glass hybrids	Dual head robotic placement systems with localized induction heating capabilities

6. Circular Economy and End-of-Life Strategies

6.1. Decommissioning Challenges and Strategies

The development of wind energy system worldwide in the last two decades has posed waste management issues. The first generation of composite wind turbine blades are approaching their end-of-life in design. Today's utility scale blades are constructed of thermosetting epoxies that are

permanently cured and cannot be melted and molded. Millions of tons of reinforced polymer waste are due for decommissioning in the wind energy sector.

Traditionally, decommissioned blades were only landfilled. This is becoming more and more forbidden in the modern European legislation, including the EU Waste Framework Directive [26]. The most primitive recycling alternative is mechanical grinding. The composite structures are shredded using large industrial shredders to create fibrous powders and short fiberglass strands. Sometimes this recovered material is used in a low grade cement kiln processing or artificial wood

decking. An overview of conventional decommissioning approaches is given in Table 6.

Mechanical grinding severely degrades the structural integrity of both carbon and glass fibers. The short, chopped strands fail to sustain the tensile loads required for secondary

aerospace or advanced automotive applications. Consequently, the economic value of mechanically recycled composites remains near zero. This prevents the establishment of a profitable circular economy.

Table 6. Conventional Decommissioning and Disposal Strategies

Disposal Methodology	Implementation Cost	Environmental Impact	Material Recovery Value	Primary Industry Limitation
Direct Landfilling	Extremely Low	Severe (Non-biodegradable)	Zero	Banned in heavily regulated European energy markets
Mechanical Shredding	Moderate	Moderate (Dust generation)	Very Low	Completely destroys the structural integrity of the fibers
Cement Kiln Co Processing	Moderate	Low (Offsets coal usage)	Low (Thermal energy only)	Residual glass fibers alter the chemical composition of the cement

6.2. Advanced Recycling Paradigms and the Circular Economy

There is active research into advanced chemical and thermal recycling technologies to recover virgin quality continuous fibers from decommissioned blades. There are two most promising approaches to obtain high value carbon fibers from degrading epoxy matrices: pyrolysis and solvolysis. Pyrolysis is the process of raising the composite structures to very high temperatures in an absolute oxygen free reactor. The polymer resin is vaporized in this thermal degradation process, leaving the underlying carbon fiber network relatively intact. Solvolysis is the chemical cleavage of the polymer bonds at low temperatures, under high pressure supercritical fluids (water or methanol).

Table 7 gives the definitions of the thermodynamic variables in this equation.

A rigorous thermodynamic analysis is needed to demonstrate the viability of these advanced recycling processes. Engineers determine the net energy recovery to make sure that the recycling process doesn't use more energy than it saves.

$$E_{net} = E_{recovered} - (E_{processing} + E_{transport})$$

Table 7. Thermodynamic Recycling Variables

Symbol	Description	Standard Unit
E_{net}	Net positive or negative energy yielded by the recycling operation	Megajoules per kilogram (MJ/kg)
$E_{recovered}$	Embodied energy saved by displacing the manufacturing of virgin fibers	Megajoules per kilogram (MJ/kg)
$E_{processing}$	Thermal and electrical energy consumed by the pyrolysis or solvolysis reactor	Megajoules per kilogram (MJ/kg)
$E_{transport}$	Energy expended physically moving the massive blades to the recycling facility	Megajoules per kilogram (MJ/kg)

7. Conclusion

The rapid growth of global wind energy capacity is dependent on the limits of mechanical material science. The traditional glass fiber reinforced polymers are structurally inefficient due to extreme mass of the materials with the development of blade architectures beyond 100m. Based on this review, it is concluded that lightweight design is one of the factors that are significant in modern energy harvesting. The most promising route to achieving the greatest

aerodynamic swept area, while reducing the effects of increased gravitational fatigue, is the strategic use of carbon fiber spar caps and intelligent carbon glass hybridization. The new automated fiber placement technologies actively reduce the microstructural defects that are usually associated with massive resin infusion processes. The most pressing problem of the industry is environmental hazards to nature. To achieve a sustainable circular economy, the commercialization of recyclable thermoplastic matrices and advanced chemical solvolysis techniques needs to be fast-tracked. This decreases the accumulation of non-biodegradable polymer matrices in energy infrastructures life cycle.

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