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Performance investigation of using composites in wind turbine airfoils: Review

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A B S T R A C T

The rising interest in renewable energy sources, notably in high-performance and light-weight wind turbines, has resulted in rapid progress in the use of composite materials used in structural and airfoil design of wind turbines. The purpose of this review is to address the use of composites in wind turbine airfoils, with an emphasis on structural, aerodynamic, and manufacturing performance. The review begins by addressing airfoil geometry and fiber reinforced composites, including conventional glass and carbon fibers as well as nanostructured or hybrid materials. Mechanical, thermal, and fatigue properties are briefly discussed and assessed in conjunctions with benefits over metallic materials. Additionally, an overview of the use of composites in commercial turbines and experimental airfoils, and issues such as cost, recyclability, and structural health monitoring are examined. Finally, the review outlines some future trends in extending the use of composites, such as advanced nanomaterials, thermoplastic matrices, and bio materials, that are crucial for the next generation of high-performance, durable, and environmentally friendly wind-turbine airfoils.

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1. Introduction

Energy can be classified into two categories: renewable (hydro, wind, solar, wave) and non-renewable (fuel, coal, natural gas). In the 19th century, after the industrial revolution, coal and then oil were used as energy sources to satisfy the demands of modern societies.6 Climate change, environmental issues, and air pollution have led to the use of renewable energy sources to solve problems, and wind energy plays a significant role among these. While wind energy is recognized as a clean source of electricity, the variability of wind presents challenges to sustainability of electricity production, which requires improved technologies to overcome [1]. Thus, due to the increase in global demand for energy and also to respond to the climate emergency, employing optimal and efficient technologies in the wind energy space has become critical [2]. The importance of renewable energies has become a crucial issue with the growth of airfoil design, especially for wind turbines. Although several research groups have conducted research on airfoils using genetic algorithms and their optimization in the past decades most of the research has been dedicated to aircraft [3]. Tangler and Summers [4] initiated work on the aerodynamic design of wind turbine airfoils and developed a family of NREL airfoils specifically tailored for turbine blades. Hicks and colleagues [5] were among the first aerodynamicists to apply numerical optimization techniques to airfoil design. Similarly, Urbahs and co-workers [6] employed numerical analysis on the wind turbine blade profile ‘SPRO’ to evaluate the lift coefficient, angle of attack, and lift-to-drag ratio. Based on computational simulations, parameters such as flow velocity reduction, ideal power output, profile and tip losses, and tip speed ratio were quantified. Furthermore, optimal aerodynamic coefficients were determined for blades with and without geometric twist.

Among the widely used airfoil series, the DU airfoil family has been extensively applied in commercial wind turbine blades due to its reduced sensitivity to surface roughness [7].

Monroy Aceves et al. [8] conducted a study on the blade structure by fabricating low-speed wind turbine blades from composite materials with a unidirectionally reinforced uniform-thickness shell. Their research demonstrated the significant impact of material selection and design methods on the performance of composite wind turbine blade structures.

In parallel, different aerodynamic and mechanical braking systems have been employed to control wind turbine overspeed in high wind speeds. With respect to aerodynamic control, the method of speed reduction is to place grooves on the chord surface of blades. This has been shown to reduce rotor speed to the acceptable range by modifying the pressure distribution on the blade surface with no considerable loss of power production [9]. As part of this effort, Kumar and colleagues [10] have conducted experimental and computational work to study the effect of different groove parameters, such as groove length and placement along the chord, on power production and have optimized groove parameters.

Annual power output from a wind turbine depends on two key points on its power curve the speeds at which the turbine will safely turn on and off to prevent damage or stress. The power curve shows how much power the turbine is capable to produce for different wind speeds [9].

Planning and siting offshore wind turbines (OWT) requires environmental impact assessments. Such assessments help developers and owners assess whether and how to balance revenue from renewable energy and protection of the environment while ensuring wind turbine sustainability and/or environmental friendly [11]. One major challenge for manufacturers and operators is that turbine rotor blade material has experienced. The inadequacy of metals has led to the construction of blades made from epoxy resin reinforced with fiberglass and polyester. Reinforcements such as Kevlar or carbon fibers are also used to prevent cracking or breakage. Enel Green Power drew inspiration from a specialized technical fabric to develop its innovative blades [9, 12].

There is a research gap in identifying the optimal airfoil shape for low-wind regions like Bangladesh. The best one to maximize wind energy was three common NACA airfoils- 0012, 2412, and 4412. Furthermore, while various composite materials have been studied for wind turbine blades, carbon nanotubes (CNTs) have received little attention despite their excellent mechanical properties. The research also compares CNT composites with conventional materials to determine the most suitable option [13].

A new composite of recycled plastics and bamboo fibers for wind turbine blades was synthesized and investigated by Andoh et al. [14] The fiber percentages varied from 2.5% to 25% among ten samples, and with increasing percentage of bamboo fibers in the sample, the results showed an increase in impact fracture and tensile strength. As a result, it was found that a composite containing 25% bamboo fibers was a suitable option for making wind turbine rotor blades.

Lamhour his colleagues [15] developed a composite of wool and woven fabrics made of alpha fiber as a reinforced epoxy resin for wind turbine blades. Millikett et al. [16] studied the performance of hybrid composites reinforced with wool and woven fabrics of alpha fiber for wind turbine blades with natural fibers such as Nacha and sisal.

Due to the increasing energy consumption, the use of different energies has become one of the most prominent concerns of scientists, and the use of wind energy has been considered and examined in this article. The mastery of wind energy is based on the use of huge wind turbines, the most important part of which is the airfoils that are located in the turbine blades.

The design of airfoils and the selection of composite materials are very significant in improving the performance of wind turbines. A comprehensive study of the structural, aerodynamic, thermal and durability properties of new composite materials, especially in turbine blades, has been conducted in this review article. The geometric principles of airfoils, the classification of composite materials, mechanical properties and manufacturing methods have been discussed in detail, and the performance of these materials has been analyzed through simulation and laboratory studies.

Here, industrial and commercial applications, challenges such as cost and recyclability, and novel functionalities such as advanced hybrid composites and nanomaterials are under special study. In general, these materials solve advanced issues of space, producing high-performance, more durable, and more environmental wind turbine airfoils while recognizing more feasible areas of innovation for future research.

2. Fundamentals of wind turbine airfoils

Wind turbines represent a key technology used to harness wind energy and turn it into valuable electrical energy. Wind turbines are made up of three components: rotor, nacelle, and tower. The rotor captures the kinetic energy of the wind and transfers this energy into rotational motion. Inside the nacelle, a generator and gearbox convert the rotational motion of the rotor into electrical energy. The tower supports the nacelle and rotor and raises the nacelle and rotor to a sufficient height in order to gain access to strong and steady winds [17].

The most technologically relevant component of the rotor is the blade. The turbine blade alleviates wind energy and initiates rotation. The design of turbine blades is especially important in optimizing energy efficiency while avoiding costs for maintenance [18].

The appropriate selection of materials and profiles in airfoils is also important relative to the performance of the wind turbine and can impact power output, maintenance, and efficiency. The attention to advanced materials and the design of optimally profiled airfoils for wind turbine blade performance has increased substantially in recent years.

Wind turbine blades are engineered to convert wind energy to mechanical power and as a result use predominantly airfoil sections in their structure. Many of the airfoils used for wind turbine blades are designed to provide high lift and low drag, at high Reynolds numbers, while being very tolerant of surface roughness, which can have a dramatic influence on the overall performance of the wind turbine [17]. The most common airfoils in use include the RISO, DU, S-series, and FFA. BEM theory is widely used in blade design and optimization. The blade twist angle is adjusted so that the angle of attack at the design point is 5 degrees; this is the angle at which the SD2030 airfoil achieves the highest lift-to-drag ratio at a Reynolds number of 5×10^5 [19].

The curved shape of a wind turbine blade converts the kinetic energy of the wind into aerodynamic forces on the airfoil. The pressure difference between the airfoil surfaces creates lift, which in turn produces power. To increase efficiency, airfoils are designed to maximize lift while minimizing drag [20].

As demand for higher capacity and economic efficiency grows, wind turbines are being built larger and lighter, which increases flexibility and increases the structural loads on the tower, blades, and drive shaft.

These loads arise from gravity, aerodynamic forces, and random changes in wind speed and direction. Due to wind shear, the speed at the top of the rotor is higher than at the bottom, and this imbalance creates additional aerodynamic loads. further, gyroscopic effects caused by the rotation of the rotor impose periodic stresses on the blades and power transmission assembly, which in the long term leads to structural fatigue [21].

2.1. Airfoil geometry and aerodynamics

In wind turbines, the rotor speed is tracked in the region below the rated power (region II) proportional to the optimum speed and is kept at a constant value in the region above the rated power (region III) by the generator torque and blade angle adjustment. Suppose the wind turbine operates in regions II or III. In that case, the full-state feedback (FSF) control system, based on a PI observer (PIO), for wind turbines is illustrated in Fig. 1 [22]. For collective blade angle adjustment, classical PI controllers mainly only stabilize the rotor speed and have no effect on reducing structural loads.

Although in today's large turbines, active control loops at resonant frequencies are used to reduce tower and torsional vibrations in the power transmission system, separate designs can cause performance degradation or instability due to the strong coupling between these loops. For this reason, researchers have developed multiple-input multiple-output (MIMO) systems to reduce structural loads and simultaneously control the rotor speed [23, 24].

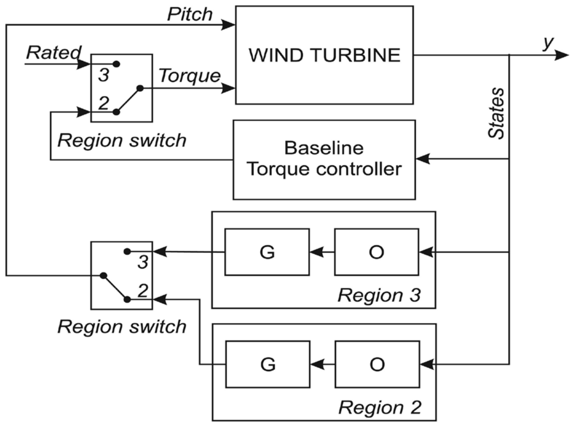

Fig. 1. System control wind turbine [25].

There are two main approaches to airfoil design: Inverse Design (ID), which is based on optimization of the gradient and fluid pressure distribution, and direct numerical optimization, which uses direct search algorithms to find the appropriate shape under geometric or aerodynamic constraints. In inverse design, the desired pressure distribution on the airfoil surface is first determined, and then the final shape is calculated by iteratively solving fluid dynamics problems (such as the Navier–Stokes, Euler, or area methods). The increase in computational power in recent years has made this method faster and more reliable, and has led to its widespread use [20].

The first studies on airfoil shape optimization based on the Navier–Stokes equations were presented by J.B. Malone [26] and L. Birckelbaw [27]. at the same time, tools based on potential flow solvers were most popular among researchers (for example, the work of B. Arlinger), although Euler equations were also used. From the early stages until now, viscous-inviscid methods have been the most important computational fluid dynamics (CFD) methods in airfoil design, as they require less computational cost and time than the full solution of the flow equations, while still providing reasonable accuracy [28].

2.2. Load conditions and performance metrics

Wind turbine components are subjected to variable stresses due to wind speed changes, which gradually cause fatigue and reduce their life. To evaluate these structural loads, the main criterion is the fatigue load, which is calculated by Miner's rule. More specifically, the total damage at each stress level can be estimated from the number of cycles to failure and obtained from the material's experimental S-N curve using Miner's law, k. When the total damage exceeds a critical value ($1 \leq i \leq k$), the part will fail.

Table 1
Comparison of airfoils in terms of Reynolds number.

Reynolds number (Re)	Flow type	Equations CFD	Model/ indicator tool for airfoil	Description	Ref.
Re < 10^4 (lower)	Laminar	Navier-Stokes	XFOIL, Simple models	No need for a specific turbulence model	[29]
10^4 < Re < 5×10^5 (average)	Transitional/Turbulent	Compressible/Incompressible RANS	Spalart –Allmaras, D'Alessandro L-T	Exact solution, laminar to turbulent transition model	[30]
Re > 10^6 (higher)	Turbulent	Compressible Euler or RANS	SST model, Reynolds Stress, Fluent	Multi-equation models and industrial solvers	[31]

In this method, for each different stress level S_i, the number of tolerable cycles N_i and the number of cycles performed n_i are obtained from material tests, and the cumulative damage is calculated according to Miner's rule [25].

$$D_{ac} = \sum_{i=1}^{k} D_i = \sum_{i=1}^{k} \frac{n_i(S_i)}{N_i(S_i)} \quad (1)$$

The damage increment (Di) and cumulative damage (Dac) are defined over the useful life of the system; when the cumulative damage reaches a certain limit equal to or greater than 1, the system fails. To analyze the variable stress spectra, the Rain-flow Counting (RFC) algorithm is used, which converts this complex spectrum into simple load levels and allows the application of Miner's law. To measure the damage over a time interval, the equivalent fatigue load DEL (DEL) is defined, which is a constant amplitude load equivalent to variable loads and produces similar damage.

$$DEL = \left(\frac{\sum_i n_i S_i^m}{N}\right)^{\frac{1}{m}} \quad (2)$$

In the above formula, N represents the total equivalent fatigue number, m represents the Wöhler profile, and both are determined by experiment [25].

The most optimal power generation is achieved by determining the angle of attack and designing the composite rotor blade with an airfoil section. In the design of small horizontal axis rotors, SG6043 and SG6042 airfoils were selected due to their high maximum lift coefficient, wide drag range and high CL / CD ratio. The optimal angle of attack was 6º degrees, which showed the highest performance for the designed rotor. In the simulation of three common airfoils NACA 2412, NACA 4412 and NACA 0012 in ANSYS Workbench software, the NACA 4412 airfoil with a lift coefficient of CL = 1.654 CL = 1.654 had the best performance at an angle of attack of 15º degrees, which can be considered as the best profile in this study [32].

2.3. Challenges in airfoil design

Airfoil design and development play a key role in the exploitation of wind energy. Today, there is an increase in the use of small-scale wind turbines for installation in buildings and urban areas, and research in these areas has become more focused [33]. Airfoil designs intended for large wind turbines are typically not effective for small turbines and should be modified/adapted. When optimizing the performance of these airfoils, there is a need for careful studies and dedicated modeling. While CFD simulations offer useful tools for this study, there is still a need for research into the credibility and efficiency of the models being used. Hence, the incompatibility of airfoil designs with different applications and the limitations of the CFD modeling is an important challenge for designers. Additionally, a majority of airfoils are developed through the inverse design method by defining the velocity distribution in specific angles of attack and extracting the final shape from it [20]. The significant limitation of the inverse design method is its inability to address multi-objective design problems, whether point or single objective. Therefore, it adds challenges to the design process. Airfoil modeling is largely dependent on parameters like penalty function coefficients, number of constraints, degrees of freedom in CST fashion, and population size in the CMA-ES algorithm. Therefore, one of the main challenges in this area is to minimize uncertainty with respect to field measurements. The unpredictable and sporadic nature of wind speed that is outside of the experimentlists control mixed with temperature and pressure fluctuations create a fundamentally chaotic environment. These factors create additional layers of complexity that cause uncertainty not only in predicting the available energy but also in creating a wider uncertainty in the analyses [34].

3. Composite materials in wind turbine applications

Composite materials are sought after for their combination of mechanical strength properties similar to a metal with the benefit of low weight. This unique combination makes composites an excellent option for applications where reducing structural weight is of primary importance. One essential property is their resistance to fatigue loading and cracking, with composites reinforced with fiber fillers exhibiting less cracking than metallic materials. Within the structures of wind turbines and rotor blades in particular, these characteristics are important for improving energy efficiency, required operational life [35, 36]. Most custom-built composites consist of multiple elements, with a core material in the form of filers (reinforcement) embedded in a matrix that ultimately increases the stiffness and strength of the structure. In wind turbines blades, the selection of the matrix and reinforcement has a direct impact on not only the distribution of stiffness, but also the ability to resist aerodynamic and gravitational loads during rotation [37]. The utilization of composite materials is a trending area in wind turbine development, particularly as it relates to reinforcements. By definition, composites are two or more different materials combined into a multitude of material types produced by a series of processes such as compression and pressing. Most people commonly think of a composite material as two materials made of a matrix and a reinforcement. Together they create materials that perform better than their individual base materials. There are many composites encountered on a daily basis, from the fiberglass in your eyeglasses, clay bricks, and concrete. The matrix is often a homogeneous polymer that protects the fibers from structural stress, and even chemical damage. It will also provide shape and stiffness, resist buckling under compressive loads, and dissipate load stress [38]. Composites are divided into four categories based on matrix phase types. These categories are metal matrix, polymer matrix, ceramic matrix, and carbon matrix. Reinforcements are usually fibers that provide stiffness. Reinforcements are classified as structural, particulate, and fibers. These materials have applications such as in aircraft bodies, buildings, bridges, and racing cars. Advanced research is underway to develop hybrids composites and improve their properties all the way down to the nanoscale. Hybrid composites note usage for combined organic and inorganic components at the molecular level. Glass-reinforced epoxies and carbon-aramid reinforced epoxies are some of the more common examples of hybrid composites. In the context of wind energy systems, polymer-matrix composites, and especially epoxy systems with glass or carbon fiber reinforcement, are the primary materials used due to their high fatigue resistance and the ease which they can be manufactured in larger dimensions [39]. Recent work is being done on the development of a new category of hybrid composites containing different fibers or matrices, and a focus on contributing to specific mechanical properties. Such hybrids include glass and carbon fiber reinforced epoxy, and a carbon-aramid hybrid that balances the strength, stiffness, and impact resistance of a material. With respect to blades, hybrids can add to blade reliability, with enhanced structural performance that is capable of adapting for changing environmental and loading conditions [40]. Some factors that contribute to the failure of wind turbine blades include creep, mechanical fatigue and high stress. Traditional wind turbine blades that are molded from one material will typically fail more often, as single material blades have a shorter life expectancy than blades made of composites. Utilizing fiber reinforced composites also improves the fatigue life, inhibits the propagation of cracking, and creates the opportunity for blades to be longer, lighter, and of aerodynamic configuration [41]. In marine applications, specifically saline environments corrosion is a significant threat to large-scale energy generation systems like wind turbines. If wind turbine rotor blades are tied to performance using composite materials, understanding their properties in harsh environments is essential for fabricating rotor blades that can withstand these conditions while maintaining improved durability and longer-term structural performance. This offers a unique composites solution for OWT where exposure to moisture and salt can accelerate the corrosion of traditional metal components [40]. Composites also offer the ability to create materials with tailored properties that cannot be achieved through conventional metallurgical methods. For instance, the specific strength of carbon and aramid fibers is approximately six times higher than that of titanium and ten times higher than steel [42].

3.1. Types of composite materials

Composite materials are further separated into various categories depending on the type of phase present. There are four types of matrix materials namely polymer matrix composites, metal matrix composite, carbon matrix composite and ceramic matrix composite [43]. Further advancements are being made to improve the structure of composites by making adjustments at nanoscale level. Hybrid composites comprise two elements at the molecular level, inorganic part and the organic part. The most common type of hybrid composites is carbon aramid reinforced epoxy and glass reinforced epoxy composite. Hence a new category of materials i.e. composite materials were experimented to replace the prevenient turbine blades and proved to be successful. to improve the properties of the composite material as we go through this paper [44, 45]. Epoxy, vinyl esters, polyesters and thermoplastics are often preferred as wind turbine blade matrices for composite materials [46]. More than 80% of reinforced composites for wind turbine blades are manufactured from thermoset plastics. Glass-reinforced plastics (GRP) are the most widely used composite materials in the wind turbine industry. Compared with glass fibers, carbon fibers exhibit lower damage tolerance, poorer compressive properties, and lower ultimate strain, in addition to being more expensive. As a result, GRP dominates the market because of its favorable mechanical properties and low cost [47]. Composite or fiber-reinforced plastic airfoils have been employed in the construction of offshore floating wind turbine (FOWT) blades. Furthermore, composite bucket foundations (CBF) have been developed as an innovative and environmentally friendly solution for supporting OWT [48]. Advanced composite materials (ACMs), a type of polymer matrix composites, possess exceptional properties such as high tensile modulus, low weight and exceptional stiffness and strength. ACMs' remarkable properties enable their increasingly popular use in critical engineering versus metallic materials. Beyond these significant mechanical advantages, ACMs feature high corrosion resistence and, in many applications, impressive electrical characteristics. The fabrication of thermoplastic composites typically follows a cycle of heating, compression and cooling phases which allow for reproducible fabrication of parts that display complex geometries [49]. Recently, progress has arisen from the implementation of low-viscosity polybutylene terephthalate (PBT) resins, enabling more effective resin infiltration, improved production throughput, and reduced cost associated with composite material production [50]. In this context, the production of carbon fiber reinforced composites is frequently optimaized as NACA 23018 airfoils in studies. This approach utilizes rotational weaving in an efficient method of producing seamless preforms that display complex geometries. In these experimental and numerical studies, biaxial and triaxial preforms were woven and then saturated with epoxy resin. The findings reported that the axial carbon fibers were optimally aligned along the longitudinal direction in triaxial composites resulting in higher mechanical properties [30]. The composite material used in the airfoil section of the blade consists of unidirectional E-glass fibers (E-glass UD) and epoxy resin, forming a four-layer sandwich structure with a total thickness of 0.2 mm and a standard layup pattern of [0° / +45° / –45° / 90°]. The number of sandwich layers varies across different regions of the airfoil, and this structural configuration is analyzed using a finite element model [51]. Nicholas and his colleagues, [52] using genetic algorithm (GA), artificial neural network (ANN) and blade element theory (BEMT), optimized the arrangement of composite layers in wind turbine blades and reported about 10% improvement in blade performance; this method helped to increase the buckling resistance of a 61-meter blade by changing the sequence of matrix fiber arrangement. Also, Grogan et al. [53] conducted a comparative study between carbon fiber reinforced composites (CFRP) and glass fiber reinforced composites (GFRP), which showed that over a 12-meter blade length, the hydrodynamic load was reduced towards the tip and the strain-to-stress ratio in GFRP layers was higher than that in CFRP.

3.2. Mechanical and thermal properties

Composites used in energy generation devices mainly have two main functions. The first category is composite materials that provide the necessary strength for structures (such as wind turbine blades), the second category is conductive polymers that are an attractive option for future energy storage due to their low weight, flexibility, high electrical conductivity (>103 S·cm−1), tunable resistance over a wide range, and reasonable cost. These conductive polymers can be easily used in composites and coated on other materials, and their physical and chemical properties (such as chemical stability, miscibility, compatibility, and cross-linking) can be controlled by modifying the chemical structure [54]. The mechanical properties of polymer composites are improved by adding nanoparticles to the polymer matrix (as a discrete phase). Boller and Strunk have shown that nanostructured materials play an important role in addressing energy and conversion challenges [55]. Due to the orthotropic mechanical properties of composites, the structural properties of the sheet depend on the fiber orientation. In their study, Turgresa et al. [56] discussed the benefits of optimizing the angle of each layer of the composite and reported that for improving turbine efficiency, the inclined structure increases the critical wind speed for the control and electrical systems by about 10%. Wind turbines are usually of the horizontal axis type (HAWT) for power generation. The development of vertical axis turbines (VAWT) has been stalled due to the low tip speed ratio and difficulty in controlling the rotor speed [44]. The main part of the turbine, which is also expensive, is the blades, which are made as curved airfoils similar to aircraft wings to create lift by creating a low pressure area. There are also mixed or smooth blades, which are not widely used due to the high drag. The tip speed ratio (TSR), which is the ratio of the rotor tip speed to the wind speed, is one of the factors affecting the performance of the blades and depends on the geometric design and number of blades. The blade structure consists of two shell surfaces connected by transverse plates or support bars. The blades are subjected to two main types of loads: flap-wise loads, which are restrained by the struts, and edgewise loads, which are carried by the edges of the airfoil. Cyclic tensile loads are applied on the pressure side of the blade and cyclic compressive loads are applied on the suction side of the blade at various locations [40]. Thermoplastics develop and solidify by first melting the material and then solidifying it, this is done very rapidly. The thermoplastic solidification process results in thermal shrinkage and internal stresses, which can be quite large due to the high melting and processing temperatures of thermoplastics. Ultimately, internal stresses have a negative impact on the mechanical properties of the thermoplastic [45].

4. Performance evaluation of composites in airfoils

The principal focus in composite design can be defined as low weight while maintaining high strength and stiffness, commonly measured as specific modulus and specific strength. The mechanical behavior of composite structures is mostly determined by the properties of the fibers and the mechanics of load transfer from the matrix to the fibers through the fiber-matrix bond. The deformation of the matrix surrounding the fibers will be a result of the applied loads [37].

4.1. Structural optimization of composite airfoils

The aerodynamic shape of a composite wind turbine blade is normally achieved through relatively thin outer casings which are aided by internal structure - like support plates or a longitudinal beam - where a significant portion of the blade load is carried, particularly in the longitudinal direction. To optimize aerodynamic performance and structural efficiency, rotor blades are often twisted and tapered. The anisotropic nature of composite materials allows for the optimization of the blade geometry and internal reinforcement layout to align fiber direction with principal load paths, improving the structural stiffness while minimizing the weight of the materials [45]. To keep the blade weight low while maintaining strength, load distributions are typically increased from the blade tip to the blade root, as allowed by the cantilevered structure. Tapering is generally designed so that the material is used equally, both in the external surfaces and in the thickness of internal structures or elements such as plates, shells and beams, up to the acceptable strain limits. In composite airfoils, this geometry optimization also helps ensure that stresses are applied evenly across the different layers of laminates to improve load-carrying efficiency and blade fatigue life [57].

It is important to understand the aerodynamic pressure distribution in order to optimize the structural response of the composite blade, as aerodynamic loads have a direct effect on internal stress and deformation of the material. Hansen, used, pressure coefficient analysis to investigate flow phenomena in an airfoil, focusing specifically on flow separation and laminar separation bubbles. Dong et al. [32], observed flow characteristics at increasing angles of attack (AoA), reporting that flow separation and transition occurred further upstream by moving towards the leading edge. They also observed that the stall angle decreased with lower Re, Additionally, the co-authors of Park indicated that increasing AoA gradient increases adverse pressure on the suction side of the airfoil which moves the separation point and the laminar separation bubble upstream. All of these factors lead to an earlier stall condition and worse aerodynamic performance of the blade.

4.2. Fatigue resistance and material durability

The orientation of fibers plays a critical role in the strength of a composite. The mechanical properties of fibers can vary depending on the type of orientation, such as continuous orientation, discontinuous orientation, or random orientation; this can give rise to stress-strain behavior for both the fiber phase and matrix phase dependent on the loading direction and volume ratio of each of the fiber and matrix phases, and may result in ultimate failure or damage of composite. One of the biggest challenges in optimizing weight and strength for composites used in unmanned aircraft is identifying orientation of the layers, fiber orientations, and loading directions which need to be properly utilized to achieve the required durability and/or performance [58]. In addition, Kanesan et al. [37] used ABAQUS software to study the deformation of a composite wing of a NACA4415 airfoil at different locations. The static analysis involved applying a distributed load on the lower wing skin directly on the main and trailing spars at different distances. The maximum deformation was determined to be near the tip of the wing and was observed to be 0.35% to 16.4% compared to the bending test in static load.

4.3. Aerodynamic performance and efficiency

The fabric that reinforces and the matrix of the composite blade can be molded into double curvature, which is necessary for complex aerodynamic forms. The core in a sandwich structure is particularly useful in providing separation between the load-bearing components and allowing loads to be transferred through shear forces within the structure [59]. Hegespo H. Mwanyika et al. [32] reported that the geometric and aerodynamic characteristics of small horizontal-axis wind turbine blades placed limits on the efficiency to extract energy. Composite blades improved energy production efficiency, but uncertainties still exist regarding optimal angle of attack determination and predicting aerodynamic performance in off-design scenarios. The SG6042 and SG6043 airfoils were chosen in the study to use in composite blades. Five turbine models were developed to have design angles of attack from 3° to 7° and CFD simulations were utilized to discover the optimal angle of attack. Performance was improved in the composite blades compared to the historical design, resulting in power production ranging from 4,966 to 5,258 watts with rotor power coefficients between 0.443 and 0.457, with optimal performance occurring at 6° angle of attack. XFOIL was also used to conduct aerodynamic performance analyses of the airfoils as it has been suggested through researchers' work to be accurate for low Reynolds numbers while also being efficient to use, replicating many of the iterations necessary for the optimization phase [60]. Singh and colleagues [61] were able to determine an optimal angle of attack that lessened the separation of the flow and increased aerodynamics and efficiency.

4.4. Environmental resistance (UV, moisture, etc.)

As demand for sustainable energy solutions continues to grow, Nguyen et al. [62] indicated that future directions in research should include a priority on the assessment of the environmental impacts associated with various materials used in wind energy systems. Life Cycle Assessment (LCA) provides a holistic way to evaluate the environmental implications of different materials and helps select less harmful materials in the future. Research is needed to develop bio-based composites that reduce environmental impact while performance is maintained. The next step in sustainability is considering the integration of recycled materials into the production of composites [63]. With advancements in the wind energy industry, the consideration of material recyclability in turbine construction has increased in importance [64]. Fischer et al. [65] emphasize the need to pursue recyclable composites that can be effectively reprocessed at the completion of the product's lifecycle. Research should examine how to retrieve and reuse materials from decommissioned turbines in order to realize a circular economy, as well as minimize waste and reduce the overall environmental impact of the wind energy systems.

5. Manufacturing techniques for composite airfoils

The vacuum-assisted resin transfer moulding is suitable for manufacturing components that are large. This technology has been in existence since the 1980s. It is a well-known method for building wind turbine blades [66]. The technology involves unidirectional fibers being positioned in the same direction as the blade length. Polymer foams or wood are sometimes used, as well. Forming the laminate involves the plies moving from the root to the tip, especially for the manufacturing of roots that are thick. With the help of the vacuum bag, these fabrics are covered. Infusion technology is often preferred for manufacturing wind turbines compared to the prepreg approach, because infusion is cheap [41]. A variety of techniques are available for manufacturing composites, including pre-pressing, compression molding, threading, vacuum molding, resin transfer molding, and pultrusion, among others [67]. To receive high aerodynamic performance, micro wind rotors are fabricated with thin airfoil profiles to reduce laminar flow separation. Although the fabrication of these blades is somewhat complex, there are common methods such as die casting and composite fabrication, which require expensive molds. Meanwhile, 3D printing is both expensive and of low quality with limited part scalability. However, accurate manufacturing of small rotors is a challenge due to the very short chord length, the combination of thin airfoil edges and very sharp ends with low Reynolds numbers [68]. The 3D printing technique used to produce the composite wind turbine airfoils employed (acrylonitrile butadiene styrene) ABS and (polylactic acid) PLA materials, selected for their affordability, wide availability, and compatibility with standard 3D printers. These plastics are among the most commonly used in 3D printing and can be easily extruded by most commercial extruders. A major advantage of PLA is that it can be printed without a heated bed, which reduces printer complexity and cost. Depending on the volume, producing 3D-printed blades using the FDM method can take between 6 and 12 hours for one-meter blades, with printing a three-blade turbine requiring approximately 5 to 7 days [69]. Due to global demand, 3D printing is widely used for fabricating the edges of turbine blades. Engineering software was employed to create detailed designs to facilitate the deployment of 3D-printed wind turbines. The horizontal-axis wind turbine was built at a small scale, reflecting increased development and production efforts. Using ABS filament helps reduce manufacturing costs and enables completion within approximately 28 hours [70].

Wind turbine blades can be manufactured using classical composite manufacturing processes. Previously, a wet lay-up process was used to produce small to medium-sized blades, in which epoxy resin was often used as a matrix, by brush or roller application, on various reinforcements, including glass fibers. Although the two skins were bonded to the struts with adhesives, this process is not recommended due to the lack of quality assurance, adverse environmental effects, and high labor costs. Recently, vacuum injection techniques and pre-mold technology have been used to overcome the challenges of the previous method, which improve quality and speed up production time. In large blades, they were manufactured by a resin injection process, in which resin is injected into the spaced fibers under high pressure and cured by heat [71]. In Fig. 2, the methods of texturing 3D composites on blades were examined. Wind turbine blades are produced in two stages, first the composite blade which is made of traditional glass fibers and is produced manually which has low efficiency and strict quality control and is also not suitable for large scale.

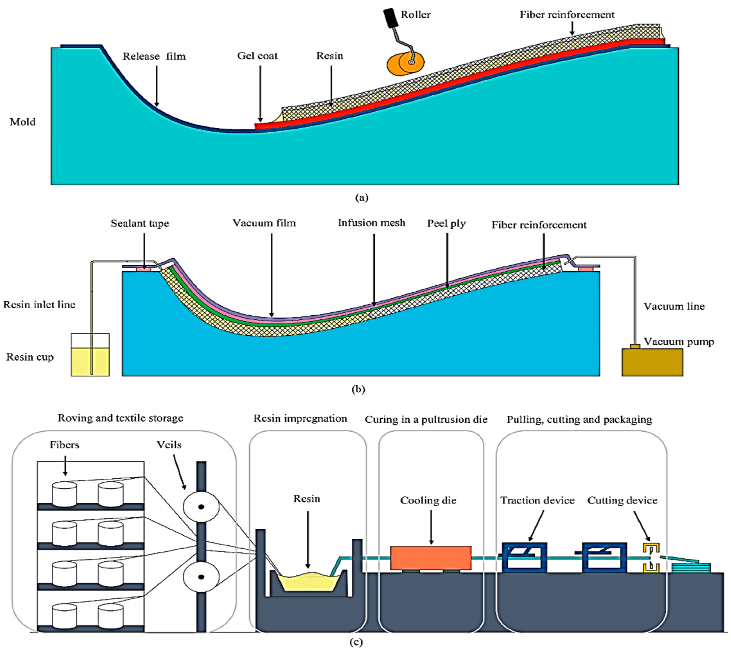

Fig. 2. The technology for manufacturing wind turbine blades includes the main steps: (a) manual layering; (b) vacuum injection process; and (c) pultrusion process [72].

Then the pre-preg vacuum bag is pressed and the resin injection is done by vacuum of the fabric. These two stages are very expensive and low efficiency and blades over 40 meters cannot be produced by this means, so some companies have used carbon fibers which although have good performance but are still expensive. In addition, the high porosity and low content of carbon fibers have limited its use. Vestas Denmark has implemented the pultrusion process on the main spar and has optimized the production of wind turbine blades using carbon fiber composites [72].

5.1. Wet hand lay-up

The earliest types of wind turbines were produced using wet hand lay-up technology (Fig. 3). Impregnation of the glass fiber was carried out with the aid of rollers and paint brushes. Using an adhesive, the shells were connected to the spars. Small and medium wind turbine blades were manufactured using this method [41].

The composite manufacturing process can be broadly classified into two types: open lamination and closed mold lamination. Among the open lamination processes, wet manual lamination is the first method for manufacturing composite parts, in which a thermosetting resin is poured onto a fabric layer and placed in a one-sided mold. Alternatively, a brush or roller may be used manually to apply pressure to the impregnated fabric layer. After this, another layer is added to the previous layer and the same process continues until the desired laminate layer is formed [73].

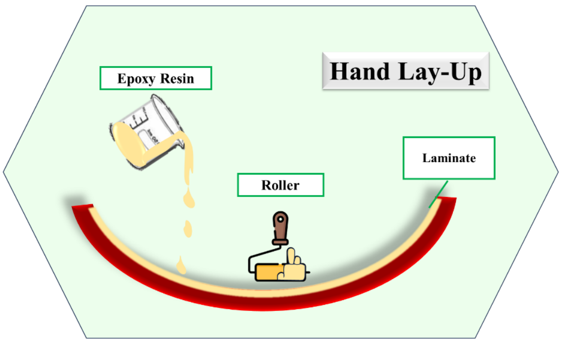

Fig. 3. Wet hand lay-up of the open lay-up process

5.2. Resin transfer molding

Today, among the available technologies, resin transfer molding (RTM) is one of the most promising technologies. RTM can produce large, advanced three-dimensional parts with high surface finish, excellent mechanical performance, and precise dimensional tolerances. The three-dimensional design of parts by RTM can create a structure similar to the final shape and, with inexpensive tooling, produce cost-effective structural parts in medium sizes. Another advantage of RTM is that it solves the problem of joints in metal structures by integrating the joining parts [74].

The RTM process first casts a reinforcing layer or preforms in a two-sided closed mold, then after the mold is closed, resin is passed through the length and width of the mold by creating a vacuum or pressure or a combination of both. After pouring the resin, the cured part is removed from the mold. This RTM process is very versatile and molding is performed without the influence of pressure and heat or with them. Of course, this method has limitations in the manufacture of turbine blades, but still RTM has many advantages over the manual layering technique [75].

Huang and Yang [76] prepared bamboo fibers with epoxy to form reinforced composites using quasi-unidirectional fibers for orientation by RTM process. The fibers were mixed with a 0.1 N sodium hydroxide solution. This alkaline solution improved the properties such as impact, tensile, and shear strength of the bamboo fiber composites.

Nabinezhad et al. [77] also produced vacuum-reinforced composites using bamboo fibers and polyesters using the same method. During their research, they treated bamboo fibers with 3, 5, and 7% sodium hydroxide and evaluated the optimal percentage of the treatment agents based on the experimental results.

5.3. Vacuum infusion

One turbine blade manufacturer is Danish company LM Glasfiber, which has produced its latest 61.5-meter-long blade using vacuum resin injection technology. First, dry fibers are coated with a polymer film that is sealed to the edge of a mold, and a vacuum draws the resin into the fibers. Once all the fibers are wet, atmospheric pressure outside the film draws the laminate to the surface, allowing the resin to cure. The airfoils and webs are manufactured separately and then assembled to form a complete blade [45].

5.4. Prepreg-based fabrication

Thermal elements of the anti-icing system in the airfoils are manufactured from Necote E-765 epoxy/fiberglass pre-preg, a product of Park Electrochemical Advanced Materials Technology Company, and the thermal element is a constantan wire (SPCC-010-50) with a diameter of 0.25 mm from Omega Engineering Company. The polymer composite layers are made with a total thickness of 1.4 mm and are made of six layers by dry manual layering. The anti-icing system is placed inside the composite airfoil, which is embedded with equal lengths and at desired distances between the composite layers. After placing three layers of pre-preg, the thermal elements are aligned perpendicular to the chord line of the airfoil and another three layers of pre-preg are placed on them [78].

5.5. Additive manufacturing

Additive manufacturing (AM) is a new technology that, unlike traditional manufacturing, uses computer data and analysis to create a three-dimensional model of the desired object layer by layer. A key benefit of this technology is that it can produce customized parts at lower costs and in limited volumes. It also enables dissimilar materials to be optimized for complex parts based on the topology and use case. This is of utmost importance in industries such as aerospace, automotive, and medical, which all together make up 18.2% of the market share globally in 2017. Aerospace components that historically receive high value from additive manufacturing processes include brackets, airliner wing centers, jet engines, and wing assemblies. Recent studies have looked to consolidate the steps of manufacturing and distribution into these processes. The most common additive manufacturing methods includes, sheet lamination, jetting, photopolymerization, material extrusion, powder bed fusion (PBF), directed energy deposition (DED), material jetting, and adhesive bonding. DED, powder bed fusion, and robotic fiber placement (RFP) are some of the methods that are used in the aerospace industry [79].

6. Applications

As modern industries continue to grow rapidly, there is an increasing interest in the use of innovative techniques in production within fields such as fiber-reinforced composites, knitting, embroidery, and filament twisting [80]. Paolo Betti and colleagues introduced a method that utilizes the chiral properties of honeycomb structures by employing fiber-reinforced composite technology. This method consists of multiple steps. The initial step involves producing thin, curved laminates using vacuum bag technology, followed by bonding the laminates together in future steps and, finally, assembling the parts to achieve a chiral topology. This specific configuration is widely utilized in deformable airfoil designs. Notably, long fiber-reinforced polymers have been employed to enhance the deformability of chiral structural topologies. Despite the unusual geometric features of the chiral composite honeycomb and the complex mechanical properties of its chiral components, this research achieved promising experimental results [81].

6.1. Commercial wind turbines using composites

Large power plants have been built across the world, both onshore and offshore, with commercial wind turbine capacities ranging from 2 to 5 megawatts [45].

For clarity, well-known observer-based full-state controllers PI and CPC are used for explanation. PI controllers are commonly used in commercial wind turbines, while one of the most advanced modern techniques is observer-based full-state control, which is used for practical turbine control [82].

McCarthy and colleagues evaluated three manufacturing methods for making blade shells and concluded that woven fabric techniques were more efficient and offered better production rates, woven structures, resistance to slippage during weaving, and impact durability. Woven fabrics are classified into two types: 2D and 3D. The former can produce tubular or flat biaxial / triaxial preforms. Circular knitting machines can create tubular parts with nearly pure shapes and significantly faster production than traditional techniques such as preforms and automatic taping [83].

One key benefit of circular weaving is its exceptional conformability, enabling the production of complex geometries nearly in net shape without the need for cutting or stitching, which lowers costs and shortens production times compared to conventional methods. Numerous commercial applications exist for woven composite structures, such as lightweight hybrid gears, structural body components for drive mechanisms, concrete reinforcement rods, fan casings, shafts, and others. For instance, Jackson fabricated four aerospace structural components using different types of prepregs, including woven fabric processes [84].

6.2. Experimental studies and simulation results

Types of woven composites, only a few of which have been investigated in detail. In particular, a number of analytical models were developed under NASA's 'ACT' program to predict the stiffness of textile composites. These models were based on the finite element method, averaging techniques incorporating iso-strain or iso-stress assumptions, and beam theory [85].

The cross-sectional geometry of an airfoil resembles the natural form of a dolphin's flipper, characterized by a rounded leading edge and a sharp trailing edge, features that are essential for efficient aerodynamic performance. Depending on curvature, the upper and lower surfaces can be either symmetrical or asymmetrical. The NACA (as shown in Fig. 4) contributed significantly to airfoil development by introducing standardized families of airfoils with well-defined cross-sectional profiles, which have been widely adopted in research and engineering applications [84, 86]. To enhance the strength and stiffness of the composite, fibrous material was embedded in a resin matrix with alternating fiber orientations. Composites offer several advantages, including high strength and stiffness, low density, relatively low weight, electrical resistivity, and corrosion resistance, all of which stem from the microstructural characteristics on scales larger than approximately (1μm) [87].

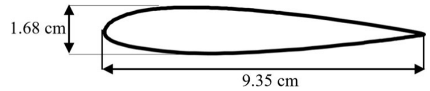

Fig. 4. Schematic of a simple, primitive NACA 23018 airfoil [84].

For the present study, a two-component epoxy resin (EP411) was used as the matrix, while T300-12K carbon fibers were arranged in axial and woven yarn configurations. The specimens were then tested using a Zwick universal testing machine (model 1446-60) in accordance with ASTM D4018-17 [84].

In their work, Jia et al. [88] presented a novel method, termed Reinforcement Learning-based Twist Angle Distribution (RL-TAD), which converges to the optimal twist angle distribution (TAD) 3 to 5 times faster than traditional genetic algorithm-based methods. Soheil and Farzaneh [89] proposed a comprehensive mathematical modeling approach aimed at maximizing the power coefficient (Cp) to optimize the tip speed ratio (TSR) and blade pitch angle. The presented model accurately considers the power losses in different parts of the wind turbine and can be used to calculate the optimal power output. This model can be applied to both gearbox and direct drive configurations

It is proposed to use airfoils with high lift-to-drag ratios in the outer regions of the rotor blades to increase the power generation of wind turbines. Therefore, in order to achieve an optimal airfoil, it is necessary to adjust the structural and aerodynamic parameters. For example, using thicker airfoils with high lift generation capability in the blade root section can be effective. Typically, wind turbines operate at a constant tip speed ratio across varying wind speeds and perform best at a single angle of attack. However, due to sudden wind speed fluctuations caused by atmospheric turbulence or delayed control system responses, airfoils must be designed to maintain high performance within a range around the optimal design point [90]. On the other hand, further investigation of design approaches based on weather data is needed, as design conditions also depend on the operating environment. Simulations showed a competition between interface separation and matrix cracking, where in the cracked regions, the interface was dominant, matrix cracking and fiber breakage were both delayed [20]. Conversely, in the regions where long matrix cracks developed, fiber cracking did not lead to interface damage. Furthermore, clustered fiber arrangements led to premature fiber failure under lower loads. Incorporating nanoreinforcements into the fiber sizes, depending on their orientation and shape, can also change the dominant failure mechanisms of the composites, from interface separation-controlled failure (in the case of horizontal cylindrical nanoparticles) to fiber-dominated failure (in the case of spherical nanoparticles) [91].

7. Challenges and limitations

The performance of a composite is strongly influenced by factors such as the manufacturing route and the selection of matrix and reinforcement. From the onset of production, structural defects must be considered, as they can initiate damage and lead to premature failure of the component. In composites, damage refers to microstructural changes that reduce load-bearing capacity and, in severe cases, cause catastrophic failure. Such defects may arise at the fiber–matrix interface or on the surfaces of the constituents [74]. Composites with glass and carbon fibers, while lightweight and corrosion-resistant, are expensive and have environmental concerns. For this reason, research has focused on replacing these materials with natural fibers and hybrid compounds with the aim of reducing costs and improving sustainability [9]. Gradient-based methods are not suitable due to the complexity of the optimization problems and the possibility of multiple local minima. XFOIL simulations can also introduce problems such as incorrect gradients and non-convergence [92]. On the other hand, ceramic matrix composites such as C/SiC are used in high-temperature parts of space vehicles, but scaling up their production from small to large parts is challenging. The future of widespread use of these materials requires solving these problems [93].

7.1. Cost and scalability

The design and fabrication of chiral composite cores has been advocated as an effective tool in the deformation of aircraft structures, and the possibility of experimental and numerical investigation is a solution designed for shells, which, in addition to its application in various engineering fields, is also associated with the limitations of chiral composite cores [81].

On the other hand, improving the aerodynamic efficiency of turbine rotor blades requires designing beyond simple shapes by combining tapering, twisting, cost-effectiveness, and optimal material selection. The hybrid use of glass and carbon composites creates a balance between improved performance and cost, which has been accompanied by a reduction in the fabrication of all-carbon blades [45].

While glass fiber (GF) reinforced composites may be perceived as more cost-effective than carbon fiber (CF) based on lower production costs and energy consumption, a more thorough assessment of life cycle benefits and the recyclability of glass fiber reinforced plastic (GFRP) materials is warranted. These approaches are key to developing lightweight and strong structures in the aerospace industry [94, 95].

7.2. Damage detection and maintenance

Health monitoring methods for wind turbine blades include aerodynamic analysis, acoustic emission, strain measurement, vibration detection, thermal and acoustic characterization, and machine vision. Statistical analysis of the available literature using Python shows that damage detection technologies are widespread. This data focuses particularly on the application of blade damage detection by detecting blade aerodynamic noise and acoustic emission (AE). The presented graphs 2c show the research trend of non-destructive testing (NDT) methods in recent years, highlighting the use of AE and 2b aerodynamic noise as key technologies (as shown in Fig. 5) [96].

Ogaili et al. [97] combined finite element analysis and machine learning methods to detect blade damage. However, damage detection due to the presence of signals in vibrations has a certain time lag. If the damage exceeds the allowable threshold, damage detection can be achieved.

They also found that all the factors that can limit the NDT-based vibration signal for detecting wind turbine blade defects include the blade and wind speed, the number of vibration signal-based damage discrimination sensors, and the signal-to-noise ratio.

7.3. Recycling and sustainability issues

In order to protect the environment and reduce energy consumption, composite recycling is being developed, aiming to produce high-value recycled products for sustainable development.

The integration of wind energy, natural fibers, and thermoplastic composites is green and economical, and helps to expand the wind industry towards sustainability. Thermosets are recycled in three ways, including chemical, mechanical, and thermal recycling. Among these three methods, mechanical recycling is the simplest method, which grinds the composites and uses them as fillers or reinforcements, but the problem with this method is that it severely damages the fibers and reduces their mechanical properties.

Shoaib and Matyonga14 were able to analyze the life cycle of vital data in mechanical recycling of GFRP using a bottom-up approach. The next method is thermal recycling, which uses heat and inert gas to decompose the resin and regenerate GF or CF [47, 98].

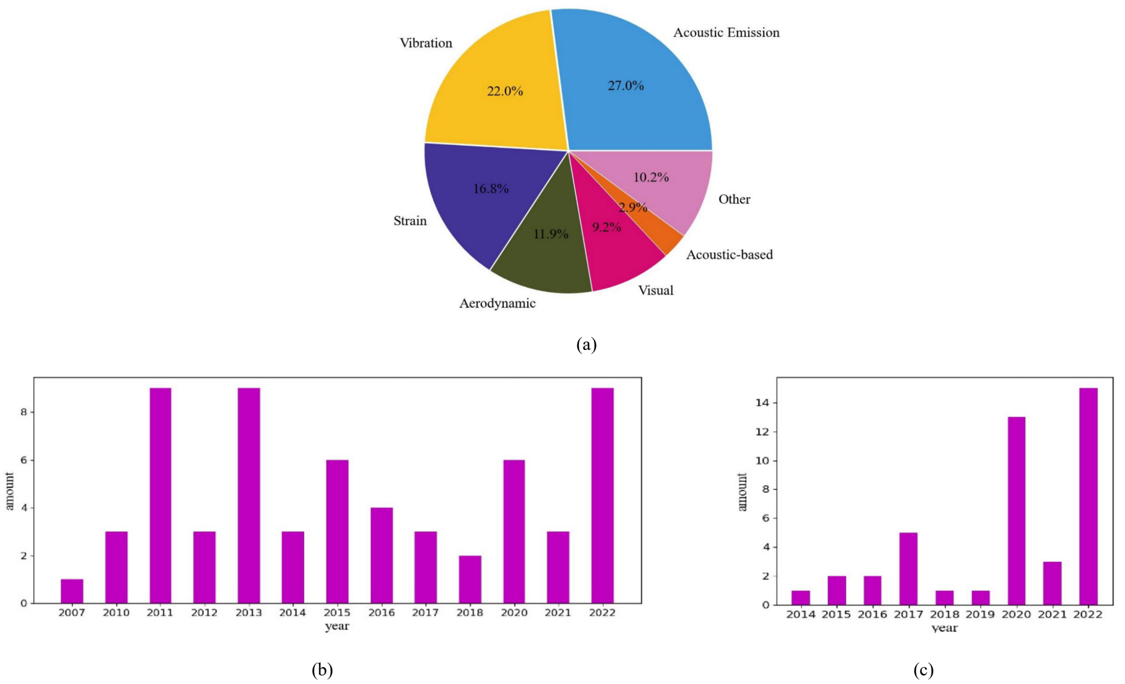

Fig. 5. (a) The distribution of possible methods for wind turbine damage detection in the literature. And of course, the number of research published in the literature based on (b) AE detection and (c) aerodynamic noise [96].

In the last method, chemical recycling also converts the resin in the composites into small molecules with the help of chemical reagents and recovers the fibers. The energy recovery method is carried out by burning the composites and recovers the heat of combustion into energy, but it has environmental problems and high production costs. Also, by burning these resins, toxic gas is produced, and the remaining ash creates secondary pollution. Some technologies have been industrialized, such as thermal and mechanical recycling, and other methods are still in the laboratory stage. Each way and method of recycling resin and fiber compounds produces products with different properties that can be used for different applications. Using several means to recycle and reuse composites will contribute to lower energy consumption, enable environmental protection, and promote sustainable technology [98].

8. Future trends

In future research, researchers should consider working on wind turbine technology by opting for more natural fibers relative to synthetic ones to enhance mechanical performance at the same time minimizing carbon impacts on the environment [72]. Also, progress in recycling and remanufacturing of thermoset composites is essential for sustainable and long-term use [47]. In addition, to improve the performance of airfoils, a deeper investigation into constraint management, parameter tuning, and validation under turbulent flow at different Reynolds numbers is needed. In addition, the development of the best composition for variable CST [99] and the increasing use of nanoparticle reinforcements will increase the strength and stiffness of composite materials, increasing their widespread application in the future [91].

8.1. Smart materials and sensing integration

In terms of fatigue damage on composite wind turbine blades, acoustic propagation waves are anisotropic and rapidly lose energy during propagation [100].

To investigate the effect of blade damage level, microphone location, and other conditions on detection performance, experiments were conducted, which showed that the active acoustic damage detection method is capable of detecting damage in wind turbine blades while maintaining the structural integrity of the cavity. One of the advantages of this wind turbine blade noise-based detection technology is the small number of pneumatic acoustic sensors required. Also, the method of using wireless sensors to detect blade surface damage was investigated [101]. In addition, Berber et al. [102] proposed a MEMS-based wireless acoustic measurement system that was cost-effective.

Researchers like Rudd and his colleagues [100] at NASA's Kennedy Space Center have introduced a Based on wave propagation structural health monitoring (SHM) technique that uses a Macro-Fiber Composite (MFC) actuator and MFC sensors. In this method, three sensors were installed on the high-pressure side and two sensors, along with the MFC actuator, on the low-pressure side of the blade to create a better and more efficient arrangement than previous wind turbine blades. These sensors are expected to be further improved in the future.

A pilot team also designed an impedance-based SHM system with six MFC sensor actuators mounted on the blade surface and an Agilent HP4192A impedance analyzer. Initially, another digital transducer was to be used, but due to performance issues, the Agilent analyzer was used. However, initial tests showed that using MFC sensors instead of PZT and mounting them on the outside of the blade provided less structural information, but damage was still detectable, and further development is needed in this area [100, 103].

8.2. Advanced simulation and optimization

During the calculations and simulations, two cases were considered: an airfoil with geometric twist and an airfoil without geometric twist. The number of blades, the rated power of the wind turbine, the gust speed, the design wind speed and other relevant parameters were used as initial input data. As a result of the simulations and calculations, the values that can be improved for several key factors, including flow velocity reduction, specific tip speed, profile losses, end losses and ideal power, were determined [6].

8.3. Hybrid composites and bio-based alternatives

Glass fiber composites come in different types. E-glass (electrical glass), S-glass (magnesium alumina silicate glass), and R-glass (calcium alumina silicate glass) [44].

Of which electric glass is currently the most widely used, and the latter two contain higher oxides and lower silica, which have 30% higher strength and 15% higher stiffness than E-glass and are under further investigation. Carbon fibers are in greater demand in the manufacture of windmill blades and spars due to their greater stiffness, high strength, and low coefficient of thermal expansion. Aramid and basalt fibers are non-glass alternatives to conventional fibers. Aramid fibers, despite their good properties, are not suitable for large-scale applications due to their degradation under UV light, moisture absorption, and low adhesion rates. But basalt fibers are better suited for use in small-scale wind turbines due to their good mechanical properties and are at least 9% lighter in weight, 15-20% stiffer, and 30% stronger than E-glass. Conventional composites have adverse environmental impacts as well as detrimental effects on worker safety. Processing of natural fibers increases the bond strength between the fibers and the matrix, providing mechanical strength and dimensional stability in the composite [16, 44, 55]. One of the world's longest wind turbine blades, measuring approximately 88 meters in length, is made using a hybrid glass /carbon composite reinforced with a resin matrix. Therefore, future research could focus more on the field of wind turbine blade materials, such as glass/carbon composites, based on hybrid composites to achieve ideal strength and weight characteristics. Nanoengineered reinforcements such as CNTs and nanoclays are promising advances for improving the properties of composites. While glass fibers are still widely used, fibers such as carbon, aramid, and basalt show greater potential, and natural fibers have also received attention due to their sustainability. Hybrid composites, combining glass, aramid, carbon, and basalt fibers, are expected to become the standard in blade manufacturing due to their superior performance and sustainability benefits. Ongoing development and testing will accelerate their adoption in the near future. Other fibers that can be used in the manufacture of wind turbine blades include natural fibers such as sugarcane, hemp, bamboo, and jute, whose main advantages are lower cost, easy availability, and environmental friendliness. A number of developing countries have conducted experiments to use wooden blades, which can also be improved [44, 104].

Composite materials are formed by reinforcing a matrix material with two or more different constituents to combine their best properties. One of the most important types of these materials is hybrid composites. To achieve higher strength and stiffness, hybrid composites commonly use combinations of fibers such as E-glass/carbon or E-glass/aramid as reinforcements within the matrix [44].

9. Conclusion

Composite materials are of interest in the design and performance of wind turbine airfoils due to their unique properties such as high strength, low weight and environmental flexibility. Offshore installations are commonly selected for their high ability to resist fatigue, corrosion, and mechanical failure in demanding conditions. The paper shows that advancements in fiber reinforcement such as glass, carbon, and aramid, and development in types of matrix such as thermoplastics, has facilitated the required mechanical and thermal properties for durability of airfoils and aerodynamic performance. However, the combination of advanced manufacturing techniques such as resin injection and weaving, and optimization strategies such as fiber orientation and thinner design, have greatly increased the functionality and longevity of these structures. Although significant advancements have been made, challenges remain in the field of composites. High costs, limits in damage detection, and complicated recycling procedures are still significant barriers to widespread application, particularly on a larger scale. Regardless, new advances such as hybrid composites, nanotechnology-enhanced matrices, and automated manufacturing all provide some promise in addressing these issues. In the future, combining smart materials with sustainable production may have significant benefits for developing airfoils for wind turbine blades. In addition, more extensive examination and research are required in order to fully exploit composites with a view to strengthening the worldwide drive towards clean, affordable, and reliable wind energy systems.

Author contributions

Younes Nasirinia: Investigation, Writing – original draft, Writing – review & editing; **Sohrab Asgaran:** Writing – original draft, Writing – review & editing; **Zahra Moazzami Goudarzi:** Writing – original draft, Writing – review & editing.

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Conflict of interest

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Data availability

No data is available.

REFERENCES

[1] A.D. Şahin, Progress and recent trends in wind energy, Progress in Energy and Combustion Science 30(5) (2004) 501-543.
[2] J. Lerche, S. Lorentzen, P. Enevoldsen, H.H. Neve, The impact of COVID -19 on offshore wind project productivity – A case study, Renewable and Sustainable Energy Reviews 158 (2022) 112188.
[3] A.F.P. Ribeiro, A.M. Awruch, H.M. Gomes, An airfoil optimization technique for wind turbines, Applied Mathematical Modelling 36(10) (2012) 4898-4907.
[4] J. Tangler, The evolution of rotor and blade design, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2000.
[5] G.N. Vanderplaats, R.M. Hicks, E.M. Murman, Application of numerical optimization techniques to airfoil design, NASA Conference on Aerodynamic Analysis Requiring Advanced Computers, 1975, pp. 749-768.
[6] A. Urbahs, N. Kuleshov, D. Titovs, L. Chernin, Calculation and simulation of aerodynamic characteristics of wind power plant turbine, Proceedings of the 18th International Scientific Conference on Engineering for Rural Development (ERD), Jelgava, Latvia, 2019, pp. 22-24.
[7] W.J. Zhu, W.Z. Shen, J.N. Sørensen, Integrated airfoil and blade design method for large wind turbines, Renewable Energy 70 (2014) 172-183.
[8] C. Monroy Aceves, M.P.F. Sutcliffe, M.F. Ashby, A.A. Skordos, C. Rodríguez Román, Design methodology for composite structures: A small low air-speed wind turbine blade case study, Materials & Design (1980-2015) 36 (2012) 296-305.
[9] M. Bošnjaković, M. Katinić, R. Santa, D. Marić, Wind Turbine Technology Trends, Applied Sciences, 2022.
[10] B. Navin kumar, S. Rajendran, A. Vasudevan, G. Balaji, Aerodynamic braking system analysis of horizontal axis wind turbine using slotted airfoil, Materials Today: Proceedings 33 (2020) 3970-3979.
[11] K. Gormley, E. Hague, C. Andvik, V. DaCosta, A. Davies, D. Diz, K. Alexander, L. McWhinnie, First port of call: a horizon scanning workshop for sustainable Arctic marine infrastructure, The Polar Journal 13(1) (2023) 146-162.
[12] M.S.H. Al-Furjan, L. Shan, X. Shen, M.S. Zarei, M.H. Hajmohammad, R. Kolahchi, A review on fabrication techniques and tensile properties of glass, carbon, and Kevlar fiber reinforced rolymer composites, Journal of Materials Research and Technology 19 (2022) 2930-2959.
[13] A. Kyawo, M.I. Khan, S.I. Chowdhury, S. Rahaman, UNVEILING AIRFOIL SUITABILITY FOR LOW-WIND CONDITIONS IN BANGLADESH'S COASTAL REGIONS.
[14] P.Y. Andoh, A. Agyei-Agyemang, P.O. Tawiah, C.K.K. Sekyere, C. Asante, Development of composite material for wind turbine blades, J. Appl. Eng. Technol. Sci. JAETS 2 (2021) 139-150.
[15] K. Lamhour, M. Rouway, A. Tizliouine, L. El Hachemi Omari, H. Salhi, O. Cherkaoui, Experimental study on the properties of Alfa/wool woven fabrics reinforced epoxy composite as an application in wind turbine blades, Journal of Composite Materials 56(21) (2022) 3253-3268.
[16] T.A. Miliket, M.B. Ageze, M.T. Tigabu, M.A. Zeleke, Experimental characterizations of hybrid natural fiber-reinforced composite for wind turbine blades, Heliyon 8(3) (2022).
[17] M. Jureczko, M. Pawlak, A. Mężyk, Optimisation of wind turbine blades, Journal of Materials Processing Technology 167(2) (2005) 463-471.
[18] S. Rehman, M.M. Alam, L.M. Alhems, M.M. Rafique, Horizontal Axis Wind Turbine Blade Design Methodologies for Efficiency Enhancement—A Review, Energies, 2018.
[19] E.A. Efkirn, T.M. Lazim, W.W. Omar, N. Mohd, M. Takeyeldein, Aerodynamic Analysis of Horizontal Axis Wind Turbine Using Blade Element Momentum Theory for Low Wind Speed Conditions, Science and Engineering 2 (2015).
[20] P. Sharma, B. Gupta, M. Pandey, A.K. Sharma, R. Nareliya Mishra, Recent advancements in optimization methods for wind turbine airfoil design: A review, Materials Today: Proceedings 47 (2021) 6556-6563.
[21] H. Hamdi, C. Mrad, R. Nasri, Effects of Gyroscopic Coupling on the Dynamics of a Wind Turbine Blade with Horizontal Axis, in: T. Fakhfakh, W. Bartelmus, F. Chaari, R. Zimroz, M. Haddar (Eds.) Condition Monitoring of Machinery in Non-Stationary Operations, Springer Berlin Heidelberg, Berlin, Heidelberg, 2012, pp. 159-174.
[22] J.H. Laks, L.Y. Pao, A.D. Wright, Control of wind turbines: Past, present, and future, 2009 American Control Conference, 2009, pp. 2096-2103.
[23] D. Duckwitz, M. Shan, Active tower damping and pitch balancing – design, simulation and field test, Journal of Physics: Conference Series 555(1) (2014) 012030.
[24] E.A. Bossanyi, Individual Blade Pitch Control for Load Reduction, Wind Energy 6(2) (2003) 119-128.
[25] M.H. Do, J.G. Njiri, D. Söffker, Structural load mitigation control for wind turbines: A new performance measure, Wind Energy 23(4) (2020) 1085-1098.
[26] J.B. Malone, J.C. Narramore, L.N. Sankar, Airfoil design method using the Navier-Stokes equations, Journal of Aircraft 28(3) (1991) 216-224.
[27] S. Eyi, K.D. Lee, INVERSE AIRFOIL DESIGN USING THE NAVIER STOKES EQUATIONS, Engineering Optimization 28(4) (1997) 245-262.
[28] M. Taiebi-Rahni, F. Ghadak, A. Ashrafizadeh, A direct design approach using the Euler equations, Inverse Problems in Science and Engineering 16(2) (2008) 217-231.
[29] S. Peigin, B. Epstein, Robust optimization of 2D airfoils driven by full Navier–Stokes computations, Computers & Fluids 33(9) (2004) 1175-1200.
[30] V. D'Alessandro, S. Montelpare, R. Ricci, A. Zoppi, Numerical modeling of the flow over wind turbine airfoils by means of Spalart–Allmaras local correlation based transition model, Energy 130 (2017) 402-419.
[31] L. Huyse, S.L. Padula, R.M. Lewis, W. Li, Probabilistic Approach to Free-Form Airfoil Shape Optimization Under Uncertainty, AIAA Journal 40(9) (2002) 1764-1772.
[32] H.H. Mwanyika, Y.A.C. Jande, T. Kivevele, Design and Performance Analysis of Composite Airfoil Wind Turbine Blade, Tanzania Journal of Science 47(5) (2021) 1701-1715.
[33] E.Y. Osei, R. Opoku, A.K. Sunnu, M.S. Adaramola, Development of High Performance Airfoils for Application in Small Wind Turbine Power Generation, Journal of Energy 2020(1) (2020) 9710189.
[34] J. Yi, F. Deng, Cooperation of Thin-Airfoil Theory and Deep Learning for a Compact Airfoil Shape Parameterization, Aerospace, 2023.

[35] P. Zuo, D.V. Srinivasan, A.P. Vassilopoulos, Review of hybrid composites fatigue, Composite Structures 274 (2021) 114358.
[36] S.A. Michel, R. Kieselbach, H.J. Martens, Fatigue strength of carbon fibre composites up to the gigacycle regime (gigacycle-composites), International Journal of Fatigue 28(3) (2006) 261-270.
[37] E.I. Basri, M.T.H. Sultan, M. Faizal, A.A. Basri, M.F. Abas, M.S.A. Majid, J.S. Mandeep, K.A. Ahmad, Performance analysis of composite ply orientation in aeronautical application of unmanned aerial vehicle (UAV) NACA4415 wing, Journal of Materials Research and Technology 8(5) (2019) 3822-3834.
[38] G.V. Mahajan, V.S. Aher, Composite material: A review over current development and automotive application, International journal of scientific and research publications 2(11) (2012) 1-5.
[39] N.M. Mathur, K. Bairwa, A literature review on Composite material and scope of Sugar cane Bagasse, International Journal of Engineering Development and Research 5(4) (2017) 125-133-125-133.
[40] L. Mishnaevsky, K. Branner, H.N. Petersen, J. Beauson, M. McGugan, B.F. Sørensen, Materials for Wind Turbine Blades: An Overview, Materials, 2017.
[41] A.G. Olabi, T. Wilberforce, K. Elsaid, E.T. Sayed, T. Salameh, M.A. Abdelkareem, A. Baroutaji, A Review on Failure Modes of Wind Turbine Components, Energies, 2021.
[42] H.A. Hegab, Design for additive manufacturing of composite materials and potential alloys: a review, Manufacturing Rev. 3 (2016).
[43] K.K. Chawla, Ceramic Matrix Composites, in: K.K. Chawla (Ed.), Composite Materials: Science and Engineering, Springer New York, New York, NY, 2012, pp. 249-292.
[44] S.S.P. Reddy, R. Suresh, H. M.B, B.P. Shivakumar, Use of composite materials and hybrid composites in wind turbine blades, Materials Today: Proceedings 46 (2021) 2827-2830.
[45] P. Brøndsted, H. Lilholt, A. Lystrup, COMPOSITE MATERIALS FOR WIND POWER TURBINE BLADES, Annual Review of Materials Research 35(Volume 35, 2005) (2005) 505-538.
[46] L. Thomas, M. Ramachandra, Advanced materials for wind turbine blade- A Review, Materials Today: Proceedings 5(1, Part 3) (2018) 2635-2640.
[47] J. Chen, J. Wang, A. Ni, Recycling and reuse of composite materials for wind turbine blades: An overview, Journal of Reinforced Plastics and Composites 38(12) (2019) 567-577.
[48] P. Zhang, X. Zhao, H. Ding, C. Le, The wet-towing resistance of the composite bucket foundation for offshore wind turbines, Marine Structures 80 (2021) 103089.
[49] M. Shahruzzaman, S. Hossain, S.F. Kabir, T. Ahmed, M.M. Islam, S. Sultana, A.K. Mallik, M.M. Rahman, Properties and Characterization of Advanced Composite Materials, in: L.M. Pandey, A. Hasan (Eds.), Nanoscale Engineering of Biomaterials: Properties and Applications, Springer Nature Singapore, Singapore, 2022, pp. 589-617.
[50] T. Abt, M. Sánchez-Soto, A Review of the Recent Advances in Cyclic Butylene Terephthalate Technology and its Composites, Critical Reviews in Solid State and Materials Sciences 42(3) (2017) 173-217.
[51] V. Martynenko, M. Hrytsenko, G. Martynenko, Technique for Evaluating the Strength of Composite Blades, Journal of The Institution of Engineers (India): Series C 101(3) (2020) 451-461.
[52] P.E. Nicholas, K.P. Padmanaban, D. Vasudevan, T. Ramachandran, Stacking sequence optimization of horizontal axis wind turbine blade using FEA, ANN and GA, Structural and Multidisciplinary Optimization 52(4) (2015) 791-801.
[53] D.M. Grogan, S.B. Leen, C.R. Kennedy, C.M. Ó Brádaigh, Design of composite tidal turbine blades, Renewable Energy 57 (2013) 151-162.
[54] K. Namsheer, C.S. Rout, Conducting polymers: a comprehensive review on recent advances in synthesis, properties and applications, RSC advances 11(10) (2021) 5659-5697.
[55] T. Trzepieciński, T. Batu, F. Kibrete, H.G. Lemu, Application of Composite Materials for Energy Generation Devices, Journal of Composites Science, 2023.
[56] A.J. Torregrosa, A. Gil, P. Quintero, A. Cremades, On the effects of orthotropic materials in flutter protection of wind turbine flexible blades, Journal of Wind Engineering and Industrial Aerodynamics 227 (2022) 105055.
[57] K. Cox, A. Echtermeyer, Structural Design and Analysis of a 10MW Wind Turbine Blade, Energy Procedia 24 (2012) 194-201.
[58] J. Lin, Y. Shi, Y. Men, X. Wang, J. Ye, C. Zhang, Mechanical Roles in Formation of Oriented Collagen Fibers, Tissue Engineering Part B: Reviews 26(2) (2019) 116-128.
[59] X. Lachenal, S. Daynes, P.M. Weaver, Review of morphing concepts and materials for wind turbine blade applications, Wind Energy 16(2) (2013) 283-307.
[60] S.N. Leloudas, A.I. Eskantar, G.N. Lygidakis, I.K. Nikolos, Low Reynolds airfoil family for small horizontal axis wind turbines based on RG15 airfoil, SN Applied Sciences 2(3) (2020) 371.
[61] R.K. Singh, M.R. Ahmed, M.A. Zullah, Y.-H. Lee, Design of a low Reynolds number airfoil for small horizontal axis wind turbines, Renewable Energy 42 (2012) 66-76.
[62] D.H. Nguyen, A. Chapman, The potential contributions of universal and ubiquitous wireless power transfer systems towards sustainability, International Journal of Sustainable Engineering 14(6) (2021) 1780-1790.
[63] P. Garrett, K. Rønde, Life cycle assessment of wind power: comprehensive results from a state-of-the-art approach, The International Journal of Life Cycle Assessment 18(1) (2013) 37-48.
[64] C.S. Psomopoulos, K. Kalkanis, S. Kaminaris, G.C. Ioannidis, P. Pachos, A Review of the Potential for the Recovery of Wind Turbine Blade Waste Materials, Recycling, 2019.
[65] J. Fischer, Comparing wind and solar energy impacts on the environment: a LCA approach using openLCA platform, (2021).
[66] D.S. Cairns, J.D. SHRAMSTAD, Evaluation of hand lay-up and resin transfer molding in composite wind turbine blade manufacturing, Sandia National Lab.(SNL-NM), Albuquerque, NM (United States); Sandia …, 2000.
[67] K. Potter, Introduction to composite products: design, development and manufacture, Springer Science & Business Media1996.
[68] J. Winslow, H. Otsuka, B. Govindarajan, I. Chopra, Basic Understanding of Airfoil Characteristics at Low Reynolds Numbers (104–105), Journal of Aircraft 55(3) (2017) 1050-1061.
[69] S. Poole, R. Phillips, Rapid prototyping of small wind turbine blades using additive manufacturing, 2015 pattern recognition association of South Africa and robotics and mechatronics international conference (PRASA-RobMech), IEEE, 2015, pp. 189-194.
[70] M.S. Davis, M.R. Madani, 3D-Printing of a Functional Small-Scale Wind Turbine, 2018 6th International Renewable and Sustainable Energy Conference (IRSEC), 2018, pp. 1-6.
[71] J.C. Watson, J.C. Serrano, Composite materials for wind blades, Wind Syst. Mag 46 (2010) 46-51.
[72] H. Teng, S. Li, Z. Cao, S. Li, C. Li, T.J. Ko, Carbon Fiber Composites for Large-Scale Wind Turbine Blades: Applicability Study and Comprehensive Evaluation in China, Journal of Marine Science and Engineering, 2023.
[73] D.K. Rajak, D.D. Pagar, R. Kumar, C.I. Pruncu, Recent progress of reinforcement materials: a comprehensive overview of composite materials, Journal of Materials Research and Technology 8(6) (2019) 6354-6374.
[74] S. Laurenzi, M. Marchetti, Advanced composite materials by resin transfer molding for aerospace applications, Composites and their properties, Ning Hu2012, pp. 197-226.
[75] M. Wimmer, Development, modelling and analysis of Vacuum Assisted Multipoint Moulding for manufacturing fibre-reinforced plastic composites, (2019).
[76] J.-K. Huang, W.-B. Young, The mechanical, hygral, and interfacial strength of continuous bamboo fiber reinforced epoxy composites, Composites Part B: Engineering 166 (2019) 272-283.
[77] O. Nabinejad, S. Debnath, J.K. Beh, Y.A. Mohammad, Mechanical performance and moisture absorption of unidirectional bamboo fiber polyester composite, Materials science forum, Trans Tech Publ, 2018, pp. 88-94.
[78] M. Mohseni, A. Amirfazli, A novel electro-thermal anti-icing system for fiber-reinforced polymer composite airfoils, Cold Regions Science and Technology 87 (2013) 47-58.
[79] S. Chinchanikar, A.A. Shaikh, A Review on Machine Learning, Big Data Analytics, and Design for Additive Manufacturing for Aerospace Applications, Journal of Materials Engineering and Performance 31(8) (2022) 6112-6130.
[80] J.K.S. Dillinger, T. Klimmek, M.M. Abdalla, Z. Gürdal, Stiffness Optimization of Composite Wings with Aeroelastic Constraints, Journal of Aircraft 50(4) (2013) 1159-1168.
[81] P. Bettini, A. Airoldi, G. Sala, L.D. Landro, M. Ruzzene, A. Spadoni, Composite chiral structures for morphing airfoils: Numerical analyses and development of a manufacturing process, Composites Part B: Engineering 41(2) (2010) 133-147.
[82] M.H. Do, J.G. Njiri, D. Söffker, Structural load mitigation control for nonlinear wind turbines with unmodeled dynamics, 2018 Annual American Control Conference (ACC), 2018, pp. 3466-3471.
[83] R.F.J. McCarthy, G.H. Haines, R.A. Newley, Polymer composite applications to aerospace equipment, Composites Manufacturing 5(2) (1994) 83-93.
[84] J. Hajrasouliha, M. Sheikhzadeh, Manufacturing a carbon/epoxy NACA 23018 airfoil skin using a circular braiding machine: experimental and numerical study, Journal of Industrial Textiles 51(4_suppl) (2021) 5543S-5559S.
[85] D.R. Tenney, J.G. Davis Jr, R.B. Pipes, N. Johnston, NASA composite materials development: lessons learned and future challenges, NATO RTO AVT-164 Workshop on Support of Composite Systems, 2009.
[86] O. Hernandez, Aerodynamic flow field characterization of airfoils with and without leading edge modifications, The University of Texas-Pan American2015.
[87] L. Gebrehiwet, E. Abate, Y. Negussie, T. Teklehaymanot, E. Abeselom, Application of composite materials in aerospace & automotive industry, International Journal of Advances in Engineering and Management (IJAEM) 5(3) (2023) 697-723.

[88] L. Jia, J. Hao, J. Hall, H.K. Nejadkhaki, G. Wang, Y. Yan, M. Sun, A reinforcement learning based blade twist angle distribution searching method for optimizing wind turbine energy power, Energy 215 (2021) 119148.
[89] K. Sohail, H. Farzaneh, Model for Optimal Power Coefficient Tracking and Loss Reduction of the Wind Turbine Systems, Energies, 2022.
[90] M. Selig, Low Reynolds number airfoil design lecture notes, VKI Lecture Series, November (2003) 24-28.
[91] L. Mishnaevsky, Composite materials for wind energy applications: micromechanical modeling and future directions, Computational Mechanics 50(2) (2012) 195-207.
[92] A. Ariyarit, M. Kanazaki, S. Bureerat, An Approach Combining an Efficient and Global Evolutionary Algorithm with a Gradient-Based Method for Airfoil Design Problems, Smart Science 8(1) (2020) 14-23.
[93] J.F. Petko, J.D. Kiser, M. Verilli, T. McCue, H.R. Gray, Characterization of C/SiC ceramic matrix composites (CMCs) with novel interface fiber coatings, 26th Annual Conference on Materials and Structures, 2002.
[94] D.A. Baker, T.G. Rials, Recent advances in low-cost carbon fiber manufacture from lignin, Journal of Applied Polymer Science 130(2) (2013) 713-728.
[95] Y.S. Song, J.R. Youn, T.G. Gutowski, Life cycle energy analysis of fiber-reinforced composites, Composites Part A: Applied Science and Manufacturing 40(8) (2009) 1257-1265.
[96] S. Ding, C. Yang, S. Zhang, Acoustic-Signal-Based Damage Detection of Wind Turbine Blades—A Review, Sensors, 2023.
[97] A.A.F. Ogaili, M.N. Hamzah, A.A. Jaber, Integration of machine learning (ML) and finite element analysis (FEA) for predicting the failure modes of a small horizontal composite blade, International Journal of Renewable Energy Research (IJRER) 12(4) (2022) 2168-2179.
[98] Y. Yang, R. Boom, B. Irion, D.-J. van Heerden, P. Kuiper, H. de Wit, Recycling of composite materials, Chemical Engineering and Processing: Process Intensification 51 (2012) 53-68.
[99] T.H. Hansen, Airfoil optimization for wind turbine application, Wind Energy 21(7) (2018) 502-514.
[100] A.R. Mark, A.P. Joshua, Structural health monitoring of wind turbine blades, Proc.SPIE, 2008, p. 69330E.
[101] C. Beale, M. Inalpolat, C. Niezrecki, Active acoustic damage detection of structural cavities using internal acoustic excitations, Structural Health Monitoring 19(1) (2019) 48-65.
[102] S. Barber, J. Deparday, Y. Marykovskiy, E. Chatzi, I. Abdallah, G. Duthé, M. Magno, T. Polonelli, R. Fischer, H. Müller, Development of a wireless, non-intrusive, MEMS-based pressure and acoustic measurement system for large-scale operating wind turbine blades, Wind Energ. Sci. 7(4) (2022) 1383-1398.
[103] D.J. Inman, Vibration Analysis and Control of an Inflatable Structure Using Smart Materials, 2005.
[104] G. Rajeshkumar, S.A. Seshadri, S. Ramakrishnan, M.R. Sanjay, S. Siengchin, K.C. Nagaraja, A comprehensive review on natural fiber/nano-clay reinforced hybrid polymeric composites: Materials and technologies, Polymer Composites 42(8) (2021) 3687-3701.