Green Roof Team

Sustainably Green Solutions

Utilizing Composite Materials for Small Wind Turbine Blade Lamination: Enhancing Strength and Performance

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I. Introduction

Wind turbine blades are subjected to extreme weather conditions, UV radiation as well as a multitude of loads classified into flapwise bending load (caused by wind pressure resisted by the spar and internal webs) and edgewise bending load (caused by gravitational forces and torque load resisted by the edges). Moreover, wind turbine blades are exposed to over 10^8 load cycles. To achieve optimal performance of wind turbine blades and prevent mechanical failure , material selection is crucial and the use of composite laminates is becoming increasingly prevalent in the wind turbine industry.

A. Importance of small wind turbine blade lamination in achieving optimal strength and performance

The use of composite materials has significantly improved the mechanical properties of wind turbine blades. Its properties when compared to other typically used materials such as wood or metals are very advantageous since they have higher specific stiffness and specific strength and their fatigue and corrosion resistance are also higher than that of common engineering metals.

The lamination process ensures that layers of composite materials that provide longitudinal strength and stiffness are tightly bonded together by a matrix that improves fracture toughness and prevents delamination. The direction in which fibers are aligned during lamination significantly affects the performance of composite materials.

The manufacturing practice of lamination in small wind turbine blades has numerous benefits. For example, it allows for optimal combination of different composites like carbon fiber and fiberglass to attain a significantly better wind turbine blade. Lamination also enables the manufacturer to use a different laminate density and width in different parts of the blade taking into consideration the requirements and loads of each section of the blade.

B. Significance of composite materials in enhancing the structural integrity of blades

Structural integrity is the ability of a body to withstand its intended loading without failing due to deformation, fracture or fatigue and is often determined by simulations and experimental testing. Composite materials play an important role in enhancing the structural integrity of blades due to their high specific stiffness, high specific strength, corrosion resistance and fatigue strength (really important property for materials used in wind turbine blades since they are continuously exposed to loading cycles) . Note that not all composites have all four of these properties, that is why combining composites during the lamination process often leads to optimal performance. Overall, composite materials have been proven to have very suitable properties to withstand wind turbine blade loads.

II. Overview of Composite Materials in Blade Lamination

A. Explanation of composite materials and their advantages in wind turbine blade manufacturing

Composite materials are materials produced from two or more constituent materials. The constituent materials generally have different chemical and physical properties and it is by combining them that a material with unique and improved properties can be created. Composite fibers are the ones used in the lamination process.

In the context of small wind turbine blades, weight is particularly important and using composite materials is a great alternative given the high strength to weight ratio of composites when compared to other materials.

The lamination process of composite materials allows for a lot of flexibility (ie: combining different composites such as E-glass/carbon, E-glass/aramid etc. or having denser areas of composite material given the loads certain regions of the blade will have to withstand). The use of composites also allows for the creation of complex airfoil geometries that could have better aerodynamic properties than those built with other manufacturing processes and materials.

B. Types of fiber reinforcements and matrix materials commonly used in composite laminates

Currently, in the wind turbine industry, fiberglass is the most used composite material. However, as turbine blades are getting longer, enabling them to capture more surface energy and hence generating more energy (see Figure 1), they are also getting more massive and other lighter composites are being investigated. The more massive the blade, the larger the loads that have to be carried by the turbine rotor and support components. It is for this reason that it is in the industry's best interest to create longer but lighter wind turbine blades. This will improve efficiency, lower LCOE and help expand the wind energy industry.

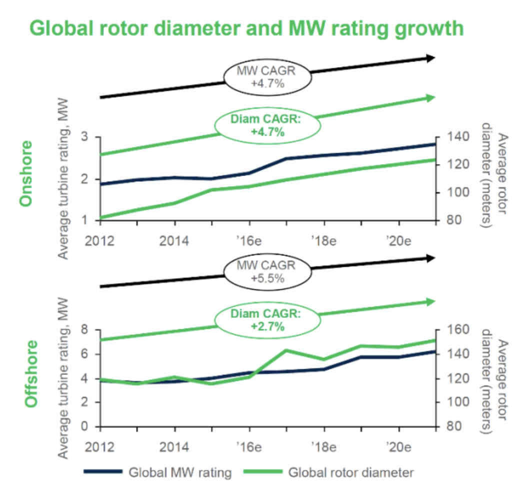

Figure 1: Wind turbine power rating as diameter changes

Carbon fiber weighs 15% less than fiberglass and has improved mass-specific strength and stiffness.[1] Other composite materials that could potentially be used are aramid, polyethylene, natural fibers such as bamboo and cellulose.

A summary of the mechanical properties of these fibers is shown in the table below:

	Fibers			Composites					
Type	Stiffness E_f GPa	Tensile strength σ_f MPa	Density ρ_f g/cm³	Volume fraction V_f	Orientation θ	Stiffness E_c GPa	Tensile strength σ_c MPa	Density ρ_c g/cm³	Merit $E_c^{1/2}/\rho_c$
Glass-E	72	3500	2.54	0.5	0°	38	1800	1.87	3.3
				0.3	Random	9.3	420	1.60	1.9
Carbon	350	4000	1.77	0.5	0°	176	2050	1.49	8.9
				0.3	Random	37	470	1.37	4.4
Aramid	120	3600	1.45	0.5	0°	61	1850	1.33	5.9
				0.3	Random	14.1	430	1.27	2.9
Polyethylene	117	2600	0.97	0.5	0°	60	1350	1.09	7.1
				0.3	Random	13.8	330	1.13	3.3
Cellulose	80	1000	1.50	0.5	0°	41	550	1.35	4.7
				0.3	Random	10.1	170	1.29	2.5

Figure 2: Mechanical properties of fibers and composites with matrices.

When it comes to matrix materials, polymer matrices divided into thermosets and thermoplastics are the most popular matrix materials. Thermoset polymers, the most commonly used matrix material, include epoxy, polyester resins and phenolic. Epoxy is particularly popular because of its high adhesion, low shrinkage, high tensile, compressive and torsional strength, low density, high temperature and fatigue resistance etc. Thermoplastic polymers include polyethylene (PE), polypropylene (PP), and polyamide (PA) and are becoming increasingly popular due to their recyclability. Other matrix materials include metal matrices, use aluminum or titanium as the matrix material and have very good thermal conductivity and are used in the automotive industry. Ceramic matrices use alumina or silicon carbide as the matrix material. They are used in very high temperature applications and in the construction industry.

C. Key properties and characteristics of composite materials relevant to blade lamination

The material requirements for a wind turbine blade are:

- High material stiffness for optimal aerodynamic performance
- Low density to reduce the effect of gravity forces
- Long fatigue life to prevent material degradation

Note that the mechanical design of a wind turbine blade is nominally a beam and the merit index ("A merit index is a combination of certain properties of a material that can be used to inform a process of materials selection for a particular set of criteria"[2]) is $M_b = E^{0.5}/\rho$, where E is the

[1] https://www.energy.gov/sites/prod/files/2019/12/f69/SAND2019-14173-Optimized.pdf

[2] https://www.open.edu/openlearn/science-maths-technology/design-innovation/design/content-section-6.5#:~:text=A%20merit%20index%20is%20a,will%20depend%20on%20the%20application.

Young's Modulus or stiffness of the material and ρ is its density. The higher merit index, the better the material properties for our application.

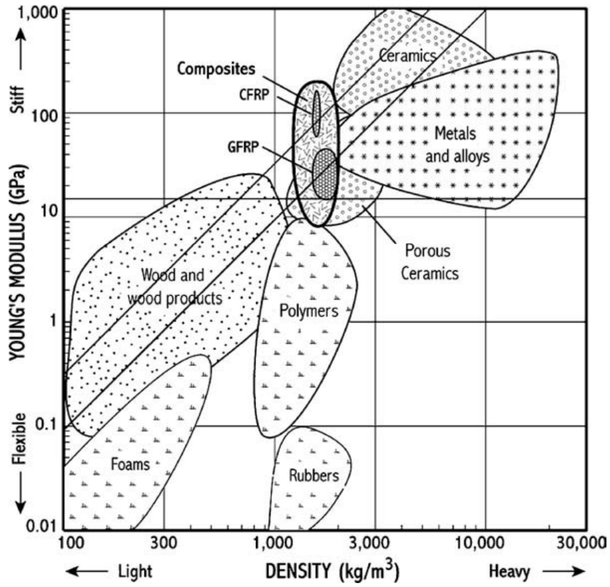

Figure 2: Stiffness vs density of possible materials. The lower diagonal line corresponds to $M_b = 0.003$ and the upper diagonal line corresponds to $M_b = 0.006$. The absolute stiffness criterion is represented by the horizontal line, with a value of 15 Gpa.[3]

The diagonal lines corresponding to different merit indices are arbitrary and just indicate materials that are equally good in terms of stiffness and density. The horizontal line however, represents stiffness on the absolute scale. Thus, the materials with the best properties for wind turbine blades are found on the upper left corner which include some wood, some composites and some ceramics.

III. Design Considerations for Composite Blade Lamination

A. Structural design principles for composite blade lamination

Loads, boundary conditions, structural requirements and failure prevention are the first design principles that need to be accounted for.

The loads that wind turbine blades have to withstand come from two different sources: loads from the wind in the flapwise direction and loads from gravity in the edgewise direction. The boundary is where the blade is connected to the hub or rotor of the wind turbine blade.

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3 https://www-eng.lbl.gov/~shuman/NEXT/MATERIALS&COMPONENTS/Pressure_vessels/FRP_Hutter_flange.pdf page 510

When designing a wind turbine blade, a balance between the aerodynamics and the structural requirements ought to be found. The flapwise loads by the wind are mainly taken by the main spar or load carrying box of the blade and the edgewise blade are withtaken by the reinforcements in the trailing and leading edge. Therefore, composite materials mainly contribute to the structural integrity of wind turbine blades when withstanding the edgewise load. Another characteristic of wind turbine blades is that they tend to be flexible, allowing them to withstand larger loads without failing.

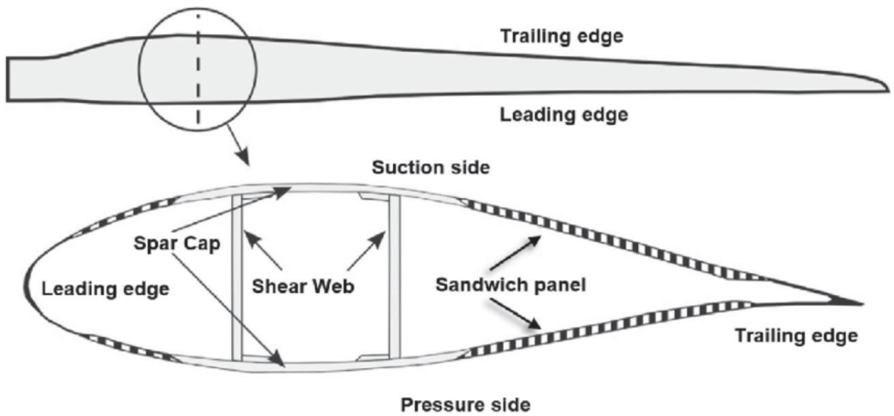

Figure 3: Components of the cross section of a wind turbine blade.[4]

Blade design requires an understanding of the blade at various scales, ranging from the full scale to molecular scale. This is of particular importance when dealing with composite structures.

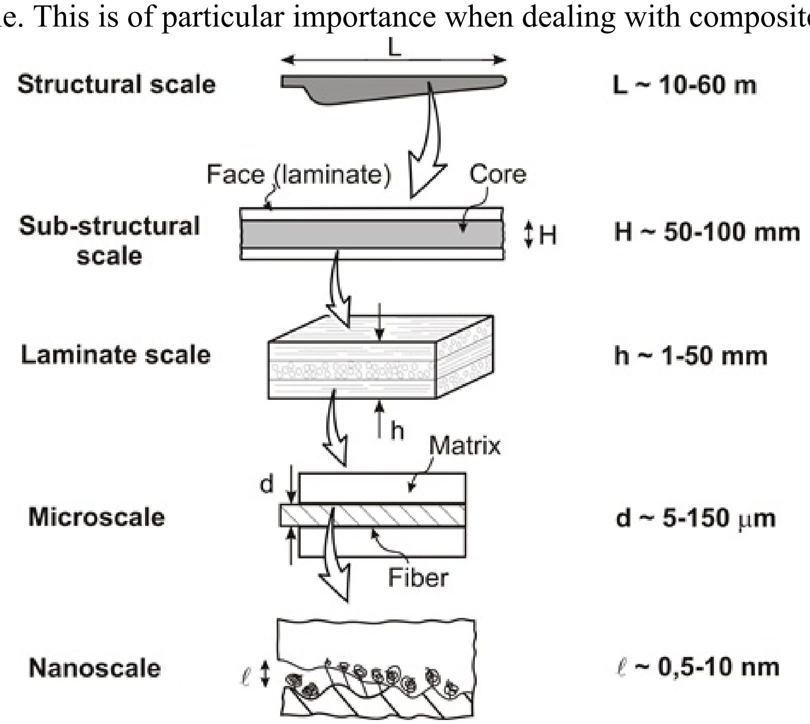

Figure 4: Multiscale approach to composite structures.[5]

[4] https://www.researchgate.net/figure/Cross-section-of-a-wind-turbine-blade_fig5_354704557

[5] https://www.dccsm.dk/overview

This approach allows for design decisions such as material selection at the sub-structural scale, composite material selection at the laminate scale, matrix selection and fiber orientation at the microscale and level of curing and adherence at the nanoscale.

There are two ways of making a structural design analysis: Blade Element Momentum (BEM) and Computational Fluid Dynamics (CFD). The most commonly used software is QBlade (BEM) and Ansys Fluent (CFD).[6] And the load envelope technique, in which the load is increased until the structure fails, is a pretty effective strategy to utilize and determine critical loads and angles.

BEM	CFD
Analytical method	Numerical method
Simple to be derived and used	Relatively complex in its formulation and application
Has relatively low computational time	Has relatively high computational time
In general, it does not consider 3D effects (just some corrections such as tip losses)	Depicts 3D effects in detail
Does not consider turbulence effects	Considers turbulence effects
Recommended for preliminary design	Recommended for detailed simulation

Figure 5: Comparison between BEM and CFD methods.

[6] https://www.intechopen.com/chapters/69636

B. Role of fiber orientations, stacking sequences, and laminate layup in optimizing strength and stiffness

Most composites are directional dependent so fiber orientation has a significant influence on the mechanical properties of the structure. The most common types of fiber orientation are shown in Figure 6.

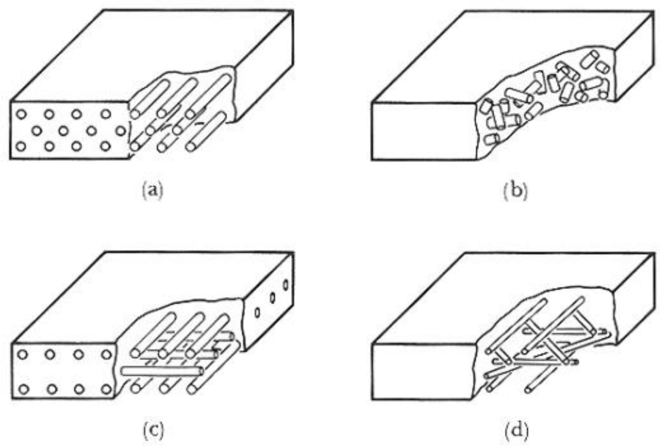

Figure 6: Fiber orientation in composite materials a) unidirectional, b) random, c) bidirectional and d) multidirectional.[7]

- **Unidirectional fibers** show very high strength and stiffness properties parallel to fiber orientation making this arrangement very suitable to withstand high unidirectional loads. However, they have low resistance to shear stress and transverse tensile or compressive loads.
- **Bidirectional fibers** provide more in-plane strength making the structure more isotropic. They are used when loads are present in multiple directions and have good resistance to both tensile and compressive loads. They do however have less strength and stiffness than unidirectional fibers along its primary axis.
- **Random and multidirectional fibers** are not as useful in applications where high strength and stiffness are required but they do however show isotropic properties, have the advantage that they can conform to complex shapes because they can easily be applied to curved surfaces and have high impact resistance since the random arrangement disperses the impact energy throughout the material thus significantly reducing the risk of cracking. Random fibers also have good vibration damping properties.

Another factor affecting material properties is the stacking sequence. Whereas fiber orientation refers to the orientation of fibers within a specific ply, stacking sequence refers to the layering or arrangement plies into what is known as a composite laminate or material. Each layer can have a different fiber orientation, thickness and material composition.

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7 https://www.researchgate.net/figure/11-Different-types-of-fiber-orientation-in-composites-a-unidirectional-b-random-c_fig10_267779397

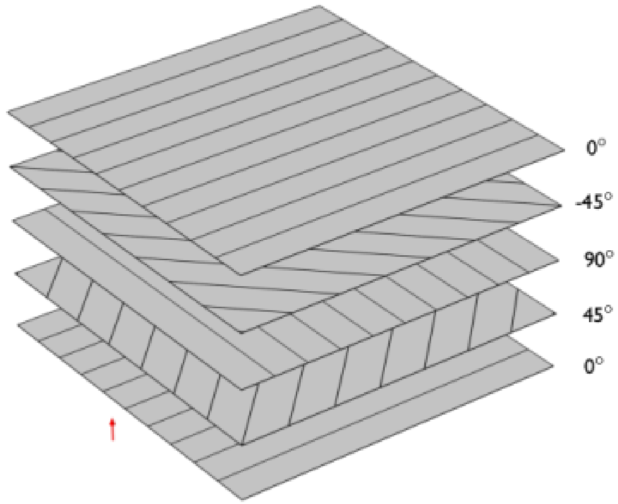

Figure 7: Sample stacking sequence *[0/45/90/-45/0]* [8]

- In the **unidirectional laminate sequence**, all plies are layers stacked with a 0° degree orientation. Very suitable for beams and columns that withstand high uniaxial loads. Delamination and fatigue failure are very common in the unidirectional laminate sequence that is why it can only withstand uniaxial loading.
- The **balanced stacking sequence** consists of plies at ±45° degrees to the primary axis load providing good strength and stiffness in the longitudinal and transverse directions. It is used in applications where loads are present in different directions and isotropic materials are required such as pressure vessels or symmetrical components. Compared to unidirectional laminates, they show improved fatigue resistance since stresses are distributed more evenly and are also a lot less prone to delamination.
- In the **symmetric laminate**, the material has mirror symmetry about the midplane. The plies are arranged in pairs and each pair has the same orientation angle but different sign. It is used when loading conditions are symmetric.
- Another very common way of stacking material is the **quasi-isotropic arrangement**. Quasi-isotropic materials are isotropic in one plane (its strength and stiffness is identical in one plane). To achieve this, plies are normally oriented with 0°, +45°, -45° and 90° with a minimum of 12.5% of the sheets in each orientation. The 0° orientation corresponds to the fiber running direction. For example, a typical quasi-isotropic carbon fiber stacking (commonly used with carbon fiber) is a 4 layer structure with laminates of the same thickness and stiffness. The 0° layer provides axial strength and stiffness, the +45° and -45° plies provide shear and torsional strength and stiffness ideal for torsion

8 https://doc.comsol.com/5.5/doc/com.comsol.help.compmat/compmat_ug_modeling.3.09.html#:~:text=Stacking%20Sequence&text=A%20composite%20laminate%20is%20defined,different%20materials%2C%20with%20individual%20thicknesses.

shafts and torsion webs such as I-beams, the 90° ply provides lateral strength and stiffness.[9]

C. Importance of load distribution and stress analysis in achieving desired performance

Wind turbine blades are subjected to permanently high loads from the wind and gravity as well as fatigue and the effects of rotation so a proper weight distribution analysis is essential to design a blade that properly distributes the loads across the structure and prevents stress concentrations. Load distribution and stress analysis can also give engineers insight into the areas that need more reinforcement and areas that can be lighter, saving cost and reducing overall weight of the turbine whilst reducing the chances of failure. Such analysis is also important to estimate service life, creep behavior and materials degradation.

IV. Material Selection for Composite Laminates

A. Comparison of different fiber reinforcements (e.g., carbon, glass, aramid) and their suitability for blade lamination

Glass fibers: Glass is generally mostly made out of SiO_2 and Al_2O_3. Glass fibers are amorphous and have isotropic properties. Type E (electrical) fibers are the most used composite. The diameter of the fiber is between 10-20 micrometers and is produced from molten glass. Glass fiber generally has moderate stiffness and density and high strength.

Carbon fibers: Carbon fibers consist of pure carbon which forms a hexagonal crystallographic lattice known as graphite. The hexagonal shape means that its mechanical properties are very high in the hexagonal plane and very low perpendicular to the planes. This leads to very high sensitivity to fiber misalignment and waviness: even small misalignments lead to a strong reduction of compressive and fatigue strength.[10] Carbon fiber is a low density material that has very high stiffness and high strength.

Aramid fibers: Aramid fibers have a high specific strength. Its comprehensive strength is similar to E-glass but shows high resistance to impact. The disadvantages of aramid is its susceptibility to water ingress, UV erosion and insect collision due to possession of good resistance to impact. It is also high enough to make a strong wind blade material because of its fatigue resistance capacity. Aramid fibers also have a low adhesion to polymer resins.

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9 https://www.cnfuturecomposites.com/News/introduction-to-the-concepts-of-isotropy-quasi-isotropy-and-anisotropy-of-carbon-fiber-sheets

10 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5706232/

	Kevlar 29 High toughness	Kevlar 49 High Modulus	Kevlar 149 Ultrahigh modulus Tensile
Tensile Strength	3.6 Gpa	3.6-4.1 Gpa	3.4 Gpa
Young's Modulus	83 Gpa	131 Gpa	179 Gpa
Elongation at break	4%	2.8%	2%

Figure 8: Aramid (Kevlar) fiber properties

A table comparing these three main fibers is provided below:

E=Excellent, G=Good, P=Poor, F=fair

	Glass	Aramid	Carbon Fibre
Cost	E	F	P
Weight to Strength Ratio	P	E	E
Tensile Strength	E	E	E
Compressive Strength	G	P	E
Stiffness	F	G	E
Fatigue Resistance	G-E	E	G
Abrasion Resistance	F	E	F
Sanding/Machining	E	P	E
Conductivity	P	P	E
Heat Resistance	E	F	E
Moisture Resistance	G	F	G
Resin Adhesion	E	F	E
Chemical Resistance	E	F	E

Figure 9: Glass, Aramid and Carbon Fiber comparison[11]

Carbon fiber has the main downside of being a lot more expensive than glass (up to 5 times more expensive) and aramid fibers and show high degradation due to UV radiation. Aramid and carbon fibers show excellent weight to strength ratio whereas glass fiber has a low specific strength. The tensile strength of all of these fibers is great and the compressive strength and stiffness of carbon fiber is the greatest. Aramid fibers have excellent fatigue resistance followed by glass and then carbon fiber. The main downside of carbon fiber is its vulnerability to degradation caused by UV radiation and its extremely high cost. The main downside of aramid fiber is the low compressive strength and relatively low resin adhesion and glass fiber have good properties but have a very low specific strength compared to the rest of the fibers. Glass fibers are the most extended fibers in the industry due to its very low cost. Another issue with carbon

[11] https://www.christinedemerchant.com/carbon-kevlar-glass-comparison.html

fiber is that it is very sensitive to fiber misalignment. However, for small wind turbine blades, the additional cost of carbon fiber is not prohibitive due to the quantity used.

B. Evaluation of matrix materials (e.g., epoxy, polyester, vinyl ester) and their impact on laminate properties

Thermoset resins are the most widely used resin type, mostly because of their superior properties in terms of their load carrying ability, resistance to environmental degradation and adhesiveness. Epoxy, polyester and vinyl ester are all thermosetting matrices.

Epoxy is a product derived from epoxy resins, a type of thermoset polymers that contain epoxide groups. Epoxy also has a low viscosity, which is very beneficial for the manufacturing process. Thanks to its good flow characteristics, it shows better impregnation properties ensuring that all the fibers are fully impregnated by the resin, has reduced void formation since it flows more easily into tight spaces and they are easier to handle. Epoxy has great mechanical properties, including high strength, high stiffness and toughness as well as good chemical resistance. Epoxy is very commonly used with carbon fiber.

Polyester resins are inexpensive compared to epoxy and are typically used with fiberglass fibers and can resist heat better than epoxy does (epoxy has a limit of 135° F whereas polyester can resist up to 175 °F). Compared to epoxy, it has lower tensile strength and stiffness and suffers degradation due to UV radiation and has lower chemical resistance.[12] Polyester resins are the hardest to process and release slightly more hazardous fumes.

Property	Epoxy	Polyester
Viscosity at 25 °C μ (cP)	12000-13000	250-350
Density ρ (g.cm^{-3})	1.16	1.09
Heat Distortion Temperature HDT (°C)	50	54
Modulus of elasticity E (GPa)	5.0	3.3
Flexural strength (MPa)	60	45
Tensile strength (MPa)	73	40
Maximum elongation (%)	4	1

Figure 10: Epoxy, polyester mechanical properties[13]

12 https://www.bestbartopepoxy.com/blogs/ultraclear/polyester-resin-vs-epoxy-resin#:~:text=Let's%20compare%20the%20two%20resin,resistant%2C%20though%20both%20are%20good.

13 https://www.ijert.org/research/optimum-and-reliable-material-for-wind-turbine-blade-IJERTV4IS020677.pdf

Vinyl ester resins offer great chemical, corrosion, and moisture resistance. Its fatigue resistance and stiffness is higher than that of polyesters but lower than that of epoxy. Vinyl ester resins have great processability and lower curing times than epoxy and polyester.

C. Considerations for selecting optimal combinations of fibers and matrices for specific blade requirements

The fibers and the matrix are combined into the composite and the mixing ratios vary. And calculating the stiffness and tensile strength of the composite material is essential to determine the suitability of the composite. The stiffness of the composite is calculated with the following formula:

$$E_c = \eta \cdot V_f \cdot E_f + V_m \cdot E_m$$

Where E is the stiffness (elastic modulus), V is the volume fraction, η is an orientation factor for the fibers and the index f is fiber and m is the matrix. When there is no porosity, the sum of the volume fractions is one. When the fibers are aligned parallel to each other and loaded along the fiber direction, the orientation factor is 1 and when they are randomly oriented, the orientation factor is $\frac{1}{3}$. Fibers are usually the materials that contribute the most to the material properties of composites but the matrix is also important.

Other important factors to take into consideration are the environment in which the composites will be used, in the case of wind turbine blades for example, UV degradation and water resistance is something to account for. Another factor is the weight and the shape required to meet the aerodynamic requirements of the blade (some fibers are more flexible and can adapt to different shapes better than others). The cost is also something that needs to be accounted for, carbon fiber and epoxy composites seem to be a very powerful mix with probably the best mechanical properties but a lot more expensive than fiberglass and polyester composites. Balancing performance and cost is something that the designer will need to take into consideration. Finally, it is worth accounting for the compatibility of the chosen fiber and matirx with each other (ie: adhesiveness) and with the selected manufacturing methods such as infusion, hand lay-up, or filament winding.

V. Manufacturing Techniques for Composite Blade Lamination

A. Overview of common manufacturing processes, such as vacuum bagging, infusion, and prepreg layup

Wet lay up (open mold) technology for composites is suitable for small and medium sized blades. Vacuum bagging is an improvement of the wet lay up process and consists of using dry fibers onto a mold surface, applying a matrix material, and then covering the mold with a vacuum bag. The sealed bag is used to remove the air and compress the laminate. Vacuum infusion and prepreg (emerged from aircraft technology and consists of using pre-impregnated composite fibers, which already contain an amount of the matrix material bonding them together using heat) technology are more modern techniques that improve the quality of the manufacturing process. Nowadays, the most widely used technology is the vacuum infusion technology where fibers are placed in closed and sealed molds and resin is injected into the mold cavity under pressure. After the resin fills all the volume between fibers, the component is cured with heat. Resin infusion technology can be divided into three groups:

- Resin Transfer Molding (RTM) (resin injection under pressure higher than the atmospheric pressure)
- Vacuum Assisted Resin Transfer Molding (VARTM) (most common and it is the process of injecting resin under vacuum or pressure lower than atmospheric, tuìcally, under a vacuum bag).
- A variation of VARTM called SCRIMP (Seemann Composite Resin Infusion Process) is quite effective for producing large and thick parts. With VARTM layers of fabrics of dry fibers, with nearly all unidirectional fibers, aligned in the direction along the length of the blade, are positioned on mold parts along with polymer foams or balsa wood for sandwich structures. In order to form a laminate that is thick by the root and gradually becomes thinner towards the tip, most plies run for the root only partly toward the tip; the termination of ply is called ply drop. The fabrics are subsequently covered by a vacuum bag and made air-tight. After the application of vacuum, low-viscosity resin flows in and wets the fibers. After the infusion, the resin cures at room temperature. In most cases, wind turbine rotor blades are made in large parts (as two aeroshells with a load-carrying box (spar) or internal webs that are then bonded together. This method can be upscaled easily since the number of suction points can be increased. The problem with upscaling is that the composite is very thick at the root section and thin at the tip and it can be a challenge to avoid the formation of wrinkles or air bubbles.

The infusion process is usually cheaper than the prepreg process. However, the prepreg composites have more stable, better and less variable mechanical properties than the composites produced by resin infusion.

Automated tape lay-up, automated fiber placement, two-pieces or segment wind blades, enhanced finishing technologies are expected to improve quality and reduce costs.

A summary of the advantages and disadvantages of some of the manufacturing processes mentioned above is provided below.

Manufacturing Technique	**Description**	**Disadvantages**	**Advantages**
Hand Lay-Up	Simplest and most common method. It is done manually by adding the resin to the dry fabric with a brush. Open mold process.	1. Often leads to a high resin to fiber ratio which leads to a low strength-weight ratio because there is no way to remove excess resin. 2. Imprecise method of controlling the amount of resin in each layer. 3. Nothing holds the fiber to the mold. 4. Limited time to lay out the fibers with the correct orientation before the resin starts becoming gel.	1. Simple 2. No extra equipment required
Hand Lay-up with vacuum bag	Consists on all the hand lay-up steps but a flexible bag surrounds the parts after the resin has been applied and a vacuum pump sucks the air out exposing the surface to 15 psi (not a lot of pressure but enough to improve the strength and stiffness).	1. Requires more equipment (pump, bag that supports the exothermic reaction from the resin curing and sealant). 2. There might still be excess resin since the resin is still applied manually. 3. Limited time to lay out the fibers with the correct orientation before the resin starts becoming gel.	1. Holds a constant pressure and can squeeze excess resin out of the material.
Vacuum Infusion	Dry fibers are placed into the mold and then a vacuum is applied. Afterwards, a flow media is used to draw the resin across the fibers allowing unlimited	1. A lot harder to do since it is extremely complicated to get the resin to flow in the desired direction and to fully wet the fibers.	1. Barely no cost increase compared to hand lay-up with vacuum bag you only need extra tubing, peel ply to separate material and a flow media. 2. Very repeatable

	to properly orient the dry fibers.		process with excellent material properties.
Pre-impregnated with vacuum bagging	Fibers are pre-impregnated with resin and partially cured. Then fibers are placed into the freezer to slow the rate of the reaction down leaving the end user with a fiber that has the appropriate resin content for optimal mechanical properties.	1. Very high costs. An auto-clave (oven that also regulates pressure of up to 180 psi) is required and a mold that is able to withstand temperatures of 400 F is too. 2. Pre-preg carbon is three times more expensive than dry carbon fiber. 3. The high temperature that resins require after curing can lead to internal stresses when the part cools down.	1. Repeatability 2. Constant resin-fiber ratio

Figure 11: Summary of the most common manufacturing methods with composites.[14]

B. Explanation of key steps involved in composite lamination, including ply cutting, layup, and curing

Ply cutting refers to the process of cutting the carbon fiber to size given the blade core. It is preferable to cut it slightly bigger (around 1 inch on each side) to ensure that the fiber can fully cover the edges.

Lay up refers to the process of arranging the plies in the appropriate fiber orientation to create a laminate. During the hand lay up it is important to flatten out the fiber ply completely and make sure that there are no wrinkles or air pockets as well as achieving the appropriate stacking sequence. Epoxy or other resin needs to be applied in between layers.

Curing is the process of applying heat, pressure or just allowing the epoxy to cure at room temperature given resin specifications.
**Make sure to wax any areas you do not want the laminate to adhere to.*

[14] https://core.ac.uk/download/pdf/19137539.pdf

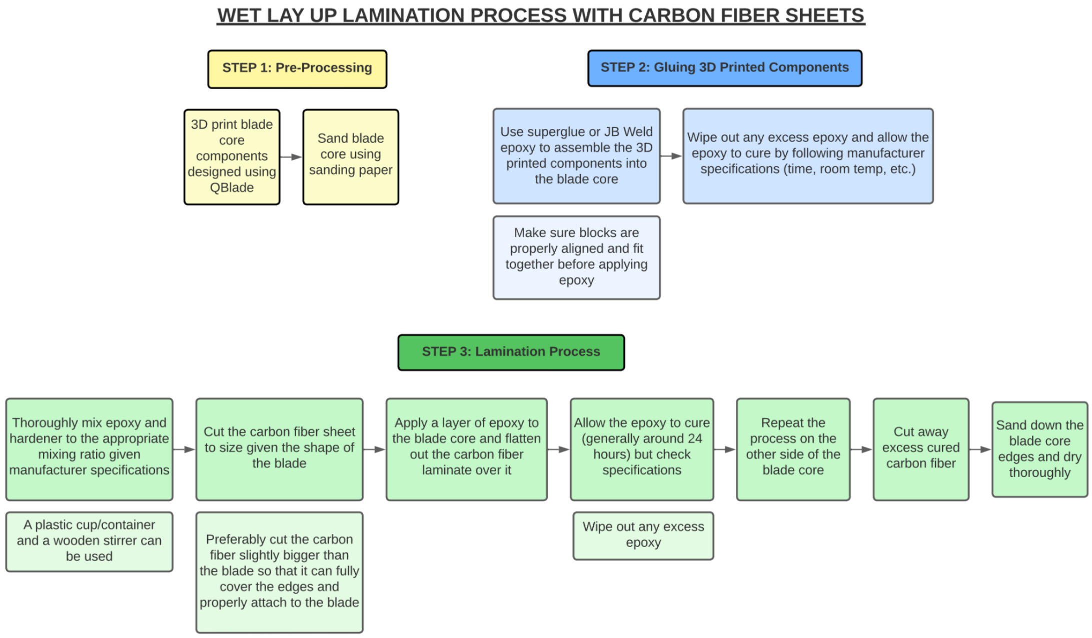

Figure 12: Process map of the hand wet lay up lamination process for a small wind turbine blade

C. Challenges and considerations in ensuring proper lamination quality and minimizing defects

There are several potential failure modes that may result from the wet lay up lamination process.

- Insufficient uniformity in the 3D printed blade core can result in poor adhesion of the carbon fiber laminate leading to a weakened structure. It is recommended to sand the blade core with a 60 or 100 grit paper.
- Inappropriate size of the carbon fiber laminate can also cause uneven stress distribution if the laminate does not fully cover the blade core. In order to avoid this, the laminate needs to be cut to 1 inch larger than the blade core on each side to cover the edges. It is also important to place tape before cutting the carbon fiber to size to avoid fraying at the edges.
- Low degree of curing also prevents the composite from achieving its full mechanical properties. Ways to prevent improper curing include leaving sufficient time for the epoxy to cure as well as ensuring the environmental conditions such as temperature, dust and humidity are appropriate.
- Insufficient consolidation pressure for the laminate can also result in major deficiencies and curing under weights or using a hand roller are possible ways to prevent it.
- Inappropriate resin impregnation or resin dripping can also result in voids and air pockets within the laminate. Actions recommended to avoid this include ensuring all the surface area of the blade core has evenly spread out resin before placing the carbon fiber laminate.

VI. Impact of Composite Lamination on Blade Performance

A. Evaluation of the mechanical properties and performance advantages of composite laminates

The mechanical properties of glass fiber, carbon fiber, kevlar and the matrix epoxy are shown in the table below.

Material	Modulus of elasticity (GPa)	Compressive strength (MPa)	Volume density (g/cm^3)
E-glass	76	1750	2.57
Kevlar	131	2750	1.44
Carbon	228	3950	1.8
Epoxy	2.8	53	1.2

Figure 13: Material Properties of Common Composites in Wind Turbine Blade Manufacturing.[15]

The mechanical properties of hybrid composites, which combine E-glass and Kevlar for improved mechanical performance have also been analyzed for some stacking sequences by Mehmet Bulut in the Journal of Composites. Kevlar has better mechanical properties than E-glass and the goal of these tests was to examine whether a certain combination of glass and kevlar could reduce cost and achieve similar performance than Kevlar alone. This is a very interesting study because it can be used in the wind turbine industry to minimize cost while still having a really good mechanical performance. The stacking sequences are shown below in figure 15.

Naming	Stacking sequence	Laminate codes	Volume fraction ratio for S-glass fiber	Volume fraction ratio for Kevlar fiber	Maximum tensile strength (MPa)	Elongation at break (%)
G10	●●●●●●●●●●	GFRP	78.95	0	441.45	3.60
G8K2	●●●●●●●●○○	H1	63.16	22.73	455.99	3.63
G6K4	●●●●●●○○○○	H2	47.37	43.48	467.04	4.00
G4K6	●●●●○○○○○○	H3	31.58	57.69	531.85	4.83
G2K8	●●○○○○○○○○	H4	15.79	71.43	547.88	4.95
K10	○○○○○○○○○○	KFRP	0	83.33	560.98	5.09

● Glass fiber; ○ Kevlar fiber; GFRP: glass fiber-reinforced plastic; KFRP: Kevlar fiber-reinforced plastic.

Figure 14: Stacking sequence of composites laminates.[16]

[15] https://www.hrpub.org/download/20151208/MST7-15490392.pdf

[16] https://www.researchgate.net/publication/281538314_Experimental_investigation_on_influence_of_Kevlar_fiber_hybridization_on_tensile_and_damping_response_of_Kevlarglassepoxy_resin_composite_laminates

The tensile properties of these composites have been examined and the results are shown below. As expected, the KRFP shows the highest tensile strength and a higher strain, showing the ductility of the material. The GFRP shows the lowest strain and stress from all the tested samples indicating a brittle property. H1 to H4 show properties in between these composites as shown in Figure 15.

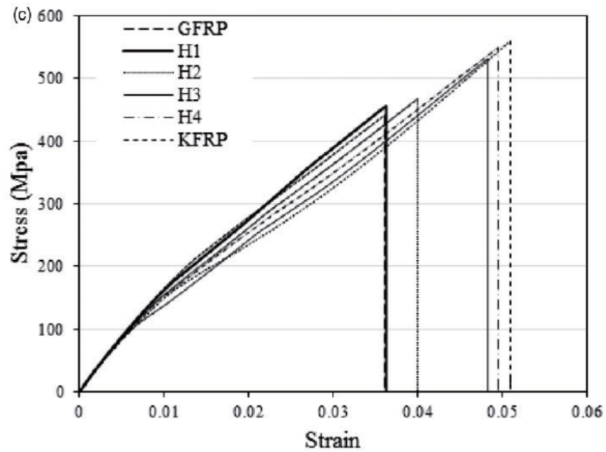

Figure 15: Tensile properties of the samples.[17]

The damping properties of samples were also investigated and the following results were obtained. The damping ratio quantifies the level of resistance to oscillation in a dynamic system which is expressed as the actual damping in a system to the critical damping. A higher damping ratio indicates more damping and thus that oscillations decay more quickly. The storage modulus measures the elastic behavior of a viscoelastic material meaning that it quantifies the ability of a material to store elastic energy when it is subjected to a stress. It indicates the material's resistance to deformation and its ability to return to its original shape. The loss modulus measures the viscous behavior of a viscoelastic material. It quantifies the ability to dissipate energy as heat when a stress is applied.

17 https://www.researchgate.net/publication/281538314_Experimental_investigation_on_influence_of_Kevlar_fiber_hybridization_on_tensile_and_damping_response_of_Kevlarglassepoxy_resin_composite_laminates

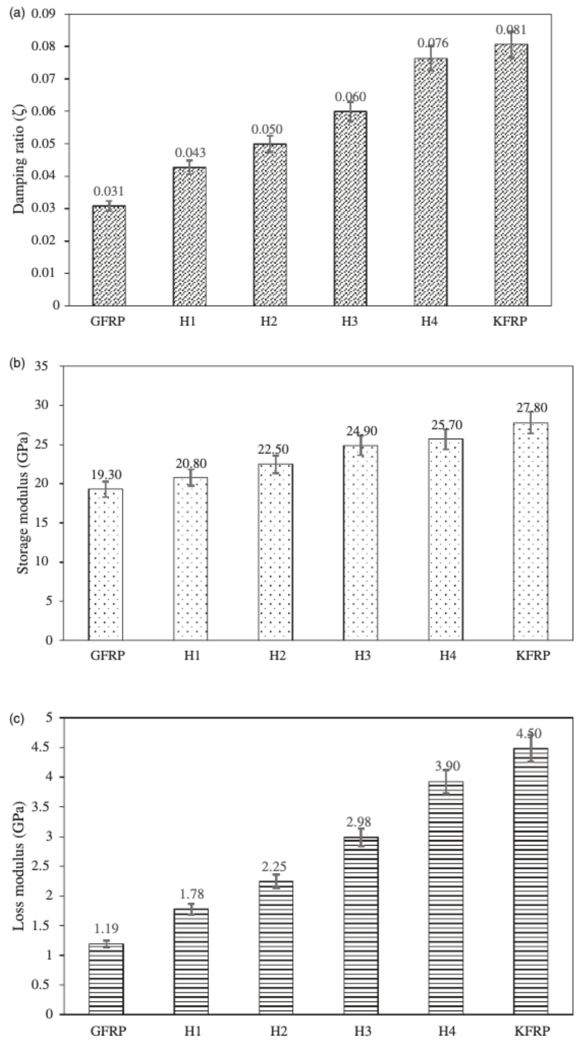

Figure 15: Damping properties of samples a) damping ratio, b) storage modulus, c) loss modulus.[18]

Overall, the inclusion of Kevlar fiber in the lamina, instead of glass fiber, resulted in a beneficial hybrid effect in terms of loss modulus. The damping properties can be ranked as follows: KFRP > H1 > H2 > H3 > H4 > GFRP. Among the hybrid arrangements, the laminate with H4 (G2K8) hybrid composite exhibited the highest damping properties, showing a 145% increase compared to GFRP and slightly lower damping values (approximately 6% lesser) than KFRP.

These findings suggest that it is possible to achieve desired damping and vibration capabilities similar to those of KFRP by substituting cheaper S-glass fibers with varying fiber mixing ratios in hybrid composite laminates.

18 https://www.researchgate.net/publication/281538314_Experimental_investigation_on_influence_of_Kevlar_fiber_hybridization_on_tensile_and_damping_response_of_Kevlarglassepoxy_resin_composite_laminates

B. Analysis of the effects of laminate design and material choices on blade strength, stiffness, and fatigue resistance

Laminate design and material choice have a very significant impact on blade strength, fatigue and stiffness. The laminate design can be subdivided into laminate stackup, fiber orientation and ply thickness.

The fiber orientation refers to the orientation of the fibers within each layer and determines whether the material is isotropic or anisotropic. Optimal fiber orientation helps align fiber with the principal directions of loading, maximizing strength, stiffness and reducing material fatigue. Laminate stackup refers to the orientation of the individual layers in a laminate and it ensures load-bearing capability in the intended directions enabling the design to reinforce regions where the loads are higher. In the laminate stackup, hybrid composites can be chosen depending on the desired properties, applications and cost of the material. Varying the ply thickness can also help optimize load distribution and improve the strength to weight ratio. Thicker plies can be used when enhancing strength is necessary and thinner plies can be used when more flexibility and resistance to delamination is necessary.

When it comes to material selection, the choice of reinforcement fibers such as glass fibers, carbon fiber or aramid fibers definitely improves the strength, stiffness and durability of the components when compared to traditional engineering materials. Carbon fiber has the best properties as of today followed by aramid and glass fibers but the use of glass fiber is more extended because of its low cost. The matrix material, typically epoxy or a polymer, provides cohesion and transfers load between the reinforcement fibers. The matrix's properties, including strength, stiffness, and resistance to environmental factors, influence the overall performance of the laminate. Choosing a matrix material compatible with the fiber being used is key for optimal performance.

C. Case studies highlighting the performance improvements achieved through composite blade lamination

LM Power, a Danish subsidiary of General Electric, has been able to create the longest wind turbine blade, the LM 88.4 P, by using hybrid carbon design and is currently using similar technology to create another record breaking onshore blade for a 142 meter rotor. The lightweight composites boost performance, minimize loads and enable industry to increase blade size and energy output without increasing mass.

Other companies that have incorporated carbon fiber in their blade design are Vestas Wind Systems (Aarhus, Denmark) and Gamesa Technology (Vizcaya, Spain). Due to the lighter weight of carbon fiber blades, the turbine tower components are required to be less robust to withstand the loads of the lighter blades and this has led to cascading cost savings for both these companies even despite the high costs of carbon fiber.[19]

[19] https://www.compositesworld.com/articles/wind-turbine-blades-glass-vs-carbon-fiber

VII. Testing and Validation of Composite Laminates

A. Overview of testing methods to assess the mechanical properties of composite laminates

The testing methods most commonly utilized to assess the mechanical properties of composite laminates are: tensile test ASTM D3039, compressive test ASTM D3410, flexural test ASTM D7264, in-plane shear test ASTM D3418, interlaminar shear stress test ASTM D2344 and fatigue tension-tension testing ASTM D3479 although there are other fatigue testing methods such as tension-compression, compression-compression, bending fatigue and fatigue crack growth.[20]

- The tensile test determines tensile strength and strain, Young’s modulus, and Poisson's ratio (ratio of change in width vs change in length).
  The specimen geometry for a tensile test is tabulated and is shown in the table below.

Fiber orientation	Width mm(in.)	Overall length mm(in.)	Thickness mm(in.)	Tab length mm(in.)	Tab thickness mm(in.)	Tab bevel angle (°)
0° unidirectional	15(0.5)	250(10.0)	1.0(0.040)	56(2.25)	1.5(0.062)	7 or 90
90° unidirectional	25(1.0)	175(7.0)	2.0(0.080)	25(1.0)	1.5(0.062)	90
Balanced and symmetric	25(1.0)	250(7.0)	2.5 (0.100)	Emery cloth	-	-
Random discontinuous	25(1.0)	250(10.0)	2.5(0.100)	Emery cloth	-	-

Figure 14: ASTM D3039 Specimen Standards for composite laminates.

- The compressive test determines the compressive strength, compressive Poisson’s ratio and compressive chord modulus of elasticity.

[20] https://www.addcomposites.com/post/mechanical-testing-of-composites

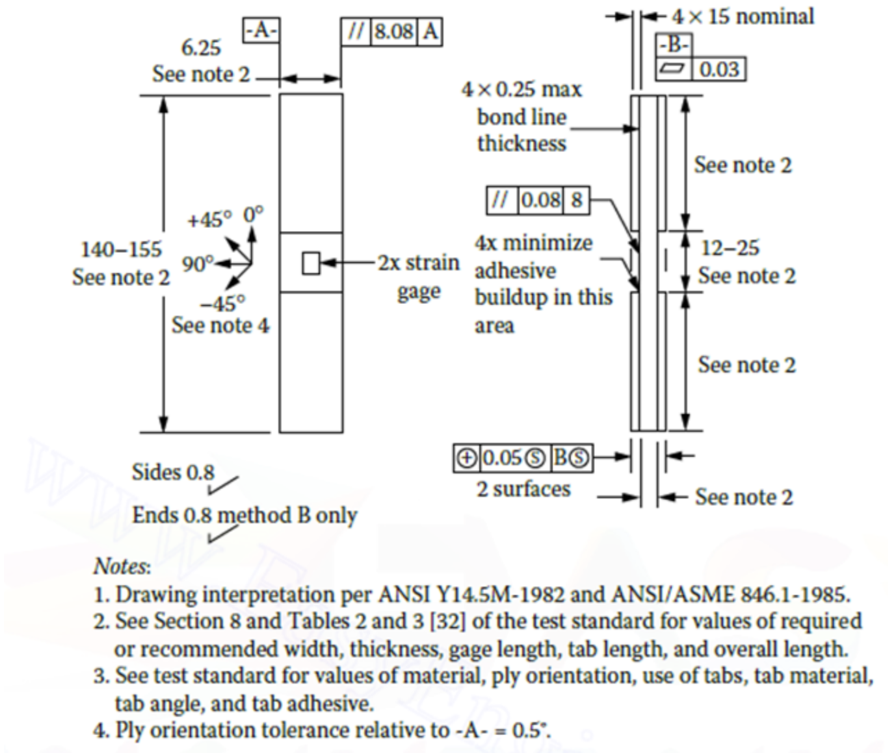

Figure 15: Compression Test Specimen Geometry

- The flexural test determines the flexural strength and the flexural cord modulus of elasticity. The flexural test can be a three point bending test or a four point bending test. The specimen requirement is a ratio between the span length and the thickness (l/t) and it is established to be 32:1.

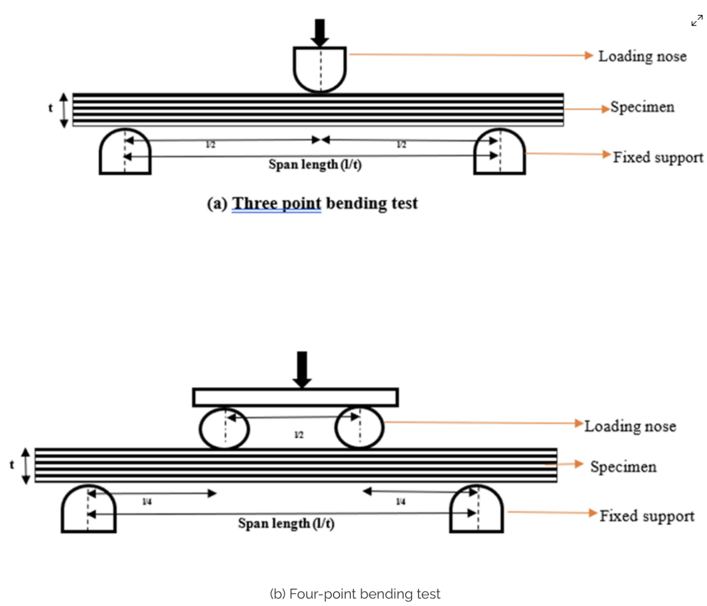

Figure 16: Three and four point bending test setup

- The plane-shear test determines the shear strength and strain and shear modulus of elasticity. The specimen has to be manufactured in ±45° fiber orientation as shown in Figure 15.

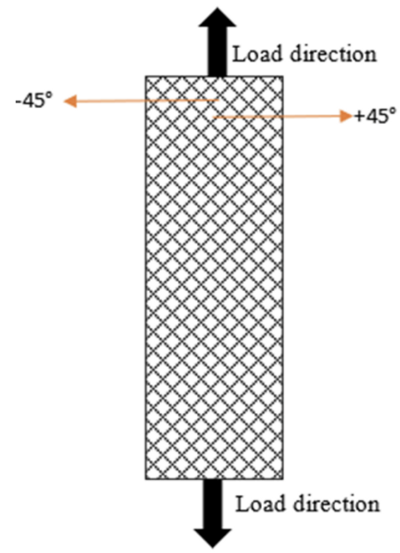

Figure 17: Specimen of in-plane shear stress

- The interlaminar shear test determines the shear beam strength. The required specimen geometry is thickness t, width should be double the thickness and length six times the thickness.

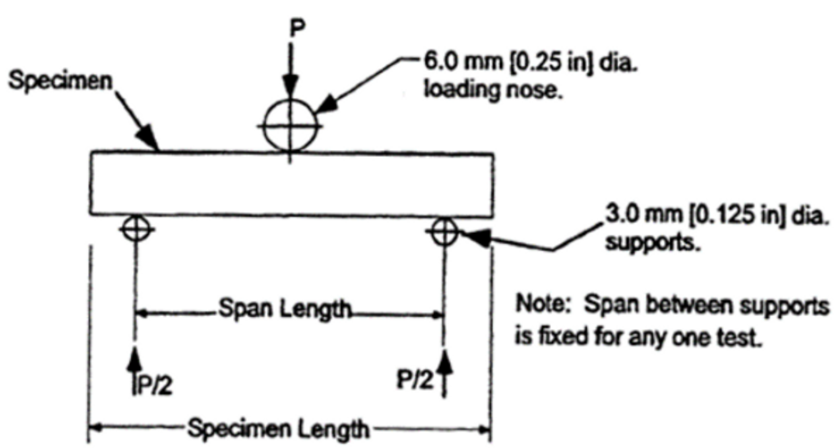

Figure 18: Interlaminar shear test set up

B. Evaluation of relevant industry standards and protocols

The most common industry standards are ASTM, ANSI, DIN, ISO and EN. When evaluating composites for different industries, it is important to understand the requirements and protocols of those industries such as automotive, aerospace, wind, marine, construction, military, etc. I have mentioned some ASTM standard tests in this paper but it is also important to take into consideration specific industry standards. For example, the AC 20-107B Composite Aircraft structure is a FAA (Federal Aviation Administration) guidance document outlining the design, manufacturing and inspection considerations in aircraft structures. For the wind turbine industry, other standards such as IEC 61400-23 (Design Requirements for Wind Turbine Rotor Blades), ASTM D8012 (Standard Practice for Safe Handling and Application of carbon Fiber Reinforced Polymer Composites) or the DWIA (Danish Wind Industry Association) are in place.

C. Importance of quality control and certification in ensuring reliable and durable laminates

Quality control is a key aspect of engineering and ensures that in this case, laminates meet customer and industry requirements in product consistency as well as durability and longevity. Without quality control, there is a much higher risk of producing defectuous products. Quality control can be done in plenty of ways including statistical processes by close monitoring and data collection, inspection and testing to verify it meets the industry safety standards, etc.

VIII. Durability and Longevity of Composite Laminates

A. Discussion on the resistance of composite laminates to environmental factors, such as UV exposure, moisture, and temperature

The long term exposure to environmental weathering such as UV radiation, moisture, temperature and oxygen can be very destructive to composites. Long term exposure to this weathering can cause a significant decrease in the glass transition temperature, storage modulus and tensile strength. [21]

Composites such as carbon fiber or glass fibers typically have very good resistance to UV radiation. However, epoxy, a very common resin matrix, despite being the best resin to withstand UV radiation compared to polyester resin and vinyl ester resin, is still susceptible to it. Epoxy has numerous advantages like low shrinkage, good chemical resistable, curable at low temperatures, etc. but their durability and mechanical properties are affected by UV radiation. To prevent this, UV blocking topcoats or paint are typically applied to maintain the overall performance of carbon fiber.

Carbon fiber and glass fibers both deal very well with moisture and a humid environment since the fibers do not absorb water. Polyester resins have worse water resistance capabilities than

[21] https://onlinelibrary.wiley.com/doi/abs/10.1002/masy.201650015

vinyl ester and epoxy resins so the latter resins are typically used in applications where water resistance is crucial, such as marine, chemical processing, and corrosive environments.
Carbon fiber has a melting point of 3000°C or 5430 °F, glass fiber has a thermal resistance ranging from 700-900 °C or 1292°F-1652°F and aramid fiber have a melting point of 500°C-600°C and 932°F-1112°F. The thermal resistance of composites is very high compared to that of resins and it is the matrix that is the limiting factor for temperature resistance. Epoxy has a limit of 57°C or 135° F whereas polyester can resist up to 80°C or 175 °F .

B. Considerations for maintenance, inspection, and repair of composite blades

Wind turbine blades are usually designed to last for over 20 years but without proper maintenance and repairs, their life will be shorter and turbine efficiency will decrease.

The European market for wind turbine blades is more regulated and recognizes that proper maintenance begins with regular and thorough inspections. “Insurers in Europe require biennial, up-close, visual inspection of every blade in every wind farm” claims Josh Crayton, blade services manager ar Rope Partner Inc. In the US regular blade inspection has not been imposed yet but progress towards doing this is being made. Commercial aircrafts for example, which have a 20,000 hour design life, receive 76 times the number of maintenance hours than wind turbine blades despite wind turbine blades suffering 48 times the hourly fatigue.

A good inspection program should identify potential problems and solutions before they affect efficiency or become fatal.

Transportation is also a challenge for wind turbine blades and composite structures suffer a lot of damage during this process. Blades are getting closer to the maximum size of road transportation and this is something that needs to be addressed since the cost of production of wind turbine blades is very high.

In very demanding environments, wind turbine blades can start showing signs of degradation as soon as two years after installation. Lightning is also something that needs to be accounted for and right now, lightning prevention technology is being improved. Blades are designed to redirect strikes to the ground via a small copper plate near the blade tip that acts as a conductor forcing the lightning through heavy wires to the base of the blade and then to the ground.

There are several ways to inspect wind turbine blades. The easiest way is to inspect the blade using a scope from the ground using NDI (Network Device Interface) technology. This is useful to identify visual damage indicators such as cracks. The problem with this is that delamination is not properly identified with this technique. Ultrasound technology is another alternative for detecting flaws within the bonding areas several centimeters into the laminate. Exova is using ultrasonic phased-array sensors to optimize the performance in curved surfaces, where it is often complicated to identify flaws in the structure. Shearography, currently used in aerospace and marine industries, can also be used for wind blade inspections. Laser technology can identify subsurface defects such as voids, air pockets, delamination, wrinkles, disbonds, porosity, core displacements, etc.

For repairs that do not need fiber reinforcement, the chosen resin can be applied to the damage area. For repairs involving the fibers, the wet layup method is the standard technique.

C. Life cycle assessment and durability predictions for composite laminated blades

Life Cycle Assessment (LCA) is an analysis that assesses the environmental impacts associated with a product including material extraction, manufacturing, use, and disposal. The life cycle environmental impact of a single 45.2 meter 1.5 MW wind turbine blade is 795 GJ of energy consumption and 42.1 tonnes of carbon dioxide emissions. Based on the 2014 installed capacity, the total mass of wind turbine blades is 78 kt, their energy consumption is 82 TJ and the carbon dioxide footprint is 4.35 Mt.[22]

As of right now, recycling wind turbine blades is a major challenge. It is important to find ways to recycle or reuse these giant structures rather than burying them in landfills since the current disposal practices of wind turbine blades are inconsistent with the sustainability goals of wind power. The cumulative mass of decommissioned blades in the US will reach 1.5 million metric tons by 2040 and 2.2 million tones by 2050.

One of the main recycling arrangements is a product of a partnership between Veolia and GE Renewable Energy. It is being started in Germany, Switzerland and Spain. These consist of shredding the blades and using them to produce alternatives to cement or separating the blade's fiberglass and polymeric resin to make reinforced industrial products. It is important to take into account that 80-90% of the mass of the blade is made out of composites and all composites are intrinsically difficult to recycle.[23] The recycling costs are very high and it is something that needs to be dealt with considering the wind turbine industry is expected to grow at an annual rate of 6.5%.

The durability predictions involve assessing the expected lifespan and serving performance. Typically, wind turbine blades last for 20 years and their life can be extended to 25 years if the environmental conditions are favorable.

IX. Future Trends and Advancements

A. Exploration of emerging materials, manufacturing techniques, and design approaches in composite blade lamination

As of right now, the industry is transitioning from fiberglass composites to carbon fiber reinforced polymers since they offer higher specific strength and stiffness. The possibility of using natural fibers in composites such as flax, hemp, and bamboo is also being explored since these fibers have a much lower environmental impact, lower cost, and better recyclability. Nanomaterials such as nanotubes and graphene are also possible candidates since they can enhance mechanical properties, improve electrical conductivity, etc. Hybrid reinforcements

[22] https://iopscience.iop.org/article/10.1088/1757-899X/139/1/012032/meta

[23] https://cen.acs.org/environment/recycling/companies-recycle-wind-turbine-blades/100/i27

(E-glass/carbon, E-glass/aramid etc.) also represent an interesting alternative to pure glass or pure carbon reinforcements.

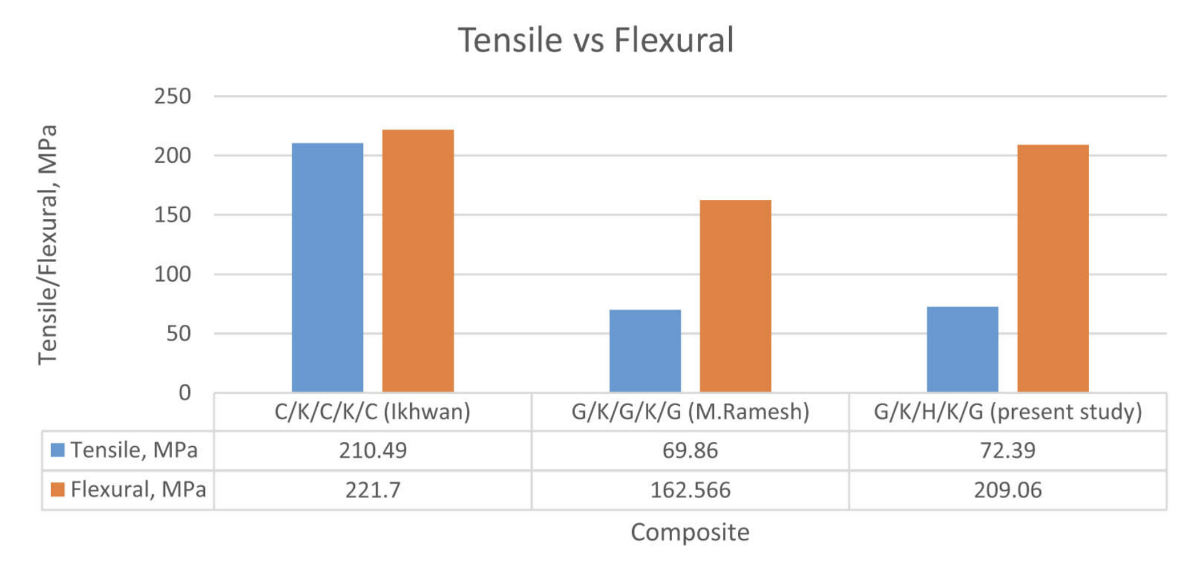

Figure 19: Tensile and flexural strength with different hybrid composites.[24]

The most novel manufacturing techniques being used in the wind turbine industry is additive manufacturing as well as automated manufacturing such as automated fiber placement (AFFP) and automated tape laying (ATL). Two piece or segment wind blades are starting to be utilized due to the increasing size of wind turbine blades. A big challenge in comparison with the automation of manufacturing in the aerospace industry is the larger thickness and amount of material that needs to be placed in the molds for blades. For some parts of the blade, 3D woven composites seem to be a promising option to the entire laminate blade core since it can produce spar caps with higher stiffness and lower weight.[25]

The prospect of installing blades that twist as they bend or extend called aeroelastic tailoring is also being further researched since it provides opportunities for enhanced energy capture and load mitigation. This can be achieved via active or passive design (preferred).

B. Anticipated improvements in blade performance, weight reduction, and cost-effectiveness

The high strength to weight ratio of composites when compared to other engineering materials such as metals or woods is significantly reducing the weight of wind turbine blades. Currently the majority of blades are made out of fiberglass and assembled by hand. If the transition to carbon fiber and automated machining like CNC process happens, the weight of the blades could decrease by 25% with improved mechanical performance.[26] In addition, lighter weights lead to

[24] https://www.degruyter.com/document/doi/10.1515/rams-2022-0299/html?lang=en

[25] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5706232/

[26] https://www.windsystemsmag.com/decreasing-turbine-weight/

lower loads and the rotor and the tower portion of the blade could also considerably decrease in weight. A switch to carbon fiber could also increase the lifetime of wind turbine blades since carbon fiber has higher fatigue resistance.[27] The decrease in weight also improves turbine efficiency since blades can be manufactured to be 5m/16 feet longer than traditional blades, increasing the sweep area of blades without any additional weight gain.[28]

The use of carbon fiber also comes with its disadvantages which is an increase in cost. Carbon fiber can be up to 10 times more expensive than carbon fiber.

C. Potential integration of advanced technologies, such as additive manufacturing and nanomaterials, in composite blade lamination

Incorporating additive manufacturing technology, an innovative and already mature technology, in the wind turbine industry could potentially accelerate innovation, reduce costs, maximize efficiency and reduce processing time to up to 50% which will accelerate the deployment of wind turbines.[29] Additive manufacturing also grants more design freedom and reduces material waste when compared to subtractive manufacturing and generates less waste than other manufacturing processes.[30] GE Renewable Energy is already starting to use additive manufacturing to speed up production. GE Renewable mentions how wind turbine blade design has opened the door for more flexibility in the design. "For example, whereas the standard design for a wind turbine at a given site might call for towers to be 90 meters tall, more detailed analyses on-site might show that in one specific section of the wind farm towers that are 120 meters tall make more sense. In that case, we can 3D print 30-meter tower components on-site to add to the existing, standard 90-meter base to get optimal performance."[31] They also mention that parts of the mechanical assembly that are usually manufactured as multiple individual components can be additively manufactured as a single unit, allowing GE to reduce the number of parts needing to be designed and manufactured, greatly simplifying the process. This also contributes to an easier recycling process.

The implementation of nanotechnology in turbine blades could improve the durability of its components, lower maintenance costs with less greenhouse gas emissions. Nanomaterials and nanosensors could also be used for renewable energy smart grid integration. Nanoscale materials are starting to be used to increase the lifespan of blades, reduce failure modes and reduce overall costs. Nanomaterials also have a very good weight to strength ratio and can help reduce the

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[27] https://www.sandia.gov/labnews/2021/01/29/carbon-fiber-for-wind-turbine-blades-could-bring-cost-performance-benefits/

[28] https://www.compositesworld.com/articles/wind-turbine-blades-glass-vs-carbon-fiber

[29] https://www.energy.gov/sites/default/files/2021-10/fy21peerreview-materialsandmanufacturing-ornl-post.pdf

[30] https://encyclopedia.pub/entry/28344

[31] https://3dprintingindustry.com/news/powering-the-renewable-energy-transition-with-3d-printing-wind-205254/

weight of blades as they continue to increase in size. Carbon nanotubes can also be used for coating the rotor blade surface and preventing the icing of the blades.

X. Conclusion

A. Summary of the benefits and considerations of utilizing composite materials for small wind turbine blade lamination

Composite materials offer high strength-to-weight ratios and excellent stiffness properties. The design flexibility composite materials offer is also something to be highlighted since it can lead to improved design and versatility as well as improved aerodynamic properties to maximize efficiency. In addition, unlike traditional engineering materials such as metals, composites are resistant to corrosion.

Important considerations when using composite materials are cost, since materials like carbon fiber can be more expensive than traditional materials, the complexity of the manufacturing processes and sustainability aspects.

B. Implications for improved blade strength, performance, and overall wind energy efficiency

Higher high strength-to-weight ratios allows for the construction of more resistant blades that can withstand higher loads and harsher environmental conditions. Lighter materials also reduce the overall weight of wind turbine blades, allowing manufacturers to make the blades a lot larger without increasing the mass; this increase in surface area maximizes energy output. Composite materials can also be molded into complex shapes allowing for optimized blade designs. The lifespan of wind turbine blades is also increased thanks to its corrosion resistance.

C. Importance of ongoing research and development in advancing composite blade lamination technologies.

The ongoing research and development is essential to make a smoother energy transition to renewables. Researchers are working on improving aerodynamic efficiency, structural integrity, durability and energy capture capabilities of wind turbine blades. Lighter, stronger and more durable materials such as composites seem to be the answer and thus a lot of R&D efforts are directed towards composites. New fiber reinforcements, resins and fiber+resin combinations are being explored. Moreover, reducing the cost of composites is something that can also be done by optimizing manufacturing methods. Advanced additive manufacturing processes for the mold as well as automated manufacturing technology for wind turbine blades are also being developed to enable the production of complex blade geometries, allow for tighter tolerances and improve the repeatability of the manufacturing process. R&D is also key to improve the sustainability of wind energy and the recycling of blades.