# Alternative Damage Tolerant Materials for Wind Turbine Blades: An Overview

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# ALTERNATIVE DAMAGE TOLERANT MATERIALS FOR WIND TURBINE BLADES: AN OVERVIEW

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## ABSTRACT

Current wind turbine blade materials may not be damage tolerant to the extent necessary to optimize the Levelized Cost of Energy (LCOE) of wind energy plants. Traditionally, wind turbine blades have been designed using a safe-life approach, but advances in inspection techniques and structural health monitoring solutions give rise to the opportunity to design wind turbine blades using a damage tolerant approach. Materials selection is a key element of damage tolerant design, so the extent of the damage tolerance of alternative materials has been analyzed through a literature review and discussions with industry leaders. Fabrics and resin selection significantly affect the damage tolerance of composites. Changes to fabric architecture may include through-the-thickness (TTT) fibers, stretch-broken carbon fiber (SBCF) composites, and aligned discontinuous fiber reinforced composites (ADFRCs). Previous research has demonstrated that using TTT fibers increases damage tolerance, but additional research is necessary to demonstrate the effectiveness of SBCFs and ADFRCs in mitigating damage. Several studies have demonstrated increased damage tolerance when toughened resin systems are used. In addition to toughened resin systems, thermoplastics have been shown to be tougher than thermosets. However, thermosets have been traditionally preferred in wind turbine blade manufacturing due to ease of manufacturing. Thermoplastic resin systems have been developed that can be used with conventional manufacturing methods but have yet to be studied for its damage tolerant capabilities. Furthermore, cost and stress analyses on where to effectively implement TTT fibers, SBCF composites, ADFRCs, and toughened resin systems must be executed prior to incorporating new materials into wind turbine blade manufacturing.

## ACKNOWLEDGEMENTS

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## ACRONYMS AND DEFINITIONS

| Abbreviation | Definition |
|---|---|
| LCOE | levelized cost of energy |
| CAI | compression after impact |
| TTT | through-the-thickness |
| SBCF | stretch-broken carbon fiber |
| ADFRC | aligned discontinuous fiber reinforced composites |
| NDI | non-destructive inspection |
| AFGROW | Air Force growth |
| OpEx | operational expenditures |
| GFRP | glass fiber reinforced plastic |
| VARTM | vacuum assisted resin transfer molding |
| OWC | orthogonal woven composite |
| AIWC | angle-interlocked woven composite |
| MLL | modified layer-to-layer |
| NCF | non-crimp fiber |
| CFRP | carbon fiber reinforced plastic |
| HiPerDiF | high performance discontinuous fiber |
| RO | randomly oriented |
| QI | quasi-isotropic |
| UD | uni-directional |
| Vf | fiber volume fraction |

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# 1. INTRODUCTION

Wind energy is the largest renewable energy generation type in the United States, accounting for 43% of all utility-scale renewable energy generation and 8% of all energy generation in 2020 [1]. While operations and maintenance (O&M) costs have decreased by 50% over the past two decades, blade failure rates are estimated at 0.5% per year or approximately 10% over a 20-year life [2]. Additionally, the contribution of rotor issues to the total downtime of a wind turbine ranges between 8% and 20% [3]. Thus, decreasing repair needs may result in a reduction of LCOE.

Wind turbine blades are typically constructed using sandwich composites, which consist of foam or balsa cores sandwiched between glass fiber reinforced face sheets. The core increases the moment of inertia which adds stiffness and increases buckling resistance while maintaining a high strength to weight ratio at a low cost. Even though using sandwich composites increases stiffness and buckling resistance, wind turbine blades are frequently damaged from manufacturing defects, mechanical fatigue, impacts, and lightning strikes. Structural damage needs to be repaired for wind turbines to continue operation, and the costs of these repairs can increase the LCOE of wind energy plants. Added costs are not only from repair equipment, labor, and material costs, but also from opportunity costs from wind turbine downtime.

Wind turbine blades are traditionally designed using a safe-life approach, but LCOE could be reduced by transitioning to a damage tolerant approach. A safe-life approach accounts for the worst combination of production defects that is likely to go undetected during production and the worst in-service damage that is likely to occur without being noticed. A damage tolerant approach is the ability of a structure to retain its load carrying capacity after the structure has been damaged. Transitioning to a damage tolerant approach requires an assessment of available damage tolerant materials.

There have been numerous publications concerning composites and damage tolerance, but to the authors' knowledge, no literature reviews have examined the possibility for alternative, more damage tolerant materials for wind turbine blade applications. Factors unique to wind turbine blades include cost-effectiveness, available material quantities, and damage types specific to wind turbine blades. Shah et al (2019) considered the damage tolerance of composite materials in general [4]. McGugan et al (2015) used a condition monitoring approach to damage tolerant design of wind turbine blades but did not consider the damage tolerance of alternative materials [5]. Mishnaevsky et al (2017) conducted an overview of alternative materials for wind turbine blades but did not examine their damage tolerance properties in particular [6]. Furthermore, the potential for alternative, more damage tolerant materials for wind turbine blade applications will be considered in the lens of factors unique to wind turbine blades.

A consideration of alternative, potentially more damage tolerant materials requires not only an evaluation of strength and failure behavior of materials through static and fatigue tests, but also fracture behavior from both impact resistance and damage tolerant tests. Impact resistance is found from drop-tower tests, and residual strength is found from compression after impact (CAI) tests. In addition to evaluations of mechanical properties, estimations of stress conditions where new materials will be implemented will be necessary. The level at which potential damage tolerant materials have been characterized varies significantly among material types, where there have been more damage tolerant studies on TTT fibers and toughened resin systems, but evaluations of impact and CAI properties of stretch-broken carbon fiber (SBCF) composites and aligned discontinuous fiber reinforced composites (ADFRCs) were not found. This is likely because SBCF composites and ADFRCs are newer technologies. Additionally, the exact locations along a wind turbine blade that would benefit from damage tolerant materials have yet to be identified. Areas that should be considered first are adhesive joints because the thick and uneven layers of adhesives limit the strength of adhesive joints and create reliability and repair issues. Other areas that should be considered are areas along the blade that are most prone to damage. Thus, damage tolerance conditions, particularly in joints, must be assessed because damage in joints can be detrimental to wind turbine blade structural integrity.

# 2. BACKGROUND

The following emphasize the necessity to consider alternative, more damage tolerant materials in wind turbine blades: damage tolerance, impact resistance, LCOE, and current wind turbine blade materials, joint geometries, and damage types.

## 2.1. Damage Tolerance and Impact Resistance

### *2.1.1. Wind Turbine Blade Design Approaches*

Hayman (2007) described three design approaches within the lens of aerospace component design, which can be used to design wind turbine blades. Hayman's three design approaches are safe-life, fail-safe, and damage tolerant. The safe-life design approach involves investigating fatigue, manufacturing defects, and in-service damage [7]. Fatigue investigations demonstrate that a structure can withstand the repeated loads expected in service. Manufacturing defects for composites can be categorized into fiber, matrix and interface. Fiber defects include the following: misalignments, fiber waviness, broken fibers, and irregularities of fiber distribution. Matrix defects can be incomplete curing and voids. Interface defects can occur when composites are bonded together and include unbonded regions on fiber surfaces and delamination between layers [8]. In-service damage can include mechanical fatigue, bird collisions, lightning strikes, and leading-edge erosion. Fatigue strength investigations using materials, substructure, and full-scale testing can be successfully used to demonstrate that wind turbine blades can withstand the expected loads in service, but quantifying production defects and in-service damage proves to be difficult when competition between manufacturers limits the amount of information they are able to share. Additionally, differences in production techniques make the production defects more manufacturer-dependent than in other industries.

Wind turbine blades have traditionally been designed using the safe-life approach because regular in-service inspection was limited or non-existent. However, non-destructive inspection (NDI) techniques such as phased array ultrasonics, acoustic emission, infrared thermography, and microwave scanning are becoming more prevalent. Some of the capabilities of these techniques have been demonstrated by Tang et al (2016), Li et al (2017), and Galleguillos et al (2015). Tang et al used acoustic emission sensors to detect damage growth, and acoustic emission monitoring also detected damage too small to be detected by visual inspection [9]. Li et al demonstrated that microwave scanning techniques can detect delamination down to a 0.2 mm width [10], and Galleguillos et al have shown that infrared thermography may be used to reveal flaws in wind turbine blades [11]. Furthermore, advances in NDI techniques have increased damage detectability in wind turbine blades. More damage detectability reduces the necessity to rely on a safe-life design approach as NDI can detect probable locations, extents, and modes of damage on a larger scale that has been previously possible.

The fail-safe approach shows that the catastrophic failure of a structure is not probable after fatigue failure of a principle structural element and that the remaining structure can withstand the maximum design loads, but with a specified reduced factor of safety. The damage tolerant approach extends the fail-safe approach to further consider the growth of damage resulting during manufacture or service usage. The basic philosophy of damage tolerant design is based upon three main criteria:

1. The acceptance that damage will occur.
2. The adequate system of inspection so the damage may be detected.
3. An adequate strength is maintained in the damaged structure [12].

Using a damage tolerant design approach results in an understanding of the structural performance in the presence of defects or damage, which is achieved through fracture mechanics, residual strength, and life prediction methodologies. Some objectives of fracture mechanics include determining:

1. The residual strength as a function of crack size.
2. The tolerable crack size at an expected service load (i.e. the critical crack size).
3. The time it takes for a crack to grow from a certain initial size to the critical crack size.
4. The size of pre-existing flaw that can be permitted when the structure starts its service life.
5. How often the structure should be inspected for cracks [13].

In homogeneous materials, cracks propagate along the same path as the initial crack direction. However, in inhomogeneous materials such as composites, a crack may propagate along a different path from its initial crack direction. Fracture, or delamination propagation, in composite materials happens in multiple phases: compliant, brittle, and tough. Toughening mechanisms can be divided into intrinsic and extrinsic properties, as shown in Figure 2-1. The inherent toughness of a material is an intrinsic property while mechanisms that are used to mitigate fracture are extrinsic. Cairns (1990) used a multiphase element to model individual fracture in each phase of delamination propagation of extrinsic properties [14]. The presence of both intrinsic and extrinsic mechanisms of toughening should be examined when considering alternative materials.

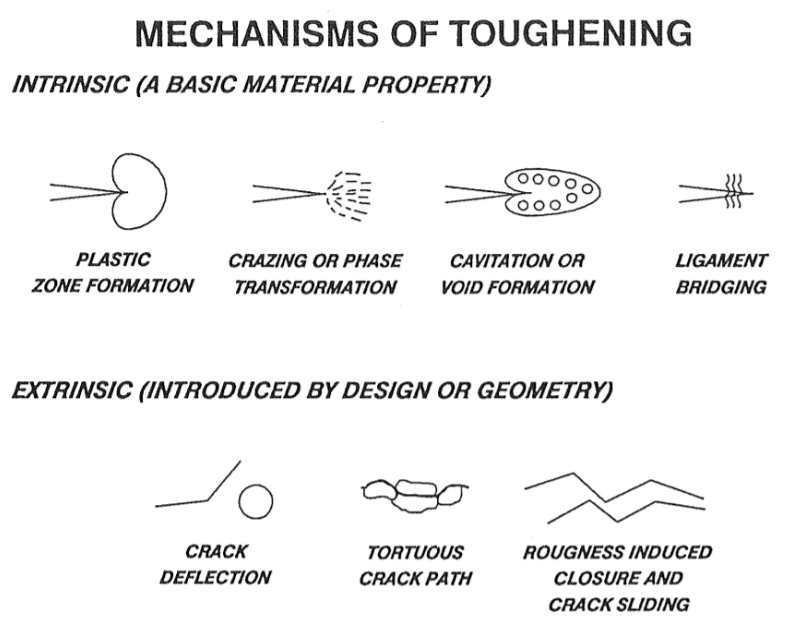


**Figure 2-1. Toughening mechanisms in multi-phase materials** [14].

Lifetime prediction models are developed by both engineering mechanical and micromechanical properties. Engineering mechanical properties include stiffness, compliance, natural frequency, damping, and residual strength, while micromechanical properties include crack density, fiber-matrix debonding and pullout, and delamination [15]. Fatigue mechanisms should also be considered in lifetime prediction. Wind turbine blades are subject to wind, gravitational, and centrifugal loads, so Hu et al (2016) developed a comprehensive fatigue analysis framework for composite wind turbine blades. The analysis included variable wind loads from wind field simulation and aerodynamic analysis, stress prediction by finite element analysis, and fatigue damage evaluation based on the resulting fatigue data [16].

The Air Force Research Laboratory has made significant developments in damage tolerant design and has created a software called Air Force Growth (AFGROW) with an accompanying handbook on damage tolerant design. The handbook provides guidelines for implementing damage tolerant methods into the design of metallic structures. Although wind turbine blades are not metallic structures, the elements of Damage Tolerant Design that are outlined in Figure 2-2 may also be used to guide composite structural designs.

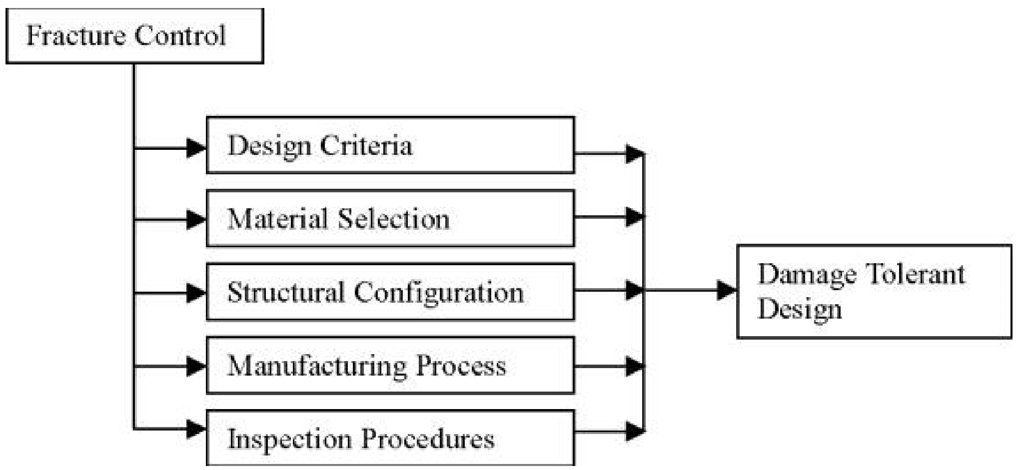


**Figure 2-2. Elements of damage tolerant design** [17].

Design criteria for wind turbine blades is to attain the highest possible power output under specified atmospheric conditions. Profits rise when elements of damage tolerant design are used such as better structural models, suitable composite materials, and efficient manufacturing techniques [18]. This overview will examine the extent of available damage tolerant analyses of alternative composite materials and will thus contribute to the damage tolerant design and profitability of wind turbine blades.

### *2.1.2. Impact Resistance*

Although commonly discussed together, the terms damage tolerance and impact resistance have different meanings. Impact resistance is the measure of the resistance of materials to mechanical impact without undergoing any physical changes [19]. Impact resistance affects residual strength, but the terms damage tolerance and impact resistance should not be used interchangeably. Often, residual strength properties are synonymously used to describe damage tolerance, which is acceptable. However, it is important to note that residual strength is just one component of the damage tolerance design philosophy. Impact resistance is measured using drop-tower tests (Figure 2-3), and residual strength is measured using CAI tests. Ultrasonic C-scanning can be used to quantify the extent of internal damage after both drop-tower and CAI tests, especially when low-velocity impact simulations are employed. Dent depth can also be used to measure damage severity

[20]. Depending on testing purposes, and intuitive within the name, CAI testing is often performed on specimens that had been drop-tower tested. Inputs for drop tower tests include a material with known properties (flexural, longitudinal, and shear moduli, Poisson's ratios, etc.) and the impact energy. Impact tests can be run to ensure full penetration or can be run to simulate low-velocity impacts. Results for impact tests that are run to ensure full penetration can include maximum force, energy absorbed to maximum force, and the total energy absorbed during the full penetration process. Low-velocity impact simulations are selected to induce local damage without penetration [21]. Impact response and the subsequent damage formation are dependent on the proportion of energy absorbed through structural response (elastic) damage [22]. Wind turbine blades are subjected to both high and low velocity impacts, so impact tests to materials of interest should be run at a range of impact energies.

**Figure 2-3. Impact tower setup** [23].

### *2.1.3. Evaluating Impact Resistance and Damage Tolerance*

Factors that affect impact resistance and damage tolerance can be divided into primary and secondary factors. Primary factors include resin toughness and fabric architecture. Secondary factors include the following: environmental conditions, fracture toughness, repeated impact, impactor geometry, fabric and matrix hybridization, and stacking sequence. Environmental conditions involve changes in humidity and temperatures. Impactor geometries can change based on differences in size, mass, and shape. Stacking sequences are influenced by ply angle, ply thickness, and coupling effects [4]. Common damage tolerance tests and outputs are listed in Table 2-1.

**Table 2-1. Common tests in in damage tolerance evaluations and associated outputs.**

| Type of Testing | Output |
|---|---|
| Double Cantilever Beam | Mode I fracture toughness ($G_{IC}$), failure modes |
| End-Notch Flexure | Mode II fracture toughness ($G_{IIC}$), failure modes |
| Drop-Tower Tests for Impact Resistance | Energy absorbed, peak force, damage extent |
| Compression After Impact | Compressive failure loads/residual strengths for varying impact energies |
| Tension or Compression Tests of Notched Laminates | Failure stress, modulus retention ratio, stress concentration factor |

In a damage tolerance evaluation, the probable modes of damage due to fatigue or accidental damage are determined and a damage extent consistent with the initial detectability and subsequent growth is established. In addition, repeated load and static analyses and the residual strength evaluation must show that the remaining structure is able to withstand the design loads. Residual strength curves plot decreasing in-plane sandwich composite compression strength as a function of increasing impact severity, as shown in Figure 2-4.

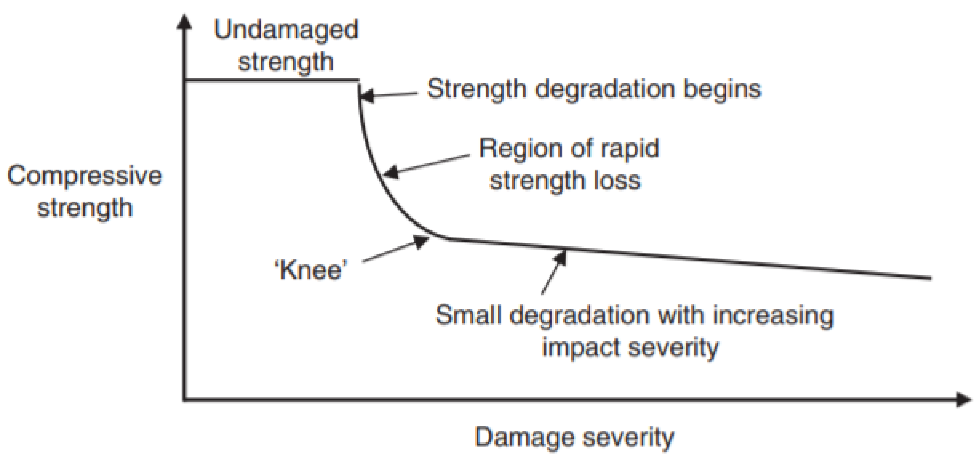


**Figure 2-4. CAI strength with respect to damage severity plot** [20].

## 2.2. LCOE

Moné et al (2017) describe many factors that contribute to LCOE, but the factor of primary concern is operational expenditures (OpEx) [24]. OpEx is generally expressed in two categories: operations and maintenance. Operations costs include scheduled plant maintenance, rent, land lease costs, taxes, utilities, and insurance payments. Maintenance costs are considered variable OpEx and include unplanned maintenance of either the plant or turbine and other costs that may vary throughout the project life. Unplanned maintenance includes repairs to wind turbine blades, which, if deemed cost-effective, are conducted after a wind turbine blade incurs structural damage that inhibits normal operation. If the sizes and quantities of repairs are minimized by using more damage tolerant materials in initial wind turbine blade design, then both scheduled and unscheduled maintenance costs of wind turbines would be reduced.

## 2.3. Current Wind Turbine Blade Materials

Figure 2-5 demonstrates the typical cross-section of a wind turbine blade. The foam or balsa core separates the two faces so that the moment of inertia of the faces is large, resulting in added stiffness and buckling resistance [25]. In addition to high stiffness and buckling resistance, the use of composites enhances fatigue life and corrosion resistance. Layers of glass fiber fabric, or laminae, are stacked with varied orientations to withstand repeated, multidirectional loading cycles.

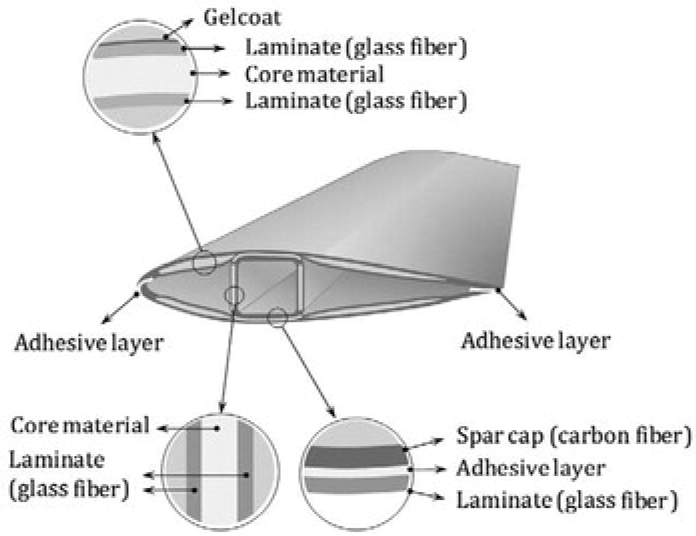


**Figure 2-5. Typical cross-section of a wind turbine blade** [26].

Glass fiber reinforced polymer (GFRP) composite wind turbine blades are manufactured using the vacuum assisted resin transfer molding (VARTM) process depicted in Figure 2-6. The VARTM process begins with stacking glass fiber fabric, peel ply, and flow media on a heated caul plate. Tacky tape is placed on the outside perimeter of the caul plate, and a vacuum bag is pressed into the tacky tape. Vacuum pressure is applied via the vacuum port. Resin is introduced through the injection port and impregnates the fabric. The heated caul plate accelerates resin cross-linking resulting in a part that can be removed from the mold and post-cured if recommended [27]. Using VARTM to manufacture composites typically increases fiber volume fractions (Vfs), or fiber to resin ratios, as opposed to other methods such as hand lay-up.

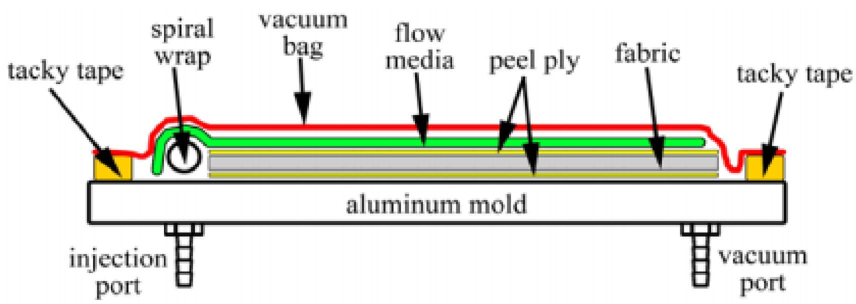


**Figure 2-6. Cross-sectional view of VARTM setup** [28]**.**

Most wind turbine blades are manufactured using thermoset resin systems such as epoxy and vinyl ester. Thermosets are commonly used for their ease of manufacturing and resistance to corrosion. However, thermosets have poor transverse properties and have poor resistance to crack initiation and growth.

## 2.4. Wind Turbine Blade Joint Geometries

An increase in wind turbine blade damage tolerance will not only require finding residual strengths of potentially more damage tolerant materials, but also a reasonable estimation of stress conditions where new materials will be used, particularly at joints. Wind turbine blade joints include: the T-bolt connections at the blade root (Figure 2-7), shear-web-to-spar-cap joints (Figure 2-8), trailing edge joints, and leading edge joints. Often, the thick and uneven layers of adhesives limit the strength of the joint and create reliability and repair issues. Damage to joints can be particularly detrimental to wind turbine blade structural integrity. Thus, increasing damage tolerance in joints may be crucial to reducing repair or blade replacement needs. Furthermore, a consideration of contact, friction, yield, and non-linear geometric deformation in wind turbine blade joints will be necessary [29].

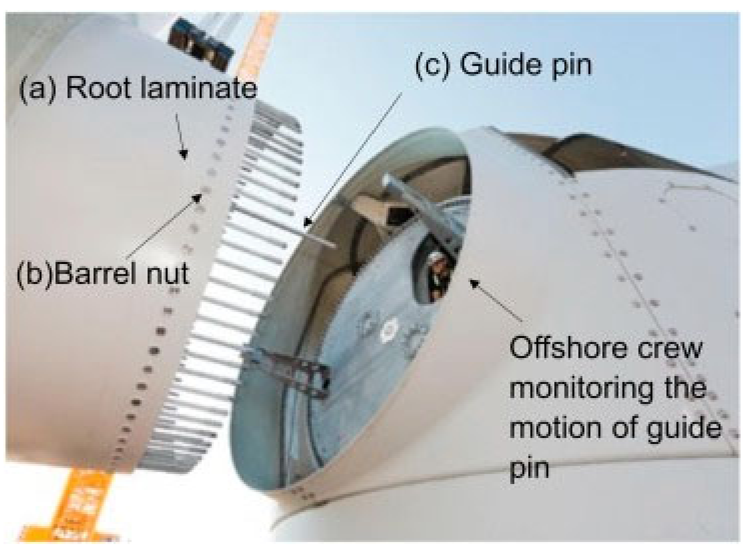


**Figure 2-7. T-bolt connections used in joining a wind turbine blade to the nacelle** [30]**.**

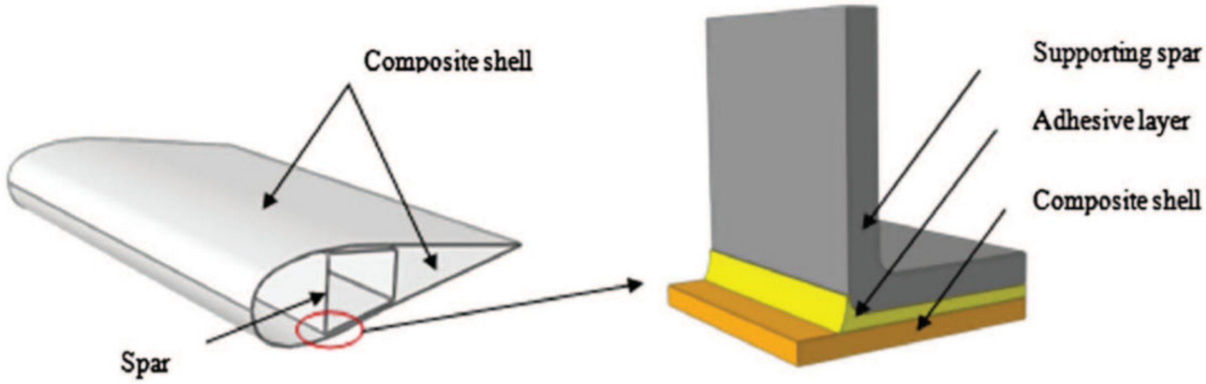


**Figure 2-8. Shear web bonded to spar caps co-infused into top and bottom blade shell halves** [31].

Leading edge and trailing edge joints are formed during blade shell assembly. Figure 2-5 shows the adhesive layer between leading edge and trailing edge joints.

## 2.5. Wind Turbine Blade Damage Types

Wind blades are subject to a variety of loading conditions, making the analysis of damage initiation and propagation highly complex. Loading conditions include flap-wise and edgewise bending, gravitational loads (mainly generate edge-wise bending), torsional loads (because the shear resultants do not go through the shear center of the blade section), axial loads due to the rotation of the blade (inertia forces), and loads due to pitch decelerations and accelerations [26]. Although sandwich composites are stiff, strong, and fatigue resistant, wind turbine blades are susceptible to a variety of forms of damage such as lightning strikes, manufacturing defects, and leading-edge erosion. All these causes can lead to failure modes depicted in Figure 2-9. It is crucial to rectify both production defects and in-service damage, as both diminish wind turbine blade performance [7].

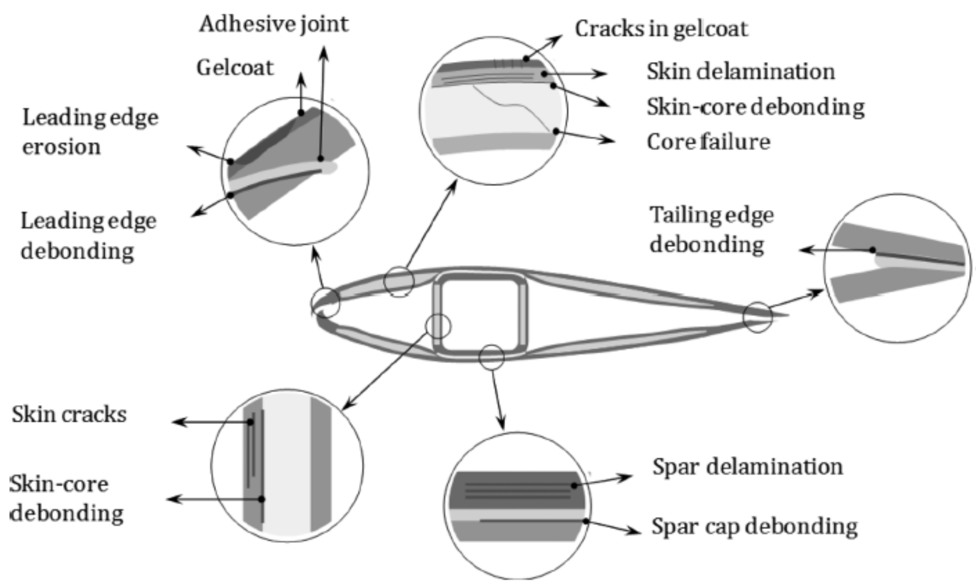


**Figure 2-9. Common damage modes in composite wind turbine blades** [26].

Damage modes include leading edge erosion, leading edge debonding, skin delamination, spar delamination, and spar cap debonding. Delamination is of utmost concern because delamination reduces the flexural and compressive strength of a laminate. Strength reductions are a result of delamination because the laminate is subdivided into thinner sub laminates with lower buckling load [32].

Impact damage modes to composites include delamination, surface buckling, matrix cracks due to shear and bending, and fiber breakage (Figure 2-10).

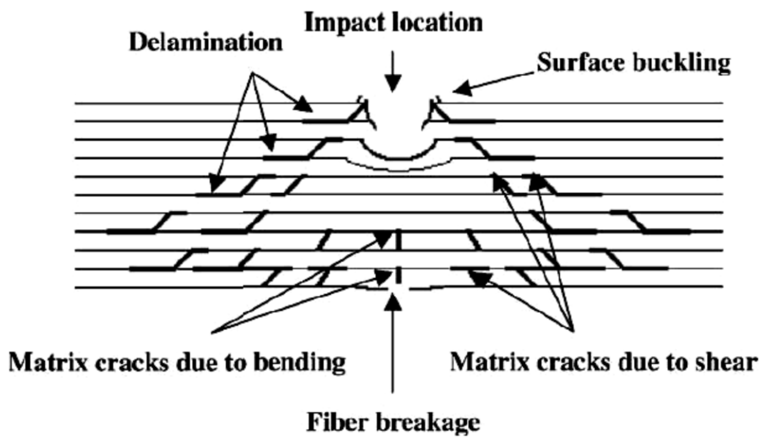


**Figure 2-10. Typical impact damage modes for laminated composites** [33].

The nature of the damage induced depends on a multitude of factors including the face sheet layup configuration and thickness, core material and thickness, interface properties between facesheet and core, fabrication techniques, impact velocity and energy, indentor shape, temperature, boundary conditions, and environmental factors. For sandwich panels with foam cores, the core-facing interface may debond in a region surrounding the point of impact and the core may experience permanent deformation. Increasing the number of facing plies may result in more core damage, and CAI tests indicated that cores providing more face sheet support had higher compressive residual strength even though delamination areas were larger [34]. A comprehensive assessment of the damage types incurred by potentially damage tolerant materials subject to impact will be necessary prior to implementation in wind turbine blades.

# 3. EXTENT OF DAMAGE TOLERANT ANALYSIS FOR ADDITIONAL MATERIAL TYPES

This review examines the extent of damage tolerant analyses for alternative materials for wind turbine blades. Since fabric architecture and resin toughness are the primary factors affecting impact resistance and damage tolerance, resin toughness and fabric architecture are the main factors considered in this review. Alternative fabrics include modified layer-to-layer woven fabrics, carbon fibers, and natural fibers. Alternative resin systems include using thermoplastics or resin additives. Other methods may involve altering ply stacking sequences and taking into consideration the criticality of adhesively bonded joints.

## 3.1. TTT fibers

Typically, composite materials are manufactured by stacking plies containing either unidirectional or bidirectional fiber fabrics. This approach is ideal to maximize the in-plane properties as the fibers, which provide stiffness and strength, are oriented within the plane. However, the out-of-plane properties of 2D laminates are limited, which is particularly critical under out-of-plane impact because delamination may develop even in the absence of visible damage in the top and bottom plies [32].

3D composites encompass composites that are stitched, Z-pinned, or woven. Stitched composites are made by mechanically driving Kevlar©, glass, or carbon fibers into composite laminates [22]. Z-pinning involves embedding small diameter pins into composites to produce a 3D fiber structure [35]. Woven laminates involve introducing yarn in the z-direction to make 3D fiber architecture [22]. In 3D composites, out of plane reinforcement in addition to in-plane reinforcement controls the overall energy dissipation and damage evolution. 3D composites have been shown to dissipate over twice the energy of 2D laminates because z-yarns delay delamination and maintain the structural integrity of a laminate, while promoting energy dissipation by tow splitting, and intensive fiber breakage at the point of impact. Modification in fabric architectures with stitching, z-pinning, and 3D weaving all increase the interlaminar fracture toughness by up to three times as compared to unmodified fabric [4].

Whether the 3D composite is stitched, Z-pinned, or woven, the primary advantage of using 3D composites is reduced delamination, and the main disadvantages are high production costs and decreased in-plane properties. TTT fibers increase structural stability, delamination resistance, and the energy absorption capability due to higher intra-layer shear strength. In-plane properties are decreased in part from the introduction of resin-rich regions around TTT fibers. Cracks may initiate in the resin-rich regions but decreases to in-plane properties may also be due to increases in fiber misalignment from in-plane fiber disturbances. A 0.25 degree fiber misalignment has been shown to decrease compressive strength of carbon fiber composites by 47%, so fiber misalignment in 3D composites could also decrease compressive strength [36].

### *3.1.1. Stitching*

Possible stitching parameters can include stitching threads, stitching speed, thread tension, type of laminate, and machine parameters. Stitching is generally considered damaging to the in-plane properties despite the improved out-of-plane properties. In addition, stitching threads can cause disturbances between in-plane fibers and lead to resin-rich regions around fibers, as shown in Figure

3-1. Furthermore, a degradation of the in-plane compression strength can generally be expected with an increasing degree of stitching density [37].

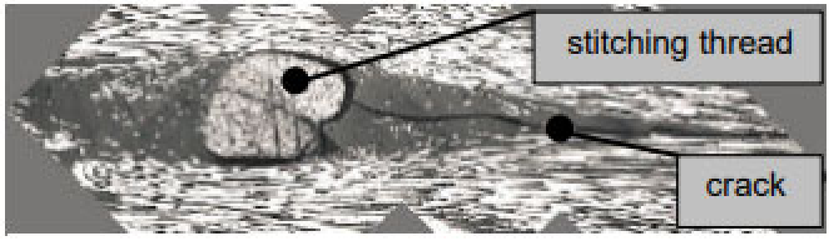


**Figure 3-1. Crack formation around a stitching fiber and into the resin-rich region** [37]**.**

### *3.1.2. Z-Pinning*

Z-pins impart massive improvements in mode I and II fracture toughness values by up to an order of magnitude. In addition, Z-pinning in combination with woven laminates could be used to produce efficient and highly impact tolerant structures [22]. A downside is that Z-pinning has been shown to reduce in-plane (compressive and tensile) properties by more than 25% [4]. Z-pinned composite structures are shown in Figure 3-2 and Figure 3-3.

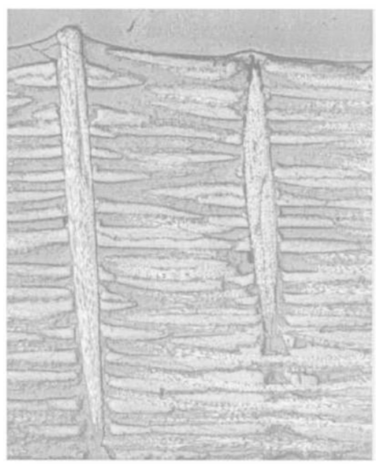

**Figure 3-2. Structure of a composite reinforced with Z-pins** [35]**.**

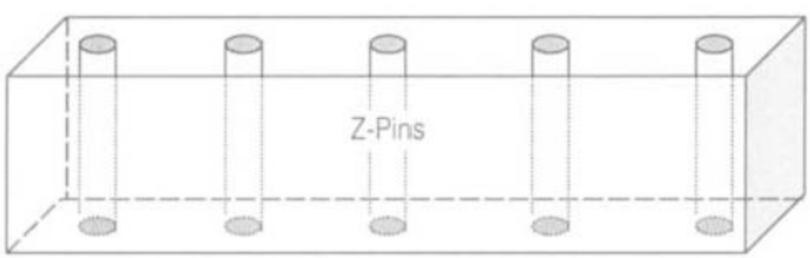


**Figure 3-3. Schematic of a Z-pinned composite** [35]**.**

### *3.1.3. Woven*

TTT reinforcement not only increases the structural stability and delamination resistance but also increases the energy absorption capability of these materials due to higher intra-layer shear strength [4]. Potluri et al (2012) demonstrated that damage to 3D woven laminates is highly localized to the area under the impactor and did not seem to spread along tows. In addition, 3D laminates have a lower rate of degradation with respect to impact energy than 2D laminates [38].

Warp yarn is the yarn along the weaving direction, and the interlacing yarn perpendicular to the weaving direction is the weft yarn [25]. Through-thickness Z-binder yarns that are interlaced with the warp and weft yarns inhibit the spread of delamination. As a consequence, 3D woven composites are capable of providing higher impact damage resistance and superior interlaminar fracture toughness than conventional two dimensional laminates [39]. The through-thickness reinforcement in the fiber architecture also gives the fabric enhanced stability and excellent transverse properties.

According to a representative at Vectorply Corporation, 3D woven fabrics cost approximately four times as much and require approximately five times more machinery to manufacture as their 2D fabric counterparts. Due to the cost and capital disadvantages, most companies that have tried making 3D fabrics have gone out of business, most notably, 3-TEX. However, Texonic Inc. in Québec, Canada currently makes 3D composites for primarily storage tanks, and thus may have the means to make 3D fabrics for wind turbine blades. In addition to Texonic, Inc., Albany Engineered Composites in Salt Lake City, UT also makes 3D reinforced composites.

There are three different types of 3D woven composites: orthogonal woven composites (OWCs), angle-interlocked woven composites (AIWCs), and modified layer-to-layer (MLL) composites. OWCs have TTT reinforcements that wrap around each stack of tows in a laminate, as shown in Figure 3-4.

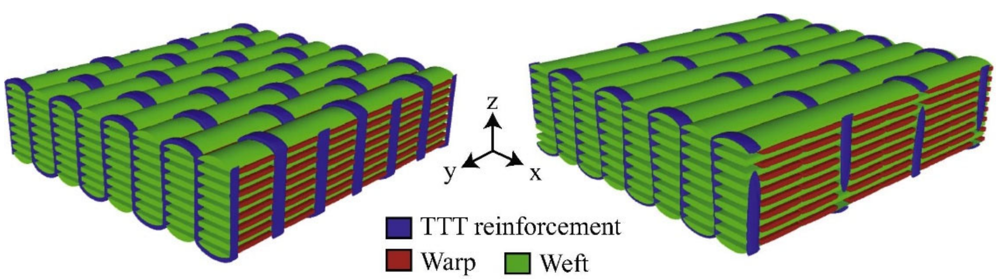


**Figure 3-4. OWC woven fabric with two different TTT binder densities** [40].

Unlike OWCs, AWICs have binder yarns weaving at angles around multiple weft tows, rather than binder yarns weaving around individual columns of tows. Tsai et al (1998) described Figure 3-5 as an AWIC [41]. However, Yu et al (2015) describe Figure 3-6b as an MLL structure [39]. Figure 3-5 and Figure 3-6b illustrate identical structures, so for clarity, the illustrations by Yu et al in Figure 3-6 will be used to describe AWICs and MLLs.

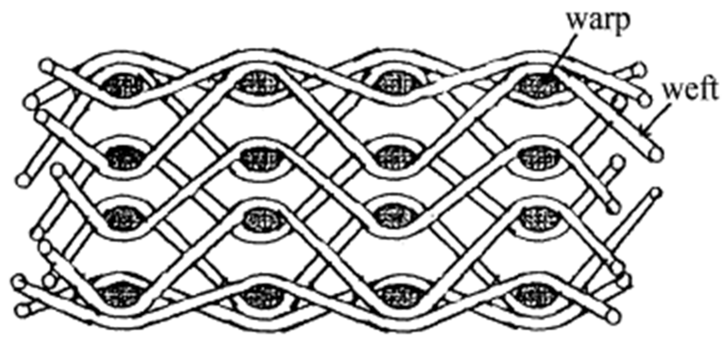


**Figure 3-5. Schematic of AWIC** [41]**.**

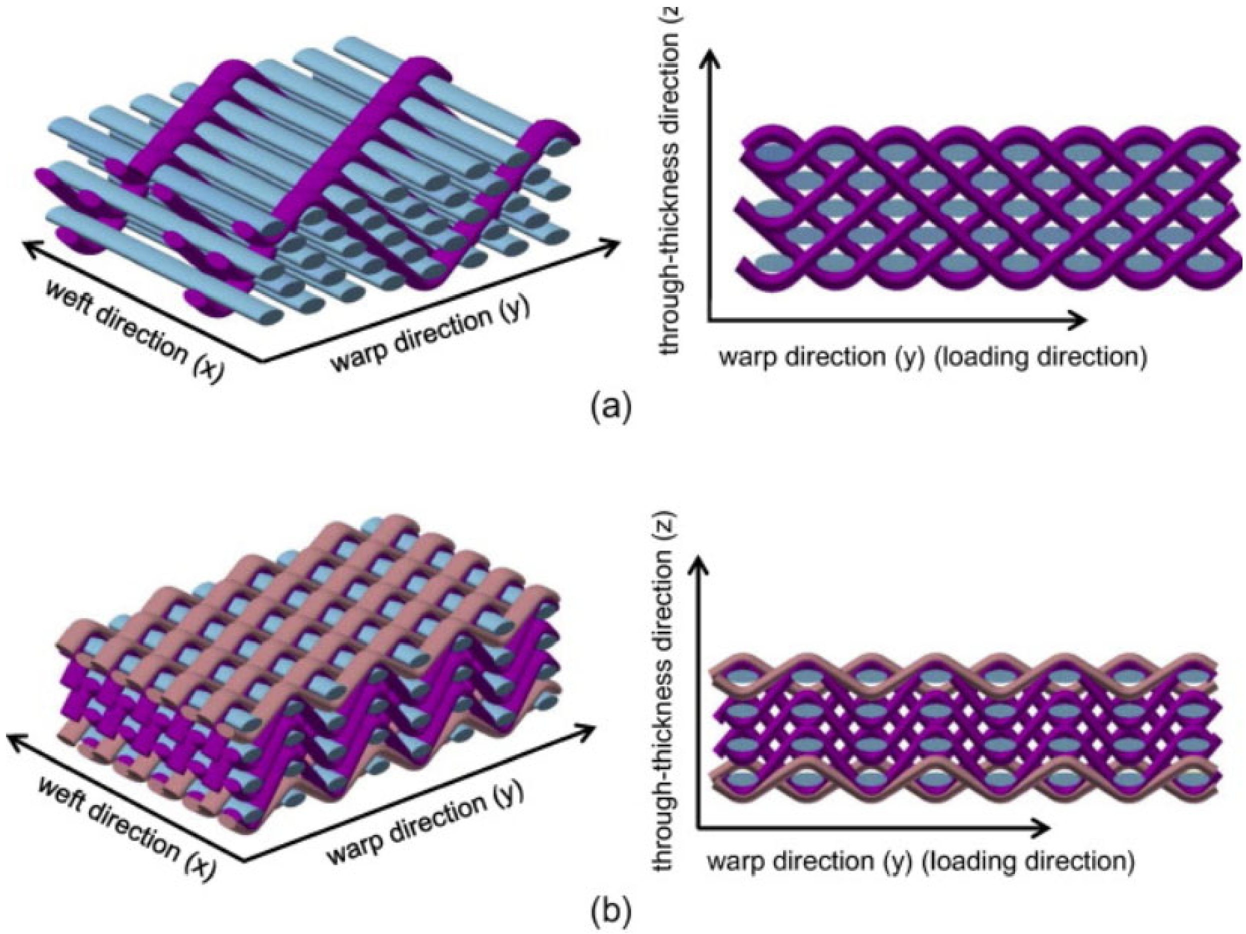


**Figure 3-6. Schematic showing (a) 3D angle-interlocked fabric (left) and its cross-section (right); (b) MLL woven fabric (left) and its cross-section (right). Weft, binder, and additional warp yarns are blue, purple, and pink, respectively. Yarn spacing and dimensions are not to scale** [39]**.**

Yu et al (2015) conducted 2D and 3D imaging of fatigue failure mechanisms of 3D woven composites and found higher crack density in AIWCs than MLL composites. In addition, transverse cracks in the weft yarns and binder debonding (delamination) have a strong influence on stiffness and fatigue properties in both 3D fiber structures [39].

Potluri et al (2012) performed impact and CAI testing on orthogonal weave, angle interlock weave, layer-to-layer interlock weave, and MLL weave materials and found that undamaged compression strength is primarily a function of average tow waviness angle and less influenced by the topology of interlacement [38]. Un-toughened resin systems were used for the study. It is possible that using toughened resin systems with 3D composites could increase damage tolerance.

## 3.2. Carbon Fiber

Carbon fiber is another material that has and should continue to be considered in wind turbine blade manufacturing, particularly in the production of thick spar caps because carbon fibers increase stiffness considerably. Ong et al (2000) found that, generally, the cost of carbon fiber replacement depends largely on the cost ratio of labor to materials [42]. Bundy (2005) emphasized the necessity to research the performance of pultruded carbon fiber in wind turbine blades, and indicated that the thick spar cap could be made using unidirectional pultruded elements [43]. Overall, carbon fibers significantly increase the stiffness for a given weight.

Ennis et al (2019) and Miller et al (2019) demonstrated the viability of using carbon fibers in wind turbine blade design. Ennis et al (2019) characterized novel heavy tow carbon fiber materials derived from the textile industry. The novel carbon fiber had improved performance-per-cost compared to baseline carbon fiber materials commonly used in the wind industry. Additionally, using carbon fiber spar caps reduced blade mass and improved fatigue life [44]. Miller et al (2019) assessed the commercial viability of lower-cost wind-specific carbon fiber composites to enable larger rotors of increased energy capture. Properties of the novel carbon fiber composites were compared with commonly used, higher-cost carbon fibers. The lower-cost carbon fibers had comparable compressive and fatigue strengths but had lower tensile strengths than the higher-cost carbon fibers. Compressive strength properties are more critical for wind turbine blade design, so low-cost carbon fibers should continue to be considered for wind turbine blade design [45].

With regards to damage tolerance, it is crucial to note that impact damage causes significant reductions in carbon fiber compressive strength. Huang et al (2017) conducted CAI tests on Non-Crimp Fiber (NCF) fabric-reinforced thermoset composites and found that compromises on the compressive load and stiffness were nearly proportional to the damage size but not sensitive to the damage type, where damage types were impact damage and slot cut. Damaged beams were tested for their fatigue performance and both the initial damage size and the fatigue history showed a significant bearing on the damage growth rate [46]. Liu et al (2016) quantified the flexural fatigue life of CFRPs and the delamination propagation mechanism was primarily matrix/fiber debonding and secondary cracking. In addition, the delamination at the interfaces of the first ply group was the major failure mode for the flexural fatigue damage [47]. Chambers et al (2006) characterized the voids in unidirectional carbon fiber materials as used by the wind turbine industry, and the static flexural and flexural fatigue properties of unidirectional carbon fiber reinforced polymers (CFRP) were investigated. Increasing void content reduced both flexural strength and fatigue performance by acting on both the initiation and propagation states of failure [48].

### *3.2.1. Carbon/Glass Fiber Hybrid Composites*

Swolfs (2017) mentions that using carbon/glass fiber hybrid composites would improve the tension-tension fatigue performance when compared to all-glass fiber composites. However, tension-compression and compression-compression fatigue modes have yet to be investigated for carbon/glass fiber hybrid composites [49]. Despite the lack of other fatigue mode investigations, Mishnaevsky et al (2017) notes that the incorporation of glass fibers in carbon fiber reinforced composites allows the improvement of impact properties and tensile strain to failure of carbon fibers [6].

### 3.2.2. SBCF Composites

SBCFs are made by breaking carbon fibers at their natural flaws to eliminate large fiber surface and internal flaws. Then, when made into a composite, the broken fibers recover load through shear lag. Since stretch breaking eliminates the largest flaws in fibers, stretch-broken fibers have the potential for using very low-cost carbon fibers with higher flaw density. In addition, stretch-broken fibers increase formability while the longer lengths of the fibers lead to mechanical properties of the final composite that are close to those of continuous fiber composites [50]. Jacobsen (2010) demonstrated that the stiffness and strength of SBCF Hexcel IM7/8552 material was statistically equivalent to the continuous material [51]. Such et al (2014) provided a short history of aligned discontinuous fiber composites and mention that SBCF composites are thought to have a promising future, at least within literature [52]. Overall, the studies currently available on SBCF composites typically address property retention after stretch-breaking rather than damage tolerance.

### 3.2.3. ADFRCs

Like stretch-broken fiber composites, aligned discontinuous fiber-reinforced composites (ADFRCs) offer better formability and comparable mechanical properties with continuous fiber-reinforced composites. High Performance Discontinuous Fiber (HiPerDiF) technology has been shown to intimately hybridize different types of fibers to achieve pseudo-ductile tensile behavior and to remanufacture reclaimed fibers into high-performance recycled composites. Failure in composites is normally catastrophic, with very little warning. Ductile failure is desirable, with no loss of modulus during reloading. Pseudo-ductility is a more achievable target for currently available materials, where non-linearity or "pseudo-yielding" is achieved during damage. Pseudo-ductility still results in a loss in modulus on reloading, but permits load redistribution around stress concentrations, which potentially makes the material less notch sensitive and more damage tolerant [53]. Pseudo-ductility is achieved when ADFRCs are manufactured using HiPerDiF technology because the stable and progressive fragmentation of low strain-to-failure fibers allows the load transfer to the higher strain-to-failure fibers without the occurrence of global material failure or catastrophic delamination. Longana et al (2019) tested randomly-oriented (RO) FRCs, quasi-isotropic (QI) ADFRCs, and UD ADFRCs in tension, and results are shown in Figure 3-7 [54].

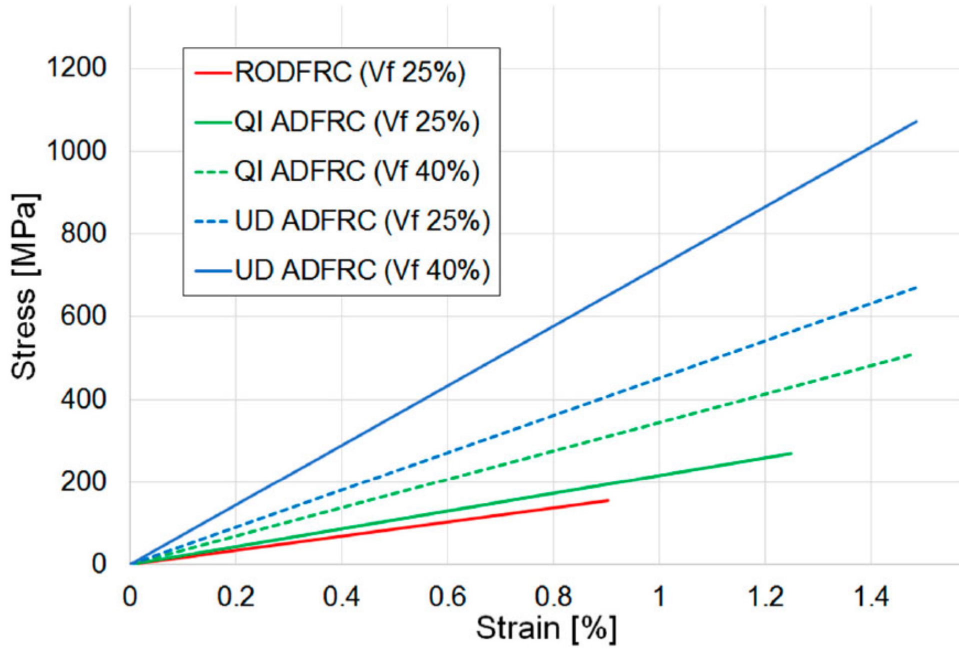


**Figure 3-7. Tensile stress-strain curves for ROFRCs, QI ADFRCs, and UD ADFRCs** [54].

Results demonstrated not only increases in moduli, but also increases in failure strain when UD ADFRCs were used. The increase in failure strain demonstrated the pseudo-ductility of ADFRCs. As would be expected, mechanical properties were ameliorated with an increase in Vf. Tension tests are only the beginning of the characterization necessary to bring the capabilities of ADFRCs to light as no fatigue, impact, or CAI studies were found on HiPerDiF-manufactured ADFRCs.

## 3.3. Natural Fiber Composites

In addition to carbon fiber composites, natural fiber composites should be considered for their damage tolerant properties. Natural fibers are often hybridized with carbon fibers. Aramid (aromatic polyamide), basalt, and flax fibers are commonly used natural fibers in composites. Aramid fibers demonstrate high mechanical strength, are tough and damage tolerant, but have low compressive strength, low adhesion to polymer resins, absorb moisture, and degrade due to ultraviolet radiation. Basalt fibers show good mechanical properties and are cheaper than carbon fibers, and results were encouraging when basalt fibers were used as hybrids with carbon fibers in small wind turbines [6]. It should be noted, however, that basalt fibers have approximately an order of magnitude higher density, which would be a concern for wind blade design.

Flax fiber composites have comparable properties to glass fiber composites. Sarasini et al (2016) produced carbon and flax fiber epoxy prepregs where some laminates had flax fiber laminates as outer layers and carbon as inner layers or vice versa. The presence of flax laminates on the outside guaranteed a higher impact tolerance than having carbon laminates on the outside. Flax laminates showed a better energy absorption capability and a lower peak reaction force compared with other configurations due to a better compliant behavior and the development of a significant internal damage [55]. Furthermore, natural fibers show potential as alternative, damage tolerant materials for wind turbine blades.

## 3.4. Altering Ply Stacking Sequences

Stacking sequences are influenced by ply angle, ply thickness, and coupling effects. 2D composites with varying stacking sequences have excellent in-plane properties, but are poor under transverse loadings [4]. Delamination migrates through layers until they reach preferential ply interfaces where the driving force and upper ply direction are coincident. By eliminating the preferential interfaces (generally 90 degree plies), damage growth can be inhibited [22]. Wagih et al (2019) demonstrated that impact tests of laminates with lower mismatch angles between plies can slightly reduce the amounts of delamination [56]. In addition, to improve damage resistance, ply grouping and stacking adjacent plies in similar orientations should be avoided [57]. Generally, matrix-dominated stacking sequences that contain a high proportion of off-axis plies are more damage-tolerant than fiber-dominated stacking sequences. Besides eliminating preferential interfaces for damage growth, using lower mismatch angles between plies, and using more matrix dominated stacking-sequences, changing the number of plies used can alter failure modes after an impact event. Shyr et al (2003) reported fiber fracture dominated a thirteen layer laminate whereas delamination dominated a seven layer laminate during an impact event [58]. Moreover, altering the stacking sequence of plies could affect residual strength properties.

## 3.5. Alternative Resin Types

### *3.5.1. Toughened Resin Systems*

To increase matrix resistance to crack initiation and growth, resin toughness can be increased by incorporating a rubbery phase, thermoplastics, fibers, or particulate fillers into a resin system [59]. Other additives may include different base epoxy materials, different curing agents, elastomeric additives, thermoplastic additives, and vinyl modifiers. In addition, the introduction of a fine thermoplastic film at the interface between plies can also improve the damage resistance of composite laminates. Some variables that affect the toughness of a final blend of synthetic or natural liquid rubber and epoxy include morphology, rubber particle size, rubber composition, and curing agent [60].

Resin toughening is a well-established method for improving delamination resistance of composites because resin toughening promotes phenomena such as crack blunting, crazing, particle cavitation, crack deflection, shear banding, and void coalescence as energy absorbing mechanisms [61]. Crazing and crack deflection are shown in Figure 3-8.

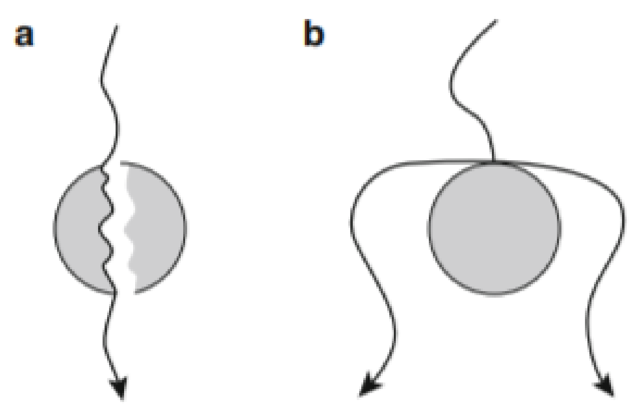


**Figure 3-8. Different crack paths in a) cavitation and b) crack deflection processes** [60].

Increasing the resin toughness increases the size of the process zone at the crack tip, promoting toughening mechanisms such as fiber bridging. A disadvantage of using a toughened resin system is that other mechanical properties tend to be reduced, particularly compression dominated properties, which may suffer due to increased matrix compliance [22]. A crucial consideration in resin toughening schemes is the resulting higher viscosity, as resins with too high of a viscosity may not fully impregnate glass fiber fabrics [38]. Hexion, Inc. is a company that manufactures the EPIKOTE Resin MGS RIMR035c epoxy resin system, which is commonly used for wind turbine blade manufacturing. Resin companies such as Hexion typically leave it up to customers to add thermoplastic fibers or fillers to toughen resin systems.

Williams et al (1982) conducted CAI tests on twenty-four different epoxy resin systems. Damage tolerance characteristics were evaluated based on the extent of damage incurred within a laminate due to local impact and on the ability of a laminate to retain compression strength under impact conditions. Of the five resins with the highest tolerance to impact, two systems had elastomeric additives, two systems had thermoplastic additives, and one system had a vinyl ester modifier. In addition, bisphenol A was the base resin used in the five materials with the highest tolerance to impact. The tensile performance of resins also had significant influences on the response of a laminate to impact, particularly ultimate tensile strengths [62].

Kargarzadeh et al (2016) conducted tensile and impact tests of synthetic liquid rubber-modified epoxy and natural liquid rubber-modified epoxy. The presence of synthetic rubber particles improved the fracture toughness of the modified epoxy, whereas the tensile strength and tensile modulus decreased. However, for natural liquid rubber-modified epoxy, both impact and tensile properties increased [60].

Nanoreinforcements are exceptionally small particles that include carbon nanotubes and nanoclay. When nanoreinforcements are added to polymer matrix composites, fiber sizing, or interlaminar layers, fatigue resistance, shear or compressive strength, and fracture toughness are increased by 30-80% [6]. Dai et al (2015) demonstrated that using carbon nanotube (CNT) reinforcements in glass/carbon fiber hybrid composites had superior fatigue performance than those without reinforcements [63].

### *3.5.2. Thermoplastics*

Besides using additives, thermoplastic resin systems could be used instead of thermosets. Thermoplastic polymers do not undergo any chemical transformations during processing. Instead, the polymer is softened from the solid state to be processed and returns to a solid after processing is completed. Generally, compared to thermosets, thermoplastic resin systems have improved toughness, low moisture absorption, and degrade less from ultra-violet radiation. In addition, thermoplastic composite parts can also be assembled through spot welding, which is a suitable alternative to mechanical fasteners because spot welding gives equivalent load bearing capability and excellent joint stiffness [4]. Moreover, transitioning to spot welding would eliminate the need for adhesive bonds between blade skins and lead to stronger, longer-lasting blades [64].

Commonly used thermoplastics include the following: polyether ether ketone (PEEK), polyphenylene sulfide (PPS), polysulfone (PSUL), polyetherimide (PEI) and polyamide-imide (PAI). Each type of thermoplastic has certain advantages. PEEK has a high fracture toughness, which is crucial for damage tolerance. PPS is a semicrystalline thermoplastic with excellent chemical resistance. PSUL has a high elongation to failure and excellent stability under hot and wet conditions, and both PEI and PAI have high glass transition temperatures [25]. The primary disadvantage of using PEEK, PPS, PSUL, PEI, or PAI is that manufacturing is difficult due to the thermoplastics' high viscosities and solidity at room temperature.

A recently developed thermoplastic resin system called Elium® is in liquid form at room temperature, which makes the resin system usable with conventional manufacturing techniques. Murray et al (2017) used VARTM manufacturing to construct a 9-meter wind turbine blade using Elium® [64]. Boumbimba et al (2017) conducted another study on Elium® where different amounts of acrylic tri-block copolymers were added to Elium® to increase damage tolerant properties. The acrylic tri-block copolymer-toughened Elium® composite plates were subjected to low velocity impact tests, and tests were performed using different impact energies and at varying temperatures. The low velocity impact results demonstrated that the addition of acrylic tri-block copolymers led to an improved impact resistance, especially at high impact energy levels [65]. Although impact test results are correlated with residual strength, CAI tests are still necessary to continue the damage tolerance characterization of Elium® composites.

## 3.6. Bonded Joint Considerations

Structural aspects such as overall geometry, local structural detail and dynamic response can all have significant effects on impact damage [22]. Thus, damage tolerance could be increased not only by using alternative materials, but also by altering joint geometries. If a joint geometry is changed, joint design should minimize peel stresses and provide shear dominant stress state [66]. Figure 3-9 demonstrates the influence of common joint geometries on bond strength in terms of substrate thickness. When designing a bonded joint, the stress/strain response of the adhesive plays a central role in determining both the load carrying capacity and the fatigue performance of the joint [67]. Additionally, effective joint testing should mimic the bonded system as closely as possible within the economic constraints of manufacturing and testing [68]. Samborsky et al (2011) conducted joint testing for wind blade paste adhesives by using double cantilever beam (DCB), end-notch flexure (ENF), and mixed-mode bending (MMB) tests to obtain static crack growth properties. Crack paths and damage characteristics were also explored using microscopy [69]. Literature was reviewed regarding the damage tolerance of the following wind turbine blade joints: blade root T-bolt connections, trailing edge and leading-edge joints, and shear webs bonded to spar caps.

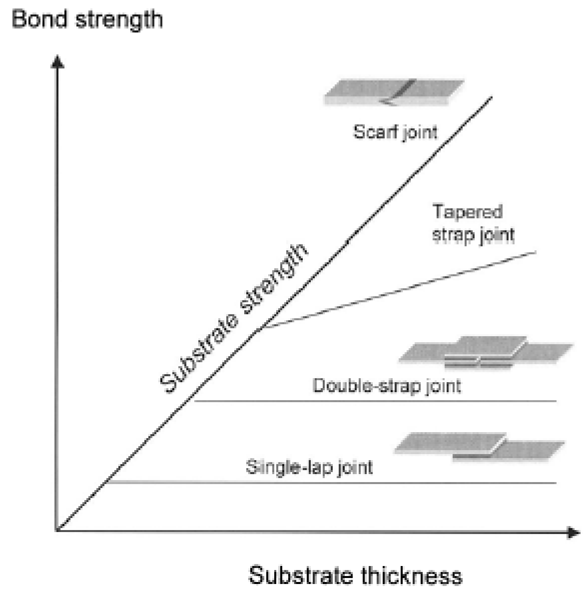


**Figure 3-9. A comparison of shear strength with respect to laminate thickness of various bonded joint geometries** [70]**.**

### 3.6.1. Blade Root T-Bolt Connections

Wind turbine blades are attached to the nacelle using T-bolt connections. The forces acting on the blades during service must be transmitted through the T-bolt connections to the hub of the wind turbine. Consequently, the connection will be subjected to heavy strains and loads and be prone to a reduction of fatigue strength or material failure [71]. Briggs et al (2015) found the ultimate bearing strengths of pin-loaded double shear and T-bolt loaded connections in thick composites. Failure modes prior to ultimate failure were primarily dominated by fiber matrix shear-out and delamination. In addition, the ultimate strength of the connection between the blade and the blade root may be increased by reducing the laminate thickness to T-bolt diameter ratio [72]. Prior to being subjected to heavy strains and loads during service, T-bolt connections are susceptible to impact during wind turbine blade installation. Verma et al (2019) investigated the sideways impact of a guiding connection at the blade root with the hub. It was found that due to impact, for all load cases examined, the guide pins were severely bent and plastically deformed. If a guide pin is damaged in a blade installation process, the blade root must be repaired by replacing a damaged guide pin with a newer one [30]. With the combined problems of impact during installation and fatigue during service, materials that are more damage tolerant could be considered in the roots of wind turbine blades.

### 3.6.2. Shear Web to Spar Cap Connection

Another joint geometry is the connection between the shear web to the spar cap. Sharp (2013) developed a Pi shaped joint for the shear-web-to-spar-cap joint (Figure 3-10) that, particularly when manufactured using 3D fabrics, eliminates catastrophic crack propagation in the adhesive layer and significantly increases the overall I-beam strength compared with the “C with L” joint structure in Figure 3-10a. Additionally, 3D woven Pi joints have twice the joint strength as conventional laminated joints [73]. Figure 3-11 shows the as-manufactured Pi joint.

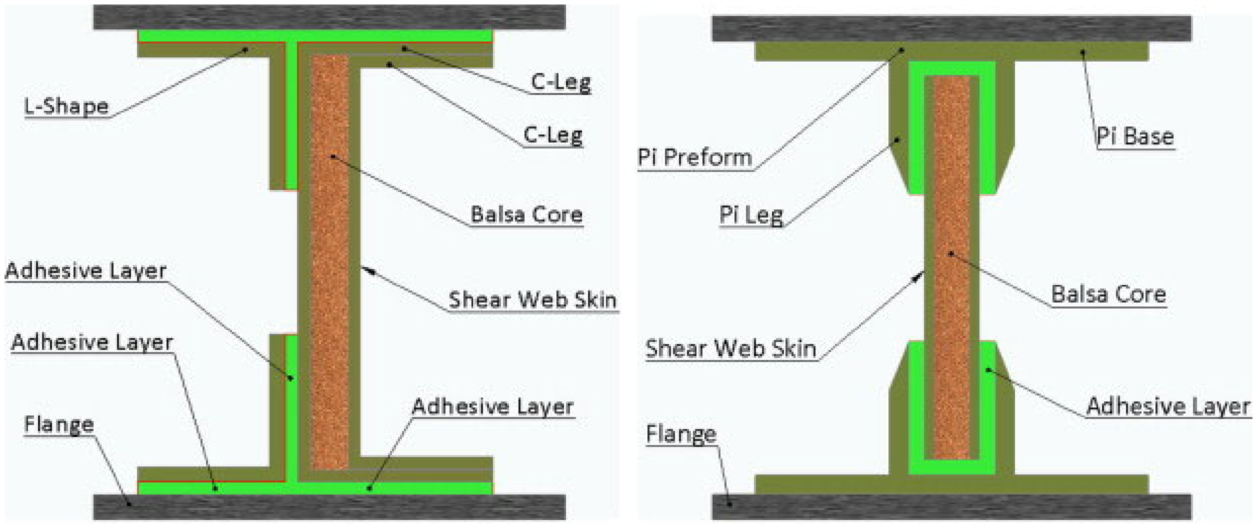


**Figure 3-10. a) "C with L" joint and b) Pi joint** [73].

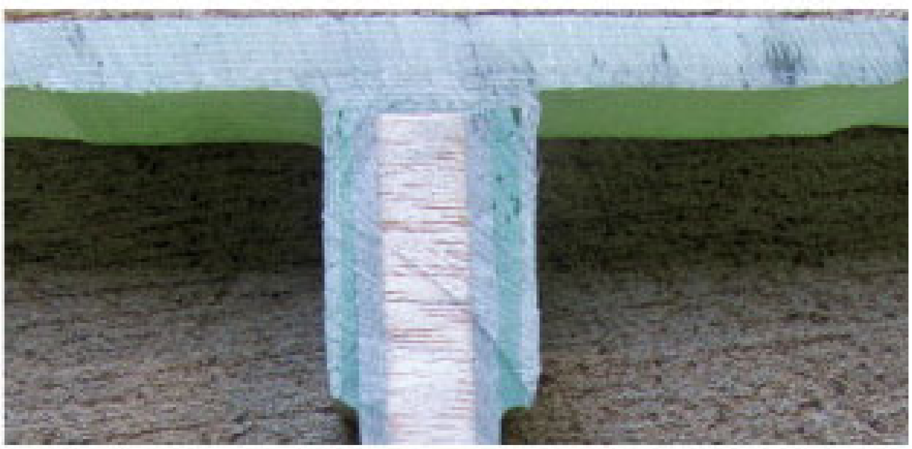

**Figure 3-11. Cross-section of manufactured Pi joint.**

### *3.6.3. Trailing Edge Joint*

The fracture process in trailing edges, even under simplistic crack extension assumptions, is highly complex, as trailing edge failure can be caused by material, geometric, stability, and load problems. Material problems could include flaws, imperfections, or residual stresses. Geometric effects can either be linear or nonlinear. Geometric linear effects include cross section warping and stress concentration zones, while geometric nonlinear effects include panel curvature and in-plane stiffness. Stability problems may include local buckling and kinking, and finally, load problems can include magnitude, direction, frequency, and wind turbine controller. A schematic of trailing edge failure causes is in Figure 3-12.

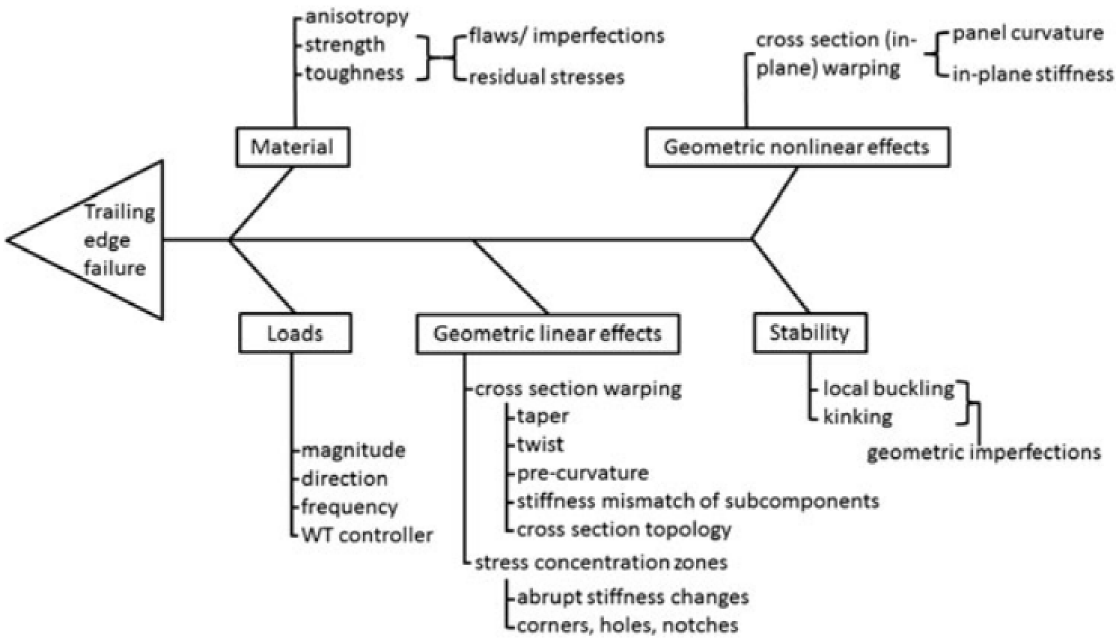


**Figure 3-12. Analysis of trailing-edge failure** [3].

Eder et al (2015) found that the flow front shape of the adhesive has a significant influence on the Mode I fracture behavior of adhesive joints, and thus advised using interface layups that endorse fiber bridging to increase fracture toughness [74]. Thus, materials that endorse fiber bridging should be considered for trailing edge joints.

### *3.6.4. Leading Edge Joint*

Solid particle erosion is a progressive loss of material from a solid surface by repeated impacts from fluid-borne solid substances [75]. Damage tolerance includes designing and manufacturing for the possibility of damage caused by erosion. During service, the leading edges of wind turbine blades are subjected to repeated impact from rain, dust, and bugs. Repeated impacts cause material removal, which can produce substantial airfoil performance degradation. Degradation yields a large increase in drag coupled with a significant loss in lift. Leading edge erosion can cause a loss in annual energy production as high as 25% due to decreased aerodynamic performance [76]. Leading edge reinforcement tape or coatings are commonly used to reduce erosion but may fall off and wear off over time. Moreover, cost estimates must incorporate decreased aerodynamic performance and leading-edge maintenance.

Erosion testing will be necessary in considerations of new materials used in leading edges. Erosion testing is used to measure decreased aerodynamic performance with time, and mainly involves whirling arm droplet impact tests. A whirling arm testing rig involves a motor spinning a shaft which is connected to a central hub to which two samples are connected at a radius from the center. At the circumference of the swing arm includes needles which provide water droplets to the rig fed by a pump on the outside of the container (Figure 3-13).

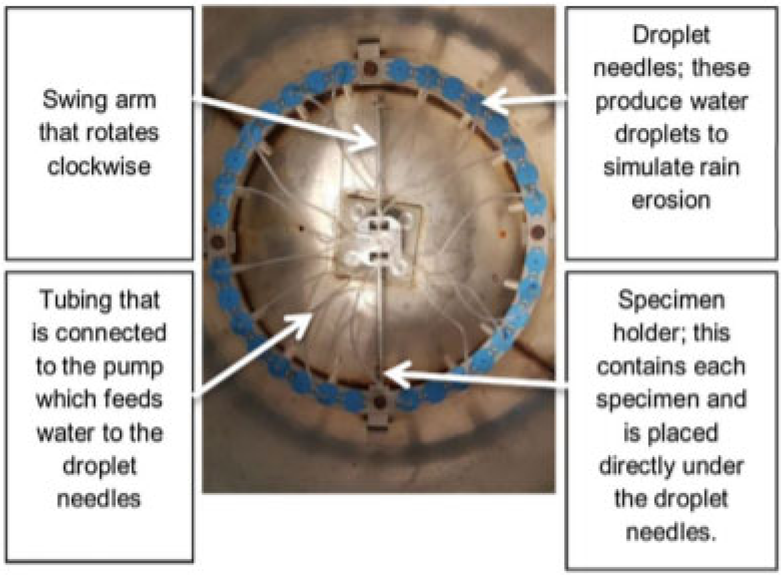


**Figure 3-13. Rain drop erosion experiment rig** [77].

Studies by Eisenberg et al (2018) and Pugh et al (2019) demonstrate how whirling arm erosion tests can be used to measure the effects of erosion on wind turbine performance. Eisenberg et al (2018) used rain erosion whirling arm tests to determine the surface impact fatigue resistance of different coatings used in the field. A leading edge erosion forecast model and an efficiency reduction model were combined to predict annual energy production loss over time due to rain-induced wind turbine blade coating leading edge erosion [78]. Pugh et al (2019) used a whirl arm rig to investigate rain erosion on wind turbine blade materials under load in the simulation of onshore and offshore environmental conditions. Results indicated that there is a difference in material behavior observed for rain erosion on a wind turbine blade when the material is unstressed compared to when the material has an applied load [77]. Eisenberg et al and Pugh et al studied rain droplet effects, but dust and bugs also cause leading edge erosion. Dust and bugs would be considered solid particle impact, so solid particle impact tests should also be considered in leading edge erosion studies. The ASTM G 76 solid particle erosion (SPE) test is used to rank materials for their relative ability to prevent SPE. Factors to consider in solid particle impact tests include the particle's mass, velocity, shape, roughness, and impact angle. Particle velocity has been shown to affect erosion by at least a factor of 2. Figure 3-14 shows the effect of solid particle impact angle on erosion.

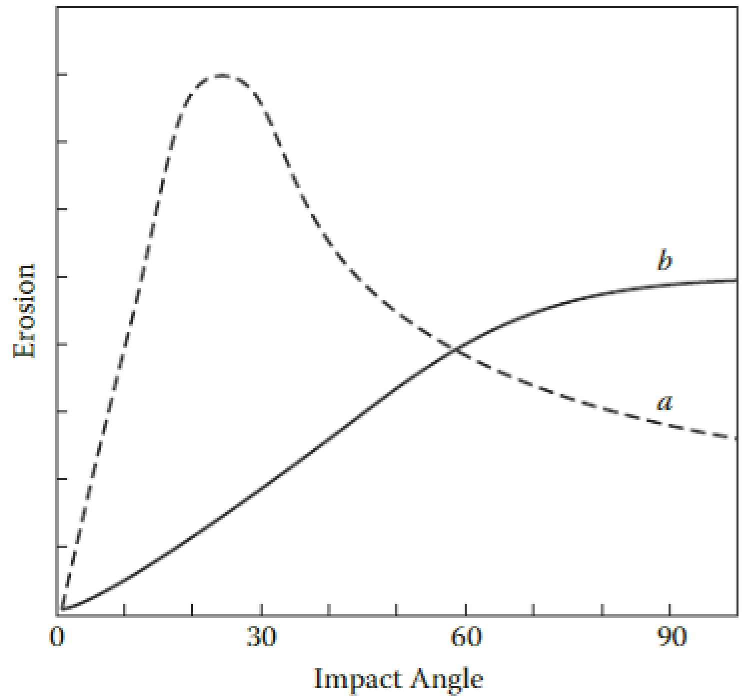


**Figure 3-14. Effect of incidence angle on the rate of solid particle erosion. The dashed curve represents ductile materials, and the dotted line indicates brittle materials** [75].

For brittle materials such as epoxy, impact angles of about 20 degrees cause the highest amount of erosion. However, varying wind speeds and directions will cause significant variation in the impact angle of rain droplets on wind turbine blade leading edges. Nevertheless, understanding how erosion affects the leading edges of wind turbine blades will assist in determining wind turbine blade lifetimes. Furthermore, erosion effects along the leading edge must be quantified in considerations of new materials to establish blade lifetime estimates.

# 4. CONCLUSIONS

The increase in inspection technology gives rise to the possibility of transitioning from a safe-life approach to a damage tolerant approach to designing wind turbine blades. Doing so would decrease the LCOE, as wind turbine blades would be able to withstand damage and repair costs would thus be reduced. Materials selection is crucial to damage tolerant design, so alternative materials were considered in the lens of increasing damage tolerance for wind turbine blades. Generally, studies concerning damage tolerant materials looked at the primary factors of fiber and resin selection, but secondary factors such as environmental conditions, fracture toughness, repeated impact, impactor geometry, fabric and matrix hybridization, and stacking sequence should all be considered in the damage tolerant design of composites.

A literature review and discussions with industry leaders examined the current extent of damage tolerant analyses of some forms of TTT composites and alternative resin systems. Multiple studies demonstrated that TTT composites tend to delaminate less than 2D composites. Sharp (2013) showed that implementing 3D composites into a shear web to spar cap connection eliminates catastrophic crack propagation in the adhesive layer. Sharp's study is an example of how implementing alternative materials can be feasible for wind turbine blade joints [73]. Yet, few other studies were found concerning the implementation of alternative materials in blade roots, trailing edges, or leading edges. Besides using 3D composites, using alternative resin systems, where resins are either toughened with certain additives or thermoplastics are used, can diminish crack growth.

Despite the damage tolerance benefits to using TTT composites and alternative resin systems, cost remains an important factor to incorporating different materials into wind turbine blades. In a correspondence with a Vectorply, Inc. representative, 3D woven glass fibers cost up to four times as much as 2D glass fibers. Due to the added costs of 3D woven fibers, it may be beneficial to only use 3D composites in locations that are more prone to delamination rather than across the entire blade. Furthermore, cost-benefit and stress analyses concerning where to implement new materials are still critical.

Carbon fiber, carbon/glass fiber hybrid, and aramid/carbon fiber hybrid have previously been implemented into wind turbine blades. Numerous damage tolerant studies exist concerning carbon fiber, but studies on resulting damage tolerant properties of the carbon/glass fiber and aramid/carbon fiber hybrid composites were scarce. However, Sarasini et al (2016) demonstrated that flax/carbon hybridization can lead to improvement in damage tolerance [55]. In addition, there remains a significant need to experimentally test the theoretical damage tolerance benefits of SBCF composites and ADFRCs.

Other methods of increasing damage tolerance included altering ply stacking sequences and using toughened resins. Altering ply stacking sequences to eliminate preferential interfaces for damage growth, using lower mismatch angles between plies, and using more matrix-dominated stacking-sequences are methods that could increase damage tolerance. Resin toughness can be increased to mitigate crack initiation and propagation by incorporating particulates such as rubber, thermoplastics, and fibers. Thermoplastics are generally tougher than thermosets and provide the possibility for blade assemblies using spot welding. Elium®, unlike other thermoplastics, can be used using VARTM, yet impact and CAI tests are still needed to quantify Elium®'s damage tolerance properties.

Bonded joint considerations will be crucial to implementing alternative materials because geometry, local structural detail, and dynamic response can all have significant effects on impact damage. The main joints of concern are the blade root T-bolt connections, the connection between the shear web to the spar cap, trailing edge joints, and leading-edge joints. Joint testing using DCB, ENF, and MMB tests combined with spectroscopy techniques will be necessary to obtain crack growth properties. The combined problems of impact during installation and fatigue during service must be addressed in a consideration of alternative materials in T-bolt connections. Of the blade joints of concern, 3D woven Pi joints in the shear web to spar cap connection is at a more advanced stage of research where an alternative, more damage tolerant material has been implemented into a blade joint. In addition, the benefit of the implementation has been demonstrated as the new joint has been shown to have twice the joint strength as conventional laminated joints. Cost-benefit, stress, and larger-scale manufacturing feasibility analyses are still needed prior to implementing a 3D woven Pi joint configuration into a wind turbine blade.

Lastly, trailing edge and leading-edge joint considerations should not be overlooked when considering new materials for wind turbine blades. Trailing edge failures are affected by material selection, linear and nonlinear geometric effects, loads, and stability. The main finding for trailing edge joints is that materials that endorse fiber bridging should be used. Leading edge joint considerations primarily involve an assessment of materials' susceptibilities to erosion. Most studies tend to examine rain droplet effects, but the combined effects of solid particles such as dust and bugs should also be considered to estimate blade lifetimes more effectively. In conclusion, there is a significant need to conduct stress, cost-benefit, and materials characterization analyses for new materials used in wind turbine blades.

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