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## **Wind Turbine Composite Blade Manufacturing: The Need for Understanding Defect Origins, Prevalence, Implications and Reliability**

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# **Wind Turbine Composite Blade Manufacturing: The Need for Understanding Defect Origins, Prevalence, Implications and Reliability**

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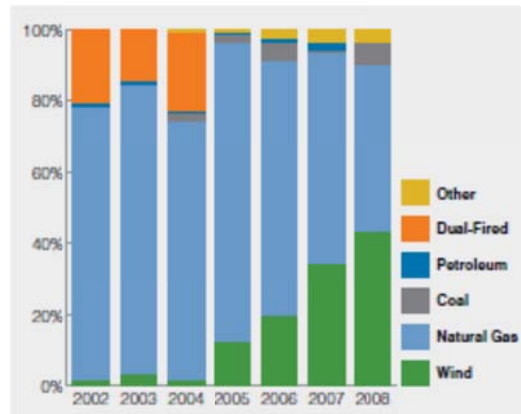
## **ABSTRACT**

Renewable energy is an important element in the US strategy for mitigating our dependence on non-domestic oil. Wind energy has emerged as a viable and commercially successful renewable energy source. This is the impetus for the 20% wind energy by 2030 initiative in the US. Furthermore, wind energy is important on to enable a global economy. This is the impetus for such rapid, recent growth. Wind turbine blades are a major structural element of a wind turbine blade. Wind turbine blades have near aerospace quality demands at commodity prices; often two orders of magnitude less cost than a comparable aerospace structure. Blade failures are currently as the second most critical concern for wind turbine reliability. Early blade failures typically occur at manufacturing defects. There is a need to understand how to quantify, disposition, and mitigate manufacturing defects to protect the current wind turbine fleet, and for the future. This report is an overview of the needs, approaches, and strategies for addressing the effect of defects in wind turbine blades. The overall goal is to provide the wind turbine industry with a hierarchical procedure for addressing blade manufacturing defects relative to wind turbine reliability.

**Keywords:** Wind Turbine Blade, Composites, Manufacturing, Defects, Damage Tolerance, Reliability

## I. INTRODUCTION

The buzz of renewable energy has been on the rise in recent years after its decline in the early 1980s as a consequence of the reduction of oil prices after the oil crisis of the 1970s. While the idea has captured the hearts and imaginations of the people, most of these technologies have yet to deliver the bottom line; profits for share holders. Wind energy is perhaps the only exception to this rule as evident by Figure 1. It can be seen in this figure that Wind Energy dwarfs all other renewable energy sources for new installed capacity and competes directly with non-renewable energy sources (1).



**Figure 1: Percentage of New Power Generation Capacity (1).**

The capacity of Wind Energy installed in the United States has been growing steadily since the late 1990s approaching a 50% increase in recent years as seen in Figure 2 (1). This increase can be attributed to the fact that wind energy is financially feasible which in turn has made it the flagship for renewable energy around the world (Figure 3).

US Department of Energy is showing its support for wind energy by implementing a policy that would achieve 20% wind energy by 2030 (3). Wind power generation must continue close to current rates in order to achieve this goal (Figure 4). While the economics are profitable for investors, the growth and wane of installations is consistent with the introduction and removal of subsidies. Wind energy, as all business, is continually looking to improve the profit margins. Top tier locations for farms are running thin. Couple this with the natural intermittency of wind and the economics begin to deteriorate. It is important that wind farms achieve maximum availability by reducing down time due to maintenance and failures as much as possible.

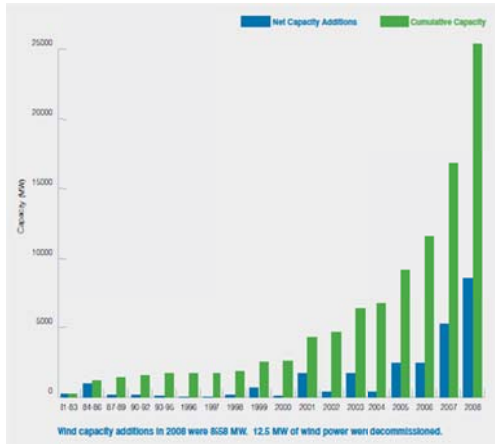


Figure 2: US Wind Capacity Growth (2).

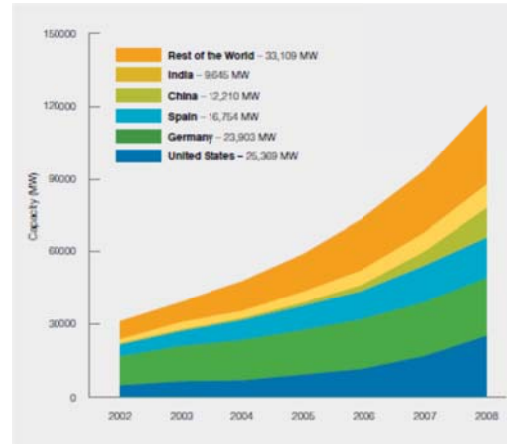


Figure 3: Wind Energy Capacity around the World (2).

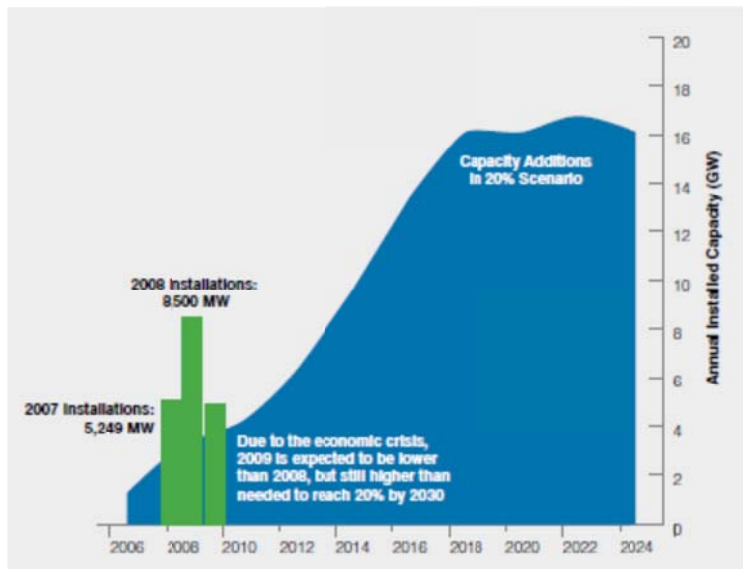


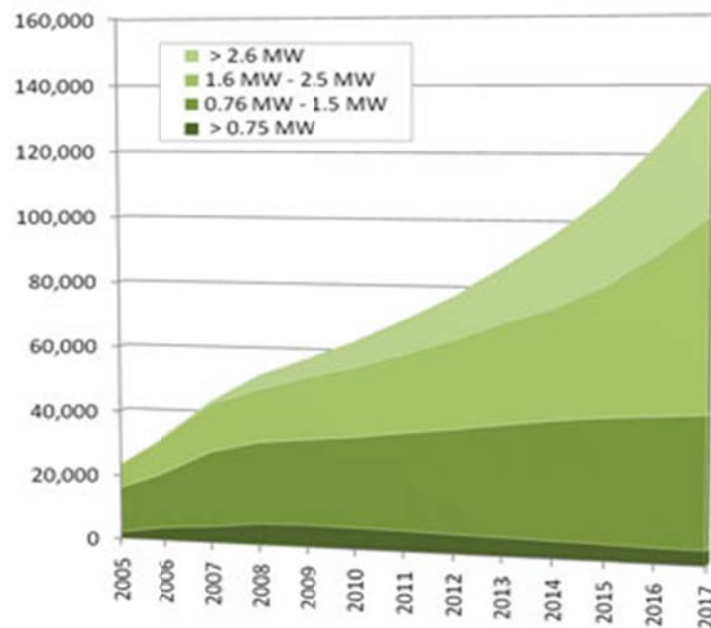
Figure 4: 20% Wind by 2030 Scenario (1).

There are many parts in a wind turbine, and a substantial amount of those are located over 60 m (200ft) above the ground. Of particular interest to reliability are the gearbox, generator, and rotor. These systems are often too large and complex to perform repairs on site. In general, repairs to these systems require the turbine to be shut down and a crane brought in to remove the problematic system. Needless to say, any time a turbine is down it is not generating energy nor is it making money. In addition, this work can be hindered due to limited safe flying time for cranes at the intrinsically windy location. In summary, a quantifiable & statistically defensible reliability program for wind turbines is required to maintain and achieve the potential of wind energy discussed.

Given the size and weight of wind turbine blades, advanced composite materials have become an optimal choice. These materials are also attractive because of the ability to make the complex shapes required for rotor aerodynamics with relatively low-cost manufacturing. In addition, composites can have superior engineering qualities such as durability over other potential materials like aluminum (4). While the design and manufacturing of blades has improved, it is not clear that it has done so at a rate

necessary to ensure a 20 year design life. Many of the blade suppliers are using technologies and techniques that were developed for structures with much lower design loads and criteria. While these methods are inexpensive, they are thought to offer questionable reliability.

Not only has the wind industry seen extreme growth, but the turbines themselves have increased in size to take advantage of economies for scale (Figure 5). The rapid deployment of turbines has forced existing technologies and manufacturing practices to be scaled rather than utilizing a costly and complex certification testing protocols (3). In order to meet the increase in size and loads, alternative materials and manufacturing techniques are being explored (5).



**Figure 5: Estimated Composite Wind Turbine Blade Unit Production (2).**

In recent years, a group industry partners and government agencies have formed the Gearbox Reliability Collaborative (GRC) to address the short comings of wind turbine gearboxes (6). A similar group was recently formed with the goal of improving blade reliability. Led by SANDIA National Laboratories, the Wind Turbine Blade Reliability Collaborative (BRC) is made up of a collaborative of wind farm owners/operators, turbine manufacturers and third party investigators.

The portion of the BRC that will focus on establishing the criticality of design and manufacturing defects will be researched by the Montana State University Composites Group (MSUCG). A statistical analysis will be performed utilizing a metric based on frequency and impacts of defects to determine what types of defects are critical. In addition, an accurate model predicting residual strength and damage growth will be developed. Coupling these elements together will yield an inspection protocol aimed at assisting manufacturers and operators with improving reliability. The purpose of this paper is to establish the need and provide direction for this research.

## II. BACKGROUND, SCIENTIFIC MERIT AND RATIONALE

Improving reliability of wind turbine blades is the primary goal of the BRC. In order to do this, a comprehensive understanding of the causes of blade failures is necessary. Classification of known defect types and establishing a criticality metric will lead to probabilistic and damage tolerance methodologies. These types of techniques have been successfully utilized to improve airline safety for decades. Implementing this information at the manufacturing level will establish quality guidelines while reducing tower down-time, rework, scrap-rates, and ensuring a successful life-cycle. In general, composites researchers have made significant headway into determining the effects of defects and utilizing non-destructive evaluation. However, a bridge is necessary to correlate this generalized information to the specific uses of composites for wind energy.

### A. Reliability Issues

Reliability is an inherent characteristic of a system, therefore it should be considered a design parameter and its assessment should be performed as an integral part of the design process. In many low cost composite manufacturing instances reliability is performed as a subjective and qualitative step rather than incorporating a quantifiable reliability metric. In order to achieve a truly reliable system, quantitative terms must be allied. For simplicity, the reliability of a wind turbine can be divided into two components; design/manufacturing and in-life evaluation. The first step in developing improved reliability is to establish which components of the system are prone to failure. According to a study performed by Institut für Solare Energieversorgungstechnik (ISET) on historical wind farm operating data, blades and rotors result in approximately 12% of a wind turbine down time (Figure 6) (7).

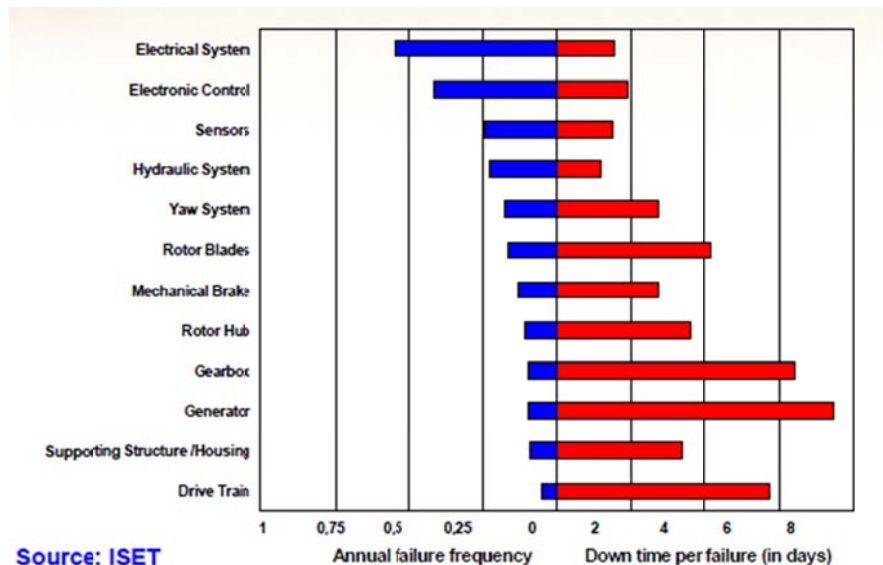


Figure 6: Wind turbine reliability from historical European data (7).

In 2008, a preliminary survey of wind turbine farm operators was performed by Sandia National Laboratory. Data collected from five wind farms showed that approximately 7% of all wind turbines blades had to be replaced. If one blade failed on a turbine at a time and each turbine has three blades, it can be assumed that approximately 20% of all turbines experienced a blade failure resulting in down-

time. The operators reported that the leading causes of failure were manufacturing defects and lightning strikes (7). However, based on discussions with a number of major wind turbine OEMs and blade manufacturers this number is probably higher (8).

Manufacturing quality is a critical issue for improved reliability. As recently as February 2010 Suzlon Energy Ltd., the world's fifth leading wind turbine manufacturer, announced a retrofit program to resolve blade cracking issues discovered during the operations of some of its S88 turbines in the United States. The six-month retrofit program will be carried out by maintaining a rolling stock of temporary replacement blades to minimize the downtime for operational turbines. The cost of the retrofit program is estimated to be \$25 million (9). Problems such as these are not exclusive to the wind energy industry. Growing use of composites in the aerospace industry, for example, has led to similar problems. In August of 2009 a Boeing supplier halted manufacturing the barreled pieces of the 787's mid-section because of a problem in the manufacturing process. This manufacturing problem resulted in microscopic wrinkles in structural stringer supports along the length of the airframe. Boeing had to develop a patch in order to repair the existing plane sections. Subsequently newer sections will be made utilizing a different manufacturing process (10).

Large blades are likely to use the heaviest possible reinforcing fabrics or prepreg ply thickness to achieve manufacturing efficiency. Increases in fabric weight—and therefore thickness—may affect basic in-plane properties, delamination, and problems associated with ply drops where the thickness is tapered as confirmed by previous MSUCG research (11). Moreover, thick composite laminates have an increased likelihood of hidden flaws and multiple flaws being grouped in the same local area. A number of production-related flaws may occur in larger structures which are more easily avoided in smaller structures, and rarely appear in test coupons. Typical of these are fabric joints and overlaps where individual rolls of fabric terminate, and flaws in fabric where individual strands terminate during production of the fabric. Other factors which are more likely in larger blades include fiber waviness, large scale porosity, large resin rich areas, and resin cure variations through the thickness (5).

It has been suggested that a flaw in a 50 meter structure is just as harmful as a flaw in a 5 meter structure (12). Moreover, utilizing a Weibull Distribution to compare the strength of a large structure to the strength of a small structure shows that larger structures have a greater probability of a critical flaw. This conclusion is valid when the distribution has the form  $(V_{\text{large}}/V_{\text{small}})^{1/m}$ , where V is the volume and m is the Weibull parameter (13).

## **B. Aerospace and Aviation Analogs**

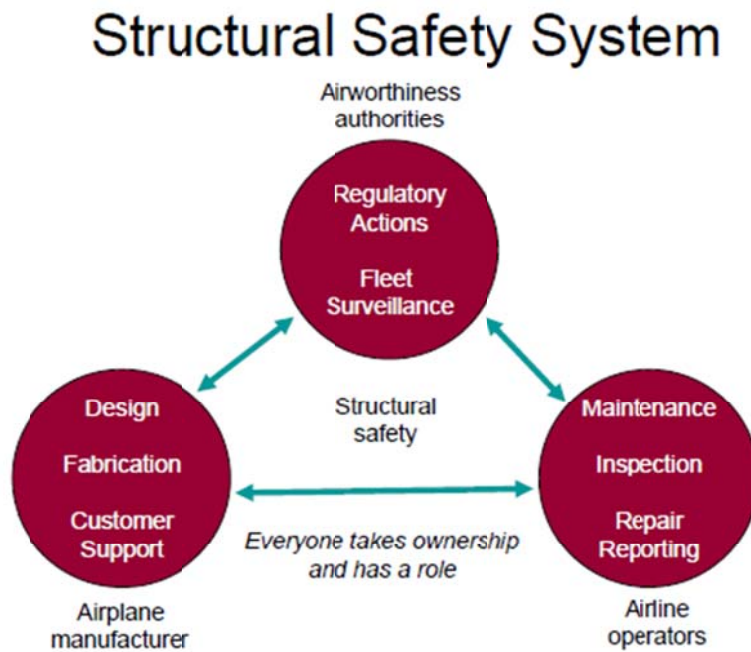
### *i. General Discussion on Aviation Safety Compliance*

There is a notable difference between military and civil aviation methods of compliance. For military aircraft, the government defines the requirements with Military Specifications and works with the manufacturer to establish the method of compliance. In civil aviation, the government defines the requirements through regulations (FAR's, JAR's) and accepted means of compliance through Advisory Circulars. Compliance must be demonstrated to the agency (FAA, JAA) and in this instance the government is a neutral third party.



The Federal Aviation Administration (FAA) regulates the safety concerns for the civil aviation industry. Their regulations stretch into the manufacturing and inspection protocols. Federal Aviation Regulation (FAR) 25.571 Damage Tolerance & Fatigue Evaluation of Structure states that “An evaluation of the strength, detail design, and fabrication must show that catastrophic failure due to fatigue, corrosion, manufacturing defects, or accidental damage will be avoided through the operational life of the airplane” (7).

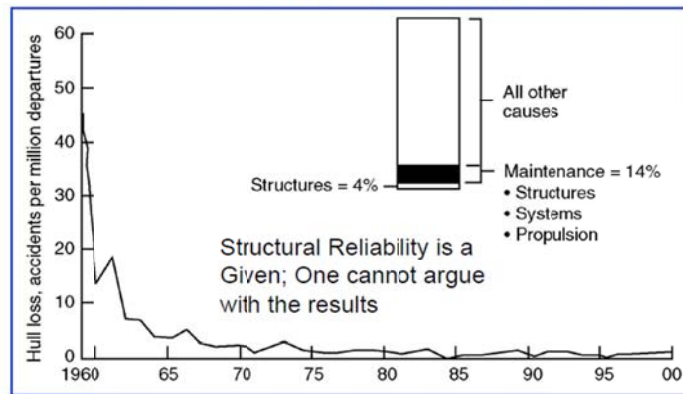
Advisory Circular (AC) 20-107B on Composite Aircraft Structure describes an acceptable means of showing compliance with the provisions of FAR 25.571 for the special case of aircraft structures involving fiber reinforced materials. Guidance information is also presented on design, manufacturing, inspection and maintenance aspects (14). This process can be seen visually in Figure 7. Unfortunately, there are no such regulations in the wind industry because failures in composite wind turbine blades are largely an economic problem, not a safety problem (15). However, the economic impact of failures could significantly affect the growth scenarios presented in Figure 1 through Figure 5 above.



**Figure 7: Flow Chart of FAA Safety Program (16).**

Since the introduction of structural reliability programs in the aviation industry, the safety record has been greatly improved as seen in Figure 8. The technological corollaries between the aviation industry and the wind industry would suggest that similar improvements could be attained by the wind industry. However, the major challenge is to determine the cost/benefit parameter which will achieve the best economic payoff for improved reliability.

## Commercial Jet Fleet Safety Record



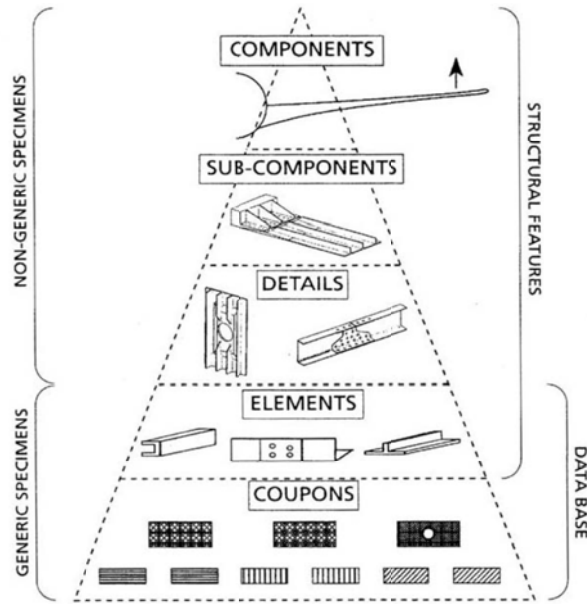
**Figure 8: Commercial Jet Safety Record (16).**

### *ii. Outline of Mil Handbook 17-3F: Damage Resistance, Durability & Tolerance (17)*

In order for the wind industry to develop a statistically defensible reliability program, specifications covering materials, material processing, and fabrication procedures must be established to ensure a basis for fabricating consistent and reliable structures. The discrepancies permitted by the specifications should also be substantiated by analysis supported by test evidence, or tests at the coupon, element or subcomponent level. Further, thorough manufacturing records are needed to record part acceptance and allowable discrepancies, common defects, damage and anomalies. Substantiating data is needed to justify all known defects, damage and anomalies allowed to remain in service without rework or repair. The Mil Handbook 17-3F offers a process for composite component conformity that has been utilized in military applications and could be applied in the wind industry to achieve these goals.

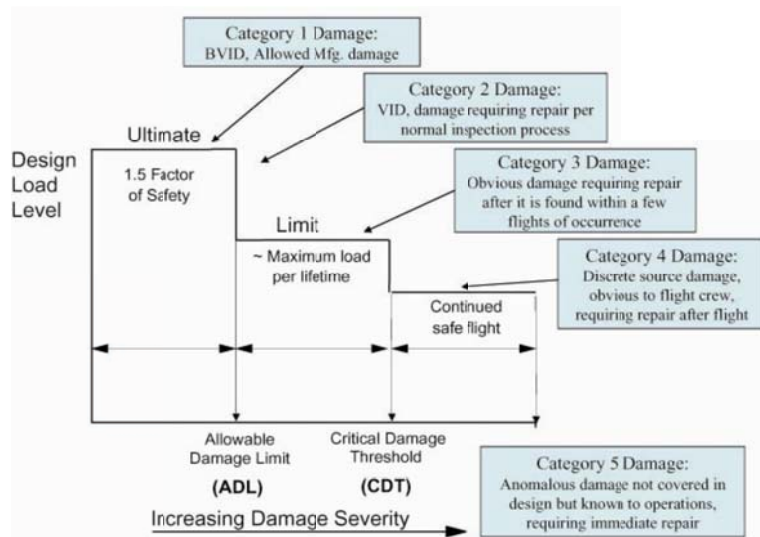
In order to back up manufacturing records, it must be known what the effects of defects are so that quality control can determine blade conformance. Thus, the defects must be understood in terms of both residual strength and damage tolerance. The structural static residual strength substantiation of a composite design should consider all critical load cases and associated failure modes. Also included should be effects of environment, material and process variability, non-detectable defects or any defects that are allowed by the quality control, manufacturing acceptance criteria, and service damage allowed in maintenance documents of the end product. The residual strength of the composite design should be demonstrated through a program of coupon to component ultimate load tests to comprehend the effects of defects from flaw to full-blade scale (Figure 9).

Successful static strength substantiation of composite structures has traditionally depended on proper consideration of stress concentrations (e.g., notch sensitivity of details and impact damage), competing failure modes, and out-of-plane loads. Component tests are needed to provide the final validation accounting for combined loads and complex load paths, which may include out-of-plane effects. When using the building block approach, the critical load cases and associated failure modes would be identified for component tests using the analytical methods, which are supported by test validation.



**Figure 9: Typical scale steps needed to get from flaw-scale to full-blade scale (18).**

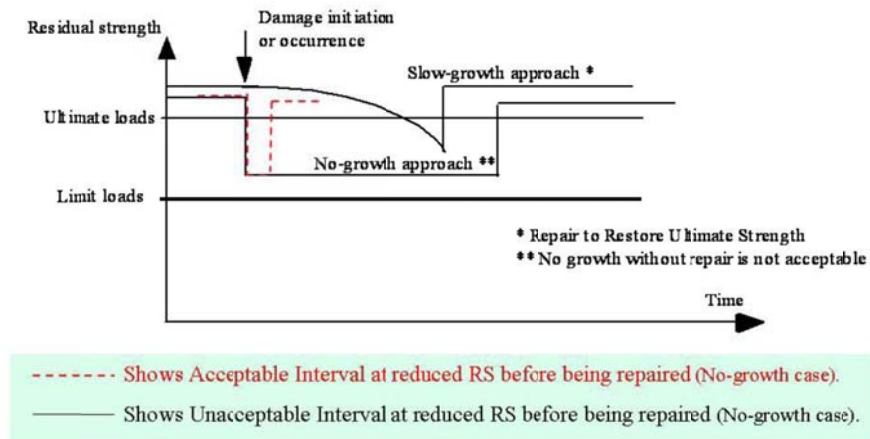
In addition, damage tolerance evaluation must show that catastrophic failure due to fatigue, environmental effects, manufacturing defects, or accidental damage will be avoided throughout the operational life of the structure. Commonly, a damage threat assessment must be performed for the structure to determine effects of locations, types, and sizes of damage considering fatigue, environmental effects, intrinsic flaws, and foreign object impact or other accidental damage that may occur during manufacture, operation or maintenance. Once a damage threat assessment is completed, various damage types can be classified into five categories of damage as shown in Figure 10.



**Figure 10: Typical categories resulting from damage threat assessments (17).**

Structure details, elements, and subcomponents of critical structural areas should be tested under repeated loads to define the sensitivity of the structure to damage growth. This testing can form the

basis for validating a no-growth approach to the damage tolerance requirements as well as determine the effects of defects, thereby establishing the criticality of each type, size and/or location. Once critical rubrics are determined, corrective action can be taken before the blade is put into service or different in-service protocol may be mandated. Regardless, inspection intervals must be established, considering both the likelihood of a particular damage and the residual strength capability associated with this damage. The intent is to ensure that the structure is not exposed to an excessive period of time with residual strength less than ultimate. Conservative assumptions for capability with large damage sizes that would be detected within a short time of being in-service may be needed when probabilistic data on the likelihood of given damage sizes does not exist. Once the damage is detected, the component is either repaired to restore ultimate load capability or replaced. A schematic showing the relations between damage initiations, residual strength and repair intervals as a function of time are shown in Figure 11 (18).



**Figure 11: Schematic diagram of residual strength illustrating that significant accidental damage with “no-growth” requires repair (18).**

The extent of initially detectable damage should be established and be consistent with the inspection techniques employed during manufacture and in-service. This information will naturally establish the transition between Category 1 and 2 damage types (i.e., inspection methods used by trained inspectors in scheduled maintenance). Documented procedures used for damage detection must be shown to be reliable and capable of detecting degradation in structural integrity below ultimate load capability. This should be substantiated in static strength, environmental resistance, fatigue, and damage tolerance. Substantiated detection procedures will be needed for all damage types identified by the threat assessment, including a wide range of foreign object impact threats, manufacturing defects (18).

Flaw/damage growth data should be obtained by repeated load cycling of intrinsic flaws or mechanically introduced damage. The number of cycles applied to validate both growth and no-growth concepts should be statistically significant, and may be determined by load and/or life considerations and a function of damage size. The growth or no growth evaluation should be performed by analysis supported by test evidence or by tests at the coupon, element, or subcomponent level. The extent of damage for residual strength assessments should be established, including considerations for the probability of detection using selected field inspection procedures. Composite designs should afford the

same level of fail-safe, multiple load path structure assurance as conventional metals design. Such is also the expectation in justifying the use of static strength allowable with a statistical basis of 95% probability with 95% confidence.

### C. Wind Turbine Blade Manufacturing Process

In current production, prepreg and vacuum-assisted resin transfer molding (VARTM) have emerged as the two most common replacements for wet layup. The majority of blade manufacturers presently use VARTM. However, it is noteworthy that two of the top four manufacturers (VESTAS, and GAMESA) use fibers with pre-impregnated resin (prepreg). In general, VARTM is a lower cost manufacturing option as compared to prepreg. However, prepreg materials offer optimized and consistent resin ratios that can vary across the area when it is infused with a vacuum process (4).

Typically, the outermost section of the blade is a gelcoat layer providing a smooth surface to enhance aerodynamic properties. A layer consisting of a soft material providing a relatively smooth, absorbent surface to improve adhesion between the gelcoat and underlying layers is added (Figure 12). Next, a double-bias stack of composite plies is made by twisting unidirectional fibers around a core at 45 degrees in both directions to make a torsion tube. At the blade trailing edge, the double-bias laminate splits into two layers to accommodate a core material such as balsa, foam or honeycomb. The core material laminate augments the buckling strength of the trailing edge of the blade.



**Figure 12: Images of the typical mold process (19).**

The interior of the midsection of the blade is made up of a composite box-spar. The outer layer of the box-spar normally consists of a double-bias lining. This lining provides strength to guard against shear and prevents the unidirectional layer below from splaying. The next layer consists of unidirectional composite laminates that primarily contribute bending strength to the box-spar. Unidirectional fibers provide tensile strength, running from the blade's tip to its root through the box-spar, around the mounting bushings and back out the root. In many cases, the double bias and unidirectional plies are interspersed to form a single laminate. The interior of the box-spar consists of an embedded core material to guard against buckling (20). Automated systems are being developed to reduce manufacturing time, improve through-put and reduce production variability (Figure 13) (21).



Figure 13: Automated blade manufacturing system (21)

#### D. Generic Composite Defect

Flaws can be broken into two distinct categories based on the method of introduction. As noted above, flaws can be introduced as the result of design. For example, since the blade narrows from the root to the tip, less material is needed at the tip resulting in plies being dropped along the length. In addition, flaws can be introduced during the manufacturing steps. While design flaws can be engineered to reduce likelihood of failure, manufacturing flaws may occur at random with respect to type, size and location. Several of said flaw types are listed:

- Porosity
- Debonding
- Delaminations
- Improper Fiber/Matrix Distribution
- Fiber Misalignment
- Improper Fiber/Resin Ratio
- Bonding Defects
- Foreign Inclusions
- Incompletely Cured Matrix
- Matrix Cracking

Examples of delamination and waviness are shown in Figure 14:



Figure 14: In-plane and out-of-plane waves and delaminations in composite materials and resulting failures (12).

These types of flaws can lead to extremely disastrous outcomes as shown in Figure 15, which shows the catastrophic failure of a wind turbine. This situation was the result of a blade failure that was attributable to a manufacturing defect.



**Figure 15: Catastrophic wind turbine failure (12).**

Significant research of composite manufacturing and design flaws has been performed by the MSUCG and others. The MSUCG has contributed by establishing a Composite Materials Fatigue Database that has tested over 4500 coupons for over 130 material systems (22). This database can be extremely useful as most of the material systems and defect types tested are those utilized and found in composite blades. An incomplete and brief overview of several studies relating to the flaws noted above follows.

In-plane waviness is a common manufacturing flaw (Figure 14) and has been investigated under compressive loading. Waves up to 1.5 layer thicknesses were tested and it was found that more severe wave geometries produced reductions in static strength up to 36% even though no wave accounted for 20% of load capacity (23). Bogetti et al found that ply waviness resulted in significant stiffness and strength reductions only in the 0 deg attributable to out-of-plane waviness (24). In addition, their results indicated that waviness induced interlaminar shear stress and that a plateau region exists below critical amplitude.

Avery et al utilized the known sensitivity of compressive strength related to fiber straightness to study structural details such as ply drops and ply joints (25). By varying parameters such as ply thickness, fraction of ply drops, location, gap and mold geometry and pressure, it was found that ply drops and joints can provide adequate compressive strength. However, severe knockdowns occurred where large fiber misalignments were induced. Cairns et al built upon this research by determining that suppressing damage and delamination in-service emanating from ply drops is not possible, though in most cases there is a threshold loading under which little growth after initiation was noted (26). Based on these results, rules were established for ply drops.

Similarly, delamination between plies is a common cause of failure of composite structures. Mandell et al established fracture mechanics based methodologies to predict delamination by determining critical strain energy release rate for mode I and mode II cracks (27). A model was built and good agreement was found between the model and physical testing. Delamination between ply drops was also

investigated exploring differences between carbon and glass fibers (28). Results indicated that ply drops for carbon fibers should be thinner than for lower elastic modulus glass fiber laminates which are commonly used in blade construction.

Cairns et al performed a generalized test to determine the influence of processing parameters for structural performance utilizing a formula to understand the fiber volume which is linked to fatigue performance (29). By combining such information with comprehensive background research, a solid foundation may be utilized to characterize and understand critical flaw types. In addition, it will allow for a mutually beneficial bridge between manufacturing and research. Overall, these studies indicate that not only will further testing of specific flaw types may be beneficial, but that with proper design and quality control these flaws are not inherently critical. Rather, it is likely that larger or combinations of flaws are needed for failure of an entire blade.

### **E. Non-Destructive Evaluation & Testing (NDE/NDT)**

The ability to detect damage is the cornerstone of any maintenance program employed to ensure the damage tolerance of a specific structure. Inspection procedures can be divided into two main classes. The first, which is most general, includes both destructive and nondestructive methods used for concept development, detailed design, production, and maintenance. The second class includes only those nondestructive evaluation (NDE) methods that can be practically used in service to locate and quantify the effects of impact damage. The second class is a subset of the first and depends on a technology database suitable for relating key damage characteristics to structural integrity (17).

After initial process qualification, testing for conformity to design requirements should continue on an appropriate frequency to ensure that the manufacturing process, materials, and associated tooling continue to operate within acceptable boundaries and thereby produce conforming parts. For accepting or rejecting cured structures, NDE equipment and procedures should be used to evaluate specified material defects resulting from fabrication and assembly operations. The NDE technique used for inspection should have the sensitivity to detect maximum allowable discrepancy type and size in the part. Specifications used by QC should define allowable limits for each discrepancy such as: adhesive voids, porosity, delaminations, damaged core, core node bond separations, potting cracks, short core, lack of adhesive, etc. (30) The need for this type of specification is a result of the relationship between the size of a flaw and the residual strength of the structure. This can be seen in the Figure 16 below.

It follows then that the larger the strength reduction is, the sooner the damage should be detected. Furthermore, these methods also consider that the need for inspection cannot disregard the likelihood of damage occurrence. The more likely the damage is, the sooner it should be detected. As a result, these methods depend on service data (17).



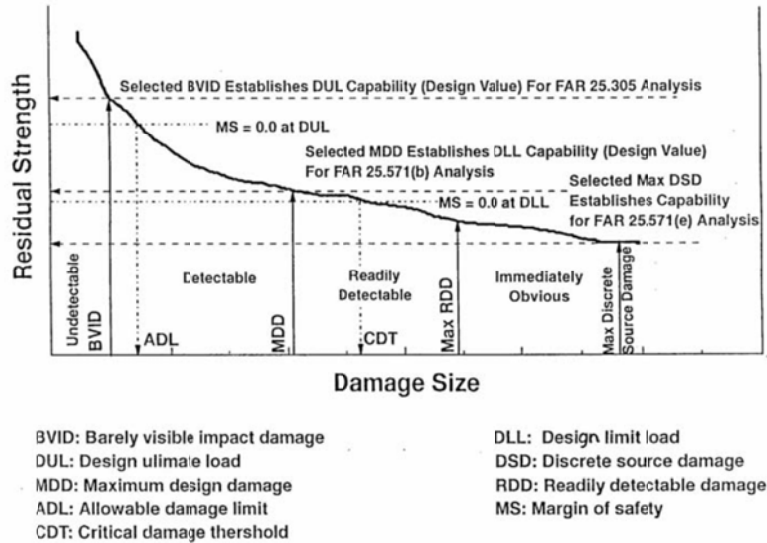


Figure 16: Residual strength requirements versus damage size (17).

Manufacturing defects as well as in service damage can be hard to detect in composite structures, particularly if the flaw is subsurface. The use of non-destructive evaluation is growing throughout the composites industry. There are a variety of NDE technologies used on composites and they all have their pros and cons. Some of the various technologies are listed below (31) (32):

- Thermography
- Leaky Lamb Waves
- Polar Backscattering
- Pulse-echo
- Through-transmission
- Ultrasonic
- Radiography
- Acoustic emission
- Interferometry (shearography)

### III. RECOMMENDATIONS

The particular focus of the effort will perform quantitative analysis based on the past performance of wind turbine blades. The key elements to consider in a reliability study of past performance are (14):

- (1) Identify areas needing structural and/or procedural reinforcement or modification
- (2) Establish chronological trends in reliability performance
- (3) Establish existing indices to serve as a guide for acceptable values in future reliability assessments
- (4) Enable previous predictions to be compared with actual operating experience
- (5) Monitor the response to system design changes

Since the aviation industry has established many probabilistic design models, similar approaches should be utilized. In order to begin this process two parallel efforts are recommended: Flaw Characterization and Effects of Defects.

#### A. Flaw Characterization

In order to develop a quality blade reliability program based on the implications of composite flaws, a study must be performed into composite defects as they relate to the wind turbine industry. Variations will exist in the type, frequency and effects of flaws between this industry and others. Therefore, it is imperative that data be generated specifically for wind turbine blades.

##### *i. Collect Flaw Data ad Develop Database*

Data should be collected from industry in the form of surveys to address the following topics:

- Flaw Type & Size Frequency
- Flaw Location Frequency
- Materials & Ply schedule
- Evaluation Techniques Utilized
- Frequency of Failures attributable to flaws
- Failure Mode

This data should then be assimilated into a database which will allow for ease of access through search fields and the implementation of a grouping criterion.

##### *ii. Investigation into Non-Destructive Evaluation Technology*

As stated earlier, flaw size is correlated to the strength of a structure and it is imperative that the right NDE technology be used. An investigation into the applicability of various NDE technologies on wind turbine blades should be performed. The results of this investigation should discuss the limitations of the different technologies as it relates to flaw size, type and location.

##### *iii. Classification of Wind Turbine Specific Defects and Their Origin*

Once the survey and NDE data has been assimilated, it will be necessary to distill it into bins that can be investigated further. This classification of flaw events will enable statistical interpretation of the criticality of various categories. Many factors will affect the categorization of events such as frequency,

implications to structural design capacity, susceptibility to environmental influences, reparability, failure mode and generic effects of defect analysis.

#### *iv. Statistical Interpretation of Defect Relevance & Criticality*

With the complete database established it becomes necessary to evaluate the criticality of flaws. Where quantifiable data is not available a simple approach to performance measurement is to apply Pugh or Rank Reciprocal methods. These methods allow for the prioritization of the various criteria relative to each other. Each data bin is then ranked in terms of severity for each criterion. The result of the analysis is a fairly objective ranking of importance for the flaw bins. These results will be combined with statistically relevant frequency data to yield a metric that develops a probabilistic approach to predicting the leading cause of failure.

#### *i. Probabilistic Modeling*

Variations in the structural behavior of composites cannot be characterized by the traditional deterministic methods that utilize a safety factors to account for uncertain structural behavior. The result of this dilemma is that structural reliability cannot be quantified. A design methodology that incorporates probabilistic modeling is needed to accurately determine the structural reliability of a composite structure (33).

#### *ii. Directives Database*

Should large amounts of data be collected, particularly from operators on a variety of machines and blade models it may be possible to set up an inspection database similar to that of the FAA Airworthiness Directives (AD) database. The AD database consists of inspection protocols specific to aircrafts or components. Non-specificity could be possible if the data collected showed strong inclinations to typical failure locations and modes that are industry wide problems. A series of directives (or recommendations) could then be developed by a standards committee which applies to all blades.

#### *iii. Generation of Distributable Defect Characterization Criteria and Flaw-to-Failure Code*

The potential may exist to distribute a flaw catalog which would be a visual database of flaw types, size and location which a technician could use to place an observed flaw into a class. This could help speed flaw evaluations and reduce the potential for incorrect classification. Another tool could be developed that incorporates damage growth/residual strength models to further predict the potential for failure.

### **B. Effects of Defects**

As noted above, current research indicates that determining critical size, type, location and combinations of flaws is needed to ensure proper design life. It has been proposed that this will be achieved by the following steps:

#### *i. Understand critical flaw types.*

Before the effects of defects can be determined, the critical flaw types must be identified from the flaw database and probabilistic modeling. This will occur in conjunction with the flaw characterization efforts noted above. In addition, a comprehensive review of relevant literature will be performed to ensure that

as much background information can be gleaned potentially reducing the workload of the latter portions of this research.

*ii. Characterize the mechanical properties of common flaws deemed critical to composite blades.*

Characterization will rely on static testing, both in-plane static and out-of-plane, utilizing the strengths of the entire MSUGC. As a parallel path, a model will also be generated and will rely on physical testing results. Fatigue testing may be utilized in latter portions of the research. A digital image correlation system (ARAMIS) will be utilized to understand stress-strain mapping associated with each flaw type.

*iii. Determine the criteria at criticality threshold of each flaw type.*

Criticality of flaw type, size and location will be determined for each flaw type such that it can be added to the flaw database to assist in quality control efforts.

*iv. Use a three-round study to develop coordinated analytical and experimental analogs for damage growth and residual strengths necessary for blade reliability.*

The first round will rely on input from other members of the BRC to determine the types of flaws that will be characterized. Characterization will rely on static testing, both in-plane static and out-of-plane, utilizing the strengths of the entire MSUGC. As a parallel path, a model will also be generated and will rely on physical testing results. This round will be complete when the model is able to somewhat accurately predict failure of a flaw-scale sample. Upon completion of this round an interim report of the results will be compiled, including specific paths for the second round.

Generally, the second round will be further coordination of experimental and analytical results and the third round will focus on an approach validation for the entire structure. Each round will culminate in a report which will include specific paths for the following round and recommendations, respectively. Other members of the BRC will be allowed to observe and testing will be coordinated to allow for group goals to be met. For example, testing may be interrupted to allow for NDE inspections by other group members. In short, this testing will not entirely take place as an independent project.

*v. Understand and model how these flaws contribute to the entire structure.*

Crucial to the outcome of this entire portion of the project is the modeling capabilities that will be generated. The intended outcome will be the ability to model flaws specific to an individual blade allowing for quality control a tool to act as a go/no-go gage. Users, likely quality control technicians, will enter critical flaw information for each flaw known to exist in the entire structure while consistent flaws (e.g. ply drops) will be embedded. The model will then analyze and evaluate the damage and output residual strength and durability information. This tool will be a significant improvement and a step toward implementing probabilistic and damage tolerance methodologies the wind industry needs.

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