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ADVANCED COMPOSITE WIND TURBINE BLADE DESIGN BASED ON DURABILITY AND DAMAGE TOLERANCE

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ABSTRACT

The objective of the program was to demonstrate and verify Certification-by-Analysis (CBA) capability for wind turbine blades made from advanced lightweight composite materials. The approach integrated durability and damage tolerance analysis with robust design and virtual testing capabilities to deliver superior, durable, low weight, low cost, long life, and reliable wind blade design. The GENOA durability and life prediction software suite was used as the primary simulation tool.

First, a micromechanics-based computational approach was used to assess the durability of composite laminates with ply drop features commonly used in wind turbine applications. Ply drops occur in composite joints and closures of wind turbine blades to reduce skin thicknesses along the blade span. They increase localized stress concentration, which may cause premature delamination failure in composite and reduced fatigue service life. Durability and damage tolerance (D&DT) were evaluated utilizing a multi-scale micro-macro progressive failure analysis (PFA) technique.

PFA is finite element based and is capable of detecting all stages of material damage including initiation and propagation of delamination. It assesses multiple failure criteria and includes the effects of manufacturing anomalies (i.e., void, fiber waviness). Two different approaches have been used within PFA. The first approach is Virtual Crack Closure Technique (VCCT) PFA while the second one is strength-based.

Constituent stiffness and strength properties for glass and carbon based material systems were reverse engineered for use in D&DT evaluation of coupons with ply drops under static loading. Lamina and laminate properties calculated using manufacturing and composite architecture details matched closely published test data. Similarly, resin properties were determined for fatigue life calculation. The simulation not only reproduced static strength and fatigue life as observed in the test, it also showed composite damage and fracture modes that resemble those reported in the tests. The results show that computational simulation can be relied on to enhance the design of tapered composite structures such as the ones used in turbine wind blades.

A computational simulation for durability, damage tolerance (D&DT) and reliability of composite wind turbine blade structures in presence of uncertainties in material properties was performed. A composite turbine blade was first assessed with finite element based multi-scale progressive failure analysis to determine failure modes and locations as well as the fracture load. D&DT analyses were then validated with static test performed at Sandia National Laboratories.

The work was followed by detailed weight analysis to identify contribution of various materials to the overall weight of the blade. The methodology ensured that certain types of failure modes, such as delamination progression, are contained to reduce risk to the structure. Probabilistic analysis indicated that composite shear strength has a great influence on the blade ultimate load under static loading. Weight was reduced by 12% with robust design without loss in reliability or D&DT.

Structural benefits obtained with the use of enhanced matrix properties through nanoparticles infusion were also assessed. Thin unidirectional fiberglass layers enriched with silica nanoparticles were applied to the outer surfaces of a wind blade to improve its overall structural performance and durability. The wind blade was a 9-meter prototype structure manufactured and

tested subject to three saddle static loading at Sandia National Laboratory (SNL). The blade manufacturing did not include the use of any nano-material. With silica nanoparticles in glass composite applied to the exterior surfaces of the blade, the durability and damage tolerance (D&DT) results from multi-scale PFA showed an increase in ultimate load of the blade by 9.2% as compared to baseline structural performance (without nano). The use of nanoparticles lead to a delay in the onset of delamination. Load-displacement relationships obtained from testing of the blade with baseline neat material were compared to the ones from analytical simulation using neat resin and using silica nanoparticles in the resin. Multi-scale PFA results for the neat material construction matched closely those from test for both load displacement and location and type of damage and failure.

AlphaSTAR demonstrated that wind blade structures made from advanced composite materials can be certified with multi-scale progressive failure analysis by following building block verification approach.

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EXECUTIVE SUMMARY

Current wind turbine blade design with advanced composites is based on high factors of safety and traditional design/stress analysis practices to ensure the target static strength levels and service life lengths. To achieve low production costs, material systems such as resin-infused woven and stitched fiberglass are utilized to try to hit an approximate \$5/lb. pound target product cost. To reduce operational costs, real-time structural health monitoring is not used to assess the condition of the blades. The design process can be described as one that focuses on service life rather than damage tolerance. In addition, composite materials have considerable scatter in nature due to voids, fiber waviness and manufacturing anomalies. Minimizing the scatter would involve considerable costly testing. Combination of these design constraints can significantly impact the turbine blade weight and performance. A design process which uses advanced damage modeling approaches for composites will lead to blades that are optimized to be damage resistant and tolerant while being light and inexpensive.

The Alpha STAR Corporation team demonstrated the ability of the GENOA advanced composite structural residual strength and life analysis software to predict the static and fatigue load response of a current Sandia wind turbine blade design to its design loads/environment envelope.

Table 1 summarizes the work performed in this study along with their status.

Table 1. Work task summary and completion status

#	Task Description	% Completed
1	SANDIA blade system design study (BSDS) analysis	100
2	Failure prediction and test validation of tapered composite under static and fatigue loading	100
3	Durability of tapered composite laminates under static and fatigue loading	100
4	Durability and reliability of composite blades using robust design approach	100
5	Durability of tapered composite laminates under static and fatigue loading	100
6	Improving wind blade structural performance with the use of resin enriched with nanoparticles	100

Five papers were written as a result of this project. These are

- 1) G. Abumeri, M. Garg, and F. Abdi, J. Paquette, “*Improving Wind Blade Structural Performance with the Use of Resin Enriched with Nanoparticles*” SAMPE Texas Conference Paper, 18 October 2011
- 2) F. Abdi, J. Paquette, G. Crans, L. Minnetyan, P. Marzocca, “*Durability of Tapered Composite Laminates under Static and Fatigue Loading*”, AIAA-SDM 2011 Conference, Denver, Colorado.
- 3) F. Rognin, G. Abumeri, F. Abdi, J. Paquette, “*Failure Prediction and Test Validation of Tapered Composite under Static and Fatigue Loading*”, SAMPE 2010, Seattle, Washington, 17-20 May 2010

- 4) H. Zhang, F. Abdi, J. Paquette, “Durability of Tapered Composite Laminates under Static and Fatigue Loading”, SAMPE 2010 Fall Technical Conference, Salt Lake City, Utah, 11-14 October 2010
- 5) G. Abumeri, J. Paquette, F. Abdi, “Durability and Reliability of Wind Turbine Composite Blades Using Robust Design Approach”, AIAA-SDM 2011 Conference, Denver, Colorado, 2011

Using GENOA’s Durability and Damage Tolerance (D&DT) methodology, time-dependent reliability analysis and micro-mechanics based progressive failure analysis was used to validate the current Sandia wind turbine blade design against full-scale laboratory test data and system dynamic modeling. The Sandia wind turbine blade concept was then re-optimized with the validated GENOA methodology to achieve a light-weight, low-cost robust design (maximum durability, reliability and longevity) that has an optimum stiffness distribution for aeroelastic and loads requirements. The design approach emphasized analytic approaches to reduce the current high design-to factors of safety and minimize non-destructive testing (NDT) and real-time structural health monitoring (SHM).

Our design/analysis approach relies on micro-mechanics-based multi-scale progressive failure analysis (PFA) that adheres to the FAA’s recommended building block verification strategy. This certification-by-analysis (CBA) approach has been shown to accurately:

- 1) Predict A-basis and B-basis allowable properties of advanced composite materials, both lamina and laminate, with reduced testing,
- 2) Estimate the mechanical and fracture properties of advanced composites and
- 3) Track FAA categories of damage composite structures under service. The FAA categories of damage are used for evaluation of composite wind blade structures under service and for demonstrating certification by analysis. ***Although requirements for aerospace are much more stringent than wind energy for safety and reliability, taking advantage of advances made in aerospace arena for composites durability and damage tolerance would enable the design of robust and cost effective wind blade structures.***

Figure 1. Two SERI 8-meter blades manufactured at WBG&AI facility for Sandia National Laboratory

Our cutting edge structural strength/life computational capabilities will provide significant risk reduction in design of advanced composite wind turbine blades and faster design turn-around times. The CBA approach allows wind turbine blade designers to use lower factors of safety, to

minimize coupon/element/component proof testing as well structural health monitoring without compromising safety and production/operating costs.

Certification-by-analysis involves an accurate simulation of physical tests using multi-scale progressive failure analysis. The scatter in physical tests is treated with probabilistic progressive failure Analysis (PPFA). The multi-scale analysis is based on a hierarchical analysis, where a combination of micro-mechanics and macro-mechanics is used to analyze materials and structures in great detail. CBA relies on physics-based failure criteria to reduce its dependence on empirical-based procedures. This is more than a simple mix of analysis and test because:

- 1) The root cause of failure at the micro-scale is modeled,
- 2) CBA is incorporated into each stage of the recommended building-block process, and
- 3) Material and manufacturing data scatter is accounted for.

The methodology is applicable to notched and un-notched coupons as well as full-scale structures and has the potential of reducing the test coupon count by over 60%. Our certification-by-analysis approach initially requires coupon testing (25 static specimens per material system) to establish the advanced composite fiber and matrix constituent structural properties (stiffness and strength). CBA was then be used to determine the maximum static loads the current Sandia wind turbine blade design can sustain as well as its anticipated service life length.

Figure 2. Predicted catastrophic fracture path damage and fracture locations and the contributing failure mechanisms under wind pressure loading conditions [12]

As an example, AlphaSTAR performed a turbine blade fatigue longevity analysis for Sandia. Durability and damage tolerance (D&DT) and fatigue life analyses of the E-glass wind turbine blade were performed with a progressive failure analysis (PFA) to determine the blade's structural integrity, under 140 mph wind pressure, and fatigue life and the associated damage under 45–56 mph wind pressures. W. Brandt Goldsworthy and Associates Inc. (WBG&AI) applied this technology to an 8-meter long wind turbine blade with a modern aerodynamic shape (**Figure 1**). **Figure 2** shows the damage propagation pattern (location) as a function of cyclic wind pressure. **Figure 2a** shows the damage initiation (red zone) in the form of matrix damage and stress interaction failure. **Figure 2b** shows that the blade starts to break at the root. **Figure 2c** shows the fracture initiation location (red zone). The contributing failure mechanisms were transverse tensile, stress interaction, and relative rotation of plies (delamination). **Figure 2d** shows the fracture propagation location (red zone).

1. INTRODUCTION

Current wind turbine blade design with advanced composites is based on high factors of safety and traditional design/stress analysis practices to ensure the target static strength levels and service life lengths. To achieve low production costs, material systems such as resin-infused woven and stitched fiberglass are utilized to try to hit an approximate \$5/lb. pound target product cost. To reduce operational costs, real-time structural health monitoring is not used to assess the condition of the blades. The design process can be described as one that focuses on service life rather than damage tolerance. In addition, composite materials have considerable scatter in nature due to voids, fiber waviness and manufacturing anomalies. To minimize the scatter would involve considerable costly testing. Combination of these design constraints can significantly impact the turbine blade weight and performance. A design process which uses advanced damage modeling approaches for composites will lead to blades that are optimized to be damage resistant and tolerant while being light and inexpensive.

The use of advanced composites in product design is becoming increasingly more attractive due to their advantageous weight-to-stiffness and weight-to-strength ratios. Increasingly, composite structures are being subjected to severe combined environments and are expected to survive for long periods of time. There is neither an adequate test database for composite structures nor significant long-life service experience to aid in risk assessment. To ensure safe designs, aerospace companies spend many millions of dollars per year on testing. Due to the difficulty and cost in assessing and managing risk for new and untried systems, the general method of risk mitigation consists of applying multiple conservative factors of safety and significant inspection requirements to already conservative designs in lieu of costly full system tests. Unfortunately, this approach can lead to excessively conservative designs and the full potential of composite systems is often not fully realized.

Determination of allowable properties is a time consuming and expensive process, since a large amount of testing is required. In order to reduce costs and product lead-time, Certification-by-Analysis (CBA) can be used to reduce necessary physical tests both for certification and for determining allowables. Whereas current advanced composite industrial practice tends to rely on expensive test-intensive empirical methods to establish design allowables for sizing advanced composite structures, the proposed CBA methodology relies on physics-based failure criteria to reduce its dependence on such empirical-based procedures.

Turbine Blade Certification-by-Analysis

An alternate design/analysis approach for turbine blades is to exploit high power computing (HPC) along with cutting-edge computational structural mechanics to achieve ***certification-by-analysis (CBA)*** for advanced composite structures. The CBA process involves an accurate simulation of physical tests using ***Multi-Scale Progressive Failure Analysis (PFA)*** including treating scatter in physical tests with probabilistic analysis. CBA can also be used to perform robust design of structures by minimizing a design's sensitivity to certain types of failures such as delamination. The multi-scale analysis utilizes a hierarchical approach where a combination of micro-mechanics and macro-mechanics is used to analyze material and structures in great detail.

Our CBA approach relies on micro-mechanics-based multi-scale progressive failure analysis that adheres to the FAA's recommended building block verification strategy. This virtual testing approach has been shown to accurately

- 1) Predict A-basis and B-basis allowable properties of advanced composite materials, both lamina and laminate,
- 2) Estimate the mechanical and fracture properties of advanced composites and
- 3) Track categories of damage composite structures under service.

Table 2. FAA Categories of Damage and Defect Considerations
Primary Composite Aircraft Structures (Courtesy of FAA)

CATEGORY	DESCRIPTION	EXAMPLES	SAFETY CONSIDERATIONS (SUBSTANTIATION AND MANAGEMENT)
1	Damage that may go undetected by field inspection methods (or allowable defects)	<ul style="list-style-type: none"> • Barley visible impact damage (BVID) • Minor environmental degradation • Scratches and gouges • Allowable manufacturing defects 	<ul style="list-style-type: none"> • Demonstrate service life • Retain Ultimate Load capability • Design-driven safety
2	Damage detected by field inspection methods at specified intervals (Repair scenario)	<ul style="list-style-type: none"> • VID (Ranging from small to large) • Manufacturing defects • Major environmental degradation 	<ul style="list-style-type: none"> • Demonstrate reliable inspection • Retain Limit Load capability • Design, maintenance and manufacturing
3	Obvious damage detected within a few flights by visual inspection (Repair scenario)	<ul style="list-style-type: none"> • Damage obvious in a 'walk-around' inspection • Due to loss of form, fit and/or function 	<ul style="list-style-type: none"> • Demonstrate quick detection • Retain Limit Load capability • Design, maintenance and operations
4	Discrete source damage known by pilot to limit flight maneuvers (Repair scenario)	<ul style="list-style-type: none"> • Damage in flight from events that are obvious to pilot <ul style="list-style-type: none"> – Rotor burst – Bird strike – Lightning 	<ul style="list-style-type: none"> • Defined discrete source events • Retain 'Get Home' capability • Design, maintenance and operations
5	Severe damage created by anomalous ground or flight events (Repair scenario)	<ul style="list-style-type: none"> • Damage occurring due to rare service events or to an extent beyond that considered in design 	<ul style="list-style-type: none"> • Requires new substantiation • Requires operations awareness for safety • Immediate reporting

These structural strength/life computational capabilities provide significant risk reduction in design of advanced composite wind turbine blades. The certification-by-analysis approach allows wind turbine blade designers to use lower factors of safety, to minimize coupon/element/component proof testing as well structural health monitoring without compromising safety and production/operating costs.

The generally accepted strategy for verifying an aircraft structural design for FAA certification is a building-block testing approach consisting of coupon, sub-element, and full-scale prototype experimental testing. Building a comprehensive certification-by-analysis database of building blocks that conforms to FAA requirements will put at designers' disposal a readily available compendium of certified designs that can be beneficially interrogated relative to the FAA certification potential of a newly proposed advanced composite structural design.

To insure advanced composite aircraft flightworthiness, the Federal Aviation Administration (FAA) requires that the aircraft builder/user address the damage levels for primary structures. Categories of damage and defect considerations for primary composite aircraft structures are outlined in [Table 2](#). Our proposed analysis approach addresses all the categories required for certification.

Damage Categories and Comparison of Analysis Methods and Test Results

Five damage categories are identified by the FAA, ranging from minor to severe. This section describes the damage and the corresponding analysis methods that can be employed to simulate the damage events of each category.

Category 1 - Damage that may go undetected by field inspection methods

Barely visible damage can occur due to matrix transverse cracking and micro-crack density formation during manufacturing and service (e.g., static loading, fatigue loading). Quantifying and characterizing the micro-cracking “transverse matrix crack” response during the composite cool down process and subsequent in-service fatigue life is important because the micro-cracks can form continuous paths through the thickness of the laminates resulting in lower stiffness, and leakage ([Figure 3](#)).

Figure 3. Typical micro-cracks in polymer matrix

Category 2-3 – Damage detected by field inspection methods

Visible damage may be observed during manufacturing such as wrinkling, fiber waviness and void distribution in thick laminates (Category 2). In addition, obvious damage may be detected within a few flights by flight operations and maintenance personnel (Category 3). Low speed impact, tool drop and part buckling are representative events of these categories.

Category 4 - Discrete source damage

Discrete source damage (DSD) can limit a structure's operational envelope. Herein, DSD is defined as a through-penetration of a structure with an area of collateral (non-visible) damage emanating from where high density projectiles impact the structure at velocities sufficient for penetration.

Category 5 - Severe damage created by anomalous events

Fracture or failure due to unforeseen loads/environments, including fire, limit a structure's safety envelope. Fire gives rise to high temperatures, which can cause epoxy resins to soften or burn, thus effectively undermining the strength of a composite part.

Building Block Approach

Within the composite engineering community, the structural substantiation process, which uses testing and analysis at increasingly complex levels, has become known as the "building block approach." Such an approach has traditionally been used to address durability and damage tolerance as well as static strength for both metal and composite aircraft structure.

The virtual (CBA) and experimental testing building-block approaches are interactive. Experimental test results are used to validate methods for analytical predictions and reduce uncertainties in CBA results. CBA provides assistance to planning and reduction of experimental testing at coupon and large component levels. With experimental verification, CBA of composite structure can be performed to understand:

- 1) Crack initiation at multiple sites,
- 2) Uncertainties in material properties,
- 3) Effects of barely visible, visible and discrete source damage,
- 4) Means of predicting damage growth and residual strength and
- 5) How to demonstrate durability and robustness to assist in the FAA certification process.

Figure 4 provides a conceptual schematic of a building block CBA approach for advanced composite structures. The building block approach focuses on hierarchical progressive failure analyses at each step of the design process to verify basic material constituents, joints, built-up substructures and the final product.

Figure 4. Schematic diagram of building block tests
(Courtesy of FAA)

Lower levels of testing are more generic and likely to be applicable to many composite structures. In order to perform these analyses, the material stress-strain curve needs to be established to failure (or a strain cutoff in the test methods) for each composite material used in the design. Analysis has proven reliable to minimize the numbers of tests needed to define this characteristic for laminated composite material forms.

Certification-by-Analysis Software

Figure 5. Virtual testing multi-scale hierarchical progressive failure analysis process

Analysis validation is an important part of the building block process because it provides a basis to expand beyond the specific tests performed in development and certification. Such validation starts with prediction of the structural stiffness, internal load paths, and stability. Verification of internal load paths may require additional building block tests, which are designed to evaluate load share between bonded and mechanically attached elements of a design. This is difficult analytically as failure is approached, where some nonlinear behavior can be expected. Combined load effects can further complicate the problem of analytical predictions.

Prediction of the effect of multiple influences (environment, repeated loads, damage, and manufacturing defects) on the failure modes that affect structural strength traditionally relies on the building block tests. Often, semi-empirical analyses have been adopted for composite strength. In such analyses, special considerations are given to structural discontinuity (for example, joints, cutouts or other stress risers) and the other design or process-specific details.

One of the most important parts of the building block analysis and test development comes in providing engineering databases to deal with manufacturing defects, field damage, and repairs likely to occur in production and service. Traditionally, not enough attention was given to these issues during composite product development and certification. This has caused significant work slowdowns and increased costs for subsequent product manufacturing and maintenance.

Each these variables will have a statistical distribution depending on how these values change from one specimen to another. Once these distributions have been defined, probabilistic analysis will then determine a specified number of specimens with a distribution of properties that have the same test scatter.

At each verification stage, materials and structures require evaluation of their mechanical properties and the corresponding uncertainties to determine the adequacy of the structure's

durability and reliability. PFA implements the basic concept that a structure will fail when defects and flaws, that may initially be microscopic, grow and/or coalesce to a critical size at which the structure no longer has an adequate strength to avoid catastrophic global fracture (**Figure 5**). Damage is considered to progress through five stages:

- 1) Initiation,
- 2) Growth,
- 3) Accumulation and coalescence of propagating flaws,
- 4) Stable propagation (up to critical dimensions) and
- 5) Unstable or very rapid propagation to catastrophic failure.

Computational PFA involves a formal procedure for identifying the five different stages of damage, quantifying the amount of damage at each stage, and relating the damage to the overall behavior of the deteriorating structure.

Certification-by-analysis involves an accurate simulation of physical tests using multi-scale progressive failure analysis at the unit cell level and for multiple failure criteria. The scatter in physical tests is treated with probabilistic progressive failure analysis (PPFA). The multi-scale analysis is based on a hierarchical analysis, where a combination of micro-mechanics and macro-mechanics is used to analyze materials and structures in great detail. CBA relies on physics-based failure criteria to reduce its dependence on empirical-based procedures. This is more than a simple mix of analysis and test because

- 1) The root cause of failure at the micro-scale is modeled,
- 2) CBA is incorporated into each stage of the FAA building-block process and
- 3) Material and manufacturing data scatter are accounted for.

Our CBA approach requires coupon testing to establish the advanced composite fiber and matrix constituent structural properties (stiffness and strength). CBA is then be used to determine the maximum static loads the current Sandia wind turbine blade design can sustain as well as its anticipated service life length.

Progressive Failure Fatigue Methodology

The evaluation of local damage due to cyclic loading is embedded in the composite mechanics module. The fundamental assumptions for cyclic fatigue are the following. Fatigue degrades all ply strengths at approximately the same rate. Fatigue degradation may be due to:

- 1) Mechanical loading (tension, compression, shear, and bending),
- 2) Thermal stresses (elevated to cryogenic temperature) and
- 3) Hygral stresses (moisture); and d) Combined effects (mechanical, thermal, hygral).

Laminated composites generally exhibit linear behavior to initial damage under uniaxial and combined loading. All ply stresses (mechanical, thermal, and hygral) are predictable by using linear laminate theory.

The composite mechanics module with cyclic load analysis capability evaluates the local composite response at each node subjected to fluctuating stress resultants. The number of cycles required to induce local structural damage are evaluated at each node. After damage initiation, composite properties are reevaluated based on degraded ply properties and the overall structural response parameters are recomputed. Iterative application of this computational procedure results in the tracking of progressive damage in the composite structure subjected to cyclic load increments. The number of cycles for damage initiation and the number of cycles for structural fracture are identified in each simulation. After damage initiation, when the number of load cycles reaches a critical level, damage begins to propagate rapidly in the composite structure. After the critical damage propagation stage is reached, the composite structure experiences excessive damage or fracture that causes its collapse. Iterative application of this computational procedure results in the tracking of progressive damage in the composite structure subjected to cyclic load increments.

Composite Material Calibration - Static Strength and Stiffness

Table 3. Comparison of Glass composites fatigue life cycles with high and low void volume concentrations [4-5]

Load	Number of Cycles to Failure				Life Increase (Times)
	10% Voids		2% Voids		
	Test (Average)	GENOA	Test	GENOA	
30%	13,200	14,770	540,000	550,000	40.9
50%	3,421	2,969	10,500	10,080	3.1
70%	572	513	630	620	1.1

Fiber and matrix properties calibration was performed in GENOA's Material Characterization Optimization module (MCO) using a reverse-optimization process to determine the matrix-strength/stiffness (stress-strain curves), and the fiber strength/stiffness to match the un-notched (longitudinal/transverse tensile strength, longitudinal/transverse compression strength, and shear strength) composite material tests at the lamina and laminate levels. The calibrated fiber and matrix "Root Finding Problem" was predicted and verified against the test data (**Figure 6** and **Table 3**). The other GENOA modules such as

- 1) MCA (Material characterization analysis) and
- 2) PFA (progressive failure analysis) can be used to perform a building block verification strategy by prediction of other ASTM standard coupon tests, sub-element tests, and element tests.

GENOA PFA can then predict the stiffness, strength, Poisson's ratio and strength of the lamina and laminates, while GENOA MUA (Material uncertainty analysis) may be utilized to identify the effects of composite fiber/matrix material property and manufacturing uncertainties on laminate response.

The GENOA virtual engineering tool was used in the design of 3TEX 3Weave /vinyl ester composite parts to effectively track the details of damage initiation, growth and subsequent

propagation to fracture for composite structures subjected to cyclic fatigue, thereby predicting the fatigue life. The material database inputs were

- 1) The experimental data for the stress-strain curve and the S-N curve for the vinyl-ester resin,
 - 2) The experimentally measured volume fraction of voids in the matrix and
 - 3) The Young's modulus and the S-N curve for the fiber.
- The last response was reverse-engineered using GENOA to match values measured experimentally for a composite with a measured volume fraction of voids.

The utility of the GENOA technology was demonstrated by predicting premature and extended fatigue lives in tensile mode of various 3TEX 3Weave (7-ply E-glass fiber)/ Dion 9800 vinyl-ester composites. GENOA predictions agree well with those measured in actual tensile-tensile fatigue tests using the R (minimum-to-maximum stress ratio) value of 0.1. Furthermore, GENOA PFA simulations quantitatively predict the effect of the void content on premature fatigue failures. Indeed, a 10% volume fraction of void defects reduces the fatigue life of the 3-D woven composite by a factor of 40 at the tensile load of 30% composite ultimate strength.

GENOA probabilistic analysis was used to determine the effects of manufacturing anomalies on the fatigue life. Five material design factors were considered, namely, braid angle, fiber volume, fiber shear modulus, matrix shear strength, and void fraction. As an example, **Figure 7** shows the probability sensitivity of these factors under tensile loading of 30% of the composite ultimate strength.

Figure 6. Fatigue comparison between experimental data and simulated results of 3TEX 3Weave/Dion 9800 composites

Figure 7. GENOA probabilistic analysis of 3TEX 3Weave / Dion 9800 vinyl-ester composites ISO tensile specimen under tensile fatigue. Voids are controlling factor that affect fatigue longevity [5].

2. OBJECTIVES

The overall goal of this effort was to perform certification-by-analysis (CBA), utilizing an accurate virtual testing approach in combination with a reduced physical test data (up to 65% reduction in coupons) to reduce the design cycle time and cost for future wind turbine blades. The first technical objective was to demonstrate the ability of the GENOA advanced structural residual strength and life analysis software to predict the static and fatigue load response of a current Sandia wind turbine blade design to its design loads/environment envelope. The second technical objective of the project was to minimize design uncertainty in terms of reduced factors of safety through certification-by-analysis, enabling more efficient light-weight, low-cost blade designs to be developed. A CBA design approach emphasizes analytic approaches to reduce the current high design-to factors of safety and minimize non-destructive testing (NDT) as well as real-time structural health monitoring (SHM). The third technical objective was to re-optimize the Sandia wind turbine blade design with the validated CBA methodology to achieve a light-weight, low-cost robust design (maximum durability, reliability and longevity) that has an optimum stiffness distribution for aeroelastic and loads requirements.

3. Methodology

All simulations in this project were performed using AlphaSTAR GENOA software. Sections below described the GENOA methodology.

Figure 8. Damage in sub-divided unit cell and delaminations tracked at micro-scale

- Damage is investigated and tracked in each subdivided unit cell**
- Delamination modes are investigated and tracked in matrix of each unit cell**
- Fiber matrix, inter-lamina and interactive failure criteria applied in GENOA**

3.1 Progressive Failure Analysis

The Progressive Failure Analysis (PFA) software, GENOA, augments finite element software by providing progressive failure analysis based on damage tracking and material property degradation at the micro-scale of fiber and matrix, where damage and delamination have their source. The GENOA software performs multi-scale (full-hierarchical) damage tracking and micro-mechanics material engineering.

The software uses micro and macro interaction methods in the composite structural PFA procedures (Figure 8). Micro-stresses and damages are computed on the constituent level and the corresponding material degradation is reflected in the macroscopic finite element structural stiffness.

Displacements, stress and strains derived from the structural scale FEA solution at a node/element of the finite element model are passed to the laminate and lamina scales using laminate theory. Unlike the process depicted in Figure 8b, most FEA analyses, which are not augmented with GENOA, evaluate failure at the lamina or laminate scale and do not pursue failure beyond this point. Unfortunately, failure does not originate at the lamina and laminate level and, instead, originates at lower scales. Hence, GENOA augments FEA analysis, with a full-hierarchical modeling that goes down to the micro-scale of sub-divided unit cells composed of fiber bundles and their surrounding matrix.

Stresses and strains at the micro-scale are derived from the lamina scale using micro-stress theory. The sub-divisions of the unit cell (small pieces of fiber and/or matrix), shown in Figure 8a, are then interrogated for damage using a set of failure criteria listed in Table 4. Similarly, matrix subdivisions in the unit cell are interrogated for delamination as depicted in Figure 8b. Once

damage or delamination occurs, GENOA determines which fiber and matrix material properties to degrade by applying a set of rules that are based on materials engineering and experience.

Table 4. Fiber and matrix failure criteria applied at the micro-mechanics scale of the composite [3]

Mode of Failure	Description
<i>Longitudinal Tensile (S11T)</i>	<i>Fiber tensile strength and fiber volume ratio.</i>
<i>Longitudinal Compressive (S11C)</i>	<i>1) Rule of mixtures based on fiber compressive strength and fiber volume ratio 2) Fiber micro-buckling based on matrix shear modulus and fiber volume ratio 3) Compressive shear failure or kink band formation, which is mainly based on ply intra-laminar shear strength and matrix tensile strength</i>
<i>Transverse Tensile (S22T)</i>	<i>Matrix modulus, matrix tensile strength and fiber volume ratio</i>
<i>Transverse Compressive (S22C)</i>	<i>Matrix compressive strength, matrix modulus and fiber volume ratio.</i>
<i>Normal Tensile (S33T)</i>	<i>Plies are separating due to normal tension</i>
<i>Normal Compressive (S33C)</i>	<i>Due to very high surface pressure, i.e. crushing of laminate</i>
<i>In Plane Shear (+) (S12s)</i>	<i>Failure due to positive in plane shear with reference to laminate coordinates</i>
<i>In Plane Shear (-) (S12s)</i>	<i>Failure due to negative in plane shear with reference to laminate coordinates</i>
<i>Transverse Normal Shear (+) (S23s)</i>	<i>Shear failure due shear stress acting on transverse cross section that is taken on transverse cross section oriented in normal direction of ply</i>
<i>Transverse Normal Shear (-) (S23s)</i>	<i>Shear failure due shear stress acting on transverse cross section that is taken on negative transverse cross section oriented in a direction of ply</i>
<i>Longitudinal Normal Shear (+) (S13s)</i>	<i>Shear failure due shear stress acting on longitudinal cross section that is taken on positive longitudinal cross section oriented in normal direction of ply</i>
<i>Longitudinal Normal Shear (-) (S13s)</i>	<i>Shear failure due shear stress acting on longitudinal cross section that is taken on negative longitudinal cross section oriented in normal direction of ply</i>
<i>Relative Rotation Criterion</i>	<i>Considers failure if adjacent plies rotate excessively with respect to one another</i>

As damage accumulates in the unit cell, the cell will eventually fracture. This means that a lamina has failed at a node of the finite element model. When all laminas at a node or element fail, the node or element is considered as fractured. Because damage is tracked at the micro-scale, it is quite possible that a node or element may experience two or more types of damages simultaneously. For example, there may be matrix cracking and fiber breaking in the same unit cell and same lamina of a particular node of the FE mesh. This behavior is especially important

when examining damage initiation, accumulation and growth. It represents a level of detail that gives GENOA [7] the foundation for the tool's remarkable accuracy.

Type Test	Longitudinal Tension	Longitudinal Compression	Transverse Tension	Transverse Compression	Shear
ASTM Number	D638 D3039	D695 D3410	D638 D3039	D695 D3410	D5379
Number Replicates	3	3	3	3	3
Loading

Figure 9. Provide 15 un-notched coupons for materials testing. Use root finding calibration process to derive fiber/matrix (non-linear) properties

3.2 Composite Material Calibration

Fiber and matrix properties calibration for GENOA is performed using a reverse-optimization process to determine the matrix-stiffness/strength (stress-strain curves), and the fiber stiffness / strength to match the un-notched (longitudinal / transverse tensile, longitudinal/transverse compression, and shear) composite coupon tests at the lamina and laminate levels (**Figure 9**, **Table 3**). Using Material Characterization and Qualification (MCQ) and PFA in GENOA, the stiffness, strength, Poisson's ratio and strength of the lamina and laminates are predicted and verified against the test data. Material Uncertainty Analysis (MUA) is performed to identify the effects of composite fiber/matrix material property and manufacturing uncertainties on laminate response.

In order to obtain the in-plane material properties five physical tests are required. These tests include tension and compression tests in the weft and warp direction and an in-plane shear test. The types of tests needed for the calibration processes are not limited to certain ASTM or other standards. The main issue is to create a good virtual counterpart of the physical tests. In other words, the material buildup, boundary conditions, loading and test conditions should be included in the model as accurately as possible. For the calibration process, the stress-strain information is used as comparison parameter between the virtual model and the physical test. To get good results, a complete experimental stress-strain curve is desired. This means that the stress-strain

(load-displacement) has to be recorded and documented through the entire test until the test structure has collapsed. It is recommended to do this for the verification of the simulation results with the tests as well.

3.3. Probabilistic and Reliability Analysis

With the direct coupling of composite micro-and-macro mechanics, structural analysis, and probabilistic methods, it is possible to simulate uncertainties in all inherent scales of composites, from constituent materials to the whole structure and its loading conditions. The evaluation process starts with the identification of the primitive variables at the micro and macro composites scales including fabrication. These variables are selectively perturbed in order to generate a database for determining the relationships between the desired materials behavior and/or structural response and the primitive variables. The approach for probabilistic simulation is shown in **Figure 10**.

Composite micro-mechanics are used to carry over the scatter in the primitive variables to the ply and laminate scales (**Figure 10**). Laminate theory is then used to determine the scatter in the material behavior at the laminate scale. This step leads to the perturbed resultant force / moment-displacement / curvature relationships used in the structural analysis. Next, the finite element analysis is performed to determine the perturbed structural responses corresponding to the selectively perturbed primitive variables.

Figure 10. Technical approach for probabilistic evaluation of wind blade composite structures

This completes the description of the hierarchical composite material/structure synthesis shown on the left side of **Figure 10**. The multi scale progressive decomposition of the structural response to the laminate, ply, and fiber-matrix constituent scales is shown on the right side of Figure 3. After the decomposition, the perturbed fiber, matrix, and ply stresses can be determined.

Multi-scale progressive failure analysis (MS-PFA) can be coupled with optimization and probabilistic methods [4] to deliver a design that is affordable, durable and reliable. However, relying on traditional computational simulation to perform robust design can be impractical due to the level of computation involved. Designers can use effectively the sensitivity analysis to identify influential material and fabrication variables that produce scatter in the blade failure load.

For the present case, MS-PFA was validated for static test simulation of the blade. Then the code evaluated the weight and D&DT contribution of key materials used in the blade. Probabilistic sensitivity analysis identified the material and properties that influence the failure load. Weight was finally reduced by iterating on percent of foam volume that can replace some of the materials without affecting the durability of the blade.

3.4 Virtual Crack Closure Technique (VCCT)

To further access the crack propagation or delamination into the ply drop coupon, the Virtual Crack Closure Technique (VCCT) was introduced to this study. VCCT is a fracture mechanics based approach to study crack propagation, which involves computing strain energy release rates, (G_I, G_{II}, G_{III}) , and comparing these values to their corresponding critical values, $(G_{IC}, G_{IIC}, G_{IIIC})$, where I, II, and III correspond to mode I, mode II, and mode III crack propagation modes, respectively. From a finite element perspective, VCCT determines the strain energy release rates from the nodal forces and displacements; thus not adding any complexity to the finite element formulation. The VCCT has been performed using the local coordinate system, based on the geometric relationships among the nodes surrounding the crack and the tip of the crack itself, to facilitate separation of the different fracture models. **Figure 11** from illustrates the scheme behind VCCT.

Figure 11. Schematic for VCCT

The basis behind VCCT is an interface element based on the modified crack closure integral (MCCI). The nodes for this element are numbered in a manner such that nodes 3 and 4 are located behind the crack, nodes 1 and 2 are located at the crack tip, and node 5 is ahead of the crack. In order to determine the nodal forces at the tip of the crack, a stiff spring is essentially placed between nodes 1 and 2. Nodes 3 - 5 do not contribute to the stiffness matrix used to calculate the nodal forces, however, nodes 3 and 4 are used to determine information concerning the opening of the crack behind its tip while node 5 carries information about the jump length in front of the crack tip. All this information combined is used to calculate the strain energy release rates. For a 2-D model, the mode I and mode II strain energy release rates can be expressed as follows:

$$G_I = \frac{Y_{12}v_{34}}{2B\Delta a} \quad G_{II} = \frac{X_{12}\mu_{34}}{2B\Delta a}$$

where G_I and G_{II} are the mode I and mode II strain energy release rates respectively, Y_{12} and X_{12} are the nodal forces in the X and Y directions for nodes 1 and 2, μ_{34} and v_{34} correspond to the X and Y displacement respectively between nodes 3 and 4, Δa is the crack extension, and B is the thickness of the model. The fracture criteria used to determine crack initiation and propagation based on the computed strain energy release rates is

$$f = \left(\frac{G_I}{G_{IC}} \right)^\alpha + \left(\frac{G_{II}}{G_{IIC}} \right)^\beta \geq 1$$

where f represents the crack growth parameter. According to reference [9] the exponents α and β are assumed to be 1. Once the crack growth parameter $f \geq 1$, the stiffness matrix associated with

the interface element is set equal to zero and crack initiation or propagation occurs. For additional information concerning the numerical methods of VCCT, please see references.

VCCT can be used with GENOA/PFA providing some knowledge of the location for crack initiation, and the path of crack propagation is provided. This information can be obtained experimentally, through a preliminary GENOA/PFA, or based on user experience. Since VCCT does not add any complexity to the finite element formulation, the need for extensive mesh preparation is eliminated.

3.5 Discrete Cohesive Zone Modeling (DCZM)

An additional method to potentially access the crack propagation or delamination into the ply drop coupon is known as Discrete Cohesive Zone Modeling (DCZM). DCZM, like VCCT, is also a fracture mechanics based approach to study crack propagation. This particular method is noted for its ability to simulate crack initiation and propagation even when various material nonlinearities are present, where VCCT is mostly used when linear elastic materials are present. DCZM essentially implements a discrete spring foundation at the process zone which is attached to the interfacial node pairs of the surfaces to be separated. In other words, a non-linear spring type interface element is placed between interfacial nodes to model the cohesive effects between the surfaces to be separated or de-cohered. **Figure 12a** illustrates this concept.

As can be seen in **Figure 12b**, DCZM uses a triangular cohesive law for mixed mode failure analysis in GENOA. The triangular form of the cohesive law is dependent on the corresponding cohesive strength and stiffness. Cohesive strength is the strength that causes the virtual spring elements' stiffness to decrease to a point where they begin to simulate non-linear responses of adhesives. The cohesive stiffness is the initial stiffness of these spring elements prior to reaching this non-linear state. In **Figure 12b**, σ_{1c} , τ_{2c} , and τ_{3c} correspond to the tensile (Mode I fracture), shear (Mode II fracture), and twisting (Mode III fracture) cohesive strengths respectively, δ_{1m} , γ_{2m} and γ_{3m} correspond to the maximum crack tip separation for a corresponding fracture mode, and δ_{1c} , γ_{2c} and γ_{3c} correspond to the crack tip separation at the associated cohesive strength for a corresponding fracture mode. For a detailed explanation concerning the interface element, equations for the cohesive stiffness,

Figure 12a. DCZM Virtual Spring Elements

Figure 12b. DCZM Triangular Cohesive Law for Mixed Mode Failure Analysis

cohesive strength, and the overall construction and implementation of the cohesive law for a 2-D case please see reference.

Crack propagation is controlled through the sequential releasing of nodes along a user-defined crack path. This takes place when the strain energy release rates, (G_I, G_{II}, G_{III}) , exceed their corresponding critical values, $(G_{IC}, G_{IIC}, G_{IIIC})$. The comparison between the strain energy release rates and their associated critical values is performed using either the B-K (Benzeggagh-Kenana) or Power Law, which is also user-defined.

As with VCCT, DCZM can be used with GENOA/PFA providing some knowledge of the crack propagation path is known. Once again, this information can be obtained experimentally, through a preliminary GENOA/PFA, or based on user experience. There are no DCZM results presented for the ply drop coupon of interest in this study, however, GENOA DCZM/PFA simulated results are going to be the topic of future work.

3.6 Insertion of Silica Nanoparticles in Matrix of Glass Composite

In the suggested approach, the effective nano composite (or enhanced matrix) material properties, where silica nanoparticles are analytically infused in the matrix. The analysis approach uses well-known Mori-Tanaka formulation for calculating the anisotropic nano-composite properties from isotropic matrix and nano-particles properties (stiffness, aspect ratio and volume fraction). For a composite material reinforced with aligned fiber-like particles, the Tandon and Weng (1984) prediction of the moduli E_{11} (aligned particle direction), E_{22} (transverse to the aligned particle direction), the in-plane shear modulus G_{12} , and the out-of-plane shear modulus G_{23} of the composite are:

$$E_{11} = \frac{E_m}{1 + f_p (A_1 + 2\nu_m A_2) / A} \quad (1)$$

$$E_{22} = \frac{E_m}{1 + f_p (-2\nu_m A_3 + (1 - \nu_m) A_4 + (1 + \nu_m) A_5 * A) / (2A)} \quad (2)$$

$$G_{12} = \frac{G_m}{1 + f_p (\mu_m / (\mu_p - \mu_m)) + 2(1 - f_p) H_{1212}} \quad (3)$$

$$G_{23} = \frac{G_m}{1 + f_p (\mu_m / (\mu_p - \mu_m)) + 2(1 - f_p) H_{2323}} \quad (4)$$

where A and A_i are constants depending on the components of the Eshelby tensor and the matrix/nanoparticles properties, and H_{ijkl} are the Cartesian components of the Eshelby tensor.

Figure 13. Micrographs of enhanced matrix [1]

A closed-form analytical solution for the complete set of anisotropic elastic properties of the composite derived by Tandon and Weng (1984) by combining the Eshelby theory and the Mori-Tanaka model, as shown in Equations (1) - (4) is used to obtain the stiffness properties of the ply with nanoparticles infused in the matrix.

The analytical approach discussed above is used to calculate the effective stiffness for the lamina after infusing its matrix with silica nanoparticles. **Figure 13** shows how the neat matrix is infused with nanoparticles to enhance its structural properties. Once the lamina or laminate properties are updated, multi-scale progressive failure analysis is then used to determine strength of the composite ply with nanoparticles. This is done by assessing failure mechanisms derived by Chamis. The ply is loaded to failure and the analysis detects laminate loading that produces damage matrix cracking and fiber failure.

4. SANDIA BLADE SYSTEM DESIGN STUDY (BSDS) ANALYSIS

Current PMC wind turbine PMC blade design is driven by high factors of safety. These cover unknowns in material properties and strengths, analysis methods simplifications, manufacturing tolerances and anomalies as well as uncertainties in the design load envelope. Cost and time constraints have limited the material and structural testing as well as non-destructive inspection (NDI). High design factors of safety are used instead to ensure adequate wind turbine blade performance. Fall-outs of high factors of safety are higher weight and thus larger gravitational loads, as well as possibly more expensive structures.

An alternative design approach is to utilize a certification-by-analysis (CBA) method. This involves a building-block approach, integrating materials and structural testing with advanced strength and life prediction analysis methods, to determine an optimum weight/cost turbine polymer matrix composite blade design that driven by durability and damage tolerance (D&DT) requirements. A CBA approach minimizes testing, NDI and active structural health monitoring through the use of sophisticated D&DT analysis methods.

The AlphaSTAR team will demonstrate the ability of its GENOA advanced structural residual strength and life analysis software to predict the static and fatigue load response of a current Sandia wind turbine blade design to its design loads / environment envelope.

Employing advanced D&DT methodology, time-dependent reliability analysis and micro-mechanics based progressive failure analysis GENOA will be used to validate the current Sandia wind turbine blade design against laboratory and system dynamics modeling data. The Sandia wind turbine blade concept will then be re-optimized with the validated GENOA methodology to achieve a light-weight, low-cost robust design (maximum durability, reliability and longevity) that has an optimum stiffness distribution for aeroelastic and loads requirements. The design approach emphasized analytic approaches to reduce the current high design-to factors of safety and minimize non-destructive testing (NDT) and real-time structural health monitoring (SHM). AlphaSTAR selected a blade design from Sandia National Lab as a demonstration of certification by analysis capability.

4.1 Blade and Material Description

The Sandia Blade System Design Study (BSDS) blade is a subscale research blade that was developed to examine several design innovations which had potential to increase the structural efficiency of utility-scale blades. The blade is 9 -m in length and was designed nominally as a 100-kW [11]. AlphaSTAR demonstrated under this grant certification by analysis capability using geometry, load, and test data from Sandia National Lab obtained through the BSDS program.

Other design features of the BSDS blade include a carbon fiber spar cap, embedded root studs and high performance outboard airfoils. A schematic of the major blade laminate regions is shown in **Figure 14**. The blade is predominately glass/epoxy with unidirectional glass in the root and a biaxial glass/balsa sandwich structure throughout most of the outboard region. The narrow carbon/glass hybrid spar cap is seen to extend for the entire length of the blade.

The blade was manufactured by first laying up dry fiber and core in skin and shear web molds. The dry fiber was then infused with epoxy using a vacuum assisted resin transfer mold (VARTM) process and cured at elevated temperature and pressure. The shear web was then glued to the low-pressure skin as bucking occurs on this surface and thus is the most critical bond. Finally, the high-pressure skin was glued to the low-pressure skin at the leading and trailing edge, along with the shear web using a blind adhesive joint. The laminate construction and adhesive joints are shown in **Figure 15**. The materials used are described in **Table 5**. **Figure 16** shows the blade finishing from reference [11]. **Figure 17** shows the BSDS blade finishing [11]. **Figure 18** shows the BSDS blade computer model. **Figure 19** shows the three saddle load applied at three airfoil stations. **Figure 20** shows the failure of the blade from Sandia test after applying 3 point saddle load and taking the blade all the way to failure. The test failure load was 48.612 KN. **Figure 21** shows the prediction for damage initiation (first onset of damage) at a load of 8.7KN due to transverse out of plane stress (delamination). This type of damage can only be detected by advanced simulation tool such as the presented in this report. **Figure 22** shows final failure prediction by AlphaSTAR simulating the

Figure 14. BSDS blade planform with major laminate regions [11].

Figure 15 – BSDS Blade Assembly Fixture [11].

same load condition as the test. The prediction of failure load by using multi-scale progressive failure analysis was 48.29 KN. **Figure 23** shows deformation from analysis of the blade at failure load of 48.29 KN. The summary results presented here illustrate the effectiveness of multi-scale progressive failure analysis in the design of wind turbine blades.

Table 5. Materials used in BSDS construction

Material	Description	Area of Use
DBM-1708/DBM-1208	$\pm 45^\circ$ stitched glass with chopped glass mat backing	Blade skins, shear web and leading edge
C520/C260/ELT5500	96% 0° , 4% 90° stitched glass	Blade skin root
Woven Rug	$\pm 45^\circ$ woven glass	Blade skin root
Carbon Triax	0° carbon stitched with 45° and -45° glass facings	Spar cap
Balsa	-	Outboard blade skin panels and shear web

Figure 17. BSDS blade finishing [11].

Figure 18. BSDS blade computer model [11]

Figure 19. Blade loading applied statically at three airfoil stations

The BSDS finite element model contained 19,400 elements. The BSDS blade finite element model along with the loads and boundary conditions (cantilevered at the root) are shown in **Figure 20**. In the figure, the different colors again represent the various laminate regions.

Loads simulating the static tests were applied to the models by using a distribution of nodal point loads along the high-pressure surface at each of the saddle locations. The point loads at each saddle location were made to be as similar as possible while applying the correct force, and with zero moment about the pitch axis. The nodes at the root end of the blade models were held fixed for the simulations.

Figure 20. Blade damage at static test peak load of 48.612KN (2 m from root of the blade); load applied at 3 stations of the blade

Figure 21. Damage initiation (in red) in composite blade at load initiation of 8.7KN predicted by AlphaSTAR simulating Sandia's test for three saddle static load.

5. Failure Prediction and Test Validation of Tapered Composite under Static and Fatigue Loading^{b 10]}

Tapered laminated structures, which are formed by dropping off some of the plies at discrete positions over the laminate, have received much attention from researchers because of their structural tailoring capabilities, damage tolerance, and their potential for creating significant weight savings in engineering applications. The inherent weakness of this construction is the presence of material and geometric discontinuities at ply drop region that induce premature interlaminar failure at interfaces between dropped and continuous plies.

A review of recent developments in the analysis of tapered laminated composite structures with an emphasis on interlaminar stress analysis, delamination analysis and crack growth analysis applied to a blade structure (Figure 23) is presented herein. A 2-ply drop-off as shown in Figure 3, is illustrated in Figure 24. The gage is 101.6 mm long and the drop off zone is 7 mm wide.

Figure 23. Simulated blade structure with material thickness transition [1]

Figure 24. Layout of a 2-ply drop-off specimen [1]

5.1 Strain Energy Release Rate

Characterization of delamination growth was performed using the strain energy release rate which is the energy dissipated per unit area of delamination growth. The energy that must be supplied to a crack tip for it to grow must be balanced by the amount of energy dissipated due to the formation of new surfaces and other dissipative processes such as plasticity.

For problems involving cracks that move in a straight path, the stress intensity factor (K) is related to the energy release rate (G). Stress intensity (K) in any mode situation is directly proportional to the applied load on the material. These load types are categorized as mode I, II and III (Figure 25). In the blade structure, the mode II is the prevailing one. Mode II is sliding or in-plane shear mode where the crack surfaces slide over one another in a direction perpendicular to the leading edge of the crack.

5.2 Experimentation

The experimental work [1] was carried out by the Department of Chemical and Biological Engineering, Montana State University as part of the DOE/MSU Composite Material database [8]. The database, maintained in cooperation with Sandia National Laboratories [9], is a collection of static and fatigue tests of a wide variety of materials used in wind turbine blades (Table 6).

5.3 Material Systems

Panels containing ply drops were infused under vacuum through two flow medium layers and one peel ply layer on the top and the bottom surfaces of the laminate. **Table 7** gives the main properties of the 4 studied laminates and **Figure 26** illustrates the Stress/strain curves of these specimens. The nominal fiber volume fraction for the ply drop panels was 54%, giving a thin-side and thick-side panel thickness of 13.7 mm and 11.5 mm, respectively.

Longitudinal Tensile Test [1]

The complex coupon with ply drops employs an unsymmetrical geometry shown in **Figures 23 and 24**. This test method required significant test development to arrive at a lay-up and dimensions which would have minimal bending, be compatible with testing machine (250 kN) capacity and grip capacity, while representing blade materials and structure of current interest (**Figure 27**).

The lay-up chosen allows convenient infusion with a variety of resins of interest for blades, and features failure modes including delamination at the ply drops, damage in the $\pm 45^\circ$ surface layers (which represent blade skin materials) and load redistribution between the surface skins and primary structural 0° plies as damage develops and extends.

The finite elements model (**Figure 28a**) contains 24,204 elements and 30,563 nodes. The applied loads and boundary conditions (**Figure 28b**) simulate a simple longitudinal tensile test.

Figure 25. Crack opening modes

Table 6. Higher order ASTM based coupon verification

Verification	
Test Description	ASTM
Double notched compression (interlaminar shear)	D3846
Four point bending	D6272
Short beam bending	D2344
Flat-wise tension	C297
Open-hole tension/compression	D766 (tension) D6484 (Compression)
Compact tension	E1802
Iosipescu (in-plane shear)	D5379

Table 7. Properties of four laminate types

Resin	Fiber Content (%)	Thickness (mm)	UTS (MPa)	Strain at UTS (%)	Initial E (GPa)
EP-1	44	4.57	168	2.4	13.4
UP-1	44	4.52	175	2.4	14.3
VE-1	46	4.21	160	3.1	17.0
VE-2	44	4.54	156	2.5	15.2

5.4 Simulation Results

Figure 26. Stress/strain curves of 4 laminate types

Figure 27. Longitudinal tensile test [1]

The methodology and its various failure criteria and material-degradation sub-models were compared and assessed by performing analyses for four material (fiber/matrix) systems: EP-1, UP-1, VE-1 and VE-2 combined with E-glass. Constituent properties of the composite laminates are derived by modeling the actual coupon tests and comparing simulation results with measured results. An optimization process is used to select the constituent properties which best fit the test data. **Table 8** describes the resin details for polyester, vinyl ester, epoxy, and toughened vinyl ester [1], all used with glass fabrics. The Calibrated S-S curves are shown in **Figure 29** and the S-N curves for fatigue tests are shown in **Figure 30**.

Table 8. Description of various resin systems [1]

Resin	Resin Details
EP-1	Hexion MGS RIMR 135/MGC RIMH 1366
UP-1	Hexion / uPICA TR-1 with 1.5% MEKP
VE-1	Ashland Derakane Momentum 411 with 0.1% CoNap, 1.0% MEKP and 0,02 phr 2,4-Pentanedione
VE-2	Ashland Derakane 8084 with 0.3% CoNap and 1.5% MEKP

Figure 28. Finite element model

Figure 29. Simulation of EP-1 matrix

Figure 30. Calibrated matrix S-N curves

The purpose of this effort is to compare composite failure predictions of GENOA against tests. Test data was collected for four tapered laminates corresponding to Longitudinal Tension. The material (fiber/matrix) constituent properties were calibrated using GENOA's Material Characterization Analysis (MCA). Note that calibration is not required if actual fiber and matrix properties are known.

Four tests were simulated in GENOA using its PFA capabilities corresponding to each material system: EP-1, UP-1, VE-1 and VE-2. An initial crack was modeled in the resin rich area. Test results [1] and [Figure 31](#) show that damage and crack initiate at the bottom of the ply drop. This is caused by a stress concentration at this location due to a higher displacement of the continuous plies compared to cut off plies: Delamination mode II.

Figure 31. Crack Initiation

Then, the crack propagates along the delamination path between continuous plies and cut-off plies. **Figure 32** show the comparison between simulated crack opening and test results. The most vulnerable lay-up to delamination is the one where the crack is located at the interface between two 0° plies (**Figure 32**, green circle), although another crack is to be considered, at the transition between 0° plies and $\pm 45^\circ$, on the inner side of the wrapping.

Figure 32. Crack propagation

Figure 33. Crack length vs. load – Simulations vs. experimental tests [1]

The length of the crack was investigated according to the applied load on the test specimen. **Figure 33** illustrates the good correlation between simulation and tests for the four material systems. For most cases, it appears that the propagation rate is slow in the beginning and rapidly growing until catastrophic failure of the laminate.

5.5 Conclusions

Tapered laminates have wide applications in engineering structures. However, the problem of predicting static strength accurately has still not been satisfactorily resolved. Many models are available but all have limitations.

Delamination at ply drops has been a tolerable problem with aerospace structures composed of relatively thin (0.15 mm) aerospace prepregs, although fatigue prone applications like helicopter blades have required careful design. Using thin prepregs, however, introduces unwanted manufacturing costs, as many plies of material must be layered to build up the necessary thickness. Therefore, manufacturers use thicker ply composites to save time and cost in manufacturing wind turbine blades. However, the problem with delamination of ply drops has been identified as a failure mode in wind turbine blades and has prompted this study of ply drop delamination behaviour.

5.6 References

- 1) P. Agastra, D. D. Samborsky and J. F. Mandell, "*Fatigue Resistance of Fiberglass Laminates at Thick Material Transitions*", 50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, May 2009, Palm Springs, California.
- 2) F. Abdi, K. Kedward, "*Simplified Analytical Procedure for Prediction of Fracture Damage in Composite Structures*", SBIR Phase II Final Report, Contract No. N00014-02-M-0144", Alpha STAR Technical Report to Navy, July 5, 2006.
- 3) D. Huang, F. Abdi, A. Mossallam, "*Comparison of Failure Mechanisms in Composite Structure*". SAMPE 2003 Conference Paper.
- 4) GENOA User Manual, <http://www.ascgenoa.com>; MCQ user manual <http://www.alphastarcorp.com>
- 5) F. Abdi, L. Minnetyan, C. Chamis, "*Durability And Damage Tolerance Of Composites*". *Book Chapter 8- "Composites, Welded Joints, and Bolted Joints."* Kluwer Academic Publisher, 2000.
- 6) X. Su, F. Abdi, R. Kim, "*Prediction of Micro-crack Densities in IM7/977-2 Polymer Composite Laminates under Mechanical Loading at Room and Cryogenic Temperatures*". AIAA/SDM 46. Austin, Texas, 2005. [Insert reference 7]
- 7) F. Abdi, T. Castillo, E. Shroyer "*Risk Management of Composite Structure*" Book Chapter 45, CRC Handbook, January 2005. [Insert reference 9]
- 8) J. F. Mandell. and D. D. Samborsky, "*DOE/MSU Fatigue of Composite Materials Database, March 25, 2009, Version 18.1*", (www.sandia.gov/wind)
- 9) T. D. Ashwill, "*Materials and Innovations for Large Blade Structures: Research Opportunities in Wind Energy Technology*", 50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, May 2009, Palm Springs, California
- 10) F. Rognin, G. Abumeri, F. Abdi, J. Paquette, "*Failure Prediction and Test Validation of Tapered Composite under Static and Fatigue Loading*", SAMPE 2010, Seattle, Washington, 17-20 May 2010
- 11) D. Berry, "*Blade System Design Studies Phase II: Final Project Report. Sandia Report SAND2008-4648*", July 2008.

6. Durability and Reliability of Wind Turbine Composite Blades Using Robust Design Approach ^[7]

The use of advanced composites in product design is attractive due to advantageous weight-to-stiffness and weight-to-strength ratios. Composite structures are being subjected to severe combined environments and are expected to survive for long periods of time. While large amounts of coupon test data exist, there is neither an adequate test database for composite structures nor significant long-life service experience to aid in risk assessment. Due to the difficulty and cost in assessing and managing risk for new and untried systems, the general method of risk mitigation consists of applying multiple conservative factors of safety and significant inspection requirements to already conservative designs in lieu of costly full system tests. Unfortunately, this approach can lead to excessively conservative designs. The full potential of composite systems is often not fully realized.

Current wind turbine blade design with advanced composites is based on high factors of safety and traditional design/stress analysis practices to ensure the target static strength levels and service life lengths. To achieve low production costs material systems such as resin-infused woven and stitched fiberglass are utilized to attempt to achieve an approximate \$5 per pound or lower target product cost. In addition, real-time structural health monitoring is not used to assess the condition of the blades. Finally, the design process can be described as one that focuses on service life rather than damage tolerance. The combination of these design constraints can significantly impact the turbine blade weight and performance. A design process which uses a composite damage modeling approach can lead to blades that are optimized to be damage resistant and tolerant while being light and inexpensive.

The objective of this work was to perform a Virtual Testing (VT) process which involves an accurate simulation of physical tests using multi-scale Progressive Failure Analysis (PFA) including the scatter in physical tests by using Probabilistic Analysis. The multi-scale analysis is based on a hierarchical analysis, where a combination of micro-mechanics and macro-mechanics is used to analyze material and structures in great detail. Certification required predictions are important for reducing risk in structural designs. Moreover, determination of allowable properties is a time consuming and expensive process, since a large amount of testing is required. In order to reduce costs and product lead-time, VT can be used to reduce necessary physical tests both for certification and for determining allowables.

In summary, whereas industry tends to rely on expensive test-intensive empirical methods to establish design allowables for sizing advanced composite structures, the developed VT methodology relies on physics-based failure criteria to reduce its dependence on such empirical-based procedures. This is more than a simple mix of analysis and test because:

- 1) The root cause of failure at the micro-scale is modeled for accurate failure and life prediction,
- 2) VT is incorporated into each stage of the building-block process and the certification categories of damage tolerance and
- 3) Natural material and manufacturing data scatter is created giving rise to the unique capability to estimate strength allowables.

6.1 Description of Blade FEA Model and Blade Materials

The blade considered was designed and built through a research partnership between TPI Composites and Sandia National Laboratories. Testing of the blade was completed by Sandia and the National Renewable Energy Laboratory. **Figure 34** shows a finite element model of the wind blade [5]. The model was used by multi-scale PFA to simulate analytically the static test. The blade was 9 meters long. It was scaled down from the initial 44 meter planform from the first phase of Sandia's Blade System Design Studies project [5]. The different colors in **Figure 34** indicate regions with different materials. These regions are referred to as ply schedules correlating distinct physical regions in the model with specific material or number of materials, layup information, thickness and other physical properties. The blade was modeled with 22,774 shell elements and 67,608 nodes. **Figure 35** shows the loading profile at three cross-sections of the blade. The loads were applied at 3, 4.8, and 6.6 meters from the root to approximate the loading of the ultimate load test. **Table 9** lists the various materials used in the construction of the blade. **Table 10** lists the type of material used in different ply schedules of the blade. More details on blade design can be found in reference [5]. The list of the blade materials was supplied by Sandia.

Figure 34. Sandia 9 meter blade finite element model with correspondent ply schedules

Figure 35. Blade bending loads applied at 3 stations

Table 9. List of materials used in blade model

Material #	Material
1	Stitched Double Bias Glass (DBM1708)
2	Balsa
3	Steel
4	Gelcoat
5	Chopped Glass Mat (0.75 oz)

Table 10. Materials and ply schedule correlation

Ply Schedule	Material #	Ply Schedule	Material #
1	3	13	4,5,1,2,1
2	4,5,1,6,7,6,6,8,6,9,6,1	14	4,5,1,6,7,6,1
3	4,5,1,6,7,6,6,8,6,9,6,1	15	4,5,1,6,7,6,1
4	4,5,1,6,7,6,6,9,6,1	16	4,5,1,2,1,1,1
5	4,5,1,6,7,6,6,9,6,1	17	4,5,1

Table 9. List of materials used in blade model

Material #	Material
6	Uni Glass (ELT5500)
7	Woven Double Bias Glass (6 oz)
8	Rod Filler (smeared stud/glass)
9	Stitched Double Bias Glass (DBM1208)
10	Carbon/Glass Triax
11*	Chopped Glass Mat (0.75oz) x10
12*	Stitched Double Bias Glass (DBM1708) x10
13*	Balsa x10

* Material with x10 stiffness & density, x0.1 ply thickness

Table 10. Materials and ply schedule correlation

Ply Schedule	Material #	Ply Schedule	Material #
6	4,5,1,10,7,10,6,9,6,1	18	4,5,1,10,7,10,1
7	4,5,1,6,7,6,6,1	19	4,5,1,10,1
8	4,5,1,6,7,6,6,1	20	4,5,1
9	4,5,1,10,7,10,6,1	21**	4,11,12,13,12
10	4,5,1,6,7,6,1	22	4,5,1
11	4,5,1,6,7,6,1	23	1,2,1
12	4,5,1,10,7,10,1		

**Used at leading edge to avoid shell radius/thickness violation.

6.2 Simulation of Blade Static Test

Table 11. Lamina properties used for ELT5500 (unidirectional glass epoxy material)

Property	Symbol	Value	Measurement
LONGITUDINAL MODULUS	E11	4.180E+04	N/(mm ²)
TRANSVERSE MODULUS	E22	1.403E+04	N/(mm ²)
TRANSVERSE MODULUS	E33	1.416E+04	N/(mm ²)
INPLANE SHEAR MODULUS	G12	2.630E+03	N/(mm ²)
TRANSVERSE SHEAR MODULUS	G23	2.323E+03	N/(mm ²)
SHEAR MODULUS	G13	2.630E+03	N/(mm ²)
POISSON'S RATIO	ν12	2.806E-01	
POISSON'S RATIO	ν13	4.534E-01	
POISSON'S RATIO	ν23	2.759E-01	
LONGITUDINAL TENSILE STRENGTH	S11T	1.125E+03	N/(mm ²)
LONGITUDINAL COMP. STRENGTH	S11C	7.492E+02	N/(mm ²)
TRANSVERSE TENSILE STRENGTH	S22T	6.083E+01	N/(mm ²)
TRANSVERSE COMP. STRENGTH	S22C	2.041E+02	N/(mm ²)
INPLANE SHEAR STRENGTH	S12S	3.020E+01	N/(mm ²)
NORMAL TENSILE STRENGTH	S33T	6.083E+01	N/(mm ²)
NORMAL COMP. STRENGTH	S33C	2.041E+02	N/(mm ²)

During testing, blade bending loads were applied at three blade stations. These loads were increased until the failure of the test article. Simulation results were obtained numerically using multi-scale multi-physics progressive failure analysis (MS-PFA) software. The analytical predictions were validated not only for ultimate failure load but also for load deflection results as well. **Table 11** lists ply mechanical properties for ELT5500 glass epoxy composite. Properties for other materials can be found in [5-6]. MS-PFA predicted damage initiation and propagation,

fracture initiation and propagation, and the final residual strength in the blade. Compared with test results, analytical simulation gives a good prediction as well as the damage progression sequence and structural response characteristics during different degradation stages. **Figure 36** shows the progressive damage in the blade under increased static loading. The initial damage started near the root of blade at load of 8.7 KN due to delamination in composite layers (**Figure 36a**). When the load reached 24.36 KN, additional damage criteria were activated: transverse tensile, longitudinal compressive, shear and delamination (**Figure 36b**). When the load applied reached the ultimate peak value of 48.29 KN, damage propagated to most zones of the blade (**Figure 36c**). At ultimate, the damage modes were longitudinal and transverse tensile failure, longitudinal and transverse compressive failure, and shear failure and delamination. The final damage of the blade from test is shown in **Figure 36d**. As indicated in the figure, test indicated extensive damage near the root consistent with the findings of the simulation. The final position of blade obtained from simulation and showing excessive deformation is presented in **Figure 36e**.

Figure 36f shows the structural response under increased static loading from simulation compared to test. The load deflection measured by string potentiometers located at three blade stations is plotted in the figure. Station SP1 is for blade station 3 meters away from the root of the blade. Stations 2 and 3 (SP2 and SP3) are located 4.8 and 6.6 meters away from the blade root, respectively. As noted in the **Figure 36f**, the results from station SP3 indicates a potential anomaly with the data collected from test. This might be attributed to a problem with the strain gage. The loads at the three stations of the blade were increased proportionally till structural failure took place. The results presented here illustrate the effectiveness of the MS-PFA approach to virtually predict behavior of wind blade structures. It provides a reliable mean to assess structural response by predicting test behavior and not replicating it.

6.3 Blade Weight Analysis

Building block strategy for robust design requires a detailed understanding of the role that each material of the blade plays with respect to contribution to weight and durability. To determine accurately the weight of the blade and identify the contribution of the various materials, weight analysis was performed. **Table 12** shows the volume and weight contribution from each material used in the blade construction. As indicated in the table, the Stitched Double Bias Glass (or DBM1708) material system constituted about 31% of the total blade weight. The DBM1708 material and Unidirectional Glass (ELT5500) undergo damage and fracture at increased loading conditions as evident by progressive failure analysis results. Working with these materials will change the damage characteristics of the blade. Enhancing the properties of materials # 1 and #6 combined with lower density can effectively reduce the weight of the blade without reducing its performance. However, this has to be done in a way that the overall shape and stiffness of the blade remain un-altered. The total weight predicted by the analysis is lower by 16 kg as compared to the one reported in [5] (113 kg from analysis versus 129 kg from the lab). The difference could be attributed to the fact that the analytical model did not include weight of steel studs extending from the blade and adhesive included in the blade when it was weighed in the lab.

Figure 36. Progressive failure analysis and test validation of Sandia's 9 meter blade under static loading

Table 12. Volume and weight contribution for various materials used in the blade design

Material System #	Total Volume m³	Density kg/m³	Total Mass kg	% of Total Mass	Material
1	1.89297E-02	1814	34.338	30.76%	Stitched Double Bias Glass (DBM1708)
2	5.29436E-02	230	12.177	10.91%	Balsa
3	6.80245E-04	7850	5.340	4.78%	Steel
4	4.88732E-03	1235	6.036	5.41%	Gelcoat
5	2.86724E-03	1678	4.811	4.31%	Chopped Glass Mat (0.75oz)
6	1.24760E-02	1874	23.380	20.94%	Uni Glass (ELT5500)
7	1.65826E-03	2076	3.443	3.08%	Woven Double Bias Glass (6 oz)
8	4.02312E-03	3006	12.093	10.83%	Rod Filler (smeared stud/glass)
9	3.52024E-04	1814	0.639	0.57%	Stitched Double Bias Glass (DBM1208)
10	3.44028E-03	1685	5.797	5.19%	Carbon/Glass Triax
11	2.48228E-05	16780	0.417	0.37%	Chopped Glass Mat (0.75oz) x10
12	1.15840E-04	18140	2.101	1.88%	Stitched Double Bias Glass (1708) x10
13	4.63358E-04	2300	1.066	0.95%	Balsa x10
Total	1.02862E-01		111.64		

6.4 Blade Durability and Damage Tolerance (D&DT) Probabilistic Sensitivity Analysis

Table 13. Summary of parametric study showing influence of mechanical properties from three material systems on blade failure load

Material System	Mechanical Property (normalized value)							Failure Load (N)	
	S11t	S11c	S22t	S22c	S12	E11	E22	Analysis	Test
DBM1708	1.1	1.0	1.0	1.0	1.0	1.0	1.0	48285	48612
	1.0	1.1	1.0	1.0	1.0	1.0	1.0	48285	
	1.0	1.0	1.1	1.0	1.0	1.0	1.0	48285	
	1.0	1.0	1.0	1.1	1.0	1.0	1.0	48720	
	1.0	1.0	1.0	1.0	1.1	1.0	1.0	51330	
	1.0	1.0	1.0	1.0	1.0	1.1	1.0	51330	
	1.0	1.0	1.0	1.0	1.0	1.0	1.1	48285	
ELT5500	1.1	1.0	1.0	1.0	1.0	1.0	1.0	48285	
	1.0	1.1	1.0	1.0	1.0	1.0	1.0	48285	
	1.0	1.0	1.1	1.0	1.0	1.0	1.0	48285	
	1.0	1.0	1.0	1.1	1.0	1.0	1.0	48285	
	1.0	1.0	1.0	1.0	1.1	1.0	1.0	48285	
	1.0	1.0	1.0	1.0	1.0	1.1	1.0	48720	
	1.0	1.0	1.0	1.0	1.0	1.0	1.1	47850	
Saertex	1.1	1.0	1.0	1.0	1.0	1.0	1.0	48285	
	1.0	1.1	1.0	1.0	1.0	1.0	1.0	48285	
	1.0	1.0	1.1	1.0	1.0	1.0	1.0	48285	
	1.0	1.0	1.0	1.1	1.0	1.0	1.0	48285	
	1.0	1.0	1.0	1.0	1.1	1.0	1.0	48285	
	1.0	1.0	1.0	1.0	1.0	1.1	1.0	48285	
	1.0	1.0	1.0	1.0	1.0	1.0	1.1	48285	

It is prudent to identify the influential material with respect to D&DT and weight. Results from D&DT and weight analysis guide the weight reduction strategy. First a parametric study was performed by varying the mechanical properties of various material systems, one at a time, to assess influence on final failure load. The static load applied is a three saddle load similar to the one applied in the test performed by Sandia (bending load at three locations along the span of the blade). **Table 13** shows the results from a total of 21 progressive failure analysis (MS-PFA) runs. A description of the perturbed properties is given here: S11t ply longitudinal tensile strength; S11c ply longitudinal compressive strength; S22t ply transverse tensile strength; S22c ply transverse compressive strength; S12 ply shear strength; E11: ply longitudinal modulus; and E22: ply transverse modulus. The table shows the normalized variable considered in each analysis run and the predicted failure load from analysis. Three material systems (DBM1708, ELT5500, and Carbon/Glass triax) were considered in the parametric study for D&DT sustainment based on initial progressive failure analysis of the blade. ELT5500 was a mixed material system that included plies with carbon fibers and others with glass fiber. While the Carbon/Glass triax is carbon fiber based material system. From the results presented in the referenced table, it is clear

that the DBM1708 material and ELT5500 play key roles with respect to the blade D&DT as their mechanical properties influences the final failure load of the blade.

Figure 37. Probabilistic scatter in blade failure load subject to static loading due to uncertainties in properties of DBM1708 material

Figure 38. Probabilistic sensitivity of random variables due to uncertainties in properties of DBM1708 material

Figure 37 shows the scatter in ultimate failure load of the blade obtained from MS-PFA analysis as a result of 5% coefficient of variation in the DBM1708 material random variables. The data shown in the referenced figure are of great importance for obtaining reliable design. For example, if the applied load is kept under 36,700 N, a reliability of 0.999 can be attained (highly desired outcome). If we produce 1,000 blades, very few will fail when the load applied is lower than 36,700 N. Most will fail when the load applied is close to the mean load (about 48,000 N). If the load applied is increased beyond 61,000 N, most blades would have failed by then. The blade failure load exhibited a scatter of 24,000 N based on the assumed uncertainties. **Figure 38** shows the results obtained from probabilistic sensitivity analysis assuming variation in the mechanical properties of the DBM1708 material. Clearly, the longitudinal stiffness and ply shear strength are very influential when it comes to affecting the blade ultimate load. Controlling scatter in these two random variables reduces variability in the blade ultimate load. With the data presented here, it is established that the DBM1708 material is of great importance when it comes to the blade failure followed by ELT5500 material. Results obtained from weight reduction are discussed next.

6.5 Blade Weight Reduction with Robust Design

Weight reduction is an important area to address since it is directly proportional to manufacturing, transportation and installation costs. Weight reduction should be done without loss in stiffness and strength or life of the blade. The authors assessed the potential for weight reduction by replacing a volume of the blade material with foam.

In the study performed, the blade was subjected to a static load similar to the one used by Sandia during testing (at 3 locations on the blade). This work presented opportunity to reduce weight without loss in stiffness or strength. The study was based on the following independent evaluations:

- 1) Replace 20% of ELT5500 material system # 6 (carbon and glass system) with foam and
- 2) Replace 15% of the DBM1708 material system # 1 with foam. The volume of the blade remained unchanged in order not to alter the aerodynamic performance.

Figure 39 shows the load displacement from three locations on the blade compared to test for ELT5500 that includes 20% foam. The weight in this case was reduced by 8.7% as it decreased from 109.4 kg to 100.4 kg with minimal loss in performance as compared to original design of the blade. The original layup and properties of ELT5500 material system were used; only the ply thickness of ELT5500 was scaled down to reflect a 20% reduction in the volume of ELT5500. Test results presented in **Figure 39** pertain to the test under static loading of the blade with the original design performed at Sandia National Laboratories. The foam inserts in ELT5500 were used by the analytical simulation. The performance with reduced weight is comparable to that of the original

Figure 39. Load displacement relationship comparing blade response under static load from test with analysis results. 20% of ELT5500 material was replaced with foam reducing weight from 112.7 kg to 103.7 kg

Figure 40. Load displacement relationship comparing blade response under static load from test with analysis results. 15% of DBM1708 was replaced with foam reducing weight from 112.7 kg to 100.2 kg

design, especially from the aspect of not affecting the overall stiffness of the blade or ultimate load as the ELT5500 material is mainly used in the root area.

Figure 40 shows the load displacement from three locations on the blade from test compared to analysis when 15% of DBM1708 material is replaced with foam. The weight in this case was reduced by 12.5% as it decreased from 109.4 kg to 96.9 kg with no loss in performance as compared to original design of the blade. Using more than 15% foam could affect the D&DT of the blade by reducing its ultimate load as compared to that of the original design. One other concern for this case is the reduction in stiffness as compared to that of original design (**Figure 40**). This was expected as the stiffness of the foam was lower than that of the DBM1708 material. The new design is more flexible than the original one. This can impact the frequency and buckling resistance of the blade and require further investigation. Further studies need to be carried out to determine what combination of ply angles can maintain the same original stiffness. Note that for this case study; one material ply property was modified. The shear strength of DBM1708 material was increased by 20% which can be obtained from commercially available enhanced resin properties. Other design variables should be considered in future work, especially those dealing with manufacturing of the composite such as ply thickness and ply orientation.

6.6 Conclusions and Recommendation for Future Work

An advanced methodology for assessing the reliability of wind blade composite structures was demonstrated. The method is a judicious combination of composite micro and macro mechanics, finite element, durability and damage tolerance, robust design and probabilistic methods. The following can be concluded from the present study:

- 1) Multi-scale progressive failure analysis identified conditions that produced damage initiation and growth including delamination for wind blade under static loading. Simulation results were in very good agreement with data from test.
- 2) Weight reduction of about 10% was obtained with some changes in the representation of few key materials in the blade.
- 3) Computational simulation validated with some testing can yield weight reduction in the weight of the blade as long as the benefit is assessed for in-service fatigue loading. This will be part of future work.
- 4) Information obtained from the probabilistic sensitivity analysis can be used as an effective guide during a test program by identifying influential variables on the design of the composite blade.
- 5) Effect of manufacturing defects on blade D&DT must be evaluated in future work. As-is versus as-built and as-designed could produce significant scatter in the blade response.
- 6) Finally, it should of course be noted that ultimately, wind turbines are evaluated based on overall cost of energy. Thus, the addition of more expensive material such as carbon and higher-grade resins result in an increase in blade cost. However, for current utility-scale machines, blades are responsible for less than 20% of overall system cost. This number decreases as turbine size increases, as well as for offshore turbines. Thus lower blade

weights could produce overall cost savings by reducing the size of supporting turbine components. Additionally, for very large turbines, blade weight will be a limiting design factor and thus reduction in blade weight will be a necessity.

6.7 References

- 1) GENOA durability and damage tolerance, life and reliability prediction software, Alpha STAR Corp., Long Beach, CA 80804, www.ascgenoa.com, 2011.
- 2) M. Garg, G. Abumeri and D. Huang, “*Predicting Failure Design Envelope for Composite Material System Using Finite Element and Progressive Failure Analysis Approach*”, SAMPE 2008.
- 3) F. Abdi, Z. Qian, and M. Lee, “*The Premature Failure of 3D Woven Composites*”, ACMA Composites 2005, Columbus, Ohio, September 28-30, 2005.
- 4) G. Abumeri, F. Abdi, M. Baker, M. Triplet, and J. Griffin, “*Reliability Based Design of Composite Over-Wrapped Tanks*”, SAE World Congress, 2007.
- 5) D. Berry, Blade System Design Studies Phase II: Final Project Report. Sandia Report SAND2008-4648, July 2008.
- 6) D. Samborsky, T. Wilson, P. Agastra, and J. Mandell, “*Delamination at Thick Ply Drops in Carbon and Glass Fiber Laminates under Fatigue Loading*,” ASME Journal of Solar Energy Engineering, Vol.130, No.3, pp.1-22, 2008.
- 7) G. Abumeri, J. Paquette, F. Abdi, “*Durability and Reliability of Wind Turbine Composite Blades Using Robust Design Approach*”, AIAA-SDM 2011 Conference, Denver, Colorado

7. Durability of Tapered Composite Laminates under Static and Fatigue Loading ^[13]

Wind turbine blades are low-cost composite structures that are subjected to highly demanding, and often unexpected, environmental dynamic loads during their operational life which can lead to catastrophic failure. Wind turbines are subjected to high numbers of cyclic fluctuations due to wind intensity in various directions, therefore, resulting in severe strain on wind turbine blades if the wind intensity is high; which can ultimately lead to failure. Wind turbine failure can have detrimental impacts in the forms of safety, downtime, and public exposure. Mechanical components, such as structural parts/housing, are estimated to account for 4% of wind turbine failures. Rotor blades are estimated to account for 7% of wind turbine failures. One aspect to account for the relatively high percentage of rotor blade failures is manufacturing defects. One such defects is delamination of the layered composite, which results in a severe loss of its structural integrity. An interesting fact is that the fracture process in layered composite materials usually initiates, and propagates, while under low loading conditions. This differentiates composite materials from metallic materials, which raises the question of whether or not traditional stress/strain analysis is sufficient for evaluating the failure of composite materials. Many theories for mechanics of composite materials exist, therefore, there are also many tools available to evaluate the failure mechanisms of fiber reinforced layered composite materials.

Tapered laminated structures, as are found in some areas of wind turbine blades, are formed by dropping off some of the plies at discrete positions over the laminate. Structural details like this and others have received much attention from researchers because of their structural tailoring capabilities, damage tolerance, and their potential for creating significant weight savings in engineering applications. The inherent weakness of this construction is the presence of material and geometric discontinuities at the ply drop region that induces premature interlaminar failure at interfaces between dropped and continuous plies.

A review of recent developments in the analysis of tapered laminated composite structures with an emphasis on interlaminar stress analysis, delamination analysis and crack growth analysis applied to a blade structure (Figure 41) is presented in this paper. A 2-ply drop-off as shown in Figure 41, is illustrated In Figure 42. The gage is 101.6 mm long and the drop off zone is 7 mm wide.

Figure 41. Simulated blade structure with material thickness transition [1]

Figure 42. Layout of a 2-ply drop-off specimen [1]

7.1 MATERIAL CALIBRATION AND VERIFICATION OF CONSTITUENT PROPERTIES

As a first step in simulating the behavior of laminated composites with complex geometric features, the fiber and matrix mechanical properties were calibrated using test data available from references [5, 6]. The referenced data pertain to lamina and laminate properties for glass or carbon based composite material systems. The calibration process is essential for determining root cause problem for composite damage and failure. Effective properties, calculated using the technical approach described in the previous section, are listed in **Table 14** for glass-epoxy material system. Note that the test data available in the reference were provided for [0/90] laminate. The in-situ fiber and matrix properties were reverse engineered as the [0/90] laminate properties were reproduced.

Table 14. Calibrated glass epoxy with fiber content of 39% and void content of 2%

Material: NB307-D1 7781 497A E-glass with Epoxy

Property	Unit	E-glass Calibrated	Epoxy Calibrated	Lamina Calibrated	Laminate [0/90] Reference [5, 6]
E11	[GPa]	62.27	4.95	19.19	19.2
E22	[GPa]	62.27	---	19.19	19.2
E33	[GPa]	---	---	11.76	---
ν_{12}	[-]	0.22	0.215	0.13	0.13
ν_{23}	[-]	0.22	---	0.26	---
ν_{13}	[-]	--	---	0.26	---
G12	[GPa]	9.4	2.037	3.95	3.95
G23	[GPa]	9.4	---	3.43	---
G13	[GPa]	---	---	3.43	---
Tensile Strength (11)	[MPa]	1408	---	337.01	337
Compressive Strength (11)	[MPa]	1408	---	496.89	497
Tensile Strength (22)	[MPa]	---	---	337.01	337
Compressive Strength (22)	[MPa]	---	---	496.89	497
Shear Strength (12)	[MPa]	---	---	115.1	115
Matrix Tensile Strength	[MPa]	---	80	---	---
Matrix compressive Strength	[MPa]	---	357	---	---
Matrix Shear Strength	[MPa]	---	179	---	---

Table 15a shows the characterization of Carbon epoxy (NCT307-D1-34-600) for [0]10 carbon/epoxy prepreg with 47% fiber and 2% Voids. **Table 15b** shows the characterization for carbon epoxy (NCT307-D1-34-600) for [0]10 carbon/epoxy prepreg laminate with 53% fiber and

2% voids. For each material, the in-situ material properties were derived using the approach described earlier in the paper.

Table 15. Comparative evaluation of analysis simulation with GENOA and test mechanical properties for various laminates without ply drops

NCT307-D1-E300 E-glass with Epoxy	Longitudinal Direction								Shear	Transverse Direction				
	Elastic Constants				Tension		Compression			Tension		Compression		
	E _L	E _T	ν _{LT}	G _{LT}	UTS _L	ε _{max}	UCS _L	ε _{max}		τ ₁₁	UTS _T	ε _U	UCS _T	ε _U
	GPa	GPa		GPa	MPa	%	MPa	%		MPa	MPa	%	MPa	%
Test	35.5	8.33	0.33	4.12	1005	2.83	788	2.22	112	51.2	0.74	168	2.02	
GENOA	35.5	8.33	0.33	4.12	1001.21	2.82	791.86	2.23	112.03	51.05	0.61	168.58	2.02	

a) E-Glass with Epoxy (NCT307-D1-E300) Ply property for [0]10 E-glass/epoxy prepreg with 47% fiber and 2% voids

NCT307-D1-34-600 Carbon with Epoxy	Longitudinal Direction								Shear	Transverse Direction				
	Elastic Constants				Tension		Compression			Tension		Compression		
	E _L	E _T	ν _{LT}	G _{LT}	UTS _L	ε _{max}	UCS _L	ε _{max}		τ _{TU}	UTS _T	ε _U	UCS _T	ε _U
	GPa	GPa		GPa	MPa	%	MPa	%		MPa	MPa	%	MPa	%
Test	123	8.2	0.31	4.71	1979	1.32	1000	0.9	103	59.9	0.76	223	2.72	
GENOA	123	8.2	0.31	4.709	1968.32	1.6	1009.2	0.82	103.56	59.91	0.73	222.93	2.72	

b) Carbon epoxy (NCT307-D1-34-600) Ply property for [0]10 carbon/epoxy prepreg with 53% fiber and 2% voids

7.2 RESULTS

Test Specimen [5 & 6] and Finite Element Modeling

Figure 43. Schematic of test specimen with typical ply drops at surface of 0 deg plies and finite element model generated for use in progressive failure analysis

The complex coupon with ply drops employs an unsymmetrical geometry shown in **Figure 43**. This test method required significant test development to arrive at a lay-up and dimensions which would have minimal bending, be compatible with testing machine (250 kN) capacity and grip capacity, while representing blade materials and structure of current interest (**Figure 43**). The lay-up chosen allows convenient infusion with a variety of resins of interest for blades, and features failure modes including delamination at the ply drops, damage in the $\pm 45^\circ$ surface layers (which represent blade skin materials) and load redistribution between the surface skins and primary structural 0° plies as damage develops and extends. The same figure shows the finite element model used in the progressive failure analysis to determine load magnitude that produce damage

initiation (matrix cracking and or delamination), damage progression, fracture initiation, and fracture propagation to failure.

Static Simulation Results

The finite elements models of flat specimen and ply drop off specimen are shown in **Figure 44a-b**. The FEM's contains 24,204 elements and 30,563 nodes. The applied loads and boundary conditions (**Figure 44b**) simulate a simple longitudinal tensile test.

Figure 44a. Finite element model used in laminate $[\pm 45/0_2/0_2/\pm 45]$ progressive failure analysis (mixed layup without ply drop)

Figure 44b. Shell finite element model for laminates with ply drops

Table 16. Static stiffness and strength (tension/compression) from simulation compared to test [5] without ply drop- $[\pm 45/0_2/\pm 45]$ - Carbon epoxy 0° plies and E-glass epoxy 45° plies

Laminate without ply drop Lay-up: $[\pm 45/0_2/\pm 45]$	Tension Modulus	Tension Strength	Tension Strain	Compressive Strength*	Compressive Strain
	GPa	MPa	%	MPa	%
Test	101	1496	1.4	1070*	1.04
GENOA	106.62	1511.5	1.426	780.19	1.01
Difference from test	-5.56%	-1.04%	-1.86%	27.09%	2.88%

* Test anomaly (reported test value is incorrect since the 0° unidirectional strength is 1000 MPa); With mixed layups, the laminate strength must be lower than that of the unidirectional lamina strength; GENOA's predictions are consistent with the physics.

Static Tests Using Building Block Validation Strategy

D&DT of flat laminate coupons (without ply drops) - PFA is used to predict failure loads and modes for flat coupons made from two material systems. The 0° plies are made from carbon fibers and epoxy matrix while the $\pm 45^\circ$ plies are made from E-glass epoxy 2-D weave system. The finite element model used in this evaluation is shown in **Figure 44a**. **Table 16** lists the

stiffness (modulus) and strength prediction of the $[\pm 45/0_8/\pm 45]$ laminates under tensile and compressive loading conditions. The prediction results matched closely those of the test (difference ranged from 2.88% to -5.56%). The analysis was able to detect a test anomaly for the compression case as explained in [Table 17](#). The strength reported for the laminate with mixed layups under compression is higher than that of the 0° ply. This is inconsistent with the physical behavior of composites. As layups other than 0° are introduced in the laminate, the laminate strength is reduced to values lower than that of the 0° ply consistent with the physics, as reported by the PFA predictions. Evaluating coupon behavior without ply drop is essential to establish a baseline. It will allow the assessment of loss in strength as the ply drops are introduced.

D&DT of Specimens with Ply drops (complex laminate configuration) Under Tensile and Compressive Load

With successful simulation of laminates for flat coupons, specimen with complex geometric features such as ply drops are evaluated under incremental static load. Ply drops effect at surface of 0° plies (on top and bottom surfaces of the structure) were evaluated by progressive failure analysis for both tension and compression static loading. The finite element model generated for PFA analysis and depicting the section with the ply drops is presented in [Figure 44b](#).

Table 17. Static stiffness and strength (tension/compression) from simulation compared to test [3] with ply drop—Carbon epoxy 0 deg plies and E-glass epoxy 45 deg plies

Laminate with ply drop	Compressive Strength (MPa)			Compressive Strain (%)		
	Test	GENOA	% Error	Test	GENOA	% Error
$[\pm 45/0_2^*/0_9/0_2^*/\pm 45]$	617	588.46	-4.63	0.64	0.57	-10.94
Laminate with ply drop	Tensile Strength (MPa)			Tensile Strain (%)		
	Test	GENOA	% Error	Test	GENOA	% Error
$[\pm 45/0_2^*/0_9/0_2^*/\pm 45]$	827	852.77	3.12	0.85	0.85	0

* *Dropped plies*

The ply drop region had to be very carefully meshed to ensure converged FEA solution. The 45 deg plies are made from the 2-D weave E-glass epoxy material while the 0° plies are made from the carbon/epoxy material. Figure 7 showed the schematic of test specimen with typical ply drops. [Figures 45a](#) and [45b](#) show the damage evolution process and associated failure mechanisms of ply drops complex laminate configuration under tensile and compressive load. Compression and tension $[\pm 45/0_2/0_9/0_2/\pm 45]$ laminate strain and strength results were obtained from the durability evaluation by PFA strength based approach. The GENOA predictions ranged from -10.94% to 3.12% as compared to test.

Figure 45a. Damage evolution process from PFA of specimen with ply drop under static tensile loading. (Red color identifies damaged elements, damage and failure modes: longitudinal tensile, compression and in-plane shear)

Figure 45b. Damage evolution process from PFA of specimen with ply drop under static compressive loading. (Red color identifies damaged elements, damage and failure modes: longitudinal compression and in-plane shear)

Fatigue Tests Using Building Block Validation Strategy

In addition to determining failure modes, location, and loads under static loading, we evaluated the fatigue life of these laminates under service loading. Wind turbine blades must be designed for adequate handling of static loads as well as very high numbers of fatigue cycles. Fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic (repetitive) loading. As a first step in the prediction process, it is important to characterize the fatigue properties of the constituents of the composite. Similar to static application, we used reverse engineering principles to derive fatigue properties of the epoxy resin that can be used in simulating fatigue behavior of composite laminates.

Figure 46. Epoxy resin S-N curve obtained by reverse engineering for use as input to PFA fatigue analysis

Figure 47. Fatigue life prediction compared to test for a $[\pm 45/0_4]$ s laminate without ply drop (carbon epoxy in 0 deg plies and e-glass epoxy for 45 deg plies and 0.1 stress ratio)

Figure 46 shows the room temperature derived fatigue properties for the epoxy resin. It is assumed that the fiber undergoes little degradation while the resin experiences significant degradation under fatigue loading. The fatigue life of the laminated coupon was then evaluated (without ply drop) subjected to a tensile loading under a stress ratio of 0.1. The stress ratio is the ratio of minimum stress to maximum stress applied during cycling. The prediction results for various applied stress levels are compared to those from tests [5] in **Figure 47**. As illustrated in the same figure, the predictions are in remarkable agreement with the reported test results. This indicates that the reverse engineered properties can be used with confidence in fatigue evaluation of any structure where the same material constituents are used including those with tapered laminates.

Figure 48. Delamination Crack Growth from pore ahead of Double Ply Drop, Carbon 0° Plies

VCCT/PFA of Specimens with Ply drops (complex laminate configuration) Under Compressive Loading

For this study, GENOA VCCT/PFA was used to simulate crack initiation and propagation, for the same ply drop composite coupon previously discussed, subject to static compressive loading. Of interest was the compressive strength and compressive strain determined through the use of VCCT/PFA compared to both the previous PFA and experiment. To assure accurate results it was paramount that the proper crack initiation point and propagation path were specified.

Pictured in **Figure 48** from [5] is the delamination pattern observed during a compression fatigue test of a similar ply drop composite coupon as the one used in this study.

Pictured in **Figure 49** is the ply drop region of the finite element model used for the VCCT/PFA compression test simulation. Using the information gained from the previous PFA in **Figure 45b**, and that pictured in **Figure 48**, the proper crack initiation point and propagation path were chosen

accordingly as can be seen in **Figure 49**. The fracture toughness values used in the VCCT simulations were: $G_{Ic} = 364 \text{ J/m}^2$ and $G_{2c} = 1829 \text{ J/m}^2$. Both values were obtained from reference [5].

The numerical results of the VCCT / PFA compression simulation are listed in **Table 18** and compared to the experimental results obtained in [5]. Pictured in **Figure 50** is the damage evolution and crack propagation process at various stages throughout the VCCT / PFA compression simulation. Lastly, **Figures 51** and **52** display load versus deflection and load versus crack length respectively between the previous PFA and the VCCT/PFA. Also displayed in these figures is the maximum load achieved experimentally.

Figure 49. Crack propagation path for compression test simulation using GENOA VCCT/PFA

Table 18. Static Stiffness and Strength (compression) from VCCT/PFA simulation compared to test from [5] with ply drop - Carbon epoxy 0 deg plies and E-glass epoxy 45° plies.

Laminate with ply drop	Compressive Strength (MPa)			Compressive Strain (%)		
	Test	GENOA VCCT/PFA	% Error	Test	GENOA VCCT/PFA	% Error
[±45/0 ₂ /0 ₉ /0 ₂ /±45]	617	611.52	-0.89	0.64	0.60	-6.25

Figure 50. Crack and Damage evolution process from VCCT/PFA of specimen with ply drop under static compressive loading. (Red color identifies damaged elements, damage and failure modes: longitudinal compression and in-plane shear)

The results of the VCCT/PFA are in agreement with not only the experimental results, but also the PFA strength based approach. **Table 18** indicates less than 1% error for the compressive strength between the VCCT/PFA and experiment, and an associated 6.25% error for the

percentage compressive strain. **Figures 51 and 52** also indicate closer results to the actual experiment than the previous PFA. In support of [7, 8] **Figure 52** illustrates that crack initiation and propagation occurred under low loading conditions. These results combined prove GENOA VCCT/PFA is a reliable and useful tool for predicting the behavior of composite structures comprised of ply drop features subject to compressive loads. GENOA VCCT/PFA and DCZM/PFA can also be used to predict the behavior of composite structures comprised of ply drop features subject to tensile loads. The results of this work will be presented in future publication.

Figure 51. Comparison of PFA and VCCT/PFA Load vs. Displacement

Figure 52. Comparison of Crack Growth due to Increasing Load

7.3 Conclusions

The effective use of computational simulation to assess the performance of wind turbine blade design concepts necessitates its validation, as demonstrated in the paper, by comparing its prediction results with test data. In this case, ply drops, a structural detail have been analyzed and compared to available test data. This process establishes confidence in the analytical tool to enable its use for enhancing the design for improved D&DT and fatigue life and reduce risk. The authors validated the progressive failure analysis approach for geometric and material features that are commonly used in wind blades under static and fatigue loading. The concept can be extended to achieve robust design of turbine blades that is tolerant to small changes in geometric parameters and material properties. This will be evaluated in a future work by coupling the analysis method with probabilistic and design optimization capabilities.

7.4 References

- 1) P. Agastra, D.D. Samborsky, J.F. Mandell, “*Fatigue Resistance of Fiberglass Laminates at Thick Material Transitions*”, 50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, May 2009, Palm Springs, California.
- 2) F Abdi, K. Kedward, “*Simplified Analytical Procedure for Prediction of Fracture Damage in Composite Structures*”, SBIR Phase II Final Report, Contract No. N00014-02-M-0144”, Alpha STAR Technical Report to Navy, July 5, 2006.
- 3) D. Huang, F. Abdi, A. Mossallam, “*Comparison of Failure Mechanisms in Composite Structure*”, SAMPE 2003 Conference Paper.
- 4) GENOA User Manual, <http://www.ascgenoa.com>.

- 5) D. Samborsky, T. Wilson, P. Agastra, J. Mandell, “*Delamination at Thick Ply Drops in Carbon and Glass Fiber Laminates under Fatigue Loading*”, ASME Journal of Solar Energy Engineering, Vol.130, No.3, pp.1-22, 2008.
- 6) T. Wilson, “*Modeling of In-Plane and Interlaminar Fatigue Behavior of Glass and Carbon Fiber Composite Materials*”. Master Thesis, Montana State University, Bozeman, Montana, January 2007.
- 7) R. Jones, “*Mechanics of composite materials*” (2nd ed.), Taylor and Francis (1998).
- 8) J.N. Reddy, “*Mechanics of laminated composite plates and shells*” (2nd ed.), CRC Press (2004).
- 9) D. Xie, SB Biggers, Jr., “*Progressive crack growth analysis using interface element based on the virtual crack closure technique*”, *Finite Elements in Analysis and Design*, 42(2006): 977-984.
- 10) B Farahmand, C Saff, D. Xie, F. Abdi, “*Estimation of fatigue and fracture allowables for metallic materials under cyclic loading*”, 48h AIAA/ ASME/ ASCE/ AHS/ ASC Structures, Structural Dynamics & Materials Conference, AIAA-2007-2381. Honolulu, Hawaii. April 23-26, 2007.
- 11) D. Xie, A. M. Wass, "Discrete Cohesive Zone Model for Mixed-Mode Fracture Using Finite Element Analysis", *Engineering Fracture Mechanics*, Vol. 73, No. 13, September 2006, pp. 1783-1796.
- 12) M. Garg, G. H. Abumeri, D. Huang, "Validation of Class of Applications Using Progressive Failure and Discrete Cohesive Zone Model for Line and Surface Cracks", AlphaSTAR Corporation, Suite 410, Long Beach, California
- 13) F. Abdi, J. Paquette, G. Crans, L. Minnetyan, P. Marzocca, “*Durability of Tapered Composite Laminates under Static and Fatigue Loading*”, AIAA-SDM 2011 Conference, Denver, Colorado.

8. Improving Wind Blade Structural Performance with the Use of Resin Enriched with Nanoparticles^[23]

Laminated fiber reinforced polymer (FRP) composites have found wide use for a range of structural and functional applications in industries such as aerospace, automobile, marine, and infrastructure including wind blade applications. FRP's are high performance materials, having high stiffness and strength-to-weight ratios compared to metals. FRP's exhibit high corrosion resistance, significant reduction in maintenance costs and, most importantly, expand a designer's horizons to design a material to meet the limit load requirements. The fibers in FRP composites reinforce mostly the in-plane properties. The weaker matrix interface dominates the out-of-plane properties, such as delamination resistance. Delamination along ply interfaces (interlaminar shear strength) due to fiber/matrix debonding is one of the major failure modes in laminated FRP's when subjected to transverse and compressive loading. Mandell et al. [1] concluded that delamination between plies is the root cause of many failures of composite materials structures such as wind turbine blades. Mandell also elaborated that design methodologies to prevent such failures have not been widely available for the materials and processes used in blades. Use of reinforcement in the matrix to enhance resistance to delamination is a benefit that would be desired for the wind blade industry.

The work described here assesses benefits resulting from the use of nanoparticles in wind blade applications under static loading. Durability and damage tolerance results from the use of nano material is evaluated analytically and compared to results from a baseline static test of a neat blade (without nano). Benefits to fatigue life are not addressed in the work presented in this paper. Any insertion of nano particles in wind blade structure must take into account the manufacturability and cost aspects. For ease of applications, the analysis assumed that strips of thin unidirectional glass composites are applied to the blade after the blade is manufactured.

Reinforcement of the matrix of laminated composites via stitching, weaving, braiding fibers or addition of toughening particles are widely used approaches to improve delamination resistance. These approaches, however, can degrade other FRP properties. For example, using toughening particles with lower stiffness than the matrix can reduce the over-all stiffness of a laminate. Improving interlaminar shear strength (ILSS) by reinforcing the laminate interface with nanoparticles such as double-walled [2] or multi-walled [3] carbon nanotubes (CNT) and nano-clay [4] have recently been considered [5]. The nano-particles used had high aspect ratios, high stiffnesses/strengths and were nano-sized. A low-weight (<15 weight %) percent of nano-particles in neat matrix can increase both the strength and stiffness of the matrix. For example, Yeh et al. [6], (2007) reported an increase of 64.6% in tensile strength and 64.8% in Young's modulus with only 2 wt. % addition of MWCNT's in phenolic matrix. Other experimentalists have reported similar improvements [7, 8]. Literature also indicates that the nano-particle related data has wide scatter: conducting experiments at the nano-scale is an extremely difficult and expensive process. To overcome this obstacle, researchers simulate the nano-particles using Molecular Dynamic (MD) simulation techniques.

Using carbon nanotubes, the ILSS of the laminated composites is usually improved by either dispersing the nano-particles in the matrix [9], or by growing CNT's around the conventional fibers [3]. Researchers have reported that adding less than 5 weight % of carbon nanotubes in the matrix material or growing carbon nanotubes around the conventional fibers can improve the ILSS for advance hybrid multi-scale composites by approximately 45% [9] and 69% [3],

respectively. Growing CNT's on conventional fibers allows larger weight percentages than mixing the CNT's in the matrix for using Vacuum Assisted Resin Transfer Molding (VARTM) manufacturing. The VARTM approach increases the viscosity during the laminate fabrication, which in turn adversely affect mixing of the enhanced matrix containing high weight percent nanotubes. It is easier for the matrix to exhibit capillary behavior in between the closely packed nanotubes, allowing a higher weight percentage of CNT's. Both approaches are affected because of the bonding between the carbon nanotubes (or nano-particles) and the matrix. Functionalization can help increase the bond (interfacial shear strength [ISS]) between the CNT (or nano-particles) and the matrix. However, using carbon nanotubes for wind blade applications is cost prohibitive. As a result, the authors only considered evaluating the blade performance assuming the matrix of thin glass composite is infused with silica nanoparticles. Then the enhanced thin glass composite is applied on the outer surfaces of the blade.

Next, the general methodology used in enriching the matrix with nano material is described. It is followed by a description of the multi-scale progressive failure analysis approach, which will be used to assess the blade D&DT with and without nano material. Then the blade geometry, loading, and boundary conditions, and materials are described. The results are then discussed followed by concluding remarks and recommendation for future research.

8.1 Wind Blade Description

The blade considered was designed and built through a research partnership between TPI Composites and Sandia National Laboratories. Testing of the blade was completed by Sandia and the National Renewable Energy Laboratory. **Figure 53** shows a finite element model of the wind blade [19]. The model was used by multi-scale PFA to simulate analytically the static test. The blade was 9-meters long. It was scaled down from the initial 44 meter planform from the first phase of Sandia's Blade System Design Studies project [19]. The different colors in **Figure 53** indicate regions with different materials. These regions are referred to as ply schedules correlating distinct physical regions in the model with specific material or number of materials, layup

information, thickness and other physical properties. The blade was modeled with 22774 shell elements and 67608 nodes.

Figure 54 shows the loading profile at three cross-sections of the blade. The loads were applied at 3, 4.8, and 6.6 meters from the root to approximate the loading of the ultimate load test. **Table 19** lists the various materials used in the construction of the blade. **Table 20** lists the materials used in different ply schedules of the blade. More details on blade design can be found in reference [19]. The list of the blade materials was supplied by Sandia. **Table 21** lists ply mechanical properties for one material of the blade (ELT5500 glass epoxy composite). Properties for other materials can be found in [19-20].

Table 19. List of materials used in blade model

#	Material
1	Stitched Double Bias Glass (DBM1708)
2	Balsa
3	Steel
4	Gelcoat
5	Chopped Glass Mat (0.75oz)
6	Uni Glass (ELT5500)
7	Woven Double Bias Glass (6 oz)
8	Rod Filler (smeared stud/glass)
9	Stitched Double Bias Glass (DBM1208)
10	Carbon/Glass Triax
11*	Chopped Glass Mat (0.75oz) x10
12*	Stitched Double Bias Glass (DBM1708) x10
13*	Balsa x10

* Material with 10x stiffness and density, x 0.1 ply thickness

Table 20. Materials and ply schedule correlation

Ply Schedule	Material #	Ply Schedule	Material #
1	3	13	4,5,1,2,1
2	4,5,1,6,7,6,6,8,6,9,6,1	14	4,5,1,6,7,6,1
3	4,5,1,6,7,6,6,8,6,9,6,1	15	4,5,1,6,7,6,1
4	4,5,1,6,7,6,6,9,6,1	16	4,5,1,2,1,1,1
5	4,5,1,6,7,6,6,9,6,1	17	4,5,1
6	4,5,1,10,7,1,0,6,9,6,1	18	4,5,1,10,7,1,0,1
7	4,5,1,6,7,6,6,1	19	4,5,1,10,1
8	4,5,1,6,7,6,6,1	20	4,5,1
9	4,5,1,10,7,1,0,6,1	21**	4,11,12,13,12
10	4,5,1,6,7,6,1	22	4,5,1
11	4,5,1,6,7,6,1	23	1,2,1
12	4,5,1,10,7,1,0,1		

** Used at leading edge to avoid shell radius/thickness violation

Figure 55. Progressive failure analysis and test validation of Sandia's 9 meter blade under static loading (neat material)

Table 21. Lamina properties used for ELT5500 (unidirectional glass epoxy material)

Property	Symbol	Value	Measurement
LONGITUDINAL MODULUS	E11	4.180E+04	N/(mm ²)
TRANSVERSE MODULUS	E12	1.403E+04	N/(mm ²)
TRANSVERSE MODULUS	E13	1.416E+04	N/(mm ²)
INPLANE SHEAR MODULUS	G12	2.630E+03	N/(mm ²)
TRANSVERSE SHEAR MODULUS	G13	2.323E+03	N/(mm ²)
SHEAR MODULUS	G11	2.630E+03	N/(mm ²)
POISSON'S RATIO	ν12	2.806E-01	
POISSON'S RATIO	ν13	4.534E-01	
POISSON'S RATIO	ν23	2.759E-01	
LONGITUDINAL TENSILE STRENGTH	S11T	1.125E+03	N/(mm ²)
LONGITUDINAL COMP. STRENGTH	S11C	7.492E+02	N/(mm ²)
TRANSVERSE TENSILE STRENGTH	S12T	6.083E+01	N/(mm ²)
TRANSVERSE COMP. STRENGTH	S12C	2.041E+02	N/(mm ²)
INPLANE SHEAR STRENGTH	S12S	3.020E+01	N/(mm ²)
NORMAL TENSILE STRENGTH	S13T	6.083E+01	N/(mm ²)
NORMAL COMP. STRENGTH	S13C	2.041E+02	N/(mm ²)

8.2 Wind Blade D&DT Results with and without Nanoparticles Test and Analysis Results with Neat Material

Sandia National Lab (SNL) tested the 9-meter using neat material (without nanoparticles). Multi-scale PFA was used to simulate the test and reproduce damage modes observed in the test. During testing, blade bending loads were applied at three blade stations. These loads were increased until the failure of the test article. The analytical predictions were validated not only for ultimate failure load but also for load deflection results as well. PFA predicted damage initiation and propagation, fracture initiation and propagation, and the final residual strength in the blade.

Compared with test results, analytical simulation gives a good prediction as well as the damage progression sequence and structural response characteristics during different degradation stages. **Figure 55** shows the damage in the blade at ultimate load. The initial damage started near the root of blade at load of 8.7 KN due to delamination in composite layers. When the load applied reached the ultimate peak value of 48.29 KN, damage propagated to most zones of the blade (**Figure 55**). At ultimate, the damage modes were longitudinal and transverse tensile failure, longitudinal and transverse compressive failure, shear failure and delamination. The final damage of the blade from test is shown in **Figure 55b**. Load-displacement from the test and the analysis for neat material are shown in **Figure 56**.

Figure 56. Load-displacement from test and analysis for 9 meter blade under static loading (neat material)

Insertion of Silica Nanoparticles in Matrix of Glass Composite

The benefits from the use of silica nanoparticles in matrix of glass composites are evaluated using in-situ effective lamina properties inclusive of enhancement in the matrix due to the addition of these particles. **Table 22** shows the derived silica nanoparticles (spherical in shape with diameter of 20 nano meter). The properties for the silica nanoparticles were calibrated to obtain changes in the unidirectional glass lamina properties similar to those obtained by Uddin and Sun [21]. The derived properties for the silica were infused in the matrix of unidirectional composite (about 50% fiber content and 2% void). The lamina properties for the glass composite were obtained from reference [22]. **Table 23** shows the improvement in glass epoxy composite properties with the use of silica nanoparticles. Significant improvements in the lamina shear and compression properties were obtained analytically as a result of infusing the matrix with silica nanoparticles. The improvements were derived using the trends reported by Uddin and Sun [21]. The enhanced unidirectional lamina with thickness of 0.25 mm is applied to the exterior surfaces of the blade to investigate potential structural benefits.

Table 22. Reverse engineered properties of silica nanoparticles infused in matrix of unidirectional glass epoxy material

Particle Material Properties	Symbol	Effective	Units
Density	ρ_p	1.22E-09	[tonne/m ³]
Young's Modulus	E_p	450	[GPa]
Poisson's Ratio	μ_p	0.19	[-]
Tension Strength	SpT	5.30E+04	[MPa]
Compression Strength	SpC	1.03E+05	[MPa]

Table 23. Enhancement of unidirectional glass epoxy material properties with the use of 15%wt silica nanoparticles infused in matrix

Material		EGLASS/LY556		
Property	Units	Neat [22]	with Silica Nanoparticles 15% wt	% Enhancement
E_{11}	[GPa]	45.6	45.6	0.00
E_{22}	[GPa]	16.2	22.8279	40.91
E_{33}	[GPa]	-	16.19	-
G_{12}	[GPa]	5.83	8.4535	45.00
G_{13}	[GPa]	-	8.4535	-
G_{23}	[GPa]	-	5.1968	-
μ_{12}	[-]	0.278	0.278	0.00
μ_{13}	[-]	-	0.278	-
μ_{23}	[-]	-	0.4002	-
S_{11T}	[MPa]	1280	1420.8	11.00
S_{11C}	[MPa]	800	1131.2	41.40
S_{22T}	[MPa]	40	52.8	32.00
S_{22C}	[MPa]	145	145	0.00
S_{33T}	[MPa]	-	52.8	-
S_{33C}	[MPa]	-	145	-
S_{12S}	[MPa]	73	105.85	45.00
S_{13S}	[MPa]	-	105.85	-
S_{23S}	[MPa]	-	77.9955	-

Glass composite layer with 15% wt nanoparticles is applied to the exterior surfaces of the blade as shown in **Figure 57**. The layer applied is coating like with a thickness of 0.25 mm. The glass composite is E-glass/LY556 with fiber content of 50% and 2% void. The mechanical properties used for the thin glass composite with nanoparticles are listed in **Table 22**. Benefits from the use of nanoparticles are discussed next.

Figure 57. Application of thin glass composite with nanoparticles on exterior surfaces of ply schedule 10, 11, 12, 13, 14, 16, 17, 18, 19 and 20 (front and back skin of whole blade)

Figure 58. Load displacement from analysis from application of 3 saddle static load (with and without nanoparticles)

Figure 59. Percent of damaged elements obtained from multi-scale PFA in 9 meter wind blade at ultimate load of 53,070 N (0.25 mm layer glass composite with silica nanoparticles applied at surface of blade)

D&DT Blade Results with Glass Composite Infused With Silica Nanoparticles

Comprehensive D&DT evaluation of the blade under static loading is performed after applying thin glass material with matrix infused with silica nanoparticles. The results obtained for the blade with the configuration identified in Figure 8 indicate that the benefits are greater when the whole blade is covered with unidirectional glass composite with the matrix infused with silica nanoparticles compared to restricting it to a small region of the blade. The overall improvement of the blade ultimate load was about 9.2% as compared to the baseline static with neat material. As illustrated in the [Figure 58](#), applying a 0.25 mm of thin unidirectional glass composite with silica nanoparticles on the skin of the blade increased the stiffness of the blade, especially for station SP3, which is desirable outcome as it helps reducing damage due to bending.

Figure 58 compares the load-displacement for the blade test with neat material to those obtained from analysis with multi-scale PFA with and without silica nanoparticles. **Figure 59** shows the overall percent of damaged elements at ultimate load obtained from analysis for the blade with nanoparticles in matrix of thin glass composite coating the blade surfaces.

The use of nanoparticles not only resulted in increase of ultimate load of 9.2% but it also contributed to making the blade more damage tolerant. This is clear from the increase in percent of damaged elements at ultimate load. With the use of nanoparticles, the blade sustained more fiber tension and compression fiber failure before it fractured as compared to the case without nanoparticles. Another benefit obtained from the use of nanoparticles is the delay in the onset of delamination. For the blade with neat material, delamination initiated at 8,700 N while with nanoparticles in glass composite applied on the exterior surfaces of the blade, delamination initiation due to transverse normal shear stress initiated at 10,440 N. That is a delay of 1,740 N in the load that causes delamination. The technology evaluated in this paper can potentially reduce the weight and cost associated with wind blades as a result of improvement of D&DT performance with nanoparticles.

8.3 SUMMARY

The authors described and applied a novel computational simulation approach to assess benefits resulting from the use of silica nanoparticles in matrix of thin glass composite applied to the surfaces of wind blade. A summary of findings is listed here:

- 1) Modeling of complex materials such as nanoparticles in matrix of glass composite is eased with the use of multi-scale composite mechanics.
- 2) At the laminate level, enhancement in strength up to 45% is obtained with the use of silica nanoparticles.
- 3) Matrix infused with nanoparticles of glass composite coating like application on blade surfaces resulted in increase in the maximum load carrying capability of the blade by 9.2% and delay in the onset of delamination.
- 4) Benefits need to be verified with building block test and simulation approach by assessing structural performance of coupons, sub-elements, elements, and blade components with application of nanoparticles.
- 5) Potential benefits under fatigue loading need to be investigated through multi-scale progressive failure analysis and through building block test program.

8.4 REFERENCES

- 1) J. Mandell, D. Cairns, D. Samborsky, R. Morehead and D. Haugen, “*Prediction of Delamination in Wind Turbine Blade Structural Details*”, Montana State University, Bozeman, Montana (2003).
- 2) Gojney, F. H., Wichmann, M. H. G., Fiedler, B., Bauhofer, W., and Schulte, K., (2005). “*Influence of nano-modification on the mechanical and electrical properties of conventional fibre-reinforced composites*”, Composites: Part A, 36, 1525-1535.

- 3) Garcia, E. J., Wardle, B. L., Hart, J., and Yamamoto, N., (2008), “*Fabrication and multifunctional properties of a hybrid laminate with aligned carbon nanotubes grown In Situ*”. *Comp. Sci. and Tech.*, 68, 2034-2041.
- 4) Njuguna, J., Pielichowski, K., and Alcock, J. R., (2007), “*Epoxy-based fibre reinforced nanocomposites*”, *Adv. Eng. Mater.*, 9, 835-847.
- 5) Veedu, V. P., Cao, A., Li, X., Ma, K., Soldano, K., S., Ajayan, P. M., et al., (2006). “*Multifunctional composites using reinforced laminae with carbon-nanotube forests*”, *Nature Materials*, 5 (6), 457-462.
- 6) Yeh, M. K., Tai, N. H., and Lin, Y. J., (2007), “*Mechanical properties of phenolic-based nanocomposites reinforced by multi-walled carbon nanotubes and carbon fibers*”, *Composites, Part A* doi: 10.1016/j.compositesa.2007.07.0101 (Article in press).
- 7) Ganguli, S., Aglan, H., Dennig, P., and Irvin, G., (2006). *Effect of loading and surface modification of MWCNTs on the fracture behavior of epoxy nanocomposites*. *Journal of Reinforced Plastics and Composites*, 25, 175-188.
- 8) Qui, J., Zhang, C., Wang, B., and Liang, R., (2007), “*Carbon nanotubes integrated multifunctional multiscale composites*”. *Nanotechnology*, 18, 11.
- 9) Fan, Z., Santare, M. H., and Advani, S. G., (2007), “*Interlaminar shear strength of glass fiber reinforced epoxy composites enhanced with multi-walled carbon nanotubes*”, *Composites: Part A*, 39, 540-554.
- 10) Mori, T., and Tanaka, K., (1973). *Average stress in matrix and average elastic energy of materials with misfitting inclusions*. *Acta Metall.*, 21, 571-574.
- 11) Tandon, G. P. and Weng, G. J., (1984), “*The effect of aspect ratio of inclusions on the elastic properties of unidirectionally aligned composites*”, *Polymer Composites*, 5, 327-333.
- 12) Tucker, C. L., and Liang, E., (1999), “*Stiffness predictions for unidirectional short-fiber composites: review and evaluation*”, *Compos. Sci. Tech.*, 59, 655-671.
- 13) Eshelby, J. D., (1957) “*The determination of the elastic field of an ellipsoidal inclusion and related problems*”, *Proc Roy. Soc. A*, 241, 376-396.
- 14) M. Garg, F. Abdi, and S. McHugh, “*Analyzing Interlaminar Shear Strength of Multi-Scale Composites Via Combined Finite Element And Progressive Failure Analysis Approach*”. SAMPE 2008, Memphis Tennessee, September, 2008.
- 15) C. Chamis, “*Simplified Composite Micromechanics Equations for Hygral, Thermal and Mechanical Properties*”, NASA Technical Memorandum 83320, Thirty Eight Annual Conference of the Society of the Plastics Industry (SPI) Reinforced Plastics/Composites Institute Houston, Texas, February 7-11, 1983.
- 16) “*GENOA Durability and Damage Tolerance, Life and Reliability Prediction Software*”, www.ascgenoa.com, Alpha STAR Corp., Long Beach, CA, 2011.
- 17) M. Garg, G. Abumeri and D. Huang, “*Predicting Failure Design Envelope for Composite Material System Using Finite Element and Progressive Failure Analysis Approach*”, SAMPE 2008.

- 18) Huang, D., Abdi, F., and Mossallam, A., (2003), “*Comparison of Failure Mechanisms in Composite Structure*”, SAMPE Conference Paper.
- 19) D. Berry, “*Blade System Design Studies Phase II: Final Project Report*”. Sandia Report SAND2008-4648, July 2008.
- 20) D. Samborsky, T. Wilson, P. Agastra, and J. Mandell, “*Delamination at Thick Ply Drops in Carbon and Glass Fiber Laminates under Fatigue Loading*”, ASME Journal of Solar Energy Engineering, Vol.130, No.3, pp.1-22, 2008.
- 21) M. F. Uddin and C. T. Sun, “*Strength of unidirectional glass/epoxy composite with silica nanoparticle-enhanced matrix*”, Composites Science and Technology Journal Composites Science and Technology 68 (2008) 1637–1643.
- 22) Hinton, M.J., Kaddour, A.S. and Soden, P.D., (2004), “*Predictive capabilities of nineteen failure theories and design methodologies for polymer composite laminates. Part B: Comparison with Experiments. Failure Criteria in Fiber Reinforced Polymer Composites: The World-Wide Failure Exercise*”, Eds. Hilton, M.J., Kaddour, A.S., and Soden, P.D., Elsevier, Kidlington, Oxford, UK, 1073-1221.
- 23) G. Abumeri, M. Garg, and F. Abdi, J. Paquette, “*Improving Wind Blade Structural Performance with the Use of Resin Enriched with Nanoparticles*”, SAMPE Texas Conference Paper, 18 October 2011

9. Simulation of a 35 Meter Wind Turbine Blade under Fatigue Loading

AlphaSTAR analyzed the durability and damage tolerance of a new optimized Sandia wind turbine blade under fatigue loading. All results are based on a stress ratio, R , of 0.1. From the simulation, the new optimized wind blade has an improved D&DT capability which shows a long fatigue life and delays damage initiation and propagation as well as fracture initiation, fracture propagation and final failure of the turbine blade.

Figure 60 shows the FEA model of a 35 meter Sandia wind blade. **Figure 61** gives boundary conditions while **Figures 62** shows the loading conditions. **Table 24** lists the material information. **Table 25** provides the ply schedule while **Table 26** lists material properties using in the simulation. The optimized ply schedules are shown in **Figure 63**. **Figure 64** shows fatigue lives of three different materials, which are reported in references [1, 2].

Figure 60. Finite element model of Sandia 33 meter blade under static loading

Figure 61. Boundary conditions of blade finite element model

Figure 62. Finite element model loading conditions

Figure 65 shows a fatigue analysis of the optimized Sandia wind under 20% of the static peak load. The initial damage starts in the root of the blade at 32,000 cycles. The damage mode shows there is matrix damage in the composite layers. When 64,000 cycles are reached, more damage is observed in the blade neck. The damage mode shows that the interactive failure is a dominant failure mechanism. When a peak load of 134,000 is reached, damage propagates and damage modes show that fiber and matrix failure are major dominant failure mechanisms.

Figure 66 shows a fatigue analysis of the optimized Sandia wind under 30% of the static peak load. The damage starts in the neck of blade at 2,000 cycles. Similar to the 20% case, damage initiates in the matrix. When 4,000 cycles are reached, more damage is observed in the blade neck and the damage mode shows that the interactive failure is a dominant failure mechanism. When a peak load cycle of 8,000 is reached, damage propagates and damage modes show that fiber and matrix failure are major dominant failure mechanisms.

Table 24. Material information for 33-meter blade under fatigue loading

ANSYS #	NuMAD Name	Description
1	GelCoat	Gelcoat Outer Layer
2	Random Mat	--
3	CDB340 Triaxial Fabric	--
4	Balsa	Wood
5	Spar Cap Mixture	70% uniaxial fabric + 30% triaxial fabric
6	Epoxy	--

Table 25. Ply schedule for 33-meter blade under fatigue loading

Ply Schedule	ANSYS Model	Material (ANSYS #)	Ply Schedule	ANSYS Model	Material (ANSYS #)
1	4	3, 5, 6, 2, 1	11	14	3, 4, 6, 2, 1
2	5	3, 5, 6, 2, 1	12	15	3, 5, 6, 2, 1
3	6	3, 5, 6, 2, 1	13	16	3, 4, 6, 2, 1
4	7	3, 5, 6, 2, 1	14	17	3, 6, 2, 1
5	8	3, 5, 6, 2, 1	15	18	3, 4, 6, 2, 1
6	9	3, 6, 2, 1	16	19	3, 5, 6, 2, 1
7	10	3, 4, 6, 2, 1	17	20	3, 4, 6, 2, 1
8	11	3, 5, 6, 2, 1	18	1001	3, 4, 6
9	12	3, 4, 6, 2, 1	19	1002	3, 4, 6
10	13	3, 6, 2, 1	20	1003	3, 4, 6

Figure 67 shows a fatigue analysis of the optimized Sandia wind under 40% of the static peak load. The initial damage starts in the neck of blade at 1,000 cycles. The damage mode shows there are matrix damage and interactive failure in composite layers. When the 1,062 cycles are reached, more damage is observed in the blade neck. The damage mode shows that the interactive failure is a dominant failure mechanism. At the peak load cycle value of 1,094, damage propagates while damage modes show that fiber and matrix failure are major dominant failure mechanisms.

Table 26. Material Properties for 33-meter blade under fatigue loading

Property	Material					
	Gelcoat	Random Mat	CDB340 Triaxial Fabric	Balsa	Spar Cap Mixture	Epoxy
Ex (Pa)	3.44E+09	9.65E+09	2.42E+10	2.07E+09	2.71E+10	2.76E+09
Ey (Pa)	3.44E+09	9.65E+09	8.97E+09	2.07E+09	7.58E+09	2.76E+09
Ez (Pa)	3.44E+09	9.65E+09	8.97E+09	2.07E+09	7.58E+09	2.76E+09
Nxy	0.3	0.3	0.39	0.22	0.37	0.3
Nyz	0.3	0.3	0.45	0.22	0.22	0.3
Nxz	0.3	0.3	0.28	0.22	0.15	0.3
Gxy (Pa)	1.32E+09	3.86E+09	4.97E+09	1.40E+08	4.70E+09	1.10E+09
Gyz (Pa)	1.32E+09	3.86E+09	2.65E+09	1.40E+08	2.65E+09	1.10E+09
Gxz (Pa)	1.32E+09	3.86E+09	3.87E+09	1.40E+08	3.87E+09	1.10E+09
S11T(Pa)	8.27E+07	7.58E+07	3.33E+08	3.22E+07	7.67E+08	8.00E+07
S11C(Pa)	8.96E+07	7.58E+07	2.78E+08	1.95E+07	6.02E+08	2.48E+08
S22T(Pa)	8.27E+07	7.58E+07	7.43E+07	1.53E+06	3.91E+07	8.00E+07
S22C(Pa)	8.96E+07	7.58E+07	2.22E+08	3.45E+06	1.28E+08	2.48E+08
S33T(Pa)	8.27E+07	7.58E+07	7.43E+07	1.53E+06	3.91E+07	8.00E+07
S33C(Pa)	8.96E+07	7.58E+07	2.22E+08	3.45E+06	1.28E+08	2.48E+08
S12S(Pa)	2.60E+07	4.00E+07	1.23E+08	3.44E+06	8.55E+07	1.43E+08
S23S(Pa)	3.44E+07	3.43E+07	7.43E+07	1.20E+06	6.43E+07	1.43E+08

The failure mechanism shows that the optimized blade has an improved durability and damage tolerance capability for fatigue loading. **Figure 68** provides the turbine blade's entire fatigue life.

Figure 63. Optimized ply schedule for the blade

Figure 64. Fatigue life of materials for the blade

Figure 65. Fatigue analysis of Sandia blade under 20% of static peak load

Figure 66. Fatigue analysis of Sandia blade under 40% of static peak load

Figure 67. Fatigue analysis of Sandia blade under 40% of static peak load

Figure 68. Fatigue life of Sandia blade

10.1 References

- 1) D. D. Samborsky, "*Fatigue of E-glass Fiber Reinforced Composite Materials and Substructures*", Master thesis. Montana State University. Bozeman, Montana. December 1999.
- 2) I. Chincea, A. Cernescu, L. Marsavina and V. a. Serban, "*Fatigue Damage Evolution in Laminate Composites with Balsa Wood*", Cellulose Chemistry and Technology, Vol. 45, Issue 5-6, pp. 421-426, 2011.

10. Fatigue Evaluation of a 9 Meter Wind Turbine Blade

AlphaSTAR analyzed the durability and damage tolerance of the 9 meter blade Sandia blade subject to 17 blocks of fatigue loading. **Table 27** lists the load sequence applied to the blade in the test. **Table 28** lists the validation of displacement from analysis with that from test for the first block of loading at the point of load application. This established confidence that the structural response under fatigue loading was captured properly with analysis. **Figure 69** shows the airfoil station where the load was applied. Displacement measurement was taken from actuator which was located at 4.8m.

During testing, Sandia's blade developed a crack running from the spar cap to the leading edge at the 1200 mm station. This shut the test down automatically. This was after 97kcycles in load block 17 were completed. Using multi-scale progressive failure analysis, structural fracture occurred at the end of block 16. Typical damage observed during cycling is shown in **Figure 70** for block 5.

Table 27. Sandia's 9 meter blade fatigue loading sequence

Load Block	Load Type	Start Cycle	End Cycle	Number of Cycles	Mean Load (N)
1	Flap	1	1045762	1045761	3797
2	Edge	1045762	2071869	1026107	797
3	Flap	2071869	2572033	500164	4271
4	Flap	2572033	3075051	503018	4659
5	Flap	3075051	3576257	501206	4929
6	Flap	3576257	4078930	502673	5489
7	Flap	4078930	4329294	250364	5962
8	Flap	4329294	4582725	253431	6388
9	Flap	4582725	4833015	250290	6989
10	Flap	4833015	5085684	252669	7783
11	Flap	5085684	5336174	250490	8166
12	Flap	5336174	5588916	252742	9094
13	Flap	5588916	5838815	249899	9941
14	Flap	5838815	6101283	262468	10748
15	Flap	6101283	6188069	86786	14252
16	Flap	6188069	6439067	250998	11873
17	Flap	6439067	6686541	247474	13026

Table 28. Validation of displacement from analysis

# of Fatigue Cycles	Analysis - Flapwise Displacement (m)	Test - Flapwise Displacement (m)
50000	0.0954	0.093
100000	0.0954	0.093
150000	0.0954	0.093
200000	0.0954	0.093
250000	0.0954	0.093
300000	0.0957	0.093
350000	0.0958	0.093
400000	0.0958	0.093
450000	0.0958	0.093
500000	0.0958	0.093
550000	0.0958	0.093
600000	0.0958	0.093
650000	0.0958	0.093
700000	0.0958	0.093
750000	0.0958	0.093
800000	0.0958	0.093
850000	0.0958	0.093
900000	0.0958	0.091
950000	0.0958	0.091
1000000	0.0958	0.091
1050000	0.0958	0.091

Figure 69. Sandia fatigue test point of load application

Figure 70. Structural damage in red obtained from analysis after applying 3.5 million cycles (end of block 5)

11.0 Summary

AlphaSTAR demonstrated advanced computational technology for wind blade analysis and design through:

- Material characterization to identify root cause for composite damage and fracture
- Multi-scale damage and fracture modeling (fiber/matrix level)
- Multi-scale damage and fracture modeling (nano level)
- Complex geometric features of composite laminates (ply dropoffs) like the ones that exist on wind blades
- Identification of differences between damage mechanics and fracture mechanics
- Robust design for:
 - Weight reduction
 - Improved reliability
 - Improved fatigue life
 - Sensitivity analysis to rank material and structures variables