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Durability and Reliability of Wind Turbine Composite Blades Using Robust Design Approach

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Abstract

The paper describes a computational simulation approach for durability, damage tolerance (D&DT) and reliability of composite wind turbine blade structures in presence of uncertainties in material properties. This computer-based prediction methodology combines composite mechanics with finite element analysis, damage and fracture tracking capability, probabilistic analysis and a robust design algorithm to reduce weight of turbine bales without loss in structural durability and reliability. 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. Analysis D&DT results were 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 of the blade ultimate load under static loading. Weight was reduced by 12% with robust design without loss in reliability or D&DT. It was achieved by replacing a small volume of key materials with foam.

Keywords: Durability and damage tolerance, Multi-Scale progressive failure analysis, Wind blade structures, delamination, robust design, reliability, probabilistic analysis.

1. Introduction

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.

The methodology used is multi-scale progressive failure analysis and is described first. It is followed by a description of the strategy for reliability based design. Then the following is discussed: (1) blade FEA model, (2) validation of the blade analytical simulation of static test, (3) weight analysis, (4) probabilistic sensitivity analysis, and (5) weight minimization without loss in D&DT.

2. Methodology

2.1. Progressive Fatigue Failure Analysis

Multi-Scale Progressive Failure Analysis of Composite Structures

The micro-mechanics composite analysis is integrated with finite element analysis and damage and fracture tracking to perform Progressive Failure Analysis (MS-PFA). The capability is integrated in the GENOA software system [1-3]. Traditionally, failure is assessed at the lamina or laminate scale. This assessment is inconsistent with the physical behavior of the composite material since damage occurs at a lower scale, that is the fiber, matrix or interface level. The methodology presented in this paper 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. The strategy for progressive failure FEA-based analysis is presented in Figure 1. The damage tracking is decomposed from global structural level to micro-scale level. As shown in Figure 2, the stresses and strain at micro level are calculated using a mechanics-of-material-approach from the finite element analysis results of the macro-mechanical analysis at each load increment. Displacements, stresses, and strains derived from the structural scale FEA solution at a node or element of the finite element model are passed to the laminate and lamina scales using laminate theory. Stresses and strains at the micro-scale are derived from the lamina scale using micro-stress theory. The latter are interrogated for damage using a set of failure criteria (Table 1). This analysis is performed progressively, enabling the analysis of damage initiation and progression including fracture initiation on a micro level.

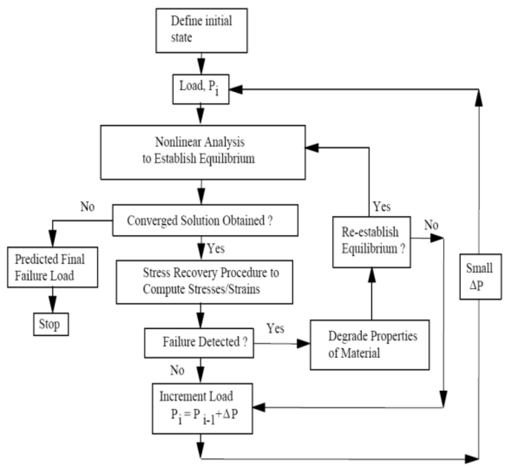


Figure 1: General flow of the progressive failure analysis methodology

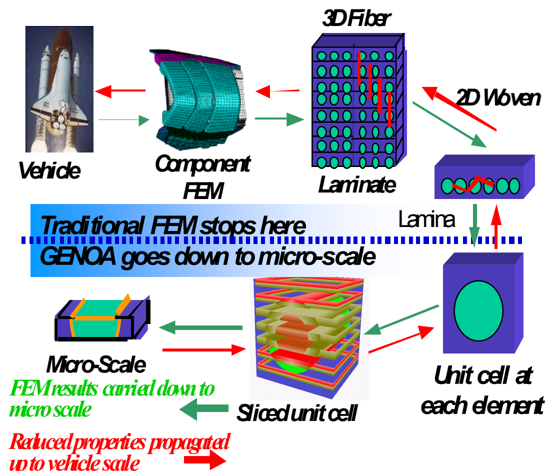


Figure 2 - Micro-macro scale interaction in GENOA progressive failure analysis

Table 1 - Fiber and Matrix Failure Criteria Applied at the Micro–Scale Level of the Composite

Mode of Failure	Event Description
Longitudinal Tensile	Failure of ply controlled by fiber tensile strength and fiber volume ratio
Longitudinal Compressive	1)Fiber/matrix delamination under compression loading, 2) Fiber microbuckling, and 3) Fiber crushing
Transverse Tensile	Matrix cracking under tensile loading, event controlled by matrix tensile strength, matrix modulus, and fiber volume ratio.
Transverse Compressive	Matrix cracking under compressive loading, event controlled by matrix compressive strength, matrix modulus, and fiber volume ratio.
Normal Tensile	Plies are separating due to normal tension
Normal Compressive	Due to very high surface pressure i.e. crushing of laminate
In- Plane Shear	Failure in plane shear relative to laminate
Transverse Normal Shear	Shear Failure acting on transverse cross oriented in a normal direction of the ply
Longitudinal Normal Shear	Shear Failure on longitudinal cross section that oriented in a normal direction of ply
Modified Distortion Energy	Combined stress failure criteria used for isotropic materials
Relative Rotation Criterion	Considers failure if the adjacent plies rotate excessively with one another
Strain failure Theory	Considers invariant through-the-thickness
Linear Elastic Fracture	Virtual Crack Closure technique (VCCT), Discrete Cohesive Zone Model (DCZM)

The integration with FEA evaluates damage and failure mechanics caused by matrix and fiber failure. The damage mechanisms account for matrix cracking under transverse, compressive, and shear loading. The ply fracture mechanisms include fiber failure under tension, compression (crushing, micro-buckling and de-bonding), and delamination. It allows: (1) use of commercial finite element stress solvers; (2) user selection of 2 or 3-D architectural details (through-the-thickness fibers, resin rich interphase layer between weave plies, fiber volume ratio, void shape, size and location, cure condition, etc.); (3) assigning static (thermo-mechanical) or spectrum loading; (4) automatic update of the finite element model prior to executing FEA stress solver for accurate lamina

and laminate properties; and (5) degradation of material properties at increase loading (including number of cycles) based on detected damage.
MS-PFA utilizes and integrates: (a) finite element structural analysis, (b) micro-mechanics, and fracture mechanics options, (c) damage progression tracking, (d) probabilistic risk assessment, (e) minimum damage design optimization, and (f) material characterization codes to scale up the effects of local damage mechanisms to the structure level to evaluate overall performance and integrity. A significant advantage of using a life prediction tool in the design process is that the number of experimental tests at the component and substructure levels can be substantially reduced and experimental testing that is done made more efficient and effective. The damage progression module relies on a composite mechanics code for composite micro-mechanics, macro-mechanics, laminate analysis, as well as cyclic loading durability analysis, and calls a finite element analysis module that uses anisotropic thick shell elements to model laminated composites. This capability predicts the loads where damage initiates and propagates, all the way to structural fracture.

2.2. Probabilistic and Reliability Analysis

With the direct coupling of composite micro-and-macro mechanics, structural analysis, and probabilistic methods [4], 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 3.

Composite micro-mechanics are used to carry over the scatter in the primitive variables to the ply and laminate scales (Figure 3). 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. This completes the description of the hierarchical composite material/structure synthesis shown on the left side of Figure 3. 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.

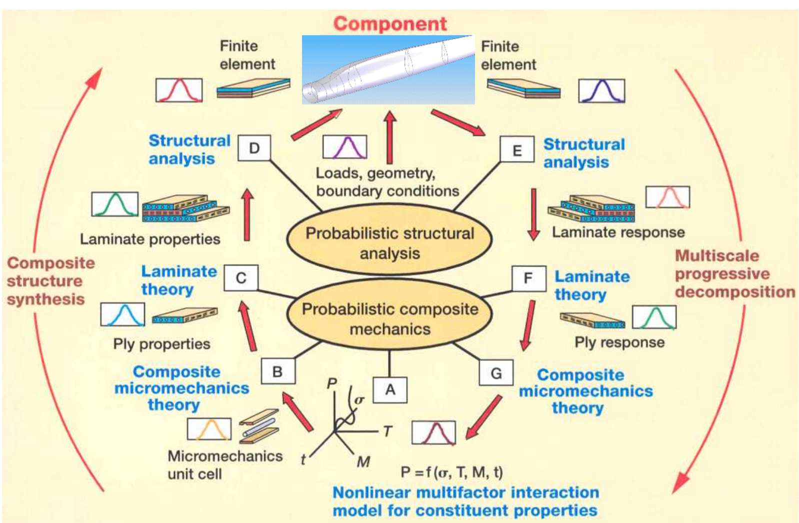


Figure 3. Technical approach for probabilistic evaluation of wind blade composite structures

Multi-scale progressive failure analysis (MS-PFA) can be coupled with optimization and probabilistic methods [4] to 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. Results and Discussion

3.1 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 4 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 4 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 5 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 2 lists the various materials used in the construction of the blade. Table 3 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.

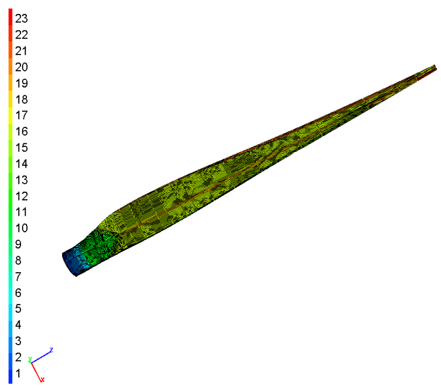


Figure 4: Sandia 9 meter blade finite element model with correspondent ply schedules

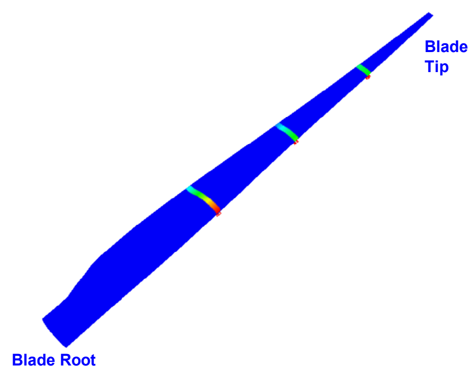


Figure 5: Blade bending loads applied at 3 stations

Table 2: List of materials used in blade model

Material System #	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 (6oz)
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 3: 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	4,5,1,10,7,10,6,9,6,1	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.

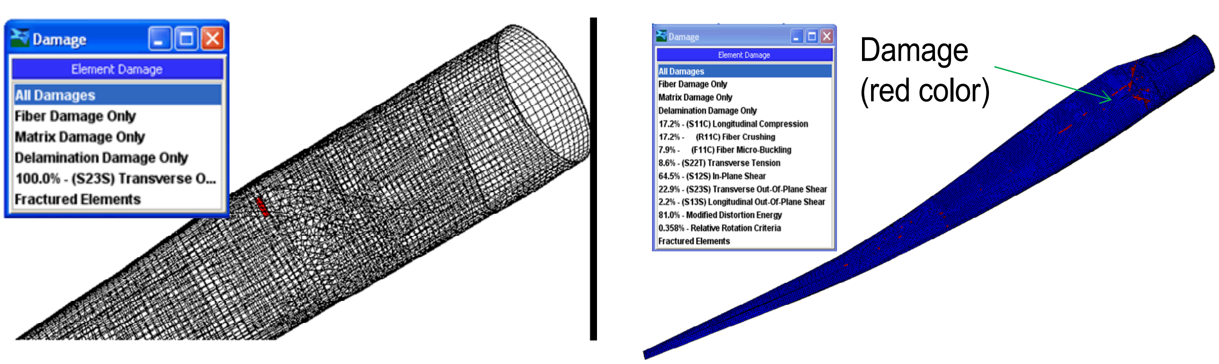
3.2 Simulation of Blade Static Test

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 4 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 6 shows the progressive damage in the blade under increased static loading. The initial damage started near the root of blade at load of 8.7KN due to delamination in composite layers (Figure 6-a). When the load reached 24.36KN, additional damage criteria were activated: transverse tensile, longitudinal compressive, shear and delamination (Figure 6-b). When the load applied reached the ultimate peak value of 48.29KN, damage propagated to most zones of the blade (Figure 6-c). 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 6-d. 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 6-e.

Table 4: Lamina properties used for ELT5500 (unidirectional glass epoxy material)

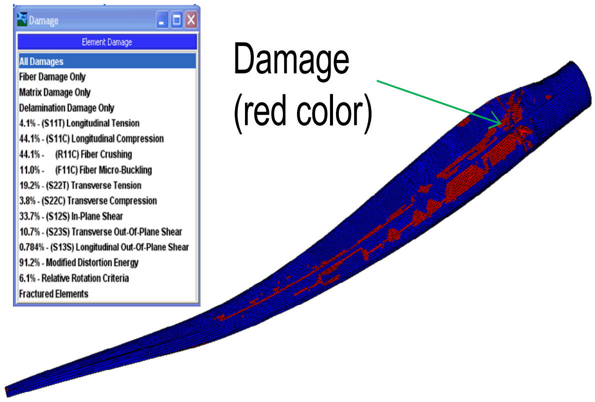
Property	Symbol	Value	Measurement
LONGITUDINAL MODULUS	El11	4.180E+04	N/(mm^2)
TRANSVERSE MODULUS	El22	1.403E+04	N/(mm^2)
TRANSVERSE MODULUS	El33	1.416E+04	N/(mm^2)
INPLANE SHEAR MODULUS	Gl12	2.630E+03	N/(mm^2)
TRANSVERSE SHEAR MODULUS	Gl23	2.323E+03	N/(mm^2)
SHEAR MODULUS	Gl13	2.630E+03	N/(mm^2)
POISSON'S RATIO	Nul12	2.806E-01	
POISSON'S RATIO	Nul23	4.534E-01	
POISSON'S RATIO	Nul13	2.759E-01	
LONGITUDINAL TENSILE STRENGTH	Sl11T	1.125E+03	N/(mm^2)
LONGITUDINAL COMP. STRENGTH	Sl11C	7.492E+02	N/(mm^2)
TRANSVERSE TENSILE STRENGTH	Sl22T	6.083E+01	N/(mm^2)
TRANSVERSE COMP. STRENGTH	Sl22C	2.041E+02	N/(mm^2)
INPLANE SHEAR STRENGTH	Sl12S	3.020E+01	N/(mm^2)
NORMAL TENSILE STENGTH	Sl33T	6.083E+01	N/(mm^2)
NORMAL COMP. STENGTH	Sl33C	2.041E+02	N/(mm^2)

Figure 6-f 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 6-f, the results from station SP3 3 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.



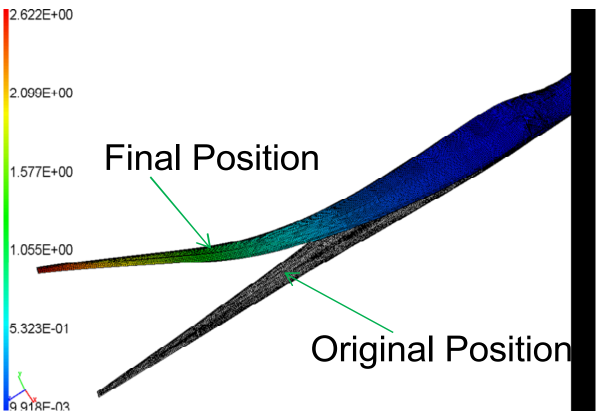
a) **Damage initiation at load of 8.7KN**

b) **Damage propagation at load of 24.36KN**

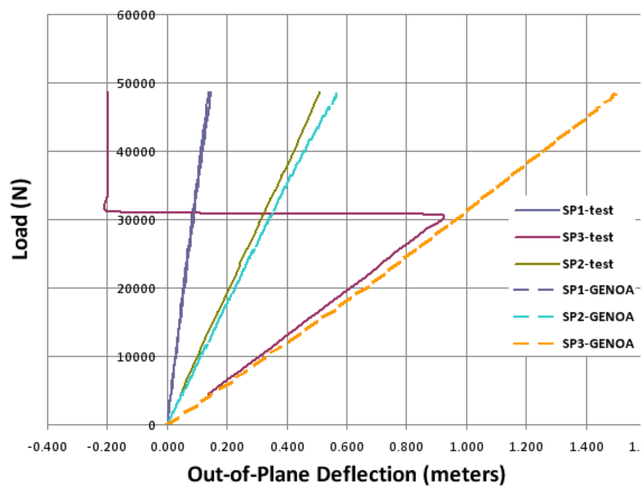


c) **Damage at peak load of 48.29KN**

d) **Damage at test peak load of 48.612KN (2 m from root of the blade)**



e) **Total displacement in meters at peak load of 48.29KN**



f) Test and predicted load-deflection for Sandia's BSDS blade under static loading

Figure 6: Progressive failure analysis and test validation of Sandia's BSDS blade under static loading

3.3 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 5 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 # 1and 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.

Table 5: Volume and weight contribution for various materials used in the blade design

Material System #	Total Volume m^3	Density kg/m^3	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 (6oz)
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***		

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

As discussed earlier, 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 6 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 7 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 1000 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 61000 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 8 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.

Table 6: 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
	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	
DBM1708	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	
	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	
ELT5500	1.0	1.0	1.0	1.1	1.0	1.0	1.0	48285	48612
	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	
	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	
Saertex	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	

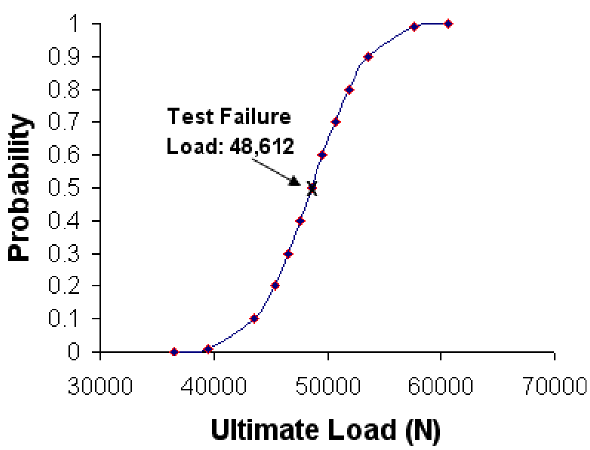


Figure 7: Probabilistic scatter in blade failure load subject to static loading due to uncertainties in properties of DBM1708 material

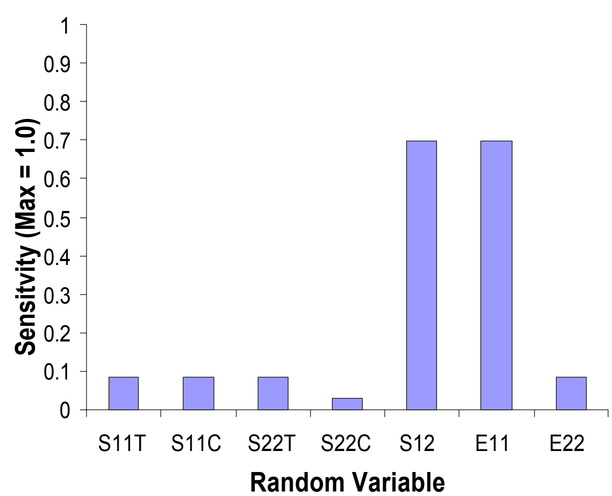


Figure 8: Probabilistic sensitivity of random variables due uncertainties in properties of DMB1708 material

3.5 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.

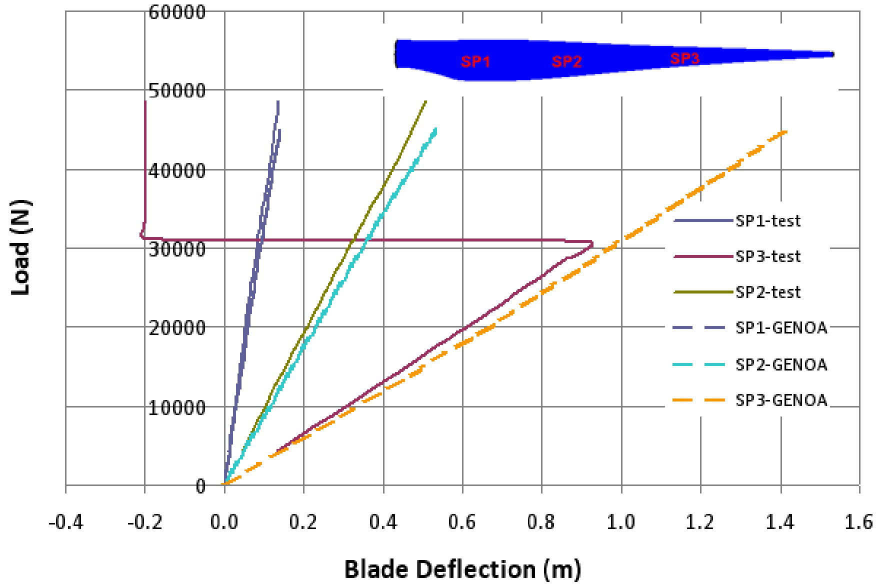


Figure 9: Load displacement relationship comparing blade response under static load from test with analysis results. 20% of ELT5500 material was replaced with foam reducing weight from 112.7 kg to 103.7 kg

Figure 9 shows the load displacement from 3 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 9 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 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 eth root area.

Figure 10 shows the load displacement from 3 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 (see Figure 10). 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.

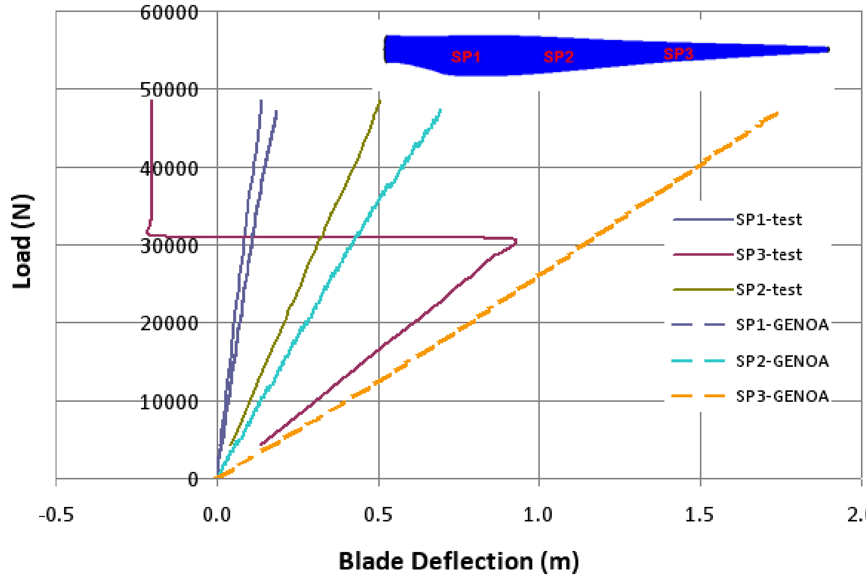


Figure 10: Load displacement relationship comparing blade response under static load from test with analysis results. 15% of DBM1708 was replaced with foam reducing weight from 112.7 kg to 100.2 kg

4. 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.

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