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Blade Reliability Collaborative: Collection of Defect, Damage and Repair Data

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Abstract

The Blade Reliability Collaborative (BRC) was started by the Wind Energy Technologies Department of Sandia National Laboratories and DOE in 2010 with the goal of gaining insight into planned and unplanned O&M issues associated with wind turbine blades. A significant part of BRC is the Blade Defect, Damage and Repair Survey task, which will gather data from blade manufacturers, service companies, operators and prior studies to determine details about the largest sources of blade unreliability. This report summarizes the initial findings from this work.

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1.0 INTRODUCTION

Blade reliability is emerging as one of the most costly elements of wind plant installation and operation because blade damage or failure can cause extensive down time and lead to extensive repairs. Blade reliability will become even more critical in the future because of the increasing numbers and sizes of operating utility-grade turbines. The growth of wind energy power production is well documented and has been on the order of 15-20% per year for the past several years in the U.S. Goals declared by several countries are to have wind power penetrations of up to 20% by 2020. DOE has a vision of 20% wind penetration of electric power by 2030 in the U.S. If such a goal is even close to being reached, this means that there will be hundreds of thousands of utility grade wind turbines operating in the U.S. alone.

Measurements of the mean-time-between failure for blades have been on the order of 12-14 years or an average annual failure rate of 6% [1], which is lower than the current design life of 20 years. Certainly when blades reach 20 years old, operators will not necessarily bring a working blade down, meaning there is a chance for increased catastrophic turbine failures unless improved inspection techniques are commercialized. However, the growth in turbine sizes makes O&M and inspection efforts are more difficult. Aging turbines and new entrants into the market are also causes for decreased reliability.

As turbines continue to increase in size, the cost of testing blades increases and inspection techniques on the manufacturing floor becomes more difficult. The manufacturing process can be a significant source of defects due to the difficulty of producing very large composite structures with inexpensive materials and processes. This can result in blades being delivered to the site in a condition that often requires additional treatment to remedy quality issues before installation. Blade repair contractors for U.S. wind plant developers and operators report that as much as 80% of the blades they repair have never been operated. In recent cases, installations have had to replace all blades after the discovery of a fleet-wide defect. Quality enhancements to blades delivered to the field can be largely achieved through improvements in quality metrics and additional use of inspection techniques. Blade reliability issues need to be identified early because of the lost energy production and high repair costs of failures.

The Blade Reliability Collaborative (BRC) was initiated by the Wind Energy Technologies Department of Sandia National Laboratories (SNL) and DOE in 2010 with the goal of gaining a better understanding of the issues surrounding operations and maintenance (O&M) of wind turbine blades both planned and unplanned. The project is led by Sandia National Laboratories (SNL), with important contributions from academic, national labs, and industrial partners. The BRC is broken down into the following tasks:

- Blade Defect, Damage and Repair Survey
- Inspection Validation
- Effects of Defects
- Analysis Evaluation
- Certification Testing
- International Standards and Industrial Partnerships

Efforts are underway in each of these areas. This report will focus on the Blade Defect, Damage and Repair Survey, which is gathering data from blade manufacturers, service companies, operators and prior studies to determine details about the largest sources of blade unreliability. In this report we will provide a more detailed overview of the BRC project, discuss results of previous surveys/studies on types of defects or failure seen in the field for utility-grade wind turbine blades and discuss the campaign to collect repair and maintenance information from blade repair and operating companies. Also included are recommendations for defect identification, repair and good design practice from IEC and DNV design/manufacturing standards. Finally, we will briefly describe the ongoing analysis and simulation of selected blade defects and efforts in characterizing a variety of NDI techniques for defect detection.

2.0 BRC OVERVIEW

The Blade Reliability Collaborative (BRC) was started in 2010 and is composed of staff from national laboratories, EPRI, universities, blade manufacturers, OEM's, operators and blade repair companies. The main thrust of the BRC is to understand the types and causes of blade defects in turbine blades today, quantify those defects, and develop ways to determine the effects of these defects. In other words, for each type of defect we want to determine how large must the defect be before it causes reduced fatigue life and how small of a defect can be "observed" by current NDI techniques either on the manufacturing floor or in the field. This main thrust of BRC will be accomplished by 1) determining limits of current inspection techniques and developing improved ways to inspect for such defects both on the manufacturing floor and in the field, 2) modeling and simulating defects to improve understanding of the effects of defects in a broad sense 3) undertaking testing of subscale blades or structures to validate modeling efforts and 4) collaboration with certification agencies and industry.

The BRC is broken down into the following specific tasks with the stated goals for each. There are ongoing efforts being made in the first four areas at this time (Fall, 2011):

- ***Blade Defect, Damage and Repair Survey:*** The survey will aggregate data from blade manufacturers, service companies, operators and prior studies to determine largest sources of blade unreliability.
- ***Inspection Validation:*** This task will evaluate the ability of inspection techniques to accurately characterize blade defects and damage in manufacturing plants and in the field.
- ***Effects of Defects:*** The goal here is to determine how common manufacturing defects affect blade strength and service life.
- ***Analysis Evaluation:*** We will assess the ability of design analysis tools to find and characterize potential failure modes.
- ***Certification Testing:*** The ability of certification testing to uncover potential reliability issues and find innovative ways for testing to provide better insight will be evaluated.
- ***International Standards and Industrial Partnerships:*** Interfacing with industrial partners will identify pathways to implementing improved design, manufacture, and inspection.

Because there are a large number of potential defects in blades, it is critical to collect enough information to prioritize the importance of defects by size and location on the blade. The characterization of these defects will be critical to identifying and improving inspection techniques, especially on the manufacturing floor where blades can more easily be repaired. In addition, we expect to obtain damaged blades to assess real defects from operating turbines and incorporate forensics on the blade to determine details of the defects. Figure 1 shows an extreme example of trailing edge damage to a fielded turbine blade. Figure 2 shows an example of extreme waviness where the material has folded back on itself resulting in a large stress concentration, and Figure 3shows incomplete bonding of a shear web to the outer skin. Figure 4 is a picture of lightning damage which is a big factor for turbines sited in many locations. Because of sensitive (IP) issues related to damaged blades, we will also proceed to build subscale blade components with embedded defects that are deemed to be the most important, and then simulate such defects and test. Companion Non-Destructive Inspection (NDI) techniques will be applied in parallel before, during and after testing to assess effectiveness of each technique with focus on continual improvements.

Figure 1: Severely Damaged Blade: Trailing Edge Separation (Courtesy of Knight & Carver)

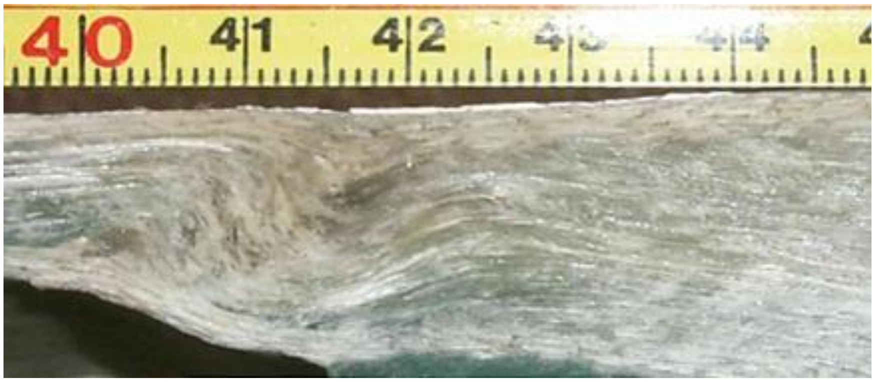

Figure 2: Extreme Fabric Waviness

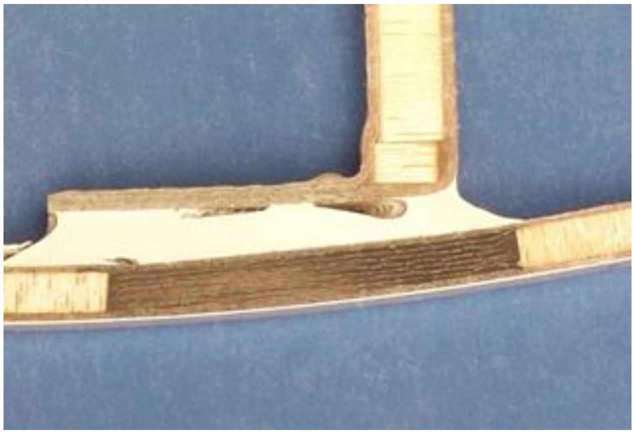

Figure 3: Poor Bonding

Figure 4: Lightning Damage

With blades becoming larger and more costly, manufacturers are under increasing pressure to minimize manufacturing complications and defects before shipping. Quality assurance relies heavily on inspection, both visual and with the use of NDI techniques. Poor bonds at the leading and trailing edges as well as at the shear web and skin interfaces are known problematic areas. Ultrasonic NDI is routinely used to check for adequate bonding by most blade manufacturers. However, inadequate bonding is still a cause of major damage. Inspection for dry spots, waviness, and other abnormalities will continue to require enhanced NDI techniques.

To collect defect information, we have started a process to set up agreements with repair companies to gather repair, maintenance and warranty data that can provide statistics on types of repairs and maintenance issues. From this information we can analyze types of defects on post-warranty blades as a function of turbine size and years of service as well as the type of manufacturing process used. Additional we have been gathering published and anecdotal information on primary causes of failure or down time due to required repair.

This information will be helpful in extending blade life and providing statistically relevant information to designers and manufacturers. The more difficult set of data to obtain will be that from blade manufactures on defects/issues that occur before the end of warranty including fixes made on the manufacturing floor.

3.0 EXISTING INFORMATION ON BLADE DEFECTS, DAMAGE AND BLADE REPAIR

We have collected reported information from a variety of sources on types of defect, damage and repair issues observed in blades. Most of such reporting has either a minimum set of data or summary observations. This section provides an overview of this information.

3.1 Delphi Meeting

On July 10, 2007, Sandia hosted a Delphi meeting via telecom to explore issues associated with the rates and causes of component failures in operating wind turbines. Opinions were sought from a variety of sources including wind farm operators, government entities, and consultants. The discussion was centered on an analysis of wind farm reliability estimates provided by Global Energy Concepts (GEC).

3.1.1 Comments on Blade Failures

During this meeting several comments were made about blade failures. A staff member from Trent Wind Farm commented that their experience with rotor blades indicated a much higher rate of failure than the generic value reported by GEC. In their operating experience since 2001, approximately 30 of 100 blades failed, including nine that summer. These failures were attributed to manufacturing defects, specifically with the laminate construction of the composite which led to the development of waviness. Furthermore, lightning hits were a significant problem. About 60 blades needed repair due to either leading edge erosion (augmented by dust and wind buffeting) or lightning strikes, and all blades were expected to require repair. Erosion was occurring mainly on the outer 10 m of the blade. This was considered to be due to a manufacturing defect more than an environmental concern, because the manufacturing process leads to weak spots in and bonds. Erosion is repaired by grounding down the leading edge and repairing the blade. Trent Wind Farm staff believes that the use of leading edge tape produced by 3M will mitigate erosion.

Trent Wind Farm staff indicated that blade repair can be a crane event, although not always, even for nonstructural failures. GEC had assumed that nonstructural failures would not require a crane. The Trent Wind Farm has two full-time cranes on site, which is unusual for the industry. They do not have a condition monitoring system, but felt that such a system would not help much, since their warranty requires that they allow the wind turbine to keep running until failure. Trent expected to use more blade crawlers in the future and may go to a sky climbing device.

A representative of AES indicated that they had successfully used leading edge tape to prevent insect contamination, and that it lasted several years. He also indicated that AES has had many blade failures related to design or construction of blades. AES has had some experiences where every blade had to be replaced. Lightning is a particular problem. One lightning storm damaged 28% of the blades on the wind farm. These are mostly fiberglass blades, which do not protect well against lightning.

3.2 Griffin and Malkin Paper

In the Griffin and Malkin paper “Lessons Learned from Recent Blade Failures: Primary Causes and Risk-Reducing Technologies” [2], the authors report on causes of blade failure based on their experience in working with wind farm operators. These causes of blade failure are identified:

- Manufacturing defects
- Progressive damage from leading-edge erosion, skin cracks, transport/handling, lightning strikes
- Excessive loads from turbine system dynamics and interaction with control system
- Out-of-plane forces & distortion of blade sections mostly in root transition due to blade loading
- Excessive loads due to unusually severe atmospheric conditions
- The leading causes of these blade failures were laminate wrinkles, bond lines and out-of-plane deformations.

3.3 Larwood Paper

In Larwood's paper "Permitting Setbacks for Wind Turbines in California and the Blade Throw Hazard" [3], he mentions several types of blade failure, as follows:

- Root connection full blade failure
- Lightning
- Failure at outboard aerodynamic device
- Failure from tower strike
- Defects
- Potential causes
    - Unusual loads
    - Control system failure
    - Human error
    - Incorrect design or poor manufacturing

3.4 Wiser Report

This report [4] does not discuss details of blade failure or repair, but does comment on O&M issues in general. It is stated that O&M costs increase with project age and decrease for more recently installed projects. As reported in 2010, O&M costs for installed turbines in 2008-09 were $0.01/kWhr. The trend is increasing for earlier-installed turbines with those costs being $0.04/kWhr for 1984 installations.

3.5 Initial National Reliability Database (NRD) Results

As reported in Ref. 5, Hill collected information concerning blade damage from several wind farm operators in the Southwest U.S. representing over 400 operating wind turbines. The information collected was general in nature as shown below:

Wind Farm A

- 0-5 years of operation
- 100+ turbines
- Two blade replacements due to lightning
- Many other strikes did not require blade replacement

Wind Farm B

- 5-10 years of operation
- 100+ turbines
- Existence of manufacturing-related issues identified as delaminations and voids
- Existence of leading edge erosion
- Existence of trailing edge splits
- Every blade was struck by lightning at least once
- $100K spent on blade repairs
- Three blades replaced due to lightning over life
- Six blades per year were replaced – one at a time
- Blades were tuned with lead shot

Wind Farm C

- 0-5 years of operation
- 0-50 turbines
- Issues with bonding, delaminations, and voids
- Blades cleaned every year
- Replaced in sets when needed – around five since start of operation Wind farm D
- 5-10 years operation
- 100+ turbines
- Issues are QC
- Bug fouling and leading edge erosion exist
- Repair have been made for lightning damage but not replacements
- Blades cleaned when gearboxes are changed (rotor down)
- Around 40 blades replaced

Wind Farm D

- 5-10 years operation
- 100+ turbines
- Issues are QC
- Bug fouling and leading edge erosion exist
- Repair have been made for lightning damage but not replacements
- Blades cleaned when gearboxes are changed (rotor down)
- Around 40 blades replaced

Wind Farm E

- 0-5 years of operations
- 50-100 turbines
- No problems

For these wind farms located in the Southwest U.S., lightning strikes are a common occurrence but only occasional repairs are required. Turbines that were 5-10 years in operation did exhibit some delaminations, voids, leading edge splits and bug fowling. Typically, 5-6 blades are replaced per year in 3 sites, two of which have more than 100 turbines, one of which has less than 50 turbines.

3.6 NREL Blade Test Experiences

The National Renewable Energy Laboratory (NREL) has tested wind turbine blades for many years in their facility at the National Wind Test Center (NWTC). Scott Hughes, lead blade test engineer at NREL, had an aggregated a set of data on types of failure modes experienced by NREL's blade testing crew over the years. This was presented at a DNV Wind Energy Blade Damage Tolerance Workshop in March 2008 [6]. Figure 5 shows the results presented under the title of Aggregate Catastrophic or Functional Failure Modes. These results are from blades representative of current (2008) in-field megawatt-scale designs. The failures noted are mostly from the fatigue testing and are broken into four broad areas of failure: laminate design/material, laminate defect, bond lines, and root fixturing. As expected, the largest number of failures occurs due to laminate defects or bond line issues in the shear web, and leading or trailing edges.

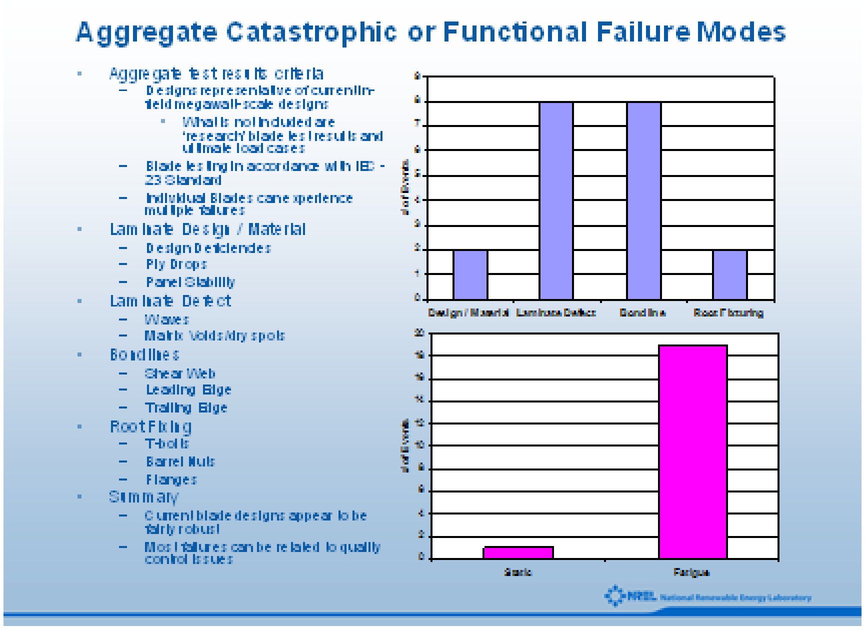

Figure 5: Aggregated Failure Modes

4.0 DEFECT DESCRIPTIONS AND REPAIR OF DEFECTS IN STANDARDS

As wind energy has become mainstream, design and manufacturing standards have been created and continually updated for wind turbine systems. Descriptions of defects, blade repair issues, and design considerations for improved quality are starting to be addressed in the standards, as well.

4.1 DNV Standards

DNV Standard DNV-DS-J102 is entitled Design and Manufacture of Wind Turbine Blades, Offshore and Onshore Wind Turbines (October 2010) published by Det Norske Veritas [7]. In Section 3 entitled Design Analysis, Table A-1 lists a set of typical composite failure mechanisms; global buckling, fiber failure, inter-laminar failure, sandwich failure, and fatigue failure. These mechanisms are critical for design and are required to be analyzed at the ply/lamina level. This specification also provides significant insight on how poor designs can lead to certain types of failure. In Section 4, entitled Blade Manufacturing Procedures, typical critical processes during blade fabrication are listed including physical characteristics, their criticality, and suggestions on how to provide quality control. Examples of the critical processes are:

- adhesion of surface paint
- air entrapment in resins or adhesive
- bad bonding to metallic bushings
- correct lay-up of sandwich core
- correct ply lay-up
- proper curing of adhesives and resins
- dry areas in laminate
- dust and moisture penetration
- flaws in adhesive joints
- incorrect alignment of skins and webs
- wrinkles in laminates
- application of too much or too little adhesive

Section 4 provides a good understanding of types of manufacturing defects and means of preventing their implementation.

DNV has also published a white paper entitled Energy Report Future Perspectives for Design and Test of Wind Turbine Blades: A White Paper on a Rational Approach to Defects and Damage Tolerance. This is a primarily a compilation of a series of presentations by attendees on a variety of topics. The NREL testing experience was presented and was discussed in Section 3.6.

5.0 IEC BLADE STANDARD

IEC has a series of standards for wind turbine design, fabrication and installation. A new blade standard, 61400-5, is being put together by a panel of IEC experts and has not been approved yet. There is much discussion on design load factors and design requirements, but also a significant amount of time is devoted to manufacturing process requirements in areas such as laminating fiber reinforced plastic, gelcoat application, lamination build-up, application of resin and adhesives, curing, sealing and de-molding and finishing. Manufacturing and quality control are discussed. Manufacturing repair processes are planned but not complete at this time. Another critical area covered is blade transport, which is a critical issue for blade damage.

Annex A [8], a proposed draft to standard IEC Standard 61400-5 states the following. "Defects appear during the life cycle of wind turbine blades (manufacturing, transportation, handling, erection or operation) because of manufacturing or other incidents. Defects can be classified into acceptable defects, reparable defects, or should-be-scrapped (no need to repair) defects. Repairing of defects could be applied during manufacturing, transportation, handling, erection or operation of the blade".

Repair requirements are discussed in detail in Annex A. The list below is reproduced from a draft of Annex A which lists classifications of defects including type, typical location and proposed inspection method. Currently, most defects can be detected through visual examination, tapping and measurements. However, improved NDI techniques may offer more reliable inspection.

- Bubble
- Aberration
- Pinhole
- Wrinkle
- Bad infusion
- Core material gap
- Lack of resin or bubble
- Bonding thickness beyond design tolerance
- Bonding width beyond design tolerance
- TE thickness beyond design tolerance
- Root circle deviation
- Bad connection of lightning system

6.0 SURVEY PLANNING AND INITIAL DATA COLLECTION RESULTS

As stated previously, our goal here is to systematically collect sets of long term data from blade repair companies, service companies and operators to determine the largest sources of blade unreliability.

6.1 Original Mechanism

To understand more about defects, failure and repair of blades, the BRC initiated a data gathering effort. This effort began as a survey to owner and operators of wind plants in the U.S., with support from the American Wind Energy Association's (AWEA) Wind Turbine Working Group. This survey was released in July 2010 to around 200 individuals and entities in an effort to get information as to those failure mechanisms currently being experienced in the field. However, the survey received a limited number of responses. It was decided that while this mechanism for collecting the data did not provide the desired results, the need for data still existed.

6.2 Expanded Mechanism

To continue the task of collecting data, the approach was modified to target new sources. The approach was also modified from that of collecting information to that of collecting actual data. This data was to be used to generate a report containing aggregate results, covering many sources of data.

Initial sources of data were envisioned as Original Equipment Manufacturers (OEMs), repair companies, inspection companies and plant owner/operators. However, approaches to OEMs for detailed failure data did not meet with the desired levels of success, so repair and inspection companies were approached to gauge their interest in sharing data.

6.2.1 3rd Party Blade Inspection and/or Repair Companies

The level of interest from 3rd party blade inspection and/or repair companies (3rd party companies) has been very promising, and eight different organizations were identified to provide data. The goal was to represent a cross-section of the U.S. wind industry and represent blade issues and failures experienced by the fleet and not focus on one technology, or one manufacturer, or one geographical area.

Initial discussions with the identified companies was very encouraging; with their display of a high level of understanding as to the need for the collection of the data and how it could benefit the BRC's research focus. Interested companies were then encouraged to participate by entering into a Nondisclosure Agreement (NDA) with Sandia Labs to ensure both parties were protected in their discussions and understanding of what was to be shared.

Nondisclosure Agreements (NDAs) are an integral aspect when dealing with Proprietary Information (PI), as they allow for the sharing of information that normally would not be shared outside of a company. In this case, the data shared with SNL would contain information that would be considered an important part of each company's competitive edge, including the locations of business activities and details regarding these activities. Additionally, the data would have extensive detail regarding the original turbine and blade manufacturers, and the issues that these manufacturers are experiencing. While this detail is essential to performing accurate analysis, release of this data would not support the goal of representing the fleet while not focusing on a given manufacturer. Thus, the NDA allows the company to share data with SNL with the assurance that it will be kept confidential and not shared without express permission of the company, for the agreed on period of time.

Additionally, the NDA discloses how SNL will use and protect the PI. In this case, the data shared with SNL would be incorporated into a database with at minimum five companies. This dataset would then be used to perform analysis that would identify the variety of failures causing wind turbine blade unreliability. These findings would then be incorporated into a public report, using aggregation techniques to hide any identifiers of original data source (e.g. repair or inspection company name, plant name), original manufacturer (e.g. blade or turbine OEM), and location (e.g. geographical).

6.2.2 NDAs with 3rd Party Companies

With extensive support by SNL legal department, NDAs were supplied to six 3rd party companies for review. This allowed each company to provide details about what they would be sharing, as well as have the legal terms reviewed by their legal representatives. Once NDAs were completed, reviewed and signed off by both parties, work could commence.

To date SNL has executed two NDAs with 3rd party companies. The other four NDAs are still in flux. The task of taking the interest displayed by companies during initial discussion through the entire process has proven to be enormously challenging.

6.2.3 NDAs with Plant Owner/Operators

With the challenges associate with the NDA process with 3rd party companies, it was decided to concurrently pursue plant owner/operators (operators) as an additional source of field failure experienced by the fleet. Again, with extensive support by SNL legal department, NDAs were supplied to 3 operators for review. To date SNL has executed one NDA with an operator. Of the other two, one is still being reviewed and the other is in having the data sharing language defined.

6.2.4 Data Collection under an NDA

With an executed NDA, detailed discussion about data and data sharing becomes possible. Discussions proved that the 3rd party companies and the operator had a wide variety of data that would provide the platform for analysis to identify if there were additional failure modes and issues to be included in this BRC research focus. To facilitate these discussions, SNL provided a draft template (Figure 6) to focus discussions on the minimum data required, and additional data that would be useful during the analysis.

Blade Data													
Plant Name	**State Located**	**Month/Year Commissioned**	**Turbine Mfr**	**Blade Mfr**									
Start Date &Time	**End Date & Time**	**Work Order #**	**Turbine Name/ID**	**Activity Type**									
				Inspection									
					Inspection Type								
						Scheduled Inspection	End of Warranty	Unusual Event	Quality Control				
					Inspection Method								
						Full Blade	Partial Blade	Details of Inspection					
					Inspector Location								
						Air			**Ground**				
							Rope	Basket		**Visual**			
											Camera	Binoculas	None
				Maintenance									
					Scheduled	Unscheduled	Maintenance Completion List						
				Blade Repair									
					Blade location during repair(s)								
						On Turbine (in air)	On Ground	Transported to repair facility	No. of Blades Repaired				
					Location of Repair on Blade	**Spanwise Location**							
							Root	Transition	Max Chord	50-100% span			
						Chordwise Location							
							HP skin	LP skin	TE	LE			
					Repair Type	Leading Edge Roughness/Erosion	Puncture	Blade Crack	Laminate Debond	Description of Repair & Cause			
				Blade Replaced									
					Failure type	Failure reason	**Replacement Delays**						
								Crane	Specialized Technicians	Weather			
					Replaced under warranty								
						Yes	No						

Figure 6: BRC Template for Data Request

Both 3rd party companies were able to provide data that contributed to the core set of fields need to perform initial analysis. They also were able to provide additional fields that, while not available from each of the companies and so not reportable, provided detail to assist in the analysis process. As expected, data transferred to SNL did not follow the same format and structure. To address this SNL created a Microsoft SQL Server 2008 R2 Development (Development) environment.

The wind farm operator was not able to provide the detailed data that would allow it to be incorporated into the database. This was primarily due to restrictions within their current information store, and the resource burden needed to compile the data. The BRC request to this operator has placed focus on this issue for the operator, prompting the assembly of a team to build a “major part” failure database for the use by their performance and analysis teams. The BRC Template (Fig. 6) is contributing to their data requirements and design.

6.2.5 Data Storage at SNL

To prepare for the transfer of data to SNL, two different databases were designed to store the data. Through collaboration between Alistair B. Ogilvie and Cody R. Bond of SNL Wind Energy Technologies department, both designs were evaluated and refined before being tested with actual data. This dual approach allowed for the evaluation of both databases once they contained a subset of the transferred data. This evaluation focused on the functionality of the databases for producing analysis results.

6.2.6 Analysis Approach

Through both the original and the expanded mechanisms, the BRC gathered information to identify failure modes and defects. While the survey did not produce hundreds of responses, it did provide insight into a portion of failures experience in the field. While the threshold of five data contributing companies was not achieved for aggregated analysis and reportable results solely from data, insight into others portion of field experience was achieved. During the process of pursuing and gathering data, numerous details were discussed and shared, and so including another layer of information. Figure 7 pictures the general locations of data sources.

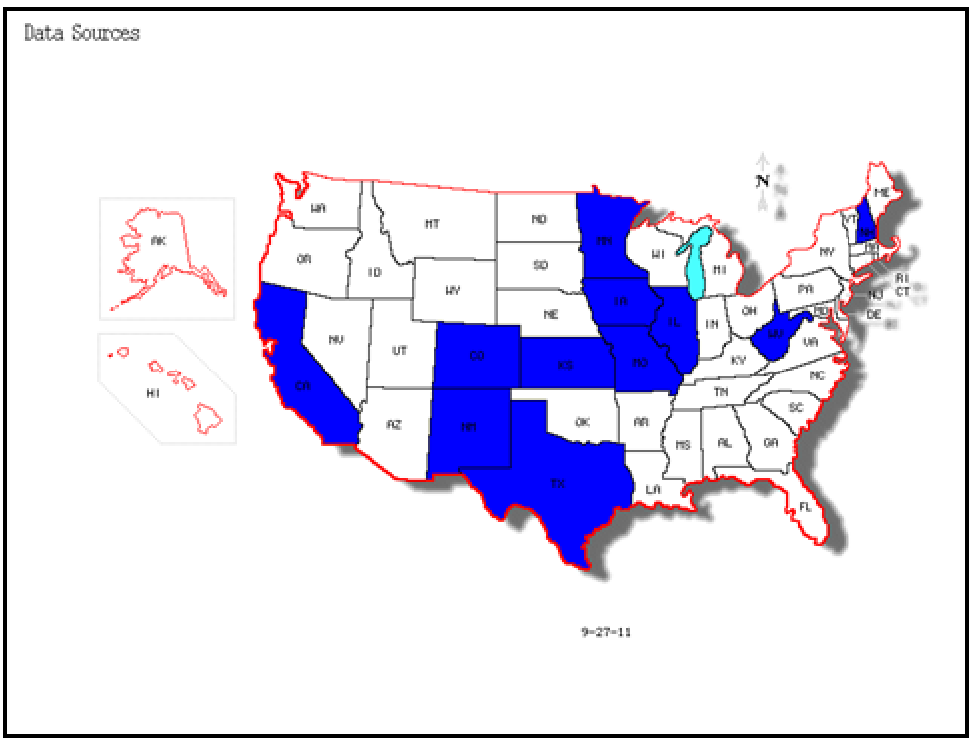

Figure 7: Data Sources

6.2.7 Analysis Results

The results included in this report are based on preliminary analysis of information from participating partners. Included in this information is aggregated proprietary data, results of surveys (both formal and informal), information resulting from discussion with industry leaders and information available through other SNL projects. It does not include information discussed in Section 3. The results also do not include information that identifies blades that have not been installed; i.e. it does not identify manufacturing defects, transport damage or installation damage. A large portion of the information is from operators and 3rd party companies; i.e. the information is based on blades nearing the end of their warranties or that are already out of the warranty period.

The preliminary analysis should be considered "directional", as the information used for analysis does not represent a large portion of the fleet. Though directional, the data and information provided by the contributors provides an initial view of fleet experience and allows the BRC to assess the focus of its research.

6.3 Key Themes in Survey Results

6.3.1 Variation

There is large variation seen across plants, operators, technologies, and geographic locations. Almost every data source included blades that had experienced no damage. There were data sources that had not experienced lightning damage, and data sources where every turbine showed some kind of lightning damage. Damage types are plotted in Figure 8.

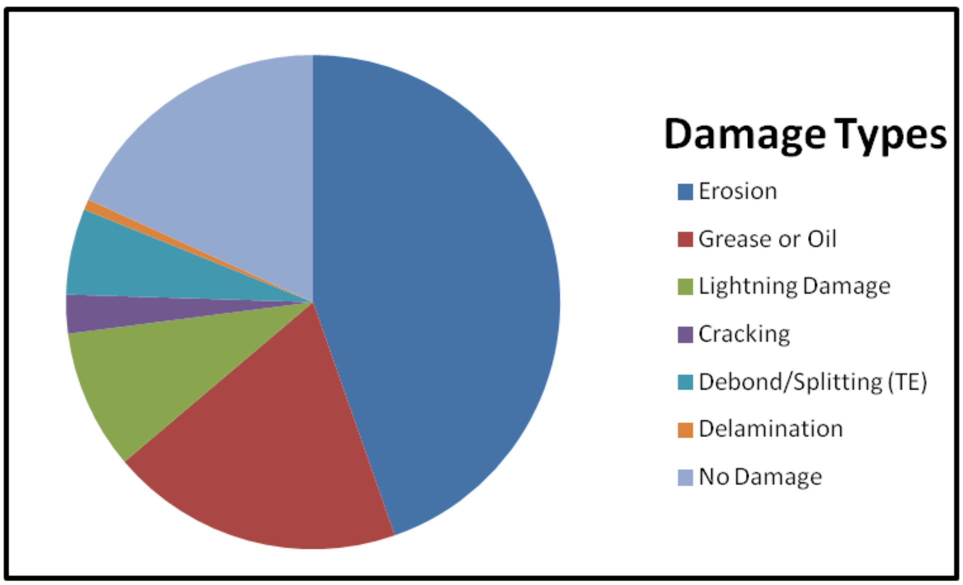

Figure 8: Damage Types

6.3.2 Erosion

Almost every data source experienced erosion to some extent. This varied from small areas of "pitting" through to larger areas where the exterior coating was worn away and exposing damaged laminates (Figure 9)

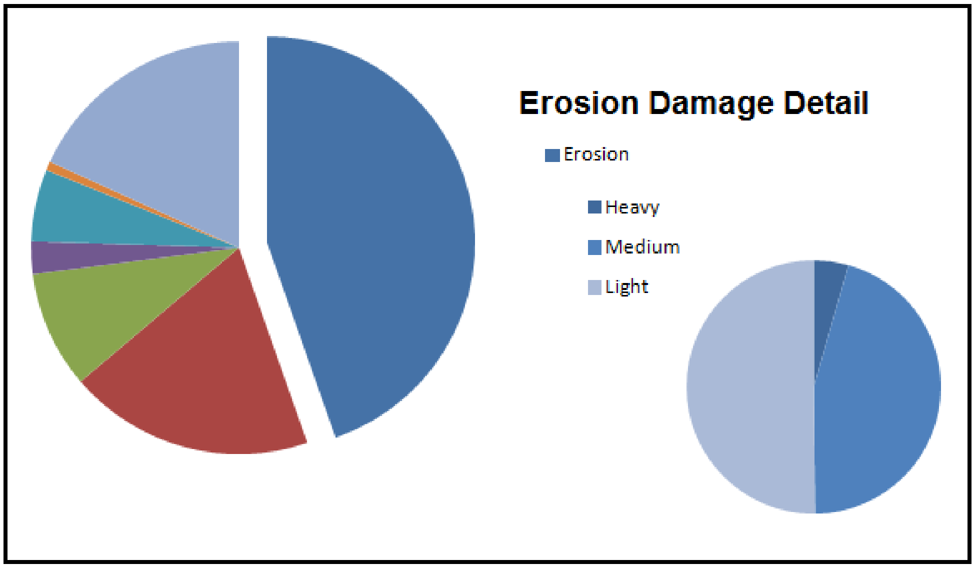

Figure 9: Erosion Damage Detail

6.3.3 Leading Edge Erosion

A substantial portion of the erosion seen occurred on the leading edge of the blades (Figure 10)

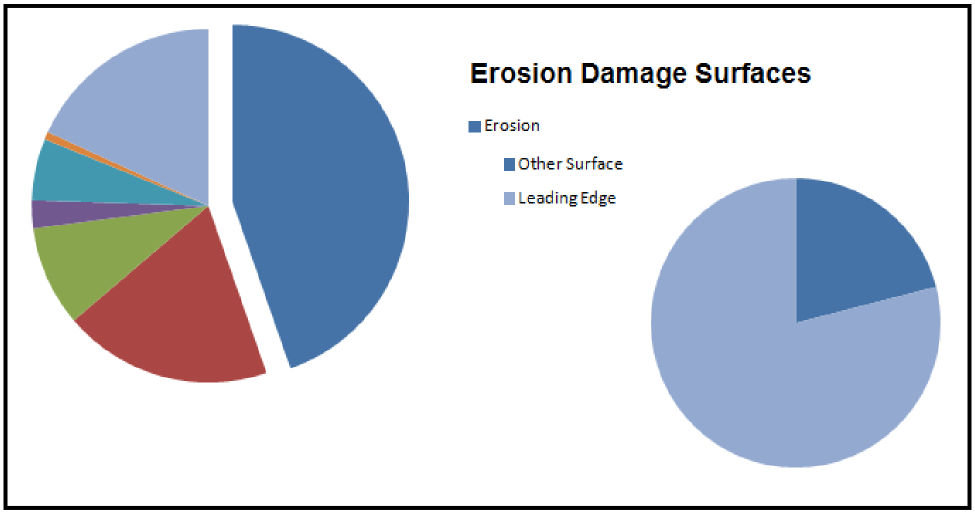

Figure 10: Erosion Damage Surfaces

6.3.4 Lightning Damage

Numerous blades at numerous plants displayed damaged by lightning. There were also a number of occurrences where lightning is suspected, but not confirmed.

7.0 ANALYSIS AND SIMULATION OF DEFECTS

As is evident in the previous discussions of published, anecdotal and survey information, there are a wide variety of defects that can occur in blade manufacturing or appear during operation. Because there is insufficient data to rank order the importance and occurrence of blade defects in a statistically relevant manner, the BRC has identified a few types of defects that are very common. These are being simulated and analyzed by members of the Blade Reliability Collaborative.

7.1 MSU Efforts

In support of the BRC, Professor Doug Cairns and his students at MSU have been performing work in two areas – Flaw Characterization and Effects of Defects. MSU research has the primary goal in supporting the BRC (and ultimately reducing the number of flawed blades that end up becoming operational) of developing a tool for use in quantifying the effects of as-built blades that contain defects. There are two parts of the MSU project that will lead to the development of this tool. As described in Ref. 9, the Flaw Characterization part will “acquire and generate flaw data that describes common defects in blades and develop a flaw severity designation system as as-built flawed structures.” As described in Ref. 10, the second part, Effects of Defects, will “develop the modeling capabilities to predict the mechanical response of flaws” described in the Flaw Characterization portion. Since the full characterization of failed and flawed blades is not complete, a rank order of critical flaw types is not complete at this time. To get started, MSU, with concurrence from the BRC, is investigating two types of flaws: porosity and laminate waves, both in-plane and out-of-plane.

Wave and porosity data were collect from a set of four blades and studied to determine sets of standard wave forms for use in substructure fabrication and companion analysis. Figure 11 shows an image of a wave on a blade section used in the data collection. Waves were discretized (Figure 12), fit with sine wave curves and characterized in terms of wavelength, amplitude and off-axis fiber angle. Further data analysis yields frequency of occurrence of a variety of wave types. Characterization of porosity can be difficult and MSU uses a microscopy technique to identify the location and size of gas inclusion. Figure 13 shows an SEM of a cross-section used to porosity test specimen. Many wave forms were collected as described in Ref. 9 are scaled in order to build coupons with wave variations. Ref. 9 also begins developing a set of criticality and severity parameters for use in the overall analysis tool to be developed. Results of the testing of coupons and companion analysis are detailed in Ref. 10.

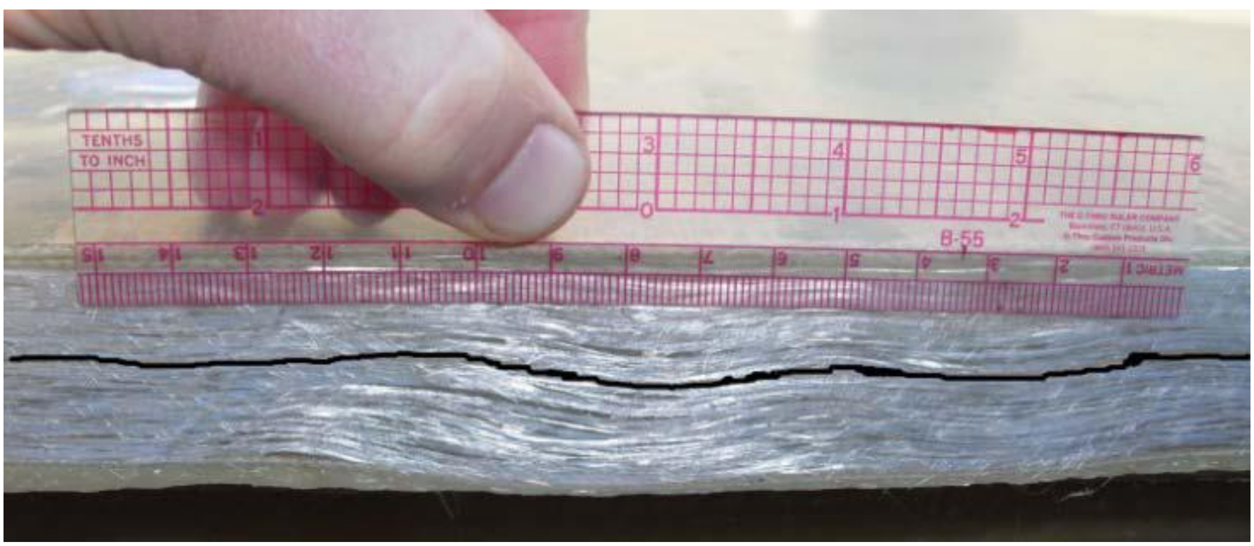

Figure 11: Measuring Waviness on a Blade Section

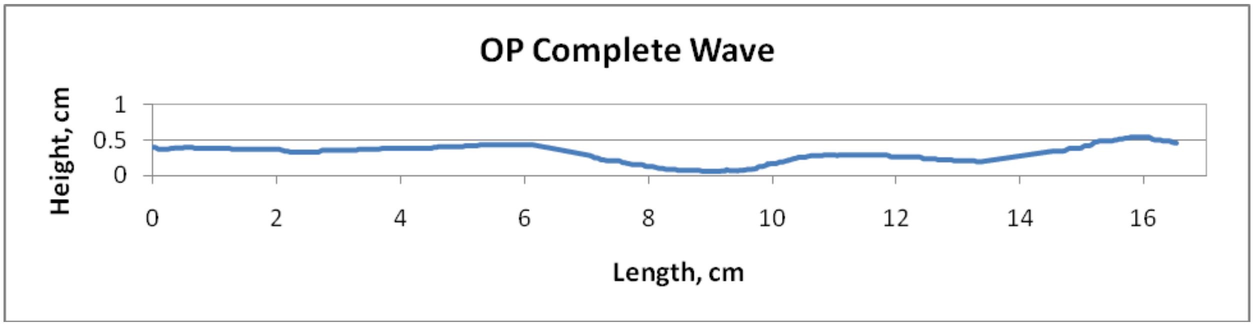

Figure 12: Example of Discretized Out-of-Plane Wave

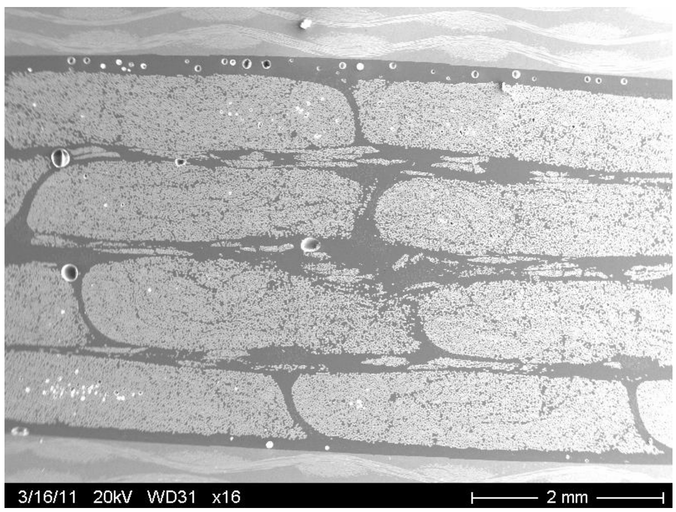

Figure 13: SEM of a Porosity Test Specimen

8.0 NON-DESTRUCTIVE INSPECTION TECHNIQUES FOR DEFECT IDENTIFICATION

In the area of non-destructive inspection for wind turbine blades, Sandia has been performing a significant amount of work for BRC. The objectives of the Inspection Validation task are to:

- Develop, evaluate and validate the array of potential nondestructive inspection methods for the detection of flaws in composite wind turbine blades
- Plan and implement a nation capability to comprehensively evaluate blade inspection techniques
- Produce optimum deployment of automated or semi-automated NDI to detect undesirable flaws in blades

This ongoing work was recently presented at a BRC meeting in July in Albuquerque [11]. This work has started with an initial screening of NDI methods to determine those that show the greatest promise for flaws detection on the manufacturing floor and in the field. Currently, the team has designed and fabricated a variety of flaw types into plates and other substructures. This is followed by the inspection of blades using a variety of NDI methods to understand challenges and ability to detect flaws. Figure 14shows some of the flaw types engineered into a flat plat and Figure 15 shows shear web and foam core specimens with engineered defects. Types of NDI methods used so far include:

- Phased Array UT with Water Shoe
- Pulse-echo UT Focused Probe

In addition the AANC (Dennis Roach and crew) have established a Wind Inspection NDI Experiment (WINDIE) that has over 20 team member that will that use their particular techniques to compare their ability to detect a standard set of defects [11].

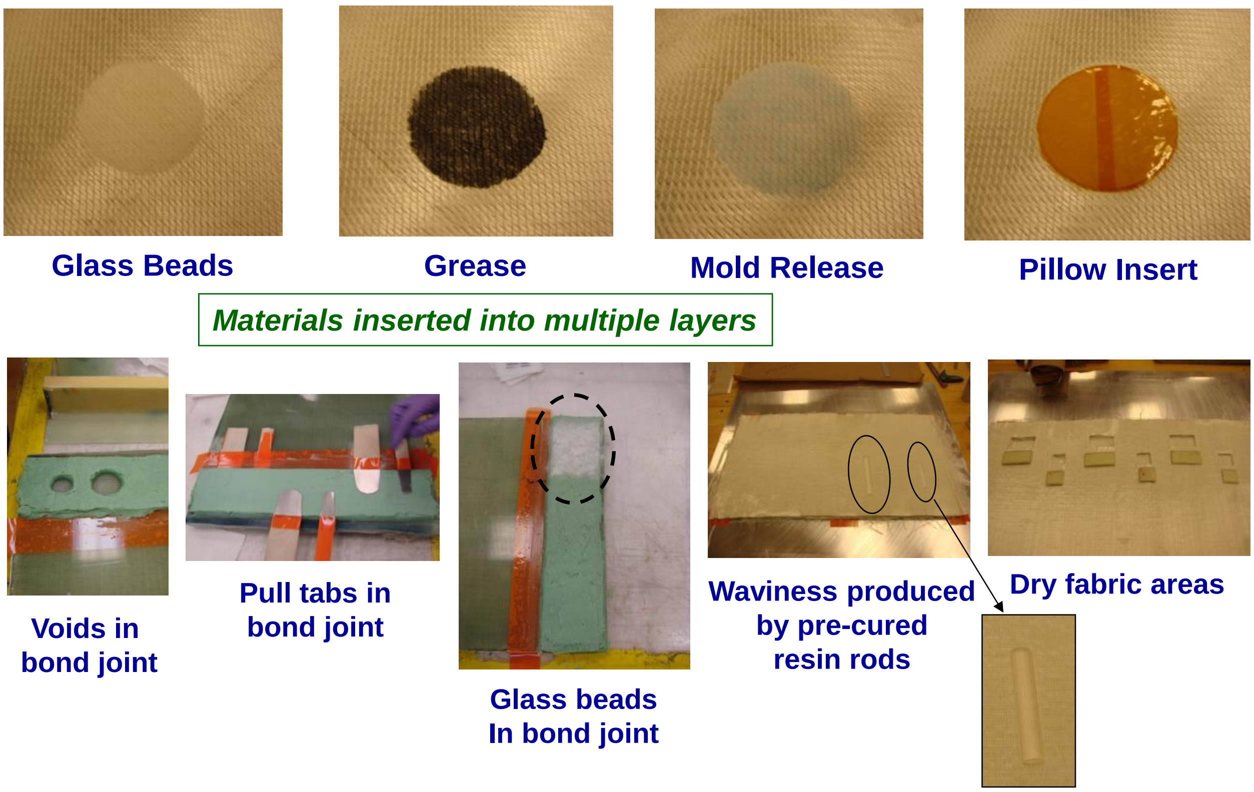

Figure 14: Different Flaw Types Engineered into NDI Feedback Specimens

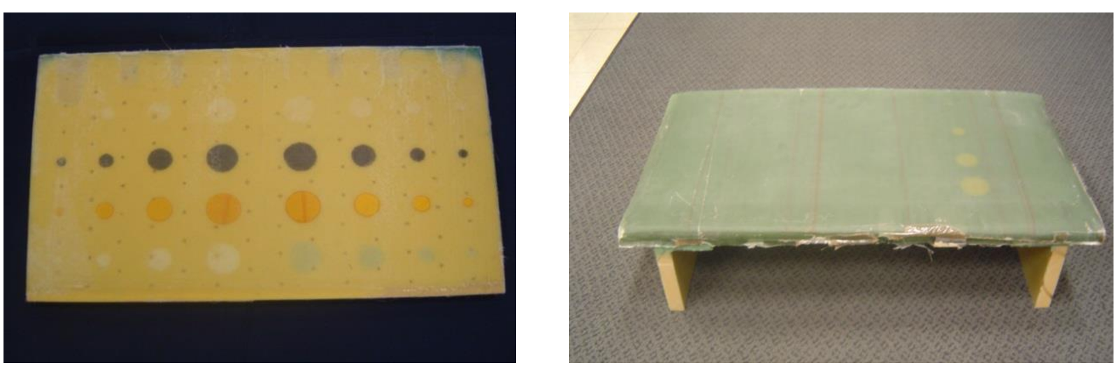

Figure 15: Foam Core with Disbonds and Delaminations (L) and Shear Webs with Waviness and Dry Regions (R)

The University of Massachusetts at Lowell, which is a member of BRC, has also been studying the effects of defects with engineered flaws in a CX-100 blade starting with digital imaging correlation (DIC).

8.1 DISCUSSION AND CONCLUSIONS

The Blade Reliability Collaborative (BRC) is using data gathering, forensics, simulation, testing and inspection to understand the types and causes of blade defects in turbine blades today, quantify those defects, and develop ways to determine the effects of these defects. The goal of the Defect, Damage and Repair Survey task is to collect data both from operating and repair companies and from reported information. This document discusses the to-date results of this data gathering effort. This report also summarizes the ongoing efforts in the other areas of BRC; 1) the analysis evaluation and inspection validation, modeling of two initial defects (waviness and porosity) and testing of coupons fabricated with these initial defects and 2) the characterization of NDI capabilities on engineered flaws in composite plates and blade substructures.

An overall summary of the types of defects or damage that are most commonly mentioned so far:

- Waviness or wrinkles
- Debonding
- Lightning damage
- Leading edge erosion
- Porosity or bubbles
- Skin cracking
- Transport damage

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