Montana State University

Blade Reliability Workshop

July 20-22, 2010

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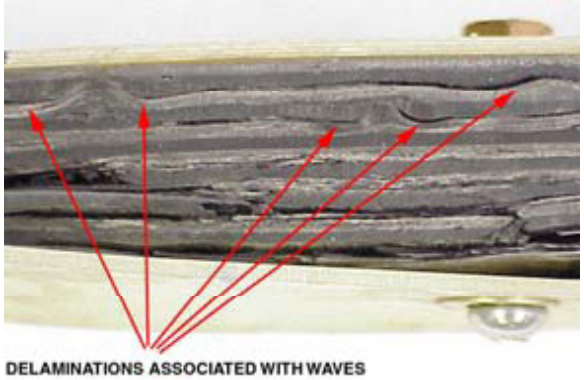
Outline

- Background & Rationale
- MSU’s role: Effects of Defects
- Project Overview
- Research Update

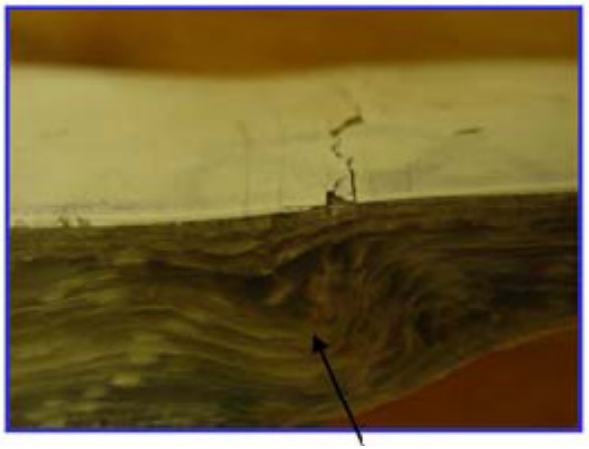
Reliability Issues

- Non-trivial number of blades in service require replacement or repair
  - Leading causes: manufacturing defects and lightening strikes
- Suzlon retrofit (Feb 2010): resolve crack issues
  - 6 months, $25 million
- Improving manufacturing is low-hanging fruit for improved reliability
  - Flaws just as harmful for large structures
  - Large structures have increased likelihood of flaws

Wind Turbine Blade Reliability – Not Just an Academic Problem



Delaminations in a Low-Cost Composite Structure



Glass Fiber Reinforced Wind Turbine Blade Local Failure at a Manufacturing Flaw

Field Failure of a Wind Turbine Blade (Judith Gap Montana 2009)

Impetus for Work

- Premature blade failures are often at manufacturing anomalies
- Composite Wind Turbine Blades have high potential for defects
  - Low cost manufacturing
  - Large material in homogeneities
  - Complicated geometrical transitions
- No industry consistency for treatment of defects
  - One manufacturer's acceptable defect may be unacceptable
  - Decision for reject or repair inconsistent

However, defects and geometric discontinuities have a quantifiable effect on the durability and damage tolerance of composite material structures

Blade Reliability Collaborative (BRC)

- SANDIA, NREL, MSU, Industry and University Partners

- Improving reliability of wind turbine blades
  - Blade Field Survey
  - Inspection Validation
  - Effects of Defects
  - Design Analysis and Validation
  - Certification and Full Scale Testing
  - Partnership Development

Montana State University's Role in the Blade Reliability Collaborative

To understand and quantify the effects of manufacturing discontinuities and defects with respect to wind turbine blade structural performance and reliability.

Parallel Path MSU Projects

Goal: Improving reliability of wind turbine blades

- Comprehensive understanding of failures
- Classification of defect types
- Establish criticality metric: probabilistic reliability methodologies
- Plan for implementation at manufacturing level

- Flaw Characterization (FC)
  - Interpreting Non Destructive Evaluation (NDE) data
  - Quantifying defect to level that it can be used in effect of defects models
- Effects of Defects
  - Characterize damage growth and residual strength of specified flaw types

Full Initiative: Time Line

[Based on Veers Rev0, Actual Dates TBD based on current schedule]

- Survey Dist
- Model Dev Begins

- FC Metric dev
- Effects of Defects
  - Rd 1 Complete
  - Rd 2 Begins

- Effects of Defects
  - Rd 2 Complete

- Effects of Defects
  - Rd 3 Complete

Spring 2010	Summer 2010	Fall 2010	Spring 2011	Summer 2011	Fall 2011	Spring 2012	Summer 2012

- Database Population
- Onsite ND & MFG Eval
- Physical Testing Begins

- 1st Interim Report
- First iteration of flaw severity

- 2nd Interim Report
- Effects of Defects
  - Rd 3 Begins

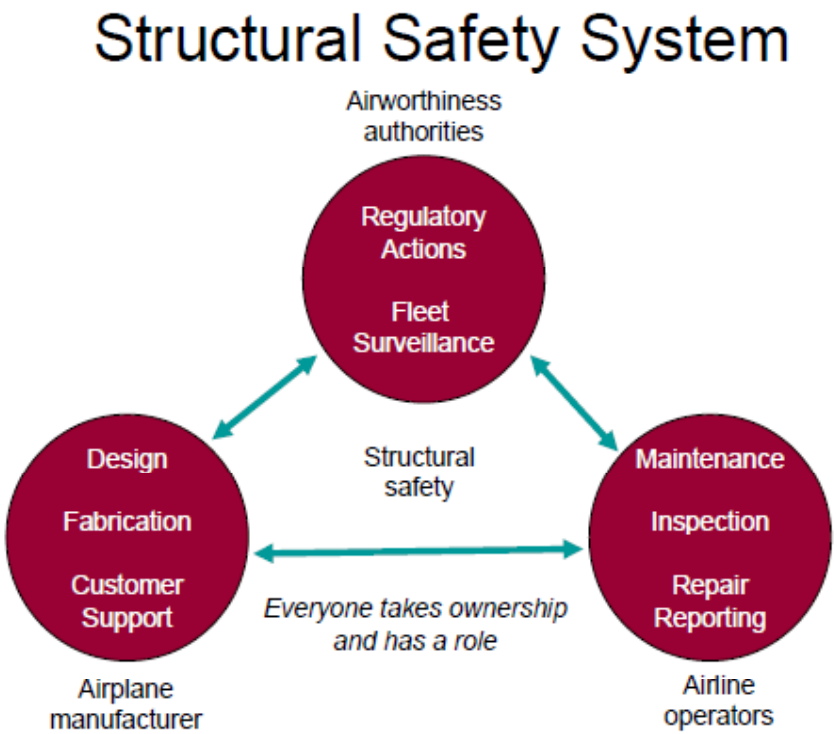
- Final Characterization report (F2F Code validation)

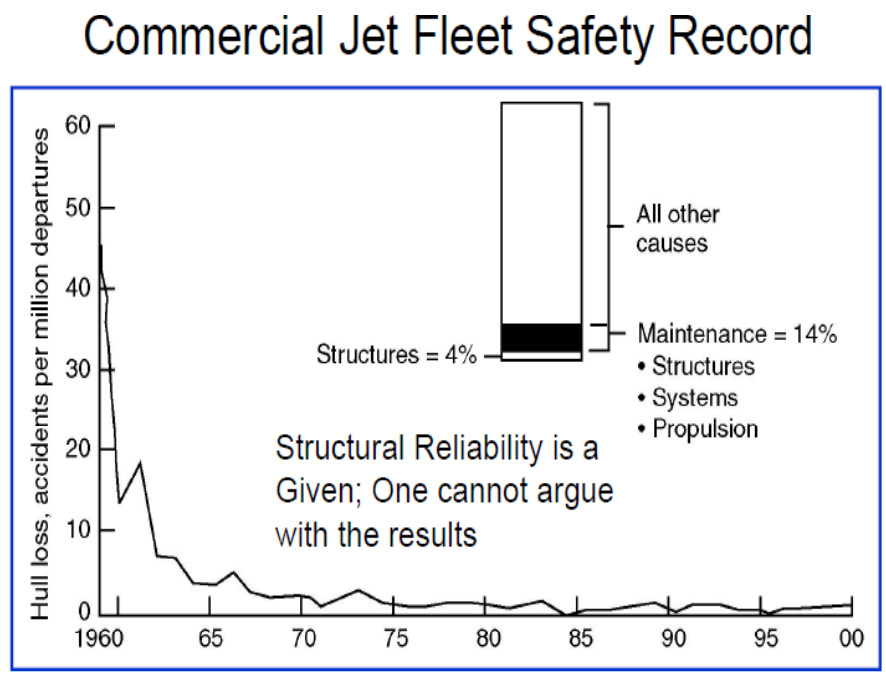
Reliability: Damage Tolerant Design Analogs

- Government regulates by defining safety and reliability requirements
- FAR 25.571:

  "An evaluation of the strength, detail design, and fabrication must show that catastrophic failure due to fatigue, corrosion, manufacturing defects, or accidental damage will be avoided through the operational life of the airplane"

Reliability: Aerospace Analogs



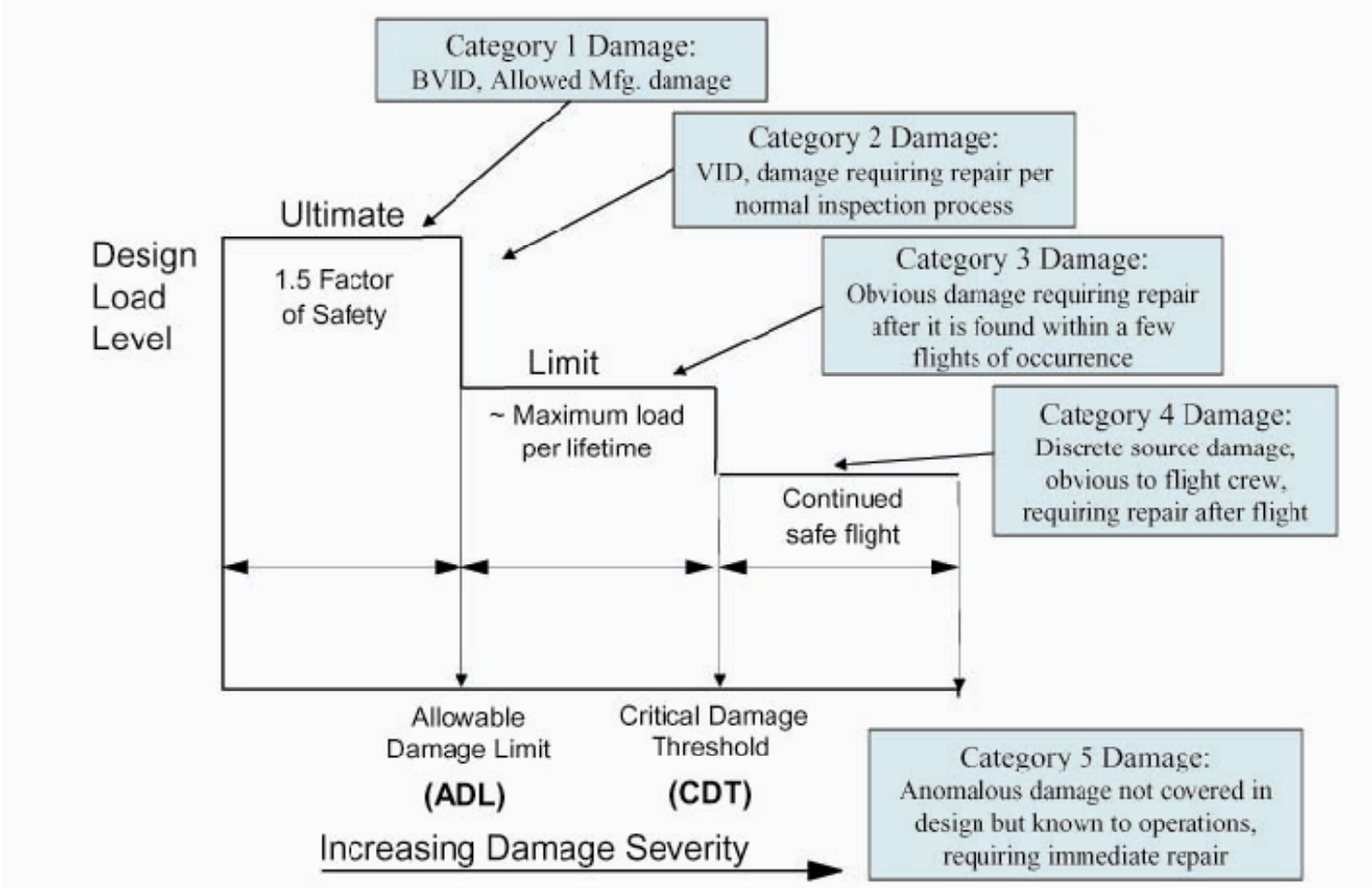


Can an affordable, meaningful approach be developed for wind turbine blade reliability?

Reliability: Composite Structures

- Composites Material Handbook (CMH) 17-3F: composite component conformity
  - Detailed manufacturing records
  - Understanding of effects of defects (damage tolerance and residual strength) to establish compliance
  - Establish inspection intervals
  - Repair/replace protocol

Reliability: Damage Tolerant Design Analog – Defect Criticality Quantification



Note: A similar hierarchical approach has been adopted and implemented by wind turbine operators for gearbox reliability

Flaw Characterization: Outline

Goal: Quantifying defects to level that they can be used in effect of defects models

1. **Database Investigation**: Interpretation of flaw data
   - Development of defect quantification metrics
   - Criticality analysis, reliability eng, database development
2. **Interpreting NDE data**
   - Develop metrics which define the critical geometric parameters of manufacturing flaws
   - Develop Image processing procedure to translate NDE data into a 3D for use in FEA structural analysis
3. **Comprehensive flaw impact study**
   - Incorporate statistical & finite element analysis
   - Development of probabilistic models

Flaw Characterization : Database Investigation

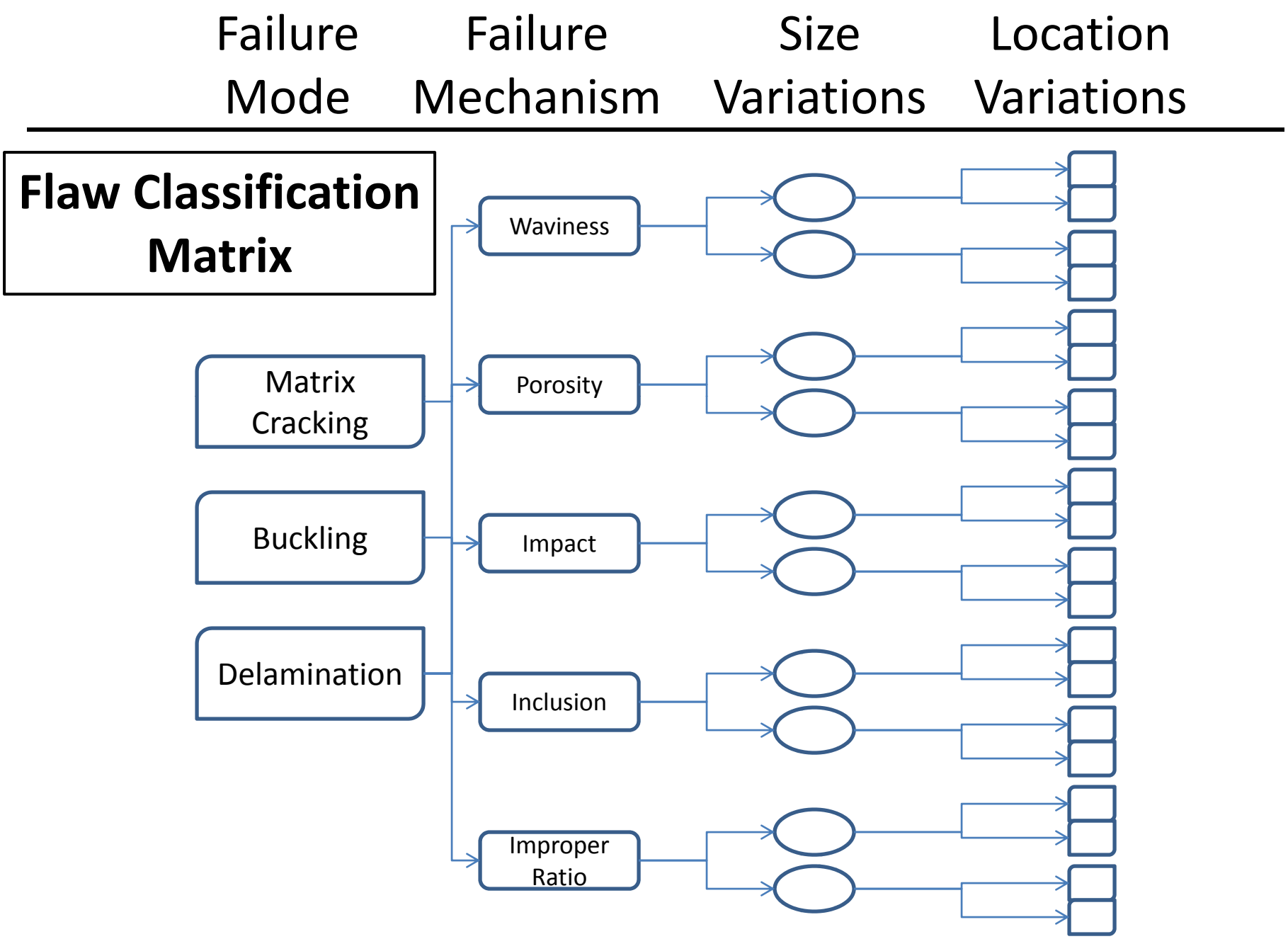
- **BRC – Sandia Blade Survey** (overview)
  - Types of damage (% of total)
  - Replace & Repair Numbers
  - Inspection Program
  - Downtime
- **MSU Follow-up Survey** (detailed)
  - *Manufacturing Defect* Type, Size, Location & Frequency
  - Specific Flaw & Failure Instance Reporting
  - Failure Mode & Time to Failure
  - Materials & Ply Schedule

Flaw Characterization: Comprehensive Database Development

- Structural design capability (Effect of Defects)
  - Initially generic, then iterative with modeling
  - Damage resistance & growth criteria, residual strength
- Environmental influence
  - Impact of temperature variations
  - resistance to fluids and UV radiation
- Manufacturing influences, ability to detect and repair
- Materials, laminate schedule and size of blade/turbine
- Failure modes
- Compounding nature with undetectable flaws
- Frequency of flaw occurrence: type, size, location

Flaw Characterization: Classification Metric

- Statistical relevance of flaw occurrence
- Incorporation of inspection limitations
  - Flaws that are there but we can't see them
  - Failed blade sections postmortem
- Severity designation (iterative)
  - Ranking of database criteria severity in relation to each other
  - Scoring flaw designations for each criteria
- Develop metrics which define the critical geometric parameters of manufacturing flaws

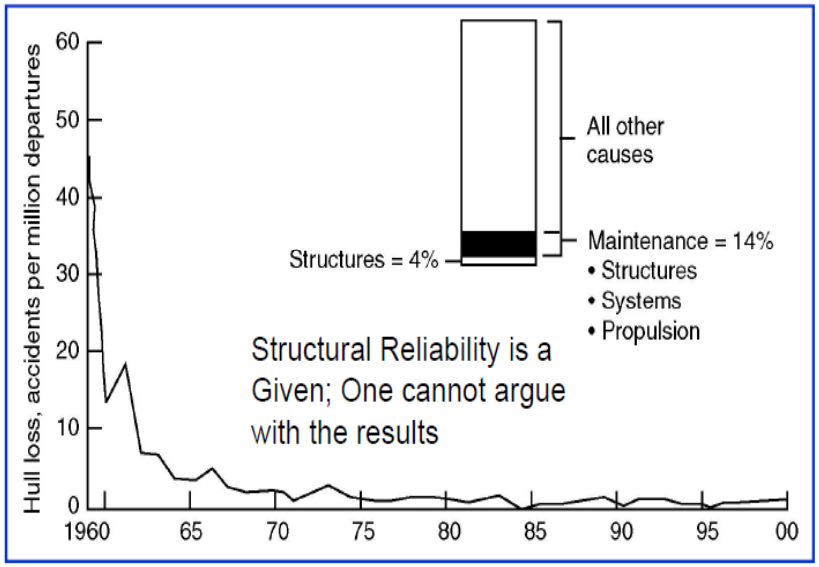

Failure Mode
Failure Mechanism
Size Variations
Location Variations
Flaw Classification Matrix
Matrix Cracking
Buckling
Delamination
Waviness
Porosity
Impact
Inclusion
Improper Ratio

Impetus for Quantitative Defect Analysis

- The first step to fixing a problem is to define the problem (Blades Fail Early) and a root cause (Manufacturing Defects)
- Quantification of defects -> development of effective reliability program
- Systematic reliability approach works

Goal: to develop an affordable approach for wind turbine blade reliability

Commercial Jet Fleet Safety Record



Flaw Characterization:
Criticality Analysis – Quantitative Cont.

- Failure Effect Probability [β]
- Failure Mode Ratio [α]
- Failure Rate [λp]
- Operating Time [t]
- Modal Criticality Number [C_m]

  $C_m = \beta \cdot \alpha \cdot \lambda_p \cdot t$
- Item Criticality Number [C_r]

  $C_r = \sum (C_m)$

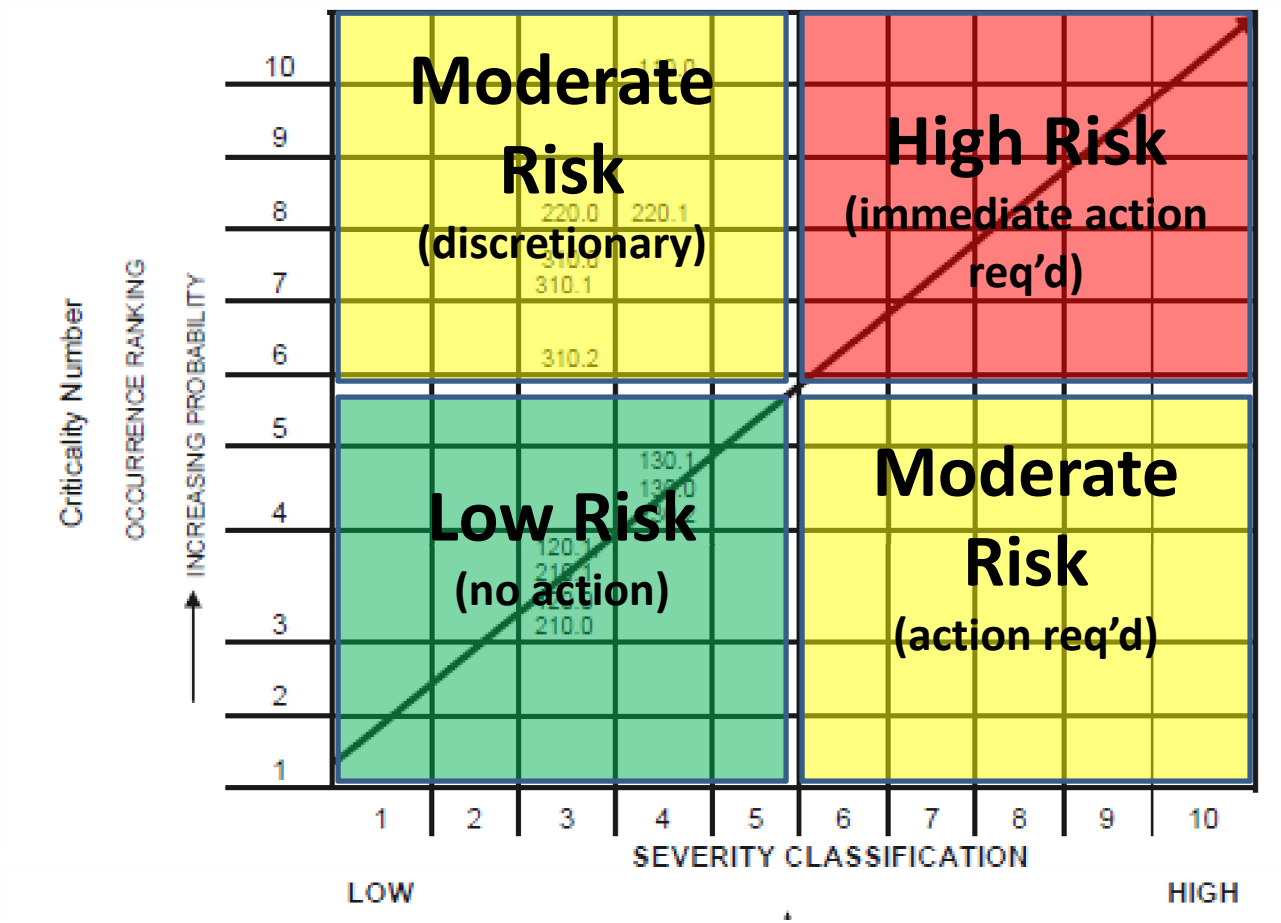
Flaw Characterization: Example Severity Categories

Ranking	Time of Detection	Comment
1	Manufacturers floor	Least impact, relative ease of repair/replace
2	In field, prior to install	Middle impact
3	Installed on operating turbine	Most expensive repair/replace

Ranking	Effect	Comment
1	<10% reduction in residual strength	
2	10-20% reduction in residual strength	
3	20-30% reduction in residual strength	
4	30-40% reduction in residual strength	
5	40-50% reduction in residual strength	
6	50-60% reduction in residual strength	
7	60-70% reduction in residual strength	
8	70-80% reduction in residual strength	
9	80-90% reduction in residual strength	
10	>90% reduction in residual strength	

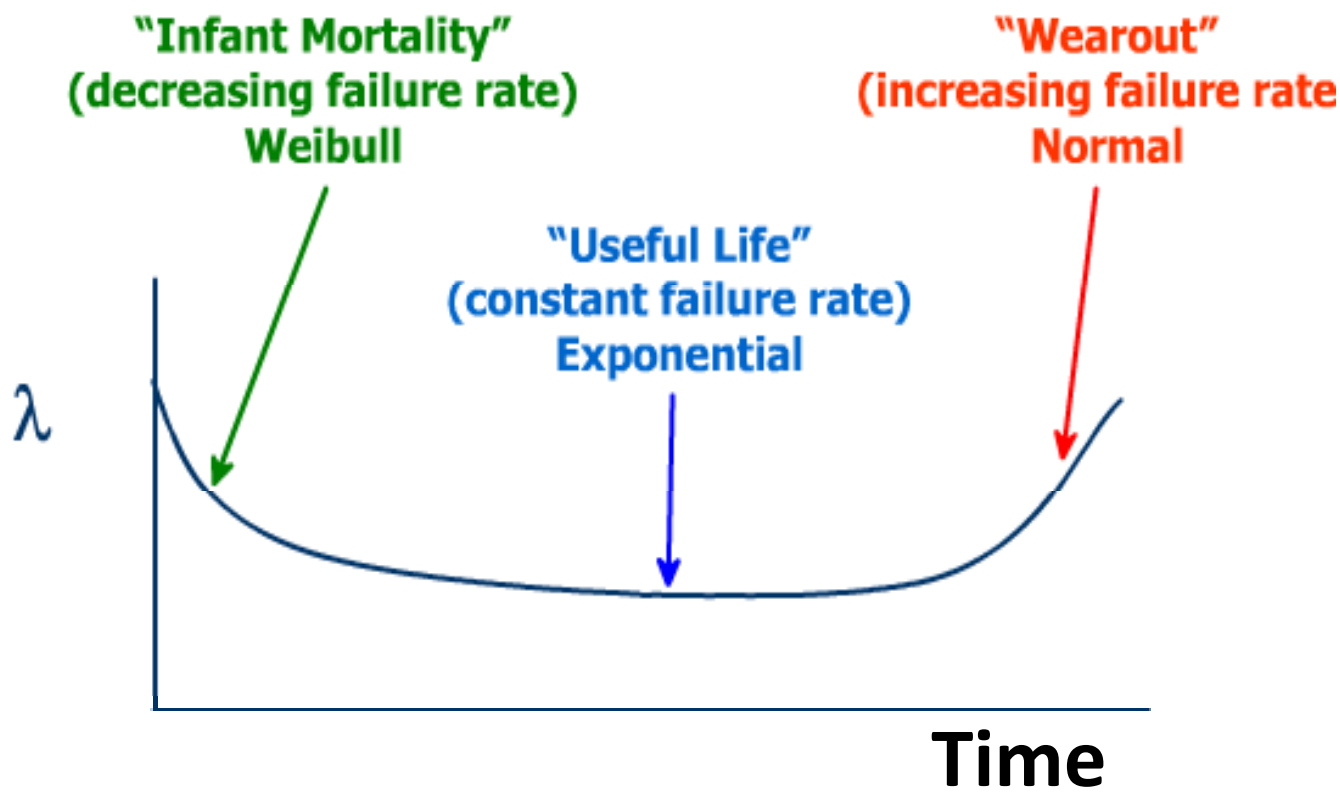
Flaw Characterization: Criticality Ranking

- Sort database by Cm, Cr, RPN, Severity
  - Build Graphical Criticality Matrix



Flaw Characterization: Reliability Life Cycle

- Develop Industry Wide Reliability Life Cycle Analysis



Source: Quanterion Solutions

Flaw Characterization

- Generate statistically relevant flaw distribution data
  - Manufacturers: NDE blades on floor
  - NREL/Sandia: Failed and to be tested blades
  - Developers/Operators: NDE Blades at wind farms
- Onsite (manufacturer) research into manufacturing process that lead to defect introduction, discrepancy reports

Success for Flaw Characterization Requires Input and Participation from all BRC Members

Utilization of the Flaw Characterization for Effects of Defects

- Combine survey data and NDE data
- Define geometric parameters of critical flaw types to investigate (experimentally and analytically)
- Build virtual solid models
  - Either CAD or FE software
- Apply permutations to flaw shape and mesh

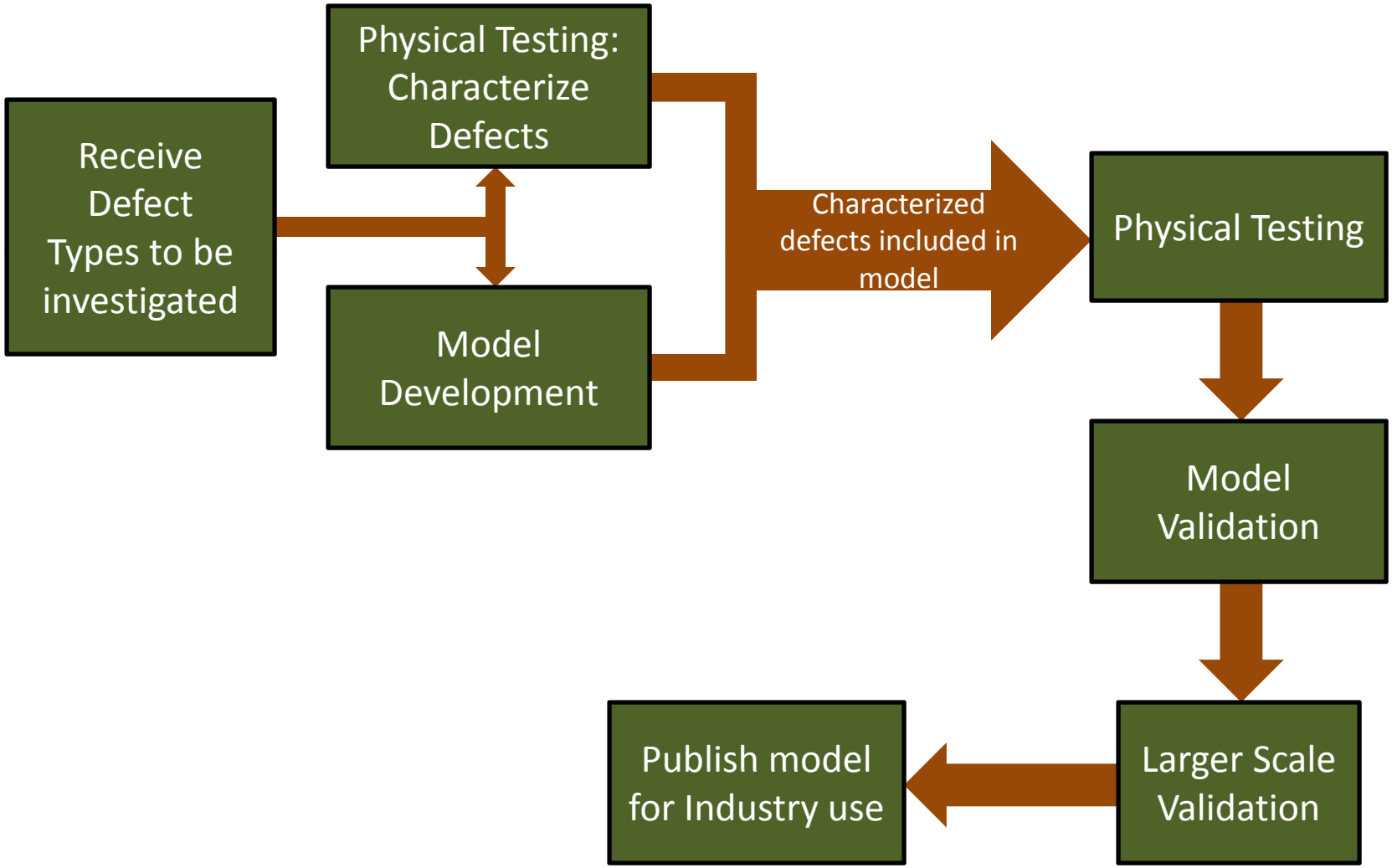
Effects of Defects: Project Goals

- Overall Goal:

  Establish the necessary damage growth and validation tools of composite wind blades to contribute toward a reliability infrastructure for the wind industry.

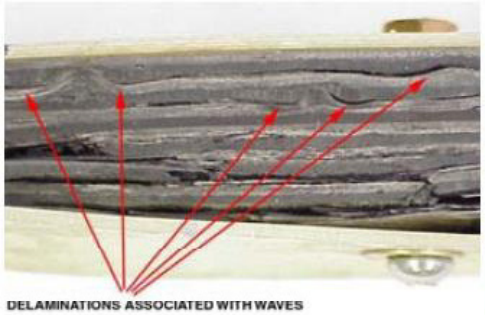
- Research Outline:
  - Characterize the mechanical properties of common critical defects
  - Develop coordinated analytical and experimental analogs for residual strengths and damage growth
  - Determine the criticality threshold of each flaw type
  - Understand how flaws contribute to the entire structure

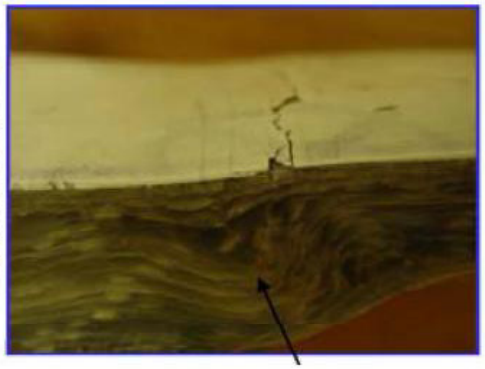
Effects of Defects: Project Summary



Effects of Defects: Typical Manufacturing Defects

- Porosity
- Debonding
- Delaminations
- Improper Matrix Distribution
- Fiber misalignment
- Improper Fiber/Resin Ratio
- Bonding defects
- Foreign Inclusions
- Incompletely cured matrix
- Matrix Cracking





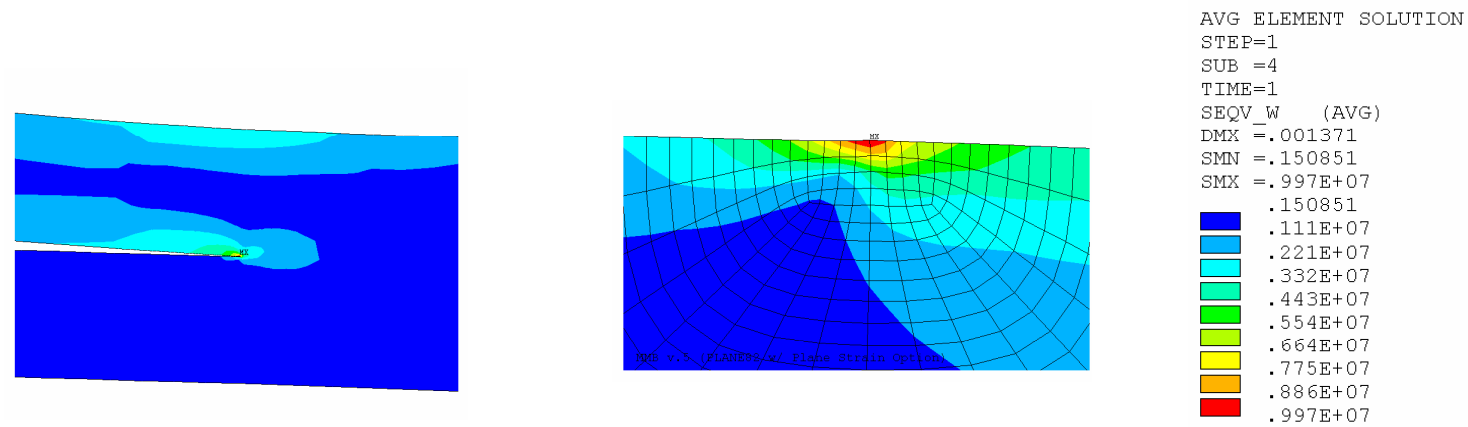
Effects of Defects: Round 1—Outline

- Establish a characterization of mechanical properties of each defect type for model development
  - Key defect types determined by BRC
- Parallel Path:
  - Model development
  - Physical (Static) testing of defect laden parts
    - Manufactured by TPI and MSU

Courtesy: NEi Software

Effects of Defects: Round 1—Model Development

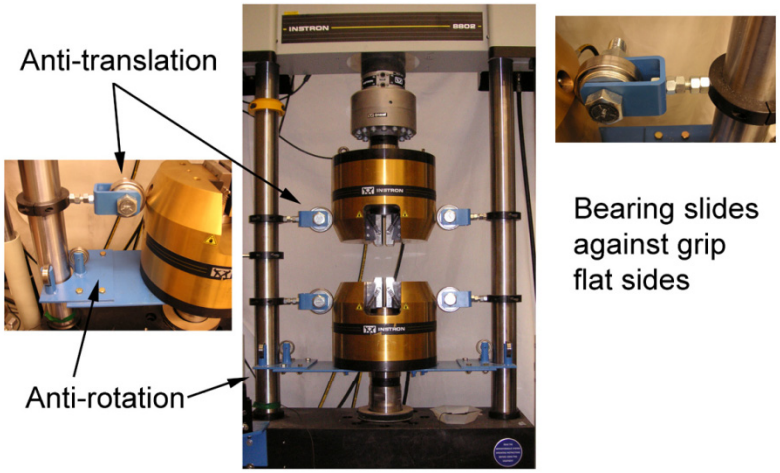
- Models will be generated for:
  - Each defect type
  - Varying defect size
  - Other factors deemed critical by BRC
- Models will be developed and tested for feasibility utilizing typical wind turbine blade material properties

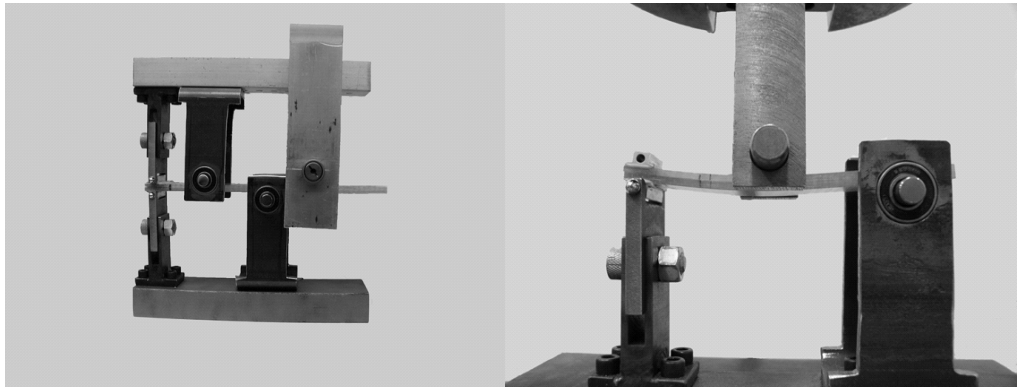


Courtesy: Tiok Agastra

Effects of Defects: Round 1—Static Testing

- Simple In-Plane
  - Tensile, Compressive and/or Shear
  - ASTM D 3039, 695, and 3518
  - Establish baseline and residual strength for comparison
- Out-of-Plane
  - Double Cantilever Beam, End-Notch Flexure and/or Mixed Mode Bending
  - ASTM D 3433, 7078 and 6671
  - Establish baseline and residual strength for comparison

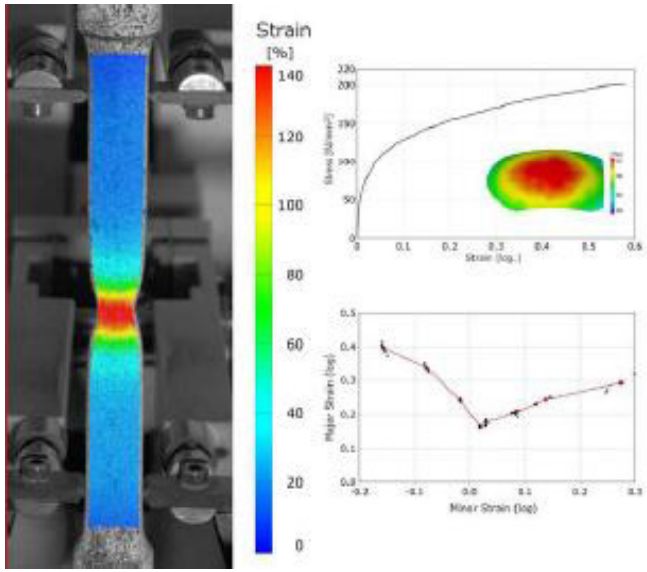




Effects of Defects: Round 1—Model Finalization

- Input data acquired from Static Testing into Models
  - Initial agreement between Testing and Models?

- Results of Static Testing and Model Development presented in Round 1 report



Aramis system in use during Tensile Test.

Effects of Defects: Experimental/Analytical Correlations

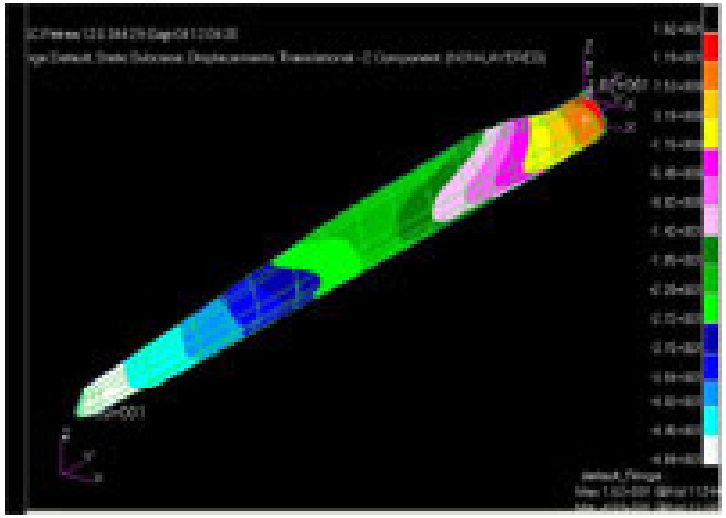
- Manufacture series of samples with *Quantifiable Representative Defects*
  - TPI and MSU
- Progressive Damage Testing
- Progressive Damage Modeling
  - Simulate testing configurations
- Correlation of data
  - Load/Deflection curves and key points in progressive damage/residual strength
  - Energy absorption
  - Strain fields
  - Others? (e.g. integrated sensors, intermediate NDE, etc.)

Effects of Defects: Round 2—Refined Experimental/Analytical Correlations

- Goal: Validate Models created in Round 1 and utilize further physical testing as needed to improve model accuracy.
- Additional defective parts will be modeled and tested for agreement of results
- Adjust Models as needed to achieve agreement between Models and Testing

Effects of Defects: Round 3—Larger-Scale Validation

- Goal: Develop Models toward full-scale blades incorporating multiple defects over larger areas.
- Increased scale from Rounds 1 & 2
- Testing of parts with several defect types, varying size and/or varying other critical defect features
  - Full Blade?
- Specifics to be outlined in Round 2 report
- Results presented in Round 3 report

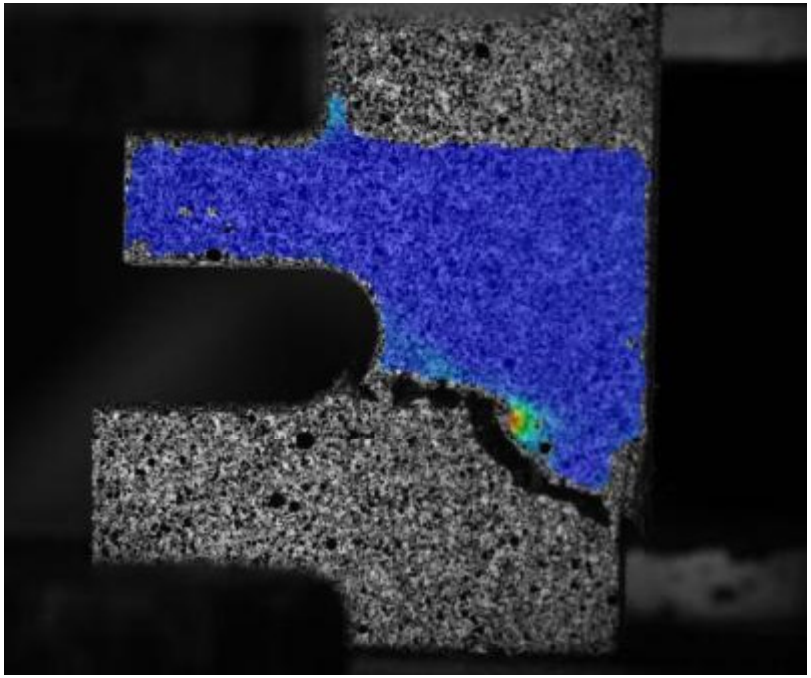


Courtesy: Solent Composites

Courtesy: LM Glasfiber

Effects of Defects: Update

- In-Plane Progressive Damage Testing of composites utilizing the ARAMIS system
  - Visual and empirical results



Summary – Flaw Characterization and Database

- Flaw Database Summary
  - Flaw distribution
  - Evaluation of How Defects are Introduced
- Flaw Characterization Analysis
  - Protocol for the interpretation of NDE data
  - Critical geometry metric
  - Severity classification system
- Flaw Catalog
  - Visual Inspection
  - Technician Oriented
- Validated, multiple source Effects of Defects reliability life cycle analysis

MSU BRC Summary

- Effects of Defects
  - Comprehensive understanding of wind turbine blade flaws
    - Damage progression and residual strength
    - Hand-in-hand with Flaw Characterization portion
  - Effects of flaws on composite structure based on size and location
  - Tool to assist in QC of blades based on included flaws
    - Section to full-scale blade analysis
    - Investigate probabilistic analysis and damage growth/residual strength criteria
  - Additional information to allow for successful Flaw Characterization research as necessary

Current Project and Future Goals

- A quantitative database of typical manufacturing flaws and probability of occurrence
- A validated approach for damage initiation and propagation near manufacturing defects and geometric discontinuities
- A collaborative government, university, industry hierarchy for addressing blade reliability
  - Certification and Regulation
  - Research Infrastructure and Education
  - Manufacturing and Maintenance