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2012 Sandia Blade Workshop

Incorporating the Effects of Defects with a Probabilistic Reliability Risk Assessment Framework

Presenter: **Trey Riddle**

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Sandia National Laboratories

Blade Reliability Collaborative (BRC)

Funded by Department of Energy

- Led by Sandia National Laboratories
- Collaborators include: Manufacturers, Academia, Wind Farm Maintenance, Government Investigators

Multi-year Program

- Blade Field Survey
- Inspection Validation
- Effects of Defects (MSU)
- Design Analysis Verification
- Certification & Full Scale Testing
- Partnership development

* **Friday Session – Josh Paquette**

Possibility of Catastrophic Failure

Recent (late April) blade failure in Ohio

- Blade debris was thrown more than 1000 feet from the turbine site

- Not considered a high wind event. Root cause unknown but thought to be anomalous

Defects!?!?

Key Elements of Reliability

Residual Strength Analysis with a Defect

+

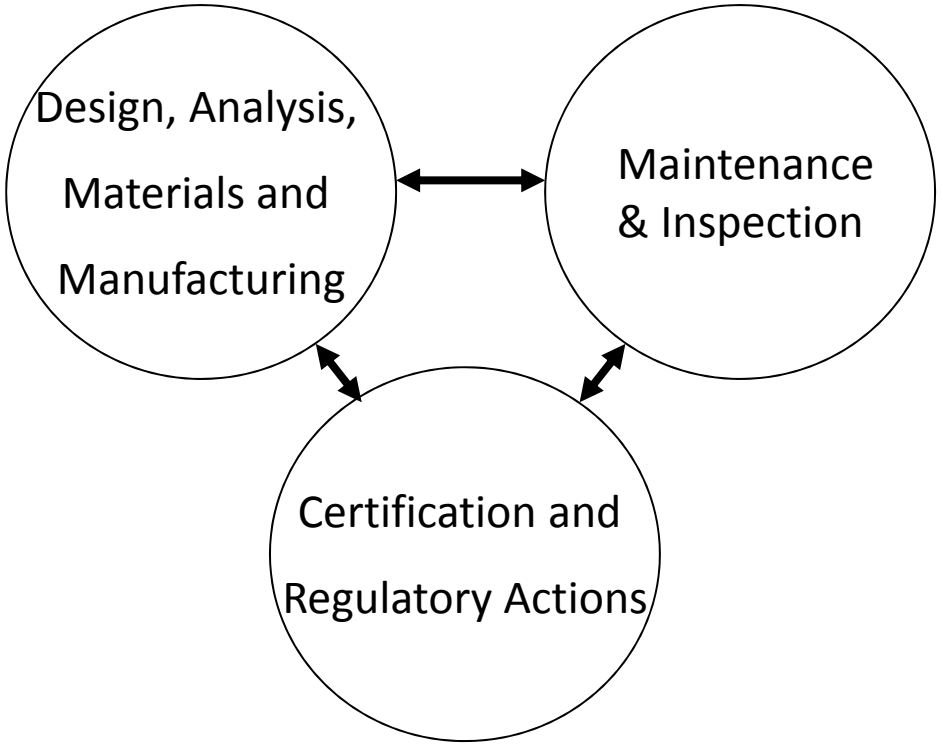
Progressive Damage Analysis (requires a damage growth model and accurate loads data)

+

Inspection Program

=

Negligible In-Service Failures



Successful Implementation Requires Participation and Integration from All Disciplines

Effects of Defects Task Summary

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

Goal: To improve/ensure blade life, improve probabilistic/damage tolerance methodology, minimize scrap rate, and minimize rework.

Task 1: Flaw Characterization

- Identify and characterize production manufacturing flaw geometries for Effects of Defects modeling.

Task 2: Effects of Defects

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

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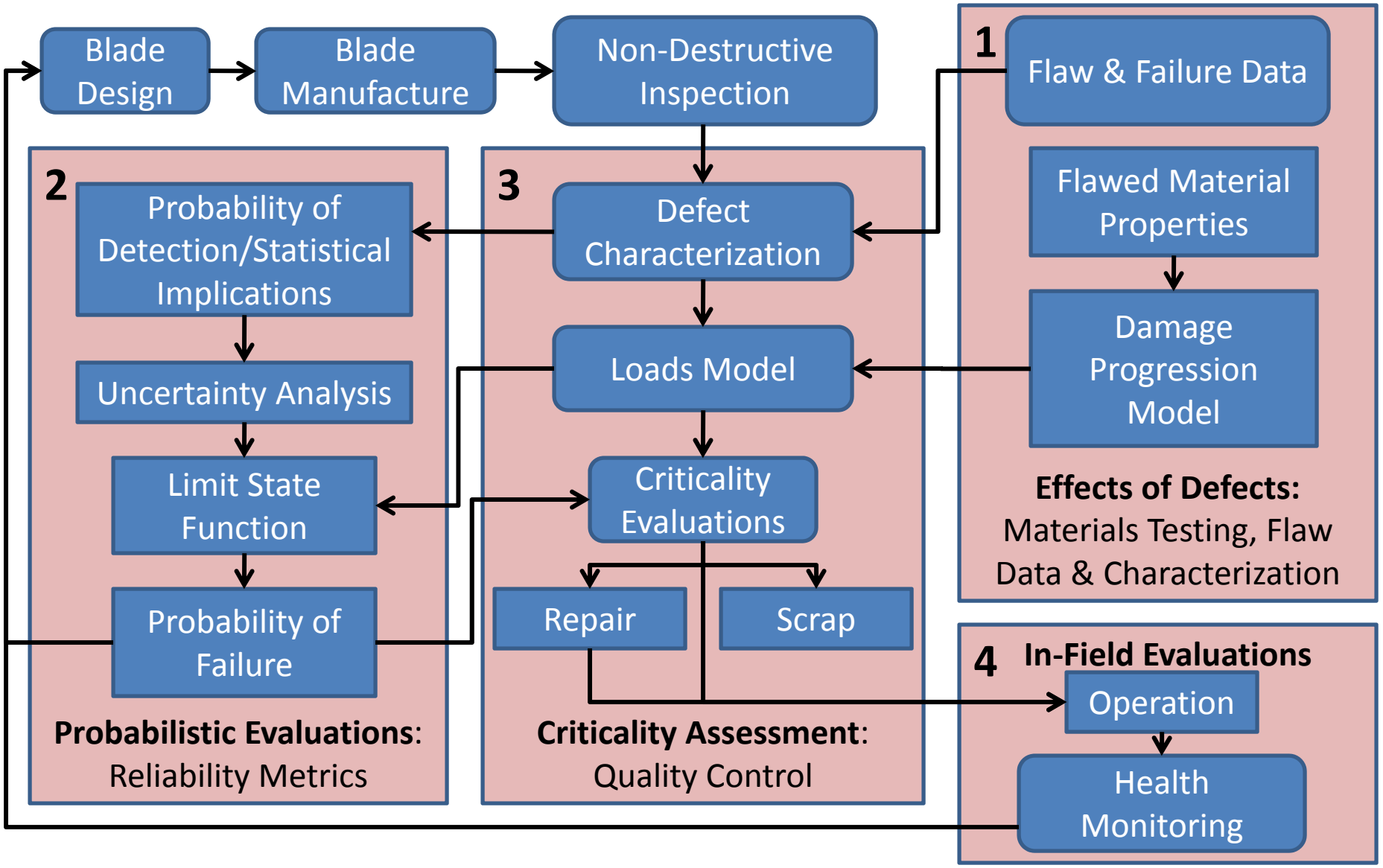
Defect Risk Management Framework



1. Effects of Defects

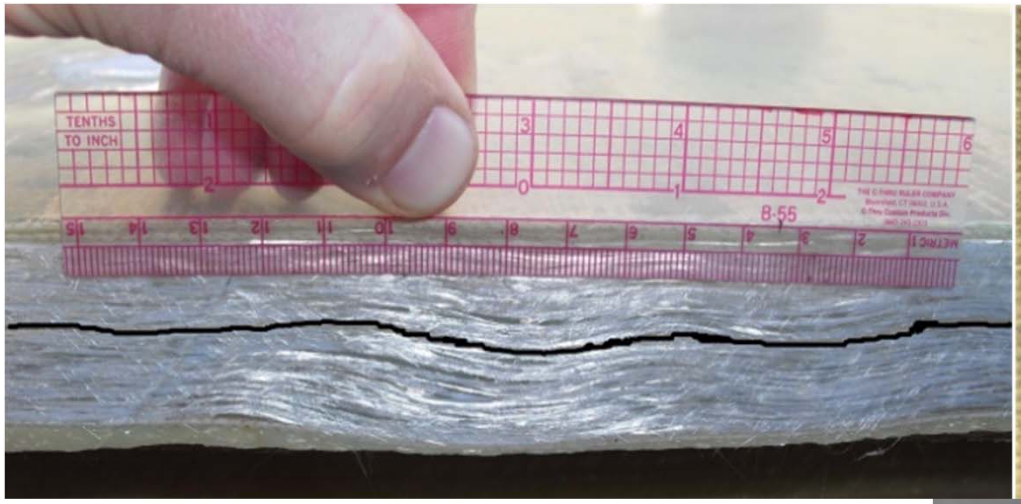
Key Elements:

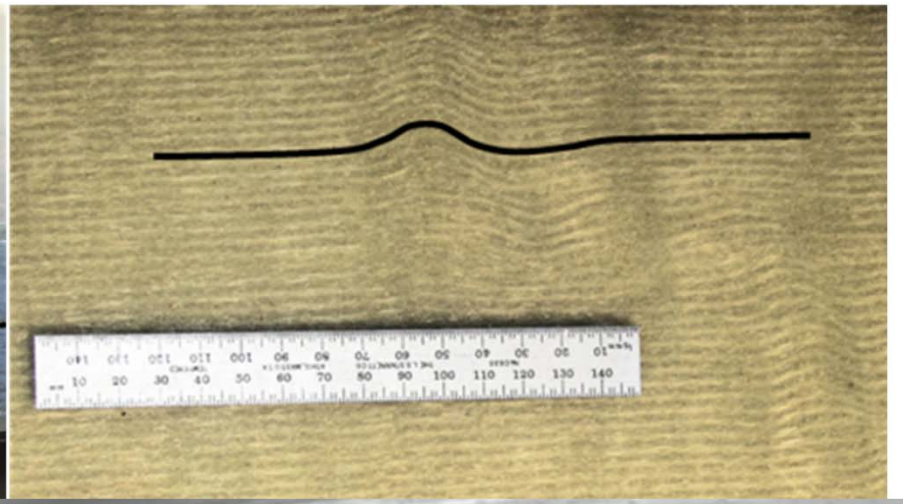
- Defect Field Data Collection
  - Develop metrics for characterization of flaws; geometric
  - Statistical analysis is performed on flaw types and sizes.
- Laboratory testing
  - Generate mechanical properties of flawed (and un-flawed) laminates which correlate to defect characterization parameters
  - Coupon level (4 ply), Thick laminate (8-20 plies), Substructure and subscale
- Development of a damage progression model
  - Assess the onset and evolution of damage
  - Nelson, et al (AIAA SDM, 2012)

Laminate Defect Types and Data Collection

Waves: Bending or waviness along fiber length

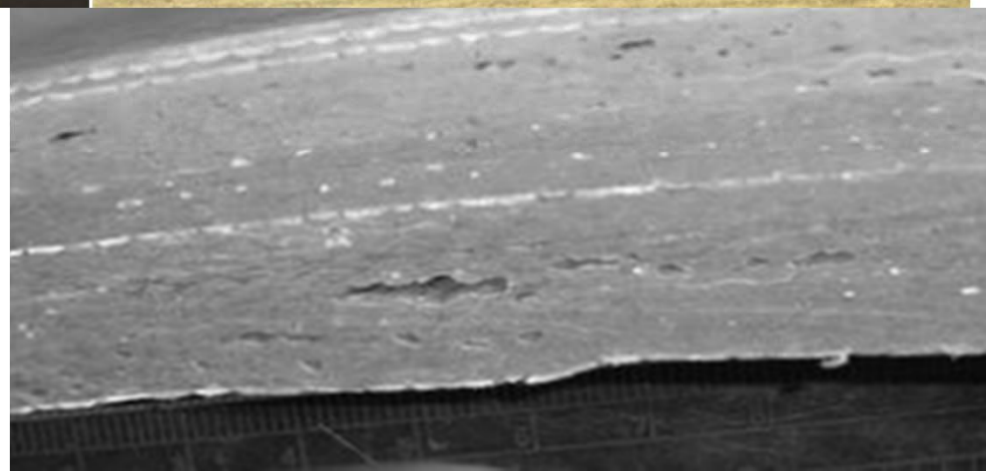
- In-plane (IP): fiber waves on surface (left)
- Out-of-plane (OP): fiber waves through thickness (right)

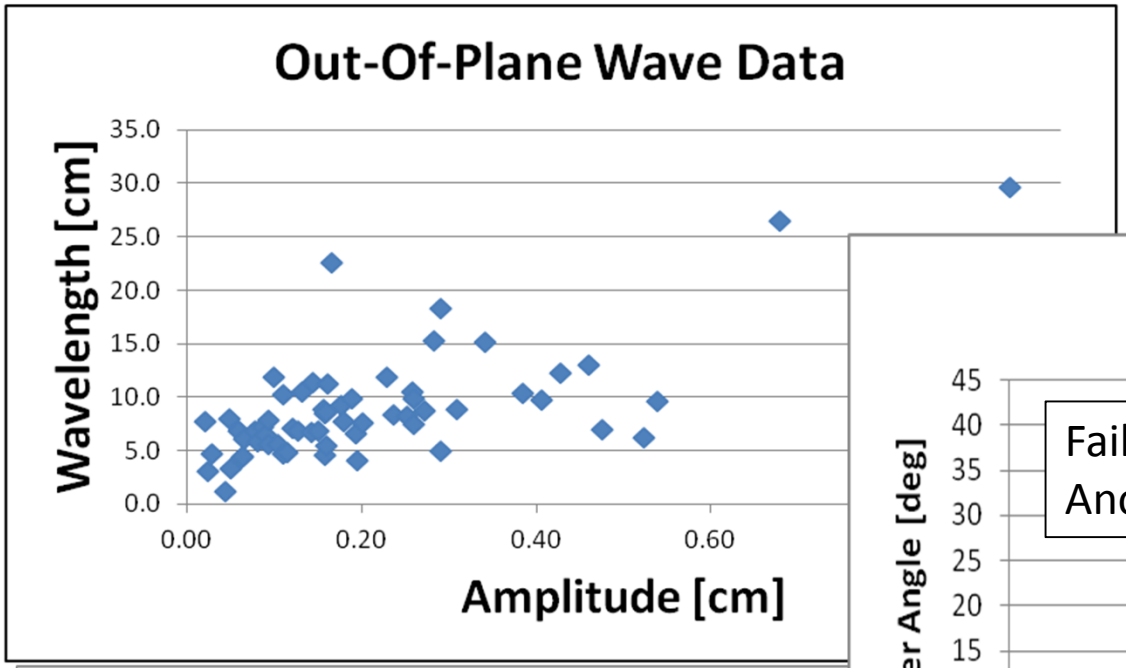


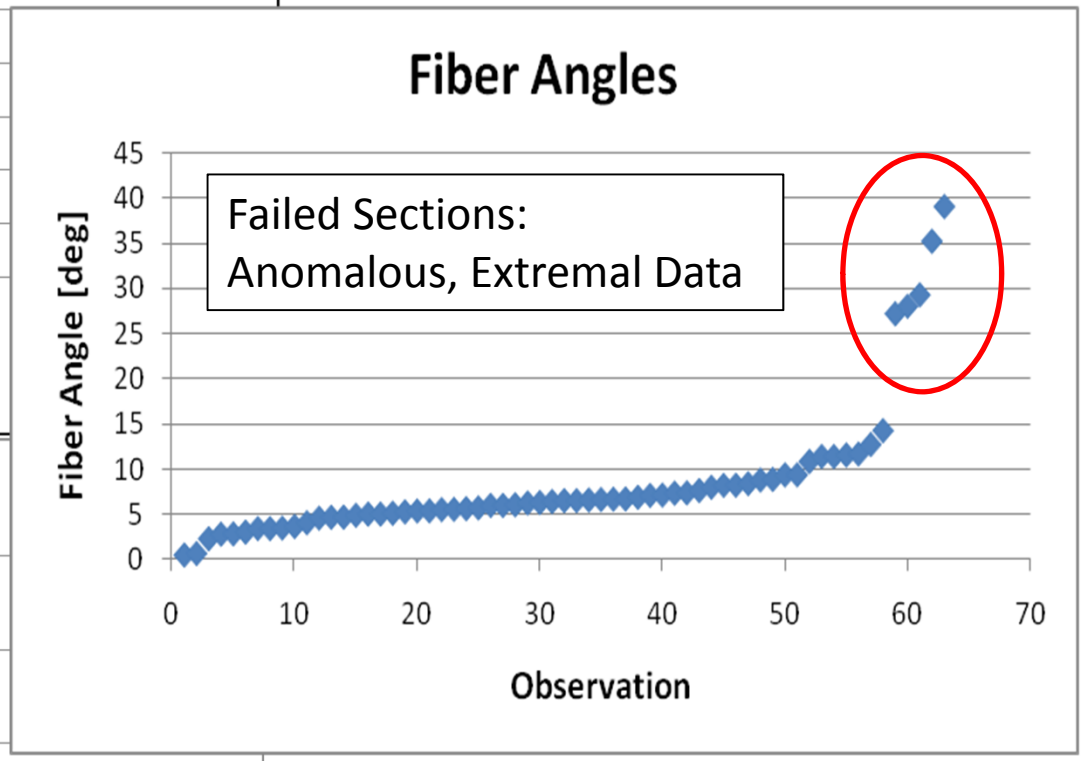


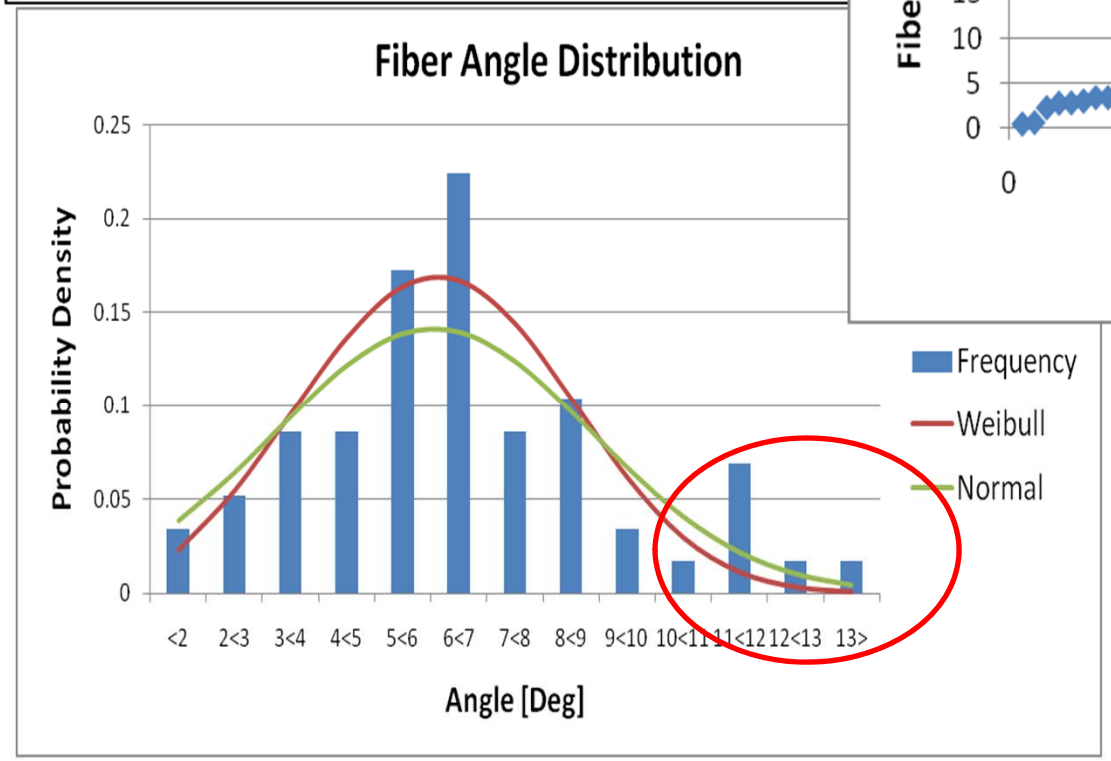
Porosity: Inclusion of gaseous pockets

- Characterized by volume percentage
- Assumed uniformity
- Large voids considered delaminations







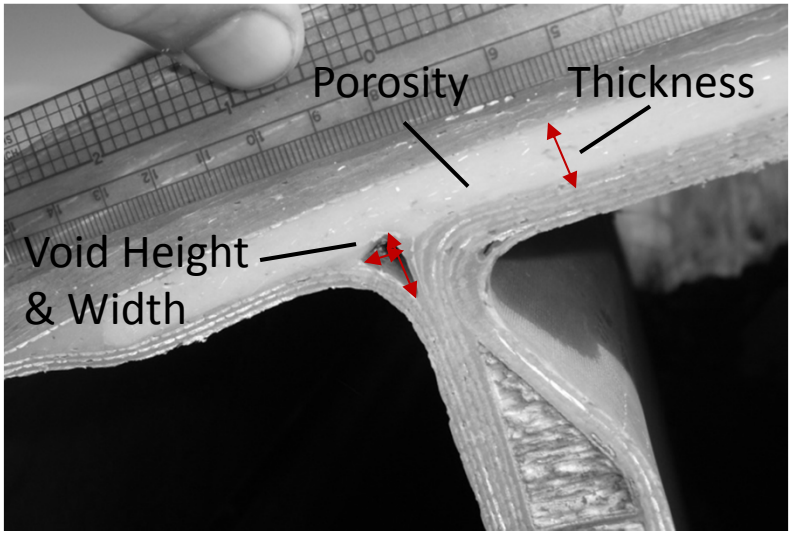


Example of collected field data and statistics for Out-of-Plane Waves

Adhesive Flaws

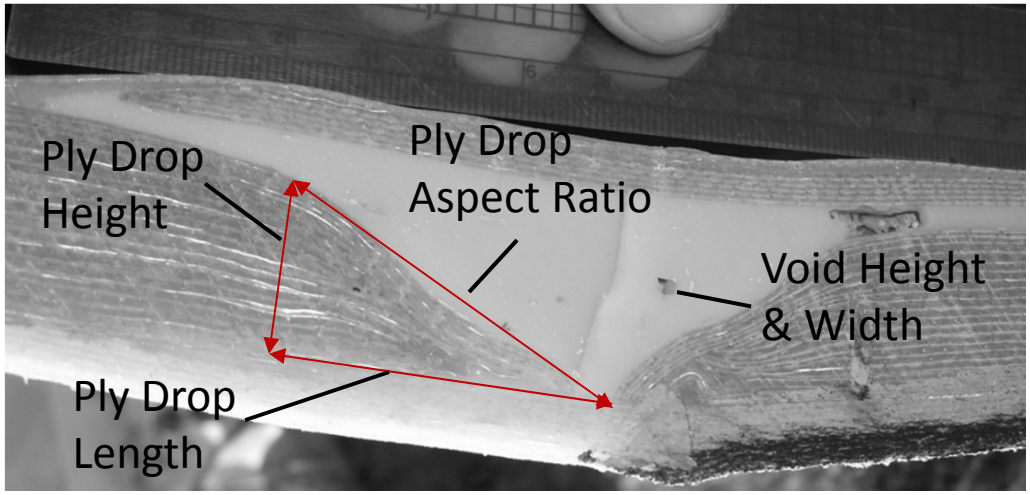
- Porosity & Voids initiate crack propagation
  - Artifact of application or mold separation
- Other issues like improper stoichometry

Spar Cap to Shear Web Bond



Spar	Thickness [cm]	Void Width [cm]	Void Height [cm]	Porosity %
Average	1.42	0.83	0.45	1.48
Min	0.70	0.22	0.13	0.71
Max	**3.05**	**3.12**	**0.89**	**2.57**

Mold Line Bond (TE & LE)



Mold Line	Void Width [cm]	Void Height [cm]	Ply Drop Length [cm]	Ply Drop Height [cm]	Aspect Ratio (L/H)
Average	0.28	0.27	3.48	1.82	1.91
Min	0.12	0.18	2.16	1.13	1.73
Max	**0.54**	**0.37**	**4.34**	**2.28**	**2.31**

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New NDI Techniques

It’s not illegal if you don’t pay them. Right?

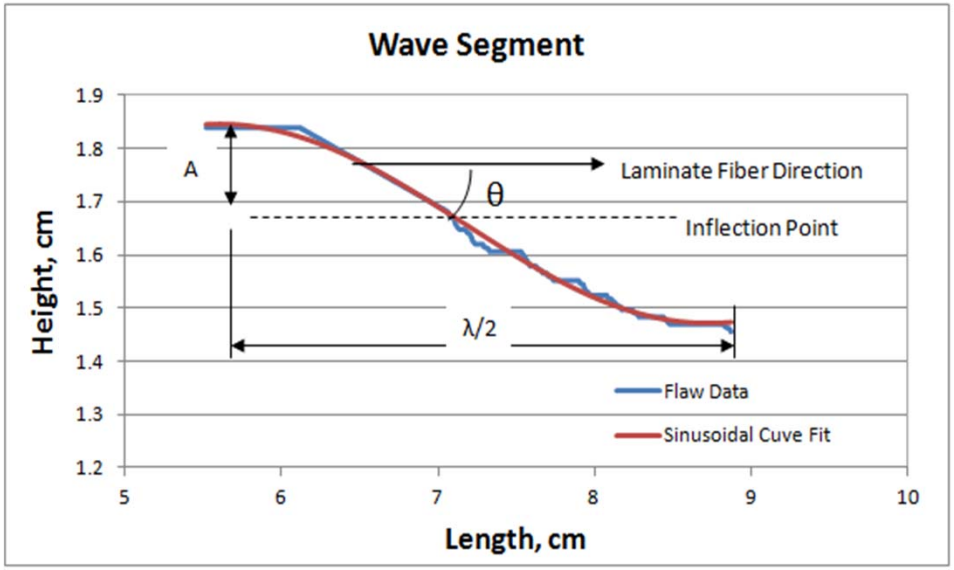
Characterization of Flaws in Test Articles

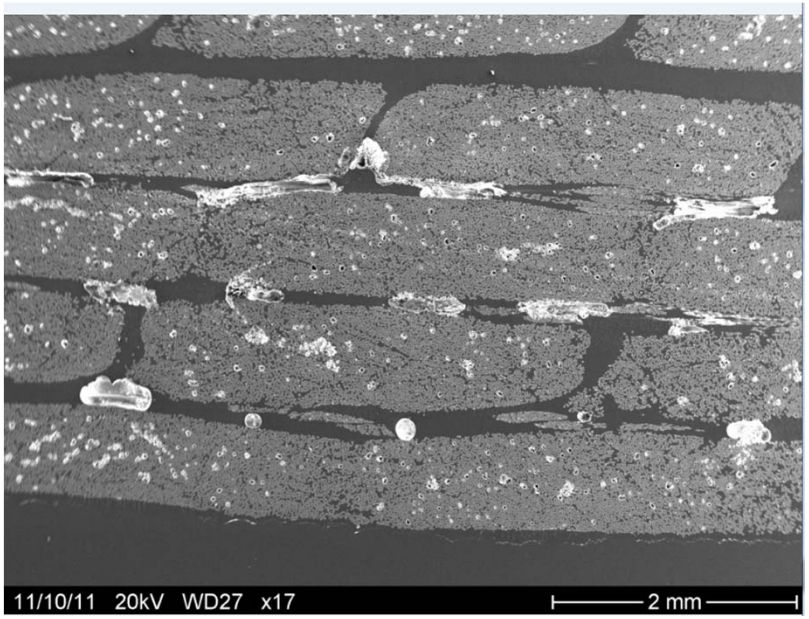
Porosity - Microscopy area fraction

- Percent of matrix by volume
- Radiodensity is under investigation

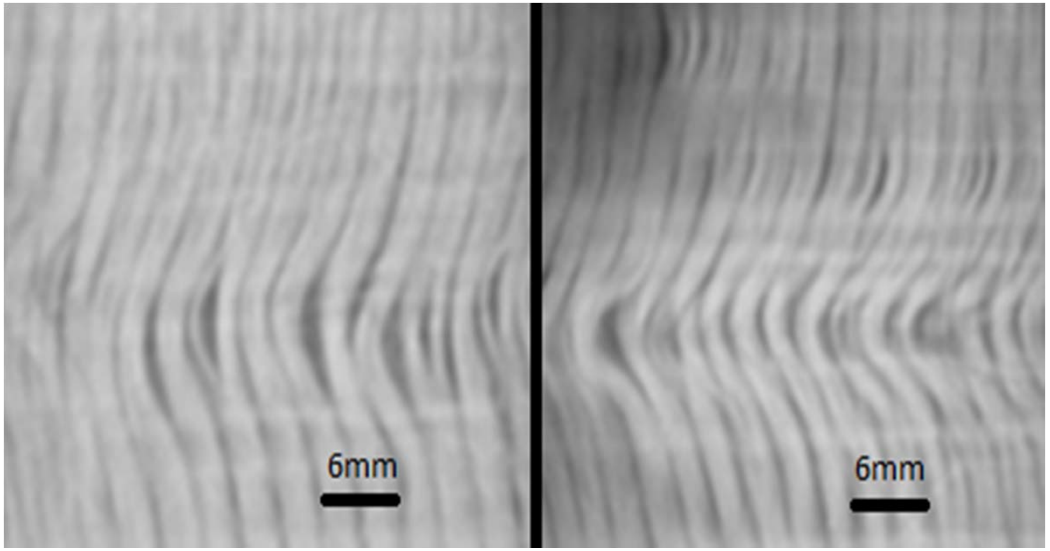
Waves – Image processing

- Best fit geometric functions
- Amplitude (A), Wavelength (λ), Misalignment or off-axis fiber angle (θ)



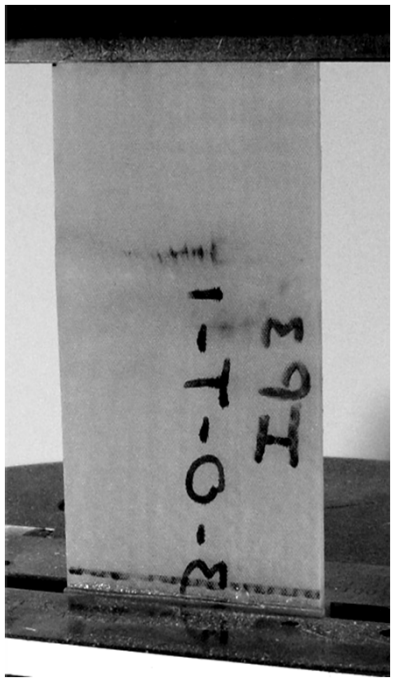
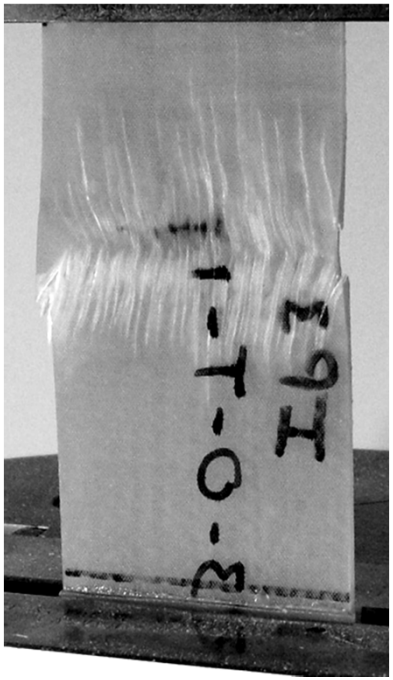


Scanning Electron Microscope (SEM)

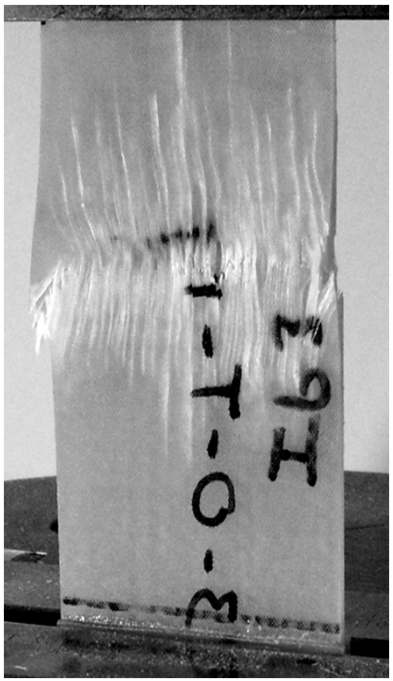
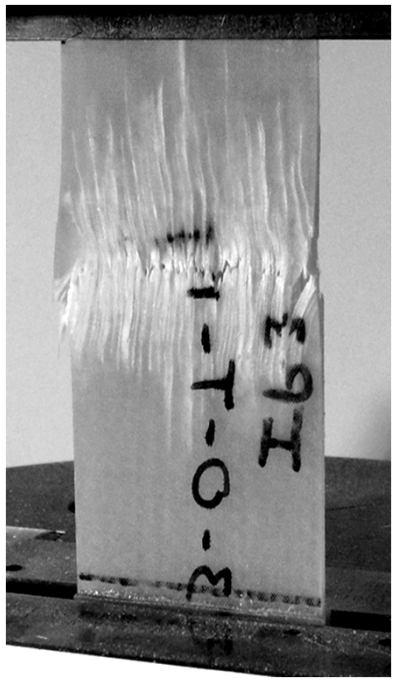


Ply by Ply Radiography (Computed Tomography)

Tension IP Wave Damage

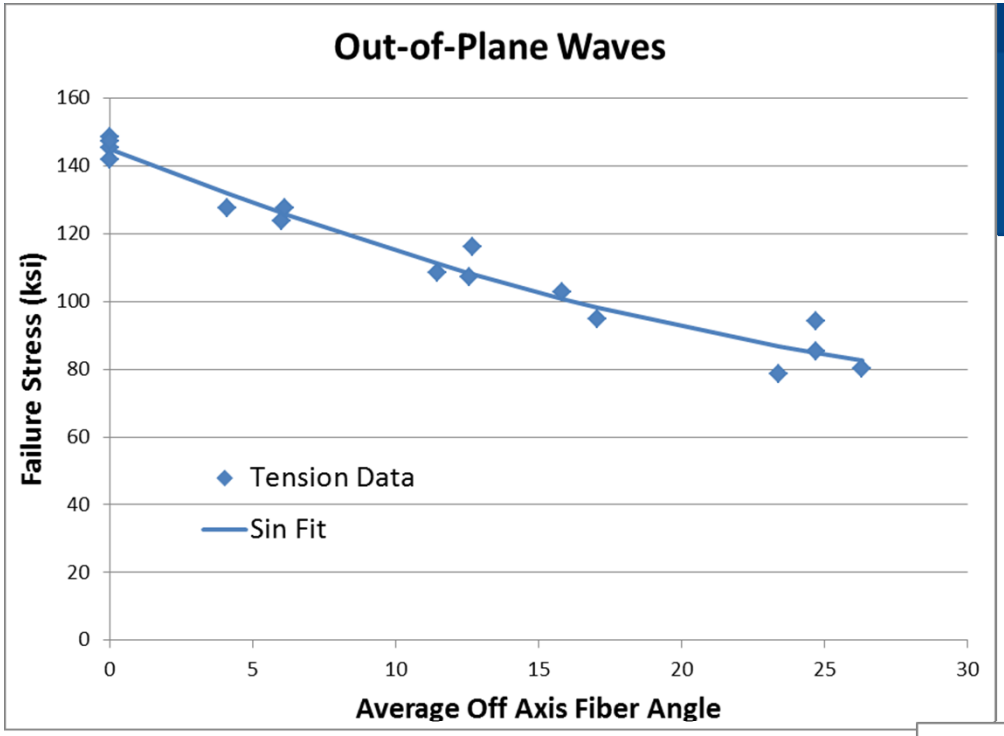
Matrix Cracking

Ultimate Ply Failure

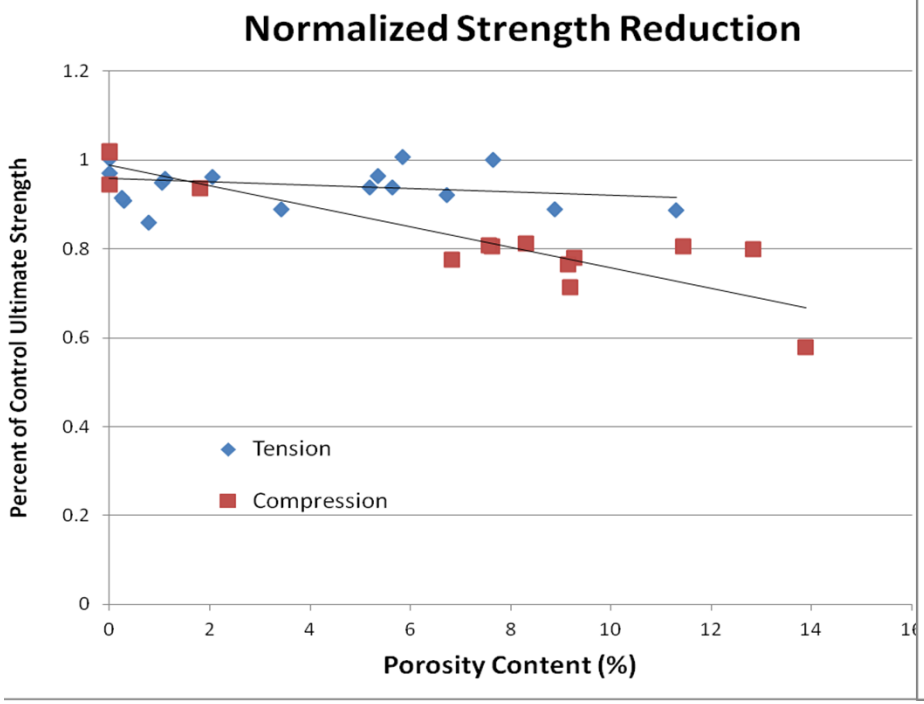
Damage visualized with images and Aramis digital image correlation (DIC) system.

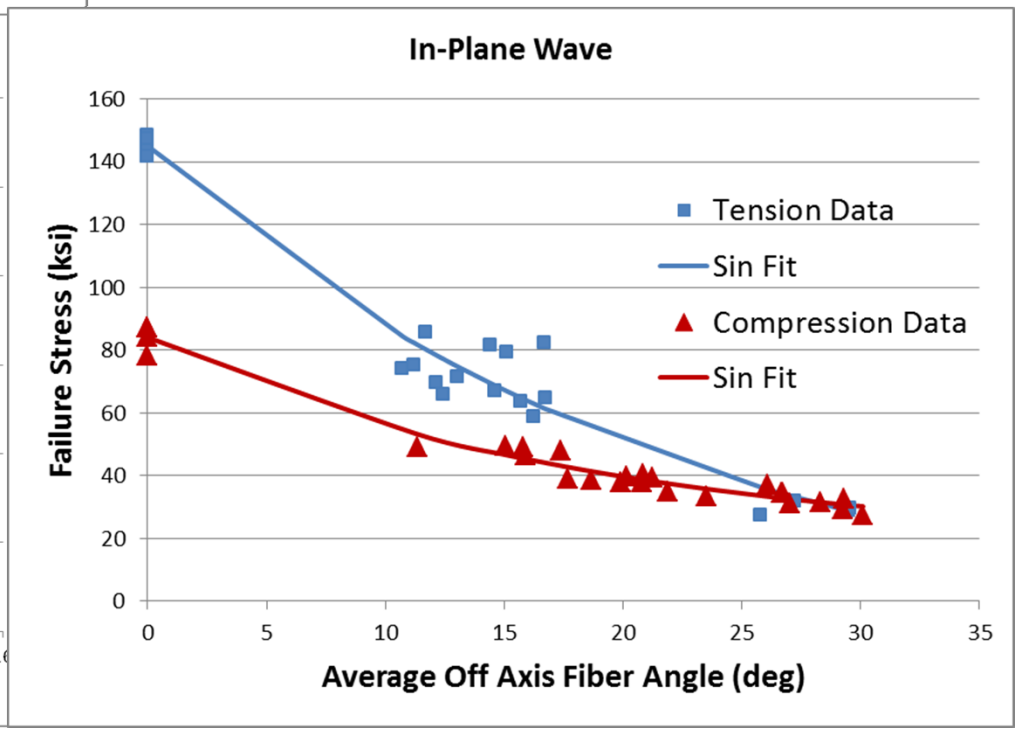
Thin Laminate Testing Failure Stress Results



Wavy Laminates - Trend well with average misalignment fiber angle

Porosity Laminates - Trend well with % by volume when accounting for fiber volume



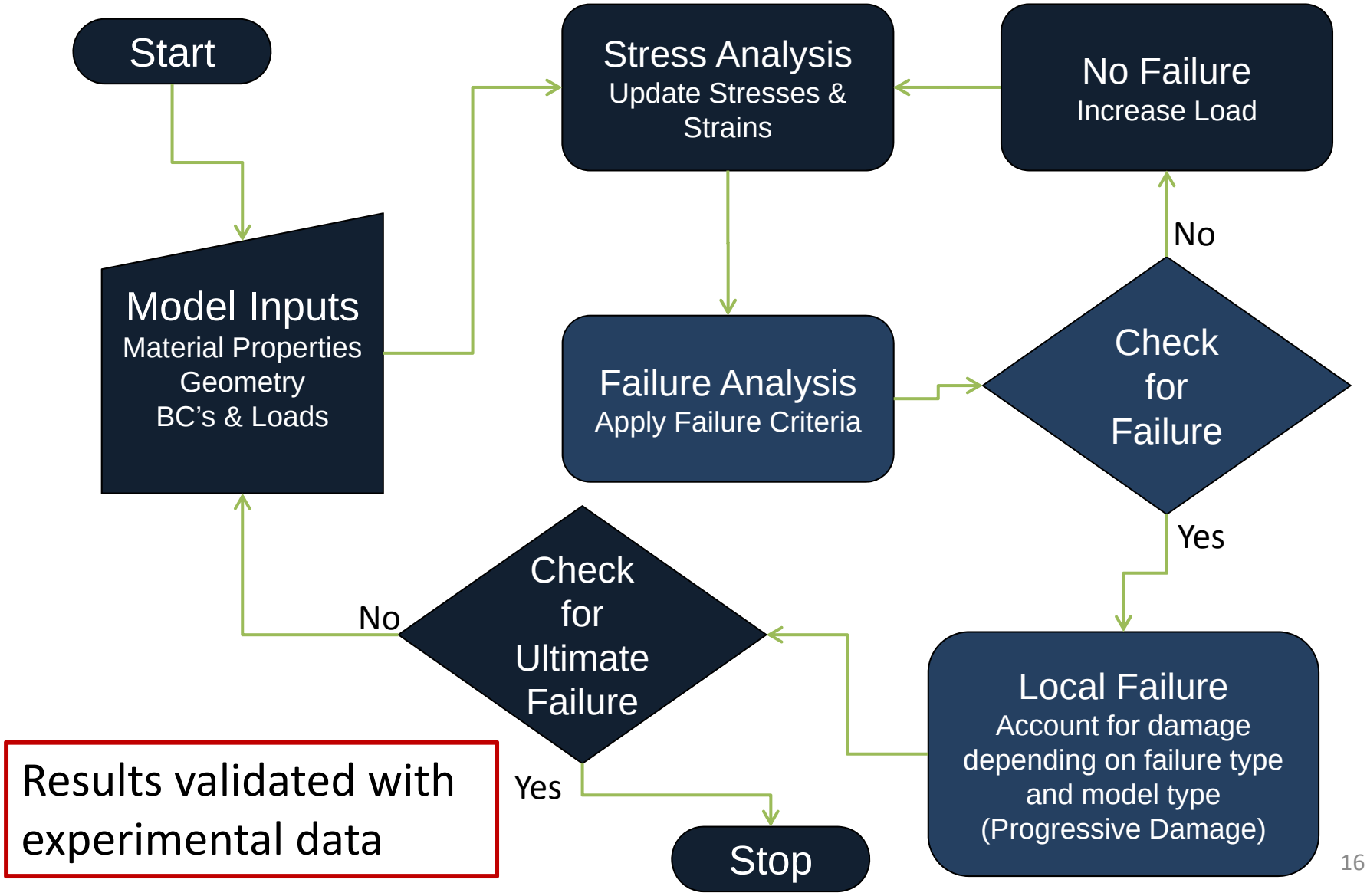


Progressive Damage Modeling

- **Goal:** *Develop coordinated experimental and analytical analogs for damage growth and residual strengths*
  - Models must be able to predict damage initiation, type, evolution and final failure
  - Key components are failure criteria, damage logic and response to damage

- **Damage Modeling Types**
  - **CDM** ≡ Continuum Damage Modeling: degrade material property to simulate damage
  - **DDM** ≡ Discrete Damage Modeling: actual damage modeled

Progressive Damage Model Logic



Results validated with experimental data

Continuum Damage Modeling Approach

- "Pseudo-Representation" - Does not model exact damage
- Updates constitutive properties as damage occurs

Matrix cracking, Fiber-matrix comp damage, Fiber failure

$$\left(\frac{\sigma_{22}}{S_{22}}\right)^2+\left(\frac{\tau_{12}}{S_{12}}\right)^2=1 \qquad \frac{\sigma_{11,C}}{S_{11,C}}+\frac{\tau_{12}}{S_{12}}=1 \qquad \frac{\varepsilon_{11,T}}{\bar{\varepsilon}_{11,T}}=1 \quad \frac{\sigma_{11,C}}{S_{11,C}}=1$$

- As the model iterates, the constitutive matrix, *C* or *S*, is updated to reflect equilibrium damage
- *C* or *S* may simplify; based on material and lay-up

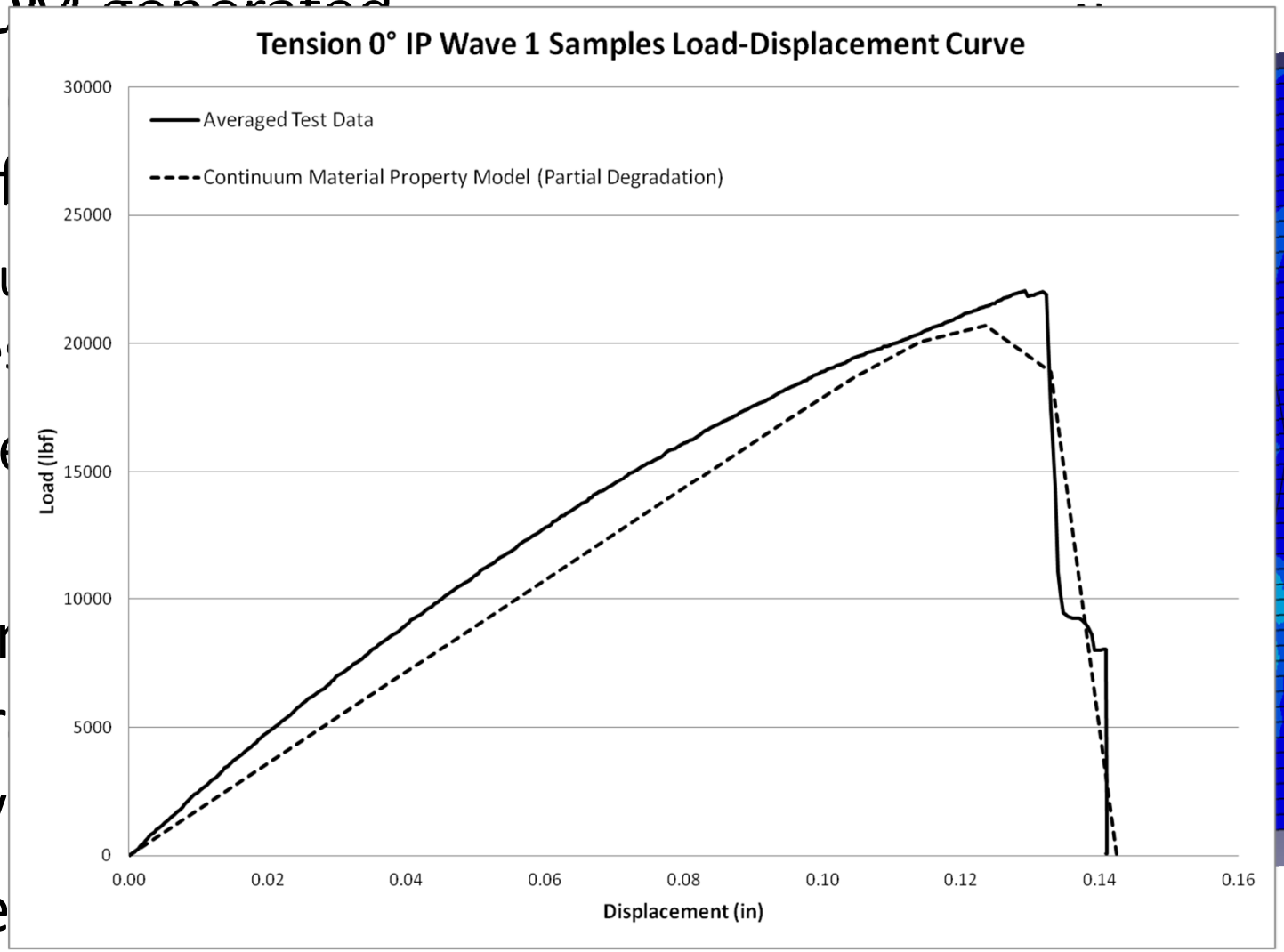
$$U=\frac{1}{2}\varepsilon_{ij}C_{ijkl}\varepsilon_{kl}$$

$$U=\frac{1}{2}\sigma_{ij}S_{ijkl}\sigma_{kl}$$

where:
U ≡ strain energy density
ε,σ ≡ strain, stress tensors
C,S ≡ stiffness, compliance matrices

CDM Efforts

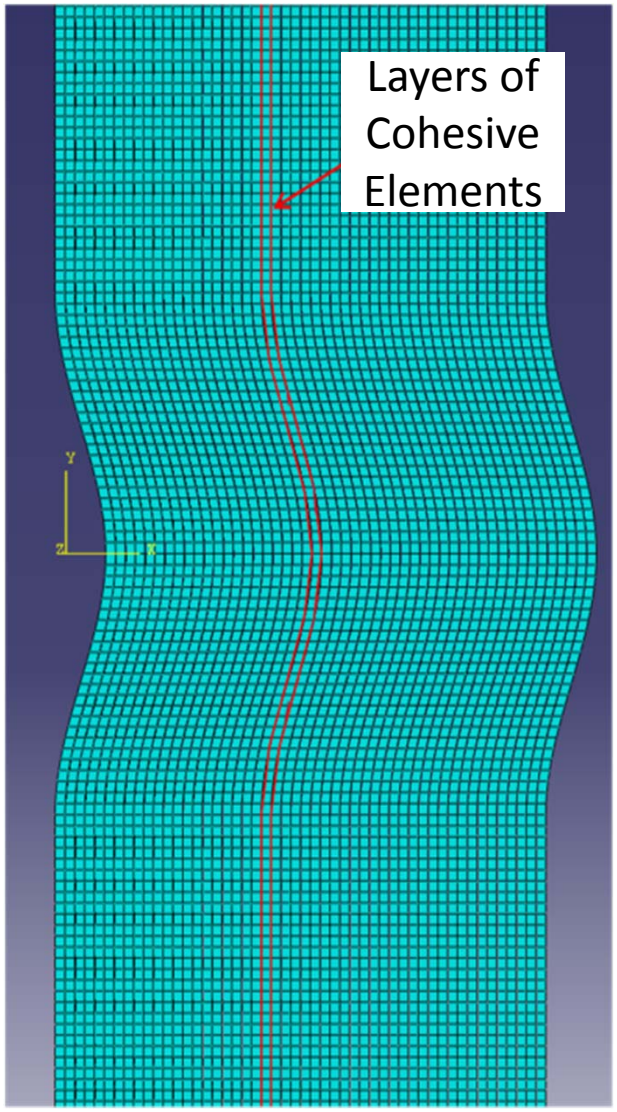
- Initial CD
  utilizing
  code as f
  – User Su
    Progres
- Generate
  surfaces
- Import ir
  to gener
- Abaqus/
  file gene



Failure in agreement

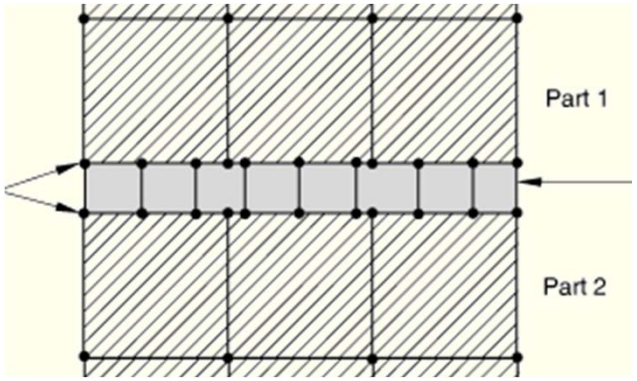
Discrete Damage Modeling Approach

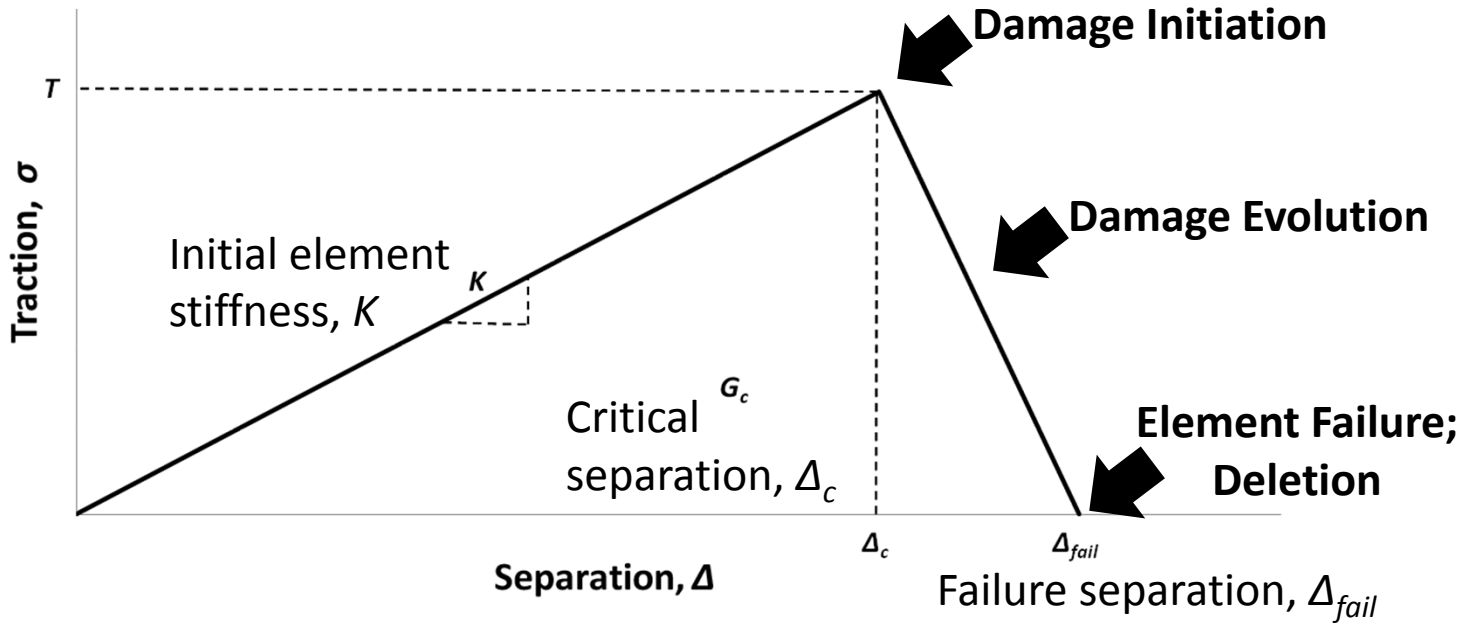
- Models the damage as it occurs (prior knowledge is helpful)
- Generally, computationally more expensive
- Utilizing Cohesive Elements; improvement on VCCT/LEFM because initial crack and crack path not necessary *a priori*



Cohesive Element Damage Criterion

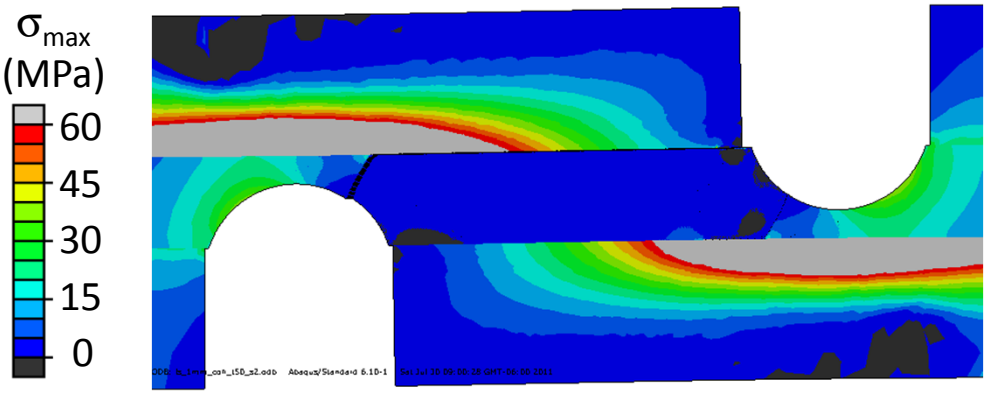
- Zero thickness elements between layers
- Models the initial loading, the initiation of damage, and the propagation of damage leading to eventual failure
- Traction-separation based modeling for bonded interfaces (composites)
  - Bi-linear criterion

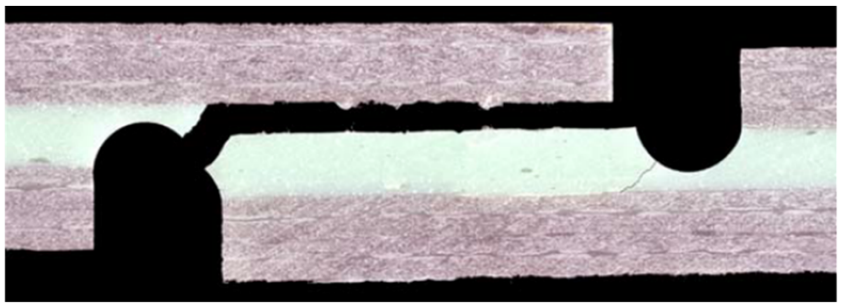




Adhesive Crack Propagation History

- Cohesive elements capture both the initiation and progression of damage at discrete locations
- Similar modeling has been performed with XFEM





Double-Notched Lap Shear - The upper crack propagated completely though the adhesive bondline; fracture path is well captured

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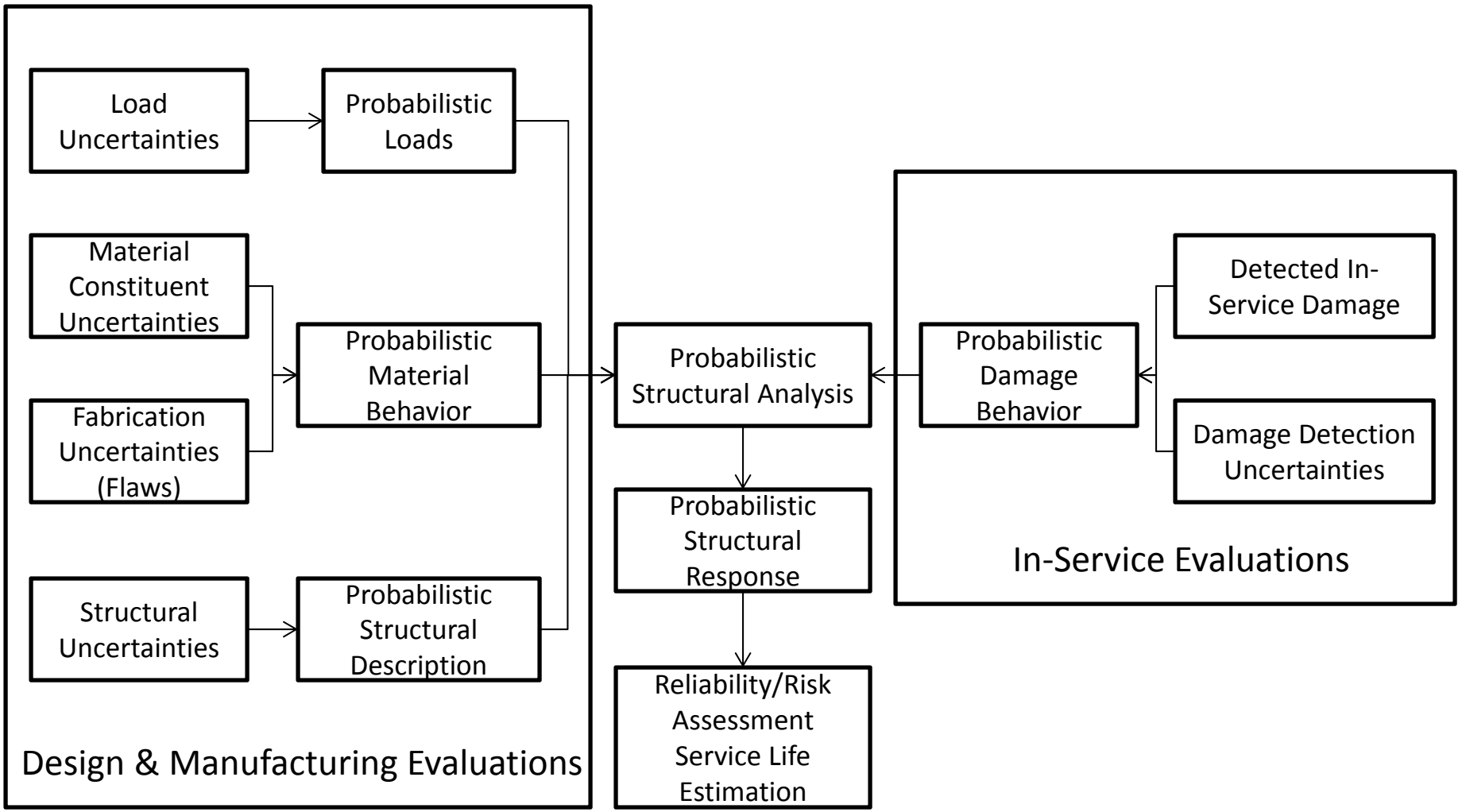
2. Probabilistic Reliability Evaluation



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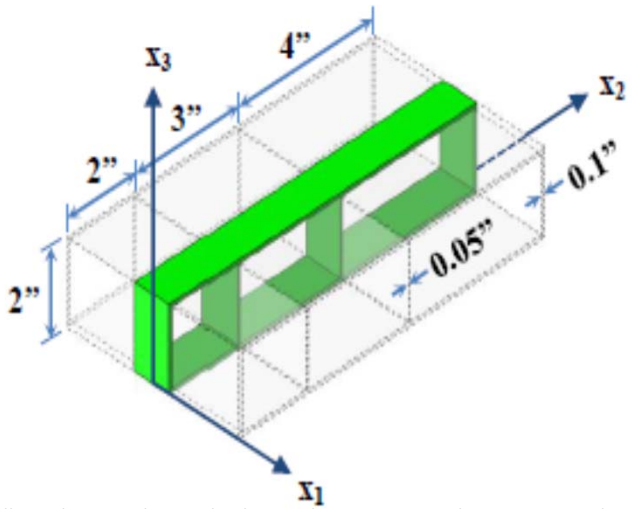
Probabilistic Reliability Evaluation

Unique to MSUCG: Assessment of as-built flawed composite structures

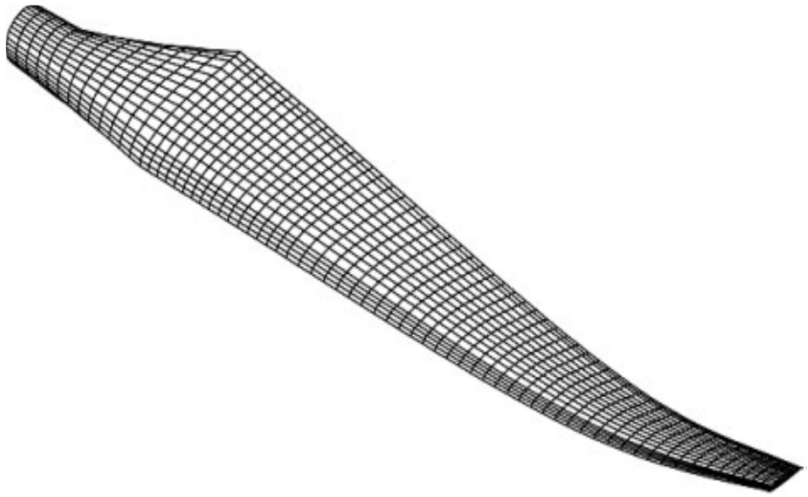
- MSUCG composite materials database and flaw testing for uncertainty variables distribution functions
- Flaw specific damage progression models for structural analyzer
- Subscale test validation

Probabilistic Structural Analysis

- Local damage progression analysis inserted into macro scale model for global structure response
- Deterministic fatigue life evaluations based limit state



Yellavenkatasunil, J. and Whitcomb, J., *Structural Dynamics and Materials Conference*, 2011



NuMAD: Wind Turbine Blade Design Tool, Sandia Natl Laboratory

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3. Criticality Analysis

- Probabilistic evaluations (Engineer Oriented)
  - Requires specialty software
  - Computationally expensive
  - Complex, multifaceted analysis
- Criticality analysis (Technician Oriented)
  - Quality control on manufacturers' floor
  - In the field; pre-service, operational assessment
  - Handheld app?
  - Support for database generation (AD?)

Predominately quantitative, two parameter (Criticality & Severity) metric for the disposition of a known flaw in structure (risk assessment)

Criticality and Severity Analysis

***Criticality**:* Incorporates damage progression, statistical variations, probability of flaw detection and combined effects of known/unknown proximity flaws. (Probabilistic/Numerical)

Symbol	Equation	Description
R	μ-t	Remainder of service life
S	$f(\sigma t,c,f)$	Residual Strength
P_f	$f(F,D,L)$	Probability of failure modifier
ζ	$f(t,S)$	Predicted time to failure
C_1	$f(P_f,\zeta,R)$	Criticality modifier: Service Life
C_2	$f(P_f,\zeta,I)$	Criticality modifier: Inspection Interval
C_3	$f(P_f,\zeta,\lambda)$	Criticality modifier: Failure Rate
C_4	$f(P_f,\zeta,\alpha)$	Criticality modifier: Time to Repair

***Severity**:* Specific to Effects of Defects; developed from user defined inputs such as material properties and specific flaw characterization parameters. (Deterministic)

Initial calculations:

$$\text{Criticality Number} = P_f.\Sigma C_{1,2,3,4}$$

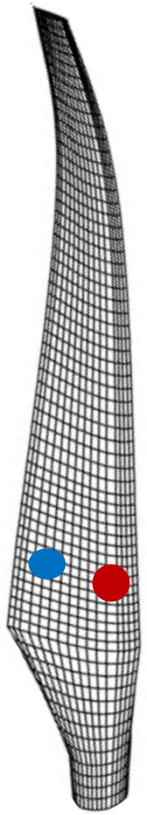
$$\text{Severity Number} = 1-\sigma_f/(P_{t,c}.\sigma_{t,c})$$

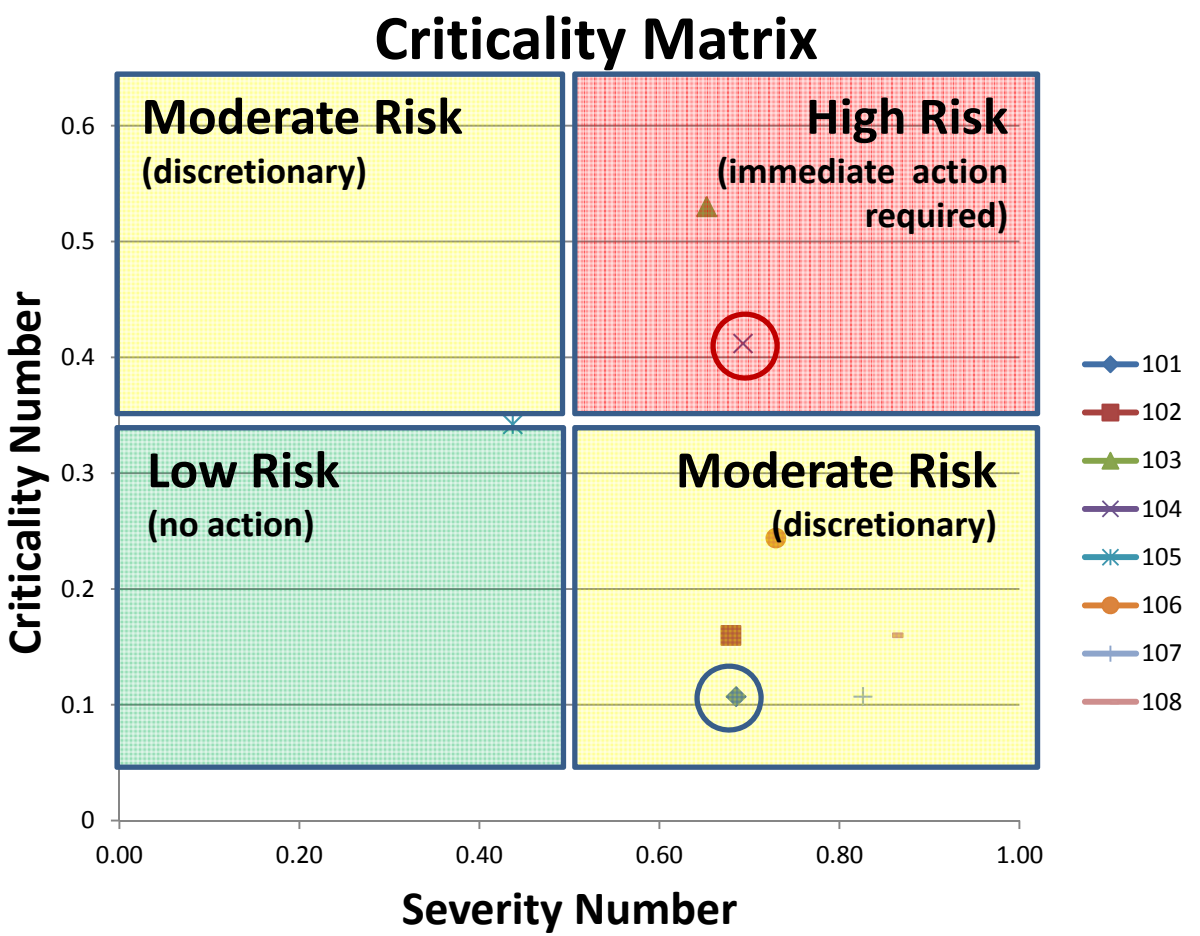
Criticality Analysis

Simple Example:

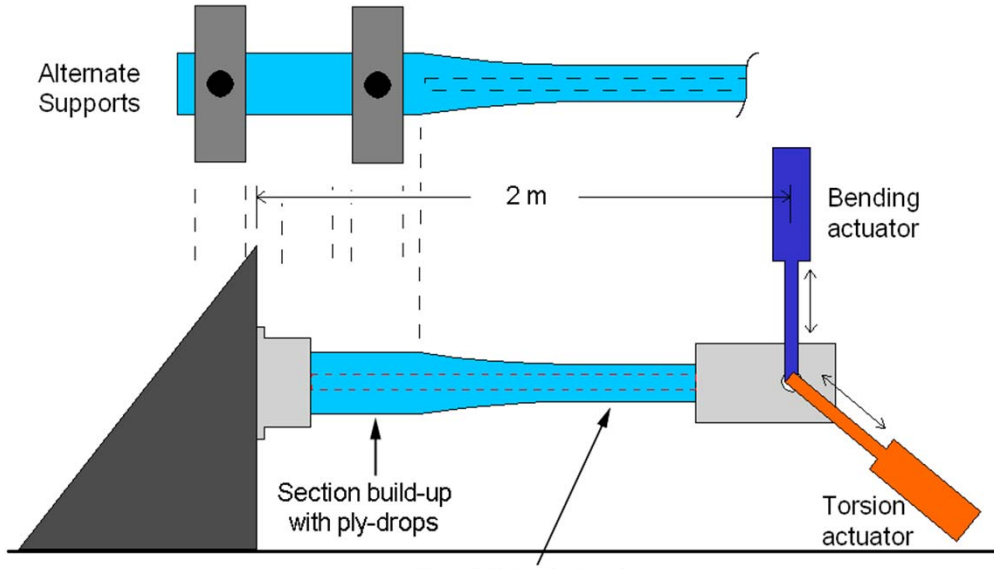
Flaws 101 and 104 have almost identical characterization parameters with significant structural implication to the local region (severity).

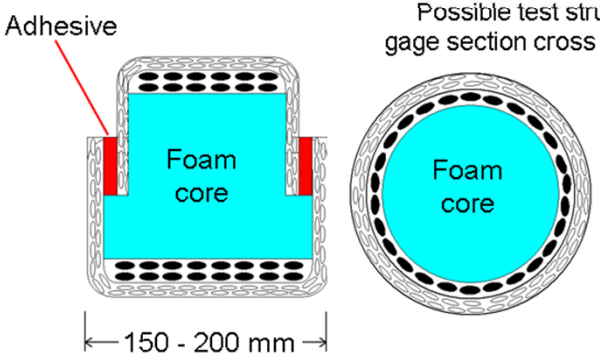
However, flaw 101 is not located in a high strain region and therefore can be consider non-critical (criticality)



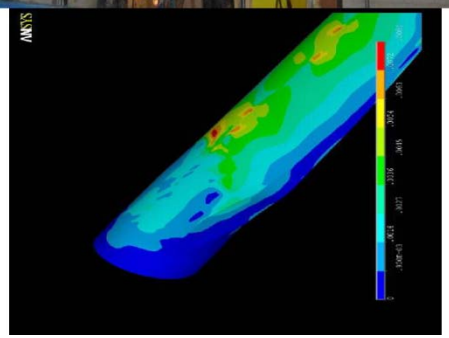


Subscale Validation





Potential geometries
Many configurations are possible



Subscale Test Facility (being designed and built by MSU)

Bridges gap between laboratory coupons and full blade structures

BRC Effects of Defects Validation Blades (to be made at TPI and tested at NREL-NWTC)

Static & fatigue testing of 9m Sandia BSDS type blades with induced flaws

4. In-Field Evaluations

Current Damage Reporting - Good framework, potential to improve

Databases Do Not Capture Necessary Information for Effect of Defects and Reliability Infrastructure

Ideal Reporting would provide feedback for reliability models validation and comprehensive in-service damage/risk assessment

- Non-Destructive Evaluations
  - Maintenance intervals or pre-service inspections
  - Need to capture more specific info
    - Criticality parameters
    - Load event histories (SCADA)
- Structure Health Monitoring
  - Currently nothing in use for blades
  - Could be monitored with SCADA similar to gearbox data
  - Incorporate damage progression and residual strength
- Development of an FAA Air-Worthiness type database

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Summary/Conclusions

- Variability exists at all level of a composite structure
  - Proper assessment of a flawed composite structure requires a comprehensive approach
  - Quick evaluations can be made based on more in-depth analysis
- The mechanical response of flawed laminates correlates well to geometric properties
  - Consistency in manufacture and testing is imperative
  - Characterization of flaws must be performed
- Damage progression analysis can be successfully implemented to describe flawed laminates

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Future Work

- Continued Flaw Characterization
  - As-built Database
  - Manufacturer and Operator Data
- Continued Damage Growth Analysis
  - Composite Laminate
  - Adhesive
- Probabilistic Criticality and Severity Analysis
- Subscale Testing and Validation
  - Effects of Defects Validation Blades
  - Subscale Test Facility
- Applications to Full Scale Blades

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Questions?

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For more detailed information see papers presented at 2011 & 2012 AIAA SDM Conference.