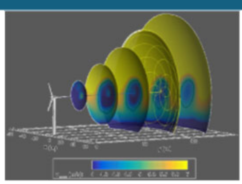
SAND2022-14637C

Sandia National Laboratories

Blade Reliability Collaborative Meeting



PRESENTED BY

Josh Paquette, Michelle Williams, David Maniaci, Ryan Clark

Agenda

8:30 Introduction

8:40 Lightning (Michelle Williams)

9:00 Erosion (David Maniaci)

9:40 Inspection (Michelle Williams)

10:00 Break

10:20 O&M Optimization (Ryan Clarke)

10:40 Defects, Damage, and Repairs (Ryan Clarke)

11:00 Blade Design and O&M Standards (Kyle Wetzel)

11:30 Group Discussion of Trends, Emerging Issues, and Future Research

12:00 Lunch

Blade Durability and Damage Tolerance Project

Objective

Produce computational tools, experimental datasets, and technical innovations that will allow blade designers, manufacturers, owner-operators, and service personnel to improve and optimize their approach to building and operating wind blades

Tasks

Robotic Inspection

Damage Tolerant Materials and Structures

O&M Optimization

Erosion

Lightning

Lightning

Michelle Williams

Problem/Motivation

Effect of lightning damage on pultruded carbon fiber laminates

Ability of inspection equipment to find damage

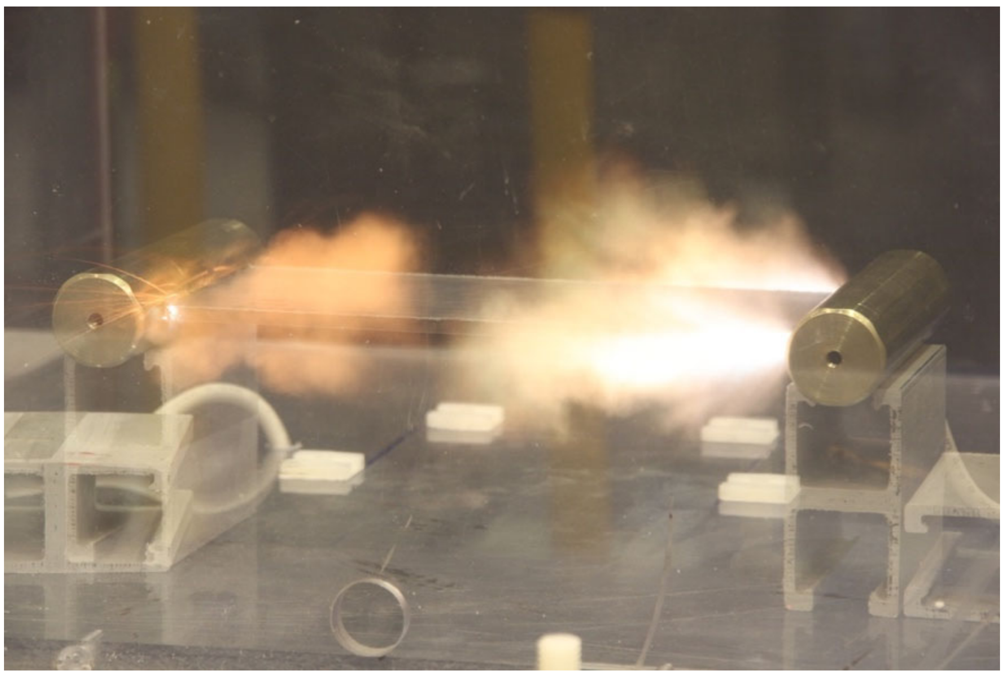
Windpowerengineering.com

What are we doing? Phase I Testing

Lightning Impulse Testing

Pre and Post-Test NDE

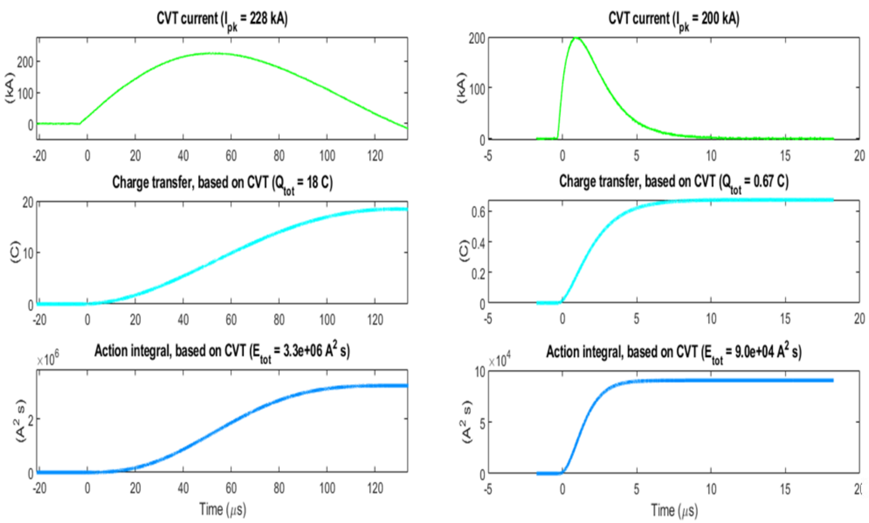
Post- Structural Testing



	30 kA peak current	200 kA peak current
1-µs pulser	50% lightning peak current 1% lightning time to peak **Current = (Ch1 + Ch2 + Ch3) * Calibration** **Calibration = 4,000** **Test day: 5/25/2021** File no. 1 VE-7A File no. 2 VE-8A File no. 3 EP-9A File no. 4 VE-9A File no. 5 EP-10A **Test day: 5/26/2021** File no. 6 EP-11A	1% lightning peak current 1% lightning time to peak 50% lightning action integral **Current = (Ch1 + Ch2 + Ch3) * Calibration** **Calibration = 20,000** **Test day: 5/4/2021** File no. 0 EP-5A **Test day: 5/5/2021** File no. 1 VE-5A File no. 2 EP-6A File no. 3 VE-6A File no. 4 EP-7A File no. 5 EP-8A **Test day: 5/26/2021** File no. 8 VE-10A
30-µs pulser	50% lightning peak current 50% lightning action integral **Current = Ch3 * Calibration** **Calibration = 50,000** **Test day: 5/20/2021** File no. 0 VE-6B File no. 1 EP-7B File no. 2 VE-7B File no. 3 EP-9B File no. 4 VE-10B File no. 5 EP-10B	1% lightning peak current 50% lightning charge transfer 1% lightning action integral **Current = Ch3 * Calibration** **Calibration = 50,000** **Test day: 5/13/2021** File no. 0 EP-5B File no. 1 VE-5B File no. 2 EP-6B File no. 3 VE-8B File no. 4 EP-8B File no. 5 VE-9B

Uman, et al., 2010. Update direct-strike lightning environment for stockpile-to-target sequence (second revision).

What are we doing? Phase I Testing

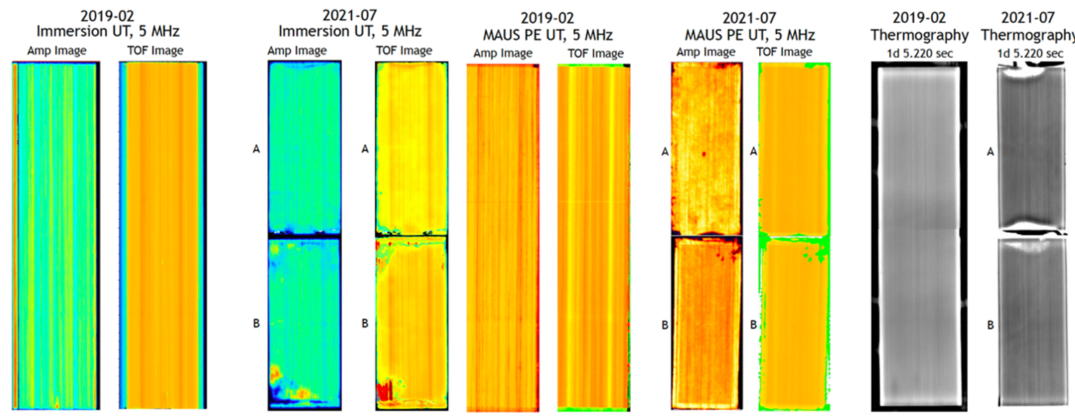


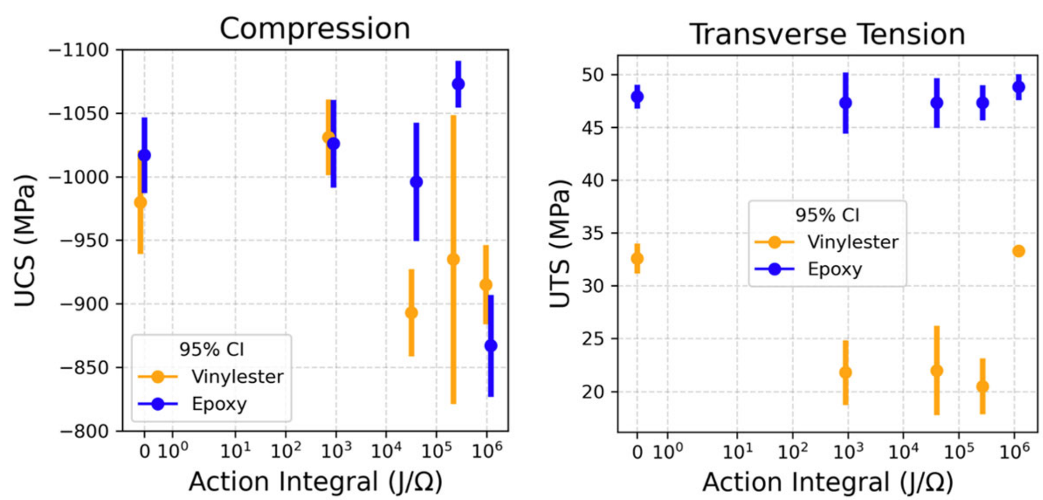
Current Viewing Transformer (CVT) (top plots)

Charge Transfer (middle plots)

Action Integral (bottom plots)

- energy deposition





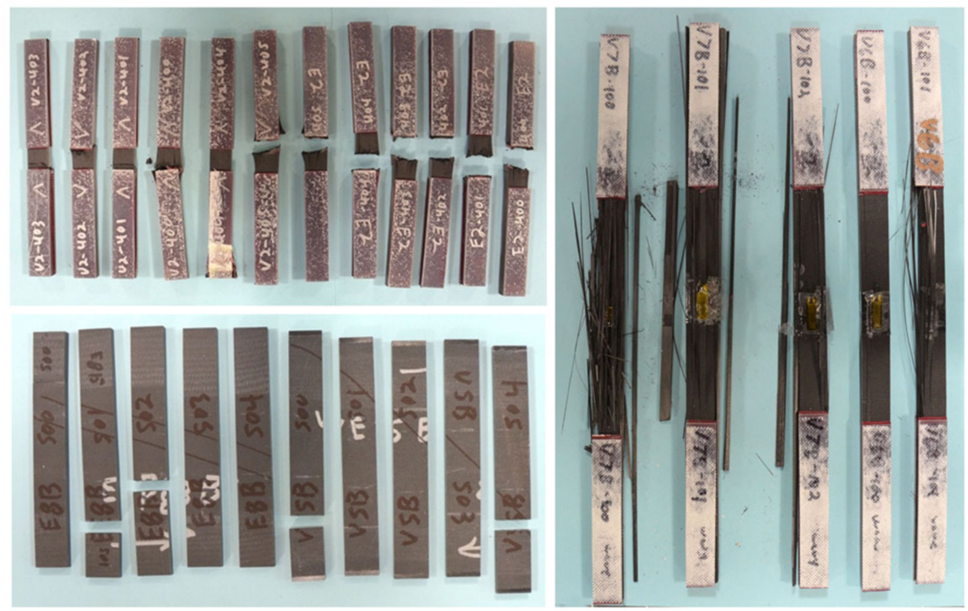
Strength vs action integral (energy per unit resistance, 95% CI)

Future: 2-Year Plan

Preliminary Design of Lightning Measurement System

Phase 2 Impulse Testing:

- Repeat on thinner specimens for improved structural testing
- Testing on adhered, stacked plates
- Multiple strike testing
- Examine edge effects



Questions

Materials: are there other materials we need to focus testing efforts on?

Are lightning/material interactions, and LPS considered during initial blade design?

Questions/Input from audience

Erosion

David Maniaci

Leading Edge Erosion Modeling and Mitigation

What are we doing currently?

- Coordination of Work Packages 2 and 3 of IEA Task 46, Wind Turbine Operation with Erosion
- Assessing LEE performance impact using statistical analysis of field data and probabilistic modeling

What do we plan on doing over the next two years?

- Continue coordination of IEA Task 46 Work Packages 2 and 3 for two more years
  - Aerodynamic benchmark, rain impingement modeling, potential of erosion safe control, validation with field data
- Develop open performance loss model
- Process and explore additional field data sets
- Release field data power performance analysis software openly and support use by external partners

IEA Task 46: Erosion of Wind Turbine Blades

Work Package	Coordinating organization(s)	work package leader / co-leaders
WP2: Climatic conditions driving blade erosion	Cornell University (US), Ørsted (DK)	Sara C Pryor , Marijn Veraart
WP3: Wind turbine operation with erosion	Sandia National Laboratories (US)	David C Maniaci
WP4: Laboratory testing of erosion	DTU (DK), Hempel (DK)	Jakob Ilsted Bech, Maral Rahimi
WP5: Erosion mechanics & material properties	CEU Cardenal Herrera University (ES), University of Bergen (NO)	Fernando Sánchez López, Bodil Holst

Coordination of technical work packages

IEA Task 46, Work Package 3: Wind turbine operation with erosion

This work package has three key overarching objectives:

1. Promote collaborative research to mitigate erosion by means of wind turbine control, assessing the viability of erosion safe mode.
2. Improve the understanding of droplet impingement in the context of erosion.
3. Improve the understanding of wind turbine performance in the context of erosion, specifically the effect of LEE surface roughness on aerodynamics.

Please reach out if interested in collaborating through IEA Task 46!

David C. Maniaci
dcmania@sandia.gov

	Activity	WP code
Year 1	Model to predict annual energy production loss on blade erosion class	WP3.1
	Report on standardization of damage reports based on erosion observations	WP3.2
Year 2	Droplet impingement model for use in fatigue analysis	WP3.3
Year 3	Potential for erosion safe-mode operation	WP3.4
Year 4	Accuracy of LEE performance loss model based on field observations (validation)	WP3.5

Erosion Classification: Background & Previous Updates

Assessment Method

- Methodology
  - Drone, Rope Access, Ground Based Cameras
- Interpretation/Subjectivity
- Inspection Quality
- Technology
  - Visual
  - NDT, Other

Blade Geometry

- Blade Area
- Blade Location (Span and Chordwise)
- Blade Cross Section
- Distinguishing Different Locations of Erosion

Subsequent Action

- Damage Progression
- Intervention Decision
  - Influence of Other Forms of Damage
  - Predicted Lifetime of LEP
- Repair Categorisation

Damage Mechanism

- Material Type
  - Leading Edge Protection - Tape, Softshell, Coating, Other…
  - Unprotected Blades
- Root Cause
- Type of Failure/Damage Exhibited
  - Erosion/Degradation
  - LEP Adhesion Failure

Performance

- Mass Loss
- Roughness
- AEP
- LEP Failure
  - Adhesion
  - Degradation
- End Of Incubation Period

Structural Integrity

- Blade Feature
- Damage Cohesion
- Damage Form/Type
- Damage Extent
- Damage Depth

Assessment Type

- Research – CFD, Wind Tunnel/Rain Erosion Testing (RET)
- Operational Turbine
- Other

Additional Context

- Number of Blades Affected
- Age of Blades
  - Lifetime Extension
- Previously Known Damages
- Expected Erosion Conditions

Erosion Classification System Example

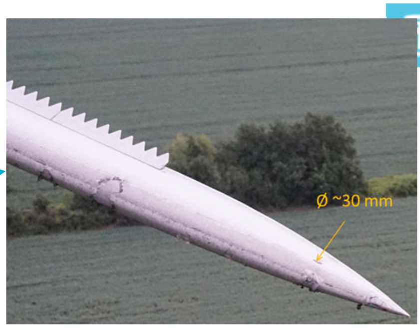
- Participants were asked to test the draft classification system on a sample of images.

Information to Categorize	Erosion Class	Note
Visual data definition	4	Large exposed surfaces of fiberglass. Signs of damage to the underlying fiberglass.
Mass-loss or Depth	4	
Aerodynamics/Performance	4	
Structural	3	

Parameter (Specified by Service Provider)	Value
Material	Laminate
Blade Length	37 m
Distance from Root	37.3 m
Length of damage	4.1 m
Width of damage	0.15 m

Erosion Classification System Test

Organisation Type		RTO	Owner/Operator	University	Turbine OEM	University	RTO	University	RTO	Owner/Operator	Turbine OEM	Median	Variance
Image 1	Visual data definition	2	1		2	0	2.5	2		2	3	2	0.85
	Mass-loss or Depth	1	1			2	1			1	4	1	1.47
	Aerodynamics/Performance	2	1	5	2.5	2	2		2	1	3	2	1.44
	Structural	1	1			0	2.5		2	2	3	2	1.06
Image 2	Visual data definition	4	4		4	3	4	5	4	4	5	4	0.36
	Mass-loss or Depth	4	4			3	3			3	5	3.5	0.67
	Aerodynamics/Performance	4	4	5	4.5	3	3.5		4	3	5	4	0.56
	Structural	4	3			0	4		3	4	5	4	2.57
Image 3	Visual data definition	1	2		2	1	2		2	1	2	2	0.27
	Mass-loss or Depth	1	1			0	1			1	1	1	0.17
	Aerodynamics/Performance	1	1		2	1	2		2	1	3	1.5	0.55
	Structural	2	1			0	2		3	1	2	2	0.95
Image 4 - Part 1	Visual data definition	3	1		2	1	2	1	2	1	2	2	0.50
	Mass-loss or Depth	2	1			1	1			1	4	1	1.47
	Aerodynamics/Performance	3	1	3	2	1	1.5		2	1	2	2	0.63
	Structural	2	1			0	2		3	2	3	2	1.14
Image 4 - Part 2	Visual data definition	2	2		1	1	2.5	1	2	1	1	1	0.38
	Mass-loss or Depth	1	2			1	1.5			1	1	1	0.18
	Aerodynamics/Performance	2	1	2	1	1	1.5		2	1	2	1.5	0.25
	Structural	2	1			0	2		3	2	1	2	0.95
Image 5	Visual data definition	1	1		1	0	0.5	2		1	0	1	0.42
	Mass-loss or Depth	1	1			0	0			1	1	1	0.27
	Aerodynamics/Performance	2	1	2	2.5	2	1		1	2	2	2	0.32
	Structural	1	1			0	1			1	0	1	0.27
Image 6	Visual data definition	1	1		1	1	1.5	1	1	1	1	1	0.03
	Mass-loss or Depth	1	1			1	1			1	1	1	0.00
	Aerodynamics/Performance	1	1		1	1	1		1	1	0	1	0.13
	Structural	2	1			0	2		2	1	1	1	0.57
Image 7	Visual data definition	2	1		1.5	0	1	1	1	1	3	1	0.69
	Mass-loss or Depth	1	1			1	0			1	2	1	0.40
	Aerodynamics/Performance	2	1		3	2	1		2	2	4	2	0.98
	Structural	1	1			0	1		2	1	1	1	0.33



- Classification is in draft form and could be refined based on discussions and feedback.

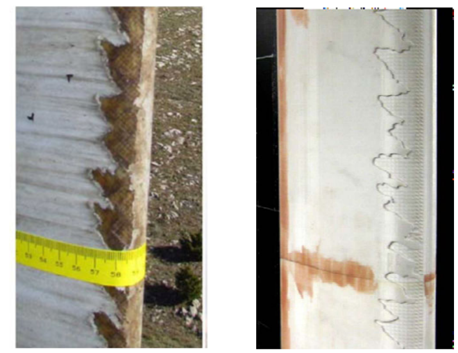
Proposed Erosion Classification System

Evaluation Criteria	Severity Level: 0	1	2	3	4	5
Visual Condition (LEP)	Initial factory condition	Lightly worn external coating/LEP Instances of reduced LEP adhesion	Notable areas of localized damage on external coating/LEP Individual Instances of LEP adhesive failure.	LEP is largely compromised over a large area and no longer providing protection to underlying layers	Delamination of topcoat with immediate layer underneath clearly visible and exposed	Notable damage to substrate
Visual Condition (No LEP)		Erosion barely visible or pinholes	Localized pitting	Widespread or coherent pits, some gouges		
Mass-loss		Coating <10% Laminate 0%	Coating 10-50%, Laminate 0%	Coating 50-100%, Laminate <10%	Coating 100% Laminate 10-100%	Coating 100%, Laminate 100%
Aerodynamic Performance		Normal surface roughness Region 2 Power loss 0 -1%	Region 2 Power loss 1%-2%	Region 2 Power loss 2%-3%	Region 2 Power loss 3-4%	Region 2 Power loss >4%
Blade Integrity		Initial erosion of topcoat	Erosion through topcoat	Initial exposure of immediate laminate layers	Erosion through immediate laminate layers	Exposure of structural laminate layers

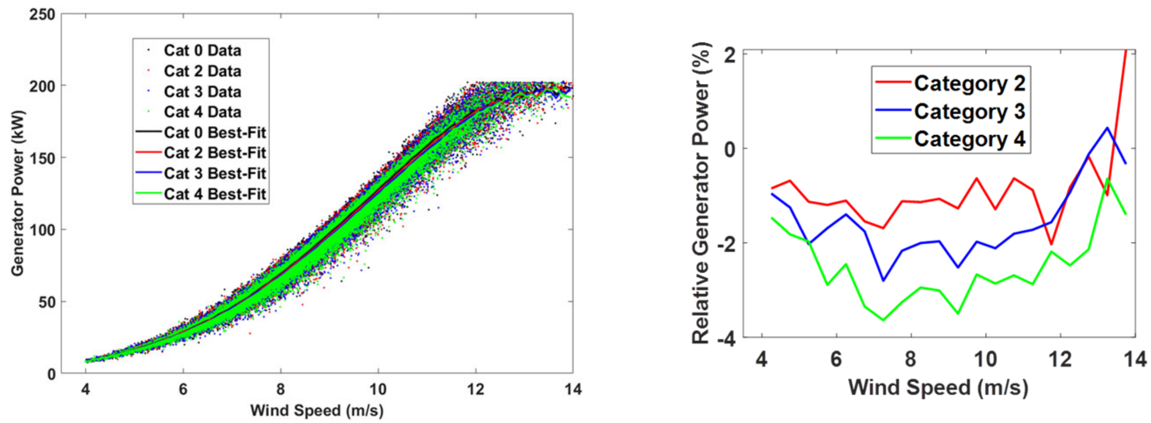
Measuring Power Loss due to Erosion

- A probabilistic model of the power loss due to erosion has been developed based on wind tunnel tests of simulated eroded airfoils
- The present work aims to validate the loss predicted in this model through the comparison of turbines with unrepaired LEE damage to repaired turbines with protection tape
- Local met tower data and archival wind plant SCADA data used from turbines classified as having undergone Category 4 erosion

Field measurements of erosion[1, 2]



Category 4 erosion wind tunnel tests



Probabilistic power curve model of erosion, categories 2-4[3]

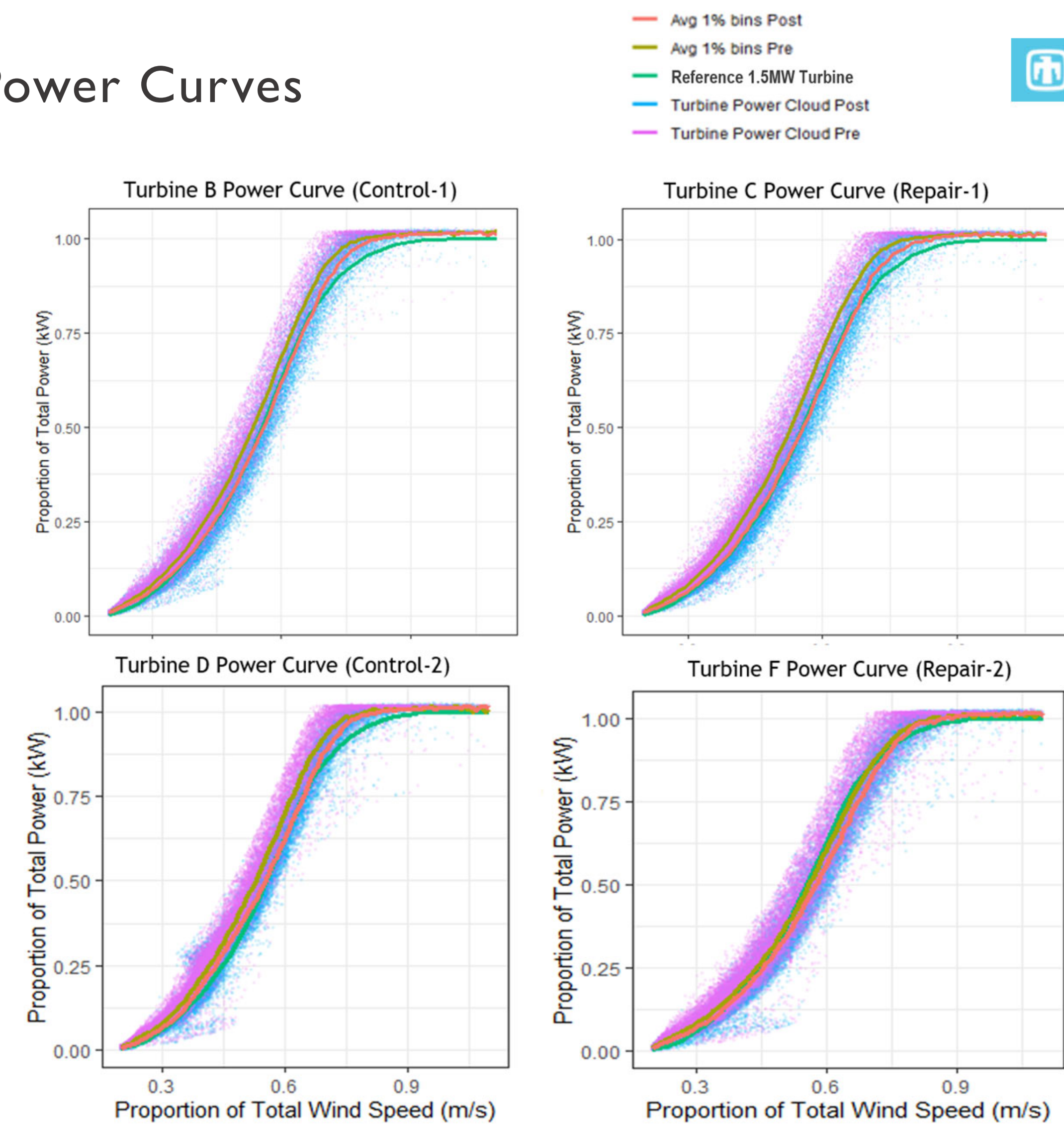
[1] Maniaci, David Charles, Ed White, Benjamin Wilcox, Christopher Langel, Case Van Dam, and Paquette, Joshua. *Experimental Measurement and CFD Model Development of Thick Wind Turbine Airfoils with Leading Edge Erosion*. United States: N. p., 2017. Web. doi:10.1088/1742-6596/753/2/022013.

[2] Ehrmann, Robert S., and White, E. B. *Effect of Blade Roughness on Transition and Wind Turbine Performance*.. United States: N. p., 2015. *Preprint, Web*. https://www.osti.gov/servlets/purl/1427238.

[3] Maniaci, D.C., Westergaard, C., Hsieh, A., and Paquette, J.A., Uncertainty Quantification of Leading Edge Erosion Impacts on Wind Turbine Performance, in Torque 2020. 2020.

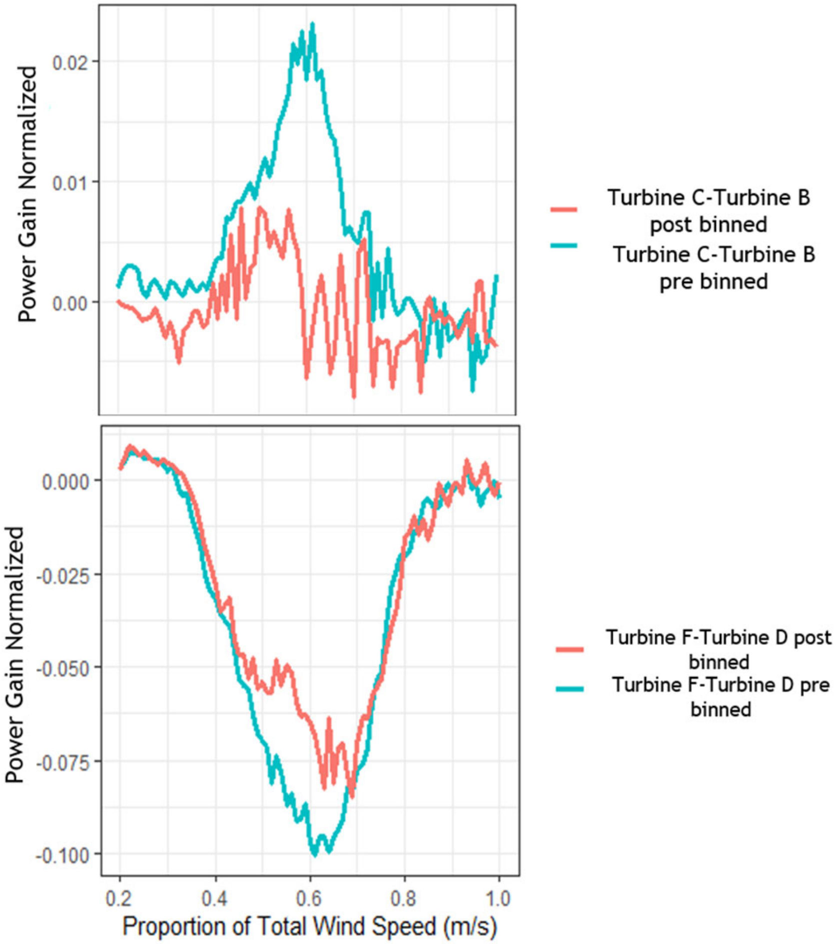
Comparing Turbine Pairs– Overall Power Curves

- While power curves for turbine look similar, slight differences in overall area toward region 3 contribute to greater differences in power performance
- Overall, turbines generated less power after the repairs to turbines C and F
    - Therefore we must compare the relative power loss for both turbines
- If turbines C and F had better relative performance, we can conclude the repair was effective
- For each month, power curves graphed for each turbine and fitted using three-parameter logistic function



Comparing Turbine Pairs– Relative Power Differences

- Turbine C was generating 1-2% more power for the same wind speed in middling wind speeds, with approximately equal production at the extremes
  - After repairs that advantage largely disappeared, resulting a net loss in relative power gain
- Turbine F was generating 5-8% less power for the same wind speed in middling wind speeds, with approximately equal production at the extremes
  - After repairs that disadvantage was mitigated slightly, resulting a net gain in relative power gain of 1-2% across middling wind speeds



Leading Edge Erosion Modeling and Mitigation

What are we doing currently?

- Coordination of Work Packages 2 and 3 of IEA Task 46, Wind Turbine Operation with Erosion
- Assessing LEE performance impact using statistical analysis of field data and probabilistic modeling

What do we plan on doing over the next two years?

- Continue coordination of IEA Task 46 Work Packages 2 and 3 for two more years
- Develop open performance loss model
- Process and explore additional field data sets
- Release field data power performance analysis software openly and support use by external partners

Questions:

- What data is needed to assess performance loss due to erosion for repair decision making (ie. AEP impact vs. erosion category)?
- What modeling or demonstration would be needed to adopt an erosion mitigation control mode?

Thank you! Contact: dcmania@sandia.gov

Inspection

Michelle Williams

What are we doing? ARROW(e)

Problem

What is ARROW(e)

Current Technology

Technology Commercialization Fund

Techno-Economic Analysis

Future: 2-year Plan – Advanced Technology

Techno-Economic Analysis

Advanced Technology: Selection, Development, Optimization, Deployment

Potential Technologies:

- Microwave
- Laser Vibrometry
- Thermography
- Mechanical Impedance
- Shearography
- Acoustic Beamforming
- Air-coupled Ultrasonics

Cnbc.com

Future: 2-year Plan – Advanced Technology

Requirements:

1. non-contact inspection (drone deployed)
2. inspect panel regions

Scaled and Field testing of down-selected methods

Robotic Inspection Technology Screening (First Pass)

Crawler					
Method	**Cost**	**Fidelity**	**Deployability**	**Speed**	**Coverage**
Thermography	Low	Medium	Low	High	Medium
Microwave	Medium	High	High	High	High
Ultrasonic	Medium	High	High	Medium	Medium
Laser Vibrometry	Low	Low	High	High	Medium
Mechanical Impedence	Low	Medium	High	Medium	Medium
UT + MIA	Medium	High	High	High	High

Drone					
Method	**Cost**	**Fidelity**	**Deployability**	**Speed**	**Coverage**
Thermography	Low	Medium	High	High	Medium
Microwave	Medium	High	Medium	High	High
Ultrasonic	Medium	High	Low	Low	Medium
Laser Vibrometry	Low	Low	High	High	Medium
Mechanical Impedence	Low	Medium	Low	Low	Medium

Questions

Public Data?

- Data regarding damage types and categories (lack of access)
- Repair costs to deal with damage

If you choose to monitor over repair, how do you monitor, and how confident are you in that method?

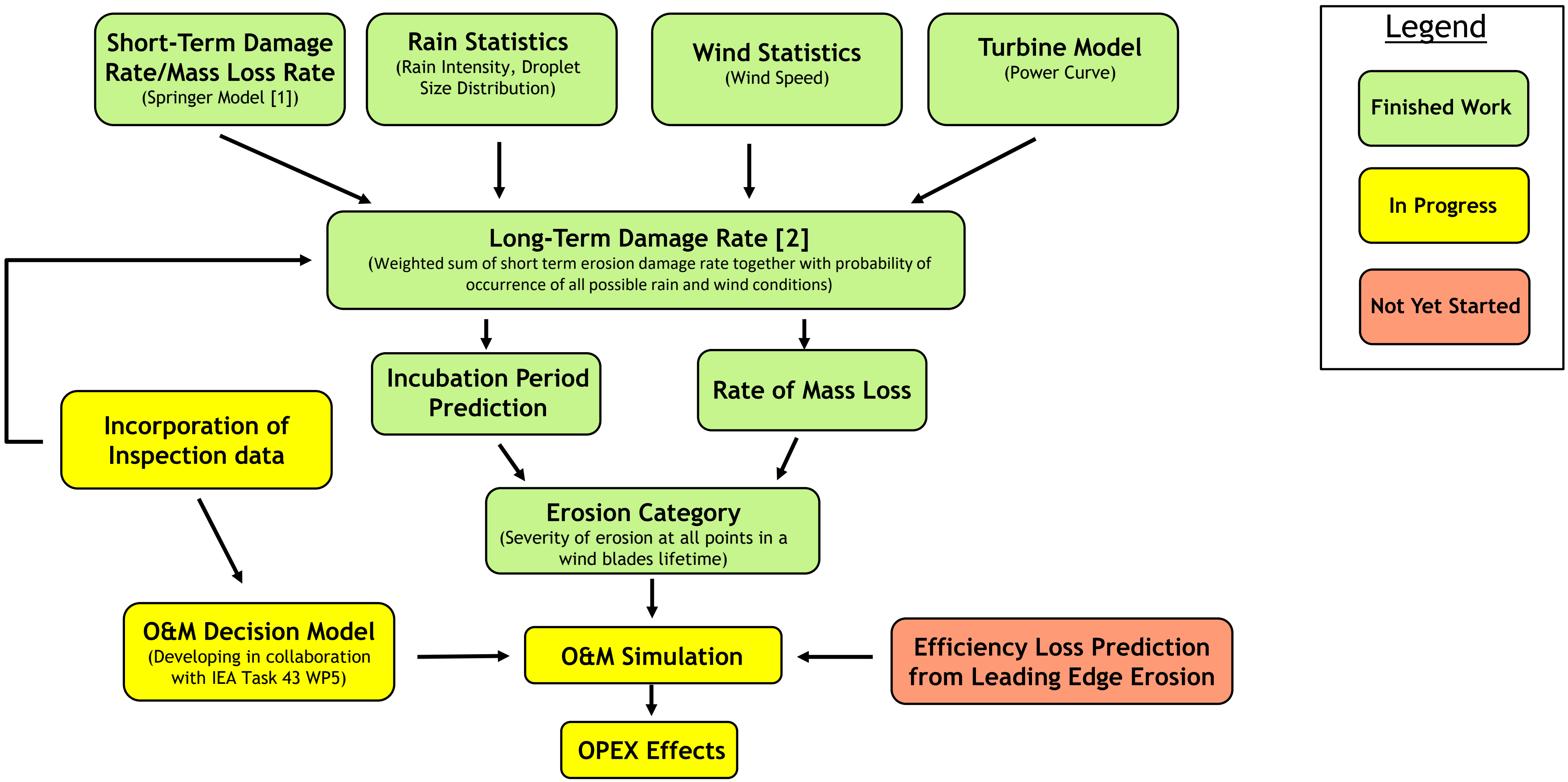
Questions/Input from audience

Break

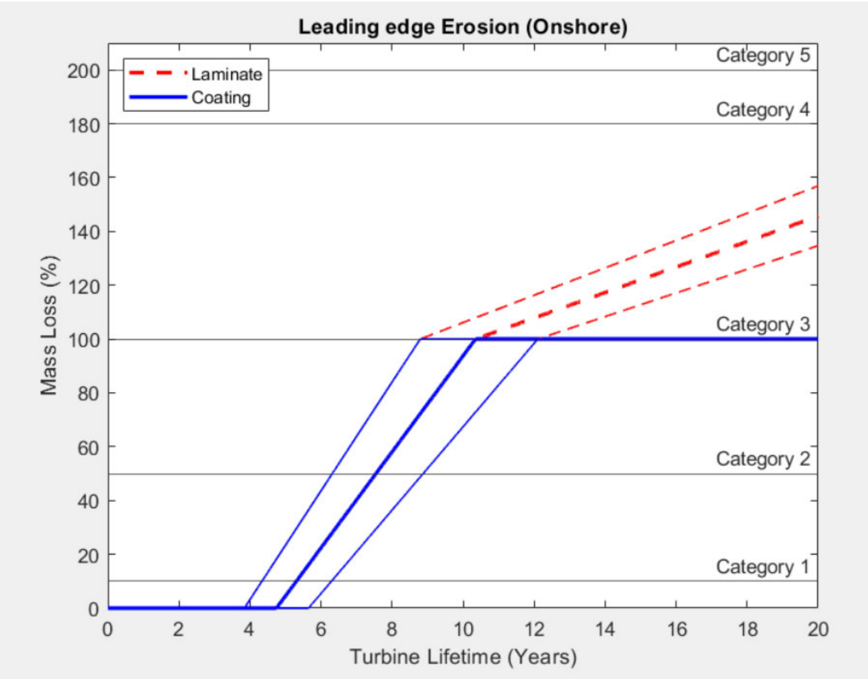
O&M Optimization

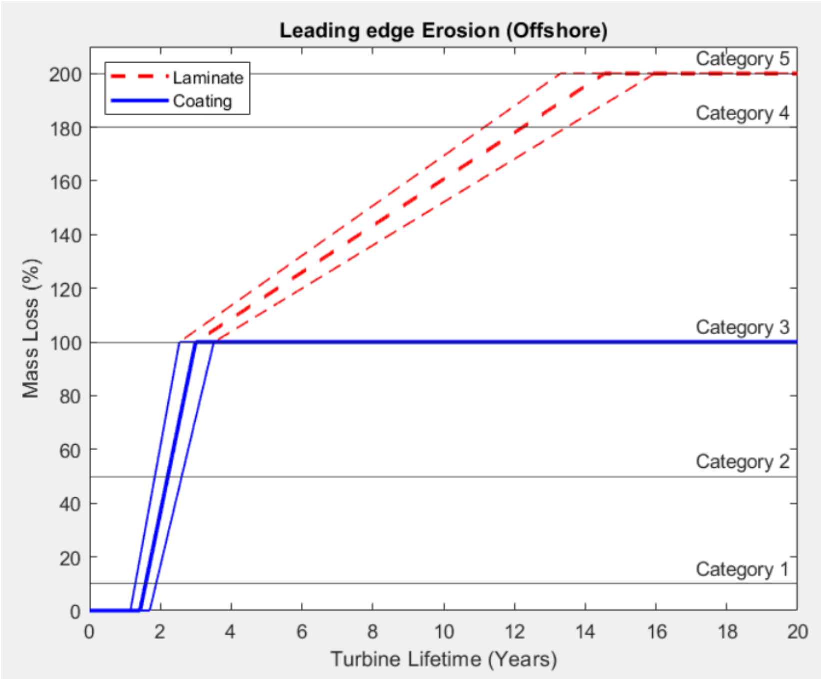
Ryan Clarke

Erosion Damage Growth Model for O&M Prediction and Optimization

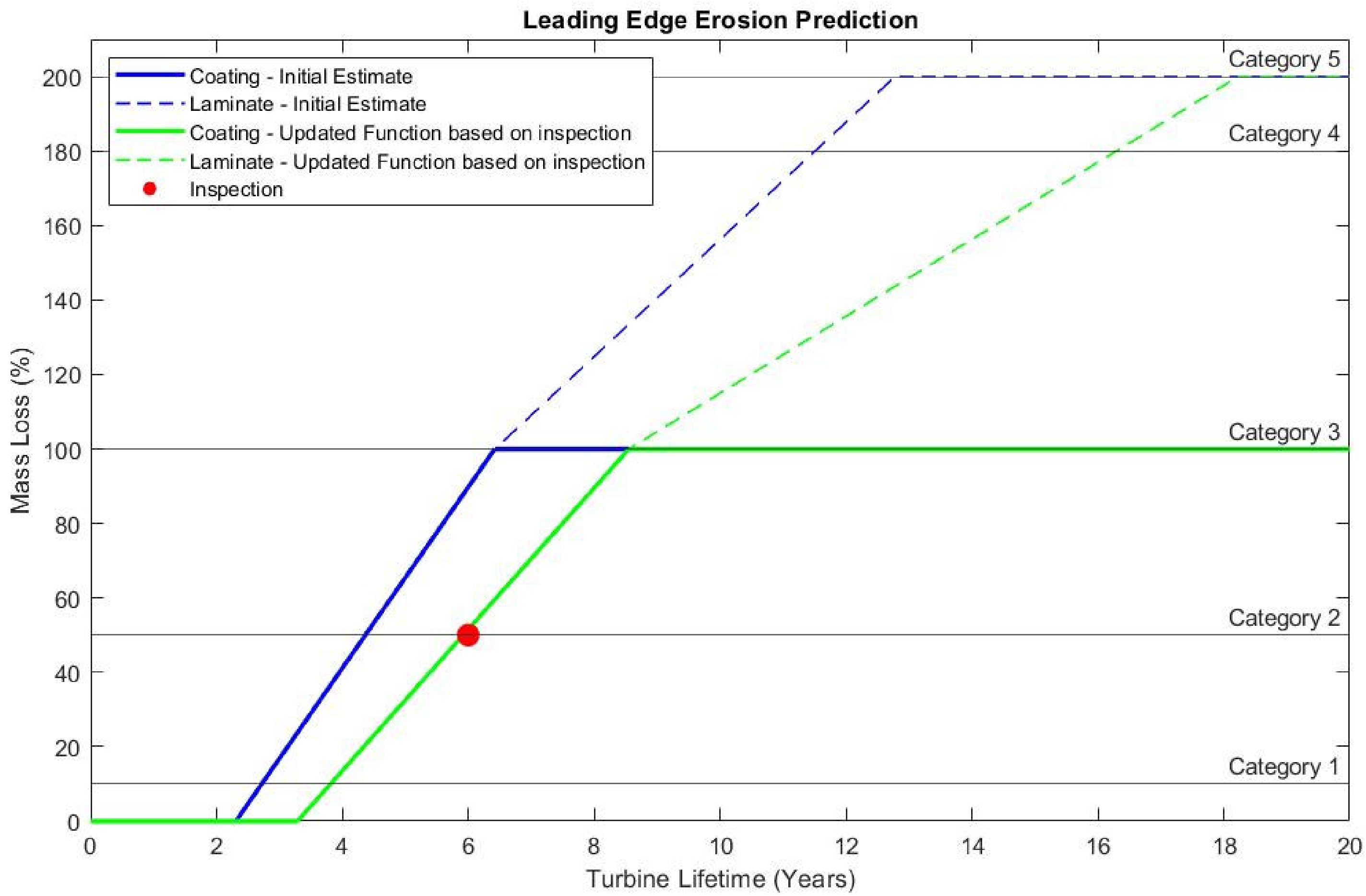


Preliminary Results

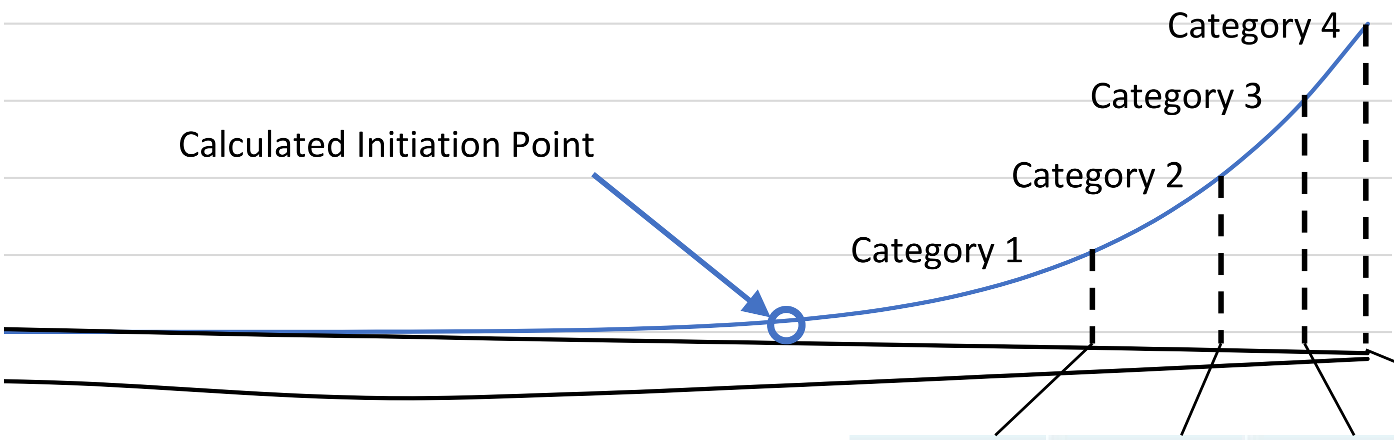




Incorporating Inspection data to reduce uncertainty



Incorporating Inspection data to reduce uncertainty



$$m \propto V^{6.4}$$

"Leading Edge Protection Lifetime Prediction Model Creation and Validation." Drew Eisenberg, Steffen Laustsen, Jason Stege. Wind Europe 2016

Erosion Damage Growth Model for O&M Prediction and Optimization

- Damage growth model and approach taken from Verma et al [2]. Extended to include:
  - Mass loss rate after incubation period.
  - Attempt to relate percent mass loss to erosion category.
  - Erosion of coated materials instead of assuming homogeneous monolithic material [1].

- The model is flexible and tailorable:
  - Through the Turbine model coarse characteristics of different turbine sizes and high level control strategy effects are captured.
  - Accounting for Rain and Wind Statistics allows the model to be tailored to specific wind plant sites.
  - Using the Springer model allows for comparisons of different materials. As well as accounting for the statistical variation in material properties through stochastic simulations.

- Future work includes:
  - Adding a decision model to pair with the damage growth model.
  - Incorporating in inspection data into prediction.
  - Incorporating the ability to account for wind turbine efficiency loss due to leading edge erosion.
  - Extending physical-based O&M modeling to other damage modes like adhesive bond line crack growth and/or lightning damage.

[1] GS Springer, CL Yang; PS Larsen, "Analysis of Rain Erosion of Coated Materials," *Journal of Composite Materials,* vol. 8, pp. 229-252, 1974.
[2] A. Shankar Verma *et al.*, "A probabilistic long-term framework for site-specific erosion analysis of wind turbine blades: A case study of 31 Dutch sites," *Wind Energy,* vol. 24, no. 11, pp. 1315-1336, 2021, doi: 10.1002/we.2634.

Questions?

Damage Tolerant Materials and Structures

Ryan Clarke

Tasks

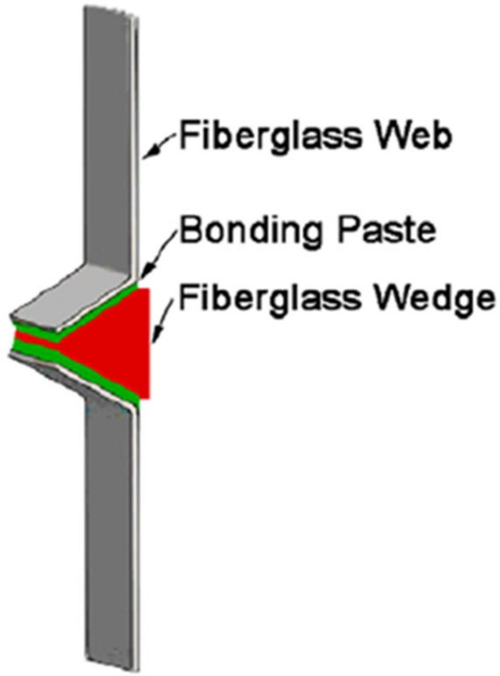
1. Testing of Trailing Edge Bondlines
2. Composite Doubler Repair Evaluation
3. Effect of Environmental Aging on Composites Structures

Testing of Trailing Edge Bondlines

Current work:

Completion of test matrix

Adhesive Bond technique	Defect Type			
	Control		Kissing disbond	
	Static	Fatigue	Static	Fatigue
Control	3-5 tests	5-10 tests	3-5 tests	5-10 tests
Alternative Joint geometries	3-5 tests	5-10 tests	3-5 tests	5-10 tests
Bolted Joint in conjunction with adhesive	3-5 tests	5-10 tests	3-5 tests	5-10 tests



Future work:

- Development of blade analysis procedures to determine impact of defect type and bond line enhancements have on damage initiation and growth in full wind blade.

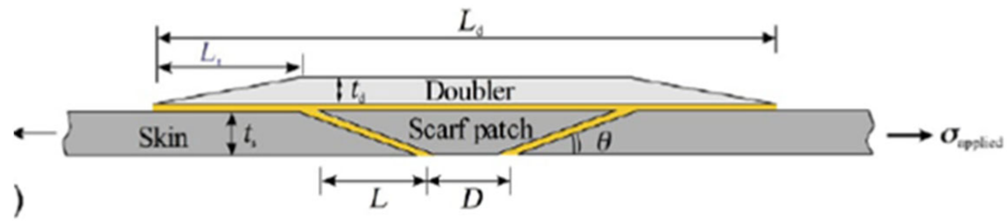
Composite Doubler Repair Evaluation

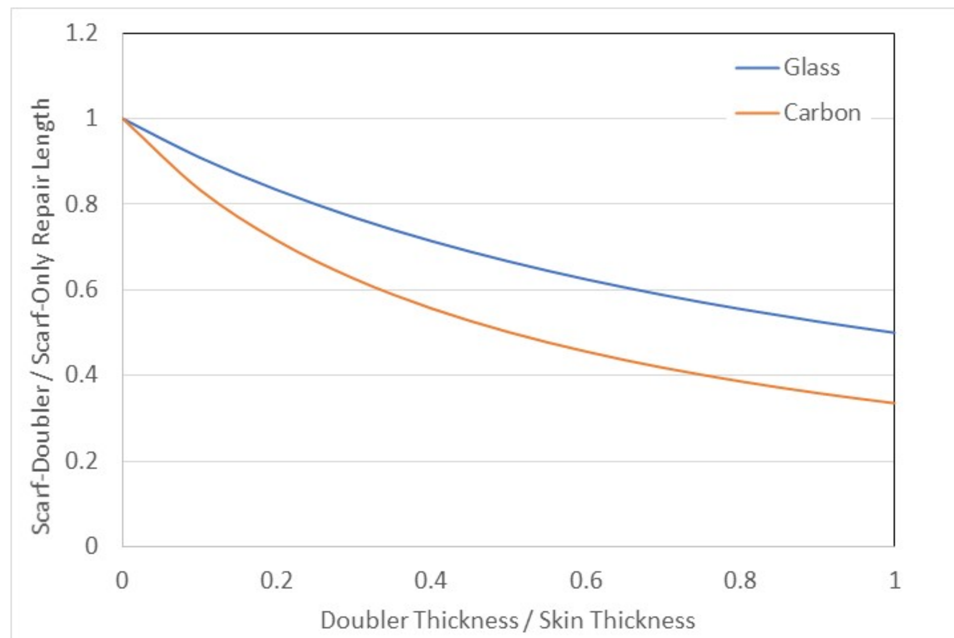
Current work:

- Completed preliminary analytical analysis for proof-of-concept

Future work:

- Static and fatigue testing of scarf and doubler+scarf repaired composite specimens for validation of concept.
- Modification of previously developed FEA analysis tools to parametrically analyze sensitivities of doubler repairs.
- Aerodynamic analyses to determine how sensitive airfoil performance is to doubler thickness.



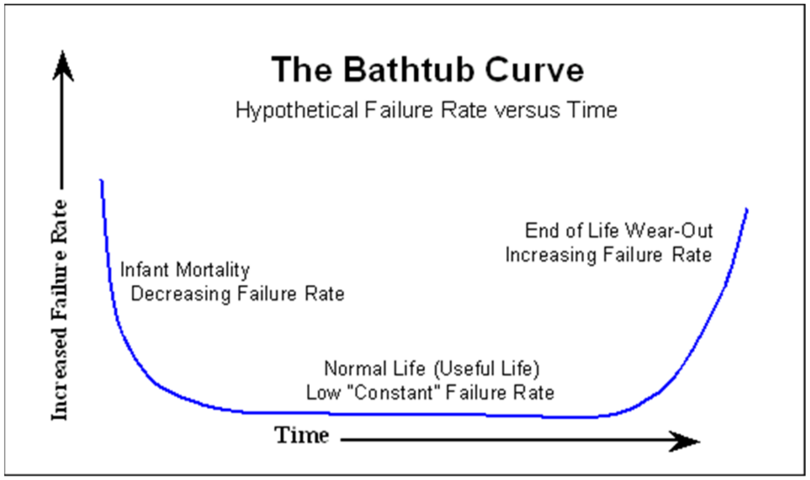


Effect of Environmental Aging on Composite Structures

- Wind blade structures and materials can undergo harsh environments, UV, icing, rain, lightning, fatigue loading, etc.

Future Work:

- Obtain operationally aged wind blade cross-sections and mechanically test and quantify the aged composites property degradation to determine the effects of realistic combined environmental factors have on wind blades.



https://www.weibull.com/

https://spectrumlocalnews.com/tx/south-texas-el-paso/news/2021/05/07/what-should-texas-do-with-its-old-wind-turbine-blades-

Questions?

Thank You