Blade Visual Inspection and Maintenance Quantification Study

Noah Myrent
Sr. Technical Leader – Wind

Lili Haus
Engineer II – Wind

Sandia Blade Workshop
October 19, 2022

www.epri.com

Damage and defect categorization survey (2020)

- Questions
  - Respondent's role in damage and defect categorization
  - Specific examples of damage and defects, including photographs, with request to categorize on a 1 through 5 scale
  - Assign a category, select action to take (monitor/repair/shut down)
  - Estimate extent of damage growth to recategorize of change action
  - Freeform question about description of blade maintenance program
  - Questions regarding frequency and methods of inspections
  - Limited information!

This damage is at 80% span on the suction side shell.

The damage measures approximately 10 cm x 3 cm.

This turbine has been running for approximately 30% of its design lifetime.

Blade damage and defect categorization system

Category	Characteristics	
1	**Description**	Minor variances from supply specifications but within acceptable (or industry typical) tolerances; may affect the appearance of the blade or blade feature. Though minor, can be useful to identify as position references, or for blade identification.
	Potential for growth	None expected.
	Impact to aerodynamics	None expected.
	Impact to life	None expected.
2	**Description**	Minor damage or defects that exceed supply specification acceptance criteria. Multiple cosmetic findings and/or a single major cosmetic finding that are damage, defects, or former repairs. Findings exceed tolerances of supply conditions or industry typical manufacturing variability. Repairs of more severe damage or defects can be recategorized to category 2 upon review of repair.
	Potential for growth	Not likely but may accelerate leading edge erosion when located on the leading edge, additionally may leave laminate or bond lines exposed to environmental degradation. Generally 100% growth in size or severity pushes finding into next category.
	Impact to aerodynamics	May have minor impact to aerodynamics depending on details, though beyond what could reasonably be measured.
	Impact to life	None expected.
3	**Description**	Moderate to minor structural damage or minor manufacturing defects in non-critical areas. Features are moderately out of compliance with supply conditions and/or below minimum typical industry practice. May present as surface indications when in fact there is damage to the underlying structural laminate. Internal inspection may be needed to determine the extent of the finding. May be particularly challenging to assess criticality due to lack of design data such as load margins. Findings may be category 3 when category 4 actions seem too drastic and category 2 is not appropriate, because there is a slight risk of loss of structural capability.
	Potential for growth	Likely to increase in size or extent over time and become more severe. Growth in size or severity by 50% or more is likely to push finding into next category.
	Impact to aerodynamics	May have an impact to aerodynamics depending on details.
	Impact to life	Life is expected to be reduced without some other measures such as monitoring or repair or engineering evaluation (in the case where there is sufficient margin).
4	**Description**	Significant damage or defects that have notable impact to structural capability and/or aerodynamic performance.
	Potential for growth	Likely to increase in size or extent over time and become more severe. Growth in size or severity of 10-50% is likely to push finding into next category.
	Impact to aerodynamics	Likely to have an impact to aerodynamics depending on details.
	Impact to life	High confidence the blade will not achieve intended life.
5	**Description**	Severe degree of damage or defect such that there is a high risk of imminent failure.
	Potential for growth	Likely to rapidly increase in size or extent.
	Impact to aerodynamics	Likely to have an impact to aerodynamics depending on details.
	Impact to life	The blade is expected to fail within a short period of time if operated.

Blade damage and defect categorization system

Category	Actions	
1	**Repair**	None needed, though some can be remedied with minimal effort in conjunction with other blade maintenance activities.
	Continued operation of turbine	Yes.
	Additional monitoring	None needed.
2	**Repair**	Evaluate cost/benefit of repairs.
	Continued operation of turbine	Yes.
	Additional monitoring	Monitor during routinely scheduled maintenance for damage initiation or progression. Depending on the damage, internal inspection may be warranted to differentiate surface cracks from more severe laminate damage.
3	**Repair**	Determine depending on circumstances, criticality, and O&M approach. If found during manufacturing, should be repaired prior to installation. Investigation and repair or replacement of missing aerodynamic devices should be performed to regain energy capture benefits. Timing of repairs can be linked to other blade-related needs. Leading edge erosion or small external cracks should be repaired to prevent damage progression.
	Continued operation of turbine	Yes.
	Additional monitoring	Inspection frequency driven by assessment of risk; may be more frequent than routinely scheduled inspections recommended by the OEM. If no growth in damage over time, an engineering assessment may downgrade finding to category 2.
4	**Repair**	Repair within a limited number of months of initial observation. Repairs may be performed uptower or blade removal and ground repair maybe necessary, depending on the finding. If found during manufacturing, should be repaired prior to installation and a manufacturing quality assessment should be undertaken to find and correct root causes.
	Continued operation of turbine	Engineering evaluation required to deem blade can operate until repair is scheduled. Operation shall stop if repair cannot be implemented within the allowable time period.
	Additional monitoring	More frequent or more comprehensive monitoring than routine inspections are required until repairs are complete.
5	**Repair**	Replace, or repair depending on repair feasibility and cost/benefit relative to replacement.
	Continued operation of turbine	The blade is not safe to operate until the damage or defect is repaired or the blade is replaced.
	Additional monitoring	If repair is implemented, repair should be deemed a Category 3 defect until sufficient operating experience is gained to provide confidence that the repair is sufficient to achieve expected remaining operating life.
	Further steps	A formal root cause analysis should be performed to ensure complete understanding of events or defects and prevent repeated occurrences.

Damage and defect categorization survey takeaways

- Category 1-3 typically operated with inspections every 6 to 12 mo.
- Category 3 or 4 typically repaired or shut down within 6 to 12 mo with inspection every 6 mo.
- Category 4 or 5 typically repaired or shut down immediately or within 12 months with monthly monitoring

Only the most severe damage and defects were considered serious enough to stop the turbine until repair.

Moderate and less serious damage were monitored once or twice a year with operation.

Wind Turbine Blade Maintenance Quantification

ISSUE

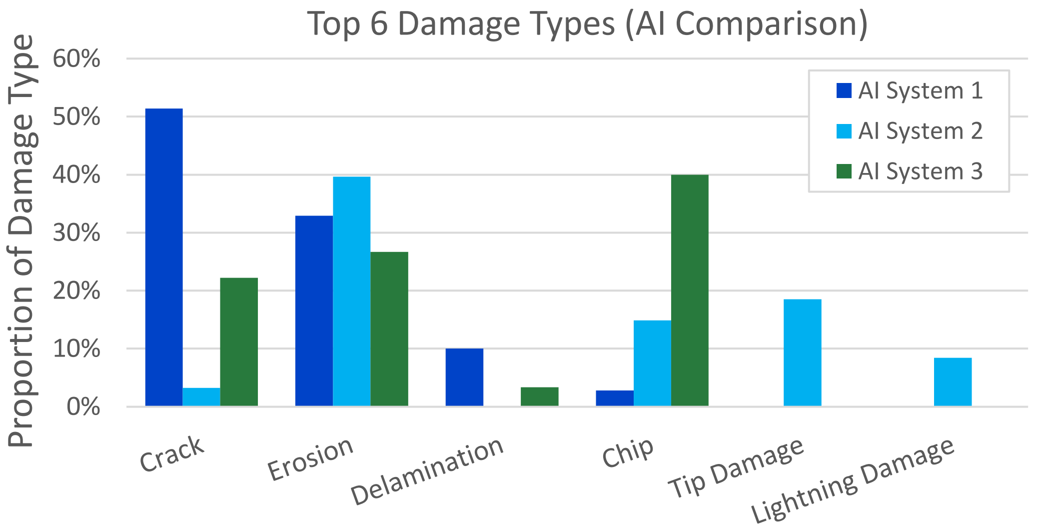
- Blade defect / damage categorization and management is highly subjective across industry, particularly when it comes to determining the right course of action for moderate blade damage.
- Visual blade data needs to be utilized for statistical knowledge and quantified decision-making for performance versus reliability.

APPROACH

- Collect and aggregate wind turbine blade data, including maintenance and failure records, inspection images, and other relevant data collected during blade maintenance.
- Quantify top blade damage types across the fleet dataset and recommend mitigation actions.
- Identify critical turbines, extent of damage and likelihoods of fault progression or failure.

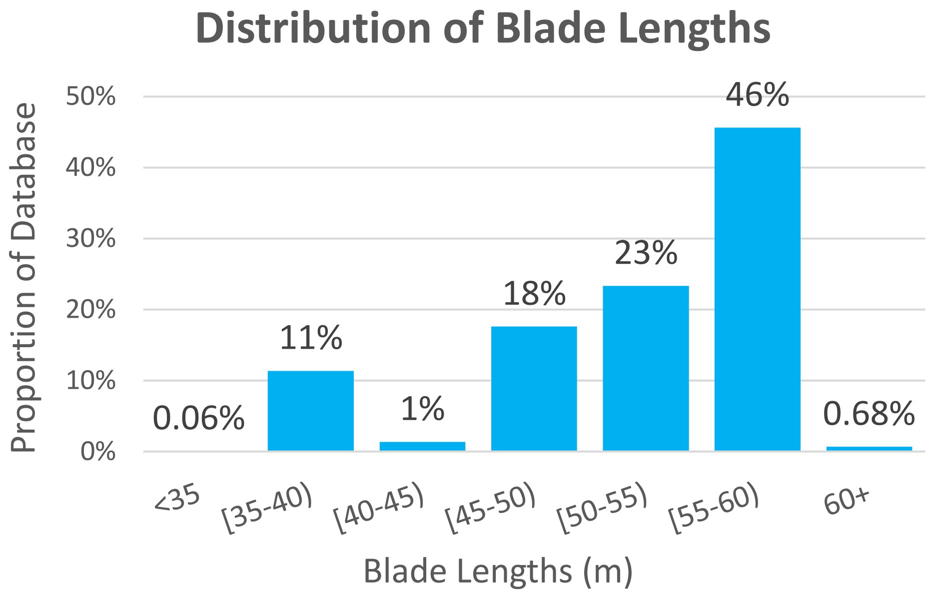
OUTPUT

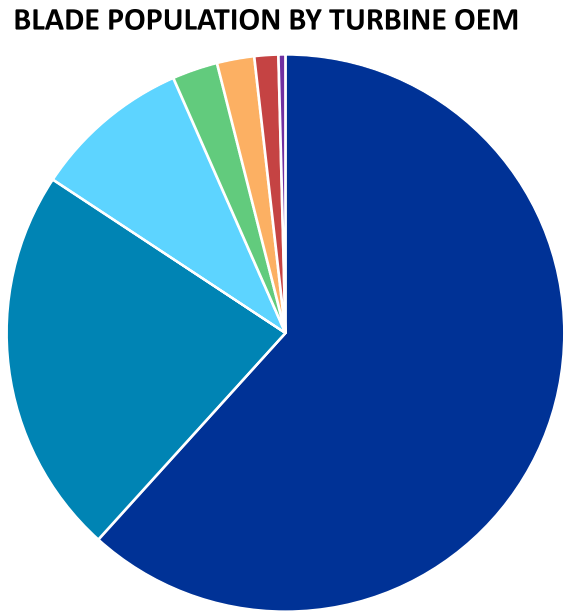
- Improved blade O&M strategies, reduced long-term costs and risks, informed warranty and field actions, and precursors to improved blade predictive maintenance.
- **2022 technical update planned for release (3002025466)**



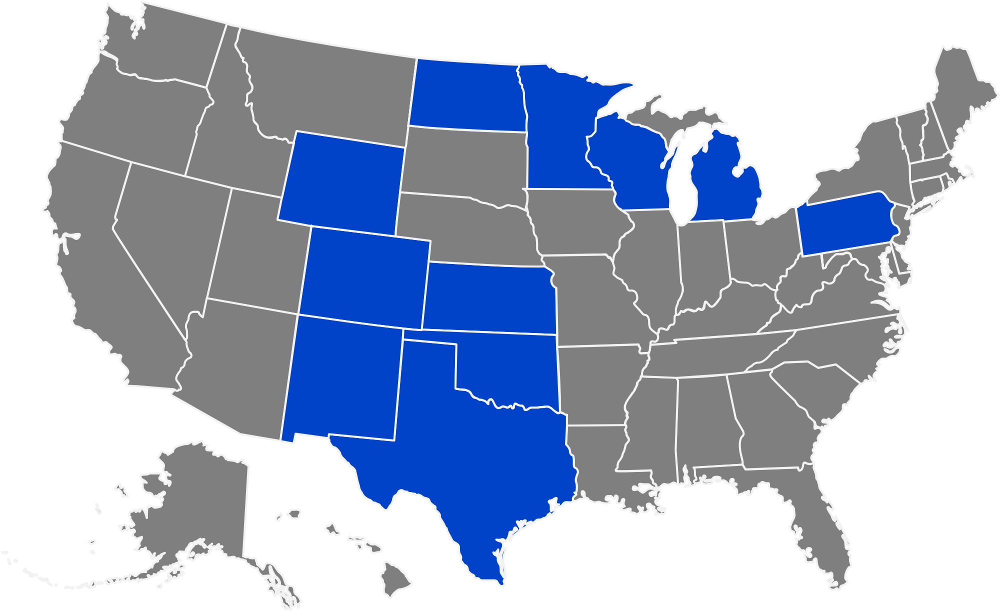
Blade Database Statistics

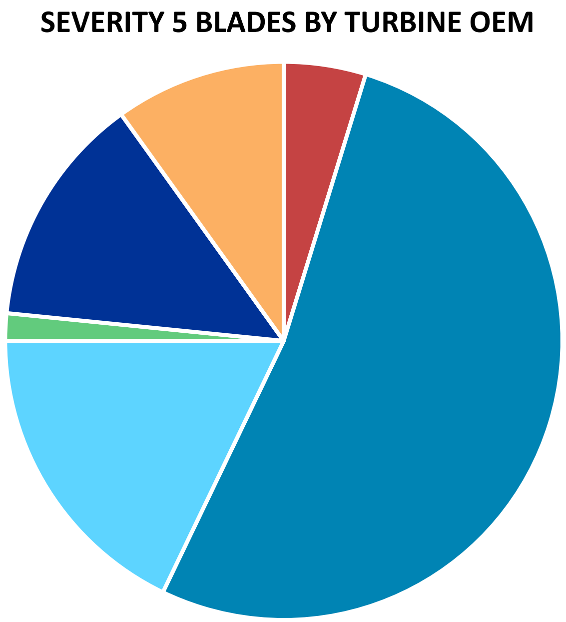
- ~3000 wind turbines
- ~50 wind farms
- 25 turbine models



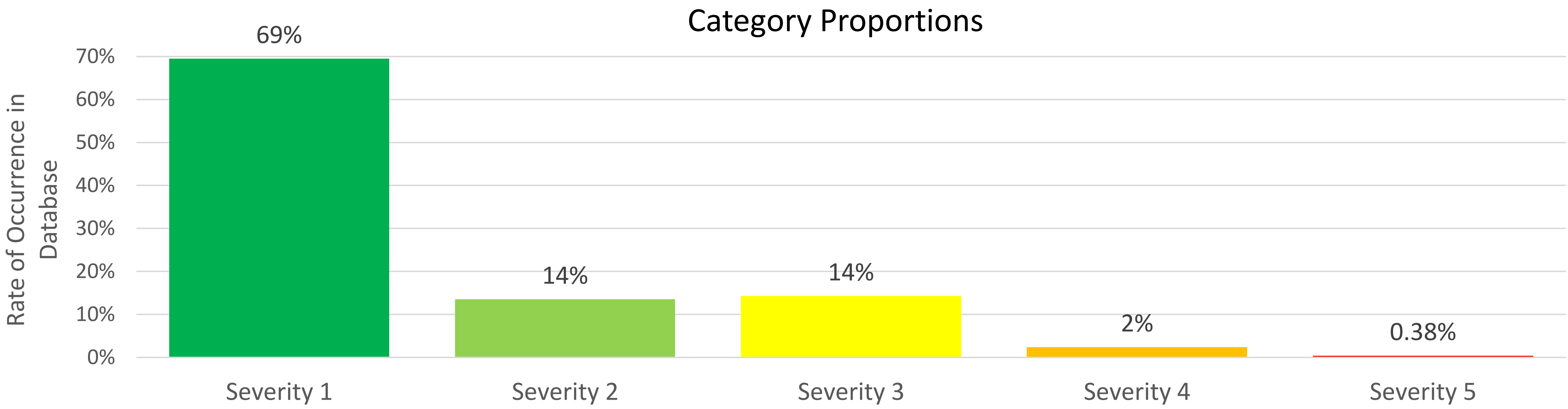


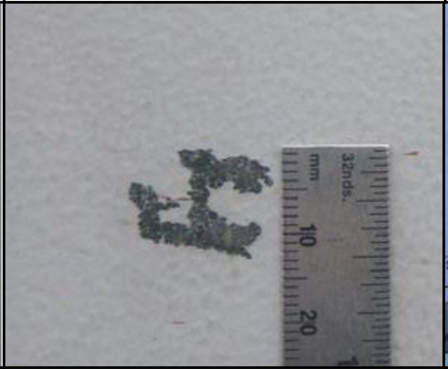
Across 11 US states:



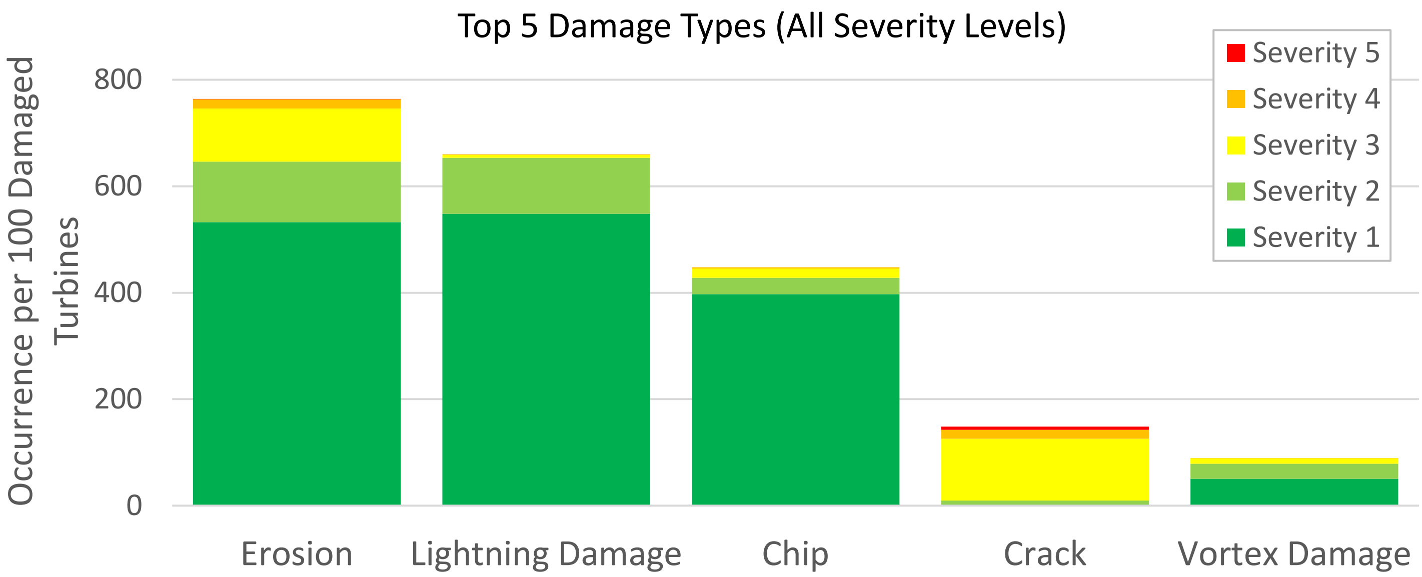


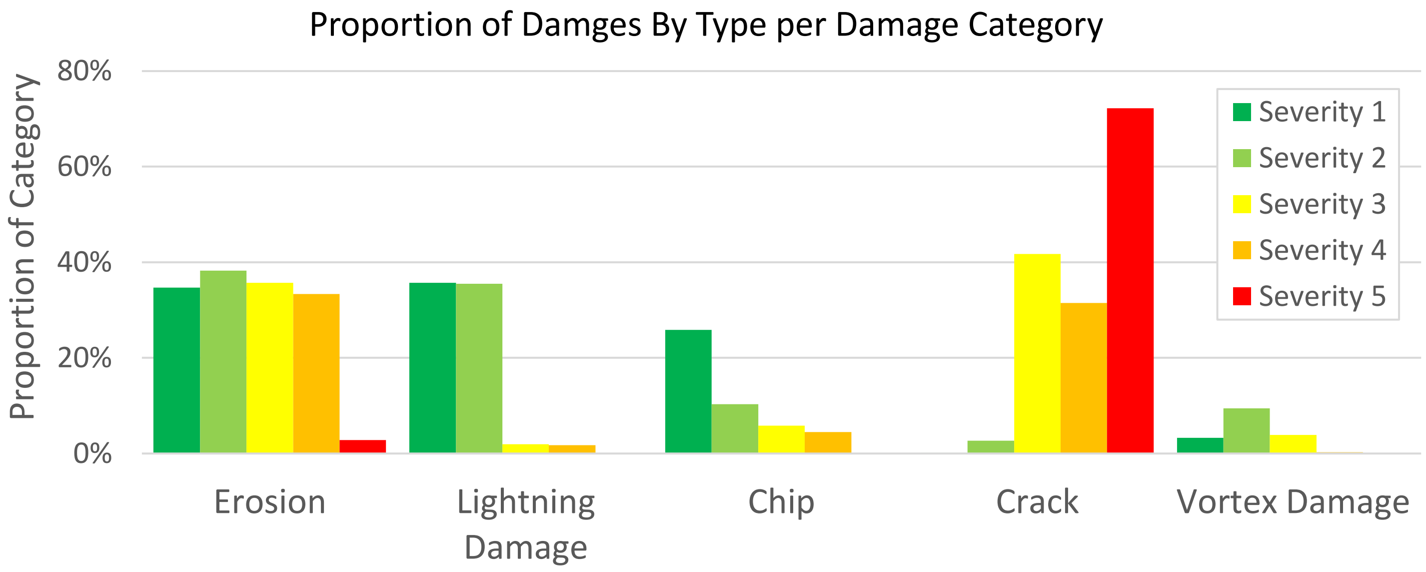
Blade Damage Trends – by Severity



Category 1	Category 2	Category 3	Category 4	Category 5
				
scratch in coating	*small region of coating damage*	*crack in structure at leading edge*	*large area of leading-edge erosion with fiberglass exposed*	*significant length of open trailing edge*

Blade Damage Trends – by Type






Erosion


Lightning Damage

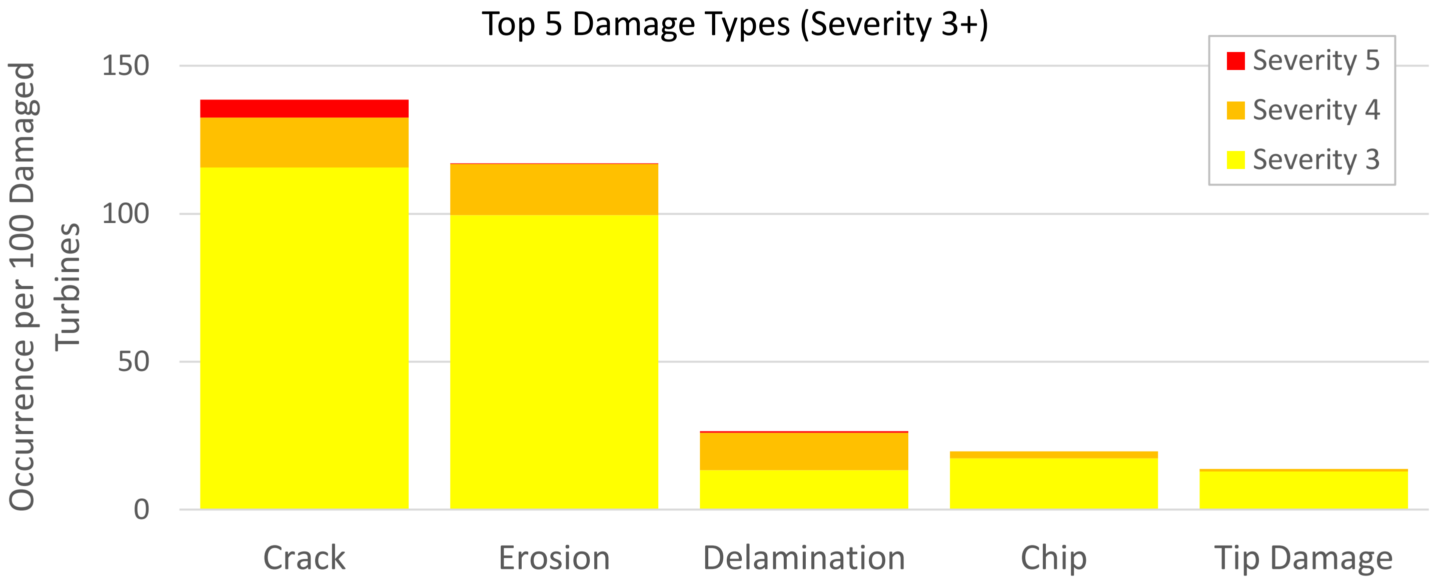

Chip

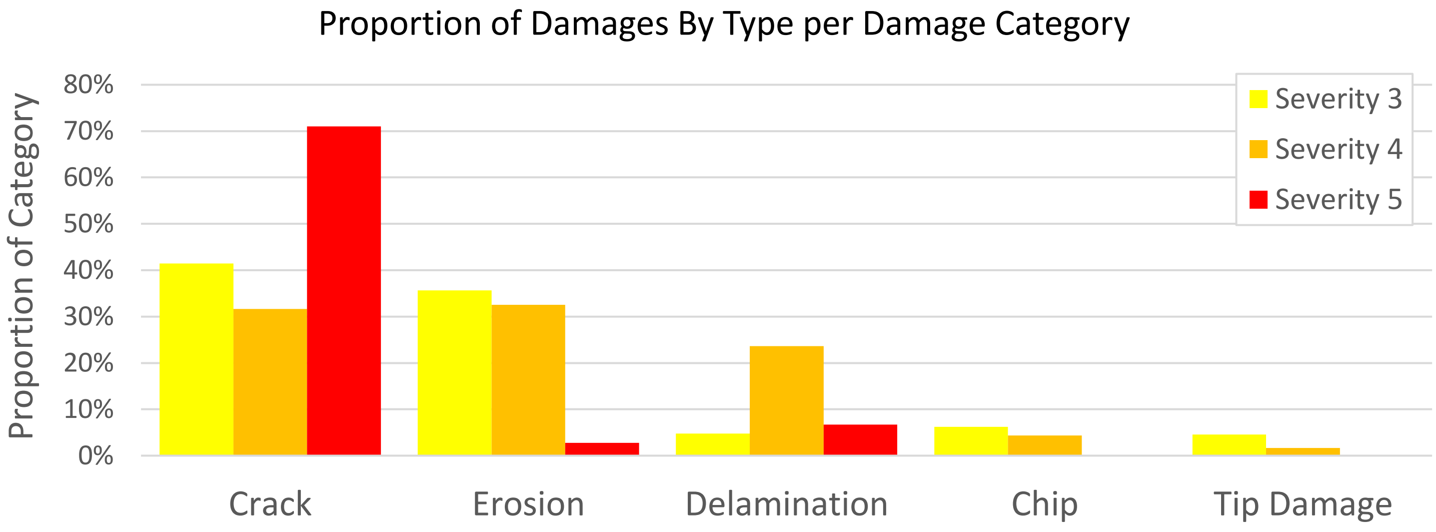

Crack


Vortex Generator Damage

- Erosion is approximately equally (proportionally) represented across Severity 1-4.
- Lightning damage is more likely to be categorized as Severity 1-2.
- Cracks are the most likely damage type to be categorized as Severity 3+

Blade Damage Trends – by Type (3+ Severity)

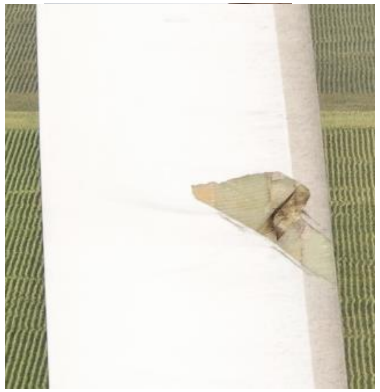





Crack


Erosion

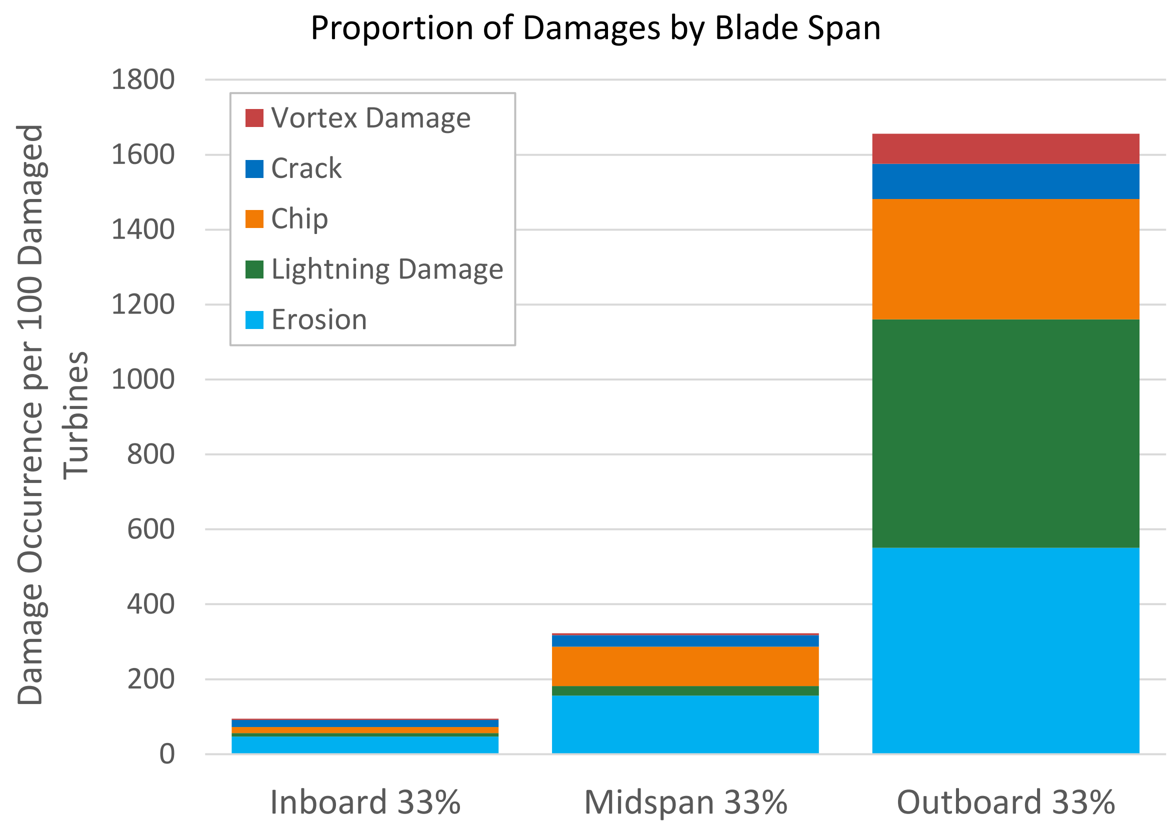

Delamination

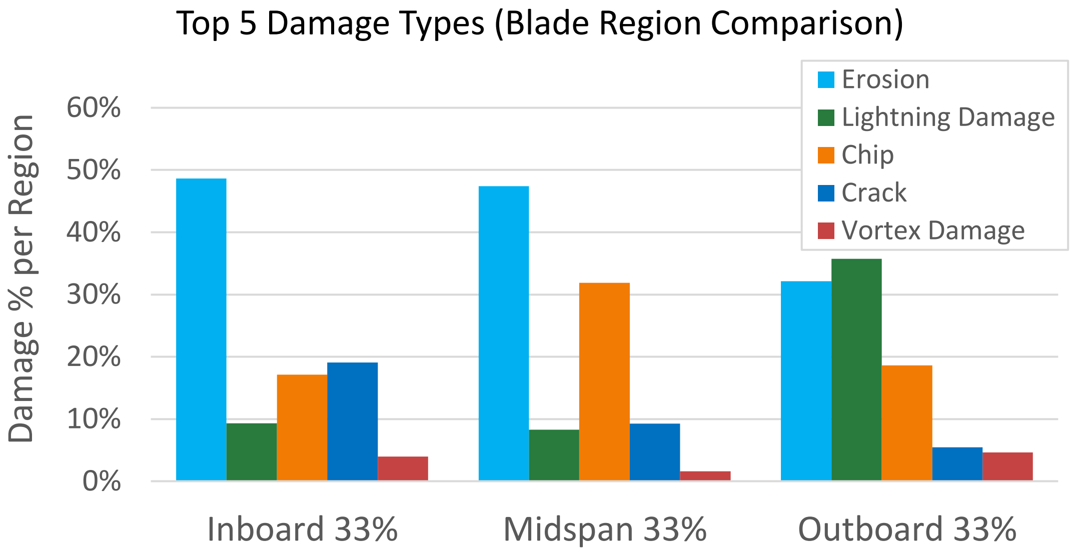

Chip


Tip Damage

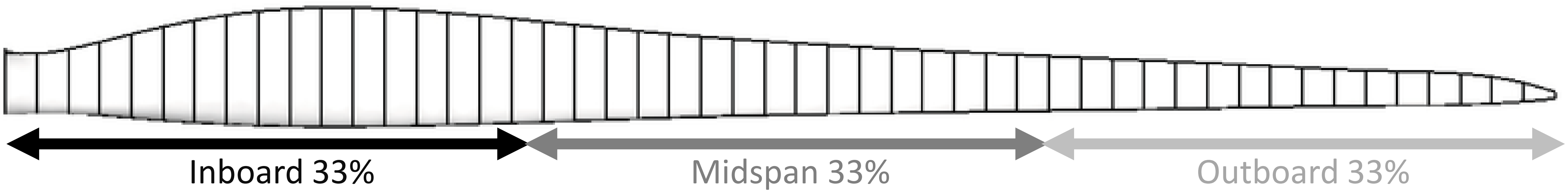
- 70% of all Severity 5 damages are cracks.
- Lightning damage and vortex damage no longer make it in the Top 5 damage types.

Blade Damage Trends – by Span Location (All Severity)

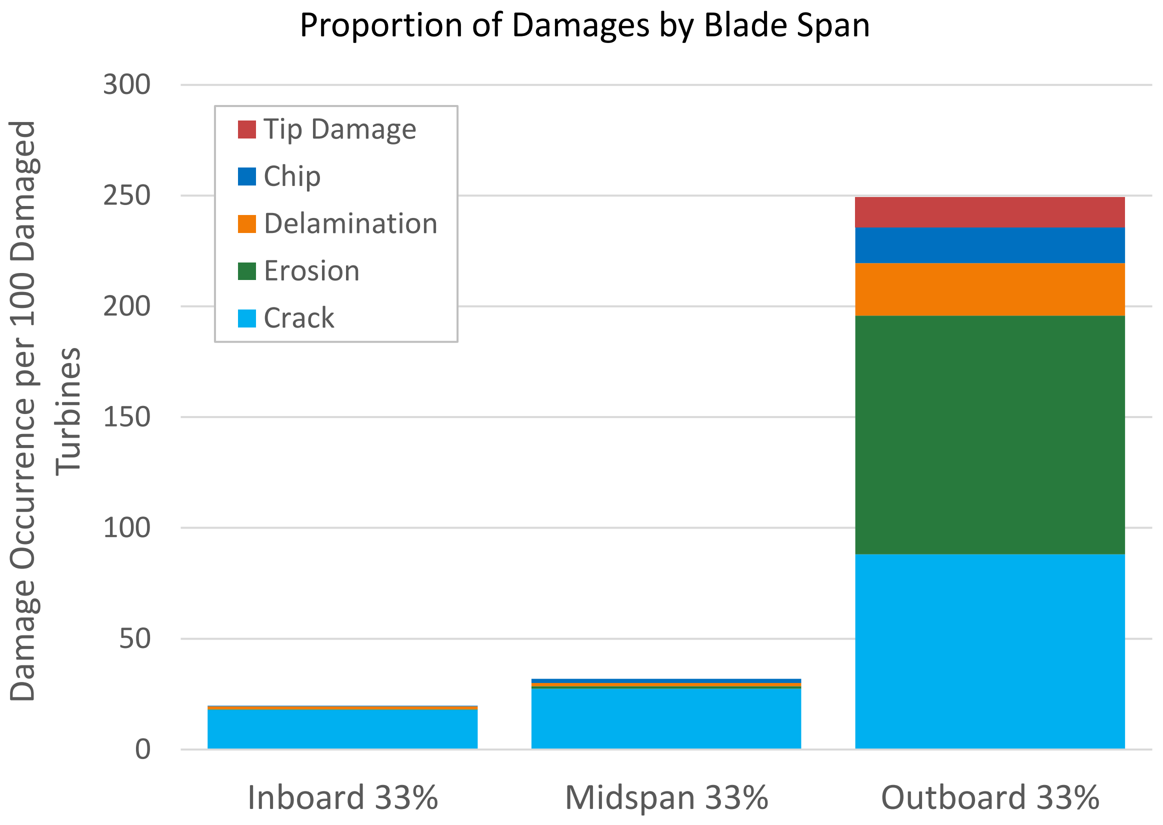


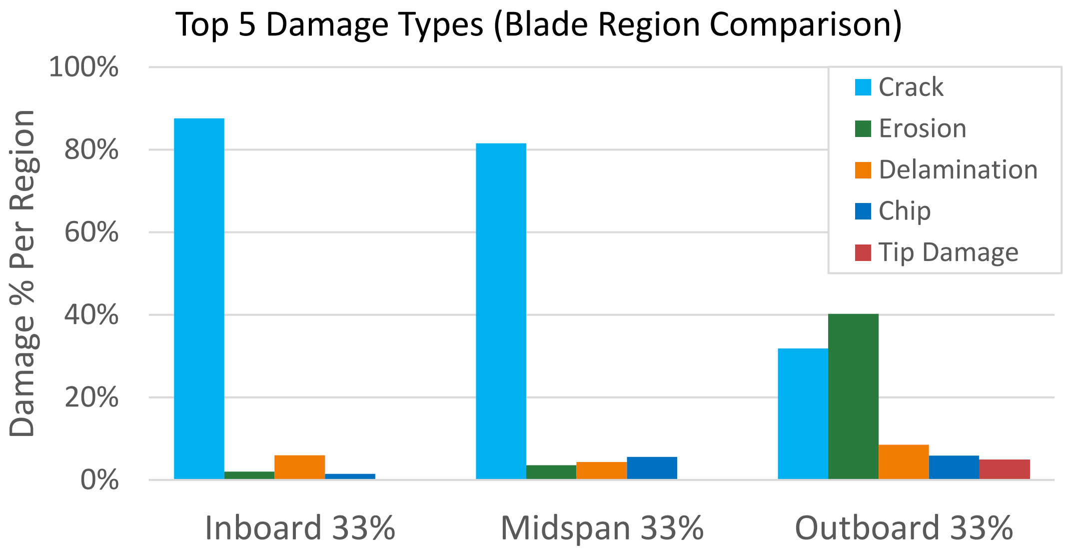


- Damage is most commonly found in the outboard 33% of the blade.
- Erosion makes up the greatest proportion of damage in the inboard and midspan.
- Lightning damage is most common in the outboard.

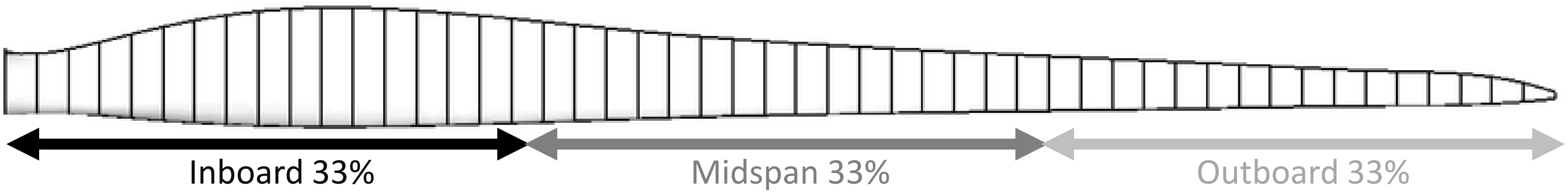


Blade Damage Trends – by Span Location (+3 Severity)

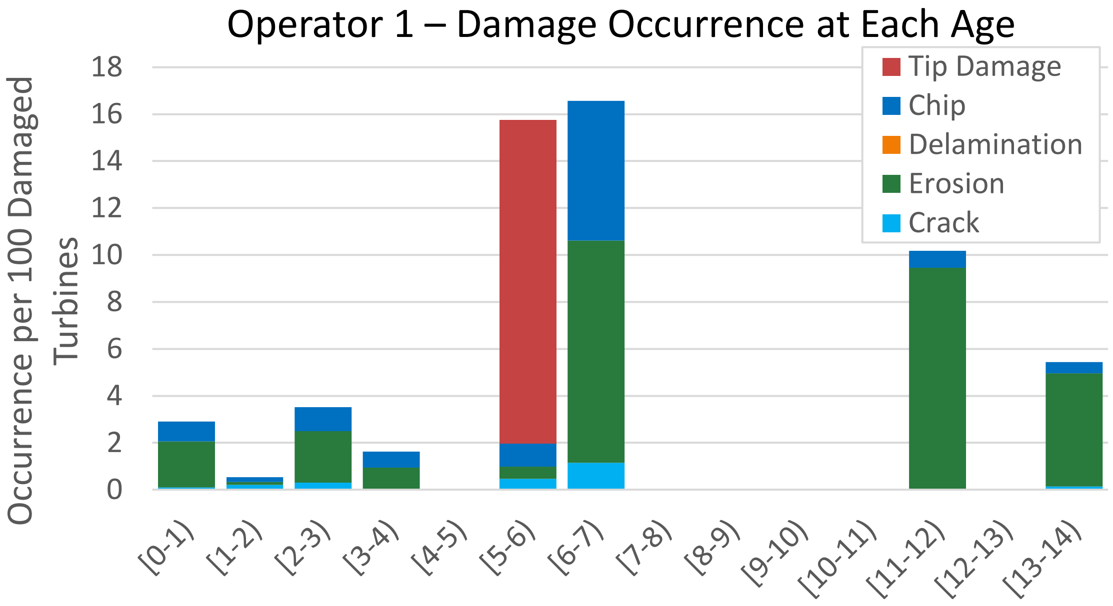


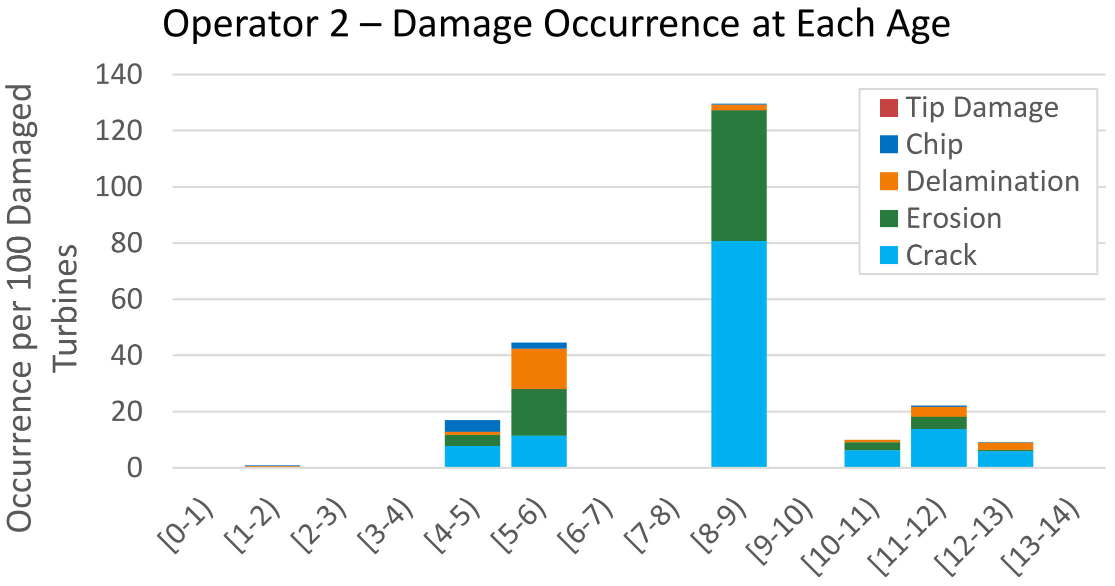


- Severity 3+ damage is most commonly found in the outboard 33% of the blade.
- Cracks make up the vast majority of Severity 3+ damage in the inboard and midspan.
- Erosion damage is most prevalent in the outboard.



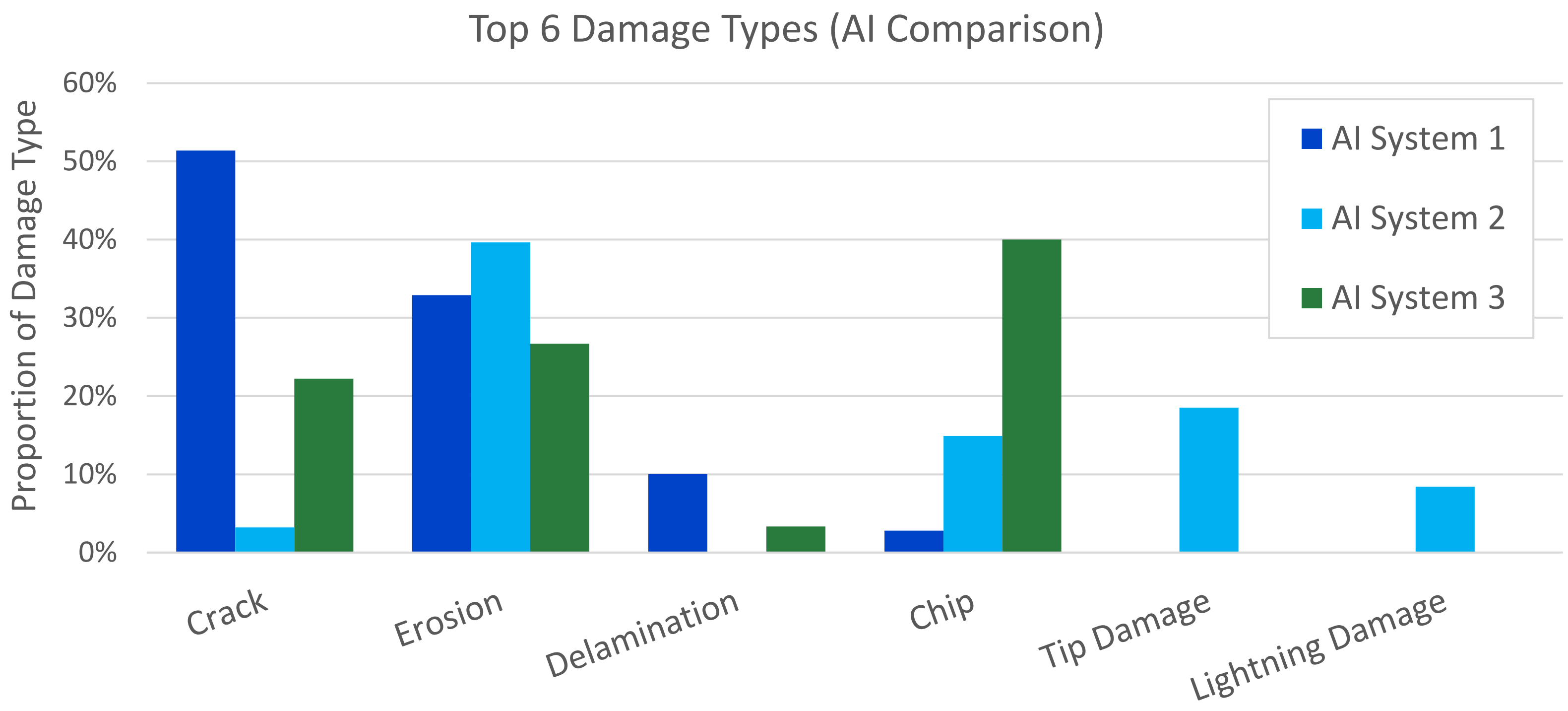
Blade Damage Trends – by Age (3+ Severity)





- Damages in distribution are Severity 3+.
- Both operators have turbines aging in age from 0 to 14 years old.
- Both operators began drone-based blade inspections in 2020.
- For Operator 1, proportional occurrence of erosion increases significantly after age 5.
- For Operator 2, proportional occurrence of cracks increases after age 8.
- These results should be used to understand the most common damage types at each age, NOT how damage occurrence rates vary with age.

Blade Damage Trends – by AI System (3+ Severity)



- The three systems detect erosion at similar rates of occurrence.
- It's important to consider that some damage categories might overlap
  - Lightning damage vs. Tip damage vs. Delamination (at the tip)
  - Erosion vs. Chips (on the leading edge)
- Evidence shows that AI has a hard time differentiating between cracks and surface debris, so false positives are likely.

AI System 1

- Highest relative rate of crack detection.

AI System 2

- Only of the 3 AI systems that appears to have a distinct category for lightning and tip damage.
- Might not have a category for delamination.
- Most conservative in crack detection.

AI System 3

- Highest relative rate of chip detection.

Damage Progression – LE Erosion

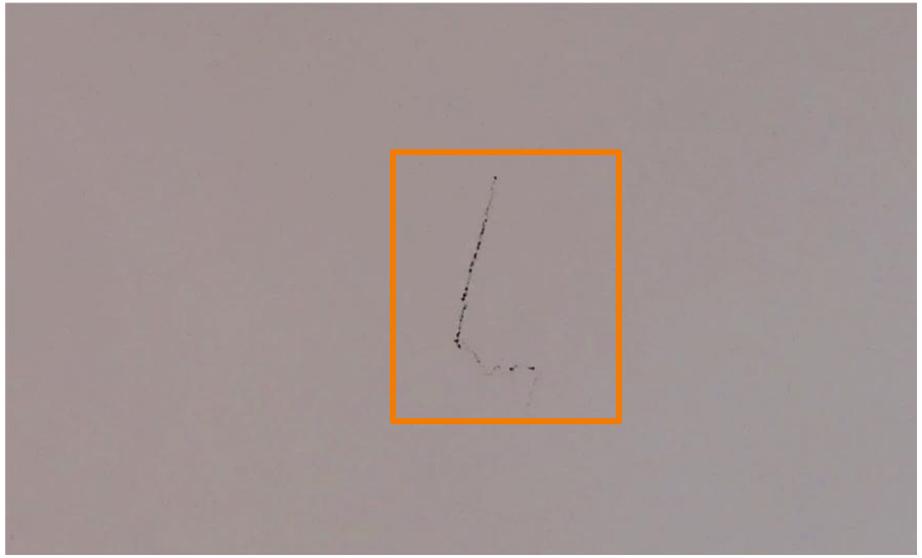
Inspection date: 1/19/2020

Severity category: 3

Inspection date: 2/8/2021

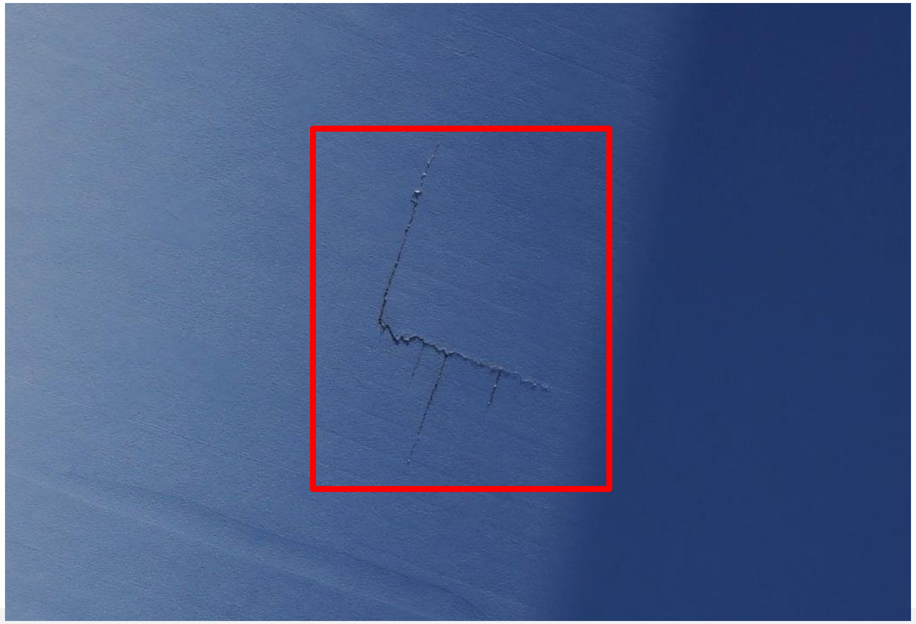
Severity category: 4

Damage Progression – Crack



Inspection date: 2/15/2020

Severity category: **4**



Inspection date: 3/11/2021

Severity category: **5**

Blade Inspection Techniques Survey

Some of the biggest challenges in the transition to more data-driven maintenance approaches include:

- Blade design complexity and variation.
- Hesitancy to share data and blueprints across industry.
- Lack of industry standards on categorizing damage or defect findings.
- Vast variation in blade inspection techniques and documentation.
- Insufficient understanding of how quickly damage propagates.
- Insufficient understanding of environmental impacts on damage propagation.

Future Work

- Technical update on the state of the industry, where we're heading and results of blade maintenance quantification preliminary study
  - To be released in 2022
- Continued collaborations to establish methodologies and standardized approaches to risk-based blade maintenance, data taxonomy, metadata, maintenance/inspection/repair processes, objective damage classification, and gaps in data standardization
- Blade maintenance field guide including damage rates from blade maintenance quantification study and methodologies to maintaining a blade fleet throughout operation
  - To be released in 2023

Wind Turbine Blade Monitoring with UMass Lowell

MOTIVATION

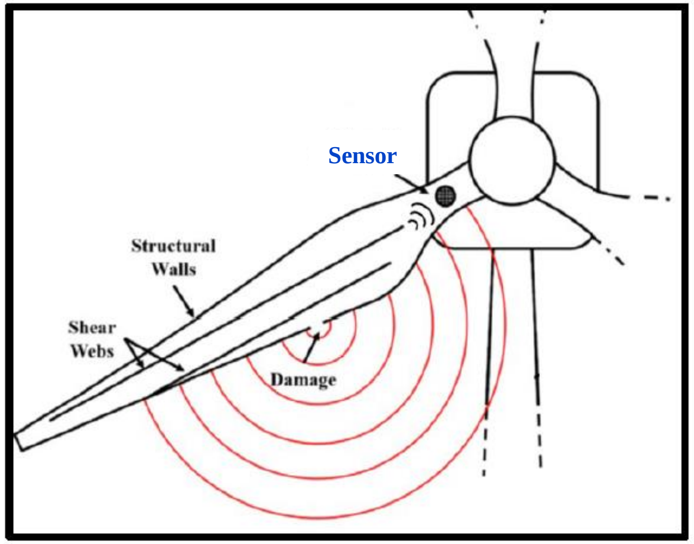
- Online condition monitoring is currently not applied to blades but can potentially detect multiple types of damage to inform better performance and risk-based decisions

TECHNICAL OBJECTIVES

- Investigate the development and feasibility of online blade condition monitoring, combining blade-mounted sensor data with other data streams, blade inspection data and metadata
- Demonstrate blade monitoring with hardware in the field at the Coastal Virginia Offshore Wind (CVOW) research project

VALUE/RELEVANCE

- Reduce blade failure rate and associated unscheduled maintenance
- Improve turbine availability while reducing blade repair costs
- Concept is universal for onshore/offshore turbines, new and existing (retrofit)



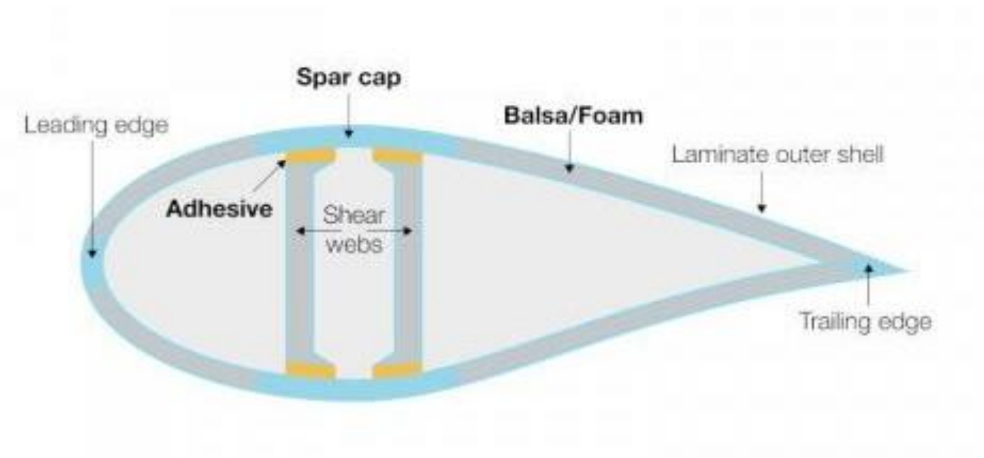
Acoustic Blade Monitoring Device

Dominion Energy CVOW Site

Verifying Offshore Wind Turbine Blade Integrity During Manufacture
National Offshore Wind Research & Development Consortium

MOTIVATION

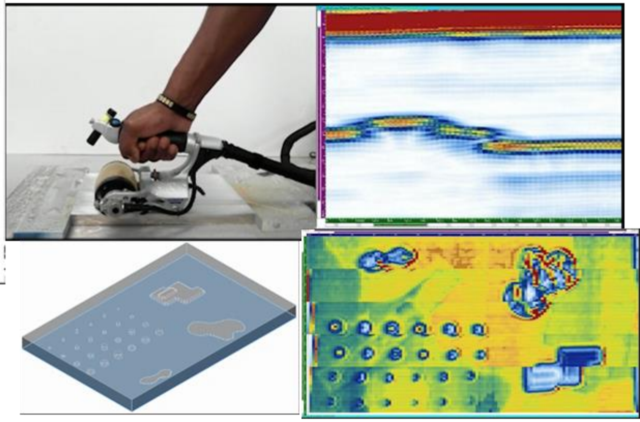
- Evaluate and determine the feasibility of applying advanced ultrasonic and microwave examination techniques to assess the structural integrity for offshore wind turbine blades to assure the highest quality during the OSW blade fabrication process



TECHNICAL OBJECTIVES

- Review OSW blade design, evaluate and determine the key inspection areas of interest during blade fabrication, and fabricate realistic test specimens with embedded flaws
- Design, develop, and test advanced ultrasonic (UT) and microwave (MW) examination techniques
- Demonstrate NDE techniques in manufacturing setting

Phased Array UT (PAUT) w/Roller Probe



Test piece (L), Imaged PAUT data (R)

VALUE/RELEVANCE

- Improves NDE techniques for blade flaw detection, classification, and quantification during blade manufacture
- Record of blade defects to improve inspection efficiency

Improves blade quality at source; reducing risk of blade failure in offshore (and onshore) applications

EPRI Reports Referenced

3002017731 Wind Turbine Blade Maintenance: With A focus on Damage and Defect Categorization

3002019669 A White Paper on Wind Turbine Blade Defect and Damage Categorization: Current State of the Industry

3002001502 Wind Turbine Blade Maintenance Guidelines: A Comprehensive Guide to Optimizing Blade Performance

3002007579 Lightning Protection for Wind Turbines: Technology and Best Practices Review

EPRI Contact Info

Name	E-mail
Noah Myrent	nmyrent@epri.com
Lili Haus	lhaus@epri.com
Brandon Fitchett	bfitchett@epri.com

Wind Power Generation - https://www.epri.com/research/programs/113055

Wind Innovator Network (WIN) - https://www.epri.com/win

WinNER - https://www.epri.com/research/products/000000003002020805

Together…Shaping the Future of Energy®