IEA Wind Task 46
Erosion of wind turbine blades

Leading Edge Erosion Classification System

Technical report

iea wind

Technical Report

Leading Edge Erosion Classification System

Prepared for the
International Energy Agency Wind Technology Collaboration Programme

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The example images of erosion were made possible by the contributions of several owner/operators, who took the effort to provide examples of a range of eroded blades to make this report possible.

Purpose

The purpose of this report is to publicly share results from work performed by IEA Task 46 on the erosion of wind turbine blades toward meeting objectives identified in a technical experts meeting. Work package 3 within Task 46 has three 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, especially the effect of LEE surface roughness on aerodynamics.

There are several deliverables planned toward meeting these objectives, the deliverable targeted by the present paper is to report on the standardization of damage reports based on erosion classification. This report is released for public dissemination.

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IEA Wind Task 46 Participants during period 2021-2025

Country	Contracting Party	Active Organizations
Belgium	The Federal Public Service of Economy, SMEs, Self-Employed and Energy	Engie
Canada	Natural Resources Canada	WEICan
Denmark	Danish Energy Agency	DTU (co-OA), Hempel, Ørsted A/S
Finland	Business Finland	VTT (co-OA)
Germany	Federal Ministry for Economic Affairs and Energy	Fraunhofer IWES, Covestro, Emil Frei (Freilacke), Nordex Energy SE
Ireland	Sustainable Energy Authority of Ireland	IT Carlow, NUI Galway, University of Limerick
the Netherlands	Netherlands Enterprise Agency	TU Delft, Suzlon, TNO
Norway	Norwegian Water Resources and Energy Directorate	Equinor Energy AS, University of Bergen
Spain	CIEMAT	CENER, Aerox Advanced Polymers, CEU Cardenal Herrera University, Siemens Gamesa Renewable Energy, Nordex Energy Spain
United Kingdom	Offshore Renewable Energy Catapult	ORE Catapult, University of Bristol
United States	U. S. Department of Energy	Cornell University, Sandia National Laboratories, 3M

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Executive Summary

The leading edge erosion of wind turbine blades is a common issue that can have a range of implications for the operation and maintenance of the turbine. A variety of methods have attempted to determine the severity of erosion damage, applied in different academic, testing and in-situ settings. This paper describes the current state of the art in categorization, and the individual drivers in assessment. From this foundation, the IEA Wind Task 46 WP3 group collated key considerations from the process of categorizing erosion damage and a proposed erosion classification system was put forward. Trial assessments were performed using the initial system, which led to adjustments to the original proposition. The refined system defines discrete severity levels that concern the wind turbine blade:

- Visual Condition (concerning blades with/without leading edge protection)
- Mass Loss
- Aerodynamic Performance
- Structural Integrity

The classification system presented is not intended to be a fixed entity. The Task 46 group has already identified specific challenges and opportunities that are applicable to individual use and the overall wind energy industry. The intention is for the system to evolve as improvements are identified, technology improves, and work progresses through other Task 46 activities. Several considerations and recommendations are discussed that could be applicable for future implementation of the system.

1. Introduction – IEA Wind Task 46 WP3 Activity 3.2

The scope of Task 46 has been established by the IEA Wind Technology Collaboration Programme (TCP), to achieve a better understanding of the key technical challenges within wind turbine blade leading edge erosion. It is aligned with two research priorities established by IEA TCP Wind, site characterization and advanced technology. The Task work plan is structured in four technical work packages (WP2-WP5) supported by a management work package (WP1).

Work Package 3 covers the topic of ‘Wind Turbine Operations with Erosion’, and 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.

These objectives will be met over the four-year course of Task 46 through five activities:

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

This report is associated with Activity 3.2, aiming to standardize the assessment of erosion damage data in several different settings; from computer simulation and the laboratory environment to in-situ wind turbine operation. The deliverable report initially covers a review to the various guises of erosion damage evaluation created in research literature, standards and commercial inspection services. The approach for determining a preliminary erosion damage classification system is then described, along with the steps taken to validate and refine the proposal. Finally, the resulting system is then presented, along with detailed definitions for evaluation criteria and severity levels.

2. Erosion Damage Categorization

2.1 Motivations for Categorization

Before laying out a standardized methodology it is important to understand the drivers for categorization. First, there is the incentive for identifying the type of damage exhibited on the wind turbine blade. Leading edge erosion is one of many damage mechanisms that can occur. By placing damage instances into distinct classifications, an immediate impression can be obtained of the damage manifestation and the possible root cause. By then assigning the severity level to that particular form of damage, an intuitive ranking is stated that implies the consequence of this instance of damage on the blade material and the overall wind turbine. This can also advise on the type of remedial actions that are required. It is imperative that the categorization is accurate and distinctive to the damage scenario and well understood.

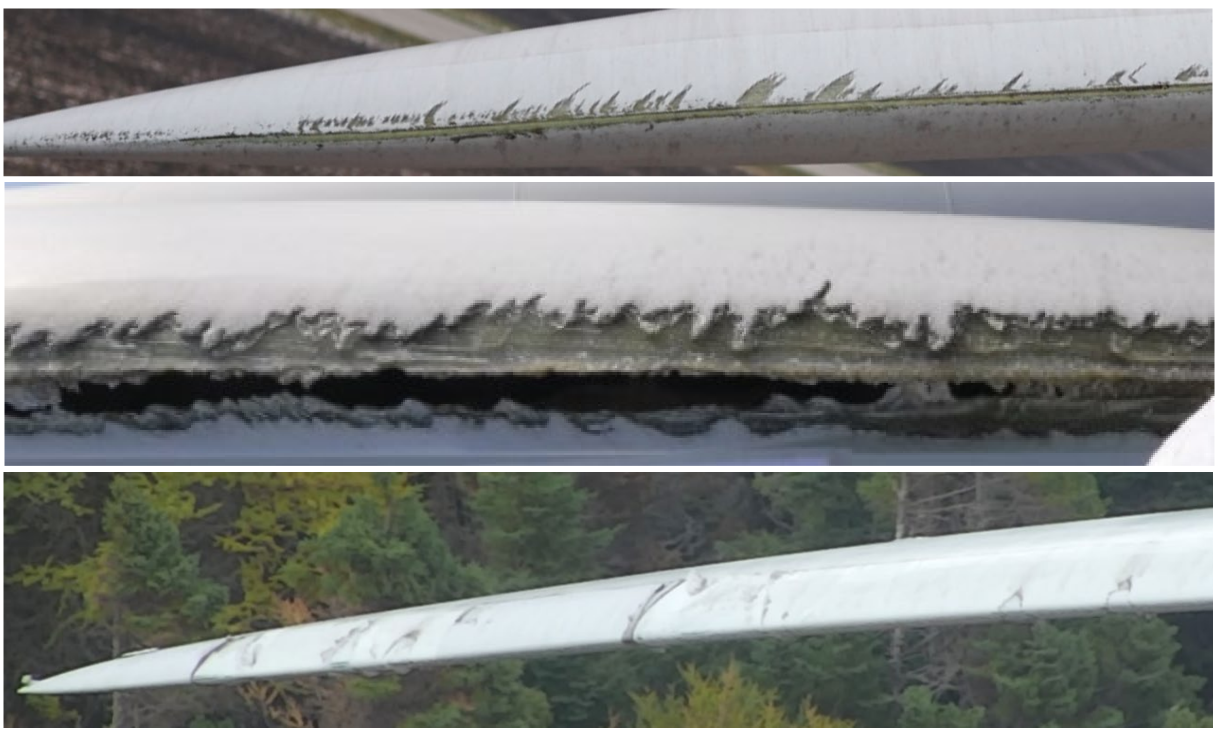


Figure 2-1 – Examples of wind turbine blade erosion damage (top - progression of leading edge erosion, middle – untreated leading edge erosion resulting in open cavity, bottom – damage to leading edge protection tape).

As indicated in Section 1, there are different techniques for categorizing wind turbine blade damage. There can also be specific motivations for individual organizations and stakeholders, depending on why the assessment is being carried out. For overall wind turbine blade damage, the main scenarios are identified in Table 2-1.

Table 2-1 – Assessment scenarios and motivations for categorization of erosion damage.

Assessment	Primary motivation
Research	Novel insights and understanding; model development
Testing and Standards	Understanding and replicating in-situ conditions to predict expected performance
Manufacturing	Quality control
Operational	Performance and structural integrity of wind turbine asset

Despite the potential for the varying kinds of damage shown in Figure 1, the main type of damage that is classified here as leading edge erosion is caused by multiple, high-velocity impacts from hydrometeors impacting the area (±5-10%) around the blade leading-edge and focused on the outer one-third of the leading edge which experiences the highest relative velocities (Letson, et al. 2020).

2.2 Examples of Categorization

Some examples of categorization for the motivation of assessment are provided in Sections 2.2.1 to 2.2.3. For the case of wind turbine blade leading edge erosion, the manufacturing setting would not be applicable for damage evaluation. However, it is important to note that the manufacturing stage can have influence on the eventual erosion experienced when a blade is deployed at a windfarm site.

2.2.1. Testing and Standards

The IEC standard for wind turbine blades (International Electrotechnical Commission, 2020) states that erosion is an 'additional failure mode', declaring in 6.6.6.2:

"Wind turbine blades are vulnerable to erosion, in particular at the leading edge and tip. This erosion can be caused by environmental exposure such as rain, dust, and sand…Relevant surface finishes should be evaluated for expected erosion, and the basis for erosion protection is to be specified for the blade."

Section 8.3.2 later describes:

"If scheduled inspections are required, the following shall be specified:

- *the type of inspection, along with its intervals and timing;*
- *the blade areas to be inspected;*
- *applicable acceptance criteria."*

The relevant DNV recommended practices for testing and evaluating wind turbine blade leading edge protection systems go into more detail of the relevant parameters to consider for assessment. As provided in Table 2-2, the outputs to consider for rain erosion testing (DNV, 2018) primarily concern the stages of erosion progress. Mass loss and failure modes are also noted, with the nominal condition stated as optional.

Table 2-2 – Relevant results parameters for rain erosion testing (DNV, 2018).

Result Parameter	Unit	Nominal Condition
Mass Loss	[grams]	Optional
Failure Modes	[-]	Optional
Stages of Erosion Progress	[-]	Reference point in time
End of Incubation Period*	[min]	document time of initial surface damage for each location
Breakthrough†	[min]	document time of breakthrough for each location

Although categorization is not detailed, a reporting template (DNV, 2020) intended for the evaluation by an end user advises reporting a variety of parameters to inform the predicted durability of leading edge protection This includes the extent from tip (in meters) for which a damage threshold=1, is exceeded. It is recommended for rain erosion tests that this threshold be the end of incubation period.

* defined as the exposure time until the first damage is visually detectable on the outer surface of the test specimen.
† defined as the point in time when the erosion breaks through the protective layer to the underlying substrate.

2.2.2. Research

There are numerous examples of bespoke categorization that have been utilized in the field of leading edge erosion research. Typically, erosion is considered in isolation and the classification has been aligned with testing matrices that have been investigated as part of a research project. One such example (Sareen, et al., 2014) describes erosion categories for different stages of erosion progression in a quantitative manner. Three features are specified (pits, gouges and delamination severity) with a defined depth, diameter and coverage on the leading edge. The test matrix displayed in Table 2-3 denotes a set density of these features that are imparted on an airfoil for wind tunnel testing.

Table 2-3 – Test matrix with the approximate number of pits (P), number of gouges (G), and magnitude of leading edge delamination (DL) on the upper surface of the erosion model for each case tested (Sareen, et al., 2014).

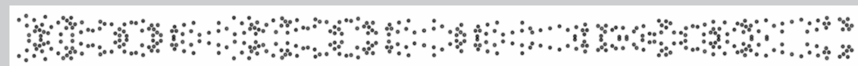
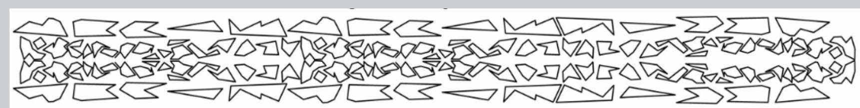
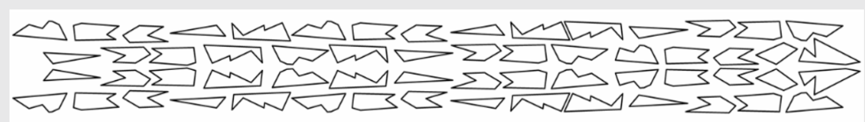
Stages	Type A Pits (P)	Type B Pits & Gouges (G)	Type C Pits, Gouges & Delamination
Stage 1	100P (1)	-	-
Stage 2	200P (2)	200P/100G (4)	-
Stage 3	400P (3)	400P/200G (5)	400P/200G/DL (7)
Stage 4‡	-	800P/400G (6)	800P/400G/DL+ (8)
Stage 5§	-	-	1600P/800G/DL++ (9)

A similar example from the literature (Gaudern, 2014) attempts to combine a qualitative description with average thresholds for the same characteristics of erosion depth, feature diameter and chord coverage. A visual impression of the erosion pattern is also detailed, as shown in Table 2-4.

‡ defined as the exposure time until the first damage is visually detectable on the outer surface of the test specimen.

§ defined as the point in time when the erosion breaks through the protective layer to the underlying substrate.

Table 2-4 – Leading edge erosion pattern category descriptions and dimensions (Gaudern, 2014).

Erosion Description	Erosion Depth [mm]	Average Feature Diameter [mm]	Approximate chord coverage	Erosion Pattern
Small pinholes of missing paint distributed across LE with some grouping.	0.1-0.2	2	3%	
Pinholes have coalesced into larger eroded patches.	0.1-0.2	15	3%	
Affected area has increased, with isolated larger patches with a greater depth.	0.3-0.5	20/40	5%	
Patches have coalesced further, and depth has increased.	0.5-0.8	40	5%	
Large areas of LE laminate exposed.	0.8-1.2	>500	8%	

Within IEA Wind Task 43: Wind Energy Digitalization, a separate objective attempted to describe an erosion class that related to coating and laminate mass loss, along with turbine mass loss (Table 2-5). IEA Wind Task 43 has suggested a method to relate erosion class to coating and laminate mass loss which can then be used to predict the erosion class at a future point in time, along with turbine power loss. This was developed as part of an algorithm to optimize maintenance operations. The process starts by using visual images to describe erosion class along the length of the blade. As the blade materials and environmental forcing function is not often known, the erosion class along the blade is fit to an exponential function of blade radius as an analog for velocity. This function is used to predict both an initiation point along the blade, as well as empirically estimate the rate of erosion mass loss according to the Springer model (Springer & Baxi, 1972). This rate is a function of the blade laminate and the environmental conditions. Assuming that the environmental conditions in the past are relatively similar to those in the future, an estimate can be made of the future erosion state. This estimate can be further refined with subsequent inspections and the uncertainty of the model can also be reduced with better measurements of either the actual mass loss, the blade construction, and the real environmental conditions. A prototypical definition of the relationship between mass loss and erosion class is given in Table 5. The model assumes different mass loss rates for coated and uncoated composites after the erosion progresses through the coated. This model is currently under development and will need to be validated against wind plant inspection and operational data, a process that is currently underway. The values given in Table 5 are initial estimates of what the relationships might look like.

Table 2-5 – Erosion class related to coating and laminate mass loss from IEA Wind Task 46.

Erosion Class	Description	Coating Mass Loss	Laminate Mass Loss	Turbine Power Loss
1	Light pitting of coating	<10%	0%	-
2	Small patches of missing coating	10% - 50%	0%	-
3	Large patches of missing coating	50% - 100%	<10%	1%
4	Erosion of laminate	100%	10% - 100%	3%
5	Complete loss of laminate	100%	100%	5%

Another endeavor by (Maniaci, et al., 2020), produced an imprint of in-situ erosion damage and tested this in a wind tunnel to understand the impact on airfoil performance. Airfoil erosion categories were defined based on interpolation of the lift/drag polar between this form of erosion damage and a ‘clean’ airfoil. Erosion rates along the blade span were then simulated using local blade velocity.

Table 2-6 Damage Category aligned with AEP Loss (adapted from (Maniaci, et al., 2020)).

Damage category	Airfoil Maximum lift coefficient	Airfoil Lift/Drag ratio	Modeled AEP loss of rotor at 6 m/s mean wind speed (%)
0	1.54 (0%)	114 (0%)	0
1	1.46 (-5%)	91 (-20%)	(not modeled)
2	1.39 (-10%)	75 (-34%)	0.9
3	1.34 (-15%)	63 (-45%)	1.6
4	1.29 (-16%)	53 (-53%)	2.6

2.2.3. Operational

In a setting that concerns real-life commercial windfarm assets, the scenarios and objectives for erosion damage classification differ. Firstly, the wind turbine is subject to a wide variety of environmental and operational circumstances that can cause blade damage, making it challenging to consider erosion in isolation. As mentioned previously, a windfarm operator will want to ensure the reasonable condition of a wind turbine to maximize energy production over its full lifecycle. For operational assessment, damage categorization attempts to ascertain the severity of damage and whether intervention is required to repair the damage. This process must also consider whether the turbine is allowed to remain operating before this is remedied.

There are different stakeholders that may evaluate erosion damage, including the turbine Original Equipment Manufacturer (OEM), the windfarm owner/operator and contracted service providers. Visual inspection is still the conventional approach, with rope access, drone and ground-based cameras common methodologies. There are also variances in inspection quality, which can make erosion, particularly the early stages, difficult to determine from inspection imagery. Depth of damage is particularly difficult to categorize from inspection imagery.

These organizations will have slightly different interpretations of damage classification as a standardized process for the wind energy industry does not currently exist. However, many will align close to a five-point scale of severity and the framework of these tend to prioritize damage mechanisms that relate to structural integrity over other considerations, such as aerodynamic performance and the resulting energy capture. Consequently, this leads to many approaches aligning the higher categories with penetration through the layers of a blade cross-section.

CATEGORY	DAMAGE	ACTION	TURBINE
1	Cosmetic Readings of lightning system below 50mΩ	No need for immediate action	**Continue Operation**
2	Damage, below wear and tear	Repair only if other damages are to be repaired	**Continue Operation**
3	Damage, above wear and tear Readings of lightning system above 50mΩ	Repair done within next 6 months	**Continue Operation**
4	Serious damage	Repair performed within next 3 months. Damage monitored	**Continue Operation**
5	Critical damage	Immediate action required to prevent turbine damage. Contact technical support	**STOP Operation** ***safety is not ensured***

Figure 2-2 – Blade damage categorization (Bladena, KIRT x THOMSEN, 2021).

Example categorization systems are available to inform requirements for evaluation. The guideline put forward by (Bladena, KIRT x THOMSEN, 2021) in Figure 2-2 lays out a brief indication of the level of damage and resulting action required. Following this approach, damaged leading edge protection and leading edge erosion down to the laminate are defined as Category 3; Category 4 pertains to erosion penetrating the first layer of laminate; and Category 5 erosion through the laminate or an open leading edge.

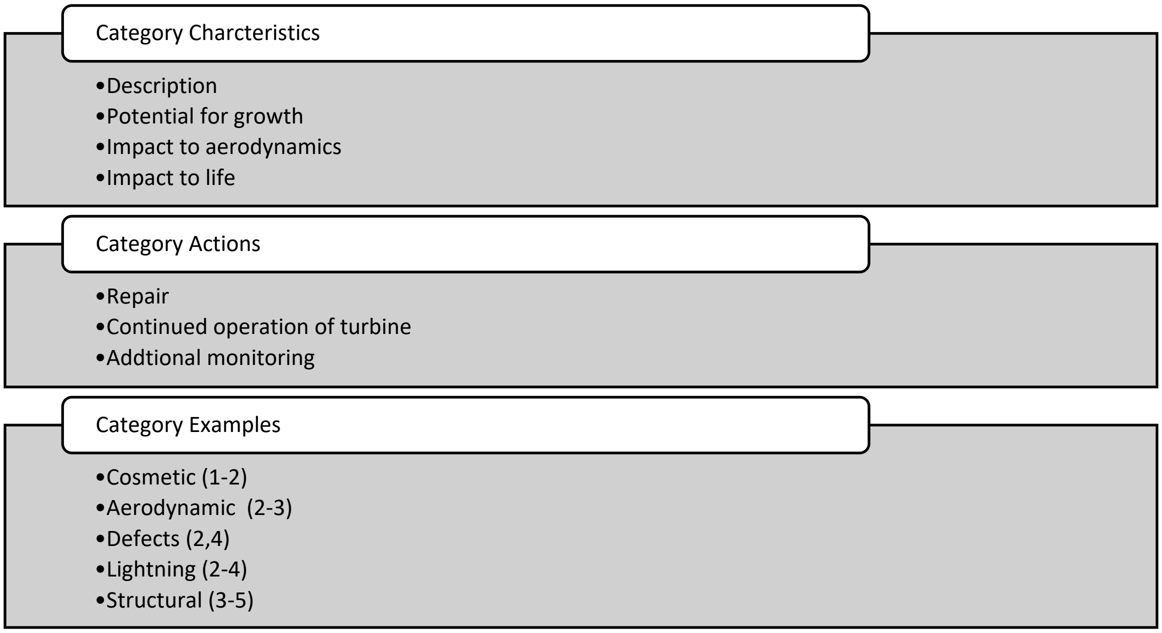


Figure 2-3 – EPRI wind turbine blade damage category considerations (EPRI, 2020).

Further guidance from EPRI (EPRI, 2020) set out considerations for each wind turbine blade damage category, consisting of: characteristics for current industry practice; recommended actions; and examples of damage. Figure 2-3 details specific considerations within these groupings.

3. Methodology

Having reviewed the custom-made approaches to leading edge erosion categorization and the relevant assessment scenarios (Table 2-1 - Table 2-6; Figure 2-2- Figure 2-3), the main considerations of all these methods were organized into several categories, as shown in Figure 3-1.

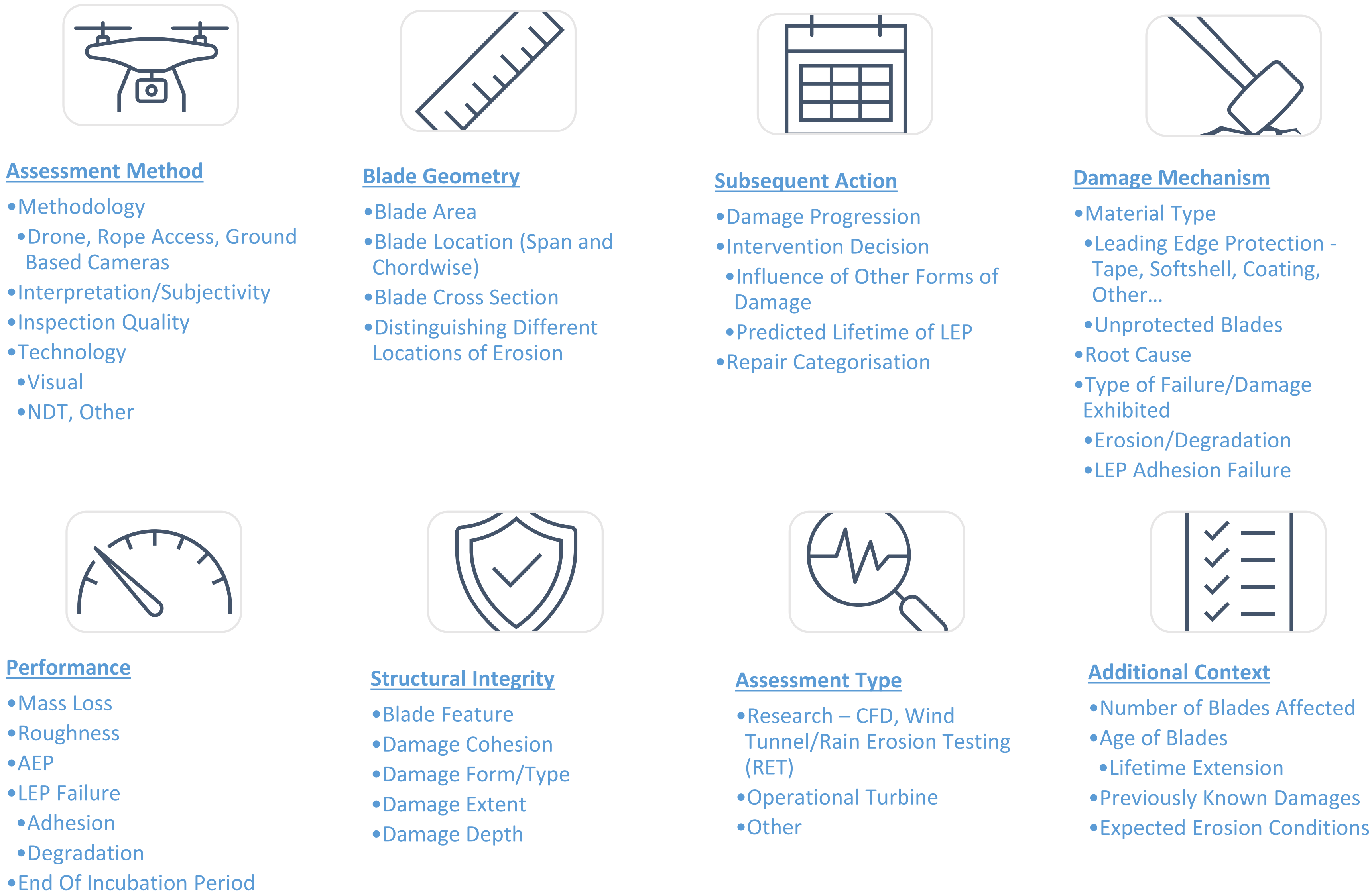


Figure 3-1 – Leading edge erosion categorization considerations.

A draft categorization system was then developed to address the needs of the various application scenarios from Table 2-1 as well as the categorization considerations from Figure 3-1. This system was modified as part of a workshop that included some initial testing of the draft system using example images of erosion. Feedback from this workshop and the testing process was then used to modify the erosion classification system.

The modified system was then tested more thoroughly using a different set of example images of leading edge erosion. This test of the draft classification system included the participation of several types of organizations with a range of application user scenarios and past experience with erosion classification; the organization types were research and technology organization (RTO), owner/operator, university researcher, and turbine original equipment manufacturer (OEM). Participants were asked to use the draft classification system to assess the sample images using four types of erosion observations:

1. Visual data definition
2. Mass-loss or Depth
3. Aerodynamics/Performance
4. Structural

The resulting scores from the assessments of each participant are shown in Figure 3-2, where the participants have been anonymized by their type of organization and the median and variance of the scores has been tallied. The images with low variance between the participants theoretically means the system was straight-forward to apply in a standard way, whereas the results with high variance indicate where efforts to improve the system should be targeted. The feedback and observations from this test were again incorporated into the revised system presented in the next section.

The main challenges with the initial classification system included:

- The variance suggests that more clear definitions are needed (either in the table or supporting report) and different people/organizations were interpreting the scoring differently.
- Variance in results due to uncertainty in what area to rate, how to rate a small area vs the entire blade, and differences in how the image was viewed (zoom level).
- Depth of damage is more difficult to assess than extent.
- There was also some discussion on how to rate an LEP system that is still intact but causing drag due to incorrect installation or aging.
- The structural category also consistently showed higher variance than other observation categories, as it was slightly shifted for some conditions.

Image	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

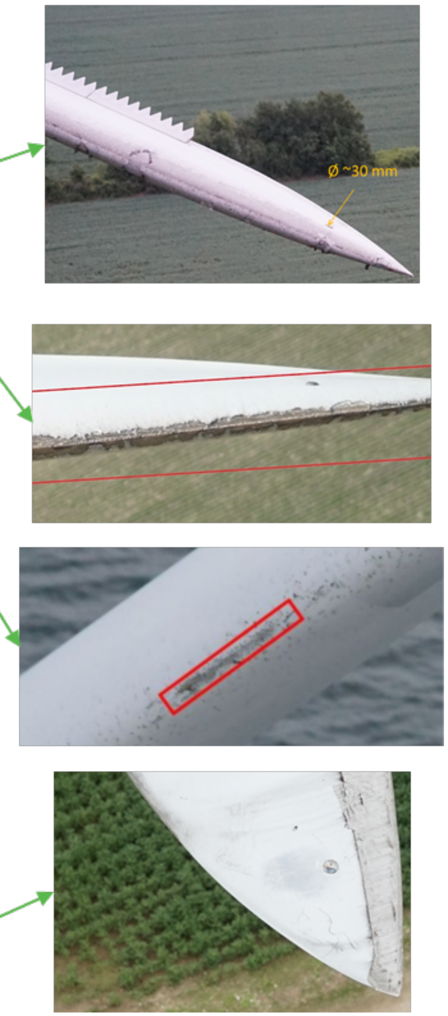


Figure 3-2 – Results of the draft erosion classification system test.

4. Erosion Classification System

The updated erosion classification system is presented in this section. It includes definitions on the different criteria, definitions of the categories for each criterion, guidelines and considerations when using this system, and some detail on use of the system. Example assessments from the original system review, and images of erosion/LEP damage are provided in the appendices, for reference.

4.1. Erosion Classification Criteria Definitions

Within the erosion classification system described in Table 4-1 there are four main criteria to consider. Each criterion is assessed individually. The motivation is not to provide an overall rating but to consider the separate concerns and impact behind each criterion.

1. **Visual Condition** – Intended to provide an immediate visual assessment of the severity of the degradation of a wind turbine blade (potentially with or without LEP) due to erosion mechanisms. This criterion is primarily concerned with the protection of the underlying substrate and is described by notable damage features and thresholds of damage areas.

2. **Mass Loss** – Considers the material loss aligned with stages of erosion typically determined in laboratory conditions (i.e., Rain Erosion Testing). Normally this would be physical mass measurement, so the classification system has attempted to include broad percentage thresholds that could be estimated visually.

3. **Aerodynamic Performance** – Concerned with the effect of erosion and leading-edge protection damage on wind turbine power and annual energy production (AEP) due to a decrease in aerodynamic performance of the blade. This can be the result of increased roughness on the blade surface or loose LEP and is quantified in terms of 'Power Loss'.

4. **Blade Integrity** – Although there is crossover with the **Visual Condition,** the severity of damage is focused on the structural condition of a blade and operation of the turbine. This is associated with damage penetration through the blade layers and does not consider LEP. There are no quantitative thresholds of area, but the subsequent layer should be obviously discernable.

4.2. Guidelines and Considerations

When using the Erosion Classification System, the following should be considered

- **Damage Assessment** – The system is exclusively concerned with leading edge erosion and leading-edge protection damage. Although other wind turbine blade damage mechanisms (i.e., surface cracks) may be influential in the progression of erosion and LEP damage, they are not in scope. The erosion classification system is intended to assess individual blades.

- **Blade Assessment** – The erosion classification system is intended to assess collated individual instances/images of damage that would be identified by inspection service providers. Certainly, there could be multiple instances of damage on the same blade that would need to be considered individually. In which case the general rule should be "*when 5% of blade span is in a given class the blade is considered that severity rating or if a higher rating changes the response, the blade rating is increased*".

- **Blade Surface Composition** – The blade or blade sample must have (as a minimum) a topcoat applied above the composite substrate to be considered by the categorization system. Modern turbine blades also include a layer of filler material between the topcoat and the laminate. Some manufacturers include a primer layer between the filler and the coating to further aid contact adhesion between the topcoat and substrate (Cortés, et al., 2017).

- **Leading Edge Protection (LEP)** – (LEP) comes in various forms, including tapes, coatings and erosion shields (predominately soft polyurethane shells). As many modern turbines now include some form of LEP in addition to a standard topcoat, it is important for damage to these solutions be included in the categorization system. Certain LEPs require adhesion to the blade surface so are susceptible to a reduction in adhesion or debonding. This failure mechanism is also considered by the categorization system.

- **Blade Damage Location –** There are blade damage considerations that would be of greater concern depending on where they are located. Blade Integrity is more consequential towards the blade root and aerodynamic performance is more critical towards the blade tip. Although no boundaries have been set, it should be considered that blade erosion (and LEP installation) is less likely to be present further away from the blade tip (spanwise) and from the leading edge (chordwise). For the purposes of the system, the severity rating of the **Visual Condition, Mass Loss, and Blade Integrity** criteria do not change depending on the location.

Table 4-1 – 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

4.3. Erosion Classification Severity Levels

The descriptions in Table 4-1 are intended to be an initial guide for the different levels of severity for each of the separate criteria. This section provides additional detail and clarification for how those different levels should be interpreted and any defined thresholds.

4.3.1. Visual Condition

Level 0 – *"Initial factory condition"*

- This is generally thought of as the condition before the topcoat or LEP is subject to erosion damage mechanisms (i.e., before operation or erosion testing).
- If damage is present, it is barely visible. There may some form of pinholes, but individual pinholes are very small (< 1mm) and are not cohesive into areas greater than 1cm^2 in area.
- The mass-loss, aerodynamic performance and blade integrity implications are thought/assumed to be negligible.

Level 1 (LEP) – *"Lightly worn external coating/LEP" or "Instances of reduced LEP adhesion"*

Damage threshold: individual instances ≥1cm^2 & individual instances ≤10cm^2

- The expectation is that the LEP is still intact and providing protection to the underlying layers.
- However, the incubation period of the LEP has ended and there are noticeable instances of localized damage on the LEP that are greater than 1cm^2 but less than 10cm^2 in area.
- Discernable peeling/reduced adhesion noted on edges of leading edge protection.

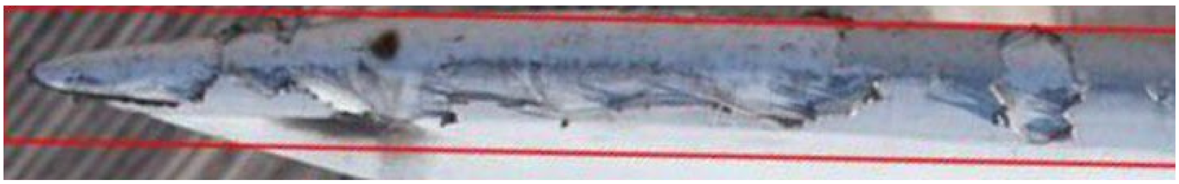
Level 2 (LEP) – *"Notable areas of localized damage on external coating/LEP or "Individual Instances of LEP adhesive failure."*

<u>Damage threshold: individual instances ≥10cm^2 & individual instances ≤ 1m^2</u>

- The expectation is that the LEP is still predominately intact, but damage has become more apparent in individual locations or is cohesive in areas greater than 10cm^2 in area.
- Breakthrough of the LEP has occurred but is not over a large area.
- Adhesion failure is noticeable across the leading edge.

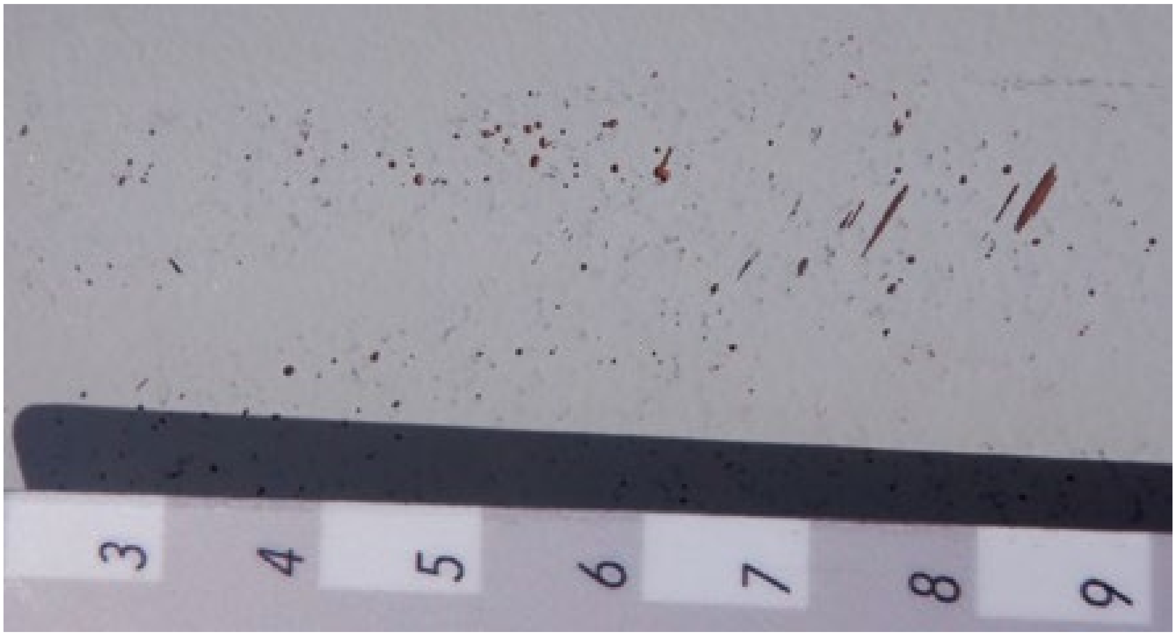
Level 3 (LEP) – *"LEP is compromised over a large area and no longer providing protection to underlying layers"*
<u>Damage threshold: destruction of LEP ≥1m²</u>

- Destruction of the LEP is obvious over a considerable length of the leading edge.
- Adhesion failure has resulted in a considerable length of the leading edge being unprotected.



Level 1 (No LEP) – *"Erosion barely visible or pinholes"*
Damage threshold: individual instances ≤1cm^2

- Erosion is observable from inspection imagery but is small/minor enough, such that it is not immediately discernable.



Level 2 (No LEP) – *"Localized Pitting"*
Damage threshold: individual instances ≥1cm²

- Multiple individual pits are noted

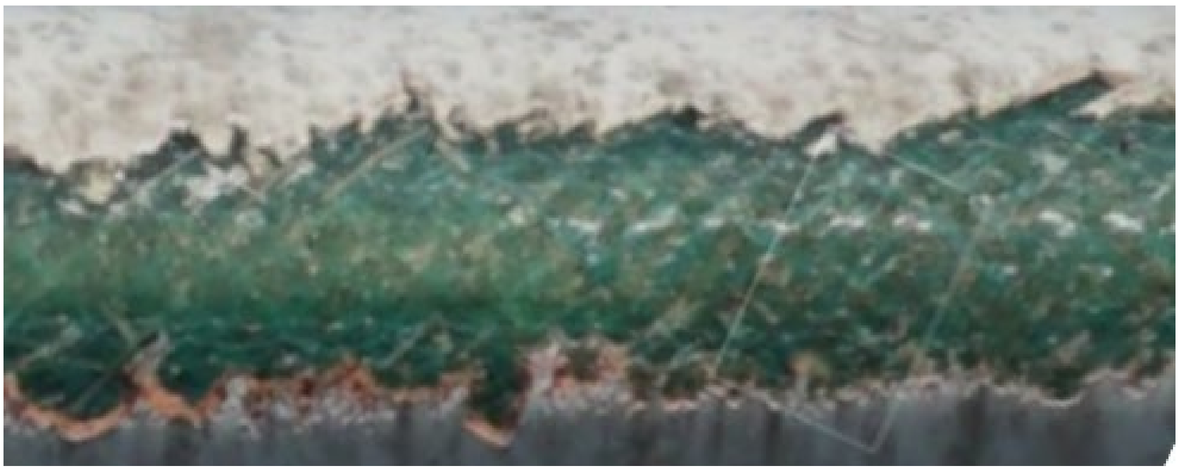
Level 3 (No LEP) – *"Widespread or coherent pits, some gouges"*
<u>Damage threshold: erosion of topcoat ≤10cm^2</u>

- Pits are widespread and cohesive over a significant continuous length of the blade.
- Underlying composite layers may be clearly visible but not over a large overall area.

***Level 4 –** "Erosion of topcoat with immediate layer underneath visible and exposed"*

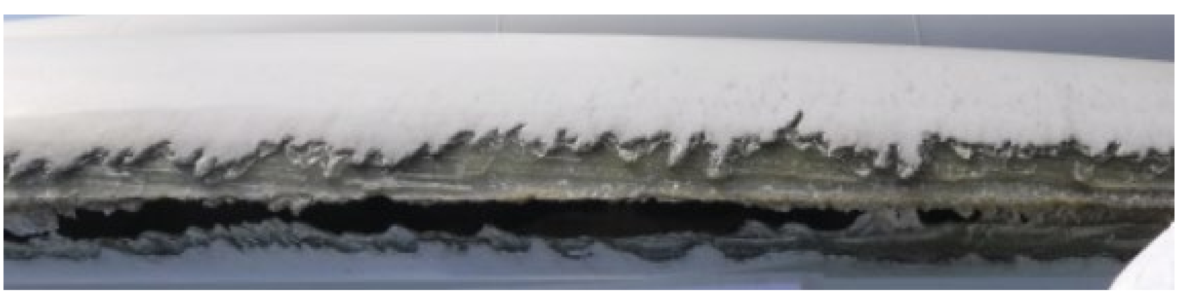
<u>Damage threshold: erosion of topcoat ≥10cm^2; erosion of laminate ≤1cm^2</u>

- Erosion has worn away to the laminate such that the filler layer or immediate laminate is observable over an area greater than 10cm^2
- Damage to the substrate is either not entirely obvious or sufficiently small/minor.



Level 5 – *"Notable damage to substrate"*
Damage threshold: erosion of laminate ≥1cm^2

- Obvious damage to the laminate layers.
- Any damage beyond the threshold will still be classed as Level 5.



4.3.2. Mass loss

The mass loss model as a method for categorization is still preliminary but is unique in that it has the potential to improve its prediction of future erosion level progression through its incorporation of inspection data. When correlated with the other erosion categories, this allows for prediction of what future performance loss can be expected and the development of future cost optimized repair schedule.

The extent of erosion is typically measured in terms of material mass loss. The Springer model which is based on a fatigue formulation of material degradation is commonly used to model mass loss. The model has three phases: incubation period, steady mass loss, and non-linear mass loss. The incubation period is described as a threshold on the number of impacts of a certain size and velocity for which there will be no mass loss. Once this threshold is reached, the mass loss proceeds to increase at a steady rate. After some period of steady mass loss, the rate becomes non-linear. The mass loss in the Springer model is dependent upon droplet velocity, droplet size, number of impacts, coating properties, and substrate properties. For a wind turbine in operation, the velocity, size, and number of impacts relates to wind speed and rainfall characteristics, along with the operational state of the turbine. These factors would vary over time and thus the calculation of the mass loss would be expressed as a time-varying summation of these factors. In practice, the rainfall characteristics are not measured at the precise location of the turbine and the material properties of the blades are not publicly available. Also, the resulting mass loss is difficult to measure. The typical information on field erosion that exists is in the form of inspection images and a resulting erosion class definition. A process has recently been proposed to relate inspection images to physics models of erosion. The process to relate erosion class to coating and laminate mass loss starts by using visual images to describe erosion class along the length of the blade. Since it is not feasible at this time for wind blade inspections to measure erosion depth or mass loss, an attempt must be made to relate visual images to erosion category and therefore a mass loss range.

One approach is to use percent eroded area of an airfoil leading edge section as a proxy for percent mass loss at that blade section e.g., if 20% of the leading-edge topcoat area is eroded away, that would correspond to a 20% mass loss of the topcoat. After leading edge erosion is detected and categorized on a blade, a function involving a combination of the Springer model weighted by rain and wind statistics can be curve fit to the inspection data, see figure below (Verma, et al., 2021) Additionally, Eisenberg observed that erosion damage is proportional to the local incoming blade velocity ($\propto V^{6.7}$); if blade radius is used as an analog for velocity than this relationship along with inspection data and the probability weighted Springer model can be used to determine either the rate of erosion loss along the entire blade and/or incubation time if erosion has not started to occur in certain areas (Eisenberg, et al., 2018). The incubation time and mass loss rate are a function of the blade laminate and the environmental conditions. Assuming that the environmental conditions in the past are relatively similar to those in the future, an estimate can be made of the future erosion state. This estimate can be further refined with subsequent inspections and the uncertainty of the model can also be reduced with better measurements of either the actual mass loss, the blade construction, and the real environmental conditions. A prototypical definition of the relationship between mass loss and erosion class was given in Table 5. The model assumes different mass loss rates for coated and uncoated composites after the erosion progresses through the coated. This model is currently under development and will need to be validated against wind plant inspection and operational data, a process that is currently underway.

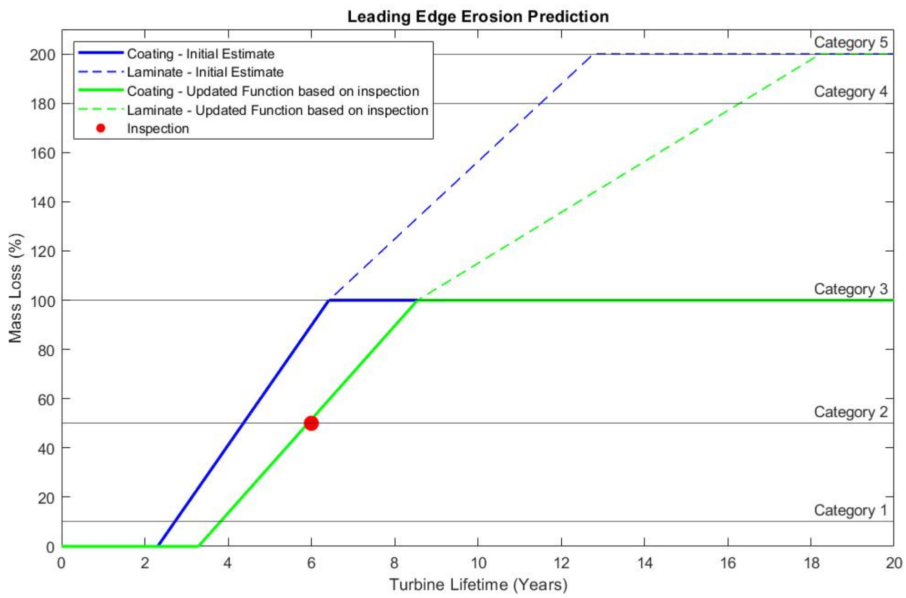


Figure 4-1 – Example plot of leading-edge erosion prediction of a wind blade airfoil section where initial model estimates are updated to better fit inspection data from the field.

4.3.3. Aerodynamic Performance

The effect of aerodynamic performance changes due to leading edge erosion can be quantified in terms of power loss for a given wind speed range or for the annual energy production, which integrates the effect of leading edge erosion on power loss across the entire wind speed range. Investigations have been made to quantify this (Maniaci, et al., 2020; Bak, et al., 2020). The erosion categories in the classification system are related to the power loss in normal region 2 operation for a variable speed, variable pitch horizontal axis wind turbine, when the turbine is operating at or near the design tip speed ratio, typically 6-8 m/s, as illustrated in Figure 4-2.

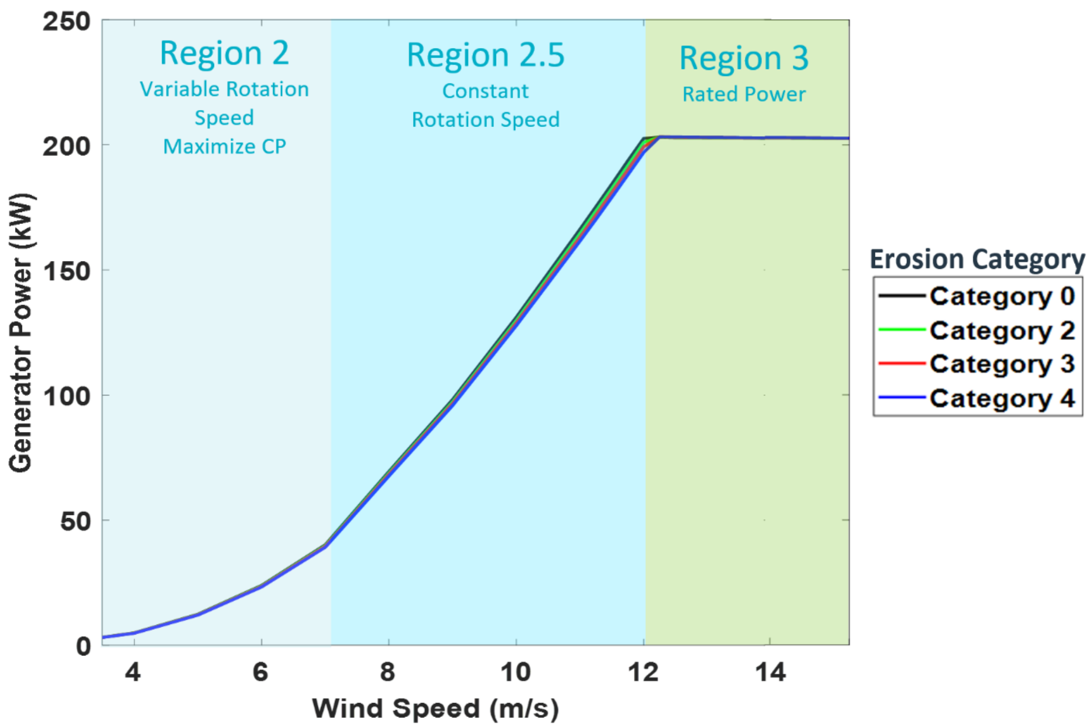


Figure 4-2 – Nominal power curve with several erosion categories. Power loss in the classification system is defined in region 2 of the power curve. Power curve from Ref. (Maniaci, et al., 2020).

Typically, a severity rating is given for an entire rotor, although there can be variation from blade to blade, and there is always variation across the blade span. The spanwise extent of erosion and blade to blade variations must be included in assessing the power loss for a turbine. In order to account for changes in the erosion category of a blade as the local conditions vary, the following rule is used (as mentioned in Section 4.2): *When 5% of blade span is in a given class the blade is considered that class or if a higher class changes the response, the blade class is increased*.

In addition to the effect on power loss, the aerodynamic performance categories are also defined by the changes in the blade boundary layer conditions due to changes in the equivalent roughness that are caused by leading edge erosion or damage to the LEP. Surface roughness changes during normal operation without any leading edge erosion due to environmental factors, namely bug adhesion, that changes with time and weather; this normal surface roughness without any material damage is typically considered as within **Category 1**, although performance loss can be higher for severe roughness. Bug adhesion and roughness can cause performance loss equivalent to category 4 or 5 erosion when severe roughness is combined with highly sensitive rotor designs, such as older stall regulated turbines. Category 1 erosion and the associated roughness causes the chordwise region of transition from laminar to turbulent flow along the airfoil to move toward the leading edge, increasing the skin friction drag on the airfoil surface. The resulting drag along the blade, mostly near the blade tip, causes less than a 1% loss in rotor power production in region 2 operation, and a smaller loss in annual energy production. **Category 2** roughness due to LEE and LEP damage causes a larger power loss, approximately 1% for the rotor, due to the transition location moving further forward, causing a decrease in lift-to-drag ratio (L/D) of 20% and in maximum lift of 5% for a nominal wind turbine airfoil near the blade tip where maximum erosion occurs. For **Category 3** erosion, the transition location moves further toward the leading edge and the flow is fully turbulent for eroded section of the blade, causing a 30% reduction in lift-to-drag ratio and 5 to 10% loss in maximum lift. **Category 4** erosion has both increased roughness as well as depth of the roughness, with forward facing steps possible, resulting in 40% loss in L/D and more than 10% loss in maximum lift, both contributing to 3-4% loss in region 2 power production. Higher power loss (>4%) can be expected when **Category 5** erosion is observed along a portion of the blade tip of all blades of a rotor, as the increased roughness, forward facing step, and even holes in the leading edge cause early flow separation and large areas of turbulent flow.

These categories are summarized as:

- **Category 0**: Flow not disturbed. Roughness effects are damped by the viscosity of the flow.
- **Category 1**: Region 2 power loss <1%. The transition point is moved forward toward the leading edge.
- **Category 2**: Region 2 power loss 1%, Moderate loss to L/D and CL_{max}, (-20% and -5%). The transition point is moved forward to the leading edge. Incubation length (distance rough element to transition point) is modified.
- **Category 3**: Noticeable loss to L/D and CL_{max} (-30% and -5-10%). The flow is fully turbulent downstream of the roughness elements in eroded regions of the blade span.
- **Category 4**: Significant loss to L/D (> -40%) and CL_{max} (> -10%). The flow separates in downstream locations due to the boundary layer weaknesses against adverse pressure gradients given by airfoil geometry.
- **Category 5**: Severe loss to L/D and CL_{max} due to flow separation and a lack of laminar flow.

The region 2 power loss from the erosion severity categories can be approximately mapped to the annual energy production (AEP) loss, as shown in Table 4-2. The results in this table are for a relatively high specific power pitch regulated, variable speed wind turbine using a Rayleigh wind distribution and did not include the category 1 and 5 cases (Maniaci, et al., 2020). The specific operating conditions of a turbine can perturb the AEP loss from this approximation, and future updates should include the sensitivity to these values to specific turbines and controllers.

Table 4-2 – Annual energy production relative to no erosion for a range of mean wind speeds using a Rayleigh wind distribution. Based on power curve cloud results from Ref. (Maniaci, et al., 2020). Note categories 1 and 5 were not modeled in the study.

Erosion Category	Mean Wind Speed (m/s)				
	4	6	7.5	8.5	10
0	0.0%	0.0%	0.0%	0.0%	0.0%
2	-1.0%	-0.9%	-0.7%	-0.6%	-0.4%
3	-1.9%	-1.6%	-1.3%	-1.1%	-0.8%
4	-3.0%	-2.6%	-2.2%	-1.9%	-1.6%

4.3.4. Blade Integrity

The severity levels for blade integrity criterion have been considered with regards to the blade composite structure displayed in Figure 4-3. If an LEP is present, initial erosion/degradation of this is still considered to be Level 0.

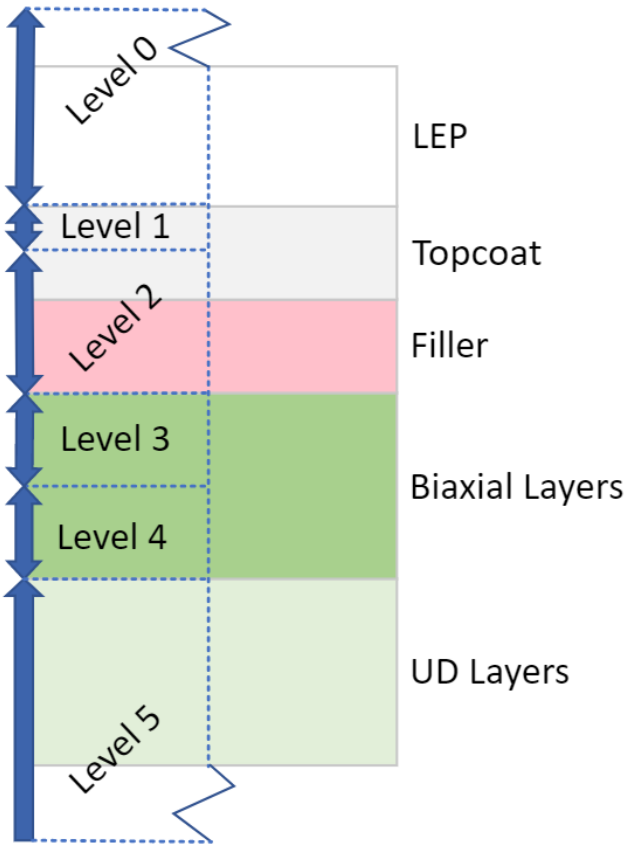


Figure 4-3 – Reference layers of wind turbine blade composition.

Level 1: Initial Erosion of Topcoat
Minor wear of the topcoat has occurred. Underlying filler is not yet visible (if present).

Level 2: Erosion Through Topcoat
Erosion has significantly worn through the topcoat (and filler, if present). Laminate is not yet visible.

Level 3: Exposure of Immediate Laminate Layers
Top layer laminates are exposed and may even have minor observable damage. Fiber damage not obvious.

Level 4: Erosion Through Immediate Laminate Layers
Erosion has significantly worn through the top layer laminates. Underlying structural laminate not yet visible.

Level 5: Exposure of Structural Laminate Layers
UD structural layers are exposed or damaged. Further damage beyond this (i.e., full cavities) are still expressed as Level 5.

5. Future Considerations

The leading edge erosion categorization system has been developed to specifically assess this form of wind turbine blade damage as it is experienced today. However, there are a range of aspirations and considerations that have not been included in this current version of the system but are worth bearing in mind for implementation in the future.

Inspection technology – Blade damage categorization has traditionally involved the visual assessment of blades by rope access technicians or from photographic imagery obtained by various means. As accurate determination of damages can be difficult due to various influencing factors, several other inspection technologies are being explored to improve upon existing practices. Although none are likely to supplant the current convention immediately, Non Destructive Technologies (NDT) could provide a more quantitative measurement of the progression and impact of erosion; therefore, making it easier to define thresholds of damage levels. Commercial technologies such as thermal imaging can help understand boundary layer behavior and transition location on operating turbines**.** Other less mature technologies, such as laser profilometry or gloss measurement (Leishman, et al., 2022) are also being explored to help determine leading edge erosion more accurately than what is currently achievable by visual imagery. With the advent of these technologies and the potential to determine the rate of erosion at an earlier stage, the proposed classification system would likely need to be adapted.

Recommended Actions – Other general damage categorization systems also include a recommendation for subsequent action. This has not been included within the scope of this report but could be a consideration for future adoption of the system. This could either be in the form of individual recommendations for severity ratings in each criterion or collectively. It is common to have blades on the same turbine to have different levels so that should be considered in the decision making. The remedial actions for the *Blade Integrity* criterion would be analogous to typical repair actions, such as those mentioned in Section 2.2.3. However, there could be unique measures that could be applicable to the other criteria. The installation of flow control devices or wind turbine control adjustments may be appropriate for aerodynamic considerations, even at early levels of severity.

Modelling – There are several potential avenues for future developments in the modelling of leading edge erosion, namely from an aerodynamics and a material perspective. Improvements in the computational modeling of the influence of erosion and roughness on blade aerodynamic characteristics are possible, which could lead to airfoil designs with more robust performance, in terms of lift and draft effects, under eroded conditions. A standard framework for modeling leading edge erosion performance loss will be developed based on the erosion classification system in this report, but other performance models will also be developed to predict loss under a range of conditions and methods to mitigate such loss. Improvements to the modeling of the material mechanisms and rates of erosion for different complex materials is also expected, which will improve the mass-loss model and enable future predictions of expected erosion given present observations. Data analysis and testing methods for performance loss are also possible, allowing for the field demonstration of erosion performance loss mitigation technology, whether on the blade such as vortex generators or due to advanced control methods.

Advancements in Blade Technology – Despite the dominance of the conventional three-bladed turbine design, blade technology has made advancements over the last decades and will continue to do so. One of the most apparent trends in turbine design is increasing turbine size and consequently the length of blades, which is yet to plateau. With the industry acutely aware of the influence of tip speed on leading edge erosion, it remains to be seen what rotational speeds or other design methodologies will be decided upon for modern machines that could affect erosion mechanisms.

Contemporary wind turbines have typically been constructed from composite materials, consisting of glass/carbon fiber reinforcement and a corresponding matrix resin. Whilst this is the case for many existing turbine assets and those under construction, there has been a growing awareness of the circular economy. In response, there have been commitments to landfill bans and scaling-up of diversified blade recycling technologies. Additive manufacturing may also play an increasing role in blade production in the future. It is important to consider the impact of materials used for additive manufacturing on leading edge erosion and damage propagation. This extends to new LEP solutions, such as metallic shields, which may differ from the status quo and would need to be accounted for in damage categorization.

6. Key Conclusions/Recommendations

We view the current document as capturing the state of the art in erosion classification, combining several systems with a range of uses and sources of information. As discussed in Section 5,there will continue to be evolution in this field, which will have a bearing on how the system is structured and utilized. Following the review of the classification by members of the WP3 (detailed in Section3), several immediate considerations were also noted:

Scope – The progression of leading edge of erosion and damage does not behave in a uniform manner, especially with the advent of protection measures that have attempted to mitigate this phenomenon. Therefore, the classification system has attempted to consider the full range of wind turbine blades and leading edge products installed at commercial windfarm projects. Accounting for these separate failure modes across the separate criteria has been a complex challenge for the construction of the classification system. It may also be appropriate in the future, to regard the interaction of erosion with other leading edge damage mechanisms and aspects of blade design i.e., lightning, icing.

Remedial actions – Thus far, the system has only been used to assess individual examples of leading edge erosion and LEP damage. A useful case study would be to evaluate the blade condition before and after a remedial/repair action has taken place. This should potentially be extended to consider the specific use of blade mounted technologies to counter the adverse effects i.e., sensors, flow control devices.

Visual imagery – The conventional method of inspecting wind turbine blades is still through visual imagery. As demonstrated in Section 3, there is still inherent error/subjectivity in assessing this form of data qualitatively, particularly the aerodynamic and mass loss criteria. Certainly, a method to more accurately determine the severity level is required. The use of machine learning, future sensing and NDT techniques could help reduce this variance in assessment.

Data provision– Related to the challenges of inspection imagery data is the associated information regarding the blade material composition and geometry, damage/erosion measurements and any other contextual that could help inform the assessment. In certain scenarios, this is not so easily obtained, but speaks to a wider issue of data sharing/IP.

System Adaptable – The classification system is intended to be generically applicable across turbine types and windfarm sites. However, there could be value gained in having adjustable severity levels that could be tuned for different scenarios, especially for those where a prediction of the expected level of erosion/LEP lifetime has been carried out. This could be more useful to the end-user for tracking damage progression and contemplating the intervention required.

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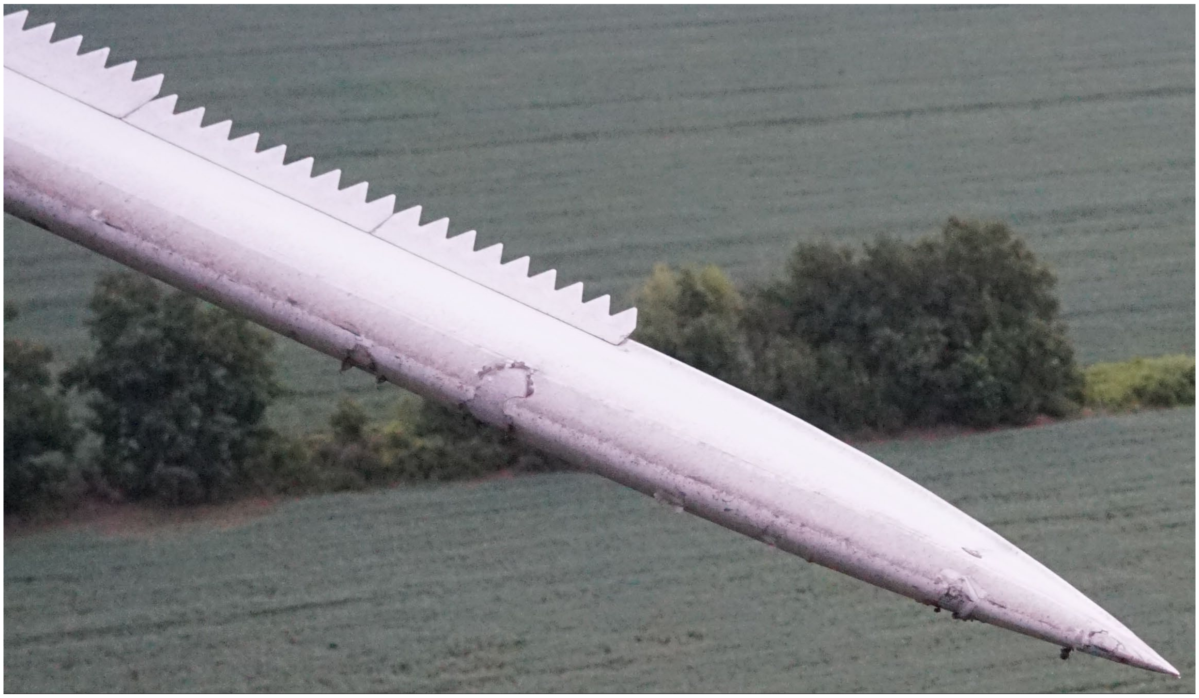
Appendix A – Example Assessments from WP3 Activity



Parameter (Specified by Service Provider)	**Value**
Material	Tape
Tape Width (Total PS & SS)	250mm
Tape Thickness	300 mm (Film)
	60 mm (Adhesive)
Blade Length	**49 m**

Criteria	**Severity Level**	**Note**
Visual Condition	2	2 where tape is peeling, 1 overall
Mass-loss or Depth	1	
Aerodynamics/Performance	2	2 where tape is peeling, 1 overall
Structural	1	

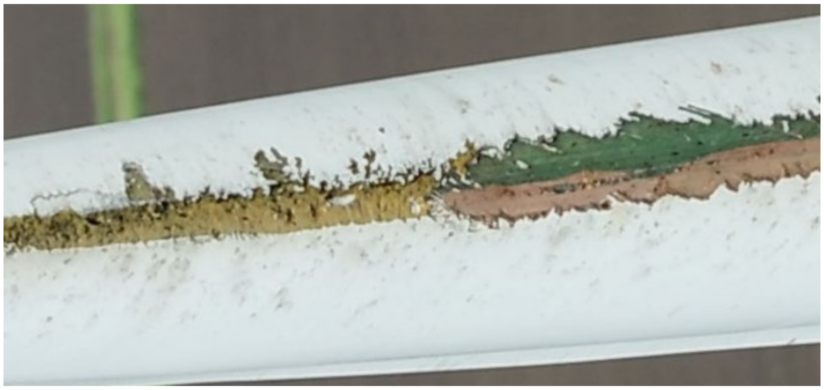
Parameter (Specified by Service Provider)	Value
Material	Laminate
Blade Length	37 m
Distance from Root	37.3 m
Length of damage	4.1 m
Width of damage	0.15 m

Criteria	Severity Level	Note
Visual Condition	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	PU Coating
LEP Width (Total PS & SS)	200 mm
Blade Length	49 m

Criteria	Severity Level	Note
Visual Condition	2	Tape is in poor condition but attached.
Mass-loss or Depth	1	
Aerodynamics/Performance	2	Tape is in poor condition, cat. 2-3 perf. loss
Structural	1	

Appendix B – Example Erosion/LEP Damage Images



The above three images are examples of category 4 erosion via visual identification. The outer layers of coating and material are completely removed along the leading edge and the underlying layers of material are now eroding. The aerodynamic loss of these areas of the blade likely falls into standard category 4 as well.

This blade shows leading edge protection delamination and peeling. The underlying blade does not appear to yet have severe erosion, category 1 with some category 2 areas; however, the areas of peeled leading edge protection material could cause aerodynamic flow transition and possibly separation over local areas, increasing the drag to equivalent of a higher blade erosion category, likely category 3 and possible even category 4 in some local areas.

This blade has experienced severe erosion. It is at the high end of category 4, with the underlying structural material exposed and eroding, and will move to category 5 if it hasn't already in local areas.

This blade shows lighter erosion and no leading edge protection. The blade would fall into category 2 due to local pitting and some areas of deeper erosion and delamination.

This image shows failing leading edge protection. The leading edge protection is rated category 3, as it is no longer providing protection on large areas of the blade. The underlying blade surface appears to have category 2 erosion in some small pockets where the protection has failed. This example shows the difficultly in local categorization versus categorizing the entire blade. It also shows the challenging nature of assessment with limited visual data, as the severity of the damage above the middle of the image (circled) is not clear and could be a structural crack or simply surface damage.

The blade in the above image appears to have category 4 erosion near the blade tip, as the fiberglass layers appear exposed and damaged. The erosion category moves to 3 further inboard and then to category 2. This is an example of classic erosion progression along the blade span. The blade could be categorized either by the maximum erosion category near the tip (4) or by the location of inboard progression using identification algorithms.

This blade appears to fall into category 4 erosion. The outer coating and layers are fully eroded at the leading edge. There is also evidence of some local peeling, which can cause even higher aerodynamic drag losses than erosion alone as the peeling can cause flow separation behind it.