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WHITE PAPER

How to protect wind turbine rotor blades from leading edge erosion?

- The main drivers of leading edge erosion and its related problems.
- Existing solutions to avoid leading edge erosion and their characteristics.
- Comparison of AEP losses between eroded blades and blades with softshell leading edge protection.

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How to protect wind turbine rotor blades from leading edge erosion?

In this white paper you will learn:

- About the main drivers of leading edge erosion (LEE) and which problems come along with it.
- Which solutions exist to avoid LEE and what their distinctive characteristics are.
- How losses in annual energy production (AEP) resulting from erosion compare to a blade with a softshell leading edge protection (LEP) applied.

Introduction

Leading edge erosion of rotor blades is a widespread damage observed on modern wind turbines. Repairs of eroded leading edges are often costly and time consuming. A forecast by the energy consultancy Wood Mackenzie shown in *Figure 1* projects that, by the end of the decade, the money spent repairing leading edges will surpass one billion dollars per year. As rotor blades become longer and tip speeds are increasing, the problem of eroded blades is affecting more and more turbines. Material developers and turbine blade manufacturers are putting significant efforts in the development of new solutions to overcome the issue of LEE and thereby minimize the negative effects on power output and maintenance cost. Putting an end to LEE requires leading edge protection solutions that are capable of withstanding higher loads and endure the degrading effects of weathering. Combining these material capabilities with simulations that can be used for predictive maintenance will be one key enabler to lower the cost of wind energy.

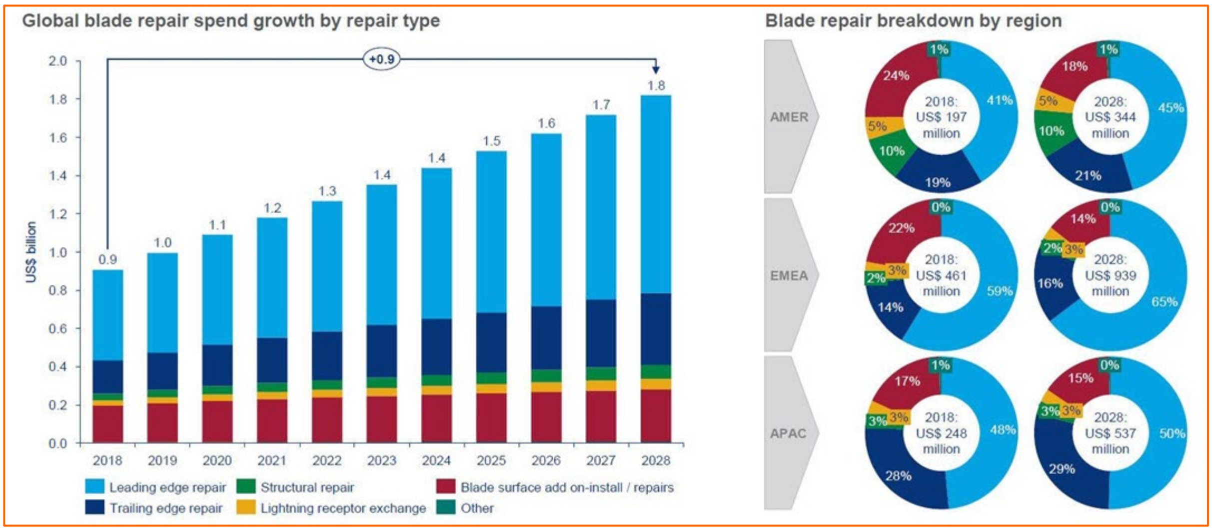


Figure 1 depicts the forecasted global blade repair spend growth by Wood Mackenzie [1].

What is leading edge erosion and what problems come along with it?

During operation, the leading edge is exposed to wear and tear, which results in blade material surface deterioration and increased surface roughness and thus reduced annual energy production (AEP). This leading edge surface erosion increases dramatically with increased rotor speed. Additionally, certain wind turbine environmental conditions, such as annual rainfall and droplet distribution can cause leading edge erosion if the blade is unprotected.

When liquid droplets impinge upon the solid blade surface, the stress created by the droplets may cause pits or cracks on the surface eventually leading to loss of material. This damage, called "erosion" or "rain erosion", will significantly weaken the material integrity, and over time the blades will suffer from losses in AEP and ultimately risk a complete blade failure. There are principally two ways that a droplet can cause damages to the material upon impact. The initial impact of the droplet causes an increase in pressure acting across the liquid-solid interface contact area, which results in a force that is normal to the solid surface. This force generates stress waves traveling along the surface and inside the material, eventually leading to cracks in the material. After the initial impact, the water droplet breaks up and the liquid escapes laterally and forms what is known as a water jet. During the incubation period where no mass loss is observed, the consequences of the water jet are negligible. However, when the first crack has appeared on the material surface, the water jet will play a significantly larger role in progressing the erosion further. The water jet will interact with small cracks and surface imperfections and tear off smaller pieces of material. This will enhance crack growth with significant crack propagation.

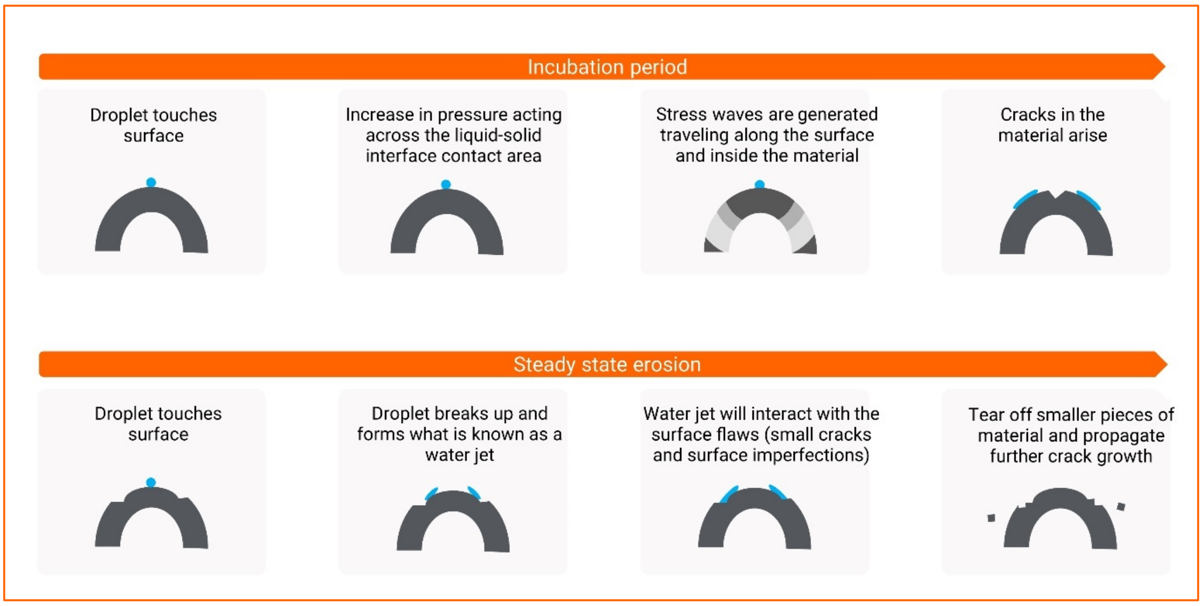


Figure 2 How rain causes progressive LEE on the blade surface.

Experimental studies have shown that the weight loss of the materials that are subjected to repeated droplet impingement varies as a function of the number of impacts [2]. During the so-called "incubation period", the weight loss is negligible. The length of the incubation period can be considered as a key material property that is used to describe the erosion resistance. After the incubation period, the rate of mass loss is constant. This period is called "steady state erosion region". In this region, mass loss increases as a function of the number of impacts. It is within this region that we observe disturbance of the aerodynamic flow around the blade that leads to losses in AEP. After the steady state erosion region, the mass loss becomes more complex. This stage is referred to as the "final erosion region". In this region, we will often see that the material used as leading edge protection will suffer from breakthrough to the substrate, and thereby expose the underlying layers for further erosion. These underlying layers typically consist of conventional coatings, fillers, and glass fiber reinforced plastics - all of which have a significantly lower erosion resistance when compared to modern leading edge protective materials. Once breakthrough has occurred, it will further accelerate the erosion of the leading edge and thereby jeopardize the structural integrity of the blade. *Figure 3* schematically depicts the erosion progression as described here.

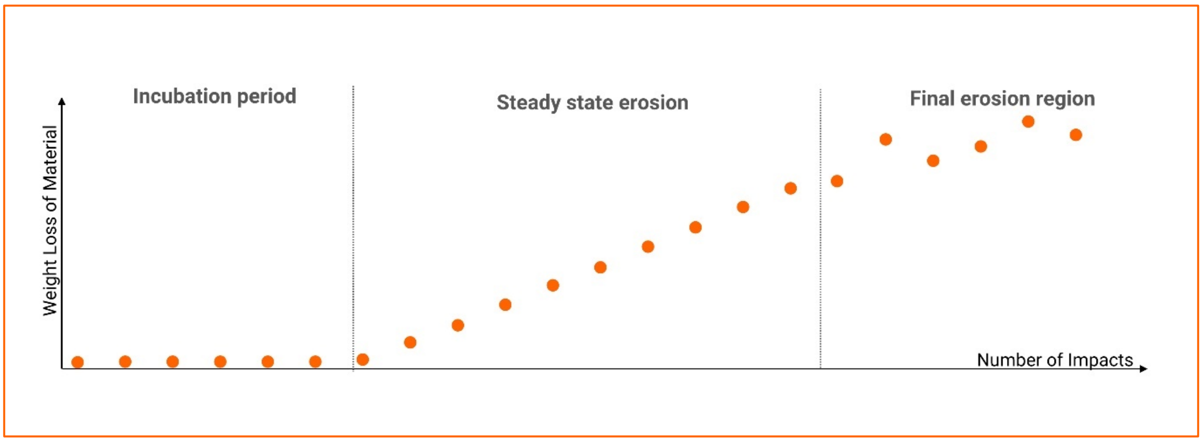


Figure 3 A principal sketch of the erosion progression for a specific material exposed to N number of impacts at a specific impact speed [2].

There are four basic ways by which erosion can be minimized or completely avoided [2]:

1) Running the turbine blade at lower speed,
2) Diverting the droplets from the surface before they hit the blade surface,
3) Breaking up droplets before they impinge upon the blade surface,
4) Using materials which can withstand the forces created by impacting droplets.

The first method will make the turbine less efficient and thus increase the cost of energy. Methods 2 and 3 are not feasible from a practical point of view considering a wind turbine and its operating environment. This leaves method 4, using materials for minimizing and preventing the damage from occurring, as the most obvious and practical approach.

To select and design materials that withstand the repeated droplet impingements, the material characteristics must be fully understood. Typically, empirical studies using whirling arm rain erosion tester are the preferred choice within the wind turbine industry to study the behavior of materials subjected to impingement of liquid droplets. Researchers and material developers subject the materials to relatively high speeds (i.e., 160 m/s) during testing and characterization. Having said that, lately testing is also being conducted at the actual operating speed of the wind turbine blade and thus improving the correlation between test conditions and real-life exposure. This means that one of the key factors for creating erosion on the leading edge of the blade surface can be understood and characterized without having to extrapolate outside the test regime.

The wind turbine manufacturers, operators, and material developers have on two occasions joined forces to create recommended practices on how to conduct rain erosion tests and which data to acquire during testing. These principles of rain erosion testing and data acquisition are published by DNV GL as "DNVGL-RP-0171 Testing of rotor blade erosion protection systems" [3]. Furthermore, a second joint industry project was established with the purpose of developing a methodology to evaluate erosion protection systems and provide input on how to perform calculations of the expected durability using results from rain erosion testing. This methodology functions as a guide for operators, wind turbine blade manufactures, and material developers to establish the needed data to evaluate the durability of erosion protection systems. The document is published by DNV GL as "DNVGL-RP-0573 Evaluation of erosion and delamination for leading edge protection systems of rotor blades" [4]. These two recommended practices are being used as the foundation for evaluating existing erosion protection systems and provide guidance for new erosion protection systems in development.

Which solutions are being used to avoid LEE?

There are different mitigation strategies used by the wind turbine blade manufacturers to avoid leading edge erosion. Typically, these solutions have been inspired by other industries that also face the challenge of erosion. Products such as liquid applied paint, either epoxy or polyurethane, and protective tapes based on thermoplastic polyurethanes have been transferred from the aviation and helicopter industry to be used on wind turbine blades. Newer products, such as shells that are installed on the finished blade made from semi-rigid thermoplastics or softer polyurethanes, have appeared on the market within the last five years. *Figure 4* provides an overview on the different solutions and their distinct features.

	Softshell	Best in Class Protective Tape	Best in class Liquid Coating	Most used Protective Tape	Most used Liquid Coating
Indicative Product Cost	100%	75%	60%	15%	15%
Indicative Lifetime Cost*	100%	180%	160%	250%	250%
Erosion Strength	100%	60%	30%	25%	10%
Application Temperature	+5 to +35°C	+8 to +38°C	-8 to +50°C	+10/+30°C	+15/+35°C
Applicati on Time	20%	10%	5%	20%	100%

■ Most desirable ☐ Least desirable

Figure 4 A comparison of different LEP systems.

**Based on 20 years remaining lifetime for a central European WTG of the 3MW class with medium rain exposure, 1 ex-change/repair for best-in-class tape and coating, 5 exchanges/repairs for most used tape and coating*

Liquid Coatings

Liquid coatings are often applied to the wind turbine blade during the final stages of the finishing. Conventional paint systems or gelcoats are applied on the entire blade surface including the leading edges. These liquid coating systems are often designed for ease of application, low cost and easy repairability, and therefore not particularly designed as leading edge protection systems. This means that they do not offer adequate protection against leading edge erosion on modern wind turbine blades. To provide better protection of the leading edges, newer, highly flexible paint systems based on polyurethanes or polyurea have been developed. Although they often provide significant improvements over conventional liquid coating systems, they are sometimes sensitive to being applied outside of the narrow application window, and smaller imperfections during application can lead to rapid failures while in operation.

Protective Tapes

Protective tapes have a long history of being used within the wind industry and have for many years been the standard solution. They are relative thin (< 0.5 mm) and are attached to the blades using an acrylic based pressure sensitive adhesive. Typically, they are made from extruded thermoplastic polyurethane. Protective tapes are still used today on wind turbine blades and are now made from polyether based thermoplastic polyurethanes and therefore more resilient against hydrolysis. When installed correctly, the protective tapes offer better erosion resistance than conventional liquid coatings. The protective tapes can be installed both on the newly finished blade inside the blade manufacturing facility or during a repair scenario on existing turbines either on the ground or up-tower. Due to their limited thickness, the time between experiencing the first crack and the subsequent breakthrough failure is often short. The remains of partly broken protective tapes can remain attached to the blade causing excessive noise and aerodynamic disturbance leading to AEP loss.

Shells

In recent years, another approach has entered the market for leading edge protection. The premanufactured shells that are specifically made to fit the turbine blades provide a readily available alternative to the other established routes of erosion protection. The manufacturing of the shells in a dedicated production environment using specialized equipment ensures high quality material production by completely avoiding mixing errors at site, low film thickness and mm size imperfections that can all lead to pre-mature erosion on the leading edge. The thick and compliant material is designed to withstand repeated impingement of rain droplets and other airborne particles. Additionally, the thickness of the softshell ensures that any smaller cracks in the material do not lead to breakthrough failure. It therefore provides the blade with protection and minimizes the aerodynamic disturbances when compared to thinner alternatives.

Basic aerodynamics and the impact from LEE and LEP on aerodynamical performance

The impact of leading edge erosion on the AEP has been subject to research and testing for several years [5]. These studies have mainly focused on the impact on the overall aerodynamical performance of the blade since this is directly related to the performance of the turbine. In general, there are two basic aerodynamical parameters that are essential for this performance: lift and drag. The lift is causing the required torque on the rotor to produce electricity, whereas the drag (also known as "air resistance") is causing a force on the blade in the downstream direction of the wind. These two forces are dependent on different parameters, such as airfoil shape, relative thickness of the airfoil, angle of attack, Reynolds number, and surface roughness, which is highly related to erosion and contamination.

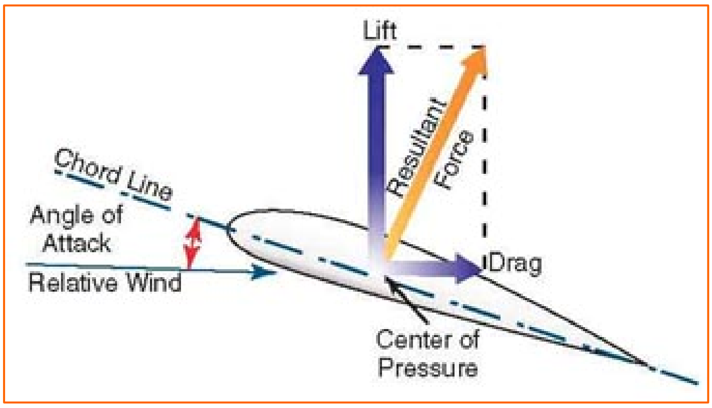


Figure 5 A schematic sketch of lift and drag on an airfoil.

Two non-dimensional parameters related to the forces are C_L and C_D, which are the lift and drag coefficients, respectively. It is the relationship between the two parameters that is essential for the performance of the turbine, as the lift has a positive impact and the drag has a negative impact on the power production. This means that a high lift over drag coefficient, $\frac{C_L}{C_D}$, is desired. This can be found from looking at the simplified expression for the viscous loss in the local power coefficient [6].

$$PowerLoss_{local,viscous,simplified} = \frac{3}{2}\frac{\lambda_{loc}}{\frac{C_L}{C_D}}$$

The power loss decreases as the lift over drag relation increases. The difference between viscous and inviscid flow and the relation to the power coefficient, together with the influence from the axial induction factor and the loss at the tip, are intentionally left out for the more interested readers to pursue themselves.

The parameter, λ_{loc}, in the expression above is called the local speed ratio. In general, the speed ratio is given at the tip as

$$\lambda = \frac{v_{tip}}{v_{wind}}$$

That means a turbine with a tip speed of 80 m/s at a wind speed of 10 m/s will have a speed ratio of 8. By introducing the speed at any radial position on the rotor, given by the radius from the center of the rotor, we can obtain the local speed ratio,

$$\lambda_{loc} = \frac{\omega \cdot r}{v_{wind}}$$

, where ω is the angular velocity and r is the radius. As derived from the equation, the local speed ratio is increasing as we move closer to the tip. This illustrates that a high lift over drag relation on the outer part of the blade is much more important than on the inner part. This is directly relatable to LEE as it is also in the outer region where most erosion appears and is therefore the most important part to protect.

The viscous power loss introduced earlier is highly related to the phenomena occurring in the vicinity of the airfoil. All around the airfoil, there is a boundary layer where the flow profile is different from the freestream flow away from the profile. This boundary layer is very sensitive to any disturbances that might appear (e.g., imperfections on the surface as erosion, contamination, etc.). The flow profile is described by the Reynolds number, whereby a low Reynolds numbers indicates a more laminar flow and high number a more turbulent flow. The Reynolds number is dependent on wind speed and some other parameters that we - in this case - assume to be constant for the sake of simplicity. An increase in wind speed will result in an increase of the Reynolds number.

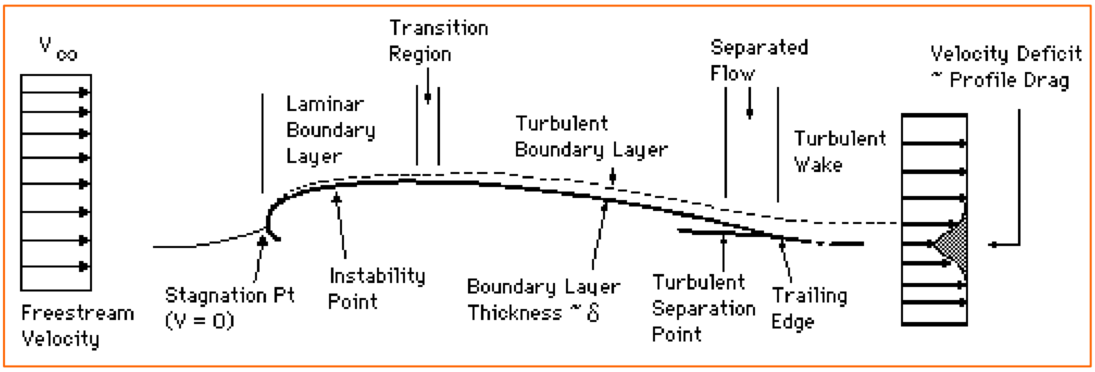


Figure 6 The laminar flow in boundary layer at different zones of the airfoil.

Figure 6 illustrates the laminar flow over the airfoil. Near the leading edge, the flow in the boundary layer can be described as laminar. As we move along the surface in the chordwise direction, a transition zone appears, where the flow changes to be dominated by turbulences. It is of great importance where this transition zone appears, as the more laminar flow we have in the boundary layer the better. The position of this transition zone is affected by erosion, contamination, or other elements that can disturb the laminar flow near the leading edge. *Figure 7* shows a picture taken in a wind tunnel with a thermographic camera. It illustrates how erosion can affect the flow and thereby shift the transition zone. The yellow line indicates the original transition zone, and the dark grey areas arising from the leading edge up to the yellow line show the desired laminar flow. The test demonstrates that erosion disturbs and can even eliminate the laminar flow.

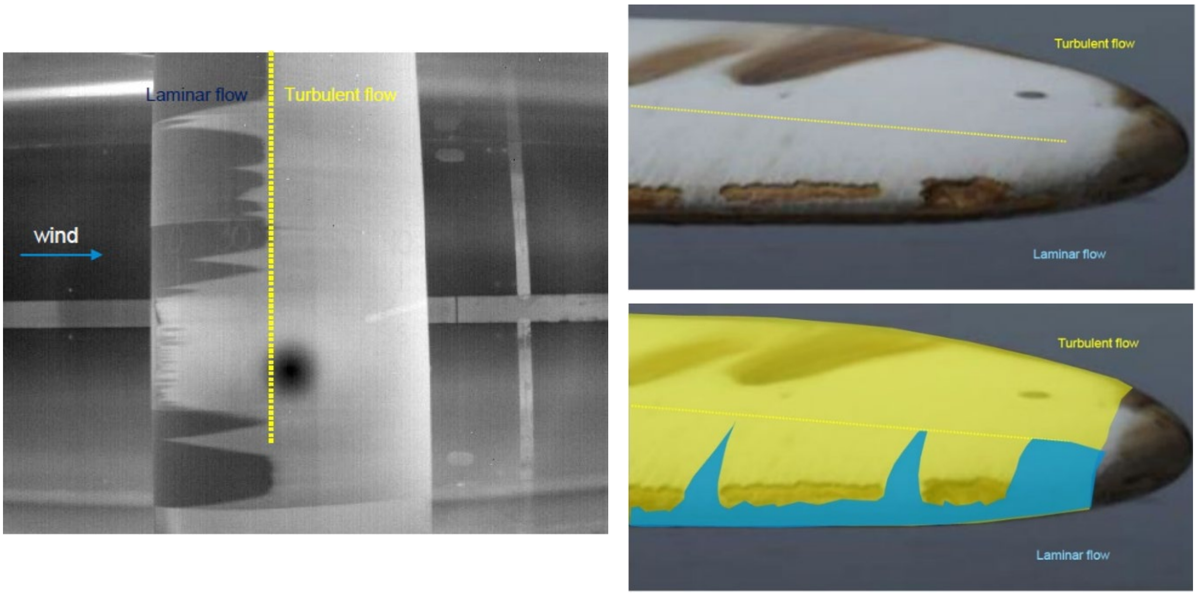


Figure 7 Shift of the transition zone from laminar to turbulent flow due to erosion within a wind tunnel setup (left) as well as for a heavily eroded blade (left).

Study on potential AEP loss

To investigate how AEP can be affected by different erosion stages, a wind tunnel test was conducted in the Poul La Cour Tunnel at the Technical University of Denmark (DTU) in 2020. The test was conducted in a collaboration between a wind turbine manufacturer, DTU and Polytech. The wind tunnel setup at DTU can be seen in *Figure 8*.

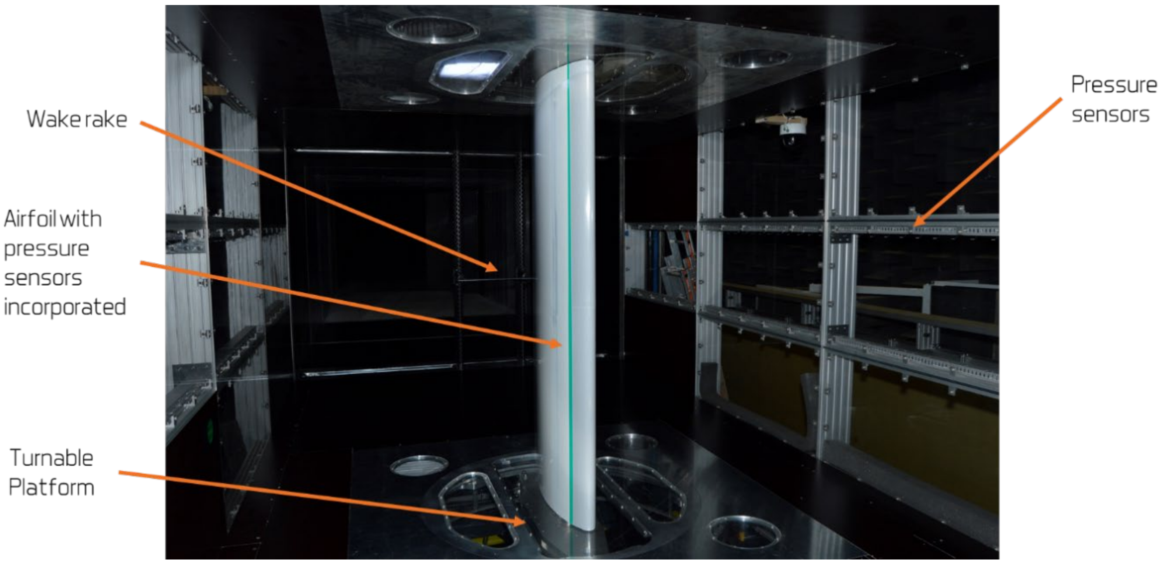


Figure 8 The wind tunnel test setup at the Technical University of Denmark (DTU)

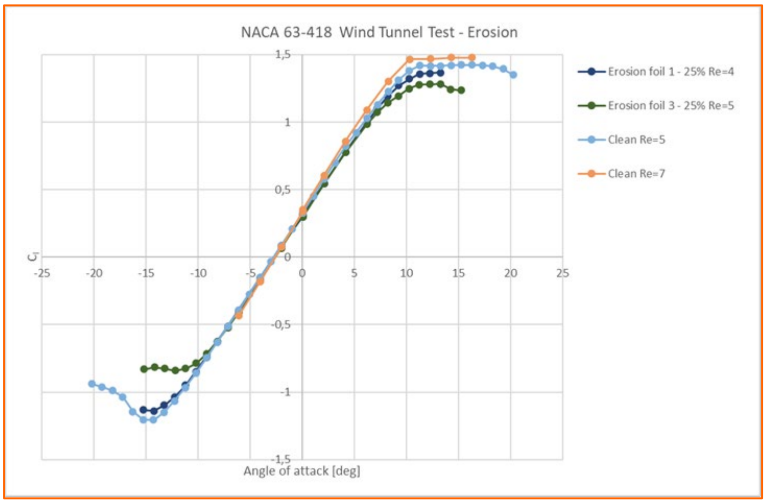
Within this test setup, the following features were tested (among others):

- Light erosion (stage 1) – 300 µm indentation
- Severe erosion (stage 3) – 600 µm indentation
- Clean blade

The erosion profiles shown in *Figure 9* were specified and delivered by the wind turbine manufacturer.

Figure 9 The 300 µm (top left) and 600 µm (top right) indentation were used within the wind tunnel test.

In the wind tunnel the drag and lift coefficient were measured according to the angle of attack, this resulted in the lift and drag curves depicted in *Figure 10*.



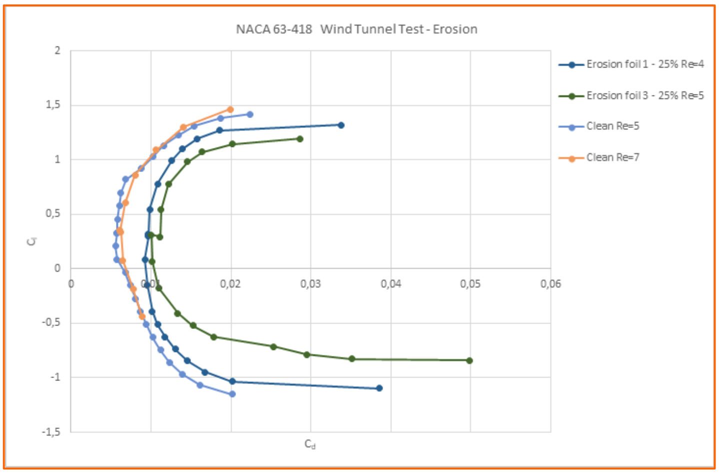


Figure 10 Showing drag vs. lift for different angles of attack.

By evaluating the results from *Figure 10* one can conclude that the erosion has an impact on both lift and drag.

A reference blade with the following specification was used to calculate the AEP impact:

- Blade length: 61.5m
- Max chord: 4.62m
- Tip speed at rated power: 80m/s
- Rated power at a wind speed of 13 m/s
- Rated power: 6MW

The AEP loss is calculated as a difference from the clean profile to the eroded one. The AEP loss in the following graphs is calculated for different spans of erosion and for wind class I, II and III.

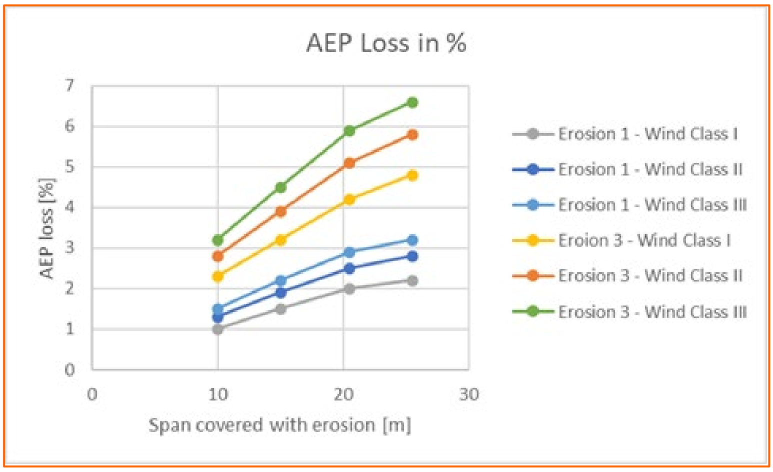


Figure 11 The AEP loss in percent for different levels of for different wind classes and spans covered.

Figure 11 shows that the light erosion profile can cause an AEP loss from 1% up to 3.2% depending on span and wind class. The severe erosion can cause a loss from 2.3% up to 6.6%.

Conclusion and Recommendation

This white paper has presented how LEE develops and propagates, which mitigation strategies exist, what their specific features are, and which recommended practices are available. Combining these with understanding the effects of LEE on aerodynamic performance and AEP, one can draw a holistic conclusion. Addressing LEE with a LEP product can not only reduce or eliminate costly repairs but can also give aerodynamic advantages compared to even slightly eroded blades. As a result, a LEP product can contribute to lowering the cost of wind energy.

We at Polytech think that a solution with a high erosion strength has the lowest lifetime cost and best potential for lowering LCOE for many sites and can be the enabler to ending leading edge erosion on modern wind turbines. Therefore, we decided to develop and constantly innovate our softshell solution, ELLE.

Any further questions?

If you have any further questions, please contact us at info@polytech.com.

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