White Paper
SGRE Wind Turbine Blades – Leading Edge Protection

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Authors
Jesper Monrad Laursen, Steffen Laustsen, Nikolai Bak Grishauge, Alex Loeven, Stefan Oerlemans, Olga Campo Ferrero, Jeffrey Elberling

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1. Introduction

Wind turbine blades are designed to operate all year around. During operation, wind turbine blades will operate under a wide range of climate conditions, varying from normal on- and offshore climate areas to sites with very heavy rainfall, high UV radiation, or areas with polar conditions. Therefore, SGRE has designed a leading edge protection system that prolongs the erosion resistance of blade leading edges.

The leading edge protection system has several advantages. Minimizing wear and tear of the leading edge can help maximize the annual energy production throughout the lifetime of the turbines, just like the cost for leading edge reconditioning can be minimized. The aim of this white paper is to describe the PowerEdge® leading edge protection (LEP) systems used by SGRE on certain turbine blades and their main function. This paper first presents a brief technical explanation of the origin of leading edge erosion and then moves on to a description of the LEP systems and the different verification tests performed by SGRE to validate the functioning and resistance of the systems.

Figure 1. Example of observed leading edge erosion in the field.

2. Leading Edge Erosion

Since field observations have shown wind turbine blade surface erosion to be confined to the leading edge region of the outer part of the rotor, the LEP focuses on adding durability to this part of the blade. The fact that blade erosion is limited to this area of the blade results from the combination of high wind speeds at the tip end and from rain droplets or other solid particles striking with the highest impact right around the flow stagnation line of the blade. The general mechanisms involved in erosion of wind turbine blade leading edges are described in Section 2.1. The description applies to all makes of wind turbine blades.

2.1. Erosion Due to Rainfall

The main source of erosion of the leading edges of wind turbine blades is rain (Keegan, 2013). The resistance against this kind of erosion is measured in a rain erosion test (RET) rig based on the natural behavior and effect of raindrops on a material surface.

Raindrops hitting a blade surface create stress waves in the coating system as shown in Figure 2. Most of the energy is absorbed in the top layer, while the remaining energy is transferred through the depth, affecting subsequent layers. Erosion due to rainfall follows a generic wear mechanism implying that a certain number of droplet impacts are required before the material (paint) begins to deteriorate.

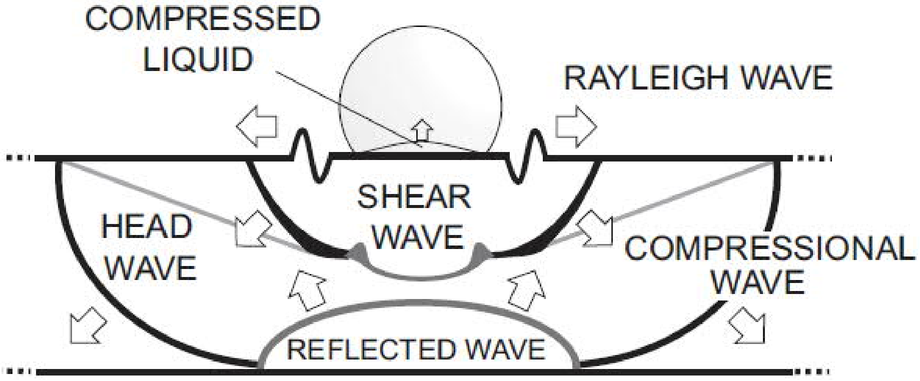

Figure 2. Principle outline of the mechanisms behind the impact of raindrops hitting a blade surface. Figure from Keegan, 2013.

The main damaging stress wave is the compressional wave, which is also called the water hammer pressure. For a relatively soft material the water hammer pressure, p_{wh}, is given by:

$$p_{wh} = \frac{\rho_L C_L}{1 + \frac{\rho_L C_L}{\rho_P C_P}} V$$

Where

ρ_L	is the density of the liquid
C_L	is the speed of sound in the liquid
ρ_P	is the density of the protective layer
C_P	is the speed of sound in the protective layer
V	is the relative speed between the liquid and the protective layer.

Thus, the properties of the liquid together with impact speed are the main factors determining the water hammer pressure. It is however important to note that the properties of the protective layer have an influence on the magnitude of the water hammer pressure. Hence by decreasing the density and the speed of sound ($\mathrm{C} = \sqrt{\mathrm{E}/\rho}$, with E being the modulus of the material) the water hammer pressure can be decreased.

The damage induced by the rain droplet impacts on each individual turbine blade scales with the precipitation history (in terms of the rain intensity distribution) and the operation velocity history (which depends on the turbine RPM and the blade length). The cyclic compression loading resembles a traditional fatigue case where the individual damage contributions can be taken into account by the Palmgren-Miner rule.

SGRE has applied existing research to develop an analytical surface fatigue model to predict the initiation of leading edge erosion due to rainfall. RETs have been used to determine the impact on the surface fatigue resistance of different coatings used in the field. The analytic model has been validated to predict the initiation of leading edge erosion by using a large data base of photos of leading edge erosion observations from the field. The aerodynamic impact of the erosion has been modeled and used to determine the expected sectional efficiency loss of the damaged airfoils. Thus, it is possible to make an estimate of the lifetime of the LEP. Moreover, by combining the leading edge erosion forecast model with the efficiency loss model, annual energy production (AEP) loss over time on different sites due to rain induced leading edge erosion can be estimated.

2.2. Erosion Due to Sand or Hail

In some geographic locations the air may hold sand at the altitude of the wind turbine rotor. In such areas, erosion of the turbine blades due to sand should be anticipated. On the other hand, this type of erosion has in more general terms not been observed to be the main driver for leading edge erosion on wind turbine blades.

Most turbines will experience hail storms during operation. As hail has been observed in diameters of up to several centimeters, the impact of a hail storm on erosion can naturally vary quite a bit, dependent on the severity of the event. As most hail events, however, involve hails of diameters of a few millimeters only, and hail storms usually have limited occurrence times, hail storms are believed to have little impact on blade erosion. Still, with the known large hail sizes from extreme events in mind, a possible erosion impact cannot be ignored.

3. Other Environmental or Design Factors Influencing Blade Erosion

External factors other than rain and solid particles can influence the development of blade erosion. The following sections briefly present both environmental factors and design factors.

3.1. Environmental Factors

Mean wind speed at site

At high mean wind speed turbine sites, found at most off-shore sites, the wind turbines run at nominal rotational speed during a large part of the total operating time. As the water droplet impact pressure increases with velocity, an increase in operating hours at nominal wind speed will tend to amplify wear on the blades.

Offshore conditions

High UV radiation exposure as well as variations in humidity and temperature generally degrade the properties of coatings, which makes the blades more prone to wear. Especially the UV radiation is known to be higher offshore due to the reflection from the sea surface. Further, the presence of salt can have a negative effect on coatings. Thus, such conditions can accelerate the propagation of leading edge erosion.

Polar conditions

Polar conditions can make the coating layers brittle, which in general terms increases the risk of cracking due to impacts.

3.2. Design Factors

Blade speed

The speed of the blade at a specific radial location depends on both the distance to the rotor center and the rotational speed. The tendency over the years has been to produce longer blades but not necessarily to increase the tip speeds. Maximum blade tip speed is determined in the design phase of the combined rotor and turbine design project, based on an optimum balance between performance and cost of the turbine as a whole. Higher tip speed increases risk of erosion.

Coating System

The coating system is applied on top of the laminate to protect it. The coating system can consist of filler, primer/top coat, and LEP system. The combination and integration of these components affect the overall erosion resistance of the surface system as well as the individual resistance of each sub component.

4. SGRE Leading Edge Protection Systems

4.1. Leading Edge Protection Type Selection

Three overall types of LEP systems have been considered by SGRE:

1. A tape solution, which will not be described in further detail in this paper.
2. A liquid LEP coating system.
3. A pre-cast soft-shell based system called PowerEdge® is further split into two product lines: PowerEdge® Premium and PowerEdge® Care.

The choice of system depends on the turbine configuration and the specific site conditions. The SGRE liquid LEP coating product consists of a two-component polymer product giving high application flexibility. The benefits are:

- RETs show that the erosion resistance of the surface top coat is improved with liquid LEP applied.
- The liquid LEP product can smoothly follow the geometry and surface structure of the leading edge.
- Defects in the applied product are easily detectable and repairable.

The SGRE PowerEdge® system is a flexible precast polyurethane based material, which can absorb the mechanical impact from solid particles and rain drops thereby reducing the impact that may result in the underlying blade surface and structure eroding. The flexibility ensures that the product can absorb the continuous vibrations of the rotating blade during its entire lifetime. The benefits are:

- longer lifetime
- very limited repair required during the lifetime of the blades.

4.2. Application Area

Based on the described erosion model and on inspections on a large number of SGRE turbines in operation at many different sites, the critical zone for erosion on the leading edge has been defined for the span wise location depending on turbine operation settings and top coat solution. In transverse direction, the liquid LEP is applied within a certain distance from the leading edge on both blade sides segregated into a primary erosion zone and a zone where layer thickness is phased down to meet requirements related to power performance and noise. Figure 3 shows an SGRE turbine blade with liquid LEP applied. The PowerEdge® system is applied similarly, but with an aerodynamically optimized geometry.

Figure 3. Liquid LEP applied to an SGRE blade.

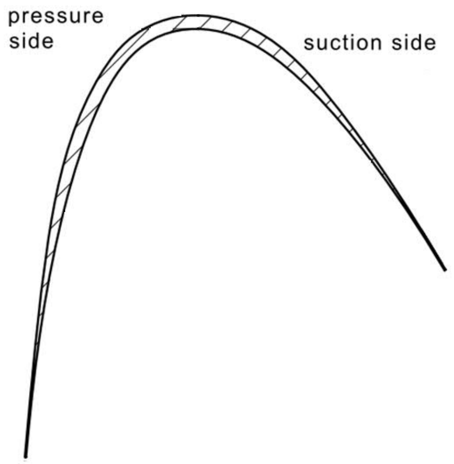

Figure 4. Cross-sectional view of PowerEdge® shell geometry.

4.3. Method of Application in Blade Production

The liquid LEP product is applied using designated spatulas. When the curing is finished, visual control of the surface is performed in order to identify any defects such as pinholes, fish-eyes, dust inclusions, etc. The layer thickness is measured non-destructively using ultrasound. The height of the step between LEP and topcoat is measured, and the adhesion of the LEP is tested using pull-off tests.

The PowerEdge® Premium product consists of precast shells, which are applied on the blades using an adhesive. When the adhesive is cured, visual control of the applied shells is performed.

4.4. Method of Application on Site

The PowerEdge® Care product consists of the same precast shells as the blade production solution. It is applied with an adhesive for onsite applications, making it possible to be applied on blades from rope access.

5. Validation

The following subsections describe the quality and functional verification tests performed during development of the blade LEP solution. The verifications done for the LEP design are the following:

- Erosion due to rainfall
- Erosion due to sand
- Adhesion
    - Peel test
- Substrate deformation, fatigue
    - At room temperature
    - At -30°C
- AEP
    - LEP impact on turbine power performance
- Noise
    - Standard IEC noise test on rotors with LEP
- Aging
    - Weathering due to UV, condensation, salt, and frost, and subsequent evaluation of above outlined performance parameters.

5.1. Resistance to Erosion Due to Rainfall

Since erosion due to rainfall is the primary reason for adopting an LEP solution to the blades, this subsection intends to elaborate on the overall principles of the RET utilized by SGRE for the described LEP solutions. A sample of findings from a typical RET comparison between different leading edge protection systems will also be shown.

5.1.1. Test Method

Resistance to rain erosion is tested according to DNVGL-RP-0171. There is no standard for RETs, but in the wind energy industry the so-called helicopter test setup described in DNVGL-RP-0171 is widely known and recognized.

In the helicopter test setup, the water is atomized to a range of droplet sizes and the spray cloud is set to cover most of the specimen resulting in wear typically initiating at the highest velocity end of the sample (160 m/s) gradually moving towards the lower velocity end of the sample (126 m/s). The test gives a relative correlation, as better test results also lead to a product performing better in real life. Thus, different surface applications can be compared against each other to prove which is the more durable, or a material can be tested against a reference for comparison.

For the RET, SGRE use a test rig as pictured in Figure 5. The test rig is based on the helicopter test setup concept outlined in DNVGL-RP-0171.

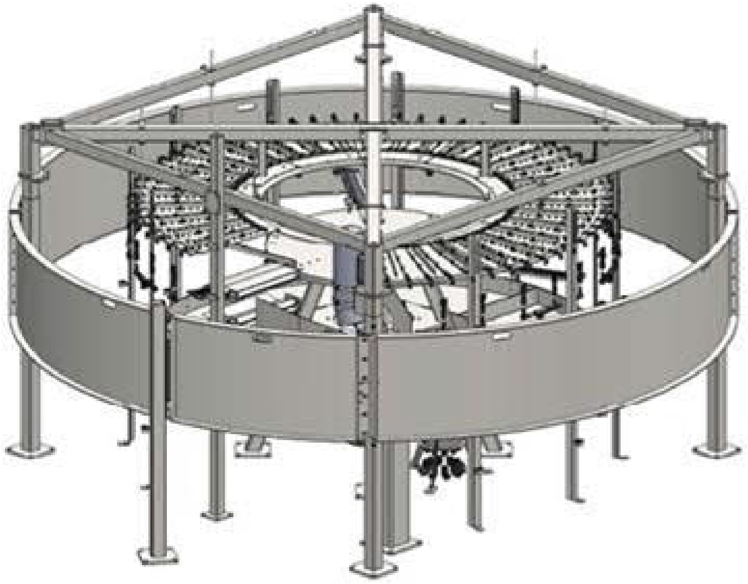

Figure 5. RET rig at SGRE.

5.1.2. RET Test Results

Tests have been made regarding the LEP systems (liquid LEP and PowerEdge®). Figure 6 shows test samples of the topcoat system, the liquid LEP, and the PowerEdge® solution described in Section 4.1. During the test, erosion begins at the outermost end of the rotating sample, where the velocity is highest. As observed from the figure, the liquid LEP shows significantly lower erosion compared to the topcoat systems, while no erosion is observed on the PowerEdge® specimens even after 20 hours of testing.

SGRE conventional topcoat without LEP - 2 hours’ testing	
SGRE next generation topcoat without LEP - 2 hours’ testing	
SGRE conventional Liquid LEP - 3 hours’ testing	
SGRE LEP PowerEdge® - 20 hours’ testing	

Figure 6. Test specimens exposed to RET.

5.1.3. RET Test Evaluation

The RET results, as shown in the examples in Figure 6, are evaluated according to DNVGL-RP-0573 to establish the durability of the SGRE blade leading edge. DNVGL-RP-0573 is a recommended practice, which consolidates the theory and methodology utilized in the analytical tool developed by SGRE as mentioned in Section 2.1.

5.2. Resistance to Erosion Caused by Sand

Erosion caused by sand has been tested according to ASTM G76 using White Fused Alumina micro particles with D50 = 9.3 μm. The sand was blasted on the surface at a speed of 80 m/s. Material removed from the samples versus the amount of sand hitting the surface was recorded. Figure 7 shows the loss of surface coating material weight as a function of the amount of sand blasted material, as applied to four test sections with different levels of surface protection.

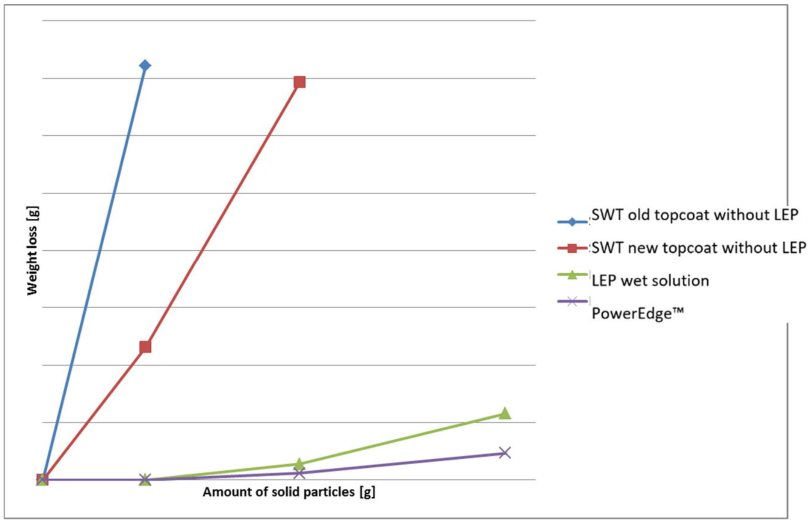

Figure 7. Test of erosion due to sand. The test specimen weight loss versus amount of sand blasted material on various test samples is shown.

5.3. Adhesion

Adhesion performance of the PowerEdge® system has been assessed according to ASTM D6862-11 (90º peel test). 90° peel tests have been conducted on the LEP soft shell blade repair system considering various substrate configurations, process settings as well as surface preparation methods. The 90° peel test has been developed to characterize the fracture toughness at the interface between the LEP soft shell and the used adhesive together with the interface between the adhesive and the underlying substrates.

This work so far has resulted in both 1) better knowledge about the adhesion performance of the PowerEdge® system and 2) its certification by DNV, the certification body.

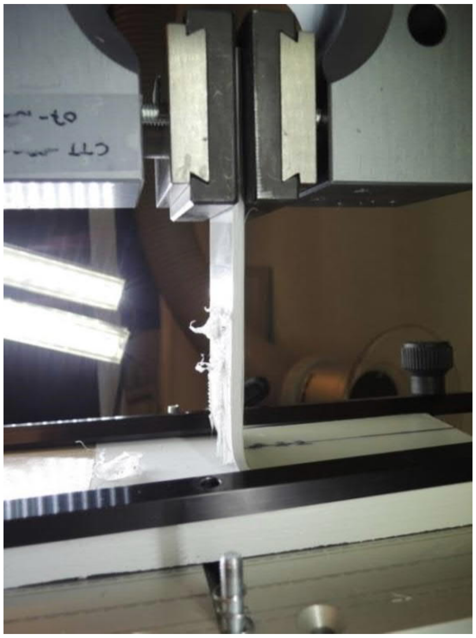

Figure 8. 90° peel test setup.

5.4. Fatigue

The described blade LEP solutions are tested to verify their capability to withstand the expected blade deformations throughout the lifetime of the turbine. The test method has been developed by SGRE and reflects the specific design of the SGRE blade, see Figure 9. The ability to withstand substrate deformations is tested as part of the material qualification of LEP. The performance is tested by tensile fatigue testing at room temperature for 2 million cycles as well as at -30° C for 250.000 cycles. The test success criteria for all fatigue tests are:

- The LEP must not crack
- The LEP must still adhere to substrate after test campaigns.

It has been concluded that the fatigue performance of the LEP systems is satisfactory.

Figure 9. Example of specimen with filler only ready for fatigue testing.

5.5. LEP Impact on Turbine Power Performance

The liquid LEP and PowerEdge® solutions used on SGRE wind turbine blades are designed to have very little impact on the annual energy production as compared to blades without these LEP solutions. Recently installed

SGRE wind turbines with these LEP solutions applied are validated including the LEP solution to ensure validated power performance including LEP. For all SGRE LEP solutions, the LEP patch made of liquid LEP coating or PowerEdge® is designed to minimize the disturbance of the local boundary layer flow as well as the overall aerodynamic performance of the blade. This is ensured by setting and meeting requirements to the design and implementation of the LEP.

The final aerodynamic requirements to the LEP are based on wind tunnel experiments in the TU Delft and Deutsche WindGuard low-speed wind tunnels (figure 10).

Figure 10. Wind tunnel tests on airfoil with LEP.

During wind tunnel testing, the LEP design and application process are optimized to minimize AEP impact. As a direct outcome of the wind tunnel tests, new airfoil polars have been constructed enabling the AEP impact to be calculated in SGRE's in-house rotor performance assessment tools.

5.6. Noise

Due to the strict power performance requirements to the liquid LEP and to the PowerEdge® system, the solutions will have a minimum impact on the local boundary layer flow of the blade sections where it is installed. Acoustic impact will depend on the application length of the LEP; using liquid LEP or PowerEdge® may imply a noise increase. Please contact your SGRE representative to learn more.

5.7. Microplastic Leakage to the Environment

Use of the PowerEdge® system on SGRE will have positive effects on the leakage of microplastics to the environment. Based on scenario simulations of a typical European offshore site with a tip speed around 90 m/s over a lifetime of 25 years, different quantities of microplastic leakage from leading edge erosion can be expected (see table 1 below). The expected material to be eroded will be a combination of coating, epoxy and primer. Different coating systems will lead to different amounts of microplastic leakage from leading edge erosion, and the reflected values should be considered a maximum of any given applied coating system

Table 1: Potential microplastic leakage over a lifetime of 25 years per turbine (3 blades) based on different applications of PowerEdge® system

Length of PowerEdge	Maximum material loss per turbine over a 25-year period [Grams]
0	35761
3	16538
6	7342
9	3034
10	2205
12	1095
15	294
17	78

It is evident that the PowerEdge® system can significantly reduce or even close to eliminate microplastic leakage to the environment, when applied in appropriate lengths.

6. Conclusion

The leading edge protection solutions outlined entail the application of a two-component PU liquid LEP product on top of the existing top coating or a PowerEdge® pre-cast material applied on top of the topcoat as an advanced solution. The outcome of the latter is high erosion resistance. With respect to erosion caused by rainfall, the design is based on the principles of the water hammer pressure failure mode, which resembles a traditional fatigue case.

Sand and rain erosion tests have been used to both qualify and validate the durability of the developed LEP systems as compared to reference top coating. By applying in-house knowledge and experience combined with high quality wind tunnel testing for the sake of high quality aerodynamics, the LEP solutions have been optimized to balance long term durability with a minimum of impact on blade performance.

The PowerEdge® system offers increased durability compared to the existing leading edge coating, whereby leading edge erosion is reduced, and the lifetime of the coating system is increased, consequently the blade structural integrity is maintained. This reduces the requirement for inspection and possible repairing.

7. Bibliography

Keegan, M. H. (2013). On erosion issues associated with the leading edge of wind turbine blades. *Journal of Physics D: Applied Physics, Volume 46, Number 38.*

ASTM G73. Standard Practice for Liquid Impingement Erosion Testing

ASTM G76. Standard Test Method for Conducting Erosion Tests by Solid Particle Impingement Using Gas Jets

ASTM D6862-11. Standard Test Method for 90 Degree Peel Resistance of Adhesives.

DNVGL-RP-0171: Testing of rotor blade erosion protection systems

DNVGL-RP-0573: Evaluation of erosion and delamination for leading edge protection systems of rotor blades

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Siemens Gamesa Renewable Energy S.A.
Parque Tecnológico de Bizkaia, Edificio 222
48170, Zamudio, Vizcaya
Spain

+34 944 03 73 52 – info@siemensgamesa.com –
www.siemensgamesa.com