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MULTILAYER LEADING EDGE PROTECTION SYSTEMS OF WIND TURBINE BLADES: A REVIEW OF MATERIAL TECHNOLOGY AND DAMAGE MODELLING

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Abstract: *The use of composites opens great prospects in the design and manufacture of the wind turbine blades due to their optimization versatility. Blade manufacturers employ polymeric surface materials to protect the composite structure from exposure to repeated impact of rain droplets which are mostly contributing to the leading edge erosion of wind turbine blades. Modelling tools considering multicomplex stress states and the material degradation are required for design purposes toward protection performance. This investigation summarizes a initial review based on two main issues: firstly, the LEP material configuration used in industry as a multilayer system considering the blade integration technology and, secondly, the modelling techniques and numerical procedures currently used to predict both wear surface erosion and interface delamination failure. The work is conducted in the framework of the IEA Wind TCP (International Energy Agency Wind Technology Collaboration Programme) - Task 46 Erosion of wind turbine blades.*

Keywords: Wind turbine blades; leading edge protection; droplet impact computational modelling; multilayer systems

1. Introduction

In the immediate future, wind power will provide more electricity than any other technology based on renewable and low-emission energy sources. As a result, the size of offshore wind turbines has increased to harvest more wind energy in order to achieve the 2050 EU carbon neutral targets. The use of composites opens great prospects due to their optimization versatility. However, composites perform poorly under rain droplet impact, perpendicular to the reinforcement direction and are sensitive to environmental factors such as heat, moisture, icing, salinity and UV.

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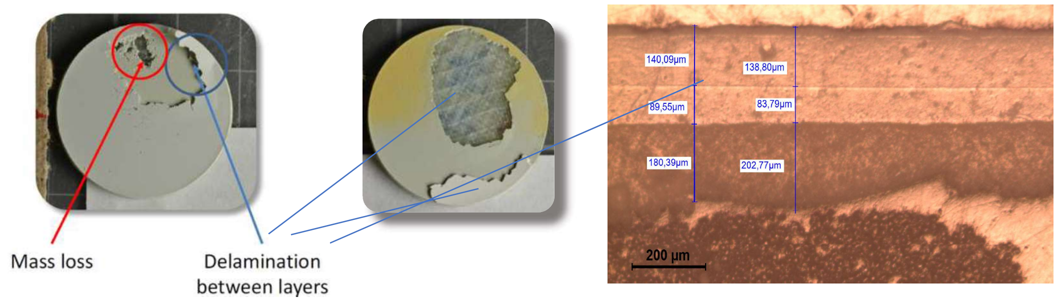
The hindering of leading-edge erosion could be obtained through its polymer-based multilayer material optimization i.e. Leading Edge Protection LEP [2]. Both the surface erosion and the material intra-layer adhesion are affected by the shock wave produced from the collapsing water droplet after impact, see Figure 1. The propagating stress waves are reflected and transmitted to the composite laminate substrate through the thickness of the LEP system [3] .It is necessary to increase the interfacial mechanical resistance of the multi-layered system from the surface to the interface boundaries to damp the surface damage and avoid subsurface delamination [4].



(a) (b)

Figure 1. (a) Rain erosion testing specimens. Erosion failure due to mass loss on surface and interface delamination. (b) Multilayer system microscopy. Two coating layers define an interface that tend to delaminate upon impingement, from [6].

Therefore, validated models considering the developed multicomplex stress states and the material degradation due to the environmental loads are required for design purposes toward anti-erosion protection performance. This investigation summarizes the initial review of the current literature conducted in the framework of the IEA Wind TCP (International Energy Agency Wind Technology Collaboration Programme) - Task 46 Erosion of wind turbine blades [5]. This review will allow for the identification of gaps within the research that can be explored during IEA Wind Task 46 on the Erosion of Wind Turbine Blades.

2. LEP material configuration and blade integration technology

2.1 LEP solutions used by industry

There are a variety of protection systems used by industry to mitigate the negative effects of erosion and extend the lifetime of the blades, including coatings, tapes, and soft shells. These are applied along the leading edge at the vulnerable portion of the blade. As shown in Figure 2, the application of coating systems is multi-layered with a filler layer used to smooth the surface before coating application. Some manufacturers include a primer layer to aid adhesion in the system. Tapes and thicker softshells are applied with adhesives directly to the blade in a single piece. Despite the different approaches, there is currently no solution that can protect blade edges for the entire lifetime of the blade. However, challenges and limitations exist with each of the current solutions, with regard to their level of rain erosion protection, challenges during manufacturing or application, failures in the adhesive used, and reduction in the aerodynamic performance of the blade due to the addition of the protection system along the leading edge.

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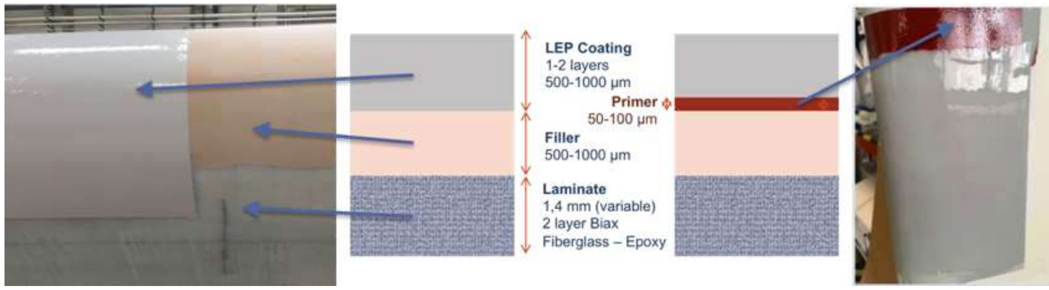

Figure 2. Leading Edge Protection (LEP) system configuration on the blade surface as a post-mould coating application multilayer system [6]

Protection systems either fail by surface erosion or delamination, with the quality of manufacture and application determining which failure mode occurs. Coatings rely on intensive manual techniques to be mixed and applied to the blade and as such can be vulnerable to defects. The defects then act as erosion initiators and encourage the development of erosion. Tapes and soft shells are manufactured away from site in controlled environments and are less prone to defects than coatings. However, if they are not effectively applied to the blade surface, wrinkles and air pockets can be introduced, reducing the adhesion of the bond. Consequently, further development in protection systems and their application is required.

The influence on the anti-erosion performance of the protection systems materials can be determined experimentally by testing, or by conducting analytical or numerical studies. The analysis (or design) of Leading-Edge Protection systems depends on the material properties in the configuration and the operational load to which it is designed during its realistic life, that is, it must be able to withstand accelerated loads and also fatigue field regimes. To make a selection or design of a specific protection system, appropriate modelling must be defined. Numerical and analytical models can be constructed with their own capabilities and limitations and, in all cases, appropriate material characterization for modelling input parameters identification is required.

3. Computational modelling techniques to predict erosion damage considering LEP multilayer protection systems

3.1 Modelling based on material fundamental properties

Several computational studies have been used to understand the mechanisms leading to damage initiation during liquid impingement. Previously, Keegan at al. [7] compiled a comprehensive review, which details modelling methods along with a number of other techniques for preventing erosion on the leading-edge erosion of wind turbine blades. Additionally, Dashtkar et al. [8] reviewed the liquid erosion mechanism, water erosion testing procedures and the contributing factors to the erosion of the leading edge of wind turbine blades, including a brief discussion on the use of carbon nanotubes and graphene nano-additives for improving the erosion resistance of the leading edge. Several reviews have been developed to contribute towards identifying the physical process of erosion and key failure mechanisms behind rain erosion, along with estimation of fatigue life of the coating material [9], [10].

Single droplet models are used to investigate the fluid-structure interaction and the stress/strain behaviour over time in multilayer systems. In most cases, these models analyse single droplet impacts and have been achieved using a variety of methods, including, a) the Lagrangian method [11], b) the Coupled Eulerian and Lagrangian (CEL) method [11, 12] and c) the smoothed particle hydrodynamics (SPH) method [13,3]. A coupled Eulerian and Langrangian (CEL) method was used by Keegan et al. [14] to model rain droplet impact on wind turbine coating materials (epoxy based gelcoat) where the materials were modelled with ANSYS-predefined epoxy resin properties. The impact pressure due to the droplet from the simulations closely correlated with the analytical water hammer pressure. Keegan et al. [15] also used smooth particle hydrodynamics (SPH) to simulate rain and hail impact resulting in high correlations with the experiments, where multimaterial systems for gelcoated substrates were explored. The contact between the material interfaces were defined as fully fixed. Verma et al. [3] used the SPH method to perform a parametric study on the effect of different environmental conditions, such as droplet sizes, impact angles and velocities, on the rain erosion performance of wind turbine blades. The authors developed a coupled fluid structure interaction (FSI) model where the numerical model consists of structure domain modelled using traditional finite element method (FEM), and the fluid domain modelled using meshless SPH. The interfaces in the materials (gelcoat-CSM (chopped strand mat), CSM/GFRP (glass fibre reinforced plastic), between GFRP layers) were modelled through cohesive interactions. For the gelcoated substrates, most of the stresses are developed on the coating surface while the substrates (consisting of CSM and GFRP experience less stress development due to single droplet impact. In addition, they studied the effect of repetitive rain droplet impacts and managed to numerically correlate the erosion damage to the number of impacts. The authors used cohesive interfaces to introduce interfacial damage in the substrate/LEP interface but did not consider the effects of viscoelastic recovery of the polymer coatings. SPH modelling has also been investigated by Astrid et al. [16] where coatings were modelled using Finite Element methods (FEM). Doagou-Rad and Mishnaevsky [17] conducted a comparison between the CEL and SPH methods, which also compared to the analytical solution of the Modified Waterhammer Equation. The two numerical methods were in good agreement, but both were found to underestimate the impact stresses compared to the analytical solution. In addition, the authors performed a parametric study in which they considered environmental (impact angle and velocity, droplet shape), manufacturing (surface characteristics) and design (density, stiffness and Poisson's ratio) aspects of the LEP systems. Finally, they showed that considering the viscoelastic effects of the polymer materials could lead to a change in the damage pattern.

An alternative method, Discrete Element method (DEM), also based on meshless formulations, was investigated by Castorrini et al. [18]. A Streamline-Upwind/Petrov-Galerkin (SUPG) and Pressure-Stabilizing/Petrov-Galerkin (PSPG) stabilisation method were used together with particle-cloud tracking approach to estimate the key regions along the blade that are critical for erosion. Isotropic materials were used in the model, where the material properties needed as input were the fracture toughness of the material, as well as Rayleigh wave velocity, density, E-modulus, and poisson ratio.

A Cohesive zone modelling approach between layers was proposed also by Cortes et al. [4] to model the interfaces between coating and composite laminate. It is therefore necessary to understand and characterise the failure behaviour of the interface boundaries in multi-layer systems. To investigate the adhesion between coating and substrate pull-off tests, peeling–adhesion tests and nanoindentation testing where performed. Fraisse et al. [19] developed a coupled Eulerian-Lagrangian symmetric model to study impact of water droplet on coated laminate of the blade. The gel-coated multilayer material was modelled in Eulerian domain, where perfect contact was assumed and the water droplet was modelled in Lagrangian domain.

Fatigue analysis based on semi-empirical analytical modelling was proposed by Springer [20]. It considers a model that relates material fundamental properties to predict the time to failure in a rain erosion test. The stress history in the coating and in the substrate has to be identified analytically. It is affected by the shockwave progression due to the vibro-acoustic properties of each layer, and by the time interval of the repeated water droplet impacts. The fatigue life of the material is then calculated, and the model can be applied to estimate the stress at different locations through the thickness, i.e., the coating surface or at the coating–substrate interface, etc. It has been applied considering in-field conditions in [21]. It is based on numerical parameters defined with specific experimental observations. Herring et al. [22] analysed how variations on material or Rain Erosion Testing configurations may include important differences and uncertainties when applied in the performance analysis. However, the experimental data used to develop the model is unrepresentative of the testing and materials currently used within the wind industry. The Springer model also ignores the multilayer configuration. Fatigue analysis of the coated substrates subjected to stochastic rain field simulation was proposed by Hu et al. [23] using the coupled SPH and FEA approach. The gel-coated samples were modelled with perfect contact between the different layers in the FEA. Other computational studies were developed for the multi-impact fatigue analysis [24]. Pugh et. al. [25] did a comprehensive review of various analytical techniques to inspect and characterize the materials used in rain erosion to evaluate the performance.

Modelling tools provide a guidance in the selection and modulation of material protection properties and should reduce the scope of testing to verify the rain erosion resistance of LEP systems. The novelty and differentiation will likewise be based on an approach to the erosion problem including the material fundamental properties and establishment of the way the erosion occurs such as progressive failure mode or interface delamination. It is required additionally to include the influence of factors which had not been entirely or accurately covered in the treated modelling when evaluating a multilayer LEP system instead of a simplified coating-substrate approach.

3.2 Material characterization required as modelling input parameters

The previously referenced models aim to quantitatively predict the erosion damage of coated materials under the previously untested conditions. In this section the review is focused on studies of the mechanical parameters that may be included in such analysis.

Modelling damage and failure in a multilayer system can be achieved with two different approaches. The first approach is by introducing damage parameters (based on continuum or fracture mechanics) for each material separately which would require an extensive material characterisation at different strain rates. The second approach would be to consider the whole multilayer system as an interface and introduce an interfacial damage law. Such an approach could for example be, Cohesive Zone Modelling (CZM) which requires as an input the fracture energy of the interface. However, once again, the main challenge is related to the fact that such a characterisation would need to take place at very high strain rates to be representative of a water droplet impact event. In both cases, rain erosion is expected to contribute to property degradation and, therefore, a fatigue law would also need to be established which takes into consideration the gradual degradation of those parameters. Other factors that are expected to contribute to property degradation are high/low temperature cycles, moisture absorption and UV radiation. In such cases, characterisation tests should be repeated in both virgin state and after environmental exposure to accurately capture accurate numerical modelling inputs. Table 1 provides an overview of the input parameters and the tests required to establish a single droplet impact model which takes material degradation, damage and failure into consideration.

Table 1: Summary of the needed material properties and required tests for the numerical modelling of water droplet impacts and progressive damage and failure

Input parameter	Test details	Test standard
Density	Water displacement testing	ASTM D792-00
Elastic modulus, Poisson's ratio, Yield stress, Failure stress, Failure strain, Complete stress-strain curve	Tensile testing	ASTM D882-18
	Compressive testing	ASTM D695-15
	Shear testing (Punch tool testing)	ASTM D732-17
Fracture toughness	Mode I: CT,SENB specimen	ISO 13586
	Mode II: TAST specimen	ASTM D5656-10
Interfacial fracture toughness	Mode I: Peel test	ASTM D1876-01
	Mode II: TAST specimen	ASTM D5656-10
	Mixed mode: Dolly test	
Fatigue crack growth rate	CT specimen	ASTM E647-15e1
Viscoelastic properties	DMTA	ASTM D5026-15
High-strain rate testing	Certain tests to be repeated at higher strain rates	Various
Degradation laws for environmental exposure	Certain tests to be repeated after environmental exposure	Various
Coefficient of linear thermal expansion	With a Vitreous Silica Dilatometer between−30°C and 30°C	ASTM D696-16
Diffusion coefficient	Gravimetric measurements	ISO 62:2008

The material properties need to be characterised at several temperatures and strain rates. Hoksbergen et al.[26] studied the sensitivity of the Springer model and stating that the Poisson ratio, strength values and fitted constants have the greatest impact on the model. They suggested utilizing numerical tools and using high-strain rate material properties to improve the accuracy of the Springer model. Domenech et. al.[27] proposed a modelling methodology to evaluate the viscoelastic behaviour of a multilayer coating system. They analysed with a simplied 1D analytical model the limits of the working frequency during a water droplet impact in a range of 0.5-7Mhz considering a multilayer configuration. Field et al. [28] did a review of well-established experimental techniques for high-rate deformation and shock studies. Poloscoser et. al.[29] subdivided dynamic range in low and high range, and drop weight principle, the split Hopkinson pressure bar test is recommended. The strain range between 10^4 – 10^8 1/s and is described with “impact” loading or “high speed velocity impact”, where plate impact test is used to acquire the desired high strain rate properties. Dynamic mechanical analysis (DMA) can be used to determine viscoelastic temperature and time (frequency) dependent behaviour. Based on this correlation the time temperature superposition principle (TTS) can be applied to determine the complex modulus and loss angle at high strain rates [30].

4. Conclusions and future work

This review will allow for the identification of gaps within the research that can be explored during IEA Wind Task 46. We aim initially to develop three main detected open issues: an interface characterisation methodology which will take into account the effect of the different layers of each LEP configuration, the strain rate sensitivity of the interface mechanical bahaviour and the analysis of the gradual property degradation due to rain erosion.

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