A NUMERICAL MODELLING APPROACH FOR INTERPHASE ADHESION OF RAIN EROSION PROTECTION SYSTEMS OF WIND TURBINE BLADES

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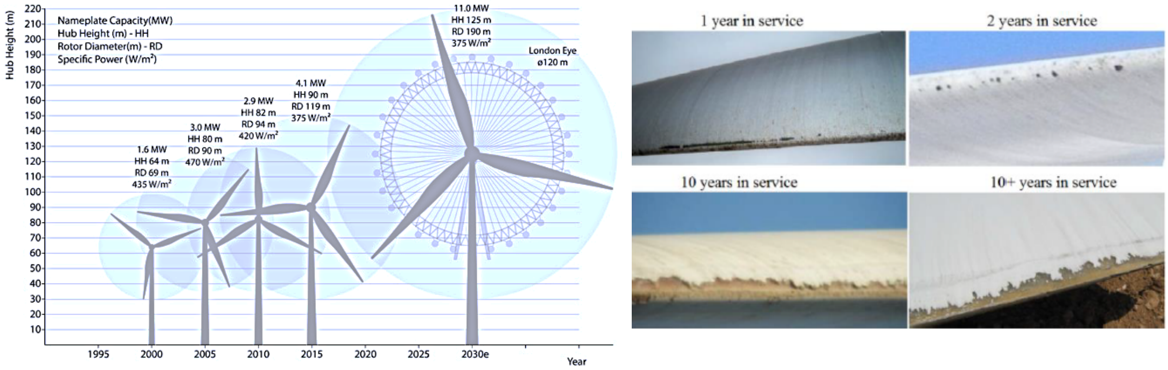
Abstract

Rain erosion damage on wind turbine blades, is a major cause for maintenance cost concern. The problem has been approached by developing new coating systems to diminish the erosion drawback. In this research, the Post-mould coatings specifically developed for the Leading Edge Protection (LEP) and usually moulded, painted or sprayed only on the frontward facing leading edges of the wind turbine blades are considered. The coating adhesion and erosion is affected by the shock wave caused by the collapsing water droplet on impact. The stress waves are reflected and transmitted to the laminate substrate. It is necessary to optimize the contact adhesion resistance of the multi-layered system interface boundaries in order to avoid failure by delamination. The experimental investigation has been directed into the interphase adhesion modelling based on the coating-laminate interphase adhesion characterization, which was assessed by pull-off testing, peeling-adhesion testing and nano-indentation testing. The work considers distinctive coating configurations as study case that ponders the inclusion of a primer layer and a filler layer on a LEP configuration system. Analytical and numerical models are used to relate lifetime prediction and to identify suitable coating and composite substrate combinations. In this work an appropriate definition of the Cohesive Zone Modelling (CZM) allowed one to account for the interface adhesion and hence to optimize manufacturing and coating processing for blades into a knowledge-based guidance for leading edge coating material development.

1. Introduction

The industry growth of offshore wind energy is a key point to achieve the worldwide policy targets regarding low carbon, secure and competitive electric energy supply. In near future, wind power will provide more electricity than any other technology in the high renewables scenario. Wind energy technologies demand further reliability to keep on reducing costs. One of the mayor sector trend to improve efficiency is based on increasing the Wind turbines rotor diameters to capture more wind energy. Bigger turbine blades will continue to be developed and installed, see Fig. 1 (a). However, this increase in diameter involves an escalation in the tip speed. When considering the impact force of rain droplets, hailstones and other particulates on the blade leading edge, the tip speed is a key contributor to erosion damage on the surface, see Fig. 1 (b). This limited lifetime influences the wind industry adversely, especially if erosion reparations are to be undertaken on offshore wind locations with restricted access and handwork conditions.



(a) (b)

Figure 1. (a) Blade size evolution trend for wind turbine blades, adapted from [1]; (b) Examples of leading edge erosion across a range of years in service, from [2]

The large and ever-growing scale of modern blades has resulted in the widespread implementation of fibre-reinforced thermosetting polymer composite technologies due to their high specific strength and stiffness properties and fatigue performance, nevertheless, composites perform poorly under transverse impact (i.e., perpendicular to the reinforcement direction) and are sensitive to environmental factors such as heat, moisture, icing, salinity and UV. Blade manufacturers employ polymeric-based surface coatings to protect the composite structure from exposure to these factors. Post-mould application is typically used to apply Leading Edge Protection (LEP) in locations where the threat of rain erosion is a concern. Industrial processes state that LEP systems can be outlined as a multi-layered system, where some manufacturers include a putty layer between the composite laminate and the coating, see Fig. 2. It also can be included a primer layer under the coating and over the filler to improve adhesion mainly on service conditions.

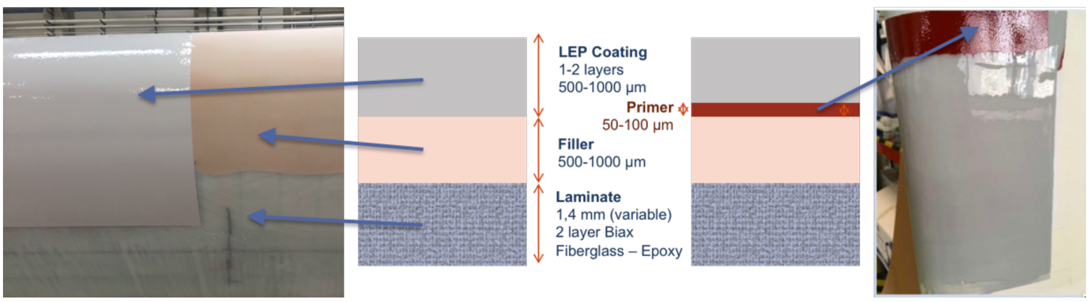


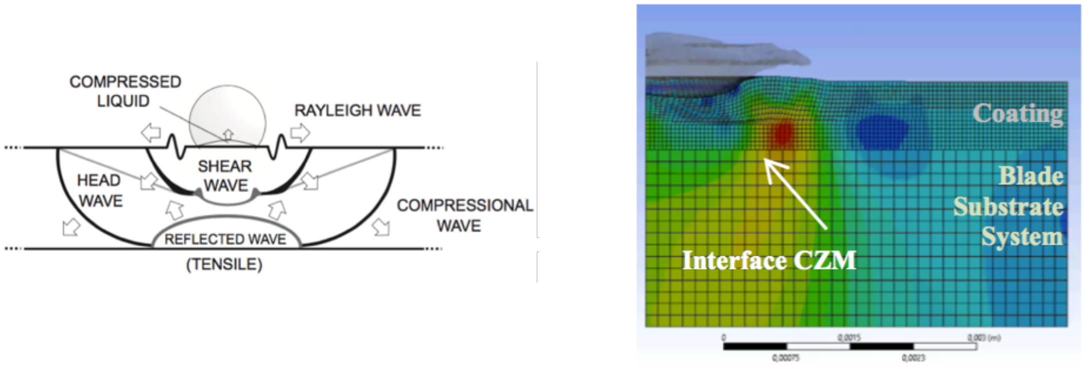
Figure 2. Leading Edge Protection (LEP) system configuration on the blade surface, [5]

Analytical and numerical models are commonly used to identify suitable coating and composite substrate combinations based on their potential stress reduction on the surface and interfaces under droplet impingement and also for lifetime erosion damage prediction. The numerical models known are limited to a linear elastic response of the polymer subjected to drop impact loads and not consider the interfaces contact failure,[3], [3], [4]. In this research, the polymeric mechanical models are used within a novel multi-parametric approach based on the viscoelastic material characterization that links the calculation of stress-strain behaviour with the service conditions conditions (temperature, rainfall intensity, droplet size, impact speed, impact frequency). A numerical tool to quantify the potential stress impact reduction when varying the material and the geometrical parameters of the LEP system configuration has been developed.

2. Rain erosion issues on Wind Turbine Blades

2.1 Liquid Droplet Impact Modelling

An essential aspect of understanding how erosion is caused on the coating material is to consider the physical effects initiated by the impingement of the liquid droplets upon the material surface. The analysis of erosion damage caused by rain droplets shows that the damage is in fact a dynamic event resulting in the propagation of shock waves, see Fig. 3. As the water droplet impinges on the surface at a normal angle, two wave fronts are created with the longitudinal compressional normal stress wave preceding a transverse shear wave. The impact gives rise to a third wave due to the water droplet deformation itself, called the Rayleigh wave, which is confined to the surface of the target [4]. The pressure generated on impact can be referred to as the water-hammer pressure and the magnitude varies depending on the acoustic properties of the target material and the liquid [3]. The duration of the impact pressure on the surface is directly related with the radius of the droplet. The maximum pressure does not occur at the epicentre of impact at the instant of first contact but at some delayed time in a ring around the midpoint at a location where the contact circle edge is reached by the initial shockwave generated by the impact [6]. Maximum shear stresses are observed on these radial locations and have a very short duration compared with the central compressional pressures. The erosion failure can be initiated by a local imbalance of tensile and shear stresses in regions that may be outside the direct impact area.



(a) (b)

Figure 3. (**a**) Illustrates the three waves that develop following the droplet collision [4]; (**b**) 3D FEM Numerical simulation of a droplet impact on a multi-layer LEP configuration. Interface CZM can be used to define the failure resistance between contact layers.

The post-impact shock wave also propagates through the LEP multi-layer system materials and depends on the elastic and viscoelastic responses and the interactions between layers, see Fig. 4 (a). Upon contact with the coating, two different wave fronts travel into the liquid and coating, respectively, as shown in Fig. 4 (b). The normal incident wave front in the coating advances towards the coating–substrate interface, where a portion of the stress wave is reflected back into the coating and the remaining part is transmitted to the blade substrate system. Due to this reflection, a new wave is now advancing in the coating with a different amplitude depending on the relative magnitude of the acoustic impedances of the coating and substrate [3]. Stress reflections oscillate repeatedly through the coating and substrate structure until dampened out by the materials' properties [6]. Numerous consecutive impact droplets result in the interaction of the reflected waves and positive wave interferences which produce tensile stresses with an amplitude that can be greater than the dynamic ultimate strength of the material under fatigue conditions. The capability of the coating to transfer wave energy in the multi-layered system can influence the erosion damage. Hence, surface and also indirect damage by delamination may occur at the interface boundaries between material layers, caused by the propagation and interaction of the compressional waves from the impact of water droplets, see Fig. 5.

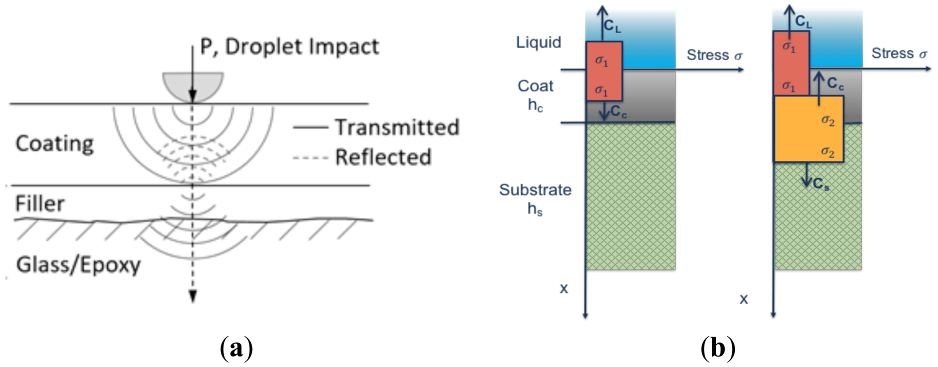


Figure 4. (**a**)Blade structure with a filler intermediate layer; (**b**) one-dimensional normal shockwave propagation depending on the relative acoustic impedances in two consecutive time instants.

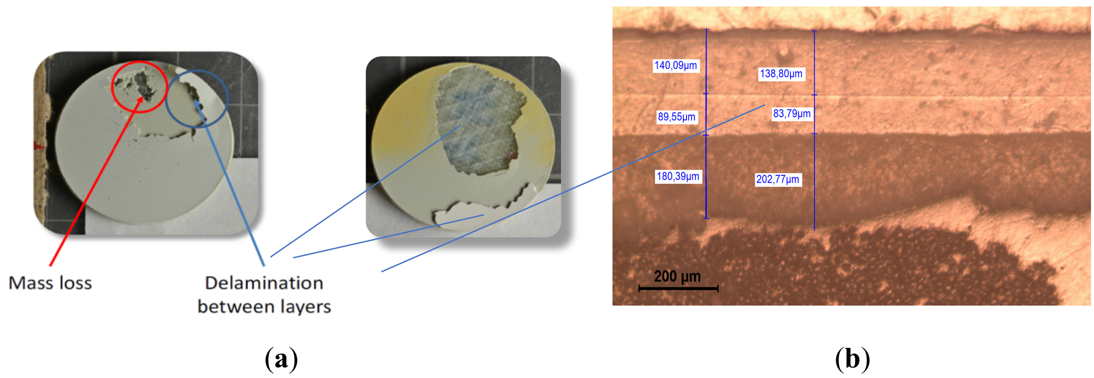


Figure 5. (**a**) Two different types of erosion failure observed in Rain Erosion Testing coupons: pits and cracks that progress with mass loss caused by direct impact and stress on surface (left) and delamination indirectly caused by the interface stresses (right). (**b**) Cross section of a multi-layered system. Two consecutive coating layers and coating–substrate interfaces that tend to delamination [5].

2.2 Lifetime prediction Modelling

The progression of erosion can be experimentally measured in a number of ways. One method is in terms of the average erosion depth versus time or mass loss versus time (directly related to the number of impacts [3], see Fig.6. There is initially an incubation period in which damage progresses without perceptible change in the material weight loss. After a sufficient amount of fatigue degradation has accumulated, the material tends to lose mass with a constant erosion rate. This marks the end of the incubation period and a steady mass loss period begins, where the weight loss varies nearly linearly with time. Fig.6 depicts the modelling proposed in [3], and is also considered as the standard to quantify the damage ASTM G73-10 (Liquid impingement erosion using rotating apparatus [6]. This analytical model has been widely referenced in flight applications [4] and recently applied successfully to wind turbine blades, as described in [8]. The model quantitatively predicts the erosion of coated materials under the previously untested conditions. In order to predict the incubation time and the mass removal rate, the stress history in the coating and in the substrate has to be identified analytically or numerically. It is affected by the shockwave progression due to the vibro-acoustic properties of each layer, and by the frequency of the repeated water droplet impacts. Fatigue life of the material is calculated using an equivalent erosion resistance with a semi-empirical approach and depends on the ultimate tensile strength and other relevant properties of both the coating material and substrate. 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. Nevertheless, it is assumed that the bond and adhesion of the boundary interface is ideally perfect, so the modelling does not account for the microstructural imperfections and lack of adhesion of such interfaces.

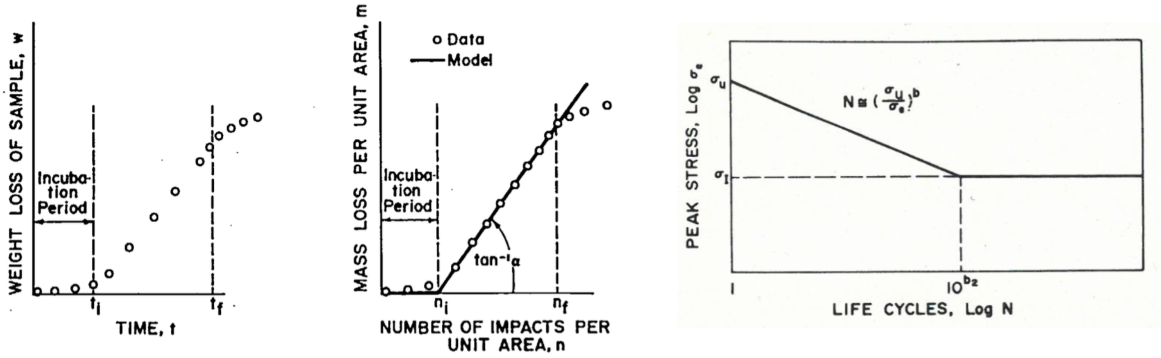


Figure 6. (**a**) Evolution of weight loss on experimental rain erosion testing coupons, from [3] (**b**) lifetime prediction model defining the incubation period and mass removal rate, **(c)** Fatigue life N approximation related with the material ultimate strength σ_u, the parameter σ_e that accounts for the "erosion strength", and the parameter b that includes the fatigue knee at the the endurance limit σ_I,

In this work it is proposed to incorporate cohesive zone modelling (CZM) between layers in the numerical modelling of the droplet impact—see Fig.3 (b). With both analytical and numerical approaches, it is necessary to model the failure resistance of the multi-layered system interface boundaries in order to use erosion lifetime prediction models such as the one described previously [3].

3. Results

In previous research of the authors [5], the mechanical characterization of a multilayer LEP configuration as despicted in Fig. 2 was evaluated to consider the effect of primer layer on the performance of Leading Edge Protection (LEP) Coatings. Pull-off testing of the samples showed the adhesive failure for the no-primer configuration (with a value of 5.6 MPa) and the cohesive failure (6.77 MPa) of the specimens that include the primer layer. The peeling testing also demonstrated the improved interphase coating–laminate adhesion response when the primer layer was included, with a force load for peeling with a value of 29.3 N (averaged across five samples), versus a value of 9.45 N for the no-primer configuration. It was clear that the primer significantly improved the adhesion of the LEP to the filler. The relative acoustic properties were quantified for the both combinations of material candidates for the multi-layered system. It could be observed that the filler layer inclusion and even the primer layer did not negatively influence the reflected and the transmitted waves to the LEP compared to the direct application of the LEP over the GFRP laminate. Moreover, considering the primer layer as a first substrate layer over the subsequent filler layer, there was a reduced value for the reflected and transmitted stress waves. These results correlate well with the similar erosion incubation time observed in both configurations (with and without a primer) in the rain erosion testing summarised in Fig. 7.

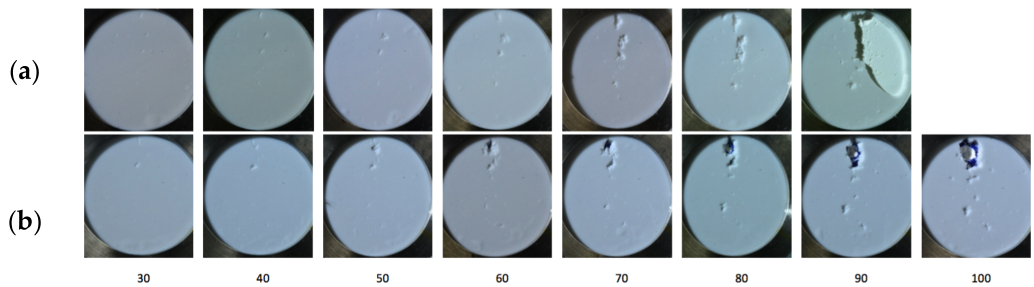


Figure 7. Images of surface and delamination damage after time interval (in minutes) of testing: (**a**) LEP coating configuration with no-primer application; (**b**) LEP coating configuration with intermediate primer layer.

3.1 Model set up

Simulations of the stresses caused in the multilayer system depending whether the primer is applied or not are showed in this section. The numerical procedure was implemented in a LEP configuration according to Rain Erosion Testing coupons as depicted in Fig. 8.

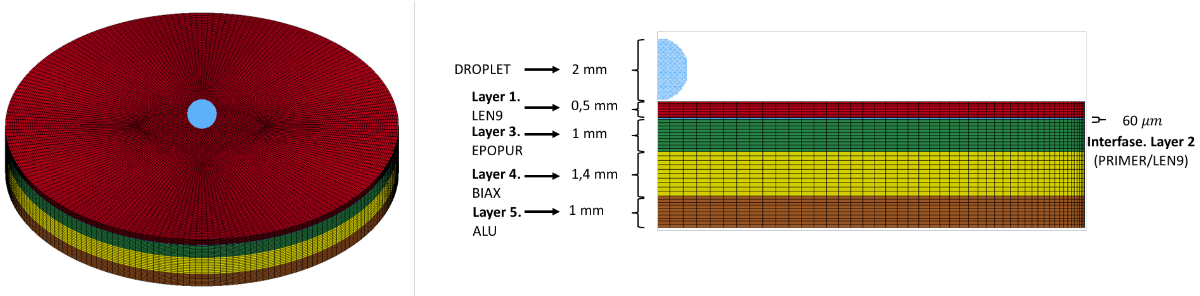


Figure 8. 3D mesh and material multilayer system configuration as RET testing coupons

3.2 Simulations

In a first case, the points analyzed in Fig.9 are in the center of the impact and along the thickness of layers 2 and 3. There are no significant differences in terms of stress between a material interface LEN9 to PRIMER, so it is necessary to include a CZM law of material in the interface that allows to predict if failure by delamination occurs.

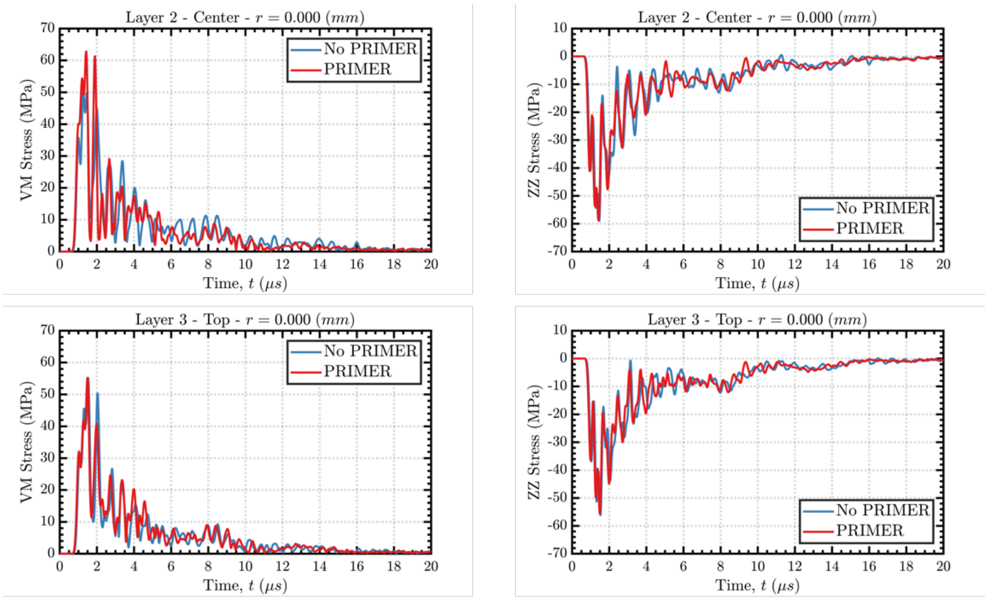


Figure 9. Stress comparison in the interface layer 2 and layer 3 with and without PRIMER assuming perfect continuity between layers

The proposed methodology states the CZM input parameters, see Fig.10, with both physical peeling testing of manufactured specimens and their numerical modelling [9][10] [11]. Once CZM has been defined, it can be used for the interface delamination modelling computed in the droplet impact analysis. The approach allows one to account for the effect of the interface LEP-Filler adhesion by means the use or not of the Primer layer. Fig.10 depicts the proposed CZM contact model to be used. The model is based on a cohesive zone formulation were knowing the experimental peeling force value, it is related numerically to the fracture energy, G_a necessary for the interface failure. In this test the vues tested are,

$G_{aPRIMER}$ =3000 J/m^2, with a Peeling force of 30 N for the Primer specimen and the with a value of G_{aNO_PRIMER}=1000 J/m^2 and a Peeling force of 10 N. for the No-Primer case. In all the simulations, it is related as a parameter value the normal traction, σ, to the normal opening displacement, δ, across the crack surface since fracture was assumed to be predominantly via a Mode I (tensile) failure. Moreover, the parametric value of σ_{max} can be also limited by the experimental value obtained from the Pull-off testing. In our case, since fatigue model described in previous section accounts for the Endurance limit instead of ultimate strength and this value may be obtained with a parameter value of b=20,9, from [3], We can assume a value of $\sigma_{max} = \sigma_{pull\text{-}off} / 2$. The area is very small G_a, and a zoom is made to see this area better. It has to be highlighted that the numer of impacts are thousands to millions.

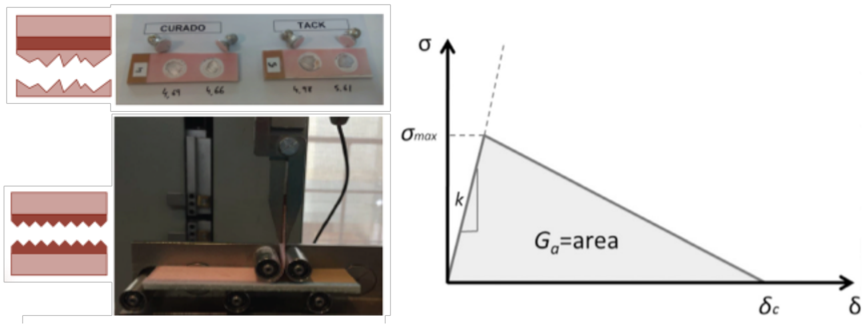


Figure 10. CZM definition based on input parameters from Peeling and Pull-off testing

Fig.11 shows how the primer coupon loss lower amount of energy under droplet collision, so correlates well with the RET testing depicted in Fig.7. No experimental validation of the number of impact required to complete the total amount of energy has been done.

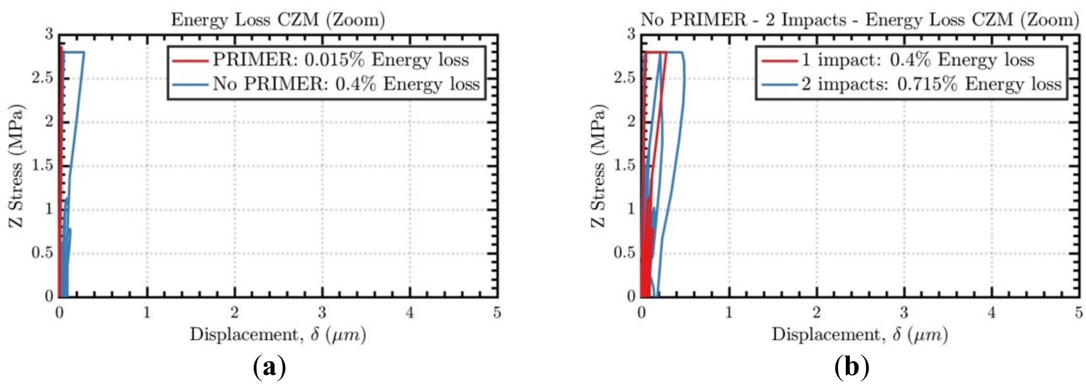
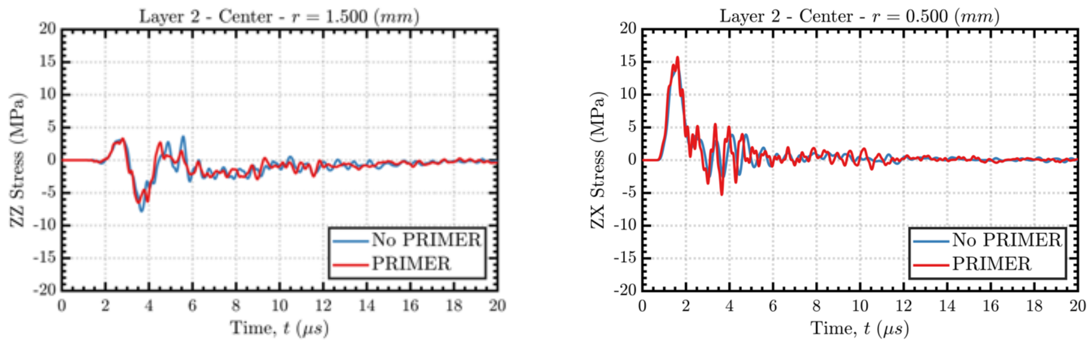


Figure 11. Acumulative Fracture energy loss comparison for one and two impacts

As depicted in Fig.12, The shear stress can be higher than normal stresses. Therefore, the effect of the shear stresses in the loss of fracture energy can be a determining factor to be taken into account. It remains for future work, to be done incluiding a Mode II peeling testing in the CZM model.

4. Conclusions

A numerical procedure to predict delamination failure analysis has been proposed. The computational tool can be used to identify suitable coating and composite substrate combinations based on their potential stress reduction on the interface layers. Further work is on development for the complete material characterization of Mode II Pelling tests and also in order to include lifetime prediction as described in previous sections.



(a) **(b)**

Figure 12. Stress comparison for the normal and shear stress

Acknowledgments

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References

[1] Available online: Lawrence Berkeley National Laboratory, "Reducing Wind Energy Costs through Increased Turbine Size: Is the Sky the Limit?", https://emp.lbl.gov, (accesed on May 2018)

[2] Keegan, M.H.; Nash, D.H.; Stack, M.M. On erosion issues associated with the leading edge of wind turbine blades. *J. Phys. D App. Phys. 2013, 46(38).*

[3] Springer, G.S. Erosion by Liquid Impact; *Scripta Technica Publishing Co.* 1976.

[4] Gohardani, O. Impact of erosion testing aspects on current and future flight conditions. *Prog. Aerosp. Sci. 2011, 47, 280–303*

[5] E.Cortés, F.Sánchez, A.O'Carroll, B.Madramany, M.Hardiman,T.M.Young; On the material characterization of wind turbine blade coatings: Effect of the interphase adhesion on rain erosion performance, *Materials; September 2017, Vol 10, 1146, doi:10.3390/ma10101146.*

[6] Zahavi, J.Indirect damage in composite materials due to raindrop impact. *Wear 1981, 72, 305-313.*

[7] ASTM. ASTM G73—10 "Standard Test Method for Liquid Impingement Erosion Using Rotating Apparatus"; *ASTM: West Conshohocken, PA, USA, 2013.*

[8] Eisenberg, D.; et al. Leading Edge Protection Lifetime Prediction Model Creation and Validation.https://windeurope.org/summit2016/conference/allposters/PO078g.pdf

[9] Ph. Martiny, F. Lani, A.J. Kinloch, T. Pardoen, Numerical analysis of the energy contributions in peel tests: a steady-state multilevel finite element approach, *Int. J. Adhesion and Adhesives, vol 28, 2008, 222-236*

[10] A.J. Kinloch, H. Koay, S.H. Lee and L. Ng, Using the simple peel test to measure the adhesive fracture energy, Ga, *Proceedings of the 35th Annual Meeting of the US Adhesion Society. New Orleans, USA, 2012.*

[11] T. Ferracin, C.M. Landis, F. Delannay, T. Pardoen, On the determination of the cohesive zone properties of an adhesive layer from the analysis of the wedge-peel test, *International Journal of Solids and Structures 40 (2003) 2889–2904*