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Composite Construction Laboratory (CCLab)
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COATING STRESS ANALYSIS FOR LEADING EDGE PROTECTION SYSTEMS FOR WIND TURBINE BLADES

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Abstract: *Offshore wind energy has high potential to generate clean energy. Wind turbine sizes are increasing and reaching above 200 m in diameter. The high velocity blade tips interact with rain droplets which cause erosion damage over time. To mitigate erosion damage, protective materials are applied to the leading edge. In order to effectively design these protection systems, the stress state in the layered material system has to be understood. The current work discusses a numerical model to predict the stress field in a co-bonded hybrid thermoplastic/thermoset layered composite system. It studies the influence of layer thickness, interphase thickness, droplet diameter and LEP material properties on the stress state in the hybrid composite coating system. It was found that the design of the system significantly influences the dynamic stress state in the layered system and as a result, the performance of these systems as protection layers for wind turbine blades gets diminished.*

Keywords: Wind energy; Leading edge protection; Numerical modeling; coating stress.

1. Introduction

Global climate accords demand lower CO_2-emissions and renewable energy is one way to achieve this. Offshore wind energy shows high potential to meet the increasing demand. Wind turbines are increasing in size, currently exceeding 200 m in diameter with corresponding tip velocities of over 100 ms^{-1}. The wind turbine blade leading edges interact with rain droplets and other airborne particles at high velocity causing erosion damage over time [1]. This leading edge erosion (LEE) is causing lower aerodynamic efficiency and hence lower annual energy production (AEP) while increasing the maintenance cost and therefore the levelized cost of energy (LCoE). In order to mitigate the erosion behavior, leading edge protection (LEP) systems are being developed in the form of liquid coatings and elastomeric tapes or shells. Since damage occurs over long periods of time, modeling is essential in order to effectively improve the performance of these LEP systems.

Liquid droplet impact causes different stress waves in an elastic solid [2]. It was shown that Rayleigh waves originate when the area under the applied load increases with the Rayleigh wave velocity. It was also shown that deformations in the solid are downward at the center of the applied load but are upward at the contact edge which ultimately causes the Rayleigh wave to exist. As contact pressure load, the Waterhammer pressure is generally used. A coating lifetime model was developed based on a 1D stress analysis through thickness of a coated substrate in [3]. It was shown that most materials fit a power law based on the ratio between the stress in the coating and the erosion strength of the material. Another method based on the Palmgren-Miner rule for fatigue analysis of the coating material has been proposed in [4]. It was shown

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that reduction of liquid impact pressures or an increased safe operation zone by developing coatings with adjustable compressive stresses would lead to a longer material lifetime. Recently, it has been shown that a one dimensional analysis based on the Waterhammer pressure lacks physical representativity and causes issues for materials with similar strength values or Poisson ratios close to 0.5 [5]. This is especially the case for modern, tailored elastomeric coatings that are being used in the wind turbine sector. An alternative approach to modeling that is more physically representative is aimed for [5].

The stress state in the coating system was shown to be dependent on the impedance ratio of the coating material to the substrate [6]. The transmission and reflection of waves at the interface is related to the bonding of the two materials. It was shown that for co-bonded polymeric materials, the bonding properties are determined by the processing conditions and a co-continuous zone is generated that results in a good bonding between the two components [7–9].

A numerical modelling framework for lifetime analysis of wind turbine blades was introduced in [10,11]. It was shown that the contact pressure is dynamic and non-uniform since high pressures are present at the contact edge. The dynamic contact pressure was defined based on impacts on a rigid surface without considering the surrounding air. An axisymmetric finite element method (FEM) model was employed to determine the stress state in the coating-substrate system. The results were interpolated to determine fatigue life of a coated-substrate based on a distributed field of droplet impacts. Similar frameworks using smoothed particle hydrodynamics (SPH) and FEM as well as coupled Eulerian Lagrangian (CEL) methods in a single fluid-structure interaction simulation, including target elasticity, were proposed in [12,13]. It was later shown that the CEL and SPH approaches give similar results and that the SPH method is generally less computationally expensive [14]. These models enable to study the influence of impact parameters, material parameters and manufacturing defects on the predicted lifetimes and damage patterns. It was shown in [15] that the damage can be accelerated by heterogeneities in the coating system. For ABS based coating systems, the damage initiates at the surface in the form of pitting and extends by a cracking mechanism to cratering which ultimately causes material loss [16].

It was shown that impact pressures significantly change when taking into account the elasticity of the target as well as the presence of surrounding air [17]. This has not been taken into account in numerical frameworks so far. The current paper discusses a FEM based coating-stress analysis that utilizes a contact pressure profile for (visco-) elastic targets including surrounding air and focuses on the effect of LEP layer thickness, interphase properties and impact parameters on the resulting stress field. This approach allows for a more physically representative stress prediction and hence a more accurate lifetime prediction.

2. Methods

For the purpose of studying the stress in the coating system, the dynamic contact pressure for liquid droplet impact on elastic targets was used. These were solved by a multiphysics model in COMSOL consisting of a fluid-structure interaction simulation for a two-phase flow based on the level-set method using the incompressible Navier-Stokes equations. The resulting dynamic pressure profiles were extracted and used in ABAQUS as pressure load input on a two dimensional (2D) axisymmetric model that includes multilayer materials and was solved using an explicit time integration scheme. A functionally graded material was used in the interphase region where the material properties were defined as a function of the thickness coordinate. The results of the simulations were the individual stress components for each time step. The initialization of the parameters and the execution of the simulations was automated using MATLAB. The materials used in the current modeling case studies are given in Table 1. Here, the epoxy material was used as backbone and the other materials were defined as the coating materials. The simulations include the variables and ranges given in

Table *2*. The current work focuses mainly on the effect of droplet diameter, LEP thickness, interphase thickness and material properties. These effects were studied independently with the exception of material parameters and LEP thickness which were analyzed simultaneously. The modeling framework returns the individual stress components which can be combined to equivalent stresses. Since the studied materials for the coating and backbone were isotropic, the Von Mises equivalent stress was considered in the analysis of the numerical modelling results.

Table 1: Material parameters used in the simulations.

Material	E [GPa]	ν [-]	ρ [kgm^{-3}]
Epoxy (backbone)	2.41	0.399	1255
TPU D60 (coating)	0.25	0.458	1100
ABS (coating)	2.45	0.408	1050
PAI (coating)	4.9	0.45	1425

Table 2: Variables and ranges considered in the simulations.

Impact velocity V [ms^{-1}]	Droplet diameter d [mm]	LEP thickness h_L [µm]	Interphase thickness h_I [µm]
100	1	250	0
110	2	500	50
120	3	750	100

The dynamic contact pressure profiles obtained from the simulation developed in COMSOL are depicted in Figure 1. It can be seen that initially, the central pressure is high but when the impact proceeds, the central pressure decreases and the contact edge pressure has a higher value. At the point where lateral jetting occurs, the pressure is released and decreases over the whole contact area, which indicates that mainly initial contact determines the pressures. Small droplets cause a narrower area with high pressure and the pressure decays earlier due to an earlier onset of lateral jetting.

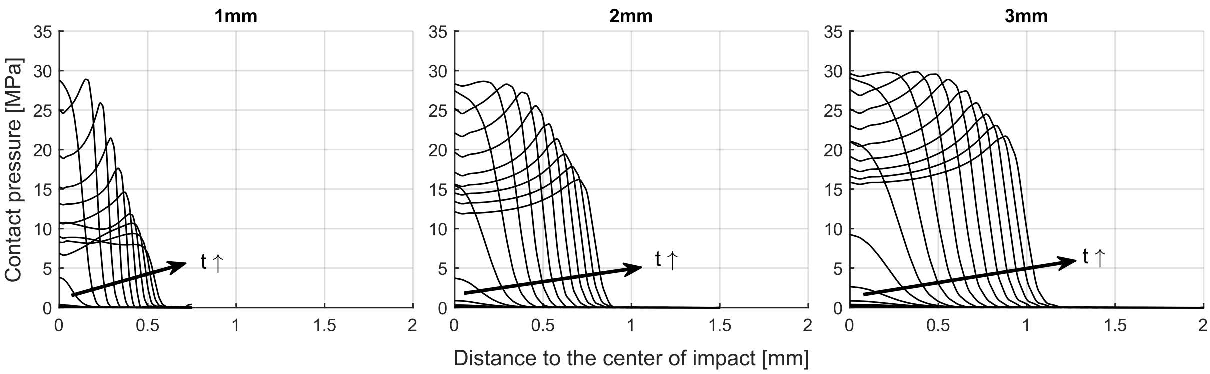

Figure 1: Dynamic contact pressure profiles for ABS coating material obtined from COMSOL and used as input for the FEM simulations in ABAQUS.

3. Results

The figures in this section show the stress field at the time frame in which the highest stress in the LEP was observed. It was found that impact velocity does not influence the shape of the stress fields but merely the magnitudes of the observed stresses.

The effect of droplet size on the stress field in the TPUD60 coating system with 500 µm LEP thickness and 0 µm interphase thickness is shown in Figure 2. It can be clearly seen that the highest stress occurs in the coating material close to the surface for small droplet diameters. For larger droplets, the interface plays an important role since reflections and transmission occur. In these cases, the highest stress was observed at a later time. This indicates that when designing LEP systems, the droplet size on site should be considered when determining the LEP thickness to apply.

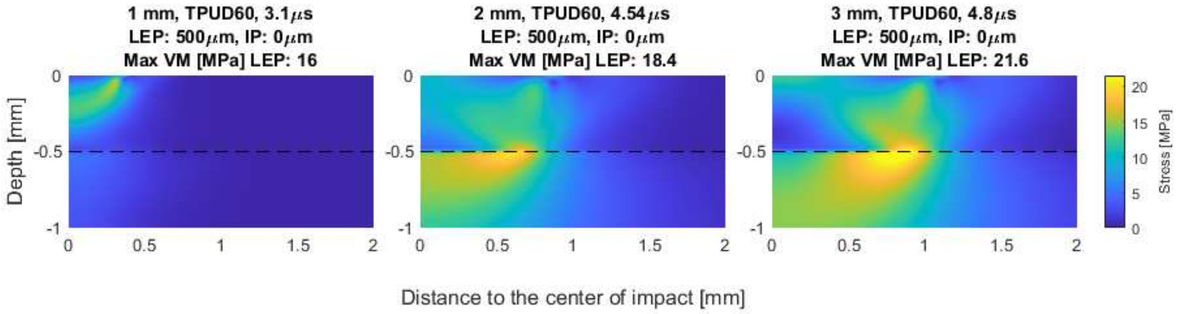

Figure 2: Effect of droplet size on the stress field in TPUD60 based coating systems.

The effect of the material properties on the stress field is shown for 250 µm, 500 µm and 750 µm LEP thicknesses and 0 µm interphases thickness in Figure 3. It can be seen that for materials where the coating properties are similar to that of the substrate (ABS), reflections at the interface only play a very minor role in the stress state. For coating materials where the properties differ from the substrate, more reflections occur that cause stress concentrations around the interface and in the LEP. This can lead to early failure, especially for small LEP thicknesses. There is a difference in time instance and location where these stress concentrations occur that seems to be related to whether the coating material is more compliant (TPUD60) or stiffer (PAI) than the substrate. Where more compliant coating materials lead to stress concentrations along the interface and stiffer coating materials lead to internal stress concentrations in the LEP caused by reflected waves.

Figure 3 also shows the effect of LEP layer thickness on the stress field. It can be seen that for ABS, LEP layer thickness does not play an important role due to the properties being similar to those of the substrate and therefore the impedance ratio being close to one. For TPUD60 and PAI however, it can be seen that the stress in the LEP is higher for lower LEP thicknesses. This is due to reflections occurring earlier in time. For small LEP thicknesses, the highest stress is driven by the reflections from the interface. For the larger LEP thicknesses, the stress is high at the surface and reflections do not seem to play a role any longer since the magnitude of the stress waves has enough time to decay due to dispersion. From this point on, the maximum stress does not change, and increasing LEP thickness further is not beneficial to have an elongated lifetime.

This suggest that there is an optimal LEP thickness that has to be designed based on the type of coating and substrate materials. It should be noted that the optimal LEP thickness is also related to the diameter of the impacting droplets as was shown in Figure 2.

Since reflections do not seem to play a role for higher LEP thicknesses, it can be argued that interphase properties do not change the maximum stress state in the system for higher LEP thicknesses. Because of this, the interphase thickness was studied only for the LEP thickness of 250 µm for both the TPUD60 and PAI materials.

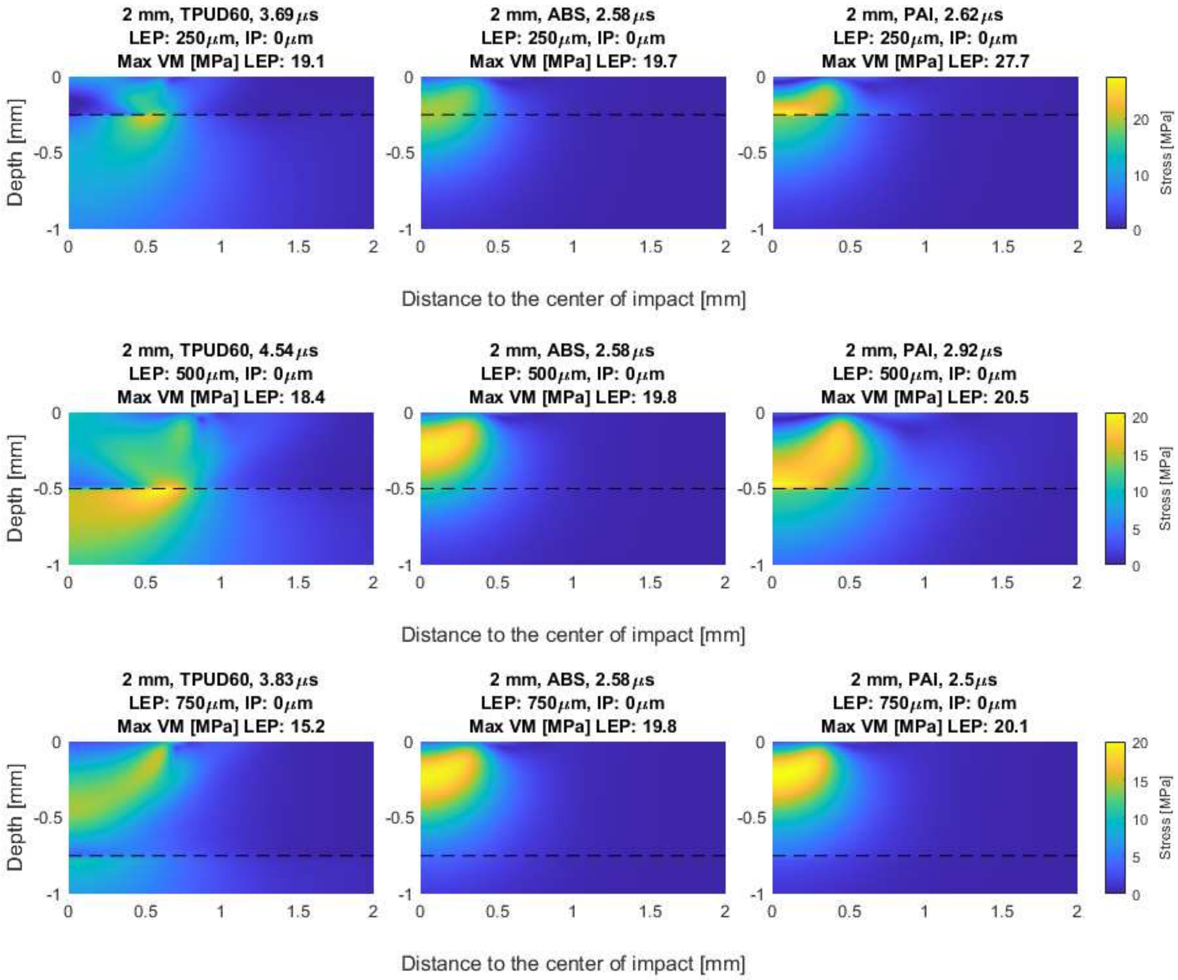

Figure 3: Effect of material properties and LEP thickness on the stress field in coated substrates.

The effect of interphase thickness on the stress field in TPUD60 based coating systems is shown in Figure 4. It can be seen that increasing interphase thickness causes the stress in the interphase to increase as well. This is likely to be caused by the interphase region beginning at a lower depth for thicker interphases. Although the stress field is spread more widely, a higher interphase thickness is not beneficial for the stress state. It should be noted that perfect bonding is assumed in the simulation and that in practical applications, the quality of the bond determines to a higher extend the effects occurring at the interphase. Also, the effect of interphase properties is less prominent than the effect of material properties as well as LEP thickness.

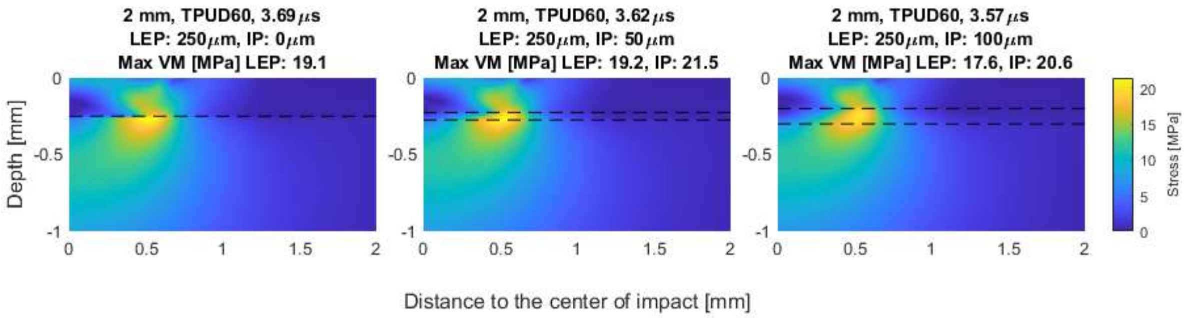

Figure 4: Effect of interphase thickness on the stress field of TPUD60 based coating systems.

A similar analysis was performed for PAI based coating systems in Figure 5. This figure clearly shows a decreasing stress with increasing interphase thickness. It is also observed that the stress field is more spread out due to the gradual transition of properties in the interphase layer. For PAI (which is stiffer than the substrate), the gradual transition results in a lower magnitude of the reflected wave leading to a lower concentration of stress in the LEP layer. This indicates that a thick interphase is desired when the LEP material is stiffer than the substrate and the highest stress in the system is caused by reflections. It should however be noted that the interphase properties might not follow a linear transition and that strength properties in the interphase region might differ from the properties of the pure polymeric materials. Experimental work is therefore required to investigate to what extend this observation can be utilized in practical applications.

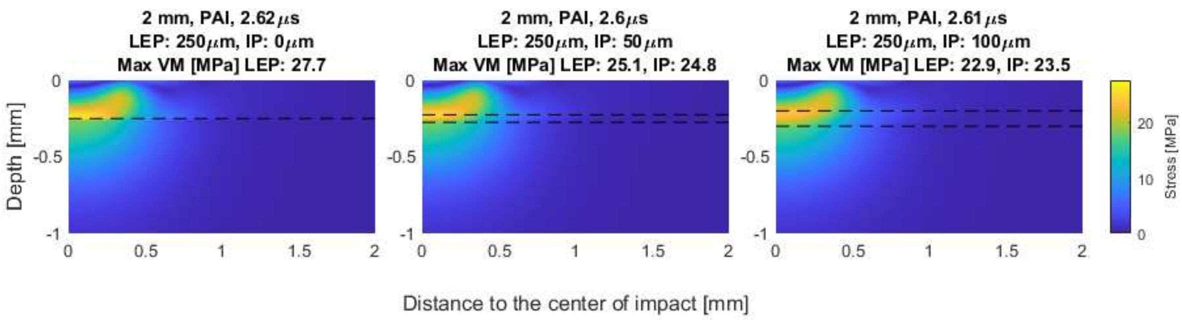

Figure 5: Effect of interphase thickness on the stress field of PAI based coating systems.

4. Conclusions

The results presented in this paper provided insight in the stress state in LEP systems for wind turbine blade protection against rain erosion. The pressure load used for the FEM simulations was based on sophisticated liquid droplet impact models and allowed for accurate prediction of stress fields. The effect of several impact, geometric and material parameters on the resulting stress field was analyzed and the following conclusions were drawn:

1. The LEP thickness is an important parameter in the lifetime of the system, an optimal thickness that induces lower stress state can be determined from the method proposed in this paper.

For thin LEP thicknesses, the maximum stress is determined by an interaction of the incoming wave and the reflected wave from the interface. There is a transition point in applied LEP thickness where this maximum stress is no longer caused by the reflection since the reflection occurs at a later point in time and the wave has a lower magnitude. Increasing the LEP thickness further has no effect on the maximum stress observed in the LEP system and therefore this analysis provides a LEP thickness design limit.

2. Droplet size affects the width and duration of the contact pressure profile resulting in through thickness changes in the stress field.

Smaller droplets result in narrower contact pressure profiles and faster decay of the pressure. Larger droplets have longer duration and broader profiles. This means that the stress propagates further through thickness before the maximum is reached and reflections play a more dominant role for larger droplets. From this it can be concluded that thicker LEP layers are required for larger droplet impact cases.

3. Interphase thickness spreads the stress waves and has an effect on the stress state in the system based on the mechanism that causes the maximum stress.

The presence of an interphase leads to a gradual transition in properties across this interphase. In cases where the maximum stress is present in the LEP and driven by reflections caused by the interphase, a gradual transition of properties lowers the magnitude of the reflected wave and therefore decreases the maximum stress. In cases where the highest stresses are observed along the interphase region, the effect of a gradual transition is not beneficial for the stress state in the system. These mechanisms seem to be related with the compliance of the LEP material in relation to that of the substrate.

There is a delicate balance between material, impact and geometrical parameters and the performance of the LEP system that should be considered when designing LEP systems. The current work numerically analyzed these relations which resulted in more insight in the origins of stress in the materials that could lead to design guidelines for LEP systems in terms of LEP layer thickness, interphase thickness and materials to be used. Generally, it can be argued that interphase regions should not contribute to dispersion of wave energy and that a thick LEP leads to more reliable results. A material with high resistance to droplet impact loading should be applied with sufficient thickness to obtain LEP systems with extended lifetimes.

Future work includes experimental validation, 3D simulations and lifetime estimations using a lifetime prediction method based on the Palmgren-Miner rule.

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5. References

[1] M.H. Keegan, D.H. Nash, M.M. Stack, On erosion issues associated with the leading edge of wind turbine blades, J. Phys. D. Appl. Phys. 46 (2013) 383001. https://doi.org/10.1088/0022-3727/46/38/383001.

[2] R.M. Blowers, On the Response of an Elastic Solid to Droplet Impact, IMA J. Appl. Math. 5 (1969) 167–193. https://doi.org/10.1093/imamat/5.2.167.

[3] G.S. Springer, Erosion by liquid impact, John Wiley and Sons, New York, NY, 1976.

[4] H.M. Slot, E.R.M.M. Gelinck, C. Rentrop, E. Van der Heide, Leading edge erosion of coated wind turbine blades: Review of coating life models, Renew. Energy. 80 (2015) 837–848.

https://doi.org/10.1016/j.renene.2015.02.036.
[5] N. Hoksbergen, R. Akkerman, I. Baran, The Springer Model for Lifetime Prediction of Wind Turbine Blade Leading Edge Protection Systems: A Review and Sensitivity Study, Materials (Basel). 15 (2022) 1170. https://doi.org/10.3390/ma15031170.
[6] E. Cortés, F. Sánchez, A. O'Carroll, B. Madramany, M. Hardiman, T.M. Young, On the material characterisation of wind turbine blade coatings: The effect of interphase coating-laminate adhesion on rain erosion performance, Materials (Basel). 10 (2017) 1146. https://doi.org/10.3390/ma10101146.
[7] J.S.M. Zanjani, I. Baran, R. Akkerman, Characterization of interdiffusion mechanisms during co-bonding of unsaturated polyester resin to thermoplastics with different thermodynamic affinities, Polymer (Guildf). 209 (2020) 122991. https://doi.org/10.1016/j.polymer.2020.122991.
[8] J.S.M. Zanjani, I. Baran, Co-bonded hybrid thermoplastic-thermoset composite interphase: Process-microstructure-property correlation, Materials (Basel). 14 (2021) 1–17. https://doi.org/10.3390/ma14020291.
[9] J.S.M. Zanjani, I. Baran, R. Akkerman, Combatting rain erosion of offshore wind turbine blades by co-bonded thermoplastic-thermoset hybrid composites, IOP Conf. Ser. Mater. Sci. Eng. 942 (2020) 012024. https://doi.org/10.1088/1757-899x/942/1/012024.
[10] B. Amirzadeh, A. Louhghalam, M. Raessi, M. Tootkaboni, A computational framework for the analysis of rain-induced erosion in wind turbine blades, part I: Stochastic rain texture model and drop impact simulations, J. Wind Eng. Ind. Aerodyn. 163 (2017) 33–43. https://doi.org/10.1016/j.jweia.2016.12.006.
[11] B. Amirzadeh, A. Louhghalam, M. Raessi, M. Tootkaboni, A computational framework for the analysis of rain-induced erosion in wind turbine blades, part II: Drop impact-induced stresses and blade coating fatigue life, J. Wind Eng. Ind. Aerodyn. 163 (2017) 44–54. https://doi.org/10.1016/j.jweia.2016.12.007.
[12] W. Hu, W. Chen, X. Wang, Z. Jiang, Y. Wang, A.S. Verma, J.J.E. Teuwen, A computational framework for coating fatigue analysis of wind turbine blades due to rain erosion, Renew. Energy. 170 (2021) 236–250. https://doi.org/10.1016/j.renene.2021.01.094.
[13] S. Doagou-Rad, L. Mishnaevsky, J.I. Bech, Leading edge erosion of wind turbine blades: Multiaxial critical plane fatigue model of coating degradation under random liquid impacts, Wind Energy. 23 (2020) 1752–1766. https://doi.org/10.1002/we.2515.
[14] S. Doagou-Rad, L. Mishnaevsky, Rain erosion of wind turbine blades: computational analysis of parameters controlling the surface degradation, Meccanica. 55 (2020) 725–743. https://doi.org/10.1007/s11012-019-01089-x.
[15] L. Mishnaevsky, S. Fæster, L.P. Mikkelsen, Y. Kusano, J.I. Bech, Micromechanisms of leading edge erosion of wind turbine blades: X-ray tomography analysis and computational studies, Wind Energy. 23 (2020) 547–562. https://doi.org/10.1002/we.2441.
[16] T.H. Hoksbergen, I. Baran, R. Akkerman, Rain droplet erosion behavior of a thermoplastic based leading edge protection system for wind turbine blades, IOP Conf. Ser. Mater. Sci. Eng. 942 (2020) 012023. https://doi.org/10.1088/1757-899X/942/1/012023.
[17] N.I.J. Henman, F.T. Smith, M.K. Tiwari, Pre-impact dynamics of a droplet impinging on a deformable surface, Phys. Fluids. 33 (2021) 092119. https://doi.org/10.1063/5.0064626.