Multiphysics Modelling of Liquid Droplet Impingement Erosion

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Motivation

Wind energy is still deemed one of the most important solutions to combat climate change and it is foreseen that the annual installation of new wind turbines will reach 280 GW in 2030. In particular, offshore wind energy is favoured mainly because of the higher wind resources and the limited socio-environmental impact. In addition, even larger wind turbines are being introduced on the market with bigger rotors and higher hub heights. The demand for turbines with higher power capacity will inevitably entail larger blade lengths. Blade tip speed is directly proportional to the blade length and modern offshore turbines are typically operating with a maximum tip speed in the range of 80 – 100 m/s. With wind turbine blades moving at such a high speed, the impact from particles like rain, hail, or sand has a devastating effect on the blade's leading edge, as shown in Fig. 1.

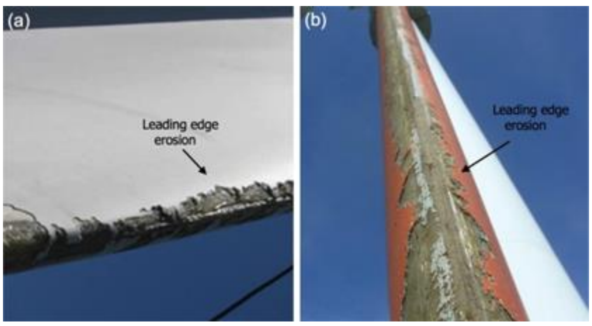

Figure 1. Leading edge damage of wind turbine tip sections [1]

Repetitive impact eventually causes the surface coating to erode. Leading edge erosion (LEE) is a severe erosive wear mechanism that involves progressive material removal from the blade-tip leading edges, due to surface and sub-surface fatigue. The repeated high-speed impact of water droplets induces severe pressure shock-waves in the blade material leading to the initiation, propagation, and coalescence of cracks and eventually material loss, pit formation, delamination, and disintegration of the structural integrity. This phenomenon of LEE has been and still is a significant financial uncertainty in the economic planning of wind turbines. Therefore, understanding the damage mechanism and failure of the wind turbine blades due to LEE will assist designers and decision makers to define inspection schedules and to provide preventive solutions.

Objectives

Furthermore, load, gravitational load, inertial load, and operational load are the main loading conditions affecting the degradation and integrity of wind turbine blades. Furthermore there are complex interactions between them during service time in harsh environments. It is crucial to develop a reliable framework for stress analysis due to droplet impact and for analyzing the fatigue damage and erosion of the surface and subsurface of the composite blade.

The Blade-Leading-Edge Erosion Prediction and Drone-based Inspection (BLEEPID) project aims to contribute to the improvement of reliability and reduction of the cost of offshore wind. A multifaceted approach, combining micro-scale modelling (using advanced numerical techniques), laboratory-scale experimentation and real-scale drone-based data acquisition will be employed to develop a framework that can predict erosion process of leading edge on offshore wind turbine. A multi-scale, integrated simulation model will be developed that accounts for droplet impact, (sub)surface fatigue damage initiation, and damage growth due to impact fatigue loading using advanced numerical modelling techniques.

The project aims to:

1. Improve the understanding of solid-fluid interaction dynamics which take place during droplet impact events and use this knowledge to develop predictive models for turbine blade surface damage modelling.
2. Understanding the damage evolution, crack propagation, and growth through the thickness of the leading edge due to the repetitive impact

Approach

The primary input available for modelling precipitation induced loads on a turbine blade will be the meteorological data from the turbine position. Stochastic rain fall models will be used to generate randomized rainfall patterns corresponding to different precipitation scenarios. Wind patterns, combined with an aerodynamic model of the blade will be used to determine blade loading for different turbine operational states.

A Fluid-Structure Interaction (FSI) model is being developed, which couples two distinct numerical models; a Computational Fluid Dynamics (CFD) model for droplet dynamics and a Computational Solid Mechanics (CSM) model for turbine blade dynamics. The input data describing rain and wind patterns will be fed to the CFD and CSM models. The CFD simulations will provide detailed insight into the physics underlying liquid droplet impingement events. The companion CSM model will provide information on how the material deforms during liquid droplet impingement, and how this deformation will affect the stress induced on the blade surface during impact. Joining the CFD and CSM mode, the combined FSI model will be able to generate pressure and stress fields in the blade material due to droplet impingement. These material response profiles will act as the primary input for the Leading Edge Fatigue Lifetime Model.

Models of the layered leading edge structure will be developed, i.e., the viscoelastic coating, the intermediate filler, and the fibre-glass reinforced epoxy, utilizing peridynamics software. Each constituent is represented by multiple material points and internal forces are expressed through nonlocal interactions between the material points, referred to as bonds. Heterogeneities in each layer can be naturally considered. First, the bond properties will be defined to match the constitutive properties of the materials. The heterogeneous nature of the protective coating system, both at the macro- and micro-scale, will affect damage evolution. Thereto, a damage evolution model will be developed and assigned to the bonds to represent the degradation of the materials and their interfaces. When a particular failure criterion is satisfied, these bonds are broken to nucleate damage and its propagation. The Peridynamic theory permits initiation and propagation with arbitrary damage paths. Constitutive and damage properties of the bonds will be based on literature data and dedicated experiments. In the first stage, 2D geometries will be modelled and simulated to evaluate the computational stability and efficiency of the developed damage evolution model. From the Peridynamic simulations, crack initiation and growth, potential coalescence, and material loss due to pit formation will be predicted in an accelerated way. The influence of macro- and microscale heterogeneity, coating quality, as well as droplet size and corresponding stress peaks, on time to failure, can be analysed.

[1] Verma, A. S., Castro, S. G., Jiang, Z., & Teuwen, J. J. (2020). Numerical investigation of rain droplet impact on offshore wind turbine blades under different rainfall conditions: A parametric study. Composite structures, 241, 112096.

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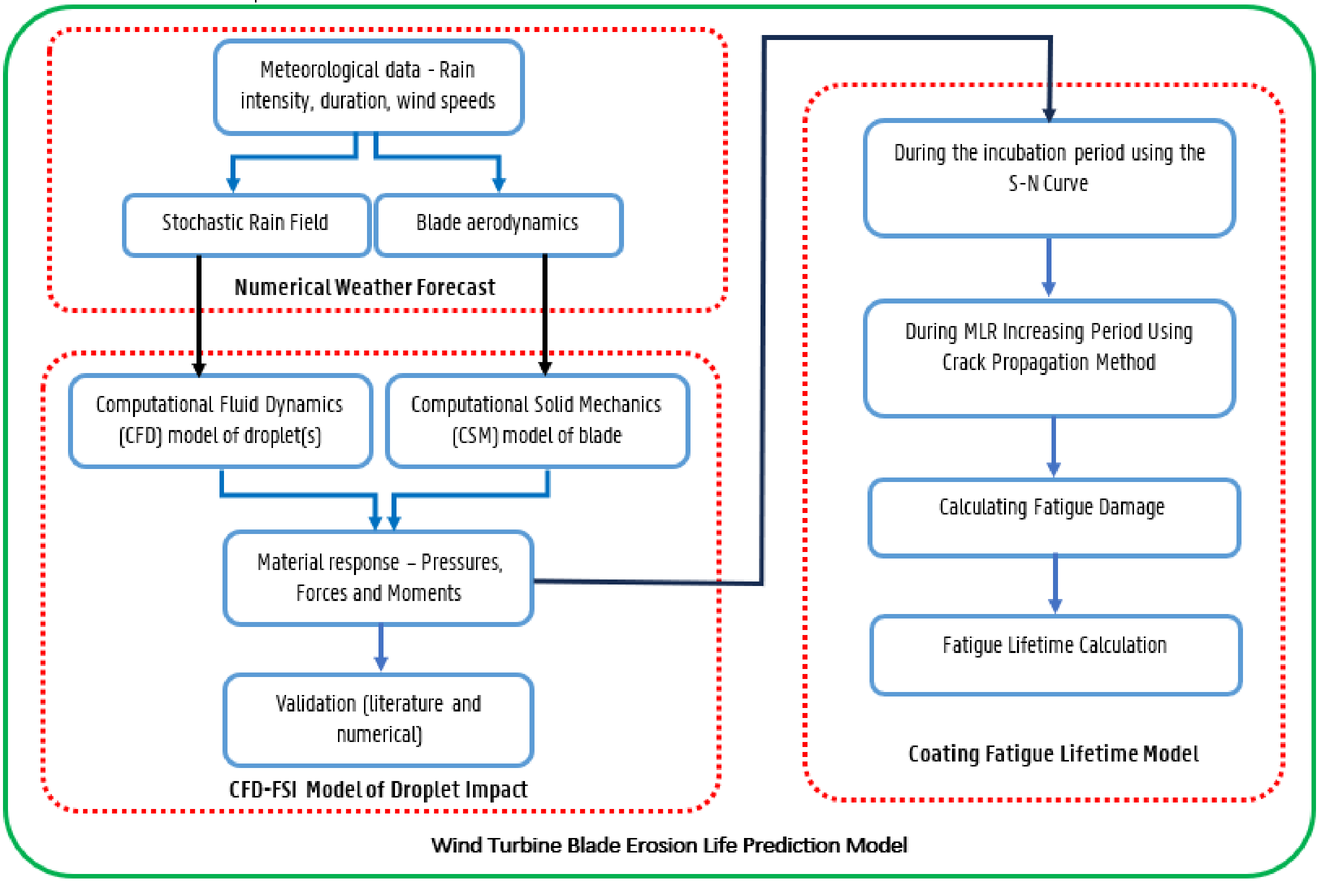

Figure 2. Methodology

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