RAIN-INDUCED EROSION AND ENVIRONMENTAL AGING OF WIND TURBINE BLADE COATING

Abstract

This thesis addresses the persistent challenge of leading-edge erosion in wind turbine blades (WTB), where repeated raindrop impacts and long-term environmental exposure progressively degrade protective coating systems, increasing maintenance costs and downtime. This work develops a physics-based computational framework to predict rain-induced fatigue damage, interlayer debonding, and environmentally assisted degradation of multilayer protective systems used on wind turbine blades. Repetitive raindrop impacts produce highly transient pressures and stress waves that drive progressive damage in the coating, putty, and their interfaces, ultimately leading to erosion and loss of leading-edge protection. To resolve these mechanisms under realistic, random rain exposure, a stochastic rain-field model is employed to generate droplet size distributions, impact locations, and temporal sequences representative of service conditions. Local impact loading is obtained using high-fidelity fluid structure interaction simulations based on the Coupled Eulerian-Lagrangian (CEL) approach, supported by sub-modeling to capture near-defect (e.g. voids/air bubbles) stress fields in structured coatings. A pressure/time-history library is constructed for droplets of multiple diameters and mapped onto the stochastic rain scenario to compute localised, repeated-impact stresses efficiently. Fatigue damage in the polymeric coating is predicted using Continuum Damage Mechanics (CDM), which enables life estimation in the presence of manufacturing flaws, such as voids, that are often neglected in conventional coating models but are known experimentally to reduce lifetime. Interlayer debonding and debonding-driven erosion are captured by inserting cohesive elements at the coating-putty and putty-composite interfaces, with fatigue evolution laws applied to both the coating and cohesive zone. The coupled damage initiation and evolution relations are implemented via user-defined subroutines in ABAQUS. Environmental ageing is integrated through a multilayer degradation model that solves through-thickness temperature, moisture, and UV attenuation fields and updates evolving properties using coupled Arrhenius-type kinetics for thermo-photo-oxidative and hydrolytic processes.

Finally, a multiscale modeling strategy is used to assess structured and reinforced polymer coatings (e.g., fiber-pulp and graphene-based reinforcements), demonstrating stress shielding around voids and reduced stress concentrations relative to unreinforced coatings. Across the thesis, model predictions are validated against published rain erosion test datasets and reported field observations. The results identify dominant failure pathways under stochastic rain loading, highlight the critical role of voids and interface debonding in erosion onset, and provide a unified methodology to support the design of more durable, erosion resistant wind turbine blade coating systems.