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DOI 10.1016/j.renene.2021.01.094

Publication date 2021 Document Version Accepted author manuscript Published in Renewable Energy

Citation (APA)

Hu, W., Chen, W., Wang, X., Jiang, Z., Wang, Y., Verma, A. S., & Teuwen, J. J. E. (2021). A computational framework for coating fatigue analysis of wind turbine blades due to rain erosion. *Renewable Energy*, *170*, 236-250. https://doi.org/10.1016/j.renene.2021.01.094

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1	A Computational Framework for Coating Fatigue Analysis of Wind Turbine Blades Due to
2	Rain Erosion
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20 Abstract

21 The rain-induced fatigue damage in the wind turbine blade coating has attracted increasing 22 attention owing to significant repair and maintenance costs. The present paper develops an 23 improved computational framework for analyzing the wind turbine blade coating fatigue induced 24 by rain erosion. The paper first presents an extended stochastic rain field simulation model that 25 considers different raindrop shapes (spherical, flat, and spindle), raindrop sizes, impact angles, and impact velocities. The influence of these raindrop characteristics on the impact stress of the blade 26 27 coating is investigated by a smoothed particle hydrodynamic approach. To address the expensive computational time, a stress interpolation method is proposed to calculate the impact stress of all 28 29 raindrops in a random rain event. Furthermore, coating fatigue analysis is performed by including 30 the fatigue crack initiation in the incubation period and the fatigue crack propagation in the mass-31 loss-rate increasing period due to raindrop impact. Finally, the proposed computational framework 32 is verified by comparing the estimated fatigue life with those obtained in literature. The results from the study show that by incorporating the statistics of rainfall data, the proposed framework 33 could be used to calculate the expected fatigue life of the blade coating due to rain erosion. 34

35 Keywords: wind turbine blade, rain erosion, raindrop impact, fatigue analysis, crack propagation,
 36 smoothed particle hydrodynamic

37

38 **1 INTRODUCTION**

Wind turbine blades (WTBs), especially at tip sections, are frequently exposed to impacts from high-relative-speed objects such as rain, atmospheric particles, hail, and sand during the service life. These impacts may induce erosion damage at the blade leading edge, thereby reducing

42 the aerodynamic performance and power output of wind turbines. In addition, such issues require 43 regular maintenance and repair, causing an increase in the cost of energy. The issue of leading 44 edge erosion (LEE) of WTBs is becoming even more crucial as wind turbines continue to grow in 45 both hub-height and rotor diameter and are associated with large tip speeds.

46 Among the above-stated impacts from relatively high-speed objects, raindrop impact is one 47 of the most important factors that contributes to LEE of WTBs. Traditionally, there are two approaches utilized for analyzing the rain erosion problem, the impact approach (e.g., [1]) or the 48 49 energetic approach (e.g., [2]). The former approach first calculates the impact pressure using either 50 explicit formulas, e.g., the water-hammer equations [3, 4], or the expensive computational fluid 51 dynamic (CFD) methods (e.g. [5]), then carries out the transient stress analysis by applying the 52 pressure force on the finite element model of a WTB (e.g., [5]). Although it is less computationally 53 intensive to calculate pressure by the explicit water-hammer equations, the following assumptions are made: (1) the impact occurs in one dimension and (2) the impact solid is a perfect rigid body 54 [3], which do not realistically represent raindrop impacts. In addition, it is difficult to take into the 55 56 account the fluid-solid interaction during raindrop impact by sequentially calculating the impact 57 pressure and the transient stress. The energetic approach attempts to relate the erosion to mechanical properties of the impact body based on the kinetic energy transmitted. Although this 58 59 approach can potentially avoid simplifications (e.g., the impact effects are independent of each 60 raindrop and the shape of raindrops is a perfect sphere), it is difficult to quantify the total transferred energy from the stochastic rain field to the WTB. 61

A high-fidelity simulation of rain events is essential for accurately predicting the erosion process. However, as rain events are complex natural phenomena, it is challenging to simulate them realistically due to varying raindrop sizes, shapes, and speeds. By integrating the micro-

65 structural properties of rain, i.e., raindrop sizes and spatial distribution, a stochastic rain texture model is developed to generate three-dimensional rain fields by Amirzadeh et al. [5]. In this model, 66 the raindrops with perfectly spherical shapes in the simulated rain event are assumed to be 67 distributed randomly in the spatial domain. However, the raindrops in the falling rain have a 68 69 complex mutual interaction with their neighbors, which causes varied velocity, sizes, and shapes, 70 as well as inflation, destabilization and ultimate fragmentation during the falling [6]. For example, 71 different raindrop shapes exist, e.g., spherical, semi-oblate, and parachute forms for raindrops 72 diameter less than 2-mm, between 2 and 5 mm, and larger than 5 mm, respectively [7]. The 73 raindrop shapes are highly dynamic in response to coalescence or fragmentation and to 74 aerodynamic forces (e.g., distorting the raindrop to a burger-bun-like shape [8]). Additionally, the 75 terminal velocity, i.e., the highest velocity attainable by the raindrop falling through the air, is 76 affected by raindrop mass, humidity, temperature, and orography, as well as wind. Thus, it is a 77 very challenging task to simulate a realistic stochastic rain field considering all the aforementioned 78 factors.

79 Calculations of raindrop impact pressure and/or impact stress is an important step before 80 evaluating the fatigue damage due to rain erosion. Due to its explicit formulation, the water 81 hammer pressure is viewed in literature (e.g., [7-11]) as a preliminary metric to evaluate the 82 raindrop impact force on solid surface. To consider the influence of the stress wave reflections, 83 Eisenberg et al. corrected the water hammer pressure by multiplying a term including impedance 84 of the substrate and the coating material [9]. By integrating the stochastic rain texture model and 85 the raindrop impact pressure profiles [5], Amirzadeh et al. further conducted the transient stress analysis in a composite WTB using finite element analysis, although the stress analysis is limited 86 to the time period before which surface roughening starts to appear (i.e., the incubation period) 87

[11]. To the authors' knowledge, there is still a lack of an efficient and accurate computational
model that well reveals the complex fatigue mechanism for crack propagation induced by the
raindrop impact.

91 In the fatigue analysis, very little research has considered the influence of complex rain-92 induced stress on the fatigue life-cycle of WTB coating, including the incubation period, the mass-93 loss-rate (MLR) increasing period, and the placid period [12], as shown in Fig. 1. The WTB 94 coating fatigue damage is initiated in the incubation period and increased rapidly in the MLR 95 increasing period. In the incubation period, the coating surface is smoother without obvious pits 96 and cracks, and there is no obvious observable mass loss due to raindrop erosion. The damage in 97 this period is mainly attributed to fatigue of the solid material under direct deformation and stress 98 wave propagation [13, 14]. As the erosion process continues and the surface roughness is increased 99 in the MLR increasing period, the lateral jetting and hydraulic penetration produce large shear 100 stress on the surface and the fatigue crack opening causing the increased MLR [15]. In the placid 101 period, as the surface roughness is severely increased, liquid material accumulates on the surface 102 and reduces the impact damage of the oncoming raindrops resulting in a decreased MLR in this period [5]. It is important to correctly estimate the time lengths of the former two periods before 103 104 the aerodynamic and structural performance of WTBs are significantly degraded. Although several 105 studies have investigated the WTB rain erosion considering the incubation period (e.g., [8, 9, 11]), 106 very few have considered both the incubation period and the MLR increasing period. For example, 107 the Miner's rule has been often applied to estimate the fatigue damage by a simple linear 108 accumulation of fatigue damage due to each stress cycle in the incubation period (e.g., [8-11, 16]). 109 Eisenberg et al. [9] derived an analytic wind turbine LEE model and found that fatigue damage 110 rate is proportional to the impact velocity and rain intensity to the power of 6.7 and 2/3,









¹⁵⁰ erosion.







The remainder of the paper proceeds as follows. Section 2 presents the detailed methodologies of the proposed computational framework. Section 3 provides a case study using the framework, followed by the results and discussion in Section 4. Section 5 gives the concluding remarks, limitations, and future work.

157 2 METHODOLOGIES

Different from the existing simulated rain fields which only include perfectly spherical raindrops (e.g., by the methods in [5]), the extended stochastic rain fields herein consists of spherical and elliptical raindrop shapes according to the work in [17]. Since the raindrop impact velocity is dominated by wind turbine rotation [5, 18], we consider the angle between the falling raindrops and the rotating blade as the impact angle, instead of using the commonly assumed vertical hitting angle of 90 degrees [11, 16]. The raindrop impact stress is calculated using SPH and the FEA methods. To simulate the coating erosion in the life cycle of the blade, the coating

165 fatigue analysis includes both fatigue incubation and crack propagation periods.

166 2.1 Extended Stochastic Rain Field Simulation

The extended stochastic rain field model is based on the stochastic rain texture model described in [5], and further considers different raindrop impact speeds, impact angles, sizes of raindrops, and shapes of raindrops in the simulated rain fields. The simulated stochastic rain field consists of three key components, including the number of raindrops in unit volume, the distribution of the size of raindrops, and the spatial distribution of raindrops with varying shapes in the simulated volume. The number of raindrops in unit volume *V*, N(V), follows a Poisson distribution expressed as [5]:

174
$$P(N(V) = k) = \frac{(\lambda V)^k e^{-\lambda V}}{k!}$$
(1)

175 where λ is the expected number of raindrops per unit volume, and P(N(V) = k) is the probability of 176 having *k* raindrops in volume *V*. Based on the relationship between the volume of water in air and 177 the rain intensity suggested by Best [19], the expected number λ of raindrops per unit volume can 178 be described by a power-law relationship with the rain intensity following Amirzadeh et al. [5]

179 $\lambda = 48.88I^{0.15}$ (2)

180 where *I* is the rain intensity in mm h⁻¹. We use Best's drop size distribution [19] to connect the rain 181 intensity with the distribution of the size of raindrops since it closely matches the experimental 182 data [5]. The cumulative distribution function *F* of the raindrop size (e.g., diameter) is expressed 183 as:

184
$$F = 1 - \exp\left[-\left(\frac{d}{1.3I^{0.232}}\right)^{2.25}\right]$$
(3)

185 where *d* is the raindrop diameter in mm and *I* is the rain intensity in mm h^{-1} .

Due to surface tension and external forces (e.g., aerodynamic force and gravity force), raindrops normally have varying shapes when impacting WTBs. In this paper, the equilibrium shape of raindrops is described by the axis ratio α , a ratio of the minor axis to the major axis of the ellipse [17]. In the measurements by Beard et al., the axis ratio α of a raindrop is found to have a linearly decreasing relationship with the equivalent spherical radius r_0 (r_0 is in the range of 0.5 – 4.5 mm), which is expressed as [17]

192

$$\alpha = 1.030 - 0.124r_0 \tag{4}$$

193 To address the varying raindrop shapes in a rain event, the equivalent spherical radii r_0 of the 194 simulated raindrops are obtained based on the Best's drop size distribution (Eq. 3). Three types of 195 raindrop shapes are considered, perfect sphere, flat ellipsoid, and spindle ellipsoid. The flat-196 ellipsoid raindrops have the longest axis in horizontal plan, while the spindle-ellipsoid raindrops 197 have the longest axis perpendicular to the horizontal plan. The horizontal cross-sectional area of 198 both flat and spindle raindrops is assumed to be a circle, and the vertical cross-sectional area is an 199 ellipse. The axis ratio of the minor axis to the major axis of the ellipse is calculated by Eq. (4). For 200 the raindrops having the same equivalent spherical radius, their volumes are the same although 201 their shapes may be different. In the experiments of McTaggart-Cowan and List (1975) [17, 20], 202 raindrop collisions were used to classify three predominate breakup types which is neck (27%), 203 sheet (55%) and disk (18%). As the raindrop shapes after collision of these three types are 204 comparable to the flat ellipsoid, spindle ellipsoid, and perfect sphere [17, 20], we select the same 205 probability of occurrence for the three raindrop shapes to be 27%, 55%, and 18%, respectively, in 206 the simulated stochastic rain event, as shown in Fig. 4.



207

Figure 4 Schematic diagram of raindrop shape and impact angle. The flat, spindle, and spherical
raindrops correspond to the three predominate breakup types (i.e., neck 27%, sheet 55%, and
disk 18% from the reference [17]).

Due to the WTB rotation and complex weather condition (e.g., wind effect), raindrops could impact the WTB at different angles (Fig. 4). The normal and tangential loads exerted due to perpendicular impact and inclined impact, respectively, could create different stress distribution in the blade coating. Thus, this paper further considers the inclined impact angle between the rotating blade and the falling raindrops. While the impact angle could range from 0 to 180° (denoted as [0, 180°] herein) as demonstrated in Fig. 4, it is assumed to follow a uniform distribution from 0 to 90° considering the symmetric impacting effect between the ranges of [0, 90°] and [90°, 180°].

As a raindrop is falling, the air resistance applied on the raindrop approaches to its gravity, which may result in a constant terminal speed. For instance, the terminal speed of raindrops with diameters larger than 3.5 mm through stagnant air is approximately 9 ms⁻¹ [18, 21]. However, as

221 a result of the high relative speed between a rotating megawatt-scale WTB and the falling 222 raindrops, raindrop impact speed at the tip of the blade could be 90-100 ms⁻¹ [18]. In addition, the 223 raindrops are considered as uniformly distributed in a tall-column volume. The height h of the 224 column is calculated by the multiplication of the impact speed v and the duration T of the simulated 225 rain event (i.e., $h = v \times T$), as also conducted by Amirzadeh et al. [5]. Given the statistical data of 226 rainfall history at a wind turbine location (see Section 3 for instance), the probability mass function 227 (PMF) of the rain intensity can be obtained and used to determine different rainfall hours per year 228 for the coating fatigue life estimation in Section 2.3.

229 2.2 Method for Raindrop Impact Stress Calculation

The raindrop impact is simulated by the transient SPH using the FEA tool in ABAQUS/Explicit [11]. This SPH approach has three merits: (1) taking into the account of large deformation of raindrops during impact on the solid, (2) directly calculating the transient stress time series, and (3) characterizing the impact wave propagation in the FEA model.

234 2.2.1 Impact stress calculation of a single raindrop

235 The SPH approach is particularly effective to solve large deformation problems that can 236 afford moderate computational cost, which is its key advantage over traditional FEA and the 237 coupled Eulerian-Lagrangian approaches. The former is not as accurate as SPH for large deformation analysis, while the latter is usually more computationally expensive than SPH. 238 Detailed theory and application of SPH can be found in literature [22-24]. Keegan et al. [25] 239 240 utilized the SPH method to simulate the effects of rain and hail on the coating materials of wind 241 turbines. The SPH method is coupled with traditional FEA to study the fluid-structural interaction between the raindrop and the WTB (e.g., Astrid et al. [26] and Verma et al. [27]). 242

243 To reflect the aforementioned complexity of raindrops in a rain event, herein the SPH analysis 244 is first applied to investigate single raindrop impact considering different raindrop sizes, raindrop 245 shapes, impact speeds, and impact angles. Specifically, we conduct varying single-raindrop impact 246 cases considering 9 raindrop sizes (equivalent diameter d = 1, 2, 3, 4, 5, 6, 7, 8, 9 mm), 3 raindrop 247 shapes (flat, spindle, spherical), 6 impact angles ($\theta = 15^{\circ}$, 30° , 45° , 60° , 75° , 90°), and 5 impact speeds (70 ms⁻¹, 80 ms⁻¹, 90 ms⁻¹, 100 ms⁻¹, 110 ms⁻¹). Detailed results and discussion are seen 248 249 in Section 4.2. The von Mises stress due to multiple-raindrops impact in a simulated rain field is 250 further calculated based on the interpolation of the von Mises stress results of the single-raindrop 251 impact cases, as explained in the following section.

252 **2.2.2 Impact stress calculation under a random rain event**

253 In a real rain event, a significant number of raindrops with varied sizes, shapes, and impact 254 speeds and angles are randomly impacting on WTBs. For a single raindrop impact simulation by 255 SPH, it costs 2 hours using a computer (Intel(R) Core(TM) i7-9700H CPU @ 3.00 GHz Processor, 256 Memory (RAM) 32 GB, 64-bit Windows Operating System). Thus, it is not practical to conduct 257 SPH simulation for all raindrops in a rain event. Instead, an interpolation method is proposed to 258 efficiently obtain the impact stress due to varied raindrop sizes, shapes, and impact speeds and 259 angles. The method utilizes pre-calculated impact stress from the single-raindrop impact cases. 260 Detailed steps are explained as follows:

261 Step 1: Create a stochastic rain field by the method presented in Section 2.1 given a rain
262 intensity and a rain duration.

263 Step 2: Obtain the impact stress of a random raindrop by interpolating the SPH impact stress
264 from the single-raindrop impact cases in Section 2.2.1. After identifying the size, shape, and the

impact angle and speed of the random raindrop, a circular domain with the impact point as the center and 10 times of the raindrop equivalent diameter as the radius is considered as the area influenced by the raindrop impact [11]. Then, choose the same type of raindrop shape, and interpolate the stress in this circular area according to the stress results of the calculated impact cases that have the closest raindrop diameter, impact angle, and impact speed.

Step 3: Repeat Step 2 for calculating the impact stress due to the other random raindrops. Since the time interval between two consecutive raindrops impact is almost three orders of magnitude longer than the time required for the stress wave generated by a single raindrop impact to disappear [11], we assume that the stress waves from different single-raindrop impacts will not interact with each other.

Through the above steps, the complex stress state under a stochastic rain field can be calculated and used for the coating fatigue analysis as follows.

277 **2.3 Coating Fatigue Analysis**

Herein we first use the traditional alternating stress (S) versus the number of cycles to failure (N), here defined as the stress life (S-N) method to calculate the fatigue life during the incubation period, then propose a fatigue crack propagation method to calculate the fatigue life during the MLR increasing period.

282 **2.3.1 Fatigue analysis for the incubation period**

The traditional S-N method has been widely used to calculate the fatigue life during the incubation period [11, 28, 29]. The S-N curve formula is expressed as:

$$\sigma_a = \sigma_f (N_f)^b \tag{5}$$

where σ_f is the fatigue strength coefficient (FSC), and b is the fatigue strength exponent (FSE), *N_f* is the number of allowable cycles under a stress amplitude σ_a . According to the fatigue experiments in [30], the values of σ_f and *b* in Eq.(5) are 83.3MPa and -0.117, respectively, for the epoxy coating used in this paper.

It is worth noting that the S-N curve formula differs at different stress ratios *R* which equal the ratio of the minimum cyclic stress to the maximum cyclic stress (i.e., $R = \sigma_{min} / \sigma_{max}$). However, due to the lack of experimental data for fatigue of the coating material under different stress ratios, a single S-N curve based on the fatigue experiments in [30] is used and the stress amplitudes are corrected according to the Goodman's equation [11]:

295
$$\sigma_a' = \frac{\sigma_a UTS}{UTS - \sigma_m}$$
(6)

where σ_a is the corrected amplitude, σ_m is the mean stress, and *UTS* is the ultimate tensile strength. The *UTS* of the epoxy material (*UTS* = 73.3MPa) from [30] is used in this paper. Substituting the σ_a in Eq. (5) by σ_a , the number of allowable stress cycles N_f can be calculated as

$$N_f = \left(\frac{\sigma_a}{\sigma_f}\right)^{1/b} \tag{7}$$

In Eq. (7), the cyclic stress should be a constant-amplitude cyclic stress, but the actual impact stress has varied stress amplitudes due to the randomness of raindrop impact. In order to have cycle-by-cycle fatigue analysis, a simple-range counting method [31] is applied to count all the half cycles, i.e., the local maximum (minimum) stress and the neighboring minimum 305 (maximum) stress are selected to constitute a half stress cycle. In this way, the complex stress 306 curve is split into half-cyclic stresses with varying constant-amplitudes and the N_f in Eq. (7) is 307 calculated for each half-cycle. Different from the rainflow cycle counting that breaks the stress 308 cycle sequence, the simple-range counting method could sequentially calculate fatigue damage for 309 each half-cycle. As a result, the fatigue damage *D* under half-cyclic stresses is linearly accumulated 310 based on the Miner's rule

$$D = \sum_{i} \frac{0.5}{N_f^i} \tag{8}$$

312 The fatigue life during the incubation period is then calculated as

313
$$t_{\text{incubation}} = \frac{t_s}{D_s}$$
(9)

314 where t_s is the duration of the simulated rain and D_s is the damage accumulated over time t_s .

315 **2.3.2 Fatigue analysis for the mass-loss-rate increasing period**

316 The MLR increasing period starts at the end of the incubation period when the surface 317 roughness increases severely [5]. According to the crack propagation law [32], we use the obtained 318 raindrop impact stress from Section 2.2.2 to calculate the crack depth, and use a crack-propagation 319 stability criterion to calculate the fatigue life of the coating during the MLR increasing period 320 when the rain intensity is larger than a threshold. When the rain intensity is smaller than or equal 321 to the threshold, the computational time using this traditional crack propagation method is 322 increased significantly. For example, using the traditional crack propagation method, the computer 323 in this study will take approximately 179.67 days to calculate a fatigue life of 11462 hours when the rain intensity equals to 5 mm h^{-1} . To overcome the computational burden, an equivalent crack 324

propagation method is proposed for estimating the total crack propagation time by calculating the equivalent stress range, when the rain intensity is smaller than a threshold. In this study, the rain intensity threshold is selected to be 10 mm h^{-1} based on our current affordable computational time. The proposed equivalent crack propagation method significantly reduces the computational time when calculating fatigue life during the MLR increasing period. For instance, it only cost 1.7 minutes to simulate the same fatigue life when the rain intensity equals to 5 mm h⁻¹.

331 The crack propagation method is first explained. Fatigue crack propagation studies are 332 performed with the cyclic-crack-tip stress state determined by a stress intensity factor range ΔK . 333 According to the Paris law [32], the crack growth rate is expressed as:

$$\frac{da}{dN} = C(\Delta K)^m \tag{10}$$

where *C* and *m* are the basic parameters describing the fatigue crack growth performance of the material, obtained from the crack growth experiments. According to Brown's experimental results [33], the crack propagation test for the epoxy material (i.e., the gelcoat of a WTB) determines these parameters to be *C*=9.7 and *m*=0.08. Considering that the von Mises stress is used in the fatigue analysis (i.e., $R = \frac{\sigma_{min}}{\sigma_{max}} > 0$), the stress intensity factor range ΔK is expressed as [28, 29]

$$\Delta K = K_{\rm max} - K_{\rm min} \tag{11}$$

341 The calculation formula of stress intensity factor *K* is expressed as [28, 29]

$$K = Y \sigma \sqrt{\pi a} \tag{12}$$

343 Therefore, the maximum stress intensity factor K_{max} and the minimum stress intensity factor K_{min} 344 can be expressed as $K_{\text{max}} = Y\sigma_{\text{max}}\sqrt{\pi a}$ and $K_{\text{min}} = Y\sigma_{\text{min}}\sqrt{\pi a}$, respectively. *Y* is a dimensionless 345 parameter related to the shape of the crack. *a* is the crack depth.

For a constant amplitude stress and the number of stress cycles *N* is small, the change in crack depth *a* is small and the stress intensity factor range ΔK is viewed as a constant. Thus the crack growth rate (Eq. (10)) under a constant-amplitude cyclic stress can be considered as a constant. As a result, the crack depth formula is approximately as

350
$$a = a_0 + \int_0^N C\left(\Delta K\right)^m dN = a_0 + N \times C(\Delta K)^m$$
(13)

where *N* is the number of applied stress cycles and a_0 is the initial crack depth, which is selected to be 12 µm according to the range of surface roughness (5 to 20 µm) used in [34]. This surface roughness range is viewed as the indicator of the start of the MLR increasing period in this paper. Since the stress time series have been split into half-cycle stresses, each half-cycle stress curve is viewed as a constant amplitude stress with the number of stress cycles 0.5 (*N* = 0.5). The crack depth a_{i+1} after one half-cycle stress cycle is calculated based on Eqs. (11) - (13)

357
$$a_{i+1} = a_i + 0.5 \times C \left[Y \left(\sigma_{\max} - \sigma_{\min} \right) \sqrt{\pi a_i} \right]^m$$
(14)

According to the elastic fracture criterion, when the maximum stress intensity factor K_{max} is greater than the fracture toughness K_{C} , the crack extends in a rapid (unstable) manner without an increase in load or applied energy [28]. Here the fracture toughness of the epoxy material is $K_C =$ 0.59 MPa m^{1/2} [33]. Here the relationship $K_{\text{max}} > K_C$ is viewed as the first criterion indicating the crack propagation has been completed. In addition, when the crack depth is greater than the coating thickness, it also indicates that the crack propagation has been completed. By satisfying either the aforementioned two criteria, the duration of the MLR increasing period t_{MLR} is obtained.

However, when the rain intensity is low, the time required for iteratively calculating the crack
depth (Eq. (14)) till the end of the crack propagation is significantly long due to the relatively small

367 impact stress. Herein for low rain intensity (i.e., $I \le 10 \text{ mm h}^{-1}$), an average stress range $\Delta \sigma$ is 368 first calculated as an equivalent constant-amplitude stress with the same applied number of cyclic 369 stresses during the simulated rainfall time, which is based on the Paris formula. Then obtain the 370 fatigue life based on accumulation of fatigue damage of multiple simulated times. Details of this 371 equivalent crack propagation method are provided as follows.

Based on Eqs. (10) and (12), the number of allowable cyclic stress N_c can be calculated as:

373
$$N_{c} = \int_{0}^{N_{c}} dN = \int_{a_{0}}^{a_{c}} \frac{da}{C \left(Y \Delta \sigma \sqrt{\pi a}\right)^{m}} = \frac{1}{C \left(Y \Delta \sigma \sqrt{\pi}\right)^{m}} \int_{a_{0}}^{a_{c}} \frac{da}{a^{m/2}}$$
(15)

374 If $m \neq 2$

375
$$\int_{a_0}^{a_c} \frac{da}{a^{m/2}} = \frac{a_c^{\left(1-\frac{m}{2}\right)} - a_0^{\left(1-\frac{m}{2}\right)}}{-m/2 + 1}$$
(16)

376 If m = 2

377
$$\int_{a_0}^{a_c} \frac{da}{a} = \ln\left(\frac{a_c}{a_0}\right)$$
(17)

378 The calculation formula of fatigue life is derived as [28, 29]

379

$$N_{c} = \begin{cases} \frac{2}{(m-2)C\left(Y\Delta\sigma\sqrt{\pi}\right)^{m}} \left[a_{0}^{\left(1-\frac{m}{2}\right)} - a_{c}^{\left(1-\frac{m}{2}\right)}\right], & m \neq 2\\ \frac{1}{C\left(Y\Delta\sigma\sqrt{\pi}\right)^{m}} \ln\left(\frac{a_{c}}{a_{0}}\right), & m = 2 \end{cases}$$
(18)

380 The parameters of the calculation formula for fatigue life (*C*, *m*, *Y*, *a*₀) are constant. Based on 381 Eq.(18), the average stress range $\Delta \sigma$ of *N* number of varied-amplitude cyclic stress can be 382 calculated as

383
$$\Delta \sigma = \begin{cases} \left\{ \frac{2}{N(m-2)C(Y\sqrt{\pi})^{m}} \left[a_{0}^{\left(1-\frac{m}{2}\right)} - a^{\left(1-\frac{m}{2}\right)} \right] \right\}^{\frac{1}{m}}, & m \neq 2 \\ \left[\frac{1}{CN(Y\sqrt{\pi})^{m}} \ln \left(\frac{a}{a_{0}}\right) \right]^{\frac{1}{m}}, & m = 2 \end{cases}$$
(19)

384 where *N* is the applied number of cyclic stress and *a* is the crack depth. By Eq. (12), the critical 385 crack depth can be obtained by setting K_{max} equal to the fracture toughness K_{C} [28, 29]:

386
$$a_{C} = \left(\frac{K_{C}}{Y\sigma_{\max}}\right)^{2} / \pi$$
 (20)

387 where σ_{max} is the maximum stress under one simulated rainfall time period t.

388 The obtained average stress range $\Delta \sigma$ and the critical crack depth a_c are then substituted into 389 Eq. (18) to calculate the number of allowable cyclic stress N_c . Assuming the fatigue damage is 390 linearly accumulated for multiple simulated rainfall times, the duration of the MLR increasing 391 period under low rain intensities can be calculated as

$$t_{MLR} = \frac{N_c}{N_t} t \tag{21}$$

393 where N_c is the allowable number of stress cycles till the end of crack propagation under low rain 394 intensities, N_t is the applied number of stress cycles in one simulated rainfall time *t*. Accuracy

results when using this approximation for calculating fatigue life under low rain intensities arediscussed in Section 4.3.

397 **2.3.3 Fatigue life calculation for wind turbine blade coating**

The total fatigue life, t_I , under a rain intensity at each element of the FEA model is calculated by adding the fatigue life during the incubation period and the fatigue life during the MLR increasing period, expressed as

$$401 t_I = t_{incubation} + t_{MLR} (22)$$

402 where $t_{incubation}$ and t_{MLR} are obtained by Eqs. (9) and (21), respectively. In the studied WTB 403 coating, as the crack grows, adjacent crack tips may interact with each other causing the crack 404 propagation path to bend and the cracks to merge. According to Li et al. [35], when the cracked 405 area accounts for 78% ~ 90% of a coating material, the cracks start to merge and the coating 406 enters into a rapid failure stage. Here, the 84th percentile (center of the 78% to 90% from Li et al. 407 [35]) of the total fatigue life of all FEA elements is selected as the fatigue life of the WTB 408 coating.

409 Combining the PMF $P_{\rm I}$ of the rain intensity and the total rainfall hours per year t_A at a WT 410 location, the accumulated fatigue damage of the WTB coating per year $D_{\rm 1year}$ considering different 411 rain intensities can be calculated as

412
$$D_{1\text{year}} = \sum_{I} \frac{P_{I} \times t_{A}}{t_{I}}$$
(23)

413 Thus, the expected fatigue life *t_f* of the WTB coating can be calculated as

414
$$t_f = \frac{1}{D_{1\text{year}}} \tag{24}$$

415 **3 CASE STUDY**

The proposed computational framework is applied in the fatigue life evaluation of a 416 417 composite panel at the tip section of a blade leading edge. The composite panel is modelled in the 418 FEA analysis as a layup that consists of a coating layer, a composite layer beneath the coating 419 layer, a foam core material layer in the middle, and another composite layer at the bottom (Fig. 5). 420 The coating material is an epoxy gelcoat, as specified in the Sandia 100-meter all-glass baseline 421 WTB [36] and has a thickness of 0.6 mm. Each composite layer consists of the composite material QQ1, which is a glass-fiber-reinforced plastic (GFRP) laminate that consists of Vantico TDT 177-422 423 155 Epoxy Resin, Saertex U14EU920-00940-T1300-100000 0's, and VU-90079-00830-01270-000000 45's fabrics [37]. The core material is selected to be CorecellTM M-Foam M200 [38]. 424 Detailed material properties are provided in Table 1. 425





	Material Types	Coating	QQ1	Foam
Material Propertie	25			
Longitudinal Young's mod	ulus E_1 (GPa)	3.44	33.1	0.256
Transversal Young's modu	lus E_2 (GPa)	3.44	17.1	0.256
Poisson's ratio v ₁₂		0.3	0.27	0.33
Shear modulus G_{12} (GPa)		1.38	6.29	0.098
Density ρ (kg/m ³)		1235	1919	200

Table 1 Material properties of the composite panel used in the FEA model [36]

428

429 The dimension of the simulated blade panel is $100 \times 100 \times 15.6$ mm. The boundary condition 430 is set to fixing the bottom surface of the panel as a typical approach for raindrop impact simulation 431 [11, 27]. Two assumptions are made here: 1) the layers in the sandwich panel are perfectly bonded, 432 as the consideration of cohesive property between layers would complicate the stress analysis; 2) 433 the effect of the blade surface curvature on the impact stress is not considered in this case study. 434 There are 10000, 50000, and 50000 SC8R elements are used to mesh the coating layer, each of the 435 composite layer, and the foam layer, respectively (Fig. 5). SC8R is an 8-node, quadrilateral, first-436 order interpolation, stress/displacement continuum shell element with reduced integration. The 437 average mesh size of the SPH particles in a raindrop is 0.1 times the diameter of the raindrop. The total number of SPH particles is $\sim 750 - 1100$ depending on different raindrop sizes and shapes. 438 439 These numbers of the SC8R elements and the SPH particles are determined based on the sensitivity analyses of different mesh sizes on the calculated stress results and the affordable computationaltime in this case study.

The proposed computational framework is validated by comparing the fatigue life of the studied WTB tip panel under different rain intensities with Bech's results in [8] with the same impact speed of 90 ms⁻¹. In addition, based on the rainfall statistics data in Miami, FL, from August 1957 to August 1958 [39], the PMF of the rain intensity is created (see Figure 6) and used to calculate the fatigue life of the studied panel. Detailed results and discussion are provided as follows.



449 Figure 6 The probability mass function of rain intensity in Miami, FL, from August 1957 to450 August 1958

451 **4 RESULTS AND DISCUSSION**

452 **4.1 Extended Stochastic Rain Fields**

453 As a demonstration, Fig. 7 shows the top views of the extended stochastic rain fields with 454 varying raindrop shapes and sizes under four rain intensities, 1 mm h⁻¹, 10 mm h⁻¹, 20 mm h⁻¹, and 50 mm h⁻¹. The flat ellipsoid, spindle ellipsoid, and spherical raindrops are indicated by red, green, 455 456 and blue solid circles, respectively. This figure clearly visualizes that as the rain intensity increases 457 the number and the size of raindrops increase accordingly. Because this research focuses on the 458 WTB coating stress and fatigue due to the raindrop impact, as elaborated in Sections 4.2 and 4.3, the complex mutual interaction and dynamic deformation of raindrops during their falling are not 459 460 considered here.



462 Figure 7 Simulated stochastic rain fields under four rain intensities: (a) 1 mm h⁻¹, (b) 10 mm h⁻¹,
463 (c) 20 mm h⁻¹, and (d) 50 mm h⁻¹.

464 4.2 Raindrop Impact Stress

The stress waves due to raindrop impact is first investigated. Figures 8 and 9 demonstrate the propagation of von Mises stress of the panel under a single spherical raindrop impacting at the panel center with 90° impact angle. The raindrop diameter is 2 mm, and the impact speed is 90 ms⁻¹. As a result of the impact, there is a Rayleigh wave generated and propagated from the impact center to the free boundary of the coating surface (Fig. 8). In addition, the impact produces longitudinal and transverse body waves that accompany stress variation inside the panel exhibiting an interference field of these waves (Fig. 9).



473 **Figure 8** Simulation of a single raindrop impact. (a-f) von Mises stress contours of the top 474 coating at six time instants (0 μ s, 10 μ s, 20 μ s, 30 μ s, 40 μ s, 50 μ s) using the raindrop diameter 475 of 2 mm and the impact speed of 90 ms⁻¹.



477 **Figure 9** Simulation of a single raindrop impact. (a-f) cross-sectional views of von Mises stress 478 contours at six time instants (0 μ s, 1 μ s, 5 μ s, 10 μ s, 20 μ s, 30 μ s) using the raindrop diameter of 479 2 mm and the impact speed of 90 ms⁻¹.

476

Two high-stress regions are observed during the raindrop impact process: the one occurring at the raindrop-coating contact surface (Figs. 8(b-f)) and the other is propagating through the thickness below the surface (Figs. 9(a-f)). The former is due to the raindrop peak impact pressure acting as the primary wave source, while the latter is caused by superposition of the stresses initiated from the shock wave front in the raindrop and from the high-pressure point. These findings further confirm that micro-crack/fatigue is possibly occurring both at the raindrop-coating contact surface and underneath the coating.

487 It is worth noting that there is a clear stress interface between the QQ1 layer and the foam
488 layer (Figs. 9(b-f)) due to the different elastic material properties of the two layers. Under the

489 assumption of perfectly bonded layers, the elastic deformation of QQ1 and foam layer is the same 490 in the interfaces between layers. As the Young's modulus of the foam layer is much lower than 491 that of the QQ1 layer (see Table 1), the stresses in the foam layer are much lower than those in the 492 QQ1 layer. This finding confirms that the foam layer plays a vital role as a stress cushion in 493 composite WTBs.

494 The influence of the raindrop size, impact speed, impact angle, and raindrop shape on the 495 stress evolution on the impacted coating is shown in Fig. 10. The coating center element with the 496 highest von Mises stress is studied here. Figure 10(a) shows the von Mises stress induced by the 497 normal impact (90°) under the same impact speed (90 ms⁻¹) and different spherical raindrop 498 diameters (1 mm, 2 mm, and 5 mm). A clear two-peak mode is observed for the stress time series 499 of all three cases, which is in line with earlier observations [5]. The gap between the two peaks is 500 increased as the raindrop size increases (Fig. 10(a)). The first stress peak is due to the direct impact 501 of the raindrop against the coating surface, while the second stress peak may be generated by the 502 shock wave front after the high density liquid region is created [40].

Figure 10(b) compares the von Mises stress under the normal impact (impact angle 90°) of a spherical raindrop (diameter 2 mm) with three different impact speeds (70 ms⁻¹, 90 ms⁻¹, and 100 ms⁻¹). It is found that three first stress peaks (44 MPa, 64 MPa, and 86 MPa) increase as the impact speed increases. The ratio among the three first-peak von Mises stresses is approximately closed to the ratio among the square of the impact speeds, which is consistent with the relationship between the kinetic energy and the impact speed of the raindrop. However, the second stress peak is not significantly influenced by the impact speed as shown in Fig. 10(b).

510 To investigate the influence of the impact angles on the stress, a spherical raindrop with 511 diameter of 2 mm and impact speed of 90 ms⁻¹ is used to impact the blade panel with three different

512 impact angles (30°, 60°, and 90°). Figure 10 (c) shows that, as the impact angle decreases, the stress
513 is dramatically reduced, especially for the first peak stress, which indicates that non-perpendicular
514 raindrop impact could significantly reduce the impact stress.

Figure 10(d) compares the von Mises stress under three different raindrop shapes (flat, spindle, spherical) with the same volume $(4/3 \times \pi \times 4^3 \text{ mm}^3)$ and the impact speed (90 ms⁻¹). For the non-spherical raindrops (spindle and flat), the two stress peaks are not as obvious as those due to the spherical raindrop. Instead, the stress corresponding to the non-spherical raindrops have a large fluctuation in the time series. In addition, the spindle raindrop creates the maximum first-peak and longest fluctuating time among the three raindrop shapes, while the flat raindrop generates smaller stress fluctuation than those by the other two counterparts, as demonstrated in Fig. 10(d).



522

Figure 10 Comparison of coating von Mises stress considering different (a) raindrop sizes, (b)
impact speeds, (c) impact angles, and (d) raindrop shapes.

525 The accuracy of the stress interpolation method proposed in Section 2.2.2 is verified by 526 comparing the interpolated impact stress with the stress directly calculated using the SPH 527 approach. As a demonstration, Fig. 11 shows an interpolated stress when a 2.5 mm diameter 528 spherical raindrop impact at the top-right corner of the blade panel with an impact angle of 80° 529 and an impact speed of 90ms⁻¹. Taking the center of the panel as the origin of the coordinate 530 system, the impact point is at (28 mm, 28 mm). The four closest cases are (spherical, d = 2 mm, θ $= 75^{\circ}$, $v = 90 \text{ ms}^{-1}$), (spherical, d = 2 mm, $\theta = 90^{\circ}$, $v = 90 \text{ ms}^{-1}$), (spherical, d = 3 mm, $\theta = 75^{\circ}$, $v = 10^{\circ}$ 531 532 90 ms⁻¹) and (spherical, d = 3 mm, $\theta = 90^{\circ}$, v = 90 ms⁻¹). Figure 11(a) compares the time series of 533 interpolated von Mises stress of the raindrop and those of the closes four raindrop impact cases. 534 As illustrated in Fig. 11(b), it is observed that the interpolated stress agrees well with the stress 535 directly calculated by the SPH approach.



Figure 11 Interpolated impact stress due to a random raindrop (diameter d = 2.5 mm, spherical shapes, impact angles $\theta = 80^{\circ}$, impacting at a top-right corner of the blade panel. (a) Comparison of the interpolated impact stress and the stresses of the four closet raindrop impact cases; (b) Comparison of interpolated stress (blue solid curve) and the SPH stress (green dash-dotted curve)

4.3 Blade Coating Fatigue

The accuracy of the proposed equivalent crack propagation method is first verified by comparing fatigue life during the MLR increasing period based on the equivalent crack propagation method and the traditional crack propagation method, as shown in Table 2. Under large rain intensities (11 mm $h^{-1} \le I \le 20$ mm h^{-1}), the relative error using the equivalent crack propagation method is less than 3% and decreases as the rain intensity decreases, while the computational time using the equivalent crack propagation method is significantly smaller than that using the traditional method. For example, the smallest relative error using the equivalent crack propagation method when rain intensity equals to 11 mm h^{-1} is only 0.06%, and the computational time using the traditional method is 718.3 times as high as that using the equivalent crack propagation method. Therefore, when the rain intensity is low (i.e., $I \le 10 \text{ mm h}^{-1}$ in this paper), the equivalent crack propagation method could indeed accurately and efficiently predict the fatigue life during the MLR increasing period.

562 Table 2 The fatigue life of the blade panel during the MLR increasing period calculated by the

- 563 crack propagation method and the equivalent crack propagation method under large rain intensities
- 564 $(11 \text{ mm } h^{-1} \le I \le 20 \text{ mm } h^{-1}).$

Rain	The crack propagation method		The equivalent crack propagation method		Relative	Computational
intensity <i>I</i> (mm h ⁻¹)	Fatigue lifetime <i>t</i> _{f1} (min)	Computational time <i>t</i> _{c1} (min)	Fatigue lifetime <i>t</i> _{f2} (min)	Computational time t_{c2} (min)	$\varepsilon = t_{f1} - t_{f2} / t_{f1}$	time ratio t_{c1}/t_{c2}
20	209	108.8	203	6.4	2.87%	17.0
19	372	347.8	366	4.5	1.61%	77.3
18	450	403.0	446	4.9	0.89%	82.2
17	781	566.4	776	3.4	0.64%	166.6
16	874	583.5	869	3.9	0.57%	149.6
15	1831	728.7	1823	3.2	0.44%	227.7
14	2637	1163.8	2631	5.9	0.23%	197.3
13	2687	1212.6	2674	4.8	0.48%	252.6
12	4541	1506.5	4538	3.0	0.07%	502.2
11	8168	1939.3	8163	2.7	0.06%	718.3

565

The influence of the rain intensity, raindrop impact speed, raindrop impact angle, and 566 raindrop shape on fatigue life are investigated. The fatigue life of the coating during the incubation 567 period, the MLR increasing period, and the total fatigue life (summation of the incubation period 568 and the MLR increasing period) under different rain intensities, raindrop impact speeds, raindrop impact angles, and raindrop shapes are provided in Table 3 and depicted in Fig. 12. 569

571 **Table 3** Coating fatigue life under different rain intensities, impact speeds, impact angles, and

572 raindrop shapes

Fixed rain parameters	Varied rain		Incubation period (h)	MLR Increasing	Total Fatigue
	param	eters	peniou (ii)	period (h)	Life (h)
		1 mm/h	10350.00	24966.67	35316.67
Impact Speed=90m/s	Rain Intensity	5 mm/h	1.53	12.50	14.03
Impact Angle=90°		10 mm/h	0.52	0.17	0.69
Raindrop Shape=spherical		15 mm/h	0.28	0.10	0.38
		20 mm/h	0.18	0.08	0.26
		70 m/s	24.36	357.33	381.69
Rain Intensity=5mm/h	Impact Speed	80 m/s	2.44	68.63	71.07
Impact Angle=90°		90 m/s	1.53	12.50	14.03
Raindrop Shape=spherical		100 m/s	0.73	1.28	2.01
		110 m/s	0.57	0.15	0.72
	Impact Angle	15°	258.33	1620.00	1878.33
		30°	57.24	610.00	667.24
Rain Intensity=5mm/h		45°	15.11	206.17	221.28
Raindrop Shape=spherical		60°	1.77	55.17	56.94
		75°	1.20	10.15	11.35
		90°	1.53	12.50	14.03
Rain Intensity=5mm/h	Raindrop Shape	Flat	1.72	37.51	39.23
Impact Speed=90m/s		Spherical	1.53	12.50	14.03
Impact Angle=90°		Spindle	0.55	0.15	0.7

573 Figure 12(a) compares the fatigue life of the blade coating under the same vertical impact (impact angle = 90°), the impact speed of 90 ms⁻¹, and the spherical raindrops with five different 574 575 rain intensities (1 mm/h, 5 mm/h, 10 mm/h, 15 mm/h, and 20mm/h). As expected, the fatigue life 576 of the coating decreases exponentially with the increase of the rainfall intensity. It is interesting to 577 find that under low rain intensity (e.g., $I < 7 \sim 8 \text{ mm/h}$) the incubation period is shorter than the 578 MLR increasing period, while it becomes longer than the MLR increasing period under large rain 579 intensity (e.g., $I \ge 10$ mm/h). This is probably due to that severer impact stress, consequently 580 severer crack propagation, occurs under larger raindrop size (see Fig. 10(a)) and more raindrops 581 hitting at large rain intensity than that at small rain intensity. This finding also indicates that a rain 582 event with a large rain intensity could more detrimentally influence the blade coating crack 583 propagation than the crack initiation.

584 Figure 12(b) compares the fatigue life of the blade coating under the same rain intensity (5 585 mm/h) and the vertical impact (impact angle = 90°) of spherical raindrops with five different impact speeds (70 ms⁻¹, 80 ms⁻¹, 90 ms⁻¹, 100 ms⁻¹, and 110 ms⁻¹). There is a significantly large 586 587 gap between the incubation period and the MLR increasing period at the impact speed of 70 ms⁻¹, 588 which means the MLR increasing period dominates the total fatigue life under small impact speeds. 589 This gap is narrowed down as the impact speed increases. The current finding also indicates that 590 the raindrop impact speed influences the MLR increasing period more severe than incubation 591 period.

Figure 12(c) compares the fatigue life of the blade coating under the same rain intensity (5 mm/h) and impact speed (90 ms⁻¹) of spherical raindrops with five different impact angles (15°, 30° , 45° , 60° , 75° , and 90°). The fatigue life during the MLR increasing period dominates the total fatigue life under small impact angle. As the impact angle increases, both the fatigue life during

the incubation period and the MLR increasing period are exponentially decreasing.

Figure 12(d) compares the fatigue life of the blade coating under the same rain intensity (5 mm/h), impact speed (90 ms⁻¹) and the vertical impact (impact angle = 90°), but three different raindrop shapes (flat, spherical, spindle). It is interesting to find that 1) under the flat raindrops the MLR increasing period is 21.8 times longer than the incubation period; 2) the MLR increasing period under the flat raindrops is 250.1 times longer than that under the spindle raindrops. These could be probably because the spindle raindrops cause larger stress peak and longer stress fluctuation than those caused by the flat raindrops (see Fig. 10(d)). 400 Incubation Period Incubation Period 10⁴ MLR Increasing Period MLR Increasing Period Total Fatigue Life Total Fatigue Life 300



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Figure 12 Coating fatigue life corresponding to different (a) rain intensities, (b) impact speeds, 605 606 (c) impact angles, and (d) raindrop shapes.

607 To further verify the accuracy of the proposed computational framework, the calculated total 608 fatigue life of the blade coating is compared with that obtained by Bech et al. [8] under the same impact speed of 90 ms⁻¹. Table 4 compares the total fatigue life under five rain intensities (20 mm 609 610 h^{-1} , 10 mm h^{-1} , 5 mm h^{-1} , 2 mm h^{-1} , and 1 mm h^{-1}). In this table, the hours per year indicate the 611 number of hours corresponding to the rain intensity in a year, which is from Bech et al. [8]. The 612 faction of life spent per year equals the hours per year divided by the calculated total fatigue life. 613 The reciprocal of the sum of fraction is obtained as the expected life in year. In general, the total 614 fatigue life under the five rain intensities are longer than those obtained by Bech et al. [8]. Using 615 the same rain hours per year data, the expected fatigue life using the proposed framework is 2.1 616 years which is slightly longer than that obtained by Bech et al. [8]. This longer fatigue life is mainly 617 because the proposed framework involves more sophisticated and realistic computational 618 approaches. For example, the extended stochastic rain field simulation considers various impact 619 angles and raindrop shapes that may alleviate the calculated stress compared with that obtained by 620 assumed vertical impact of all perfectly spherical and fixed-diameter raindrops used in Bech et al. 621 [8]. Given that very few WTB rain erosion experimental data are available in literature, this 622 comparison still shows that the proposed computational framework could produces reasonable 623 rain-erosion fatigue life for WTBs. It is worth noting that the fatigue life here is based on the 624 assumption that the blade is under continuous raindrop impact throughout its service life and could 625 be conservative.

626

627

629 Table 4 Comparison of the total fatigue life in this study and from Bech's result under different630 rain intensities

Rain	Hours	Blade tip	Total	Fraction of life	Total	Fraction of
intensity	per year	speed (m	fatigue life	spent per year	fatigue life	life spent
(mm h ⁻¹)	(h yr ⁻¹)	s ⁻¹)	(Bech's	(Bech's result)	(this study)	per year
			result) (h)	(%)	(h)	(this study)
						(%)
20	1.8	90	3.5	51	4.2	42.9
10	8.8	90	79	11	192.7	4.6
10	0.0	20		11	172.7	4.0
5	88	90	3600	2.4	14463	0.6
2	263	90	7.5×10^{5}	$3.5 imes 10^{-2}$	1.6 x 10 ⁶	$1.6 imes 10^{-2}$
1	438	90	2.8×10^{9}	$1.6 imes 10^{-5}$	4.5 x 10 ⁷	9.7 × 10 ⁻⁴
Sum of fraction (%):				64.4		48.1
Expected life (year):				1.6		2.1

631

Based on the rainfall statistics data in Miami, FL, from August 1957 to August 1958 [39],
the rain-erosion fatigue life of the Sandia 100-meter all-glass baseline WTB is ~ 1.3 years using
the proposed computational framework and the above expected fatigue life calculation method.
This indicates the necessity of the blade surface repairing as early as 1.3 years after installation.

636 5 CONCLUSIONS

For analyzing WTB coating fatigue due to rain erosion, this paper presents a state-of-the-art computational framework that including an extended stochastic rain field simulation (considering varied raindrop sizes, impact speeds, impact angles, and raindrop shapes), SPH-and-interpolation hybrid raindrop impact stress calculation, and coating fatigue analysis (considering both the incubation period and the MLR increasing period for the first time). Based on this new framework, some interesting results are obtained and summarized as follows:

643 1) Both surface Rayleigh wave and longitudinal and transverse body wave of impact stress are
644 generated by raindrop impact accompany with high-stress regions during the propagation of
645 these stress waves in the WTB.

646 2) The influence study of the raindrop size, impact speed, impact angle, and raindrop shape on
647 the stress evolution on the impacted coating shows that the inclined impact of flat-ellipsoid
648 raindrops could produce smaller stress fluctuation than the vertical impact of spindle-ellipsoid
649 raindrops do.

3) The proposed stress interpolation method and the equivalent crack propagation method could
 efficiently and accurately calculate the impact stress and fatigue, respectively, under a
 stochastic rain event.

4) The influence study of the rain intensity, impact speed, impact angle, and raindrop shape on
the fatigue life reveals that i) a rain event with a large rain intensity could more detrimentally
influence the blade coating crack propagation than the crack initiation; ii) the MLR increasing
period dominates the total fatigue life under small impact speeds (e.g., 70 m/s) and the raindrop
impact speed influences the MLR increasing period more severe than incubation period; iii)

658		the vertical impact of spindle-ellipsoid raindrops could cause significantly larger fatigue
659		damage than the inclined impact of flat-ellipsoid raindrops do.
660	5)	The proposed framework is verified by comparing the calculated fatigue life with existing
661		results in literature, and is readily applicable to predict WTB coating fatigue life due to rain
662		erosion given rainfall statistic data at a location.
663		Although the current research provides innovative contributions for predicting the WTB
664	coa	ating fatigue life due to rain erosion, limitations and future work may include:
665	1)	The usage of the proposed framework for WTB design and maintenance has not be investigated
666		in this paper. Future work may be the application of the framework to design of new WTB
667		coating and to optimal control of wind turbine rotation to reduce the rain erosion for WTB, as
668		well as to predictive maintenance (for example, determine the time when the predictive
669		maintenance due to rain erosion is necessary based on the fatigue damage calculated by the
670		proposed framework).
671	2)	The rain-wind correlation, the moisture effect, the chemical corrosion from insects, and other
672		object impacts (e.g., atmospheric particles, hail, and sand) have not considered in this paper.

WT damage calculation considering these factors and the validation with real experimentalresults are worth investigating in the future.

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761 ACKNOWLEDGEMENTS

- 762 This work is supported by the National Natural Science Foundation of China (Grant No.
- 763 51905475) and the National Key R&D Program of China (Grant No. 2019YFB1705200,
- 764 2018YFB1201802-1).

765 NOMENCLATURE

- *a* Crack depth
- a_0 Initial crack depth
- a_c Critical crack depth
- 769 b Fatigue strength exponent (FSE)
- *C* Exponential parameter describing the fatigue crack growth performance of the material
- 771 d Raindrop diameter
- *D* Fatigue damage
- D_{1year} Accumulated fatigue damage of the WTB coating per year
- D_s Damage accumulated over time t_s .
- h Hight of the tall-column
- I Rain intensity in mm h⁻¹
- *K* Stress intensity factor
- $K_{\rm C}$ Fracture toughness
- K_{max} Maximum stress intensity factor

780	K_{\min}	Minimum stress intensity factor
781	m	Linear parameter describing the fatigue crack growth performance of the material
782	N(V)	Number of raindrops in volume V
783	Ν	The number of stress cycles
784	Nc	Number of allowable cyclic stress till the end of the MLR increasing period
785	N_f	Number of allowable cycles in the S-N method
786	N_t	Applied number of stress cycles in one simulated time <i>t</i>
787	P_{I}	Probability of the rain intensity I
788	r_0	Equivalent spherical radius
789	R	The ratio of the minimum cyclic stress to the maximum cyclic stress
790	t_A	Total rainfall hours per year at a WT location
791	t _{c1}	Computational time by the crack propagation method
792	t _{c2}	Computational time by the crack equivalent crack propagation method
793	t_f	Expected fatigue life of the WTB coating
794	$t_{\rm f1}$	Fatigue life during the MLR increasing period by the crack propagation method
795	$t_{\rm f2}$	Fatigue life during the MLR increasing period by the equivalent crack propagation
796		method
797	t _{incubation}	Fatigue life during the incubation period
798	t _I	Total fatigue life under a rain intensity

799	<i>t_{MLR}</i>	Duration of the MLR increasing period
800	t	Duration of the simulated rain in equivalent crack propagation method
801	t_s	Duration of a simulated rain event
802	Т	Duration of the simulated rain event
803	UTS	Ultimate tensile strength
804	v	Impact speed
805	V	Unit volume
806	Y	A dimensionless parameter related to the shape of the crack.
807	α	Axis ratio
808	ΔK	Stress intensity factor range
809	Δσ	Average stress range in equivalent crack propagation method
810	θ	Impact angles
811	λ	Expected number of raindrops per unit volume
812	σ_a	Stress amplitude
813	$\sigma_{a}^{'}$	Corrected stress amplitude
814	$\pmb{\sigma}_{_f}$	Fatigue strength coefficient (FSC)
815	$\sigma_{_m}$	Mean stress
816	$\sigma_{\scriptscriptstyle{ m max}}$	Maximum stress under one simulated rainfall time period