

Jakob Ilsted Bech

wes-2025-247 (author) – Author Comments (AC)

Title: Fatigue crack growth in elastomers for leading edge erosion protection of wind turbine blades

Author(s): Jakob Bech and Jamie Simon

We thank the reviewers for their constructive feedback.

Below, we address the reviewers' comments and questions one by one.

RC1: '[Comment on wes-2025-247](#)', Anonymous Referee #1, 16 Jan 2026

Dear reviewer1,

Thank you for your constructive and useful feedback.

Below, we address your comments and questions one by one. We use your input to improve the manuscript.

This manuscript investigates fatigue crack growth in a TPU elastomer used for wind turbine blade leading-edge protection. The work is motivated by the idea that repeated liquid-droplet impacts can be treated as a cyclic loading process. The authors conduct plane-strain double-slit crack-growth tests on sheet specimens. A pulse–dwell displacement waveform is designed to represent the transient response and the time interval between impacts. The crack driving force is described using a tearing-energy framework, where tearing energy is extracted from the measured work evolution and the measured crack-length growth during the test.

The main recommendations are as follows:

Comment 1: Correlation between the proposed fatigue test and actual rain erosion: The manuscript introduces a pulse–dwell fatigue loading scheme as a surrogate for repeated droplet impacts. To further strengthen the motivation, the authors are encouraged to provide additional discussion on how this laboratory loading is closely relates to rain erosion on blade leading edges.

Author response:

In our paper we propose using a cyclic fracture mechanics test for characterizing the material properties that govern fatigue crack growth in LEP materials. In order to strengthen the motivation and emphasize the correlation between leading edge erosion and fatigue crack growth we will add the following to the manuscript:

To be added to section 1.4 “Motivation and problem statement”:

“In rain erosion, droplets impacting on the surface generate stress waves, which propagate through the material, potentially causing transient opening and closing of the cracks. Under such cyclic loading, cracks may propagate, due to the increase of strain energy in the material near the crack tip. The correlations between crack tip loading, and fatigue crack growth rate can be characterized by fracture mechanics testing.”

To be added as introduction to section 3 “Results and discussion”:

Jakob Ilsted Bech

“The current analysis considers an LEP layer with pre-existing cracks, as illustrated in Figure 1. When droplets impact the surface, stress waves propagate through the material, potentially causing transient opening and closing of the cracks. Under such cyclic loading, a crack may grow by a distance da , depending on the crack tip loading and the material’s resistance to crack growth.

In this work, the crack growth behaviour is characterised in terms of the relationship between crack growth rate, da/dN , and crack tip loading expressed as tearing energy, T . This relationship is determined experimentally using a cyclic plane strain fatigue test with two slits, in which two cracks are subjected to controlled cyclic loading. A dwell time is incorporated between loading cycles to account for the time-dependent response of the material.

This approach enables direct measurement of da/dN as a function of T under conditions relevant to rain erosion. For viscoelastic materials, the stress–strain response depends on the time interval between successive loads. On a wind turbine blade, the time between rain droplet impacts varies with rain intensity, droplet size, and blade velocity. By introducing a dwell period in the fatigue crack growth test, this effect is explicitly represented in the experimental methodology.”

Here are some minor comments that the reviewer would like to point out:

Comment 2: Page 6, line 165: The spelling of the word "ssuggestions" is incorrect.

Corrected!

Comment 3: Page 8, figure 2: Please provide a three-dimensional schematic of the specimen and clarify the viewing angle used in the plan view. The solid lines labeled a1 and a2 are inconsistent with the images in subsequent Figures 3 and 4. If a perspective transformation or coordinate mapping is used, please add explicit explanations in both the text and the figure.

Authors response: Figure 2 shows the x_1, x_2 projection of the plane-strain specimen with two slits. We will add a x_2, x_3 projection to figure 2. We will emphasize that Figure 2 shows the specimen in its unloaded condition, where the cracks are closed, whereas, Figure 3 shows the loaded specimen with open cracks.

Comment 4: Page 9, line 191: Reorganize the language and text "As the cracks progress with increasing ..." as "As the cracks propagate with increasing cycle count, the remaining ligament between the crack tips decreases; consequently, the load and the work required to stretch the specimen also decrease. "

Authors response: Thank you! We adopted your proposal.

Comment 5: Page 11, figure 5: There is a problem with the color differentiation of A, B, and C. The upper surface color of the lower grip device does not distinguish between A and B. Additionally, the dimensions related to the device introduced in the text should be marked in the figure.

Authors response: We will either update the figure as suggested, or replace it with frontal view and side view projections for clarity.

Jakob Ilsted Bech

Comment 6: Page 12, line 228: Reorganize the language and text " In the crack growth test ..." as " In the crack growth test, the period between successive droplet impacts is simulated by applying a dwell time, , between load pulses.

[Authors response:](#) Thank you! We adopted your proposal.

Comment 7: Page 13, figure 6: The image below is redundant, or please add a description

[Authors response:](#) lower image is removed

Comment 8: Page 19, figure 10: The caption in the figure, which reads "a,d,f) crack length versus number of cycles.", should be corrected to read "a,d,g) crack length versus number of cycles."

[Authors response:](#) Thank you! We corrected it.

Dear referee #2,

Thank you for useful comments and inputs. We address them point by point below.

RC2: '[Comment on wes-2025-247](#)', Anonymous Referee #2, 13 Apr 2026

A well-written paper with clear explanation of the testing method and data. The double-slit plane strain setup is appropriate, and the novel grip design solves a real practical problem. The key finding, tearing energy collapses the dwell-time dependence while peak strain does not, is meaningful and well-supported experimentally.

Main concerns

Comment 1: The tearing energy part is quite simple. The method relies on w being uniform and stationary in zone C throughout domain II, but this is assumed rather than verified. A cycle-by-cycle plot of w would directly confirm this.

Authors response: The interval of domain II is chosen such that there is an approximately linear correlation between w and $(a_1 + a_2)$, as shown in figure 10 c, f and i. The linear correlation confirms that the strain energy per unit width in zone C is constant along the 1-direction. R^2 of the linear regression for the 3 cases shown in table 1 will be included, to support the linear correlation.

Comment 2: Each test gives only a single T value, the Paris-law curve in Figure 14b is assembled across specimens. Scatter in T could reflect between-specimen variability rather than material behaviour. More specimens near threshold would help.

Authors response: This paper proposes to focus on fatigue crack growth when evaluating LEP materials, and we introduce a method for characterizing the resistance against crack growth of LEP materials. For future use and publication we work on a procedure for determining the threshold with higher accuracy, including more tests near the threshold.

Comment 3: The threshold $T \approx 2100 \text{ J/m}^2$ is based on very few data points. For something proposed as a curtailment criterion for erosion-safe operation, the physical sources of scatter need disentangling.

Authors response: We agree that for practical use, a more accurate determination of the threshold should be pursued. Regarding scatter, the largest source of uncertainty is related to the position of the crack tip. The pixel size corresponds to 0.02 mm, and uncertainty of crack tip position is estimated to be +/- two to three pixels. Below the threshold, the crack growth and tearing energy are typically evaluated over 1 mm crack growth, leading to uncertainties above 10%. Above the threshold the evaluation length is roughly 10 mm, and the uncertainty is roughly 2%. This applies both to the da/dN and the tearing energy based on $dw/(da_1 + da_2)$. This will be discussed in section 3.3 "The effect of strain and tearing-energy on crack growth rate". Other sources of uncertainty are the load, 1% the position, 1%.

Comment 4: No fitted crack growth law ($da/dN = B \cdot T^n$) is reported. This is straightforward from Figure 14b and would make the results immediately comparable with known elastomers.

Authors response: We will include a fit $da/dN = B \cdot T^n$ to the results section

Jakob Ilsted Bech

Comment 5: Is there any way to validate the crack propagation and link it with the dwell time via a stress relaxation model? The paper shows phenomenologically that T collapses the dwell-time effect, but does not explain why. A Prony series or fractional viscoelastic model fitted to the stress relaxation data could predict the stabilised strain energy as a function of t_d , providing that mechanistic link.

Authors response: Figure 8 shows hysteresis loops at different dwell times, and the text in section 3.1 elaborates on the correlation between dwell time and tearing energy for a given strain amplitude. The shorter the dwell time, the less stiff is the material, due to stress softening, and “permanent” elongation (Mullins and Payne effects). This is the reason why the strain energy for a given elongation, or peak strain, depends on the dwell time.

A viscoelastic stress relaxation model can potentially capture the dwell time effect. This is being examined in a separate paper, which is in writing. However, a viscoelastic stress relaxation model will not predict how da/dN depends on T .

Comment 6: "Strain energy" and "work of deformation" are used somewhat interchangeably.

Authors response: We will seek to harmonize this in the manuscript, and mainly use “strain energy”

Comment 7: For a material with significant hysteresis, only the recoverable elastic part maps strictly to w in the Rivlin-Thomas sense. This may partly explain why the 1.0 s dwell data sit slightly above 0.1 s even on the T -axis, viscoelastic dissipation at the crack tip is rate-dependent and not fully captured by the global W measurement.

Authors response: The material does exhibit significant hysteresis, which depends on both the rate and dwell time between successive load cycles. The recoverable elastic part of the strain energy may be more important in monotonic crack growth. For fatigue crack growth, with dissipation, the tearing energy, T , is not equivalent to stored elastic energy (such as the Energy release rate in linear elastic fracture mechanics). Here T serves as a crack driving parameter for the phenomenological da/dN versus T . And yes, near the crack tip, the local strains are greater than the global strain, and dissipation may be even more pronounced. Whether this would give rise to dwell time dependent differences is an interesting hypothesis.

Comment 8: The sentence "thereby increasing the energy release rate" (page 24) would benefit from inserting strain energy into the causal chain: work imparted $\rightarrow$ strain energy stored $\rightarrow$ energy release rate $\rightarrow$ crack driving, as discussed previously.

Authors response: Thank you for addressing this. Referring to your comment 7, we prefer to omit the term “energy release rate” from the discussion of fatigue crack growth in elastomers. We will change “Implying that longer dwell times permit a greater amount of work to be imparted into the system, thereby increasing the energy release rate, which facilitates both crack initiation and accelerated crack growth.” To:

“Implying that longer dwell times permit a greater amount of strain energy to be imparted into the system, thereby increasing the tearing energy, which facilitates both crack initiation and drives the fatigue crack growth.”

Jakob Ilsted Bech

Comment 9: There are many places missing a comma, making it hard to read, for example, page 5, "For the plane strain tensile test the grips need to be wide to ensure the plane strain constraint", there should be a comma after the "plane strain tensile test, ". The authors need to correct them all.

[Authors response:](#) We will go through the manuscript and correct for commas