Test Methods for Evaluating Rain Erosion Performance of Wind Turbine Blade Leading Edge Protection Systems

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Test Methods for Evaluating Rain Erosion Performance of Wind Turbine Blade Leading Edge Protection Systems

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Spring 2020
Technical University of Denmark
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Throughout this project, Siemens-Gamesa has been a steadfast partner helping with both materials for testing and rain erosion results. Specifically, I would like to thank Kasper Bondo Hansen, Michael Caspersen, Ane Blennow and Anette Struve Nielsen for facilitating my contact with Siemens Gamesa.

Equally as necessary for the project has been my close collaboration with Hempel A/S. A special thanks to Svava Davidsdottir for help and guidance early on in the project and to Pablo Bernard and Maral Rahimi for continuing to support my work here in the latter part of the project.

I would like to thank Arms-Gallery, bringing me into contact with my supervisor Jakob Ilsted Bech. Had they not mentioned that they already had sold one air gun to DTU wind, for them to shoot at turbine blades with, this partnership with DTU Wind might never have happened. Furthermore, I would like to thank Yukihiro Kusano and Leon Mishnaevsky at DTU Wind for their theoretical input. For help with construction and testing on the SPIFT, I would like to thank Lars Lorentzen and Gitte Christiansen.
Finally I would like to extend my thanks to the supervisory team. Professor Per Møller for acting as the initial primus motor in getting the Fast-Track project off the ground and motivating me to begin to investigate rain erosion. Jakob Ilsted Bech for helping with all the day-to-day minutiae of conducting PhD work. And as a fantastic sparing partner on all the technical and theoretical issues that popped up along the way. Despite "only" being co-supervisor on paper, Jakob has gone above and beyond in making this thesis possible.

Last but not least I would like to thank Professor Christian Nørdson for his help with getting the thesis to a much more polished state.
Abstract

In this thesis, two issues relating to conventional rain erosion testing are addressed: Firstly, erosion performance of a coating system has traditionally been expressed in hours to failure. Secondly, in an R&D A/S whirling arm rain erosion tester (RET) droplet impacts are distributed randomly; thus, information from the individual impact is lost.

The first problem with the time-based performance metric is that these results are often not reproducible on other testing set-ups. The second problem is that repeated droplet impacts at a single point with speeds over 100m/s are almost impossible and impractical for erosion testing. This type of high strain rate impact fatigue cannot be performed on traditional cyclic fatigue testers.

To solve the first problem of making RET data reproducible standards and best practices such as the ASTM G73-10 and DNVGL-RP-0171 exist. These are used to evaluate results from the new R&D A/S style RET, however, neither provide a full framework for rationalising erosion performance.

The second problem of isolating the effect of a single impact has previously been attempted by water jet based testers. These are capable of impacting a single point with a jet or mist of water, however, all of these testers are still only approximations of actual droplets.

In this thesis, the first problem of making the RET data more reproducible, was solved by combining methods from both standards with a statistical approach to the data analysis. To solve the second problem of repeated impacts, the water droplet impact was substituted by an impacting polymer ball, fired by the newly developed Single Point Impact Fatigue Tester (SPIFT). By firing polymer balls at the target coating a high strain rate impact can be generated. In traditional cyclic fatigue this would result in unnatural heating of the sample, which is avoided in the SPIFT by a combination of impact rate control and forced air cooling.

By using both the new SPIFT and the RET, three different coating systems were tested at different droplet sizes and impact speeds. Afterwards, all samples were evaluated using the new methods to evaluate the data and construct SN Curves. The SPIFT was used to establish a link between internal heat generation, resulting from impact, and the dynamical mechanical properties of the material.

The new evaluation methods allowed comparison of results from all the different tests and testers. We expect this method to significantly increase the usability of RET data while making the data more suitable for predicting actual erosion lifetime. The SPIFT provides a new tool for evaluating fatigue performance of new coating systems, as well as providing more insight into the nature of impact fatigue. Comparing RET and SPIFT, a tentative severity factor of $F_0 = 0.25$ between
RET and SPIFT was found. It was found that impact heating could be correlated to the material property $\tan\delta$ at high frequencies using time-temperature superposition DMA data.
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Chapter 1

Abbreviations

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<tr>
<td>ASTM E739-91</td>
<td>Standard TITEL</td>
</tr>
<tr>
<td>DMA</td>
<td>Dynamic Mechanical Analysis</td>
</tr>
<tr>
<td>DNVGL-CP-0424</td>
<td>Recommendation</td>
</tr>
<tr>
<td>DTU WIND</td>
<td>Technical University</td>
</tr>
<tr>
<td>GC</td>
<td></td>
</tr>
<tr>
<td>HAWC2</td>
<td></td>
</tr>
<tr>
<td>LCOE</td>
<td>Levelized Cost of Energy</td>
</tr>
<tr>
<td>PED</td>
<td>Point Erosion Damage</td>
</tr>
<tr>
<td>RET</td>
<td>Rain Erosion Tester</td>
</tr>
<tr>
<td>RPM</td>
<td>Rotation per minute</td>
</tr>
<tr>
<td>SN</td>
<td></td>
</tr>
<tr>
<td>SPIIFT</td>
<td>Single Point Impact Fatigue Tester</td>
</tr>
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<table>
<thead>
<tr>
<th>Greek letter</th>
<th>Unit</th>
<th>Description</th>
</tr>
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<tr>
<td>$\delta t_{speed}$</td>
<td>s</td>
<td>Time to approximate thermal equilibrium for a certain speed</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>N/m</td>
<td>Surface tension</td>
</tr>
<tr>
<td>$\psi$</td>
<td>Unitless</td>
<td>Volume concentration</td>
</tr>
<tr>
<td>$\varphi$</td>
<td></td>
<td>Coverage ratio</td>
</tr>
<tr>
<td>$\rho$</td>
<td>kg/m$^3$</td>
<td>Density of water</td>
</tr>
<tr>
<td>$\rho_l$</td>
<td>kg/m$^3$</td>
<td>Density of liquid</td>
</tr>
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### Chapter 1. Abbreviations

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<th>Symbol</th>
<th>Unit</th>
<th>Definition</th>
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<tr>
<td>$\theta$</td>
<td>rad</td>
<td>Coverage angle</td>
</tr>
<tr>
<td>$\omega$</td>
<td>rad/s</td>
<td>Angular velocity</td>
</tr>
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<table>
<thead>
<tr>
<th>Symbols</th>
<th>Unit</th>
<th>Definition</th>
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<tr>
<td>$A$</td>
<td>m$^2$</td>
<td>Area under rain field</td>
</tr>
<tr>
<td>$a$</td>
<td>m$^2$</td>
<td>Projected area of impinging drop</td>
</tr>
<tr>
<td>$b$</td>
<td>m$^3$</td>
<td>Volume of impinging droplet</td>
</tr>
<tr>
<td>$C$</td>
<td></td>
<td>Constant</td>
</tr>
<tr>
<td>$c_l$</td>
<td>m/s</td>
<td>Speed of sound in liquid</td>
</tr>
<tr>
<td>$d$</td>
<td>m</td>
<td>Droplet diameter</td>
</tr>
<tr>
<td>$d_{needle}$</td>
<td>m</td>
<td>Needle diameter</td>
</tr>
<tr>
<td>$f_i$</td>
<td>Hz</td>
<td>Specific impact frequency</td>
</tr>
<tr>
<td>$F_{full}$</td>
<td>Hz</td>
<td>Full deformation characteristic frequency</td>
</tr>
<tr>
<td>$F_g$</td>
<td>N</td>
<td>Gravitational force</td>
</tr>
<tr>
<td>$F_{peak}$</td>
<td>Hz</td>
<td>Peak impact magnitude characteristic frequency</td>
</tr>
<tr>
<td>$F_\gamma$</td>
<td>N</td>
<td>Surface tension force</td>
</tr>
<tr>
<td>$g$</td>
<td>m/s$^2$</td>
<td>Gravitational acceleration</td>
</tr>
<tr>
<td>$G'$</td>
<td>Pa</td>
<td>Storage modulus</td>
</tr>
<tr>
<td>$G''$</td>
<td>Pa</td>
<td>Loss modulus</td>
</tr>
<tr>
<td>$h$</td>
<td>m</td>
<td>Height of single impingement</td>
</tr>
<tr>
<td>$H_0$</td>
<td>m</td>
<td>Incubation Impingement</td>
</tr>
<tr>
<td>$H(t)$</td>
<td>m</td>
<td>Impingement</td>
</tr>
<tr>
<td>$I$</td>
<td>m/s</td>
<td>Mean rain intensity</td>
</tr>
<tr>
<td>$I_r$</td>
<td>m/s</td>
<td>Rain intensity as a function of radius</td>
</tr>
<tr>
<td>$K_e$</td>
<td>J</td>
<td>Kinetic energy</td>
</tr>
<tr>
<td>$l_{gz}$</td>
<td>m</td>
<td>Length of exposed blade</td>
</tr>
<tr>
<td>$m$</td>
<td>kg</td>
<td>Mass, or Unitless</td>
</tr>
<tr>
<td>$m$</td>
<td>Unitless</td>
<td>Parameter from ASTM E739-10</td>
</tr>
<tr>
<td>$N$</td>
<td>Unitless</td>
<td>Number of cycles</td>
</tr>
<tr>
<td>$\dot{N}$</td>
<td>#Impacts/s · m$^2$</td>
<td>Impacts per square meter per second</td>
</tr>
<tr>
<td>$N_0$</td>
<td>Unitless</td>
<td>Specific impacts for incubation</td>
</tr>
<tr>
<td>$p$</td>
<td>Pa</td>
<td>Impact pressure</td>
</tr>
<tr>
<td>$P$</td>
<td>m$^3$/s</td>
<td>Water flowrate</td>
</tr>
<tr>
<td>$q$</td>
<td>#Droplets/m$^3$</td>
<td>Number of droplets per unit volume, in the rotor plane</td>
</tr>
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### Chapter 1. Abbreviations

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<th>Unit</th>
<th>Description</th>
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<td>$Q$</td>
<td>J</td>
<td>Heat energy</td>
</tr>
<tr>
<td>$r$</td>
<td>m</td>
<td>Droplet radius</td>
</tr>
<tr>
<td>$r_0$</td>
<td>m</td>
<td>Outer radius of rain field</td>
</tr>
<tr>
<td>$r_i$</td>
<td>m</td>
<td>Inner radius of rain field</td>
</tr>
<tr>
<td>$S$</td>
<td>m/s</td>
<td>Impact speed</td>
</tr>
<tr>
<td>$S(N)$</td>
<td></td>
<td>Stress as a function of impacts</td>
</tr>
<tr>
<td>$t$</td>
<td>s</td>
<td>Exposure time</td>
</tr>
<tr>
<td>$t_0$</td>
<td>s</td>
<td>Incubation time</td>
</tr>
<tr>
<td>$U_i$</td>
<td>m/s</td>
<td>Column of water hitting sample per second</td>
</tr>
<tr>
<td>$U_r$</td>
<td>m/s</td>
<td>Rain Intensity</td>
</tr>
<tr>
<td>$v$</td>
<td>m/s</td>
<td>Impact speed</td>
</tr>
<tr>
<td>$v_{\text{drop,rp}}$</td>
<td>m/s</td>
<td>Droplet velocity</td>
</tr>
<tr>
<td>$v(r)$</td>
<td>m/s</td>
<td>Local rotor speed</td>
</tr>
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Chapter 2

Outline of the Dissertation

This thesis is structured as a monograph. The focus of the thesis is on the testing and analysis methods needed for evaluating rain erosion performance. Two styles of testing set-ups were used in this project: Firstly that of the R&D A/S style whirling arm tester of which the theory and data analysis methods are described in Chapter 8. The second test method covered in this thesis is the SPIFT (Single Point Impact Fatigue Tester) which is detailed in Chapter 6.

During the PhD study many different material systems were tested not all of which could be presented here. The following systems will be treated:

In the thesis three main coating systems were tested on both SPIFT and RET. These systems are GC, GA and GS as covered in Chapter 9. These coatings are representative of wind turbine blade coatings in use.

In Chapter 7 three pure polyurethane resins were tested. These were provided by Covestro AG as part of the Duraledge IFD project. These coatings were used to investigate impact heating effects as a function of material properties.

2.1 Manuscripts (not included in the Thesis)

During the PhD study a set of articles were co-written and published one pending submission. As the thesis is structured as a monograph these are not directly included. In this thesis these manuscripts will be referenced by their uppercase roman numerals as listed below.

I Y. Kusano, V. Fedorov, M. McGugan, T. Andersen and N. Frost-Jensen Johansen, *Impact*
Chapter 2. Outline of the Dissertation

* damage reduction by structured surface geometry*, Materials Letters, vol. 221, pp. 296–300.15 June 2018[1]


In the following the contributions by the PhD student to each of the manuscripts will be outlined.

### 2.1.1 Contributions to [I]

In Paper [I] *Impact damage reduction by structured surface geometry*. The PhD student contributed with the following. Design, construction and build of the SPIFT. All experimental work related to generating SN curves. All data treatment related to the SN curves.

- Assisted in setting up acoustic emissions systems and measuring acoustic emissions.
- Assisted in measuring impact fatigue damage using ultrasonic scanning.
- Measured material properties for use in the FEM modelling.

### 2.1.2 Contributions to [II]

In Paper [I] *Impact fatigue damage of coated glass fibre reinforced polymer laminate*. The PhD student contributed with the following. Design, construction and build of the SPIFT. All experimental work related to generating SN curves. All data treatment related to the SN curves.

- Assisted in setting up acoustic emissions systems and measuring acoustic emissions.
Chapter 2. Outline of the Dissertation

2.1.3 Contributions to [III]

In Paper [III] Rain erosion and the effect of air bubbles in the top coat on wind turbine blade. The PhD student contributed with the following.

Design of droplet experiment. Setting up and conduction in-field test with high speed imaging.

Analysing droplet paths from the high speed recordings tracking droplet paths.

2.1.4 Contributions to [IV]

In Paper [IV] Impact damage reduction by structured surface geometry. The PhD student contributed with the following.

Design, construction and build of the SPIFT. Experimental work related to generating SN curves. All data treatment related to the SN curves. All work involved in rationalising droplet impacts in the whirling arm RET.

Assisted in analysing x-ray tomography data.

2.2 Conferences Contributions

i 2016-10-27 Speaking at ATV-SPEAPP event at LORC test centre, presenting about the effects of rain erosion on wind energy production

ii 2018-02-22 Speaker at Offshore Energy A/S conference held at DTU Risø

iii Torque 2018 conference in Milan with a poster presentation. On the paper Investigation of droplet path in a rain erosion tester


v 2020-02-(04-06) Presenting at the, International Symposium on Leading Edge Erosion of Wind Turbine Blades, at DTU Wind Energy, Risø
Chapter 3

Introduction to rain erosion

Wind turbines are an ever more important part of the energy mix, especially here in Denmark with the latest numbers from 2018 showing that 40.68% of our electricity comes from wind energy, as can be seen in Figure 3.1. There are of course several factors that have helped facilitate this growth, with government funding historically being one of the main drivers behind wind energy

Figure 3.1: Fraction of wind energy in the Danish electric energy mix. Data from the Danish Energy Agency published May 2019, with wind energy being 40.68% .
Chapter 3. Introduction to rain erosion

proliferation. However, as the technology has matured we have seen a significant decrease in the Levelized Cost of Energy (LCOE) as seen on Figure 3.2. This has been driven by the economics of scale from a maturing industry but also reduced government subsidies. We are now at a point where wind energy is arguably the cheapest means of power generation in northern Europe.

![Figure 3.2](image-url)

**Figure 3.2:** The graph shows how the LCOE evolved during the last decade, the highlighted green line showing how the price per MWh for onshore wind has reduced 68% from 135 $/MWh in 2009 to just 42 $/MWh in 2018.

This has resulted in many of the wind turbines erected being privately funded. It is seen as a good low risk investment by large investment funds, with typical total Return of Investment being around 5% over a 20 year period. However, all these calculations rely on some assumptions on what the operational cost of the turbines will be. Obviously predicting component lifetimes 20+ years into the future is challenging. Presently excellent numerical tools exist such as HAWC2 by DTU WIND, which can predict and calculate the various mechanical loads on the static and rotating structures. Using such tools, manufacturers and operators can predict the service life of individual components at a given site to a reasonable degree. There is, however, one significant part of the turbine for which there does not exist the same frame work for predicting lifetime. This is the coatings covering the blades which are the most repaired parts of the wind turbine.

The turbine blades represent the single most expensive part of the turbine. The blades are key components in capturing the kinetic energy of the wind and converting it to usable torque. The condition of the blades play a large role in the energy production of the turbines, both in regards to total lifetime and energy output.
Chapter 3. Introduction to rain erosion

As mentioned, one part of this is protecting the blade from structural damage and fatigue, but the other part is protecting the composite blade from the operating environment, meaning UV radiation and moisture that can degrade the integrity of the composite structure.

Typically this is achieved by the application of a paint system to the blade protecting the composite from the environment, with present standards such as DNVGL-CP-0424 that provides a framework for qualification of coating system. These tests cover various static mechanical parameters and environmental degradation mechanisms.

3.1 The cost of erosion

Despite the industry’s best efforts, leading edge erosion is the most common type of damage observed on wind turbines. Examples of such damage can be seen in Figures 3.3.

<table>
<thead>
<tr>
<th>Erosion Level</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Example Picture</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
<td><img src="image4" alt="Image" /></td>
</tr>
</tbody>
</table>

*Figure 3.3: Examples of erosion level damage seen on one blade at different radii as evaluated by Siemens Gamesa in [7].*

As the turbine rotates, the leading edge of the blade is subject to impinging impacts from rain, dust and hail-stones. Of these impinging damage drivers, rain droplets are presumed to be the main damage driving factors behind this erosion. The Anholt offshore wind farm commissioned in 2012 is an example of how critical leading edge erosion can be. The farm rapidly started exhibiting signs of severe rain erosion damage. As of 2018 the blades are now being removed from the turbines in order to be re-coated. After which they will be replaced on the turbines. Having to periodically replace turbine blades is of course unsustainable in the long run. According to a review by [9] the operations and maintenance costs of 750 kW turbines might account for about 25% -30% of the
overall energy generation cost or 75–90% of the investment costs during a 20 year lifespan.

Although a significant cost driver, the cost of blade repair and maintenance is difficult to evaluate. The price of the repair is highly dependent on the type of repair solution chosen be that liquid paint, tape or prefabricated shell solutions. To complicate the calculations further repairs are rarely performed on a per turbine basis but rather in the form of larger repair campaigns, as of such it is inevitable that some turbines at a given installation are going to be operated with some amount of leading edge erosion. Therefore there is a large focus on annual energy production AEP(Annual Energy Production) losses related to operating with leading edge erosion. Depending on how severely the AEP is affected by different levels of leading edge erosion it might be financially favourable to extend to the service intervals.

However, accurately evaluating AEP losses is difficult as several factors regarding the turbine and its operation come into play. Firstly it is important to understand, that modern turbines operate following a power curve\[10\] as illustrated in Figure 3.4. As seen on Figure 3.4 the power output of a wind turbine increases with wind speed until the turbine reaches rated power. At wind speeds above the level needed to attain rated power, the output of the turbine plateaus. This is done by controlling the pitch of the turbine blades limiting the power production. So when a turbine is operating at or above its rated power some of the potential energy in the incoming wind is being wasted. The result of this control strategy is that power output is only directly influenced by the aerofoil efficiency below rated power.

It can therefore be very challenging to accurately evaluate the influence on AEP, as meteorological site conditions play into how much of the time a given turbine is at rated power.

Different opinions are found in the literature on to the potential AEP losses. A. Sareen\[11\] calculated potential AEP losses of between 4.5-25%, whereas Siemens Gamesa \[7\] report AEP loses of 1.7% at a erosion level 3 as seen on Figure 3.3. At 9th International Conference Advances in Rotor Blades 2019 Vestas A/S presented the Figure 3.5 list AEP losses between 0.7-5%. In a Report from Sandia National Laboratories \[12\] evaluated the potential AEP loses to be between 5-8%.

It should be noted that both Siemens Gamesa and Vestas as OEMs do have some vested inserts in potential AEP effects of leading edge erosion. Similar the work of A. Sareen \[13\]\[11\] has been conducted in collaboration with 3M who as OEM of LEP solutions do have an interest in AEP.

In Sandia’s 2017 report \[12\] the largest cost associated to erosion loss was on a 5MW turbine operating in an IEC 61400-1 Class II, wind class area. In this case the predicted annual cost was between $30’000-$36’000.
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Figure 3.4: Illustration of a typical power curve adapted from [10]. The curve illustrates the power output of a typical modern wind turbine as a function of wind speed.

Figure 3.5: Images of different stages of erosion with indicative resulting AEP losses adapted from a presentation by Vestas at the 9th International Conference Advances in Rotor Blades 2019.

3.2 Erosion drivers

One of the main reasons can be put down to the ever increasing size of modern wind turbines as seen in Figure 3.6.

In order to understand why larger turbines are advantageous consider the following equation for
Figure 3.6: Illustration showing how blade size has increased over the last 30+ years. The figure is from [13].

Theoretical max power output of a turbine following Betz’s law [15]:

\[ P = \frac{16}{27} \rho v^3 \pi r^2 \]  

(3.1)

Where \( P \) is the theoretical max power output, \( \rho \) is the density of air, \( v \) is the wind speed and \( r \) is the radius of the turbine. So if we want a turbine to produce more power the only parameter we can control is the size of the rotor.

As can be seen from this equation the tip speed is not directly linked to the size of the rotor. However, the power generated is proportional to the torque times angular velocity. Higher torque means higher loads on blade roots, gears, shafts, and bearings. In order for power to remain constant while lowering torque, the RPM of the turbine must be increased, which again leads to higher tip speed.

Looking at data from an operational turbine we see that there seems to be a correlation between size and increasing tip speed as seen in Figure 3.7. Traditionally tip speed has been kept under 90m/s due to noise concerns.

As turbines have increased in size, particular with offshore wind turbines, the tip speeds have increased as noise is less of a concern. The problem is that for a large turbine to maintain a low tip speed the RPMs of the turbine have to be kept low. To produce the same power at a low RPM means that the force or torque applied by the rotor has to increase. This increased torque can lead to failure in mechanical components like the gearbox, which has traditionally troubled many turbines.
So in order to reduce the load on the mechanical components tip speeds have been raised. This increases the force imparted by impacting rain droplets as described in section 3.2. This increase has brought the coating systems being used on turbines to their limit, and we therefore need to employ new test methods in order to develop new and better protection systems.

![Figure 3.7: The graph shows data collated\[16\] from different turbines where the tip speed of the turbines is plotted versus the rotor diameter. It can be seen, that the tip-speed tends to increase with rotor diameter.](image)

When looking at the existing literature in the field of rain erosion one quickly realizes that this field of research has its origins in the 1950’s Jet-Age\[17\]. Focus was on the polymers used for cockpit canopy\[18\] and the polymer shell covering the radar equipment, the so-called Radome\[19\] as this needs to be transparent to radio signals and is typically mounted in the nose of the air plane, and as such is subject to impingement by incoming rain.

The findings of the time showed that rain erosion on polymeric materials progresses similar to cyclical fatigue. Whereby each individual impact lacks the force to damage the material, but with successive impacts damage accumulates in the material until the point of material loss. From this we get the theory of the peak impact pressure\[17\]\[20\] or the water-hammer\[21\] pressure being the driving factor behind droplet erosion.

In the following two sections we shall evaluate two of the main theories of droplet impact severity that of transferred kinetic energy or water hammer impact pressure. The choice of model here greatly influenced the results generated, leading to different conclusions. It is therefore important to understand the basis for each model. Concluding these two sections will be a discussion as to why neither of these models are implemented in the thesis due to their potential to introduce errors and unneeded complications.
3.2.1 Kinetic energy transfer

The simplest way to evaluate the impact from each droplet is to consider kinetic energy transfer. Here it is assumed that the kinetic energy of the impacting droplet is transferred to the coating. The energy can be calculated as

$$K_e = \frac{1}{2}m v^2 = \frac{4}{27} \left( \frac{d}{2} \right)^2 \rho v^2$$

(3.2)

where $m$ is the mass of the droplet, $d$ is the droplet diameter, $v$ is the impact velocity, $K_e$ is the kinetic energy and $\rho$ is the density of the liquid.

This approach is typically used in regards to soil erosion studies\[22\][23] where kinetic energy is used to evaluate the severity of soil erosion.

In regards to using kinetic energy transfer on droplet impact on a solid surface, there are some issues. Using Equation 3.2 it is assumed that all kinetic energy is transferred to the impacted solid. This is only valid in the case of a plastic impact in which no mass is lost. However, this is not the case for an impacting droplet as it would require the droplet to permanently stick to the surface. Instead during impact the droplet is broken apart and spread laterally across the surface. In this process, some part of its kinetic energy is conserved in the lateral velocity of the spreading droplet. This fact alone negates the theory that the kinetic energy is fully transferred to the impacted solid. Some amount of energy is transferred to the solid, but evaluating this analytically is almost impossible, as measuring the remaining kinetic energy in the laterally jetting water is not practically possible.

In general, the kinetic energy transfer model will tend to overestimate the severity of larger impacting particles as the kinetic energy scales with the power of three to the radius. Thus it predicts that larger droplets are much more damaging. This is also why the model generally would predict that hail events would be much more severe than any normal precipitation event. It might be that the kinetic energy model is more applicable to hail events as the impacting particle is solid thus resulting in more kinetic energy transfer during the impact. However, some amount of energy is still translated into lateral dispersion of ice particles during the impact event.

I concluded that unless all factors are included to account for all of the kinetic energy during the impact, the model is not suitable for rain erosion studies.

3.2.2 Water hammer and Springer damage model

When it comes to analytically describing rain erosion, the most common model by far is the Springer model by George Springer citeSpringer1976[24]. The model attempts to combine several measurable material parameters with erosion performance as well as combining the effect of different sizes and
impact speeds. At the core of the Springer model is the assumption, that the impact pressure at the initial stages of the impact results in stress cycles in the material leading to fatigue damage. The effects of the multiple stress cycles is accounted for by using The Palmgren–Miner linear damage rule \[25\] \[26\] from accumulated fatigue damage. The model assumes that if the fatigue process can be represented linearly on a log-log SN curve as seen in Figure 3.8.

![Figure 3.8: Illustration from [27] showing the Palmgren-Miner linear damage hypothesis, used on the continuous linear segment of the SN curve. Some materials might exhibit different behaviour at very high cycle fatigue thus changing the slope of the curve as seen on the figure.](image)

By this model the fatigue life of a material subjected to impacts at different stresses levels can be expressed as a sum of fractional damages:

\[
\frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + \cdots + \frac{n_q}{N_q} = a_1
\]  

(3.3)

Here \(n_q\) is the number of stress cycles the material is subjected to at a given stress level \(S_n\) as illustrated on Figure 3.8. Failure is reached once these fractions sum to one following the specific fatigue curve of the material.
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Interface stresses liquid impact on a homogeneous solid

The following section will be presenting the Springer methodology for calculating the peak impact stress/pressure adapted from Springer’s 1976 book [28].

In order to simplify the process of the impacting droplet the Springer-model uses the following assumptions:

1. The effects of the lateral outflow are negligible
2. The pressure is uniform and constant over the entire contact area
3. The problem is one-dimensional.

To use this for a basis of a semi-analytical fatigue failure model Springer needed a method to evaluate the stresses of impacting raindrops. Springer chose to focus on the initial stages of impact which were found By Engel [17] to be associated with the highest impact pressures. This situation of a liquid impacting a solid can be seen in Figure 3.9, this type of impact if commonly referred to as a water hammer impact.

When looking at the literature using a version of a water-hammer impact to evaluate the magnitude of impact stress is among the most common starting points, see [30] [31] [32] [7] [20] as well as many more examples of its ubiquity. Commonly one will find this impact pressure presented in a very simplified form as:

\[
P = \rho CV \tag{3.4}
\]

There \( P \) is the pressure \( \rho \) is the density of the impacting liquid, \( C \) is the speed of sound in that liquid and \( V \) is the impact velocity. This is, however, a heavily simplified version of the interaction between liquid and solid. It is my opinion that if this model is to be employed, a deeper understanding of this model is needed. In the following I will therefore bring a simplified explanation of the water-hammer equation as presented in Springer’s 1976 book - Erosion by Liquid Impact [28]. This is done since the 1974 paper by Springer [24], which is cited by most, still, only brings a simplified version as compared to the book. Unfortunately, the book is no longer in print nor available in a digital version. I therefore find it prudent to present some of the methodology here in this section. Consider the scenario in Figure 3.9 where the impact between solid and droplet is simplified to a collision between a liquid and a solid cylinder. It is assumed that there is perfect contact between the liquid and solid. From the point of contact two shock waves now travel, one through the solid and the second through the liquid. Upon impact, a one-dimensional stress wave
Figure 3.9: Illustration from [28] who adapted the illustration from [29]. Collision between a droplet and a semi-infinite surface idealised as a collision between a liquid and a solid cylinder. The velocities shown refer to the stationary X-Y reference frame.

propagates into the solid and into the liquid with velocities $U_s$ and $U_L$. Each of these waves is also associated with a particle velocity $u_S$ and $U_l$ which comes from the material displacement resulting
in a displacement velocity. Knowing $U$ and $u$ the pressure over this forefront can be expressed as:

$$\Delta \sigma_s = \rho_s U_s u_s$$ \hspace{1cm} (3.5)

$$\Delta \sigma_L = \rho_L U_L (V - u_L)$$ \hspace{1cm} (3.6)

Where $\Delta \sigma_s$ is the stress across the solid wave, $\Delta \sigma_L$ is the stress across the liquid wave, $\rho_L$ is the density of solid and liquid and finally $V$ is the impact velocity of the droplet.

Let us first consider the case of the stationary solid. For a given material there is a relation between the stress gradient across the way front $\delta \sigma$ and the particle velocity $u_s$ during a shock loading is known as the Rankine-Hugoniot relationship. An example of such a curve can be seen in Figure 3.10(a). It is seen that for increasing particle velocities there is a trend in increasing stress differential across the way front.

![Figure 3.10: Illustrative Rankine-Hugoniot curve for a material. In (b) Rankine-Hugoniot curves for different materials are shown. Illustrations from [28]](image)

Using the Rankine-Hugoniot curves for droplet liquid and the impacted solid it is possible to calculate the surface impact pressure by applying the following assumptions. Firstly, we assume perfect contact between the liquid and a solid this means that the particle velocities at the interface must be equal.

For the solid, the particle velocity $u_s$ is set to be zero far away from the surface. At the surface there is assumed perfect contact resulting in identical particle velocity for liquid and solid:

$$u_L^0 = -u_s^0 = u^0$$ \hspace{1cm} (3.7)
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Here the superscript 0 denotes that the values are at the solid liquid interface.

Furthermore, it is assumed that at the point of contact the stresses in liquid and solid are identical.

$$\Delta \sigma^0_s = \Delta \sigma^0_L = \Delta \sigma^0$$  \hspace{1cm} (3.8)

With these assumptions Rankine-Hugoniot curves can be combined as seen in Figure 3.11(a) in order to find the magnitude of the impact pressure/stress $\Delta \sigma^0$.

![Figure 3.11](image)

**Figure 3.11:** In Subfigure (a) it is shown how Rankine-Hugoniot curves can be used to find the $\Delta \sigma^0$ stress at the interface between droplet and solid. In Subfigure (b) $\Delta \sigma^0$ is found using the assumption of a linear relationship between $\Delta \sigma$ and the particle velocity as illustrated in Figure 3.10(a). Illustrations is taken from [28].

In practice this is achieved by finding the intersection between the regular Rankine-Hugoniot curve for the impacted material and the "flipped curve" for the impacting liquid. For the impacting liquid $\Delta \sigma$ equals zero when the particle velocity equal to impact velocity $V$ as can be seen from equation 3.6.

However, constructing Rankine-Hugoniot is a non-trivial test and as such curves for different materials can be difficult to obtain. One of the best commonly available databases "LOS ALAMOS SERIES ON DYNAMIC MATERIAL PROPERTIES" [33]. However, for many materials finding material curves can still be challenging. Especially data for polymers and elastomers is very limited.

In lieu of Rankine-Hugoniot curves for a given material and a linear dependence between $\Delta \sigma$
is often assumed. This is based on observations that when \( u \rightarrow 0 \) the \( \Delta \sigma \) vs. \( u \) curve can be approximated by the linear dependence:

\[
\Delta \sigma = \rho C \tag{3.9}
\]

Where \( C \) is the speed of sound in the undisturbed media, this dependence is illustrated on figure 3.10(a). This trend of reasonably linear dependence at low velocities. This can be seen on the example Rankine-Hugoniot curves on Figure 3.10(b). This relation can also be illustrated by the equation (3.5) that has been rearranged and divided by \( C^2 \):

\[
\frac{\Delta \sigma}{\rho C^2} = \frac{U u}{C C} \tag{3.10}
\]

Firstly, it can be seen that for low particle velocities \( u \) the following term approaches zero:

\[
u \rightarrow 0 \quad \frac{u}{C} = 0 \tag{3.11}
\]

\[
\frac{\Delta \sigma}{\rho C^2} = \frac{U}{C} \tag{3.12}
\]

Springer [28] cites the power series proposed by Heymann [34] as a way of expressing ratio between \( U/C \) as a function of \( u \):

\[
\frac{U}{C} = 1 + B_1 \left( \frac{u}{C} \right) + B_2 \left( \frac{u}{C} \right)^2 \tag{3.13}
\]

In this power series \( B_1 \) and \( B_2 \) are constants and are based on observations from experiments with Rankine-Hugoniot testing of various materials. Where it is typically observed that \( U \) approaches \( C \) for small values of \( u \) [34].

The equations (3.12) and (3.13) can be combined and evaluated at cases where particle velocity \( u \) us much smaller than the speed of sound \( C \) with this Springer[28] shows the following:

\[
U \rightarrow C \quad \text{When} \quad \frac{u}{C} \ll 1 \tag{3.14}
\]

\[
\frac{\delta \Delta \sigma}{\delta u} \rightarrow \rho C \quad \text{When} \quad \frac{u}{C} \ll 1 \tag{3.15}
\]

It is assumed that wave-velocity is equal to \( C \) and that the slope of the \( \Delta \sigma \) curve is linear and equal to \( \rho C \). From this we get the simple "water-hammer" equation:

\[
\Delta \sigma = \rho CV \tag{3.16}
\]

\[
= ZV \tag{3.17}
\]
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Where \( Z \) is the dynamical impedance. Applying the conditions from equation (3.7) and (3.8) the intersection between the two linear functions can be found as shown in Figure 3.11(b). This can be calculated as follows:

\[
\Delta \sigma^0 = \frac{\rho_L C_L V}{1 + \rho_L C_L / \rho_s C_s}
\] (3.18)

This is what Springer refers to as the impact pressure on a homogeneous solid. The particle velocity at the interface can be calculated using:

\[
\frac{u_0}{C_s} = \frac{V}{C_s} \frac{1 + \rho_s U_s / \rho_L U_L}{1 + \rho_s U_s / \rho_L U_L}
\] (3.19)

\[
\frac{u_0}{C_L} = \frac{V}{C_L} \frac{1 + \rho_s U_s / \rho_L U_L}{1 + \rho_s U_s / \rho_L U_L}
\] (3.20)

As Springer notes this straight-line approximation is reasonably accurate near the origin of the Rankine-Hugoniot curve. Where the following inequalities are valid:

\[
\frac{u_0}{C_s} \ll 1
\] (3.21)

\[
\frac{u_0}{C_L} \ll 1
\] (3.22)

This tends to be valid for many solid materials and impact conditions, as the speed of sound in the material tends to be much higher than the particle velocity. Looking at the diagram in Figure 3.11(a) the particle velocity at the interface \( u^0 \) will always be some value less than the impact velocity \( V \):

\[
u_0 < V
\] (3.23)

Based on these inequalities Springer constructs the following criteria for what the maximum impact speed \( V_{\text{max}} \) is for which the straight line approximation is valid:

\[
V_{\text{max}} = 0.3C \left( 1 + \frac{Z_s}{Z_L} \right)
\] (3.24)

Where \( C \) is the speed of sound. In these calculations the lowest value of \( C \) should always be chosen whether that be the liquid or the solid. In the Table 3.1 below can be seen \( V_{\text{max}} \) according to Springer calculations using both values from Springer book and from H. Slots review paper.

Discussion on the applicability of the Springer model on Elastomers

When looking at the materials considered in the Springer book most materials end up having a \( V_{\text{max}} \) much higher than the typical tip speed of \( \approx 90 \text{m/s} \) observed on wind turbines. However, most of these materials including the polymers are likely what would be considered as "Hard".
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Table 3.1: The table shows maximum impact speeds $V_{max}$ that Springer recommends using the straight line approximation of the Rankine-Hugoniot curve. The first set of data in the table is from Gorge Springer’s book [28] material data for rubbers and elastomer is from Slot [31]

In the world of coatings these polymers might be mostly equivalent to the Gel-coats applied to early turbines. However, as observed by M. Keegan [16], H. Slot [31] and M. Elhadi [32] elastomeric materials are currently considered to be among the best candidates for erosion resistant coatings.

Using the elastomer material data provided in Slot’s paper [31], and applying equation (3.24) $V_{max}$ can be calculated as seen in Table 3.1. Here it is clear that according to equation (3.24) the straight line approximation is not applicable for calculating the impact pressures $\Delta \sigma^0$ even at the relatively low impact speeds on wind turbines.

If it is assumed that the actual Rankine-Hugoniot curve for the elastomer follows the trend seen in Figure 3.10(a) we would expect the linear model to under predict $\Delta \sigma^0$ compared to the diagram constructed of measured Rankine-Hugoniot curves. This situation of under prediction can be seen in Figures 3.11(a) and 3.11(b).

However, due to the viscoelastic behaviour of some of these materials, namely polyurethane, the actual Rankine-Hugoniot curves might be more complex.

It is my opinion that the linearised approach inherent in the standard 'Waterhammer' equation (3.18) is no longer applicable when dealing with "modern" Polyurethane coating systems.
3.2.3 Impacts to failure \( n_i \)

The most enticing part of the Springer model is that it provides a tool for predicting the number of impacts to failure on a given material impacted by a known quantity of droplet impacts:

\[
\begin{align*}
    n_i &= a_1 \left( \frac{S}{P} \right)^{a_2} \frac{4}{\pi d^2} \quad \text{(impacts/m}^2\text{)} \\
    n_i &= 7 \times 10^{-6} \left( \frac{S}{P} \right)^{5.7} \frac{4}{\pi d^2}
\end{align*}
\]

Where \( a_1 \) and \( a_2 \) are arbitrary fitting parameters, \( S \) is typically referred to as the 'strength' of the material and \( P \) is the impact pressure typically calculated as \( 3.18 \) and \( d \) is the diameter of the droplet in meters. The most common version of this equation is the reduced version where \( d \) is in millimetres:

\[
\begin{align*}
    n_i &= 8.9 d^2 \left( \frac{S}{P} \right)^{5.7} \\
    n_i &= 7 \times 10^{-6} \left( \frac{S}{P} \right)^{5.7} \frac{4}{\pi d^2}
\end{align*}
\]

The material 'strength' \( S \) is in Springer’s model expressed as:

\[
\begin{align*}
    S &= \frac{4\sigma_u(b-1)}{(1-2\nu)[1-(\sigma_I/\sigma_u)^{b-1}]} \\
    S &\approx \frac{4\sigma_u(b-1)}{1-2\nu}
\end{align*}
\]

Where \( \sigma_u \) is the ultimate material strength of the material, \( b \) is the slope of the SN-curve of the material i.e. the Wöhler exponent, \( \nu \) is Poisson’s ratio and \( \sigma_I \) is the fatigue limit for the material. Most commonly only the simplified version, seen in equation \( 3.29 \), is used.

At the core of this material 'Strength' \( S \) is a set of assumptions on the failure mechanism. Firstly it is assumed that the failure is fatigue driven following a Palmgren-Miner rule as shown in Figure 3.8 and expressed in equation \( 3.3 \).

In order to calculate the lifetime based on this, \( n_q \) needs to be evaluated, e.g. the magnitude and number of stress waves “felt” at an arbitrary spot on the surface. Here Springer chooses to reduce the droplet impact to a point force on the surface as illustrated in Figure 3.12.

The magnitude of these point forces \( F \) is calculated as:

\[
F = \frac{\pi d^2}{4} P
\]

where \( P = \Delta \sigma^0 \) as calculated in \( 3.18 \). Depending on the distance \( r \) from Point B the magnitude of this force is attenuated. Springer assumes an attenuation similar to a surface body wave citing Timoshenko.

\[
\sigma(r) = \frac{F(1-2\nu)}{2\pi r^2}
\]
This means that there is an inherent $1/r^2$ attenuation of impacts. Whether or not it is these body waves that are the main damage driver, it has been suggested that Rayleigh surface waves might be the more driving type of stress wave in regards to rain erosion damage.

One will typically come across an illustration such as the one seen in Figure 3.13. These observations have their origin in soil mechanics where wave propagation originating from a point excitation has been extensively studied. As can be seen from Figure 3.13 R. Woods found that the majority of the impact energy (67%) is contained in the Rayleigh waves. As can be seen from the illustration, Rayleigh waves attenuate as $1/r$ meaning that they decay much slower.

For a full explanation of Springer’s material strength $S$ the reader must refer to Springers’ book.

The goal of this simplified explanation of some of the Springer methodology is to provide the reader some understanding of the multitude of effects inherent to this model. The fact that some have had success with the model might be due to the many possible fitting parameters. Furthermore the model requires parameters obtained from measured VN curves e.g. Wöhler exponent $b$, which might explain why the model can be made to fit.

As a final remark we see the influence of the Springer model in the DNVGL-RP-0171 as the output of the calculations herein is rationalised as $[\text{impacts/m}^2]$ making the result directly applicable to the Springer methodology. As opposed to the method of evaluating impingement $H_0$ or dimensionless impacts $n_0$ as used in ASTM G73-10.
3.2.4 Springer model internal reflection

A further complication that is often included in the Springer model is internal reflections\cite{7}.

In order for internal reflections to occur, a characteristic time $t_L$ is defined. $t_L$ is the time, it takes for the initial shock wave to travel from the front of the droplet to the back of the droplet and return to the interface.

Looking at Figure 3.9 we can see the wave travelling upwards towards the back of the droplet, with a velocity $U_L$. Once the wave reaches the back of the droplet it is reflected back. This is taken as the duration within which the peak stresses are likely to occur, as it allows for the possibility of constructive interference of the shock waves resulting in increased damage.

If we again assume that the wave velocity $U_L$ is equal to the speed of sound $C_L$ the impact duration is calculated as:

$$t_L = \frac{2d}{C_L} \quad (3.32)$$

Where $t_L$ is the duration of impact.
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If we apply this idea of travelling waves interfering we could imagine what a wave travelling in the solid could reach a new material interface and be reflected back.

Reflection is possible any time there is a discrete jump in acoustic impedance. These layered structures could be coated materials, sandwich or composite laminates. At these interfaces some fraction of the shock waves will reflect back.

Following the same logic as before we can postulate that if this wave were to be reflected back to the surface within the impact duration e.g. \( t_L > t_s \), constructive interference can occur increasing the interface pressure. Using this, one can calculate the minimum material thickness for reflection to be negligible:

\[
 h_s > 2d \frac{C_s}{C_L} \tag{3.33}
\]

For most metallic materials, this minimum layer thickness for reflection to be negligible can be fairly large, as the speed of sound in the material is much higher than in water. Examples of \( h_s \) values can be seen in Table 3.1. Here it can be seen that \( h_s \) is about \( \approx 14 \text{mm} \) for an assumed 2 mm droplet diameter.

However, applying this to polyurethane and elastomer materials, results in much lower minimum layer thickness with as low as 254 \( \mu \text{m} \). Typically LEP coatings and protection strategies tend to be in excess of 500 \( \mu \text{m} \). For some solutions, like the PolyTech ELLE[41], the coatings can be several millimetres thick.

Based on Springer’s considerations it is unlikely that there will be any significant internal reflections in modern polyurethane based coating systems generally. Applying the Springer methodology of wave reflections on coating/substrate interfaces, may just add unnecessary complication to an already complex problem.

3.2.5 Conclusions on the Springer model

In conclusion, there are many fascinating observations in the Springer methodology. However, it is also very evident that the model is primarily focused on hard/linear elastic materials. After considering the go no-go criteria expressed in equations (3.33) and (3.24), the choice was made not to apply the Springer methodology to any of the data in this thesis. For this study SN-curves will only be plotted as impact speed \( S \) versus impingement \( H_0 \) or dimensionless impacts \( n_0 \) as used in ASTM G73-10[40].
Chapter 4

Review of rain erosion test methods

As already mentioned in Section 3.2, the field of rain erosion testing has seen substantial development since the early 1950s. As such various testing setups have been designed to simulate rain erosion, to either generate a more controlled failure or to do accelerated testing. An excellent overview of some of the different speed ranges and situations in which rain or liquid impingement erosion can occur is summarised by Mohamed Elhadi [32]. This can be seen in Figure 4.1.

![Figure 4.1: Table adapted from [32] covering applications and situations where droplet erosion can occur and the range of impact speeds](image)

<table>
<thead>
<tr>
<th>Application</th>
<th>Parts Affected</th>
<th>Impact Speed</th>
<th>Droplet Diameter</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam Turbine</td>
<td>Blades of the low-pressure stage</td>
<td>400–900 m/s</td>
<td>50–400 μm</td>
<td>[17,18,33]</td>
</tr>
<tr>
<td>Gas Turbines</td>
<td>Compressor blades</td>
<td>100–600 m/s</td>
<td>200–600 μm</td>
<td>[21]</td>
</tr>
<tr>
<td>Wind turbine</td>
<td>the outer power-producing part</td>
<td>70–150 m/s</td>
<td>0.5–5 mm</td>
<td>[6,34]</td>
</tr>
<tr>
<td>Nuclear Power Plants</td>
<td>Cooling pipes</td>
<td>~200 m/s</td>
<td>60–80 μm</td>
<td>[35]</td>
</tr>
<tr>
<td>Aero engine</td>
<td>fan blade</td>
<td>200–400 m/s</td>
<td>1–5 mm</td>
<td>[23]</td>
</tr>
<tr>
<td>Aircrafts</td>
<td>Rain erosion of different parts.</td>
<td>Civil airplanes ~ 250 m/s</td>
<td>1–5 mm</td>
<td>[25,36]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fighter Jets ~ up to 5 Mach</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As can be seen from Figure 4.1 [32], droplet erosion covers a large range of speed and droplet sizes. Due to the wide range of droplets and impact velocities there is no one test method that can
Chapter 4. Review of rain erosion test methods

cover all conditions. The highest speeds are attributed to turbine blades and aircraft applications. Considering the range of droplet sizes and impact speeds, it is not surprising, that the different scenarios require different protective solutions and as a result also different testing methods.

Another excellent overview is found in Shizhong Zhang’s paper[42] as seen in Figure 4.2. It is evident that there is a multitude of different test methods, each with its own accompanying pros and cons.

The goal in this chapter is not to provide a full overview of all the different types of RET testers, but rather to provide some relevant commentary on some selected testers. Some of the limitations of the different testers will be discussed e.g. impact speed, impact rate, "size" of droplet and adaptability to different test materials.
## Chapter 4. Review of rain erosion test methods

### Historical overview of liquid erosion experiments.

<table>
<thead>
<tr>
<th>Type of water erosion</th>
<th>Rig names</th>
<th>Relevant parameters</th>
<th>Advantages</th>
<th>Drawbacks</th>
<th>First time reported</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impacting continuous water jets</td>
<td>Wheel and jet [14–16]</td>
<td>Jet diameter 0.3–2.5 mm. Maximum impact velocity 600 m/s. Impact velocity 0–40 m/s. Impact angle 90°.</td>
<td>Simple fabrication and operation.</td>
<td>Poor reproducibility.</td>
<td>1924</td>
</tr>
<tr>
<td></td>
<td>WJA (conventional water jet erosion apparatus) [44]</td>
<td></td>
<td></td>
<td></td>
<td>1997</td>
</tr>
<tr>
<td>Impacting water jet slugs</td>
<td>MIJA (multiple impact jet apparatus) [6,23,26,30,36,38]</td>
<td>Impact velocity 30–600 m/s. Nozzle orifice to specimen 10 mm. 20 impacts per minute.</td>
<td>Inexpensive rig. Well controlled testing parameters. Reproducible results. Reproducible jet profile. Narrow velocity spread (0.5–1.5%). Flexible sample size, shape and material.</td>
<td>High experimental skills required. Only jets can be generated.</td>
<td>1991</td>
</tr>
<tr>
<td></td>
<td>Discrete jet (or interrupted jet) [1,6,31,32]</td>
<td>Not available</td>
<td>Cheap to fabricate and operate. Useful for a limited range of materials.</td>
<td>Inaccurate results.</td>
<td>1957</td>
</tr>
<tr>
<td></td>
<td>GRCI Ballistic range [6,23,36,38]</td>
<td>Droplet size 1.5–5.0 mm. Impact angle 0–60°. Impact velocity 100–1000 m/s. Maximum cylinder diameter 20 mm.</td>
<td>Both spherical and distorted water drops can be generated. Both single and multiple impacts modes available. Excellent reproducibility. High velocity available. Consistent correlations between impact velocity, droplet size and impact angle. Direct correlation between cause and effect. Excellent for erosion mechanism study.</td>
<td>Expensive fabrication. Low test velocity. Short useful testing time. Unrealistic droplet concentration. Temperature difficult to control. Droplet size hard to control. Results difficult to compare with other rigs. Extremely expensive to fabricate and test. Samples suffering from shock wave effect. Different water drop concentration distribution. Low test efficiency.</td>
<td>1976</td>
</tr>
<tr>
<td></td>
<td>Wind tunnel [6]</td>
<td>Artificial rainfall 0.31/s. Water concentration 50–100 times higher than real environment. Impact velocity 200–275 m/s. Useful test time 100 s. Specimen diameter 260 mm.</td>
<td>Results correlate well with practical flight testing.</td>
<td>Expensive fabrication. Low test velocity. Short useful testing time. Unrealistic droplet concentration. Temperature difficult to control. Droplet size hard to control. Results difficult to compare with other rigs. Extremely expensive to fabricate and test. Samples suffering from shock wave effect. Different water drop concentration distribution. Low test efficiency.</td>
<td>1965</td>
</tr>
<tr>
<td></td>
<td>Holloman Rocket sled [6,36,38]</td>
<td>Rainfall 1800 m. Maximum velocity 2000 m/s. Impact angle 0–70°.</td>
<td>Consistent data. Results correlate with practical flight testing. Extremely high impact velocity possible. Small to full-scale objects can be exposed.</td>
<td></td>
<td>1957</td>
</tr>
</tbody>
</table>

*Figure 4.2: Table by [42], Overview table listing different types of rain erosion testers. The blue references refer to the original references as found in the paper [42]*
4.1 Stationary sample jet impacted

Another category of RET is where the sample is stationary which is impacted by accelerated water. Here the entire relative impact velocity $\Delta V$ of the impact comes from the velocity of the water jet.

The advantage here is that the sample can easily be observed in-situ, and sample holding is overall a simpler process.

The difficulty in this method is, that accelerating individual droplets above the terminal velocity is almost impossible without the droplet breaking up, due to aerodynamic forces resulting in ballooning of the droplet [43]. This was also observed in our own small experiment, see 8.2.

In the face of these challenges several types of jet based erosion testers exist. In the following subsection some of these will be discussed, considering the advantages and disadvantages of each.

4.1.1 Interrupted jet

Among the most typical approaches to the problem of making a high velocity droplet analogue, is to chop a fast moving stream of high pressure water [44][42][45]. Typically the stream of water is chopped by a spinning disc with a set opening angle. One such machine is the Pulsating Jet Erosion Test rig (PJET) developed at EADS, IW, which can be seen in Figure 4.3. The droplet length can then be calculated as:

$$L_{\text{droplet}} = \frac{V_{\text{stream}}}{\alpha \omega}$$

(4.1)

Where $L_{\text{droplet}}$ is the length of the chopped stream, $V_{\text{stream}}$ is the velocity of the stream of water, $\alpha$ is the angle of the opening and $\omega$ is the angular velocity of the chopping disk. The width of the
Chapter 4. Review of rain erosion test methods

droplet can then be set by the water nozzle diameter.

One potential issue with this approach is that the impact rate will be coupled to the droplet size. If we consider the simplest setup with a stationary sample and a single slot chopping disk. Then the impact rate will be:

\[ \dot{n} = \frac{\omega}{2\pi} \]  

(4.2)

where \( \dot{n} \) is the impact-rate. There are ways of getting around this issue of \( \dot{n} \) being linearly proportional to \( \omega \). One solution is to have a continuously moving sample as in [42][46] which reduced the effective impact rate a given point on the surface. Another possible solution could be to have two chopping discs, one to set the droplet length and a slower rotating disk setting the impact rate.

In general it has been found that this type of impactor yields inconsistent results [46]. It has been speculated that residual water on the surface could affect the erosion process. It could also be due to impact rate problems, where some materials might need several seconds to fully recover.

There is also the issue of the chopped stream not having a droplet shape and possibly breaking up before impact.

4.1.2 Impacting water jet slugs

Another iteration on the jet impactor is the impacting water jet slug’s type erosion tester known as the multiple impact jet apparatus (MIJA)[47][48][49]. Here the core concept is that instead of having a continuous stream of water that is chopped up into droplets, a small amount of water is fired as a jet towards the sample.

Typically, this is achieved by impacting water confined in a cylinder with a piston, forcing it out of a small nozzle. The piston is then impacted by a fast moving slug, typically made of metal. The impacting metal slug transfers its kinetic energy through the piston, forcing the water out the nozzle at high speed.

Despite the nozzle diameter being smaller than the desired droplet size, the high exit velocity of the ejected stream results in a wider spray as seen in Figure 4.4(b). From the paper [51] it is reported that different choices of nozzle size and impact force can mimic a range of impact speeds and droplet sizes.

However, this type of tester can at best produce an approximated droplet. The umbrella shaped front of the jet actually consists of many micro droplets. In addition, the difficulty in maintaining an identical "droplet" shape across a wide range of impact speeds is a severe limitation.

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Chapter 4. Review of rain erosion test methods

Figure 4.4: In (a) a schematic illustration of the multiple jet impact apparatus MIJA\textsuperscript{[50]} is seen. In (b) a single high-speed photograph of a jet from a 0.8-mm nozzle is shown. Here it can be seen how the jet spreads out in an umbrella shape larger than the original nozzle diameter. Image from \textsuperscript{[48]}

The advantages to the setup is, that it provides excellent control over the impact position which can even be computer controlled\textsuperscript{[47]}. This allows for batch testing or even simulated distributed impacts. Impact rate is also very well controlled and can be varied independently of impact speed.

The development of this test method was driven by Cavendish Laboratory at Cambridge. Unfortunately, it seems that development on the MIJA has effectively ceased as of 2011\textsuperscript{[47]}, due to the complexities of replicating the setup and the difficulty in verifying the nozzle jet patterns, It seems unreasonable for anyone outside of the Cavendish Laboratory research group to take on the task of replicating the MIJA.

4.2 Whirling arm testers

As opposed to the impacting jet tester, as described above, whirling arm testers supply the needed $\Delta V$ by moving the sample. This approach removes the complexities related to trying to accelerate a droplet but does introduce its own set of challenges.

In the following section we shall explore some of the approaches to designing whirling arm testers. Including advantages and disadvantages of these.
4.2.1 Wheel and jet

A test method that can potentially cover a wide range of impact speeds is that of the wheel and jet RET\textsuperscript{52}. As illustrated in Figure 4.5, this type of Rain erosion tester substitutes individual droplets for a continuous stream of water.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{wheel_and_jet RET}
\caption{Illustration from \textsuperscript{52}, illustration of a wheel and jet style RET with two sample holder arms.}
\end{figure}

The assumption is, that impacting a cylinder of water results in a similar type of impact to that of impacting an individual droplet. Considering the Springer methodology, impacting the side of an infinite cylinder should be very equivalent to the droplet impact.

The impacts from this type of RET is what is termed as a non-distributed impact. This means that the same spot on the sample is hit on each revolution. Therefore, damage on this type of tester is likely to occur along a line on the sample.

Due to the relatively small testing coupon used in these types of testers they can be relatively flexible with regard to sample geometry. Most of the chopped stream RETs tend to use flat coupons.
Chapter 4. Review of rain erosion test methods

due to the ease of manufacture, however, aerofoil shaped specimens are not uncommon.

Controlling the impact speed in the RET is achieved by adjusting the rotational speed as the impact speed is calculated as:

\[ V = \omega r \]  \hspace{1cm} (4.3)

Where \( V \) is the impact speed, \( r \) is distance from the centre of rotation and \( \omega \) is the angular velocity.

However, the impact rate is also proportional to the impact speed. The impact rate \( \dot{n} \), of a single arm tester can be calculated from the angular velocity \( \omega \) or from the RPM as:

\[ \dot{n} = \frac{\omega}{2\pi} = 60 \cdot \text{RPM} \]  \hspace{1cm} (4.4)

For many, mostly linearly elastic materials like metals and ceramic materials, a high impact rate is likely no big problem. However, nearly all polymeric materials and coatings exhibit some degree of viscoelastic behaviour. Especially the polyurethane elastomers commonly used for LEP applications exhibit a high degree of viscoelasticity. At the most basic level an increased impact rate can result in an elevated sample temperature as will be shown in Chapter 7.

4.2.2 Whirling arm distributed impacts

The whirling arm with distributed impacts rain erosion tester is presently the de facto test method within the wind turbine industry. With the most prolific single machine being the RET, developed and manufactured by R&D A/S with 6 machines in commission as of primo 2020.

As the R&D A/S style RET has been used extensively in this project, more detailed description of its operation and how to evaluate the results generated can be found in Chapter 8.

On a more general note, this style of tester is characterized by generating randomly distributed impacts across a sample surface. This is achieved by having the sample mounted on a whirling arm, which rotates in a simulated rain field.

Despite the relative simplicity of this concept, different design approaches have been tried. Differences between machines lie in their approach to rain-field generation, number of samples, size of samples and shape of samples.

On the subject of rain field generation, machines generally fall into one of two categories:

- Sprayer type
- Individual droplet nozzles
Chapter 4. Review of rain erosion test methods

The sprayer type system relies on a number of nozzles spraying water out over the rotor plane.

In general, this results in a uniform rain field over the rotor plane. Typically, this type of rain field generation results in a fairly broad droplet size distribution.

Despite the fact that a broader droplet size distribution might be closer to the conditions found in nature, it is often of greater interest to study the effect of a single droplet size. Depending on the damage inducing mechanism, that is assumed to drive the erosion, the droplet size might be a significant parameter, see Section 3.2.

One way to attain a narrower droplet size distribution is to use individual nozzles or needles to generate the rain field. This is the method used in the R&D A/S style RET as will be further described in Chapter 8. However, to round off this comparison, the use of individual needles for droplet generation gives the possibility of controlling the size and amount of droplets. This is done by changing the size of needles and the flow rate of the water.

It can also give the possibility of varying the impact rate by blocking some of the needles, thereby reducing the relative rain intensity. I am not aware of any such experiments having been carried out.

Historically, whirling arm style test samples tended to be small, typically flat coupons \[53\]. These coupons are then mounted in the outermost radial position on the arm.

If the test coupon is significantly smaller than the radius of the whirling arm, it is a fair approximation that the impact speed does not vary across the sample. This makes damage evaluation relatively simple, as mass loss measurements can be carried out relatively simply along with other evaluation methods such as optical transmission\[40\], sometimes used for translucent material e.g. PMMA.

The limitation in this sample geometry is that in order to construct SN-curves covering a wide range of speeds, many individual tests have to be run.

A solution to this is to use long aerofoil shaped test samples, as in the R&D A/S style tester. With a sample length of \(\approx 40\%\) of the overall arm radius, the velocity gradient across the sample is significant.

The result of this is, that one test can potentially provide several data points for lifetime at different impact speeds.

This does complicate the failure time measurements as will be described in detail in Chapter 8.5.

As mentioned, the flat samples used in the R&D style tester use aerofoil shaped samples. This
helps reduce turbulence in the chamber helping in maintaining control over droplet paths [III]. The convex shape of these samples does make coating application more difficult. This limits its versatility for coating materials that are in the design phase and not yet ready to be applied. Using flat specimens such prototype coatings can potentially be cast instead of painted.

In conclusion, the modern whirling arm RET is likely the closest analogue to the real wind turbine conditions. Its complexity does induce some limitations to its flexibility as a design tool.

### 4.3 Solid projectile impacts testers

The solid projectile impact tester substitutes the water droplet impact for a physical impacting solid material. The motivation here is to remove the complexity and uncertainty related to actual droplet generation and impacts and replace it with known and controlled impacts.

Solid projectile impact testers for coating evaluation are not a new concept [54]. Mainly these type of testers have been used as single impact test such as the drop test [55].

Other testers utilise a steam of small particles or beads to impact the material causing erosion of the material [56]. The issue here is that the impact rate typically is very high and impacts are randomly distributed across the impact area.

A final approach is to fire individual projectiles at a target sample. The first mentioning of this approach used to replicate droplet erosion, is by G. Prayogo [57]. Here polymeric beads are used as a substitute for water droplets. This provides a very controllable impact at a single point. The Single Point Impact Fatigue Tester (SPIFT) was inspired by this concept and will be described in detail in Chapter 6.

### 4.4 Transferring RET to real world turbines

As the goal with performing RET testing is to evaluate the life time, it is worth considering how to transfer the results to real world turbines.

This is very much a non trivial task and no easy formula or factor exists that can transfer a given amount of hours into one universal lifetime.

The problem is that over an assumed 25+ year lifespan different turbines are likely to experience wildly different meteorological conditions. Here in order to evaluate the erosion potential of a given site, high temporal resolution rain data is needed. Another problem is that despite the large number
Chapter 4. Review of rain erosion test methods

of turbines in operation, which can potential yield real world coating life data, the material and RET data are essentially unknown.

One approach, as used by Eisenberg⁷, has been to use meteorological data and in-field observations of erosion and combined this with the Springer model to fill in the blanks when RET data was missing. It is claimed in the paper that the model shows good correlation to real world turbines. However, as the underlying material and meteorological data is proprietary, it is difficult to verify or use this model. Furthermore, as explained in Section 3.2.2 there are several limitations to the Springer model in regards to non linear materials.

Another approach is the one used by Jakob Ilsted Bech in ⁸. This model uses high temporal resolution rain and wind data from DMI (the Danish Meteorological Institute) measured at selected locations in Denmark.

Detailed RET testing was then conducted on a reference coating, in a whirling arm RET. Ratiosisations as will be described in Chapter 8 was used to generate a reference curve for the coating life. Then, based on the the meteorological times series, all rain events were evaluated for the damage potential. Afterwards, the real world lifetime was calculated using Palmgren-Miner ²⁵. This model is still in development, but shows promise as a method for transferring RET results to real world conditions.

However, as the availability of high temporal resolution rain data is limited, using this model is outside of the scope of this thesis. The hope is that at some point a tool similar to the New European Wind Atlas (NEWA) ⁵⁸ could be made for rain erosion potential.
Chapter 5

Wind turbine rain erosion tests standards

The following chapter will shortly outline the present standards for rain erosion testing, in regards to wind turbines.

As with any field of engineering, there are standards and recommended best practices that aim to provide a foundation for quality assurance in regard to rain erosion. However, the pace of the industry is at present outstripping that of the standardisation organisations. The need for long 25+ year continuous operation at speeds of around 100 m/s with potentially high rain loads is poorly accounted for in the older standards. The focus here is to highlight the standard used in this thesis, which has been used to ensure a thorough analysis of the data in a repeatable framework.

5.1 ASTM E739 - 10: Standard Practice for Statistical Analysis of Linear or Linearised Stress-Life (S-N) and Strain-Life ($\epsilon$-N) Fatigue Data

It is assumed that a fatigue process in the coating in which stress cycles are induced by repeated impacts drives rain erosion, and we therefore expect the data to be similar to that of an S-N curve. ASTM E739 - 10\cite{59} covers a statistical approach to analysing these fatigue data providing a means of evaluating the quality of the obtained fatigue data. It should however be noted that the standard assumes that $N$(the number of cycles) is always the dependent variable and that the $S$(stress,strain...
or speed) is the independent variable. This assumption works when applied to conventional cyclic tests or to the SPIFT but does not work when applied to the whirling arm RET as described in Section 8.6. For use on whirling arm RET data N must be assumed to be independent and S to be the dependent variable.

The statistical model used a log-normal distribution to calculate the various statistical parameters. Citing [59] "The distribution of fatigue life (in any test) is unknown (and indeed may be quite complex in certain situations). For the purposes of simplifying the analysis (while maintaining sound statistical procedures), it is assumed in this practice that the logarithms of the fatigue lives are normally distributed, that is, the fatigue life is log-normally distributed"

Valid arguments can be made that another statistical distribution, e.g. Weibull, could be used instead. However, as ASTM E739 - 10 is a recognised standard for use on fatigue, both at DTU and in the industry at large, the choice was made to not change the distribution.


ASTM G73-10[40], is an older standard that cover a wide gamut of Test Method for Liquid Impingement Erosion Using Rotating Apparatus. This includes both randomly distributed droplet impacts and repeated impacts at a single point. The standard focuses on identifying the incubation period of a coating, as it recognises that post incubation erosion can behave unpredictably. The standard uses two main rationalisations of the fatigue load, that of total impingement $H_0[m]$ and the dimensionless number of impacts "specific impacts" $N_0$. As further explained in Section 8.6, the use of $H_0$ and $N_0$ provides a better foundation for comparing results between testing set-ups like the new SPIFT. However, it does also make it easier to transfer lifetime to real world conditions as results are ideally machine agnostic.

5.3 DNVGL-RP-0171: Testing of rotor blade erosion protection systems

The DNVGL-RP-0171 [39] a newly published recommended best practice, for rotor blade erosion testing. At its core DNVGL-RP-0171 elaborates upon ASTM G73-10, by modifying the testing and data analyses to better suit the new style of tester developed by R&D A/S. This is necessary as ASTM G73-10 is designed to use small test coupons rotating in a uniform rain field, whereas
the R&D A/S style tester uses a diverging rain field and long blade samples. This results in a radial speed and rain intensity gradient in the tester as explained in Chapter 8.5. This difference in design also means that incubation detection cannot be performed by mass loss data but rather uses optical methods as described in Section 8.4. There is however, a point of contention between DNVGL-RP-0171 and ASTM G73-10 in that DNVGL-RP-0171 does not use impingement $H_0$ as a rationalisation but relies solely on a modified "specific impacts" to failure which in the case of DNVGL-RP-0171 is expressed as $impacts/m^2$ not the dimensionless $N_0$ of ASTM G73-10. In this thesis, only the ASTM G73-10 definition will be used.
Chapter 6

Single Point Impact Fatigue Tester SPIFT

The following Chapter deals with the function and operation of the Single Point Impact Fatigue Tester (SPIFT), which was designed and built as part of the present PhD study. After the initial concept phase all design and development work was carried out by the PhD student. Construction was carried out by both the student and the Risø Workshop. All control electronics were designed and constructed by the student.

Figure 6.1: An illustration of the SPIFT set-up consisting of the air gun, the speed trap, the camera system, pressure regulation system and the digital control system

As is exemplified in Chapter 4 several designs for rain/impact erosion testing systems already exist, so why is it necessary to design another? For the SPIFT the justification can be summed up
in three parts.

1. Impact rate and temperature control

2. Repeatable impact position

3. low cost of both machine and samples

1) Impact rate and temperature control is of paramount importance when testing high strain impact fatigue. This is best exemplified in the concluding remarks in William D. Weigel’s 1996, 288 page report "Advanced Rotor Blade Erosion Protection System"[60] citing:

"It is accordingly proposed to develop a cyclic test apparatus that can produce high strain repetitive loadings that can be used to rank the erosion resistance of candidate coatings. The DYNA3D simulations point toward an instrument that cyclically applies a nearly hemispherical indentation at high rates. Issues which will have to be resolved include the unnatural heating of the specimen if the indentations are too closely spaced in time and the form of the deflection verses time relation."

- end citation.

In the study [60], it was observed that, due to the highly viscoelastic nature of the polyurethane elastomers, it was not possible to perform conventional cyclical fatigue testing. If tested cyclically at a high strain rate and strain the viscous losses in the material lead to an "unnatural heating of the specimen"[60]. This elevated temperature causes changes in the mechanical properties and can potentially result in diminished sample lifetime, as it will be further discussed in Chapter 7.

2) As was also indicated in[60] a setup that can generate repeated impacts at a single location can be advantageous when developing Finite Element Models (FEM) of the impact fatigue process. The reasoning is that by comparing the type, position and number of impacts to failure, it is possible to draw comparisons to stresses and strains calculated in the FEM. Using this it would hopefully be possible to construct generalised criteria for the fatigue life of a given material based on material data.

3) Finally having a setup, that is both cheaper to manufacture and operate, makes the technology much more accessible. Therefore, the objective has been to base the design around commercially available components.

### 6.1 Design of the apparatus

The inspiration for the initial design of the SPIFT came from the work of G. Prayogo[57] who cites Adlers 1999 paper[61] work on hyper-sonic rain erosion. Adler noted that nylon pellet impacts[54]
provide better results than jet based systems.

The goal with SPIFT was to iterate on this concept but with a focus on impact speeds of wind turbine tip speeds of \(\approx 90\text{ m/s}\) and a high number of impacts. With target lifetimes of blade coatings of 25+ years the potential number of impacts can be in the tens of thousands requiring some degree of automation.

![Figure 6.2: An illustration of the SPIFT set-up consisting of the air gun, the speed trap, the camera system, pressure regulation system and the digital control system](image)

The choice was made to base the design around commercially available High Pressure Air (HPA) hardball firing systems. Enthusiast HPA equipment uses electro-pneumatic firing engines to fire 6mm diameter plastic pellets. Firing speeds range from 60-200 m/s and is controlled by air pressure and metering the amount of air released.

A typical HPA electro-pneumatic firing engine costs about DKK 3,000-4,500, and includes all the core electronics needed to control the solenoids and timings. Being a commercial product, spare parts are readily available. This is important, as wear and fatigue on the machine parts are inevitable due to the high cycle count in this intended application.

In addition, by leveraging the economics of scale, the price to quality of these off-the-shelf components far exceeds any custom one-off solution.

The SPIFT uses the Valken V12 electro-pneumatic firing engine, fired using compressed air. This specific electro-pneumatic firing engine is unfortunately no longer in production, however, the
PolarStar Fusion Engine V2 could be used as a drop in replacement.

The exit velocity of the ball depends on the length of the barrel, the pressure of compressed air, the mass of the ball and the size of the nozzle.

The schematic setup is illustrated in Figure 6.1 an image of the set-up can be seen in Figure 6.2. The balls are fed by gravity into the firing mechanism from a vibrating magazine hopper. The plunger lets the balls into the chamber one by one. After entering the chamber, the rubber ball is loaded into the barrel, at which point compressed air is released to accelerate the rubber ball through the barrel. After leaving the barrel, the rubber ball passes through an optical speed trap (Airchrony Mk.3) recording the exit velocity of the rubber ball. Having passed the speed trap, the rubber ball hits the target. The setup can shoot up to five rubber balls per second with velocities ranging from 90 to 170 m/s. The applied air pressure regulates the velocity.

The time interval between shots and the number of shots in a series are controlled by a programmable microprocessor. The output from the microprocessor triggers the Valken V12 built-in control electronics, which in turn controls the electro-pneumatic valves. This approach retains the built-in safety features which are released once the lid of the test chamber is closed.

### 6.2 Ball material

As most HPA Airsoft guns are designed around a 6mm diameter pellet the choice was made not to experiment with different pellet diameters.

Normally airsoft pellets are made of biodegradable poly lactic acid (PLA). Initial experiments show these to result in inconsistent results. This could in part be due to the brittle nature of PLA, which tends to shatter during high speed impact as can be seen in Figure 6.3. As the pellet shatters, it becomes difficult to account for the momentum of the pellet.

There might be some use of PLA pellets in replicating hail impacts, as these also tend to shatter on impact. It was also judged to be unnecessarily wasteful to have pellets that can only be used one time. Based on these observations an alternative ball material was sought.

Eventually nitrile rubber balls, designed for use in valves, was chosen. Nitrile rubber is known to have a good impact resistance and in our testing this was found to be true with no discernible damage after repeated use. The nitrile balls were also readily available in large quantities.

As can be seen in Figure 6.6 the ball experiences significant deformation during impact. Physical characteristics of the ball are:
Figure 6.3: In (a) is shown a highspeed image of a PLA pellet fired at 150 m/s, the image is at 10µs after first contact, (b) shows the same pellet 68µs later.

- Diameter: 6 mm
- Shore A hardness: 60
- Mass: $1.43 \times 10^{-4}$ kg SD: $7.59 \times 10^{-7}$ kg
- Density: 1263kg/m$^3$

By using a high-speed camera(Phantom v2512 fast) the deformation as well as incoming and rebound speed was measured as can be seen in Table 6.1. Assuming the steel target to be perfectly rigid, a significant amount of the impact energy is dissipated in viscous losses in the ball.

With the recorded high-speed videos of impacts it should be possible to determine the viscoelastic properties by inverse modelling.

Dynamical Mechanical Analyses(DMA) has also been conducted on the nitrile rubber. From this, a master curve of the frequency response has been generated. Here it is again evident that the nitrile rubber exhibits significant viscoelastic behaviour.

With this knowledge of the high strain rate, it should be possible to construct accurate FEM models for the impacts as was shown in our paper [I]. These data will also feed into future work in FEM in the Duraledge IFD project.
Table 6.1: The table shows results of impacting the nitrile rubber Balls in to a rigid steel target, resulting in the deformation seen on Figure 6.6. From this full deformation height and width was measured, as well as incoming and outgoing speeds of the projectiles. Data was captured using a Phantom v2512 fast at 350'000 fps.

It is difficult at this point in time to judge if the choice of nitrile rubber, leads to better results than the nylon used in [57][61][53]. It would, however, seem that when impacting soft compliant coatings that the compliant nature of the nitrile rubber might better capture the soft body interactions between coating and droplet.
Figure 6.4: DMA master curve for the nitrile rubber ball showing the frequency response of the storage modulus \( G' \), the loss modulus \( G'' \) and the loss factor \( \tan \delta \)

6.3 Data detection

As the primary means of damage detection, high-resolution digital video was captured at a 3.1 Megapixel (2048x1534 @10 Hz) with an AM7915MZTL long working distance USB microscope from Dino-lite. Using a working distance of 120 mm, an 18x13 mm field of view is obtained, resulting in 13.5 pixels/mm². For flexibility and ease of use, video preferable over individual, images were taken using an intervalometer. Firstly, the use of video ensures that all the recorded damage is directly tied to a precise time stamp, which is important for determining the number of impacts to failure. Secondly, the use of inter-frame compression in video can significantly reduce the resulting file size compared to individual images. This is due to the mostly static nature of the recorded video, in
which inter-frame compressing mostly only updates the parts of the image that changes between frames. As an example, a 30 minutes long experiment at 10 fps results in 18,000 images. At 350kB per image this would end up taking up 6.5 GB, the equivalent video recording would only take up 430 MB with no loss in quality.
6.3.1 Damage classes

The challenge in this optical approach is, that it is up to the operator to judge when a given system has achieved a given damage state. This means that robust and repeatable criteria are needed in order to evaluate the SPIFT generated data. From working with many different coating systems on the SPIFT, we have identified three damage states that can be identified from the visual record.

- First visual damage: Very first damage less than $1\text{mm}^2$
- Beginning of radial/annular crack growth: The point of first significant cracks longer than 2 mm, either radial or annular
- Material loss: the point of first or significant material loss.

Examples of how these damage states can look are seen in Figure 6.2. It is evident that both material and impact speed can change the way damage presents itself.

Looking at Figure 6.3, three SN curves representing the three damage states described above are seen. What is evident is that all three curves have very similar slopes just offset by the number of impacts to failure. What is also evident is that the spread on the Green curve representing the first damage states is much higher than the later damage states. This reflects the challenges in detecting these small damages. Fitting improves when using the radial/annular damage state, but in general first material loss gives the best data.
### Table 6.2

This table shows examples of the three different damage states as seen on GC, GA and GS systems. A more detailed comparison for GC can be found in Figure 9.1. A more detailed comparison for GA can be found in Figure 9.2. A more detailed comparison for GS can be found in Figure 9.22.

<table>
<thead>
<tr>
<th>First visual damage</th>
<th>GC system: 120m/s</th>
<th>GA system: 120m/s</th>
<th>GS system: 163m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radial cracking</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(d)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material loss</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(g)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8mm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a), (b), (c), (d), (e), (f), (g), (h), (i)
Chapter 6. Single Point Impact Fatigue Tester SPIFT

6.4 Data analyses

When analysing fatigue or erosion data the most commonly employed representation is the SN curve or Wöhler diagram \[62\], where the fatigue data is presented on a semi log plot with the magnitude of the load S plotted along the y-axis and the number of fatigue cycles N is plotted along the x-axis, on a log scale. Depending on the material being investigated and the imposed load, this curve can present itself in various shapes as outlined in \[62\]. However, the most common curve shape seen on erosion or fatigue data is the power law, a near straight line when plotted in an appropriate coordinate system. As the erosion data generated in this project conforms well to a straight line when plotted on in the Wöhler diagram, all SN data were fitted following the linearised approach power law of ASTM E739-91\[59\]. With this statistical approach, it is important to the quality of

![Figure 6.5: An example of a SN curve created by detecting visual damage states from the in situ optical system. The red curve corresponds to first material loss as defined in Figure 9.1(g)(h)(i), the blue curve represents the first radial cracking as defined in Figure 9.1(d)(e)(f), the green curve represents the visual damage of any kind as defined in Figure 9.1(a)(b)(c). All three data sets were fitted as pr. ASTM E739 - 10\[59\]](image-url)
the fitted curve, which parameter is assumed to be independent or dependent. The independent value is the value, which is controlled. In the case of the SPIFT, this would be the impact speed $S$, which is set by adjusting the air pressure. The dependent variable in this experiment is the number of impacts $N$ to failure, as this is not known. So in short for the SPIFT, speed is independent and $N$ is dependent. This is identical to the majority of fatigue testing where the stress or strain $S$ applied to the sample is fixed and known, and the experiment is allowed to run until failure has occurred at some unknown number of cycles $N$. This does not hold for RET experiments and will be further discussed in Chapter \[8.5\].

The statistical approach of ASTM E739-10 allows us to quantify the quality of the data in several fashions. For brevity, we limit our analysis to the visual inspection of the fitting interval of the mean fit as seen in Figure \[9.1\], where a tighter interval around the fitted mean curve is indicative of a better fit.

### 6.4.1 Calculating total impingement for SPIFT

By the nature of the SPIFT, the number of impacts to failure is always known, but as will be discussed in Section \[8.6.2\] the total impingement is an important parameter in evaluating rain erosion performance. So in order to be able to compare SPIFT results with those generated in the RET a method is needed that can convert number of impacts in the SPIFT to total impingement $H_0$.

In this project, we propose two methods for converting impacts to impingement.

The first is to reverse the procedure used to calculate impacts from impingement as will be described in Section \[8.6.4\]. Here it is assumed that the affected area by an impacting droplet is equal to its projected area as can be seen in Figure \[8.15\]. From this the impingement from each droplet would be the height $h$ of the resulting cylinder seen in Figure \[8.15\]. For a pellet 6 mm in diameter the impingement per impact can then be calculated as

$$H_0(n_0)(6\,mm) = \frac{2d}{3} \cdot n_0$$

$H_0(1) = 4[mm]$  \hspace{1cm} (6.1)

$h_0$ is number of impacts. This results in a 4 mm impingement per impact. However, from investigations performed using high-speed imaging the contact area is known to be larger than the projected area as can be seen on Figure \[6.6\].

From this, the diameter of the fully deformed pellet can be measured. The measured values can be seen in Table \[6.1\]. From the values in Table \[6.1\] it can be seen that the relation between the deformed height and the impact speed can be approximated by a linear function. For the nitrile
rubber balls impacting a steel target this function is:

\[
d_{\text{deformed}}(v) = 1 \times 10^{-5}v + 0.006[m]
\]  \hspace{1cm} (6.2)

Using this equation the impingement as a function of the impact speed can be expressed as:

\[
H_0(v,n_0) = \frac{2}{3} \frac{d^3}{(d_{\text{deformed}}(v))^2} \cdot n_0 = \frac{2}{3} \frac{d^3}{(1 \times 10^{-5}v + 0.006)^2} \cdot n_0[m]
\]  \hspace{1cm} (6.3)

With this it is possible to refine the SPIFT to RET conversion by including impact speed: However, it should be noted that this relation is based purely on empirical observations, but without further analyses this seems like a good starting point.
Chapter 7

Thermal effects

If impacting perfectly elastic materials, no heating would be expected, but as established when dealing with polymers some amount of viscous behaviour is almost unavoidable. In straightforward terms, viscous behaviour results in the material absorbing some amount of kinetic energy when impacted.

The impact energy can go into a host of different effects; crack growth, breaking of chemical bonds and reorganisation of the microstructure. However, the most straightforward possible interpretation of viscous losses is that it is converted directly into heat.

7.1 Heat limited impact rate

It is well known from fatigue testing on glass fibre reinforced composite materials that cycling the load too fast can lead to heating which degrades the fatigue properties. A similar effect is observed in the SPIFT, where high impact rates result in excessive heating, which can drastically reduce erosion performance. It is therefore of utmost importance that we know what causes the heating and how to mitigate the effects in testing.

In a perfectly elastic impact, all impact energy is conserved, resulting in no heating. The opposite case would be an utterly plastic impact where all the impact is absorbed into the material in the form of heat. Moreover, elastic impact is by far the more straightforward case to consider and for a percentage of the materials and applications, assuming elastic behaviour is a good approximation. For some polymers and applications, an assumption of elastic behaviour can be acceptable. An example could be thermosetting epoxies, with high solid filler fraction, such as traditional gel-
coats. However, with the industry shifting towards polyurethane elastomer-based coating systems, the plastic/viscous behaviour needs to be considered. Especially, the thick 300\(\mu\text{m}\) polyurethane elastomer coatings being applied exhibit a large fraction of viscous behaviour.

A screening test of the dependence of impact rate in the SPIFT and coating life time was conducted for the GS system as can be seen on Figure 7.1.

![Figure 7.1: The graphs show the number of impacts to failure as a function of the impact frequency tested at a single impact speed of 165 m/s. The material tested is the GS coating system.](image)

What is readily evident is, that lifetime is strongly dependent on the impact rate. Using thermal imaging the surface temperature was measured during testing. At a 5Hz impact rate the temperature would reach 165°C within five seconds. It seems that this elevated temperature caused the premature failure of the coating.

As noted earlier in Chapter [6] being able to control the impact rate if the SPIFT as to avoid unnatural heating[60] is among the core design goals of the SPIFT.

### 7.2 Materials

In order to gain some understanding of what core material properties influence impact heating, a set of pure polyurethane resins were investigated. Three pure polyurethane coatings were chosen in order to investigate the impact heating effect. These three coatings were formulated by Covestro AG and cast as 10mm layer on top of a glass fibre substrate. The three different coatings are listed
below with basic quantitative and qualitative feel.

- **296-2**
  - Qualitative feel: Very soft, can be indented by a fingernail
  - Storage modulus at 1 Hz, $20^\circ C \ G' = 25\text{MPa}$

- **296-3**
  - Qualitative feel: Very hard, fingernail skates over the surface
  - Storage modulus at 1 Hz, $20^\circ C \ G' = 549\text{MPa}$
  - Same base chemistry as 296-4 but with an increased hard/soft segment ratio

- **296-4**
  - Qualitative feel: Soft, has a rubbery feel when scratched by a fingernail
  - Storage modulus at 1 Hz, $20^\circ C \ G' = 367\text{MPa}$
  - Same base chemistry as 296-3 but with an increased soft segment

As listed above, coatings 296-3 and 296-4 are based on the same polyurethane formulation, but the mechanical properties are tweaked by altering the hard and soft segment ratios. Dynamical mechanical analysis (DMA) was performed by Covestro on the systems. The results can be seen in Figures 7.2(a) and 7.2(b). Storage modulus listed above are taken from the DMA curves on figure 7.2(a).

Here the coating was loaded cyclically, while the temperature was swept from $-50^\circ C$ to $100^\circ C$. From this the storage modulus $G'$ and loss modulus $G''$ were extracted. The storage modulus $G'$ is the dynamical equivalent to Young’s modulus whereas $G''$ represents the viscous losses in the material. By looking at the graph of $G'$ 7.2(a) it can be seen that the values at $20^\circ C$, as listed above, correspond to the qualitative feel, where two is the softest, three is the hardest, with four being in-between the two. What is also evident is that all three coatings are susceptible to temperature.

This also illustrates that the dampening properties of polyurethanes are highly non-linear.
Figure 7.2: In graph (a), DMA results for 269-2, 296-3 and 296-4 can be seen plotted as the storage modulus $G'$ this is equivalent to Young’s modulus in linear elastic materials swept over a range of temperatures. In graph (b) the loss modulus $G''$ is plotted over the same temperature range. In graph (c) the loss factor tanδ is plotted as a function of temperature. All DMA Curves were measured at 1Hz.

7.3 Impact speed vs peak temperature

To investigate this effect, experiments were performed in which different materials were impacted at a range of different impact speeds. In between impacts the coating was allowed to cool down to a Δ1°C of ambient for 25°C.

Temperature data was collected using a microbolometer based thermal camera (Optris Pi 640)
capable of 120Hz recording, with a 0.1°C temperature resolution. From the camera an image of the temperature distribution at the impact cite is generated as seen on Figure 7.3(b).

In Figure 7.3(b) it can be seen that the peak temperature occurs at some radius away from the centre of the impact. This annular shape corresponds to the location of peak impact stresses during a droplet impact \cite{63}, under the assumption that there is a correlation between the droplet and the rubber projectiles used in the SPIFT. This is in line with analytical models\cite{17} and observations from FEM models\cite{I}.

![Figure 7.3](image)

**Figure 7.3:** Graph (a) shows the time-temperature diagram from impacting the 269-03 material, where it is seen that the impact speed of 171.6 m/s results in instantaneous heating of the sample which is then allowed to cool to within $\Delta 1^\circ C$ of ambient. Figure (b) shows a map of the temperature right after the impact of 296-3 at 170 m/s.

Looking at Figure 7.3(a) it is seen that the temperature increase from the impact is near instantaneous to within the 1 ms time resolution of the microbolometer based thermal camera.

Since the heat increase is near instantaneous to within the limitations of the thermal imaging system, the heat increase is assumed adiabatic. This means that due to the rapid increase in heat, there has been no thermal exchange with the surrounding material by thermal diffusion to the air, by emission, or by convective cooling.

Since the impact speed/energy is measured and controlled, any difference in peak temperature at a specific speed must be material dependent ($\Delta T(v,m)$).

By impacting the three materials at different impact speeds and plotting the increase in peak
temperature yields the graphs in Figure 7.4. From this it is evident that there is a significant difference between the three materials in regards to heating. Coating Issut-269-2 shows significantly higher heating compared to Issut-269-3 and -4.

### 7.3.1 Comparing $\Delta T$ with static material properties

One hypothesis for the difference in observed heating is a result of the loss modulus $G''$. Using the DMA results we can compare the loss modulus $G''$ at room temperature to the observed $\Delta T$ as can be seen in Figure 7.5. Here we see that there is no apparent correlation between the observed heating and the relative values of $G''$ at 20°C.

Often $\tan\delta$, also known as the loss factor, is a better parameter for judging the ability of a material to dampen mechanical energy. This is due to $\tan\delta$ a function of both the stiffness $G'$ and the dampening $G''$.

Comparing values for $\tan\delta$ in Figure 7.6 with $\Delta T$ values. Here we see that coating Issut-269-2 exhibits a much higher $\tan\delta$ value at 20°C fitting with the higher peak temperature. However, the relative temperature increase for coating three and four does not fit the DMA values.
Chapter 7. Thermal effects

Figure 7.5: In this figure $G''$ values at room temperature (Green line) is compared to the observed $\Delta T$. The arrows are intended to guide the eye when comparing the two graphs.

Figure 7.6: In this figure $\tan\delta$ values at room temperature (Green line) is compared to the observed $\Delta T$. The arrows are intended to guide the eye when comparing the two graphs.

From this, we must conclude that evaluating the properties of a material from a simple DMA curve is not useful. There is no good correlation between values at ambient temperature and the observed relative $\Delta T$ measurements.
7.3.2 Time-temperature super-position

The problem with only using a single DMA curves measured at a single test frequency, is that it does not capture the strain-rate dependence of the material properties.

Ideally, we would want to measure a DMA curve across a wide frequency range going up to high frequencies. We can get a feel for the magnitude of the frequency by looking at the specific impact duration of the SPIFT. From high-speed camera investigation, we measure a total time to full deformation of about $25\mu s$, but analyses show that peak impact magnitude occurs after about $2\mu s$ so the characteristic frequency of this impact would be

$$F_{\text{full}} = \frac{1}{25\mu s} = 40000\,Hz \quad (7.1)$$

$$F_{\text{peak}} = \frac{1}{2\mu s} = 500000\,Hz \quad (7.2)$$

It is, however, not generally possible to reach frequencies anywhere close to those associated with droplet impacts.

To get around this problem, DMA curves measured at different test frequencies can be combined to construct a 'Master-curve'. This is known as time-temperature superposition whereby values obtained at different testing frequencies and temperatures can be mapped to each other [64].

In order to do this for the four materials in this study DMA curves were measured at 1-,10-100- and 500Hz. Using this approach we can construct curve showing stiffness versus frequency as seen in Figure 7.7. Here the general trend can be seen that stiffness of the polyurethanes increases with frequency.

![Figure 7.7](image)

*Figure 7.7: In this figure is shown the time-temperature super position of $G'$, for the three different polyurethanes*
Chapter 7. Thermal effects

Using this same principle the Dampening can also be mapped over to the frequency domain as seen in Figure 7.7. When looking at the highest extrapolated values from the master curves, there seems to be a correlation between relative values of $G''$ and $\Delta T$.

This starts to highlight the limitation of DMA testing since the time-temperature super-position models at this is towards the outermost edge of what is generally accepted as the usable range of this type of superposition. Since there are limits to how far the data measured at 1-, 10-, 100- and 500Hz can be extrapolated.

![Figure 7.8](image)

**Figure 7.8:** In this figure $G''$ values at the highest extrapolated frequency are compared to the relative temperate increase $\Delta T$. The arrows are intended to guide the eye when comparing the two graphs.

Applying the same analysis to superposition data of $\tan \delta$ yields the graph seen in Figure 7.9. Again here we see much the same picture as for $G''$. In both cases costing Lssut-269-2 show higher values compared to coating three and four. The difference between three and four is less pronounced, but maintains the same relative positions as was seen in Figure 7.4. It is also seen that despite differing significantly in mechanical at static conditions at room temperature, at high frequencies they are much more similar.

The conclusion of this small study into the relationship between impact heating at DMA results and high frequency extrapolated time-temperature superposition data. This also shows how the SPIFT might be used to evaluate the dampening properties of different polymers at high strain rate impacts.
7.4 Determining maximum impact frequency for the SPIFT

It was observed on several samples that if heat was allowed to accumulate coating lifetime could be reduced by up to 100 times as seen in Figure 7.1. As such it is important to be able to control this heating effect while not lowering impact frequency so much that tests become overly long.

In the SPIFT setup, there are presently two ways of managing temperature, either by forced air-cooling or by adjusting the time between impacts. We can observe the effect of cooling in Figure 7.10 we observe a similar peak $\Delta T$ between the two 170 m/s impacts. However, it is clear that the sample with no cooling (Red line) is much slower at approaching thermal equilibrium compared to the forced air sample (Blue line).

As the goal of this investigation is to determine an impact frequency that minimises cumulative heating. For the three systems in this study GC, GA and GS the following times were judged to be sufficient to avoid heating when impacted at 170 m/s.

- No cooling: 16 Seconds
- With cooling: four Seconds

The results of this are that experiments performed with cooling can be performed with an impact rate four times higher than with no cooling resulting in a four-fold decrease in test time. This applied to the GC coating system we can see from the SN curve in Figure 9.1 that the mean lifetime at 170 m/s is about 1000 impacts meaning that forced air cooling reduces the test time...
Figure 7.10: Comparison of peak temperature as a function of time of The GC coating system impacted at 170 m/s. The red curve shows the temperature profile with no cooling, the blue line is with forced air-cooling from \( \approx 4:26 \) h (16000 s) to \( \approx 1:06 \) h (4000 s) a reduction of 3:20 h. So it is clear that this provides a very significant reduction in testing time, but a 4s impact interval is still relatively slow. If we refer again to the SN curve in Figure 9.1 we can see that at a lower speed, e.g. 120 m/s we predict lifetimes of \( \approx 13'000 \) impacts which at 4s impact interval results in a test time of \( \approx 14:26 \) h. We would like to reduce this test duration.

Comparing the time it takes to reach ambient temperature at a lower impact speed as seen in Figure 7.11. By measuring the cool down time at different impact speeds it was observed that the peak heating \( \Delta T(v) \) is linearly proportional to the impact speed:

\[
\Delta T \propto v
\]  

(7.3)

If a linear relation between time to thermal equilibrium and impact velocity \( v \) is assumed, we can define a linear function for the impact delay as a function of the impact velocity when measured at two different impact speeds.

\[
\delta t(v) = \frac{(\delta t_{\text{high}} - \delta t_{\text{low}}) v}{v_{\text{high}} - v_{\text{low}}} - \frac{(\delta t_{\text{high}} - \delta t_{\text{low}}) v_{\text{low}}}{v_{\text{high}} - v_{\text{low}}} + v_{\text{low}}
\]

(7.4)

Where \( \delta t_{\text{high}} \) and \( \delta t_{\text{low}} \) is time to approximate thermal equilibrium at high and low speeds, \( v_{\text{high}} \) and \( v_{\text{low}} \) is the high and low impact speeds.
Figure 7.11: Comparison of peak temperature as a function of time of The GC coating system impacted at 170 m/s Red line and at 100 m/s Blue line. Both tests performed with forced air-cooling.

For the GC, GA and GS coating systems, this results in the following testing parameters:

- Fast impact:
  - \( v_{high} = 170 \text{ m/s} \)
  - \( \delta t_{high} = 4 \text{ s} \)

- Slow impact:
  - \( v_{low} = 100 \text{ m/s} \)
  - \( \delta t_{low} = 1 \text{ s} \)

- Impact interval as a function of \( v \)
  - \( \delta t (v) = 0.0429 \cdot v + 3.2857 \)

The choice of a linear model should also mean that the cool-down time should be somewhat conservative, as the cooling efficiency is inversely proportional to the \( \Delta t \). This would mean that the actual cooling curve \( \delta t(v) \) would be a power function. However, for the scope of these tests, the linear assumption is sufficient.
Chapter 8

Whirling Arm Rain Erosion Tester RET

The following chapter deals with the operation and data analyses involved in rain erosion testing on a R&D A/S style tester. A large part of this project revolved around comparing results from this traditional tester to the results generated by the SPIFT. Beyond this, the R&D style tester is still fairly new to the industry and the operation and data analysis is still not fully standardised. As of now the R&D A/S style RET is covered by DNVGL-RP-0171[39], it should still be noted that this is a recommended practice and not a full standard. As such, there might still be some room for further improvement and refinement.

The fundamental operating principle of the R&D style RET is that of a distributed impacts tester per ASTM G73-10 as seen in Figure 8.1. The RET utilising many radial droplet manifolds with a total of 600 stainless needles to form a rain field with a controlled mean droplet diameter. As seen the RET has three blades based on an NACA 634-021 profile. The test sample is the convex leading edge of the blade, which consists of a removable glass fibre shell that is coated by a leading edge protection system. The 430mm length of the test samples means that a single test can potentially probe a range of local impacts speeds, as the tip moves at a higher relative velocity than the root of the blade.

The degree of erosion of the samples can be monitored in sets of discreet intervals by use of the in-line optical camera system, a departure from the conventional mass-loss based measurements of most other test set-ups.

As might be evident from this brief description of the R&D style, it does provide a wide array of capabilities to the industry. However, with these increased capabilities come increased complexities in the analysis of the results generated. It is the goal with the following chapter to provide an
Figure 8.1: The 3D rendering shows a whirling arm type rain erosion tester, Designed by R&D A/S

insight into the use and analysis methods possible on the RET. All to provide a robust framework for evaluating the erosion performance across testing conditions and machine, in such a fashion that the results can indicate potential real-world performance.

Droplet size

The droplet generation system relies on Blunt-Tip hypodermal medical needles to provide a controlled mean droplet size. This droplet size can be controlled by changing to a needle with another G-number, e.g. G20 and G27.

The G-number is the gauge size of the needle following the Birmingham Gauge system, which is commonly used in medicine to express the outer diameter of hypodermic needles and the like. Applied to this specific case, G20 means that the needle, used to generate the droplet, has an outer diameter of 0.9081mm, whereas a G27 needle has an outer diameter of 0.4128mm. The reasoning behind choosing needles for the droplet generation system is that the size of a hanging droplet, a so-called pendant drop, is primarily determined by the diameter of the support and the surface tension of water. The force of the surface tension $F_\gamma$ is given as:

$$F_\gamma = \pi d_{\text{needle}} \gamma$$  \hspace{1cm} (8.1)

Where $d$ is the diameter of the needle and $\gamma$ is the surface tension of water. From this, the maximum droplet size is determined to the point when the force of gravity $F_g$ on the pendant drop exceeds
the force of surface tension $F_\gamma$. Assuming a spherical drop, this size can be expressed as:

$$F_g = F_\gamma$$  \hspace{1cm} (8.2)
$$F_g = \frac{4}{3} r^3 \pi \rho g$$  \hspace{1cm} (8.3)
$$\frac{4}{3} r^3 \pi \rho g = \pi d_{needle} \gamma$$  \hspace{1cm} (8.4)
$$r(d_{needle}) = \sqrt[3]{\frac{4 \gamma d_{needle}}{3 \rho g}}$$  \hspace{1cm} (8.5)

Where $r$ is the drop radius, $g$ is the gravitational acceleration, and $\rho$ is the density of water.

This is only valid under ideal conditions, but it serves as a frame of reference as to why the choice of needle size influences the droplet size. It is evident that a larger circumference results in higher total force from surface tension, thus resulting in larger droplets.

One thing that should also be considered is that the surface tension of water is not constant and can vary with temperature, ion-concentration, and pH-value. Beyond this, the surface of the needle can also affect droplet formation, whereby oils or other contaminants might influence the droplet formation. The droplet size needs to be experimentally determined for the particular set-up. In this work, the following droplet sizes where used:

- G20: diameter 3.5mm
- G27: diameter 2.4mm

8.1 Droplet path during operation


As will be explained, the R&D style RET employs a diverging rain field, the implications of which is explained in Section 8.6.2 For the calculations in Section 8.6.2 to be correct, it is important that the droplet do deflect overly much from their release position. As is described in the paper[III], the CFD models predict that the airflow in the tester should ensure minimal deflection of the droplet.

It should be noted that in these simulations the droplet is a solid sphere with a size and density of the actual droplet, and does as such not account for the possible deformation of the droplet as a result of turbulent conditions inside the RET. Figure 8.2 shows an example of how a droplet might deform when falling into a region of fast moving air, perpendicular to the droplet path. As can be seen from the image, as the droplet enters the air stream, the droplet starts to flatten out faster while it rapidly inflates. At some point, the surface tension of the water is no longer enough to
hold the droplet together, and the 'balloon' bursts into many small droplets. This flattening of the droplet results in a larger frontal area relative to the air stream, which might result in increased deflection of the droplet.

In order to investigate if the integrity of the droplets remain intact during operation of the RET,

Figure 8.2: The composite image of the droplet during its fall, showing a water droplet falling from the pipette down into a layer of fast moving air just over the surface of the glass plate. The video was recorded using a Phantom v2512-fast high-speed camera recorded at 20,000 frames per second. The full video can be found at https://data.dtu.dk/articles/Waterdrop_falling_into_a_layer_of_fast_perpendicular_wind/9942899
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Figure 8.3: The figure shows the tangential deflection of droplets in the RET. To the left is shown an illustrative droplet path as seen from the point of view of the camera. In the centre is shown a composite image of a 3.5mm droplet that managed to fall through the rotor plane without hitting the blade. To the right a graph from the paper showing the tracked droplet path of seven droplets and three simulated droplet paths can be seen.

A high-speed camera was placed inside the tester. Figure 8.3 shows images and plotted droplet paths as seen from the side of the rotor. The centre image illustrates a worst-case scenario in regards to droplet integrity, as the test was carried out at the maximum rotor speed of 1350RPM and using the largest 3.5mm droplet. With these testing parameters, the droplet barely misses the rotor, resulting in the droplet exiting the rotor plane without impacting a rotor, but rather passing directly through the wake of the blade. From the graphs of the seven tracked droplets, the observed tangential deflection is between 2-5cm forward (in the direction of rotation) of the release position. This small deflection was judged to be small enough as to not influence the rain field calculations, as tangential deflection is less critical for the calculations. It should however be noted that these are results for the large 3.5mm droplets, and that for smaller droplets this deflection is larger. In one experiment with \(\approx 1\)mm droplets, up to 20cm of tangential deflection was observed, in the direction of rotation.

Looking at the radial deflection as seen in Figure 8.4 we see that there is only a small radial deflection of 0-2cm. As we see a tendency that the droplets deflect inwards during the first part of the droplet path. Then as the droplets get nearer to the blade rotor plane, they are pushed outwards.
Figure 8.4: The figure shows the radial deflection of 3.5mm droplets in the RET operated at 1.350 RPM. To the left is shown an illustrative droplet path as seen from the point of view of the camera. In the centre is shown a composite image of a 3.5mm droplet that impacted the rotor blade. To the right can be seen a graph from the paper showing the tracked droplet path of seven droplets and three simulated droplet paths.

again. For the droplets used in this test it was judged that correcting for any radial deflection was not necessary. Anecdotal information from other RET operators do, however, suggest that when testing with sub 2mm diameter droplets the deflection might be more significant.

The centre composite image of Figure 8.4 shows the outline of the droplet just after impact with the blade. As is evident this splash zone extends many times beyond the diameter of the original droplet. The high speed imaging was performed at 3.000 fps meaning that from the point of first contact between the blade to the point where the droplet has spread to the outline seen in the image, less than 3.33ms passed. Judging from the splash area this would result in a minimum average speed of the jetting water of 48m/s.

In conclusion, the amount of radial and tangential deflection is not excessive at the tip position. Based on these observations modifying the calculation for the rain field is not justified.

8.2 Detection of damage

One of the central problems in dealing with rain erosion is the detection and measurement of damage. In the following section, different methods of detecting and measuring damage will be discussed.
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The most straightforward and direct method for quantifying erosion is mass loss measurement by weighing of the sample. As a result of this, it is possible to directly correlate the amount of test material loss as a function of the type and duration of the impinging material as seen in Figure 8.5(a).

![Figure 8.5](image)

**Figure 8.5:** The first picture (a) illustrates the fundamental process of erosion by normal impingement of outside objects, which over time fatigues the material to the point where cracks form and at some point converge/merge resulting in material loss i.e. end of incubation. Figure (b) shows an illustrative graph of a typical erosion process, beginning with an incubation period followed by steady state erosion.

8.2.1 In System Image acquisition

The rain erosion tester built and developed by R&D A/S features an in-system image acquisition system. This system allows for imaging of the eroded profile without unmounting the profile. This is done by turning off the rain field and then spinning the rotor down to 5rpm, at which point a 0.4Mpx (2352x174 px) image is captured as the profile passes between the illumination as seen on Figure 8.6. Both proper placement and type of illumination are essential for good image acquisition. A good solution, as used in the set-up, is long diffuse illumination on both sides of the sample. Camera placement and optics also play an essential role, in general the further away from the sample, the better. This reduces the distortion of the image due to parallax and barrel distortion. The in-line camera is placed more than 1.5m from the camera and uses a telezoom lens to frame the sample tightly.

Due to the high amount of water that is flushed through the system in order to assure a stable rain field, imaging intervals are limited to 10-15min. Otherwise, the water conditioning system cannot maintain sufficient water flow for extended operation.
Figure 8.6: The image shows parked blade, at the spot where the RET would perform the imaging operation. As can be seen there is a light fixture, which is mirrored below this ensures proper evenly lighting of the sample during the imaging process.

8.3 Classifications of damage types from visual observation

Following the new recommended practice from DNVGL-RP-0171 the detection of erosion damage from visual inspection is the recommended method. In order to best employ this method, classes of damage need to be established. The following text serves as a suggestion of how best to identify and differentiate these damages. Some of these damages can be readily identified from the in-line vision system, as described in Section 8.2.1. These damages are mainly point erosion and substrate erosion. Other damage types require more detailed visual investigations either by use of macro photography or microscopy. The following classification is limited to what can be seen by optical photography.

8.3.1 Detectable from in-line camera

The first two classes, point/incubation and substrate/breakthrough erosion, are the main types of damages that can be identified from the in-line vision system and are as such the main types
of damages to look for when constructing an SN-curve for a given system. The following text
gives recommendations as to how to identify and register these damages in order to extract the
maximum level of usable data from the test. Multiple new points of local erosion may occur from
one inspection to the next. This will typically result in multiple data points from each time-slice
from each blade, and does as such provide a more statistical robust foundation for data analysis.
Compared to identifying just one erosion front at each time slice.

**Point erosion**

Point erosion is the smallest damage that can reliably be identified by use of the in-line vision. The
general characteristics of point erosion can be summarised as:

- Size: 0.1-2mm Ø
- Isolated from other damages
- Damage confined to top-layer
- No visible glass-fibre substrate
- Only damages resulting from impacts normal to the surface are considered.

The reason we chose to focus on point erosion for evaluating coating performance is, that it is
the damage type that most closely relates to the end of incubation as defined in Figure 8.5(b). It
presents small isolated damages resulting in a small loss of coating, corresponding to the very first
mass loss. Further, we assume that since the damage is small and isolated, the local airflow remains
similar to that of the undamaged profile. Thus, we can assume that the results from this test can
be applied to any aerodynamic profile subjected to droplet impacts, normal to the leading edge.

**Surface cracking**

Surface cracking/crazing can often be seen as a precursor to material loss, e.g. point erosion, of
which examples can be seen in Figure 8.8. An argument can be made that the appearance of
surface cracking can serve as a better indication of coating lifetime than point erosion. However,
the difficulty in identifying damages of this minute size via the in-line optical system places practical
limitations to the use of surface cracking as a lifetime indicator.

The hypothesis is that this surface cracking, as can be seen in Figure 8.8 is the pre-stage to what
we define as point erosion. A lifetime curve based on this criteria, would be linearly offset in a
similar fashion as was seen with the different damage stages seen on the SPIFT test in Figure 6.5
Figure 8.7: The first picture (a) shows an example of how point erosion can present itself on an RET sample showed at roughly a 1:1 size scale. (b) shows a close up on point erosion showing both a small circular area of lost topcoat and even smaller areas of lost coating and (c) illustrative shows the size and shape of damages that fall into the category of point erosion.

Substrate erosion

Substrate/breakthrough erosion is the second type of damage that readily can be identified by the use of the in-line vision system. It presents itself as damage through all layers of coating, exposing the glass-fiber epoxy substrate. The general characteristics of substrate erosion can be summarised
Figure 8.8: On (a), (b), (c), and (d) can be seen high magnification examples of surface cracking from a sample tested in the RET. These damages are too small to be readily detectable using the in-line camera system, but represent the pre-stages to the point erosion damage. (e) shows a close up of a RET sample that is exhibiting surface cracking and one large point erosion area. The marked point erosion is an example of a comparatively large isolated erosion damage that occurred during an observation interval, but is still considered as a single damage, as it is isolated from other damages.

as:

- Size: <2mm
- Irregular shape
- Often merges with other damaged areas
- Damage penetrating all coating layers
- Damage can extend beyond the area of normal impacts
- Damage can be both cohesive and adhesive
8.4 Identifying failure mode - adhesive or cohesive

In most cases, substrate erosion can be observed following the appearance of point erosion, and as described in section 8.3.1, the damage progresses into the laminate substrate, thus indicating that the failure was cohesive. However, there can also be cases where substrate erosion is not preceded by any clear point erosion. This might indicate that the failure mode was an adhesive break between the coating system and the laminate. Also called debonding, which is typically related with a weak interface.

![Image of cohesive failure and adhesive failure](image)

*Figure 8.9: The first picture (a) shows an example of cohesive failure of the coating system, this is evident from the exposed glass-fibre and the irregular shape of the damaged area. The crack propagates along the direction of the fibres, where the fracture energy is smallest. (b) illustrates an example of substrate erosion resulting from adhesive failure between the coating system and the laminate, which is evident by the presence of the peel-ply structure on the exposed laminate, furthermore, the exposed laminate shows little to no damage i.e. exposed glass-fibre.*

By looking at the inner edge of the erosion front (closest to the rotor hub), we get the first indication of the failure mode. As seen in Figure 8.9(a) exposed and broken glass fibres can be seen up to the edge of the coating. The shape of the area of exposed substrate also indicates the failure mode. Specifically, the presence of structured damages that have an angle of roughly 45°, as seen in figure 8.9(a) indicates cohesive failure. The slanted 45° orientation of the damage results from biaxial glass fibres used for the substrate. The fibre orientation provides a direction of least
resistance for the coating to peel away. Peeling force is assumed to result from the jetting forces from the droplet spreading out upon impact. This jetting water impacts the sheer sides of the initial erosion hole. The forces impacting the shear ledge results in a high torsional moment focused on the fibres, resulting in shearing and peeling of the glass fiber matrix.

In the case of adhesive failure, the damage is expected to look as in Figure 8.9(b). Here the damaged area will tend to be one large connected area, with comparatively even edges. By looking closely at the surface in Figure 8.9(b) the regular imprint resulting from the peel-ply layer that was used as the outer layer during the layup of the glass fibre. This peel-ply is then peeled away just before the coating process providing a clean and rough surface. Cracks propagating inside the substrate indicates a relatively strong interface bond. Crack propagating as a debonding along the original interface indicates a relatively weak interface. Therefore the presence of a undisturbed peel-ply structure, indicates that the coating removal process could proceed relatively unhindered along the substrate interface, therefore not resulting in the peeling along fibre direction as seen in Figure 8.9(a).

### 8.4.1 Damages detectable by closer investigation

Some types of damages are not readily identifiable by the use of the in-line vision system. Due to limits of optics, illumination and resolution. In these cases, investigations that are more detailed can complement the observations from the in-line vision system. These methods include, but are not limited to, macro-photograph, optical-microscopy, scanning electron microscopy, and x-ray tomography.

![Figure 8.10: The image shows a SEM image of a sample that exhibited adhesive failure during the erosion process, evident by cracking along the peel-ply interface.](image)
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Pealing/de-bonding

Besides the shape of the damaged area as discussed before, adhesive failure can be identified by looking at the inner most erosion front as seen on Figure 8.9(b) where the exposed substrate shows a clear rough structure, a texture, which is the imprint of the peel-ply. This structure results from the peel-ply that was removed just before coating application. Peel-ply is a removable cloth that is treated with a release agent that ensures that it can peel away the cured surface. The peel-ply is applied to the outermost layer of the GF part and is removed just before coating. On Figure 8.10(a) the effect of the peel-ply can be seen. The just exposed surface should provide a surface that is both rough, clean and chemically activated enough to provide a good bond between the coating and substrate.

Looking at an SEM image in Figure 8.10(a) we see that there is no connection between the filler and the epoxy. Furthermore, the exposed epoxy appears smooth and unbroken in-line with the theory that the failure mode was adhesive.

In the case of cohesive failure, one would expect to see the failure go from the coating into the laminate evidenced by broken fibres.
8.5 Rationalising whirling arm RET data

The goal of performing whirling arm RET is to get data on the potential lifetime of the material being tested, in order to be able to compare the performance of different systems, and for the use in life time prediction for field applications. In this section graphs using the GC data set will be used. For a more complete analyses of the GC data set see Section 9.1.

Despite the relative simplicity of this statement, there are many different ways to present the data acquired from the whirling arm tester. Each of these methods carries inherent advantages and disadvantages when it comes to comparing results. Be that comparing between coatings, testing machines or different test parameters. For the most part the RET results, is covered by ASTM G73-10[40] and the new DNVGL-RP-0171[39]. At its core, NVGL-RP-0171 builds on ASTM G73-10. However, there are some differences in the implementation in DNVGL, which is specifically designed to accommodate the R&D tester. On a more fundamental level there is a difference between ASTM G73-10[40] and the new DNVGL-RP-0171[39] in the definition of specific impacts $N_0$.

An overview of parameters and comparison between ASTM G73-10[40] and DNVGL-RP-0171[39] can be found in table 12.1 in the appendix. Here all relevant variables and symbols used can be found. The table also denotes the definitions adopted in this thesis drawing from both ASTM G73-10[40] and DNVGL-RP-0171[39] into what we feel to be a robust framework suitable for the R&D RET and the SPIFT.

8.5.1 Single time to failure pr sample

The simplest metric to evaluate erosion performance is to simply state the number of minutes or hours that a given material or coating lasted in the test. This could look something like what is seen in Figure 8.13(a) where a sample is run for a given time in the whirling arm tester, and when evaluating the data, the time to failure is noted.

This gives a single data point per sample being the time to failure. The advantage of this approach is, that it quickly provides a performance metric for the coating being tested, and if all tests are performed under identical test conditions a comparison is very simple; the longer the time to failure the better. Moreover, to a large extent this has been the standard performance metric used for LEP coatings. The reason for this is that prior to the explosive interest in LEP solutions, within the last 3-5 years, the volume of testing being performed was small enough that most manufacturers had all test performed at a few independent test providers e.g. Poly-tech[66]. Therefore, since everyone tested at the same machine under comparable conditions there was little drive to refine the analysis any further.
Nevertheless, as stated, this metric is only useful when comparing like for like. However, the fact of the matter is that industry is no longer all testing on the same machine. A further problem with the single time based metric is that modern RET machines tend to use long, blade shaped test samples, and not the short test coupons.

This means that there is a significant difference in local impact speed $v(r)$ along the blade. For the most part it is safe to assume that damage will initiate at the outer part. However, damage occurring at smaller radius is poorly covered. Examples of how damage occurs along the blade length can be seen in Figures 9.2, 9.13 and 9.24.

We are now in a situation where materials are being tested on different machines, under different conditions be that RPM, Droplet size, Rain intensity etc. Therefore, it no longer makes sense to use this outdated metric. This is also reflected in the DNVGL-RP-0171 recommend practices, which departs from the purely time based metric.
8.5.2 Many failures per sample

As described in section 8.3.1, point erosion is local removal of the small area of coating corresponding to the end of incubation. When looking for this type of erosion damage, it is not uncommon to observe many failures at each inspection or time slice. These types of damages are recorded by measuring the radial position of all point erosion damages (PED) at each given time slice. Since the RPM of the rotor is fixed and known during an experiment, each position on the rotor has a fixed local rotor speed normal to any droplet impact. As given by equation 8.6

\[ v(r) = r_{\text{damage}} \cdot \frac{2\pi}{60} \cdot RPM = r_{\text{damage}} \cdot \omega \]  \hspace{1cm} (8.6)

As a result of this it is possible to construct an SN curve with many more data points than the ones provided by just measuring breakthrough time or erosion front. It is not uncommon to get between 20-80 PED’s from a single erosion sample. With the large amount of data points, it allows for a more statistical approach to evaluating the performance of different coating systems. As described in the section 6.4 the data can be fitted to a power function.

\[ S(N) = C \cdot N^{-m} \]  \hspace{1cm} (8.7)

Fitting this to data gives a function that describes the mean lifetime of the coating in the specific test, but no information on expected upper and lower lifetimes.

The typical method for performing statistics on SN data is described in the ASTM E739-10 standard. The model assumes that the data follows a power law and can therefore be fitted with a linear function on a log-log plot. With the method outlined in the standard, the lifetime curve can be fitted to the data along with the ±95% confidence interval for that fit, and the uncertainty on the exponent \( m \). The slope of the fitted curve is determined by the parameter \( m \).

There is however, one potential pitfall when using ASTM E739 when evaluating RET data, and this is the choice of dependent and independent variables. In conventional cyclic fatigue testing a single sample is mounted in the cyclical fatigue tester where a cyclic load with fixed stress or strain amplitude is applied to the sample. The sample is then observed using various methods in order to determine the number of cycles it took to bring the sample to failure. Therefore in this type of testing the Stress \( S \) is the independent variable since it is selected and controlled variable. Whereas the number of cycles it takes to bring the sample to failure \( N \) is the dependent variable as it is dependent on the applied \( S \) but not controllable.

This is, however, not the case when measuring multiple PED’s in the RET. The simplest way of explaining the difference is to view each blade in the RET as being an infinite array of cyclical fatigue samples being tested in parallel. Where the Stress or Speed \( S \) is defined by the radial position of the failure, and the \( N \) being proportional to the time the sample is subjected to rain impacts in the RET. It is not possible to perform continuous measurements of the leading edge while testing, but only at discrete intervals as illustrated in Figure 8.13(a). Therefore we have to
Figure 8.11: The figure shows the result of choosing $S$ ("$S$ dependent") or $N$ ("$N$ dependent") as the dependent variable, it is clearly evident that the curve passes better through the data points if $S$ is the dependent variable as opposed to $N$

view the $N$ as being the independent variable not $S$ as would be normal in fatigue testing.

This is because the RET is applying a range of stresses to the material all at once: When the RET is stopped for inspection at pre-set intervals (time slices), the time or number of impacts is the independent variable. By measuring the positions of damage, we are essentially measuring the stresses or impact velocities, that resulted in damage during the interval $N$. Thus, the local velocity at damage becomes the dependent variable.

The Practical consequences of this can be seen on Figure 8.11.

Here it is clearly seen that if $S$ is assumed to be the independent parameter, and not $N$ the fit is much worse. The difference in fitting quality is also evident when looking at the uncertainty interval on the exponent $m$ as seen below:

$$S(N) = C \cdot N^{-m}$$

- $N$ dependent
  - $C = 1.26 \times 10^{10}$
  - $m = 3.37 \pm 0.2318$

- $S$ dependent
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\[ C = 1.42 \times 10^{12} \]
\[ m = 4.35 \pm 0.0158 \]

As is evident the choice of \( N \) dependence (\( N \) is the dependent variable) results in a much wider confidence interval for the exponent \( m \) compared to the \( S \) dependent fit. This would lead to significant systematic errors if not properly addressed. This effect can also be seen in the data structure e.g. the vertical lines clearly visible at the higher speeds. At high speeds, it is more likely that damage can occur during the first time slice. If performing longer tests, with many inspection intervals this structuring of the data becomes less noticeable, showing that, in an ideal case, where continuous observation is possible, this distinction between dependent and independent variables is no longer as critical to the quality of fit.

8.6 Rationalising Fatigue cycles \( N \)

In order to make RET results transferable between different test machines, testing conditions and potentially real-life turbines, it is necessary to normalise or rationalise the fatigue cycles \( N \).

For this purpose evaluating the performance based on time to failure is woefully inadequate if for no other reason than that, rain intensity in the tester is much accelerated compared to real world conditions. The mean rainfall intensity in the rain field follows:

\[ I_{\text{rain}} = \frac{\text{Flow}(m^3s^{-1})}{\pi (R_{\text{outer}}^2 - R_{\text{inner}}^2) \cdot \varphi} \]  
(8.8)

Where \( \varphi \) coverage ratio of the rain field. There can be some variation in water flow between test, but the main difference comes from changing droplet needles, with typical flow for G20 needles being 120l/h and 60l/h for G27 needles and a coverage ration \( \varphi = 0.85 \). The result of this is that the average rain intensity in the test can vary from 32mm/h to 64mm/h, making the comparison of time to failure between two droplet sizes inherently flawed.

Furthermore, different normalisations can provide insight into the driving forces behind the erosion e.g. number of impacts, amount of rain and so on. In the following subsections, some of these different normalisations will be discussed and analysed to the test performed in this project.
8.6.1 accumulated rain fall/total water flow

So one normalisation already hinted at in the section above is the total rainfall measured under the rotor plane as illustrated as height 1 in Figure 8.12. This is the simplest normalisation of the rain load. Since we know from equation 8.8 that the total rainfall under the rain field is a direct function of the water flow and the time. This makes it much more reliable to compare identical tests across different test machines, despite small variations in water flow. However, more important, it makes the comparison between large and small droplets more direct, since the reduced water flow with G27 needles is defiantly one of the factors that increases the test duration.

With this normalisation we see in Figure 8.13 that the gap between small and large droplets is significantly reduced when compared to the time based rationalisation on Figure 8.13(a). Considering that both the 3.5mm droplets of G20 and 2.4mm droplets of the G27 are both what would be considered large for rain, a smaller difference between the curves is expected. A further point in favour of this method is the apparent intuitive coupling to real world meteorological conditions, as anyone with a rain gauge can measure the rainfall at the turbine location and directly compare the results from the RET to actual lifetime.
Figure 8.13: In (a) machine test time to failure is plotted for two identical coating systems, but at two different droplet sizes 2.4mm G27 and 3.5mm G20. In (b) erosion performance is plotted as a function of mean rainfall under the rotor. In (c) the same data is rationalised to be the total impingement on the rotor during the test.

8.6.2 Total impingement

Despite rainfall under the rotor plane being a better rationalisation, there is however, one major flaw with this normalisation, which is that it does not account for the number of droplets that
actually hit the blade. This is due to the fact that the amount of droplets impacted is a function of the impact speed and rain intensity and falling velocity of the droplets. This can be illustrated by considering the case in which a blade that is standing still while rain is falling, the still standing blade will have no droplet impacts. Whereas a blade moving very fast will hit many droplets. The result of this is that tests performed at different RPMs cannot be compared directly, thus we must calculate the actual number of droplets that impact the blade.

On the fundamental level two things determine the amount of water impacting an object moving through air containing water. Firstly, the amount of water in the air, known as volume concentration \( \psi \):

\[
\psi = \frac{I \omega}{v_{\text{drop,rp}}} \tag{8.9}
\]

Where \( I \) is the rain intensity measured in \( \text{m/s} \), and \( v_{\text{drop,rp}} \) is the falling velocity of the droplet when entering the rotor plane. By multiplying this dimensionless quantity \( \psi \) with the velocity \( v(r) \) of the rotor traveling through the rain we get the amount of water impacting pr. second, also known as the impingement rate:

\[
U_i = \psi \cdot v(r) \left[ \frac{\text{m}}{\text{s}} \right] \tag{8.10}
\]

Where \( v(r) \), in terms of the RET, is the so called local rotor velocity, which is a function of the angular velocity and the radial position:

\[
v(r) \left[ \frac{\text{m}}{\text{s}} \right] = \omega [\text{rad/s}] \cdot r [\text{m}] \tag{8.11}
\]

\[
= \frac{2\pi}{60} \cdot N_{\text{rpm}} \cdot r \tag{8.12}
\]

Where \( \omega \) is the angular velocity and \( r \) is the radial position. So for a rotor turning in uniform rain, such as a wind-turbine during rain, the total impingement can be calculated as:

\[
H(t) = U_i \cdot t [\text{m}] \tag{8.13}
\]

\[
= \psi \cdot v(r) \cdot t [\text{m}] \tag{8.14}
\]

\[
= \frac{I \omega}{v_{\text{drop,rp}}} v(r) \cdot t [\text{m}] \tag{8.15}
\]

\[
= \frac{I}{v_{\text{drop,rp}}} \frac{2\pi}{60} N_{\text{rpm}} \cdot r \cdot t [\text{m}] \tag{8.16}
\]

However, when performing tests in an R&D style RET, the rain field is not uniform, since the needles are positioned equidistantly along the radial droplet manifolds. This can be visualised by looking at Figure 8.12 where bucket two represents the reading of a rain gauge placed close to the inner radius, and bucket three represents the reading of a rain gauge placed at the outer radius. From this it is readily evident that the rain intensity varies with the radius. So in order to calculate the total impingement (8.29) we need to express the rain intensity as a function of the radial position
on the blade.

For the R&D RET we know that the rain generation system is an open ring shape as seen on Figure 8.14 with radially positioned droplet manifolds.

![Coverage angle: θ](image)

Figure 8.14: Schematic illustration showing how the droplet generation manifolds are radially aligned around the active rain field area within the coverage angle θ.

Water flow $P_{\text{water}}$ in the system is constant, and from the geometry we know that the distance along the circular path between the manifolds is directly proportional to $r$. We therefore know that the local rain intensity $I(r)$ must follow:

$$I(r) = K \left[ \frac{\text{m}}{\text{s}} \right]$$

With $K$ being a proportionality factor. Since the total water flow $P$ over the coverage area must
be the integral of the rain intensity over the coverage area, \( K \) can be found as:

\[
P = \int_{r_i}^{r_o} I(r) \cdot \theta \cdot r \cdot dr
\]

\[
= \int_{r_i}^{r_o} K \cdot \theta \cdot dr
\]

\[
= K \cdot \theta \cdot (r_o - r_i)
\]

\[
\hat{=} \tag{8.21}
\]

\[
K = \frac{P}{\theta \cdot (r_o - r_i)} \tag{8.22}
\]

where \( r_o \) is the outer radius and \( r_i \) is the inner radius. We can now insert \( 8.22 \) in \( 8.17 \):

\[
I(r) = \frac{K}{r} = \frac{P}{\theta \cdot r \cdot (r_o - r_i)} \left[ \frac{\text{m}}{\text{s}} \right] \tag{8.23}
\]

This can now be combined with equation \( 8.10 \) to get the following expression:

\[
U_i = \psi \cdot v(r)
\]

\[
= \frac{I(r)}{v_{\text{drop,rp}}} \cdot v(r) \tag{8.24}
\]

\[
= \frac{I(r)}{v_{\text{drop,rp}}} \omega \cdot r \tag{8.25}
\]

\[
= \frac{P}{\theta (r_o - r_i) \left[ \text{m} \right] v_{\text{drop,rp}} \left[ \frac{\text{m}}{\text{s}} \right]} \left[ \text{m/s} \right] \tag{8.26}
\]

From this we see that the impingement rate \( U_i \) is independent of the radial position \( r \), and is only dependent on the flow rate \( P \), angular velocity \( \omega \) and the coverage angle. If we want to determine the total impingement \( H(t) \) we need to multiply \( U_i \) with the fraction of time spent in the active rain field this fraction is:

\[
\varphi = \frac{\theta}{2\pi} \tag{8.28}
\]

With this, we can calculate the impingement:

\[
H(t) = U_i \cdot t \cdot \varphi
\]

\[
= U_i \frac{\theta}{2\pi} \cdot t \tag{8.29}
\]

\[
= \frac{P \omega}{\theta (r_o - r_i) v_{\text{drop,rp}} 2\pi} \cdot t \tag{8.30}
\]

\[
= \frac{P \omega}{2\pi (r_o - r_i) v_{\text{drop,rp}}} t [\text{m}] \tag{8.31}
\]

As can be seen this results in \( \theta \) cancelling out. In addition, the radius cancels out. This is because of the special case that the rain intensity decreases linearly with radius. If plotted as on Figure \( 8.13(c) \) we see that due to the high rotational speed the blade impacts more than 15m of water.
during a test. At first glance when comparing the 8.13(b) and 8.13(c) the data might seem to be merely scaled, but upon closer inspection it is evident that some of the columns of PED’s are shifted in relation to each other. This is a result of the test data originating from a data set, comprising of four different rotational speeds:

- 800 RPM
- 1.065 RPM
- 1.193 RPM
- 1.350 RPM

This means that the resulting SN-curve is in effect independent of the testing set-up and can be compared to any other machine or transferred to a real world turbine.
8.6.3 impacts pr. m²

Following DNVGL-RP-0171, the number of impacts per square meter is one of the recommended rationalisations. DNVGL has confusingly also named this parameter specific impacts, as in ASTM, despite the difference in units. The reason, that the DNVGL approach differs from ASTM, can be tracked down to the fact, that DNVLG do not use Impingement \( H(t) \), but skips directly to impacts.

This is done by converting the volume concentration \( \psi \) to a droplet concentration \( q \):

\[
q = \frac{\psi}{V_{drop}} \quad \text{[droplets/m}^3]\]  

(8.33)

Where \( V_{drop} \) is the volume of a drop. This is then treated in the same fashion, as \( \psi \) was before, by multiplying it with the impacts speed \( v(r) \) and the test time \( t \)

\[
N = q \cdot v(r) \cdot t \quad \text{[droplets/m}^2]\]  

(8.34)

\[
N = P \cdot \omega \cdot t \quad \text{[droplets/m}^2]\]  

(8.35)

Perhaps it would seem natural to use this value to figure out how many impacts a leading edge could withstand. However, there is a problem in using this parameter:

Let us assume that a material is tested and found to be able to withstand \( 1 \times 10^6 \) [droplets/m²], the operator knows that the area of the blade, subjected to direct rain impingement, is \( 10 \) [cm²] resulting in a predicted lifetime of 1.000 impacts. This might seem fine and good. But what happens if we want to calculate how many impacts \( 0.2 \) [mm²] can withstand?

\[
N = 1 \times 10^6 \text{[droplets/m}^2] \cdot 0.2 \text{[mm}^2] = 0.25 \text{[impacts]} \]  

(8.36)

This is of course a non-physical result, as it would mean that less than one impact would break the coating. In essence, the lifetime of any coating would be zero if considered at an infinitesimal small area. In order to avoid this problem, the affected area of each droplet needs to be considered: This is what is done in ASTM’s definition of specific impacts, as described in the following section.

This choice of units seems most likely stems from a desire to have the output of the analysis directly compatible with the Springer model, as described in Section 3.2.
8.6.4 Specific impacts

There is some discrepancy between the new DNVGL-RP-0171 and the older ASTM-G73-10, as to what is understood by specific impacts. According to DNVGL, specific impacts is defined as the number of impacts per unit area. ASTM-G73-10 specific impacts is a dimensionless value.

As shown in section 8.6.2, given testing parameters, one can easily calculate the impingement at any given time as $H(t)$, which gives the column of water that impacts a given spot on the surface normal to the impact direction. However, we know, that discrete droplets, and not a solid column of water impact the blade. In addition, we assume that erosion is a consequence of repeated stress cycles arising from droplet impacts. So we need some method of going from column to a number of discreet impacts, taking into account the area affected by a droplet impact. The method proposed by ASTM-G73-10 is to use the ratio between the projected area $a$, and the volume $b$ of the impacting droplet. The idea can be seen in Figure 8.15 where we project the droplet unto the impacting

![Figure 8.15: Schematic illustration showing the idea behind the projected area of the droplet](image)

$$V_{\text{cylinder}} = V_{\text{sphere}}$$
$$h = \frac{b}{a}$$
surface. Using this approach the height \( h \) of the resulting cylinder can be calculated as:

\[
V_{\text{sphere}} = V_{\text{cylinder}} \tag{8.37}
\]

\[
\frac{4}{3} \left( \frac{d}{2} \right)^{3} \pi = \left( \frac{d}{2} \right)^{2} \pi h \tag{8.38}
\]

\[
\downarrow \tag{8.39}
\]

\[
h = \frac{4}{3} \left( \frac{d}{2} \right)^{3} \pi = \frac{b}{a} = \frac{2d}{3} \text{[m]} \tag{8.40}
\]

Where \( d \) is the diameter of the droplet, \( b \) is the volume of the droplet, \( h \) is the height of the projected cylinder and \( a \) is the projected area of the droplet. To get the number of impacted drops, the total impingement \( H_{0} \) \( \tag{8.29} \) is divided by the height \( h \) of the projected cylinder:

\[
N_{0} = \frac{U_{i} \cdot t \cdot \varphi}{h} = \frac{P\omega}{2\pi (r_{o} - r_{i}) v_{\text{drop.rp}} h t} \tag{8.41}
\]

\[
= \frac{P\omega}{2\pi (r_{o} - r_{i}) v_{\text{drop.rp}} \frac{a}{b} t} \tag{8.42}
\]

\[
= \frac{P\omega}{3 \left( \frac{r_{o} - r_{i}}{v_{\text{drop.rp}}} \right) \frac{3}{2} d t} \tag{8.43}
\]

So with this we can now calculate the specific impacts, for any spot on the surface without the problems described in section \( \text{8.6.3} \). The results of the RET can now be compared to results from discrete impacts testers such as the SPIFT.
Chapter 9. Correlating whirling arm RET with SPIFT

Chapter 9

Correlating whirling arm RET with SPIFT

The following chapter deals with the central thesis of the work, which is to establish if there is a correlation between the damage induced by the SPIFT and RET. To establish a connection between the SPIFT and the whirling-arm RET (henceforth referred to RET), identical coating systems were tested on both systems. To compare the data across the two vastly different testing machines, RET data was rationalised according to the methods described in Section 8.5.

The limiting factor in performing the comparison between SPIFT and RET is that attaining RET data for a given coating is a costly and time-consuming process comparing to SPIFT, as such the comparison between RET and SPIFT is limited to three coating systems.

- GC
- GA
- GS
9.1 Comparison of RET and SPIFT on GC system

The data set GC represents the most complete data set in the comparison. This coating system was supplied by a partner in the IDF Erosion project, as a representative erosion-resistant blade coating. The coating is a one layer commercial elastomeric PU coating. The Whirling arm test performed on this coating system was carried out in conjunction with two different rain erosion projects, IFD Erosion, and IFD Duraledge. Within IDF Erosion, the focus was to establish the relationship between droplet size and erosion across tests performed at different rotational speeds.

9.1.1 SPIFT test on GC

SPIFT was performed on GC samples to establish an SN fatigue curve. The goal here was to establish a SN-curve with a good overlap between the results obtained from the RET. It was, however, not possible to reach the lower impact speeds from the RET of $80.3 \text{ m/s}$ due to the required test time.

The experimental parameter is as follows:

- Number of samples: 8
- Speed range: 175.4 - 119.6 m/s
- Cooling: Forced air, ambient temperature
- Impact Interval: $\delta t(v) = 0.0429 \cdot v + 3.2857$
- Test end at material loss
- Damage assessment method: In-situ, optical microscope video.
- Registered types of damage:
  - First visual damage: as seen in Figure 9.1(a)(d)(g)
  - Radial cracking: as seen on Figure 9.1(d)(e)(f)
  - First Material Loss: as seen on Figure 9.1(g)(h)(i)

With a lower impact speed of 119.6 m/s, there is an overlap of 49 m/s between the RET and SPIFT SN curve. The reason for not testing all the way down to the lowest possible impact speed of $\approx 100 \text{ m/s}$ that the SPIFT is capable of is due to time constraints, as the test at 119.6 m/s took 7h:26m and a test at 100 m/s would potentially take more than 22h. Each test was terminated at the point of evident material loss. The entire damage process is captured as a high-resolution video.
Chapter 9. Correlating whirling arm RET with SPIFT

Table 9.1: The images (a), (d), (g) were tested at 119.6 m/s. The images (b), (e), (h) were tested at 150.8 m/s. The images (c), (f), (i) were tested at 175.4 m/s. The first row (a), (b), (c) shows the first observable damage on the samples. The second row (d), (e), (f) shows the onset of the radial cracking damage phase. The third row (g), (h), (i) shows point of first material loss.
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at 2.592x1.944px, which allows the user to determine different damage states after the completion of the test. Video was chosen over pictures taken at set intervals, due to the increase in data size due to the loss of inter-frame compressing compared to still images. This is because most of the frame remains constant between image frames allowing for efficient compression. Furthermore, the use of video provides us with a very reliable time measurement for the entire test.

From the Visual record of the damage progression two damage states were chosen. The first stage as seen on Figure 9.1(d)(e)(f) is the beginning of radial cracking. The second damage state is seen on Figure 9.1(g)(h)(i) which represents the point of first material loss.

As can be seen from the three selected speeds and corresponding damages in Figure 9.1, they do visually differ from each other. Therefore, there is bound to be a subjective element to the damage identification. If it is assumed that the SPIFT does induce damage by fatigue and that the damage states identified are consistent, it should be possible to fit the data set to a power curve as per ASTM E739-10[59] as can be seen in Figure 9.1.

From Figure 9.1, it is clear that each of the three damage criteria results in a separate damage curve. From the graph it is evident that the three curves have roughly the same slope as the graph is plotted on a semi-log and the curve if a power function it is the exponent $m$ that dictates the slope see equation (8.7). As has been discussed in Section 6.3.1 that although the "first visual damage" criteria might be closer to the end of incubation, the detection of these small damages introduces more uncertainty to the failure evaluation. This is evident when looking at the 95% uncertainty interval for the plotted mean life as shown by the dashed green line in Figure 9.1. Looking at the radial cracking criteria on the blue line, the uncertainty interval is slightly tighter, as the damage is more evident. However, judging the exact cut-off point is challenging. Finally looking at the red line curves representing first material loss the uncertainty interval is much tighter. This shows that it is much easier to evaluate visually when the first material is lost. One way to evaluate this reduction in uncertainty is by looking at the slope $m$ and its corresponding uncertainty as calculated according to ASTM E739-10[59] using a 95% level of confidence as listed below:

- First damage:
  \[ m = 7.90 \pm 3.67 \]

- Radial cracking:
  \[ m = 9.15 \pm 2.65 \]

- Material loss:
  \[ m = 7.33 \pm 0.93 \]
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Figure 9.1: SN curve created by detecting visual damage states from the in-situ optical system. The red curve corresponds to first material loss as defined in Figure 9.1(g)(h)(i), the blue curve represent the first radial cracking as defined in Figure 9.1(d)(e)(f). The green curve represent the first persistent visual damage as seen on Figure 9.1(b)(e)(h). Data set were fitted as pr. ASTM E739 - 10 with along with the 95% confidence interval of the fitted mean life time curve.

Summary on SPIFT on GC

In summary it is evident that the uncertainty on the slope/exponent($m$) is much lower using the material loss damage criteria. In general all three damage criteria yield similar slopes within the uncertainty of the fit.
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9.1.2 RET on GC

Beyond SPIFT, a substantial amount of rain erosion tests were performed on the Vestas system. Consisting of eight separate experiments totalling 24 samples, covering four different rotational speeds and two droplet sizes.

![Area with point erosion](image)

**Figure 9.2:** This figure is an example of erosion progression on a single blade coated with the GC system and tested at 1.350RPM using the large G20 needles. The area where the first PED was detected is highlighted on the image.

- **Rotational speed:**
  - 800 RPM
  - 1.065 RPM
  - 1.193 RPM
  - 1.350 RPM

- **Droplet size**
  - G27: diameter 2.4mm
    - * Water flow: 60 l/h
  - G20: diameter 3.5mm
    - * Water flow: 120 l/h

**G20 droplets on GC system**

As discussed in Chapter 8.5 there is a multitude of ways to rationalise rain erosion data. For this analysis and comparison the analysis is limited to incubation impingement $H_0(m)$, as discussed in Section 8.6.2 and specific impacts to end of incubation $N_0$ in alignment with ASTM-G73-10[40], and discussed in Section 8.6.4.
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Under the assumption that it is the cyclic loading from the repeated droplet impacts that are the
driving factor, \( N_0 \) is among the most commonly used rationalisations.

In order to calculate the dimensional-less value specific impacts \( N_0 \), that the coating can withstand
at a specific local rotor speed, we need the following information.

- Droplet Diameter: \( d = 3.5 \text{mm} \)
- Water flow: \( P120l/h = 3.33 \times 10^{-5} \text{m}^3/s \)
- Coverage angle: \( \theta = 305^\circ \)
- Local rotor speed: calculated from RPM and radial position
- Droplet velocity: \( v_{drop,rp} = 2.25 \text{m/s} \)

With this the number is easily calculated using equation (8.43). Applying these calculations to the
RET data results in the graph in Figure 9.3. From this plot, we see that there is a reasonable fit
with the standard power fit used to model fatigue. The quality of the fitting can be judged by the
95\% interval plotted along the fit in Figure 9.3, this interval is the 95\% confidence interval for the
filled line. This means that the tighter this interval is to the fitted line, the surer we can be that
the fitted function is reliable, and it also serves as an indication of how good the data is.

In summary we can see that impacts to failure range between 360-4.300, the mean lifetime to
failure follows the SN curve:

\[
N_{GC,G20,N_0} = 1.42 \times 10^{12} \cdot S^{-4.23}
\]
\[
C = 1.42 \times 10^{12}
\]
\[
m = 4.35 \pm 0.30
\]

(9.1) \hspace{1cm} (9.2) \hspace{1cm} (9.3)

However as discussed above in Section 8, many things can potentially influence the size of droplets,
which can result in varying amounts of specific impacts \( N \). Based on this it is also desirable to remove
the effect of droplet size on the results, one way to do this is by plotting the total impingement
\( H(t) \) as described in Section 8.6.2. Using this gives the total column of water that impacted the
surface and is as such no longer dependent on the droplet size, see equation (8.29).

Not surprisingly, this curve is not radically different in shape or in the quality of fit. We see that
the mean lifetime follows the SN curve:

\[
N_{GC,G20,H_0} = 3.30 \times 10^9 \cdot S^{-4.23}
\]
\[
C = 3.30 \times 10^9
\]
\[
m = 4.35 \pm 0.30
\]

(9.4) \hspace{1cm} (9.5)
Figure 9.3: RET data performed on the GC system using G20 droplet size. The data was rationalised as specific impacts $N_0$. Data set where fitted as pr. ASTM E739 - 10, with $v$ being the dependent variable and $N_0$/ being the independent variable.

G27 droplets on GC system

The following deals with the test using the G27 needle to generate smaller droplets with a diameter of 2.4. The smaller droplet size is a result of the decreased outer diameter, from 0.9081mm for the G20 down to 0.4128mm. The test parameters for this set of experiments are as follows:

- Droplet Diameter: $d = 2.4\text{mm}$
- Water flow: $P_{60l/h} = 16.67 \times 10^{-6}\text{m}^3/\text{s}$
- Coverage angle: $\theta = 305^\circ$
- Local rotor speed: calculated from RPM and radial position
- Droplet velocity: $v_{\text{drop,}\text{rp}} = 2.25\text{m/s}$
Figure 9.4: RET data performed on the GC system using G20 droplet size. The data was rationalised as total impingement $H_0$. Data set were fitted as pr. ASTM E739 - 10, with $v$ being the dependent variable and $H_0$ being the independent variable.

As we can see the change to the G27 needle, also results in a reduction in water flow. In practice, this reduction in flow means that the G27 test took significantly longer to perform at low RPMs. At 800 RPM the test using G27 needles took 17h as opposed to five hours when using the G20. If one does not apply any normalisation or rationalisation on the data this would lead to the conclusion that small droplets are many times less damaging. As before we can calculate the specific impacts to incubation $N_0$ (8.43), resulting in the graph seen in Figure 9.5.

Here we again see a very good agreement between the data and the fit, with a very narrow confidence interval for the fit. From this, we can express the mean life form the SN curve:

$$N_{GC,G27,N_0} = 3.64 \times 10^{15} \cdot S^{-5.93}$$  \hspace{1cm} (9.6)

$$C = 3.64 \times 10^{15}$$  \hspace{1cm} (9.7)

$$m = 5.93 \pm 0.20$$  \hspace{1cm} (9.8)
Figure 9.5: RET data performed on the GC system using G27 droplet size. The data was rationalised as specific impacts \( N_0 \). Data set where fitted as pr. ASTM E739 - 10, with \( v \) being the dependent variable and \( N_0/ \) being the independent variable.

As discussed before the \( N_0 \) is dependent on knowing the size of the droplet, is subject to influence from external parameters see Section 8. Therefore the data was again plotted as a function of the total impingement \( H_0 \) in Figure 9.6.

Unsurprisingly the good fitting quality remains, with a mean life fitted on the SN curve as:

\[
N_{GC.G27.H_0} = 5.83 \times 10^{12} \cdot S^{-5.93} \\
C = 5.83 \times 10^{12} \quad \text{(9.10)} \\
m = 5.93 \pm 0.20 \quad \text{(9.11)}
\]

Summary of RET using G20 and G27

Both set of droplet sizes yielded fits with a narrow confidence band. This is also expected when using the statistical approach of [59]. This is due to the large number of measurements despite the
**Figure 9.6:** RET data performed on the GC system using G27 droplet size. Data sets were fitted as per ASTM E739 - 10, with $v$ being the dependent variable and $n$ being the independent variable. Relatively noisy data.
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9.1.3 Comparison of RET on G20 and G27 on the GC system

It is well known that droplet size in rain is not just one size, but varies with rain intensity and a host of other factors\[67\]. As such, it is natural to consider the effect of droplet size on the severity of erosion. Without going into too much detail, there are two schools of thought on the subject. Firstly, that the peak pressure induced during the impact is the main driving factor, here most models predict that the peak impact pressure is agnostic to the droplet size, and is proportional to the impact speed $P_{\text{droplet}} \propto V$. It should be noted here that this analysis is solely limited to the very initial damages of the outermost layer of the protective coating as defined in section 8.3.1. Secondly, there are various arguments for a droplet size-dependent damage model, one could be kinetic energy, or jetting effects and some studies have found various relations between droplet size and erosion severity some models predicting a 4..67th power of the droplet diameter effect\[68\]. Therefore, the goal here is to see if it is possible to establish some relation between the droplet size and the severity of erosion.

The first comparison we can perform is to see if the number of impacts to failure $N_0$ differs between the two tests as plotted in Figure 9.8.

As we see, there is not a very large difference between the two droplet sizes. In fact, the two curves intersect at 143m/s. If there was a clear effect of droplet size we would expect a clear separation between the two curves. However, as a whole, the large G20:3.5mm droplets seem to induce damage earlier, and the slope of the G20 curve is steeper also indicating a more severe erosion progression. However as mentioned in Section 8, of all the controllable machine parameters, the droplet size is the least well defined, which can in turn severely influence the number of impacts. However if the droplet size does indeed have a strong effect on the damage, we would expect to see this effect even if we do not directly calculate the number of impacts $N_0$ but instead look at the total impingement $H_0$ which is solely derived from the water flow $P$. If the data is plotted in this fashion as seen Figure 9.7(b) we see that the slope of the curve remained the same, but the constant $C$ is now very close to each other bringing the two curves closer together. Moreover, we saw a large difference in the number of impacts to failure at lower impact speeds before. Now the relative difference in total impingement is much smaller.

One possible explanation to the small difference between the curves in Figure 9.7(b) could be that there was no difference in droplet size during the test, and the only difference came from difference I (water flow). If it is assumed that both droplet sizes are the same at 2.4mm, we get the plot in Figure 9.7(c) As we now see, the shape of the curves is the same as we saw with the total impingement in Figure 9.7(b). This is by no means conclusive, but it might indicate that there could be issues with the droplet size during the test.
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Figure 9.7: RET data performed on the GC system using G27 and G20 droplet size. Data sets were fitted as pr. ASTM E739 - 10, with \( v \) being the dependent variable and \( n \) being the independent variable. In (a) data from the G20 and G27 is rationalised as the specific number of impacts \( N_0 \). In (b) the total impingement \( H_0 \) is compared. In (c) the specific impacts to failure \( N_0 \) is compared under the assumption that both droplet sizes were 2.4mm in diameter.

Summary RET on G20 and G27 test on GC system

In summary no clear distinction between the two droplet sizes is evident. There are crossovers in the absolute values. The clearest distinction is in the slope. The larger 3.5mm droplet yields a
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steeper slope to the SN data potentially indicating a more aggressive impact.
9.2 Comparison RET and SPIFT on GC system

In this Section, erosion data on the GC system using both SPIFT and RET will be compared. As the goal of developing the SPIFT was to emulate rain erosion in a controlled fashion, it is important to establish if there is a relation between the two tests. The comparison will be carried out using the rationalisations from the above sections, specific impacts $N_0$ and total impingement $H_0$. For both rationalisations, damage factors will be calculated, to transfer SPIFT results directly to RET.

9.2.1 RET vs. SPIFT Specific Impact on GC system

As discussed in the sections above we can rationalise the fatigue load imposed by the RET as a number of specific impacts $N_0$ if we compare this directly to the SN curves for the three different damage states for the SPIFT we get the graph is seen in Figure 9.8.

Had there been a clear 1:1 correlation between the SPIFT and RET, we would have expected the SPIFT curve to be a natural extension of the RET curve. However, as can be seen, there is an apparent offset between the SPIFT and RET curves. What should be noted is that despite the offset between data sets, there is some overlap of the green curve, denoting the very first damage observed and the data set and as a whole the slopes of the curves are quite comparable. What this indicates is that as a whole, the SPIFT is less aggressive in inducing erosion compared to the RET. This difference is most likely due to the lack of a strong material removal mechanism in the SPIFT. In the RET an impacting droplet will quickly begin to spread out during the impact. This jetting water serves to remove material from the surface. Therefore, it might also serve as an accelerating effect once the integrity of the surface is broken. As a broken-up surface gives ledges or steps that the jetting droplet can push against.

This suggests why the very early damage stage, detected in the SPIFT is closer to the RET curve as this type of damage might be percussive to the incubation spots detected on the RET samples, but just accelerated by the jetting effects.

To calculate severity factors that can equate the SPIFT results with RET results, the SPIFT results will be multiplied by the severity factor $F_0$. To attain $F_0$ will be solved so that the fitted SN curve intersects both G20 and G27 curves, for this test the intersection is at:

- Impact speed: 143.6 m/s
- $N_0$: 582 Impacts
- Calculated severity factors $F_0$
  - First material loss: $F_0(\text{Full}) = 0.1629$: 6.14x less damaging
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Figure 9.8: The graph shows data from the G20 and G27 is rationalised as the specific number of impacts \( N_0 \). SPIFT data showing the three failure states in is plotted in green, orange and black. Fitted according to ASTM E739 - 10

- Radial cracking: \( F_0(\text{Radial}) = 0.2543 \): 3.93x less damaging
- First observable damage: \( F_0(\text{First}) = 0.5764 \): 1.73x less damaging

As we see from Figure [9.9(a)] safety factors \( F_0 \) are between 0.16-0.58 for the different damage stages.

Summary impacts to damage of SPIFT vs. RET on GC

In summary the SPIFT is between 6.14 to 1.73 times less damaging compared to the RET test. Applying a safety factor in this way does of course not change the slope of the curve as we see from the unchanged exponent \( m \) only translating the entire curve to the left.
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9.2.2 RET vs. SPIFT total impingement on GC system

As discussed in section 8.6.2, the total impingement $H_0$ might be a better choice for an erosion load parameter in the RET due to the uncertainty regarding the droplet size. Therefore, it would be desirable to convert the SPIFT results into impingement. This can be done using Equation (8.40) setting the diameter to 6mm if we follow the same method as used for the droplets as per ASTM G73-10. This results in the graph seen in Figure 9.10. We see that the difference between SPIFT and RET is larger than when comparing impacts. With this rationalisation applied, we would judge the SPIFT to be even less damaging compared to RET.

To calculate severity factors that can equate the SPIFT $H_0$ with RET $H_0$, the SPIFT results will be multiplied by the severity factor $F_0$. To attain $F_0$, the factor will be fitted so that the fitted SPIFT curve passes through the midpoint between the G20 and G27 curves at 143.6 m/s:

- Impact speed: 143.6 m/s
- $H_0$: 1.1224 m
- Calculated severity factors $F_0$
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Figure 9.10: The graph shows data from the G20 and G27 is rationalised as impingement $H_0$, plotted together with the three failure states detected in the SPIFT. fitted according to ASTM E739 - 10

- First material loss: $F_0(\text{Full}) = 0.08$: 12.7x less damaging
- Radial cracking: $F_0(\text{Radial}) = 0.12$: 8.2x less damaging
- First observable damage: $F_0(\text{First}) = 0.28$: 3.6x less damaging

As we see from Figure 9.9(a), severity factor $F_0$ are in the case of total impingement between 0.08-0.28 for the different damage stages. This means that the SPIFT is between 12.7 to 3.60 times less damaging compared to RET test.

As established in section 6.4.1, the deformation of the pellet during impact results in a projected contact area that is larger than the 6mm diameter of the pellet. From the high-speed imaging an empirical relation between the deformation and the speed of the pellets was established. By applying this model to the data it is possible to calculate the impingement as a function of impact speed $v$. Applying this calculation yields the curves seen in Figure 9.11.
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Figure 9.11: The graph shows data from the G20 and G27 droplets on the GC system. Data is rationalised as impingement as a function of impact speed $H_0(v)$, plotted together with the 3 failure states detected in the SPIFT on the same system. Fitted according to ASTM E739 - 10

To calculate severity factors for this modified SPIFT impingement $H_0(v)$ with RET $H_0$, the SPIFT results will be multiplied by the severity factor $F_0$. To attain $F_0$, the factor will be fitted so that the fitted SPIFT curve passes through the midpoint between the G20 and G27 curves at 143.6 m/s:

- Impact speed: 143.6 m/s
- $H_0$: 1.1224 m
- Calculated severity factors $F_0$
  - First material loss: $F_0(\text{Full}) = 0.12$: 8.3x less damaging
  - Radial cracking: $F_0(\text{Radial}) = 0.21$: 4.9x less damaging
  - First observable damage: $F_0(\text{First}) = 0.47$: 2.1x less damaging
As can be seen from Figure 9.11, the modified impingement calculation results in less impingement per impact. For the GC system this results in the data shifting closer to the RET data.

**Summary of impingement to damage RET vs. SPIFT on GC**

In summary when calculating the impingement generated by the SPIFT the offset is larger compared to $N_0$. Modifying the impingement to account for the deformation of the pellet results in SPIFT being between 2.1 to 8.3 times less damaging.
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9.3 Comparison of RET and SPIFT on GA system

The GA system was supplied by Olsen Wings A/S, and is used as an example of a generic blade coating system. This system was tested on both the RET at R&D A/S, and the SPIFT. The main goal of testing on the GA system is to provide another point of comparison between SPIFT and the RET in order to establish a correlation between the two systems.

9.3.1 SPIFT test on GA

SPIFT was performed on GA samples to establish an SN fatigue curve.

The experimental parameter is as follows:

- Number of samples: 6
- Speed range: 168.2 - 119.7 m/s
- Cooling: Forced air, ambient temperature
- Impact Interval: \[ \delta t(v) = 0.0429 \cdot v + 3.2857 \]
- Test end at material loss
- Damage assessment method: In-situ, optical microscope video.
- Registered types of damage:
  - First observable damage: as seen in Figure 9.2a
  - Radial cracking: as seen on Figure 9.2c
  - First Material Loss: as seen on Figure 9.2g

The registered failure detected in the RET covers an impact speed range of 168.6-99.6 m/s, resulting in considerable overlap of 48.5 m/s between SPIFT and RET testing.

Damage states were registered as per the method described in Section 6.3.1 using the in-line camera system. Examples of theses damage states can be seen in Figure 9.2.

The first two damage states observed on the GA system are similar to the damage observed on the GA system, as seen in Figure 9.1. The GA system differs from the GC system when considering the final damage state in which the first material loss is observed. In the case of the GC system material loss results from the circular and radial cracks reaching a critical density as seen in Figure 9.1.
Table 9.2: The images (a)(d)(g) were tested at 119 m/s and show the three damage states: (a): first visual at 755 impacts, (d): first circular crack at 1,612 impacts, (g): first material loss at 1,875 impacts. The images (b)(e)(h) were tested at 149 m/s and show the three damage states: (b): first visual at 87 impacts, (e): first circular crack at 123 impacts, (h): first material loss at 157 impacts. The images (c)(f)(i) were tested at 168 m/s and show the three damage states: (c): first visual at 43 impacts, (f): first circular crack at 56 impacts, (i): first material loss at 60 impacts. The red dotted lines indicate the area of first material loss.

The GA system differs although the sample starts to exhibit annular cracking at the centre of the sample before the cracks can grow together resulting in material loss, the sample will show first material loss outside the impact area.
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This effect can be seen in Figure 9.2g(h)(i) where damage is outside the impact area, as is highlighted by the red dotted line. From the recorded video (link to which can be found in the footnote) the coating removal progresses rapidly after the first material loss. From the shape and look of the damaged area, the hypothesis is that the crack originated in the pink filler layer underneath the topcoat at the canter of the sample. From the centre, this crack gradually progressed outwards until it surfaced outside of the impact area.

Figure 9.12: SN curve created by detecting visual damage states from the in-situ optical system. The red curve corresponds to first material loss as defined in Figure 9.4g(h)(i); the blue curve represents the first annular cracking as defined in Figure 9.4d(e)(f). All data sets were fitted as per ASTM E739 - 10

The fatigue life of the six test samples was evaluated by measuring the number of impacts required to reach the three damage states. These three data sets were then fitted as per ASTM E739 - 10. As was seen on the GC system, the three damage criteria result in separate SN curves with roughly similar slopes. Again, the quality of each fitted curve is represented in the 95% confidence interval.

[https://data.dtu.dk/s/c69c20bea718e9b1752a](https://data.dtu.dk/s/c69c20bea718e9b1752a)
interval plotted in the figure with the dotted lines. However, the difference in uncertainty is not as pronounced as was observed when testing the GC system, which is evident from looking at the exponents \( m \) in the list below:

- First damage:
  \[-m = 8.30 \pm 2.42\]

- Annular cracking:
  \[-m = 9.32 \pm 2.90\]

- Material loss:
  \[-m = 9.38 \pm 2.51\]

However this is based on a limited number of tests, and as such, the particular uncertainties, observed in this test might change with a larger sample size. It is still our belief that the material loss damage criteria provide the most robust damage evaluation criteria.

### 9.3.2 Summary of SPIFT test on GA system

In summary the GA system exhibited tendencies to brittle failure in the filler layer.


9.3.3 RET on GA

Figure 9.13: This figure is an example of erosion progression on a single blade tested at 1.350RPM using the large G20 needles. Point erosion is observed at 30min after this only substrate erosion is seen as the coating was rapidly peeled away before more PEDs could form.

This next subsection deals with the whirling arm rain erosion testing (RET) performed on the GA system. Just as on the GC system, these experiments were performed on the RET facility at R&D A/S. Test parameters are listed below, with the main difference between this test, and the GC test being the lack of testing at 800RPM. Furthermore, in many cases, these tests were conducted in conjunction with the GC experiments, as the structure of the data analyses mirrors that of the Previous GC system with some omissions for the sake of brevity. In the GC section 9.1.2 the possibility that there might not be any difference in droplet size between G20 and G27, which is omitted in these analyses, was discussed.

- Rotational speed:
  - 1.065 RPM
  - 1.193 RPM
  - 1.350 RPM

- Droplet size
  - G27: diameter 2.4mm
  -  Water flow: 60 l/h
  - G20: diameter 3.5mm
  -  Water flow: 120 l/h
Summary of RET on the GA system

In summary GA system differs significantly from the GC system when looking at the post-incubation erosion, as can be seen in Figure 9.13 when compared to the equivalent GC test as seen on Figure 9.2. We see that on the GA system that after the coating exhibits that first point erosion damages (PED) at the 30min time mark coating removal progresses very rapidly. As described in Section 8.4 this type of post-incubation failure is indicative of adhesive failure between the filler layer and the GF-matrix. Less PEDs are detected in this test compared with a test on the GA system. This is a result of the coating peeling away before the surface layer reaches its incubation threshold.

This seems in line with the observations of failure in the primer layer in SPIFT testing.
9.3.4 RET G20 droplets on GA system

In the same way as with the GC system, in Section 9.1.2, the first set of test data to be analysed is the tests carried out using the large G20 needles.

As the assumption that it is the cyclic loading, from the repeated droplet impacts that are the driving factor, specific impacts $N_0$ are among the most commonly used rationalisations.

In order to calculate the dimensional-less value specific impacts $N_0$, that the coating can withstand at a given local rotor speed, we need the following information.

- Droplet Diameter: $d = 3.5\text{mm}$
- Water flow: $P120\text{l/h} = 3.33 \times 10^{-5}\text{m}^3/\text{s}$
- Coverage angle: $\theta = 305^\circ$
- Local rotor speed: calculated from RPM and radial position
- Droplet velocity: $v_{drop,rp} = 2.25\text{m/s}$

By measuring time and position of failure as described in Section 8.6, $N_0$ is calculated and fitted to the modified pr. ASTM E739-10 results in the graph in Figure 9.14 with $v$ being the dependent variable and $n$ being the independent variable.

From this plot, we see that there is a reasonable fit with the standard power fit used to model fatigue. The quality of the fitting can be judged by the 95% confidence interval. This shows the 95% confidence interval for the filled mean lifetime line, meaning that the tighter this interval is to the fitted line the surer we can be that the fitted function is reliable, and it also serves as an indication as to the quality of the data.

From this analysis, the mean lifetime until the end of incubation can be expressed by the following:

$$N_{GA.G20,N_0} = 6.22 \times 10^{13} \cdot S^{-4.98}$$  \hspace{1cm} \text{(9.12)}

$$C = 6.22 \times 10^{13}$$  \hspace{1cm} \text{(9.13)}

$$m = 4.98 \pm 0.53$$  \hspace{1cm} \text{(9.14)}

Overall, there seems to be a good agreement with the filled power curve. However if we compare the uncertainty of the exponent $m$ with that obtained in the GC testing of $m_{GC} = 4.35 \pm 0.30$ it is clear that the quality of fit is not quite to the level of the GC data set. This can be explained by the fact that due to the failure mode of the GA system, fewer PEDs were detected. Secondly due to the lack of testing at 800RPM the there are no data points covering the sub 100m/s speed range.
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![Graph](image-url)

**Figure 9.14:** RET data performed on the GA system using G20 droplet size. Data sets were fitted as per ASTM E739 - 10, with \( v \) being the dependent variable and \( n \) being the independent variable.

Just as with the GC system, it is also of interest to evaluate the erosion performance in relation to the total impingement \( H_0 \), as this value is mostly independent of droplet size and distribution. Only the droplet speed is slightly affected by the droplet size.

The data is again fitted as per ASTM E739 - 10, with \( v \) being the dependent variable and \( H \) being the independent variable as can be seen in Figure 9.15.

This results in a mean life time curve expressed as:

\[
N_{G.A.G20,H_0} = 1.45 \times 10^{11} \cdot S^{-4.2} \quad \text{(9.15)}
\]

\[
C = 6.22 \times 10^{13} \quad \text{(9.16)}
\]

\[
m = 4.98 \pm 0.53 \quad \text{(9.17)}
\]

There is a linear relation between \( n \) and \( H \) and as expected we see that the exponent \( m \) remains the same using this representation just as was the case in the GC data set.
Summary of RET using G20 droplet on GA system

In summary it was possible to construct SN curves based on observed PEDs prior to complete coating failure. This highlights the importance of separating incubation damage from breakthrough times, as incubation is a measure of material strength and breakthrough/peeling is likely due to bad application of the coating.

Figure 9.15: RET data performed on the GA system using G20 droplet size. With the total impingement $H_0$ plotted versus the impact speed $v$. Data set were fitted as pr. ASTM E739 - 10, with $v$ being the dependent variable and $H$ being the independent variable.
9.3.5 RET of G27 droplets on GA system

This second part of the analysis deals with results obtained the G27 needle to generate a smaller droplet diameter of 2.4mm. The smaller droplet size is a result of the decreased outer diameter, down from 0.9081mm for the G20 down to 0.4128mm using the G27. The test parameters for this set of experiments are as follows:

- Droplet Diameter: \( d = 2.4 \text{mm} \)
- Water flow: \( P = 60 \text{l/h} = 1.67 \times 10^{-5} \text{m}^3/\text{s} \)
- Coverage angle: \( \theta = 305^\circ \)
- Local rotor speed: calculated from RPM and radial position
- Droplet velocity: \( v_{\text{drop, rp}} = 2.25 \text{m/s} \)

The G27 needle results in a reduction in water flow, halving it to 60l/h. This results in a large increase in testing time, further highlighting the need for normalisation of fatigue cycles. Again the specific impacts \( N_0 \) were calculated for this data set and fitted as before as can be seen in Figure 9.16.

From these analyses, the mean lifetime until the end of incubation can be expressed by the following:

\[
N_{\text{GA,G27},N_0} = 1.96 \times 10^{20} \cdot S^{-7.95}
\]
\[
C = 1.96 \times 10^{20}
\]
\[
m = 7.95 \pm 1.23
\]

Again, we see a good agreement between the fitted power curve and the data set. However, as in the previous GA test, the lower number of data points compared to the GC test results in larger uncertainties regarding the fit, as can be seen from the exponent \( m \).

As before the data analysis was repeated substituting, the \( N_0 \) for the total impingement \( H_0 \) as seen in Figure 9.17.

This results in a mean life time curve expressed as:

\[
N_{\text{GA,G27,H0}} = 1.45 \times 10^{11} \cdot S^{-4.2}
\]
\[
C = 6.22 \times 10^{13}
\]
\[
m = 4.98 \pm 0.53
\]
Summary of RET of G27 droplets on GA system

Changing the droplet size had an appreciable effect on the failure mode of the coating, compared to the G20 test.
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9.3.6 Comparison of RET with G20 and G27 droplet on GA system

As described in section 9.1.3, there are differing theories as to the potential effect of droplet size on erosion performance. Therefore, an important part of this investigation is to compare the two tested droplet sizes against each other on near-identical systems.

The comparison of the two droplet sizes can be seen in Figure 9.18. Here we once again see a similar trend to what was observed on the GC system in Figure 9.7, as two curves exhibit a large amount of overlap. There is, however, some difference in the droplet size dependence compared to the GC system. Primarily the fact that regardless of whether the data is normalised as $N_0$ or $H_0$ the mean lifetime curves intersect which was not the case for the specific impacts for the GC system, see Figure 9.7(a). However, a trend that both the GA and GC system exhibit is that the larger 3.5mm G20 droplets result in a steeper curve than the smaller 2.4mm diameter G27 droplets.

Figure 9.17: RET data performed on the GA system using G27 droplet size. With the total impingement $H_0$ plotted versus the impact speed $v$. Data set were fitted as pr. ASTM E739 - 10, with $v$ being the dependent variable and $H$ being the independent variable.
Figure 9.18: RET data performed on the GA system using G27 and G20 droplet size. Data sets were fitted as pr. ASTM E739 - 10, with $v$ being the dependent variable and $n$ being the independent variable. The red line and dots represent test data using the smaller G27 needle resulting in an assumed droplet diameter of 2.4mm. The blue line and dots represent test data using the larger G20 needle resulting in a assumed droplet diameter of 3.5mm. In (a) data from the G20 and G27 is rationalised as the specific number of impacts $N_0$. In (b) the total impingement $H_0$ is compared.

droplets. Looking at the curve, it seems that at high impact speeds the smaller G27 droplets are potentially more damaging whereas, at lower impact speeds, the larger droplets become comparably more damaging.

However, the reason for this is not immediately apparent. Since we consider impact energy to be a driving factor, we would expect large droplets to be much more damaging at high impact speeds. However, to a large extent this trend could also be due to the nature of the test. When testing at higher impact speeds at 1.350RPM and with large G20 needle size, it is not uncommon to see the PEDs in the first 10min time slice, resulting in poor temporal resolution. Whereas when using the G20 needles with the accompanying halved water flow this results in more extended tests allowing for more observations during each test. This effectively increases the temporal resolution of each the test.

Summary of RET with G20 and G27 droplet on GA system

In summary there is no clear difference in the absolute number of impacts to failure between the two tests. The same trend of G20’s 3.5mm droplet resulting a steeper slope is observed.
9.4 Comparison RET and SPIFT on GA system

In this section, erosion data on the GA system using both SPIFT and RET will be compared. The comparison will be carried out using the rationalisations from the above sections, specific impacts \( N_0 \) and total impingement \( H_0 \). For both rationalisations, damage factors will be calculated, to transfer SPIFT results directly to RET.

9.4.1 RET vs. SPIFT Specific Impact on GA system

Comparing the whirling arm RET to the SPIFT, the most intuitive comparison is by comparing the number of stress cycles or impacts the coating was subjected to expressed as the dimensionless value \( N_0 \). For the SPIFT, this is achieved by counting the number of impacts, whereas in the RET this is an inferred value based on testing parameters. This comparison can be seen in Figure 9.19.

**Figure 9.19:** On the graph can be seen the fitted mean lifetime from the previous graphs 9.18(a) and 9.12 fitted according to ASTM E739 - 10
From the comparison, the immediate conclusion is that when testing on the GA system the SPIFT is much more damaging than the RET. By comparing the SPIFT performance with the RET curves, at the point where the red and blue RET curves cross over, we can assign a relative severity factor as listed below:

- Impact speed: 154 m/s
- RET \( N_0 \): 582 Impacts
- Calculated severity factors \( F_0 \) Compared to RET
  - First material loss: \( F_0(\text{Full}) = 5.2 \): 5.2x more damaging
  - Annular cracking: \( F_0(\text{Annular}) = 5.9 \): 5.9x more damaging
  - First observable damage: \( F_0(\text{First}) = 11.2 \): 11.2x more damaging

Compared to the results from the GC system where the SPIFT was much less damaging compared to the RET, the GA system shows the opposite trend. As we see, the SPIFT samples are damaged much earlier and depending on damage criteria range between 5.1-11.2x more damaging. However, the slope of the fitted curves are still very similar and well within the uncertainty interval of the SPIFT data.

A possible explanation as to why the difference between the two systems is so pronounced, could be down to the filler layer. As previously commented on the failure observed in this system when testing on SPIFT seems to originate from a brittle or perhaps adhesive failure originating in or at the filler to GF-matrix interface. It seems that the larger 6mm diameter impacting pellets of the SPIFT can transfer more force to the seemingly brittle filler layer.

From the RET, the adhesion between the filler and the substrate was also shown to be a limiting factor in the lifetime of this coating system although the SPIFT failed to generate results that are directly transferable to the GA system. Both tests were able to identify the filler as the weak component in this coating system. Moreover, from the failure mode observed in the SPIFT, we get indications that damage in the filler layer can extend way beyond the initial impact site. This effect might contribute to accelerated coating removal seen in the RET, as illustrated in Figure 9.13.

### 9.4.2 RET vs. SPIFT total impingement on GA system

As impingement is an important rationalisation when dealing with RET results, it is also important to see how applying this rationalisation to the SPIFT influences the comparison with the RET. The fit method of converting the SPIFT impacts into impingement is described in section 6.4.1 and
results in a 4mm impingement per impact. Applying this rationalisation to the SPIFT results leads to the curves seen in Figure 9.20.

As was the case with the GA system, this rationalisation results in a shift of the SPIFT data towards the right. Therefore, for the GA system this results in a relative better agreement between the two tests. In order to quantify the difference between the SPIFT and RET linear safety factors are calculated. The safety factors are evaluated at 135m/s as both RET curves intersect at this point.

- Impact speed: 135 m/s
- $H_0$: 3.5 m
- Calculated severity factors $F_0$
  - First material loss: $F_0(\text{Full}) = 1.68$: 1.68x more damaging
  - Annular cracking: $F_0(\text{Annular}) = 1.934$: 1.93x more damaging
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– First observable damage: $F_0(First) = 4.38$: 4.38x more damaging

As was also established in Section 6.4.1, the deformation of the pellet during impact results in a projected contact area that is larger than the 6mm diameter of the pellet. From the high-speed imaging, an empirical relation between the deformation and the speed of the pellets was established. Nevertheless, applying this model to the data, it is possible to calculate the impingement as a function of impact speed $v$. Applying this calculation yields the curves seen in Figure 9.21.

![Graph showing fitted mean lifetime from previous graphs 9.18(a) and 9.12](image)

**Figure 9.21:** On the graph can be seen the fitted mean lifetime from the previous graphs 9.18(a) and 9.12 fitted according to ASTM E739 - 10

Compared to the unmodified impingement as seen in Figure 9.20, the significant difference is that this calculation yields a smaller impingement at the high testing speed in this particular example ranging between 2.44-2.78mm per impact down from the 4mm of the unmodified calculation. The result of this can be seen on the graph as a shift of the curves to the left relative to the RET curves.

As we see from Figure 9.9(a), severity factor $F_0$ are in the case of total impingement between 0.08-0.28 for the different damage stages. This means that the SPIFT is between 12.7 to 3.60 times less damaging compared to RET test.
In order to quantify the difference between the SPIFT and RET linear safety factors are calculated. The safety factors are evaluated at 135m/s as both RET curves intersect at this point:

- Impact speed: 135 m/s
- $H_0$: 3.5 m
- Calculated severity factors $F_0$
  - First material loss: $F_0(\text{Full}) = 2.54$: 2.54x more damaging
  - Annular cracking: $F_0(\text{Annular}) = 2.89$: 2.89x more damaging
  - First observable damage: $F_0(\text{First}) = 6.36$: 6.36x more damaging

As can be seen this overall reduced impingement per impact results in higher damage factors for the SPIFT.

9.4.3 Summary RET vs. SPIFT on GA system

As a whole, it seems that the brittle nature of the GA system is poorly suited to the SPIFT if direct 1:1 lifetime comparisons are needed.

However these results might be an indication of how this coating system would perform under a more extreme load such as hail impact.

As seen from RET testing, the weak link in this system was the filler layer. The SPIFT testing was able to provoke the failure in the filler layer earlier than compared to RET. This highlights the use of the SPIFT as a potential screening tool.
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9.5 Comparison of RET and SPIFT on GS system

The following section deals with the SPIFT and RET experiments performed on a coating system supplied by a project partner. At the time of project start in 2016 this system represented the state of the art of rain erosion protection systems for leading edges. The system consists of three main layers, a pink filler, the white polyurethane topcoat and second thick 500\(\mu\)m over solid content PU elastomer coating serving as leading-edge protection.

9.5.1 SPIFT on the GS

SPIFT was performed on the GS system to establish an SN fatigue curve. The experimental parameters are as follows:

- Number of samples: 10
- Speed range: 130 - 177 m/s
- Cooling: Forced air, ambient temperature
- Impact Interval: \(\delta t(v) = 0.0429 \cdot v + 3.2857\)
- Test end at material loss
- Damage assessment method: In-situ, optical microscope video.
- Registered types of damage: as seen on Figure 9.22
  - First observable damage
  - Radial cracking
  - First Material Loss

Damage states were registered as per the method described in Section 6.3.1 using the in-line camera system. Examples of theses damage states can be seen in Figure 9.22.

As can be seen in Figure 9.22, these damage states are akin to the types of damage observed on the GC system in Figure 9.1. One factor that makes these samples more challenging to judge is the presence of the small black dots. These dots are due to bubbles that were trapped in the PU layer during curing in which black residue from the pellets accumulates during testing. This makes it difficult to judge the point of the first failure precisely. The remaining two failure modes: radial cracking and the first material loss criteria are, however relatively easy to identify.
Based on these criteria an SN curve can be constructed similar to GC and GA as can be seen in Figure 9.23. The fatigue life of the 11 test samples was evaluated by measuring the number of impacts required to reach the three damage states. These three data sets were then fitted as per ASTM E739 - 10. This results in three separate SN curves with roughly similar slopes. Again the quality of each fitted curve is represented in the 95% confidence interval illustrated by the dotted lines. Here it is seen that the green line representing the first damage state has the largest associated uncertainty. As described above this is due to the difficulty in separating the initial damage area from the black spot resulting from the trapped air bubbles in the coating. This uncertainty is also evident from the exponent as listed below together with the exponents for the remaining damage criteria:

- First damage:
  - $m = 4.65 \pm 8.36$

- Annular cracking:
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First SPIFT First: \( N = 8.45 \times 10^{12} \times S^{-4.65} \)

95% conf interval

Radial SPIFT Radial: \( N = 1.23 \times 10^{14} \times S^{-4.89} \)

95% conf interval

Full SPIFT Full: \( N = 5.21 \times 10^{17} \times S^{-6.40} \)

95% conf interval

Impact Speed (m/s)

Specific impacts (n)

Figure 9.23: SN curve created by detecting visual damage states from the in-situ optical system. The red curve corresponds to first material loss, the blue curve represents the first radial cracking, and the green curve shows the first visually observed damage. All data sets were fitted as per ASTM E739 - 10. The dotted lines on both sides of the fitted mean lifetime curves represent the 95% confidence interval for the fitted curve:

- \( m = 4.89 \pm 3.37 \)

- Material loss:
  - \( m = 6.40 \pm 4.47 \)

Summary of SPIFT testing on GS

In general, this system follows a trend similar to that observed in both GA and GC systems in that the later damage states yield better data than the first damage states. However, in the case of the GS system the final damage state yields slightly worse data. An explanation to this could be that
the SPIFT only simulates the impact component of a droplet impact and not the subsequent jetting effects thus the removal of material is limited. As a result observing the end of incubation might be ambiguous. System GS was very susceptible to premature failure due to impact heating. This was mitigated by cooling and controlling impact rate

9.5.2 RET on GS system

As part of the collaboration with Siemens Gamesa we revived RET results for the GS system with the LEP applied. The system as tested at their own RET facility at Siemens Gamesa in Aalborg. Tested at the following parameters:

- Rotational speed:
  - 1.240 RPM
- Droplet size
  - G27: diameter 2.4mm
  - Water flow: 70 l/h

This is the same R&D style of RET that was used for the previous experiments on the GA and GC systems. There are, however, some differences in the testing procedures because the machine at Siemens Gamesa does not use an in-line camera system for documenting the progression of the erosion. In the tester at Siemens Gamesa, samples are removed from the tester for inspection and photographing after each time using a dedicated photo rig with a Nikon D5300 to photograph the samples before remounting in the machine. In practice, however this should not influence the results obtained compared to the other RET used. Figure 9.24 shows an example of how erosion progresses on this system. In general, this seems similar to the GC system in the sense that erosion starts at the PEDs, which gradually erode further down to the GF-substrate. Again this system exhibits the characteristic 45\(^\circ\) slanted shape to the damaged area, resulting from the fibre direction in the biax GF used in the laminate. From this, we can see that as a whole, the system does not seem to be failing due to poor adhesion as was seen with the GC system.

By applying the calculation from section 8.6.4, the number of impacts to failure is calculated and fitted to the SN curve as can be seen in Figure 9.25.

From this analysis, the mean lifetime until the end of incubation can be expressed by the following:

\[
N_{SiemensG270} = 2.88 \times 10^{26} \cdot S^{-10.79}
\]  
\[
C = 2.88 \times 10^{26}
\]  
\[
m = 10.79 \pm 1.73
\]
Figure 9.24: This figure is an example of erosion progression on a single blade tested at 1.240RPM using the small G27 needles at the RET facility at Siemens Gamesa in Aalborg. The tested system consists of three main layers, a pink filler, the white polyurethane topcoat and second thick 500µm love solid content PU elastomer coating serving as leading-edge protection.

Overall, there seems to be a good agreement with the filed power curve. However, if we compare the uncertainty of the exponent \( m \) with that obtained in the GC testing of \( m_{GC} = 4.35 \pm 0.30 \) the fit was not quite as good. The difference in the quality of fit is most likely due to the reduced number of data points and the reduced range of impact speeds tested.

Repeating the analysis for the impingement yields the curve, as seen in Figure 9.26.

From this analysis the mean lifetime until end of incubation can be expressed by the following:

\[
H_{GSG27} = 4.61 \times 10^{23} \cdot S^{-10.79} \quad (9.27)
\]

\[
C = 4.61 \times 10^{23} \quad m = 10.79 \pm 1.73 \quad (9.28)
\]
Figure 9.25: RET data performed on the GS system using G27 droplet size. Data sets were fitted as pr. ASTM E739 - 10, with $v$ being the dependent variable and $n$ being the independent variable.

Summery of RET tesing on GS

In summery it was possible to construct SN curves based on PEDs. The data does not cover the same range of impact speeds or droplet sizes as GA and GC, but the general failure is comparable to GC. The RET testing yielded a relativtly flat SN curve as is evident from the -10.79 exponen.
Figure 9.26: RET data performed on the GS system using G27 droplet size. Impingement data was calculated then fitted as pr. ASTM E739 - 10, with $v$ being the dependent variable and $H_0$ being the independent variable.

9.6 Comparison RET and SPIFT on GS system

In this section, erosion data on the GS system using both SPIFT and RET will be compared. The comparison will be carried out on using the rationalisations from the above sections, specific impacts $N_0$ and total impingement $H_0$ and the impact speed depend on impingement. For both rationalisations, damage factors will be calculated, to transfer SPIFT results directly to RET.

9.6.1 RET vs. SPIFT Specific Impact on GS system

Comparing the whirling arm RET to the SPIFT, the most intuitive comparison is by comparing the number of stress cycles or impacts the coating was subjected to expressed as the dimensionless value $N_0$. For the SPIFT, this is achieved by counting the number of impacts where, as in the RET, this is an inferred value based on testing parameters. This comparison can be seen in Figure
Figure 9.27: On the graph can be seen the fitted mean lifetime from the previous graphs in Figures 9.26 and 9.23 are fitted according to ASTM E739 - 10

As this system was only tested at one droplet size choosing a point on the RET curve to compare to the SPIFT curve it is not as obvious. What can be seen from the curve in Figure 9.27 is that the RET curve intersects the SPIFT curve for first observable damage at 159 m/s and 489 impacts. Based on this the damage factor $F_0$ will be evaluated in this point.

- Impact speed: 159 m/s
- RET $N_0$: 489 Impacts
- Calculated severity factors $F_0$ Compared to RET
  - First material loss: $F_0(\text{Full}) = 0.14$: 7.1x less damaging
  - Radial cracking: $F_0(\text{radial}) = 0.23$: 4.3x less damaging
  - First observable damage: $F_0(\text{First}) = 0$: No difference

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Chapter 9. Correlating whirling arm RET with SPIFT

Comparing the RET and SIFT results on the GS system would indicate that the point of first damage detected, on the SPIFT yields the closest relation to the RET. The other two damage criteria would indicate that the SPIFT is less damaging than the RET. However, the slope of the SPIFT curves is much steeper than that of the RET. This steeper curve means that when tested in the SPIFT, the fatigue properties of the coating is less impact speed-dependent compared to the RET.

The fact that the SPIFT seems to be less damaging compared to the RET might again be related to the lack of an active material removal process, e.g. water jetting.

9.6.2 RET vs. SPIFT total impingement on GS system

As with the other two coatings system, the RET and SPIFT results will also be compared using the impingement as the rationalisation. Again both the standard impingement per impacts of 4mm as well as the impact speed-dependent impingement $H_0(v)$ will be compared.

The results using the non-impact speed-dependent calculation yields the graph in Figure 9.28. As with the other two systems the impingement rationalisation translates the SPIFT results to the right compared to the RET results. For consistency, the damage factors will be evaluated at the same impact speed of 159m/s.

- Impact speed: 160 m/s
- $H_0$: 0.8 m
- Calculated severity factors $F_0$
  - First material loss: $F_0(\text{Full}) = 0.041$: 24x less damaging
  - Annular cracking: $F_0(\text{Radial}) = 0.082$: 12x less damaging
  - First observable damage: $F_0(\text{First}) = 0.4$: 2.8x less damaging

The trends are the same as observed when comparing impacts in Figure 9.27. However, as seen on the two other systems, GC in particular, the $H_0$ rationalisation translates the graphs more to the right. Nevertheless, other than that, then comparison remains similar.

As with the other comparisons, the GS data set was also rationalised using the impact speed-dependent impingement $H_0(v)$ the results of which can be seen in Figure 9.29.

Compared to the unmodified impingement, as seen in Figure 9.28 the significant difference is that this calculation yields a smaller impingement that the high testing speed. The result of this can be seen on the graph as a shift of the curves to the left relative to the RET curves.
Chapter 9. Correlating whirling arm RET with SPIFT

In order to quantify the difference between the SPIFT and RET linear safety factors are calculated. The safety factors are evaluated at 159 m/s, similar to the two previous comparisons.

- Impact speed: 159 m/s
- $H_0$: 0.8 m
- Calculated severity factors $F_0$
  - First material loss: $F_0(\text{Full}) = 0.08$: 13x more damaging
  - Annular cracking: $F_0(\text{Annular}) = 0.15$: 6.5x more damaging
  - First observable damage: $F_0(\text{First}) = 0.7$: 1.5x more damaging

Overall the reduced impingement per impact when using the $H_0(v)$ results in a better correlation between RET and SPIFT.
Figure 9.29: On the graph can be seen the fitted mean lifetime from the previous graphs 9.26 and the three fitted mean impingement $H_0(V)$ according to ASTM E739 - 10

9.6.3 Summery of RET vs. SPIFT on GS system

On summery we observe the same trend of the SPIFT being less damaging compared to RET as was seen on the GC system. This reinforces the observation that the failure on the GA system was provoked by a weak filler layer. Comparing GA and GS that both had Strong fillers failure originated from the top coating layer.
The following section includes comparisons between the tested systems in order to illustrate their relative performance. All the following comparisons will be based on the results from testing using the 2.4mm diameter droplets from the G27 needles. Comparison of results from impingement, are omitted as the trends are the same as for the specific impact results.

comparing specific impacts to failure of: GA, GC and GS coating systems for both RET and SPIFT can be seen in Figure 10.1
Chapter 10. Comparing Tested Systems

10.1 Comparing RET results for GC, GA and GS

In figure 10.1(a) RET the results for the three systems are compared. By looking at the curves it is evident that the GC system performed comparatively worse than the two other systems as can be seen from the horizontal offset of the curve. What is interesting in the comparison with the GA system, is that at a cursory glance the GC system might seem to perform better since the coating removal on the GA system is much more severe as can be seen when comparing Figures 9.13 and 9.2. Here the seemingly more severe damage was due to an adhesive failure between the filler and the GF-matrix. This also highlights the importance of PED over breakthrough or full failure of coating, when evaluating LEP systems.

Evaluation of the failure mode once the erosion has reached the substrate can still yield important information as to how the system will ultimately fail. These results are very dependent on the construction of the sample and local aerodynamics and is therefore not directly transferable to a real blade.

Figure 10.1: (a) Shows RET data for the dataset GA, GC and GS all using the small G27 needle size to produce 2.4mm diameter droplets. The raw data is shown along with the fitted mean lifetime as denoted by the solid line. In order to make the comparison easier the mean lifetime was extrapolated to cover the range of impact speed found in the GC data set. (b) shows the SPIT data for the GA, GC and GS systems. The second SPIFT failure mode the radial/annular cracking was chosen for the comparison. The raw data is plotted alongside the fitted mean and the extrapolation. The extrapolation is performed so that the curves can be easily compared to the RET results.
10.1.1 Summery of RET results for GC, GA and GS

In summary coating GS and GA performed best in the RET ret. This highlights the importance of evaluating incubation damage and not breakthrough time. Had GA been evaluated based on breakthrough i would have been the worst performing by a wide margin. Combining the knowledge of incubation life and failure in the filler layer a manufacturer could optimise the application process or find another better filler.

10.2 Comparing SPIFT results on systems GC, GA and GS

On figure 10.1(b) SPIFT results for GA, GC and GS are compared. To compare the coatings with each other the second damage state (annular or radial cracking) was chosen as it provides both statistically good data and results that are closest to the RET results on average.

As can be seen on figure 10.1(b) the relative performance of the coatings in this test is not the same as seen in Figure 10.1(a). Most notably GA now performs significantly worse in comparison to the RET testing. As explained in Section 9.3.1 the seemingly brittle nature of the filler might have resulted in the premature failure of this system. As such, it is more interesting to compare the performance of the GC and GS systems. GC and GS show similar relative performance to what was observed during RET testing. The main difference between the GC and GS RET and SPIFT results can be seen in the slope. In Figure 10.1(b) the slope of the blue GS curve is significantly steeper than the red GC curve. From the data analysis in section 9.5.1 we see that the quality of fit is rather poor on the GS system. If datapoints below 140m/s is omitted from the analysis the resulting curve can be seen on the dotted blue line. The slope of the dotted blue line shows the trend expected from the RET test.

If we assume that the GC and GS results (Red and blue data) are more representative of the erosion data RET and SPIFT data can be correlated by use of the following linear severity factors:

- GC system: \( F_0(\text{Radial}) = 0.25 \): 4.0x less damaging
- GS system: \( F_0(\text{Radial}) = 0.23 \): 4.3x less damaging

Based on these limited data it should be possible to transfer SPIFT results to RET results by multiplying SPIFT results with a damage factor of \( F_0 = 0.25 \). As the SPIFT seems to be four-fold less damaging per impact compared to the RET.

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10.2.1 Summery of SPIFT on GC, GA and GS

In summery coating GC and GS showed the same relative performance in the SPIFT. Coating GA showed much lower performance, which is likely due to failure in the filler layer. It is tentatively suggested that the SPIFT is 4 times less damaging when comparing mean incubation damage to first radial cracking in SPIFT.
Chapter 11

Conclusion

In conclusion, in this project we were able to construct a new Single Point Impact Fatigue Tester (SPIFT). The SPIFT can induce high strain rate fatigue damage in a coated laminate by repeated impacts. Damage to the sample can be monitored in-situ. By controlling the impact rate in relation to the impact speed unnatural heating phenomena, inherent to most other fatigue tests, were avoided.

Fatigue data from the SPIFT can be used to construct SN-curves following a power-law. Based on the results of this project, we defined damage factors that relate SPIFT results to RET results. In general the shape and the slope of SN-curves generated in SPIFT and RET were found comparable. We found impact heating to have a high effect on coating lifetime when testing in the new SPIFT. Increased temperatures result in reduced fatigue life.

Analysing data from whirling arm rain erosion testers, the following conclusions were drawn: Erosion incubation can be detected using in-line camera imaging samples at a set interval during erosion testing. Registering all point erosion damages at a given time interval yields better statistical data. These data can be used to construct various SN-curves describing the fatigue life of the coating. Tracking the progression of damage after incubation does not yield data that can be tabulated in an SN-curve, and it is not transferable to real-life blades. RET data should be rationalised as either the dimensionless variable "Specific Impacts" $N_0$ or as the "total impingement" $H_0[m]$ as defined by ASTM G73-10. With the application of proper rationalisation of the rain load in the form of $N_0$ and $H_0$, RET results from different test machines can be compared and replicated. From high-speed camera imaging during operation of the RET, tangential and radial deflection of 2.4-3.5mm diameter droplet was found to be within tolerable limits.

In the end, we found the SPIFT to be an excellent complementary test to the RET. While a
1:1 correlation between the results may not always be possible, depending on the failure mode in a particular system, it allows the user to observe in detail how damage initiates and progresses in a given system to a degree not possible with the distributed impacts of the RET. The SPIFT also allows for investigations not possible or practical on the RET. These include testing of new materials that cannot easily be applied to the convex RET samples. This allows screening of new potential systems.

Internal heat generation resulting from repeated impacts was investigated using the SPIFT and thermal imaging. It was found that there was no direct correlation between static material properties and the observed heating. Using time-temperature superpositioned DMA data it was possible to draw correlations using extrapolated high frequency material properties. Based on this, safe limits to impact rate was calculated based on observations of reduced sample life at elevated temperatures.

11.1 Future work

Going forward with the SPIFT future goals are to implement environmental control in the form of temperature regulation. This is to investigate how coatings perform at different temperatures, building on the observations in the thesis.

The detailed observations of projectile deformation in the SPIFT will be used to aide future FEM work supplementing the work from [I]and [IV]. The hope is that this can eventually lead to a tool that can predict impact fatigue failure, based on material properties.

Extensive work in correlating the mechanical properties and rain erosion performance is currently being conducted. The hope is to be able to establish links between material properties and erosion performance on the Issut-269 coatings from Chapter 7. Due to experimental difficulties these data could not be included in the thesis.
Chapter 12

Appendix
<table>
<thead>
<tr>
<th>Variables</th>
<th>Our definition</th>
<th>ASTM</th>
<th>DNVGL</th>
<th>Units</th>
<th>Formula</th>
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<tbody>
<tr>
<td>( I )</td>
<td>Mean rain intensity</td>
<td>N/A</td>
<td>Mean rain intensity</td>
<td>m/s</td>
<td>( I = \frac{P}{A} )</td>
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<tr>
<td>( A )</td>
<td>Area under rain field</td>
<td>N/A</td>
<td>Area under rain field</td>
<td>m²</td>
<td>( A = \pi (r_{20}^2 - r_i^2) \phi )</td>
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<td>Rain intensity as a function of radius</td>
<td>N/A</td>
<td>Rain intensity as a function of radius</td>
<td>m/s</td>
<td>( I(r) = \frac{P}{\theta \phi (r_{20} - r_i)} )</td>
</tr>
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<td>( r )</td>
<td>Radius</td>
<td>Radius</td>
<td>Radius</td>
<td>m</td>
<td>( r )</td>
</tr>
<tr>
<td>( r_c )</td>
<td>Centre point of specimen</td>
<td>N/A</td>
<td>Centre point of specimen</td>
<td>m</td>
<td>( r_c )</td>
</tr>
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<td>N/A</td>
<td>Outer radius of rain field</td>
<td>m</td>
<td>( r_o )</td>
</tr>
<tr>
<td>( r_i )</td>
<td>Inner radius of rain field</td>
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<td>Inner radius of rain field</td>
<td>m</td>
<td>( r_i )</td>
</tr>
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<td>( l_g )</td>
<td>Length of exposed blade</td>
<td>N/A</td>
<td>Length gauge zone</td>
<td>m</td>
<td>( l_g )</td>
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<tr>
<td>( \theta )</td>
<td>Coverage angle</td>
<td>N/A</td>
<td>Coverage angle</td>
<td>rad</td>
<td>( \theta )</td>
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<tr>
<td>( \varphi )</td>
<td>Coverage ratio</td>
<td>N/A</td>
<td>Coverage ratio</td>
<td>( \frac{\theta}{2\pi} )</td>
<td>( \varphi )</td>
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<tr>
<td>( P )</td>
<td>Water flow rate</td>
<td>Water flow rate</td>
<td>Water flow rate</td>
<td>m³/s</td>
<td>( P )</td>
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<tr>
<td>( a )</td>
<td>Projected area of impinging drop</td>
<td>N/A</td>
<td>Projected area of impinging drop</td>
<td>m²</td>
<td>( a = \left( \frac{d}{2} \right)^2 \pi )</td>
</tr>
<tr>
<td>( h )</td>
<td>Volume of impinging droplet</td>
<td>V_{drop}</td>
<td>Volume of impinging droplet</td>
<td>m³</td>
<td>( h = \frac{4}{3} \left( \frac{d}{2} \right)^3 )</td>
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<tr>
<td>( d )</td>
<td>Diameter of impinging droplet</td>
<td>Diameter of impinging droplet</td>
<td>Diameter of impinging droplet</td>
<td>m</td>
<td>( d )</td>
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<tr>
<td>( a/b )</td>
<td>Impingement per impact</td>
<td>Ratio between projected area and droplet volume</td>
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<td>( \frac{a}{b} )</td>
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<td>( h )</td>
<td>Height of single impingement</td>
<td>N/A</td>
<td>N/A</td>
<td>m</td>
<td>( h )</td>
</tr>
<tr>
<td>( f_i )</td>
<td>Specific impact frequency</td>
<td>Specific impact frequency</td>
<td>Specific impact frequency</td>
<td>s⁻¹</td>
<td>( f_i )</td>
</tr>
<tr>
<td>( H(t) )</td>
<td>Cumulative impingement</td>
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<td>N/A</td>
<td>m</td>
<td>( H(t) )</td>
</tr>
<tr>
<td>( N_0 )</td>
<td>Specific impacts for incubation</td>
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<td>N/A</td>
<td>m</td>
<td>( N_0 )</td>
</tr>
<tr>
<td>( H )</td>
<td>Incubation time</td>
<td>Incubation time</td>
<td>Incubation time</td>
<td>s</td>
<td>( H )</td>
</tr>
<tr>
<td>( N )</td>
<td>Impacts per square meter per second</td>
<td>N/S</td>
<td>Specific impact frequency</td>
<td>m⁻²</td>
<td>( N )</td>
</tr>
<tr>
<td>( \nu )</td>
<td>Column of water hitting sample per second</td>
<td>Impingement rate</td>
<td>Impingement rate</td>
<td>m/s</td>
<td>( \nu )</td>
</tr>
<tr>
<td>( v_{drop,rp} )</td>
<td>Droplet velocity</td>
<td>Droplet velocity</td>
<td>Droplet falling velocity</td>
<td>m/s</td>
<td>( v_{drop,rp} )</td>
</tr>
<tr>
<td>( v_r )</td>
<td>Local rotor speed</td>
<td>V</td>
<td>Impact velocity of droplet</td>
<td>m/s</td>
<td>( v_r )</td>
</tr>
<tr>
<td>( \psi )</td>
<td>Volume concentration</td>
<td>Volume concentration</td>
<td>Volume concentration</td>
<td>m³/m³</td>
<td>( \psi )</td>
</tr>
<tr>
<td>( q )</td>
<td>Number of droplets per unit volume in the rotor plane</td>
<td>N/A</td>
<td>Droplet concentration</td>
<td>m³/m³</td>
<td>( q )</td>
</tr>
<tr>
<td>( \omega )</td>
<td>Angular velocity</td>
<td>Angular velocity</td>
<td>Angular velocity</td>
<td>rad/s</td>
<td>( \omega )</td>
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Table 12.1: The table is a overview of the different variables and definitions used in ASTM G73-10[40] and in DNVGL-RP-0171[49]
Chapter 13

Bibliography


