

DTU



Leading edge erosion of wind turbines blades: damage, material properties and load mitigation

Jakob Ilsted Bech, Charlotte Hasager, Christian Bak, Leon Misnaevsky, Søren Fæster Nielsen, Nicolai Frost-Jensen Johansen (DTU Wind Energy, Denmark)

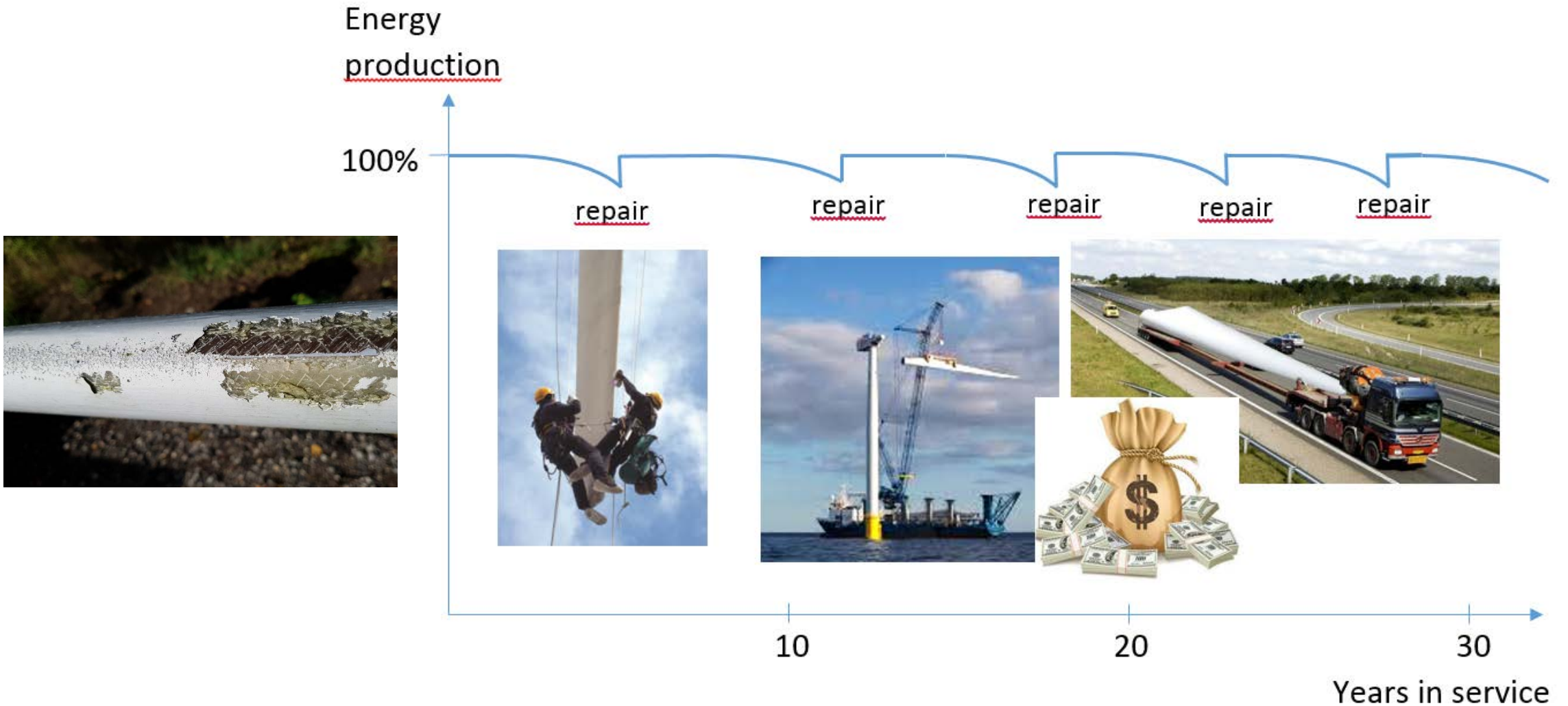
International Workshop on the Specific Issues of Taiwan Offshore Wind Farm, Taipei, Taiwan, Aug. 22-23 2019

Visit to Taiwan Power Company Research Institute, Taipei, Taiwan, 20 Aug. 2019

Contents

- Leading edge erosion (LEE) – problem and solutions
- Understanding LEE
- Materials, structures and damage
- Erosion performance test
- Life time prediction
- Life extension by erosion safe operation

Leading edge erosion and its consequences



IOP PUBLISHING
 J. Phys. D: Appl. Phys. **46** (2013) 383001

TOPICAL REVIEW On erosion issues associated with the leading edge of wind turbine blades

M.H. Keegan¹, D.H. Nash² and M.M. Stack²



Journal of Physics: Applied
 and Industrial Physics
 journal homepage: www.elsevier.com/locate/jweia

Materials (Basel), 2017 Oct; 10(10): 1146.
 Published online 2017 Sep 28. doi: [10.3390/ma10101146](https://doi.org/10.3390/ma10101146)

On the Material Characterisation of Wind Turbine Blade Coatings: The Effect of Interphase Coating-Laminate Adhesion on Rain Erosion Performance

Enrique Cortés,¹ Fernando Sánchez,^{2,*} Anthony O'Carroll,³ Borja Madramany,¹ Mark Hardiman,³ and Trevor M. Young³

PMCID: PMC5666952
 PMID: [28956841](https://pubmed.ncbi.nlm.nih.gov/28956841/)

Procedia
 12th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2015
 8 (2015) 263 – 275

Droplet Erosion Protection Coatings for Offshore Wind Turbine Blades

Valaker^a, S. Armada^b, S. Wilson^b

J. Phys. D: Appl. Phys. **46** (2013) 383001

JOURNAL
 doi:10.

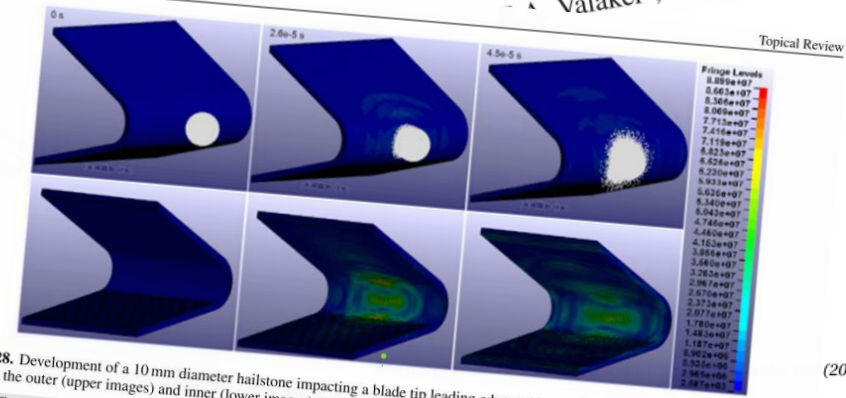


Figure 28. Development of a 10 mm diameter hailstone impacting a blade tip leading edge at 100 m s⁻¹, showing contours of von-Mises stress on the outer (upper images) and inner (lower images) surfaces. Source: [65].

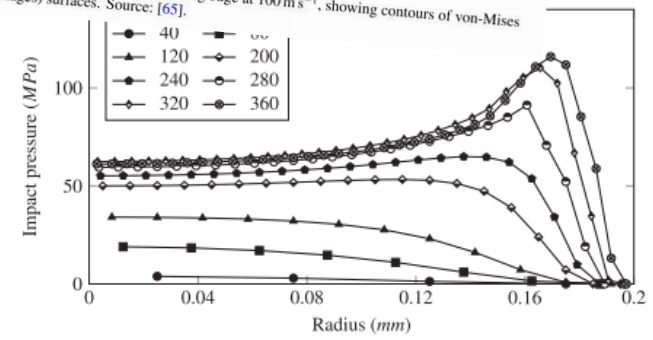


Fig. 12. A snapshot of the impact pressure at various mesh resolutions from 40 to 360 cells per diameter. The diameter is 2 mm.

A computational framework for the analysis of rain-induced erosion in wind turbine blades, part I: Stochastic rain texture model and drop impact simulations

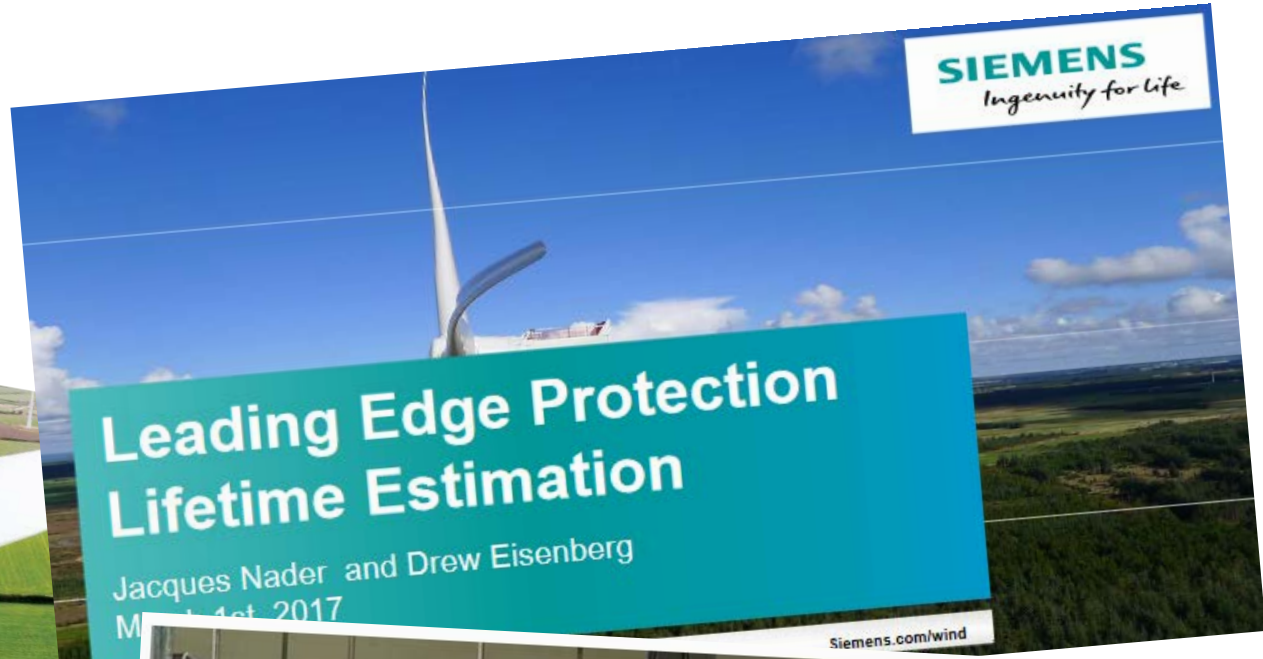
B. Amirzadeh, A. Louhghalam, M. Raessi, M. Tootkaboni*

OEM solutions



Leading Edge Protection

Protect your blades against intense conditions and prevent a lifetime AEP loss of up to 7%*



Rain Erosion Test Center

Photo courtesy of Windtrust

The Rain Erosion Test Center tests the endurance of our protective coatings on a glass fiber specimen shaped like a blade leading edge. Three whirling arms rotate at high speeds under an artificially-generated rain field, with a rotational speed of 234-640 kilometers per hour (145-398 miles per hour)!

LM WIND POWER
a GE Renewable Energy business

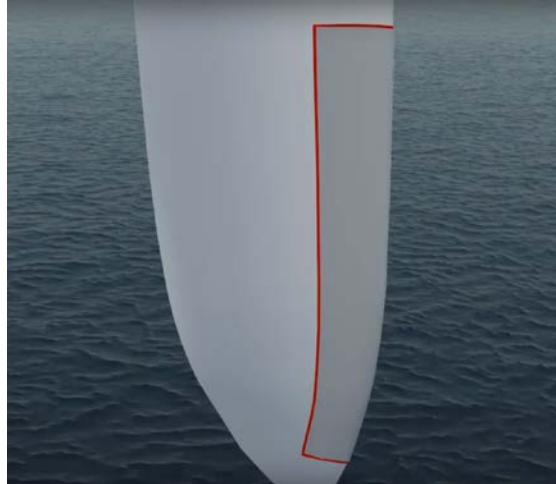
Protective 3rd party products

Coating systems



Superior edge protection
for rotor blades

Shields



Danish company behind
long-awaited technology for
wind turbines

Tapes



Latest Protection Methods
Against Leading Edge Erosion
For Increased Tip Speeds

Solutions are two-fold (at least...)

Erosion safe operation

- Impact fatigue performance
- Monitoring
- Forecasting
- Turbine control

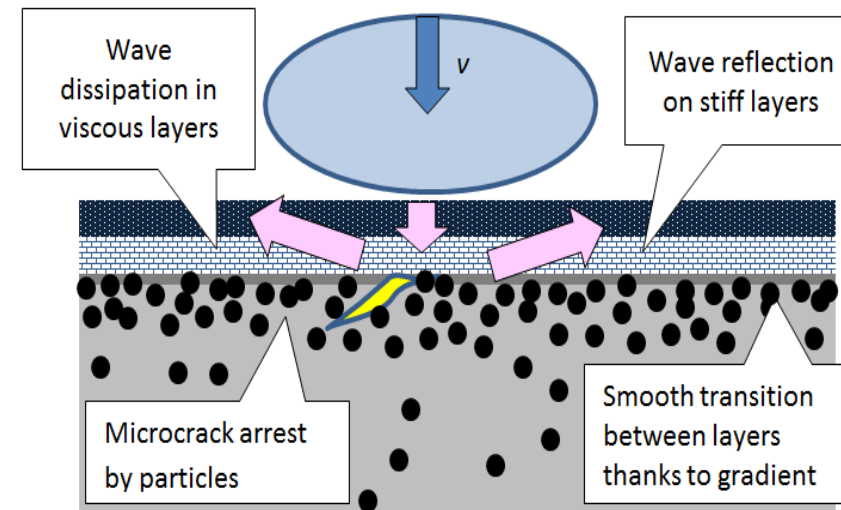


Innovation Fund DK – EROSION

www.rain-erosion.dk

Durable leading edges

- Damage mechanisms
- Mechanical properties
- Materials
- Structural design



Innovation Fund DK - DURALEGE

www.duraledge.dk

Innovation fund DK DURALEEDGE

“Durable leading edges for high tip speed wind turbine blades”. November 2018 to October 2021

1. UNDERSTAND MECHANISMS
2. COMPUTATIONAL MODELLING of LEE
3. DEVELOP PROTECTIVE SYSTEM
4. GUIDELINES, VALIDATION and EXPLOITATION

Published: 4 July 2019

WIND ENERGY

REVIEW ARTICLE

Toolbox for optimizing anti-erosion protective coatings of wind turbine blades: Overview of mechanisms and technical solutions

Leon Mishnaevsky Jr.

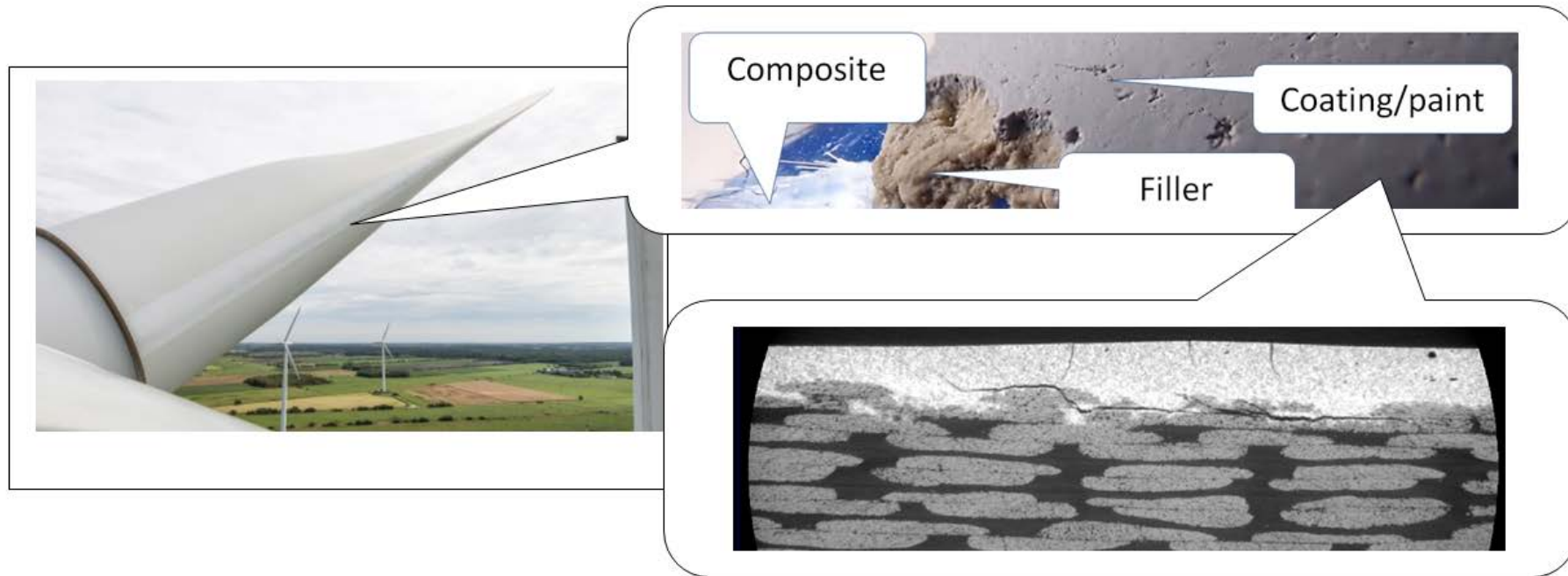
First published: 04 July 2019 | <https://doi.org/10.1002/we.2378>

PDF TOOLS SHARE



Mapping and characterisation of damage mechanisms

- Field observations
- SPIFT - Single point impact fatigue test
- Rain erosion test



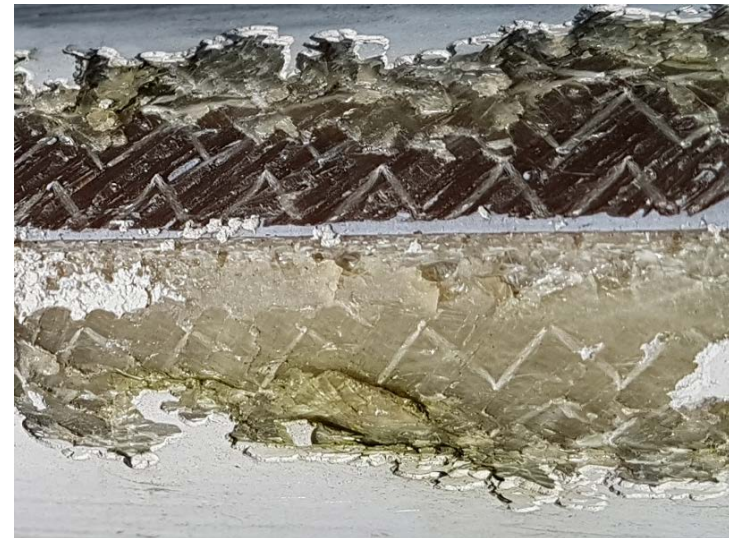
Damage analysis

- Visual inspection
- Light microscopy
- Scanning electron microscopy
- X-ray CT
- Infrared scanning
- Others...

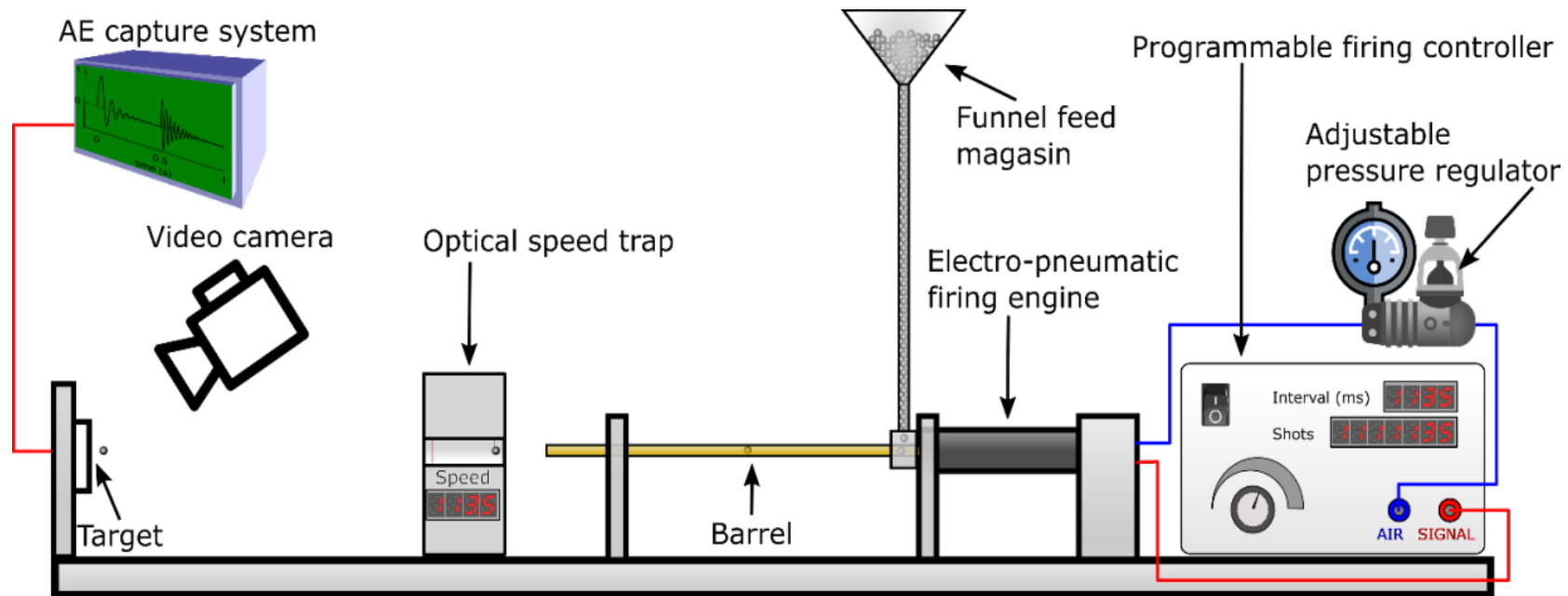
Damage mechanisms

- Surface cracks
- Subsurface cracks
- Interface debonding
- Others.....

Field observations

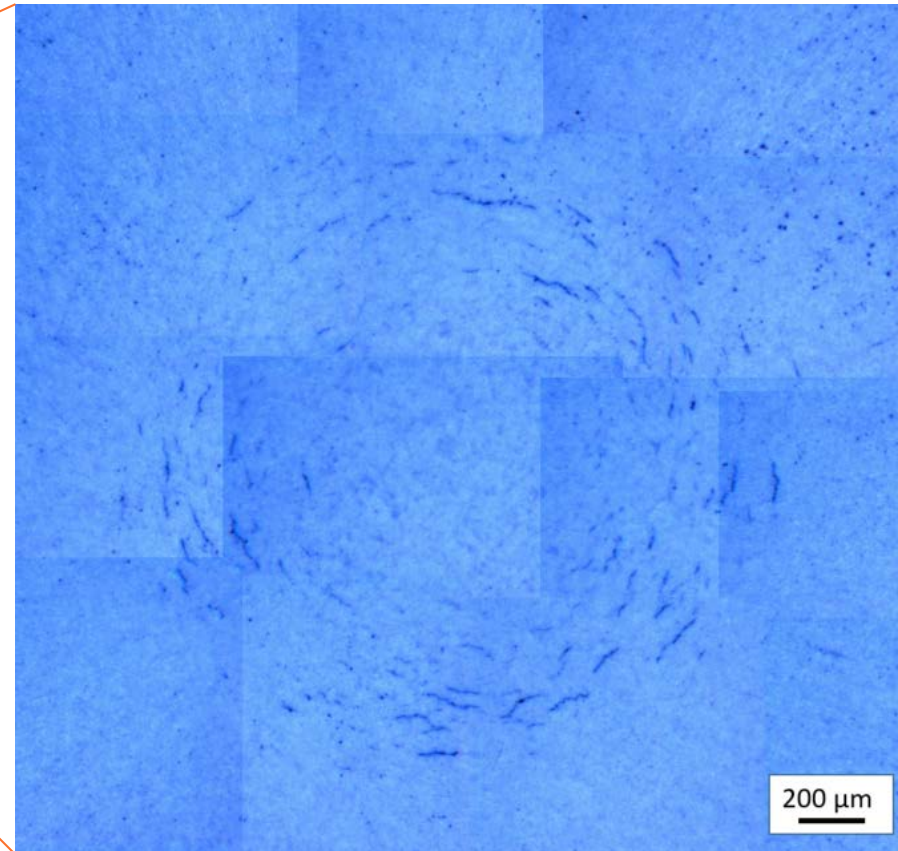
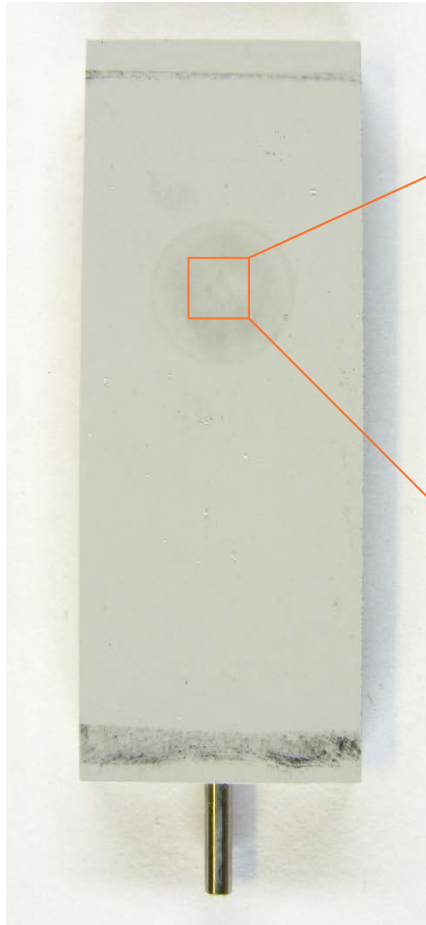


Single point impact fatigue tester



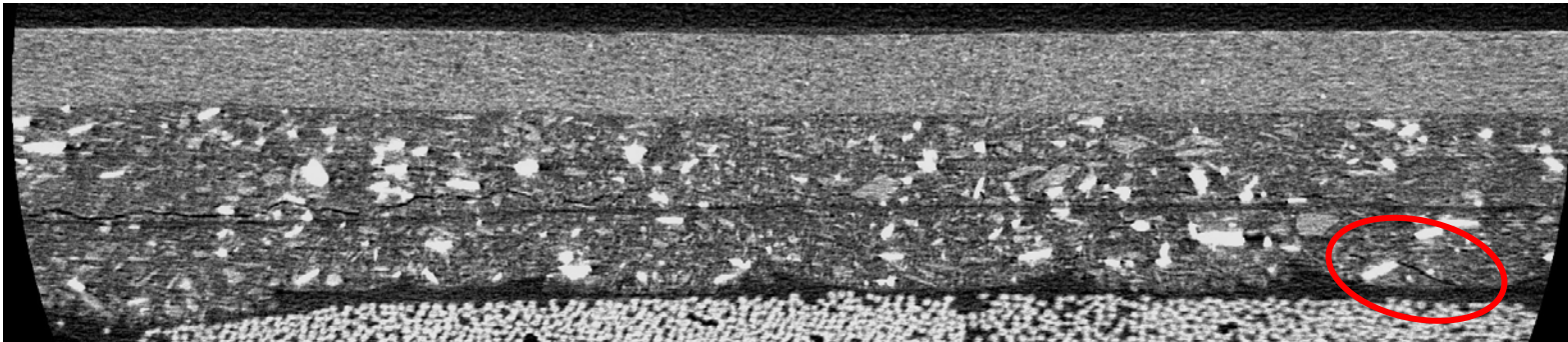
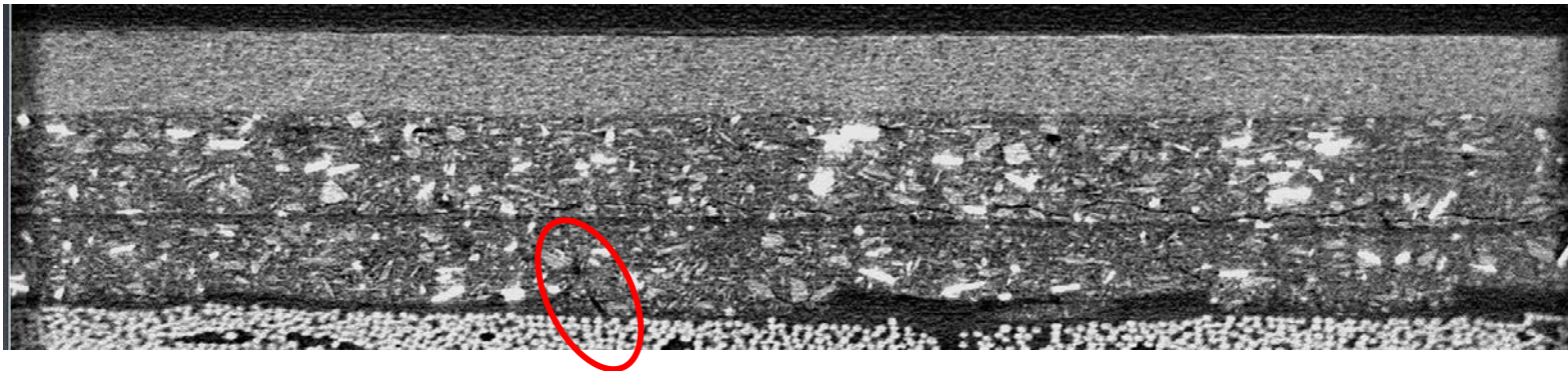
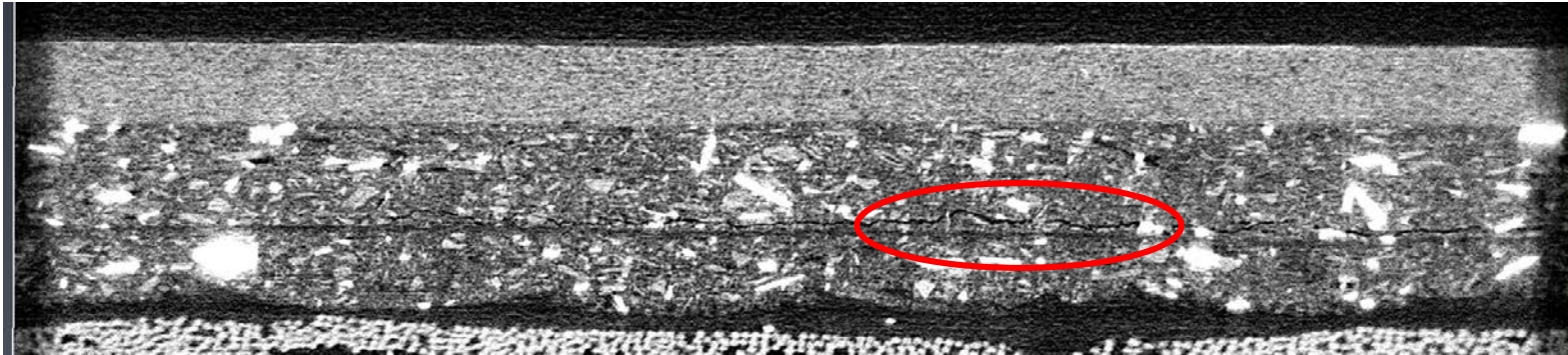
- Repeated impacts with rubber balls
- 90-170 m/s

Study of impact fatigued specimen

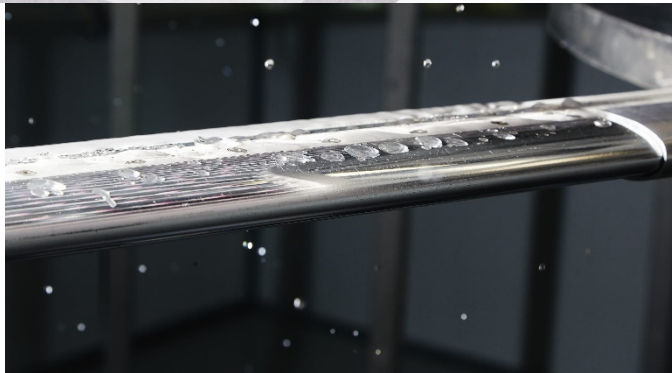
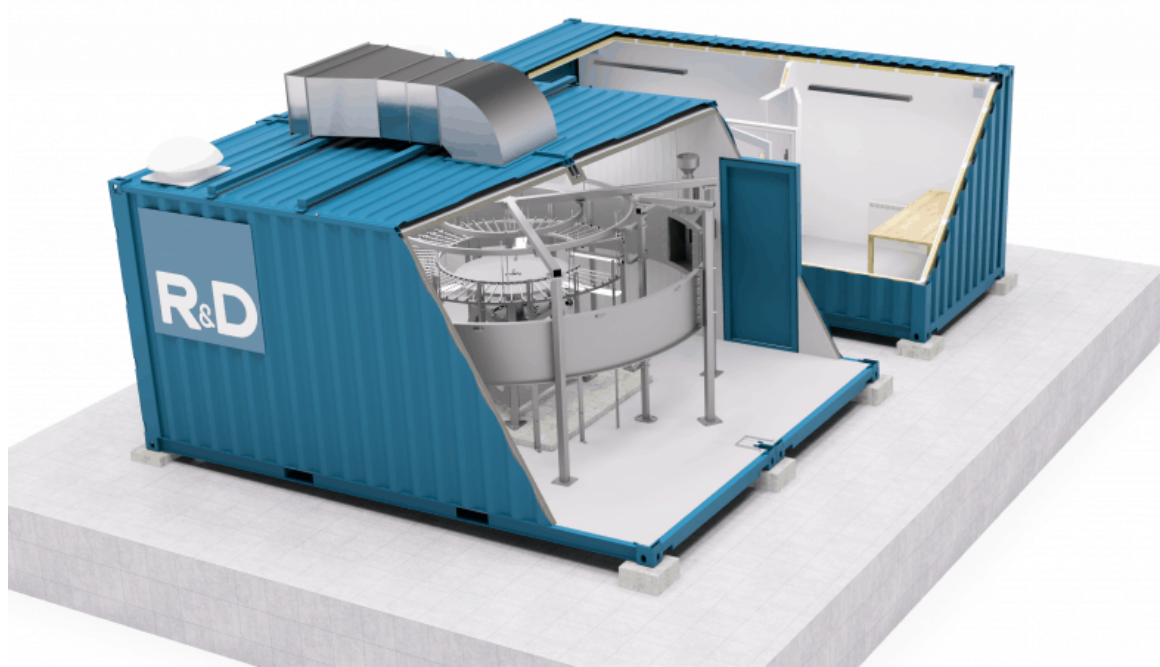


Stitched optical microscopy
(Leitz Aristomet)

X-ray CT observation of Sub-surface cracks



Rain erosion testing



www.rd-as.com



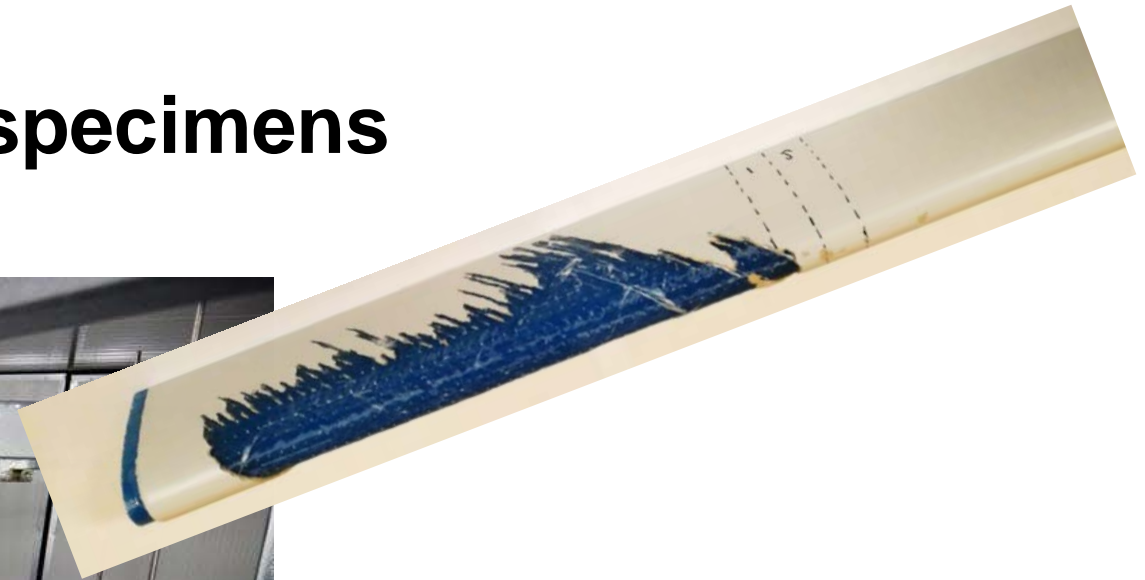
RECOMMENDED PRACTICE

DNVGL-RP-0171

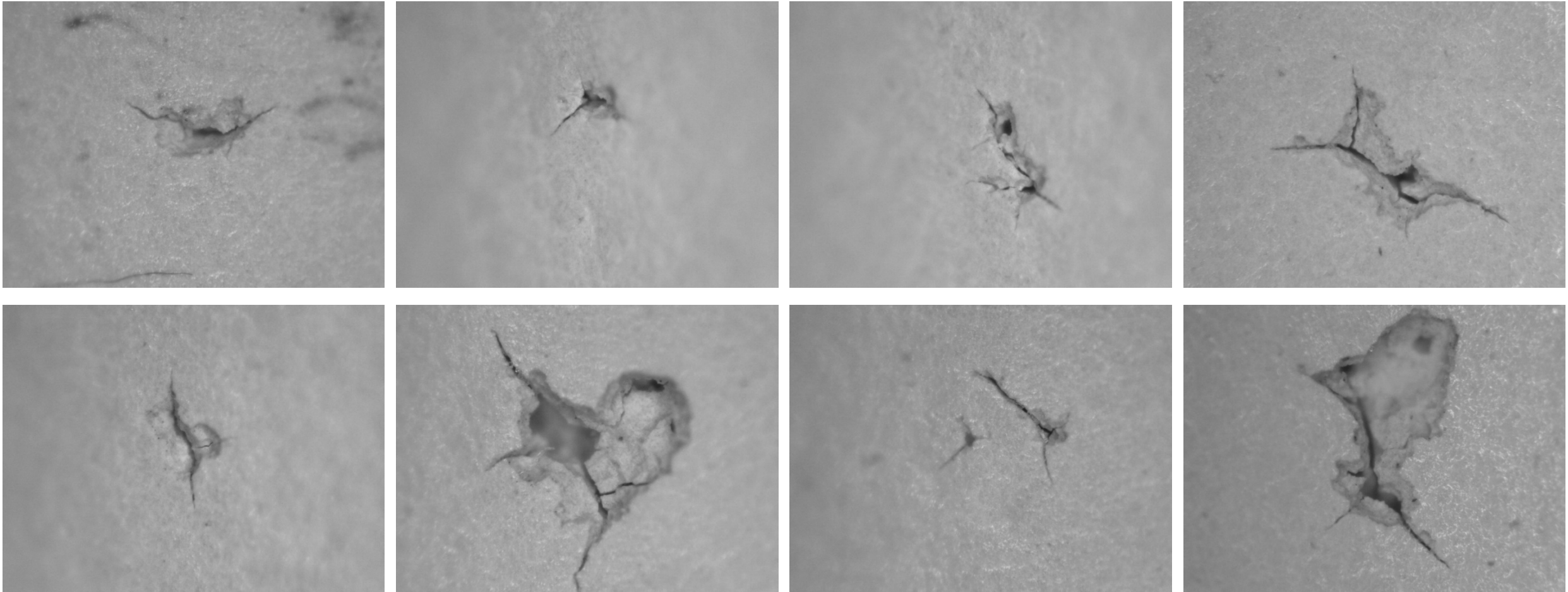
Edition February 2018

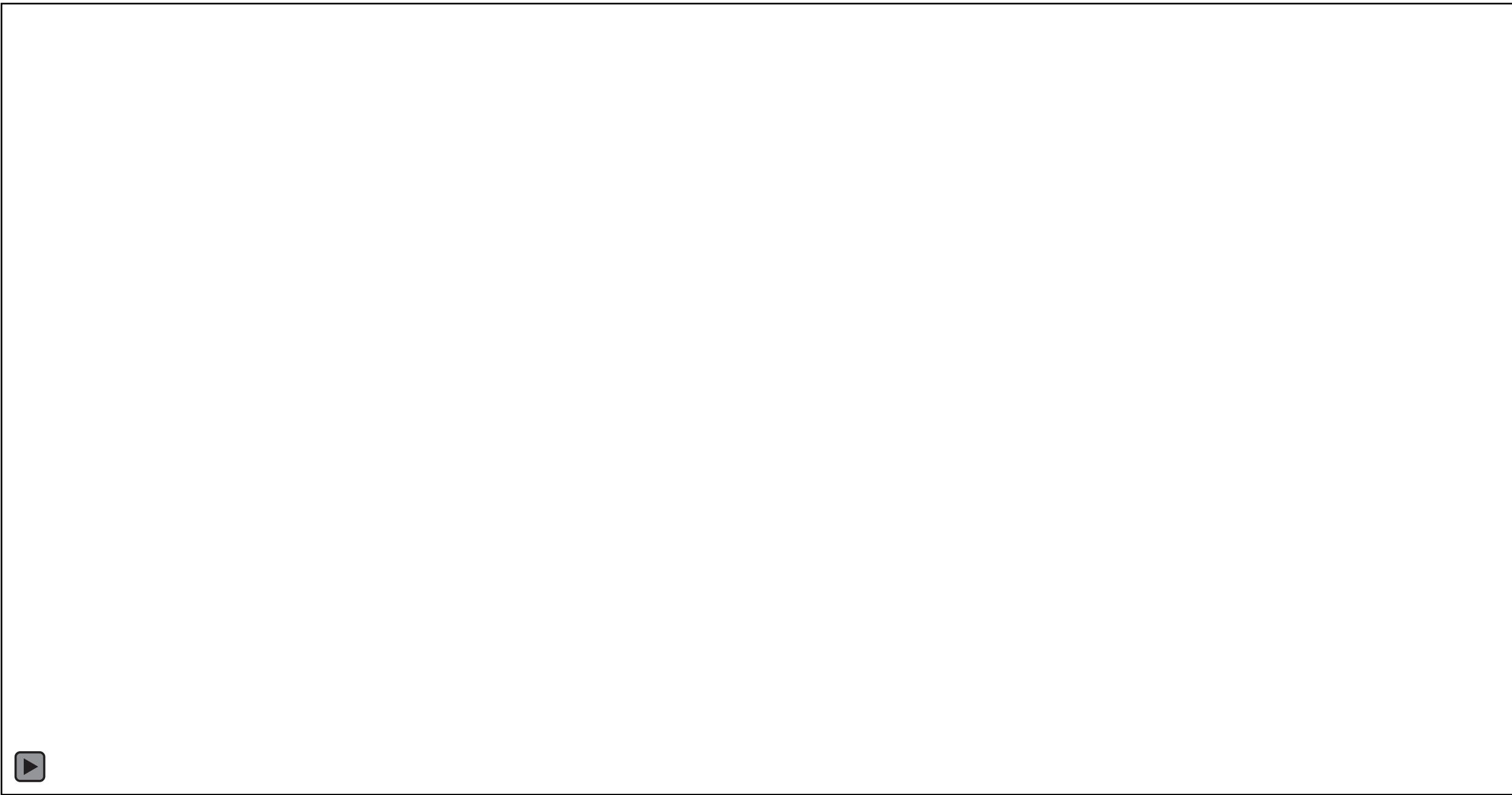
Testing of rotor blade erosion protection systems

Study of rain erosion test specimens

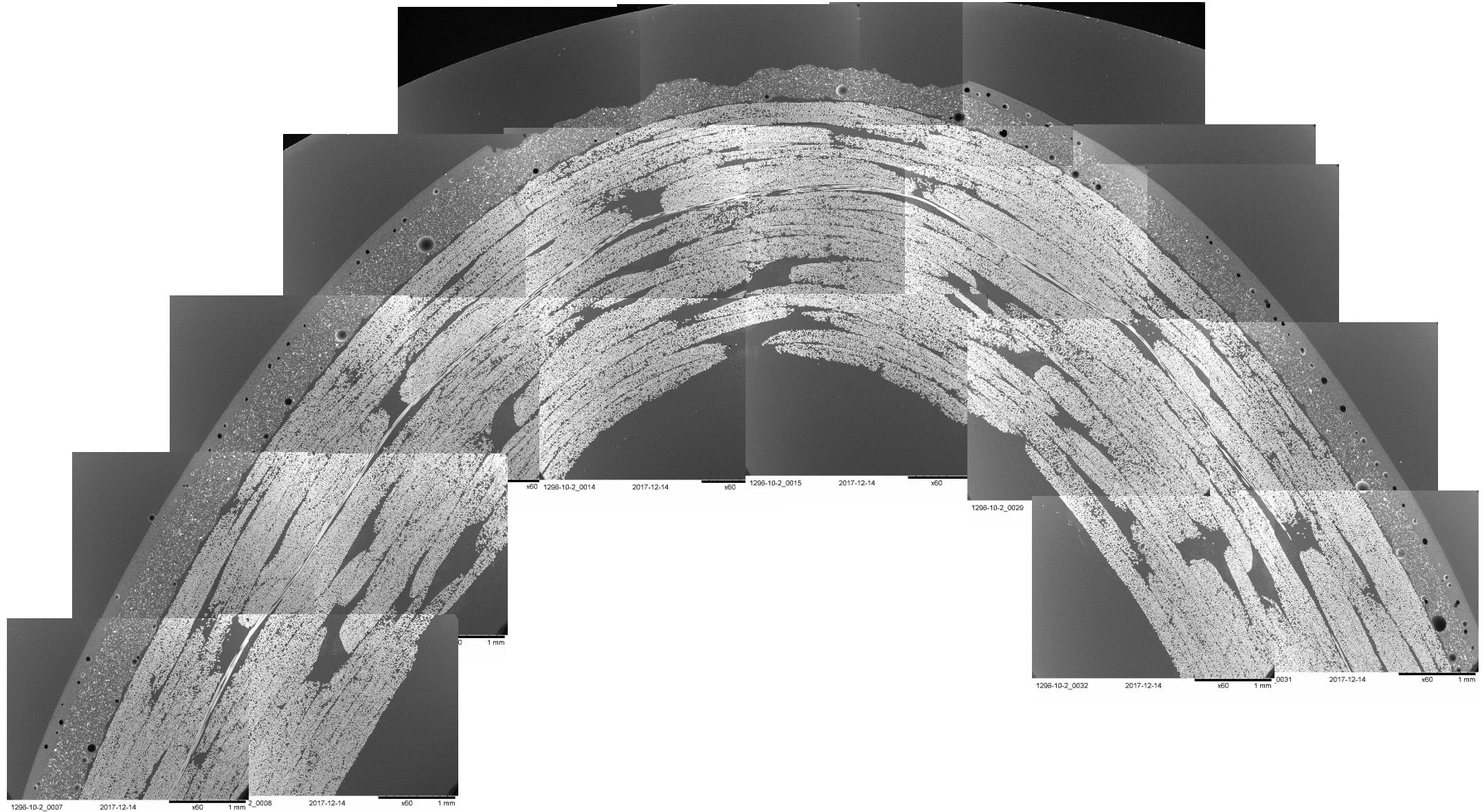


Holes and cracks at surface of leading edge protection

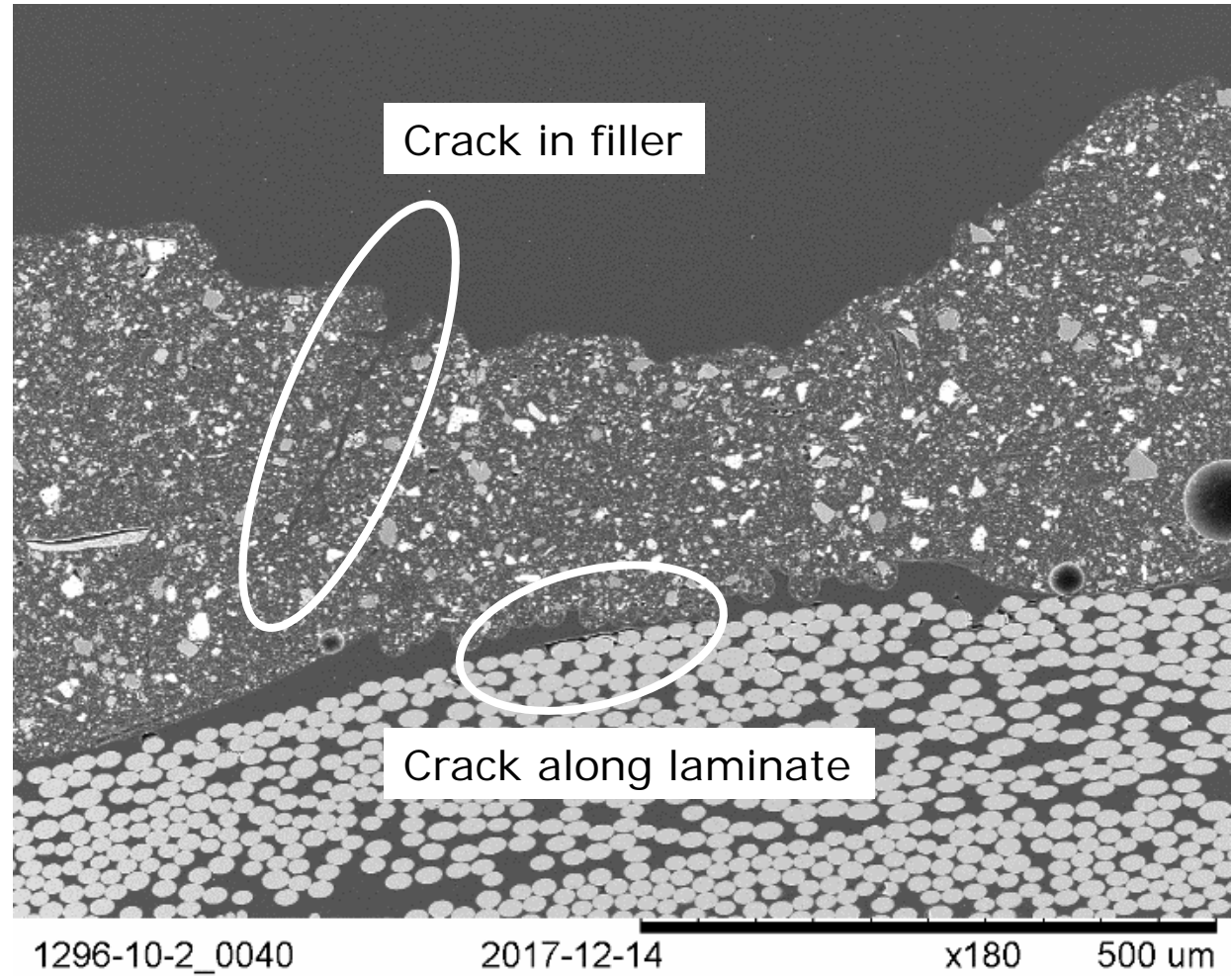
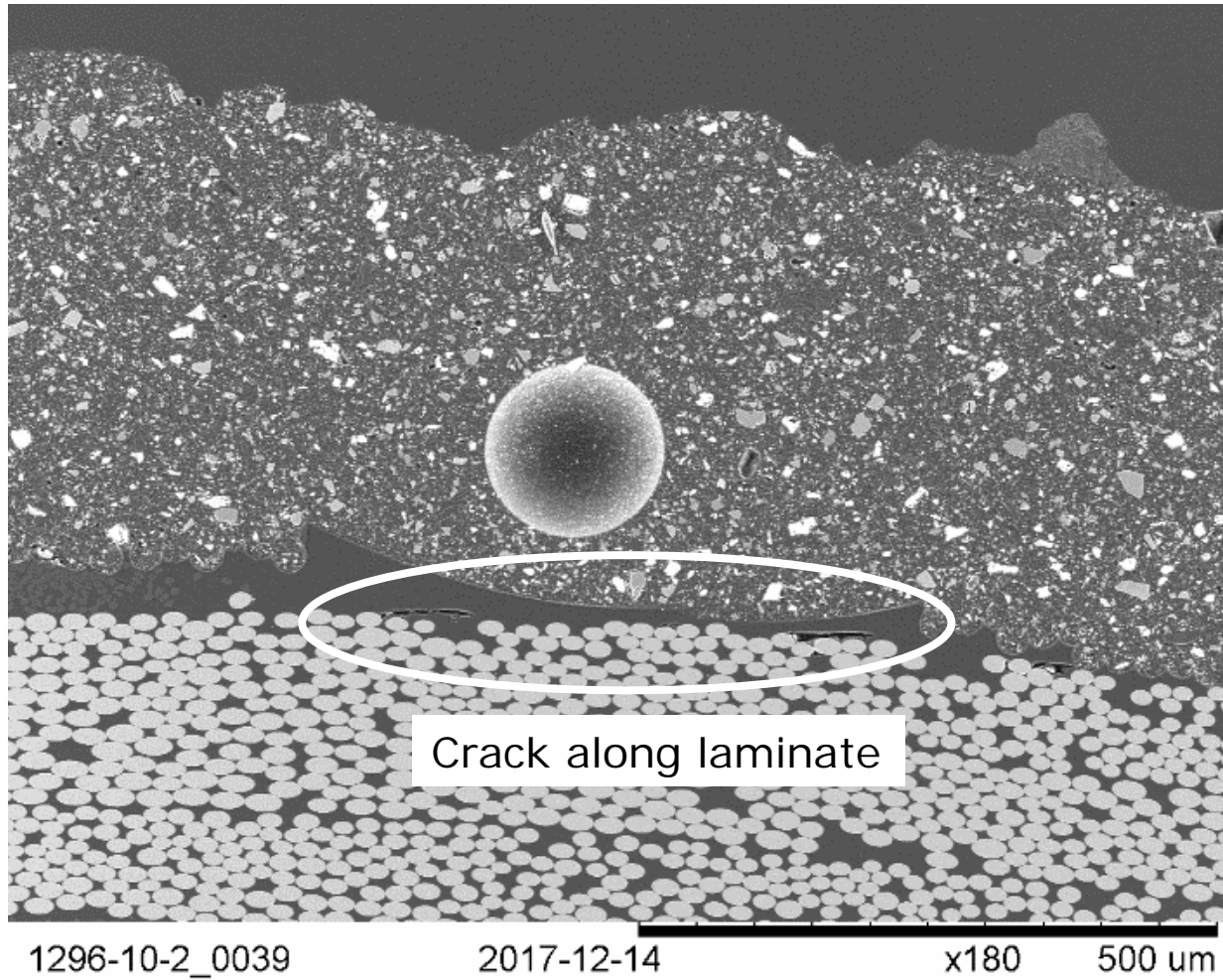




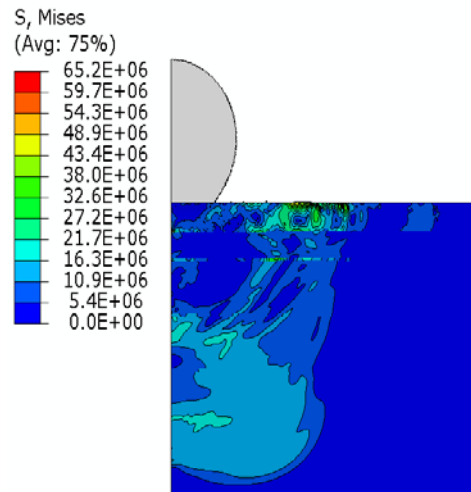
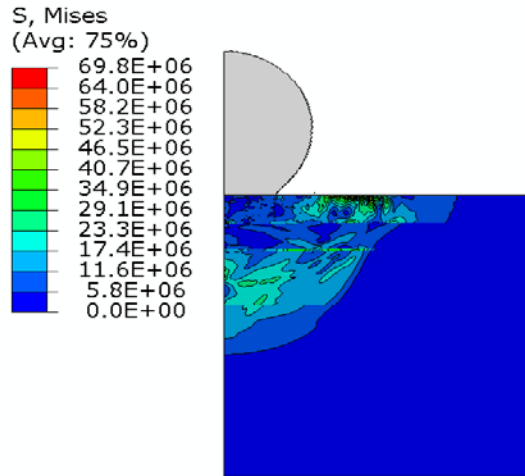
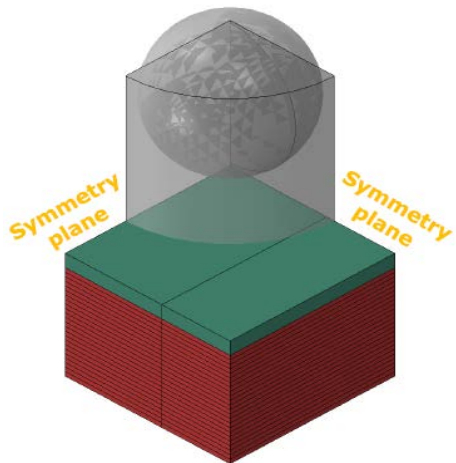
SEM image



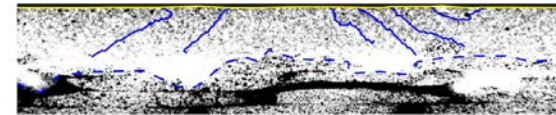
SEM image



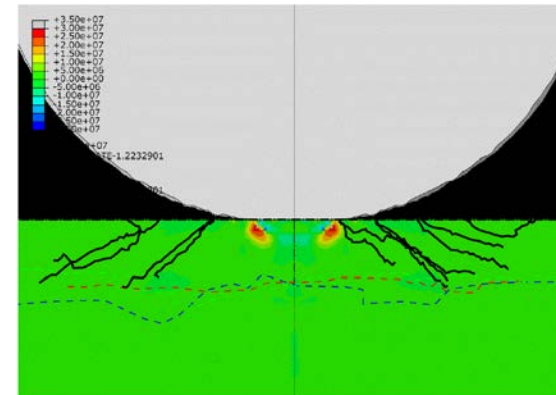
Computational modelling of impact stresses, fatigue and damage initiation



Correlating model stresses to observed cracks



CT scan



Shear stresses in FEM

Development of new binders for coating systems

- Tailoring of mechanical properties
 - Damping'
 - Stiffness
 - Damage tolerance
 - Strain rate dependency
 - Temperature dependency
- Manufacture
 - Applicability
 - compatibility

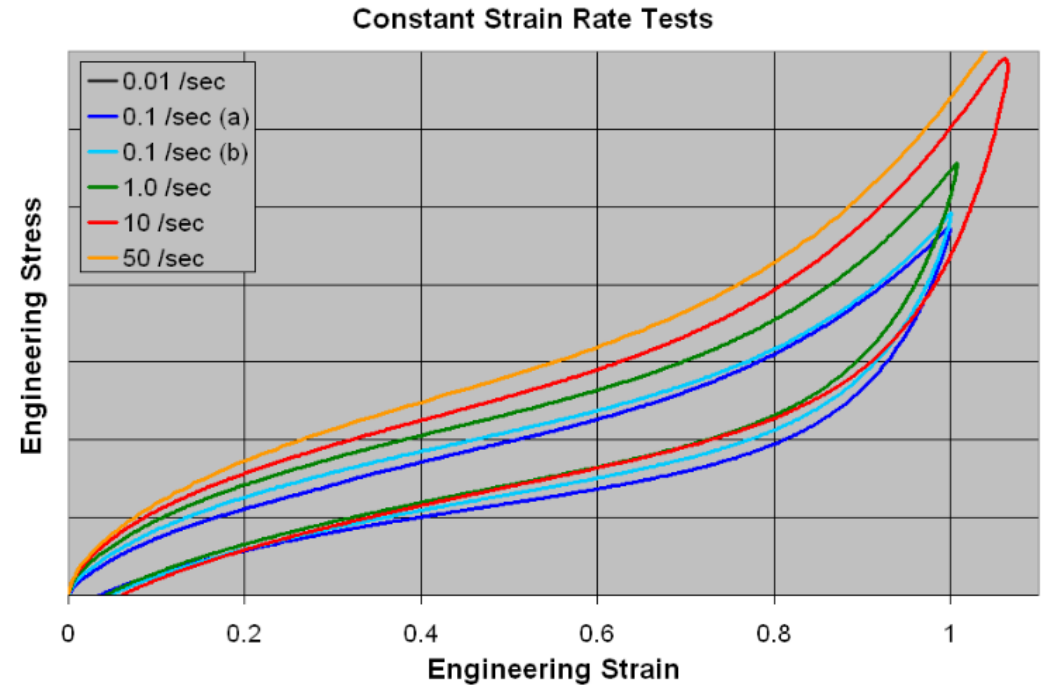
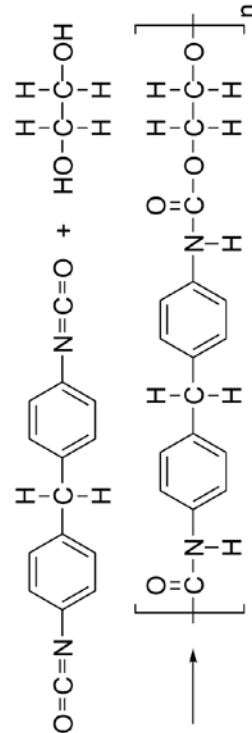
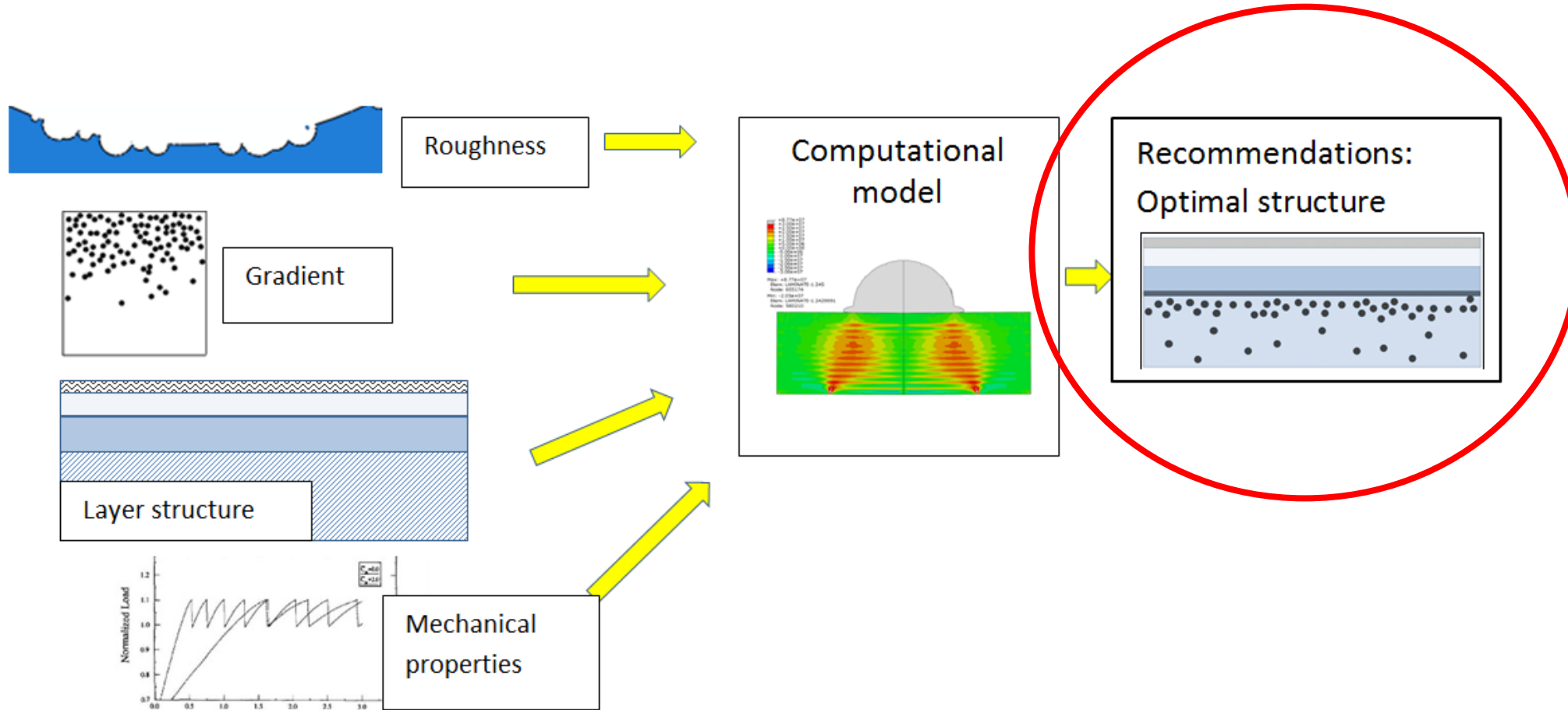


Figure 14. Family of constant strain-rate dynamic testing, load / unload (100% Strain).

T. Dalrymple
J. Choi, 2007

Modelling for design & new solutions. Optimizing particulate fillers and layer structure





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Wind Energ. Sci., 3, 729–748, 2018
<https://doi.org/10.5194/wes-3-729-2018>
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Extending the life of wind turbine blade leading edges by reducing the tip speed during extreme precipitation events

Jakob Ilsted Bech, Charlotte Bay Hasager, and Christian Bak

Department of Wind Energy, Technical University of Denmark, Roskilde, 4000, Denmark

Correspondence: Jakob Ilsted Bech (jakk@dtu.dk)

Received: 31 December 2017 – Discussion started: 21 February 2018

Revised: 9 June 2018 – Accepted: 26 July 2018 – Published: 19 October 2018

Abstract. Impact fatigue caused by collision with rain droplets, hail stones and other airborne particles, also known as leading-edge erosion, is a severe problem for wind turbine blades. Each impact on the leading edge adds an increment to the accumulated damage in the material. After a number of impacts the leading-edge material will crack. This paper presents and supports the hypothesis that the vast majority of the damage accumulated in the leading edge is imposed at extreme precipitation condition events, which occur during a very small fraction of the turbine’s operation life. By reducing the tip speed of the blades during these events, the service life of the



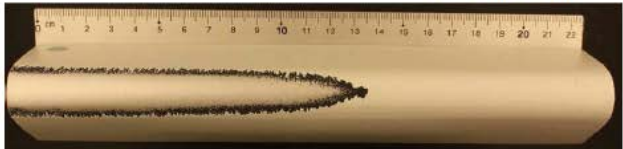
Erosion test for material performance



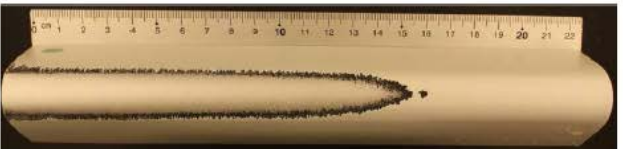
0 HOURS



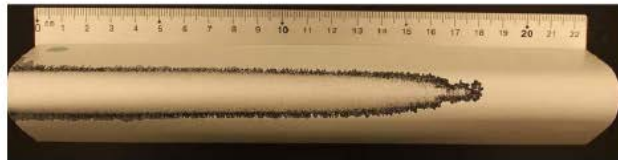
0.5 HOURS



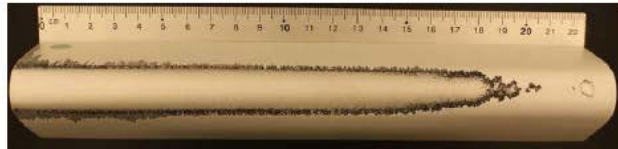
1.0 HOURS



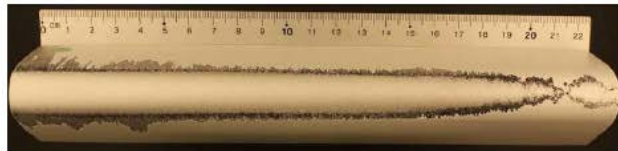
1.5 HOURS



2.0 HOURS



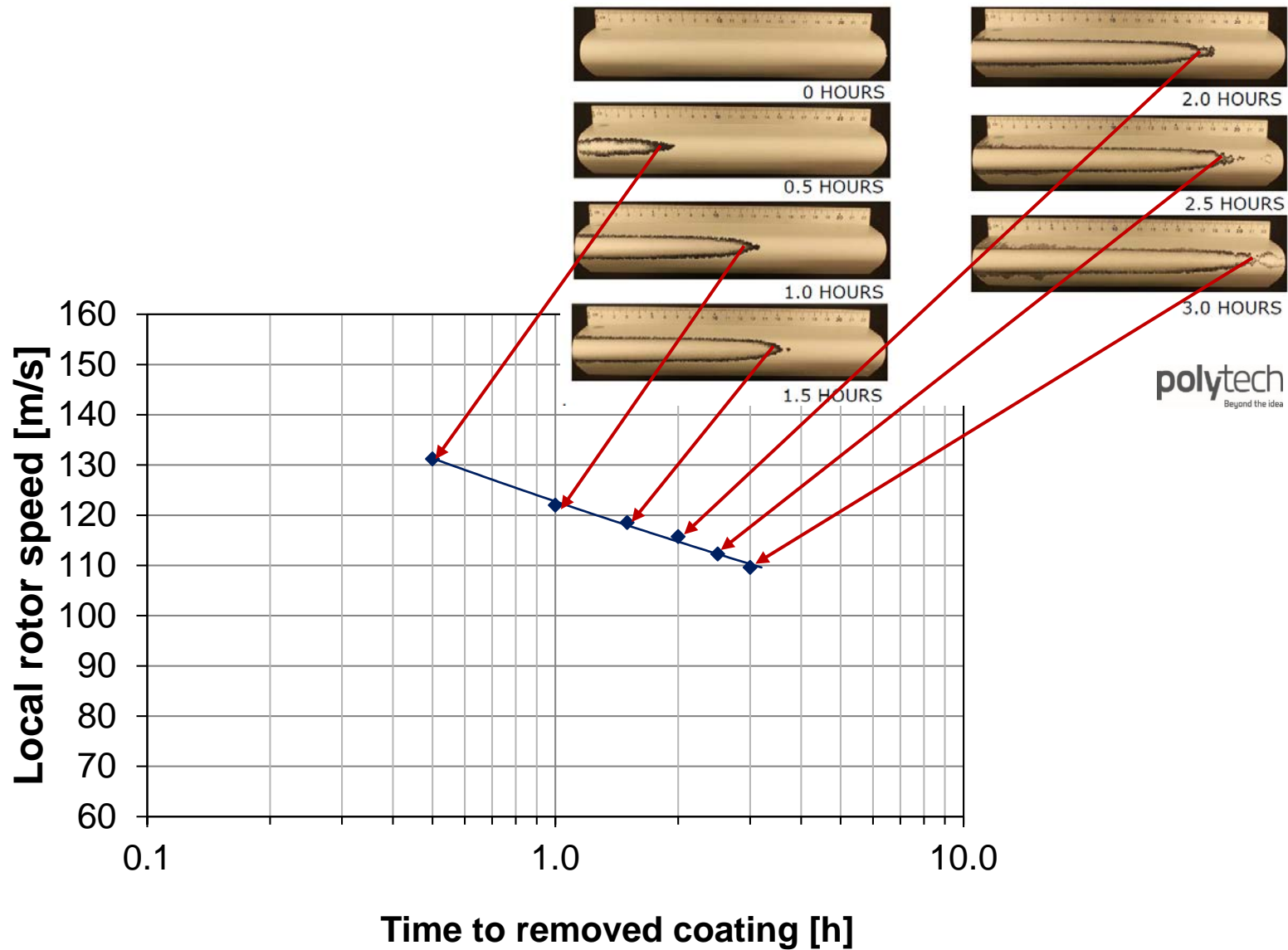
2.5 HOURS



3.0 HOURS

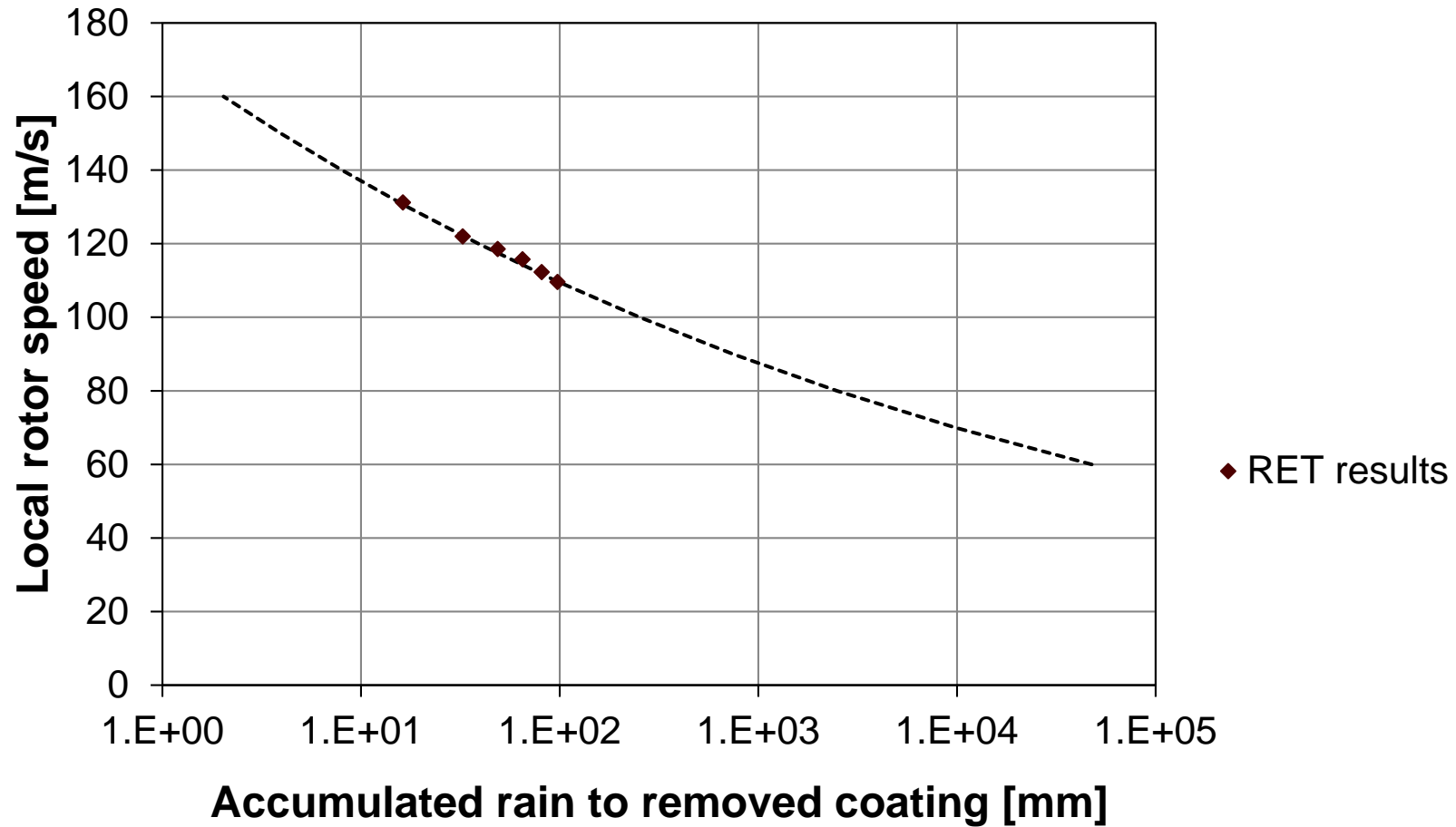
polytech
Beyond the idea

Plot of test data to Wöhler curve



polytech
Beyond the idea

Impact fatigue properties



Life time prediction

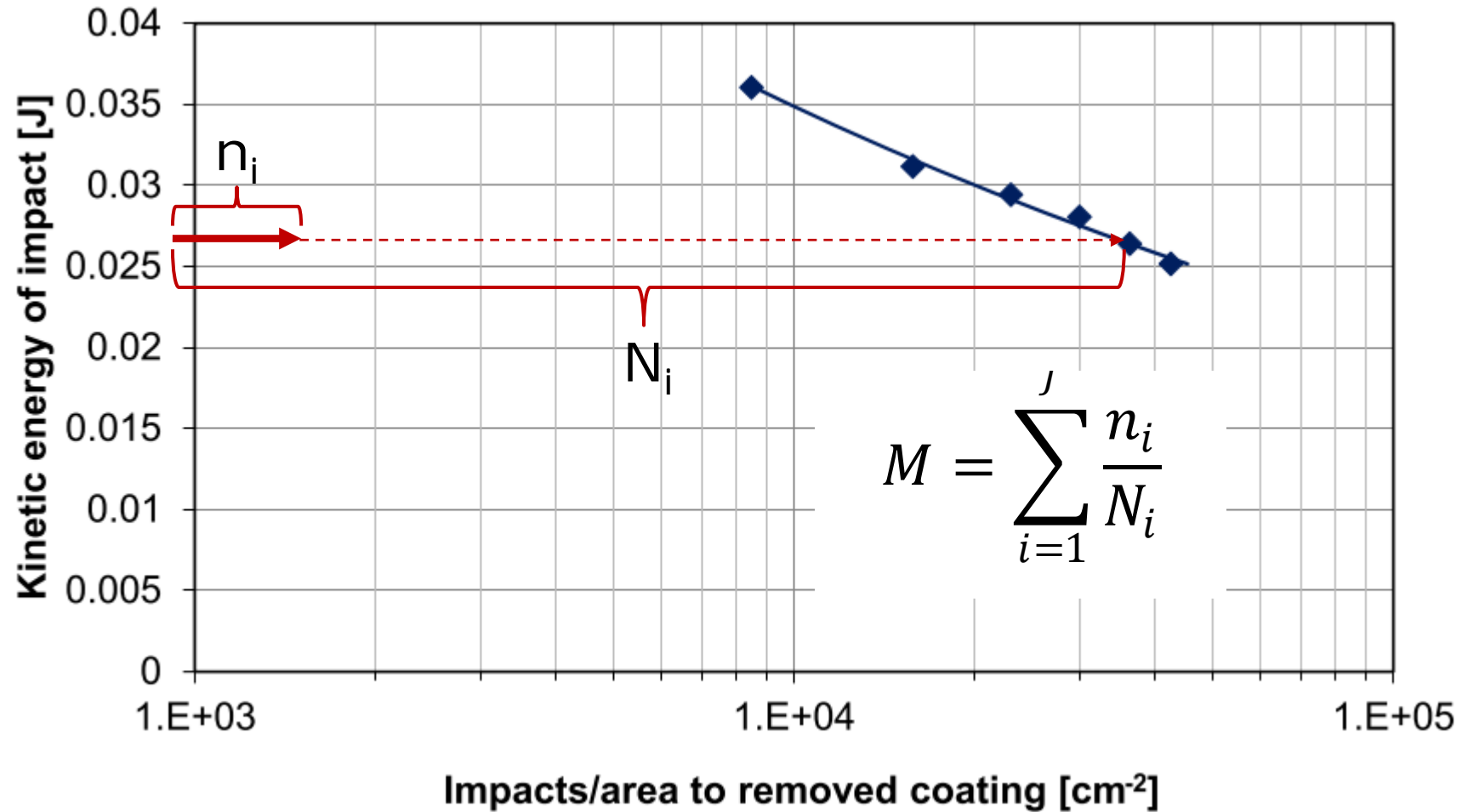
- From time series to incremental damage - Operation and loads
- Leading edge impact fatigue performance – Wöhler curve
- Damage accumulation law – Palmgren – Miner summation of damage increments

Rotor speed & rain intensity

$$N = cv^{-m}$$

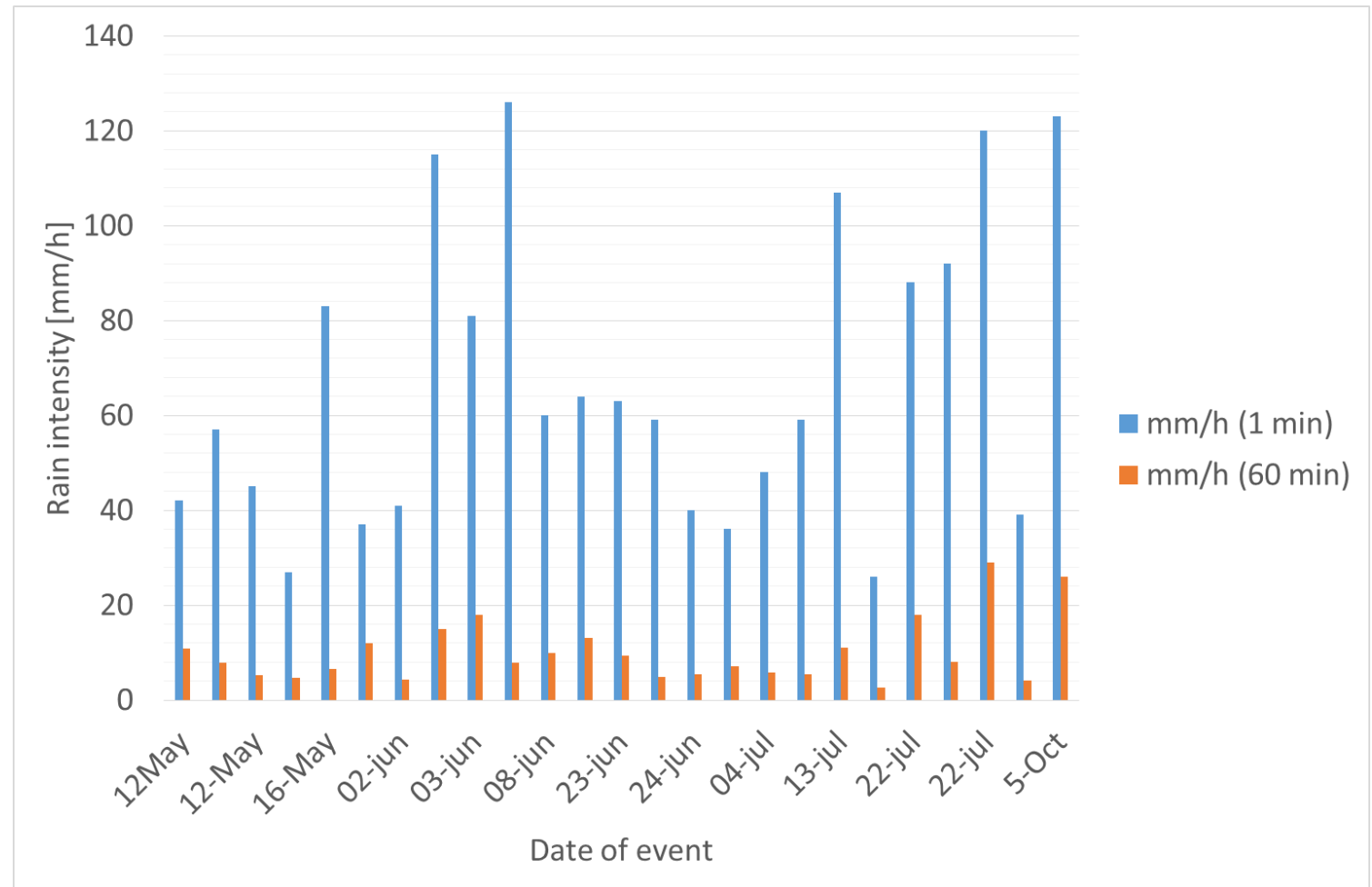
$$M = \sum_{i=1}^J \frac{n_i}{N_i}$$

Damage increment



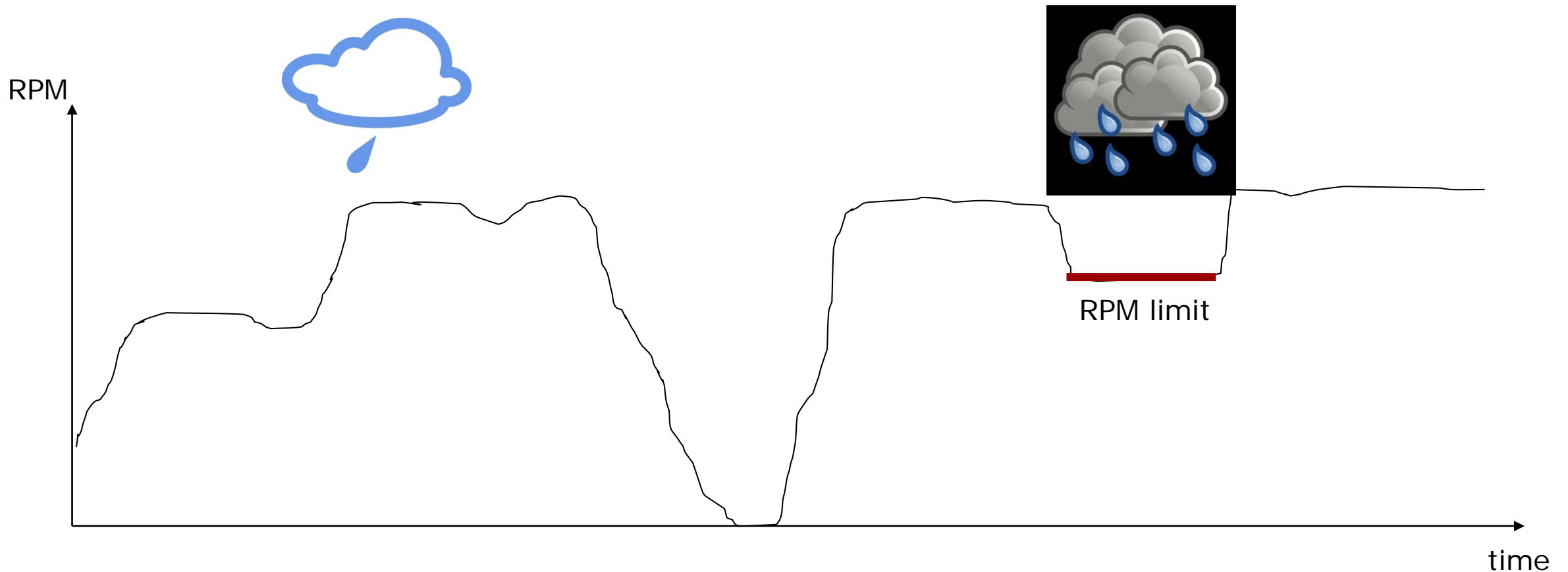
Rain intensity on 1 min and 60 min resolution

- High resolution wind and rain data gives more precise life predictions



(Smith et al., 2009)

Erosion control strategy: RPM (tip speed) limit at high rain intensity



Expected erosion life standard operation: 1.6 year

Rain intensity [mm/hr]	Droplet size [mm]	Percent of time [%]	Hours pr year [hrs/year]	Blade tip speed [m/s]	Hours to failure [hrs]	Fraction of life spent pr year [%]
20	2.5	0.02	1.8	90	3.5	51
10	2.0	0.1	8.8	90	79	11
5	1.5	1	88	90	3606	2.4
2	1.0	3	263	90	745710	0.0
1	0.5	5	438	90	2830197826	0.0
Sum of fractions [%]:						64
Expected life [years]:						1.6

Erosion life with erosion control strategy: 54 years

Rain intensity [mm/hr]	Droplet size [mm]	Percent of time [%]	Hours pr year [hrs/year]	Blade tip speed [m/s]	Hours to failure [hrs]	Fraction of life spent pr year [%]
20	2.5	0.02	1.8	60	222	0.8
10	2.0	0.1	8.8	70	1036	0.8
5	1.5	1	88	70	47514	0.2
2	1.0	3	263	90	745710	0.0
1	0.5	5	438	90	2830197826	0.0
Sum of fractions [%]:						1.9
Expected life [years]:						54

Conclusions

- Durable leading edges
 - Understand impacts dynamics
 - Understand damage mechanisms
 - Develop protective materials and structures
- Erosion control
 - Site specific rain and wind statistics for life prediction and control strategy
 - Monitoring and now-casting of precipitation
 - Erosion safe operation of turbines

Thank you for your attention

