DTU

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

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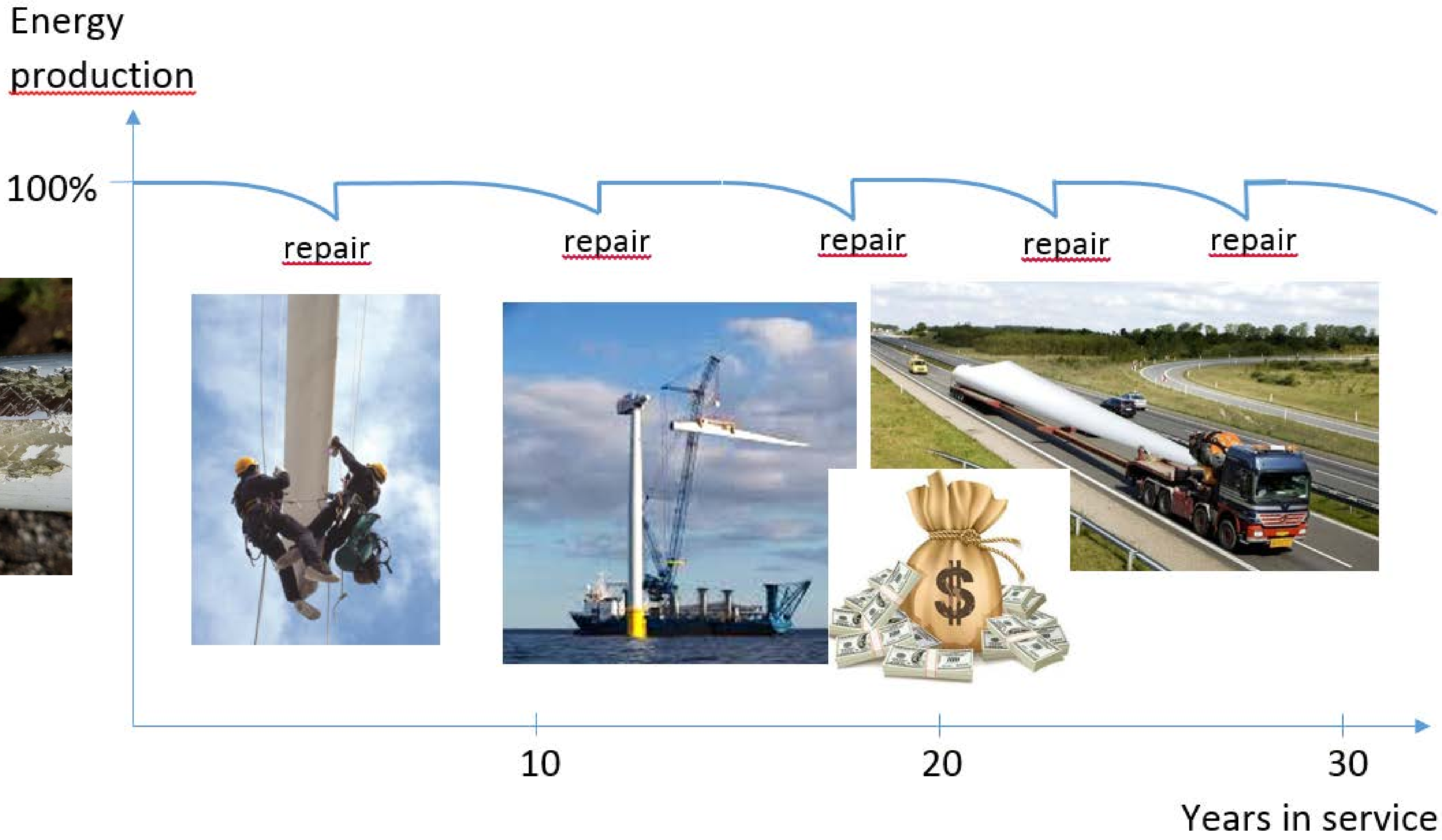
International Workshop on the Specific Issues of Taiwan Offshore Wind Farm, Taipei, Taiwan, Aug. 22-23 2019

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

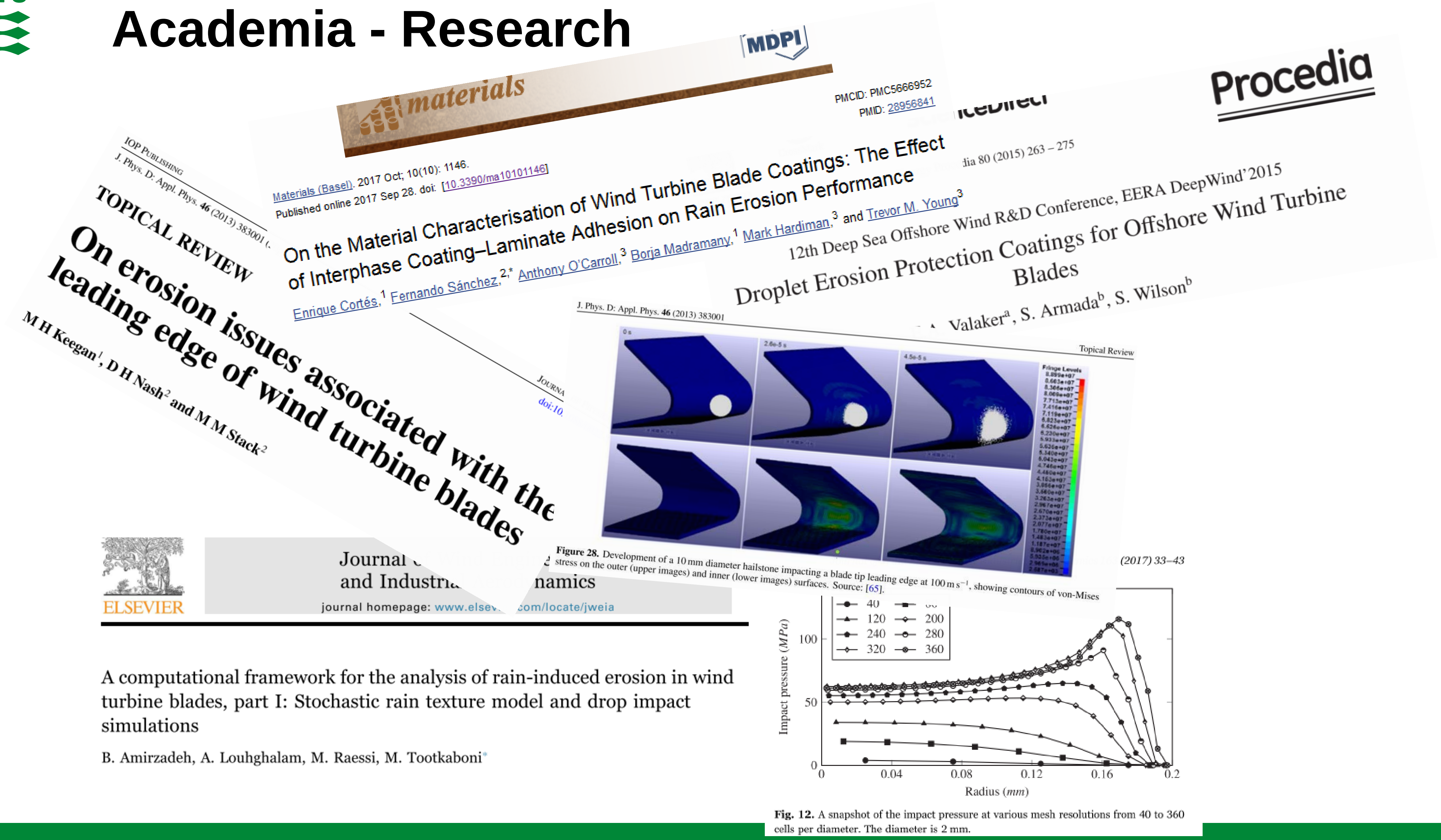
Contents

- 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

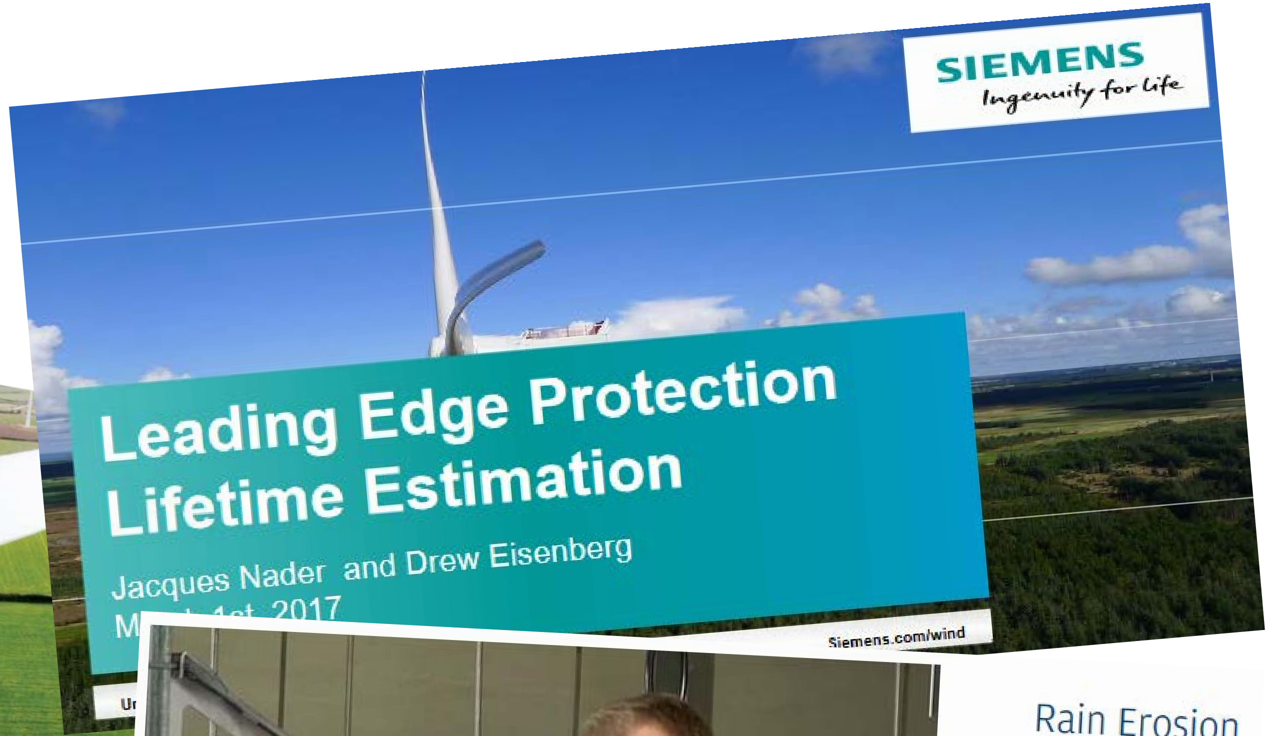
Leading edge erosion and its consequences



Academia - Research



OEM solutions

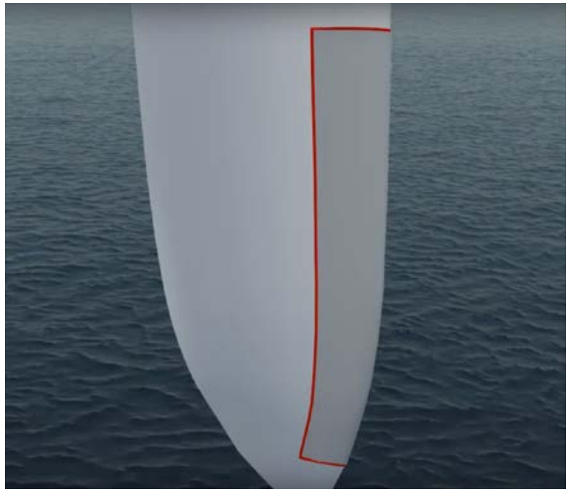


Protective 3rd party products

Coating systems

Superior edge protection for rotor blades

Shields



Danish company behind long-awaited technology for wind turbines

Tapes

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

Erosion safe operation

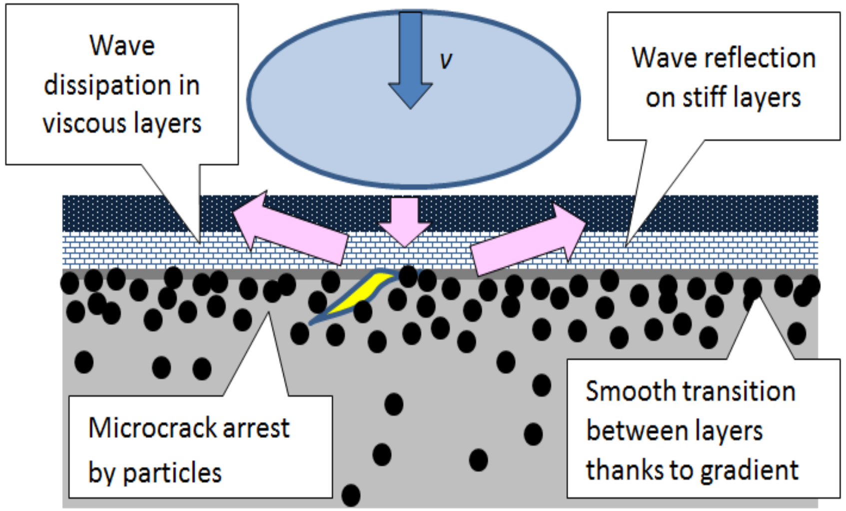
- Impact fatigue performance
- Monitoring
- Forecasting
- Turbine control

Innovation Fund DK – EROSION

www.rain-erosion.dk

Durable leading edges

- Damage mechanisms
- Mechanical properties
- Materials
- Structural design



Innovation Fund DK - DURALEDGE

www.duraledge.dk

Innovation fund DK DURALEDGE

"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

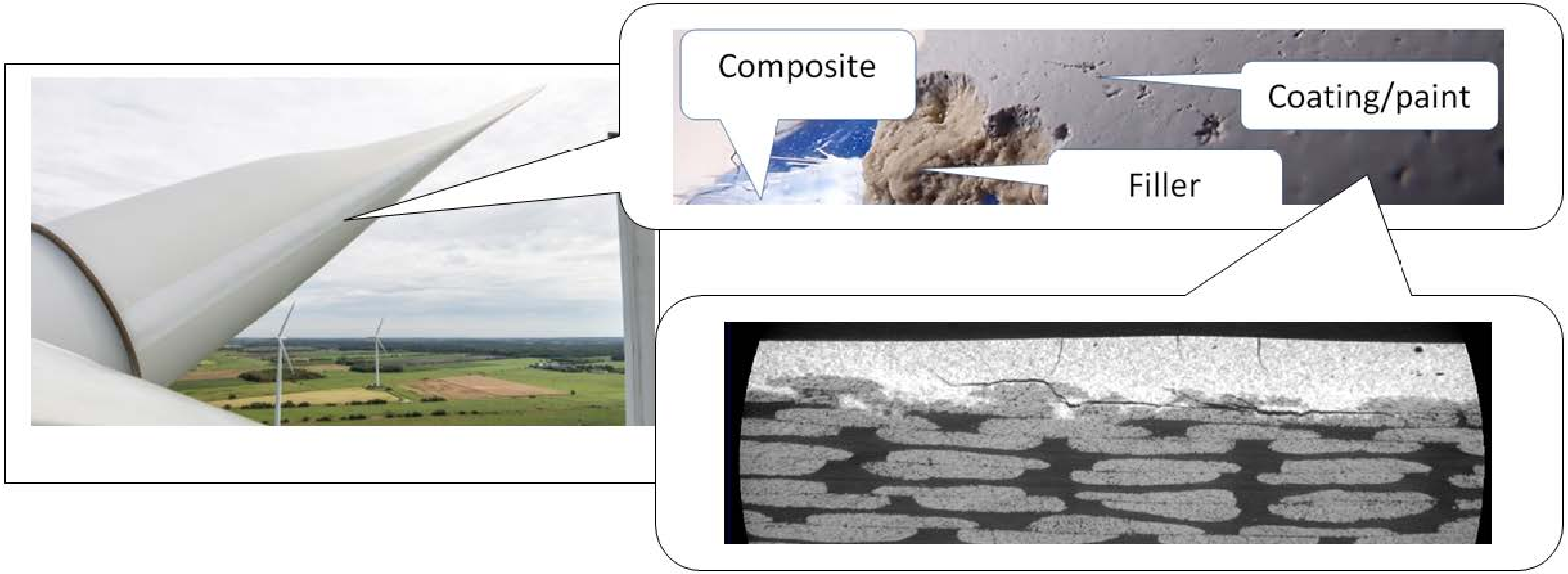
Leon Mishnaevsky Jr.

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



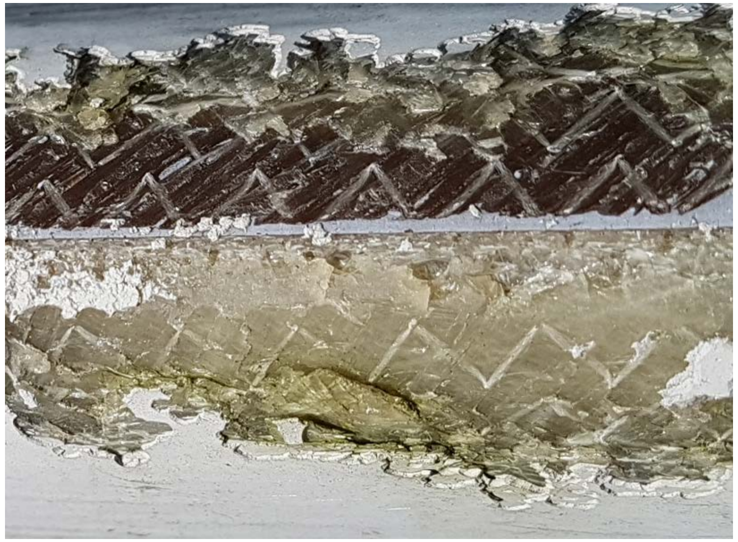
Damage analysis

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

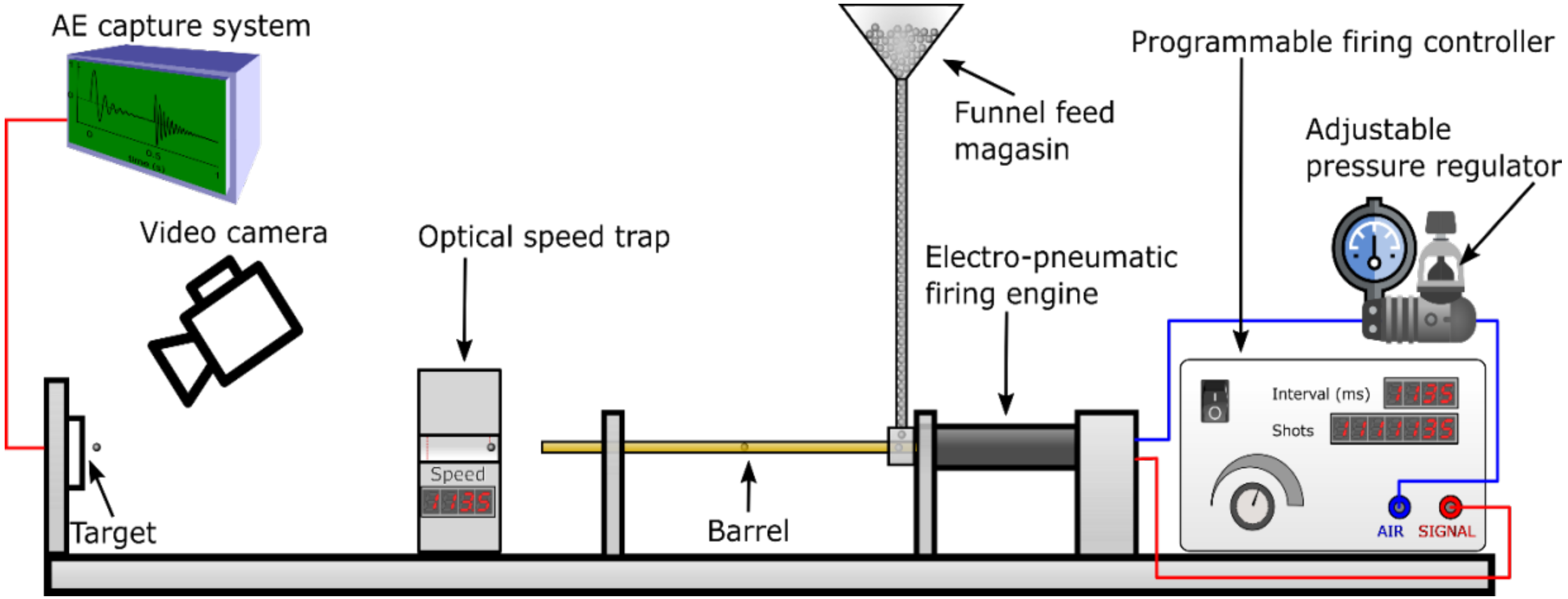
Damage mechanisms

- Surface cracks
- Subsurface cracks
- Interface debonding
- Others……

Field observations

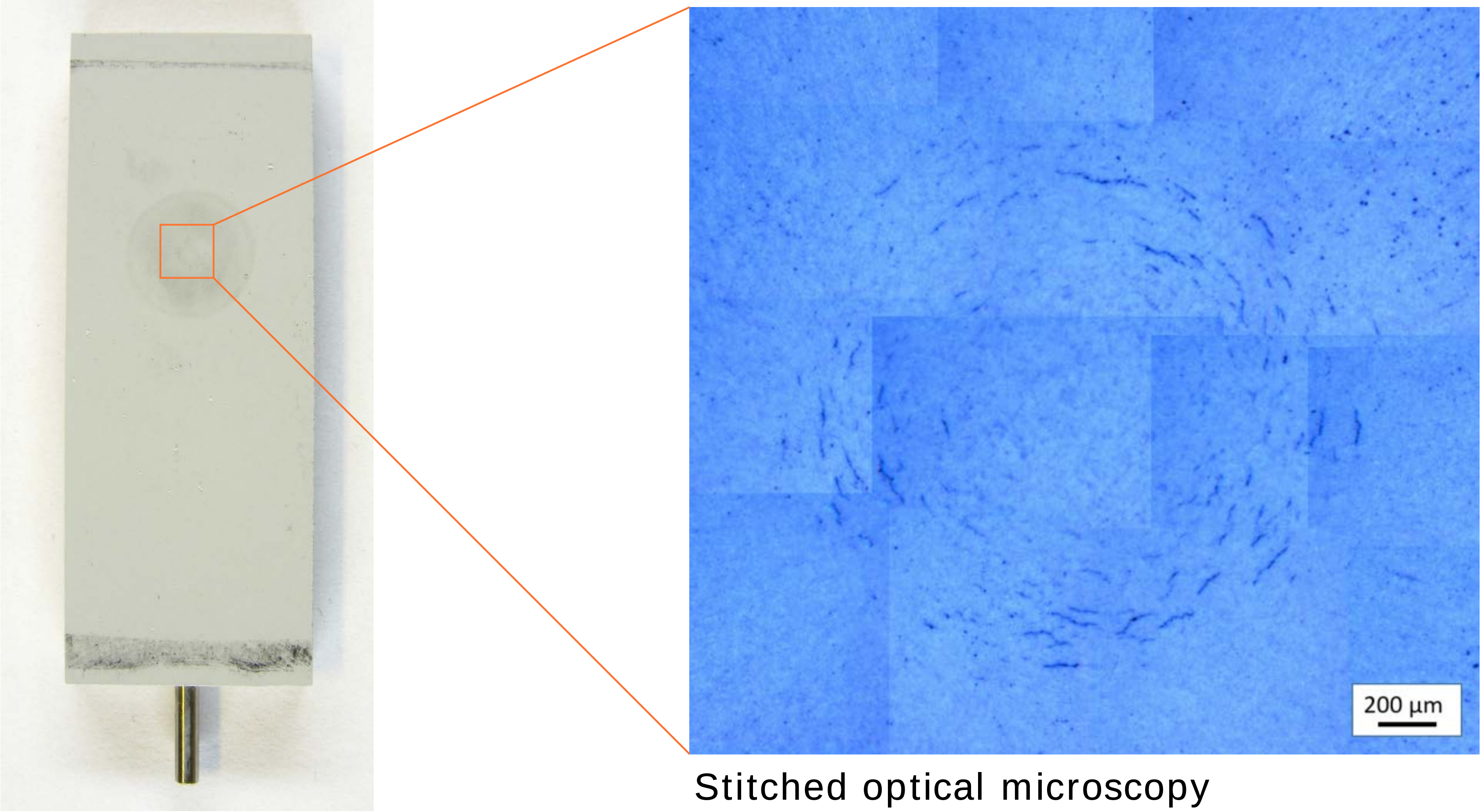


Single point impact fatigue tester



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

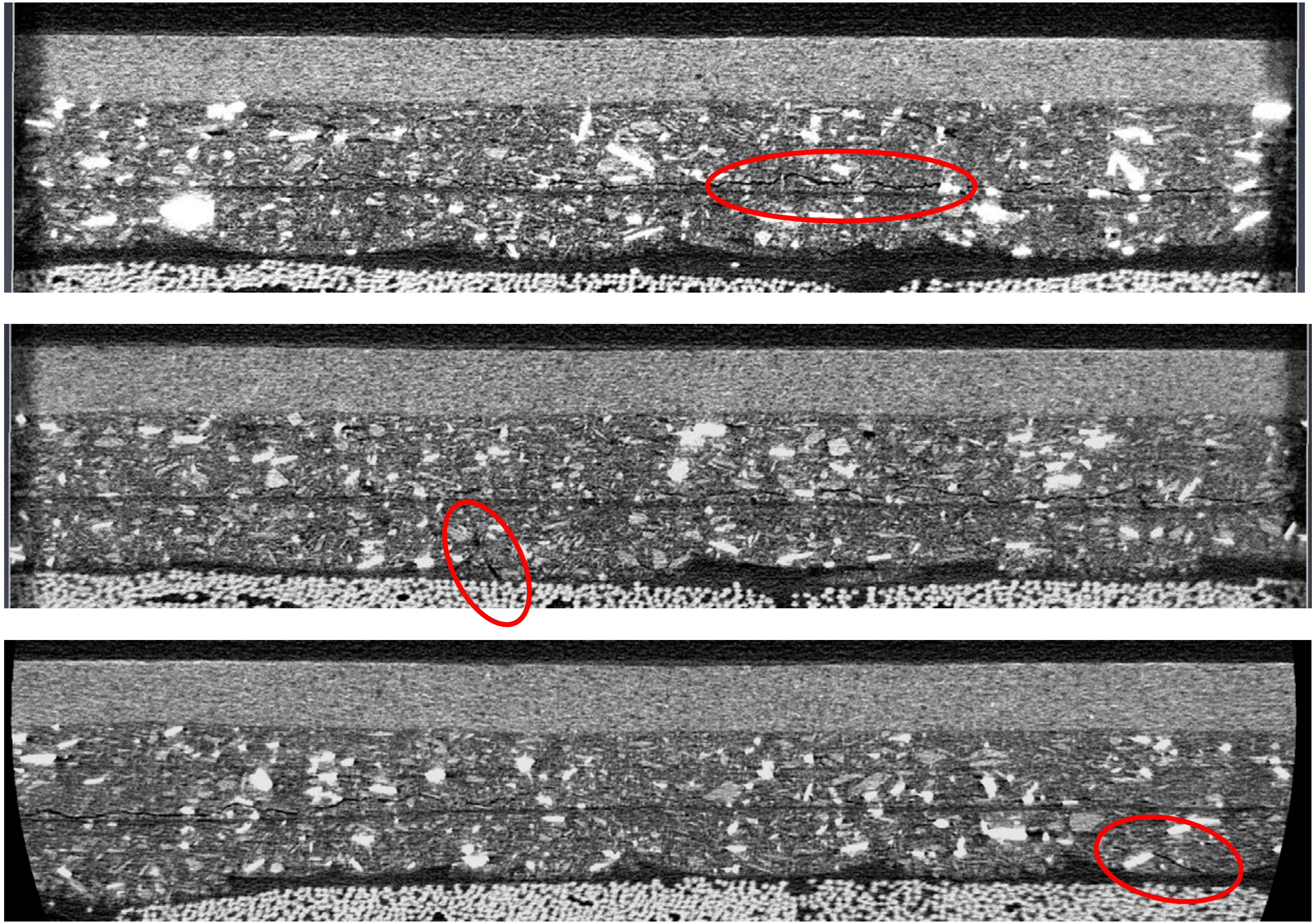
Study of impact fatigued specimen



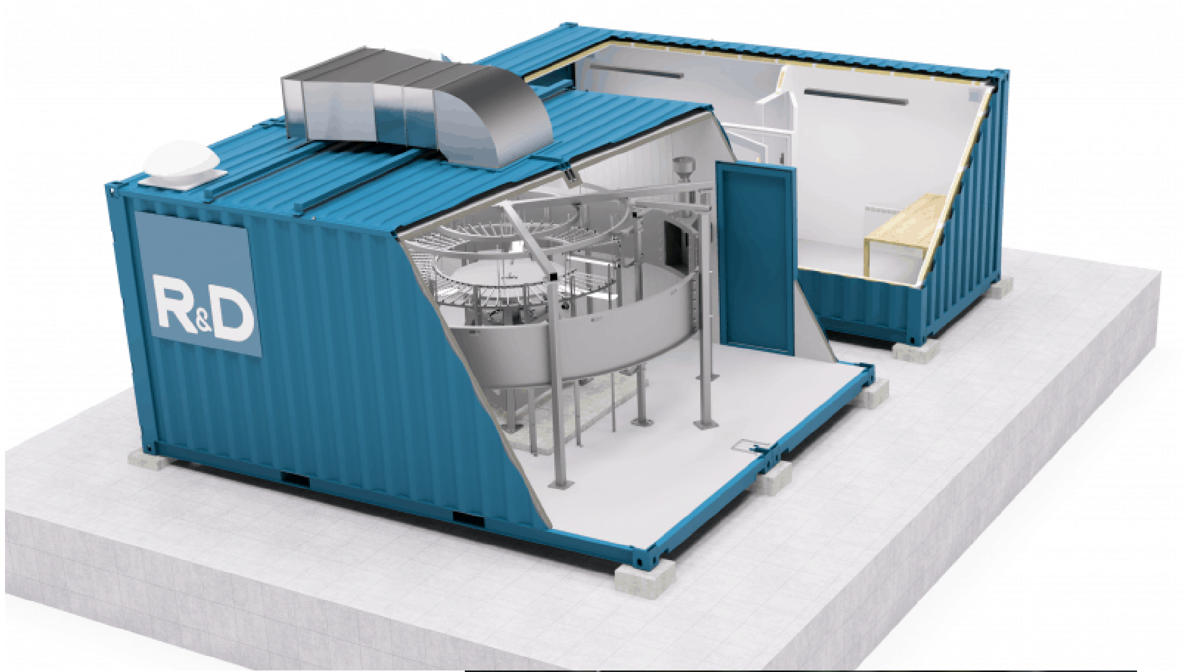
Stitched optical microscopy

(Leitz Aristomet)

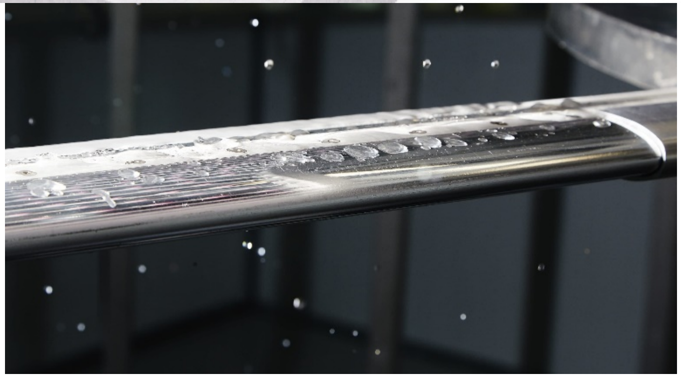
X-ray CT observation of Sub-surface cracks



Rain erosion testing



www.rd-as.com



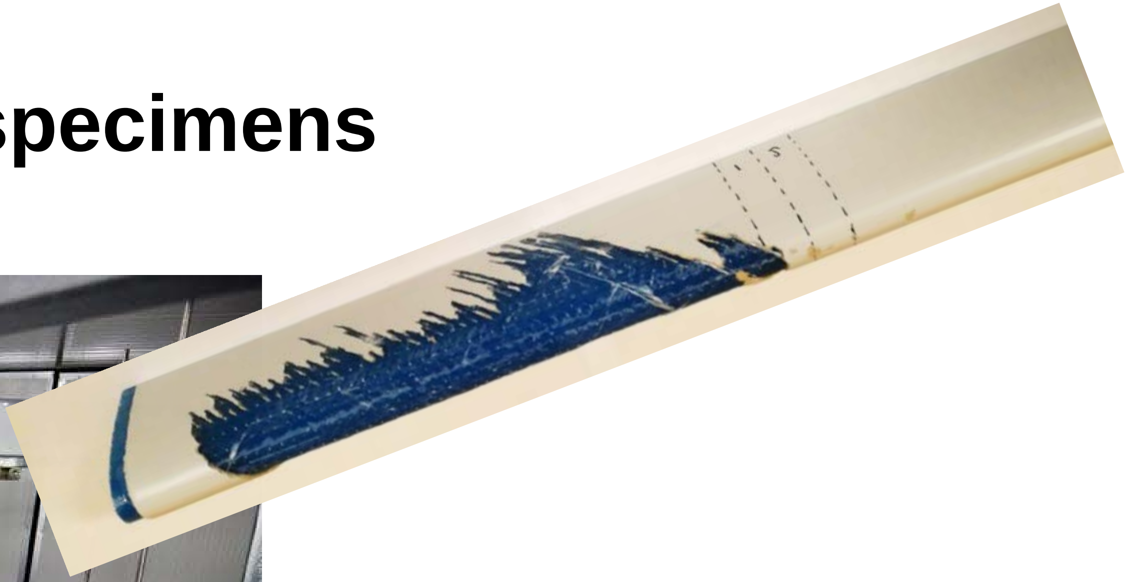
DNV·GL

RECOMMENDED PRACTICE

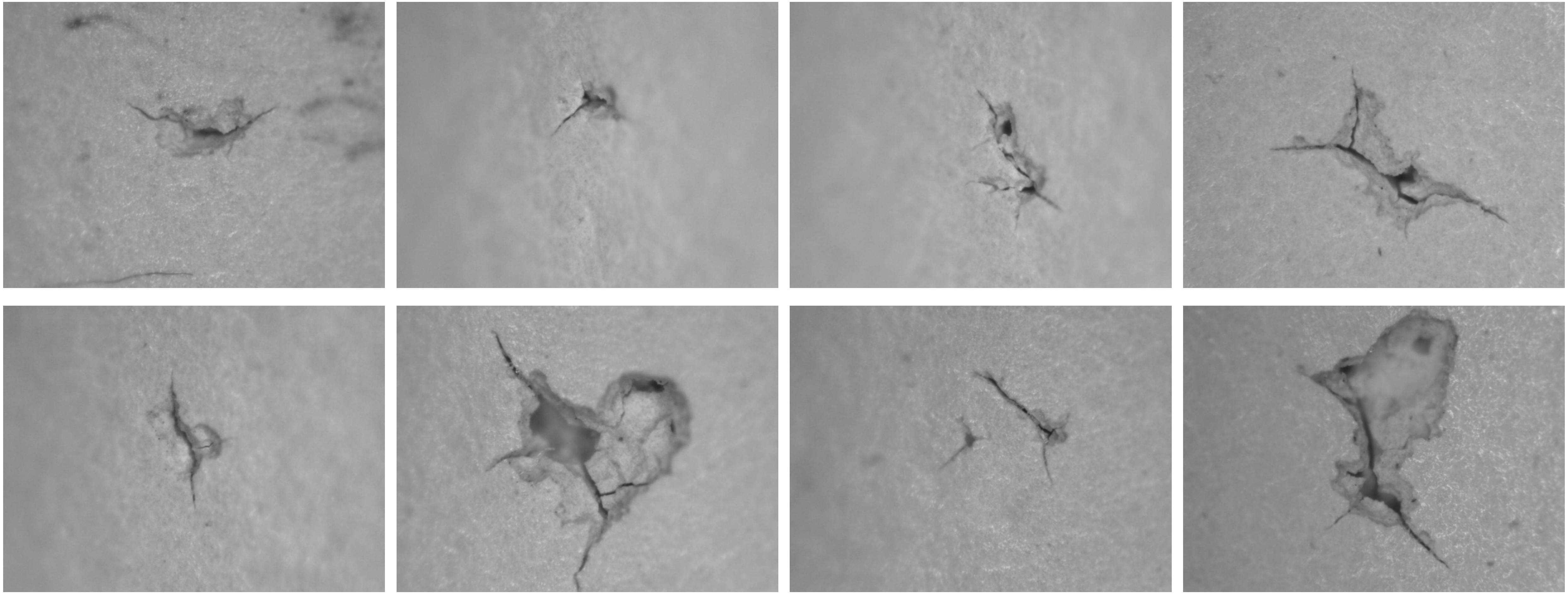
DNVGL-RP-0171 Edition February 2018

Testing of rotor blade erosion protection systems

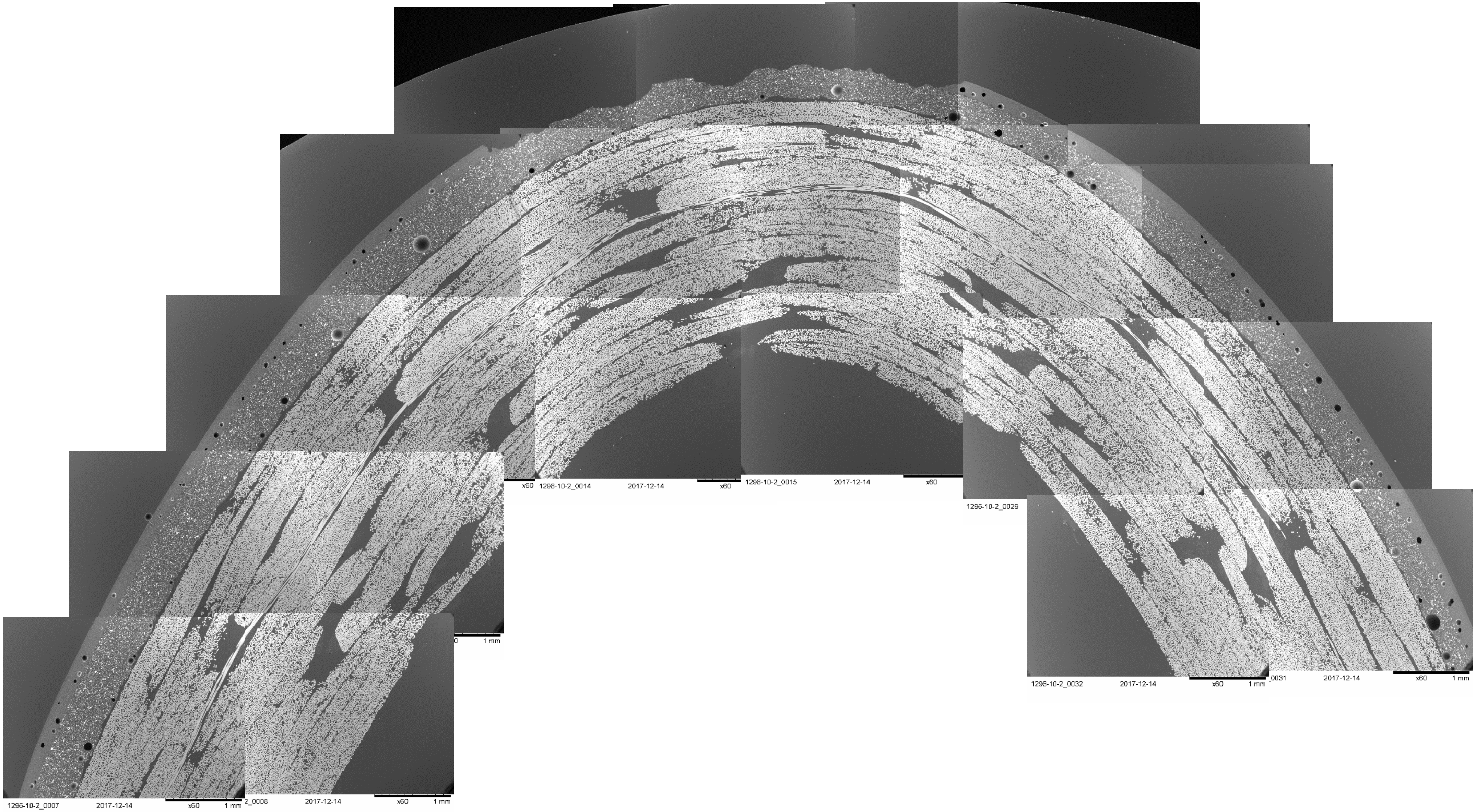
Study of rain erosion test specimens



Holes and cracks at surface of leading edge protection



SEM image



1296-10-2_0007
2017-12-14
x60
1 mm
2_0008
2017-12-14
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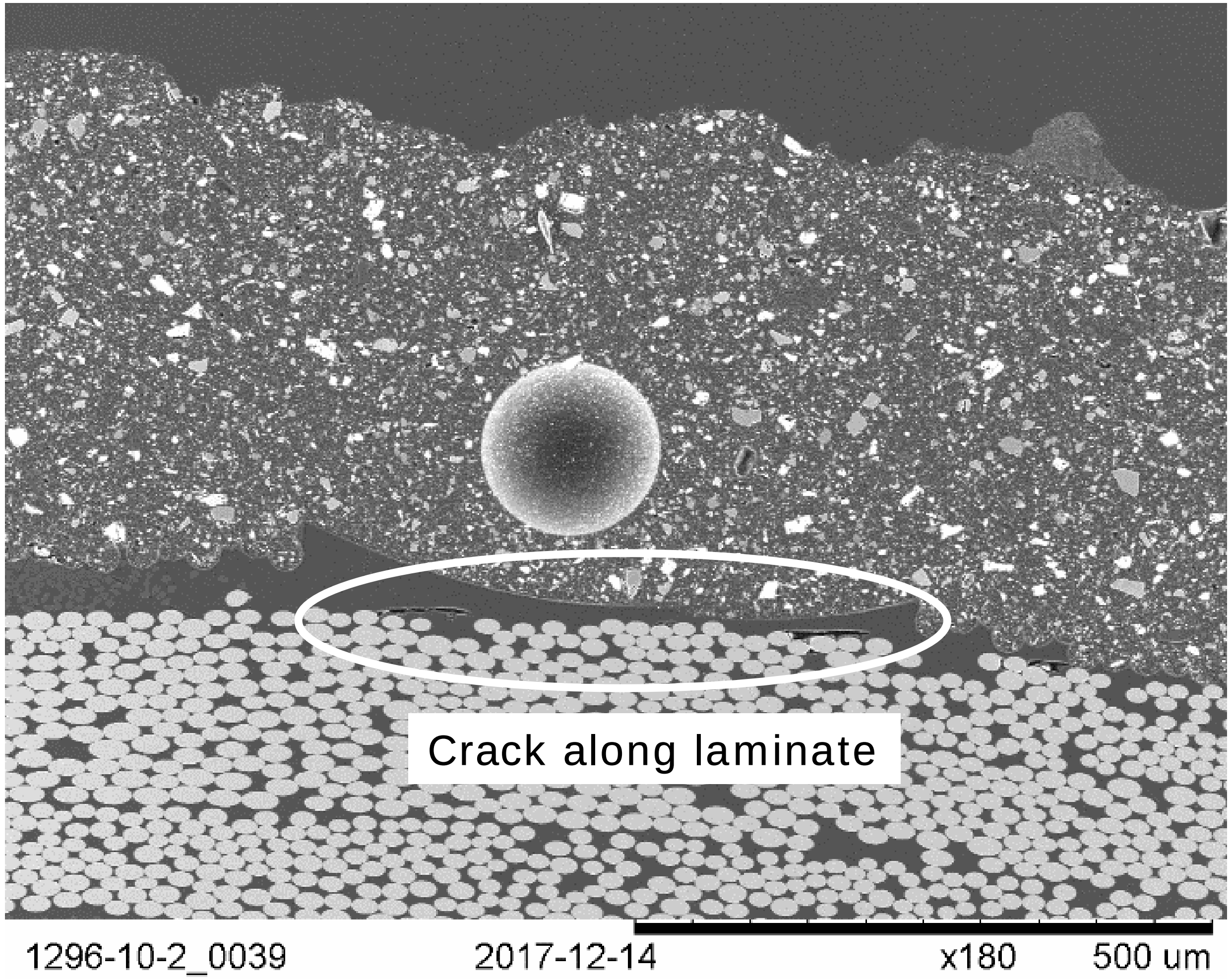
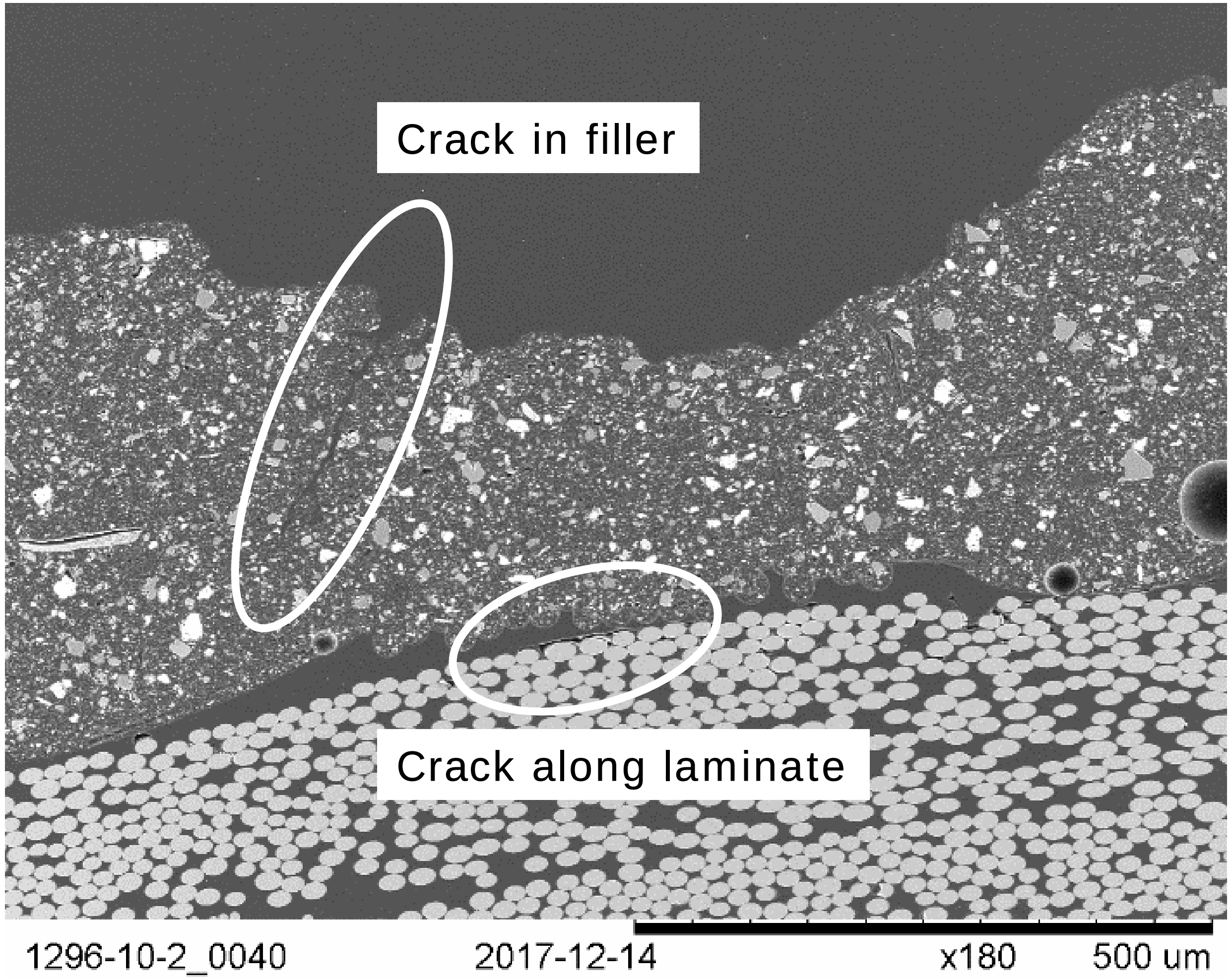
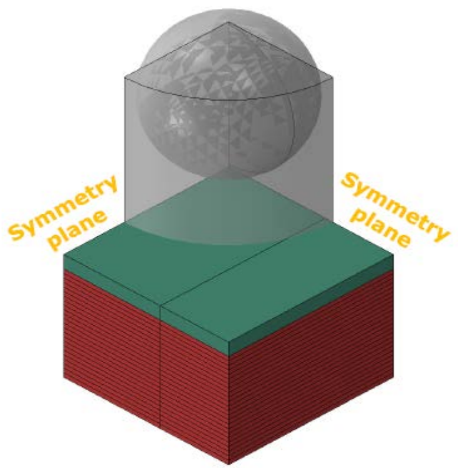
1 mm
x60
1296-10-2_0014
2017-12-14
x60
1296-10-2_0015
2017-12-14
x60
1296-10-2_0029
1296-10-2_0032
2017-12-14
x60
1 mm
_0031
2017-12-14
x60
1 mm

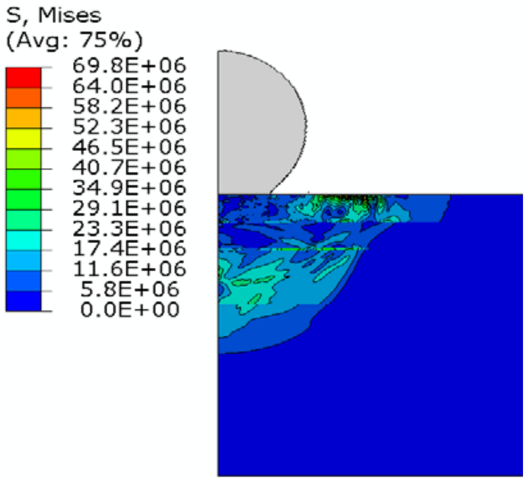
SEM image

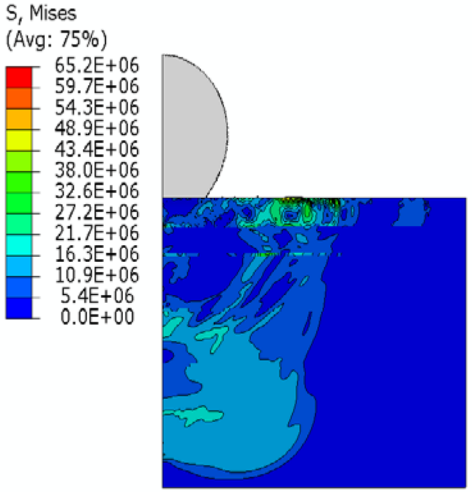

Crack along laminate
1296-10-2_0039
2017-12-14
x180
500 um


Crack in filler
Crack along laminate
1296-10-2_0040
2017-12-14
x180
500 um

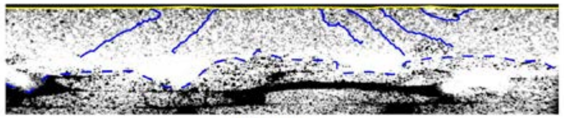
Computional modelling of impact stresses, fatigue and damage initiation



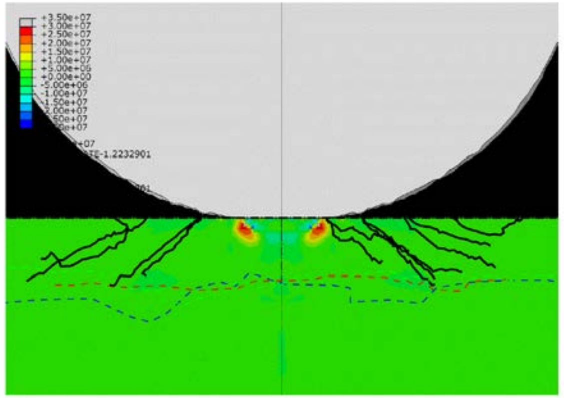




Correlating model stresses to observed cracks



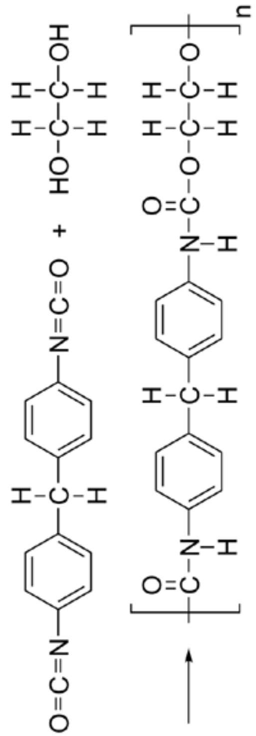
CT scan



Shear stresses in FEM

Development of new binders for coating systems

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



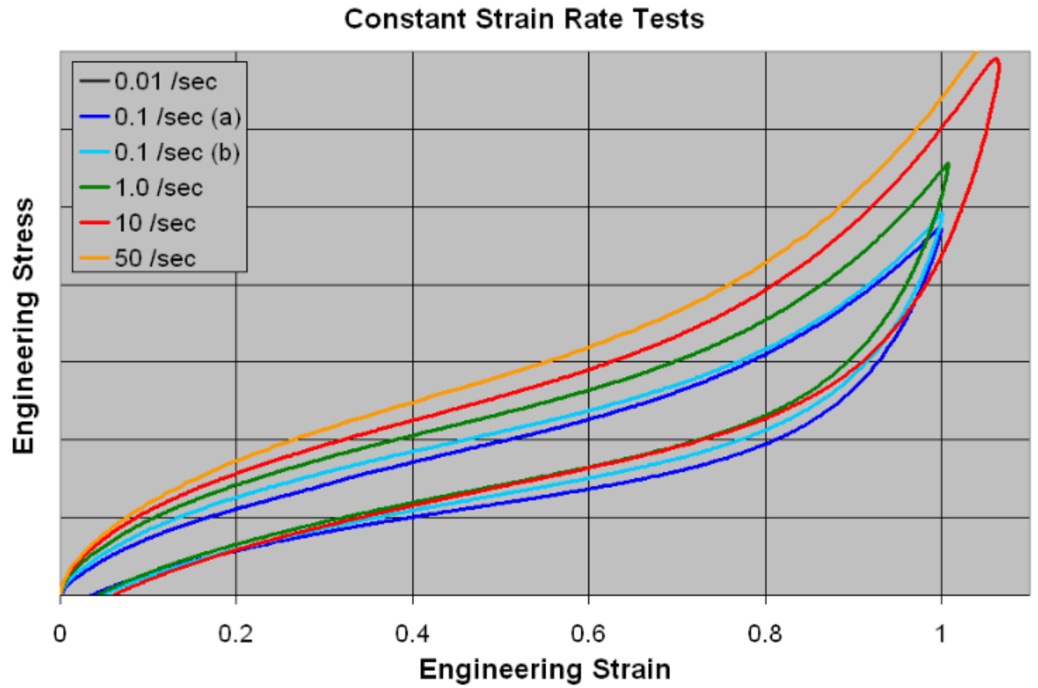
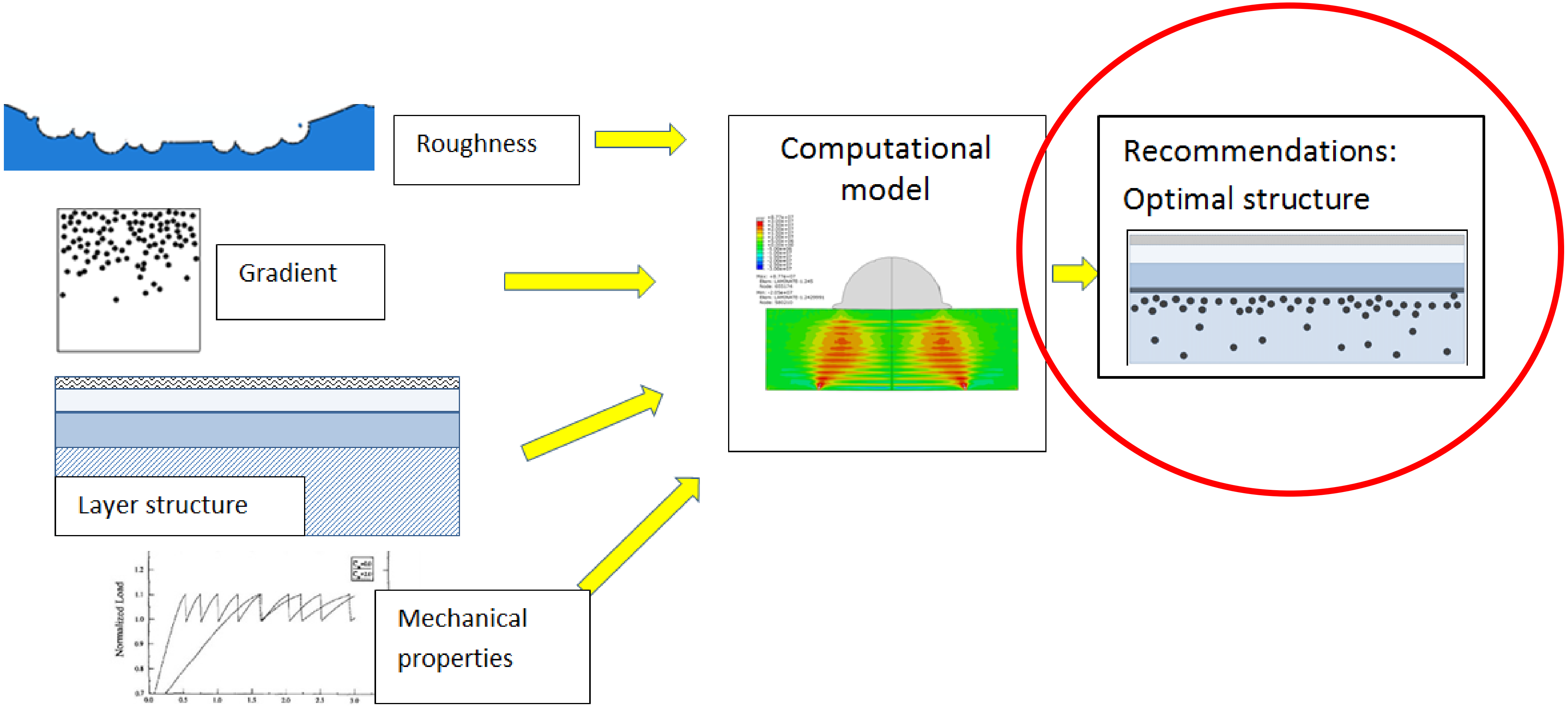


Figure 14. Family of constant strain-rate dynamic testing, load / unload (100% Strain).

T.Dalrymple
J. Choi, 2007

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



Innovation fund DK EROSION

"Reducing the largest uncertainties". April 2017 to March 2020

Published: 19 October 2018

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

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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

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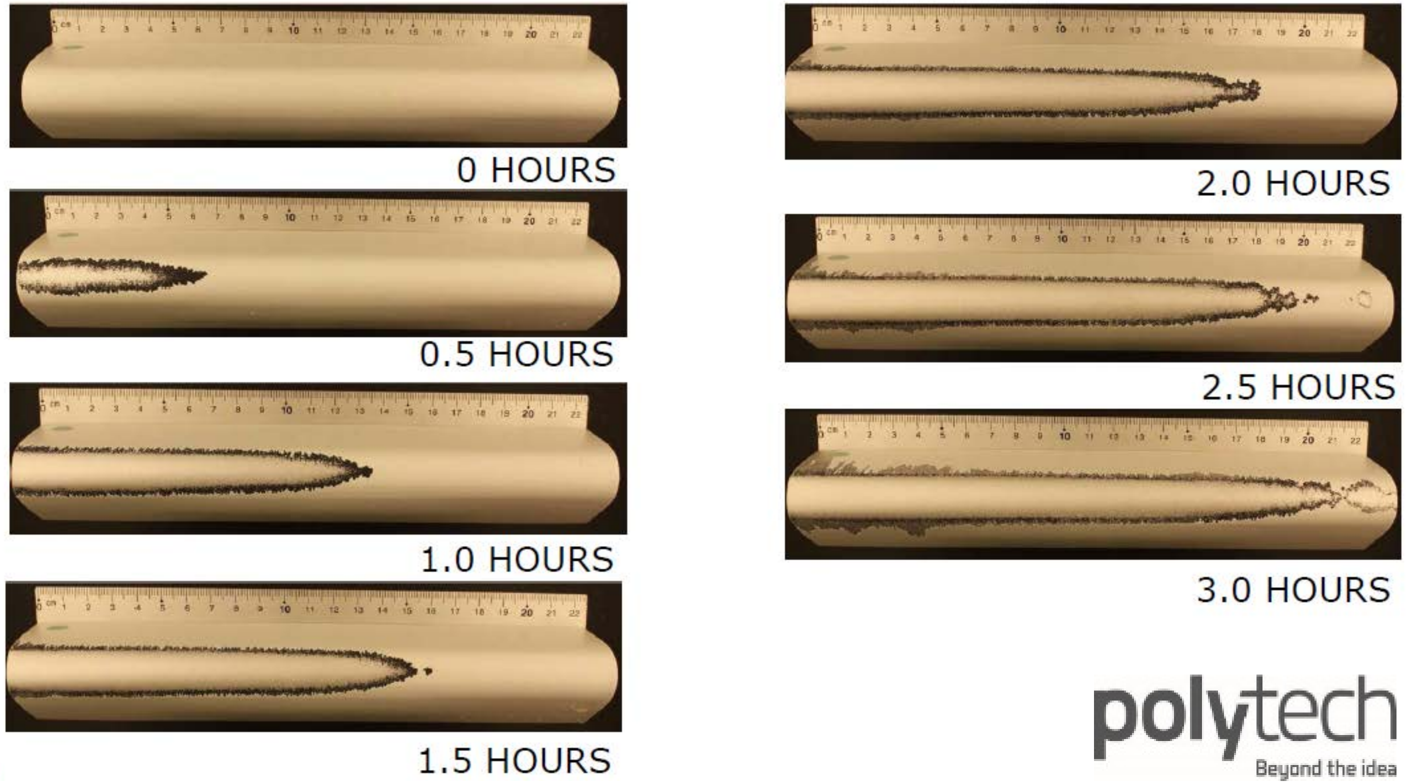
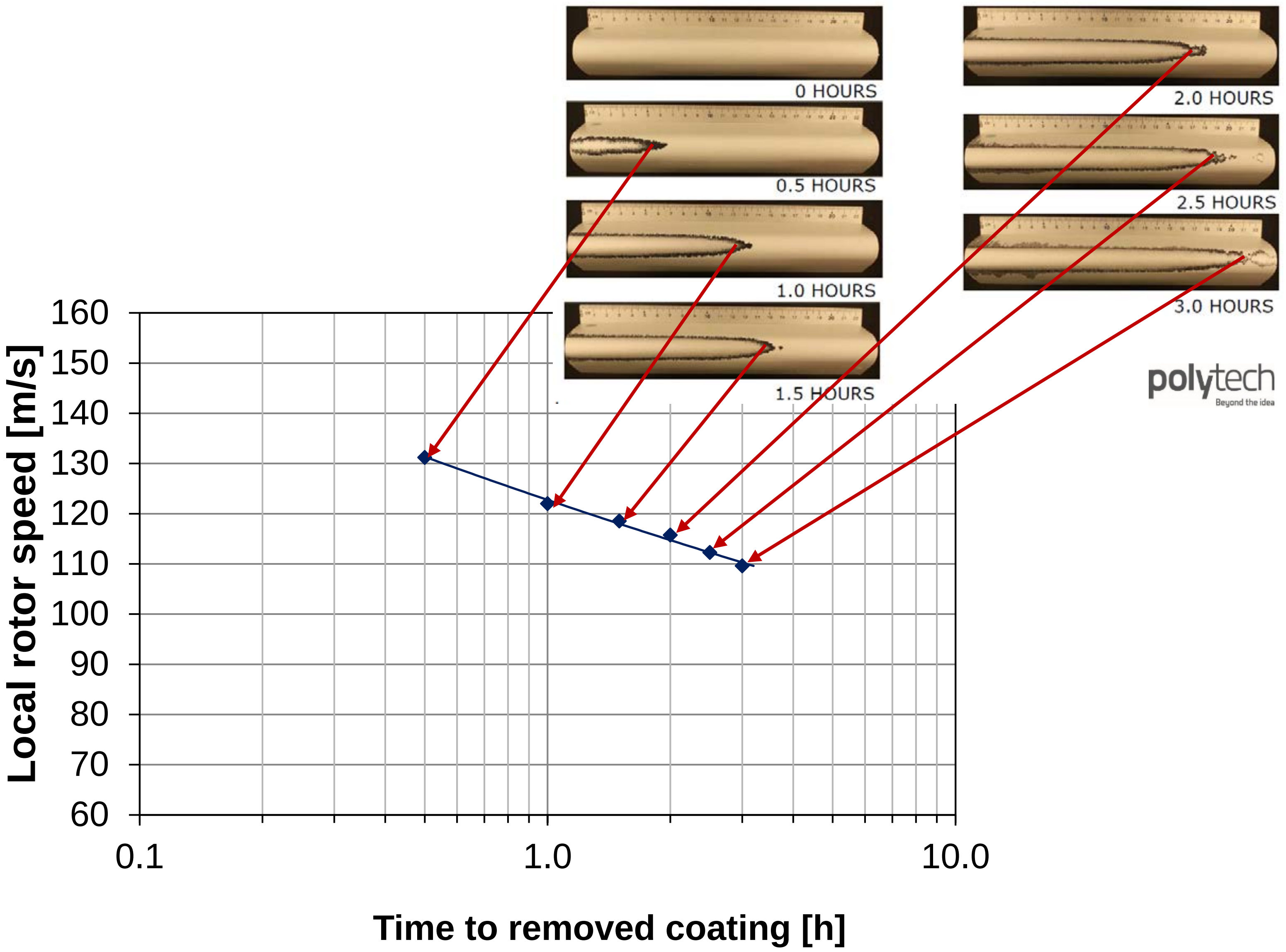
Erosion test for material performance

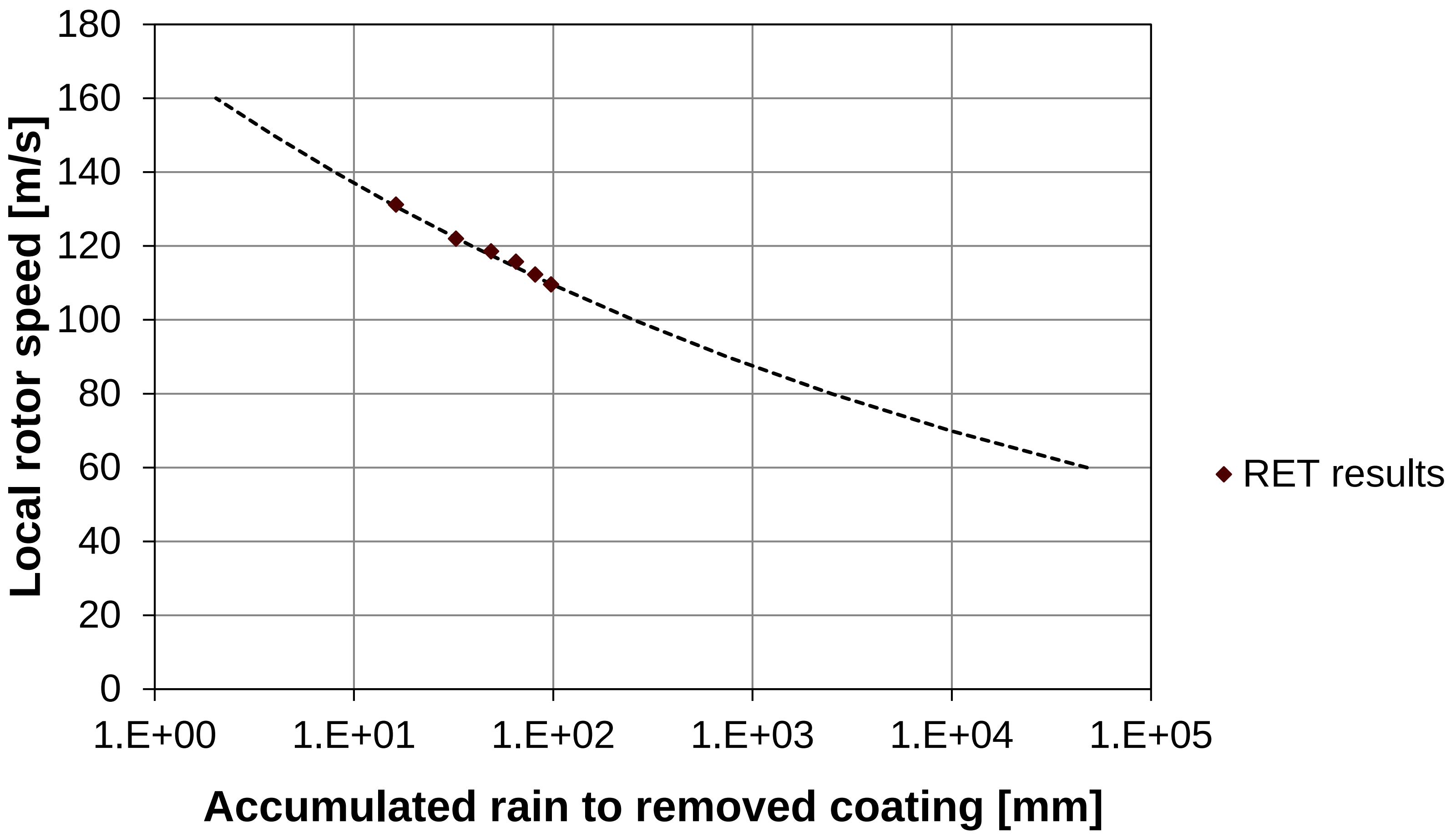


polytech
Beyond the idea

Plot of test data to Wöhler curve



Impact fatigue properties



Life time prediction

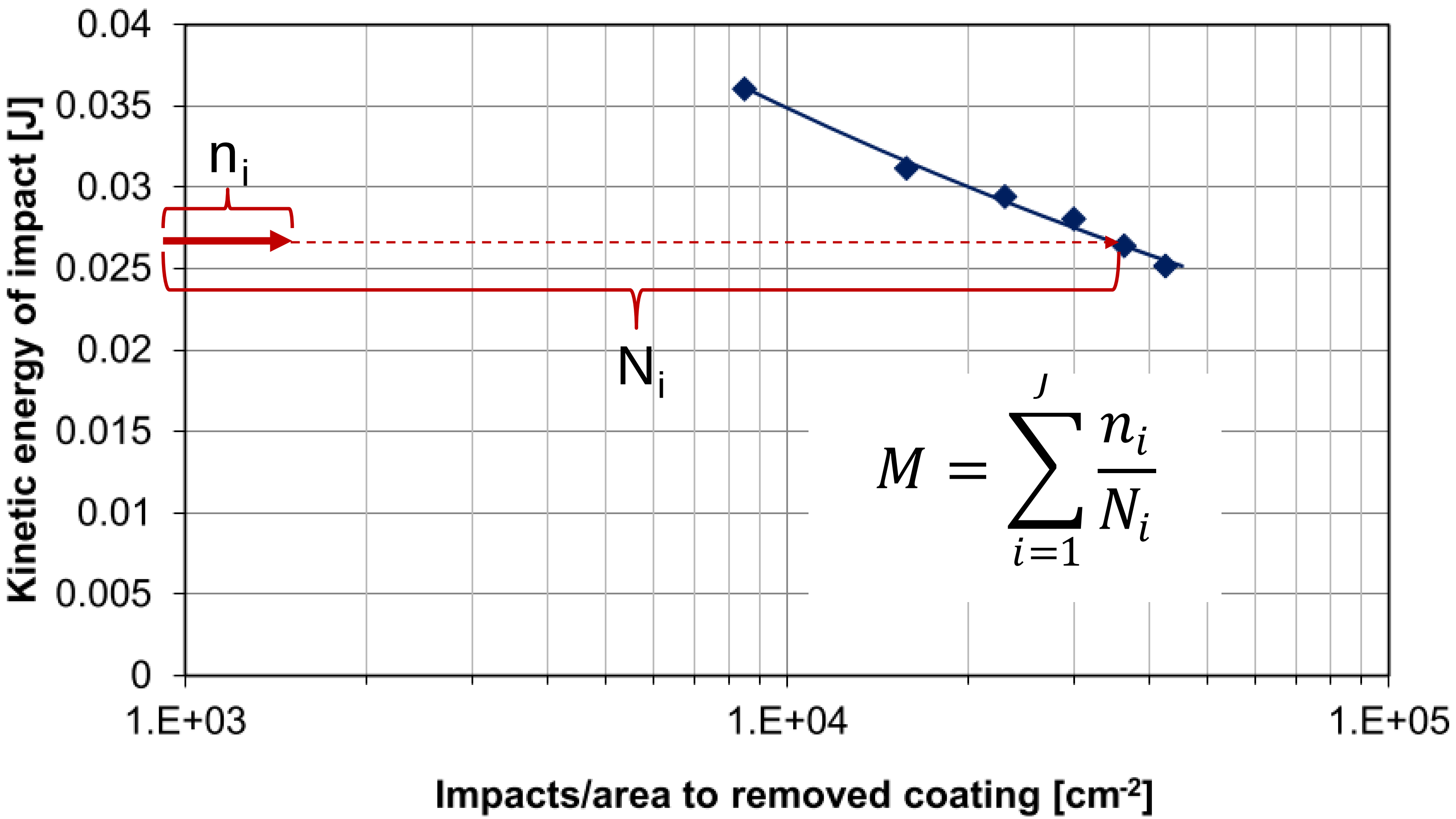
- From time series to incremental damage - Operation and loads
- Leading edge impact fatigue performance – Wöhler curve
- Damage accumulation law –Palmgren – Miner summation of damage increments

Rotor speed & rain intensity

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

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

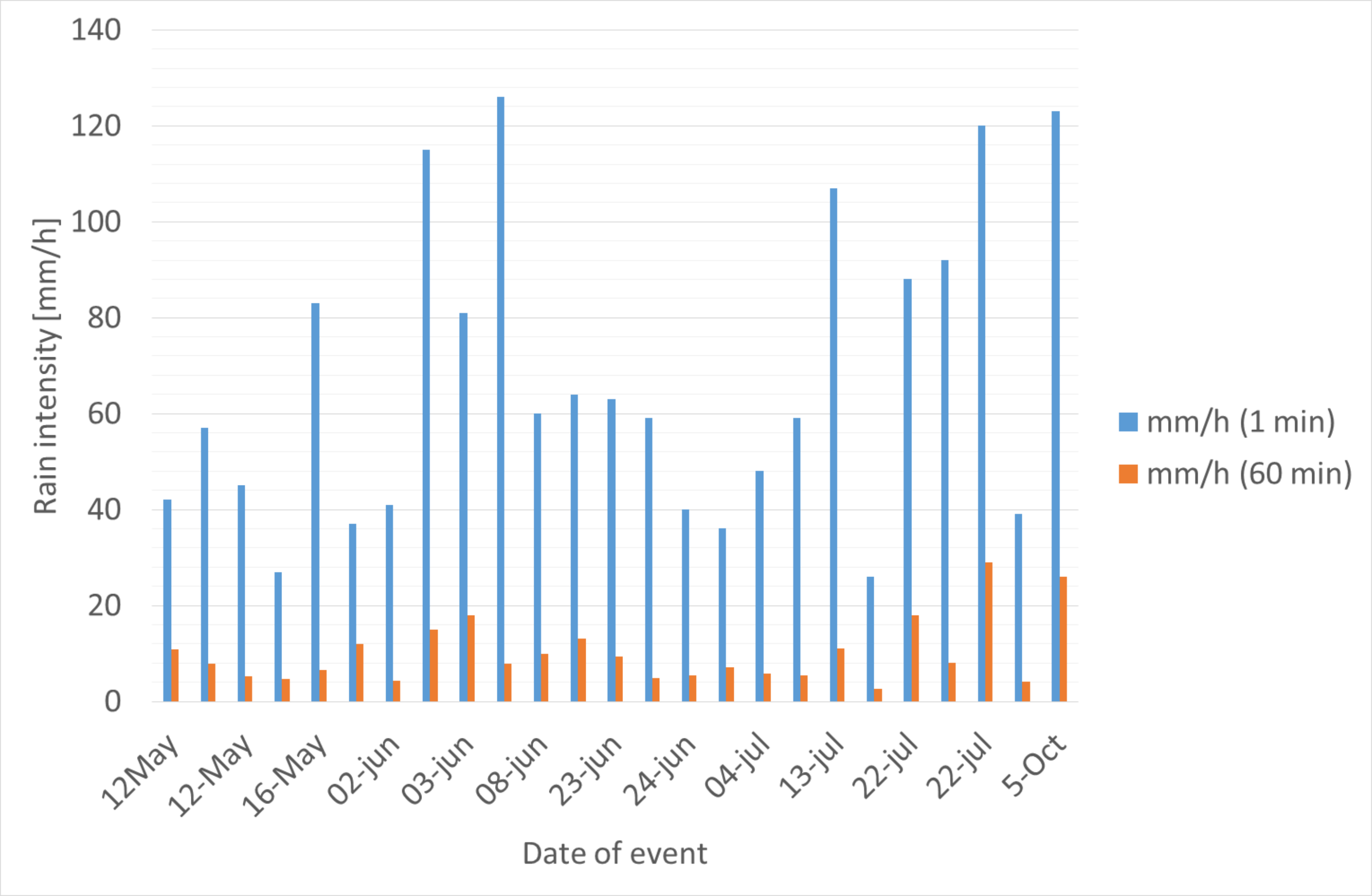
Damage increment



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

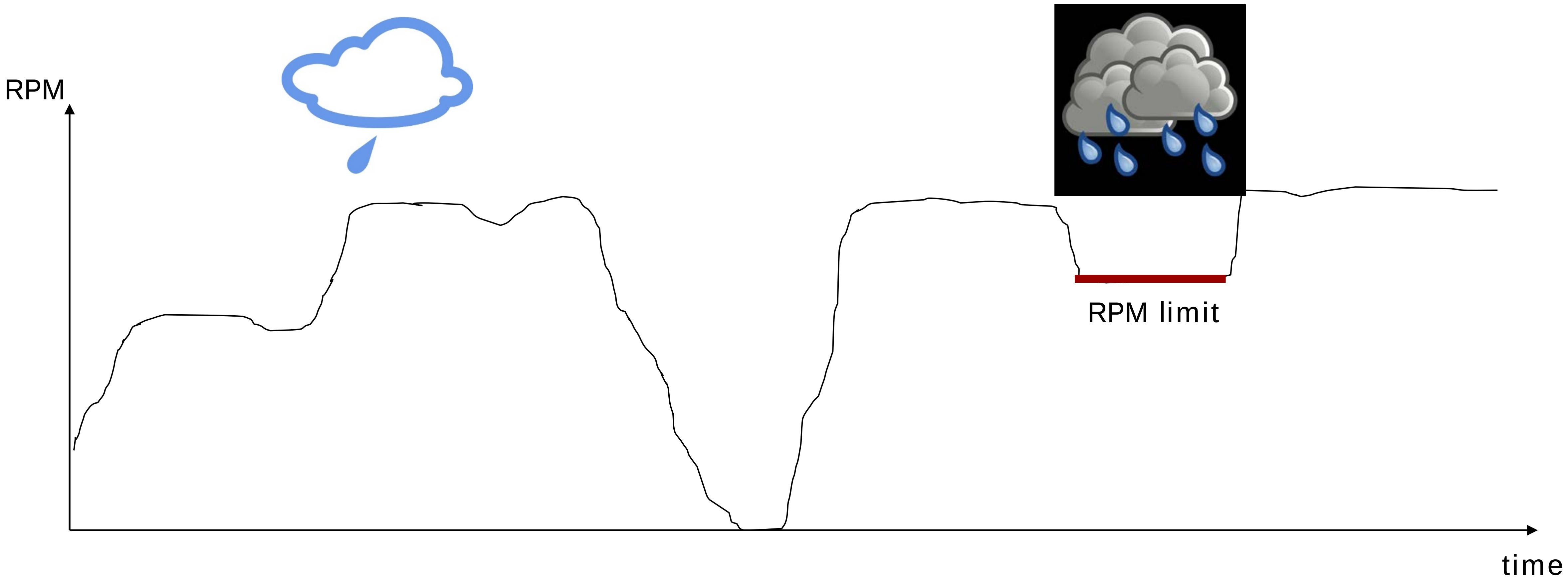
Rain intensity on 1 min and 60 min resolution

- 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