Computational modelling of leading edge erosion

Overview and next steps

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Problem

a) b) c)

- Due to leading edge erosion, up to 25% annual energy loss can be expected.
- LEE can be seen 2...3 years after installation of WT.

Main steps of LEE modelling

1. **Estimation of loading:** Rain density, dropplet size distribution, dust, flow velocity
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Estimation of loading

Amirzadeh, et al JWind Engineering and Industrial Aerodynamics 2017:

- ❑ Stochastic model of rain texture
- ❑ Used rainfall data for the city of New Bedford 1992- 2000
- ❑ Raindrop size distribution by Best $F = 1 - exp\left[-\left(\frac{d}{1.3\ I^{\ 0.232}}\right)^{2.25}\right]$

d is the drop diameter in mm, *I* is the rain intensity in mm/h and *F* is the fraction of liquid water in air comprised of drops with a diameter smaller than *d*

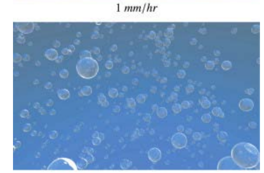
- ❑ Rain as homogeneous spatial Poisson process. Number of drops in volume V follows a Poisson distribution

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

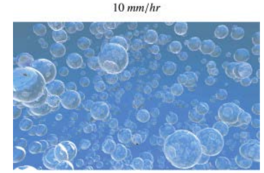
λ the expected number of raindrops in volume *V* and P(N(V)=k) the probability of finding *k* raindrops in volume *V*.

- ❑ Rain scenario (3D field of raindrops) is created

1 mm/hr



10 mm/hr



100 mm/hr

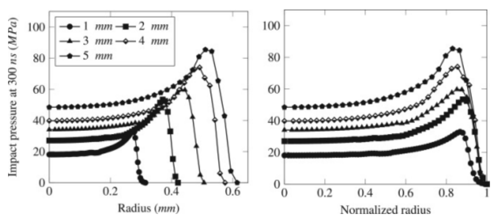
Estimation of loading

Castorrini et al, Computers and Fluids, 2016:

- ❑ FE particle tracking cloud method.
- ❑ Turbulent flow modelled.

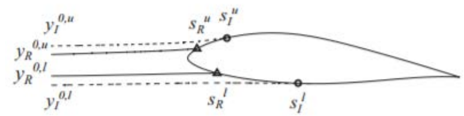
Amirzadeh, et al J Wind Engnrng Industrial Aerodynamics 2017:

- ❑ Taking into account time dependency of water pressure during the contact
- ❑ CFD simulations. Equations of conservation of mass and momentum. Impact velocity 100 m/s. Impacts are normal to a rigid smooth surface.



Fiore, Selig, Wind Engineering, 2015

- ❑ simulation of airborne particle collisions with a 38 m, 1.5 MW horizontal axis wind turbine blade



- ❑ Calculation of trajectory and velocity of impringing particles and insects

Eisenberg, Laustsen, LEP Protection lifetime prediction model et al, windeurope.org/summit2016

- ❑ Use probability distribution of rain droplets from Best, A. C., Quart J Royal Meteorological Society, Volume 76: pages 16–36, 1950.

My opinion: due to rough input data, exact numerical solution of complex fluid equations is not justified

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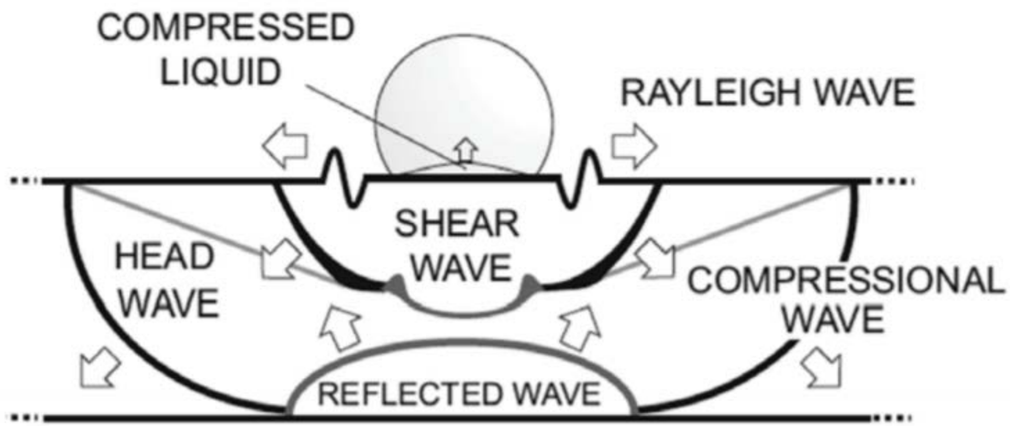
5. **Solutions:** New coatings

Impact contact and transient stresses

How it looks like



Bulk waves decay with $1/r$ into the solid and with $1/r^2$ at the surface. Raleigh waves decay at $1/\sqrt{r}$.

Impact contact and transient stresses

Water hammer equation and modified version

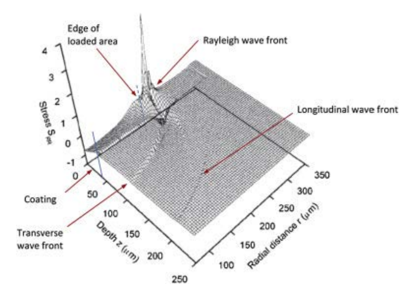
$$P = \rho_0 c_0 V_0$$

$$P = \frac{V \rho_l c_l \rho_s c_s}{\rho_l c_l + \rho_s c_s}$$

P -pressure created during impact, ρ0 is the density of the fluid, c0 is the speed of sound in the undisturbed liquid and V0 is the impact velocity, and l and s as subscript refers to liquid and solid bodies, Dear JP, Field JE. J Applied Physics. 1988;63:1015

H.S. Kim et al, J Appl Mech, 68 (2) (2000

thin hard elastic coating. Reflection at the coating–substrate interface is taken into account



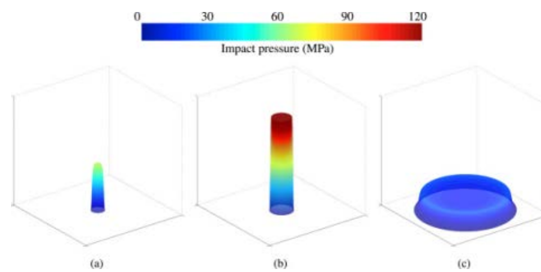
Impact contact and transient stresses

W.F. Adler, D.J. Mihora,
Waterdrop impact modeling,
Wear, 186–187 (1995**:**

- FEA of a water droplet impacting thick compliant coatings.
- Deep craters develop in impacted polyurethane coatings which probably alters the evolving water drop shape, substantially.
- Impact by a single water droplet cannot initiate failure for polyurethane coatings

Amirzadeh, et al J Wind Engnrng Industrial Aerodynamics 2017:

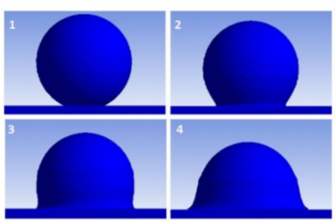
- FE transient stress analysis for various raindrop sizes
- Modelling entire layup structure and only Gelcoat layer with rigid bottom (difference in stresses only 5%)
- Raindrop load defined using VLOAD subroutine

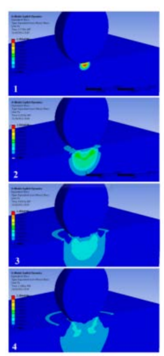


Impact contact and transient stresses

Keegan, Nash, Stack, Margaret (2012) **Modelling rain drop impact.** In: ASME Turbo Expo

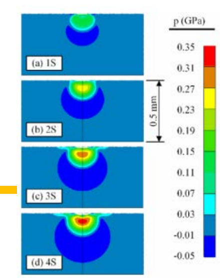
- ❑ combined Eulerian/Lagrangian approach
- ❑ Explicit Dynamics tool in ANSYS
- ❑ Stresses in composite and deformation of droplet modelled





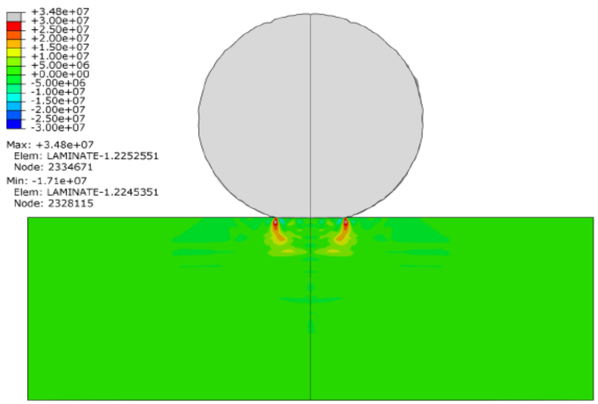
Cho, Journal of Mechanical Science and Technology 29 (9) (2015)

- ❑ Lagrangian approach
- ❑ Water hammer pressure for initial loading (first stage, the water drop behaves as a compressible body) and Bernoulli's stagnation pressure (second stage, incompressible fluid behavior)
- ❑ thermodynamic states of the water is described by the Mie-Gruneisen equation of state

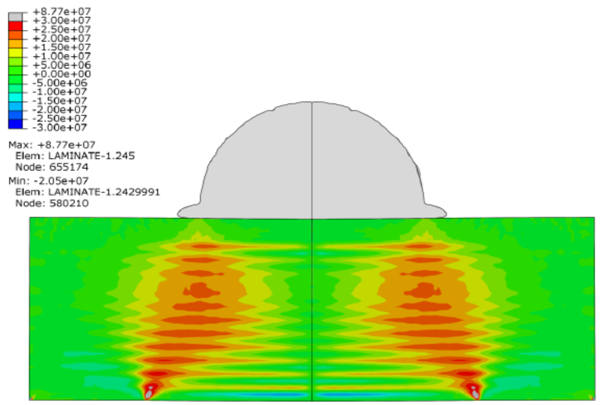


FE simulations of stress waves in LE

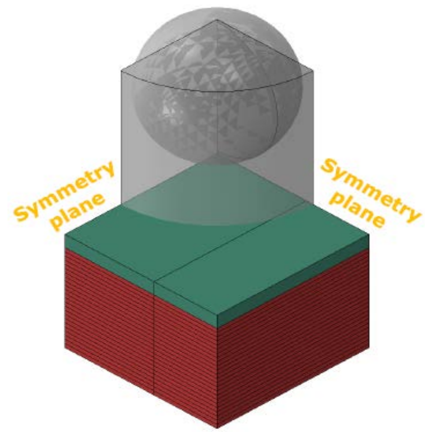
- Ball impact simulations in hyperelastic/elastic laminate. Explicit method.
- FEM/Abaqus of impact onto the coated laminate was developed to study internal transient stresses. The target laminate was modelled using the commonly used Eulerian domain. Water droplet specified in the Lagrangian domain, where the material was not fixed to the mesh but flew through it.
- At the beginning (transient stage of the impact), the highest stress is localised under the contact surface, at the quasi-static stage the highstress region forms in the depth under the surface. Similarly, rather high shear stresses form at the angle 30º to 45º under the contact surface.



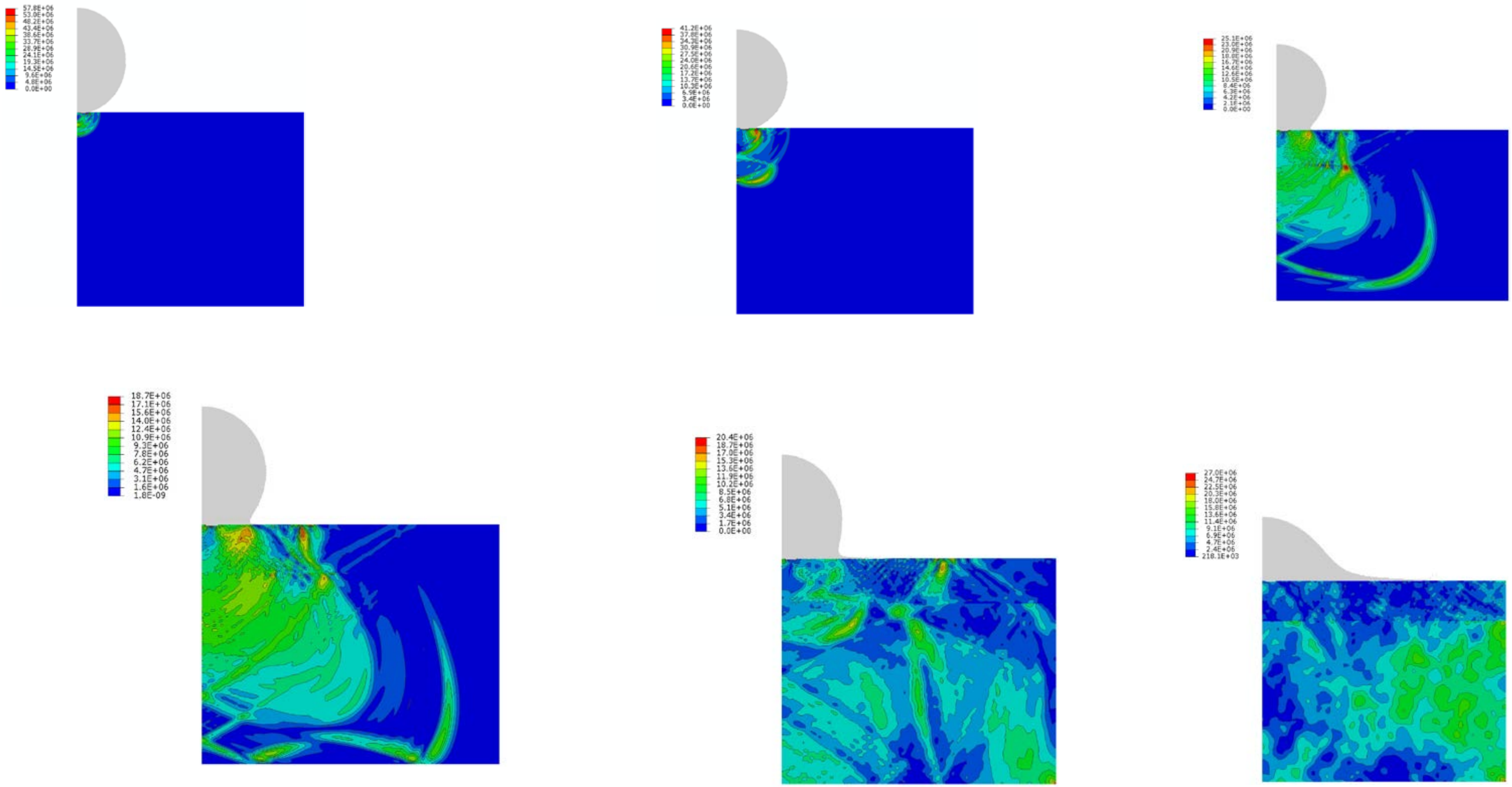
Transient stage: Shock waves



Quasi-static stage



Coupled Eulerian Lagrange simulation of raindrop / surface interaction



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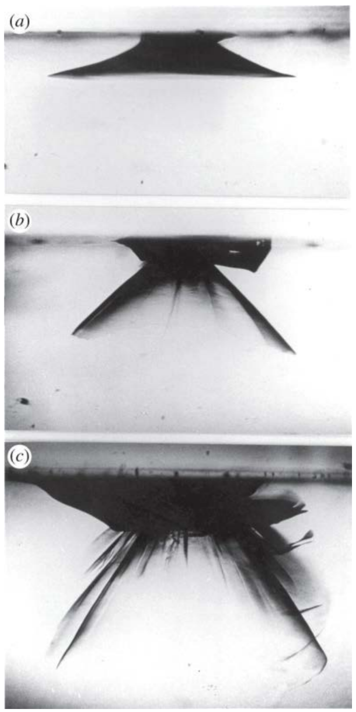
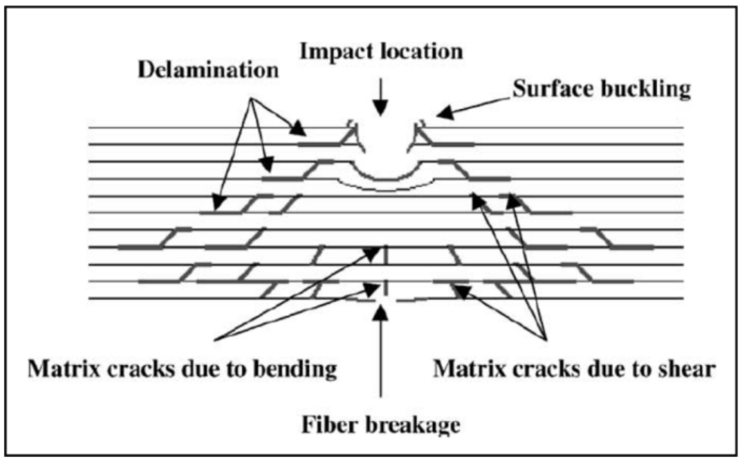
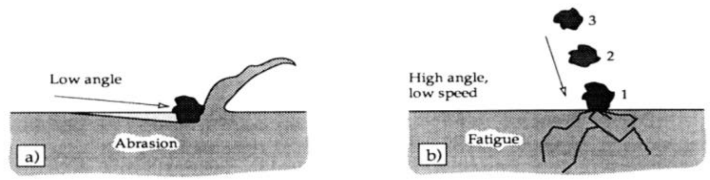
Damage

How it looks like







Espallargas N. Tribology and Surface Technology:TMM 4205. Course 2014

Damage: Simple Models

Erosion damage at arbitrary angles E(α)

$$E(\alpha) = g(\alpha)E_{90} \qquad g(\alpha) = (sin\alpha)^{n_1}(1 + H_V(1 - sin\alpha))^{n_2}$$

g(α) -impact angle dependence of normalized erosion at 90o, Hv denotes the material hardness given in GPa, and n1 and n2 are exponents

Oka YI, Mihara S, Yoshida T. 17th Int Conf Wear of Materials. 2009;267

Different erosion mechanisms areactive. (a) direct deformation (b) stress wave propagation (c) lateral outflow jetting (d) hydraulic penetration (Adler, 1979).

Damage Threshold Velocity (DVT) =lowest velocity which could cause damage in the target material.

$$V_{DT} \approx 1.41\left(\frac{K_{ic}^2 c_R}{\rho_w^2 c_w^2 d_w}\right)^{1/3}$$

VDT =DVT, K2 fracture toughness of the target material, cR the Rayleigh wave velocity on the target material, ρw the density of water, cw the compressional wave speed in water, and dw is the diameter of the water droplets, Evans AG, ET AL. Impact Damage in Brittle Materials in the Elastic-Plastic Response Regime. Rockwell 1978;361:122-136.

Nader, Eisenberg, Siemens, LEP Lifetime estimation:

$$S = \frac{4\sigma_u(b-1)}{1-2\nu} = erosion\ strength$$

ν: *Poisson's ratio*

σ_u: *Ultimate tensile strength*

b: Wöhler slope

Damage: Simple Models

Springer, Yang A model for rain erosion, 1972:

$$N_i = \frac{8.9}{d^2}\left(\frac{S}{P}\right)^{5.7} = \textit{number of impacts until failure}$$

Larger drops cause more damage per impact

d : *Diameter of droplet*

S: *Coating Strength*

P: *Water Hammer Pressure*

Eisenberg, Laustsen, **LEP Protection lifetime prediction model et al,** windeurope.org/summit2016

- ❑ non-dimensional number of impacts required until erosion begins

$$N_i^* = 7 * 10^{-6}\left(\frac{S}{P}\right)^{5.7}$$

S is the erosive strength of the material that has been determined through rain erosion testing and the P is the pressure of the water droplet impact

- ❑ rate of damage

$$\dot{D}_i = \frac{q * V_s * \beta(d)}{\frac{8.9}{d}\left(\frac{S}{P}\right)^{5.7}}$$

γ is the number of droplets per cubic meter of air, ̥0 is velocity of the material in m/s, ☐(◌)is the impingement frequency as a function of droplet diameter, and ◌ is the droplet diameter in mm.

Damage

Amirzadeh, et al J Wind Engnrng Industrial Aerodynamics 2017:

- ❑ Equivalent stress condition
- ❑ Fatigue damage at given point=superposition of damages from individual raindrops

Castorrini et al, Computers and Fluids, 2016:

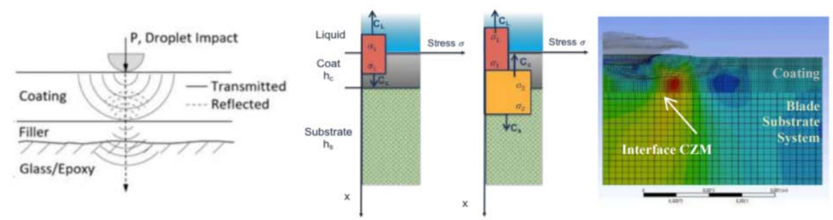
- ❑ Use DVT equation
- ❑ Assume that the damage is proportional to the impact force and the number of droplets impacting

$$\Delta D = \Delta n_w \frac{F_i}{F_D} H\left(\frac{F_i}{F_D} - 1\right),$$

Where ΔD-damage during the time step Δt, Δn_w is the number of droplets impacting during Δt, per unit surface area, and $H(\cdot)$ is the Heaviside step function, F_D, minimum impact force that causes damage to the blade, Fi=mi*vi^^2/dw - impact force of a droplet, m_w representing the mass of a water droplet, and v_i its impact velocity.

Cortés et al, Manufacturing issues which affect coating erosion performance in wind turbine blades:

- ❑ Two wave fronts – into liquid and into coating
- ❑ Interface delamination: Cohesive zone modelling of coating-substrate interface



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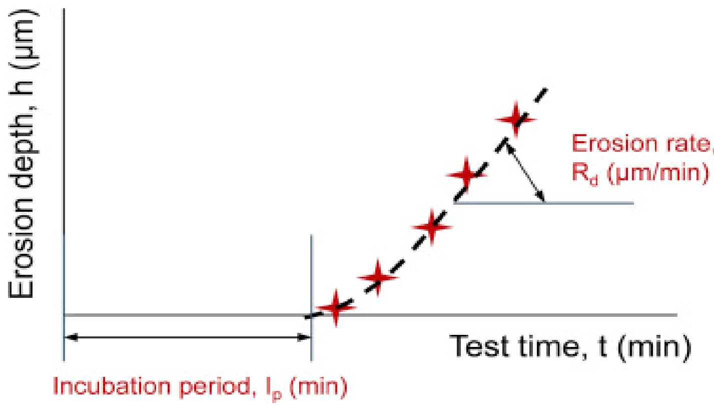
Fatigue

H.M. Slot et al, Renewable Energy 80, 2015, Surface fatigue model = removal of particles detached by fatigue arising from cyclic stress variations



Main points:

- Palmgren–Miner rule
- Damage evolution as a function of stress
- Cumulative fatigue damage equation

Amirzadeh, et al J Wind Engnrng Industrial Aerodynamics 2017:

- Miner-Palmer fatigue ruke
- Damage accumulation linear (proportional to time)
- Rainflow counting

My opinion: too simple fatigue models (typically, Miner rule) makes it senseless to use very complex rain models as input

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Solutions

Industrial solutions:

- ❑ Repair: epoxy putty and a gel coat
- ❑ ProBlade Collision Barrier by LM Wind Power
- ❑ Arkema KYNAR PVDF-acrylic hybrid emulsion coating
- ❑ 3M Polyurethane Coatings , W4600
- ❑ Polyurethane Tape (Bergolin, Duromar)
- ❑ Enercon two component polyurethane coating system
- ❑ Blaid Protective Sheet, by IER Fujikura
- ❑ Belzona 1331 and Belzona 1381, erosion resistant coatings based on immiscible blend of a tough ductile phase within a hard epoxy matrix

M. Legault, Wind blades: Progress and challenges, CW, 10/1/2013

Observation

- There is a very simple “default” analytical solution of the problem:

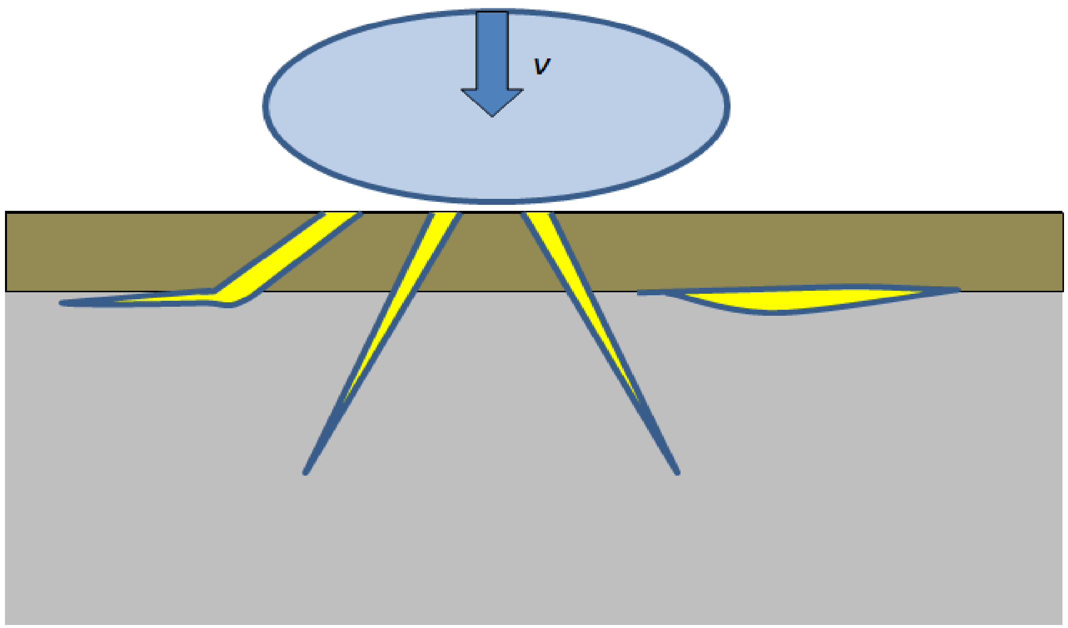
Water hummer equation for contact pressure
+
Hertzian contact problem with cone crack
+
Damage model
+
Miner rule

- Elements of this simple model chain are often embedded in complex models

Why these models are not enough

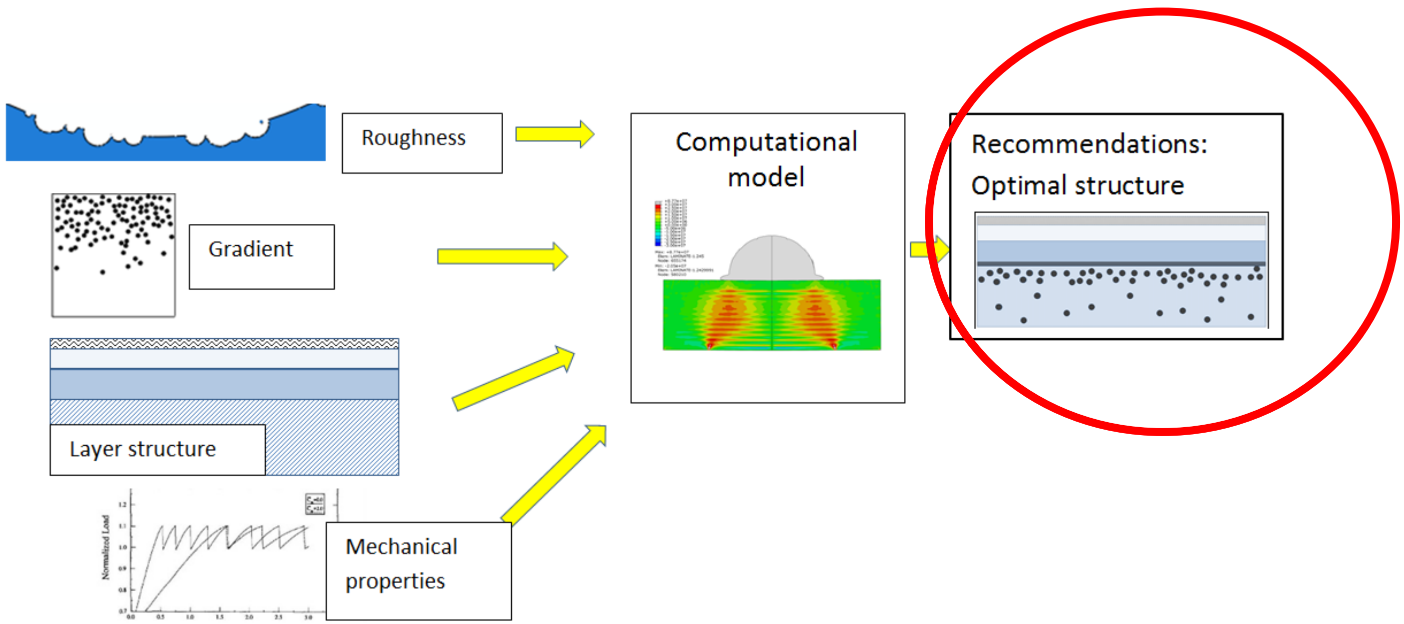
- **Oversimplified model of fatigue:**
  - Miner damage accumulation rule, instead of mechanism based models

$$\sum_{i=1}^{k} \frac{n_i}{N_i} = C$$



Next steps

- **Application to coating development:**
  - Models of LEE should lead to new coatings



Conclusions

- There exist **a number of good models**, from good analytical approximations to complex multistep “all aspects of real life” models
- Many multistep models allow very complex simulations (turbulent flow, real rain statistics), but use very rough assumptions of other steps.
    - Does it make sense to use very exact models at step 3 if we use rough model at step 7? Errors accumulate
- The expected output of these models – to design new, better coatings is still far away.
    - Many models have no output to coating development.

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