ESI CHAIR NETWORK WORKSHOP IN ADVANCED MODELLING AND SIMULATION

RECENT PROGRESSES AND FUTURE PROSPECT

VALENCIA, SPAIN,16-20 MARCH 2016

On the rain erosion modelling of in-mould coating composites of wind turbine blade applications

Enrique Cortes[1], ***Fernando Sanchez**** [*2], Manuel Ibañez[2]
Trevor M.Young[3], Anthony O'Carroll[3], Francisco Chinesta[5]
[1] Aerox Advanced Polymers, [2] Universidad Cardenal Herrera-CEU,
[3] University of Limerick, [5] Ecole Centrale Nantes

The very begining, problem statement: Rain impact modelling

After a while and deep scientific discussions… a first real time solution

Damage erosion? Let's Get Crackin'…

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Content Outlook:

1. Introduction. Wind turbine blade technology trends
2. Erosion issues associated with the leading edge of wind turbine blades
3. Blade surface coating. Material and Manufacturing approach in product performance.
4. Rain Erosion Testing. Evaluation and quantification of erosion damage in surface coatings.
5. On the modelling of rain drop impact in wind turbine blades
   - Liquid impact phenomena
   - Rain droplet impact performance of in-mould coatings
   - Rain droplet impact performance of flexible coatings
   - Rain droplet impact induced erosion on a composite substrate
6. Discussion. Further Work

1. Introduction. **Wind turbine blade technology trends**

2. Erosion issues associated with the leading edge of wind turbine blades

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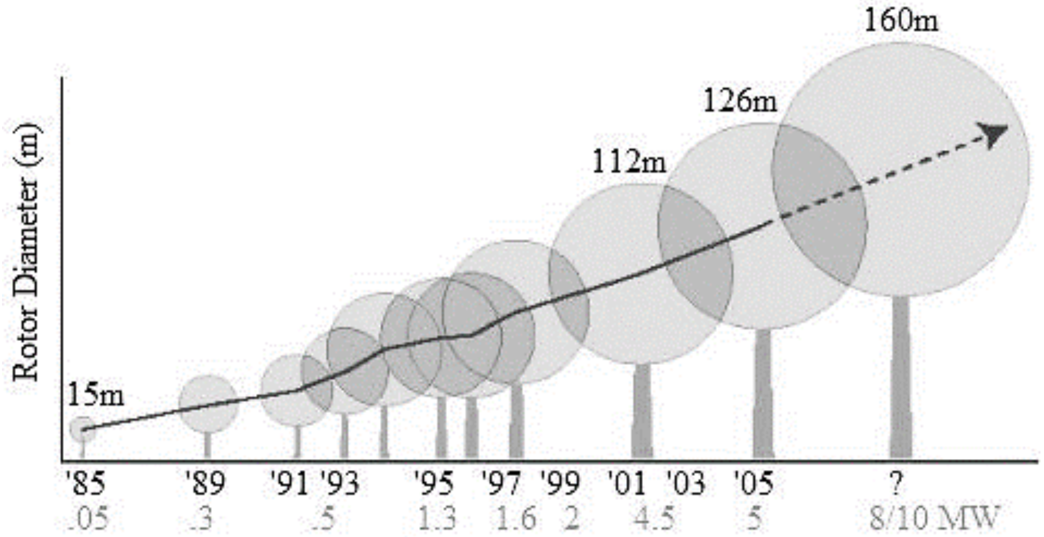
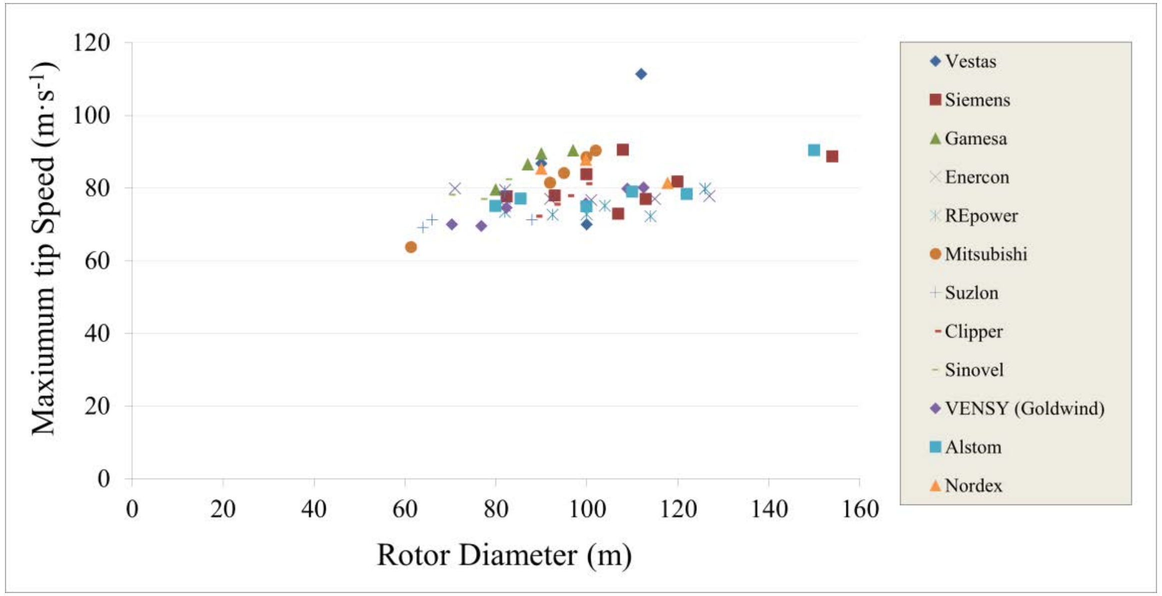
- The **renewable energy sector** has to be severely expanded in order to supply **20% of electricity from renewable sources to 2020**. The **EU wind energy capacity should be extended by two orders of magnitude**. To achieve this goal, it is required the installation of very large wind turbines (10MW and higher) standing in wind farms of several hundred MW, in deeper offshore waters (not only on-shore). In this case, wind blades of length of 80 m and probably up to 110m in the near future, with **increased tip speeds from 80 m/s to over 100 m/s** will be operating....


Rotor Diameter (m)
15m
112m
126m
160m
'85
'89
'91 '93
'95
'97 '99
'01 '03
'05
?
.05
.3
.5
1.3
1.6 2
4.5
5
8/10 MW


Maxiumum tip Speed (m·s⁻¹)
Rotor Diameter (m)
Vestas
Siemens
Gamesa
Enercon
REpower
Mitsubishi
Suzlon
Clipper
Sinovel
VENSY (Goldwind)
Alstom
Nordex


A380
79.8 meter
154 meter
SWT-6.0-154

2. Erosion issues **associated with the** leading edge **of wind turbine blades**

3. Blade surface coating. Material and Manufacturing approach in product performance.

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- An average **tip speed** around and in excess of 80 m/s are now common in many wind turbine design. However the tip speed will also be heavily dependent on turbine operational strategy and control.
- A typical wind **turbine may be expected to operate continuously for approximately 15 years** over its service life. During these years, the materials of the blade are exposed to a varied environmental conditions and fatigue load. The **erosion of wind turbine blade leading edges has seen a dramatic increase** in both the frequency of occurrence, and the rate at which leading edges are eroding. Erosion has been seen to be occurring **within 2 years in off-shore blades** and in 5 year warranty period in onshore applications.




- The **costs associated with erosion in terms of loss of power performance and repair** and downtime costs have a large impact on the LCoE (Levelized Cost of Energy) for wind. **An erosion solution needs to be developed**.

2. Erosion issues **associated with the** leading edge **of wind turbine blades**

3. Blade surface coating. Material and Manufacturing approach in product performance.

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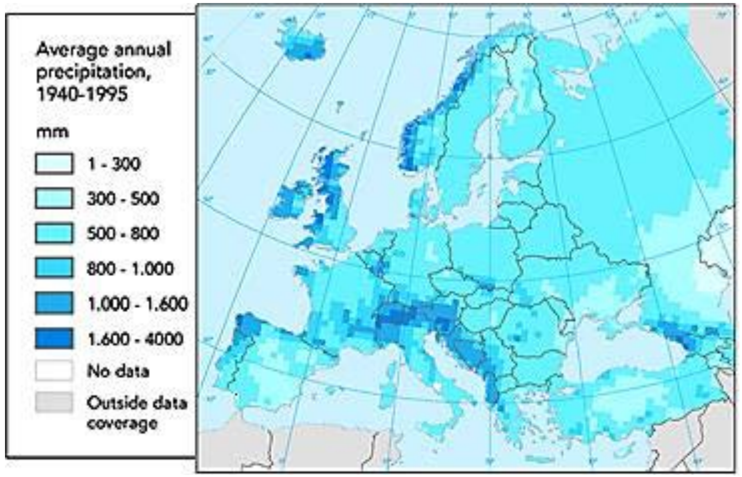
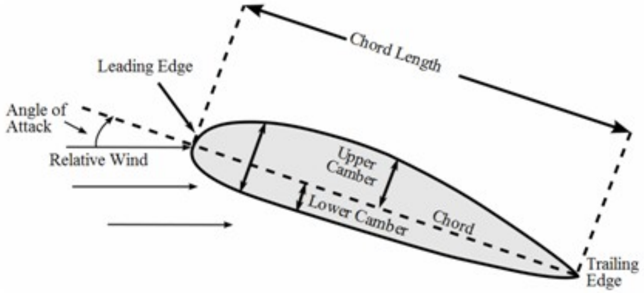
- When considering the **impact of rain**, hailstones and other particulates on the leading edge, the **tip speed is a key issue** and also the **environmental conditions** (average precipitation, raindrop size, UV protection, moisture, …)





3. **Blade surface coating.** Material and Manufacturing approach **in product performance.**

4. Rain Erosion Testing. Evaluation and quantification of erosion damage in surface coatings

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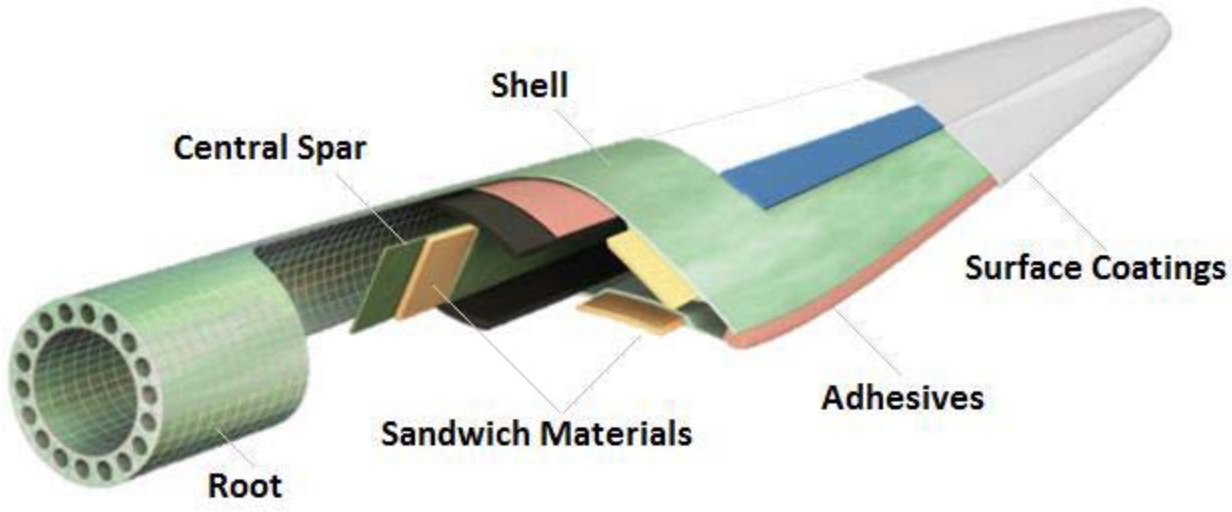
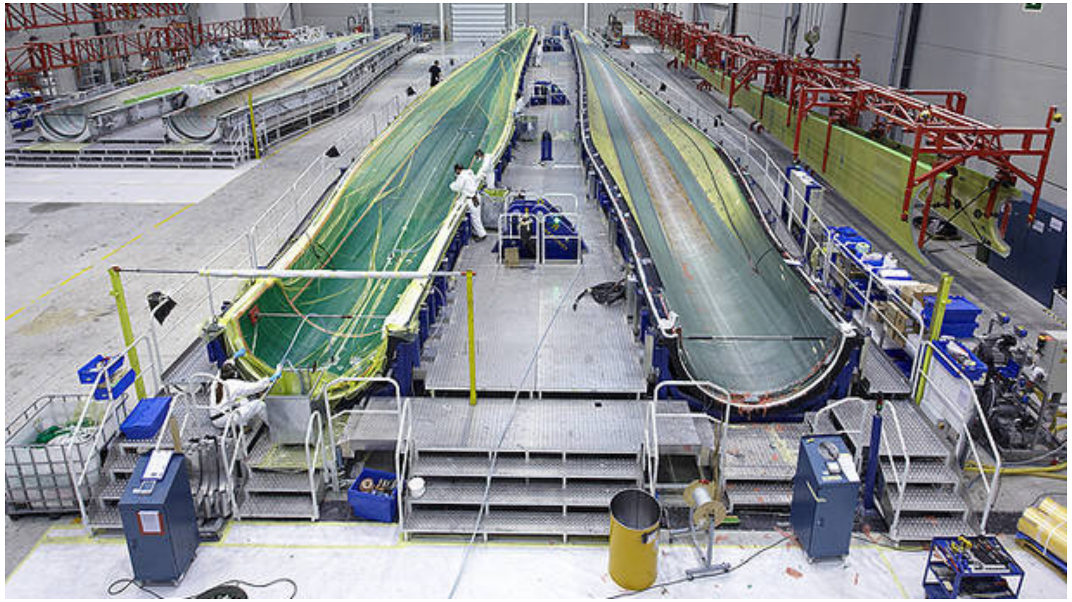
- ❑ The large and ever-growing scale of modern blades has resulted in the widespread implementation of fiber reinforced thermosetting plastic **composite technologies due to high specific strength and stiffness properties and fatigue** performance.
- ❑ Composites **perform poorly under transverse impact** (i.e perpendicular to the reinforcement direction) and being sensitive to environmental **factors such as heat, moisture, salinity, UV**.Blade manufacturers **employ surface coatings** to protect the composite structure.
- ❑ Two most common technologies used are **In-mould coating** (a moulded layer of a similar material of the matrix material used epoxy/polyester) or a **post-Mould application** (applied after moulding through painting or spraying with different material choice)





3. Blade surface coating. Material and Manufacturing approach in product performance.

4. Rain Erosion Testing. Evaluation and quantification of erosion damage in surface coatings

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- **The in-mould coating plays a key role in the product performance**. It is often required an optimum interphase adhesion and surface finish for mechanical performance or durability reasons.
- **Objective: Determine the effect of surface coating on the characterization of the process dynamical behavior** during mold filling in Liquid Resin Infusion. **Processing window requirements**

Coat	$\Delta H_{exothermic\ peak}$ (J/g)	α (%)
Total reaction enthalpy	329,296	0
Coat 2. 40' a 45 ºC	134,12	59,3
Coat 1. 24 horas a 25ºC	5,891	89,7

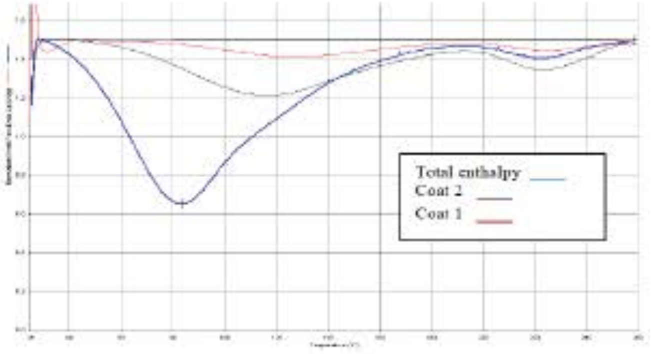

Figure 1: Degree of conversion (α) measured with DSC in the two experimental samples

3. Blade surface coating. Material and Manufacturing approach in product performance.

4. Rain Erosion Testing. Evaluation and quantification of erosion damage in surface coatings

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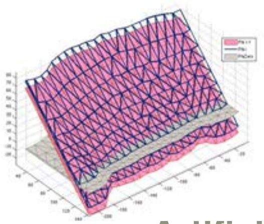
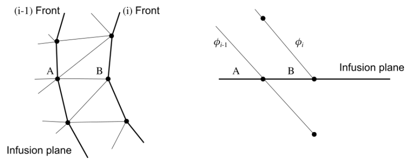
- ❑ **Material Characterization during filling.** A novel mixed numerical/experimental technique based on artificial vision for estimating the induced effect of the surface coating curing in the laminate impregnation and the flow front advance during filling

Darcy's Law:
$$\underline{v} = -\frac{\underline{\underline{K}}}{\varphi \cdot \mu}\nabla P \quad \Rightarrow \quad \underline{v} = -\underline{\underline{M}}\cdot\nabla P$$

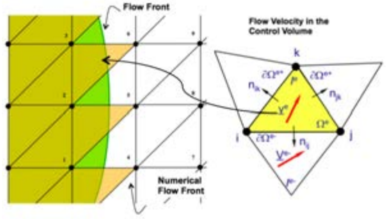




Artificial Vision+LevelSet Velocity computation

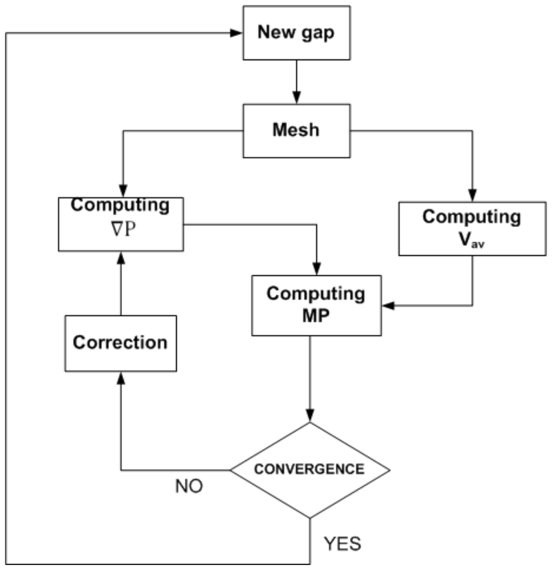
Assuming Isotropy
$$M = \frac{\|v\|}{\|\nabla P\|}$$

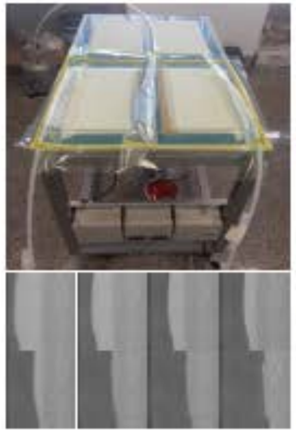
FEM Simulation of Velocity field

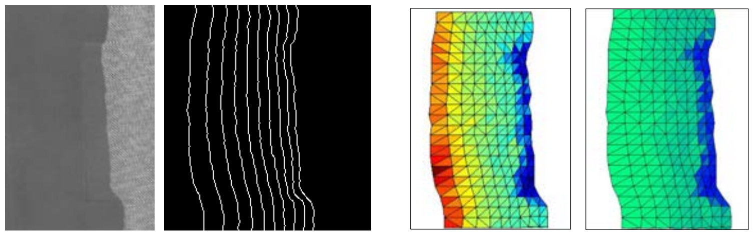


$$M^{est} = \frac{\|V_{AV}\|}{\|\nabla P(M^{est})\|}$$

$$M^{est}_{K+1} = \frac{\|V_{AV}\|}{\|\nabla P(M^{est}_{K})\|}$$







3. **Blade surface coating.** Material and Manufacturing approach **in product performance.**

4. Rain Erosion Testing. Evaluation and quantification of erosion damage in surface coatings

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- **<u>Objective:</u> Determine mechanical characterization** of coating-laminate interphase depending on processing (curing) conditions

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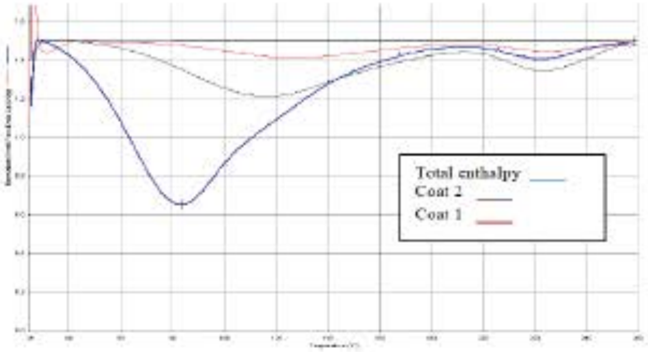

Figure 1: Degree of conversion (α) measured with DSC in the two experimental samples

Figure 3: Pull-off strength testing of composite laminates used for coating adhesi show the failure in the laminate

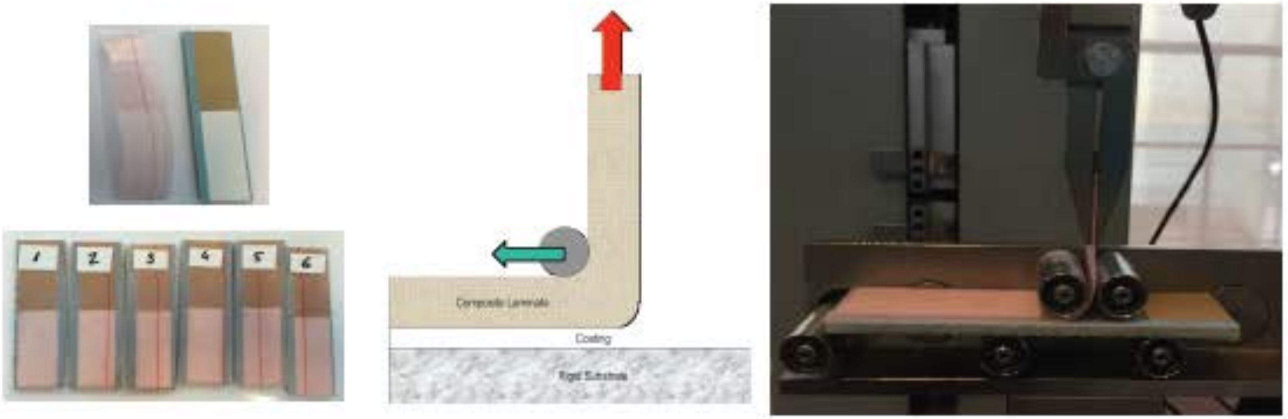

Figure 4: Developed peeling testing for interphase coating-laminate adhesion response quantification

3. **Blade surface coating.** Material and Manufacturing approach **in product performance.**

4. Rain Erosion Testing. Evaluation and quantification of erosion damage in surface coatings

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- ❑ <u>**Objective:**</u> **Determine mechanical characterization** of coat-laminate interphase depending on processing (curing) conditions
- ❑ **Further work:** polymer characterization through the thickness depending on differential adhesion during curing

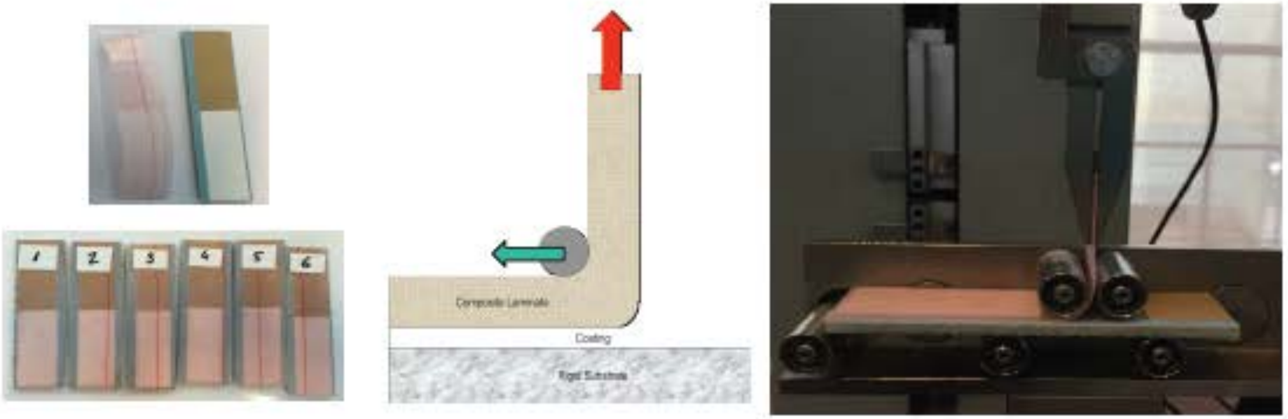

Figure 4: Developed peeling testing for interphase coating-laminate adhesion response quantification

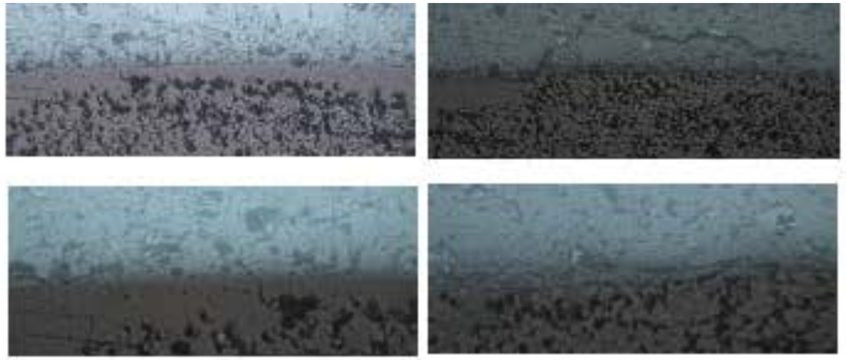

Figure 5 Microscopy samples for interphase chemical adhesion. Coat 1 (cured) left, Coat 2 (tack) right.
Zooming X100 Upper images, x200 lower images

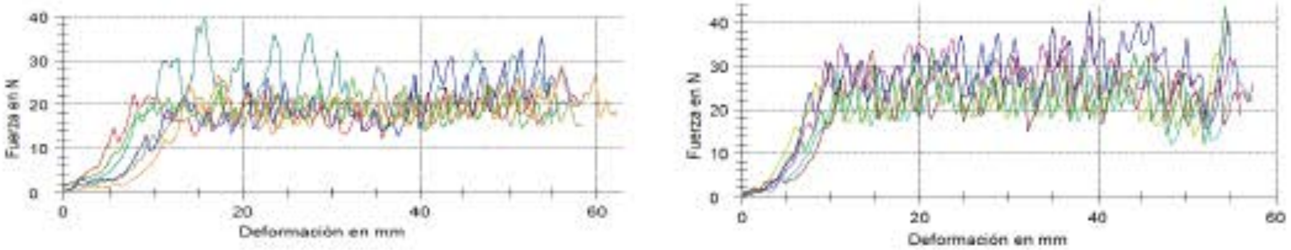

Figure 6 Force of failure for interphase adhesion testing. Coat 1 (cured) left, Coat 2 (tack) right

4. Rain Erosion Testing. **Evaluation and quantification of erosion damage in surface coatings.**

5. On the modelling of rain drop impact in wind turbine blades

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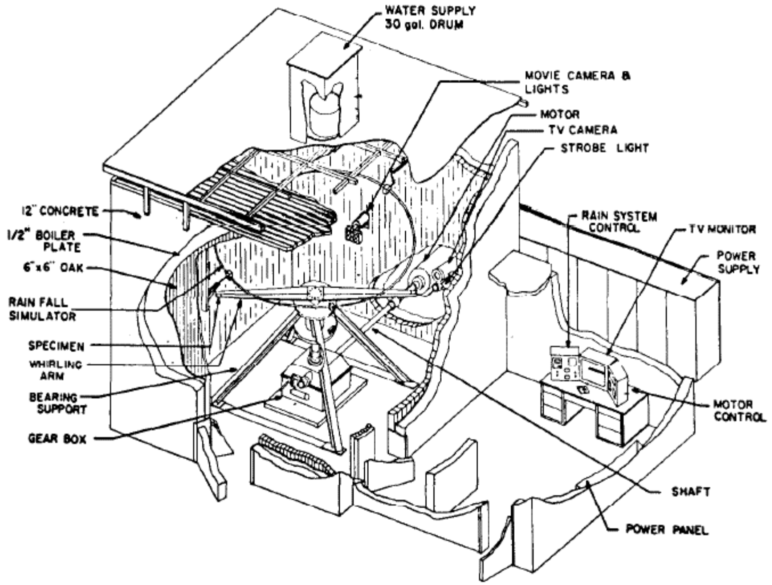
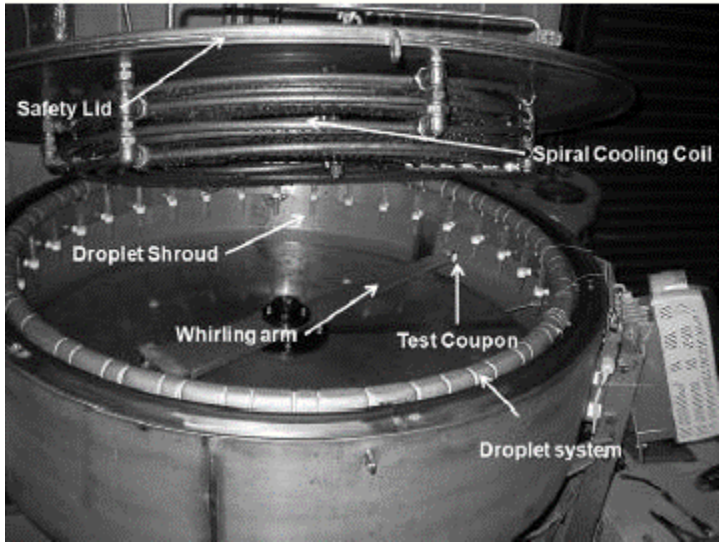
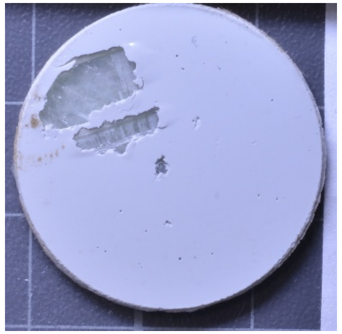
- There is no quantifiable measure to determine the level of erosion on a wind turbine blade in operation or during coating evaluation testing. In the **absence of suitable rain erosion testing standards within the wind sector**, the industry has instead looked to the aerospace sector. It is typically performed using the helicopter type rain erosion test to **ASTM G73-10 Liquid impingement Erosion Using Rotating Apparatus'.** Mass loss has proved inefficient, as it doesn't distinguish between erosion depth and area losses. There is no method currently to correlate between testing and in-service erosion**. It has been adopted as 'best fit' for rain erosion testing** and **can prove helpful in rating rain erosion resistance of materials** and characterizing the induced damage.







4. Rain Erosion Testing. **Evaluation and quantification of erosion damage in surface coatings.**

5. On the modelling of rain drop impact in wind turbine blades

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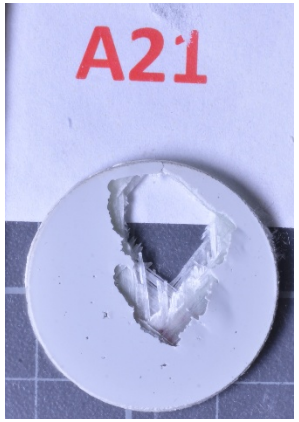
- **Objective: Determine Interphase coating-laminate relation with mass loss in erosion. Determine elastic material properties relation with erosion.**
- Rain erosion testing has been conducted in a whirling arm rain **erosion facility (WARER, University of Limerick),** which generates a nominal rainfall rate of 25.4 mm/h and a droplet size of 2 mm. The test procedure, which is based on ASTM G73-10, evaluated the candidate coatings at impact speeds up 129 m/s. The evolution of damage has been monitored through mass loss and visual examination of the specimen surfaces



Samples for testing at WARER

- Laminate substrate: 27x1,4 mm (2 layer biaxial epoxy-GF, x700 μm thickness).
- Gel Coat layer 300μm. In white or Transparent
- Overall dimensions. 27x1.7 mm

The test procedure is defined to evaluate the candidate coatings:

1. -Coat Epoxy GC E 135 (**Cured, Rigid**). **SAMPLES C1, C2, C3, C4, C5**
2. -Coat Epoxy GC E 135 (**Semicured, Rigid,** tacky surface). **SAMPLES S1, S2, S3, S4, S5**
3. -Coat LEP (**Elastic/Plastic**, transparent) **SAMPLES B1, B2, B3, B4, B5**
4. -LEP commercial product (**Elastic, with postCured**). **SAMPLES A11, A12, A13, A14, A15**
5. -LEP commercial product (**Elastic without postCured**). **SAMPLES A21, A22, A23, A24, A25**

4. Rain Erosion Testing. **Evaluation and quantification of erosion damage in surface coatings.**

5. On the modelling of rain drop impact in wind turbine blades

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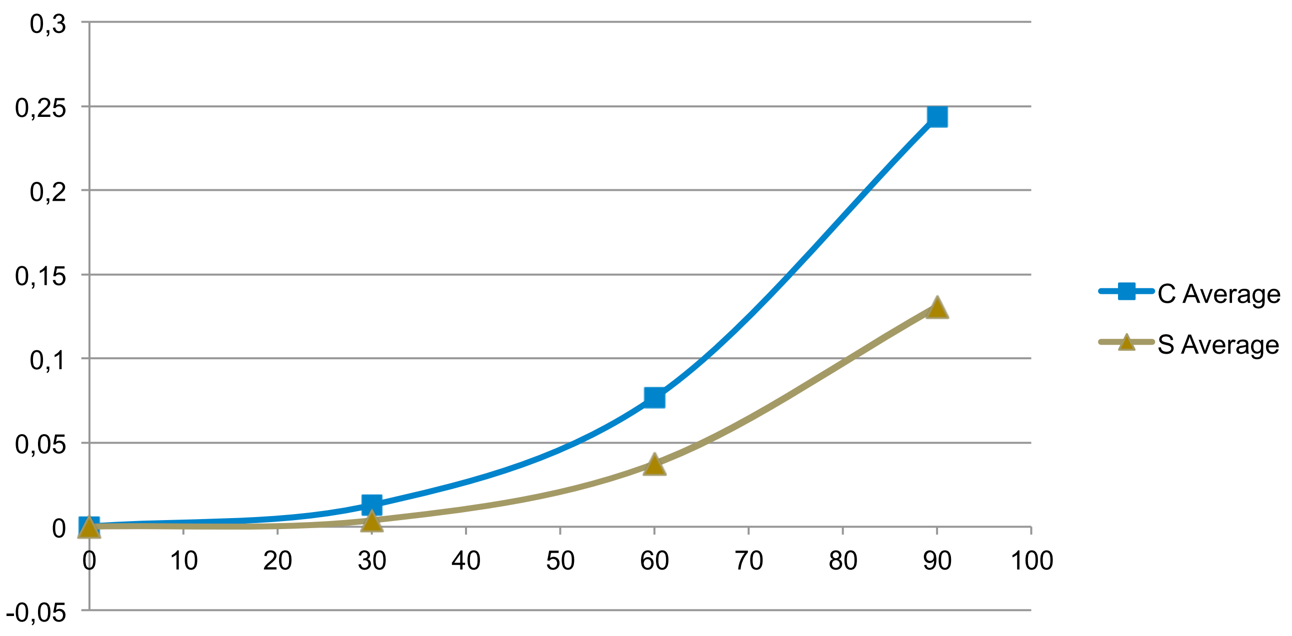
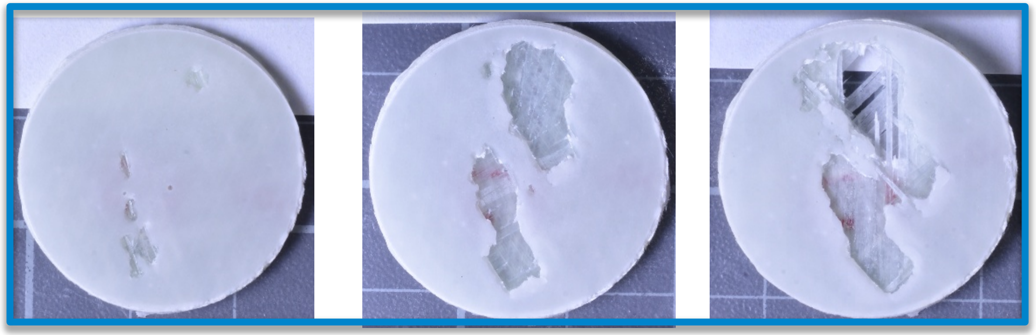
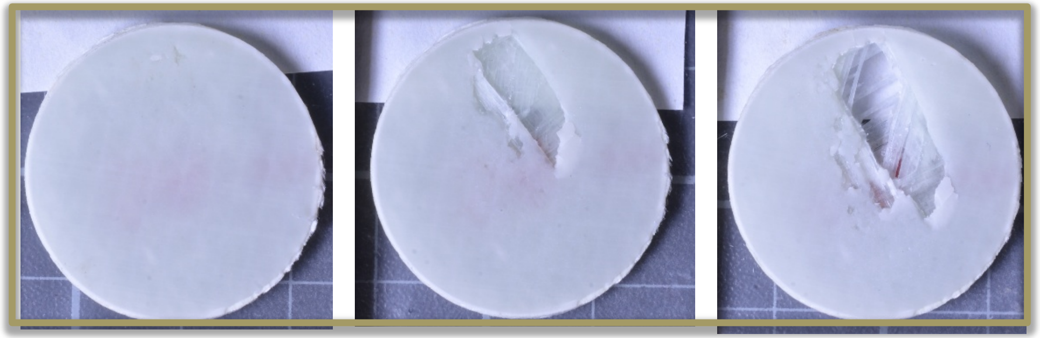
Comparison of coatings ***Mass Loss/Time (min)***







4. Rain Erosion Testing. **Evaluation and quantification of erosion damage in surface coatings.**

5. On the modelling of rain drop impact in wind turbine blades

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- **Objective: Determine elastic material properties relation with erosion.**

The test procedure is defined to evaluate the candidate coatings:

1. -Coat Epoxy GC E 135 (**Cured, Rigid**). **SAMPLES C1, C2, C3, C4, C5**
2. -Coat Epoxy GC E 135 (**Semicured, Rigid,** tacky surface). **SAMPLES S1, S2, S3, S4, S5**
3. -Coat LEP (**Elastic/Plastic**, transparent) **SAMPLES B1, B2, B3, B4, B5**
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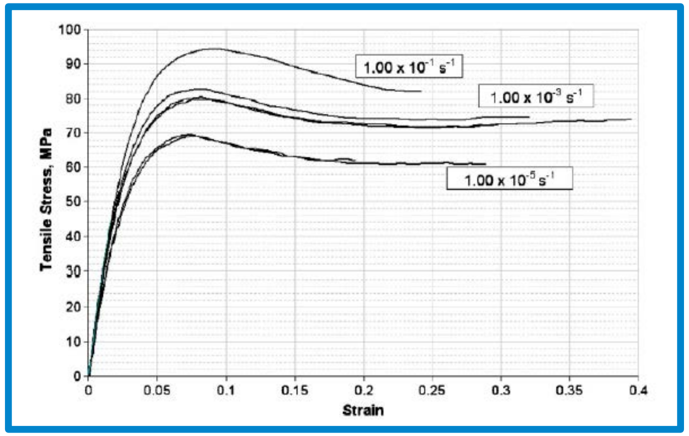
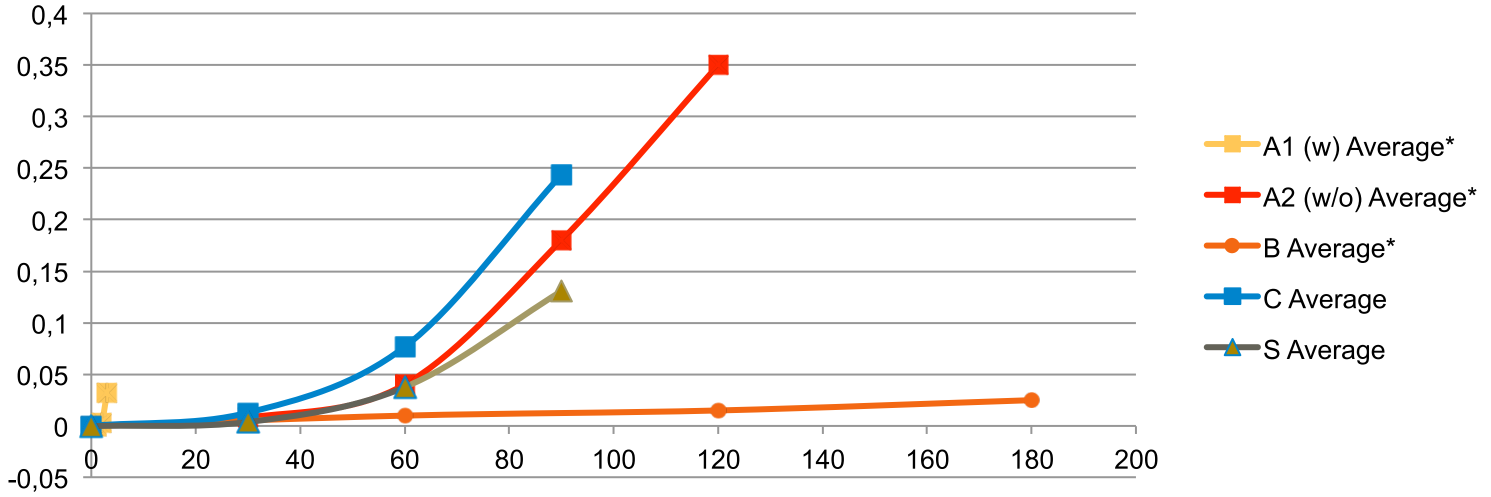
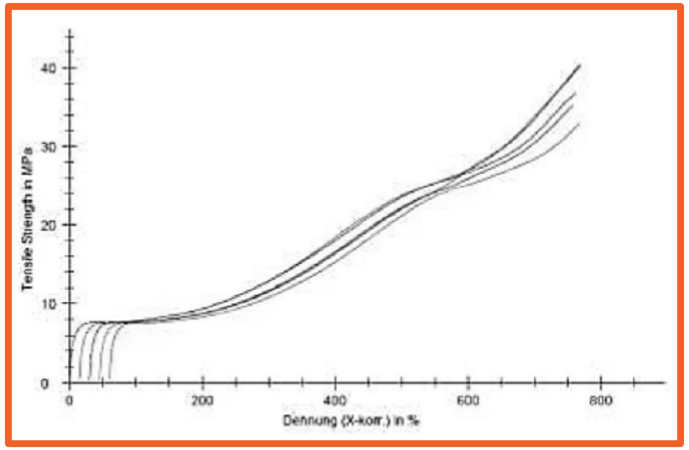


Comparison of coatings ***Mass Loss/Time (min)***

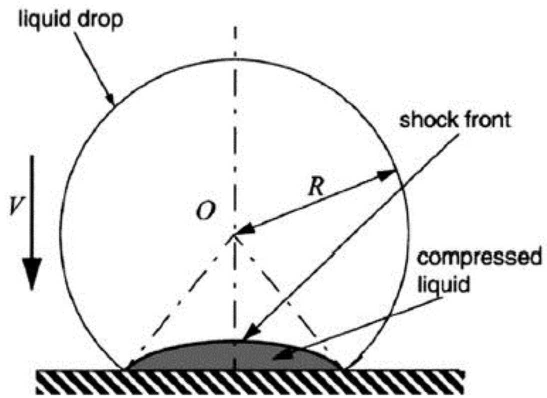


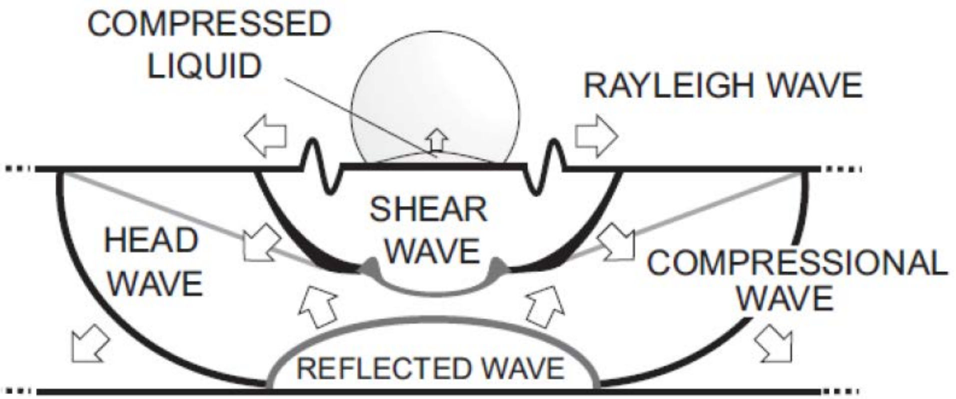


5. On the modelling of rain drop impact in wind turbine blades

- **Liquid impact phenomena**

- <u>**Objectives:**</u> **Understanding the physical of failure** of the Leading Edge Erosion on turbine blades. Develop/state appropriate <u>**numerical models**</u> and generate a tool to effective leading edge material design. Develop/state a rain erosion prediction model. **Determine <u>coating factors</u> which affect erosion performance**: will be performed on the various effects of the **mechanical characterization**, **coating application method and curing**, **adhesion to substrate, coating film thickness** and **coating defects** on the erosion degradation process using both laboratory techniques and rain erosion tests to develop optimization guidelines for coatings.
- The adhesion and erosion is affected by the **shock wave caused by the collapsing water droplet on impact**, and the **elastic and viscoelastic responses** of the **blade structure**, **surface preparation** and **coating application** and the **interactions** between them. The <u>**understanding of these interactions**</u> through the numerical modelling is limited but thought to be of key significance.





5. **On the modelling of rain drop impact in wind turbine blades**
   - Liquid impact phenomena
   - **Rain droplet impact performance of in-mould coatings**

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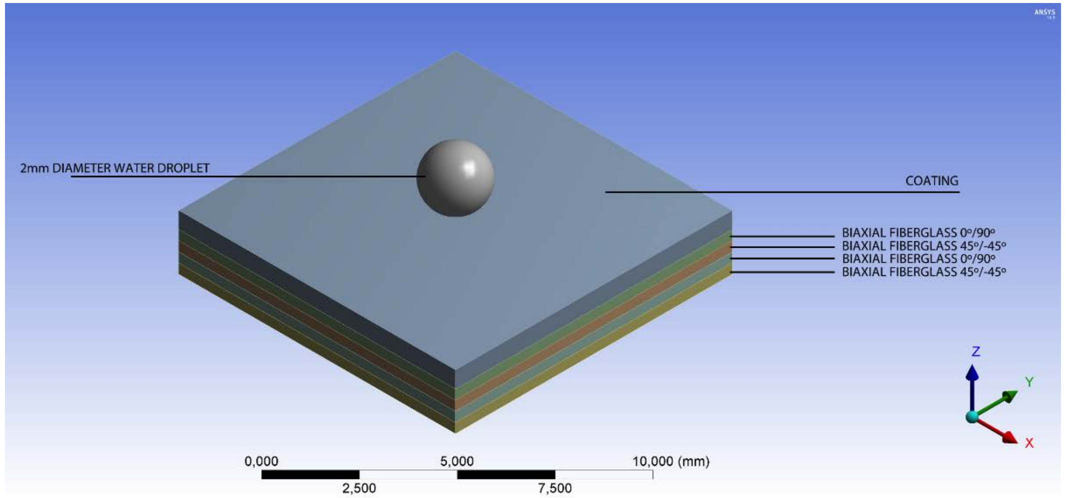
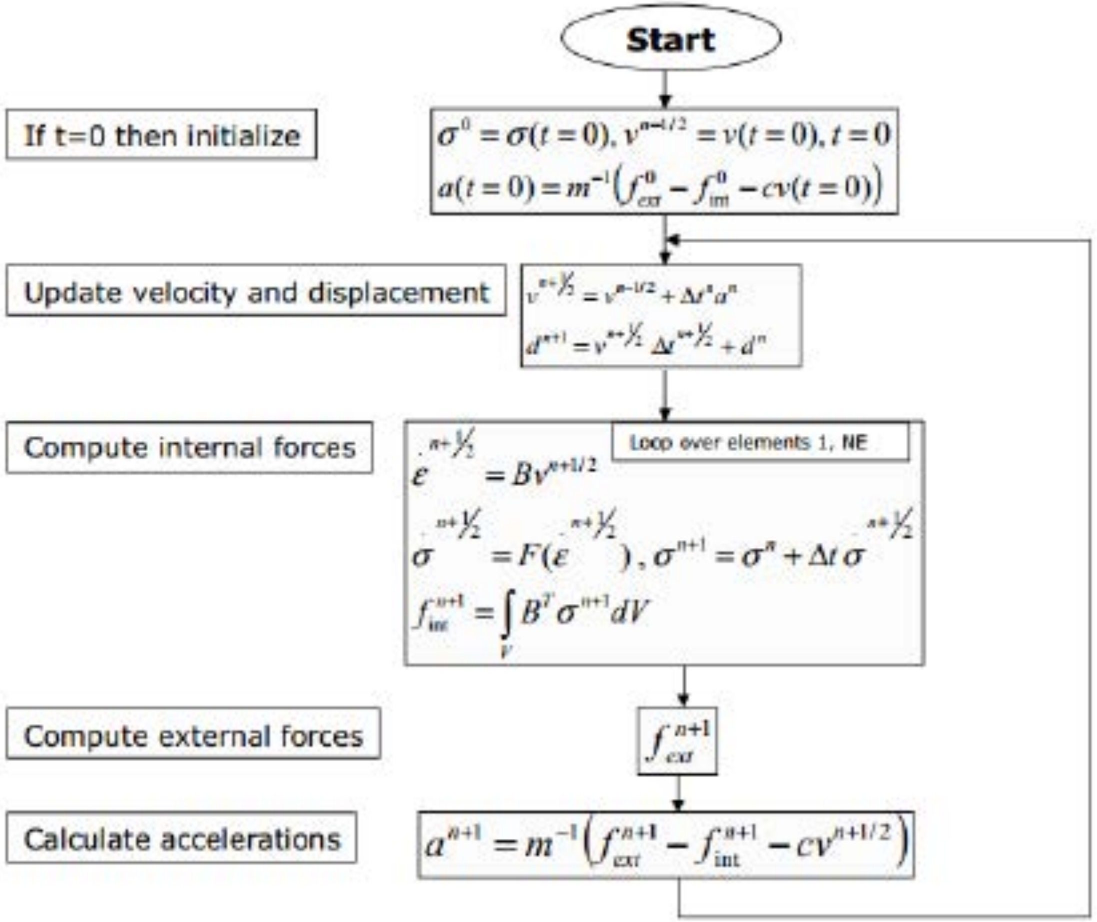
❑ **Numerical Modelling.** Commercial software tools: ANSYS Autodyn and ANSYS LS-Dyna





5. On the modelling of rain drop impact in wind turbine blades

- **Rain droplet impact performance of in-mould coatings**

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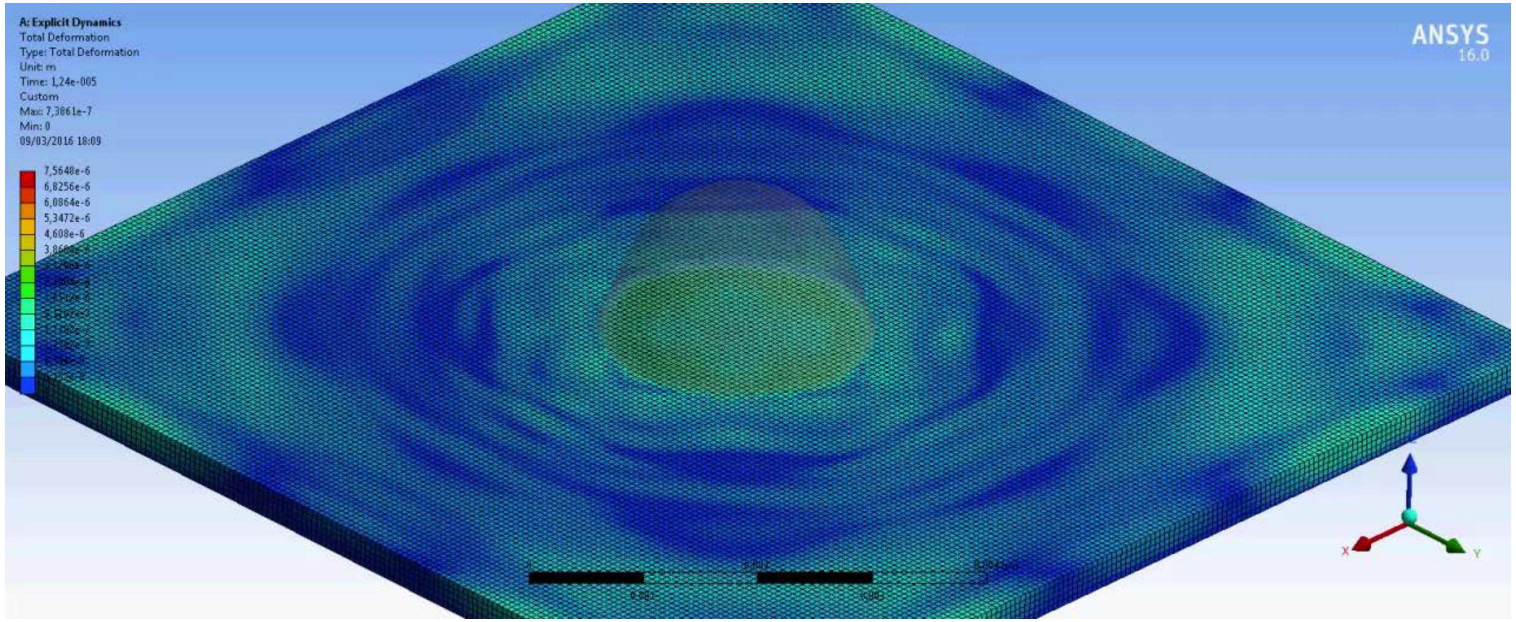
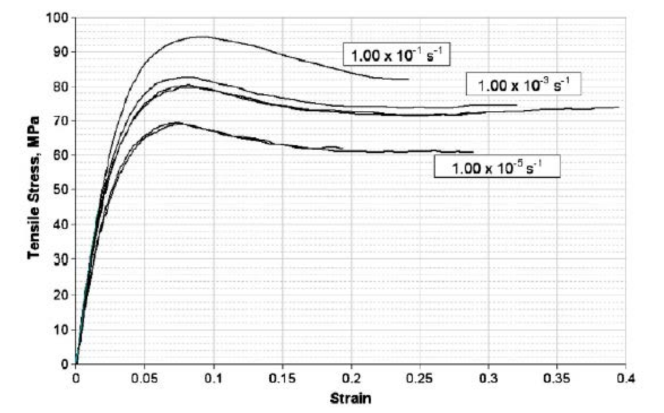
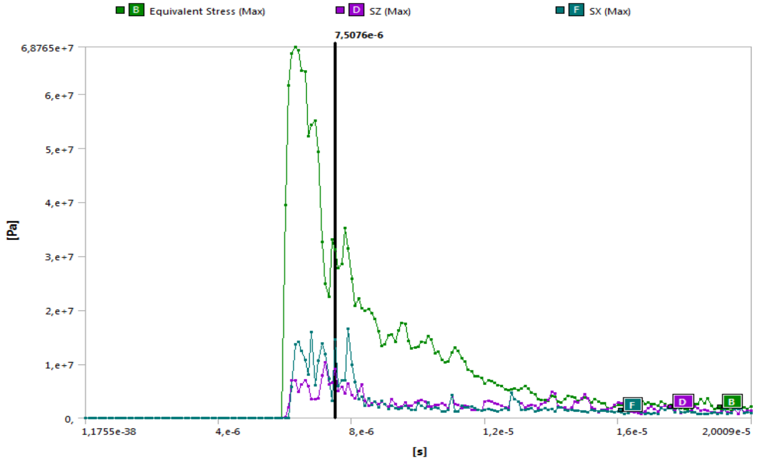
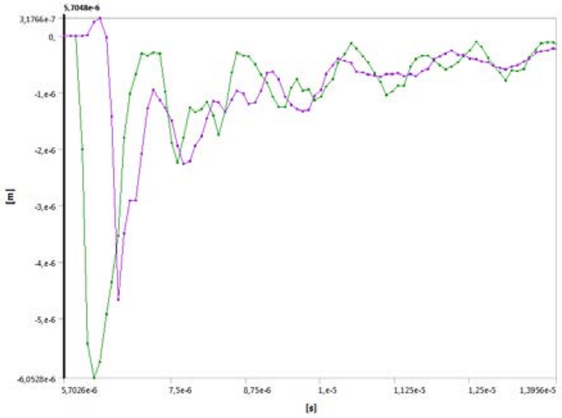


- **<u>Numerical Modelling.</u>**
  Stress V_M
- Coat Epoxy GC E135
  Cured. Rigid





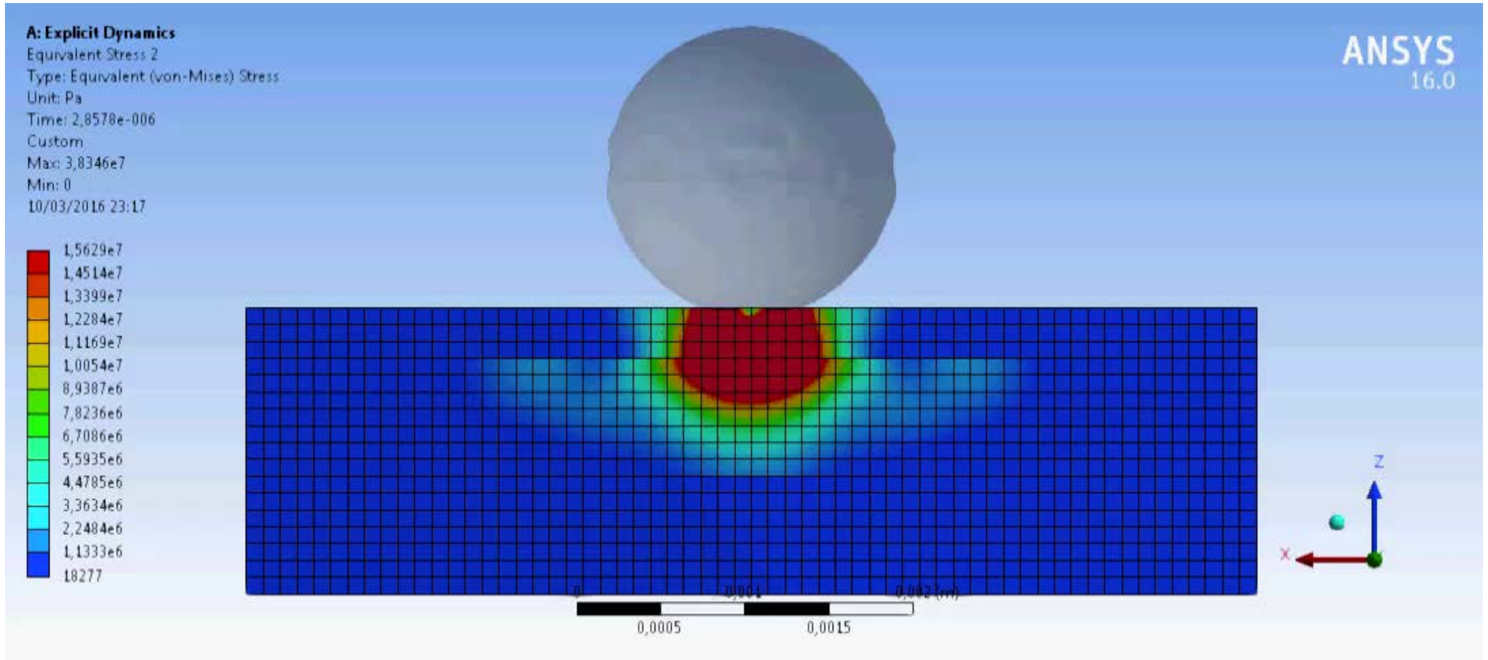


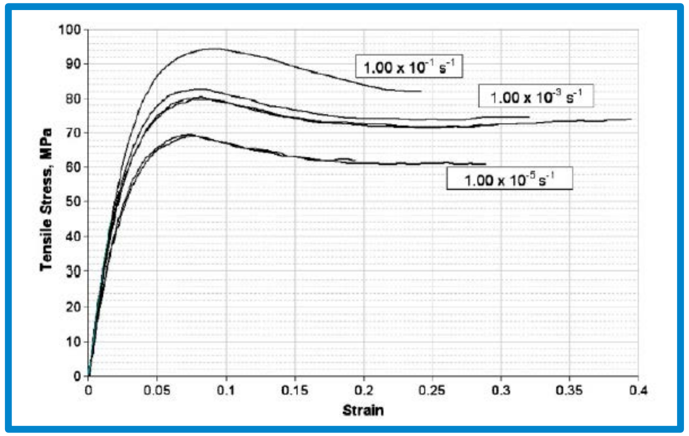
5. On the modelling of rain drop impact in wind turbine blades

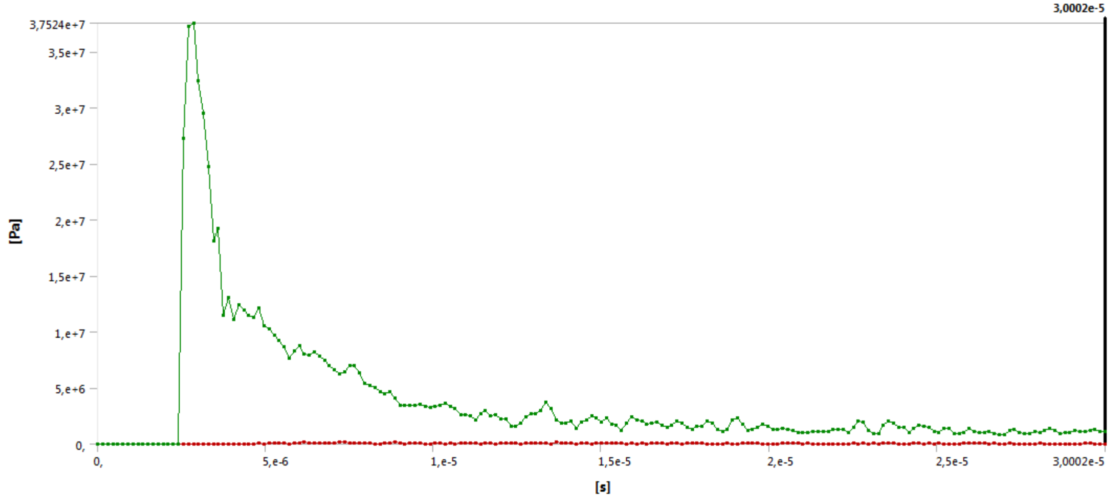
- Rain droplet impact performance of in-mould coatings + Composite Substrate …

❑ **Numerical Modelling.**
Stress V_M

❑ Coat Epoxy GC E135
Cured. Rigid





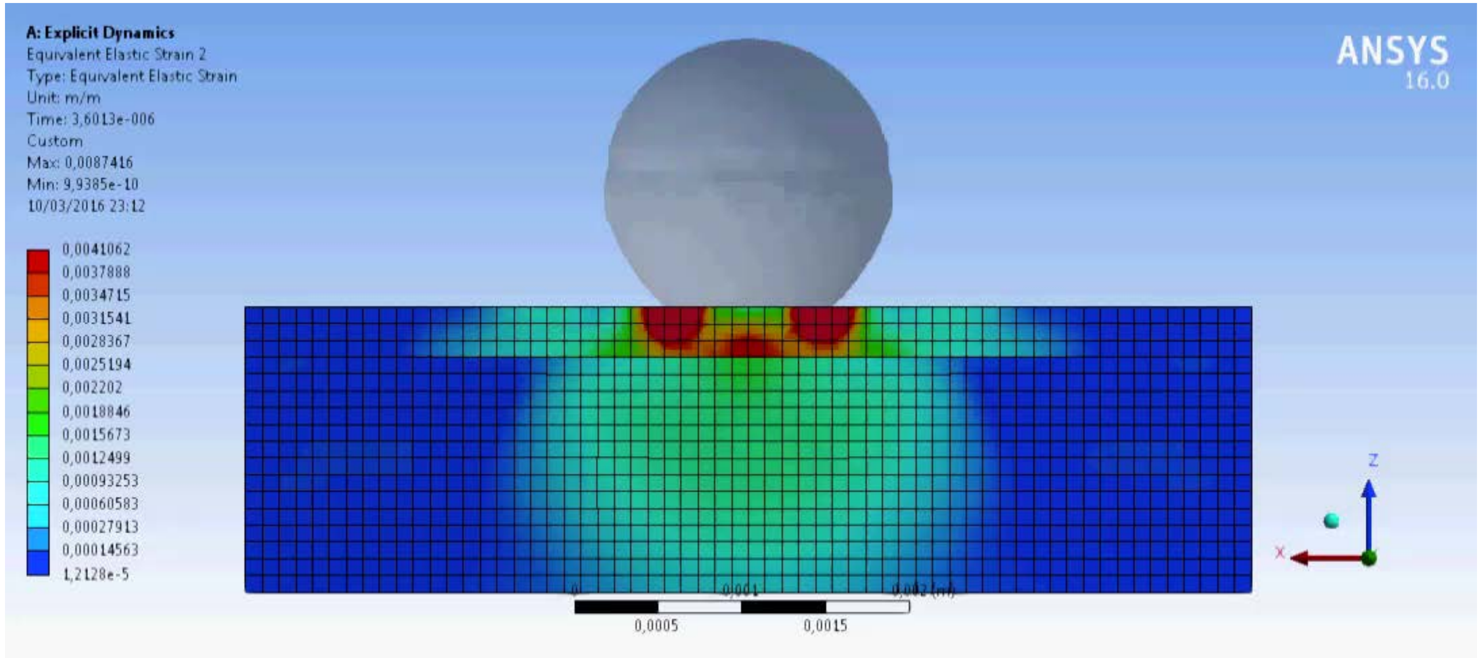


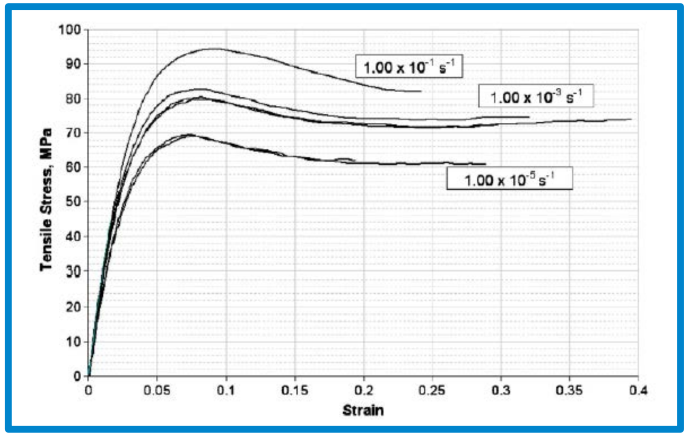
5. On the modelling of rain drop impact in wind turbine blades

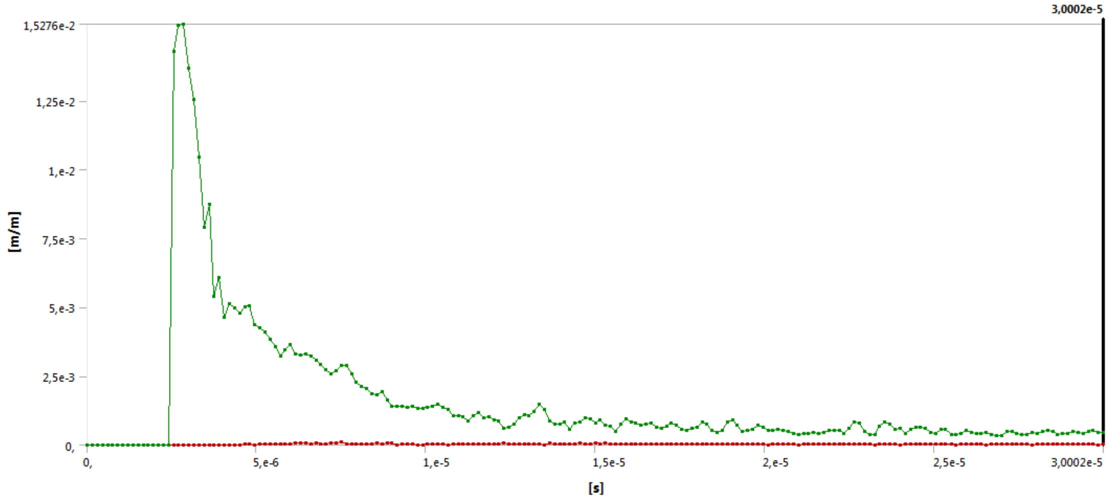
- Rain droplet impact performance of in-mould coatings + Composite Substrate …

❑ **Numerical Modelling.**
Elastic Strain

❑ Coat Epoxy GC E135
Cured. Rigid





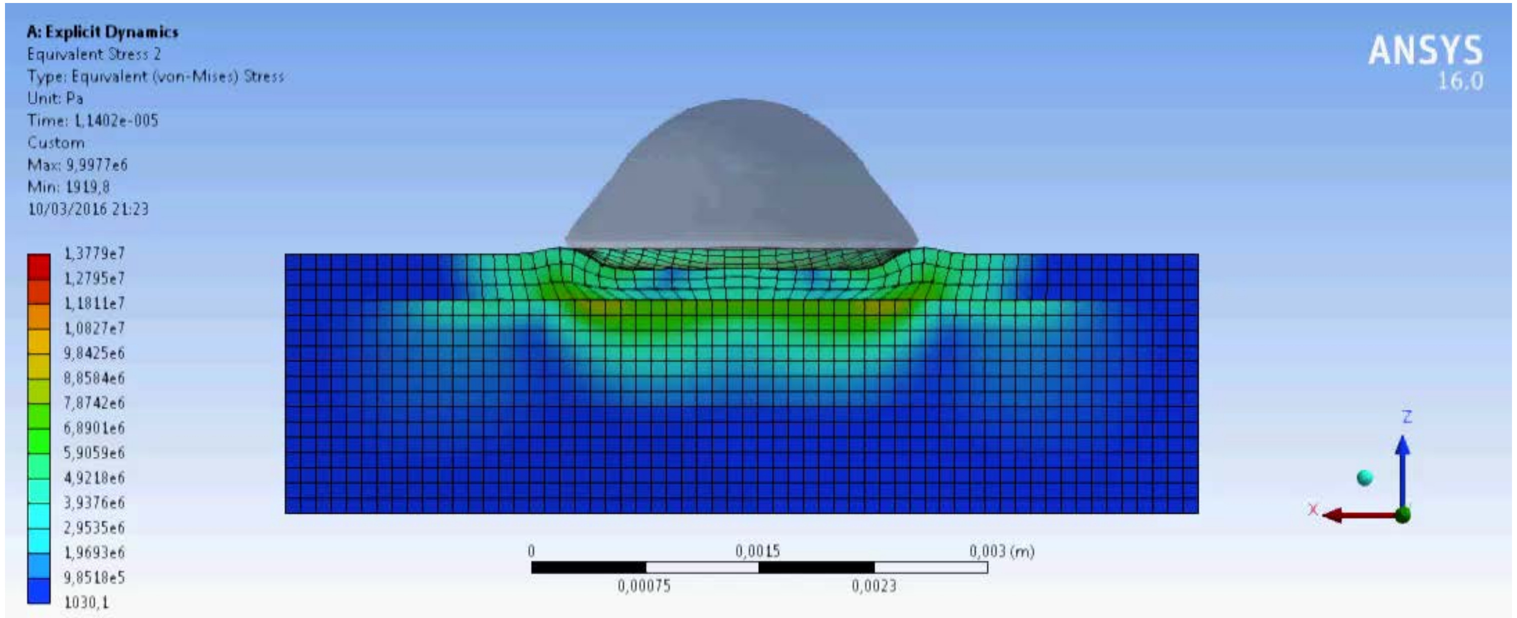


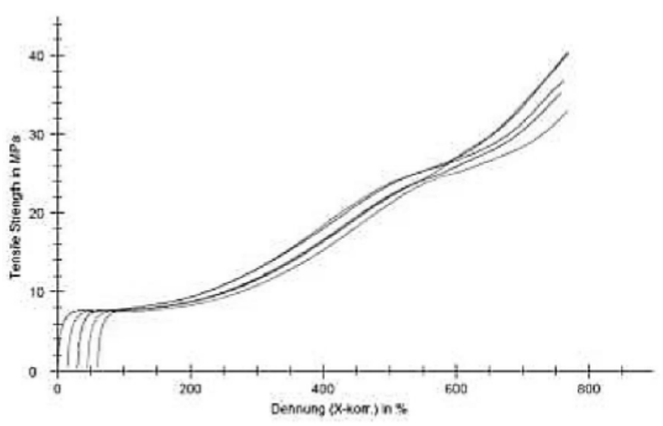
5. On the modelling of rain drop impact in wind turbine blades

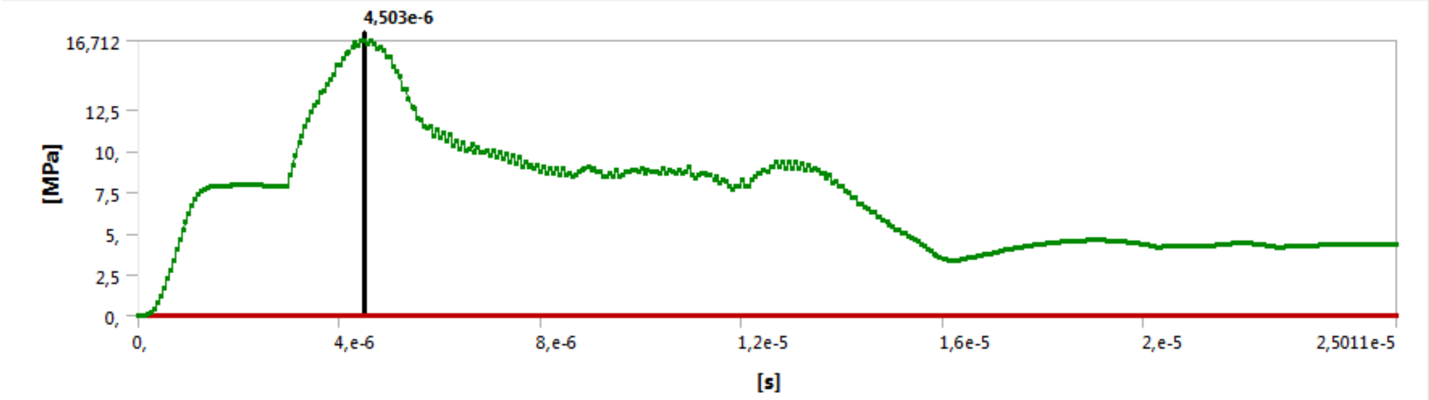
- Rain droplet impact performance of in-mould coatings + Composite Substrate …

❑ **Numerical Modelling.**
Stress V_M

❑ Coat LEP Elastic/Plastic



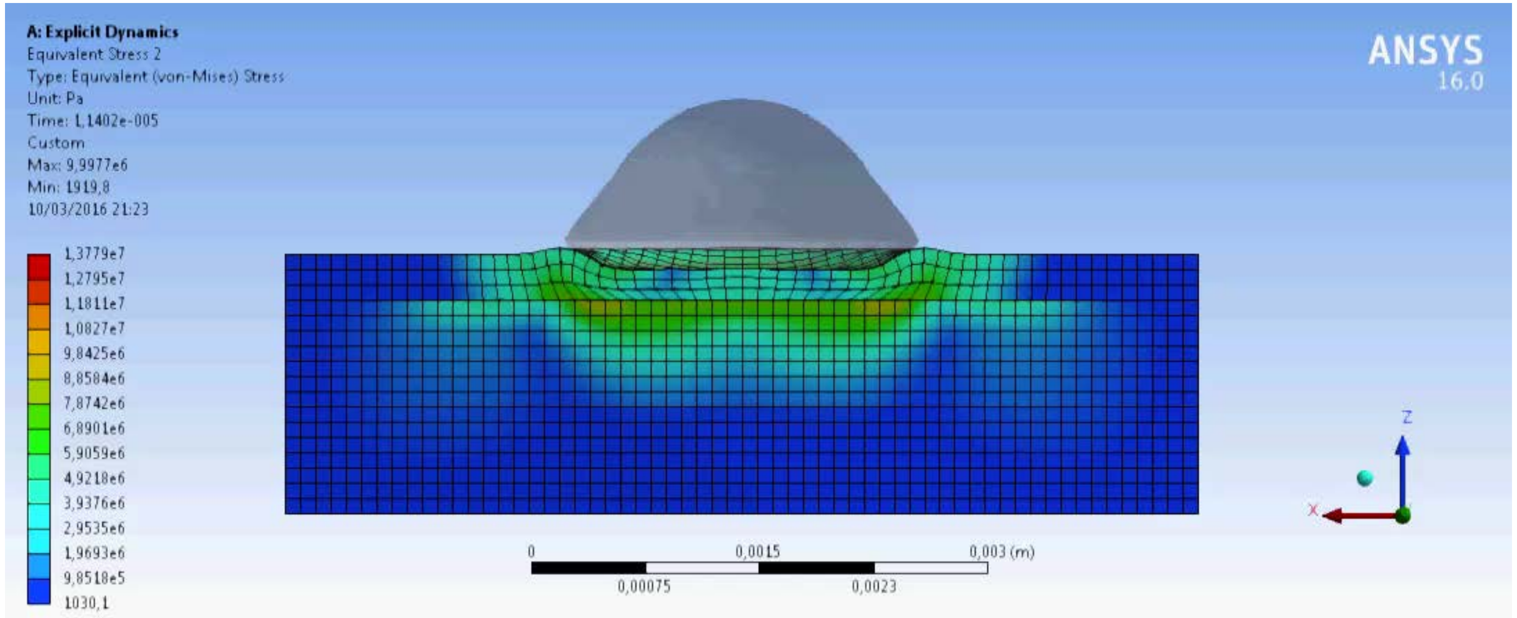


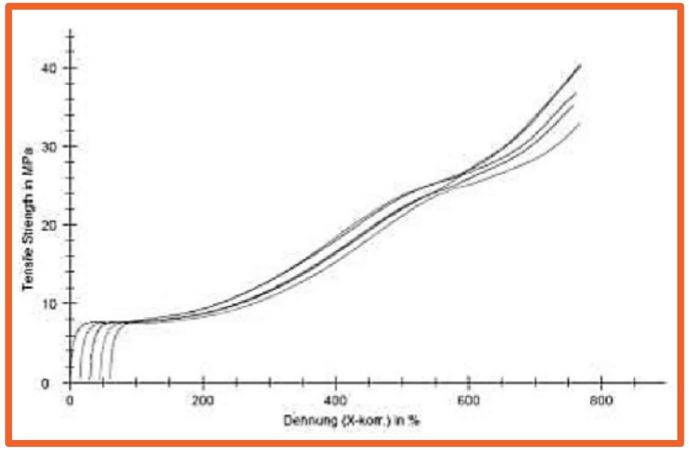


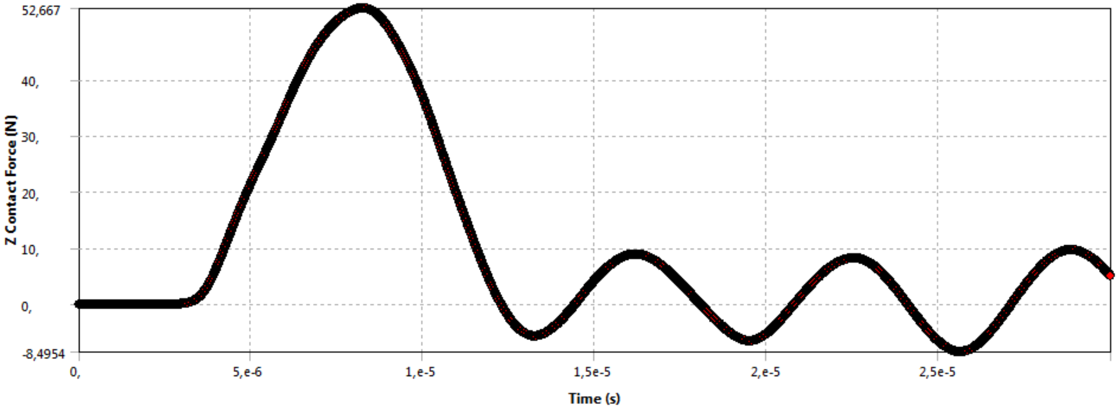
5. On the modelling of rain drop impact in wind turbine blades

- Rain droplet impact performance of in-mould coatings + Composite Substrate …

- ❑ **Numerical Modelling.**
  Stress V_M
- ❑ Coat LEP Elastic/Plastic





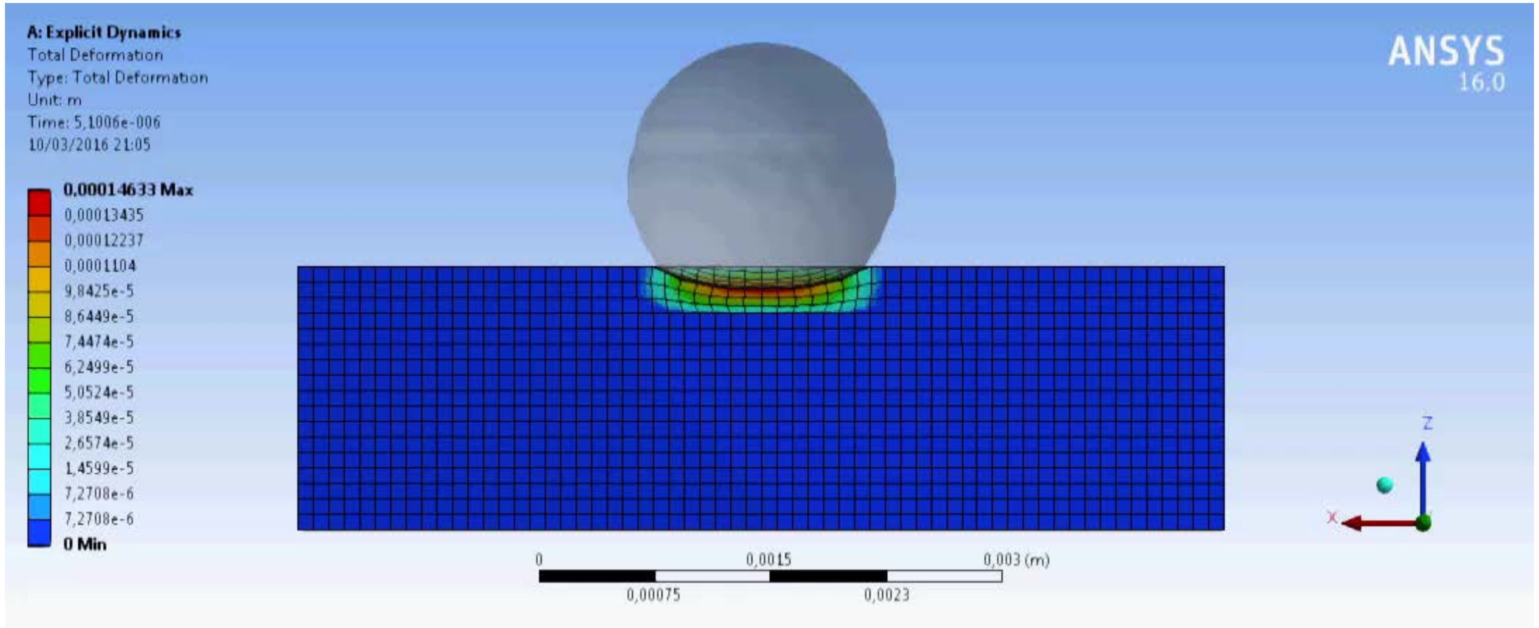


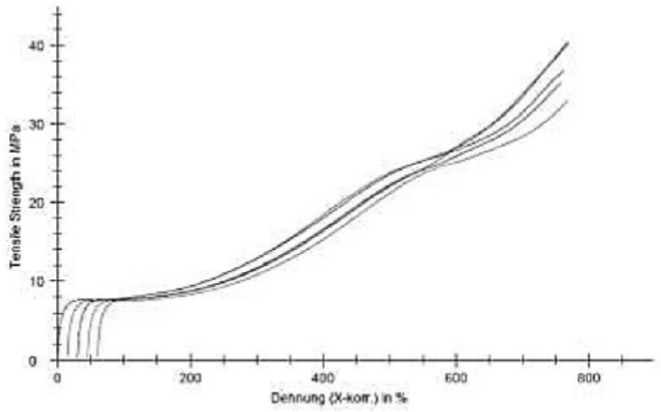
5. On the modelling of rain drop impact in wind turbine blades

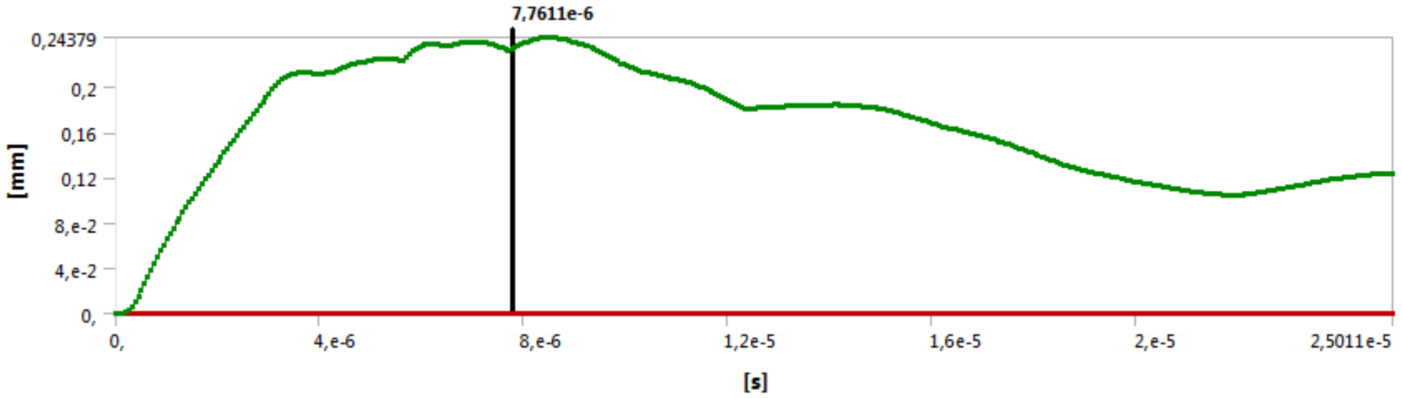
- Rain droplet impact performance of in-mould coatings + Composite Substrate

…

- ❑ **Numerical Modelling.**
  Total Deformation
- ❑ Coat LEP Elastic/Plastic





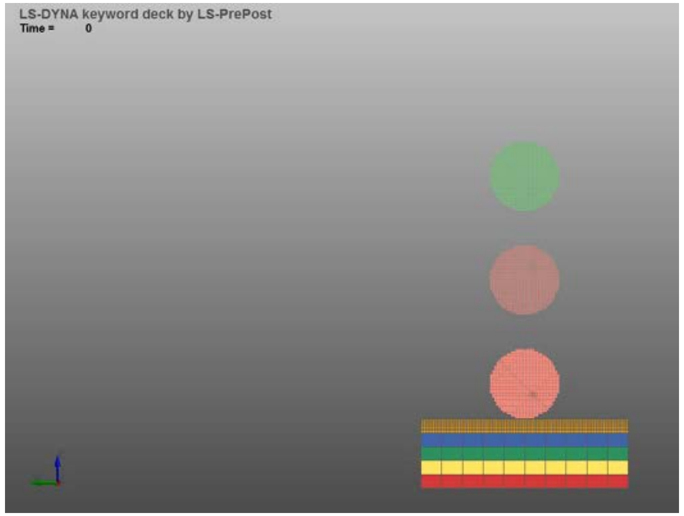


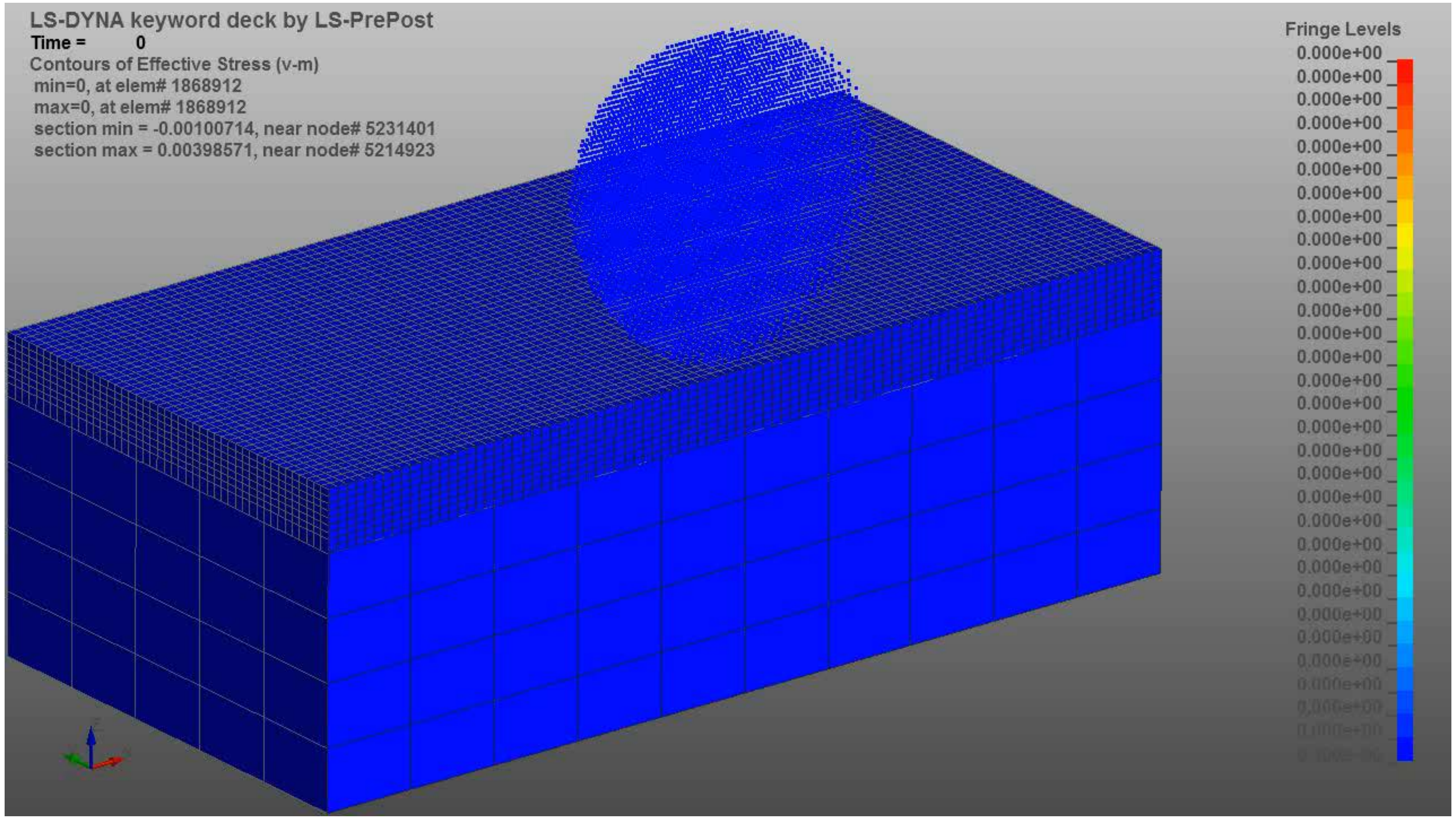
5. On the modelling of rain drop impact in wind turbine blades

- Rain droplet impact induced erosion on a composite substrate

…

❑ **Numerical Modelling**. Rain Erosion induced damage





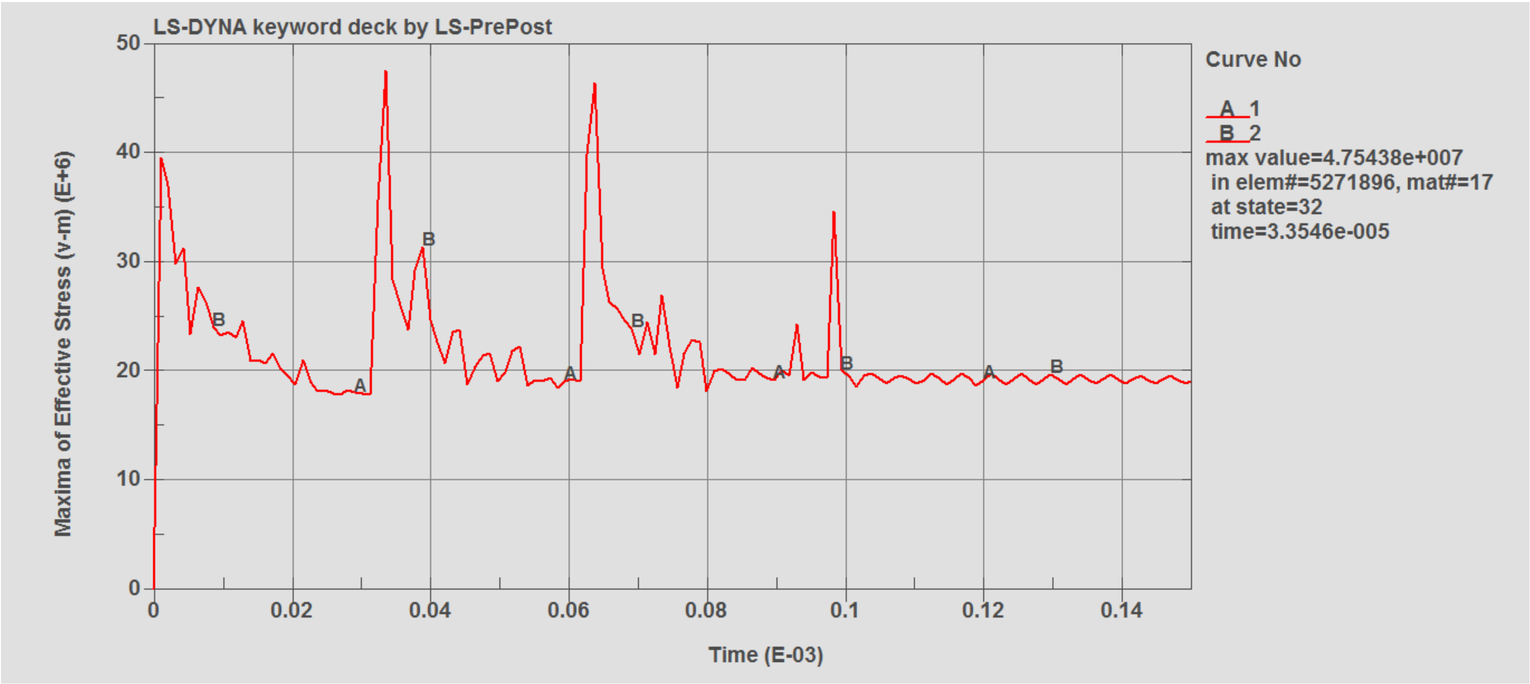
5. On the modelling of rain drop impact in wind turbine blades

- Rain droplet impact induced erosion on a composite substrate

6. Discussion. Further Work

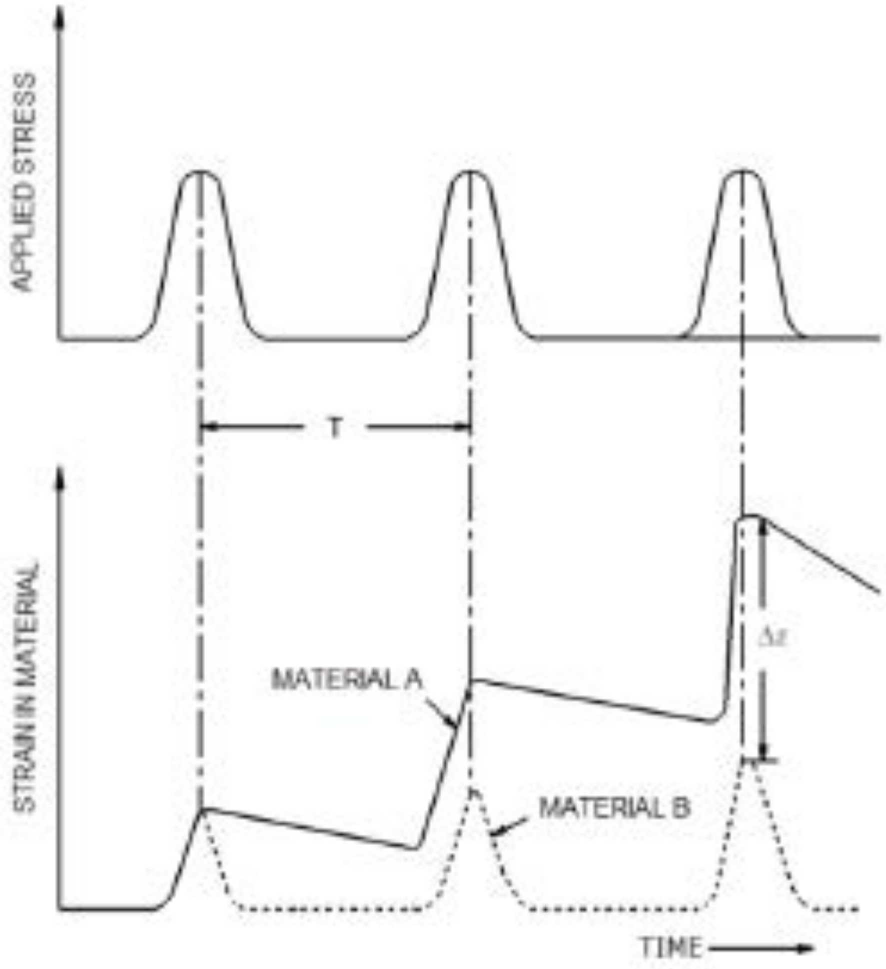
…

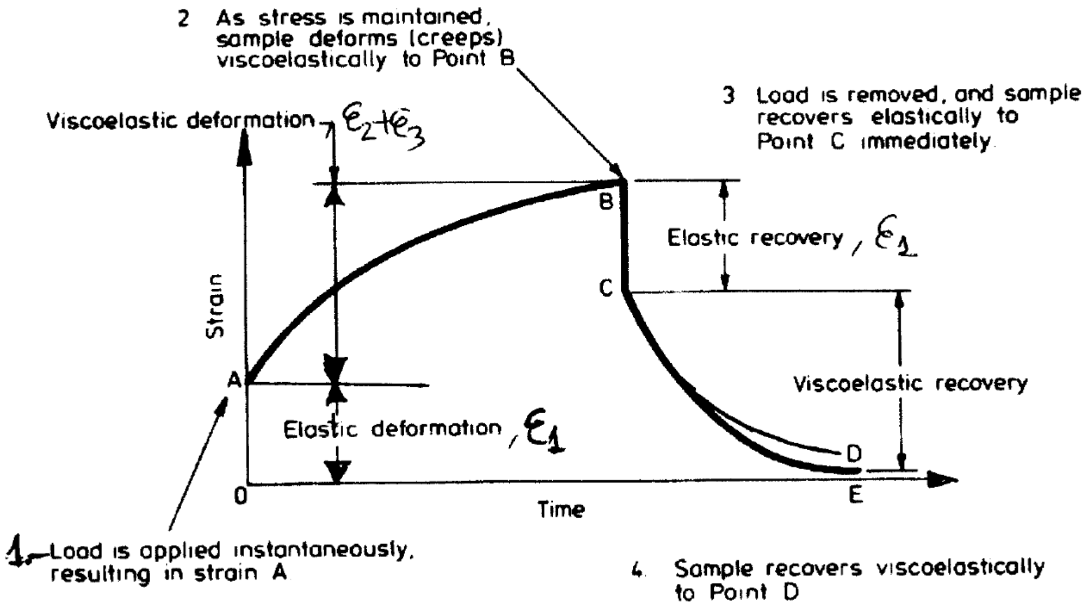
- ❑ **Numerical Modelling**. Rain Erosion induced damage
- ❑ Frequency of droplet impact??
- ❑ Plastic strain increasing under repeated impact??
- ❑ Criteria to define damage? Permanent strain? Stress?
- ❑ Randomly approach for the droplet size and impact location?



6. Discussion. Preliminary results!! Further Work …

❑ **Erosion induced damage under repatead impacts. Viscoelastic approach?**

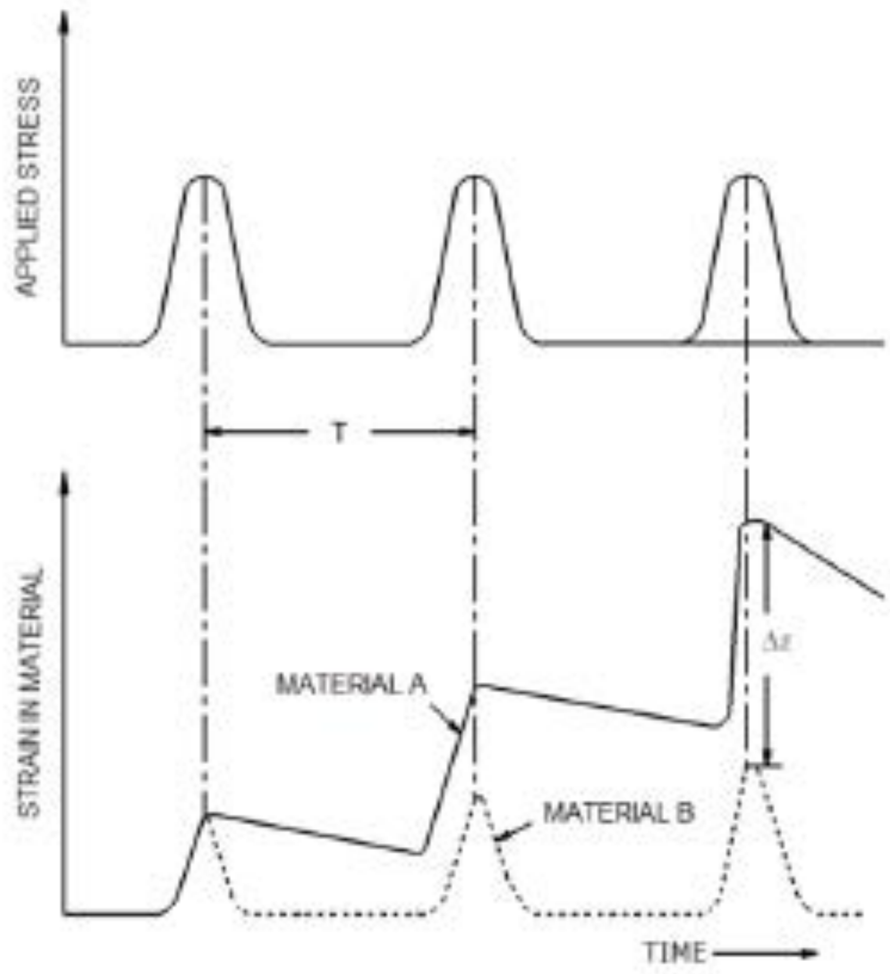


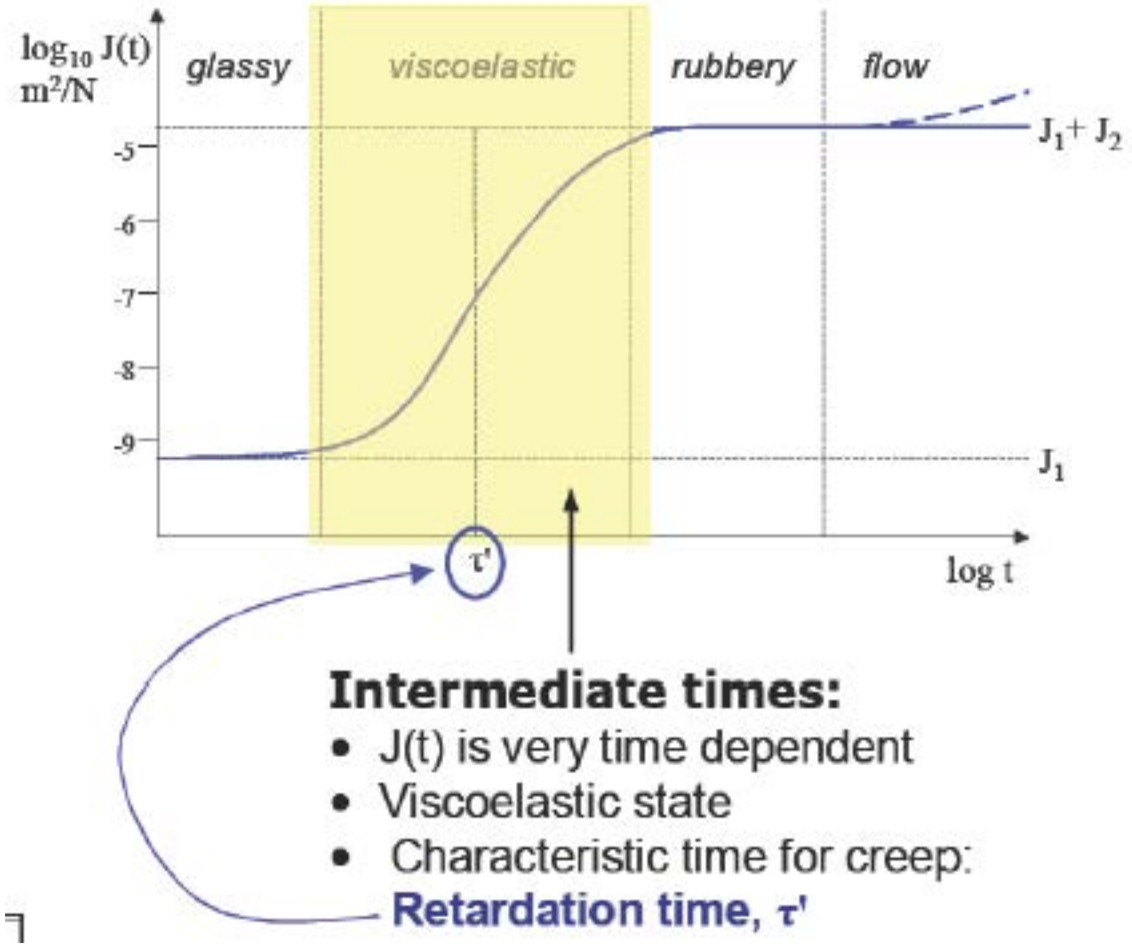


6. Discussion. Further Work

…

❑ Erosion induced damage under repatead impacts. Viscoelastic approach?





6. Discussion. Further Work

…

- ❑ **Interphase Adhesion Modelling. Determine modelling for contact conditions.**
- ❑ **<u>Objective:</u> Define experimental approach for characterize mechanical and chemical adhesion through the coat thickness**

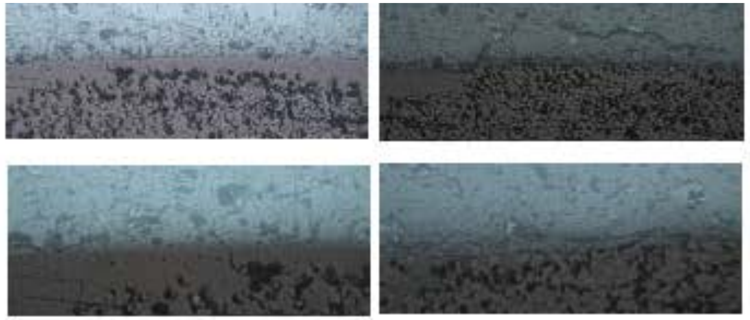


Figure 5 Microscopy samples for interphase chemical adhesion. Coat 1 (cured) left, Coat 2 (tack) right. Zooming X100 Upper images, x200 lower images

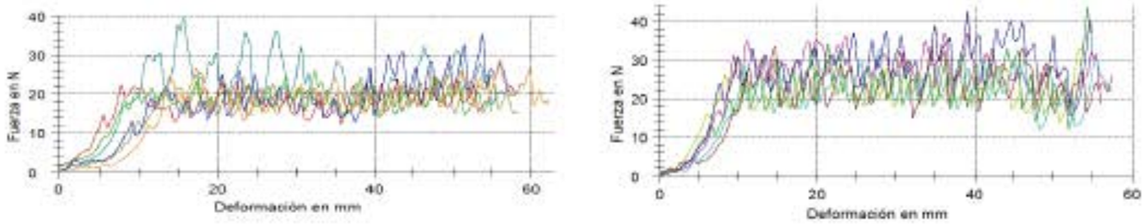
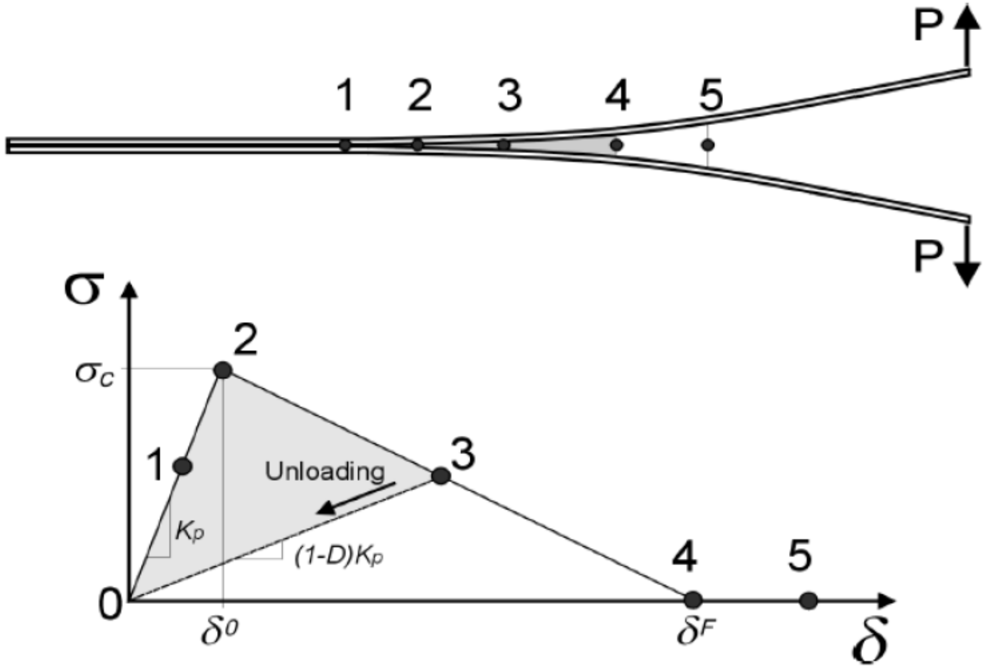


Figure 6 Force of failure for interphase adhesion testing. Coat 1 (cured) left, Coat 2 (tack) right



6. Discussion. Further Work

…

- ❑ **Interphase Adhesion Modelling. Determine modelling for contact conditions.**
- ❑ **<u>Objective</u>: How affect coating curing conditions during processing to coating mechanical characterization for coating erosion numerical modelling?**

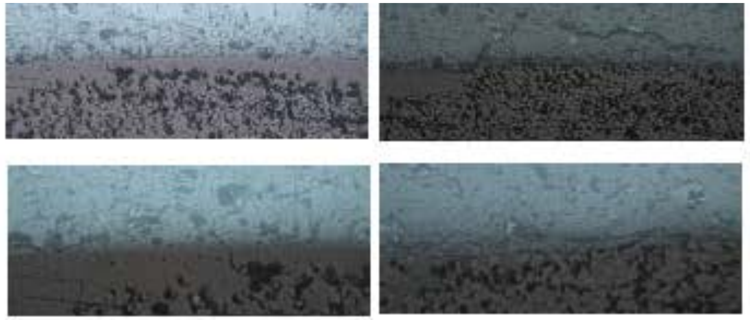


Figure 5 Microscopy samples for interphase chemical adhesion.
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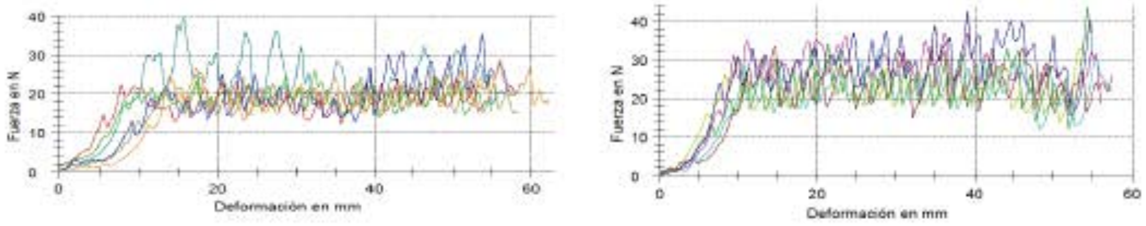
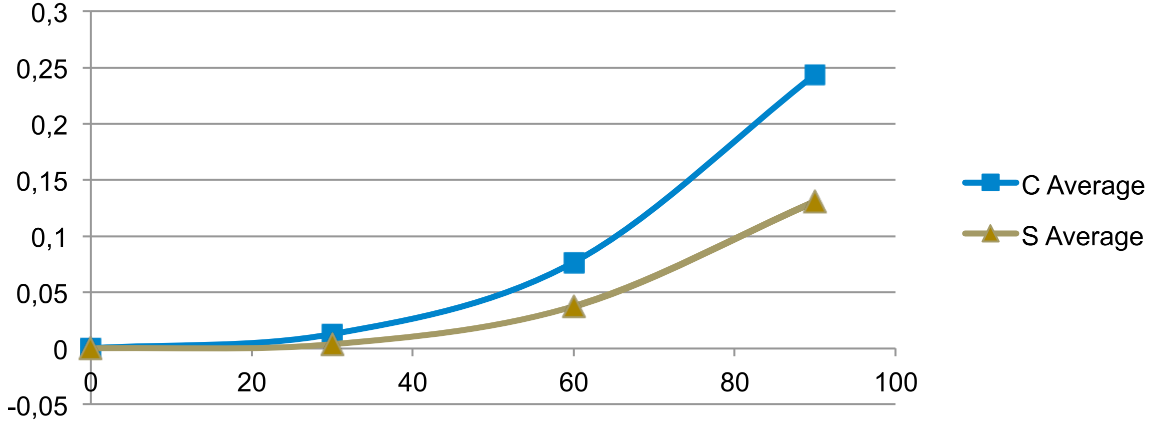


Figure 6 Force of failure for interphase adhesion testing. Coat 1 (cured) left, Coat 2 (tack) right

Comparison of coatings ***Mass Loss/Time (min)***



ESI CHAIR NETWORK WORKSHOP IN ADVANCED MODELLING AND SIMULATION

RECENT PROGRESSES AND FUTURE PROSPECT

VALENCIA, SPAIN,16-20 MARCH 2016

On the rain erosion modelling of in-mould coating composites of wind turbine blade applications

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THANKS FOR YOUR ATTENTION!!