TOWARDS RAIN EROSION CHARACTERIZATION OF WIND TURBINE BLADE COATINGS: EFFECT OF THE IN-MOULD CURING CONDITIONS ON THE COATING-LAMINATE INTERPHASE

Enrique Cortes[1], Fernando Sanchez[*2], Trevor M.Young[3], Anthony O'Carroll[3], D.Busquets[4], Francisco Chinesta[5]

[1] Aerox Advanced Polymers, [2] Universidad Cardenal Herrera-CEU,
[3] University of Limerick, [4] U. Politécnica de Valencia, [5] Ecole Centrale Nantes

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6. **Discussion. Further Work**

- 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....

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

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

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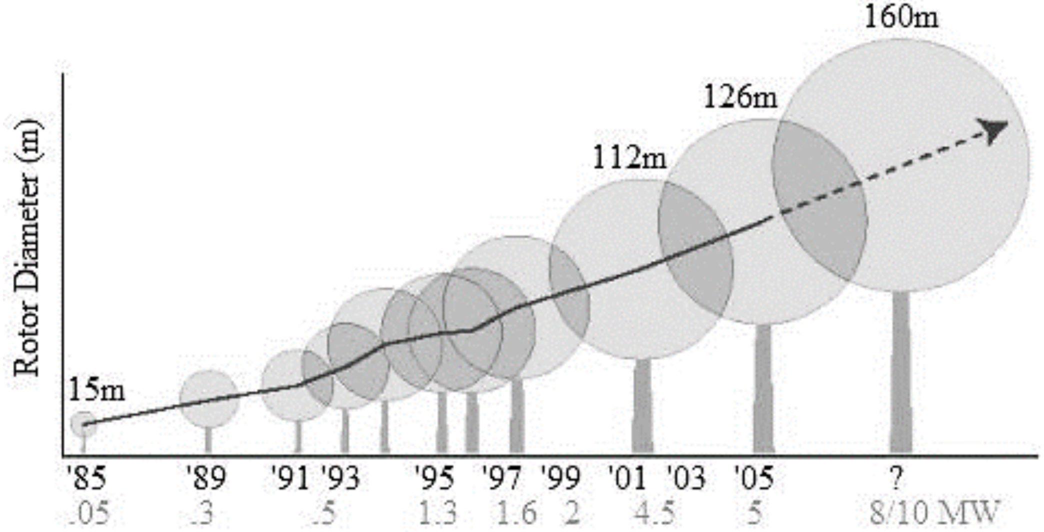

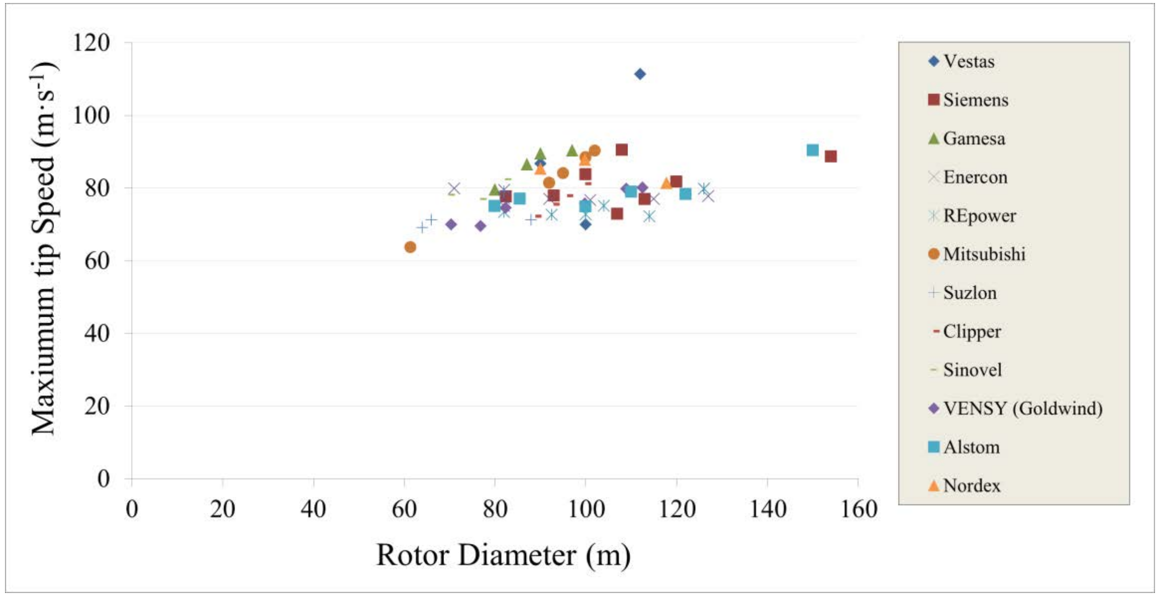

2. **Motivation. Erosion issues associated with the leading edge of wind turbine blades**

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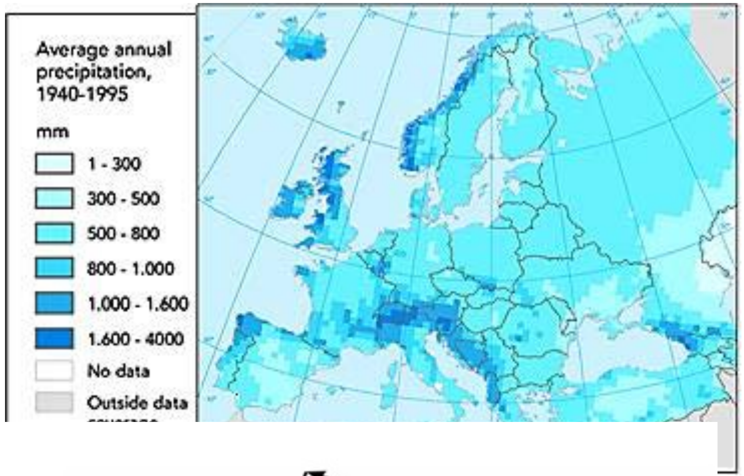
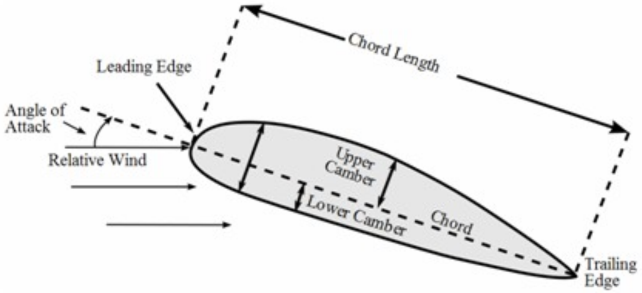
- When considering the **impact of rain**, hailstones and other particulates on the leading edge, the **<u>tip speed is a key issue</u>** and also the **environmental conditions** (average precipitation, raindrop size, UV protection, moisture, …).





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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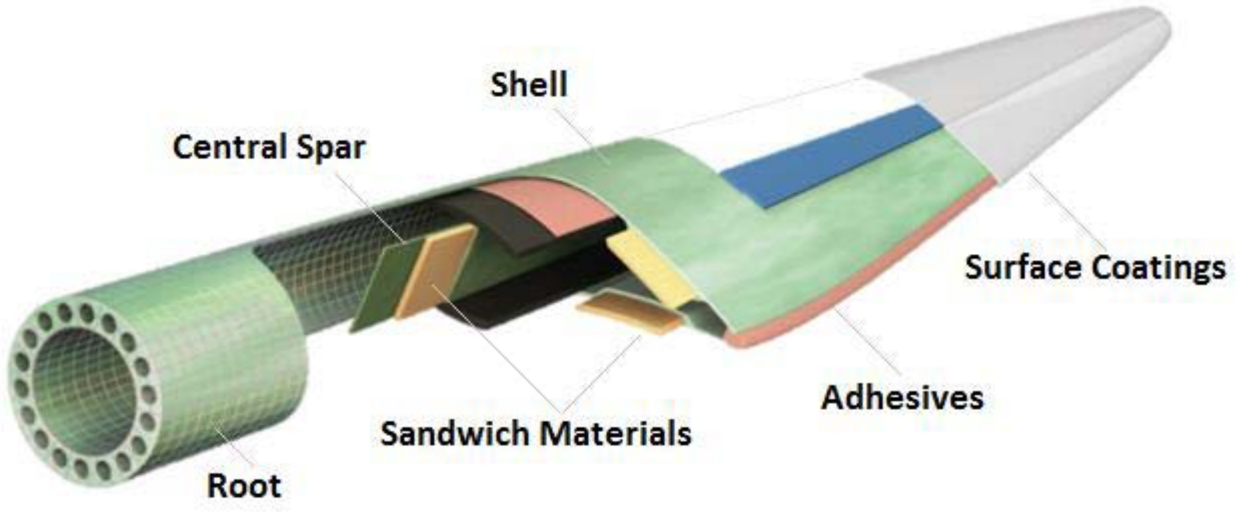
- ❑ The large and ever-growing scale of modern blades has resulted in the widespread implementation of fiber reinforced thermosetting plastic **composite technologies due to high specific strength and stiffness properties and fatigue** performance.
- ❑ Composites **perform poorly under transverse impact** (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 one epoxy/polyester) or a **post-Mould application** (applied after moulding through open moulding, 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 <u>in-mould coating</u> 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. **A <u>post-mould solution</u> LEP** has been developed by AEROX at TRL5 based on a **hybrid polyurethane-urea technology.**
- **<u>Objectives:</u>**
  - ✓ <u>1.</u> **Determine the effect of surface coating on the process dynamical behavior** during mold Infusion. **<u>Processing window requirements for in-mould coatings</u>**
  - ✓ <u>2.</u> To match the developed LEP coating properties to the blade structure of the fabric. Relation with laminate and **<u>integral solution.</u>**
  - ✓ <u>3.</u> Develop an optimised **manufacturing and coating process** for blades into a **<u>knowledge-based guidance</u>**

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

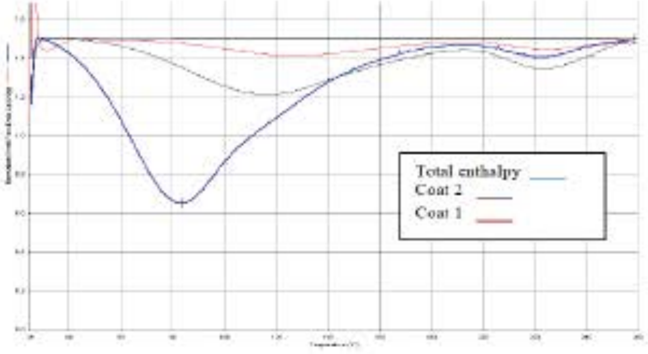
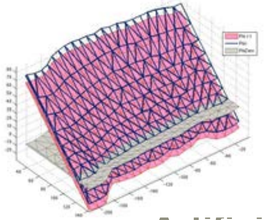


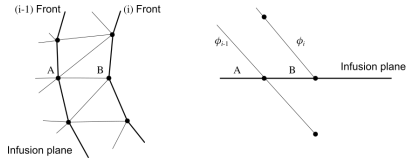
Figure 1: Degree of conversion (α) measured with DSC in the two experimental samples

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

- **Previous Results. 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. **Extend technology to open post-mould processing**.

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



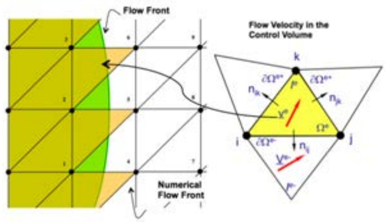


Artificial Vision+LevelSet Velocity computation

Assuming Isotropy

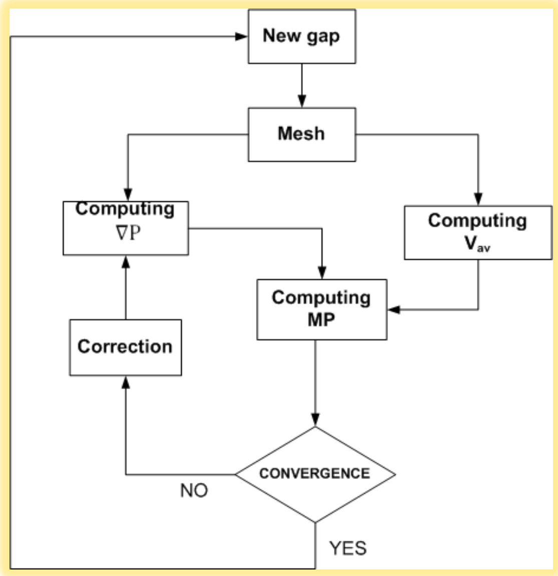
$$M = \frac{\|v\|}{\|\nabla P\|}$$

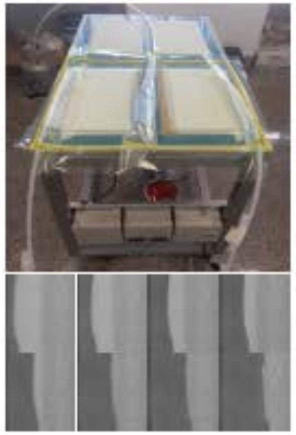
FEM Simulation of Velocity field

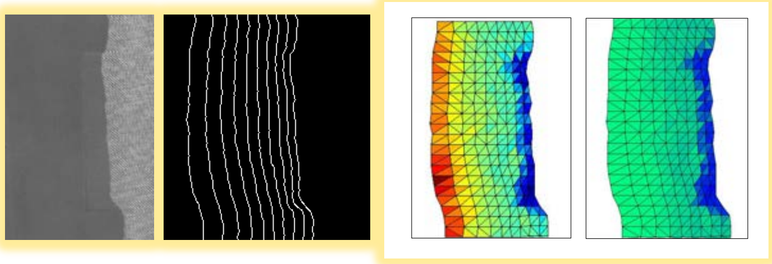


$$M^{est} = \frac{\|V_{AV}\|}{\|\nabla P(M^{est})\|}$$

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







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

❑ Approach:

- ✓ **Determine mechanical characterization** of coating-laminate **interphase adhesion** depending on processing (curing) conditions.
- ✓ Minimize coating defect level and maximize the level of adhesion

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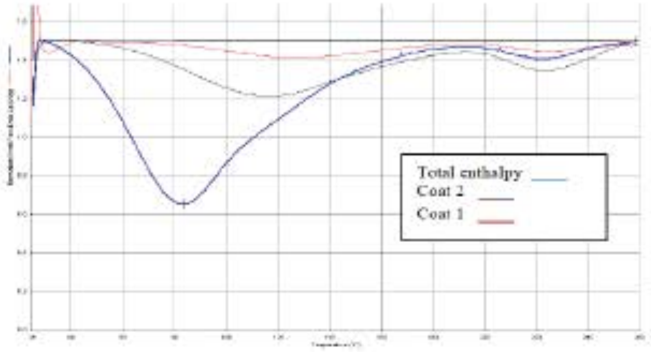


Figure 1: Degree of conversion (α) measured with DSC in the two experimental samples

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

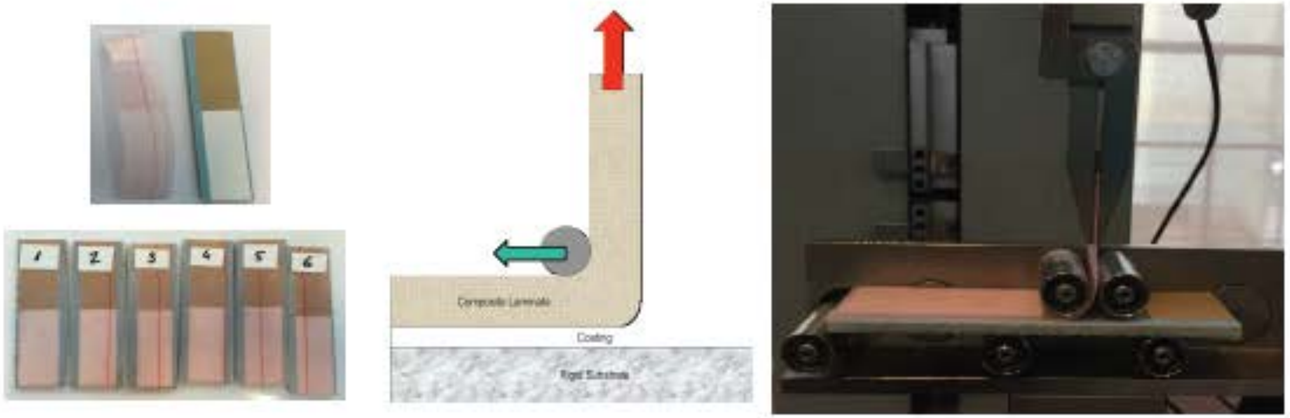


Figure 4: Developed peeling testing for interphase coating-laminate adhesion response quantification

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

❑ **Approach:**

✓ **Development of coating and optimization of coating/blade system.**

✓ Polymer characterization through the thickness depending on differential adhesion during impregnation and curing.

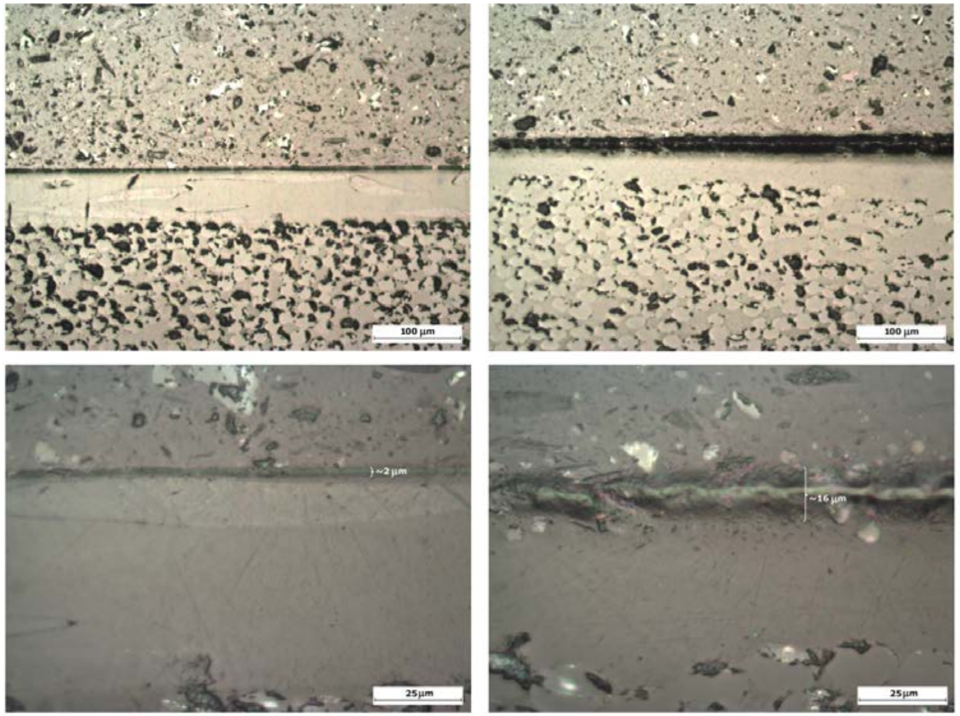
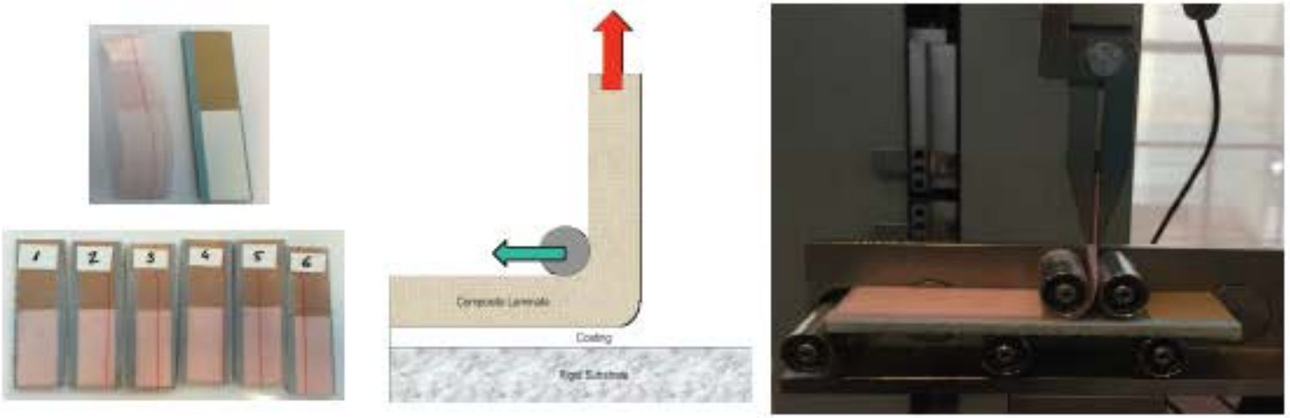


Figure 8. Microscopy samples for interphase chemical adhesion: Coat 1, i.e. cured (left) and Coat 2, i.e. tack (right) (zooming: x100 upper images and x400 lower images)



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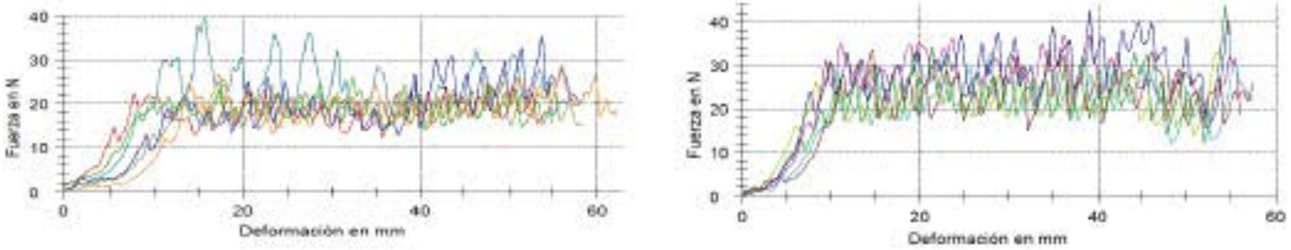
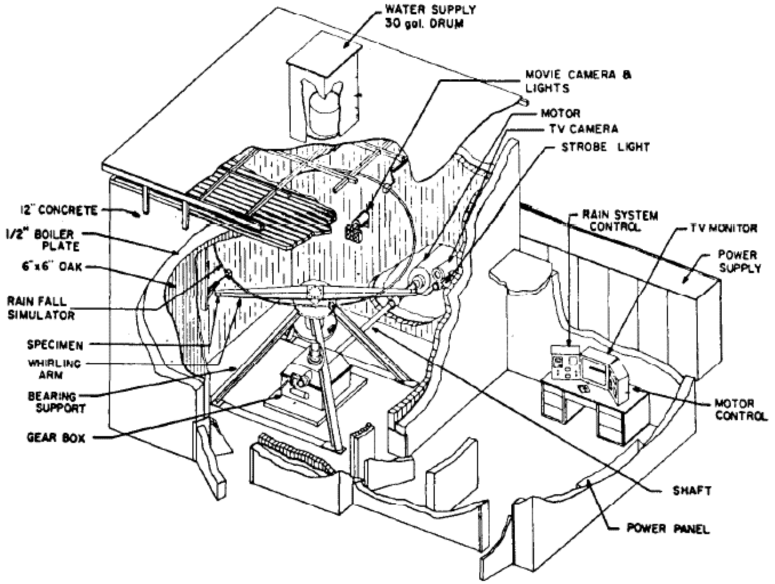
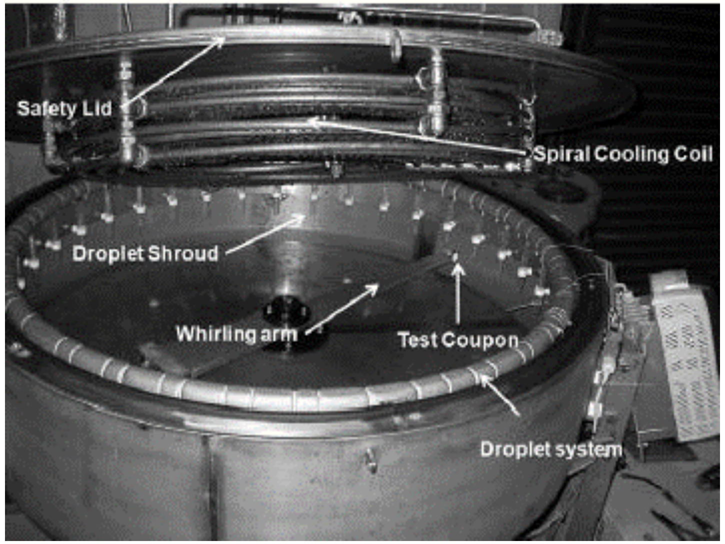


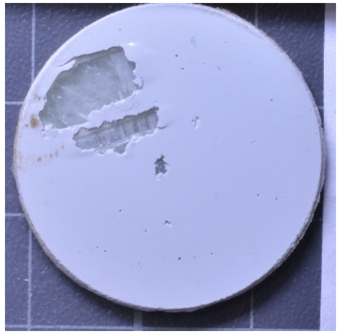
Figure 6 Force of failure for interphase adhesion testing. Coat 1 (cured) left, Coat 2 (tack) right

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

- 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 Test method. Evaluation and quantification of erosion damage in surface coatings.

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

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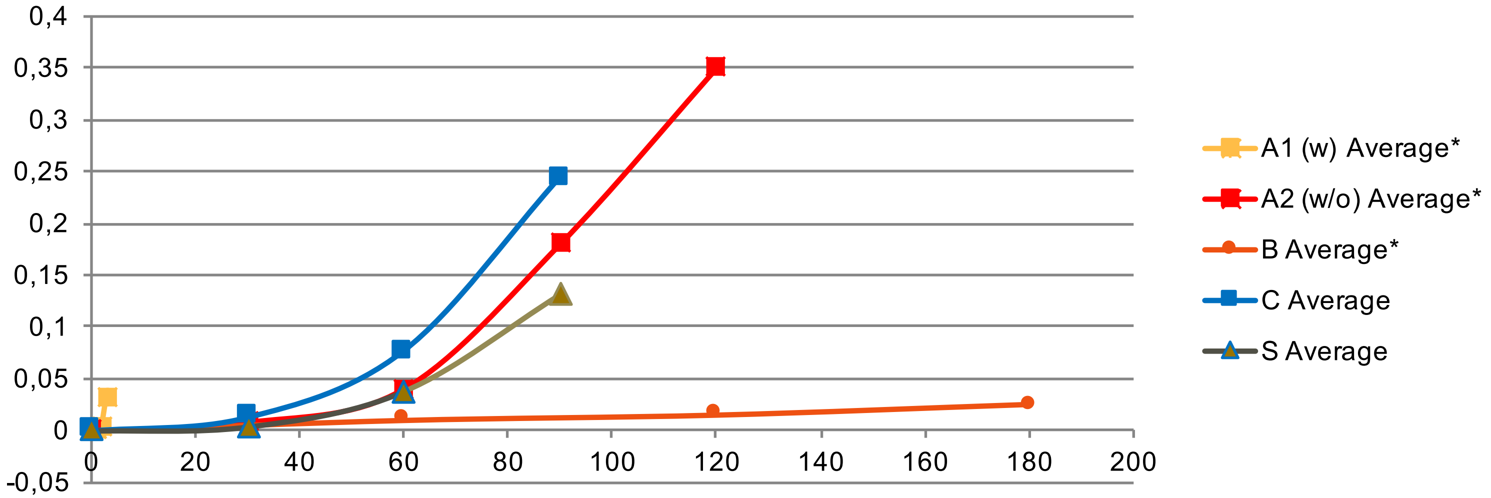
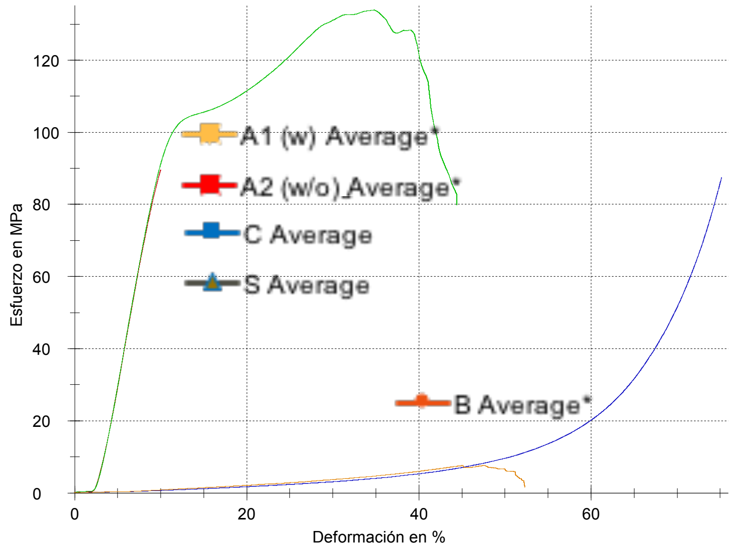
Comparison of coatings ***Mass Loss/Time (min)***





❑ **Objective:** Determine **Interphase coating-laminate relation** with mass loss in erosion

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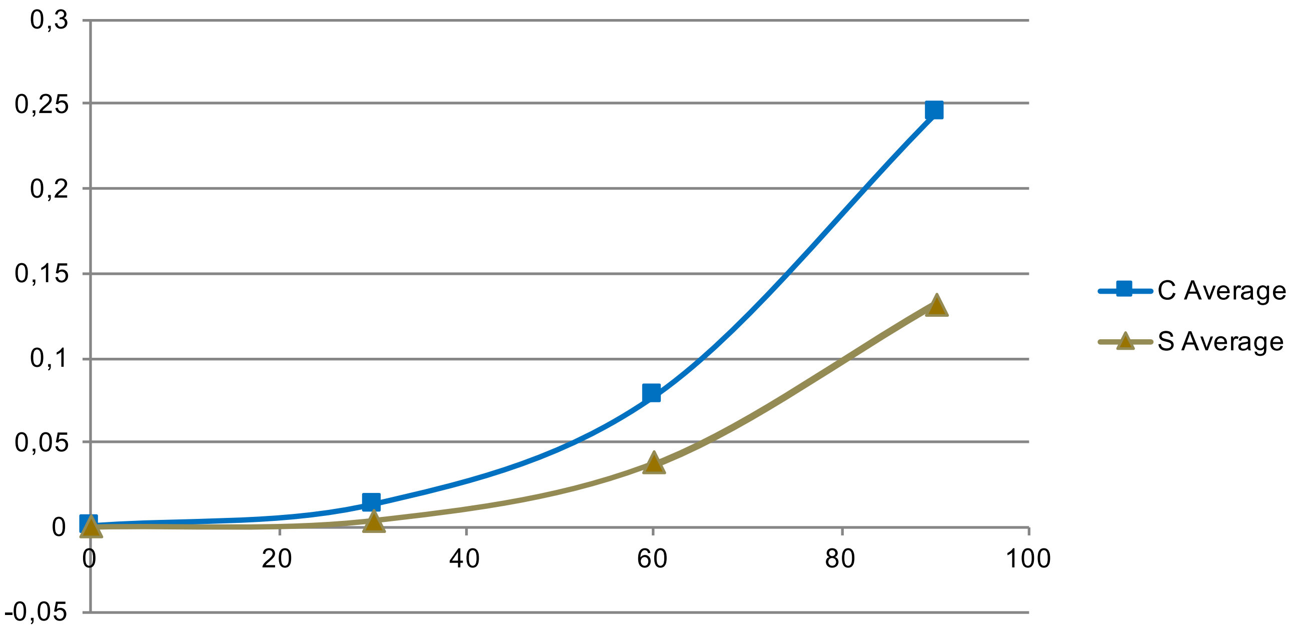
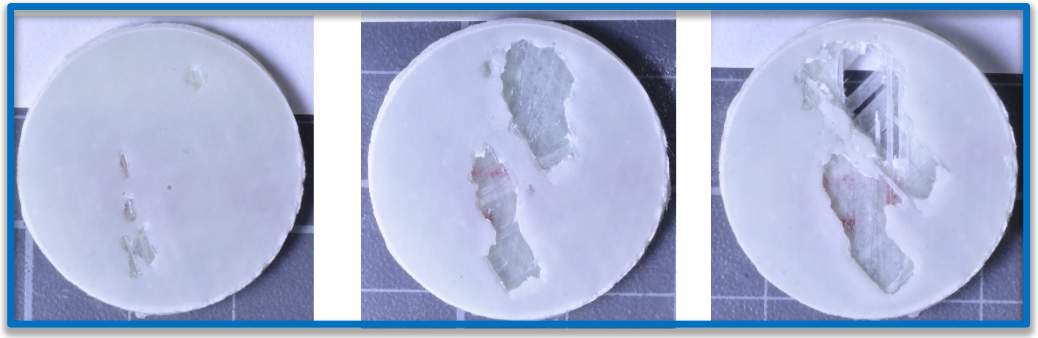
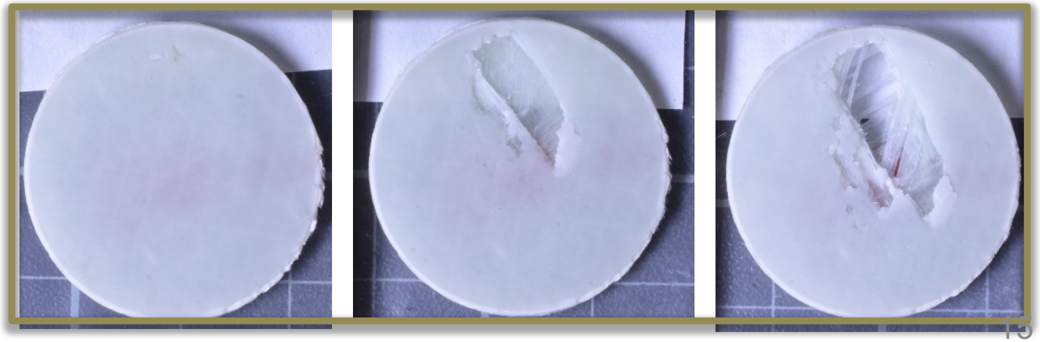
Comparison of coatings ***Mass Loss/Time (min)***







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

- ❑ Approach: Determine Interphase coating-laminate relation with mass loss in erosion

- ❑ **On going approach:** Extend to **vibroacoustic properties** of coating/blade interphase.

The test procedure is defined to evaluate the candidate coatings:

1. -Coat Epoxy GC E 135 (**Cured, Rigid**). **SAMPLES C1, C2, C3, C4, C5**
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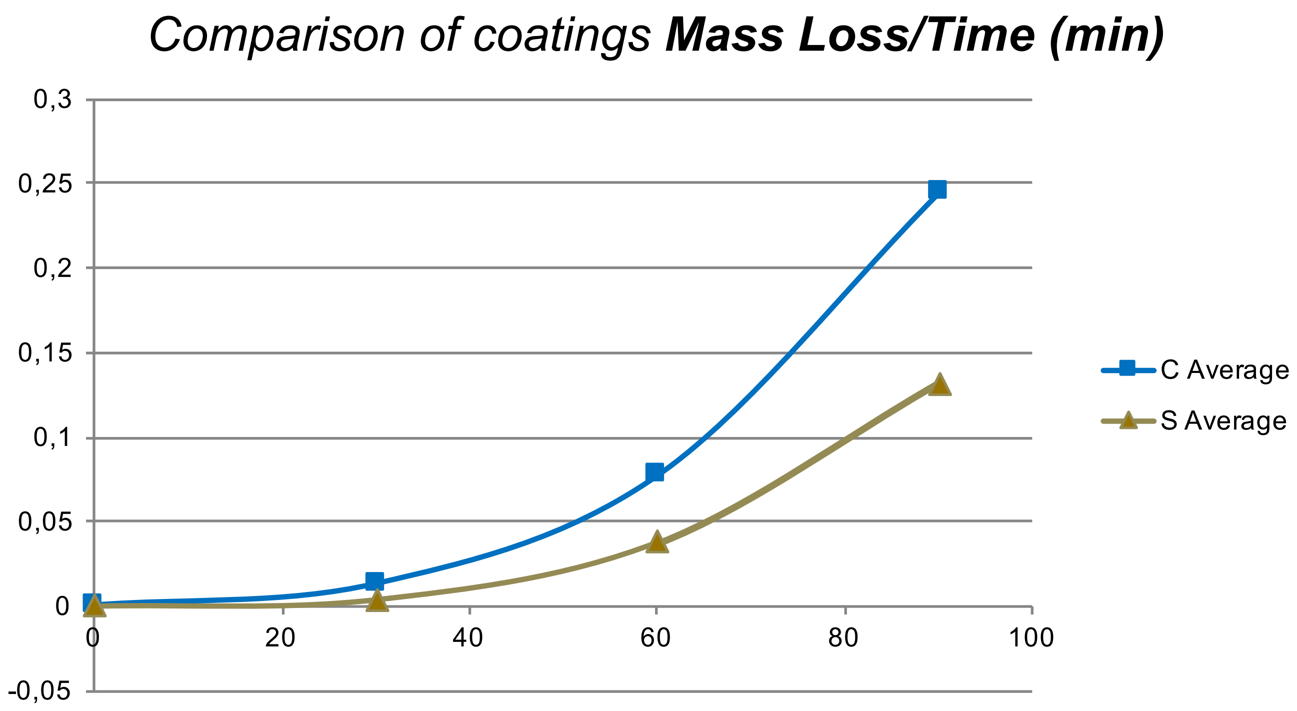


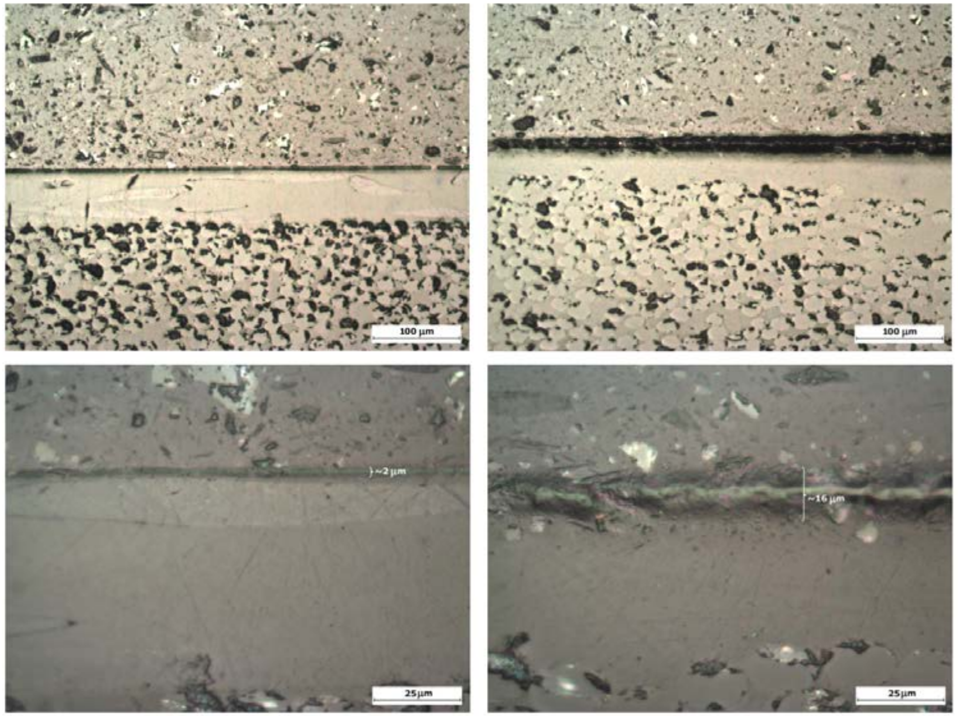
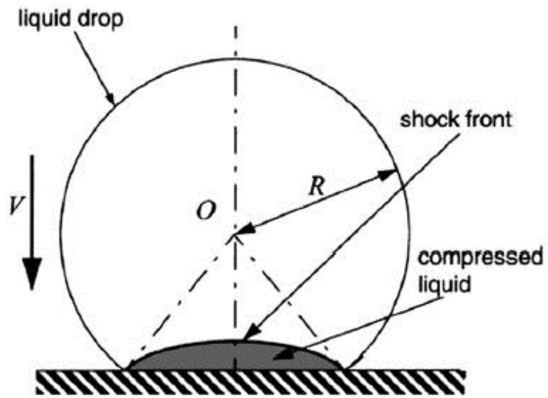


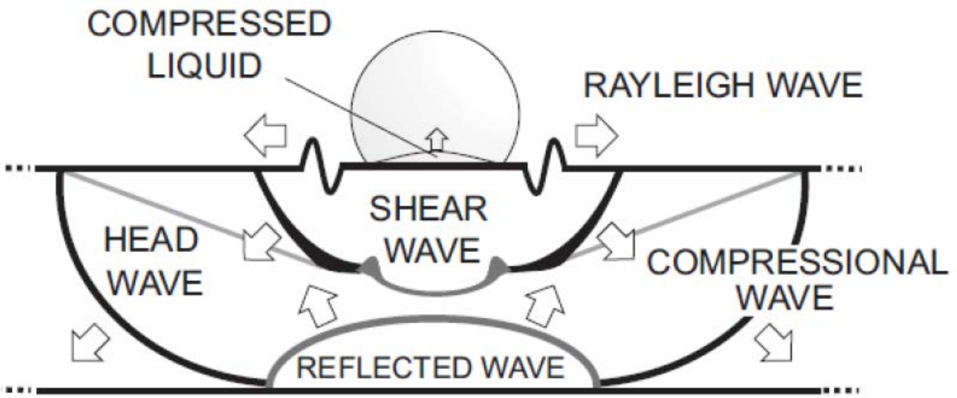
Figure 8. Microscopy samples for interphase chemical adhesion: Coat 1, i.e. cured (left) and Coat 2, i.e. tack (right) (zooming: x100 upper images and x400 lower images)

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

- **Liquid impact phenomena**

- **<u>Approach:</u> Understanding the physics 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 **<u>develop optimization guidelines for coatings</u>** and blade design.
- The adhesion and erosion is affected by the **<u>shock wave</u> 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. WP1

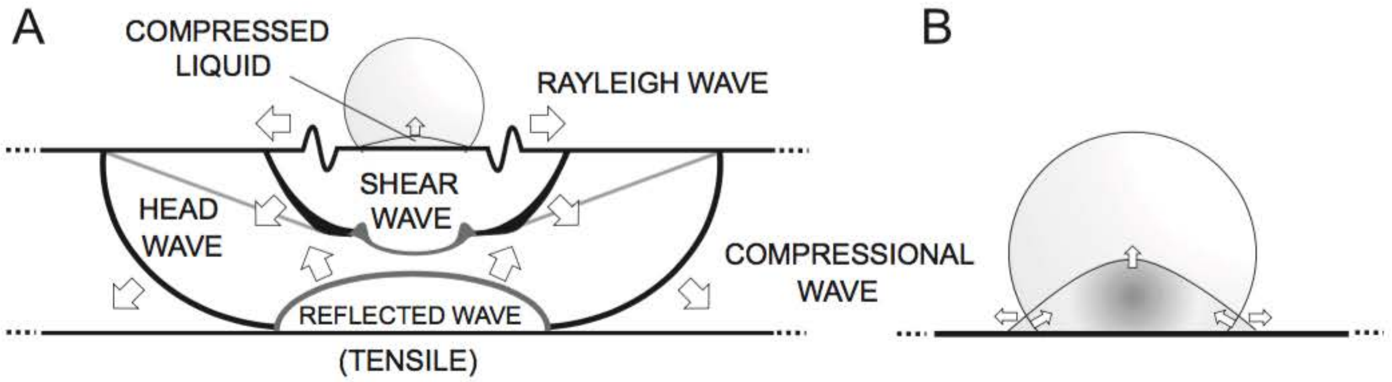
- **Liquid impact phenomena**

$$c_L = \left\{\frac{E}{\rho(1+\nu)}\left(\frac{\nu}{1-2\nu}+1\right)\right\}^{1/2}$$

$$c_T = \left(\frac{E}{\rho(2+2\nu)}\right)^{1/2}$$

$$c_R = \left(\frac{0.862+1.14\nu}{1+\nu}\right)\left(\frac{E}{2(1+\nu)\rho}\right)^{1/2}$$

$$P_I = v\left(\frac{\prod_{i=1}^{2}\rho_i \check{C}_i}{\sum_{i=1}^{2}\rho_i \check{C}_i}\right)$$



- As the **water droplet impinges the surfaces** at a normal angle, two wave fronts are created with the **longitudinal wave** (with C_L speed) preceding the **transverse wave** (C_T). The impact gives rise to another wave, called the **Rayleigh wave** (C_R) which is confined to the surface of the specimen and is responsible for **2/3 of the collision energy**.
- The impact of a liquid sphere onto a solid surface can conventionally be divided into two different progression stages. The first stage is the main one and is governed by compressible effects where a **water-hammer pressure P_i** is produced.

5. **On the modelling of rain drop impact in wind turbine blades.**
    - **Liquid impact phenomena. Modelling to identify suitable coating and substrate and its interface**.

- Analytical model [*Springer*] used to identify **suitable coating and substrate combinations and their potential stress reduction on the interface** has the following underlying **assumptions:**
    - The **coating and substrate are homogeneous**.
    - The substrate extends semi-infinitely with its thickness
    - The speed of the stress waves into the coating and the droplet is equal to the speed of sound.
    - The material is unstressed prior to liquid impact.
    - The **stress wave is one-dimensional** and **propagates normal** to the specimen.
    - Further, stress waves parallel to the specimen surface are neglected.

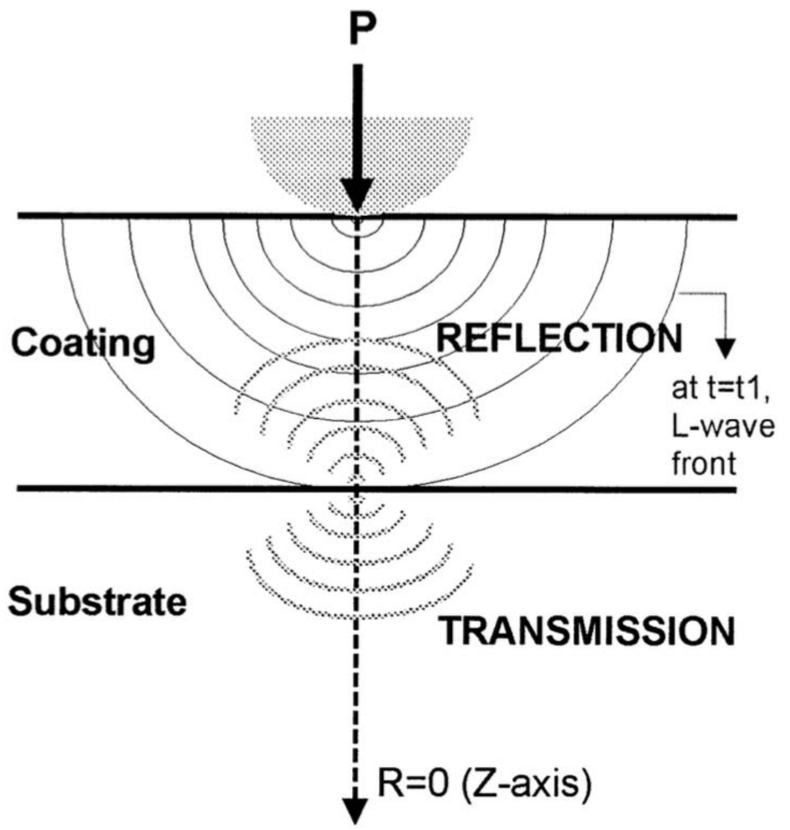


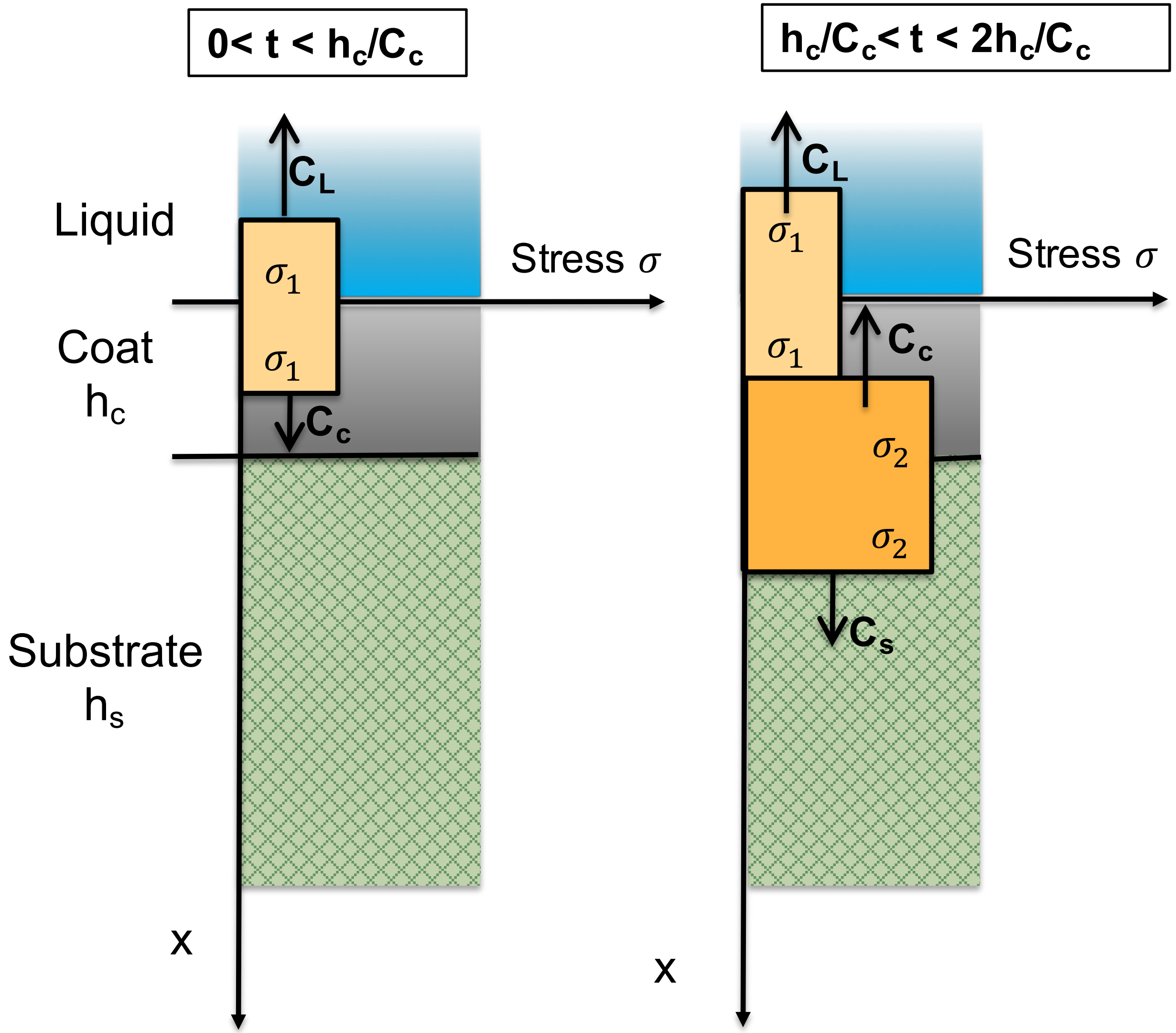
Fig. 2—Reflection and transmission of the normally incident longitudinal wave on the interface of the coating/substrate system.

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

- **Liquid impact phenomena. Modelling to identify suitable coating and substrate and its interface.**

- This formulation examines the impact of a liquid **droplet with diameter *d***, onto a **two layered structure** with the first layer formed by the coating and the second layer by the substrate.
- Upon impingement on the coating two different wave fronts travel into the liquid and coating respectively. **The wave front in the coating** further **advances towards** the coating-substrate **interface,** where a portion of the stress wave is **reflected back** into the coating **and** the **remaining** part is **transmitted to the substrate**.
- Due to this reflection a new wave is now advancing in the coating with a different **amplitude** depending on the **acoustic impedances** of the coating and substrate

$$Z = \rho C \; ; \; \varphi_{Lc} = \frac{Z_L - Z_c}{Z_L + Z_c} \quad ; \quad \varphi_{sc} = \frac{Z_s - Z_c}{Z_s + Z_c}$$



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

- **Liquid impact phenomena. Modelling to identify suitable coating and substrate and its interface.**

- The magnitude of the traveling waves propagating upwards the **coating-liquid interface**, and traveling waves propagating downwards the **coating-substrate interface**, are expressed with the *k* **number of reflections** as:

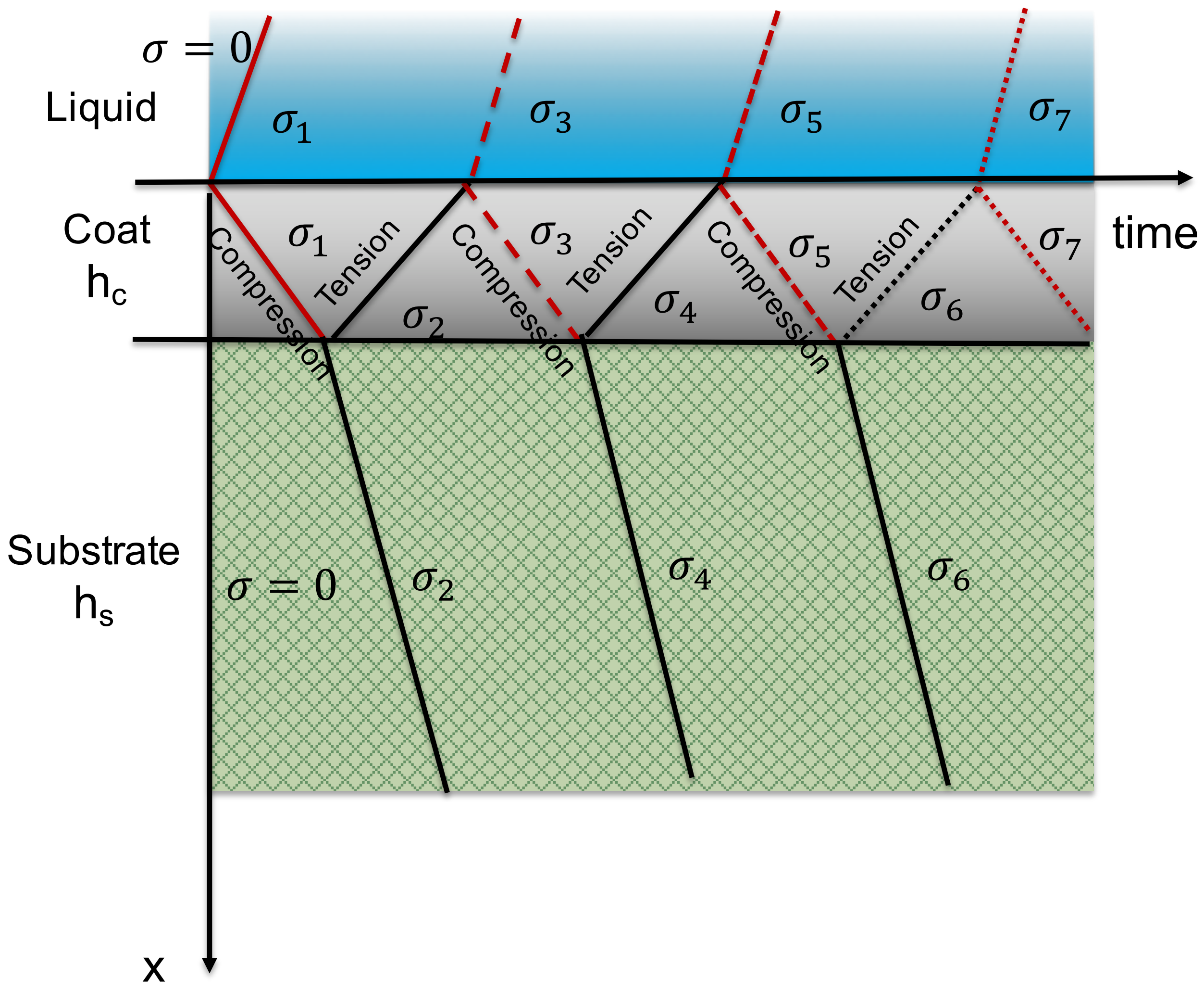
$$\frac{\sigma_{2k}}{\sigma_1} = \frac{1+\varphi_{sc}}{1-\varphi_{sc}\varphi_{Lc}}\left[1-(\varphi_{sc}\varphi_{Lc})^k\right]$$

$$\frac{\sigma_{2k-1}}{\sigma_1} = \frac{\sigma_{2k}}{\sigma_1} - \varphi_{sc}(\varphi_{sc}\varphi_{Lc})^{k-1}$$

$$Z = \rho C \;;\;\; \varphi_{Lc} = \frac{Z_L - Z_c}{Z_L + Z_c} \;\;;\;\; \varphi_{sc} = \frac{Z_s - Z_c}{Z_s + Z_c}$$

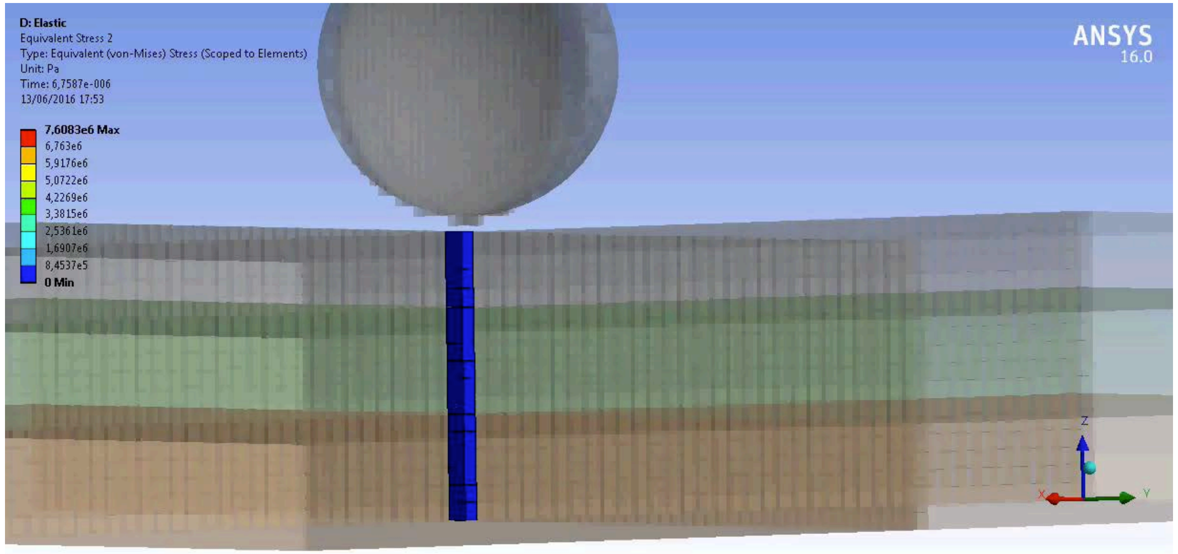
Where the Water-hammer Pressure defines the impact pressure $\sigma_1 = Pi$ and the **stress at the interface** can be approximated as:

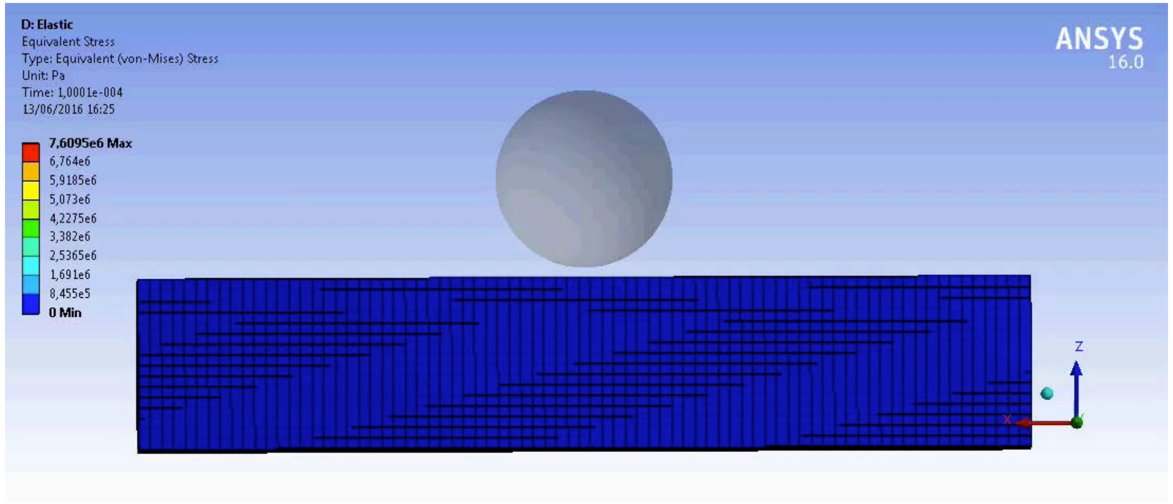
$$\sigma_\infty = \sigma_1 \lim_{k\to\infty} \sigma_{2k} = \sigma_1 \frac{1+\varphi_{sc}}{1-\varphi_{sc}\varphi_{Lc}} = \sigma_1 \frac{1+\frac{Z_L}{Z_c}}{1+\frac{Z_L}{Z_s}}$$

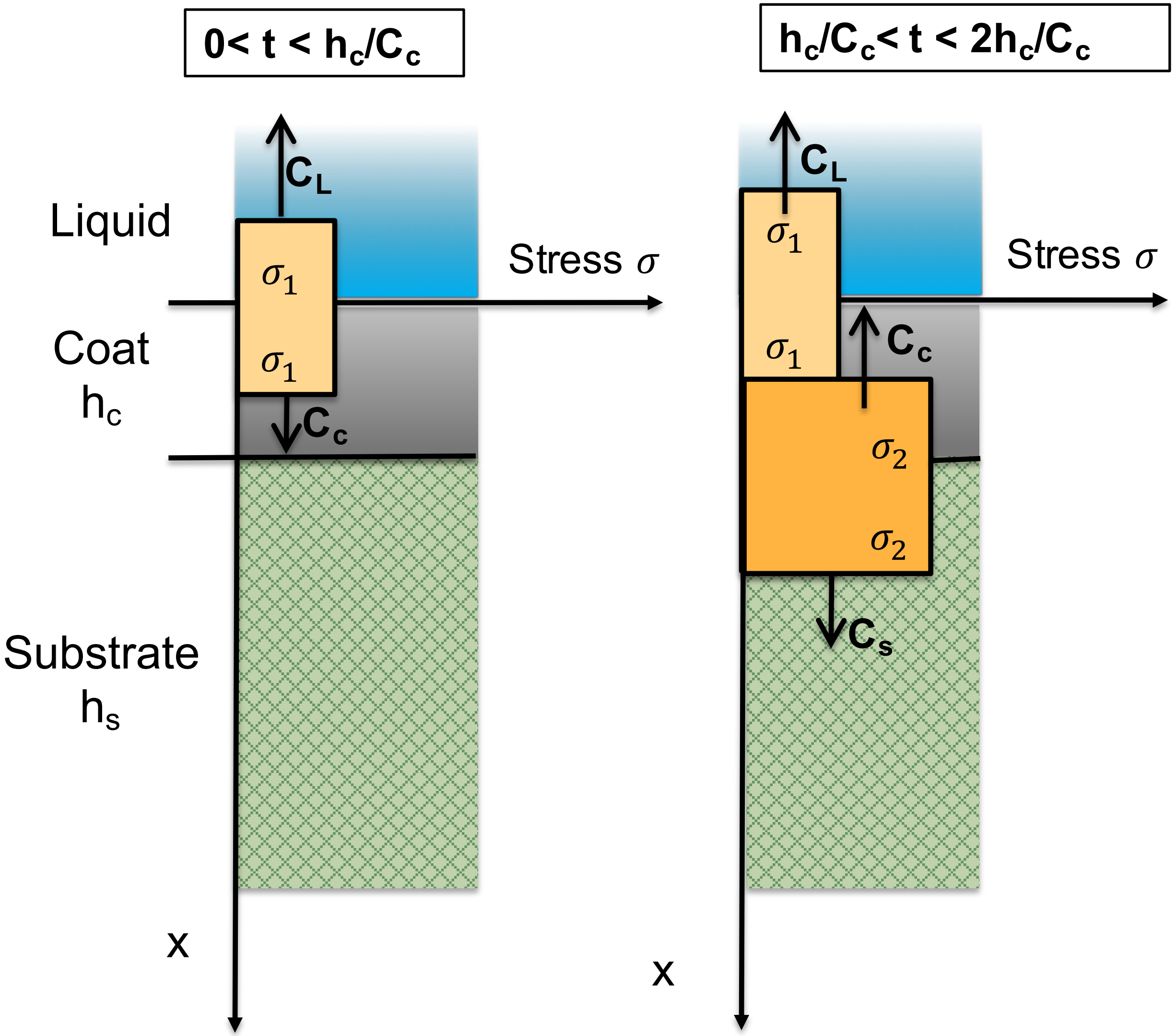


5. On the modelling of rain drop impact in wind turbine blades.

- **Liquid impact phenomena. Stress Reduction on the Substrate by Usage of a coating layer**

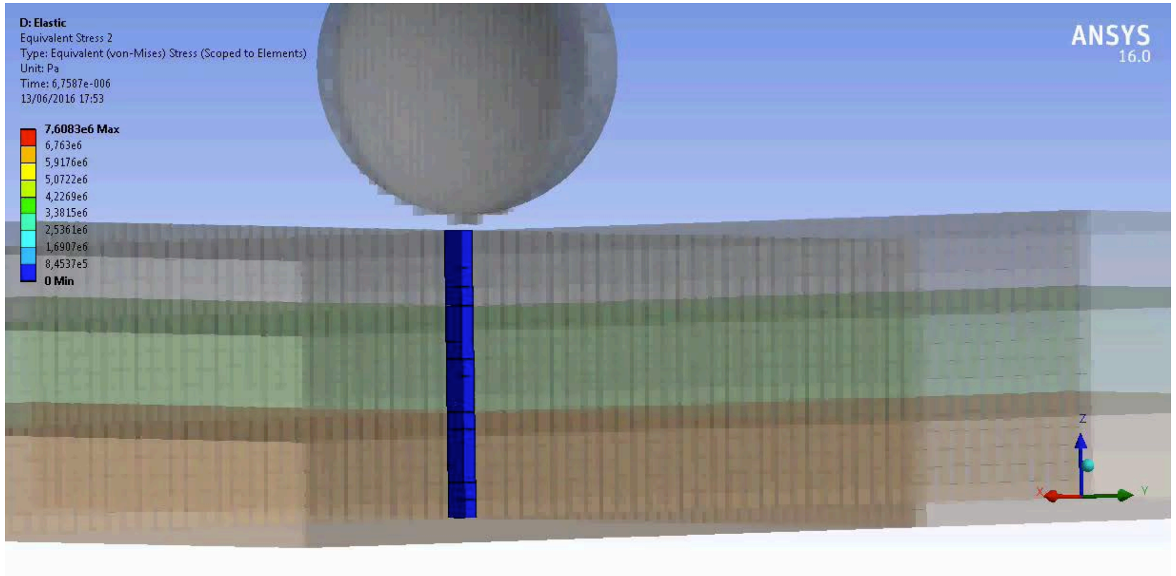


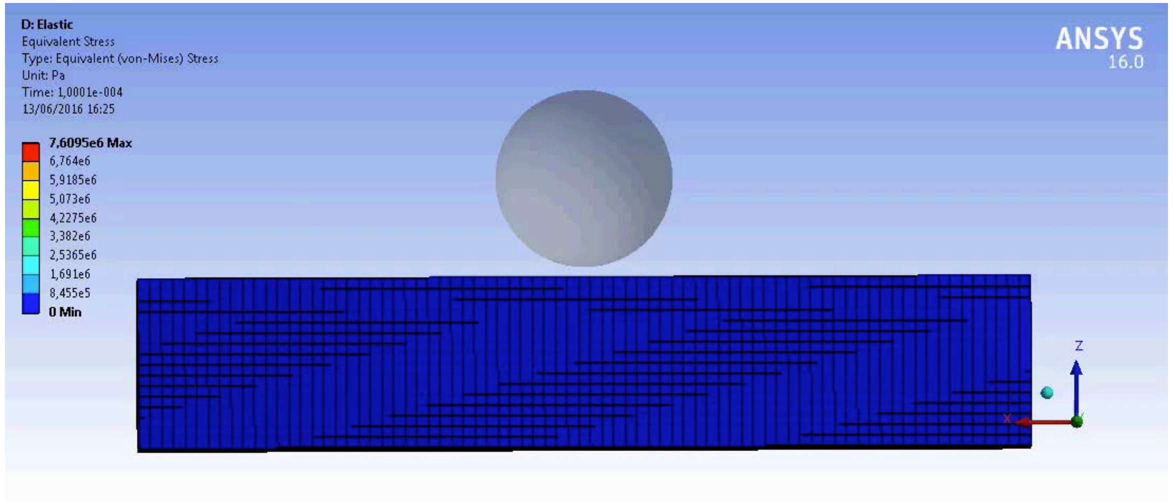


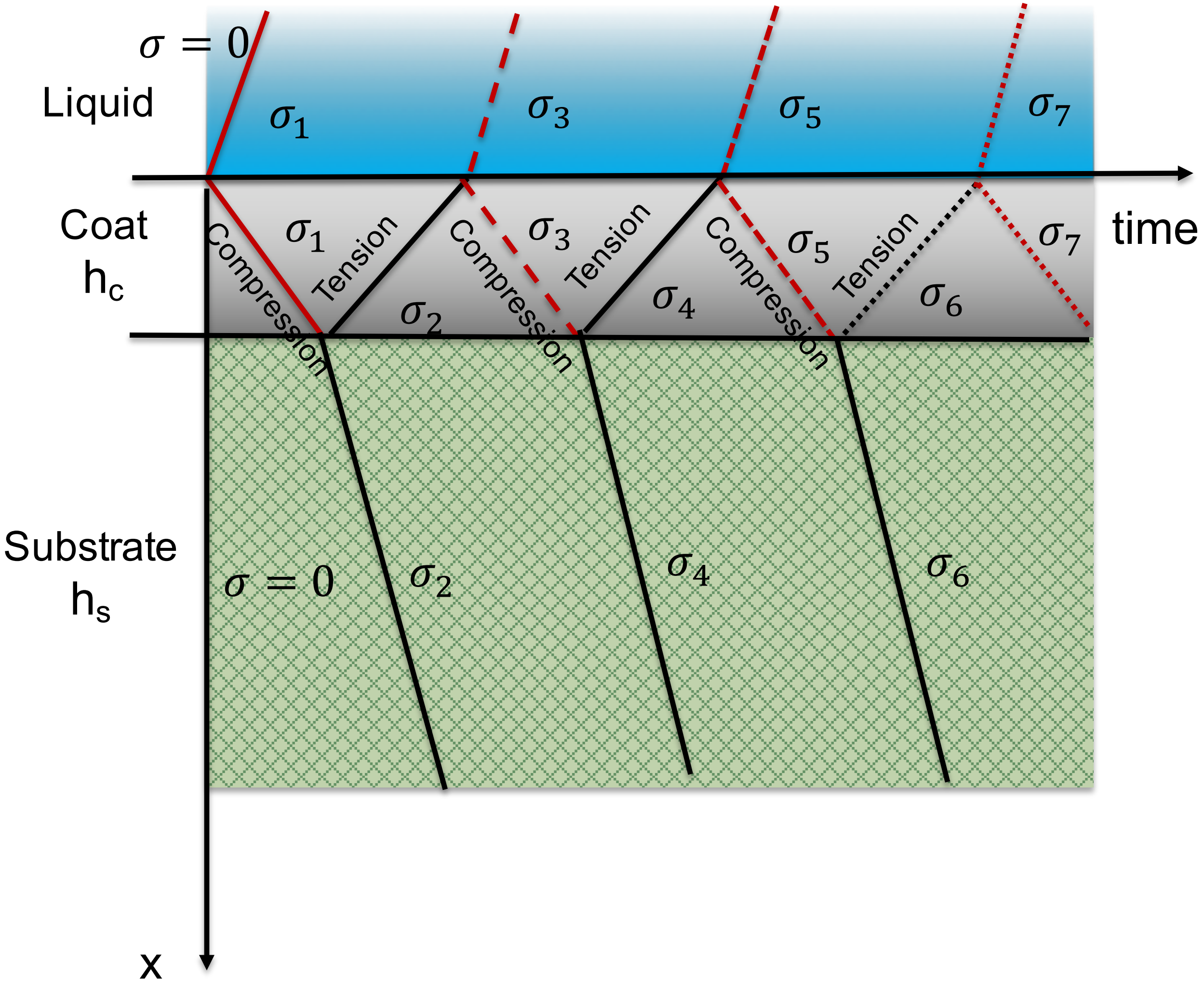


5. On the **modelling of rain drop impact** in wind turbine blades.

- **Liquid impact phenomena. Stress Reduction on the Substrate by Usage of a coating layer**







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

- Liquid impact phenomena. **Modelling to identify suitable coating and substrate and its interface.**

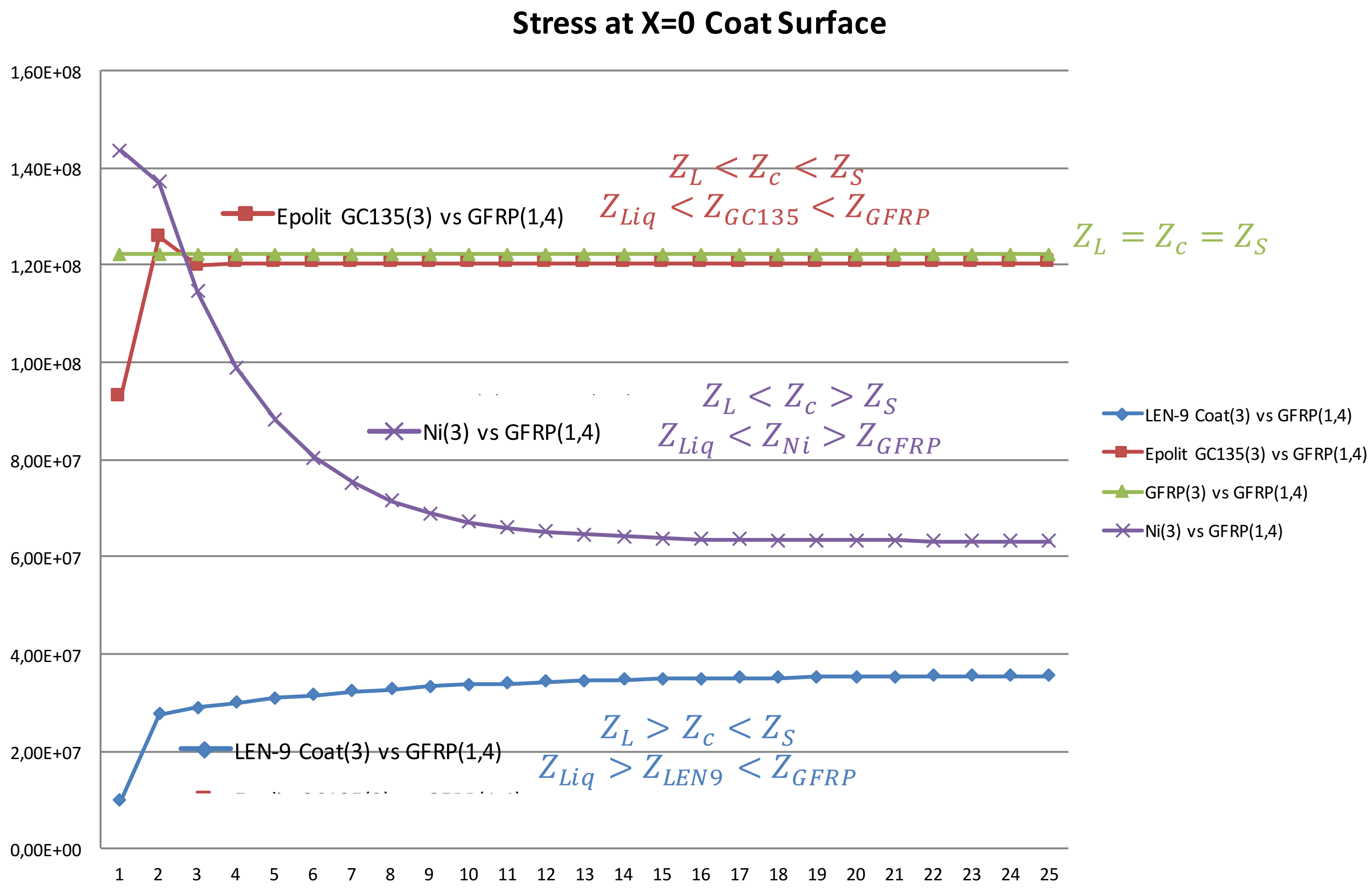
- In order to reduce the stress in the substrate and determine the suitability of the candidate materials for leading edge applications, the **approach** can be used to **identify suitable coating and substrate combinations** and their **potential stress reduction on the substrate interface** and also on the surface.

Stress in the substrate is **reduced** :

$$Z_L < Z_c > Z_S$$
$$Z_L > Z_c < Z_S$$

Stress in the substrate is **enhanced**

$$Z_L < Z_c < Z_S$$
$$Z_L > Z_c > Z_S$$



Stress history (Mpa) depending the number of reflections for different combinations of materials as coating with a substrate of GFRP.
Best Protection system at coat surface for elastomeric coating

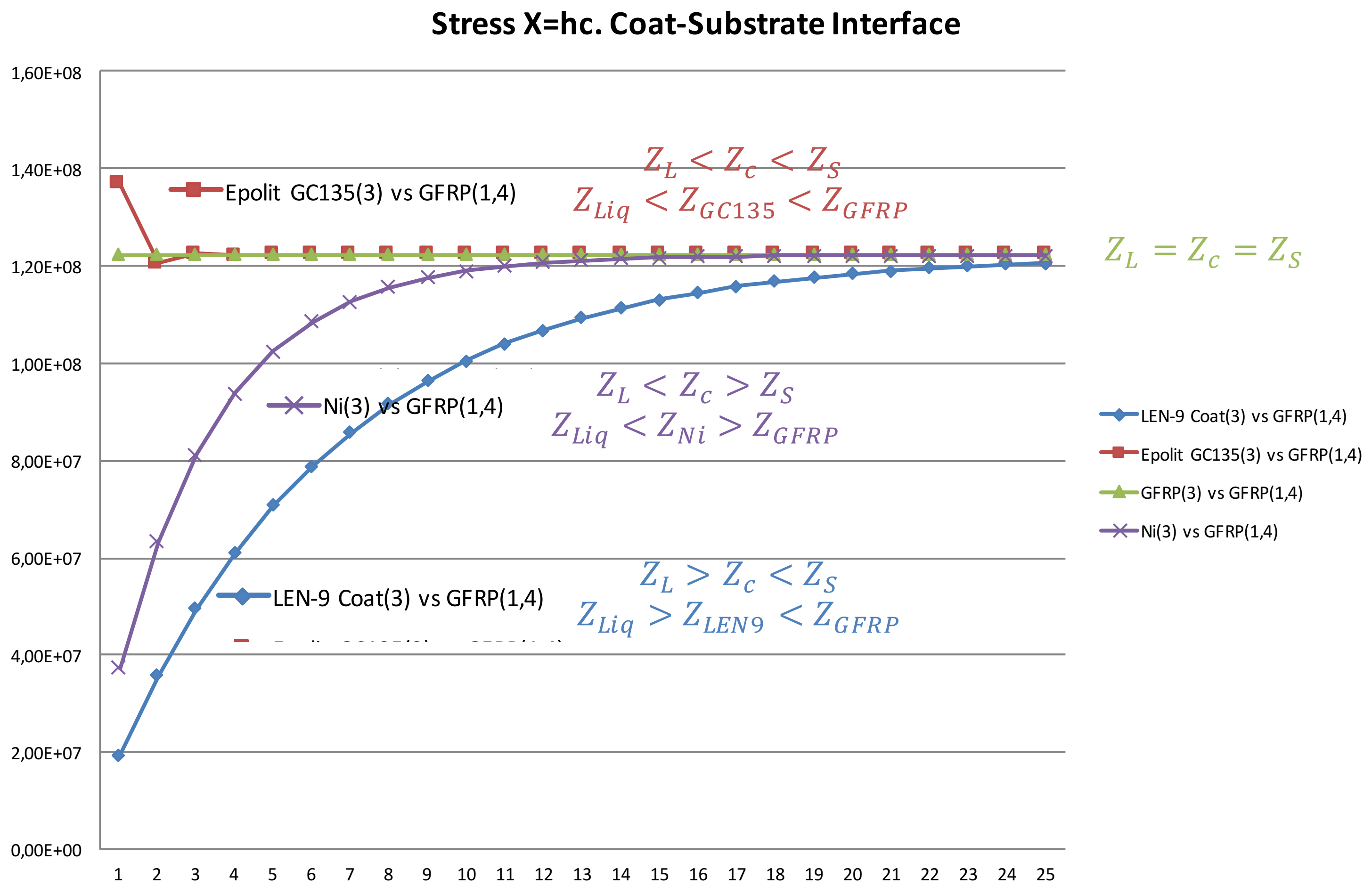
5. On the modelling of rain drop impact in wind turbine blades. WP1

▪ Liquid impact phenomena

- ❑ In case the **substrate** is more rigid (Glass-reinforced epoxy resin composite) delamination may occur and **coating capability of loss/transfer wave energy** will allow avoid damage.

- ❑ An **elastomeric material coating** with low modulus and high resilience will damp the stress waves insofar as the recovery time of the material is rapid. **Lowest impedance value**

- ❑ **Brittle/Rigid coating materials vs elastomeric**

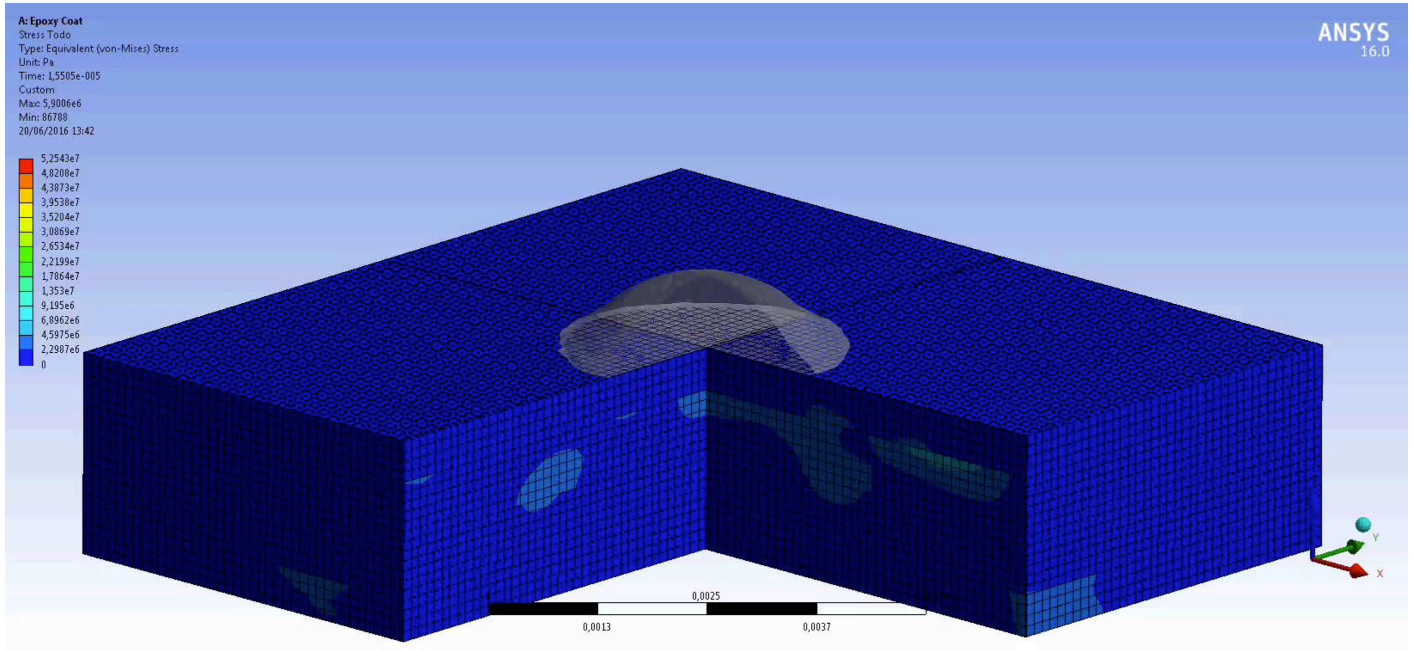


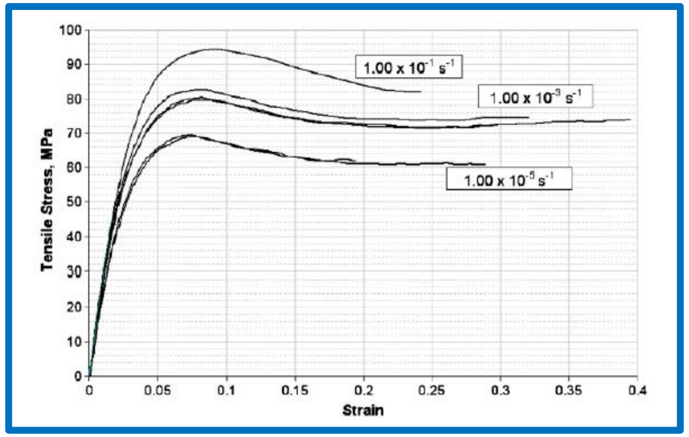
Stress history (Mpa) depending the number of reflections for different combinations of materials as coating with a substrate of GFRP.
Best Protection system at interface for Elastomeric material

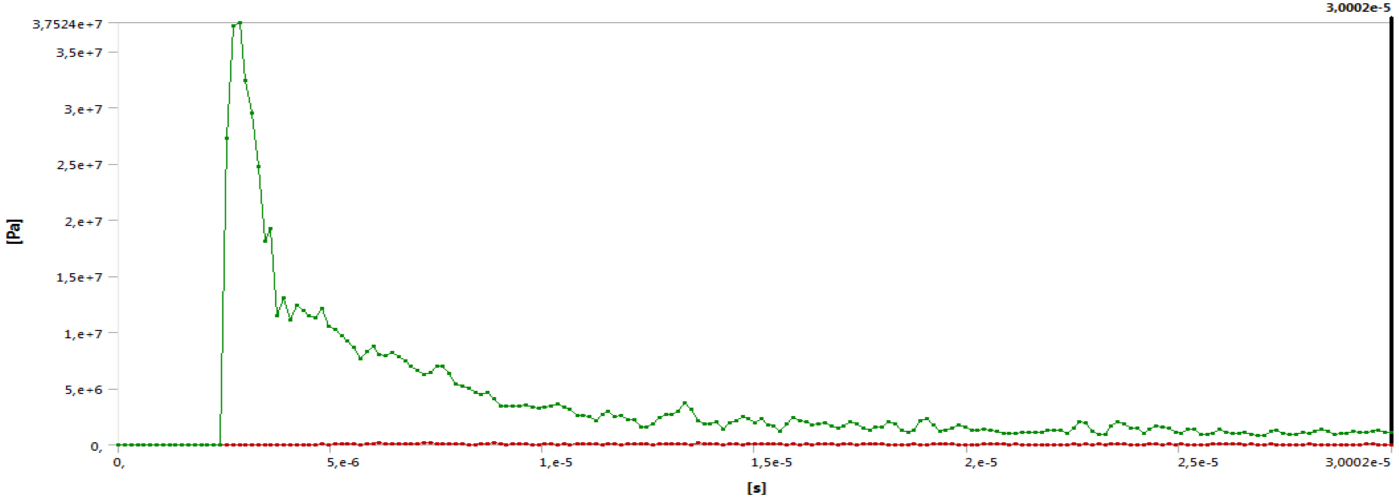
5. On the modelling of rain drop impact in wind turbine blades

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

- **Numerical Modelling.** **Stress Von Misses**
- Coat Epoxy GC E135 Cured. Rigid





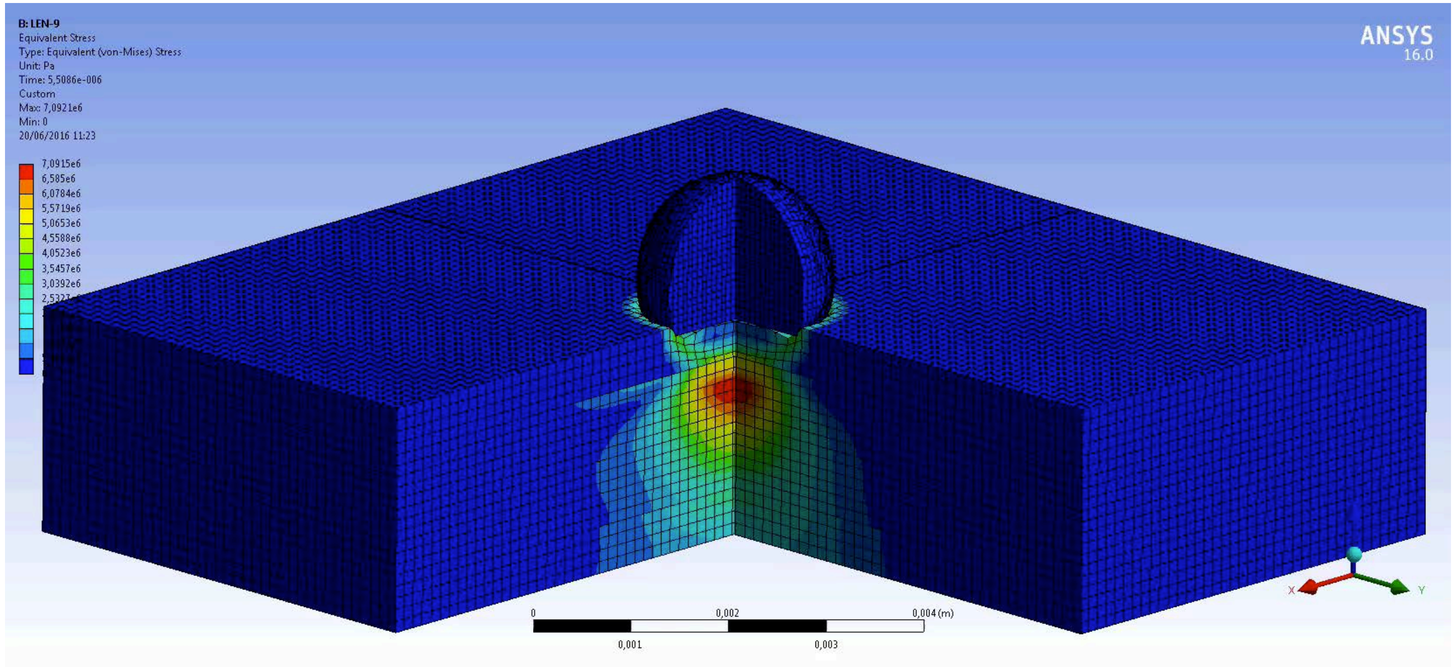


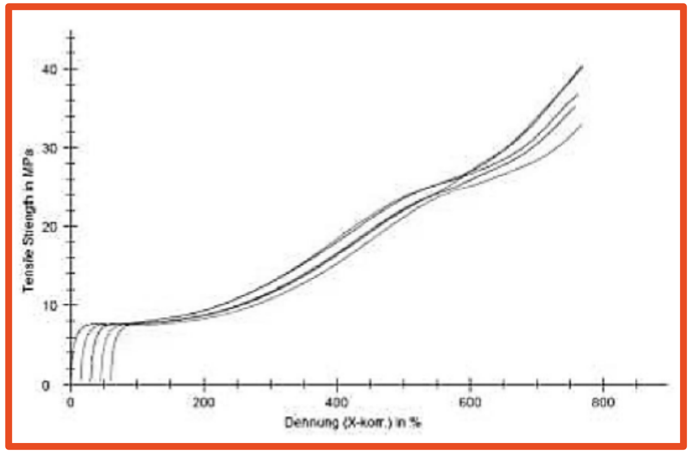
5. On the modelling of rain drop impact in wind turbine blades

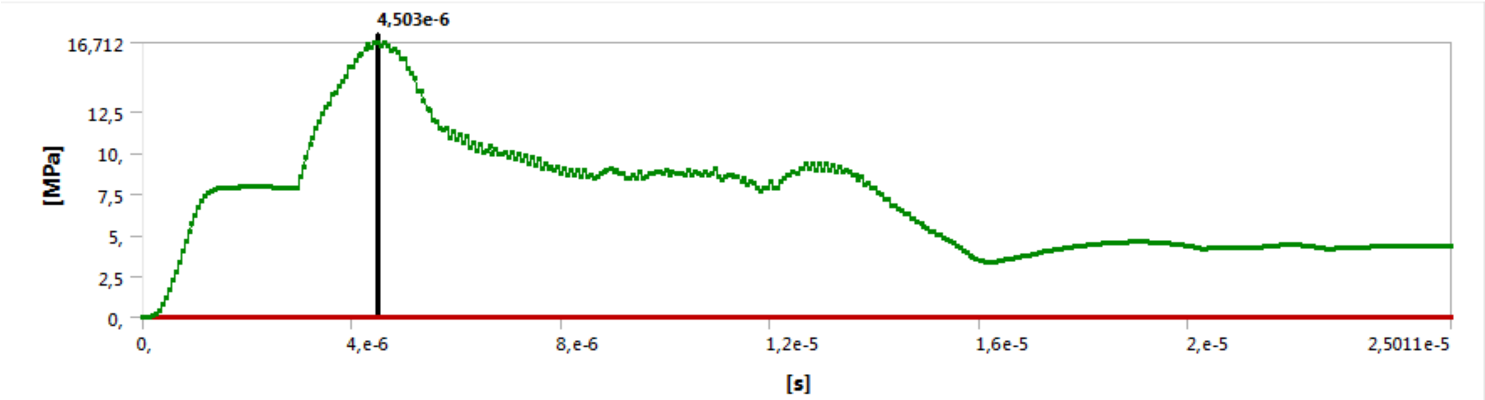
- **Rain droplet impact performance of in-mould coatings + Composite Substrate**

…

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







6. Discussion. Further Work

- The mechanical characterization of coat-laminate interphase, depends on processing (curing) conditions
- The rain erosion testing indicated that samples manufactured with a **higher degree of cure (as determined using DSC), performed worse** in regard to erosion compared to those that had a lower degree of cure.
- **Erosion testing** results **correlate with the peeling tests** where the moulded coating had a lower value of the force of failure for interface adhesion testing.
- The coating-laminate adhesion and erosion is **affected by the repetitive shock wave** caused by the collapsing water droplet on impact, and the mechanical response of the blade structure and coating application and the interactions between them.
- The **stress waves will be transmitted to the substrate interface.** In case the **substrate** is more rigid (Glass-reinforced epoxy resin composite) interface delamination may occur and the **coating capability of loss/transfer wave energy** will allow avoid damage.
- An **elastomeric material coating with low modulus and high resilience will damp the stress waves insofar as the recovery time of the material is rapid** (depending on the dynamic properties and the thickness).
- On Going work: Determine variable properties characterization **through the coat thickness and its vibro-acoustic** properties. Develop r**eflecting interfaces as impact shockwave diminisher**

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