IEA WIND TASK 11 TOPICAL EXPERT MEETING #98

EROSION OF WIND TURBINE BLADES

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On the tools and criteria development for rain erosion performance analysis

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CONTENT OUTLOOK

1. **Motivation.**

2. **Analysis of LEP Performance. Methodology & Technology Inputs**

3. **Study Cases. Tools for material characterization & Erosion Performance Evaluation**
    - **Case 1: Case 1: Computational modelling for Single droplet impact analysis**
    - **Case 2:** Modelling to **identify suitable coating and substrate**. Acoustic mismatch on interface
    - **Case 3: Single droplet impact** analysis for **multilayered** configuration. FO Sensor integration
    - **Case 4: Interface Delamination.** Contact Modelling & Characterization

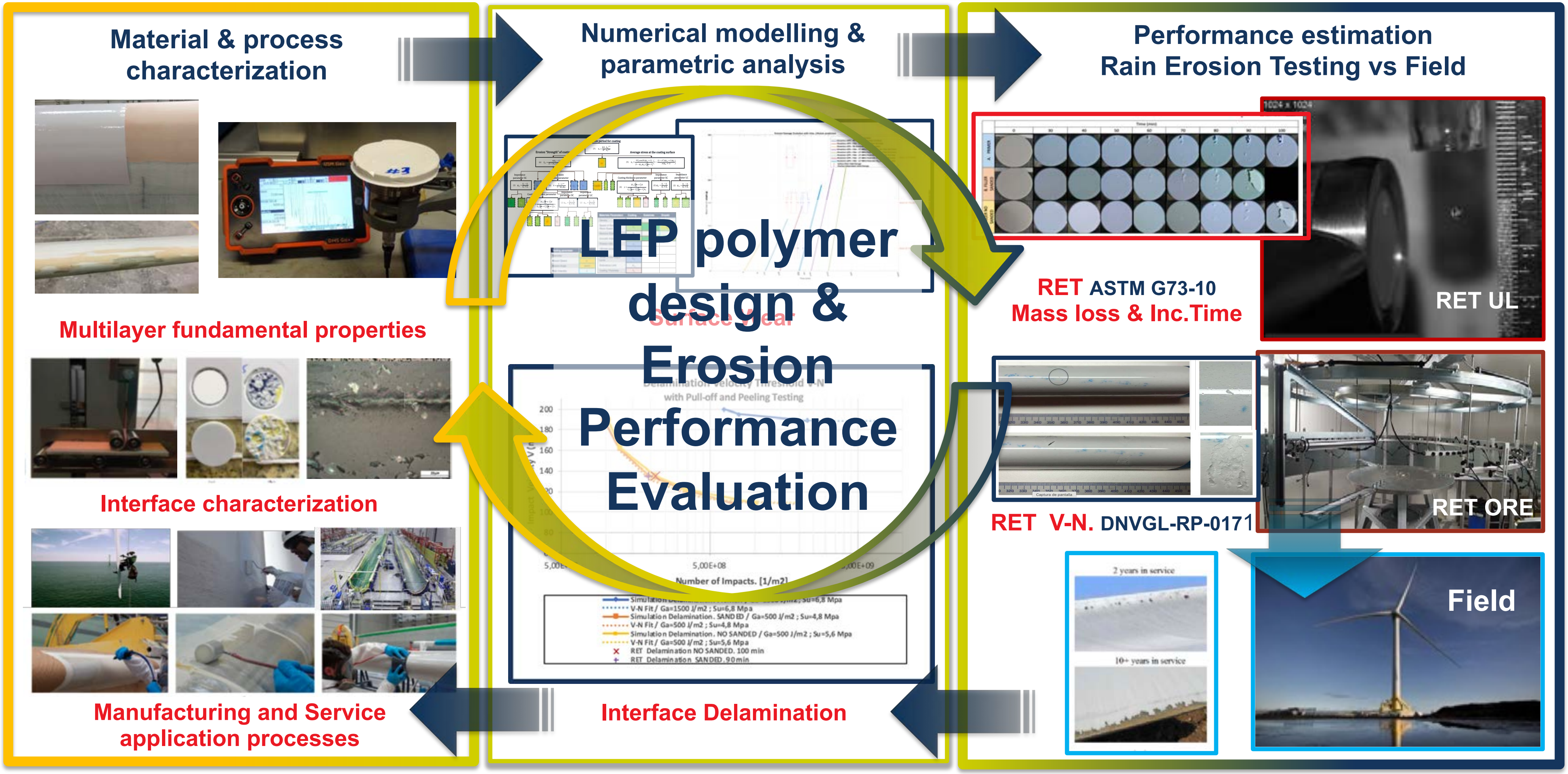
4. **Conclusions and Further Work**

CONCLUSIONS AND FURTHER WORK

- **On the improvement** of appropriate numerical and analytical models as **tools to analyse LEP fundamental material properties that affect erosion** performance. The **modelling framework** allows a **parametric analysis and a guidance** in the selection and modulation of coating properties.
- On the validation of **complex material models** to consider the **highly transient** material behaviour during waterdrop collisions that require to define the range of frequency of its data set **to account for strain rate & stress relaxation** dependence for the **impact event series.** The construction of **impulse response** and the **recovery time** for the computational modelling may be done by the **transformation of the frequency and time domain**.
- **Simplified numerical procedures** to predict both **wear surface erosion and delamination failure** are **used & developed to define criteria** for identifying suitable LEP coating and composite substrate combinations. **RET testing** needs to be used as the experimental **key metric to evaluate the response** of the material and complete the modelling data.
- There is **no current comprehensive model** linking the operational conditions with debonding mechanisms. Research on going to define an approach based on a **cohesive zone model (CZM) based on pull-off and peeling testing** to evaluate the mechanical **response of the multilayer interfaces.** This would allow one to define **debonding failure criteria as a first step** prior of delamination lifetime prediction models.
- Erosion is an **open Research & Development topic** in Wind Industry

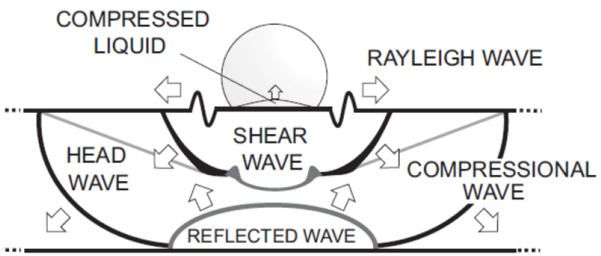
❑ Analysis of LEP Performance

▪ **Methodology &** Technology inputs

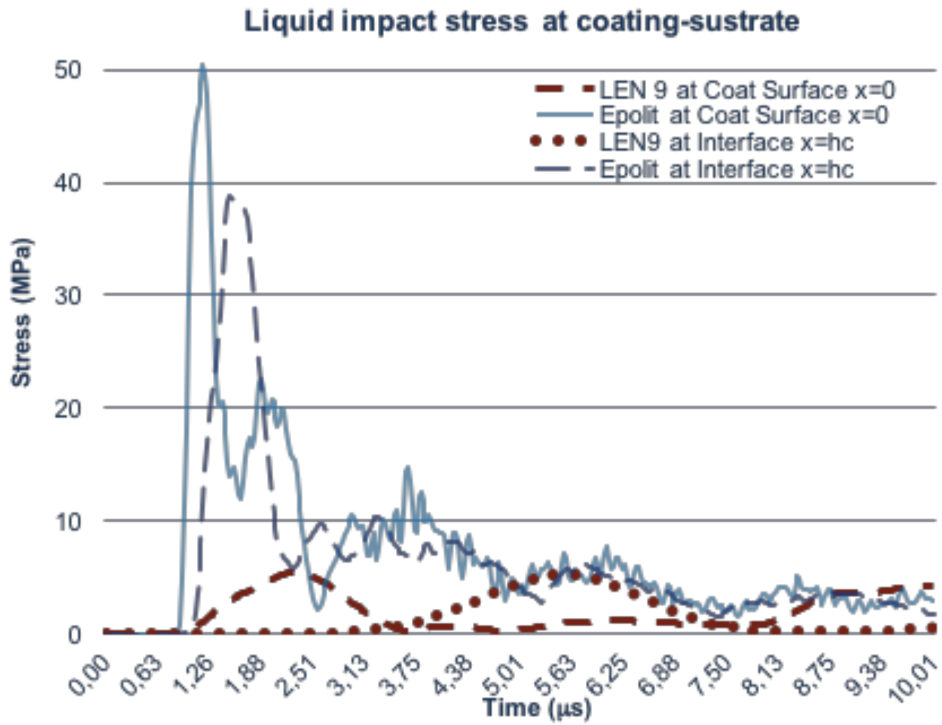


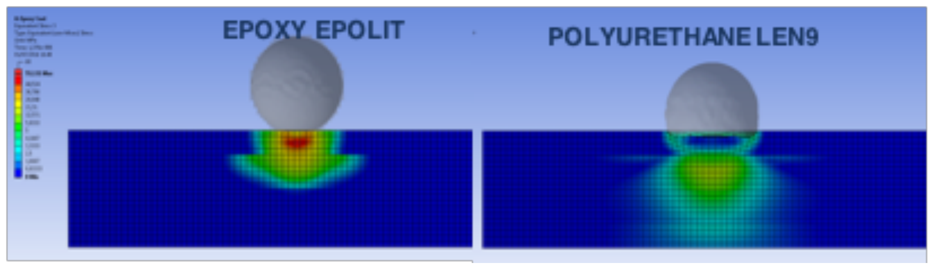
❑ **Case 1:** Computational modelling for **Single droplet impact analysis**

❑ The erosion and interface adhesion are affected by the **shock wave caused by the collapsing water droplet on impact. Laminate blade structure**, **surface preparation, coating application** and the **interactions** between them are related with the stress-strain LEP performance trough the multilayer system.



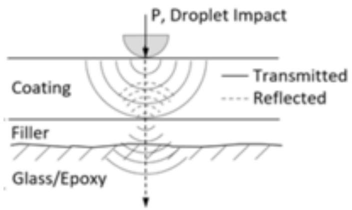
❑ **Understanding the physics of failure.** The analysis of erosion caused by rain droplets shows that the damage is in fact a 3D **dynamic event** resulting in the **propagation of shock waves**.

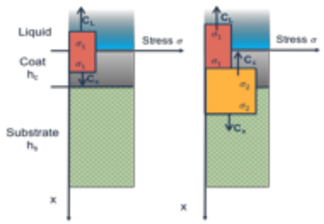


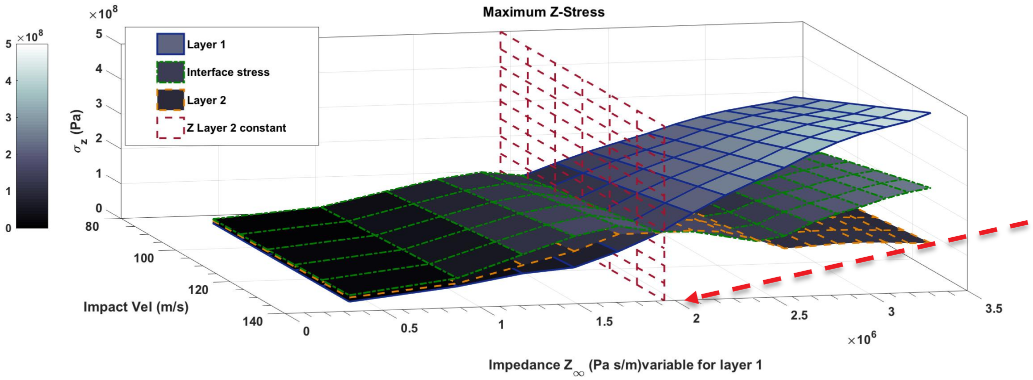


Computational modelling.

Study Case: Modelling to **identify suitable** coating and substrate. **Material Design Factors**





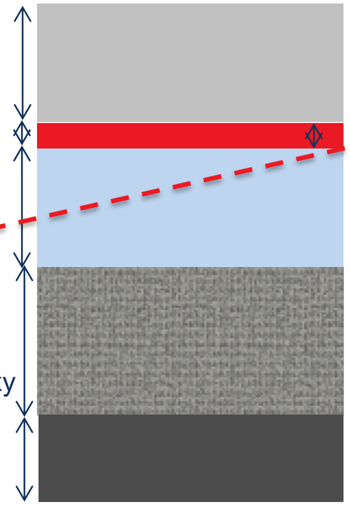


- Maximum Z-Stress evolution in different layers with the impedance computation assuming **E_∞ for a parameter range** on the frequencies of interest and with the **impact velocity defined also as a parameter**. The values are computed for Layer 1 (in blue), Layer 2 (in orange) and their interface (in green) on the central point of impact. It is very interesting to observe that when the impedance value of Layer 1 is higher than a given constant value of Layer 2 (in red), the Maximum Z-Stress occurs on the surface of Layer 1, and when the impedance is lower than this threshold value, it occurs at the interface. This result is very useful for the modelling of **suitable materials combinations** to be used as a multilayer scheme, and **allows one to match the acoustic material properties in order to minimize the stress reflections and transmissions through the laminate thickness**.

Range of parameters. definition

LEP (E_0, E_∞, τ) & $Impact\ (t, V_{impact}, d_{size})$

$F_{WaterHammer}(t, Vimpact, d_{size})$



X_1 $\begin{cases} E_1 = (E_0, E_\infty, \tau, \alpha, \beta) \\ \rho_1 = 1150\ kg/m^3, L_1\ 750\mu m \end{cases}$

X_2 $\begin{cases} E_2 = \textbf{set value}\ (Pa), \\ \rho_2 = 1200\ kg/m^3, L_2\ 50\mu m \end{cases}$

X_3 $\begin{cases} E_3 = cte\ (Pa), \\ \rho_3 = cte\ kg/m^3, L_3\ 950\mu m \end{cases}$

X_4 E_4, ρ_4, L_4

X_5 E_5, ρ_5, L_5

$$u(x, y, z, \omega, E_0, E_\infty, \tau) \approx \sum_{i=1}^{N} \mathbf{X}^i(x,y) \circ \mathbf{Z}^i(z) \circ \mathbf{W}^i(\omega) \circ \mathbf{E}_0^i(E_0) \circ \mathbf{E}_1^i(E_\infty) \circ \mathbf{T}^i(\tau)$$

❑ Computational modelling. Versatile PGD Framework

[…] The interested reader can also refer to the recent published paper at **ECCM18 Proceedings.**


18[TH] EUROPEAN CONFERENCE ON COMPOSITE MATERIALS. ECCM18-ATHENS

Analysis of Liquid Impact Phenomena Affecting Rain Erosion Failure in Wind Turbine Blades. A parametric study

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Abstract. Rain erosion damage, caused by repeated droplet impact on wind turbine blades, is a major cause for concern, even more so at offshore locations with larger blades and higher tip speeds. Due to the negative economic influence of blade erosion, all wind turbine Original Equipment Manufacturers (OEMs) are actively seeking solutions. In most cases, since the surface coating plays a decisive role in the blade manufacture and overall performance, it has been identified as an area where a solution may be obtained. In this research, two main coating technologies have been considered: In-mould coatings (Gel coating) applied during moulding on the entire blade surface and the post-mould coatings specifically developed for Leading Edge Protection (LEP). The coating adhesion and erosion is affected by the shock waves created by the collapsing water droplets on impact. The stress waves are reflected and transmitted to the laminate substrate, so microstructural discontinuities in coating layers and interfaces play a key role on its degradation and may accelerate erosion by delamination. Analytical and numerical models are commonly used to relate lifetime prediction and to identify suitable coating and composite substrate combinations based on their potential stress reduction on the surface and interface. The numerical models usually applied for the analysis of rain erosion impact are limited to a linear elastic response of the polymer subjected to drop impact loads. It is important to note that polymeric materials response depend on temperature and frequency of impact fluctuations. If these parameters are not incorporated in the mechanical modeling, the predicted stresses of the coating materials behavior under impingement may wrongly consider the material capabilities. In order to develop an appropriate multi-parametric approach based on the viscoelastic material characterization, it is also necessary to consider a computational tool that allows one to design and validate the proposed modelling. In this research, a tensional analysis of candidate materials in the temporal and frequency domain is developed. The work is focused on carrying out an exhaustive analysis with the objective of understanding its behavior in the numerical approximations. This work proposes an integral numerical model that links the calculation of stress with the service conditions (temperature, rainfall intensity, impact speed, impact frequency) treated as parameters and considering the construction of the pulsed material response for the computational modeling.

Keywords: wind turbine blades; rain erosion; coatings; leading edge protection; computational modelling ; PGD-Proper Generalized Decomposition

- ❑ The PGD solution in the separated form has been **implemented** on a first application case in **Leading edge protection** systems design based on the modelling parameters to be analysed: layer **thickness, Temperature, frequency, storage modulus, density, relaxation time…**

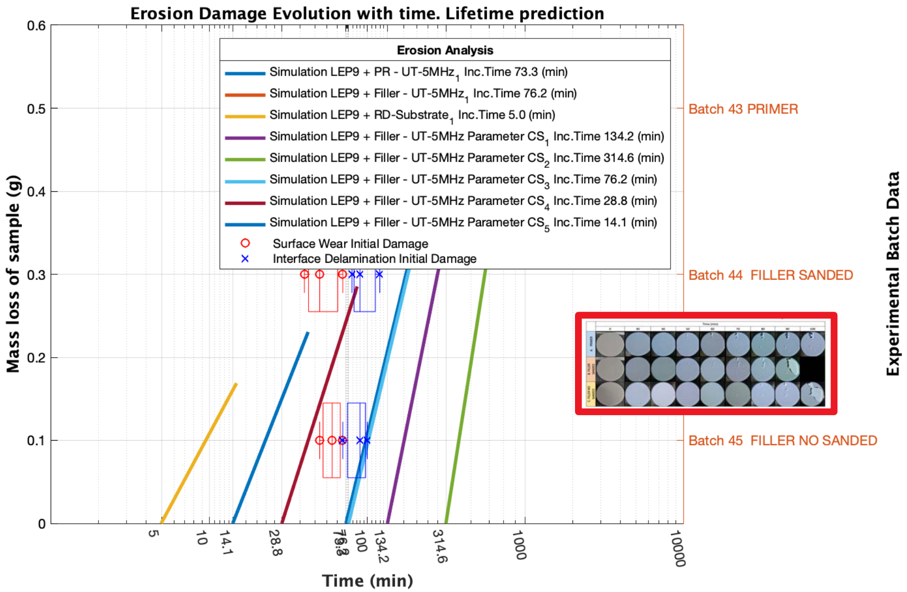
$$u\left(x, y, \varphi_z, \omega, L_{1,} \ldots, L_{\mathcal{L}}, T\right) \approx \sum_{i=1}^{N} \mathbf{X}^i(x, y) \circ \mathbf{Z}^i(\varphi) \circ \mathbf{W}^i(\omega) \circ \mathbf{L}_1^i(L_1)\ \mathbf{E}_1^i(E_\infty)$$

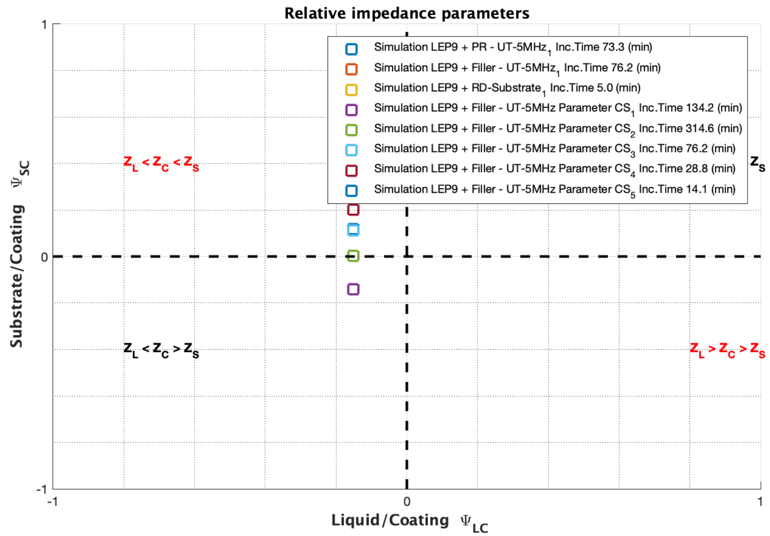
$$u(x, y, z, \omega_1, E_s, \rho_1, E_2, \rho_2, E_3, \rho_3) \approx \sum_{i=1}^{N} \mathbf{X}^i(x, y) \circ \mathbf{Z}^i(z) \circ \mathbf{W}^i(\omega) \circ \mathbf{E}_s^i(E_s) \circ \mathbf{P}_1^i(\rho_1) \circ \mathbf{E}_2^i(E_2) \circ \mathbf{P}_2^i(\rho_2) \circ \mathbf{E}_3^i(E_3) \circ \mathbf{P}_3^i(\rho_3)$$

$$u(x, y, z, \omega, E_0, E_\infty, \tau) \approx \sum_{i=1}^{N} \mathbf{X}^i(x, y) \circ \mathbf{Z}^i(z) \circ \mathbf{W}^i(\omega) \circ \mathbf{E}_0^i(E_0) \circ \mathbf{E}_1^i(E_\infty) \circ \mathbf{T}^i(\tau)$$

3. Study Cases. Tools for material characterization & Erosion Performance Evaluation

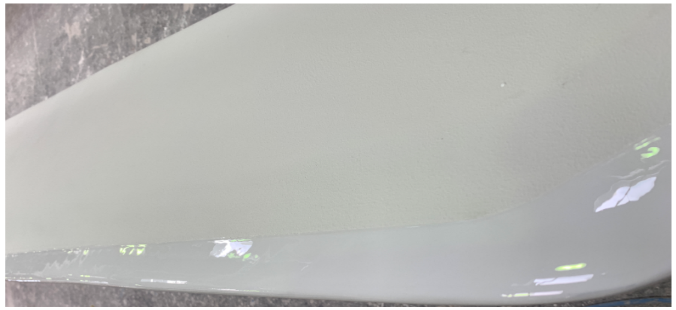
❑ **Case 2:** Modelling to **identify suitable coating and substrate**. Acoustic mismatch





❑ Depending on the **relative acoustic properties LEP-Substrate**, the erosion **lifetime can be optimized**





3. Study Cases. Tools for material characterization & Erosion Performance Evaluation

- **Case 2:** Modelling to **identify suitable coating and substrate**. Acoustic mismatch

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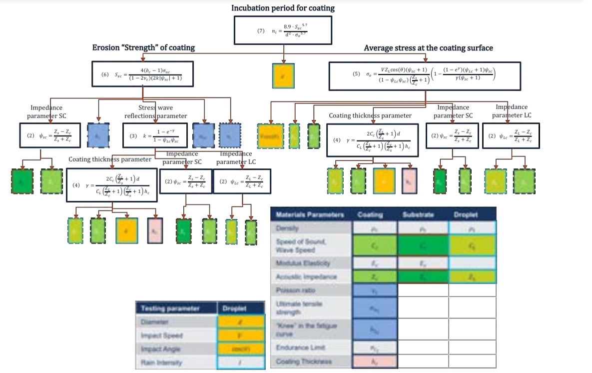
$$\left.\begin{aligned} n_i &= n_i(d, S_{ec}, \sigma_o) \\ S_{ec} &= S_{ec}(b_c, \sigma_{uc}, \nu_c, k, \psi_{sc}) \\ \sigma_o &= \sigma_o(V, Z_L, \psi_{sc}, \psi_{Lc}, \gamma) \\ &\vdots \end{aligned}\right\} \Longrightarrow n_i = n_i(b_c, \sigma_{uc}, \nu_c, V, C_L, C_c, C_s, \rho_L, \rho_c, \rho_s, h_c, d)$$

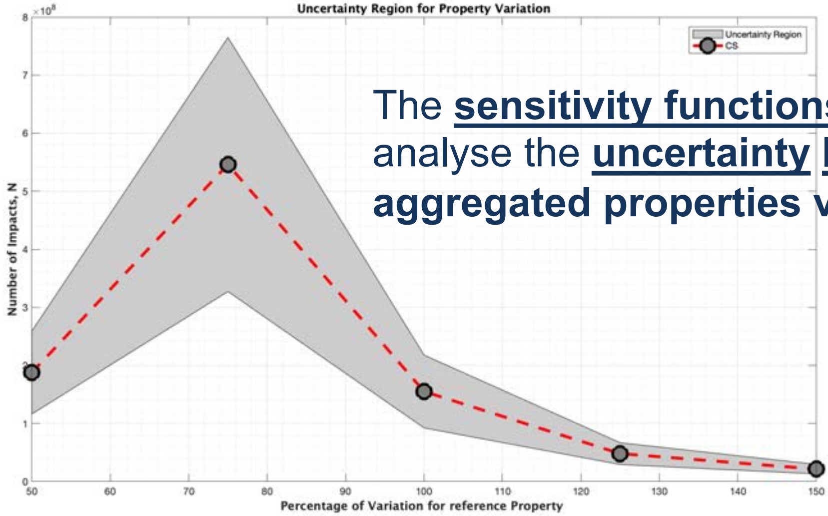


$$dn_i = \frac{\partial n_i}{\partial b_c} db_c + \frac{\partial n_i}{\partial \sigma_{uc}} d\sigma_{uc} + \frac{\partial n_i}{\partial \nu_c} d\nu_c + \frac{\partial n_i}{\partial V} dV + \frac{\partial n_i}{\partial C_L} dC_L + \cdots$$

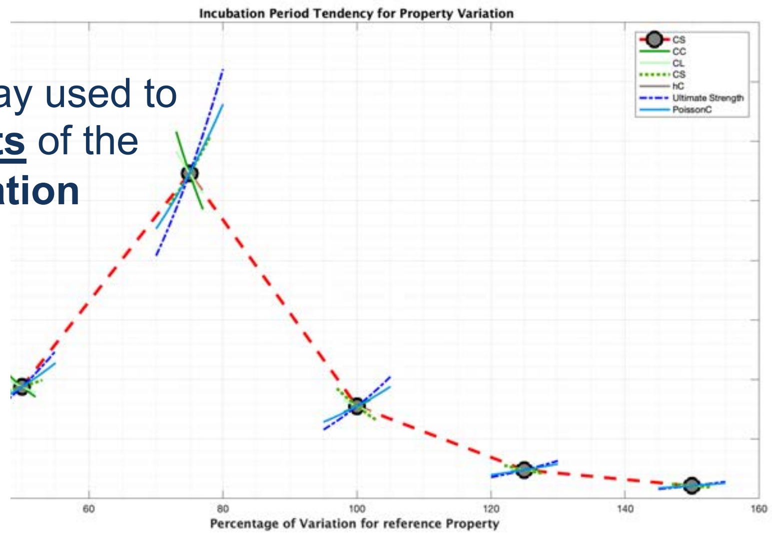
the variation on
given property,
dependence w

$$\frac{\partial n_i}{\partial \sigma_{uc}} = \Big(\frac{\partial}{\partial}$$

Analysis of the ***varia***
different material ca
coating property suc



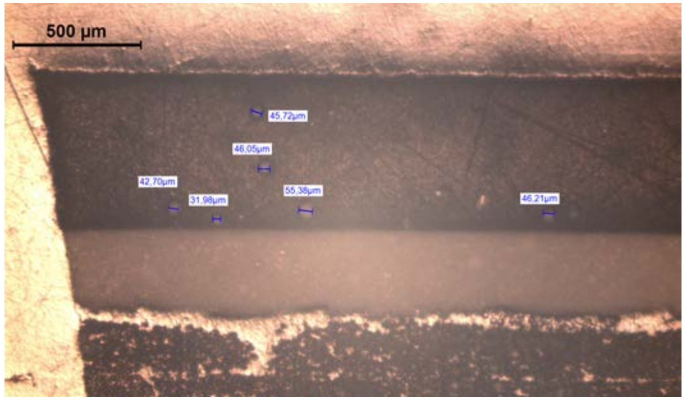
The **sensitivity functions** may used to analyse the **uncertainty limits** of the **aggregated properties variation**



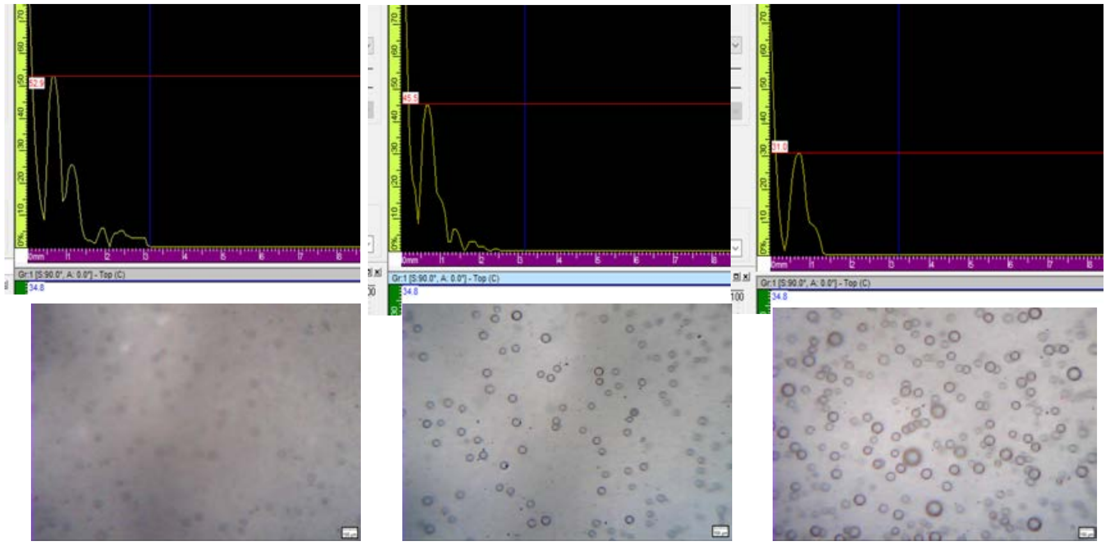
👍 The **optimized selection of the filler** may increase lifetime by means of **stress reduction at interface**
👎 But the same argument of **LEP-substrate impedance mismatch** may **lower the lifetime.**

❑ **Case 2:** Modelling to identify suitable coating and substrate. **Acoustic mismatch**

- ❑ Coating **capability of loss/transfer wave energy** will allow avoid damage
- ❑ **Work in progress**: Determine **variable properties characterization through the thickness** and its vibro-acoustic properties. Develop **reflecting interfaces (void content)** as impact shockwave diminisher.



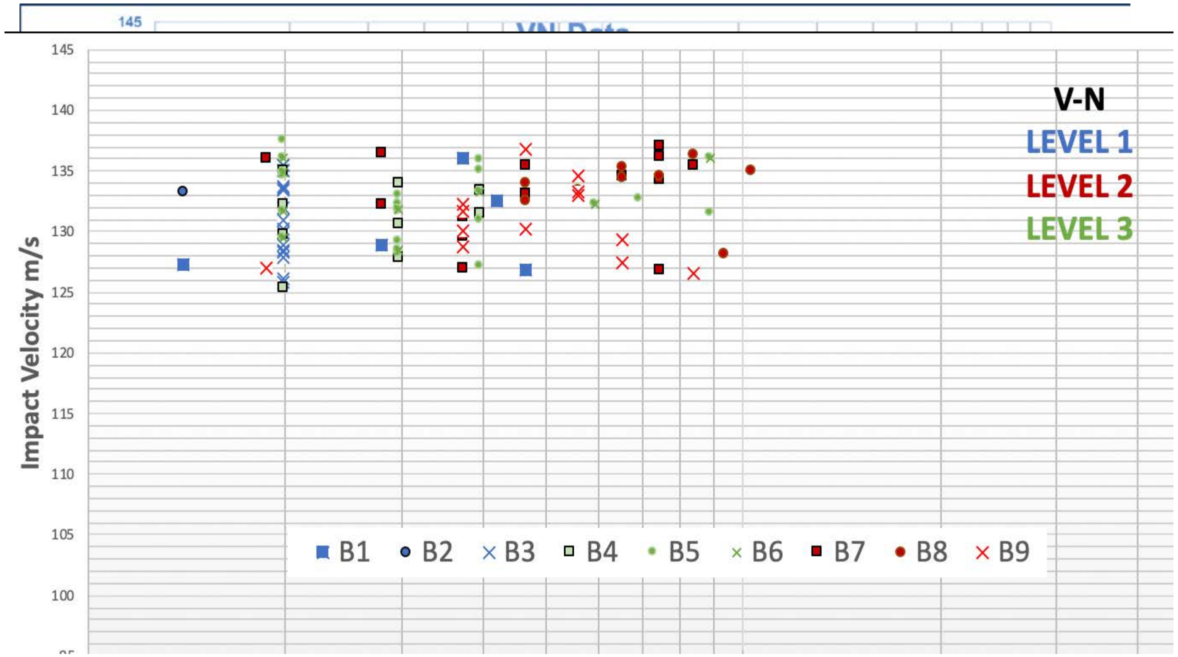
Coating acoustic reflected wave variation depending on void content



👍 The **more void content** the better for **coating impedance reduction effect for stress attenuation**
👎 But void acts as **stress concentrator** [2], so **cracking initiation and propagation may be** enhanced.

- ❑ The **capability of LEP thickness** will act **circumventing the negative bubble effect** on surface. **Droplet size-void size ratio** to be analyzed. **On going studies**

- **Analysis of Top Coating Performance depending on application issues.**
  - <u>**Void content**</u> affecting erosion damage anticipation



✓ **Number of of bubbles/voids** in a RET sample **<u>does not correlate</u>** with the **Incubation time** for initial failure.

✓ **Number of of bubbles/voids** in a RET sample **<u>correlates</u>** with the **number of failure locations** in same coupon.

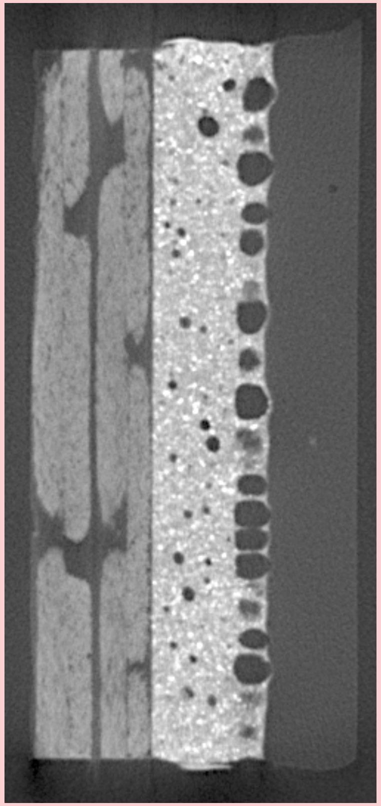
👎 But void acts as **stress concentrator** [2], so **cracking initiation and propagation** may be enhanced.

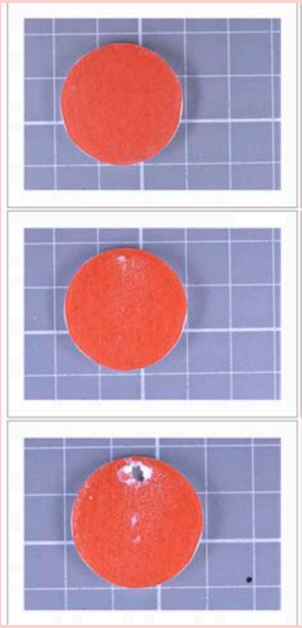
The **<u>capability of LEP thickness</u>** will act **<u>circumventing the negative bubble effect</u>** on surface.
Droplet size-void size ratio to be analyzed. On going studies

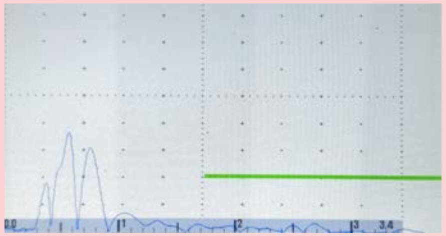
3. Study Cases. Tools for material characterization & Erosion Performance Evaluation

- **Case 2:** Modelling to **identify suitable coating and substrate**. Acoustic mismatch

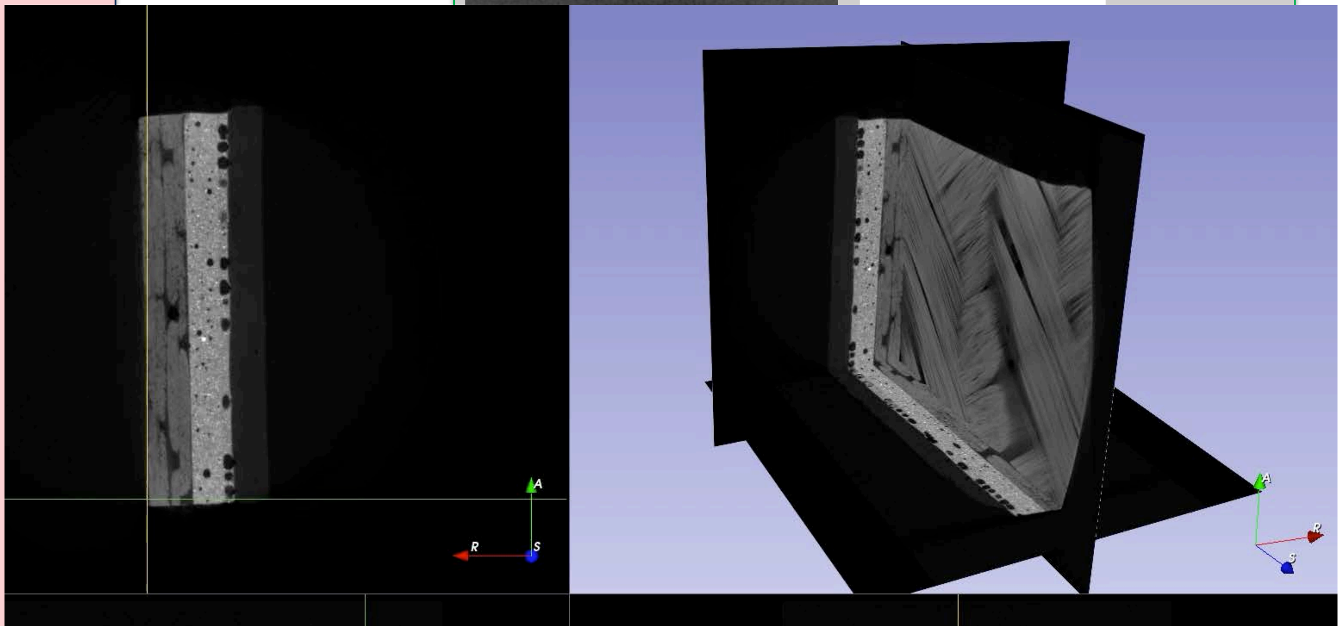
- **On the Development Criteria** for **processing internal defects (Bubbles)** on LEP multilayer system

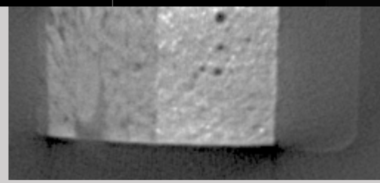


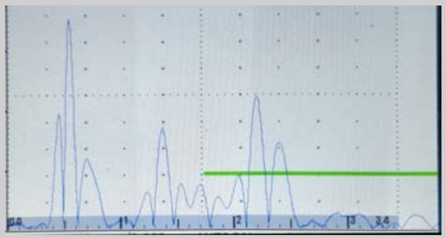




Damaged 45 min RET.







No Damage 900 min RET.

❑ **Case 3: Single droplet impact analysis** for multilayered configuration. **FO Sensor integration**

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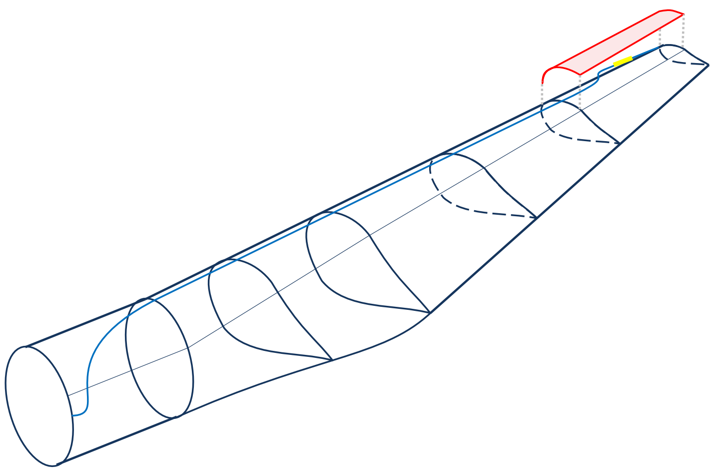
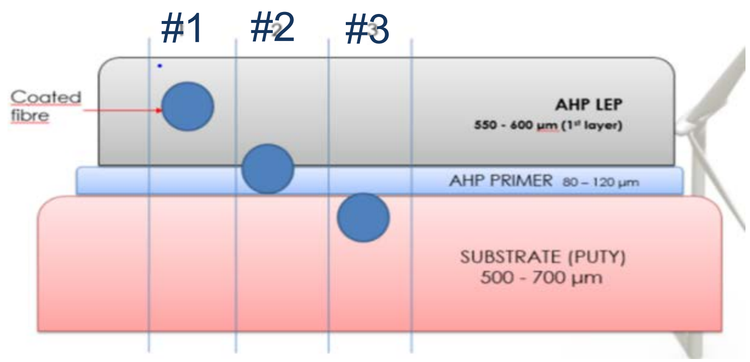
❑ Analysis of **top coating performance** in the **Integration of fiber optics sensors** for leading edge erosion monitoring. In order to study this sensor principle for LEP coatings, **two main questions needed to be answered:**

1. *Is the **mechanical stability** of the sensor fibres in the LEP coating sufficient to perform measure erosion*? Especially so, since significant **droplet impact forces** act on the coating (and the fibre).

2. *Are the **LEP** formulation, **moisture transport** and mechanical properties (relative stress/strain) **compatible** with the moisture **sensing fibres to function as an erosion sensor**?*





❑ The **sensor feasibility** is evaluated regarding **sensor location** It's performance has been evaluated at **three positions regarding humidity detection and LEP lifetime** when running rain erosion tests.

❑ **Case 3: Single droplet impact analysis** for multilayered configuration. **FO Sensor integration**

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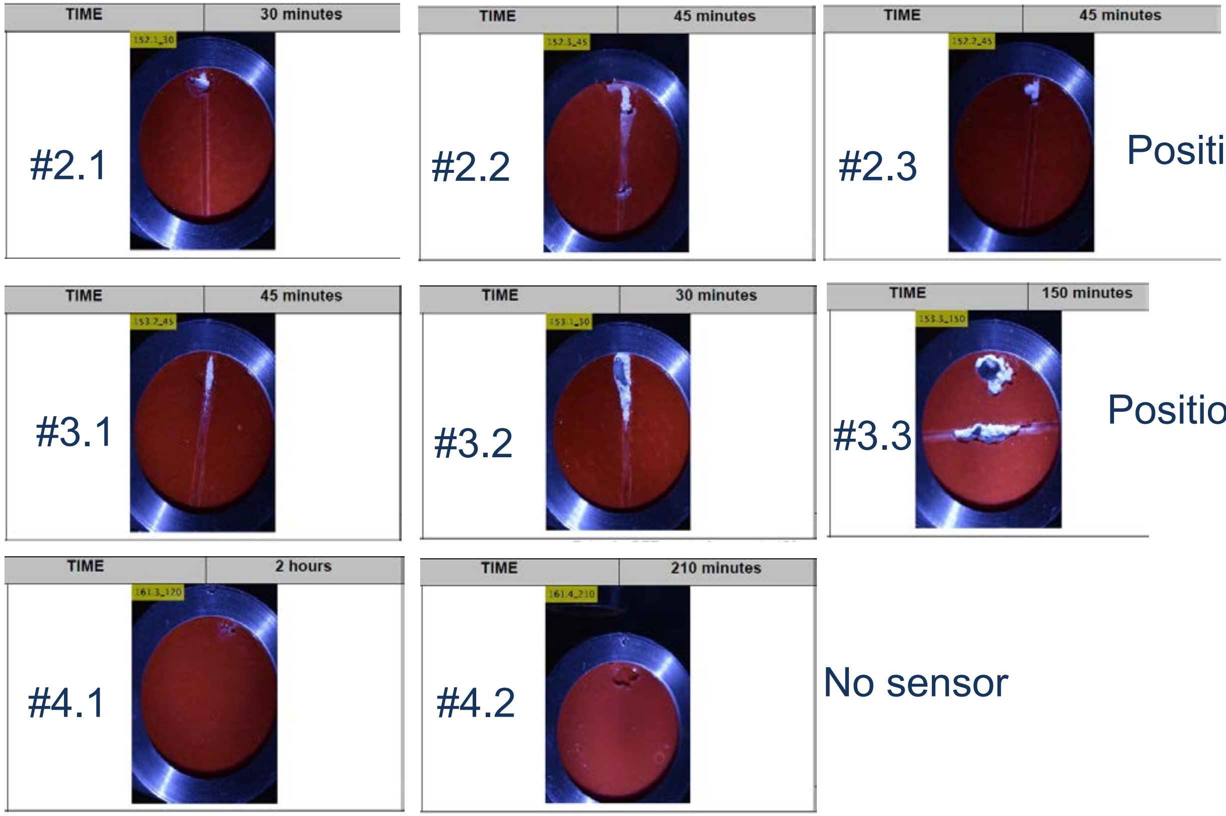
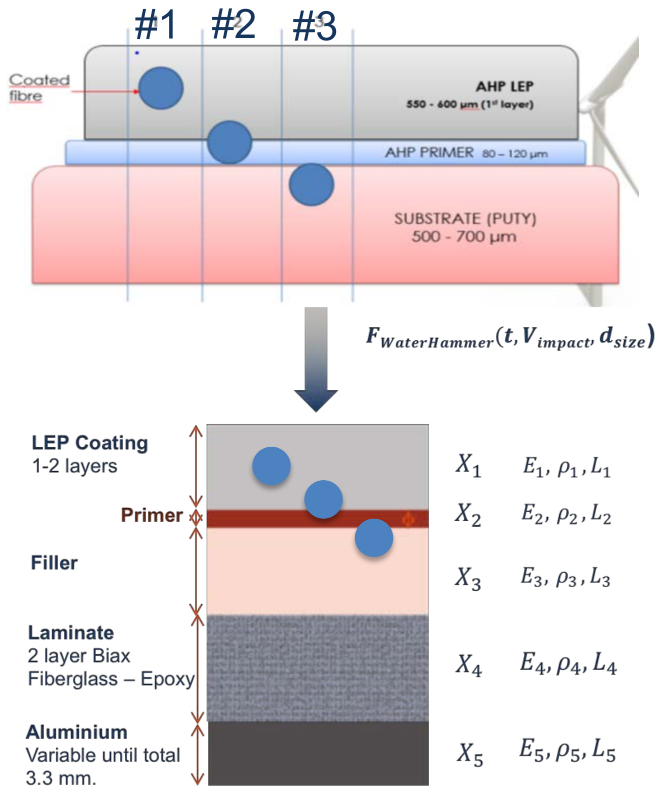
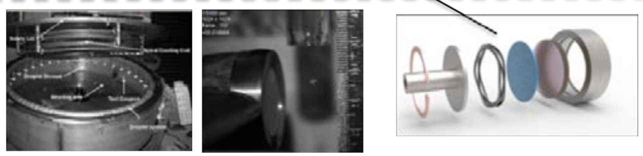
❑ RET samples with TNO sensor for Limerick WARER.

System Configuration. Sensor Location Effect





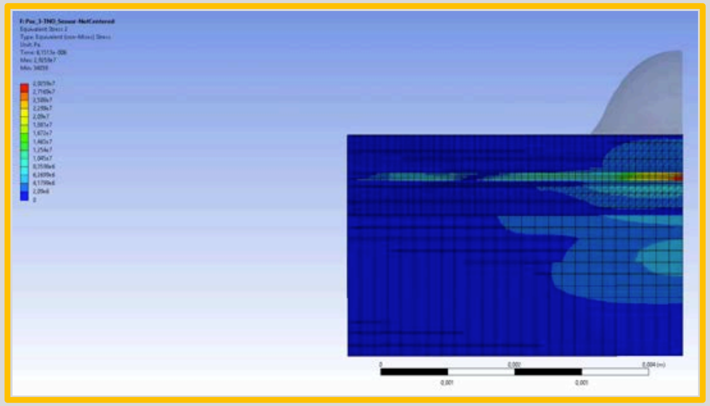


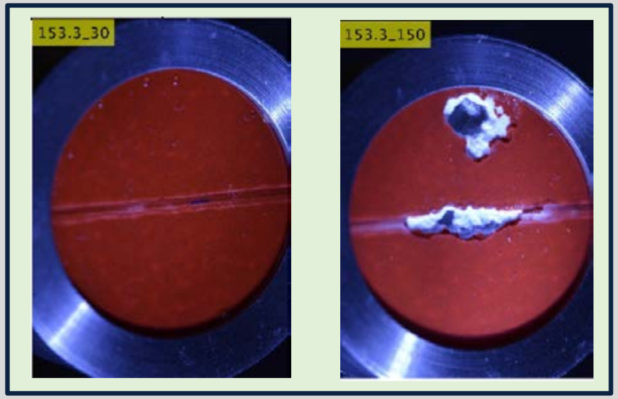
❑ **Negative Effect** in all cases. To better understanding and analysed

❑ **Case 3: Single droplet impact analysis** for multilayered configuration. **FO Sensor integration**

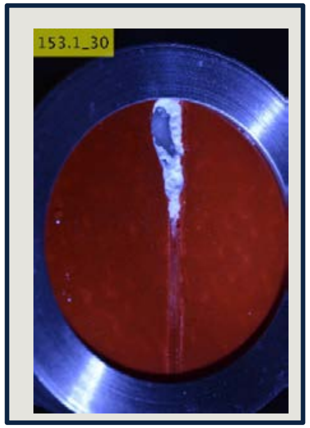
- ❑ RET samples with TNO sensor for Limerick WARER.

  System Configuration**.** Sensor Location Effect **& Distance to droplet impact. 3D analysis required**

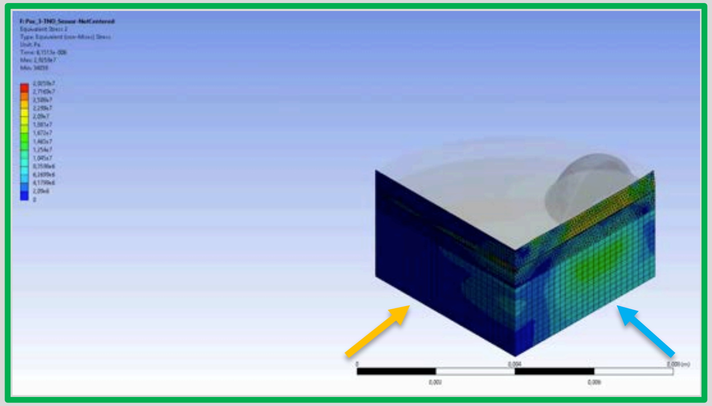


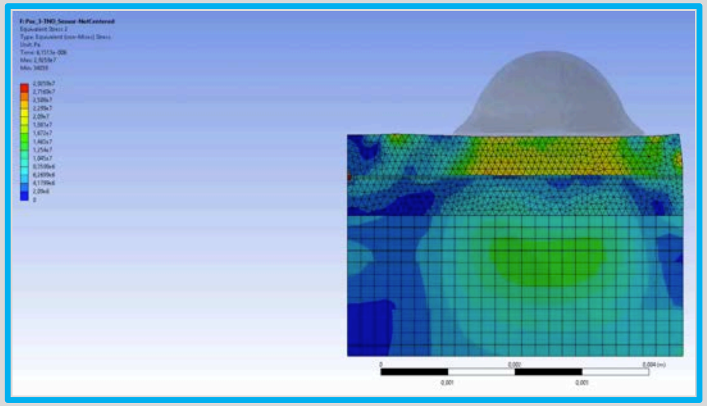


POSITION 2.
SAMPLE 152



POSITION 3
SAMPLE 153





- ❑ **Sensor fibre acts** a medium for fast **propagation of impact stress waves**

❑ **Case 3: Single droplet impact analysis** for multilayered configuration. **FO Sensor integration**

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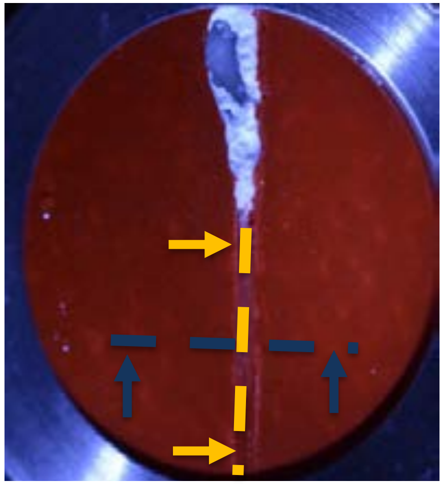
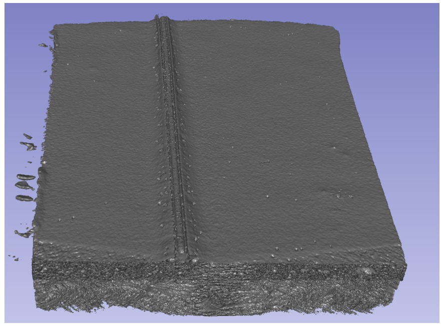
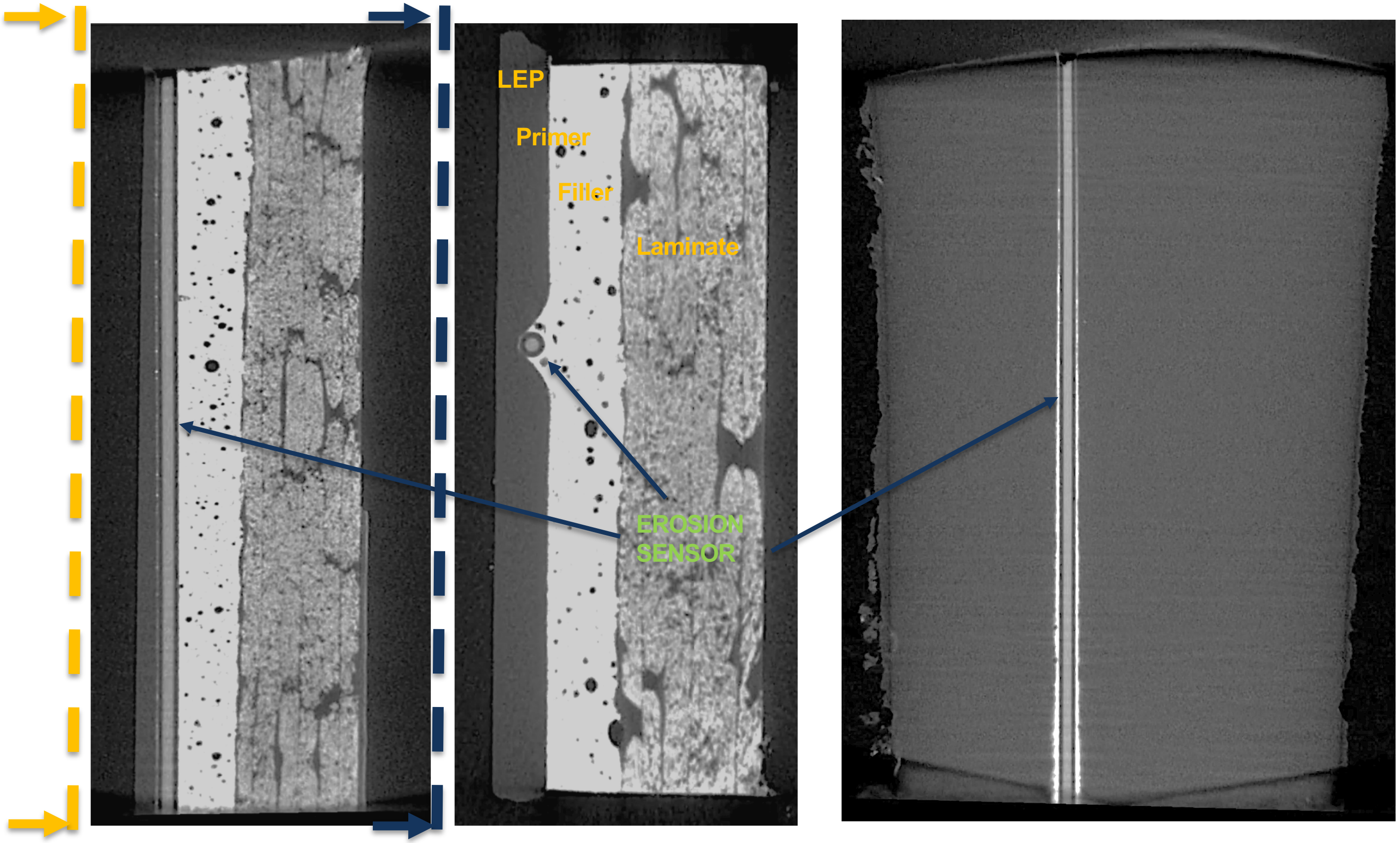
❑ **MicroCT Testing.** System Configuration. Sensor Location Effect







Sensor oriented vertically in position 2**. Previous To Damage**

- **Case 3: Single droplet impact analysis** for multilayered configuration. **FO Sensor integration**

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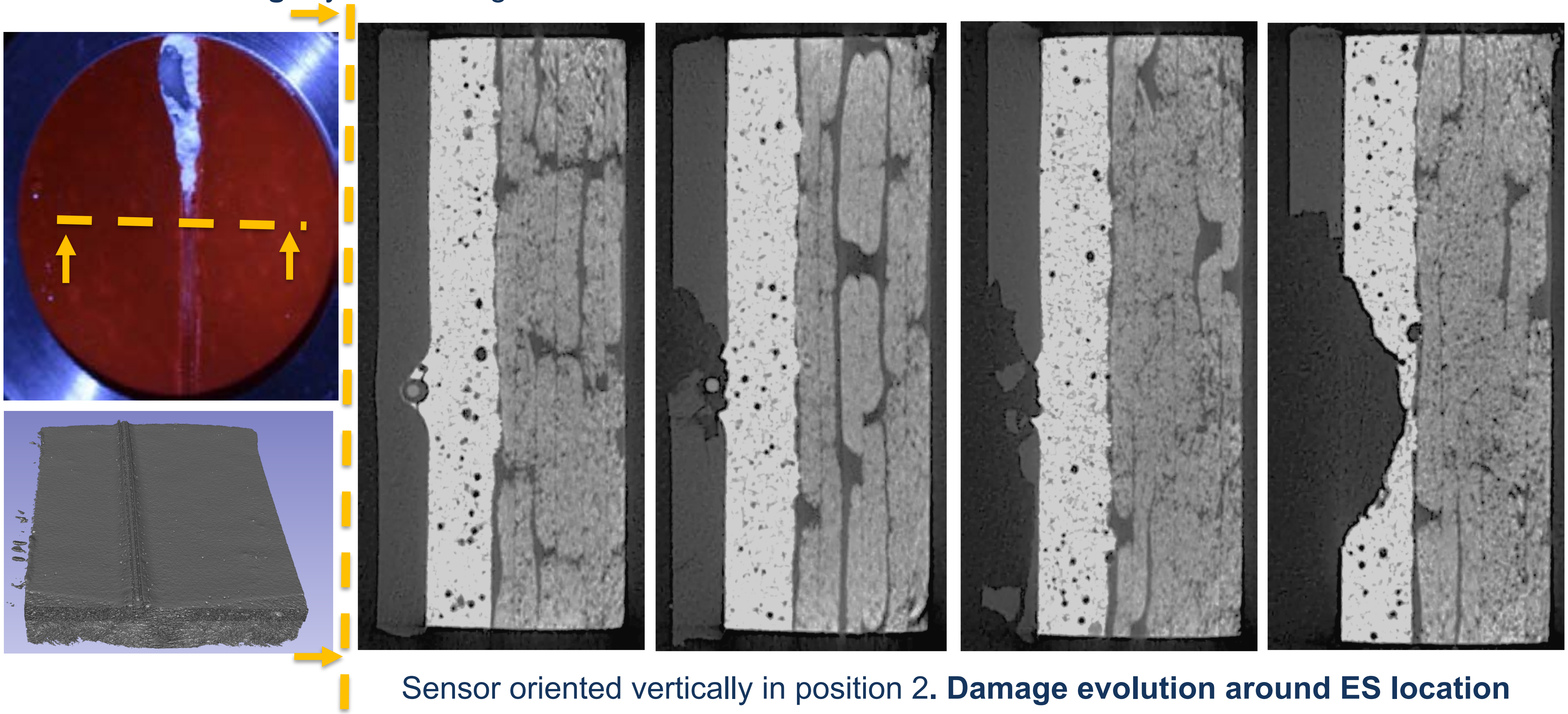
- **MicroCT Testing.** System Configuration. Sensor Location Effect

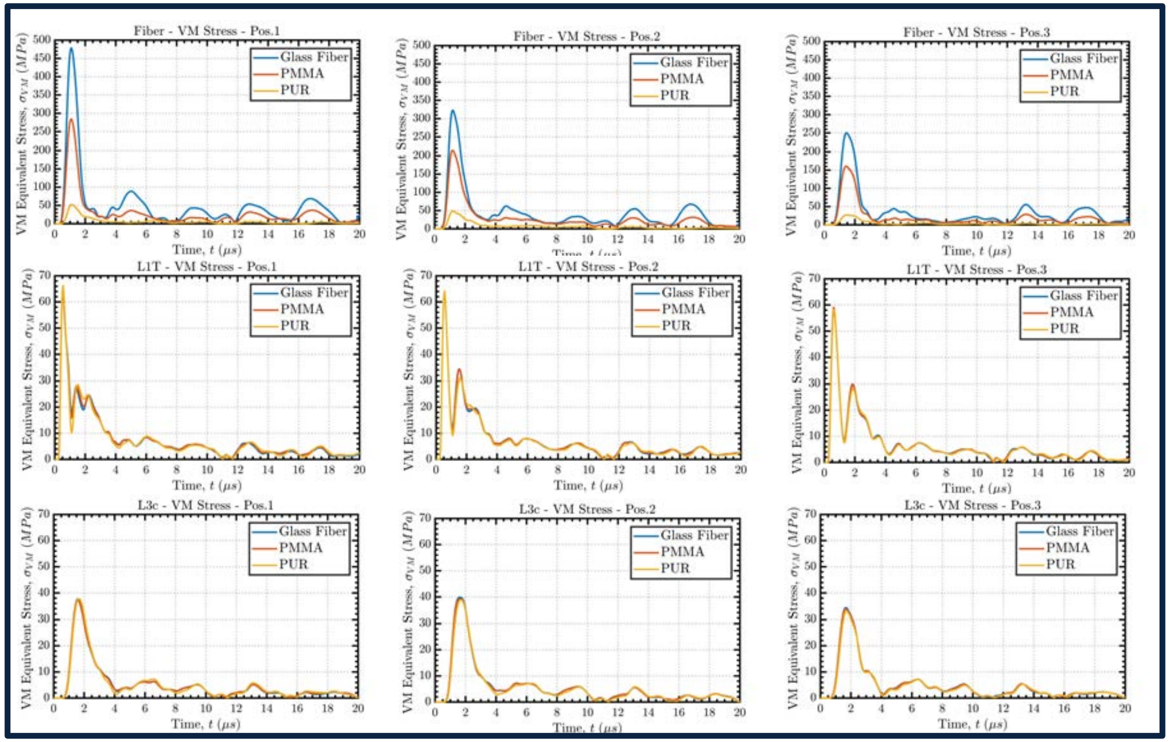


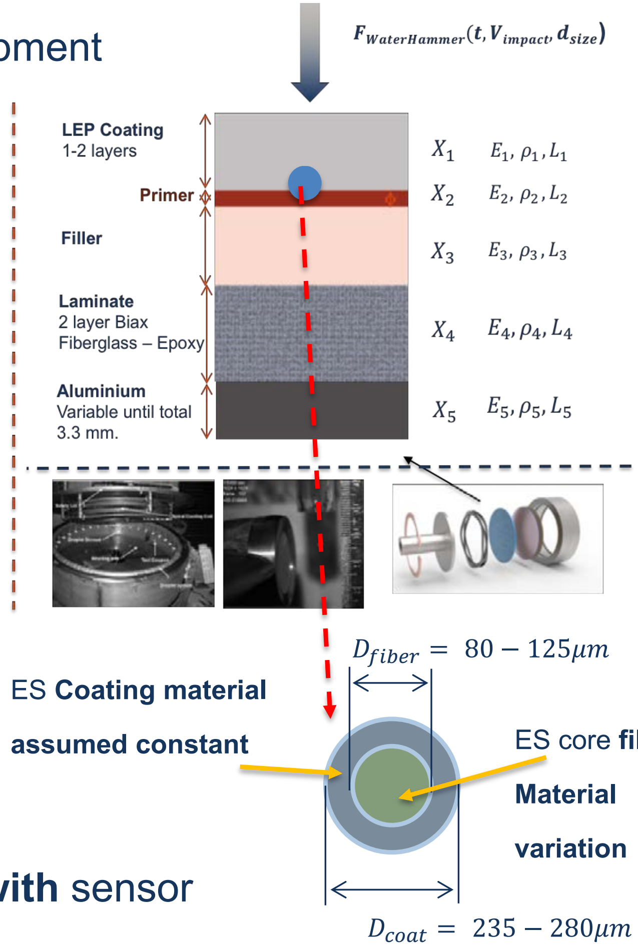
Sensor oriented vertically in position 2**. Damage evolution around ES location**

❑ **Case 3: Single droplet impact analysis** for multilayered configuration. **FO Sensor integration**

❑ Rain droplet Single impact Simulation of RET samples with TNO sensor for Limerick WARER.

To **match acoustic relative properties on interfaces**. Material development





❑ Stress on ES fibre is maximum and Stress on LEP has **<u>no correlation </u>with** sensor **core fibre material** variation. **<u>ES coating material provoques failure.</u>**

❑ **Case 4: Interface Delamination.** Contact Modelling & Characterization

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❑ **Effect of primer** on the performance of Leading Edge Protection (LEP) coatings

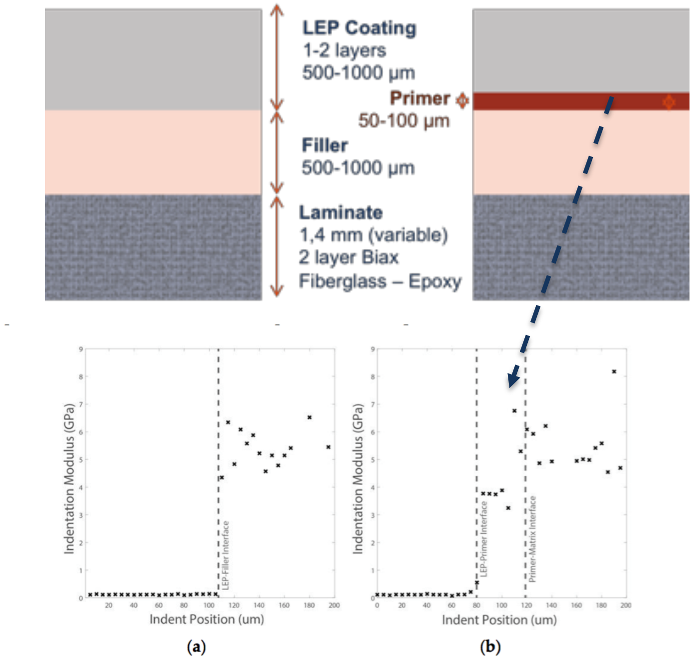
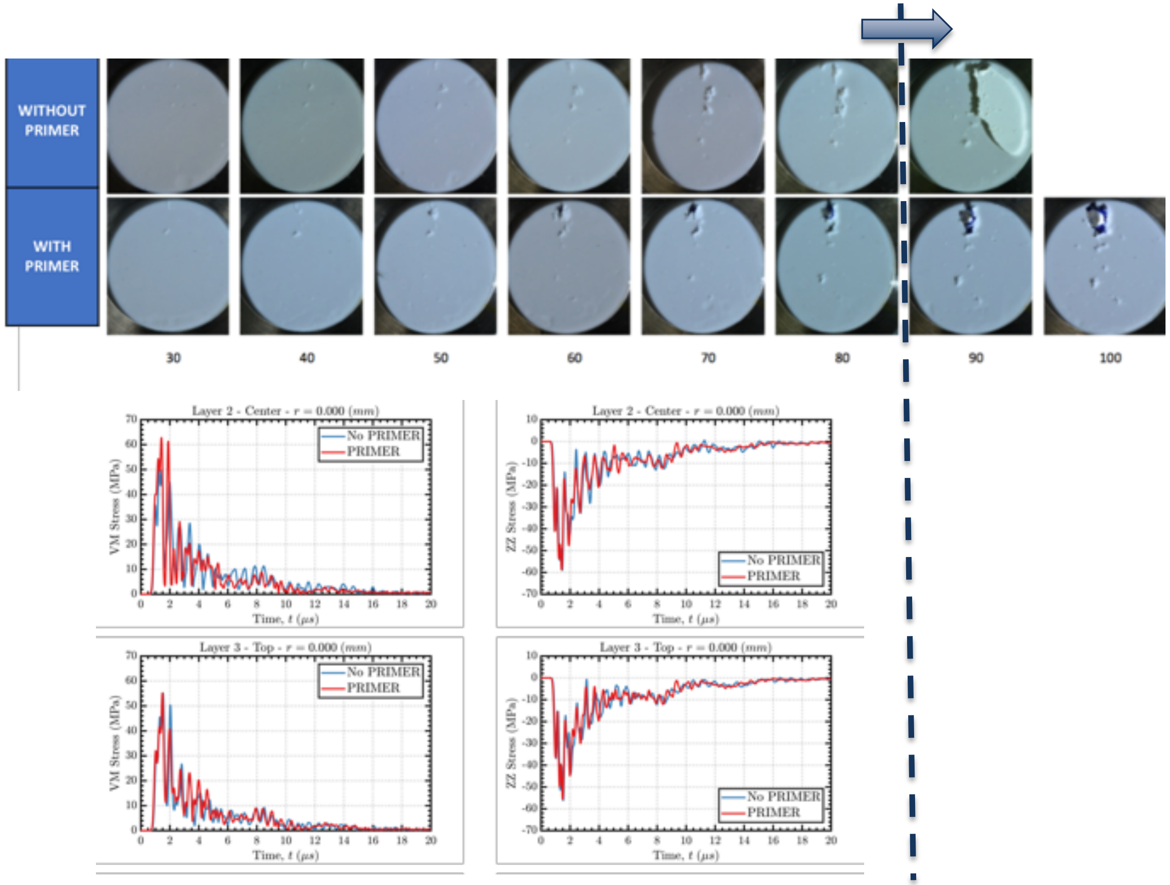


Figure 27. Series of indents across leading edge protection coating configuration with two distinctive interfaces. (a) LEP–filler interface and (b) LEP–primer–filler interface.

WITHOUT PRIMER	WITH PRIMER
Nanoindentation Testing	



❑ **Case 4: Interface Delamination.** Contact Modelling & Characterization

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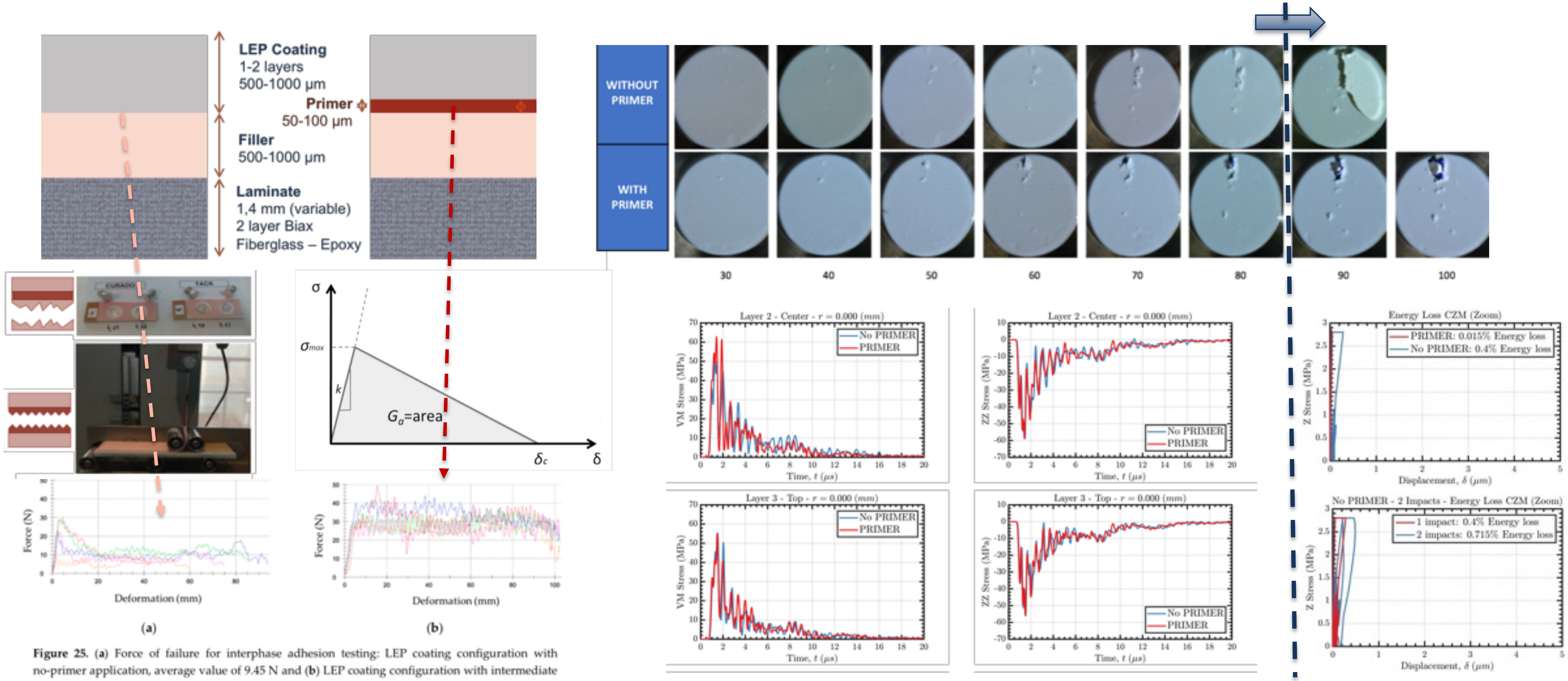
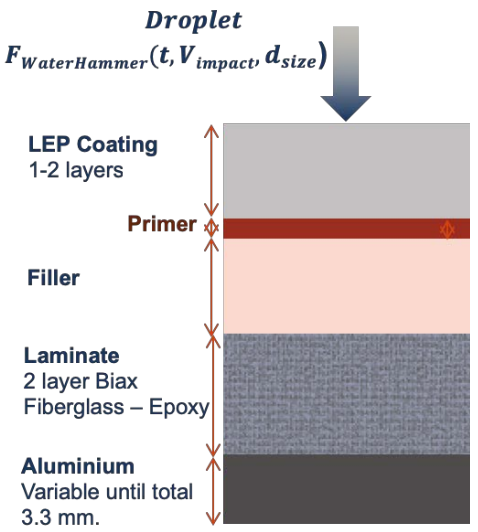


Figure 25. (**a**) Force of failure for interphase adhesion testing: LEP coating configuration with no-primer application, average value of 9.45 N and (**b**) LEP coating configuration with intermediate primer layer, average value of 29.31 N.

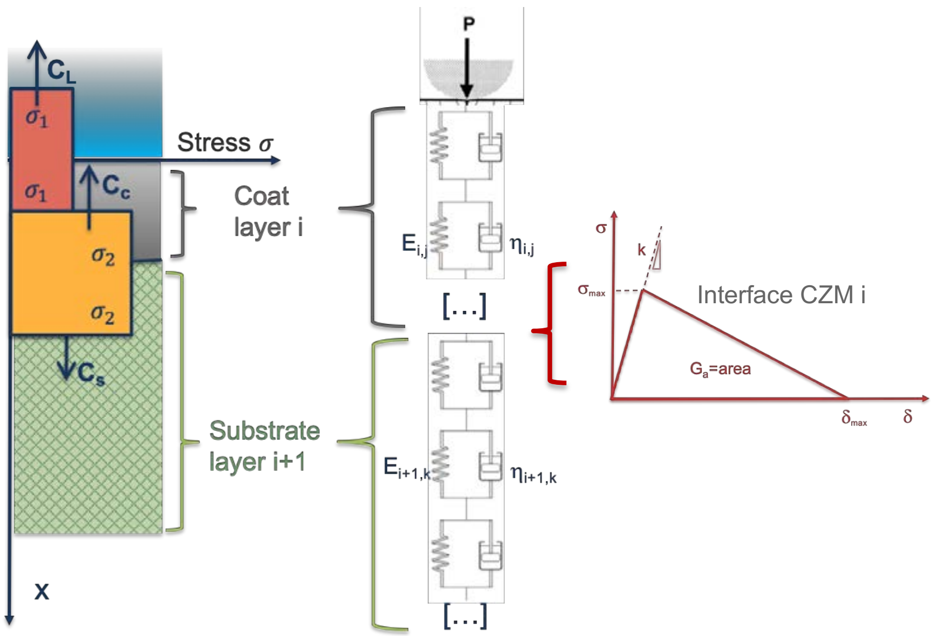
❑ Case 4: Interface Delamination. Contact Modelling & Characterization

- The analysis of the behavior of a **1D single waterdrop** impact is a **meaningful point for investigating the multiple** impact **sequences** that produce leading edge erosion. The failure process is complex, however the work completed provides a **quantitative approach for a physically realistic failure model**.

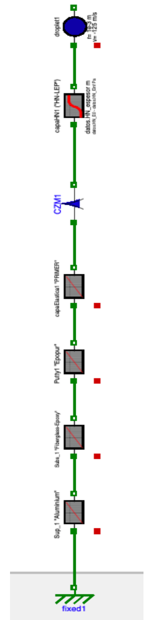
- **Approach: Extending the 1D single droplet impact model to include** measured **multilayer elastic and viscoelastic properties** at rain impact strain rates in coating and substrate layers through the thickness. The **interface contact** modelling is considered based on a **cohesive zone formulation CZM.**



LEP multilayer configuration



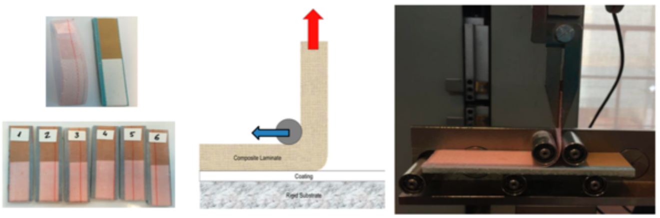
Define Material models and input parameters



Computational Analysis with Matlab and OpenModelica

❑ **Case 4: Interface Delamination.** Contact Modelling & Characterization

- The interface modelling is based on a **cohesive zone formulation CZM,** were knowing the experimental **peeling force** related numerically to the **fracture energy, G_a** necessary for the interface failure, **and pull-off** values that define the maximum value for the **tensile stress σ_{max} assumed at interface.**



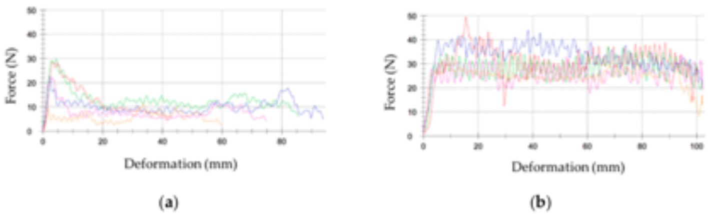
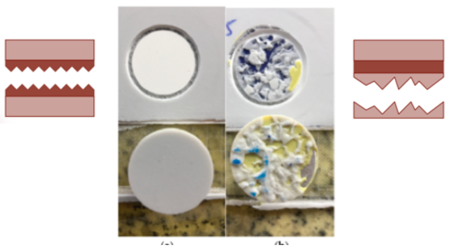
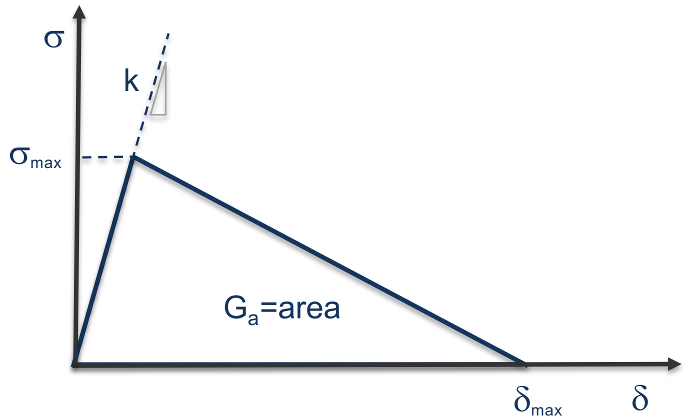
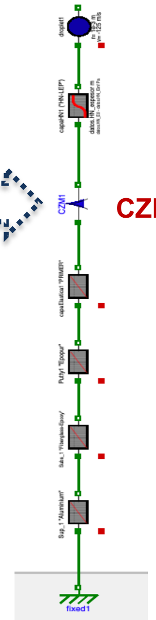


Figure 25. **(a)** Force of failure for interphase adhesion testing: LEP coating configuration with no-primer application, average value of 9.45 N and **(b)** LEP coating configuration with intermediate primer layer, average value of 29.31 N.







Computational Analysis with Matlab and OpenModelica

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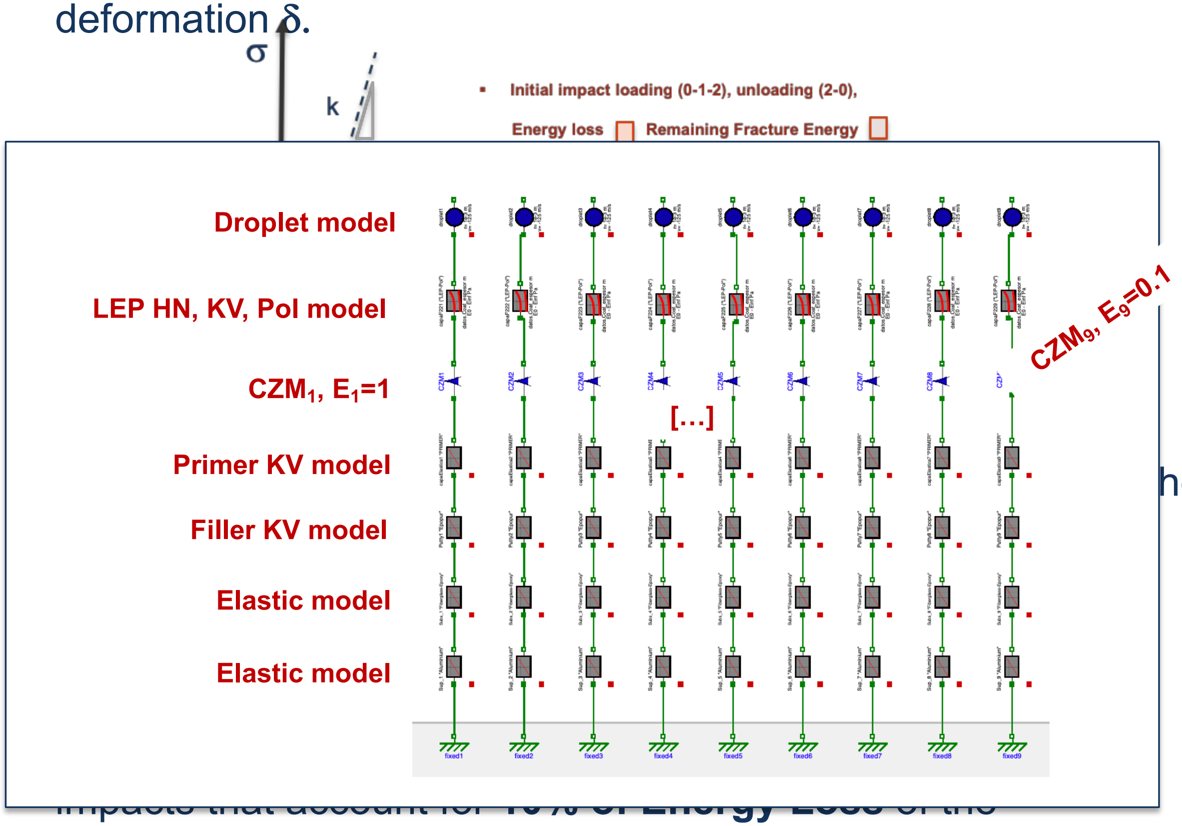
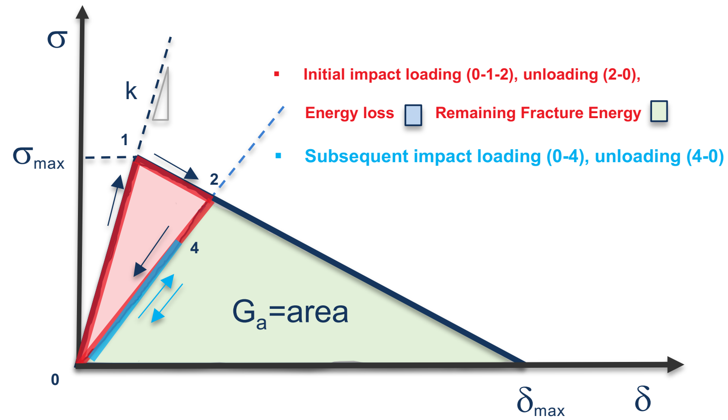
❑ **Case 4: Interface Delamination.** Contact Modelling & Characterization

❑ The single impact wave **stress evolution** at **CZM** is conditioned by the total area defined by the **Fracture Energy G_a** the maximum stress **σ_{max}** , and the slope of **parameter k** that relates the stress with the deformation δ.





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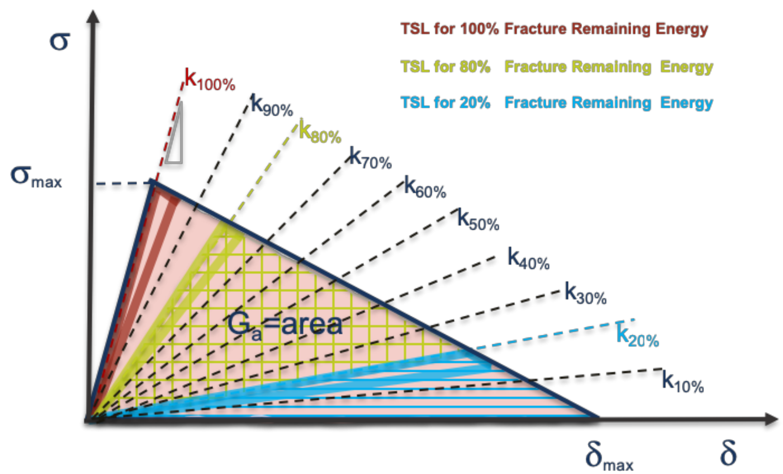
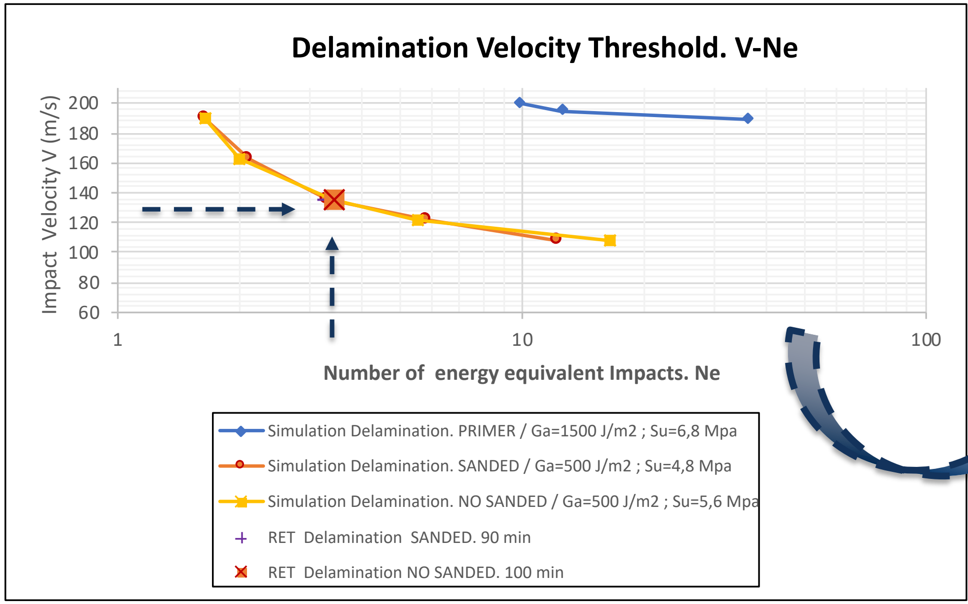
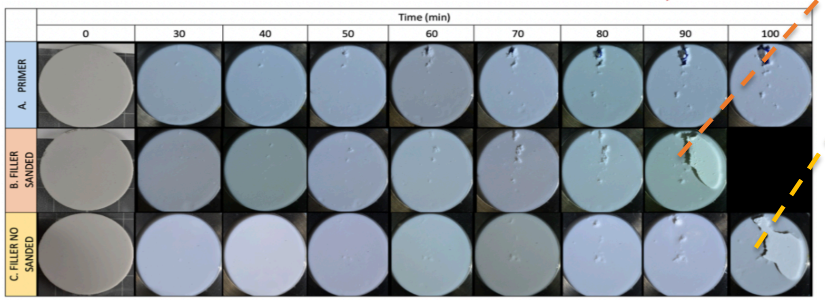


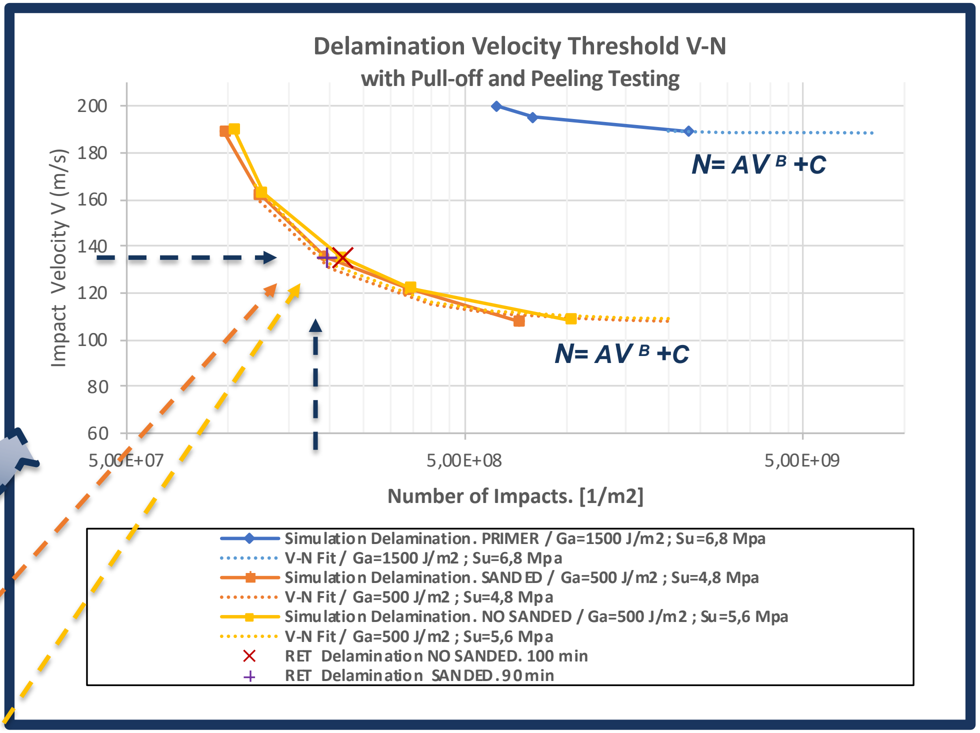
impacts that account for 10% of Energy Loss of the initial one.

❑ **Case 4: Interface Delamination.** Contact Modelling & Characterization

❑ **On the Criteria for** debonding failure estimation. **Number of impacts until Delamination *N*** by means of the **RET input data (V-N @ Delamination). Studies On going**







CONCLUSIONS AND FURTHER WORK

- **On the improvement** of appropriate numerical and analytical models as **tools to analyse LEP fundamental material properties that affect erosion** performance. The **modelling framework** allows a **parametric analysis and a guidance** in the selection and modulation of coating properties.
- On the validation of **complex material models** to consider the **highly transient** material behaviour during waterdrop collisions that require to define the range of frequency of its data set **to account for strain rate & stress relaxation** dependence for the **impact event series.** The construction of **impulse response** and the **recovery time** for the computational modelling may be done by the **transformation of the frequency and time domain**.
- **Simplified numerical procedures** to predict both **wear surface erosion and delamination failure** are **used & developed to define criteria** for identifying suitable LEP coating and composite substrate combinations. **RET testing** needs to be used as the experimental **key metric to evaluate the response** of the material and complete the modelling data.
- There is **no current comprehensive model** linking the operational conditions with debonding mechanisms. Research on going to define an approach based on a **cohesive zone model (CZM) based on pull-off and peeling testing** to evaluate the mechanical **response of the multilayer interfaces.** This would allow one to define **debonding failure criteria as a first step** prior of delamination lifetime prediction models.
- Erosion is an **open Research & Development topic** in Wind Industry