ICCS23 & MECHCOMP6

Thursday, September 3 (Mid-morning)
Conference 2440

ICCS23 - 23rd International Conference on Composite Structures &
MECHCOMP6 - 6th International Conference on Mechanics of Composites

FEUP-Faculty of Engineering, University of Porto, Portugal, 1-4 September 2020

Towards rain erosion delamination damage prediction in Wind Turbine Blades: Interface modelling approach

Luis Domenech[1], Enrique Cortés[2], **Fernando Sánchez[1] ***
[1] ESI Chair at CEU-UCH, Universidad Cardenal Herrera-CEU, CEU Universities, 46115 Valencia, Spain. Email: ***Corresponding author:** fernando.sanchez@uchceu.es

[2]AEROX Advanced Polymers, 46185 Pobla Vallbona-Valencia, Spain

CEU Universidad Cardenal Herrera

Aerox ADVANCED POLYMERS

CONTENT OUTLOOK

1. **Motivation. Leading Edge Protection problem**
   - **Industrialization** process **vs Service** conditions**.** A **multilayer** system

2. **Analysis of LEP Performance. Methodology & Technology Inputs**
   - **Material & process characterization**
   - **Numerical modelling & parametric analysis**
   - Performance Lifetime estimation. **Rain Erosion Testing vs Field**

3. **Study Cases. Tools for material characterization & Erosion Performance Evaluation**
   - **Case 1:** Modelling to **identify suitable coating and substrate**. Acoustic mismatch on interface
   - **Case 2: Interface Delamination.** Contact Modelling & Characterization

4. **Conclusions and Further Work**

❑ **Motivation.** Leading Edge Protection problem

CEU Universidad Cardenal Herrera

- ❑ The **EU objective** to cut greenhouse gas emissions by 80–95% by 2050 has severe implications for the energy sector. By 2050, **wind power will provide more electricity than any other technology** in this sector. There is a need to improve existing technologies by **increasing the size of offshore wind turbines** to capture more wind energy. The installation of very large wind turbines (10 MW and higher), will be necessary in pursuit of this. Wind turbine blades with a length of up to 90 m are already in operation.
- ❑ When considering the **impact of rain droplets, the tip speed is a key contributor** to **erosion damage**.
- ❑ We are all observing **blades that only after a few years of operation need to repaired**.

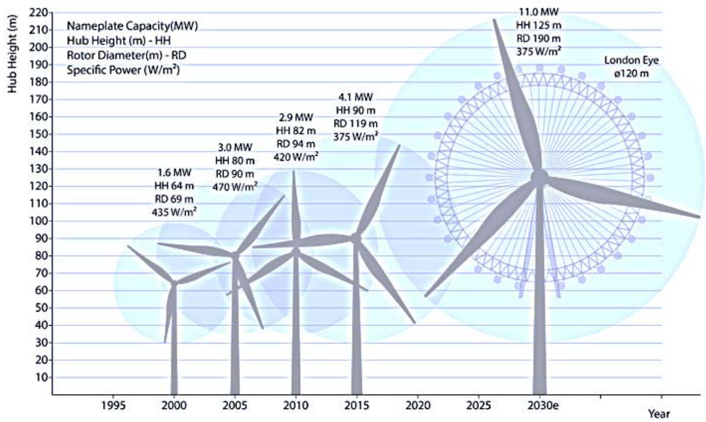
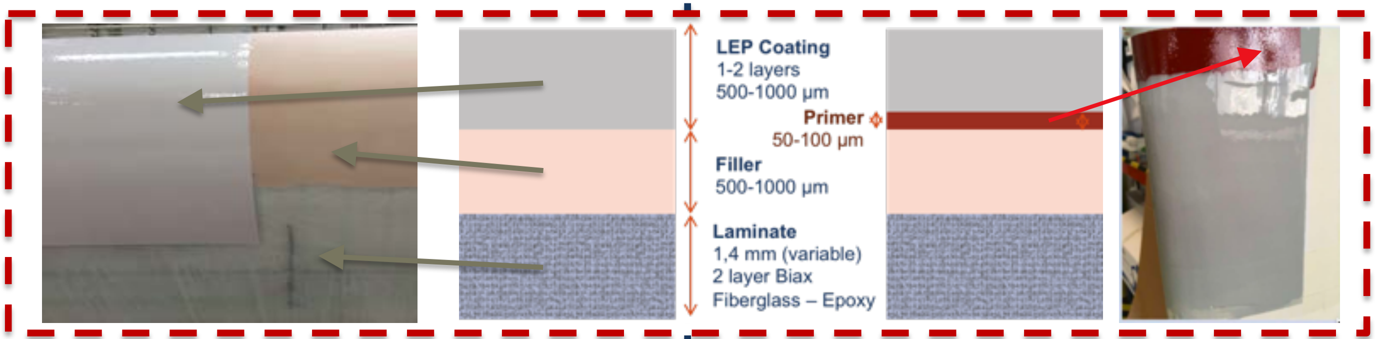


Figure. Blade size evolution trend for wind turbine blades, adapted from [1];

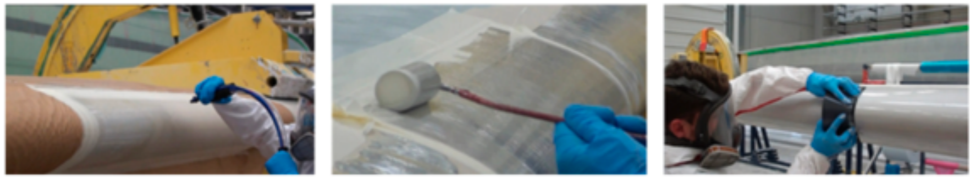
- ❑ The sector is in the **need for a robust product and application process**

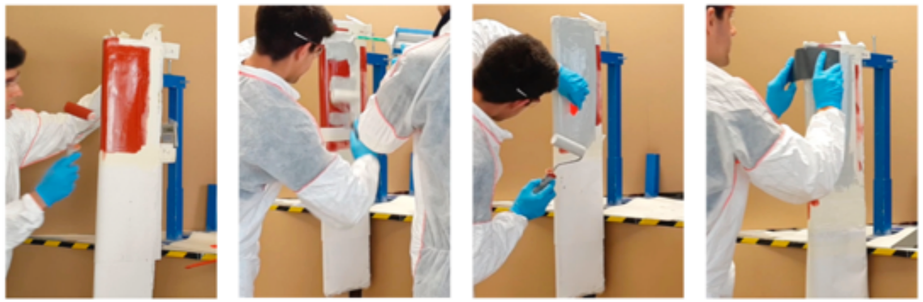
- **Motivation.** Leading Edge Protection problem
  - **Industrialization** process **vs Service** conditions

CEU Universidad Cardenal Herrera




(a) (b)


(a) (b) (c)

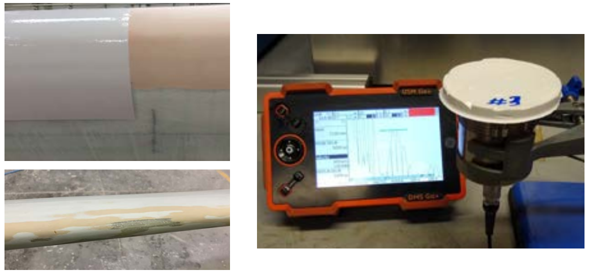

(a) (b) (c) (d)

❑ Analysis of LEP Performance

- **Methodology** & Technology inputs

CEU Universidad Cardenal Herrera

Material & process characterization



Multilayer fundamental properties

Interface characterization

Manufacturing and Service application processes

❑ Identifying and **controlling the material capabilities to withstand failure modes** (Wear & Debonding) of selected LEP system by means of the definition of **mechanical testing** and sample coupons preparation.

- ✓ To consider: **Tensile-Compression** tests (Evaluation at different **strain rates**), **Viscoelastic characterization** DMTA, DETA (10E2Hz – 10E7Hz), **Impedance** analysis at working frequency with **Ultrasonic testing.**

❑ **Adhesion between LEP layers** is a parameter that ensures that **loads are transferred** to the substrate **guarantying interface continuity** .

- ✓ To consider: **Peeling and pull-off** for interface adhesion, and **nanoindentation** for impedance matching between layers

❑ **Processing quality checks parameters** have to be **examined analytically** to quantify its impact on the strength of the LEP system..

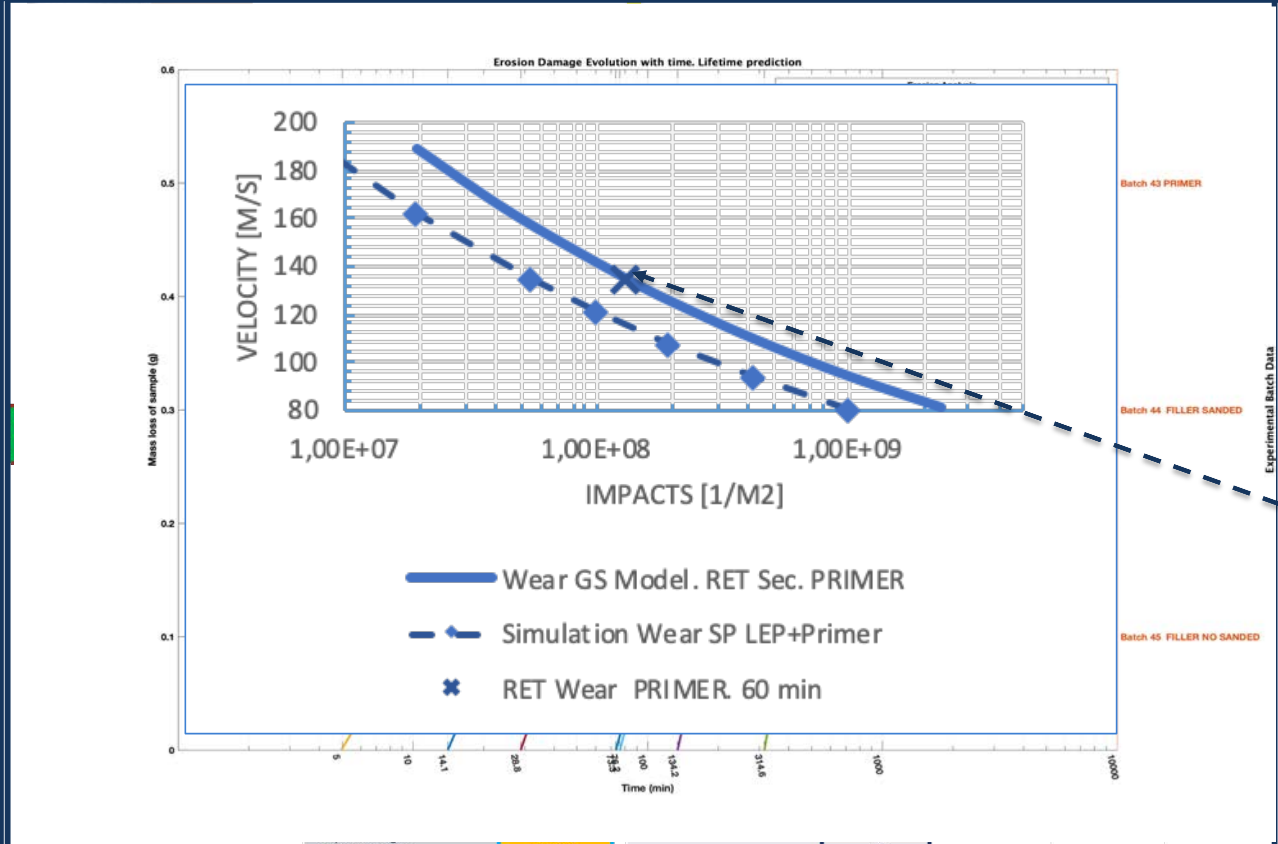
- ✓ To consider: Size and number of **bubbles** in each layer and interfaces may be characterized with optical **microscopy and microCT**. Layer **thickness** can be determined with **Ultrasonic** testing and **surface roughness** with **nanoindentation**

❑ Analysis of LEP Performance

- **Methodology &** Technology inputs

CEU Universidad Cardenal Herrera

Material & process characterization ➡ **Numerical modelling & parametric analysis**



Rain Intensity | I | Coating Thickness | h_c

❑ A modelling **framework** based on 1D Springer' allows to examine the effect of the selected coating properties and operational conditions **on the <u>wear erosion performance</u>**

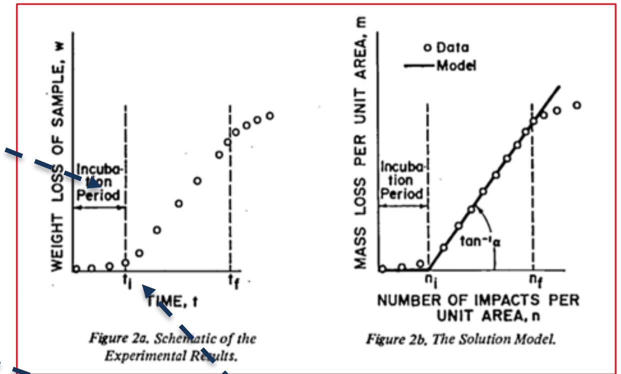
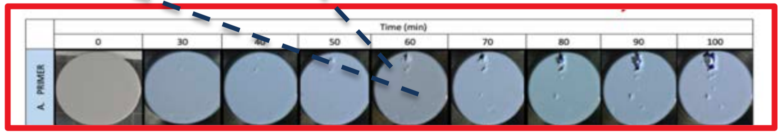
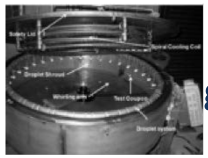


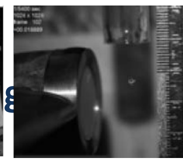
Figure 2a. Schematic of the Experimental Results.

Figure 2b. The Solution Model.



❑ ... m ... sion ... g ... ng

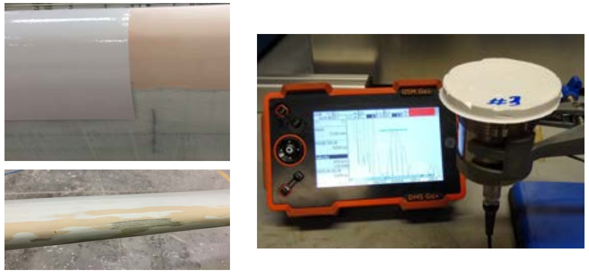




❑ Analysis of LEP Performance

▪ Methodology & Technology inputs

Material & process characterization

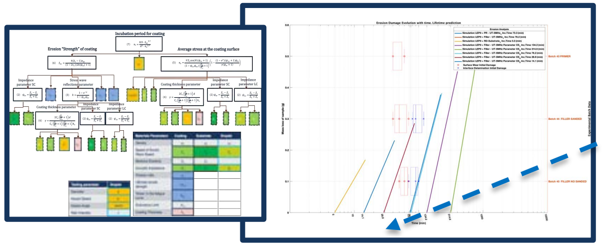


Multilayer fundamental properties

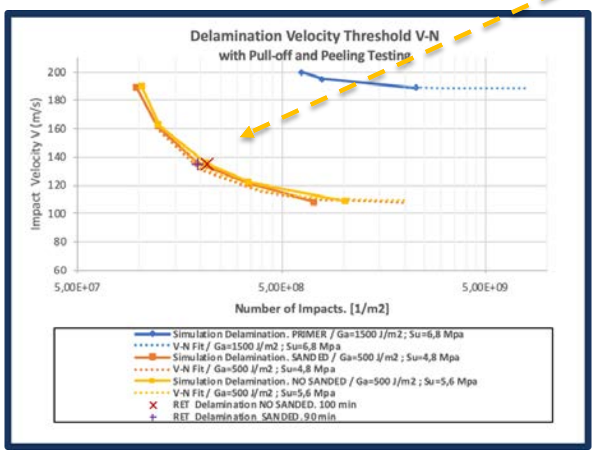
Interface characterization

Manufacturing and Service application processes

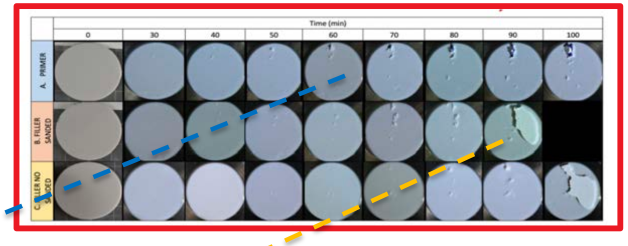
Numerical modelling & parametric analysis



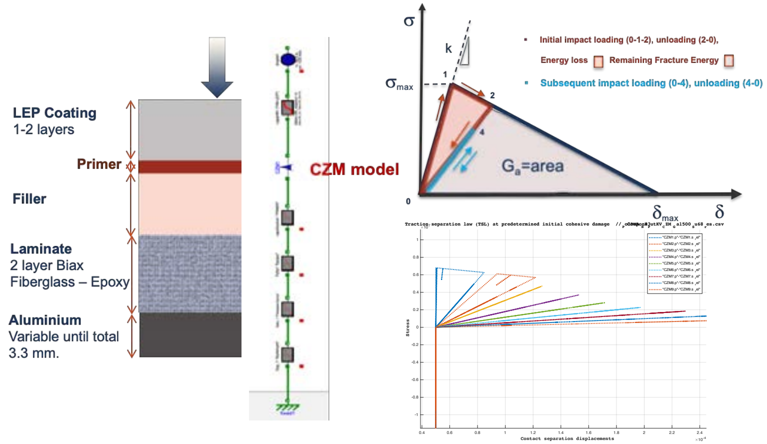
Surface Wear



Interface Delamination



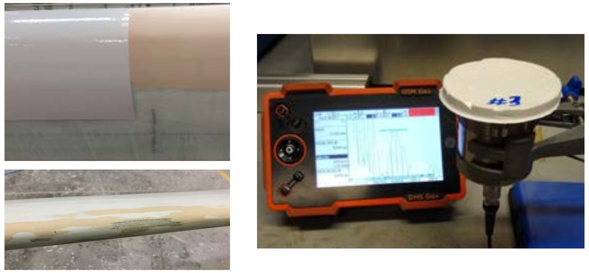
❑ The interface modelling is based on a **cohesive zone formulation CZM,** were knowing the experimental **peeling force and pull-off,** estimate the delamination failure **at interface** for a complete lifetime V-N curve



❑ Analysis of LEP Performance

- **Methodology &** Technology inputs

Material & process characterization

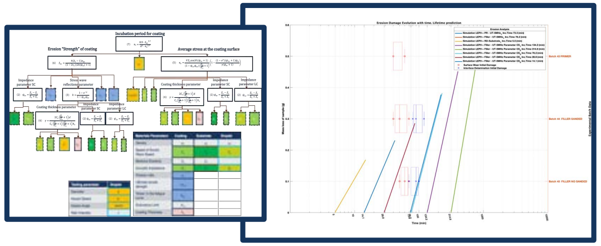


Multilayer fundamental properties

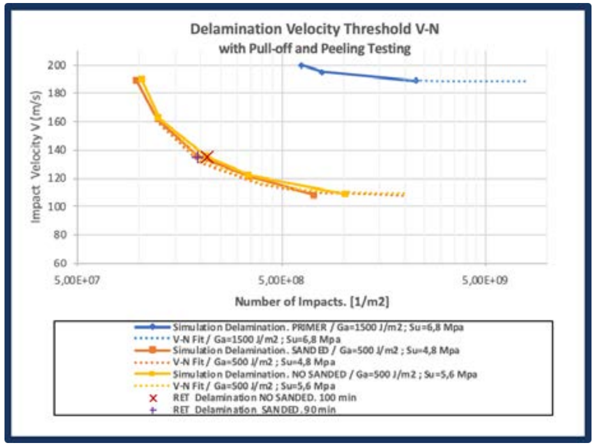
Interface characterization

Manufacturing and Service application processes

Numerical modelling & parametric analysis

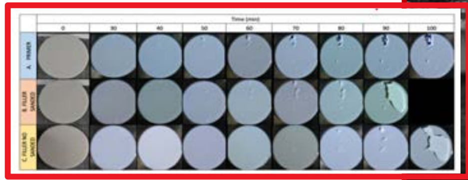


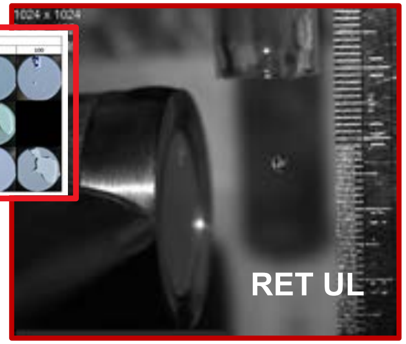
Surface Wear



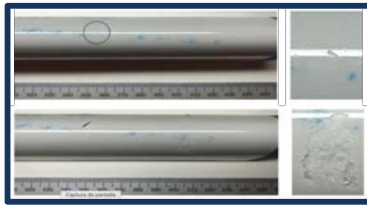
Interface Delamination

Performance estimation Rain Erosion Testing vs Field





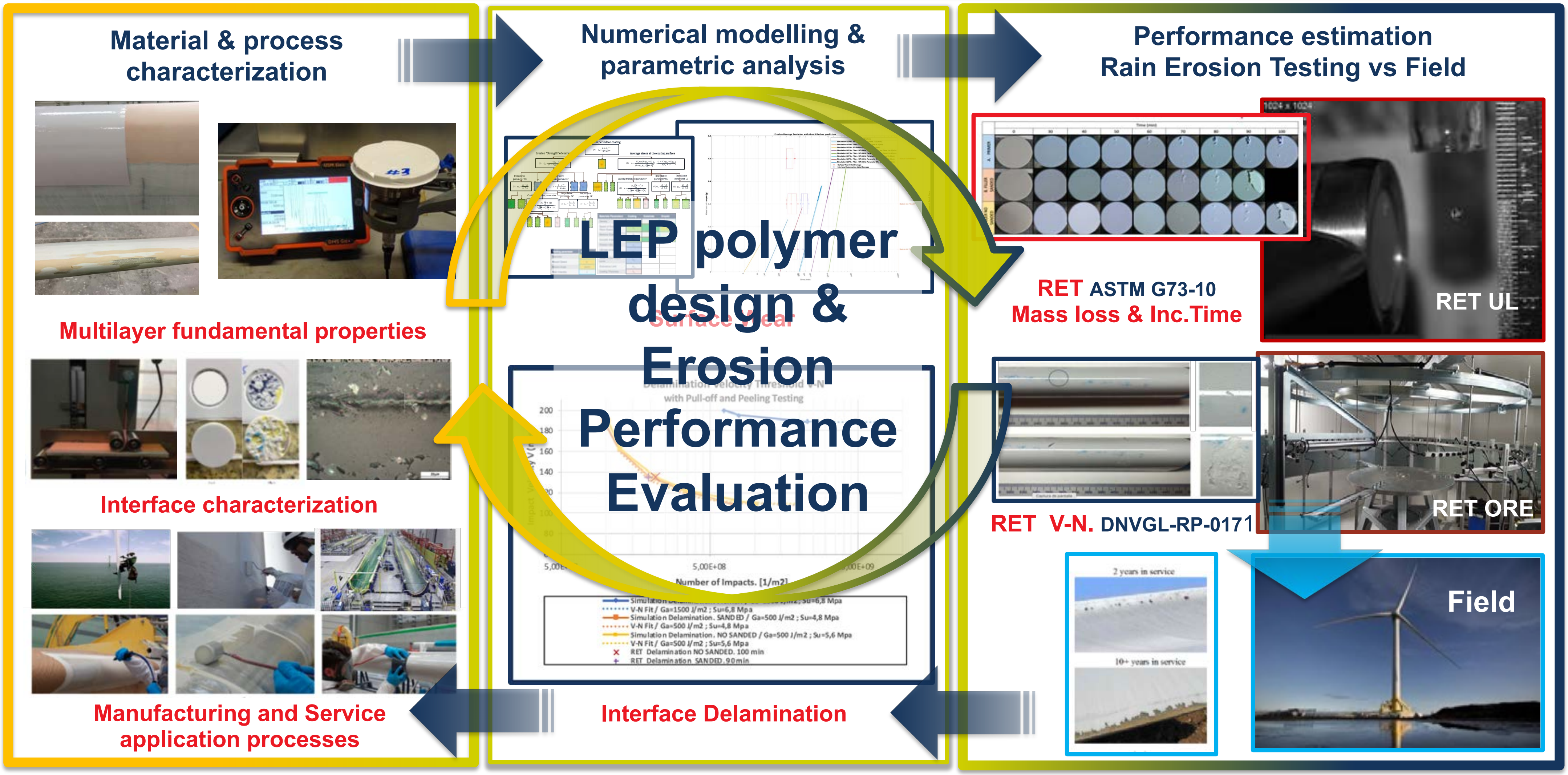
RET ASTM G73-10
Mass loss & Inc.Time



RET V-N. DNVGL-RP-0171

❑ Analysis of LEP Performance

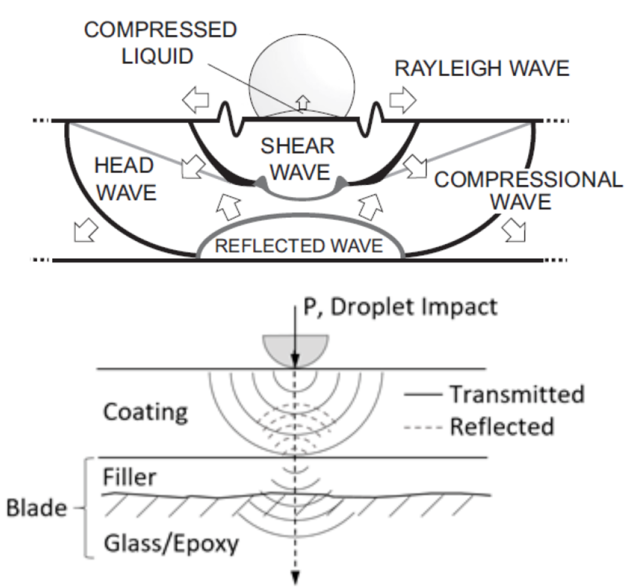
- **Methodology &** Technology inputs

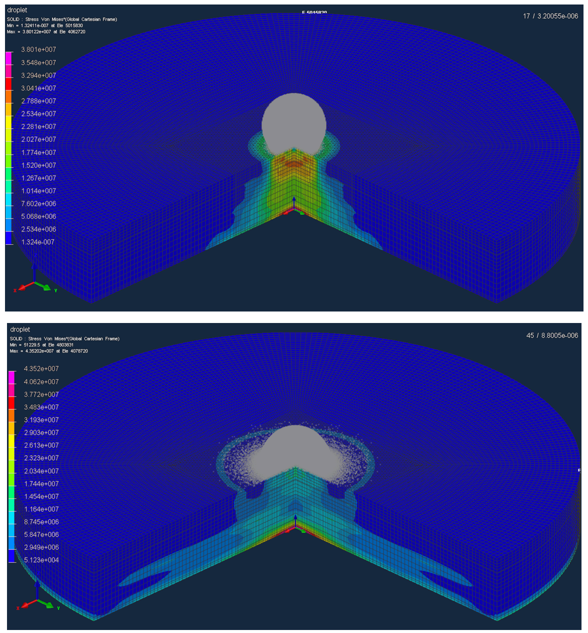


- **Case 1:** Modelling to **identify suitable coating and substrate**. Acoustic mismatch

CEU Universidad Cardenal Herrera

- 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.

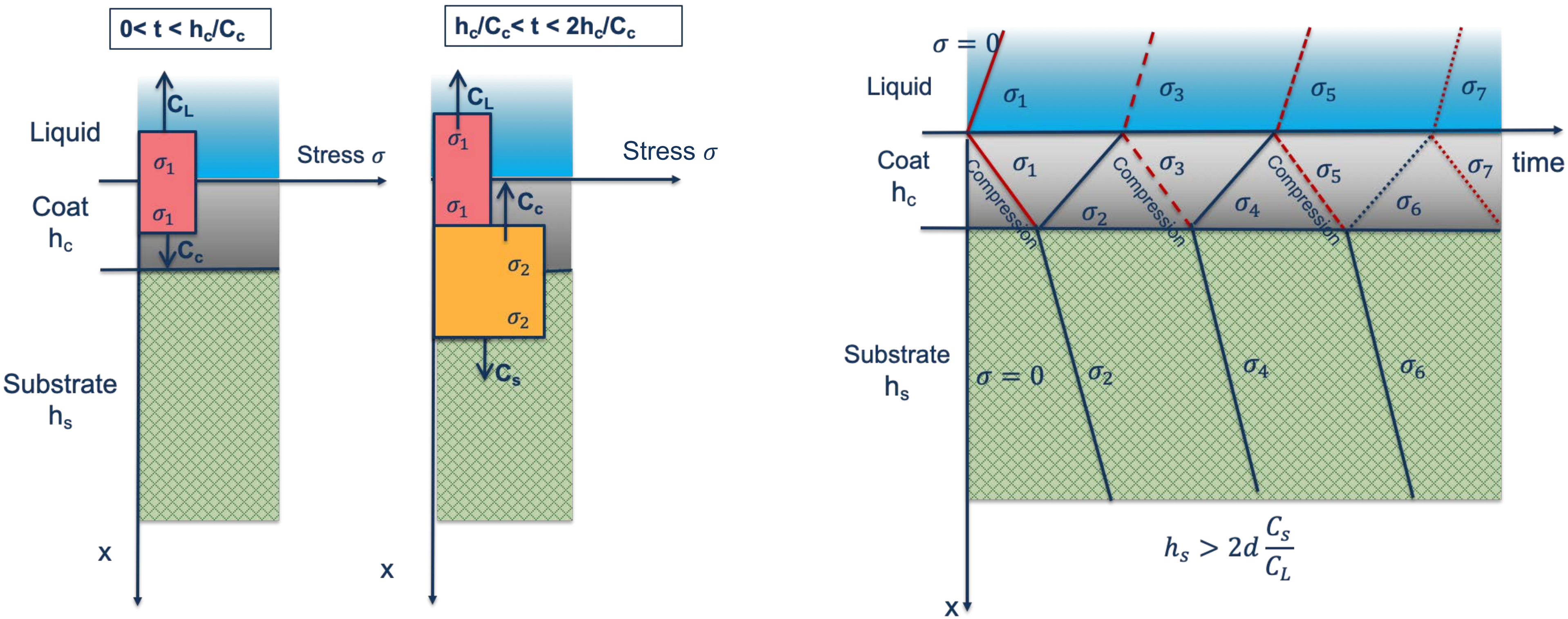




- **Understanding the physics of failure.** The analysis of erosion caused by rain droplets shows that the damage is in fact a 3D **dynamic event** resulting in the **propagation of shock waves**.

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

- **Case 1:** Modelling to **identify suitable coating and substrate**. Acoustic mismatch

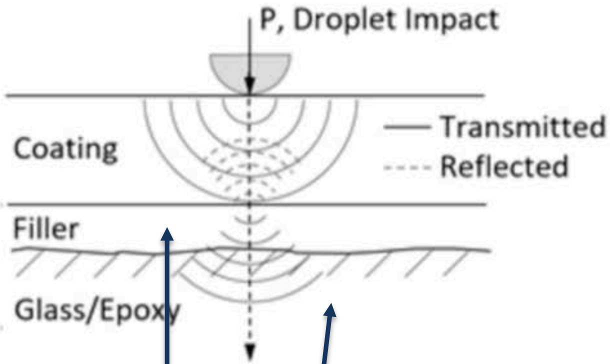


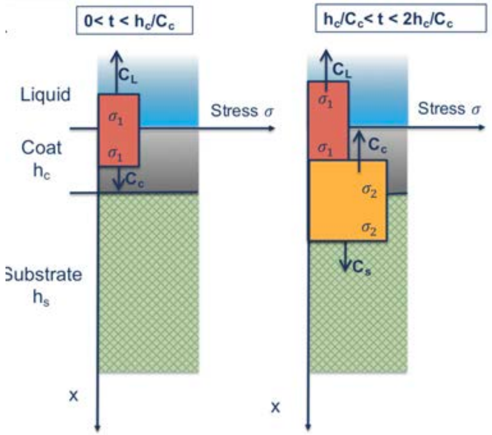
- Based on **Springer Model the main modelling limits are:**
  - **1D formulation** examines the impact of a liquid **droplet as a pure elastic event** onto a **two layered structure** with the substrate assumed semi-infinite.
  - **No viscoelastic** consideration for **high transient strain rate** deformation and **damping** capabilities
  - **No contact modelling** for **delamination failure** analysis. Assuming perfect adhesion on interface.

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

- **Case 1:** Modelling to **identify suitable coating and substrate**. Acoustic mismatch

- Upon impingement, the wave front in the top coating further advances towards the coating-substrate interface, where a portion of the **stress wave is reflected back into the coating** with a different amplitude **depending on the relative material acoustic impedances** and the remaining part is **transmitted to the substrate**.





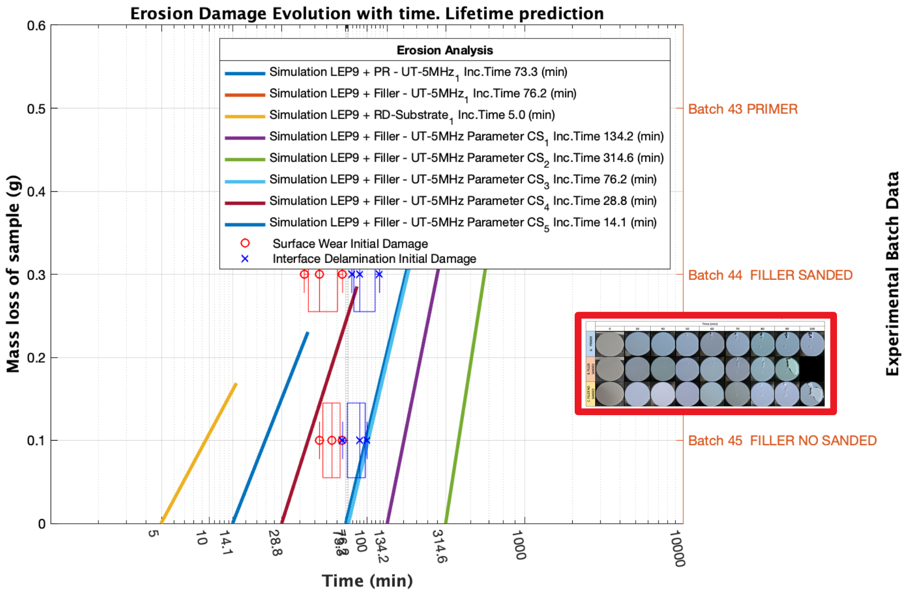
$$\frac{\sigma_{R_{LC}}}{\sigma_{I_{LC}}} = \frac{Z_L - Z_C}{Z_L + Z_C} \; ; \; \frac{\sigma_{T_{LC}}}{\sigma_{I_{LC}}} = \frac{2Z_C}{Z_L + Z_C}$$

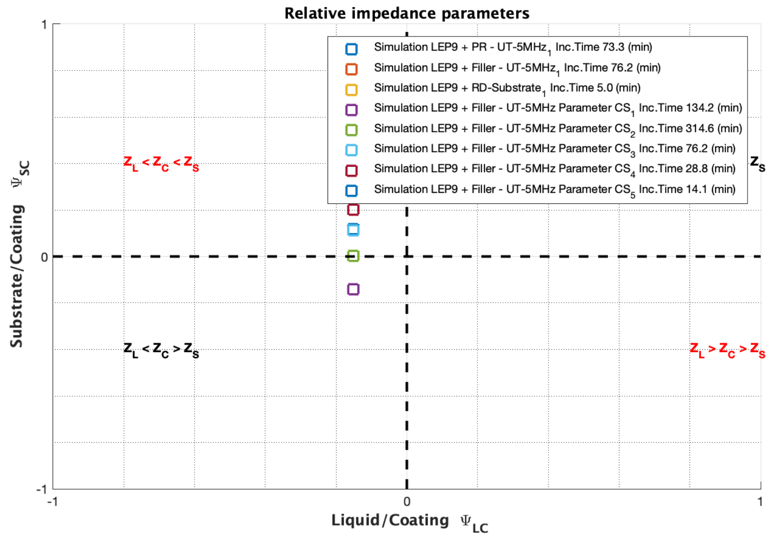
$$\frac{\sigma_{R_{CS}}}{\sigma_{I_{CS}}} = \frac{Z_C - Z_S}{Z_C + Z_S} \; ; \; \frac{\sigma_{T_{CS}}}{\sigma_{I_{CS}}} = \frac{2Z_S}{Z_C + Z_S}$$

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

❑ **Case 1:** Modelling to **identify suitable coating and substrate**. Acoustic mismatch

CEU Universidad Cardenal Herrera



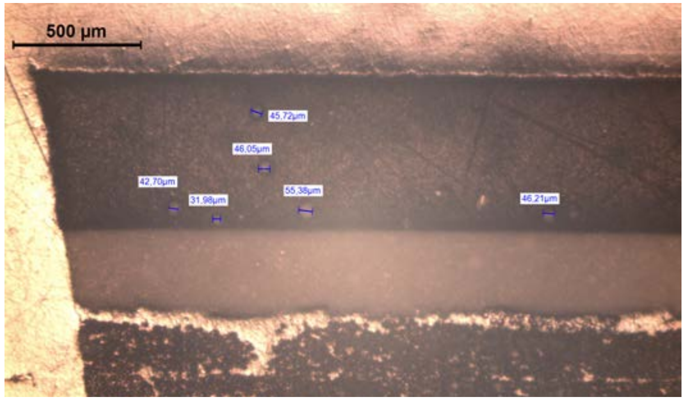


❑ Depending on the **relative acoustic properties LEP-Substrate**, the erosion **lifetime can be optimized**

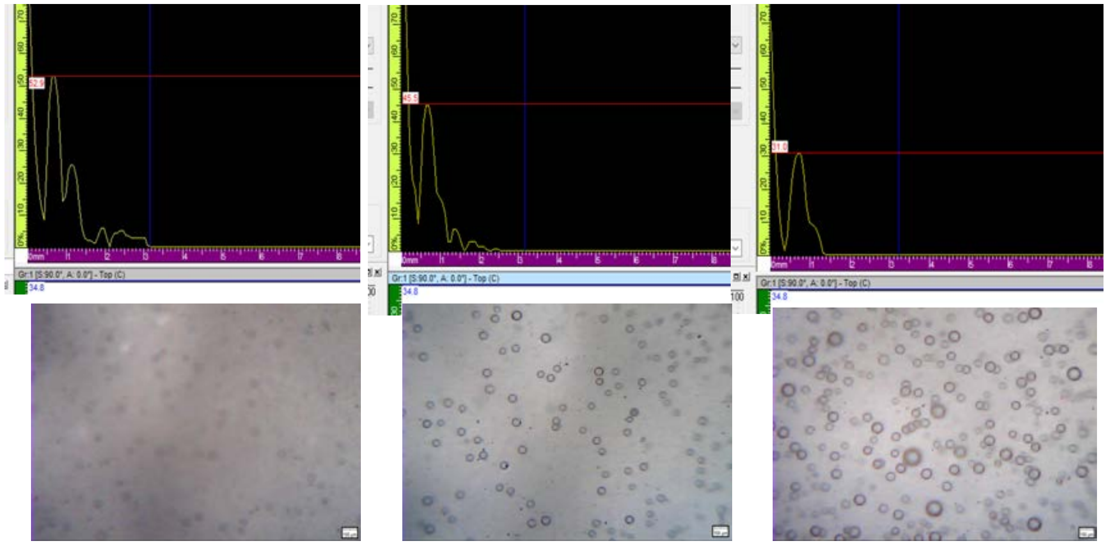
CEU Universidad Cardenal Herrera

❑ **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



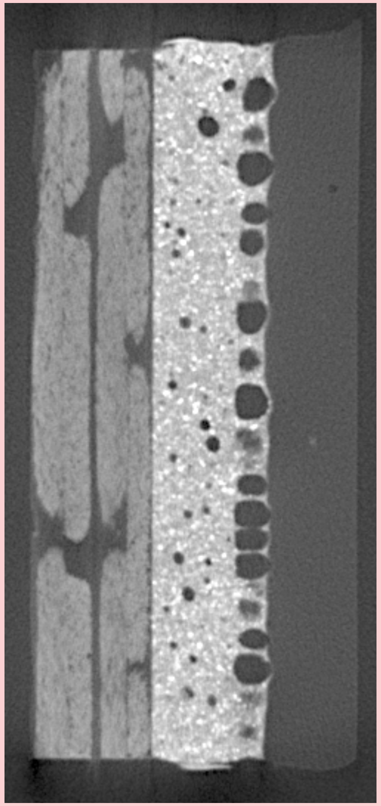
👍 The **more void content** the better for **coating impedance reduction effect for stress attenuation**
👎 But void acts as **stress concentrator** [2], so **cracking initiation and propagation may be** enhanced.

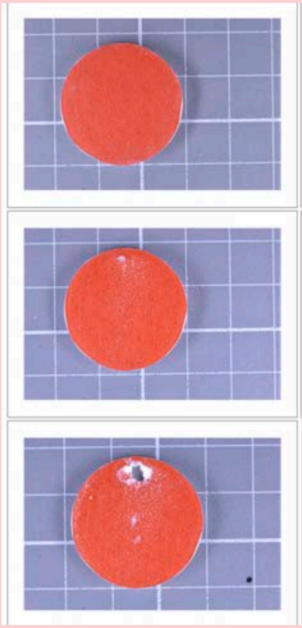
- ❑ The **capability of LEP thickness** will act **circumventing the negative bubble effect** on surface. **Droplet size-void size ratio** to be analyzed. **On going studies**

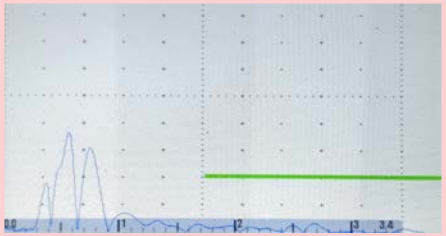
- **Case 2:** Modelling to **identify suitable coating and substrate**. Acoustic mismatch

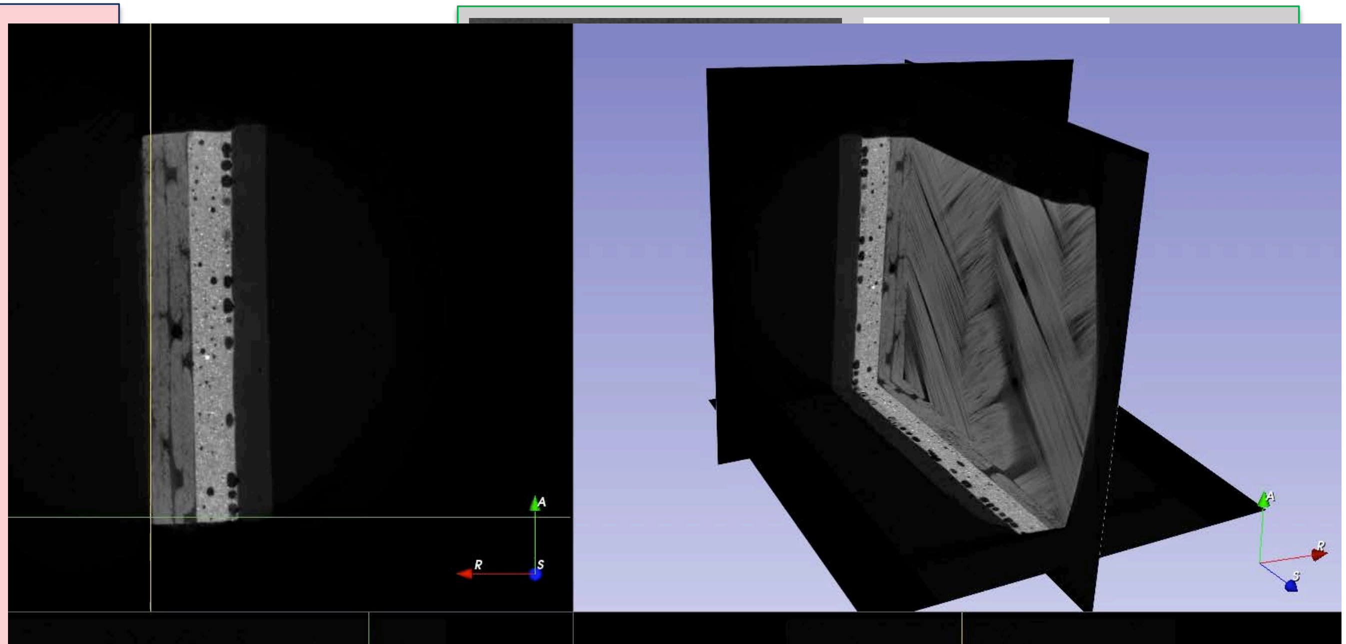
CEU Universidad Cardenal Herrera

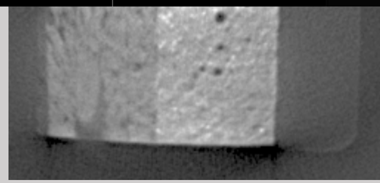
- **On the Development Criteria** for **processing internal defects (Bubbles)** on LEP multilayer system

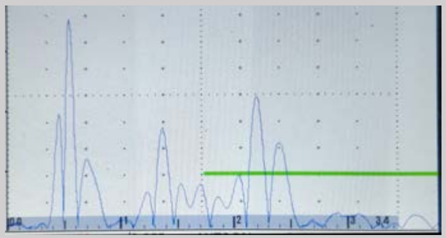












Damaged 45 min RET.

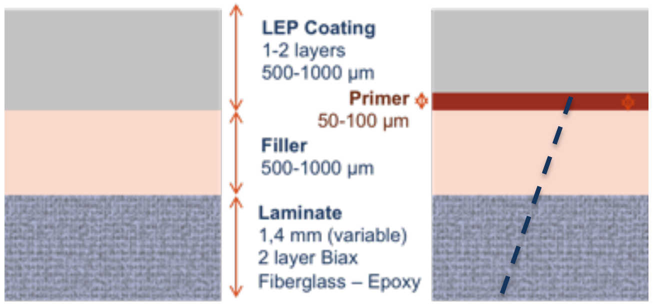
No Damage 900 min RET.

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

❑ **Case 2: Interface Delamination.** Contact Modelling & Characterization

CEU Universidad Cardenal Herrera

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



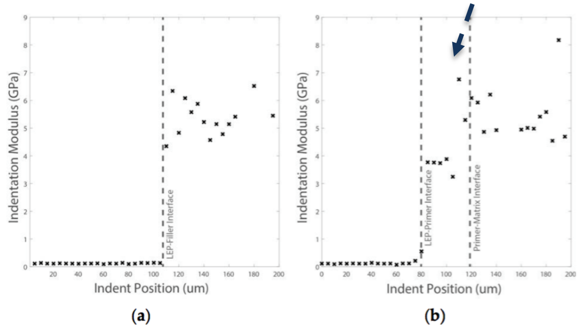
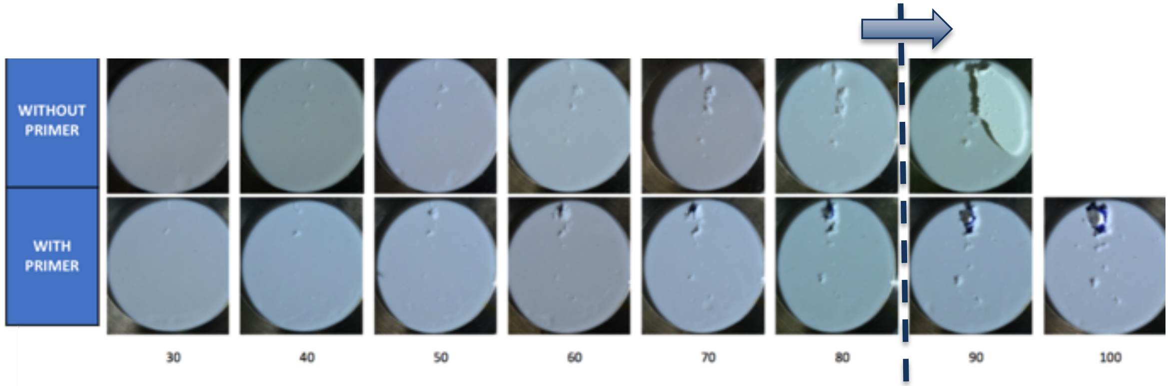
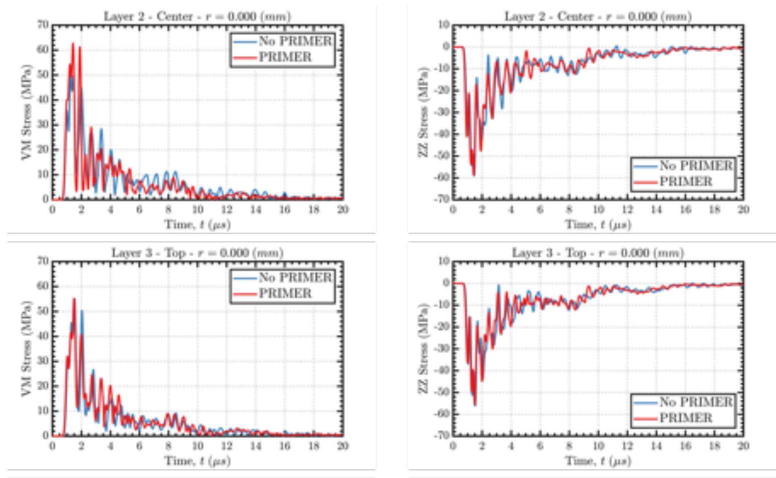


Figure 27. Series of indents across leading edge protection coating configuration with two distinctive interfaces. (a) LEP–filler interface and (b) LEP–primer–filler interface.

WITHOUT PRIMER	WITH PRIMER
Nanoindentation Testing	





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

❑ **Case 2: Interface Delamination.** Contact Modelling & Characterization

CEU Universidad Cardenal Herrera

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

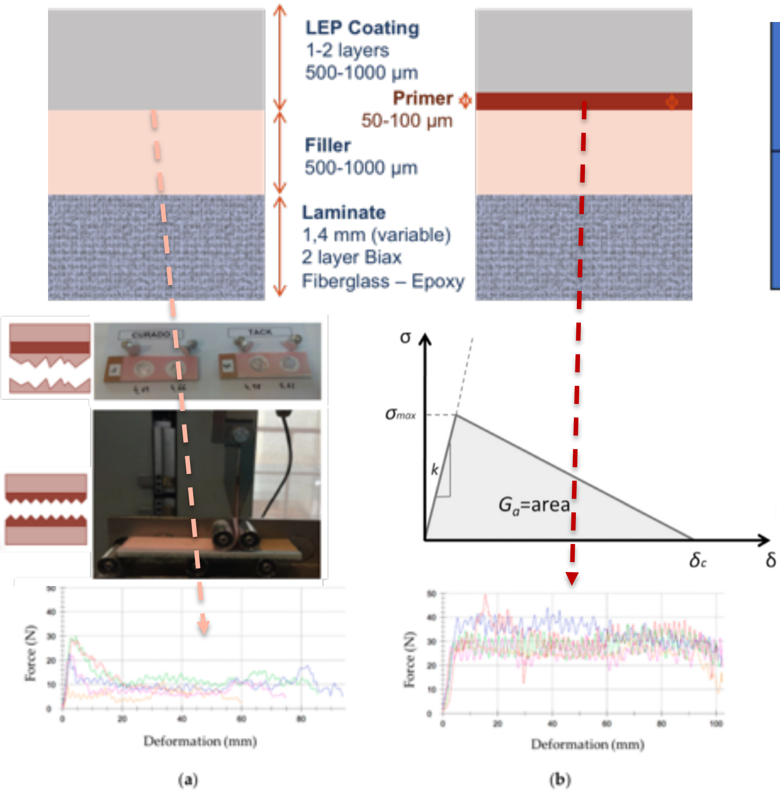
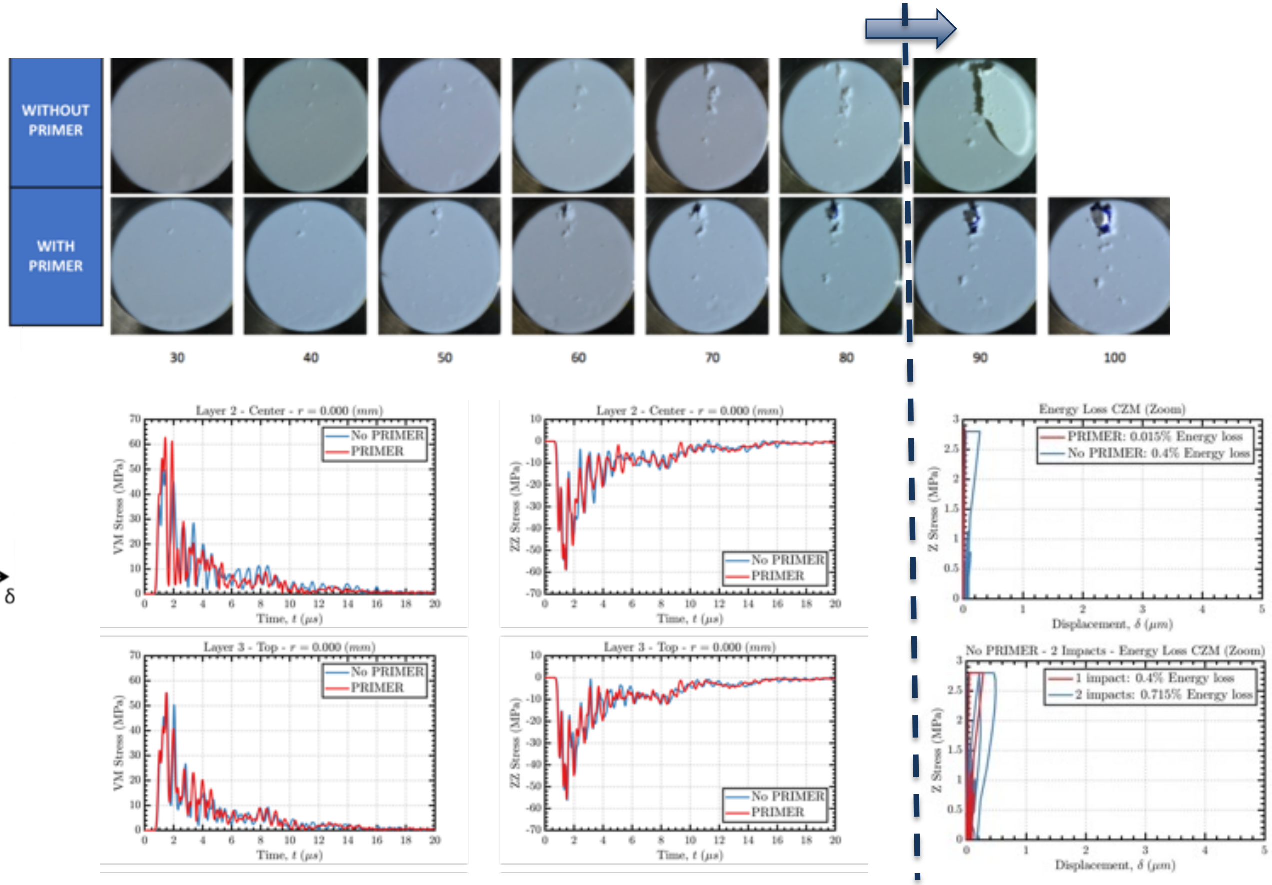


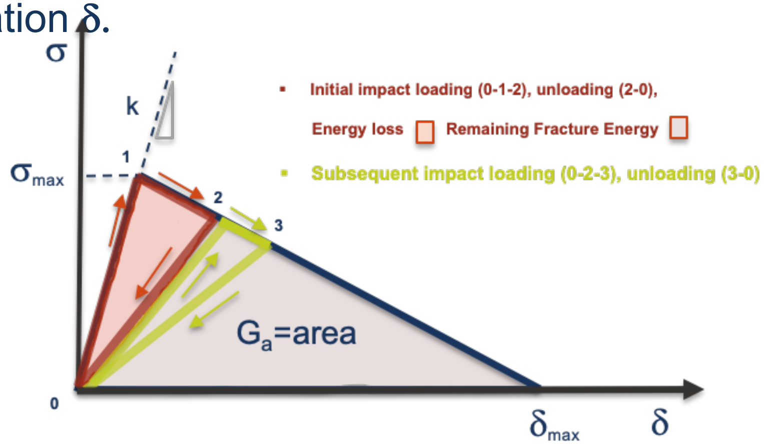
Figure 25. **(a)** Force of failure for interphase adhesion testing: LEP coating configuration with no-primer application, average value of 9.45 N and **(b)** LEP coating configuration with intermediate primer layer, average value of 29.31 N.

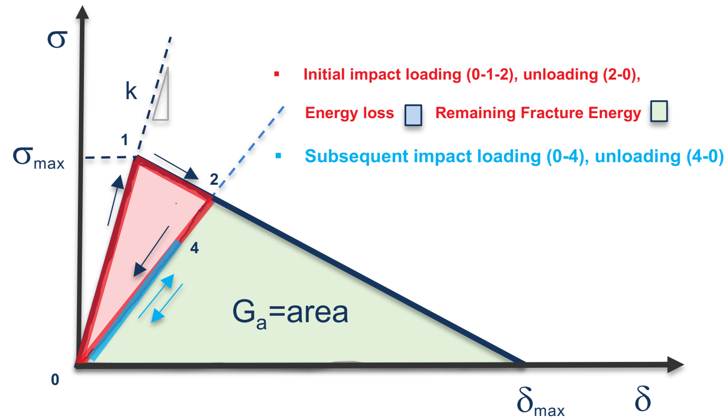


❑ **Case 2: Interface Delamination.** Contact Modelling & Characterization

CEU Universidad Cardenal Herrera

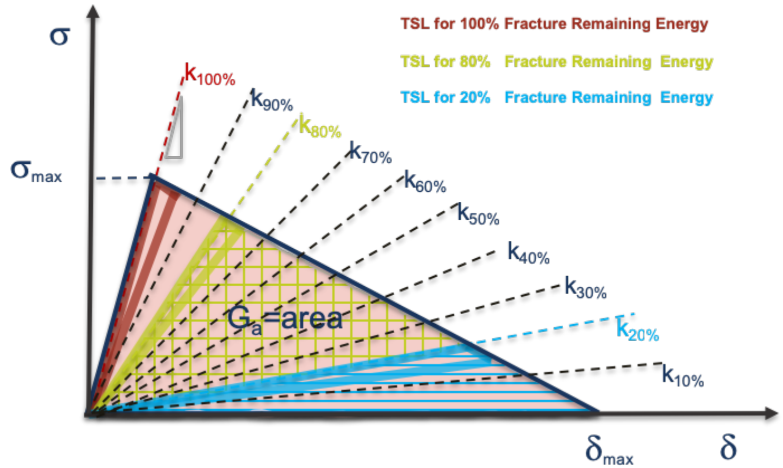
❑ The single impact wave **stress evolution** at **CZM** is conditioned by the total area defined by the **Fracture Energy G_a** the maximum stress **σ_{max}** , and the slope of **parameter k** that relates the stress with the deformation δ.





❑ The procedure accounts for <u>**interface delamination**</u> in case the remaining Fracture Energy (area) **G_a vanishes after a given number of impacts n.**

❑ In order **to track for** the **complete system lifetime until delamination damage,** one may consider the total **Fracture Energy divided in 10 periods** of impacts that account for **10% of Energy Loss** of the initial one.



❑ **Case 2: Interface Delamination.** Contact Modelling & Characterization

CEU Universidad Cardenal Herrera

- ❑ The **accumulated <u>Damage</u> *D*** for a given instant may be defined as a relation of the already **energy loss** (or damaged) **over the total Fracture Energy** required for complete delamination

$$(2.1)\qquad D = \frac{G_{Damaged}}{G_{Total}}\ ;\ D \in [0,1]$$

- ❑ The **<u>Remaining energy</u> *E*** is defined as the **available fracture energy** to account for subsequent impact stresses and decreases with the increasing of damage

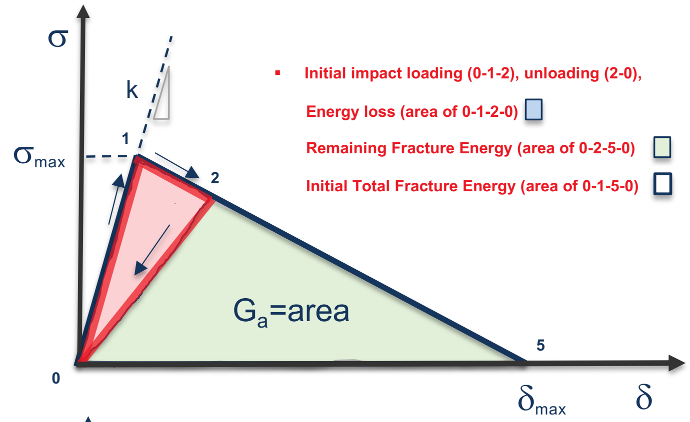
$$(2.2).\qquad E = 1 - D = 1 - \frac{G_{Damaged}}{G_{Total}}\ ;\ E, D \in [0,1]$$

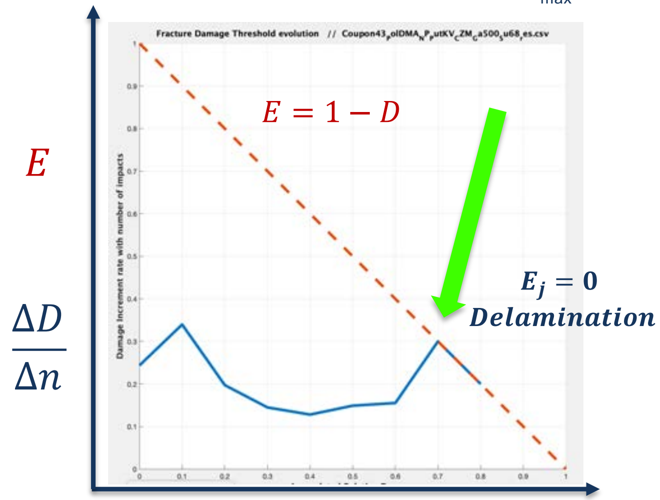
- ❑ The **evolution of the damage at interface** for a given number of impacts *n* from impact event *i* to impact event *j*, can be tracked from repeated single impact events as:

$$(2.3).\qquad \frac{\Delta D}{\Delta n} = \frac{D_j - D_i}{n_j - n_i} = \frac{\sum_{n=i}^{j} d_i}{n_j - n_i}\ ;\quad E_j = E_i - \frac{D_j - D_i}{n_j - n_i};\quad E, D \in [0,1]$$

- ❑ The value of the **Remaining Energy *E*** after a series of impacts gives a **<u>Threshold value</u>** to track for **<u>interface Delamination, when E_j=0</u>**

$$(2.4)\qquad E_j = 0\ \rightarrow\ E_i = \frac{D_j - D_i}{n_j - n_i};\quad E, D \in [0,1]$$





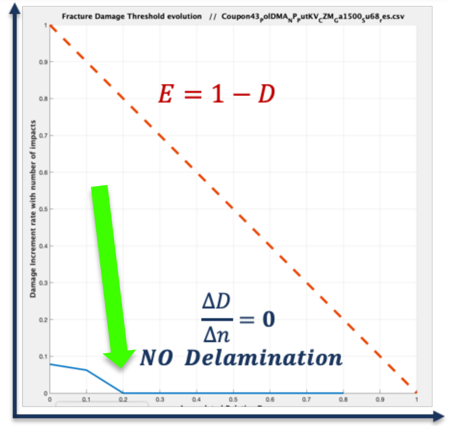
$$D = \frac{G_{Damaged}}{G_{Total}}\ ;\ D \in [0,1]$$

❑ **Case 2: Interface Delamination.** Contact Modelling & Characterization

CEU Universidad Cardenal Herrera

- The system will **avoid delamination** if the value of the **Remaining Energy *E*** after a series of impacts from impact event *i* to impact event *j*, does not decrease, **when $E_j = E_i$**

$$(2.5) \qquad E_j = E_i \rightarrow \frac{\Delta D}{\Delta n} = \frac{D_j - D_i}{n_j - n_i} = \frac{\sum_{n=i}^{j} d_i}{n_j - n_i} = 0; \quad E, D \in [0,1]$$



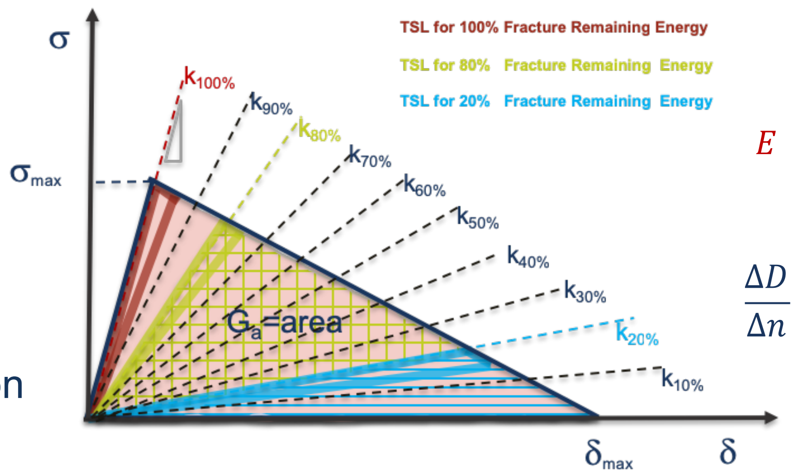
$$D = \frac{G_{Damaged}}{G_{Total}} \; ; D \in [0,1]$$

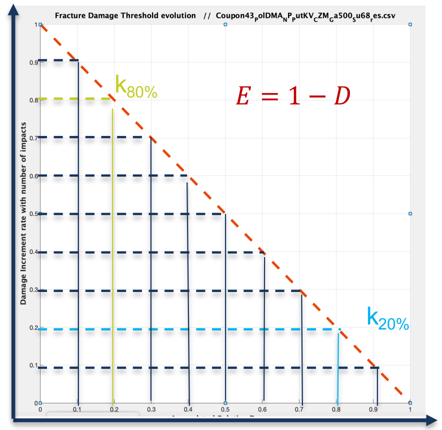
- **Initial conditions** would **consider** a decreasing value of the Remaining Energy ***E_i***, (with corresponding ***D_i***) for each of these impact periods

$$(2.6) \qquad E_j = E_i - \frac{\sum_{n=i}^{j} d_i}{n_j - n_i}; \quad E, D \in [0,1]$$

$$E_i = \{1, 0.9, 0.8 \ldots, 0.3, 0.2, 0.1\}$$

- The **TSL** is computationally **updated** for new corresponding **initial parameter values k_i, E_i, D_i** for each impact period on any **subsequent stress cycles**.





$$D = \frac{G_{Damaged}}{G_{Total}} \; ; D \in [0,1]$$

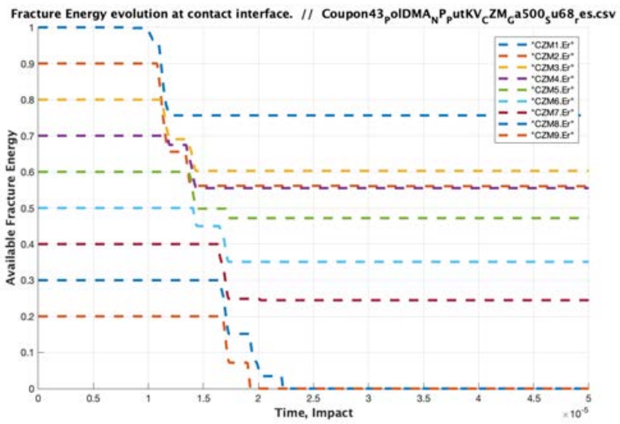
3. Study Cases. Tools for material characterization & Erosion Performance Evaluation

❑ **Case 2: Interface Delamination.** Contact Modelling & Characterization

CEU Universidad Cardenal Herrera

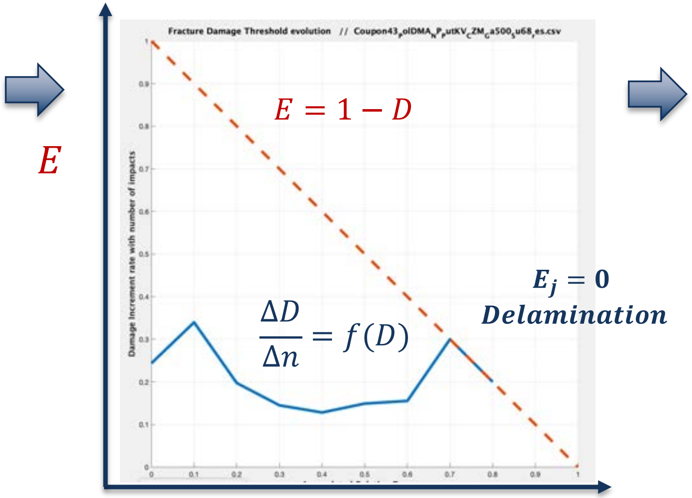
- ❑ In order to estimate the **Lifetime prediction until complete delamination**, the **energy equivalent number of impacts N_e** is assumed to be related to the Fracture Energy loss during the complete series of impacts from impact ***0* to impact N_e**
- ❑ **Delamination time** is then computed based on the **accumulated <u>Damage</u> *D* evolution for the total lifetime** of the system. One may consider:

$$(2.7) \qquad \frac{\Delta D}{\Delta n} \approx \frac{dD}{dn} = f(D);\ D \in [0,1] \ \rightarrow \ \int_0^1 \frac{1}{f(D)} dD = \int_0^{N_e} dn = Ne$$

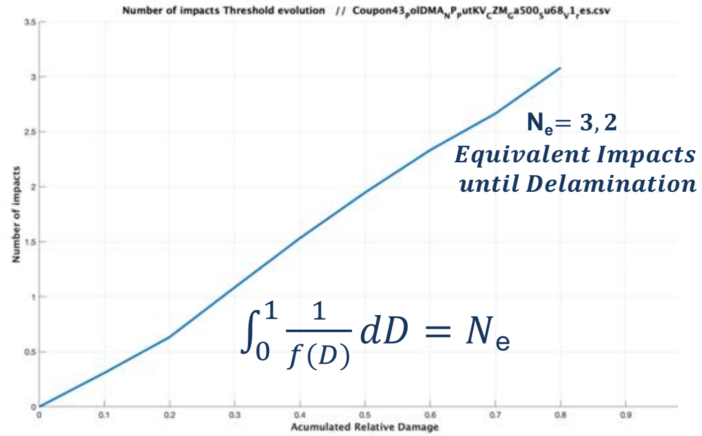


$$(2.6) \qquad E_j = E_i - \frac{\sum_{n=i}^{j} d_i}{n_j - n_i};\ \ E, D \in [0,1]$$

$$E_i = \{1, 0.9, 0.8 \ldots, 0.3, 0.2, 0.1\}$$



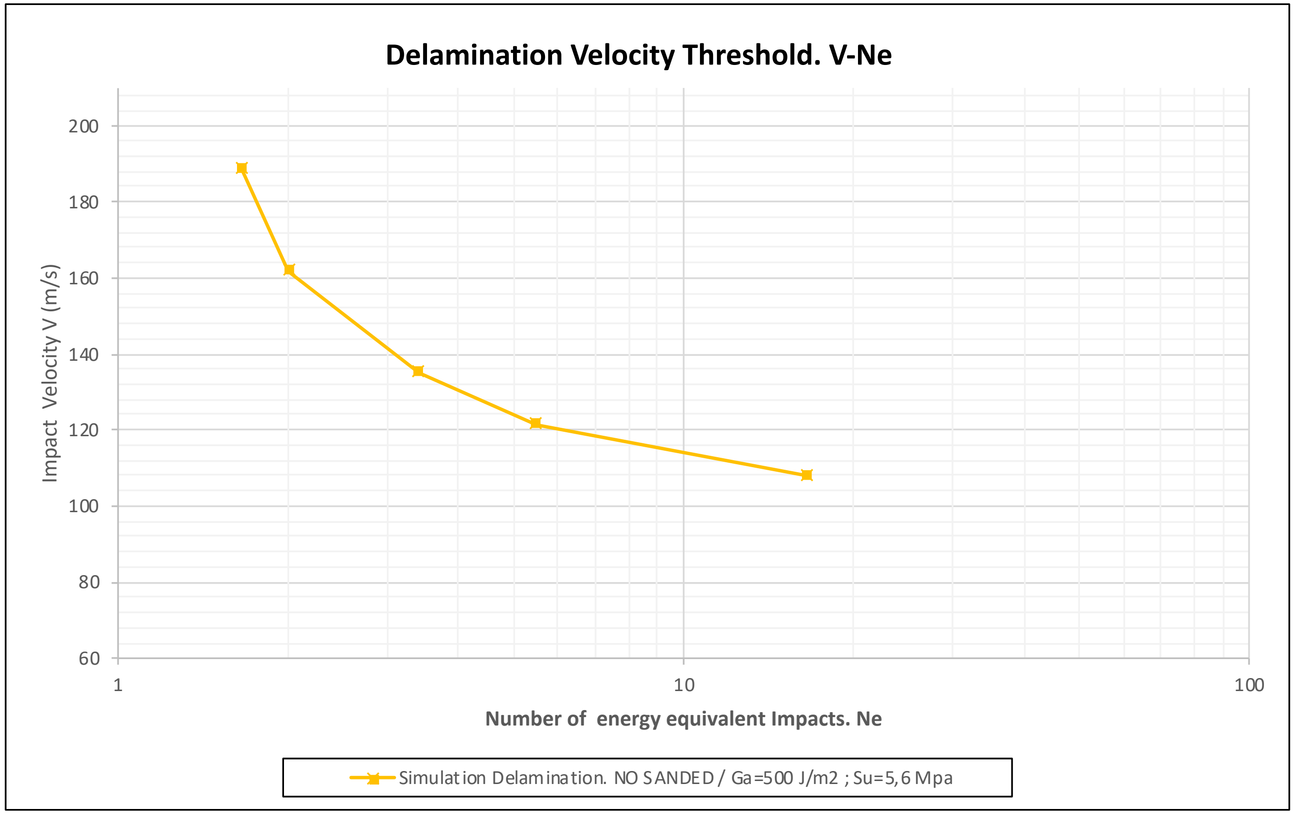
$$D = \frac{G_{Damaged}}{G_{Total}}\ ;\ D \in [0,1]$$



❑ **Case 2: Interface Delamination.** Contact Modelling & Characterization

CEU Universidad Cardenal Herrera

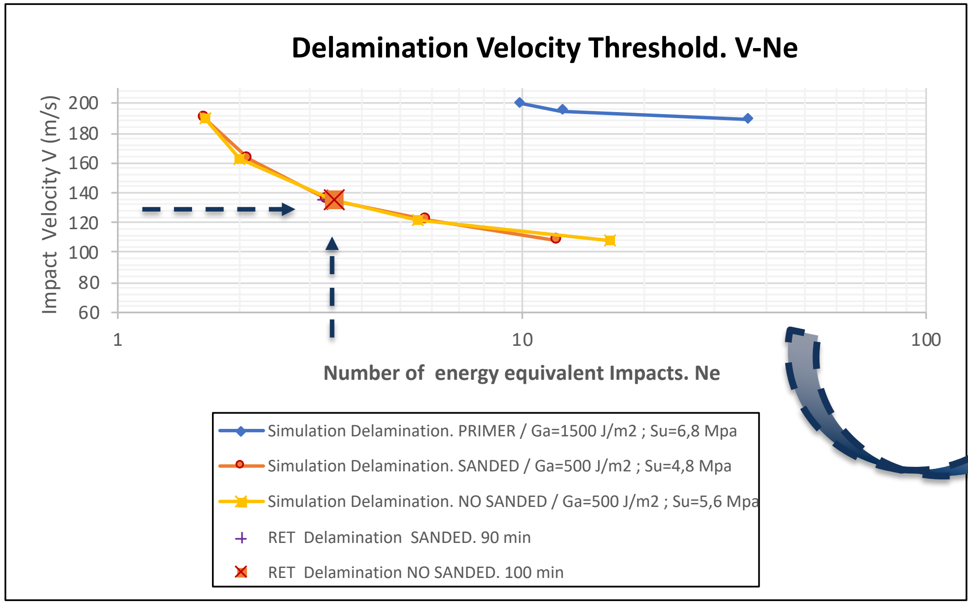
- ❑ The complete series of impacts from impact ***0* to impact *N_e*** is computed for different Impact Velocity values so a comprehensive **V-N plot** is stated for determining the **Delamination Threshold Velocity:**

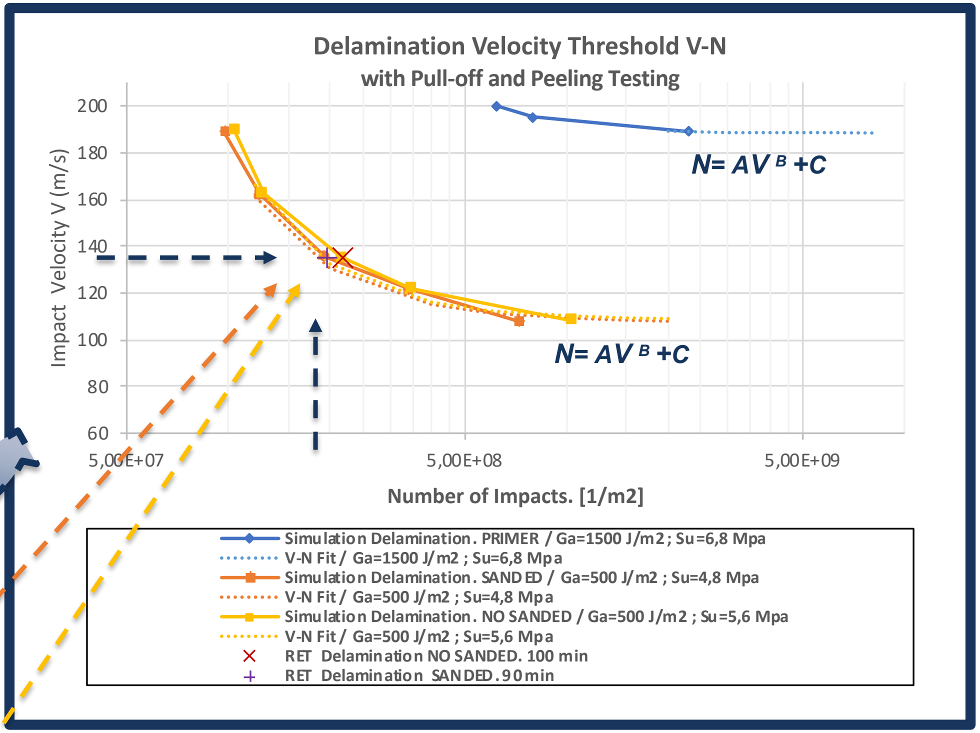


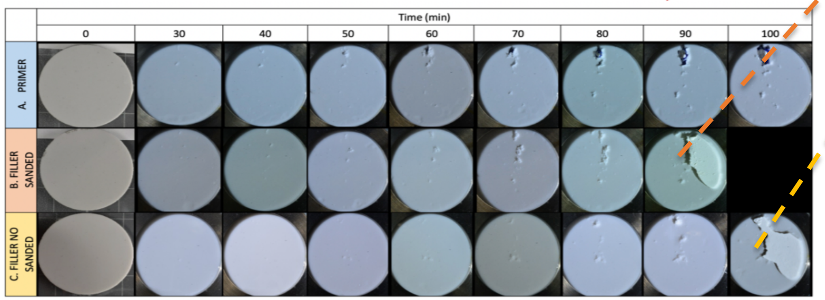
❑ **Case 2: Interface Delamination.** Contact Modelling & Characterization

CEU Universidad Cardenal Herrera

❑ **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 **a tool 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