MANUFACTURING ISSUES WHICH AFFECT COATING EROSION PERFORMANCE IN WIND TURBINE BLADES

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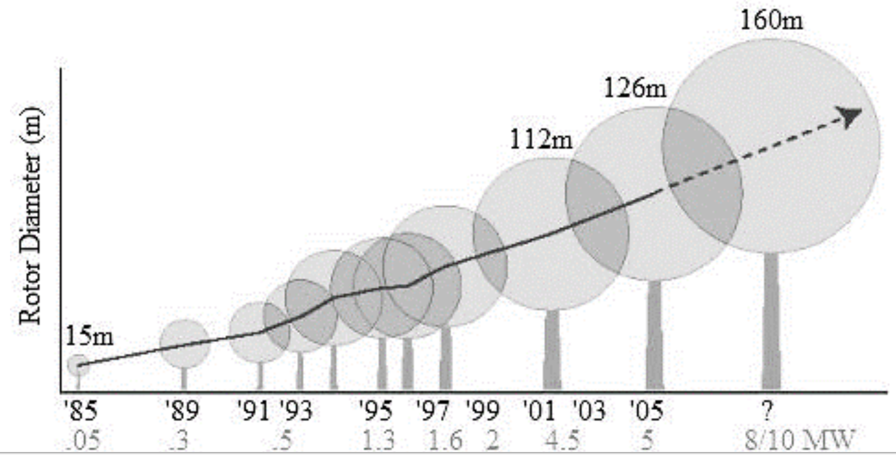
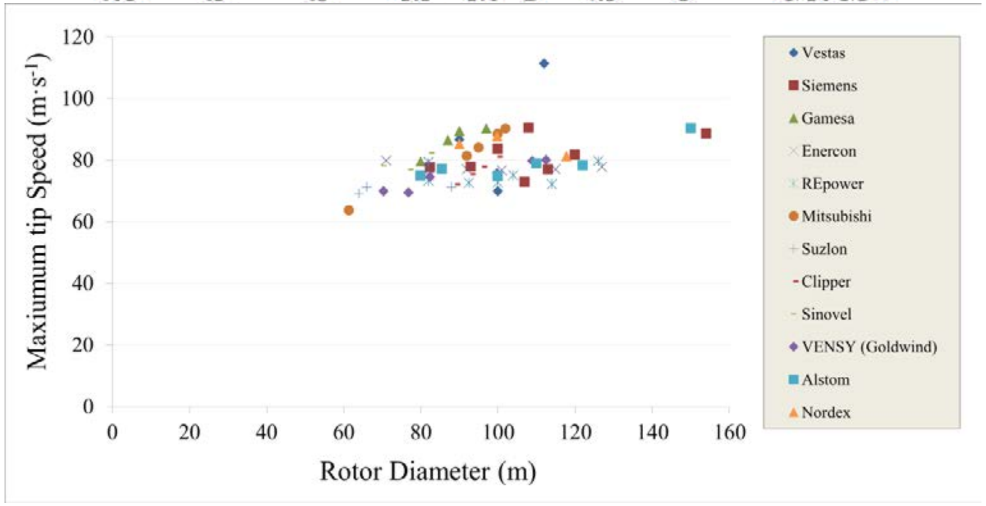
1. Introduction. Wind turbine blade technology trends

- 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**....**

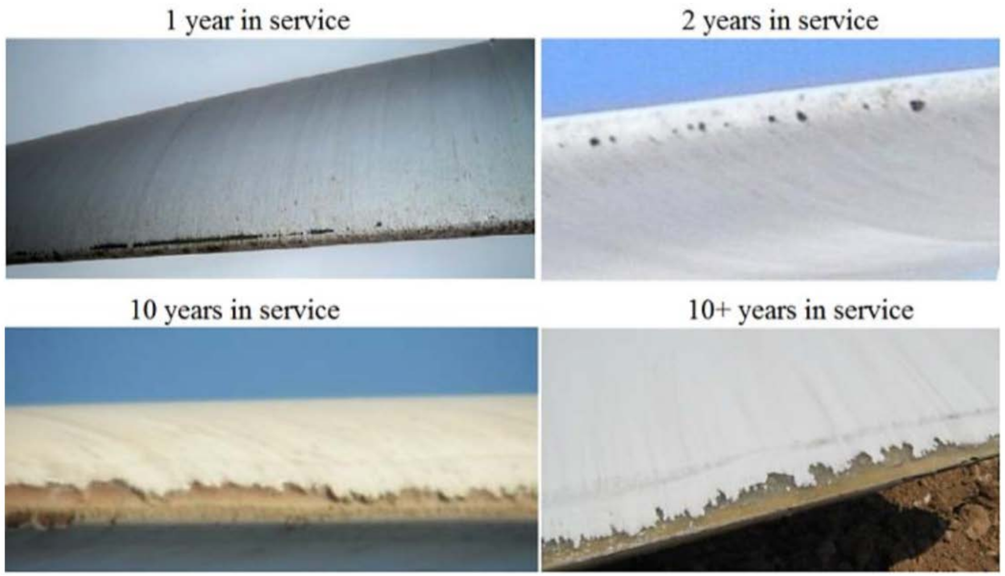
1. Introduction. Wind turbine blade technology trends

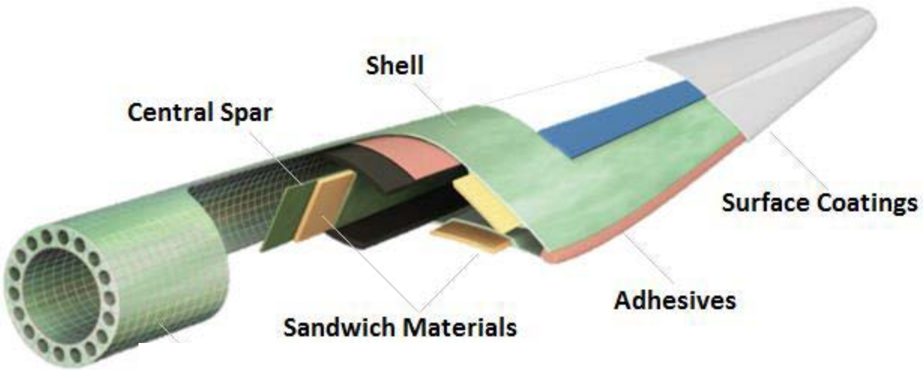


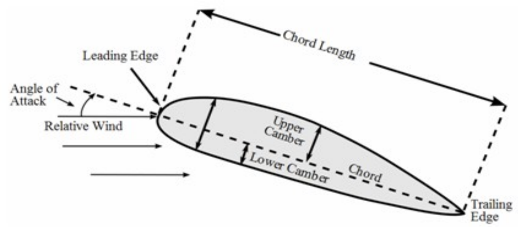


2. **Motivation.** Leading Edge Protection

- 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.



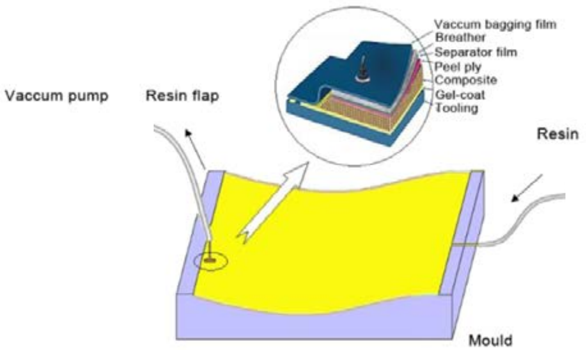




- The **costs associated with erosion in terms of <u>loss of power performance and repair</u>** and downtime costs have a large impact on the LCoE (Levelized Cost of Energy) for wind.
- **<u>An erosion solution needs to be developed</u>**.

3. **Key issues on coating development**. Industrial Manufacturing

- Two most common technologies used:
  - **In-mould coating** (a moulded layer of a similar material of the matrix one epoxy/polyester)

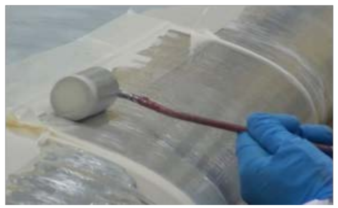


  - **post-Mould application** (applied after moulding through open moulding, painting or spraying with different material choice). **Leading Edge Protection** applied on the affected area, near blade tip.

- The **coating application during processing** is a major **concern on erosion performance**. Industrial process with a fewer number of coating layers are recommendable because of the **reduction of interfaces**.

AEROX
AHP LEP **910 VS**
(Spray application)

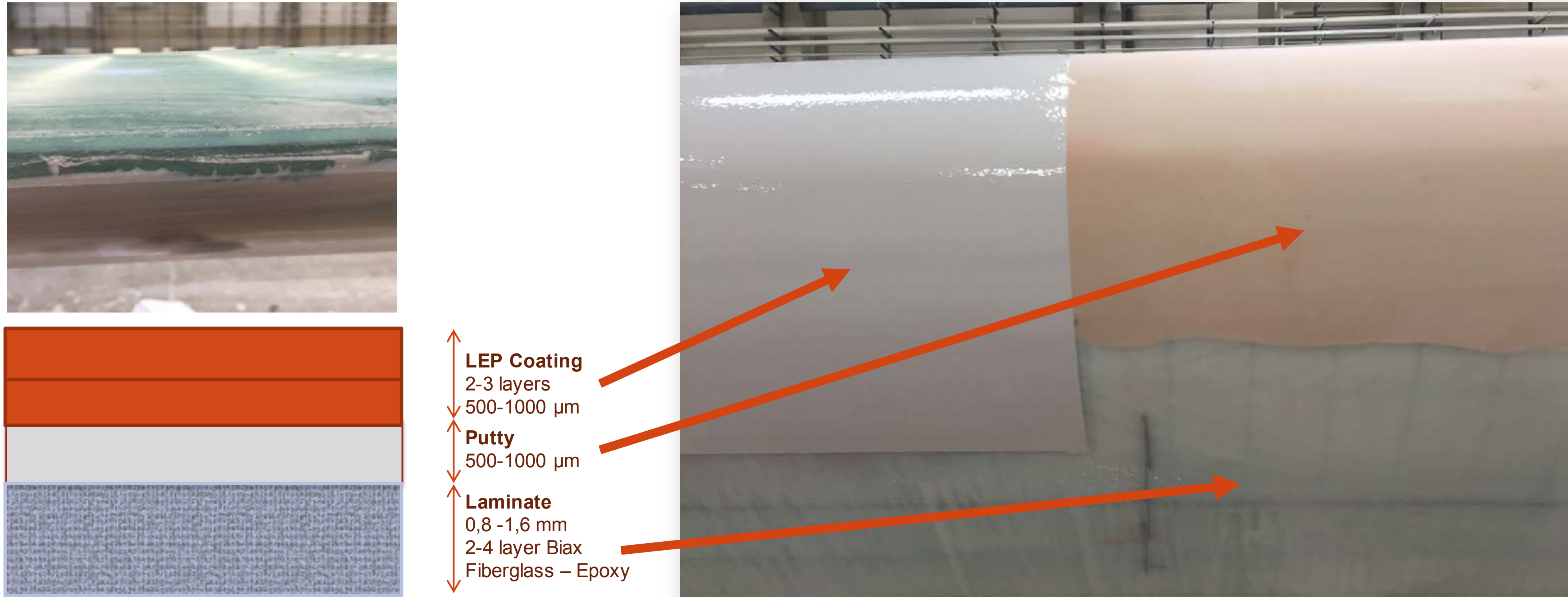
AEROX
AHP LEP **910 VF**
(Roller application)



AEROX
AHP LEP **910 VE**
(Trowel application)

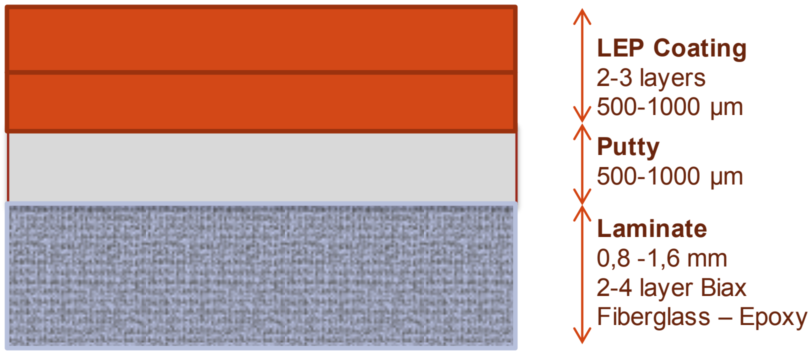
3. **Key issues on coating development.** Multilayer system

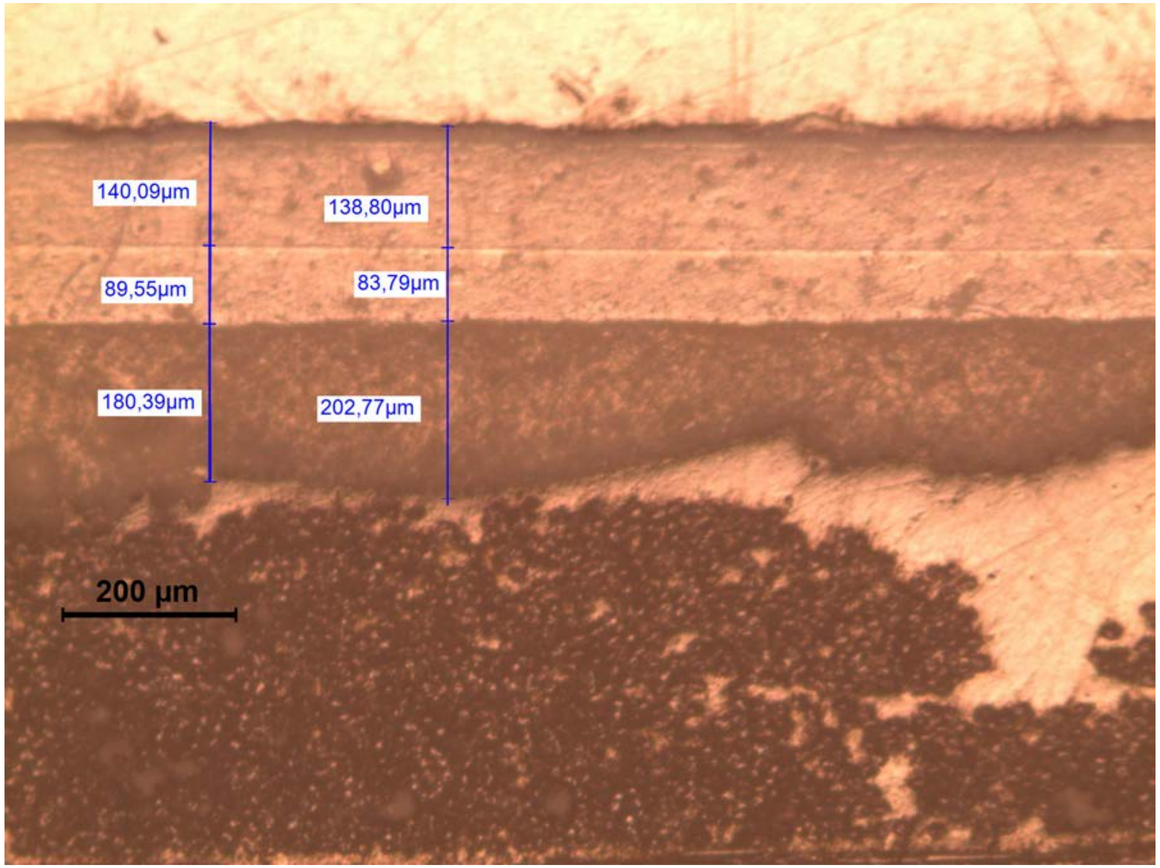
- **Industrial process** defines **the Leading Edge Protection** system on the blade surface.



3. **Key issues on coating development.** Multilayer system

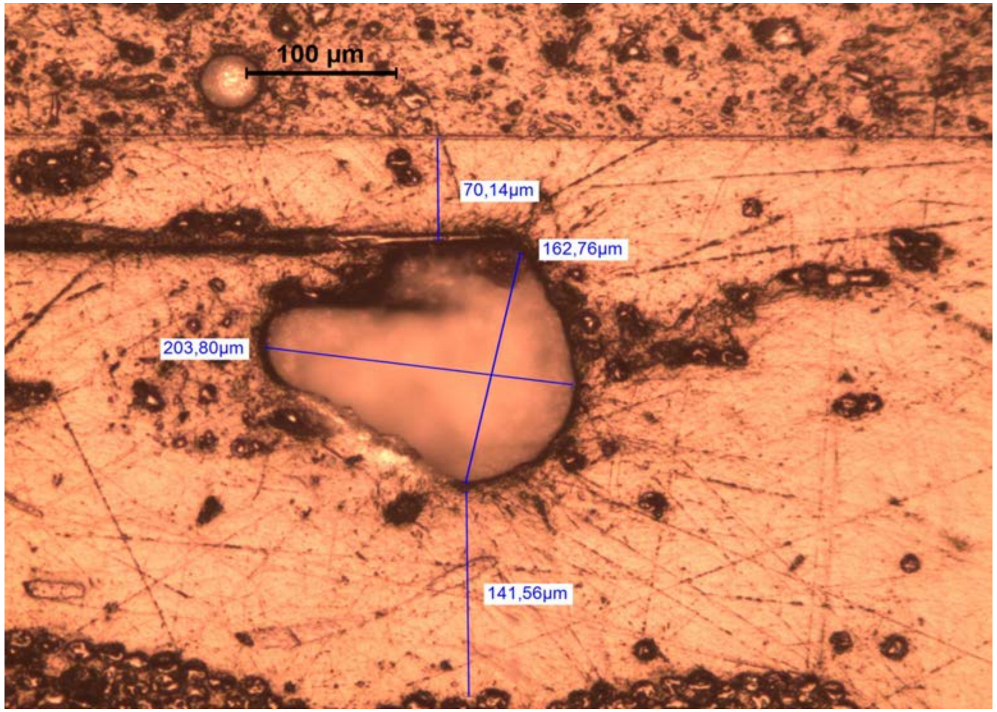
- **The theoretical versus real configuration**
- Standard industrial systems are based on a **multilayer system**, with a **high number of interphases that** tend to accelerate **erosion** by **delamination**

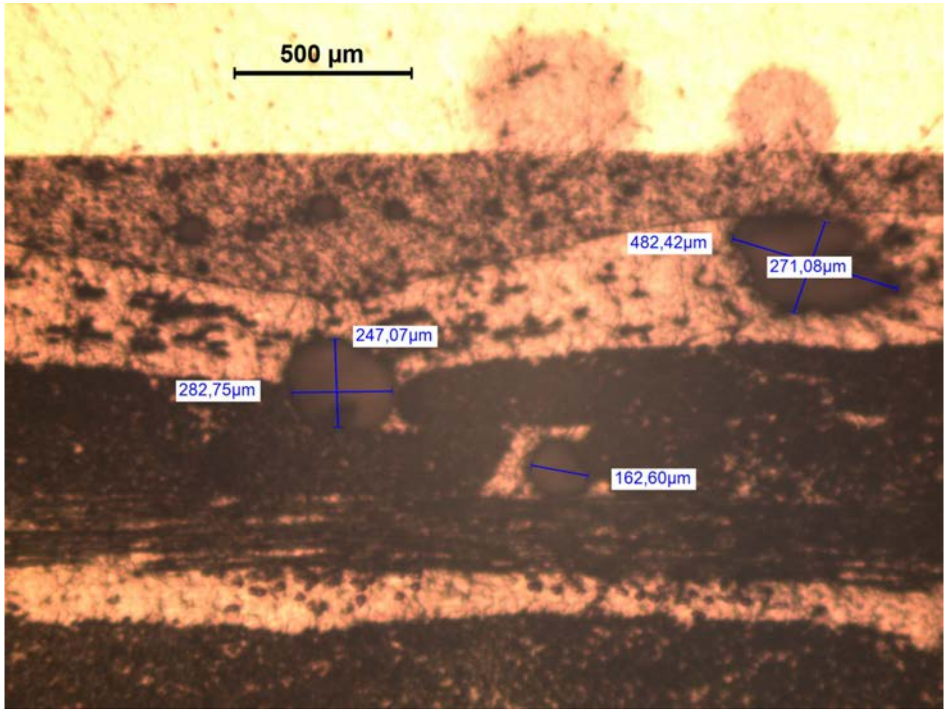




3. **Key issues on coating development.** Industrialization process

❑ **Defects induced** from industrialization process

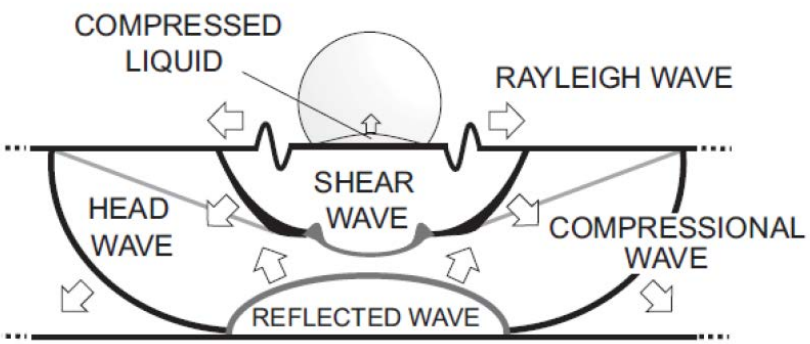


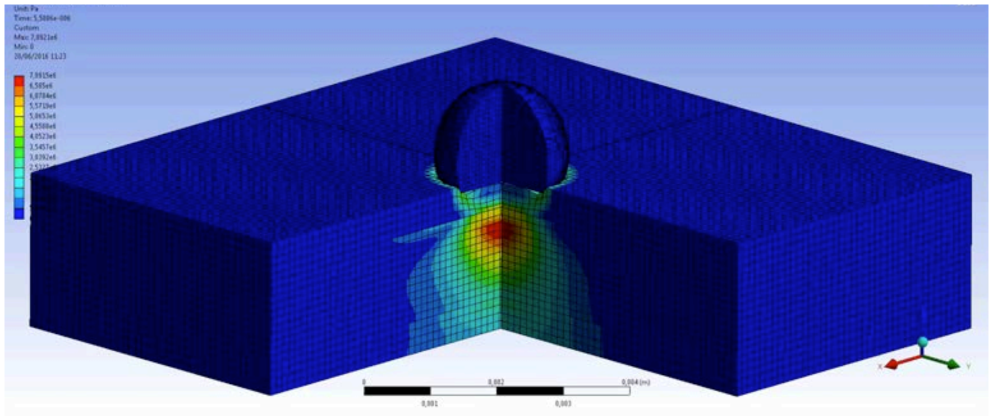


4. On the modelling of rain drop impact in wind turbine blades.

- **Liquid impact phenomena**

- **Approach: Understanding the physics of failure** of the Leading Edge Erosion on turbine blades.
- 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 **understanding of these interactions** through the numerical modelling is limited but thought to be of key significance.



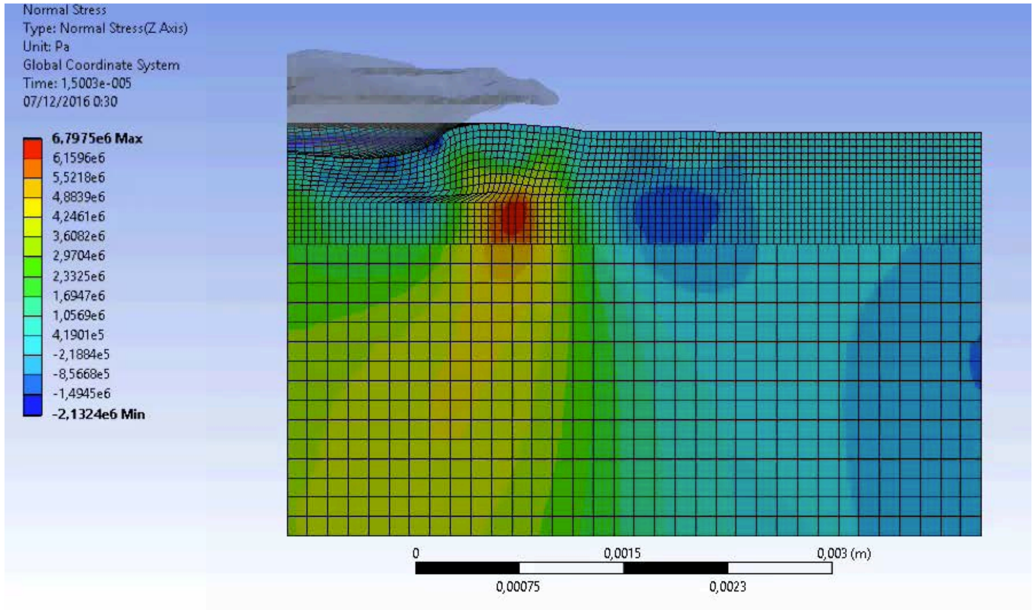


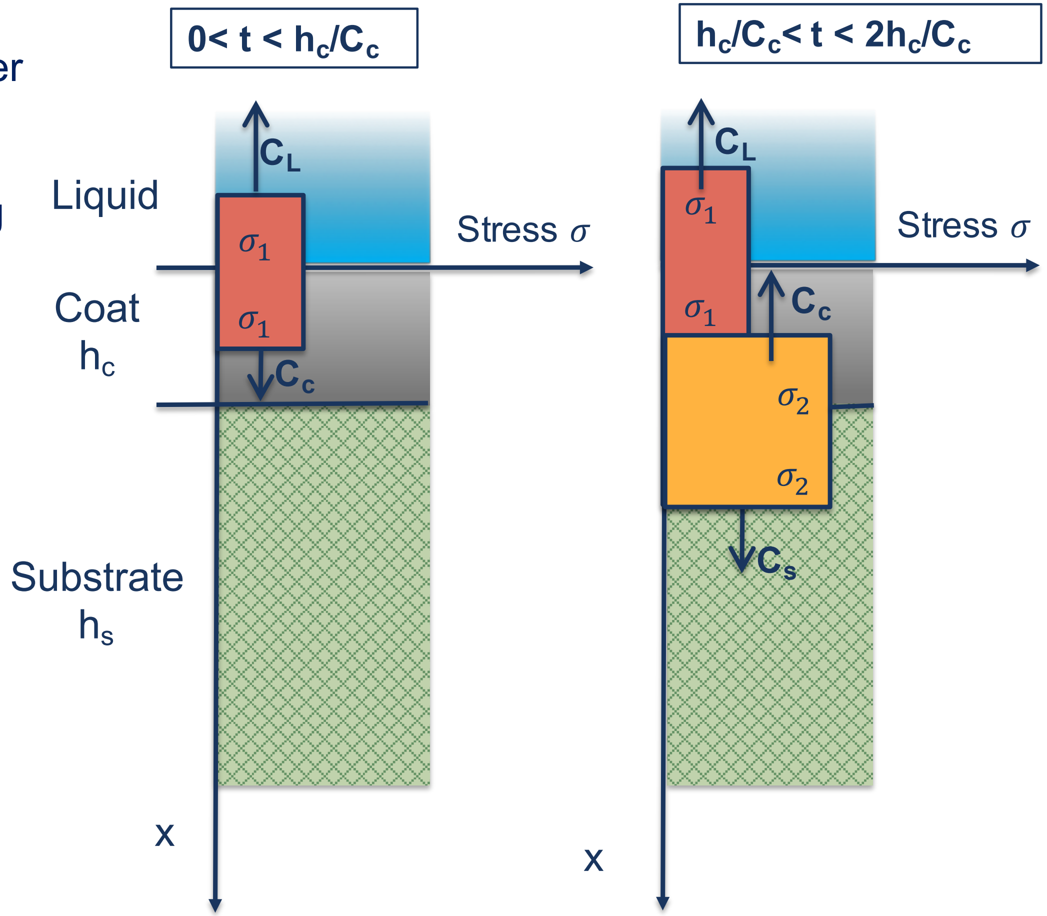
- **Objective:** Develop/state appropriate **numerical models** and generate **a tool to effective leading edge material design**. Develop/state a **rain erosion prediction model**.

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

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

- Upon impingement, 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** with a different amplitude **depending on the material acoustic impedances** and the remaining part is transmitted to the substrate.





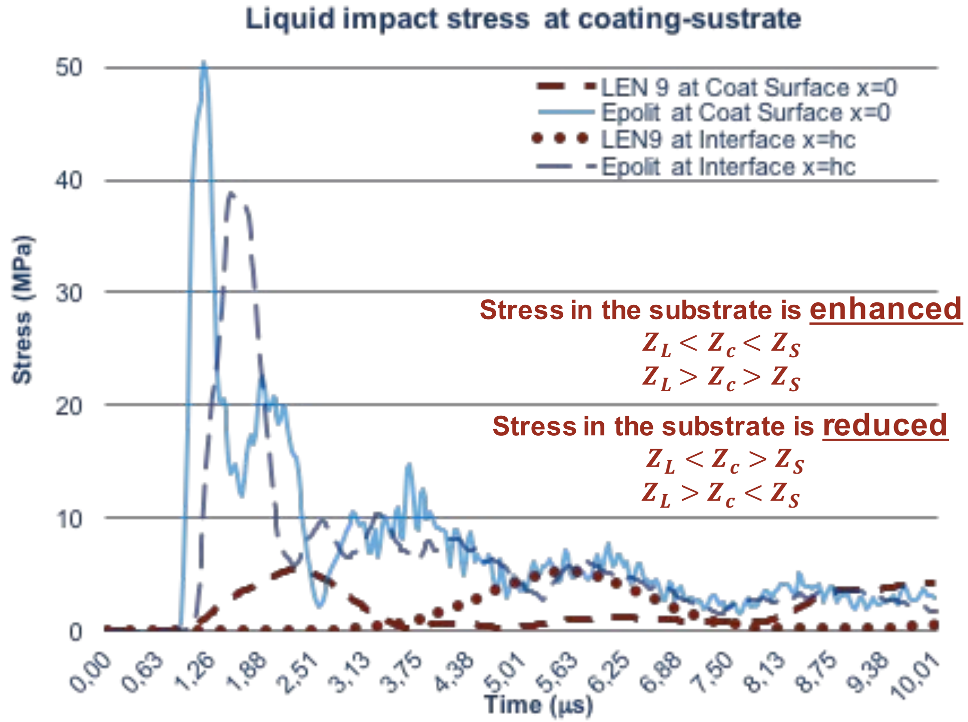
4. On the modelling of rain drop impact in wind turbine blades.

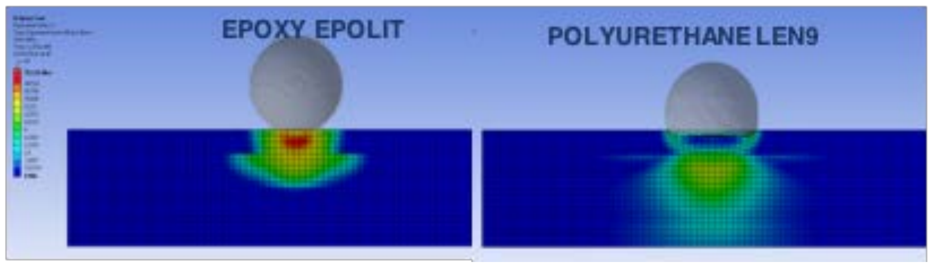
- **Stress reduction on the substrate by usage of a coating layer**

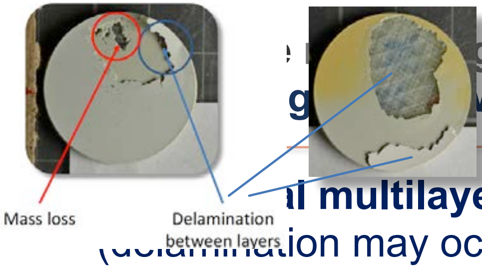
- In order to reduce the stress in the substrate and determine the suitability of the candidate materials for leading edge applications, the **approach** can be used to **identify suitable coating and substrate combinations** and their **potential stress reduction on the substrate interface** and also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

- 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**



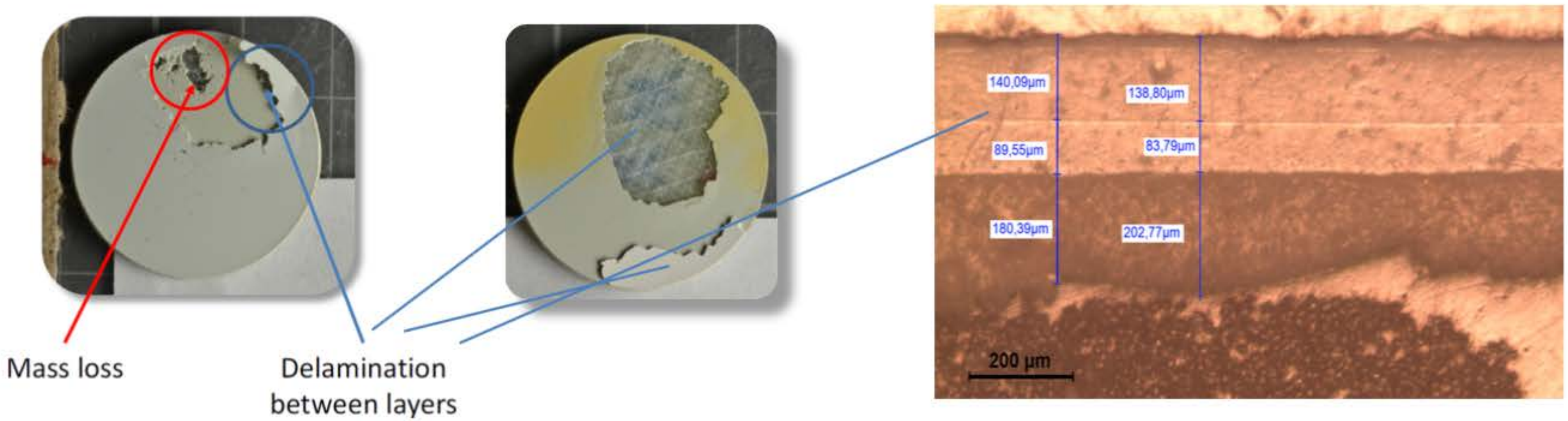




g of rain drop impact **in wind turbine blades.**

which affect erosion performance: adhesion to substrate

l multilayer scheme, the lack of adhesion at interface play a key role on its deterioration ion may occur at interface or **between layers**). The impingement shock wave is reflected wherever the acoustic impedance properties differ locally.

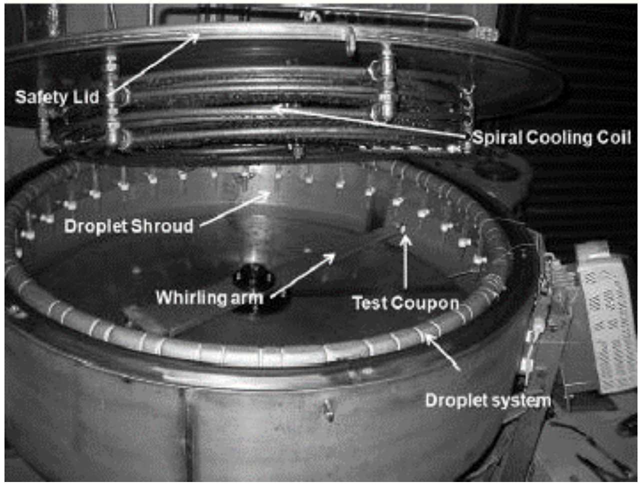


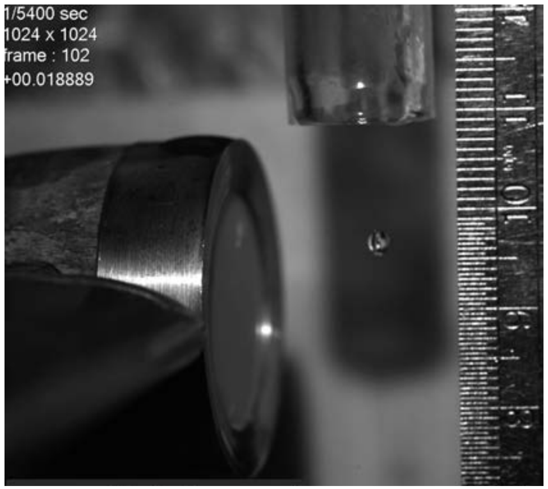
(a) (b)

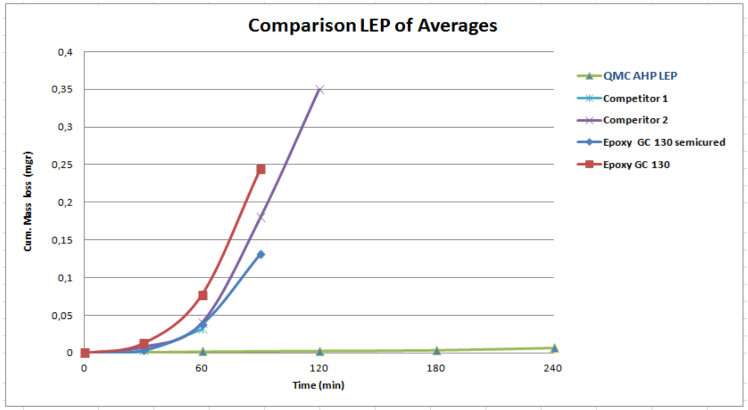
FIGURE 5. (a) Rain erosion testing specimens. Erosion failure due to mass loss on surface and interface delamination. (b) Multilayer system microscopy. Two coating layers define an interface that tend to delaminate upon impingement.

4. On the modelling of rain drop impact in wind turbine blades.
Evaluation and quantification of erosion damage in surface coatings. Rain Test

- ❑ 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. Currently there is **no universally accepted method 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.





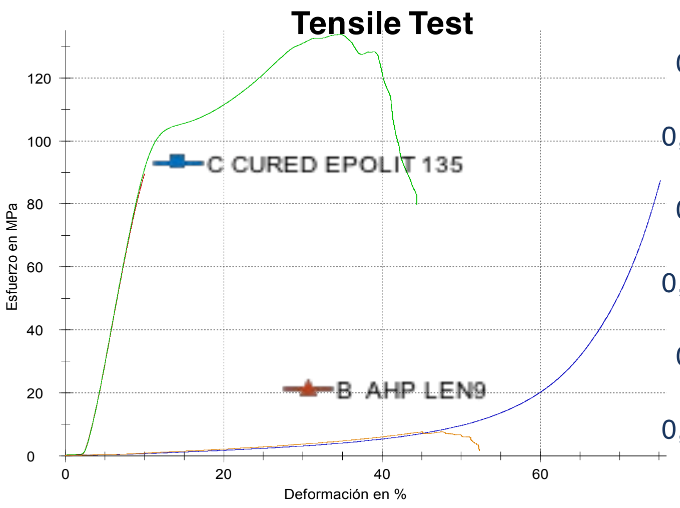


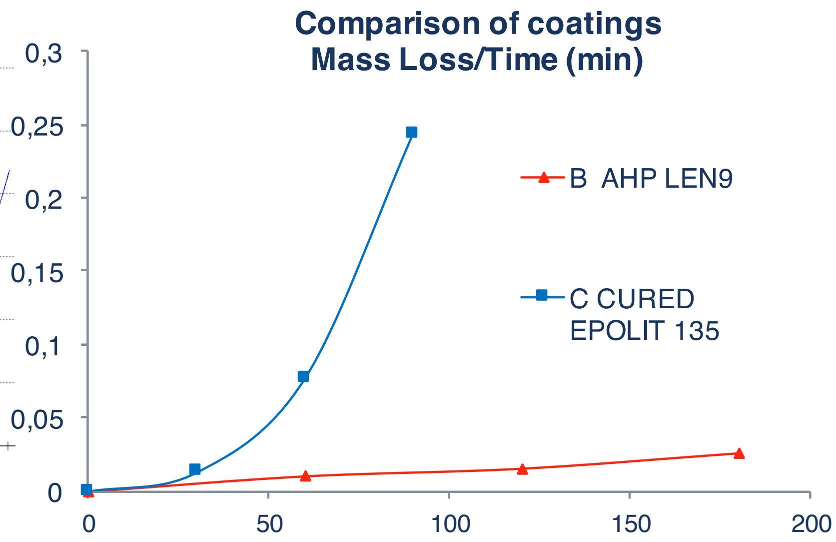
4. On the modelling of rain drop impact in wind turbine blades.

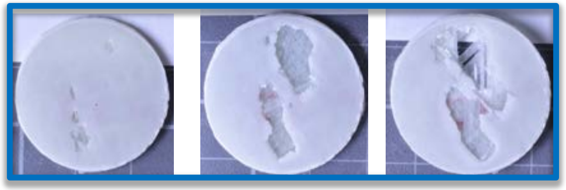
Coating factors which affect erosion performance: mechanical properties

- **Objective: Determine mechanical properties relation with mass loss in erosion.**

- The **rain erosion testing** quantified that samples of laminate substrate with two layer biaxial epoxy-GF, 0.7 mm thick and two different gel coat layer of 0.3 mm behaved different.
- A **Polyurethane based polymer coating LEN9**, showed better results comparing with **Epoxy EPOLIT** ones as predicted by the modelling.

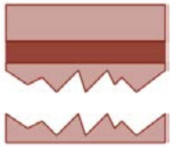






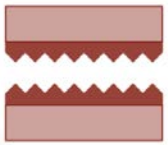
4. Coating factors which affect erosion performance:
Coating application method and curing ; adhesion to substrate

- **Approach: Determine interface adhesion** coating-laminate **depending on coating curing.**



- Asses the macroscopic behavior of the interface, **Pull-off strength testing** of the samples showed the failure in the

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



- Specifically developed **Peeling test for interface** quantified the force of failure with a value of 19,3(N) for the cured coating and of 25,1(N) for the less cured one.

Coat	ΔH $_{exothermic\ peak}$ (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

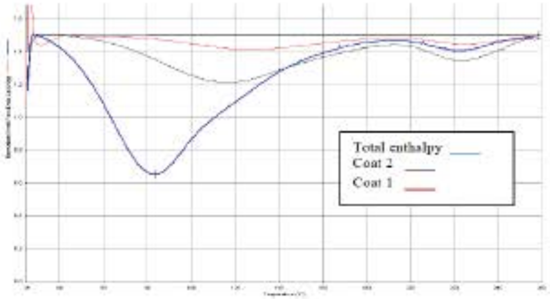


Figure 1: Degree of conversion (α) measured with DSC in the two experimental samples

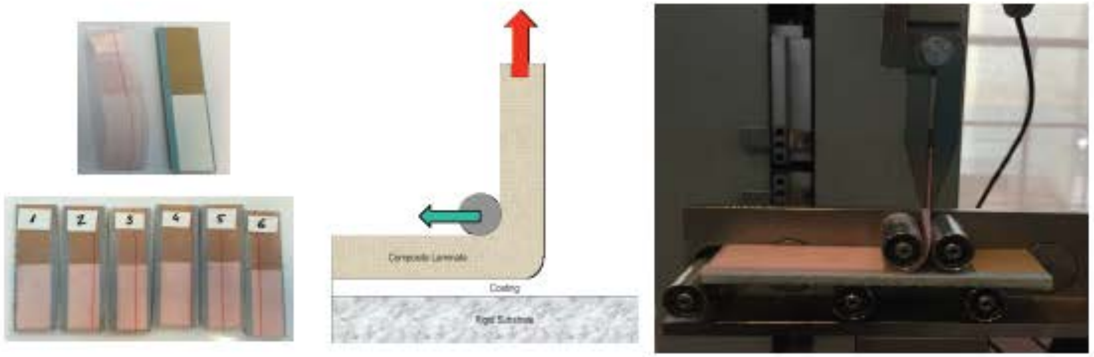


Figure 4: Developed peeling testing for interphase coating-laminate adhesion response quantification

4. Coating factors which affect erosion performance:
Coating application method and curing ; adhesion to substrate

- Specifically developed **Peeling test fo interface** showed the force of failure with value of 19,3 (N) for the cured coating and c 25,1 (N) for the less cured one (tack).

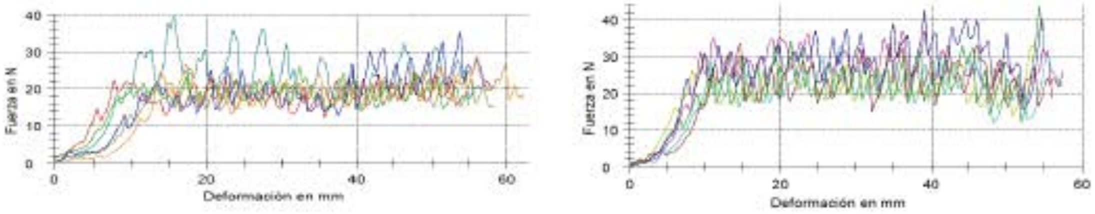
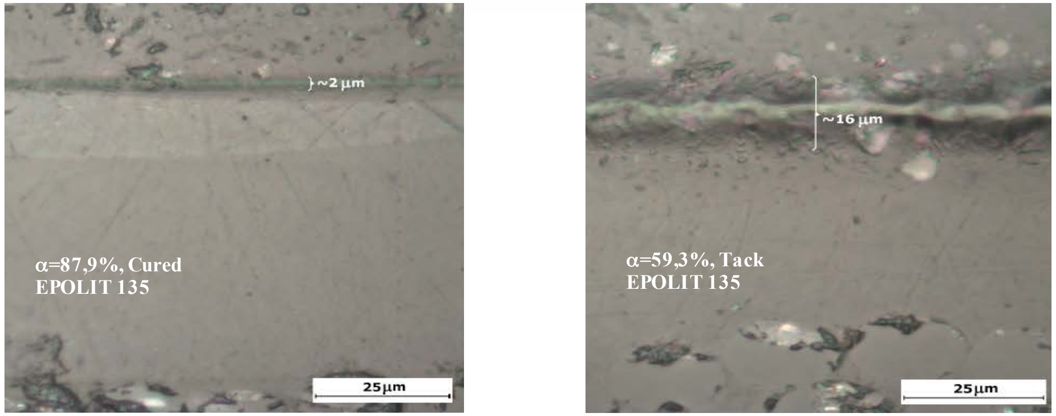


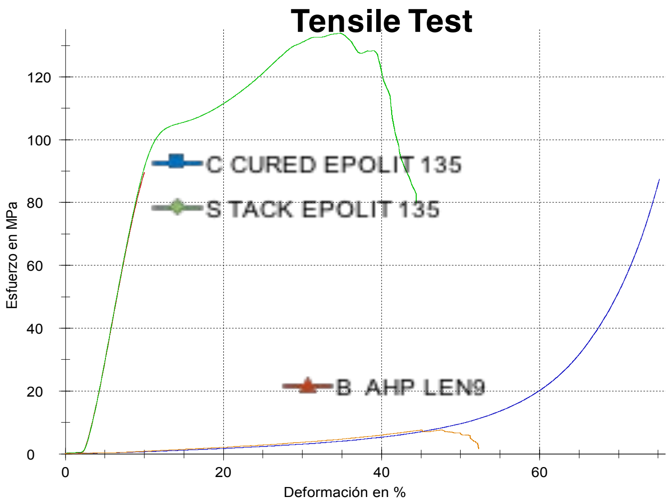
Figure 6 Force of failure for interphase adhesion testing. Coat 1 (cured) left, Coat 2 (tack) right

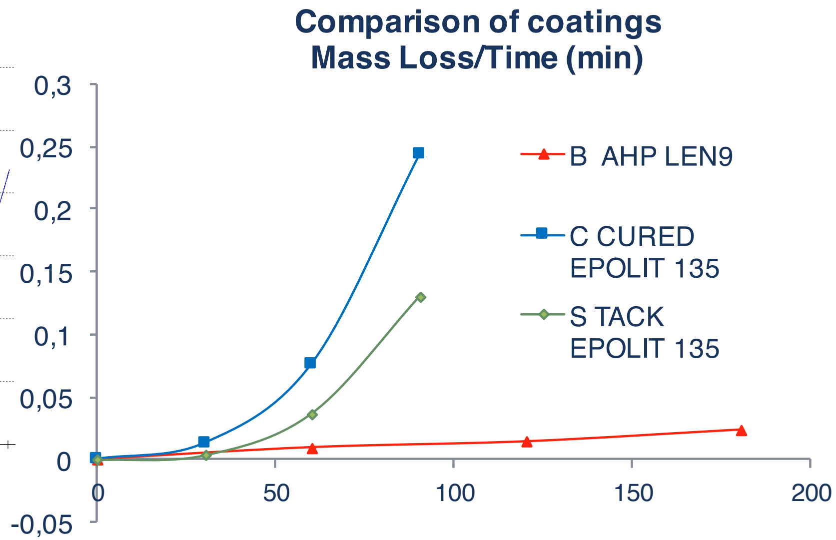
- It can be observed how the **less-cure coating** (curing conversion α=59,3% instead of α=87,9% for the same **epoxy based polymer, EPOLIT**) defines a **broader interface area** with the infused GF laminate with epoxy resin due to a **higher chemical adhesion**.

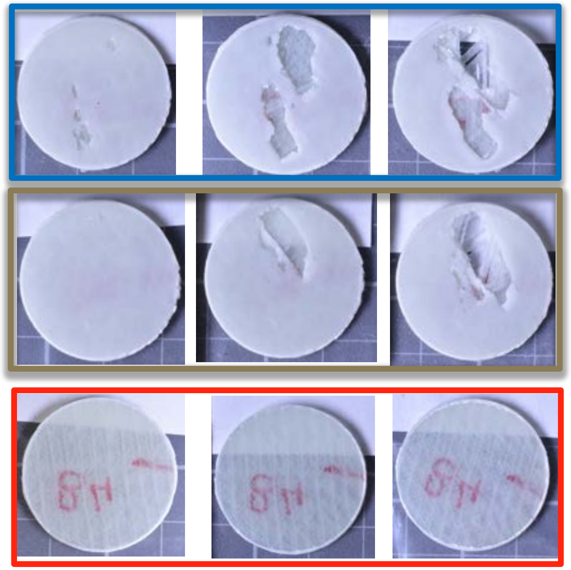


4. Coating factors which affect erosion performance:
Coating application method and curing ; adhesion to substrate

- **<u>Objective:</u> Determine <u>Interfase coating-laminate relation</u> with mass loss in erosion.** Extend to **vibroacoustic properties** of coating/blade interphase.
- The **rain erosion testing** indicated that samples of laminate substrate with two layer biaxial epoxy-GF, 0.7 mm thick and a gel coat layer of 0.3 mm, manufactured with a **higher degree of cure coating**, **performed worse**. These **results correlate with peeling testing**. A **Polyurethane based polymer coating LEN9**, was also tested showing better results comparing with **Epoxy EPOLIT** ones

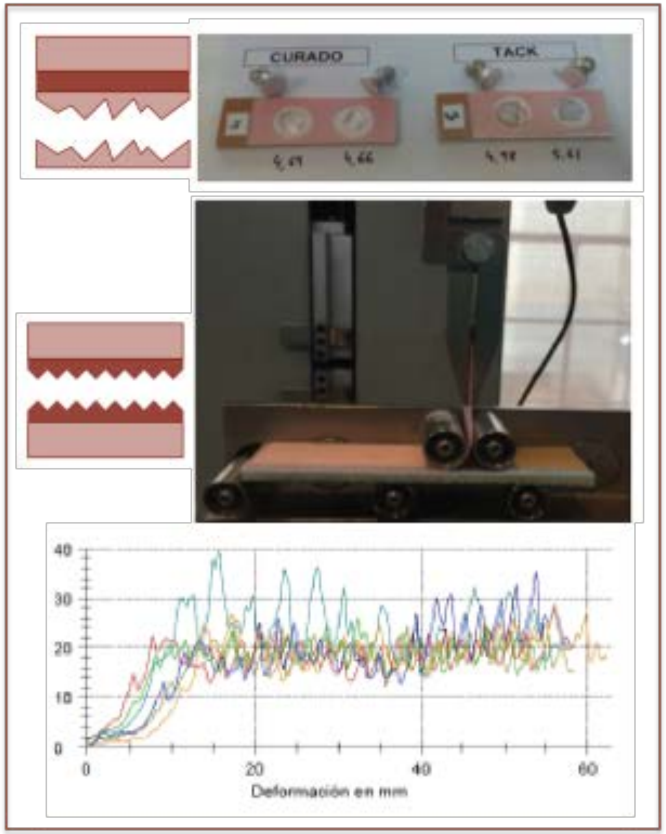






4. **Coating factors which affect erosion performance**: adhesion to substrate depending on curing

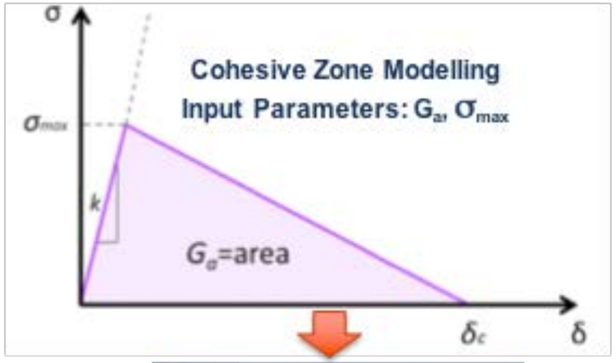
❑ **Objective: Modelling manufacturing factors** that affect Interface coating-laminate relation with mass loss in erosion. **Determine input parameters for Cohesive Zone Modelling in Peeling test**

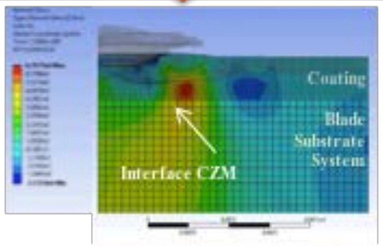


Manufacturing factors affecting erosion

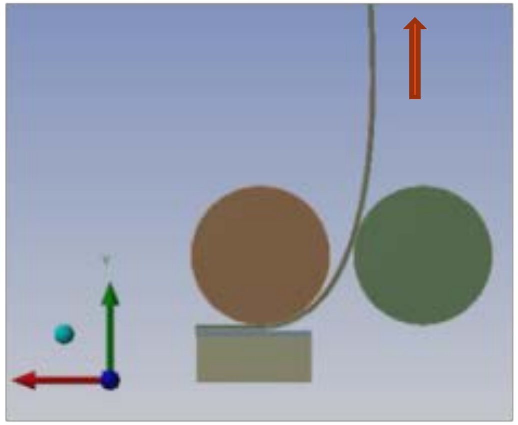
Pull off and Peeling testing. Lab scale specimens

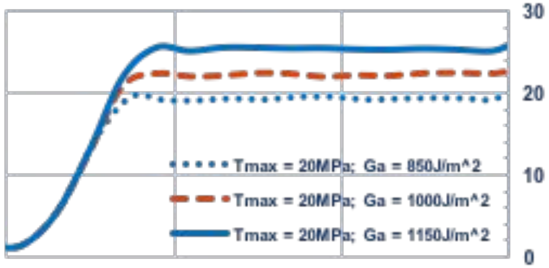
Numerical Modelling Peeling testing. Parametric study





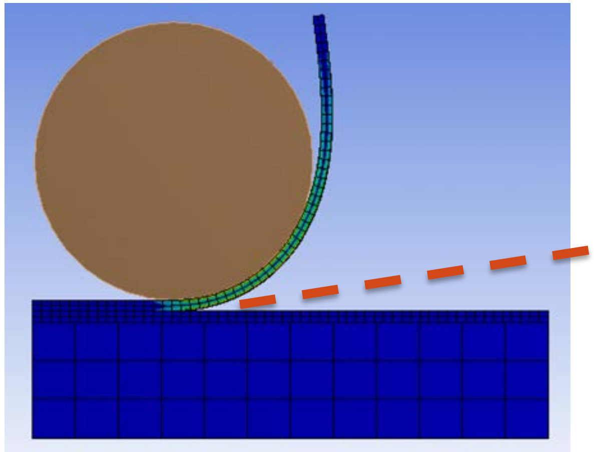
Numerical Modelling Rain Droplet impact and Lifetime prediction

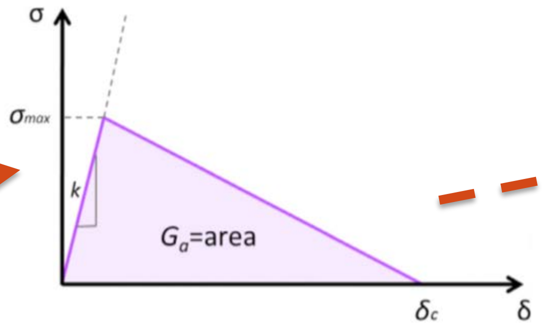




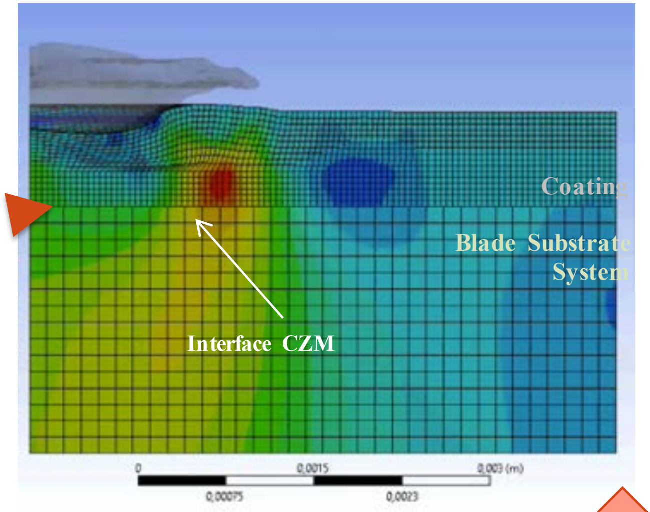
4. Coating factors which affect erosion performance:
adhesion to substrate depending on processing

- **<u>Objective:</u> Modelling manufacturing factors** that affect <u>Interface coating-laminate relation</u> with mass loss in erosion. **Cohesive Zone Modelling for <u>droplet impact modelling and erosion lifetime prediction</u>**



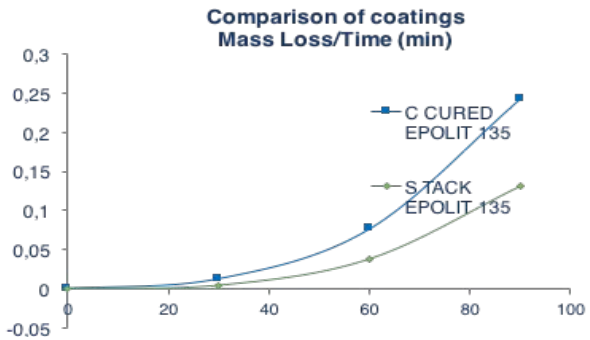


CZM Used in **droplet impact** Interface Contact Modelling



Manufacturing Factors (curing, sanding, spray, roller, trowell **[…]**

Erosion Lifetime Prediction

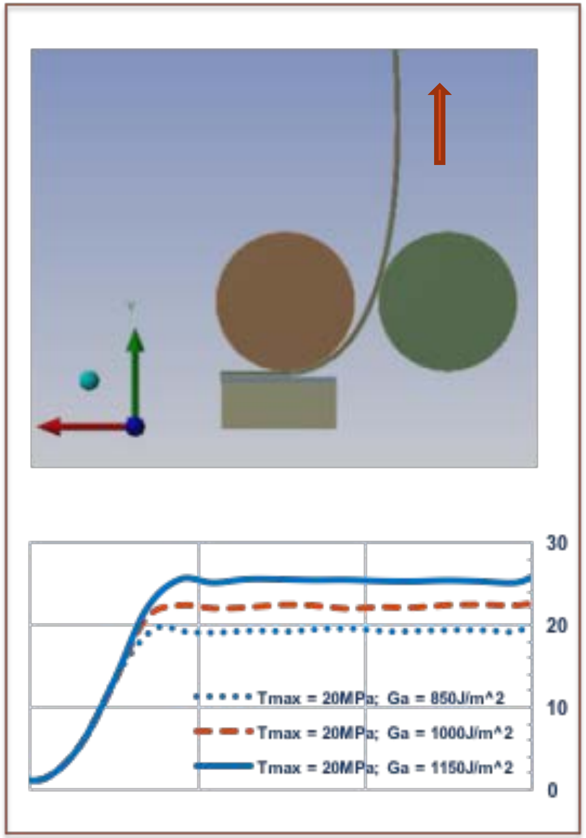


4. **Coating factors which affect erosion performance**:
CZM modelling

- The model is based on a **cohesive zone formulation** were knowing the experimental peeling force value (of 19.3 N for the cured specimen and the less-cured coating with a value of 25.1 N.), it is **related numerically to the fracture energy, G_a necessary for the interface failure**

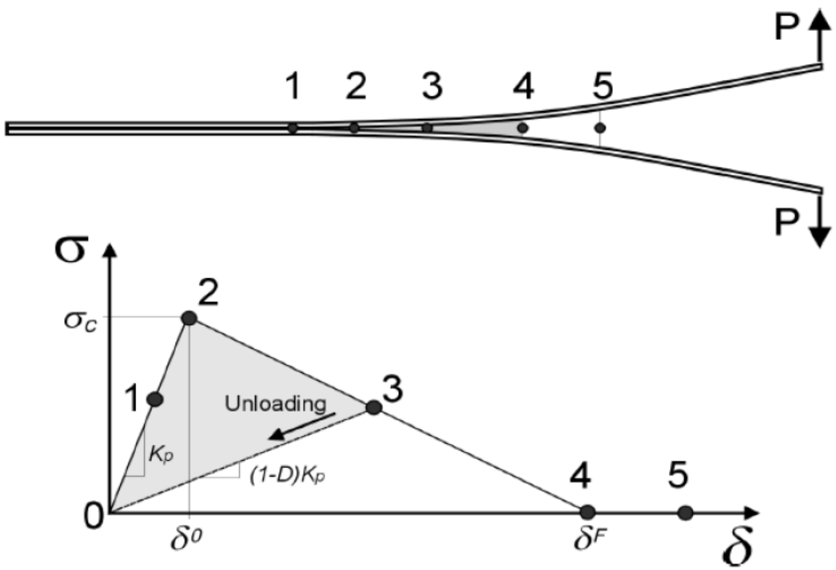
- Since **the peel energy, G_{input} is experimentally measured** with the **peeling testing** and the energy associated with the bending, G_{bend}, of the peel arm may be considered constant in both cases (since the curing only affects the interface and not the arm), we then have a first approximation for the fracture energy based on simulation results as
- $G_a = G_{input} - G_{bend}$
  - G_a =850 J/m2 for the cured coating
  - G_a=1150 J/m2 for the tack coating.

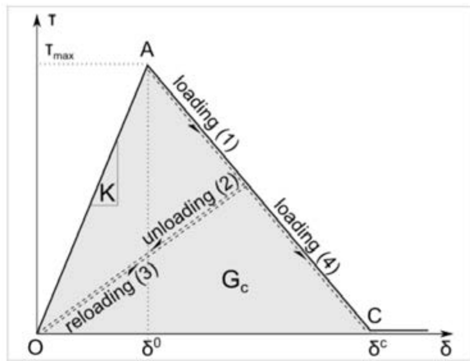
- Fracture was assumed to be predominantly via **a Mode I (tensile) failure.** In all the simulations, it is related as a parameter value the normal traction, σ, to the normal opening displacement, δ, across the crack surface. σ_{max} can be also limited by the experimental value obtained from the **Pull-off testing**

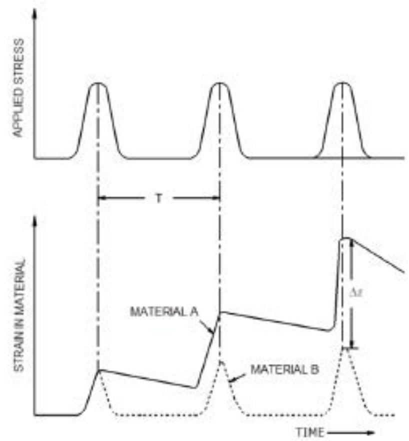


4. Coating factors which affect erosion performance:
CZM modelling

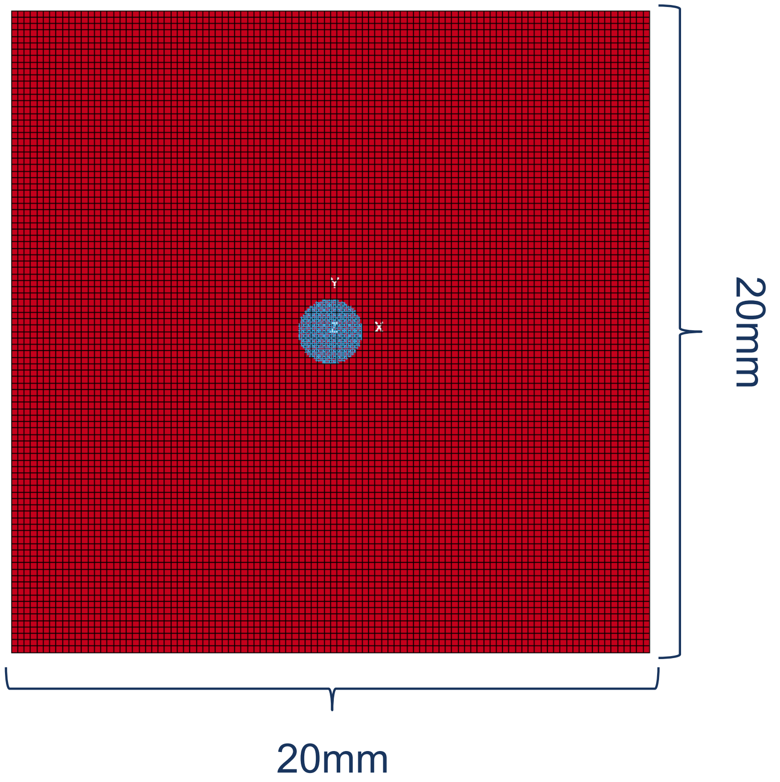
- <u>**Objective:**</u> **Modelling manufacturing factors** that affect <u>Interface coating-laminate relation</u> with mass loss in erosion. **Determine input parameters for Cohesive Zone Modelling in Peeling test**

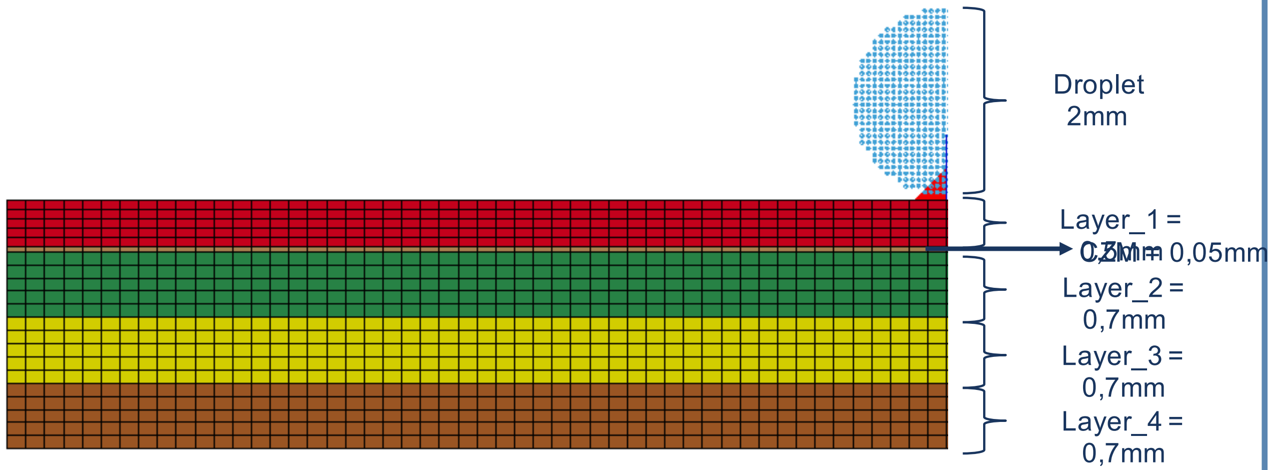






5. Results, discussion and further work. CZM Modelling

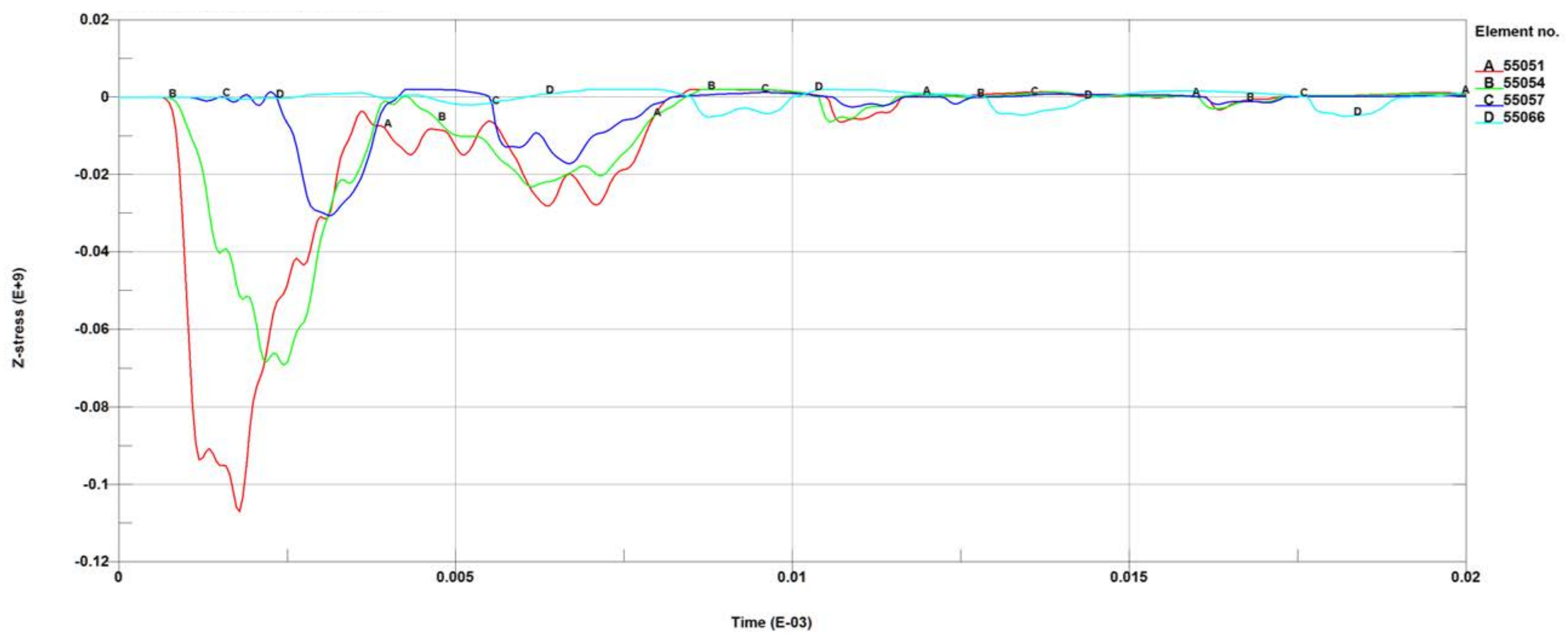




5. Results, discussion and further work. CZM Modelling

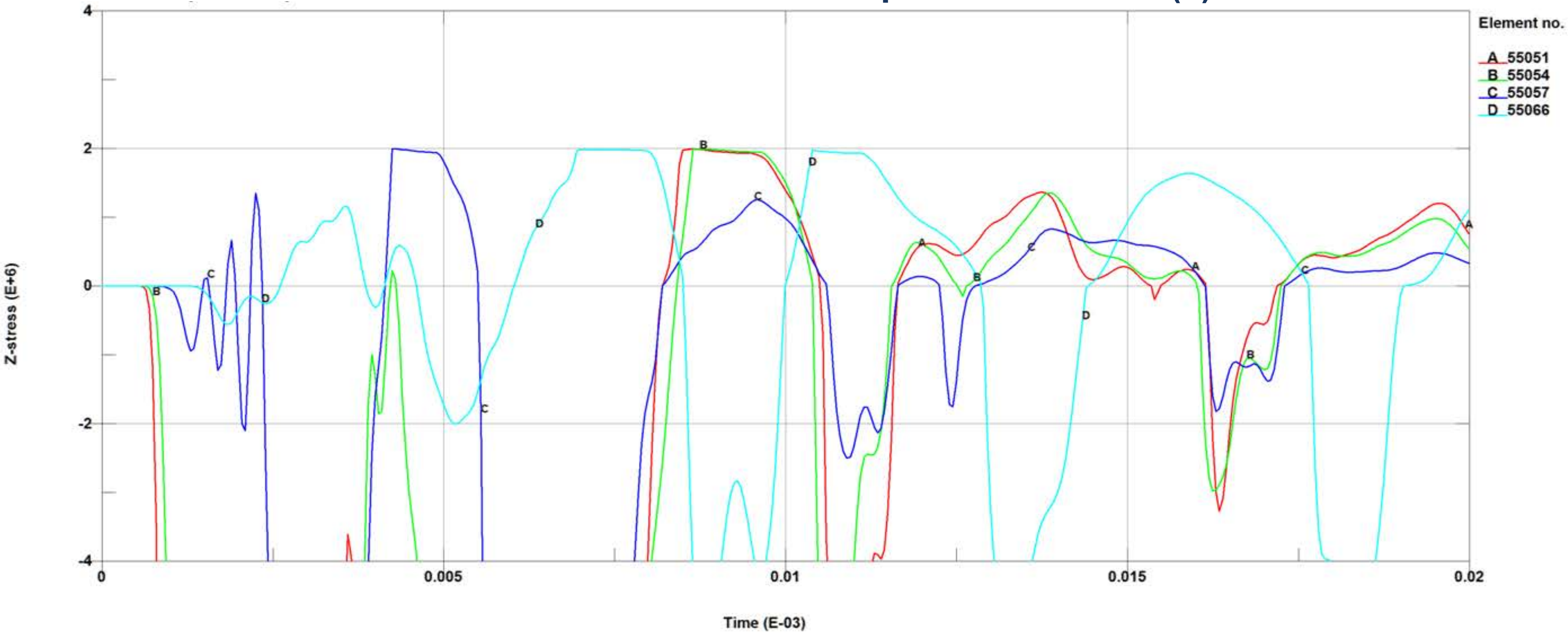
26th-28th April 2017, Dublin City University,
ESAFORM2017 DCU
MANUFACTURING ISSUES WHICH AFFECT COATING EROSION PERFORMANCE IN WIND TURBINE BLADES

Z-Stress evolution on
Central element and radial desplaced elements



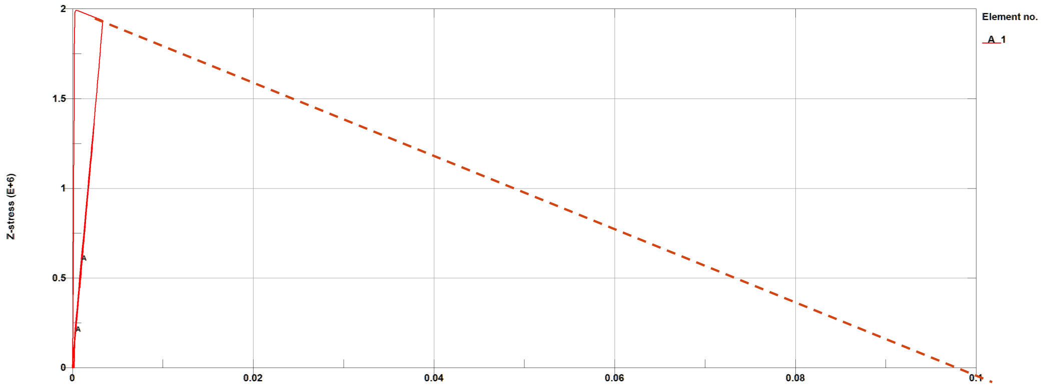
5. Results, discussion and further work. CZM Modelling

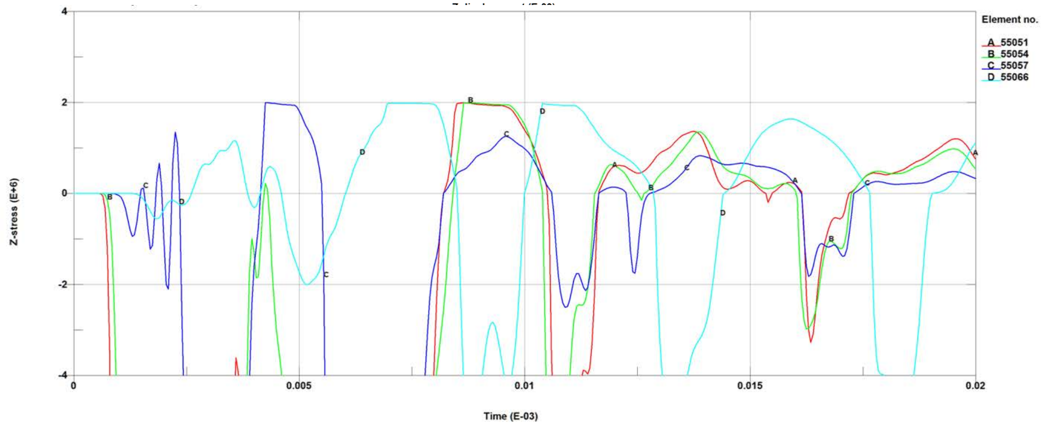
Z-Stress evolution on Central element and radial desplaced elements (2)



5. Results, discussion and further work. CZM Modelling

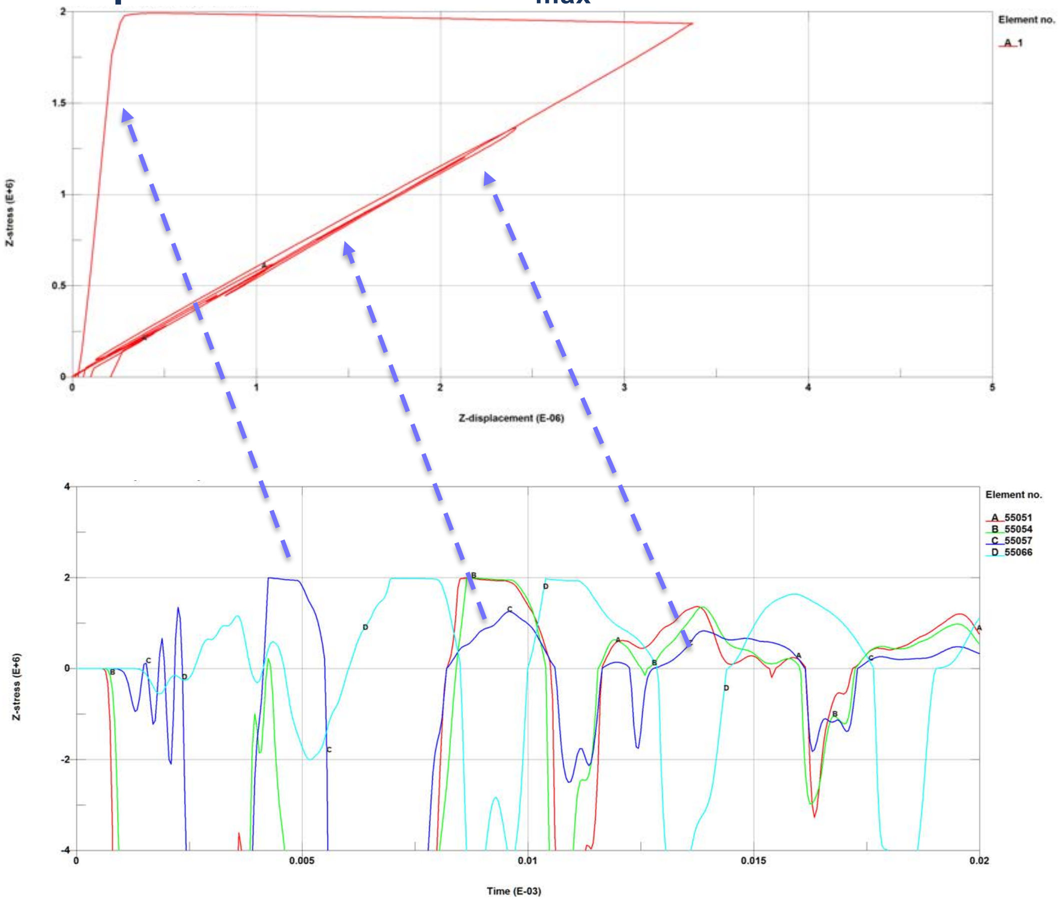
CZM Single impact
Z-Stress evolution on elements



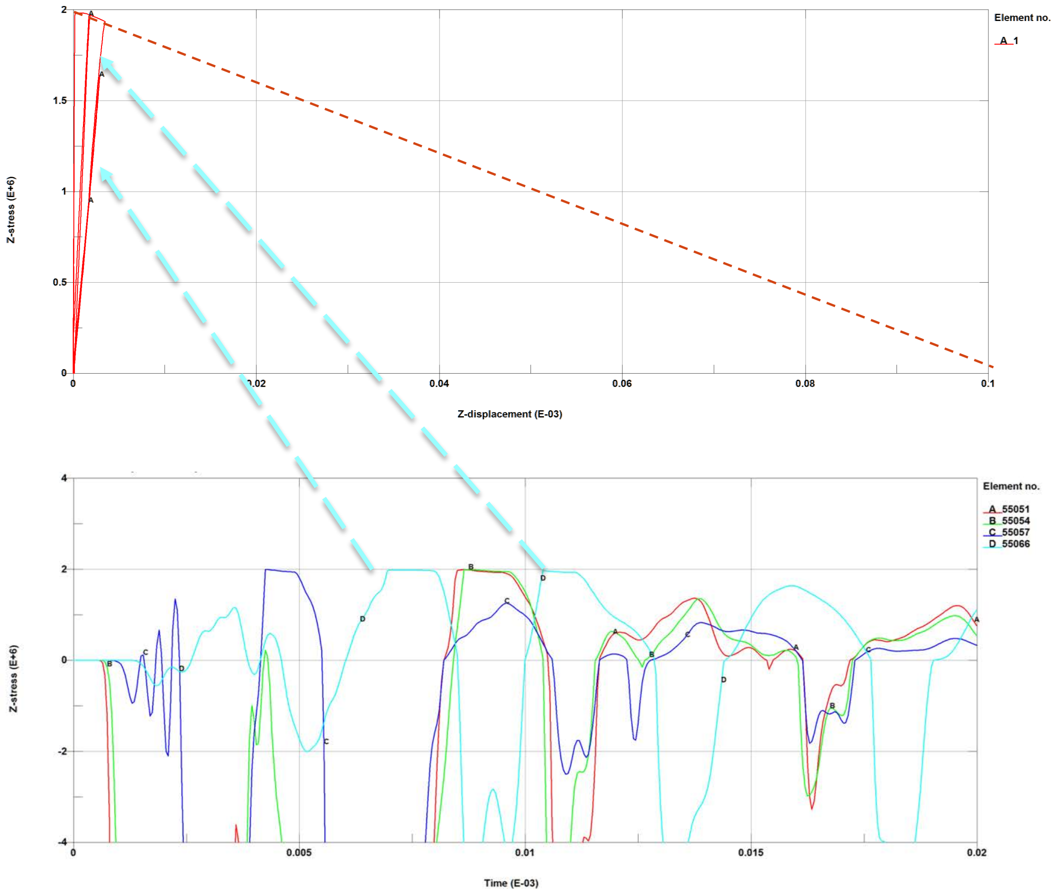


5. Results, discussion and further work. CZM Modelling

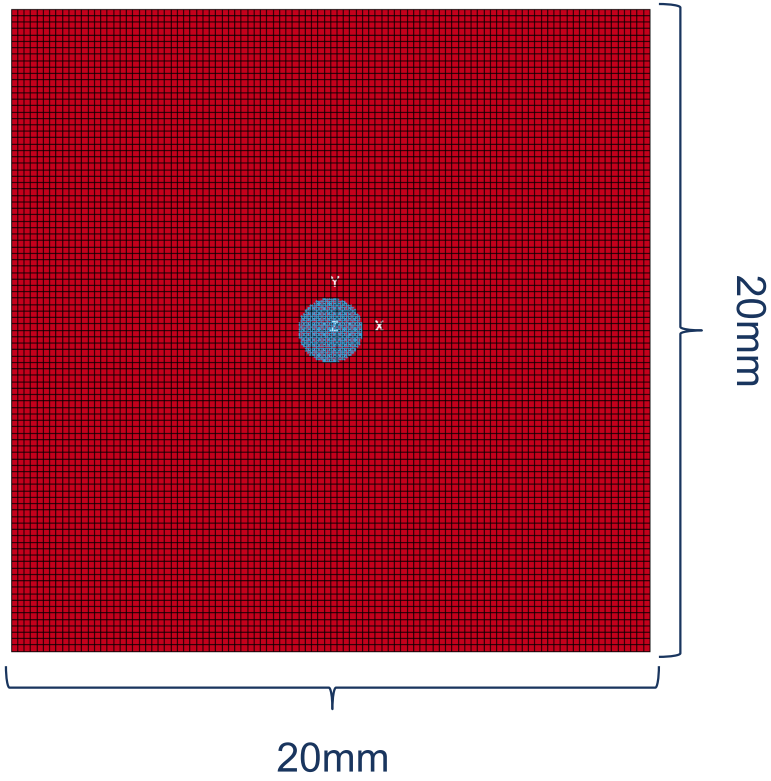
CZM Single impact & Z-Stress evolution on a radial displaced element with σ_{max} once

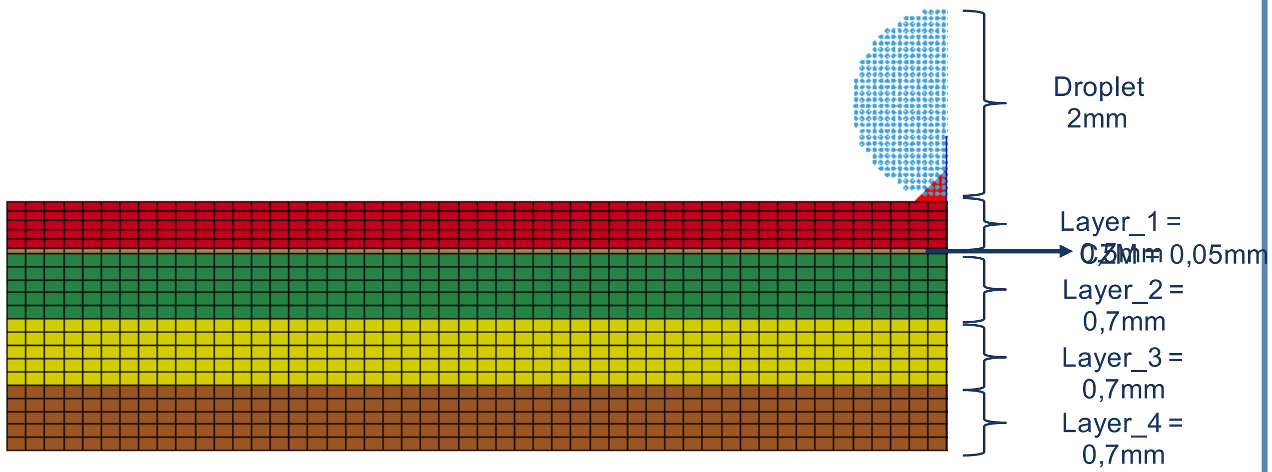


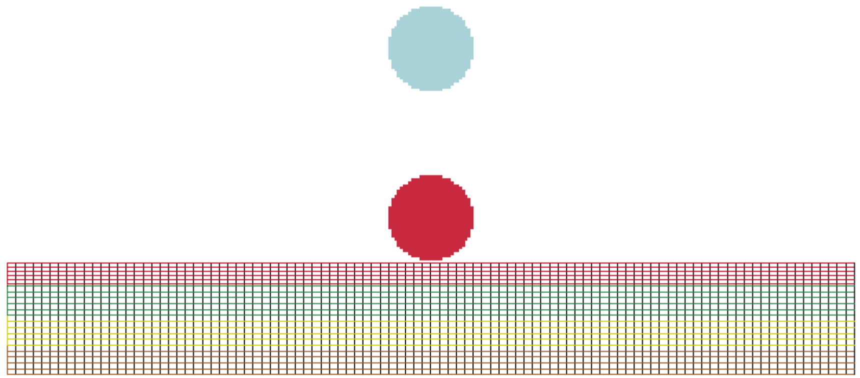
CZM Single impact & Z-Stress evolution on a (2) radial displaced element with repeated σ_{max}. Adhesive fracture energy G_a loss



5. Results, discussion and further work. CZM Modelling

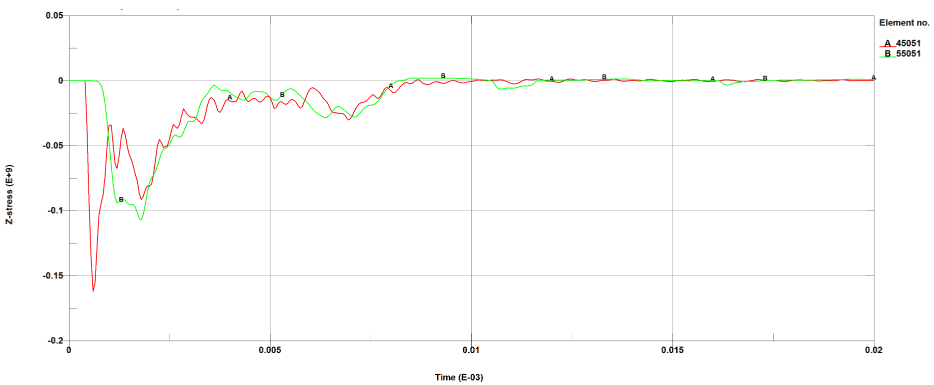


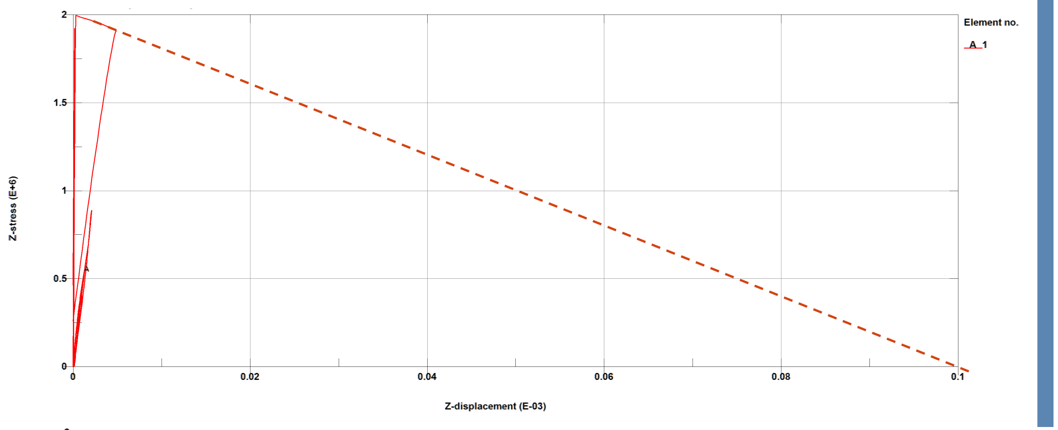


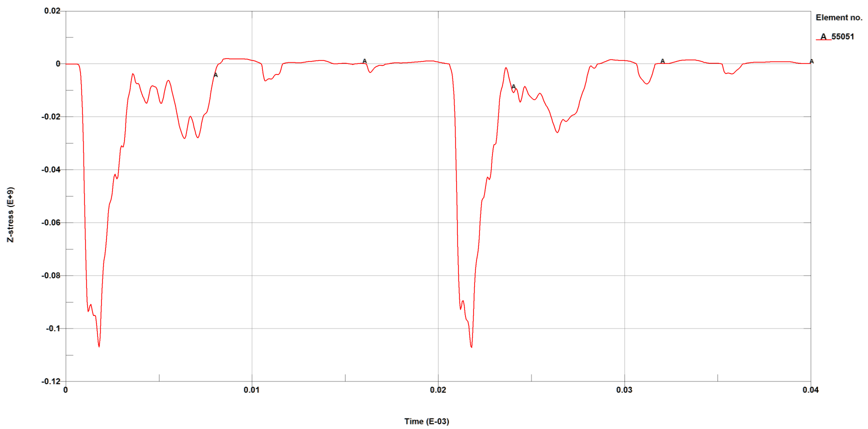


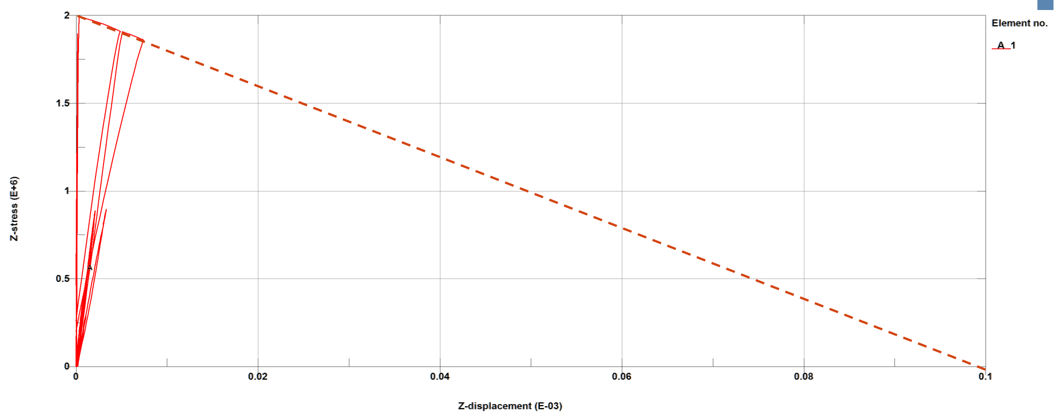
5. Results, discussion and further work. CZM Modelling

CZM Single impact Versus repeated impact & Z-Stress evolution on a (2) radial displaced element with repeated σ_{max}. Adhesive fracture energy G_a loss



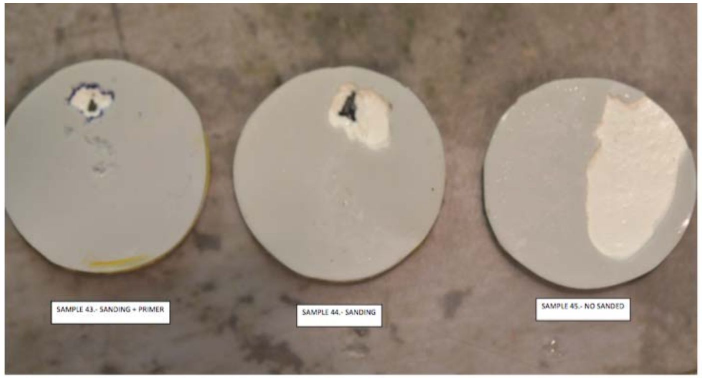


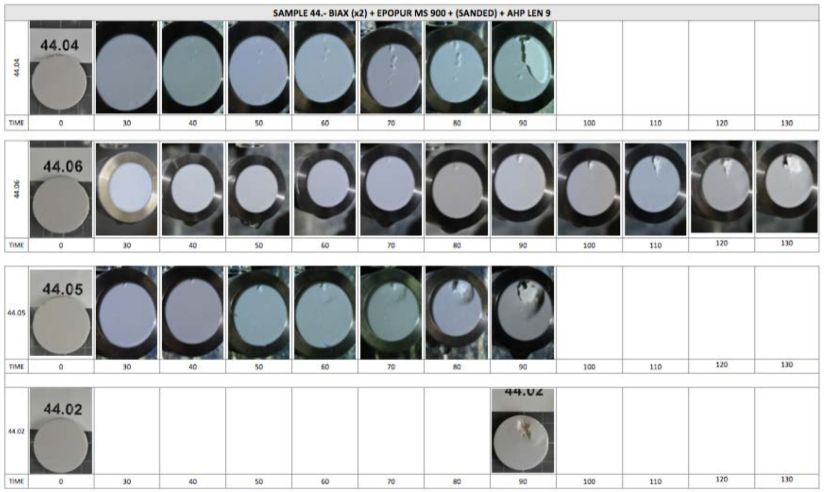


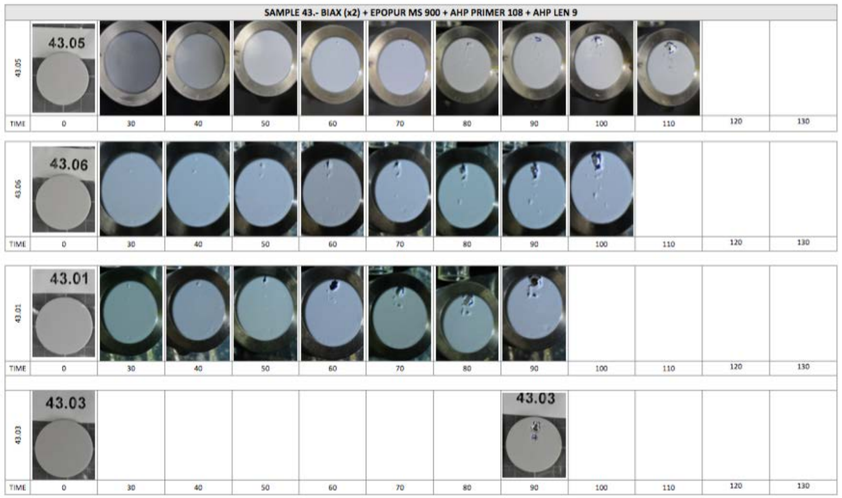


5. Results, discussion and further work. New Rain erosion testing campaign

Rain erosion testing correlate with Peeling testing for Primer, sanding and no sanding processing. CZM under development







5. Conclusions

1. The analysis of the behavior of a **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.**
2. Apropriate numerical models as **a tool to effective leading edge material properties modulation and design**. Novel rain erosion prediction models will be used in order to determine coating factors which affect erosion performance **under the particular conditions** of the experimental validation.
3. The **stress waves will be transmitted to the substrate interface.** In order **to reduce the stress in the substrate** and determine the **suitability of the candidate materials for leading edge applications**, an **acoustic and viscoelastic approach** will be used. Surface erosion and delamination may occur and the **coating capability of loss/transfer wave energy** in the integrated **multilayered system** will allow avoid damage.
4. Model setting and **relation of the manufacturing process requirements** and the rain erosion damage with the polymer performance. Mechanical characterization of coating-laminate **interphase adhesion due to application process by means of CZM**. Need for fatigue Analysis
5. Need for **model linking the lab-testing and service condition** (environmental loading of blade coatings, rain intensity, other impacting factors, others) **with their** damage and debonding mechanisms. The **highly transient material behaviour** during waterdrop collisions require to define **the range of frequency** of its data set (Storage and Loss Modulus).

Questions??