19th X-ray & CT Forum

September 10th-12th 2024
Hamburg (Germany)

ADVANCES IN XCT: from the auxiliary role of AI to the study of in situ processes

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GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

December 2019 – December 2023

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Where are we?

Ubicación de Getafe en España.

Ubicación de Getafe en Comunidad de Madrid.

wikipedia.org

tecnogetafe

espormadrid.es

instituto imdea materiales

http://materials.imdea.org

madridiario.es

- **Public research centre since 2007.**
- **16 research groups.**
- **120 JCR published papers per year.**
- **> 150 people.**
- **> 70 R&D private contracts.**

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In-situ processing and mechanical characterization of materials group

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The X-Ray Laboratory

- Coordinated by the “In-situ processing and mechanical characterization of materials” group.
  - Advanced characterization of materials, including microstructural, chemical, and crystallographic information on various scales of magnitude using different techniques.
- Key laboratory in a research line focused on multi-scale characterization of materials and processes.
- We are going several times per year to different European synchrotrons (ESRF, SLS, DESY, BESSY, ALBA).

The X-Ray Laboratory

Phoenix (GE) Nanotom 160NF – Lab tomograph (absorption)

phoenix

Zeiss Xradia 620 Versa – Lab tomograph (absorption, phase & diffraction)

zeiss.com

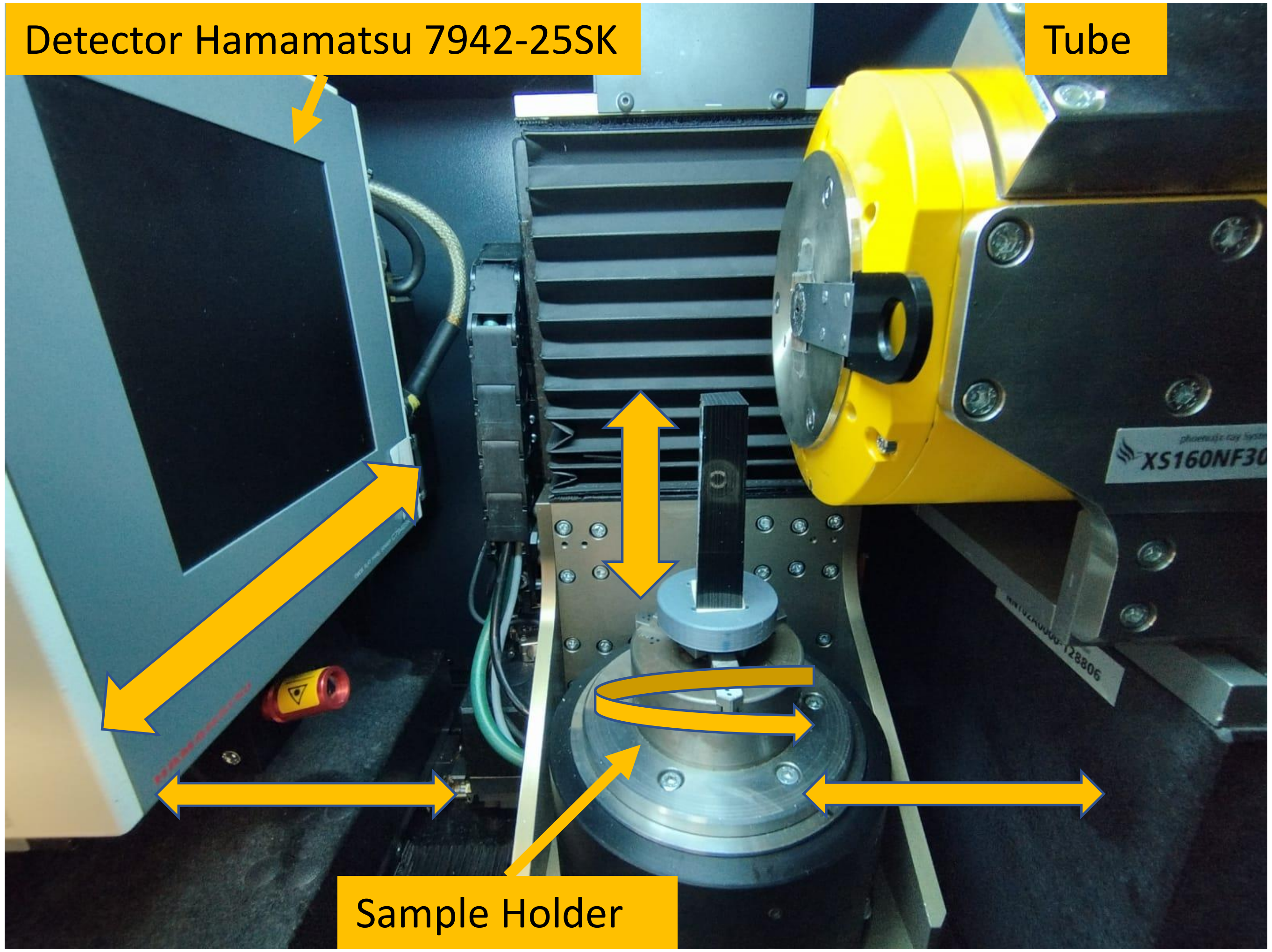
PANalytical Empyrean – Lab diffractometer (diffraction & reflection)

malvernpanalytical.com

The X-Ray Laboratory

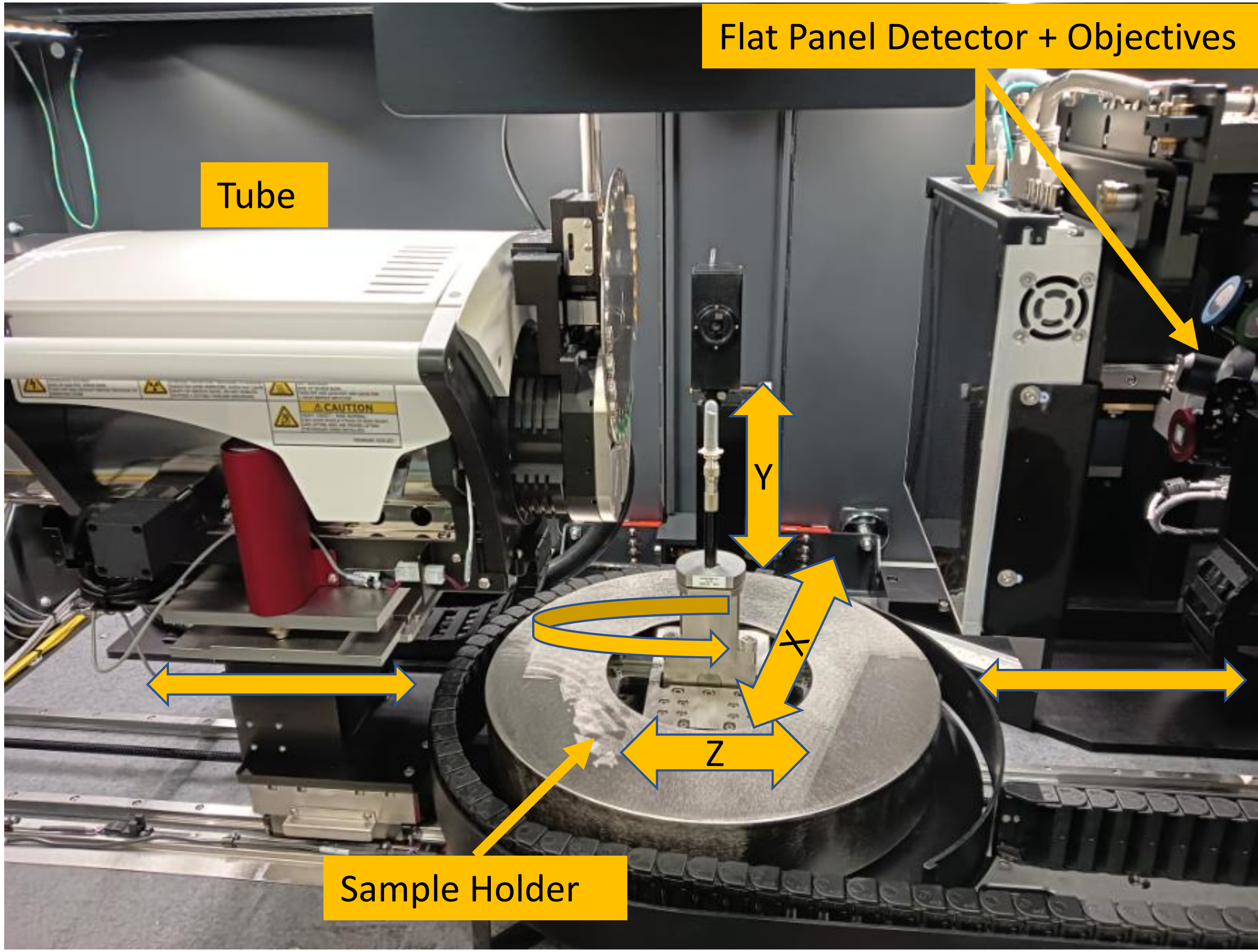
suplitec-ndt.com

- **Max voltage: 160 kV.**
- **Targets: Mo and W.**
- **Voxel size: from 30 to 1 µm/px.**
- **Detector area: 2300×2300 (pixel side 50 µm).**
- **Three virtual detectors.**
- **Up to 9 radiographs per second.**

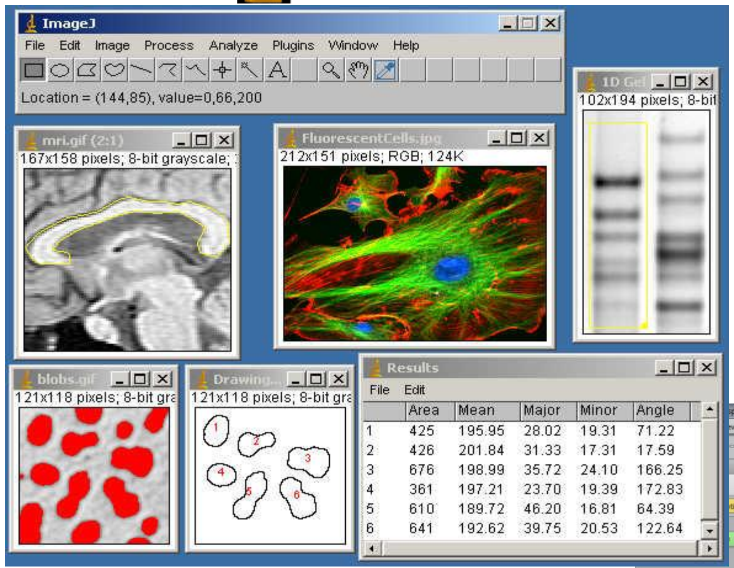


The X-Ray Laboratory

- Max voltage: 160 kV.
- Target: W.
- Voxel size: from 57 to 0.3 µm/px.
- Detector area: 3072×1944 (FPX, 75 µm) and 2048×2048 (CCD, 14 µm).
- Objectives: 0.4X, 4X, 20X, 40X.
- DCT option is available.

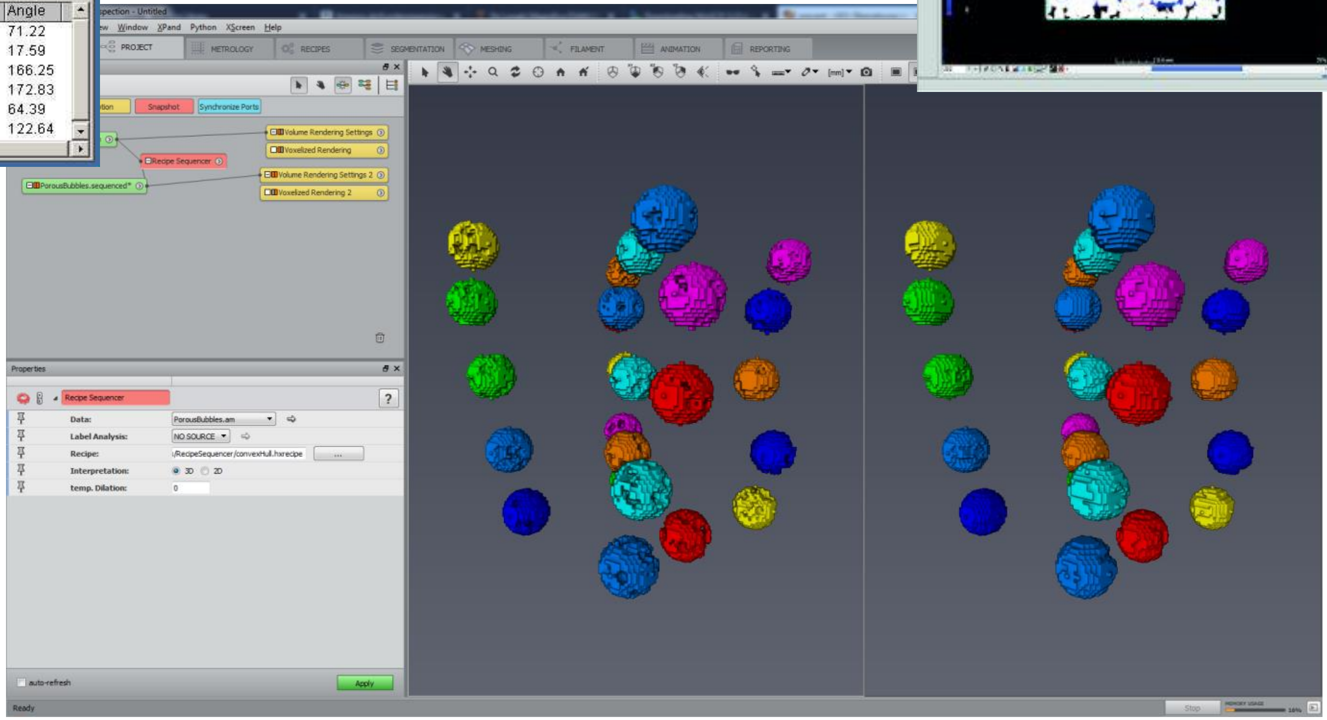


The X-Ray Laboratory

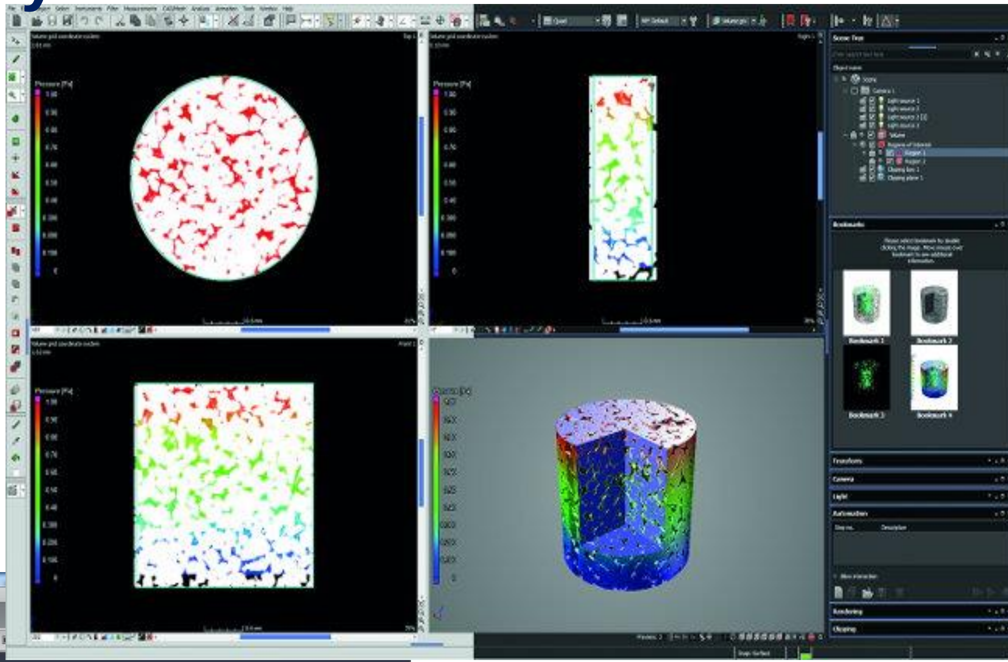


University of Arizona

Avizo®



xtras.amira-avizo.com



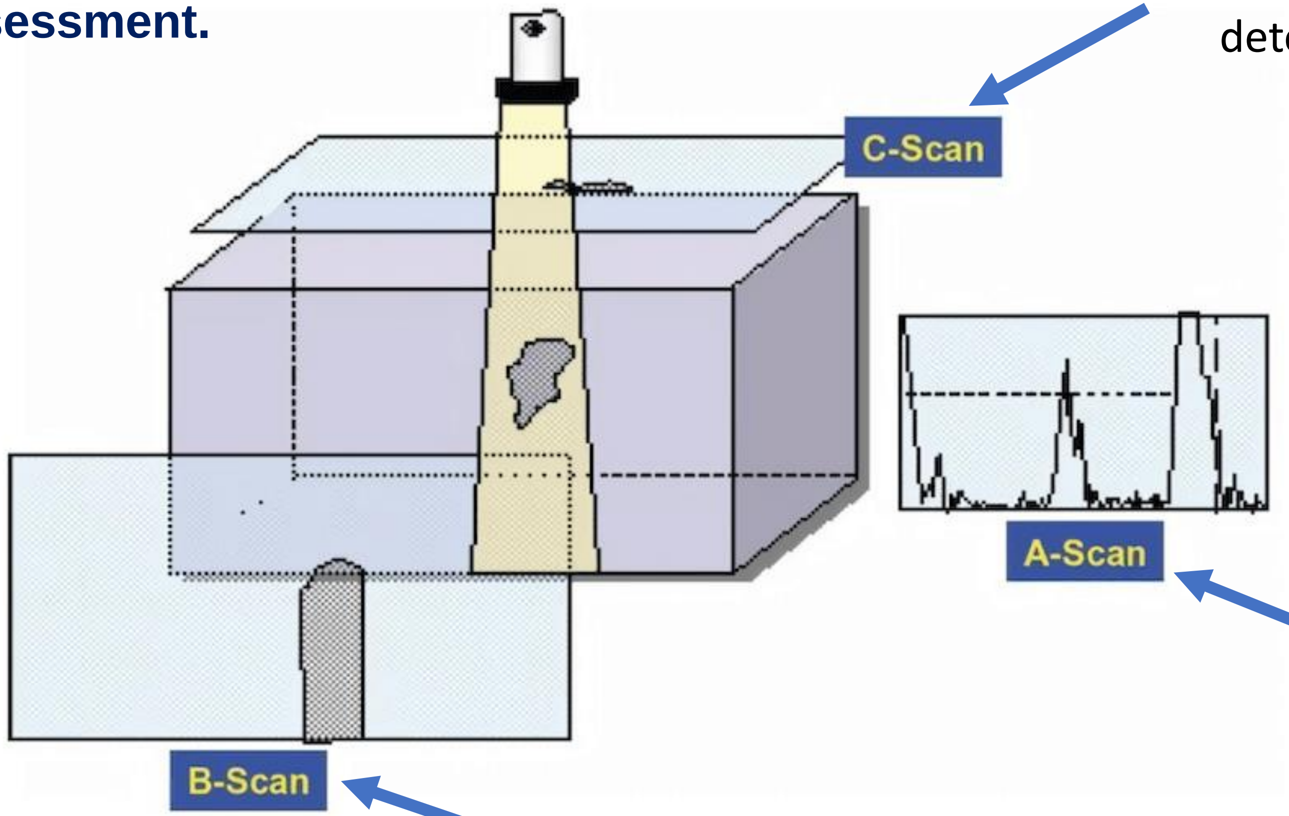
ndt.net

Combining XCT with ultrasonic tests (UT) for CFRP composites

More details? alberto.vicente@imdea.org

XCT vs UT

- **UT is a non-destructive technique.**
- **High frequency sound is reflected by defects.**
- **Applied for quality assessment.**

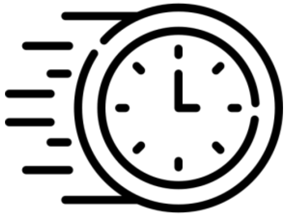
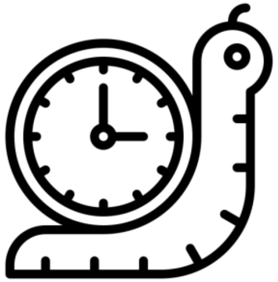


<u>Projected defectology</u>
Ideal for defect detection in large areas

<u>Signal amplitude *vs* time</u>
Ideal for thickness measurement and defect detection

<u>2D image of cross-sections</u>
Ideal for defect location and size determination

XCT vs UT

• Ultrasound Testing	• X-Ray Computed Tomography
Fast 	Slow 
Low detail 	Detailed 

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XCT vs UT

- **Our goal is to combine the scan speed of UT with the quality of XCT.**
- **Deep learning approach is the most convenient.**

• Ultrasound Testing		• X-Ray Computed Tomography
Fast	Fast	Slow
Low detail	Detailed	Detailed

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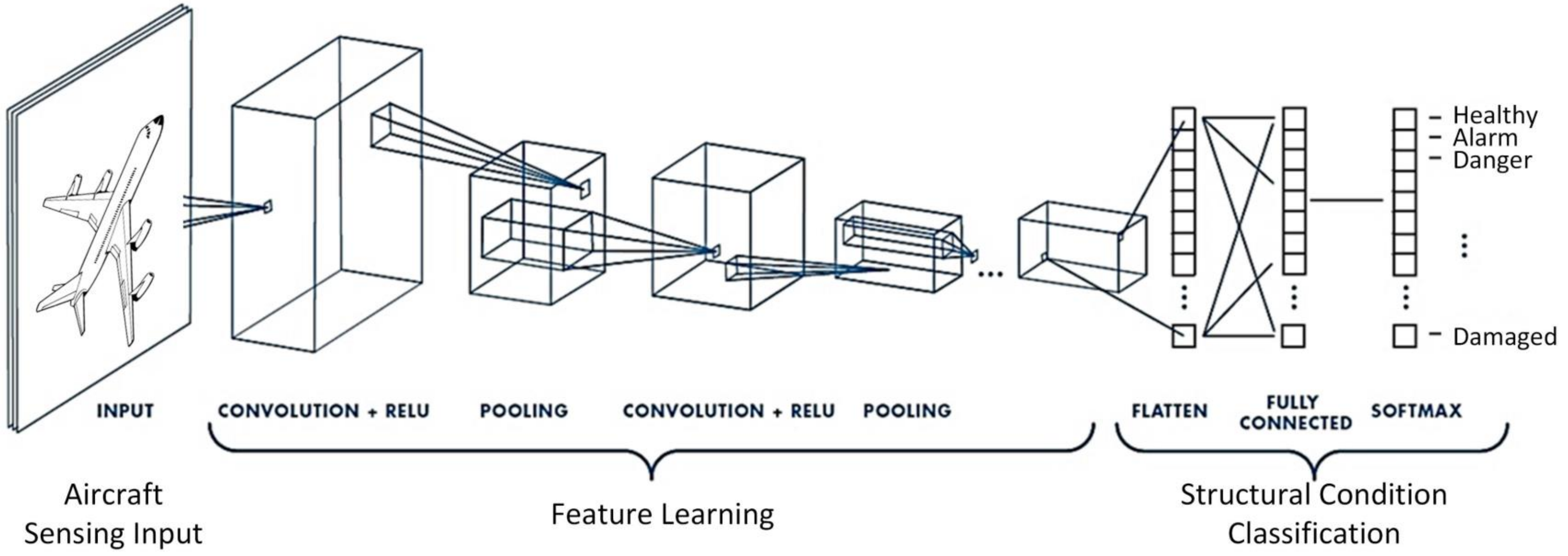
XCT vs UT

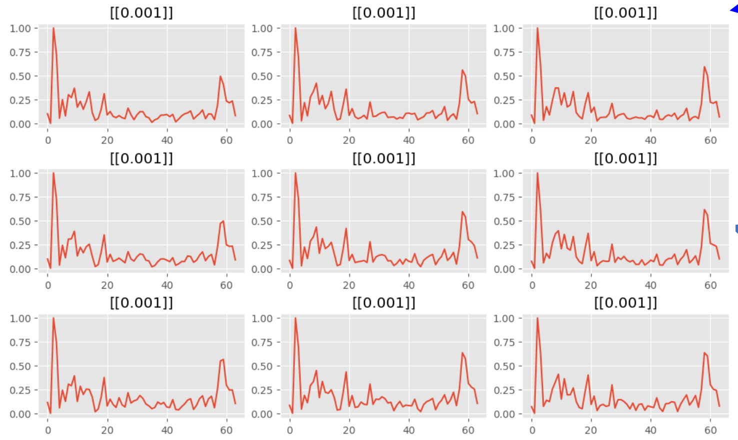
- UT output is a 3D volume of information (X, Y, time window).
- Normally, ultrasound volume is converted into C-scans.
- We can think about that an ultrasound volume is a stack of A-scans.
- This information can be treated using a Convolutional Neural Network.



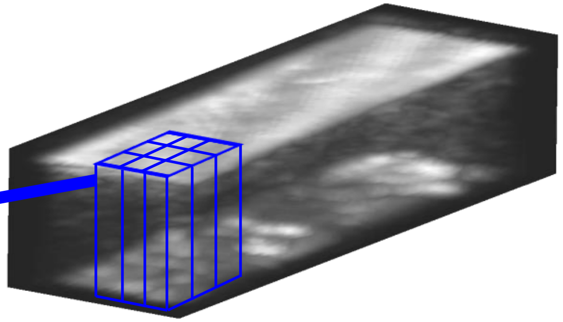
XCT vs UT

- **Key points to do in the future:**
  - **Measurement in UT of the volume porosity.**
  - **Measurement in UT of the area porosity along the sample thickness.**

3×3 kernel in A-scan (64-point depth)



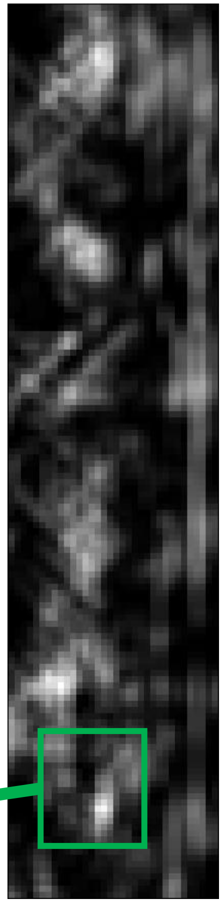
IA model



UT volume
Res: 1mm/pixel XY
0.11mm/pixel Z

Model

Blurred XCT Projection (our 2D Ground truth)



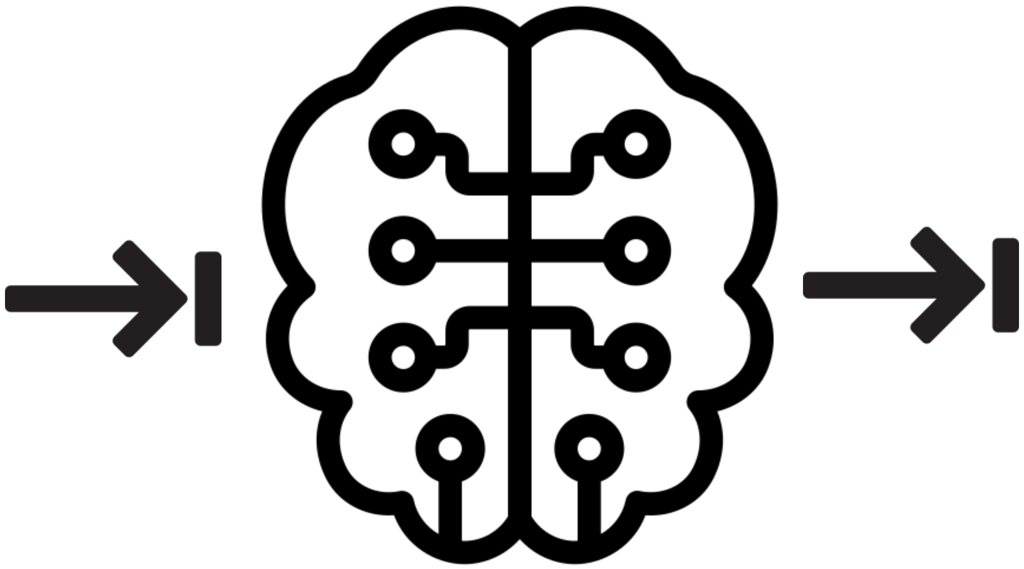
Res: ≈20µm/pixel isotropic

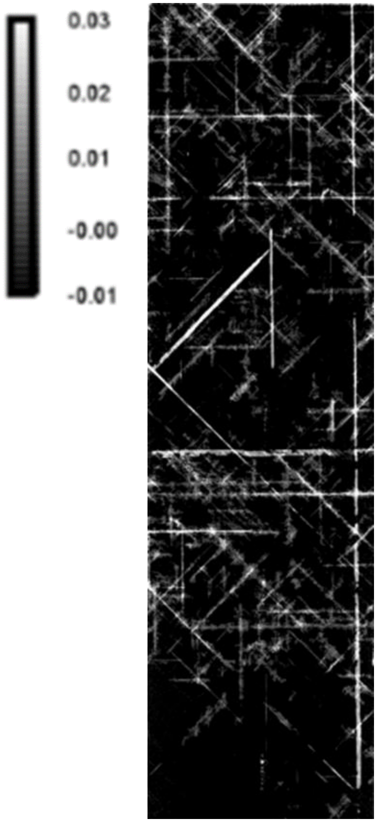
Pore volume fraction in the XCT projection along the thickness = 2.6%

XCT vs UT

- For a good dataset, dozens of samples must be measured using both techniques.
- The regression-CNN we are using has 6000 points, and the feature extraction is performed in UT and XCT volumes.
- The trained model will learn to improve the measurement performed in UT giving a “XCT-quality” scan.

Ultrasound Testing





X-Ray Computed Tomography

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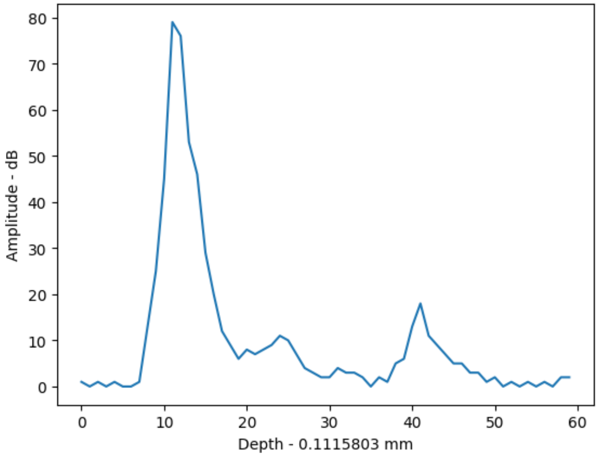
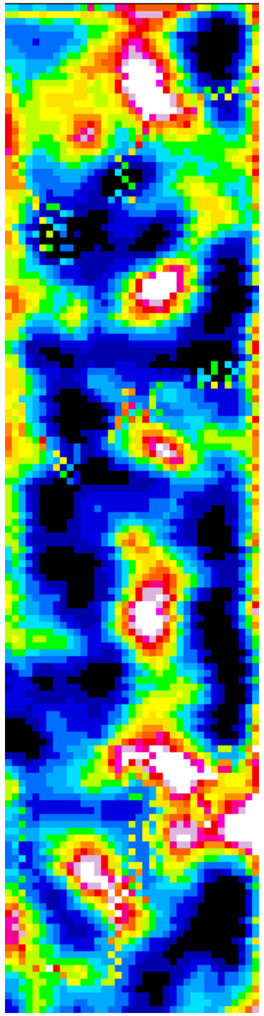
XCT vs UT

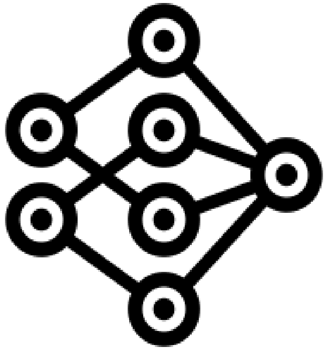
A-scan



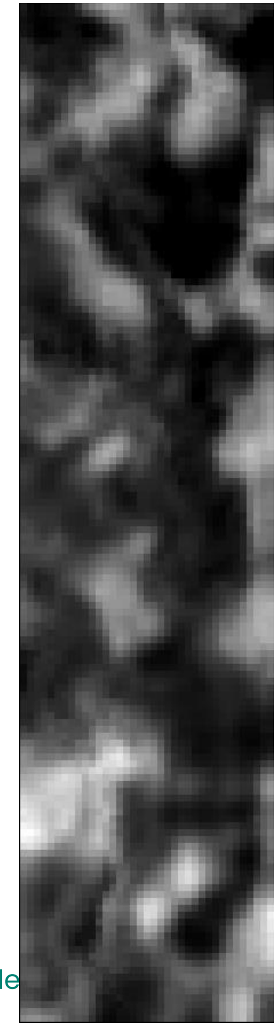
A-scan set obtained at 5 MHz

Attenuation C-scan





2D Prediction



Comparison

2D Ground truth (XCT)

IM7/M56 laminate (16 plies)
$[+45/0/-45/90]_{4s}$
Hand lay-up
Size: $150\times40\times5$ mm^3

Damage assessment in CFRP composites after tensile and fatigue tests

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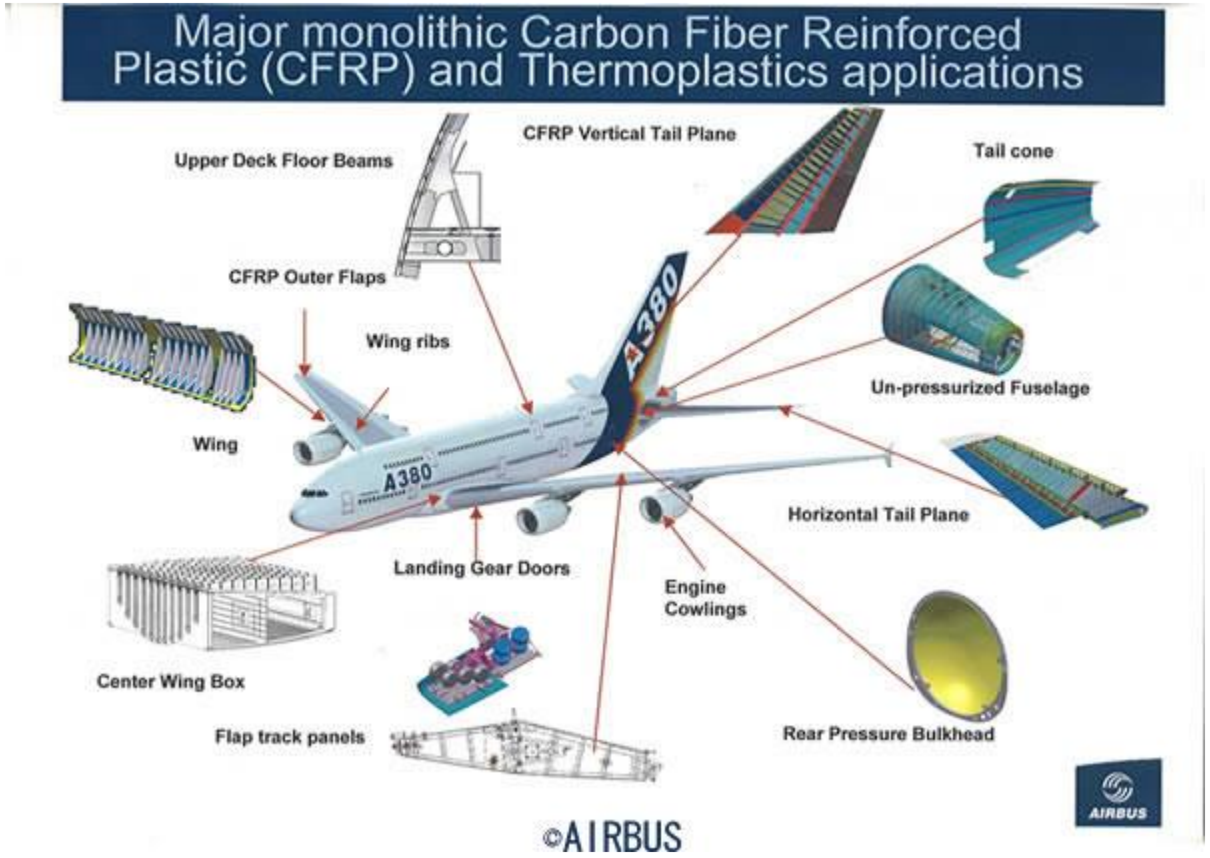
More details? alba.pascual@imdea.org

Damage assessment

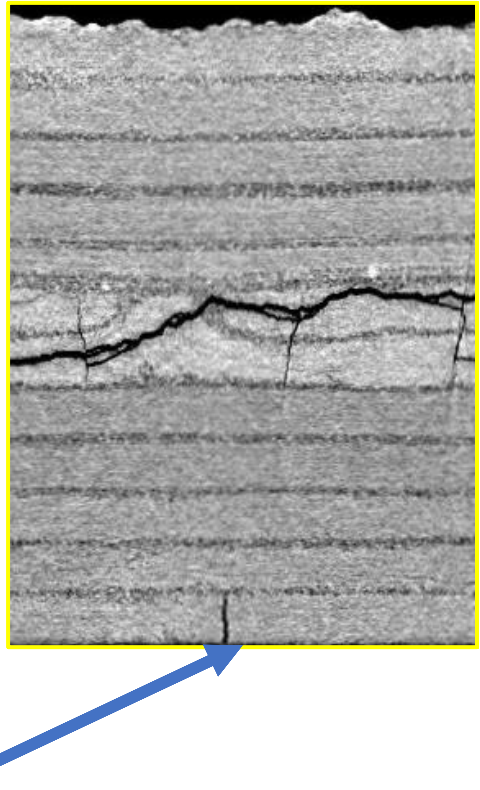
- Aircraft weight is reduced using CFRP in several parts.
- Less weight means less fuel: cost savings and less pollution.
- However, it is necessary to know the behaviour of CFRP under aggressive conditions.
- Depending on the stacking sequence, cracks and delamination have different development.



www.carbonfiber.gr.jp

Damage assessment

- Three segmentation paths can be followed:
  - BINARIZATION
    - Time saving
    - Easy to implement
    - Less human error
    - Implemented in ImageJ



Good contrast, good SNR, easy to identify borders and defects

Damage assessment

- **Three segmentation paths can be followed:**
  - **DEEP LEARNING**
    - **Takes time to train the model**
    - **Easy to implement once the model is trained**
    - **Implemented in Avizo**

Good quality, easy to manually label the defects

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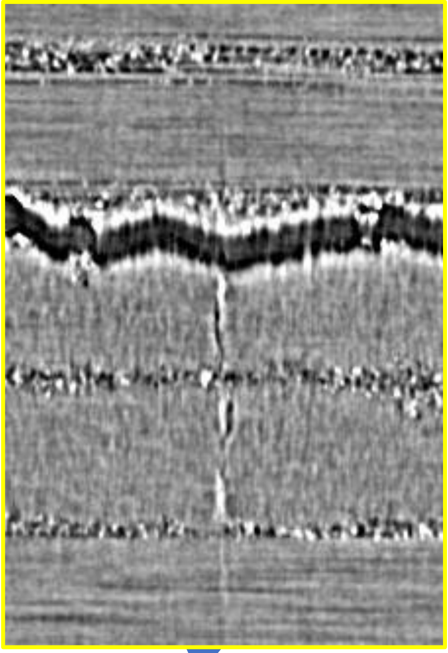
Damage assessment

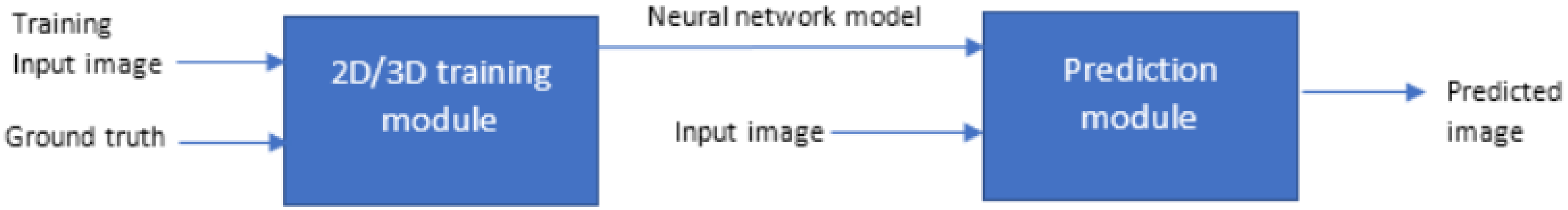
- **Three segmentation paths can be followed:**
  - **MANUAL**
    - **Time consuming**
    - **Non generalizable for other samples**
    - **High human error**
    - **Implemented in ImageJ and Avizo**



High phase contrast enhancement

Damage assessment

- **Avizo implements several modules focused on deep learning methods.**
- **Two phases:**
    - **Training**
    - **Prediction**

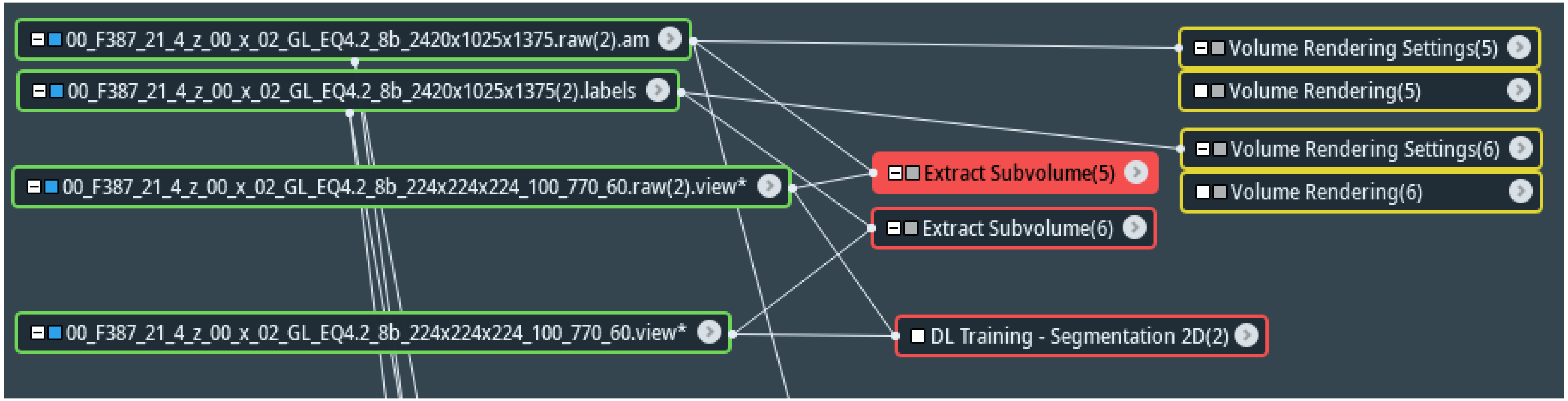


Damage assessment

- **TRAINING:**
- **Segmented ground truth is necessary. Labelling will help to classify different defects (AI Assisted Segmentation, implemented in Avizo, too).**
- **The module needs as inputs the segmented ground truth and the grey-level original.**
- **Avizo uses a shallow fully convolutional neural network for image semantic segmentation.**
- **Possibility to select the number of epochs and elastic deformation.**
- **The training can be done at specific regions, but the prediction is computed on the whole volume.**

Damage assessment

- **TRAINING:**
- **Extract Subvolume to extract regions from the ground truth grey-level volume and its labelled counterpart.**
- **Cubic subvolumes with the feature we need to identify are the best choice.**
- **DL Training – Segmentation 2D module trains the set with variants of U-Net model (VGG, ResNet…).**



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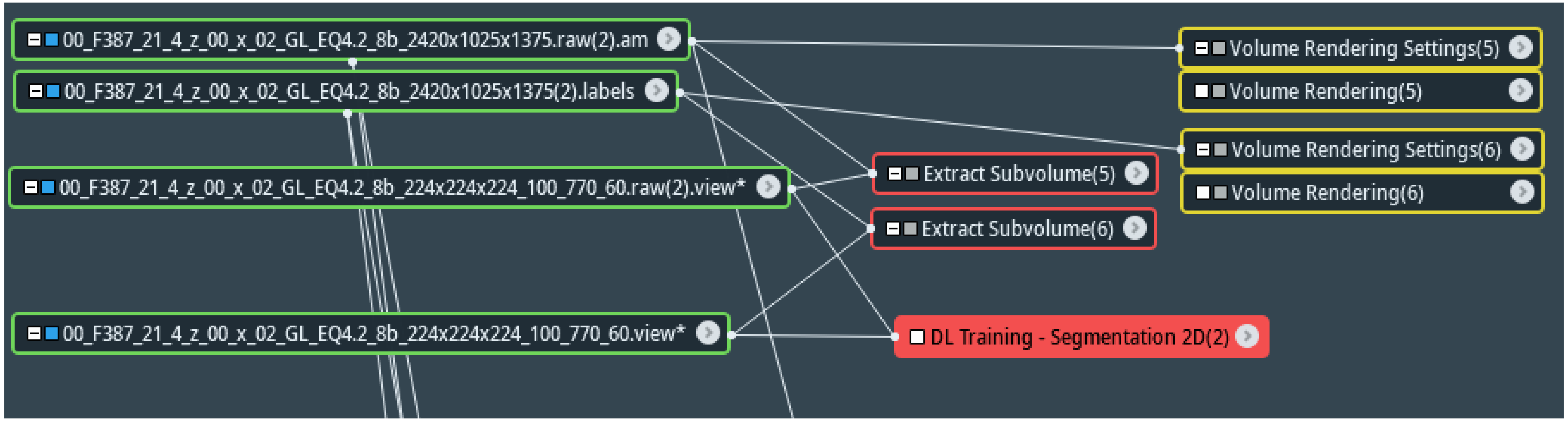
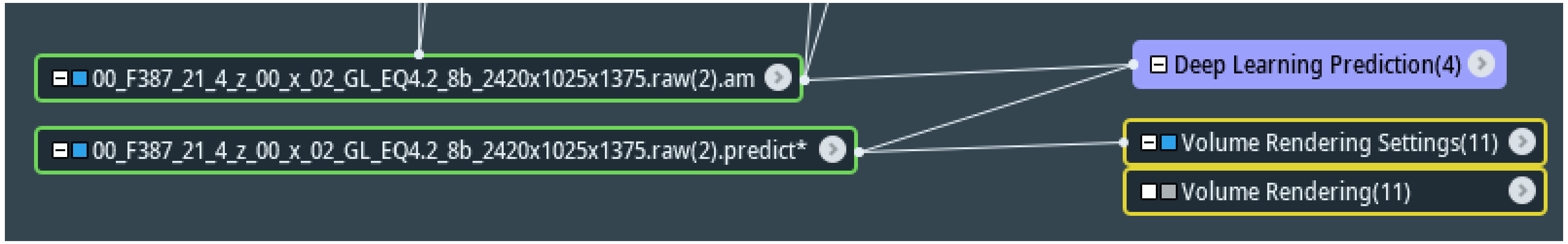
Damage assessment

- **TRAINING:**
- **Train Learning Curve and Validation Learning Curve will verify the goodness of the model.**
- **Loss function must be at the minimum value and accuracy near 1.**
- **Try to avoid underfitting and overfitting!**
- **Check the proportion between train and validation datasheets.**



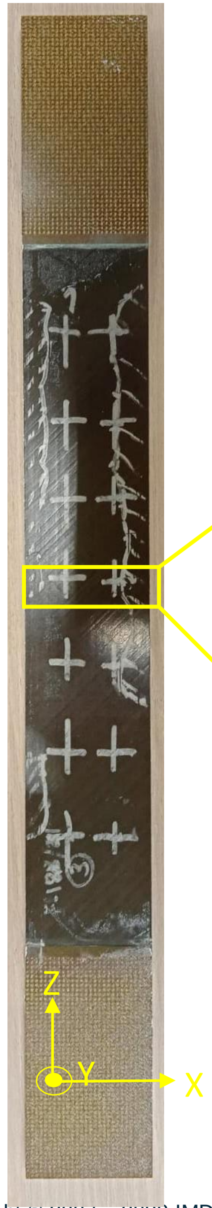
Damage assessment

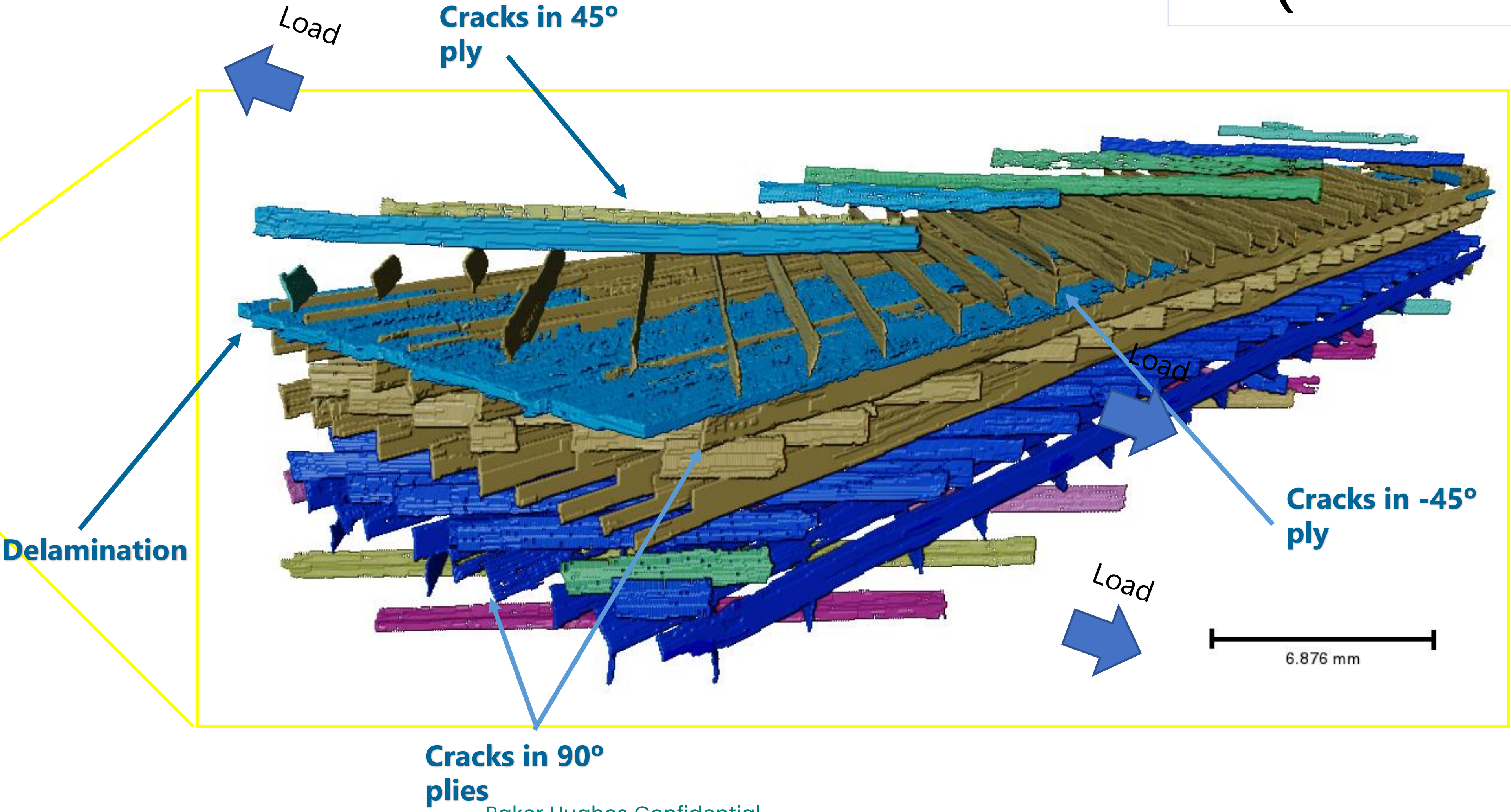
- **PREDICTION:**
- **Load the volume to segment. It has to be similar to the ground truth volume.**
- **The trained classifier has the architecture and weights. These parameters can be adjusted, too.**
- **The prediction can be done for the whole volume or applied as overlapped regions.**



Damage assessment

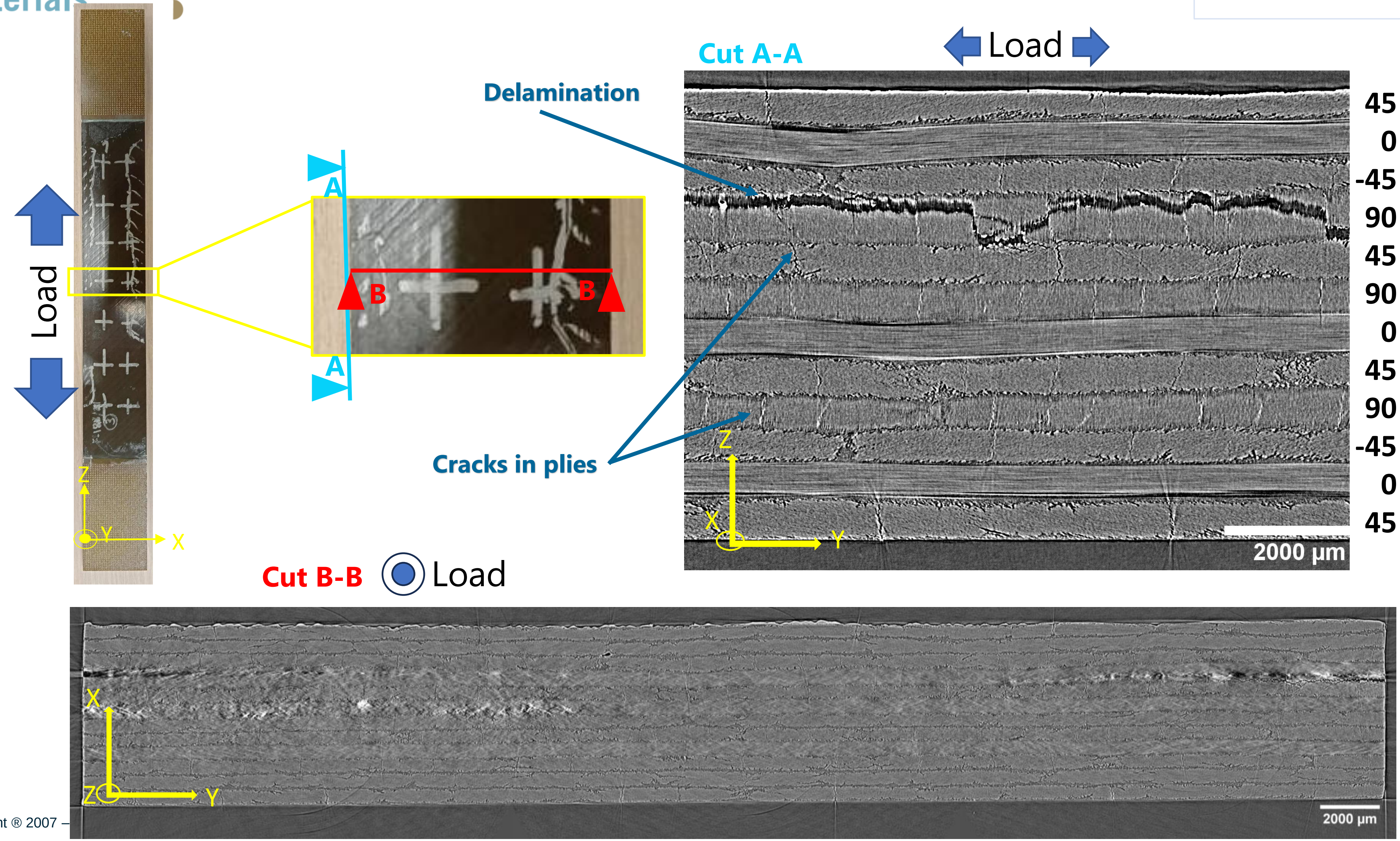
F188_21_3
(133.5 kN)





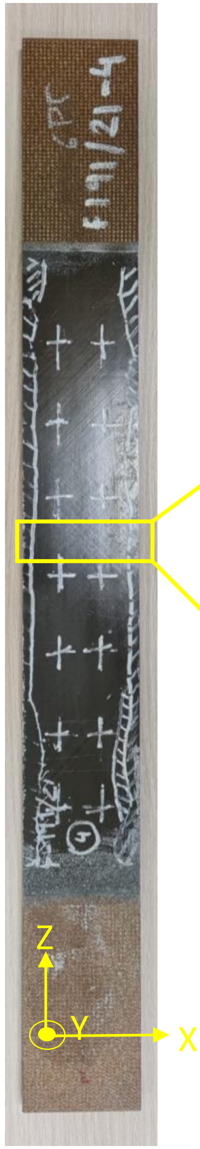
Damage assessment

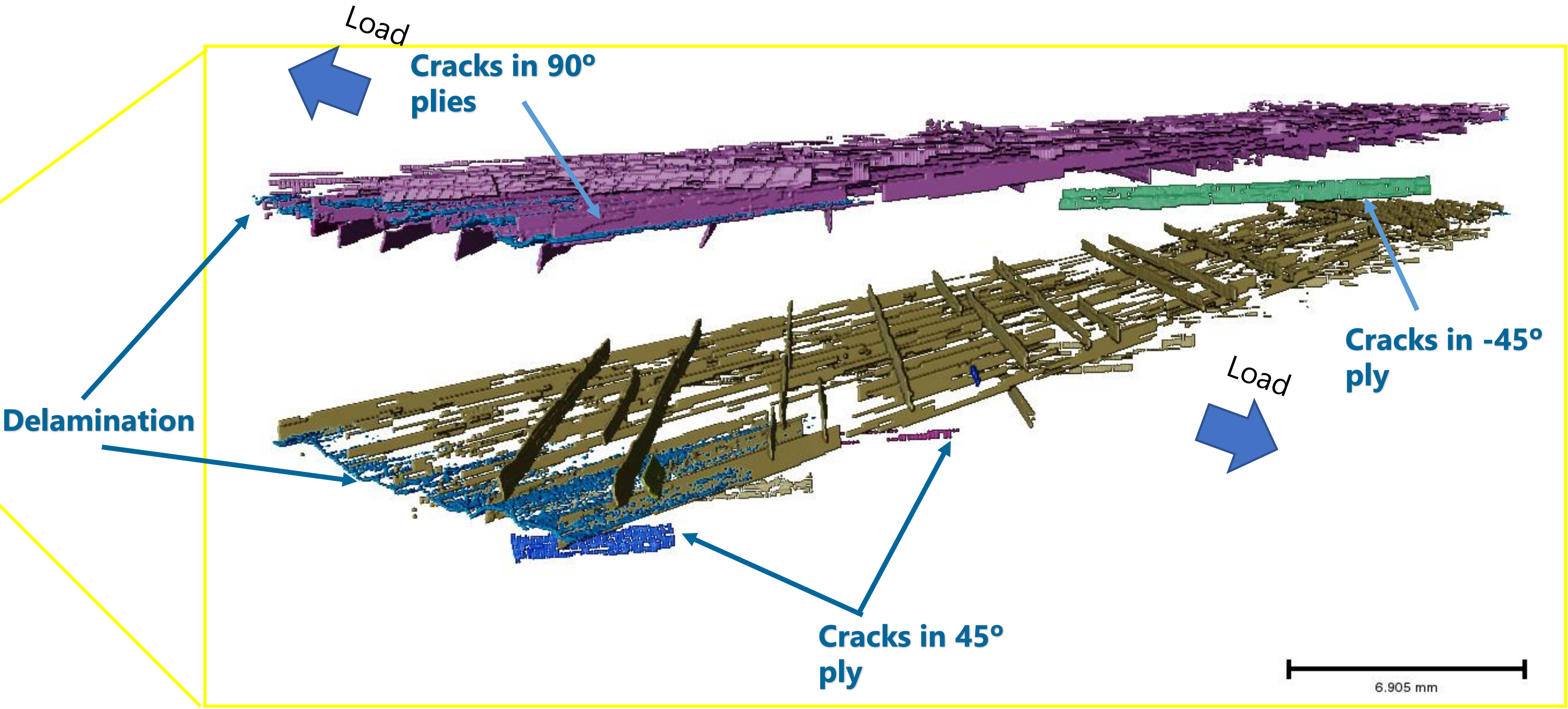
F188_21_3



Damage assessment

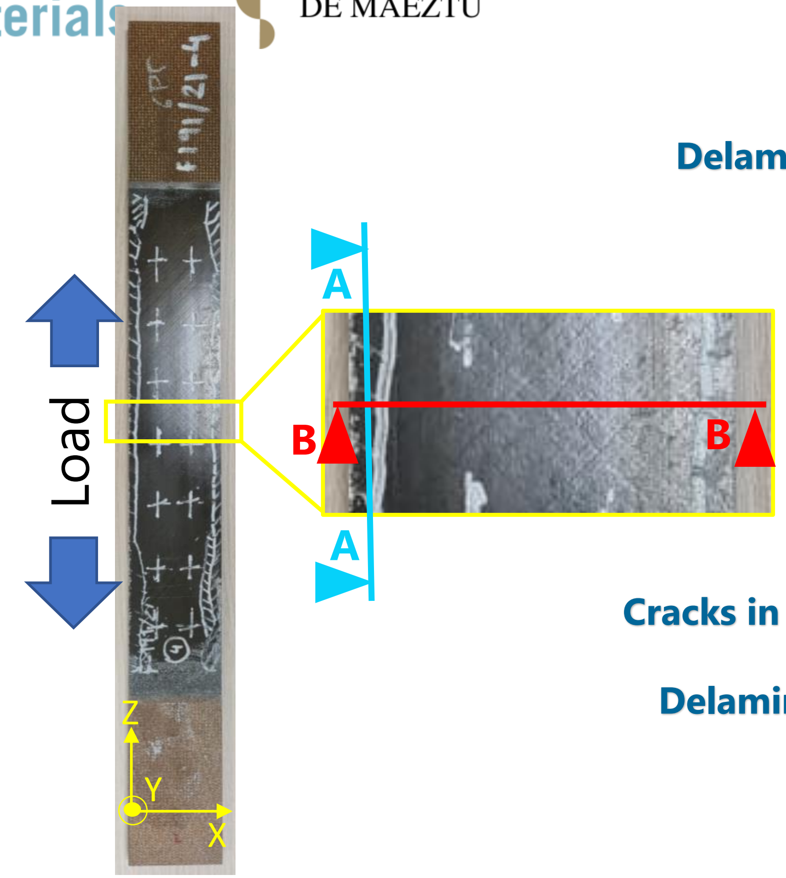
F191_21_4
(120 kN)

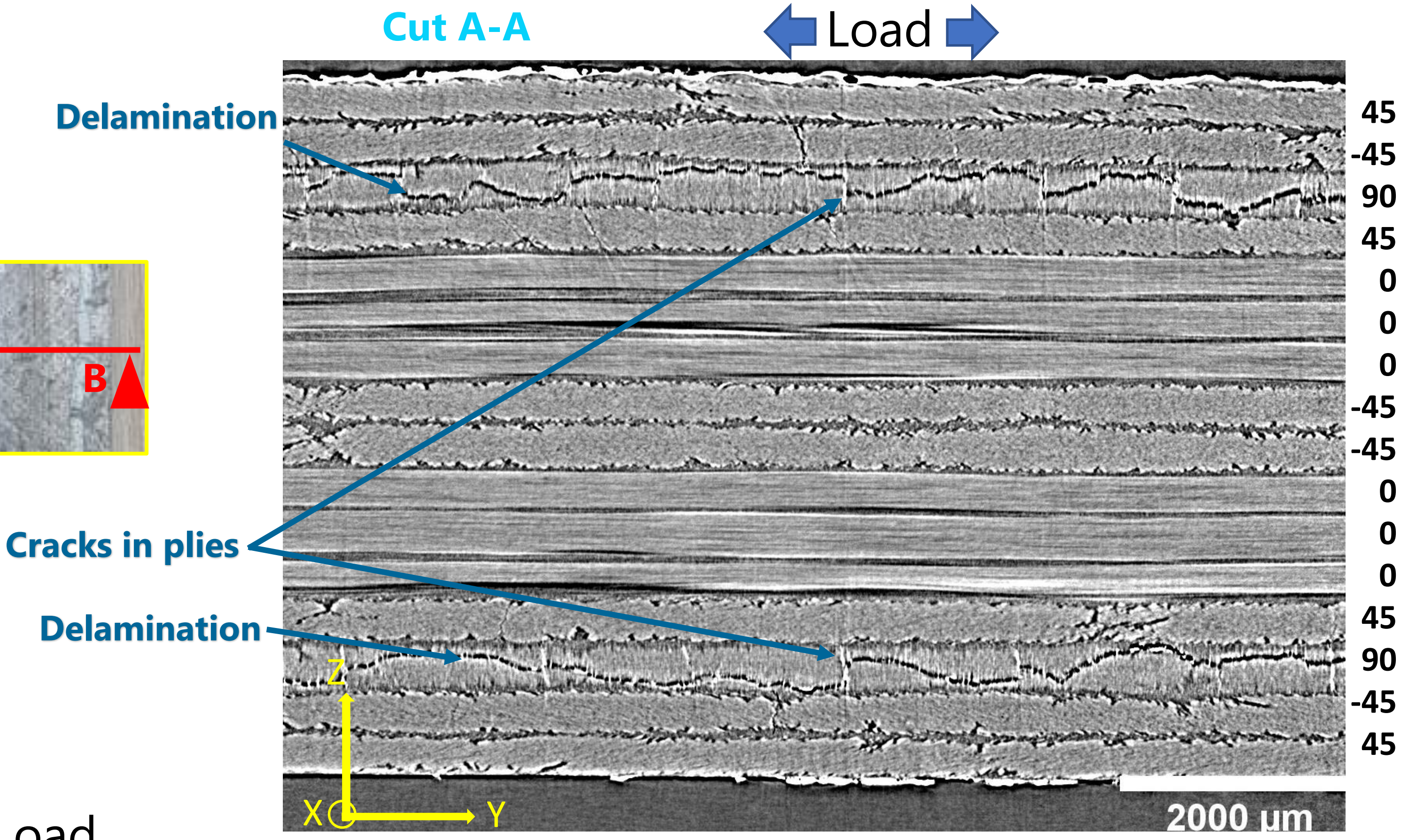


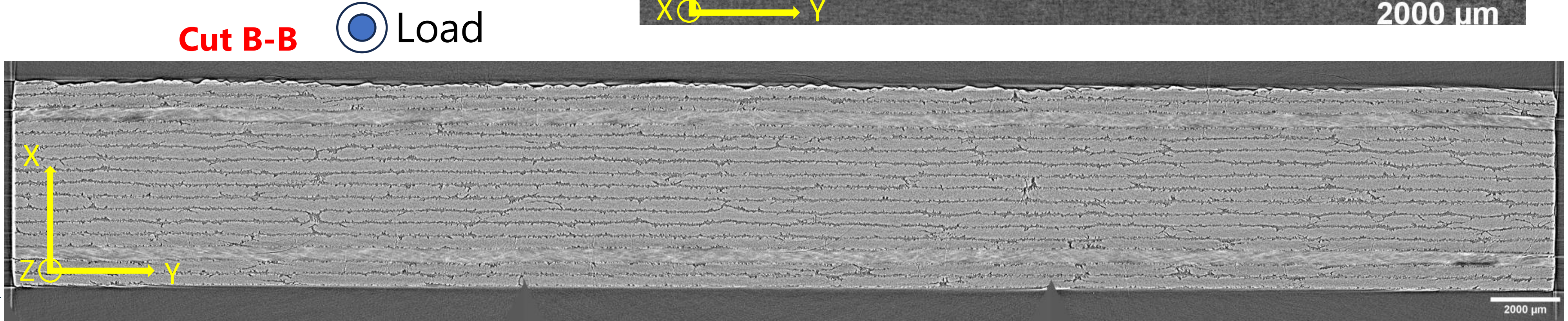


Damage assessment

F191_21_4

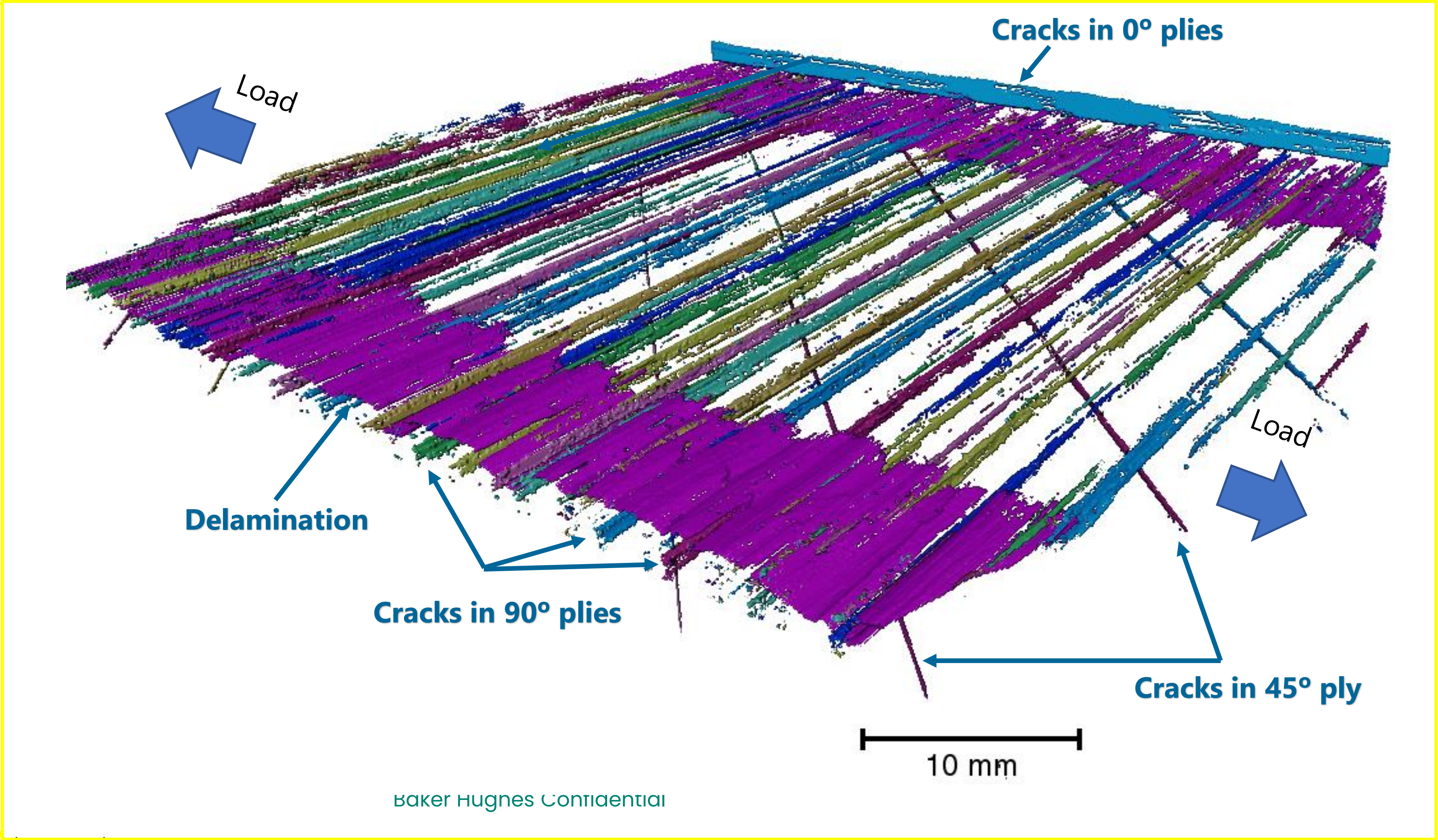






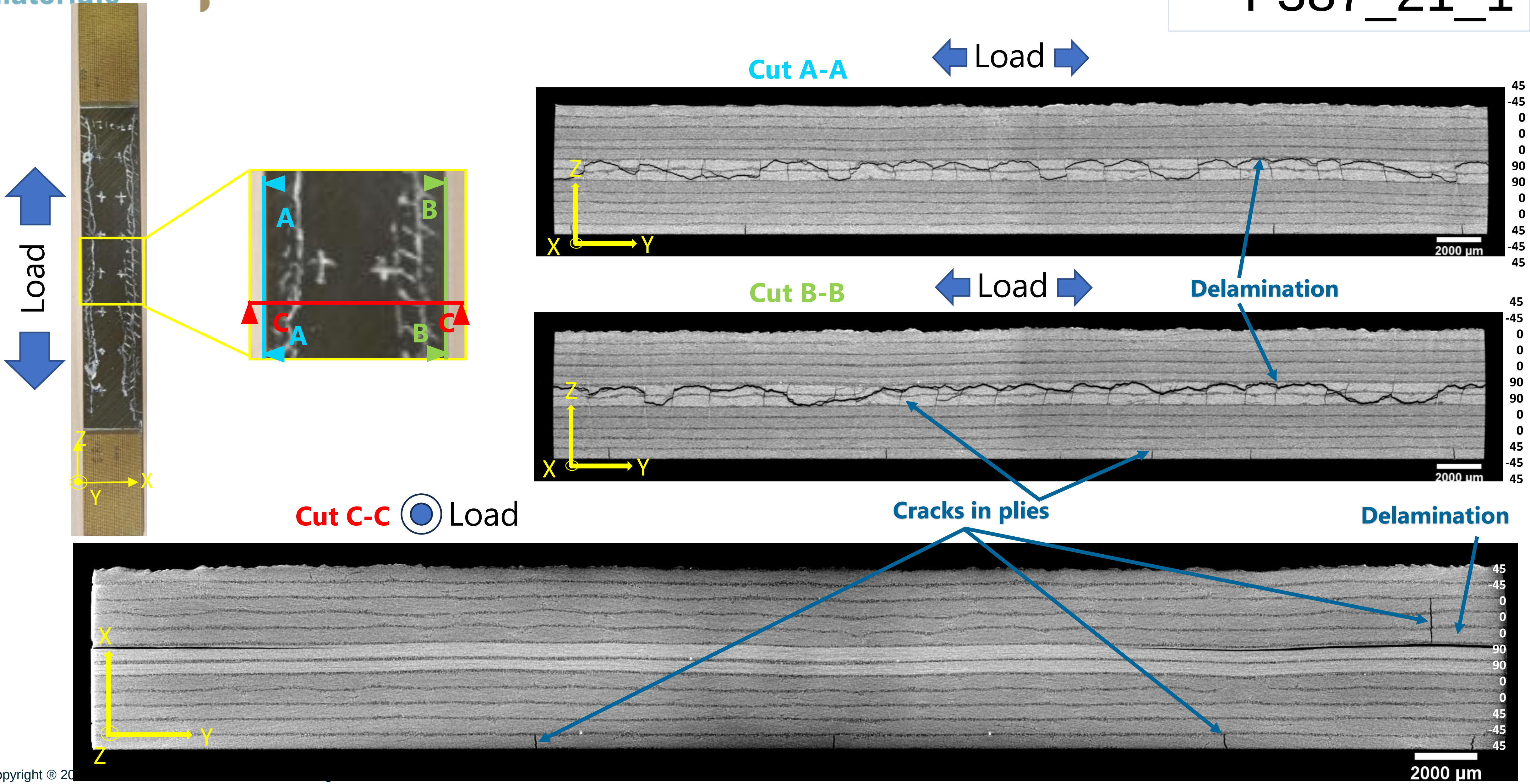
Damage assessment

F387_21_1
(90 kN)



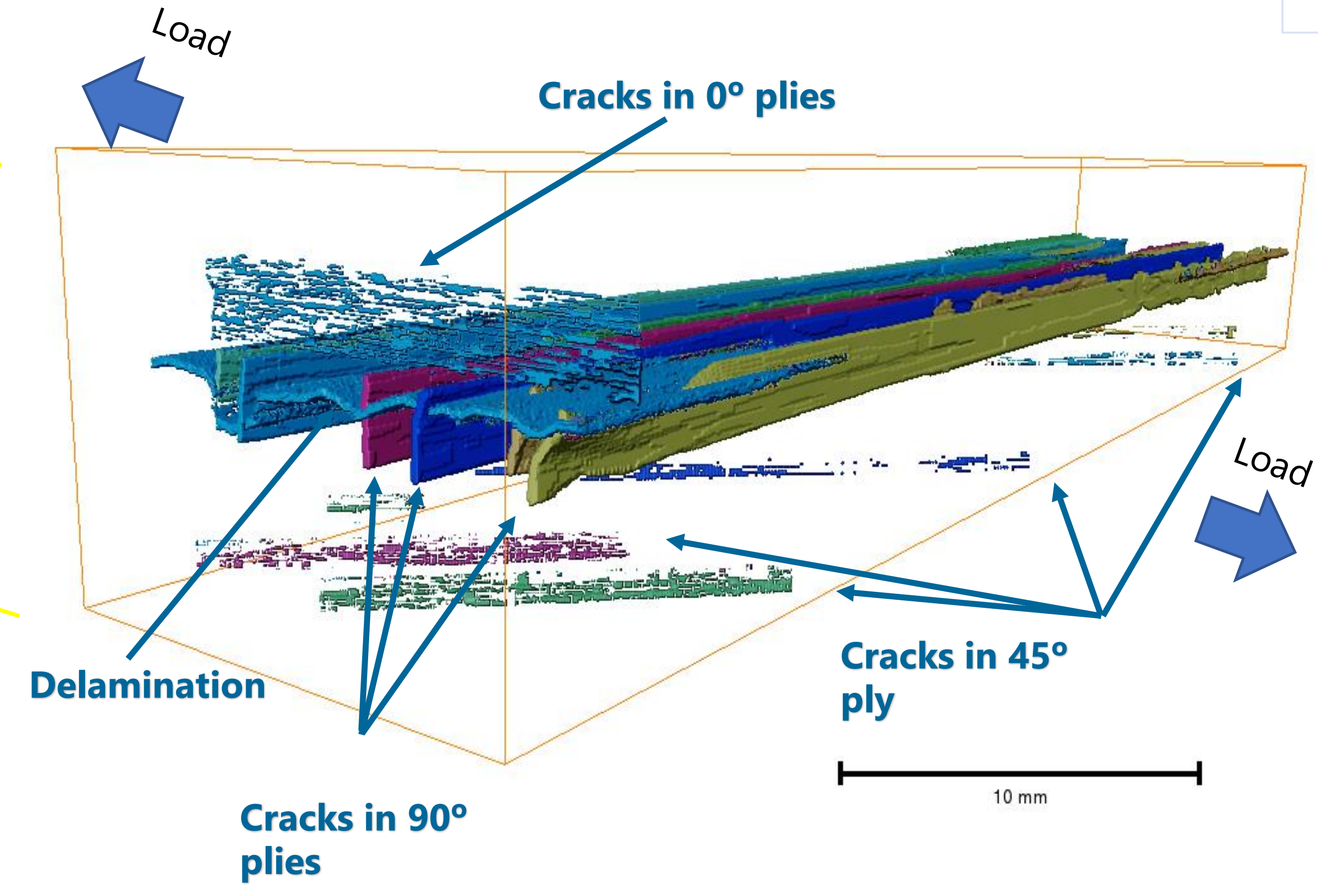
Damage assessment

F387_21_1



Damage assessment

F387_21_4
(120 kN)



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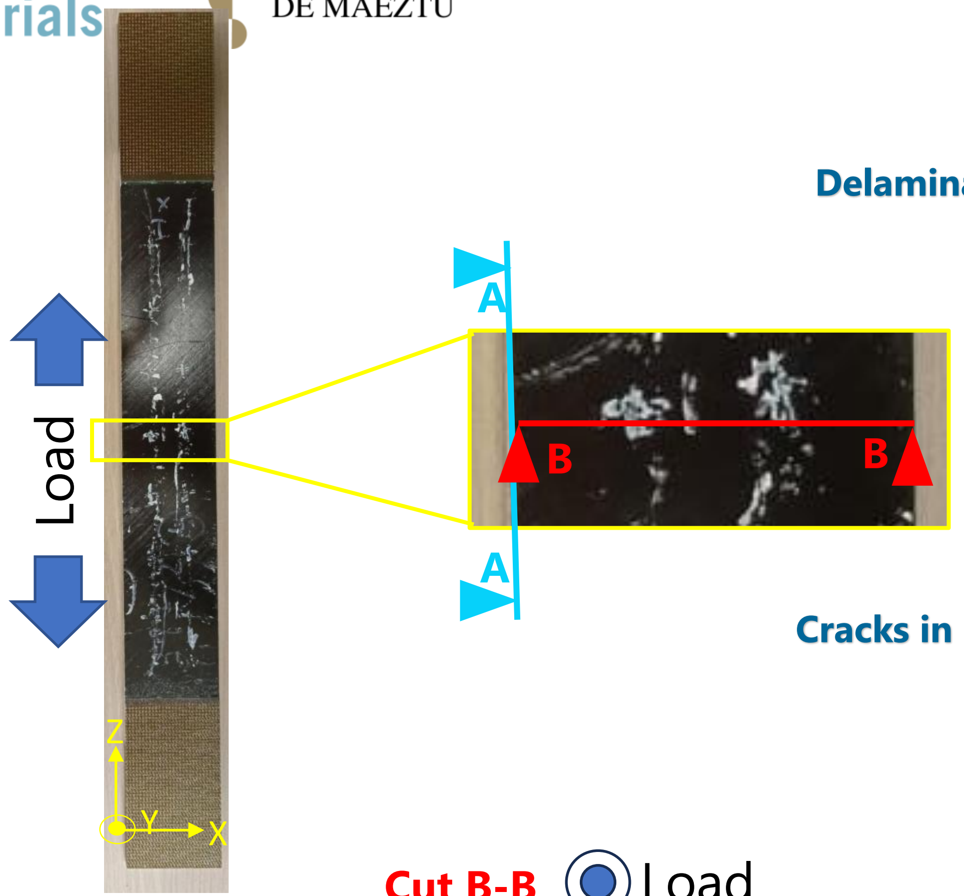
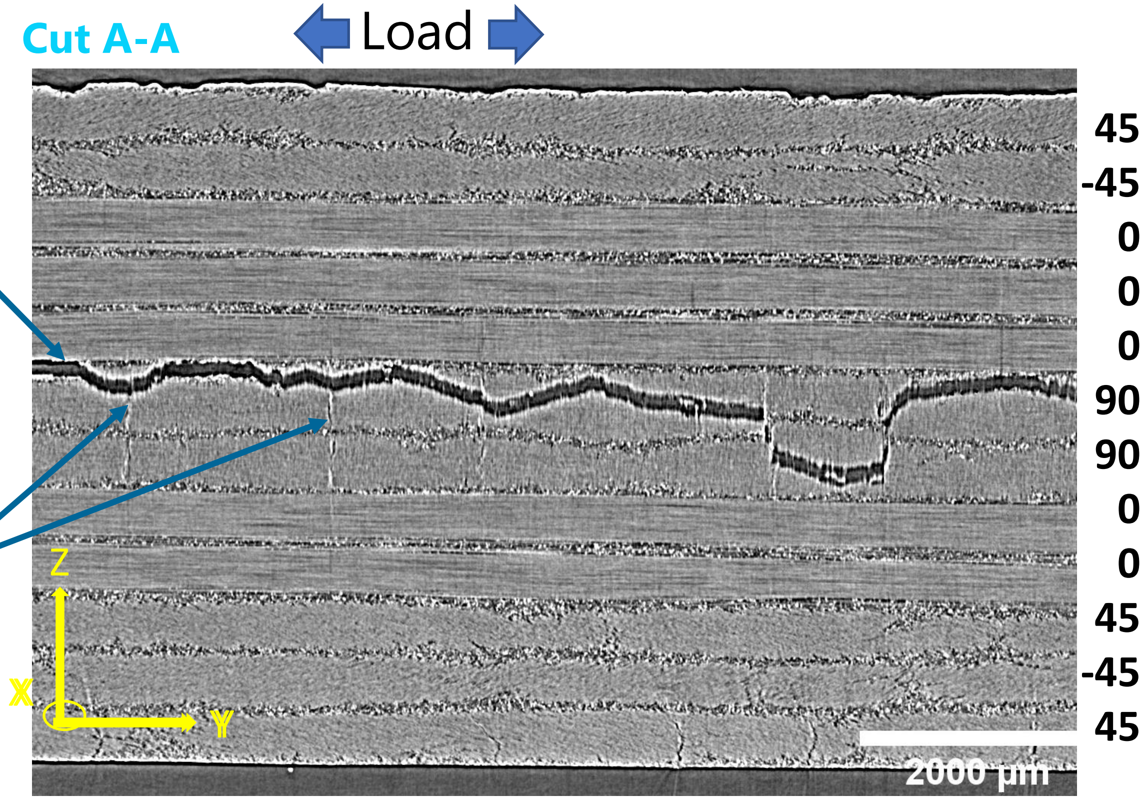
Damage assessment

F387_21_4





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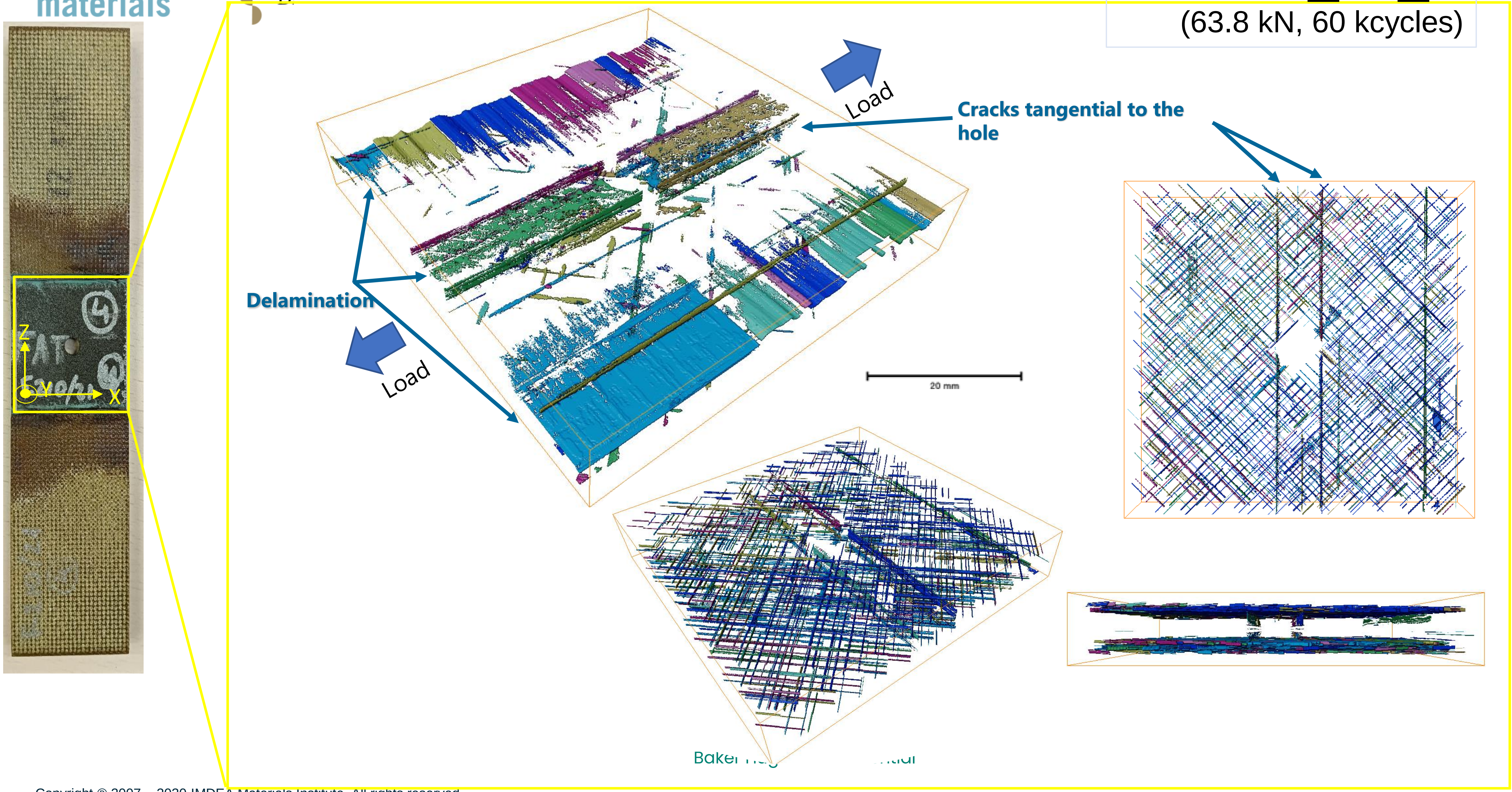
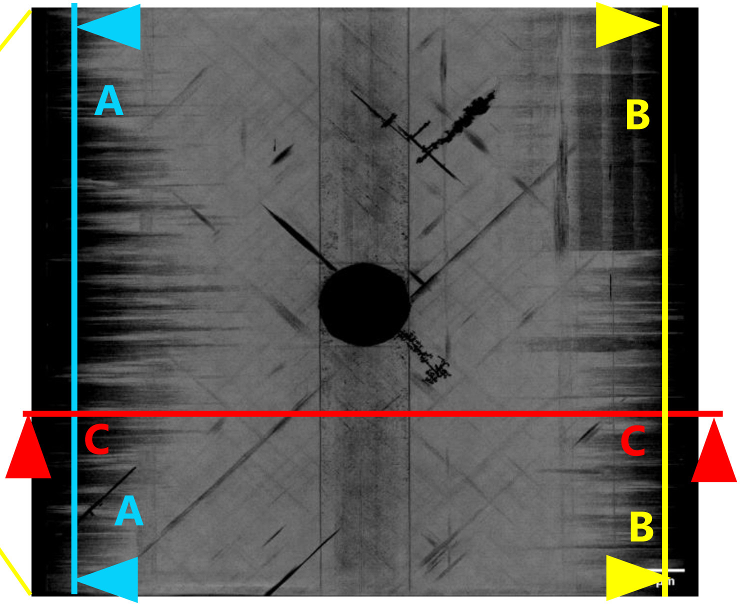
Damage assessment

F210_21_4
(63.8 kN, 60 kcycles)



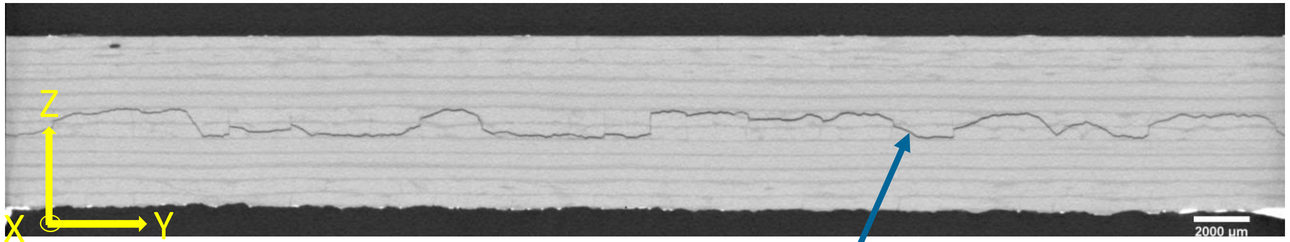
Damage assessment

F210_21_4



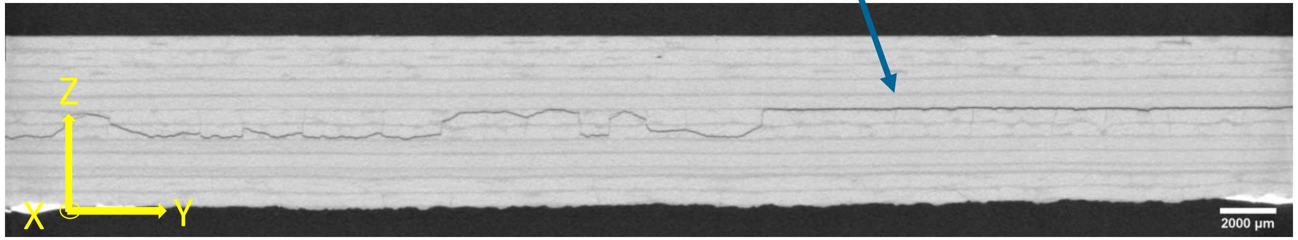
Load

Cut A-A



Delamination

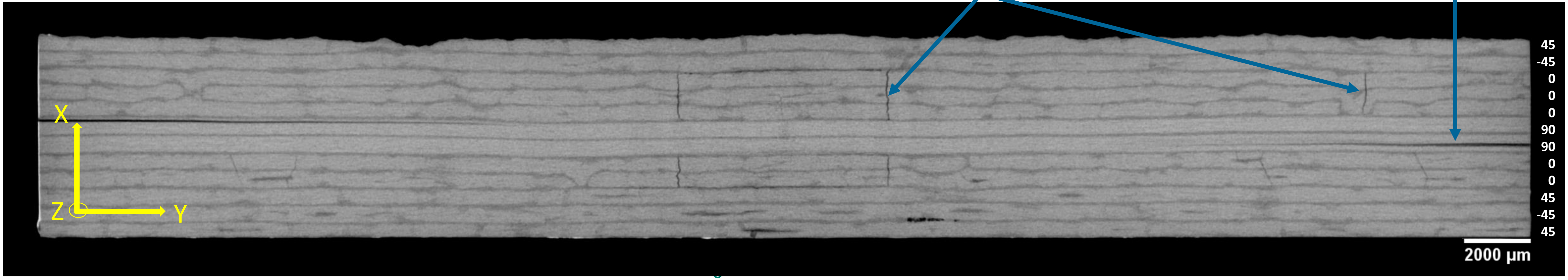
Cut B-B



Cut C-C Load

Cracks in plies

Delamination



Damage assessment

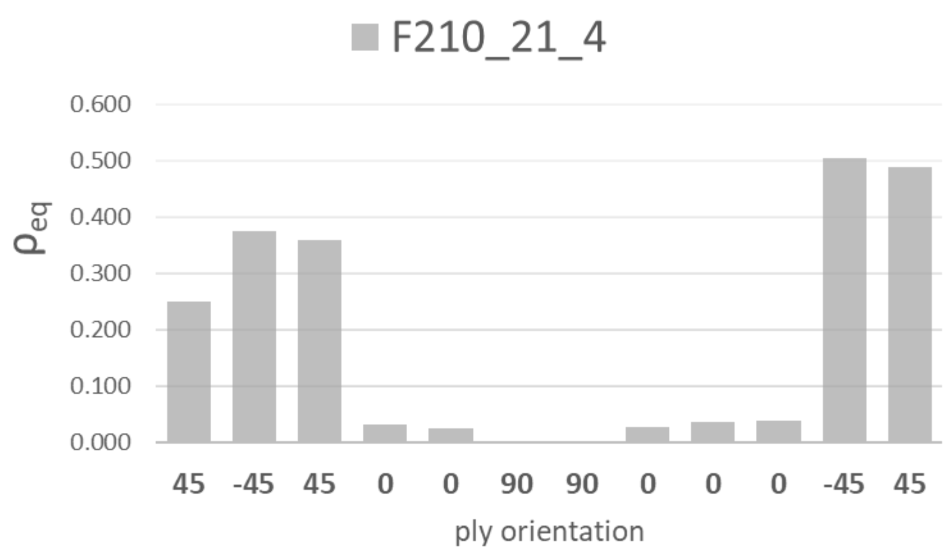
$$\rho_{eq} = \frac{L \cdot t}{A} \begin{cases} \rho_{eq} = \text{Crack density per ply} \\ L = \text{Sum of the length of each crack in the ply} \\ t = \text{Thickness of the ply} \\ A = \text{Area of the analyzed ply} \end{cases}$$

Crack density per ply in tensile samples

Damage assessment

$$\rho_{eq} = \frac{L \cdot t}{A} \begin{cases} \rho_{eq} = \text{Crack density per ply} \\ L = \text{Sum of the length of each crack in the ply} \\ t = \text{Thickness of the ply} \\ A = \text{Area of the analyzed ply} \end{cases}$$

Crack density per ply in fatigue sample



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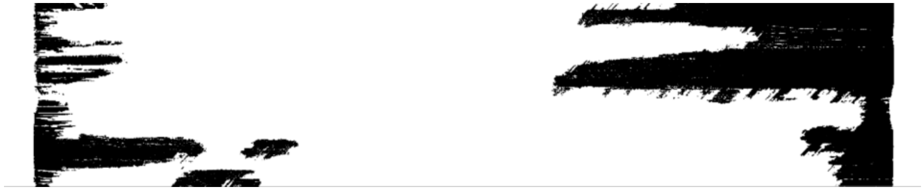
Damage assessment

$$A_{delaminated}/A_{analyzed} = \frac{Area}{Nominal\ Area}$$

Delaminated area in all samples

F188_21_3



F191_21_4

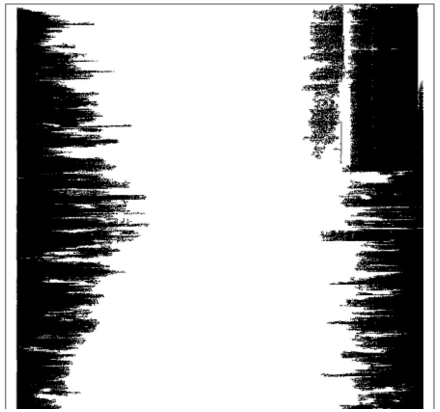
A

B

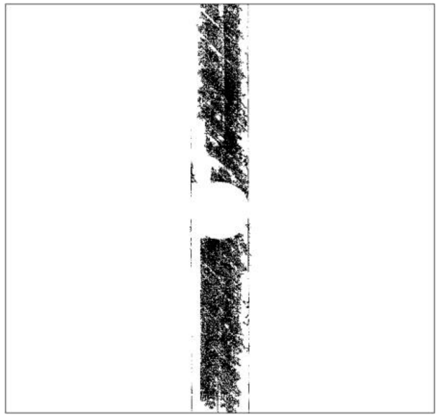
F387_21_4

F210_21_4

A

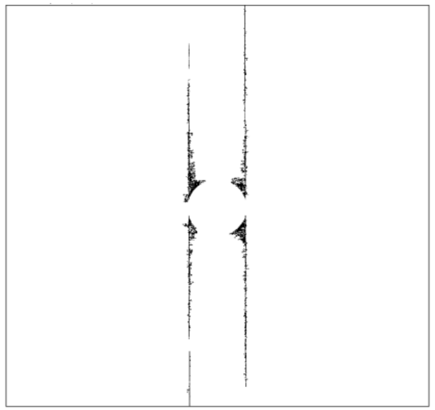


C

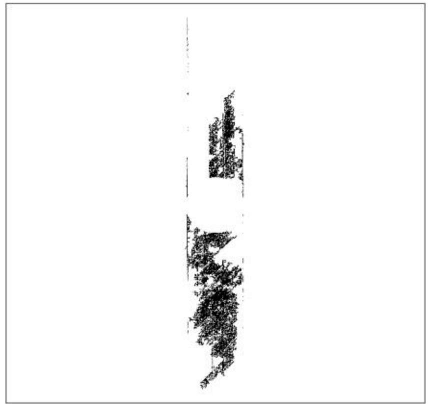


E

B



D



Understanding degradation behavior of Mg scaffolds manufactured via LPBF

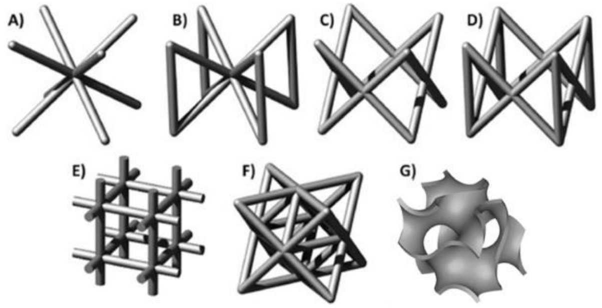
More details? mariadolores.martin@imdea.org

Degradation of scaffolds

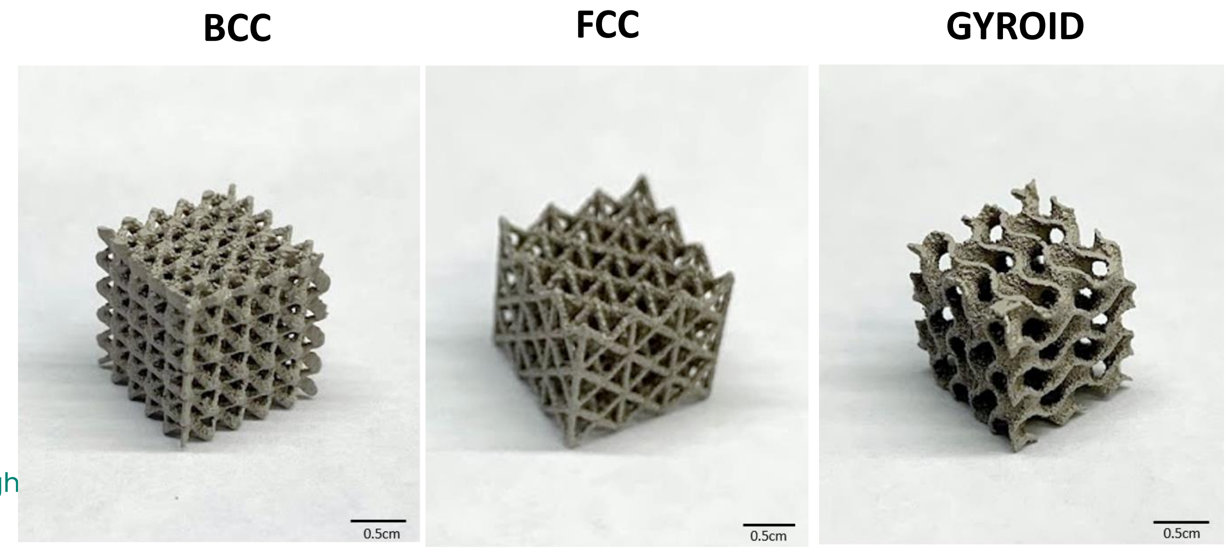
- Materials in health must fulfil three requirements:
  - Biocompatibility
  - Biodegradation
  - Similar mechanical properties

Degradation of scaffolds

- Magnesium alloys can verify these requirements.
  - Avoids stress shielding and body rejection.
  - Rapid degradation rate.
- Additive Manufacturing (AM) can build complex geometries that can be fitted to precise body parts. Selective Laser Melting (SLM) is a good choice.
  - High precision and flexibility fabrication
  - Enhancement of surface properties after Plasma Electrolytic oxidation (PEO) treatment.

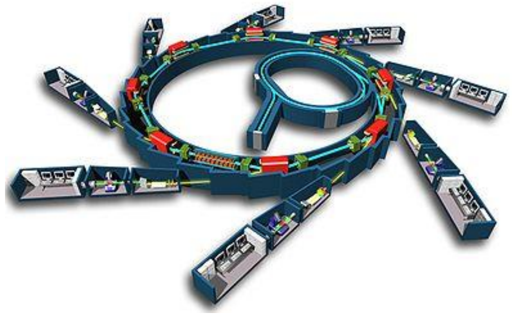


Baker Hugh

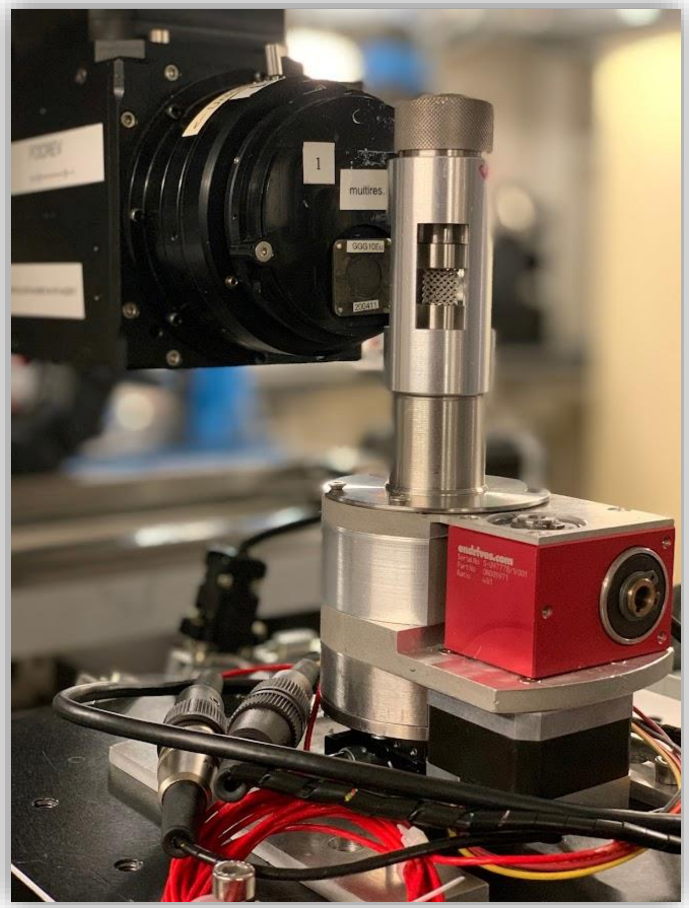


Degradation of scaffolds

- **WE43-PEO BCC, FCC, and gyroid scaffolds were built.**
- **They were immersed into SBF for 0, 7, 14, and 21 days.**
- **Interrupted in-situ compression tests were conducted at room temperature at the microtomography ID19 beamline of the European Synchrotron Radiation Facility (ESRF) in Grenoble (France).**
  - **Voxel size: 6.5 µm.**
  - **Monochromatic energy: 80 keV.**
- **In situ test machine developed at IMDEA Materials.**



ESRF
The European Synchrotron



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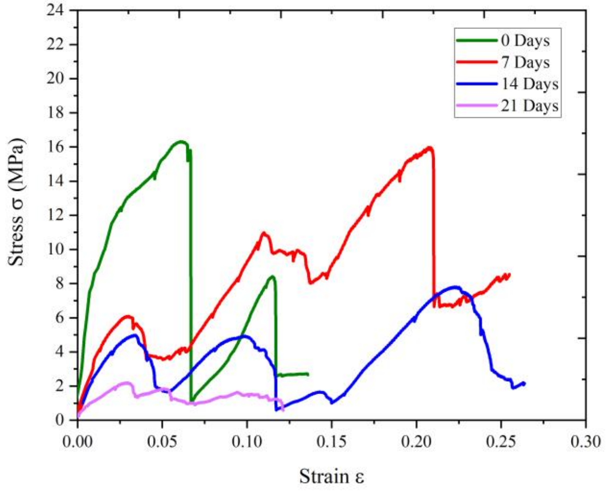
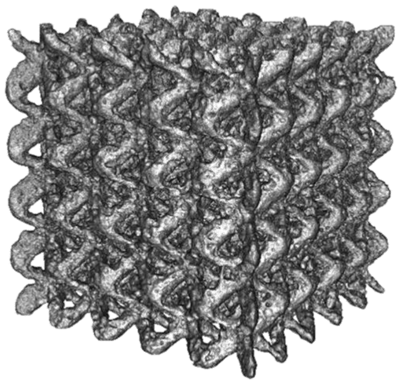
Degradation of scaffolds

- **The maximum strength of the scaffolds decreases substantially when immersing in SBF.**
- **Only BCC scaffold will be shown in this presentation.**
- **Digital Image Correlation (DIC) and Digital Volume Correlation (DVC) are implemented in all the samples to evaluate the damage evolution.**

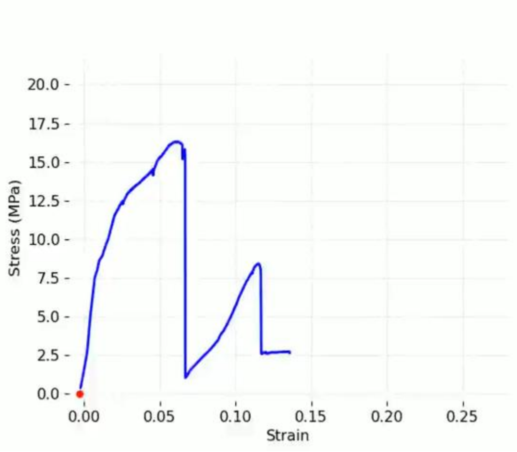
WE43-PEO BCC

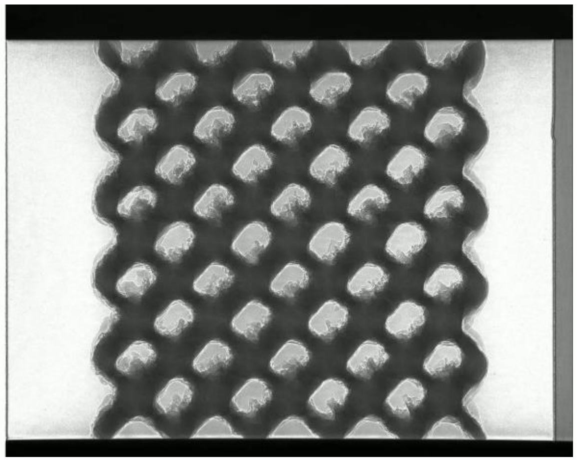


WE43-PEO BCC 0 days



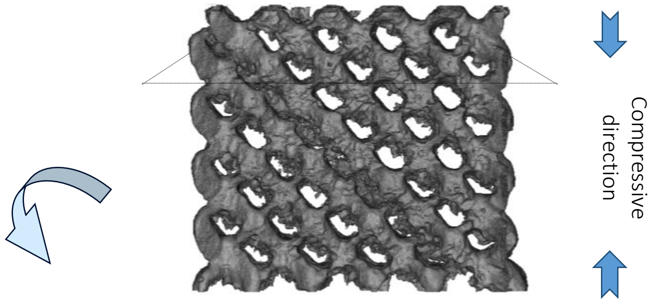
WE43-PEO BCC 0 days

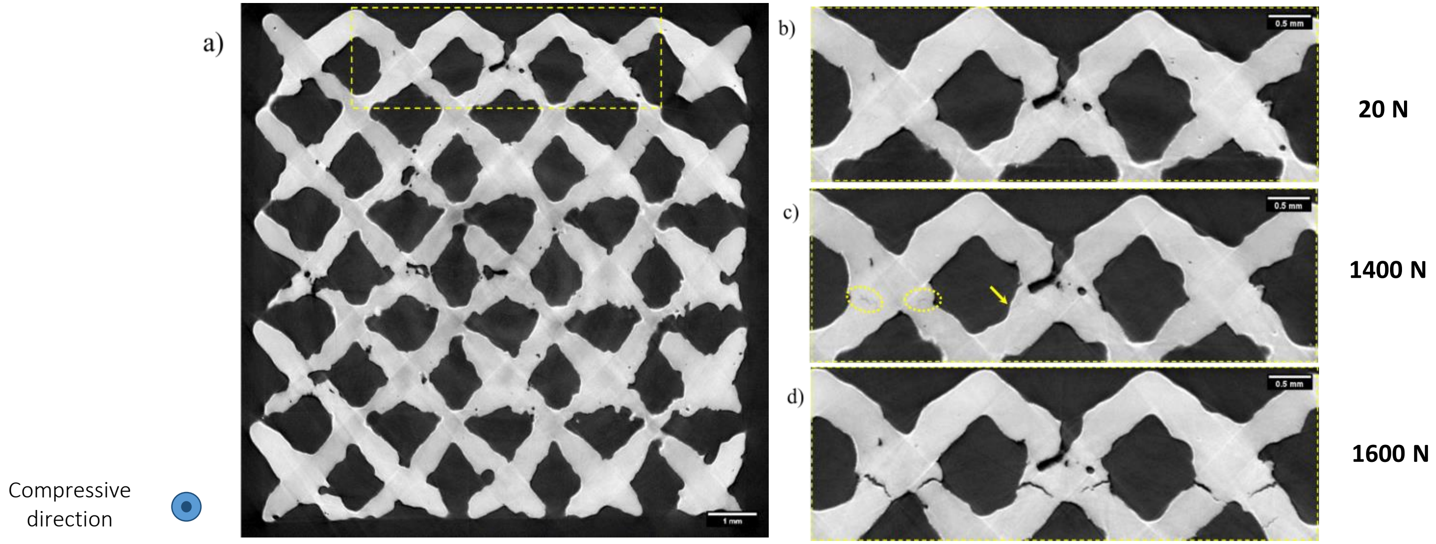




Degradation of scaffolds

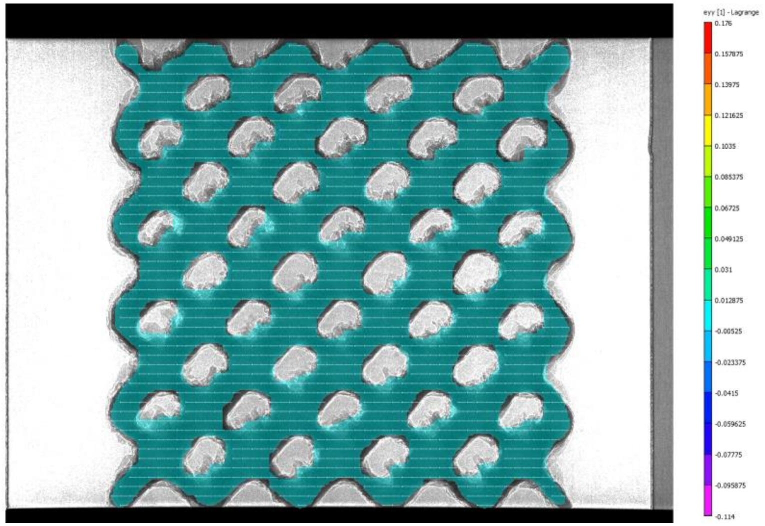
WE43-PEO BCC

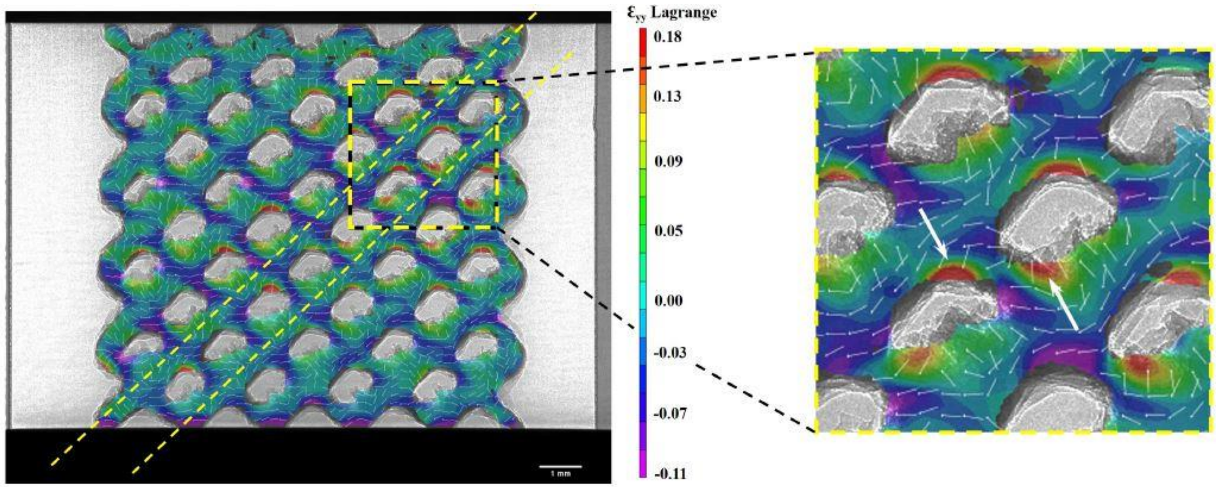




Degradation of scaffolds

- **BCC structure was found to be liable for development of localized deformations.**
- **Global strain: ε = 11 %.**





(a) BCC scaffold ϵ=11%

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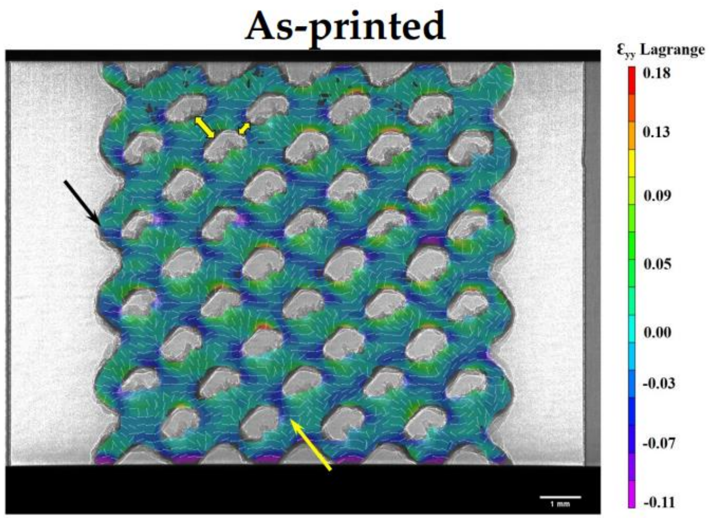
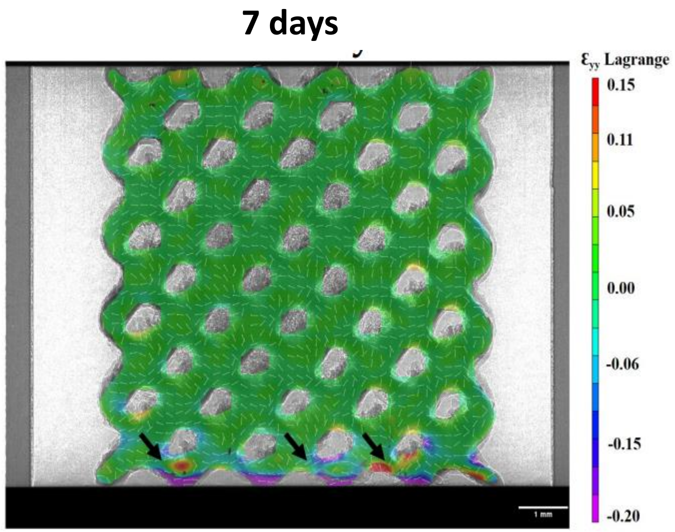
Degradation of scaffolds

- **AM defects, like heterogeneous strut size, serves as stress concentrators for crack initiation.**
- **Degraded parts after SBF immersion caused failure location.**

Blue deformations are more prevalent in some diagonal struts, indicating higher compressive deformation.



(a) BCC scaffold ϵ=9%

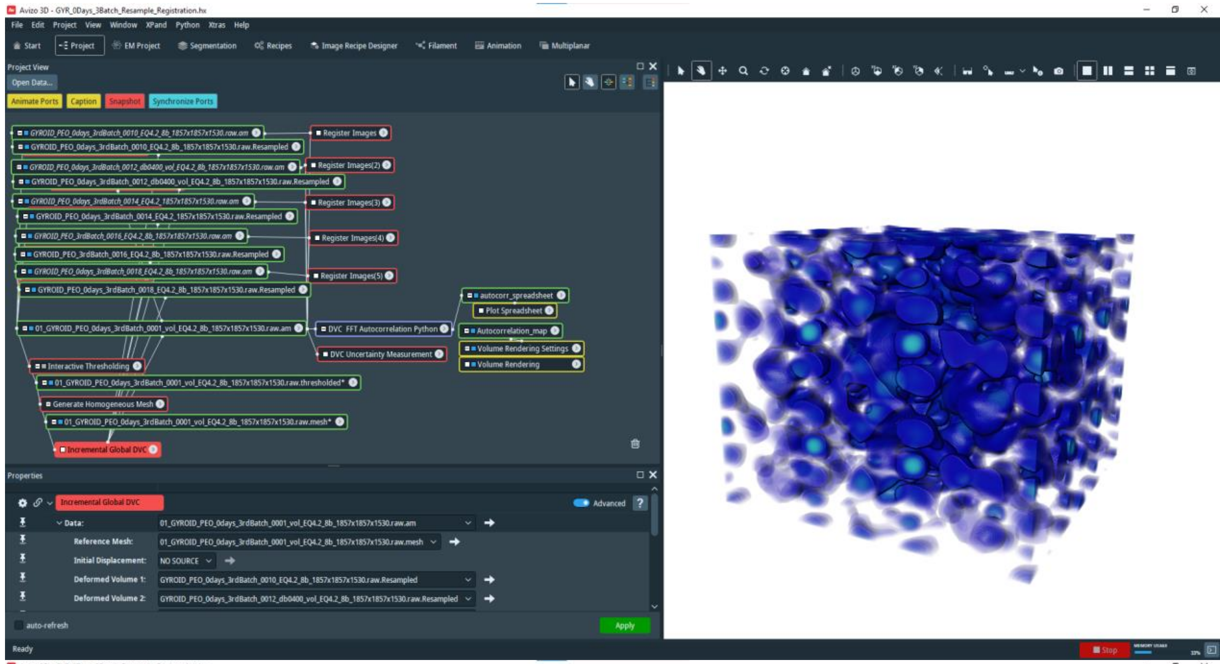


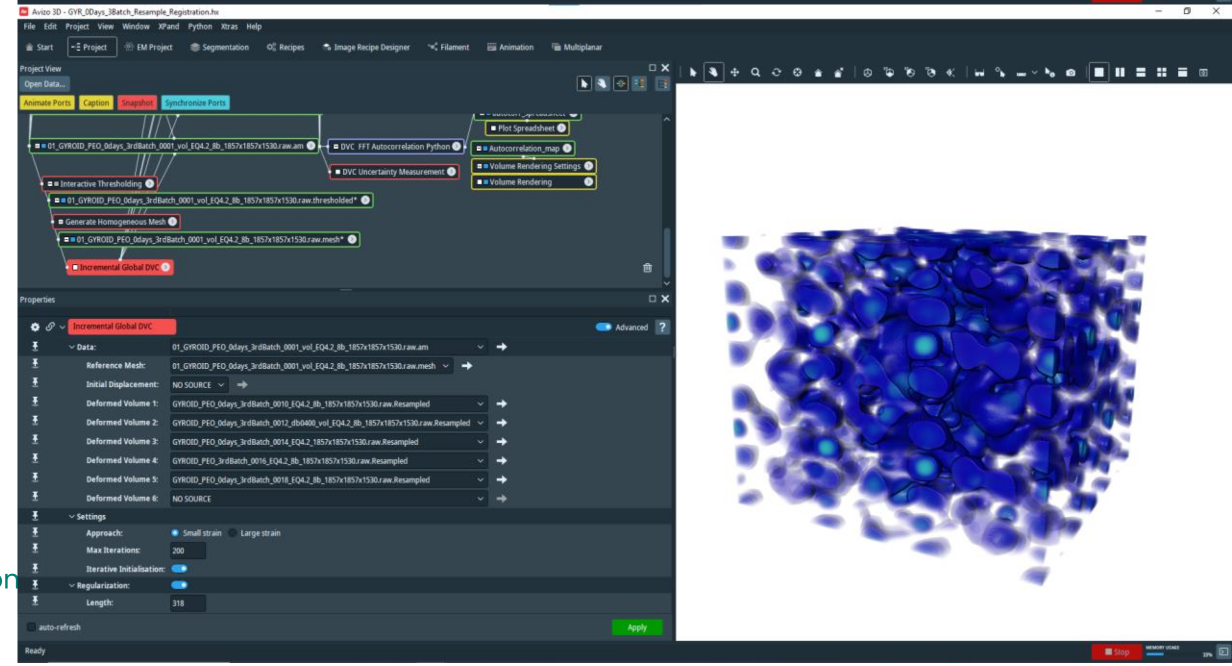
(b) BCC scaffold ϵ = 7%

Failure location is transferred to the more damaged parts, not the diagonal struts.

Degradation of scaffolds

- **DVC is an Avizo module:**
  - **Successive steps are not very distant from each other.**
  - **Registration is mandatory.**
  - **Resampling can reduce the computing load.**
  - **Autocorrelation.**
  - **Uncertainty.**
  - **Meshing.**
  - **Global DVC.**

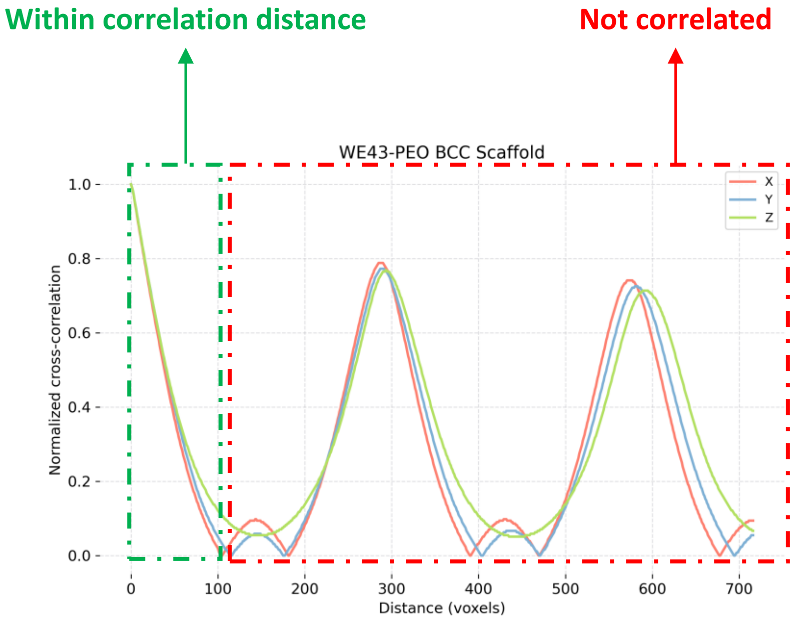


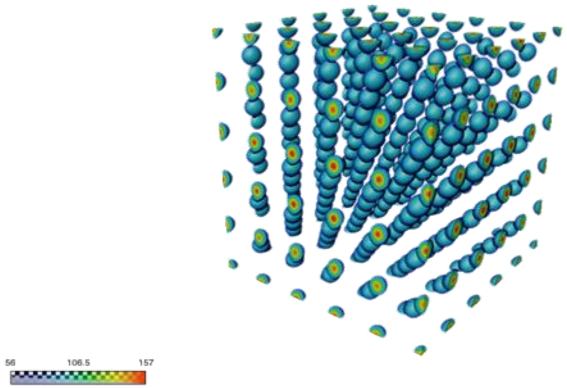


Baker Hughes Con

Degradation of scaffolds

- **Autocorrelation:**
  - **DVC relies on naturally occurring texture to perform registration between two successive 3D volumes.**
  - **Correlation measurements reveal the spatial arrangement of features within the material's microstructure.**
  - **They guide the selection of an optimal mesh cell size.**

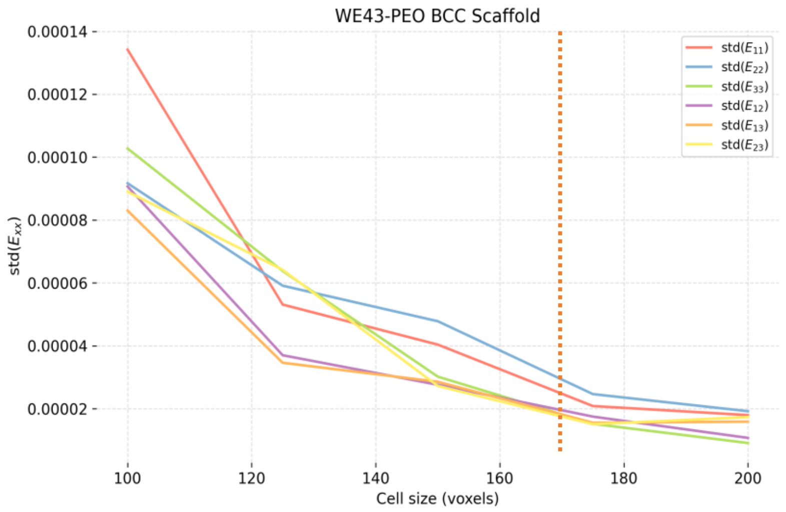




Baker Hughes Confidential

Degradation of scaffolds

- **Uncertainty:**
  - **Once a range of mesh sizes was selected, the uncertainty assessment for different mesh sizes was carried out to find out the strain error for each mesh size.**
  - **Resolution and precision were obtained, with strain errors no greater than 0.08 %.**

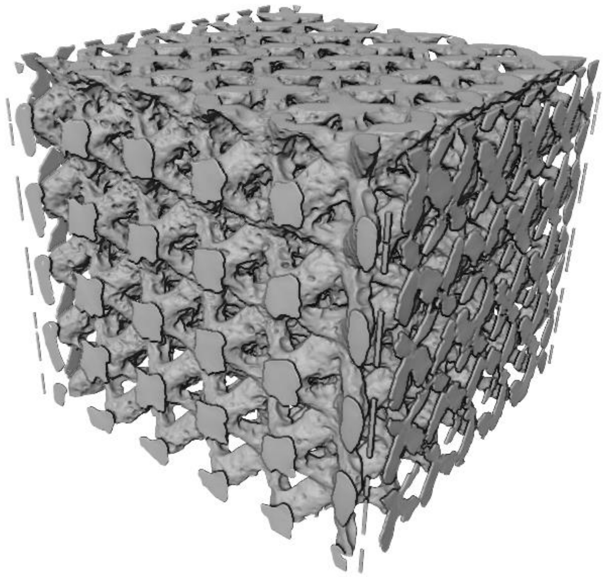


ε_{error}=0.002-0.003%

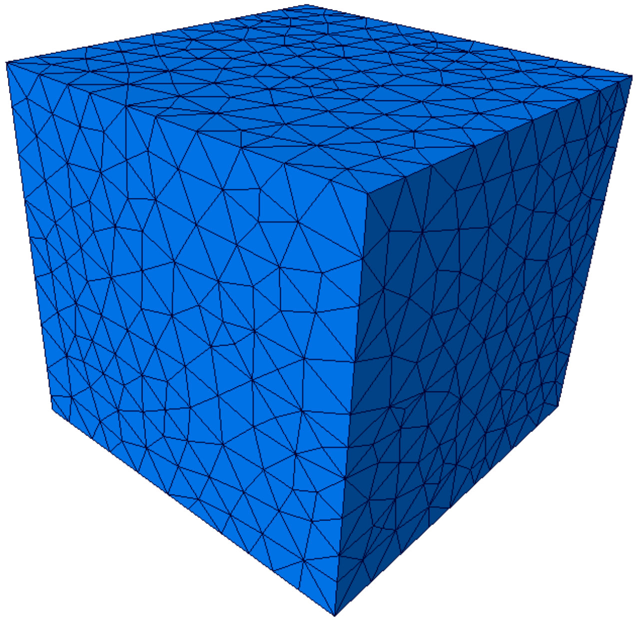
Degradation of scaffolds

- **Grid generation:**
  - **Performed automatically by the software.**
  - **It is dependent on the ROI to study.**

BCC Scaffold



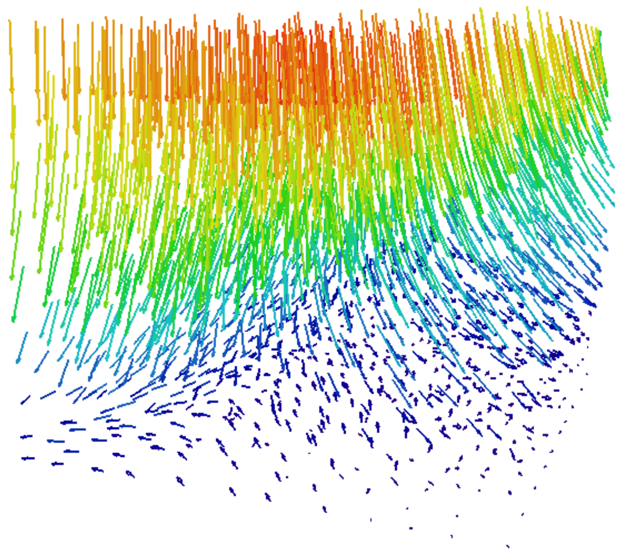
Mesh (170 Cell Size)



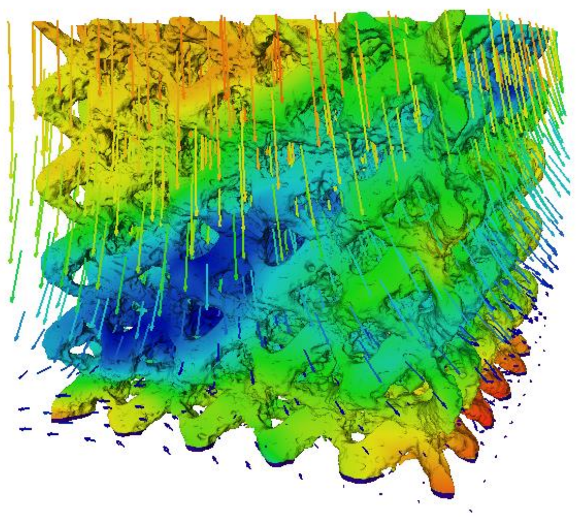
Degradation of scaffolds

- **Global DVC output:**
  - **Displacement field composed of vectors from each point from their initial positions to their current positions.**
  - **Strain map with a representation of deformations when the material elements were stretched, compressed or sheared.**

Displacements WPB_0005

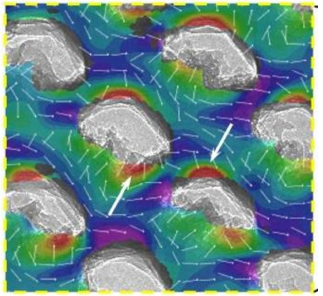


ε_3 Strain Map WPB_0005

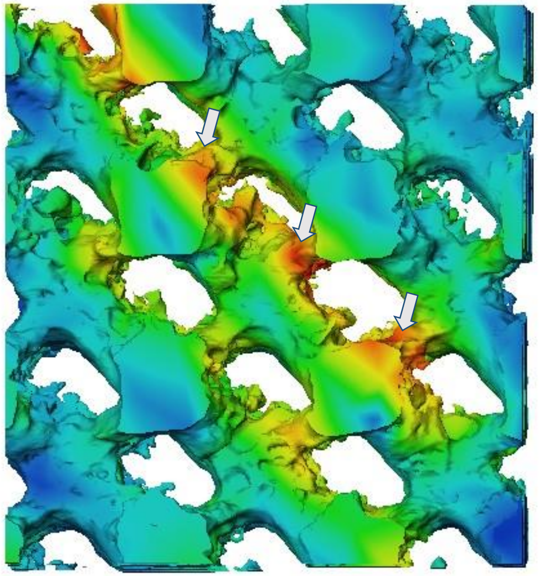


Degradation of scaffolds

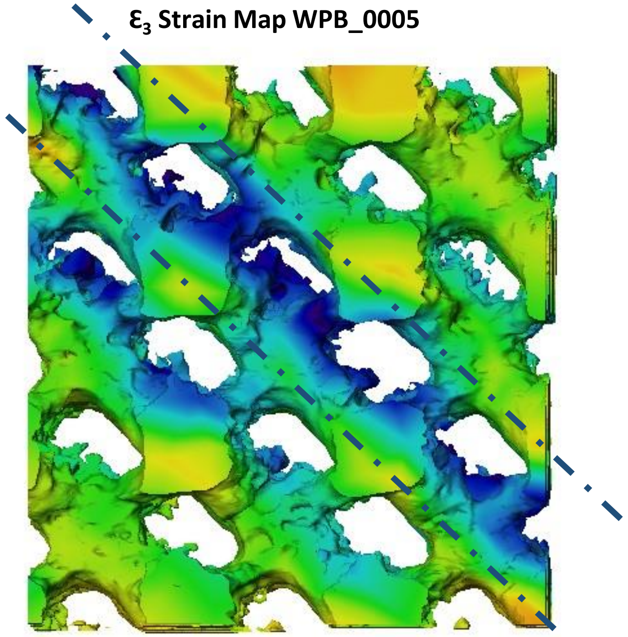
- Maximum, ε_1, principal stress → Maximum stretching deformation.
- Minimum, ε_3, principal stress → Maximum compressive deformation.
- The shear band is detected with the maximum compressive deformation.
- Stretching deformation zones acted as catalysts for the shear banding.



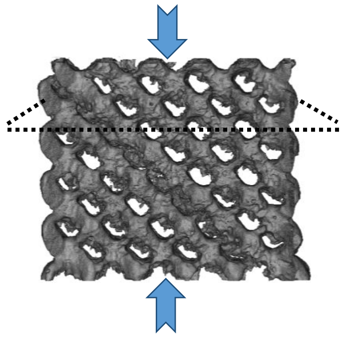
ε_1 Strain Map WPB_0005

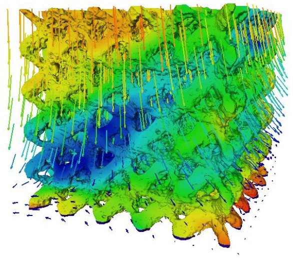


ε_3 Strain Map WPB_0005



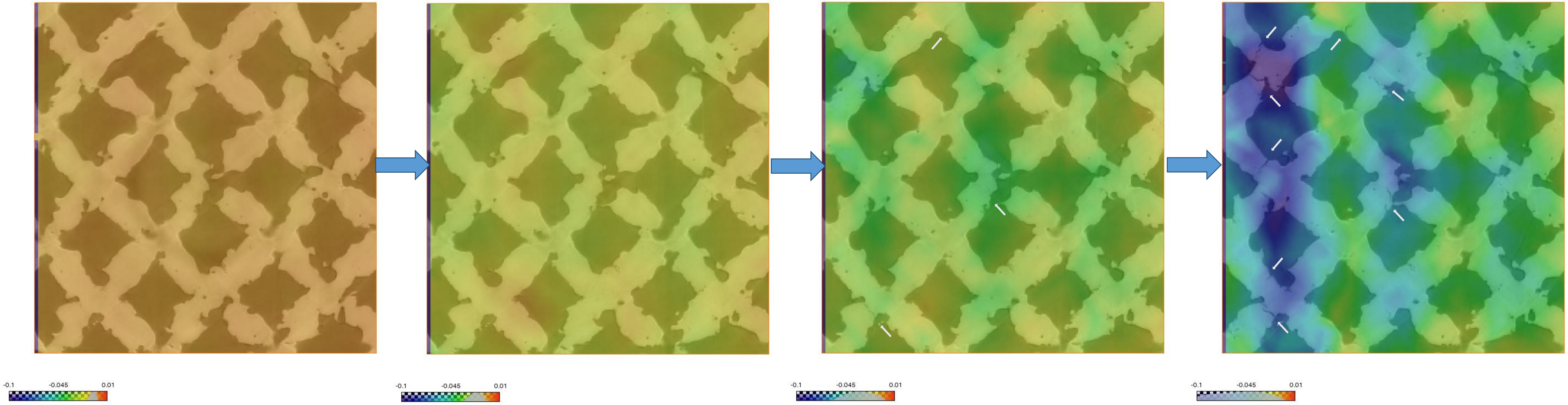
Degradation of scaffolds





- For a particular slice, the evolution of the strain field with the compression load can be seen.
- Highly deformed regions were located at the intersection of nodes and struts, typical zones for crack initiation.

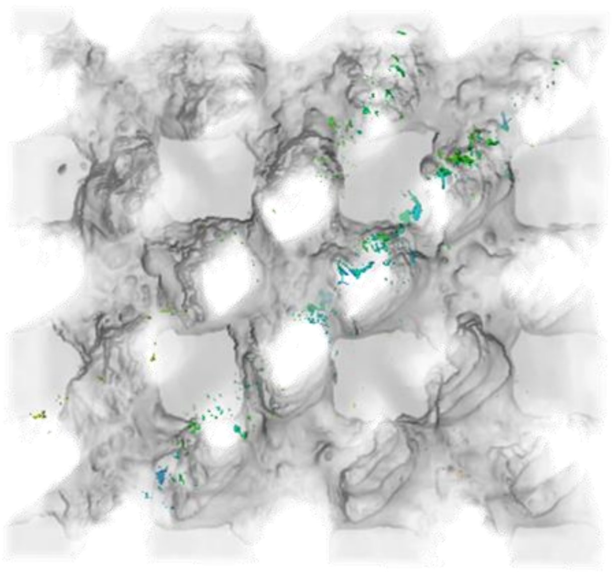
ε_3 Strain Maps

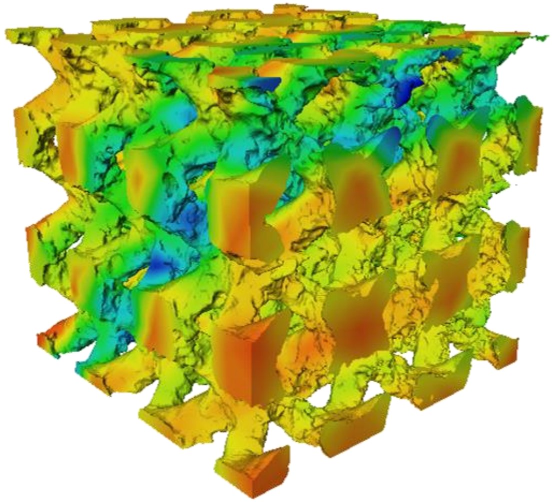


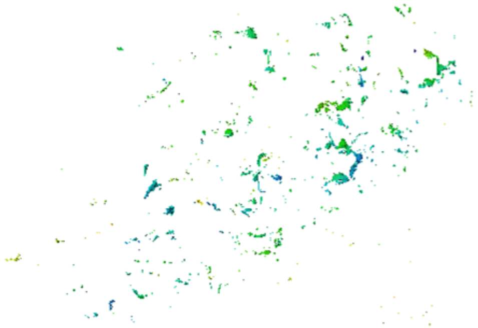
WPB_002 (ε=0.9%) | WPB_003 (ε=2.5%) | WPB_004 (ε=5.0%) | WPB_005 (ε=6.0%)

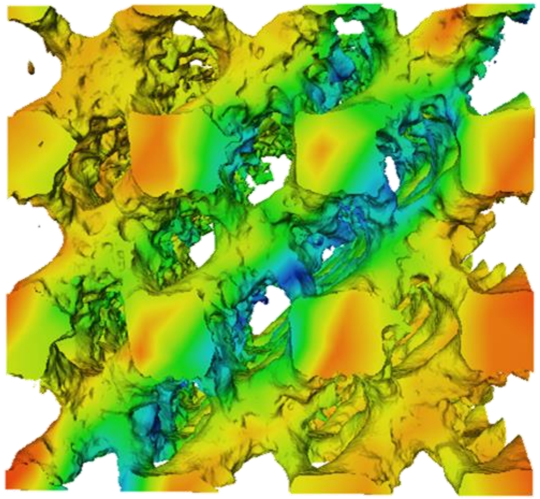
Degradation of scaffolds

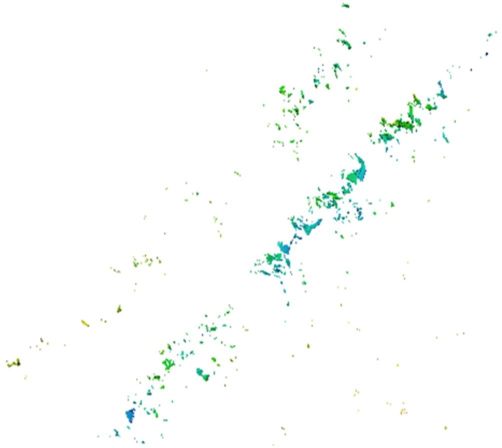
- **With the residual from the correlation maps, it was possible to segment and extract the cracks.**
- **They were located at the diagonal intersections.**











Summary

Summary

- UT is a fast technique, and its precision and detectability can be improved by artificial intelligence.
- XCT scans will feed the model.
- A massive set of scans is necessary, so the model will identify several types of defects (cracks, bubbles, resin pockets, delamination…).

Summary

- Segmentation process plays a key role in a damage assessment workflow.
- Depending on the scan output and reconstruction artefacts several approaches can be applied.
- Training the model is the most time-consuming step.
- With a well-trained classifier the automated detection will be fast.

Summary

- In-situ scans are a good option to understand the mechanical properties of materials.
- The analysis of XCT volumes can be complemented with correlation techniques.
- Image and volume correlation allow to identify regions with high deformation, where crack initiation is more probable.

Thank you very much!
Questions?