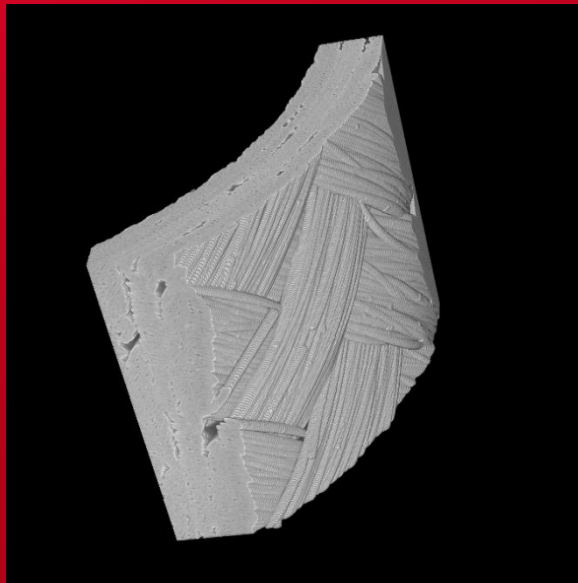


DE LA RECHERCHE À L'INDUSTRIE



Effects Of Braid Angle On Damage Mechanisms In SiC/SiC Composite Tubes Characterized By X-ray Computed Tomography

<u>Y. Chen</u>	CEA/SRMA/LC2M Gif-sur-Yvette, France
L. Gélébart	CEA/SRMA/LC2M Gif-sur-Yvette, France
M. Bornert	Laboratoire Navier, ENPC, Marne-la-Vallée, France
C. Chateau	Laboratoire Navier, ENPC, Marne-la-Vallée, France
C. Sauder	CEA/SRMA/LTMEX Gif-sur-Yvette, France
A. King	PSICHE, Synchrotron SOLEIL, France

41th International Conference and Expo on Advanced Ceramics and Composites
Daytona Beach – 24/01/2017

- Context and material
- Experimental method
- Qualitative observations of cracks
 - Braid angle effects
- Crack quantification method
- Conclusions and future work

CONTEXT AND MATERIAL

- Industrial context

Fuel cladding tube in Gas-cooled Fast Reactors (GFRs)

High T°
resistance

Silicon Carbide (SiC)

Deformability

SiC/SiC composite

- Studied material

Fibrous preform (SiC fibers)

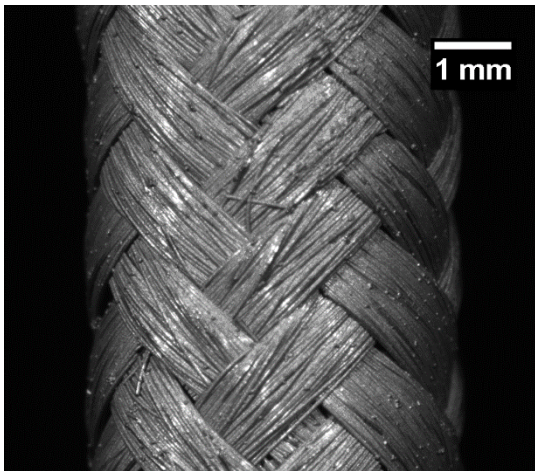
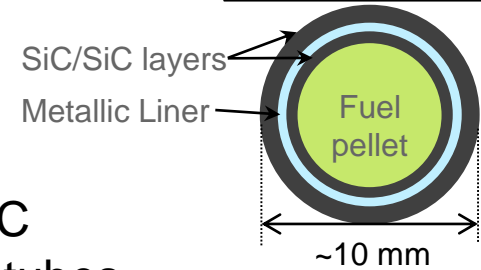


Pyrocarbon, SiC Matrix

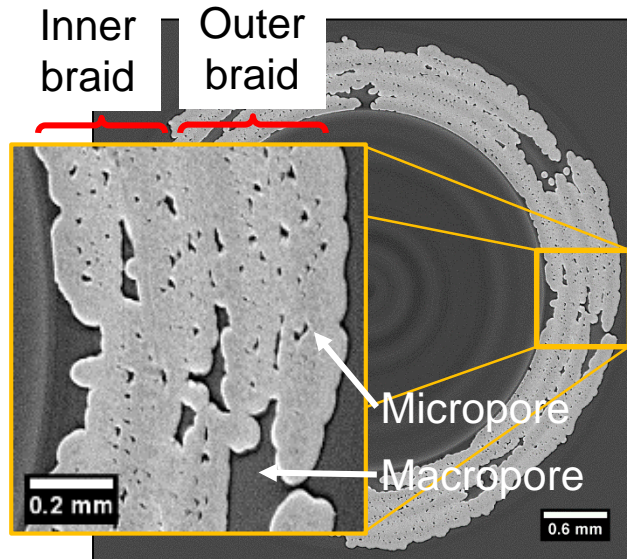
Chemical Vapor Infiltration (CVI)



SiC/SiC composite tubes



2D braided



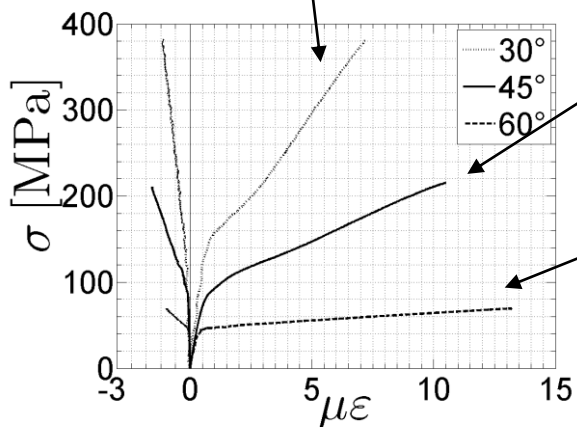
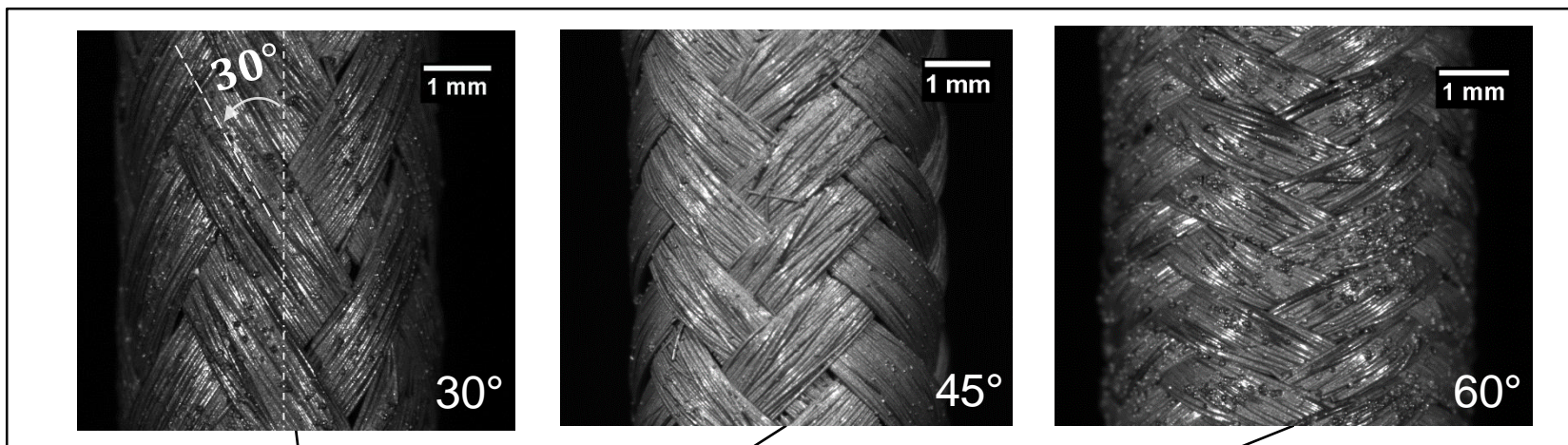
CONTEXT AND MATERIAL

Macroscopic behavior



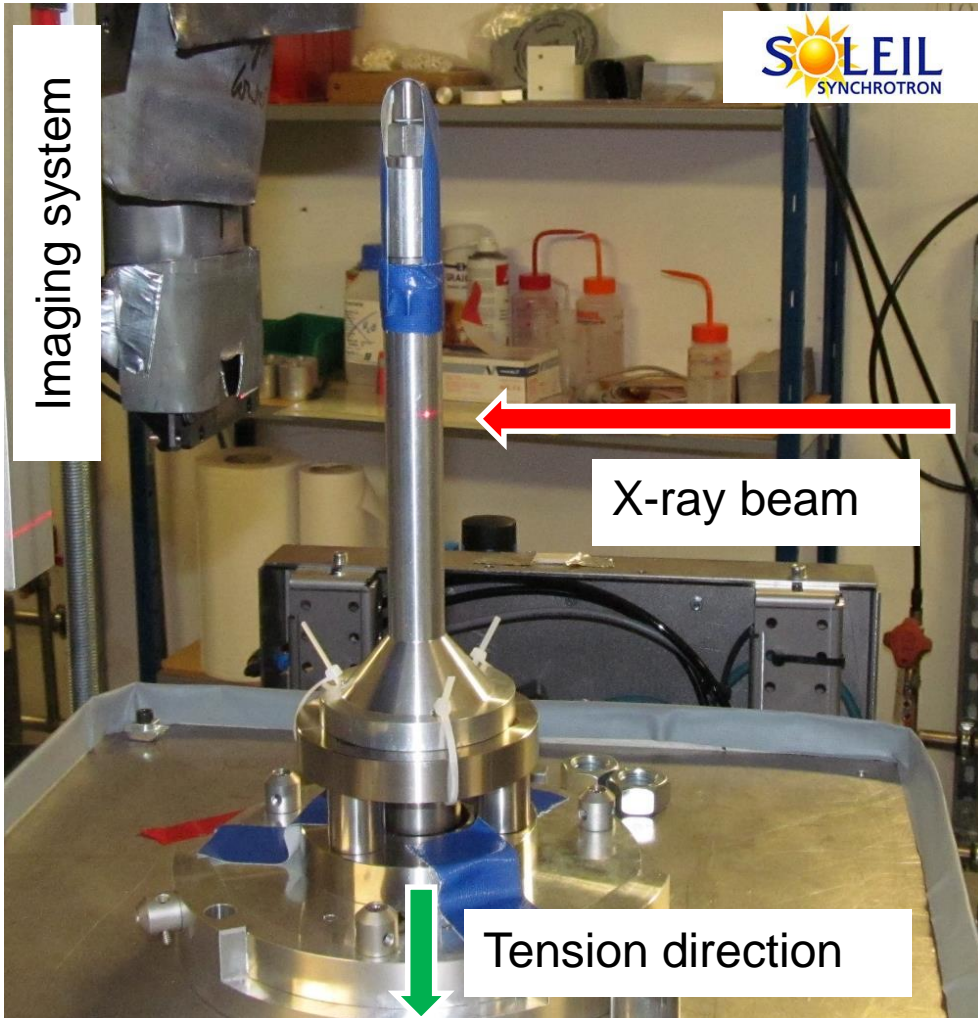
Micro-cracking

- Fiber-matrix interface
- Porosity fraction
- Braid pattern
- **Braid angle**



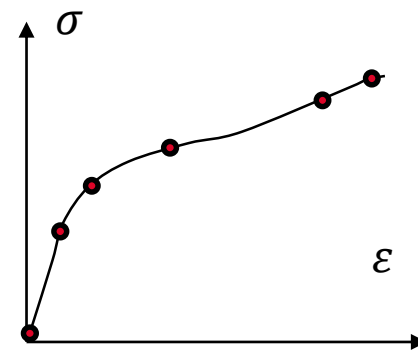
Studied materials:

- **Braid angle: 30°, 45°, 60°**
- 2 layers of braided composites
- ~5 mm diameters
- Porosity: 15% ~ 20%
- Braid pattern: 2-2 cross-over



In situ experimental setup
at Synchrotron SOLEIL, France

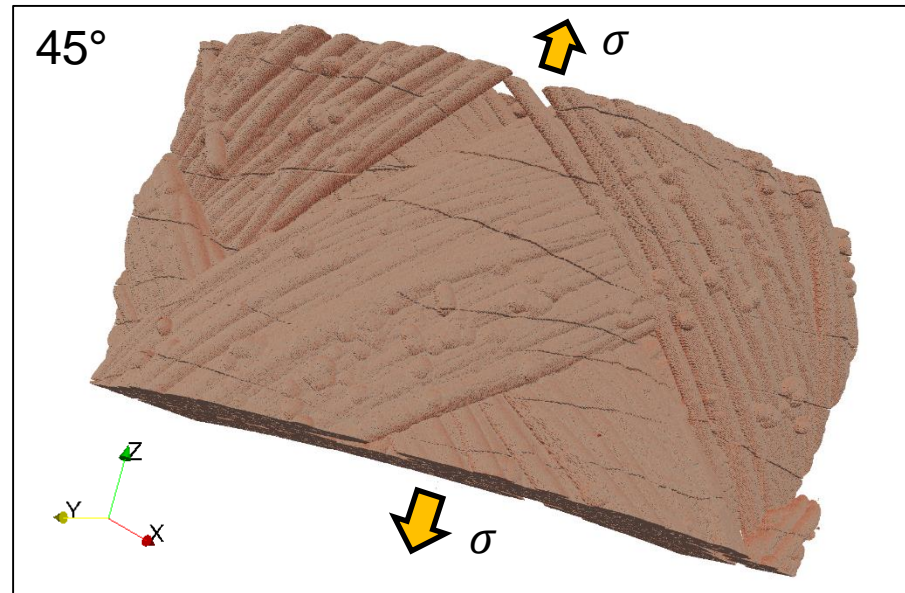
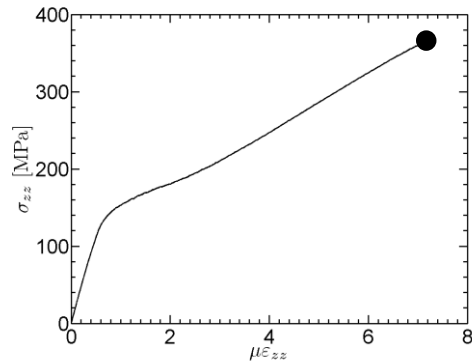
- Monotonic tensile test
 - Synchrotron beam
 - Voxel size: 2.6~2.8 μm
- For comparison:
fiber diameter $\sim 15 \mu\text{m}$



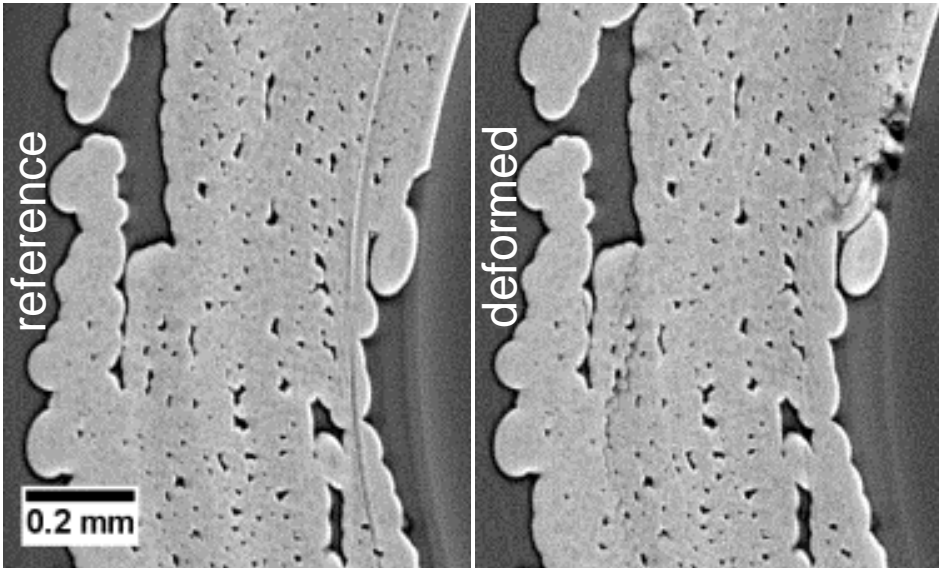
XRCT → Raw data: 3D digital images

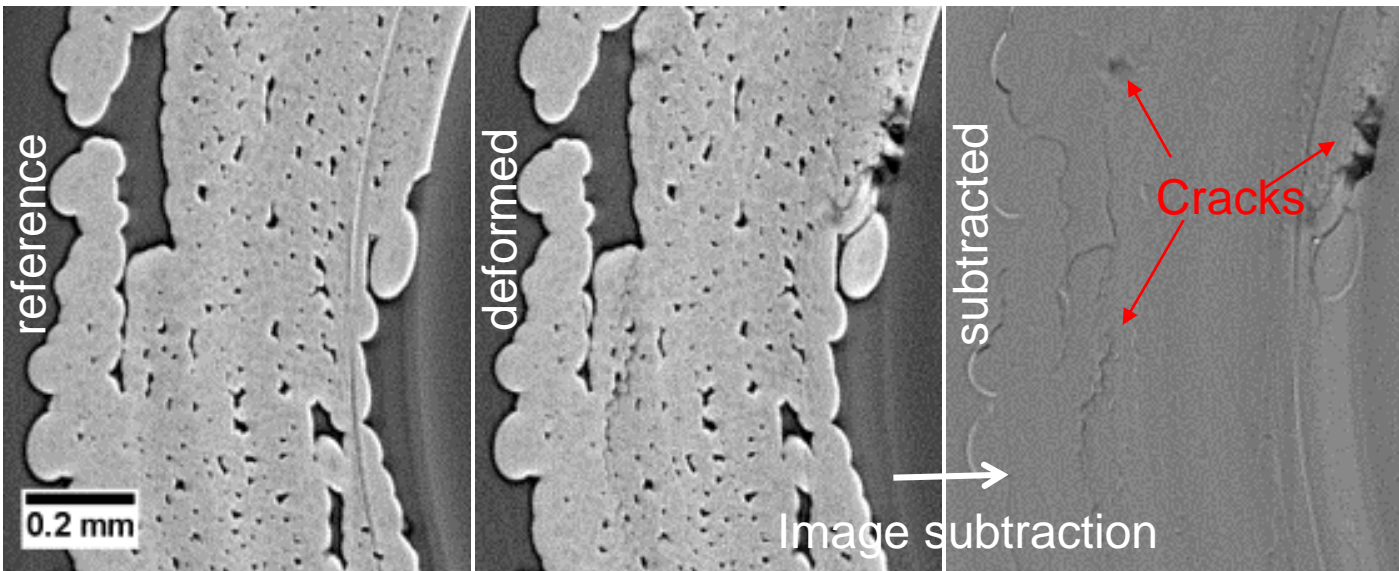


- Qualitative analyses (visualization) → braid angle effects
- Quantitative analyses → geometry parameters of cracks (to be completed)

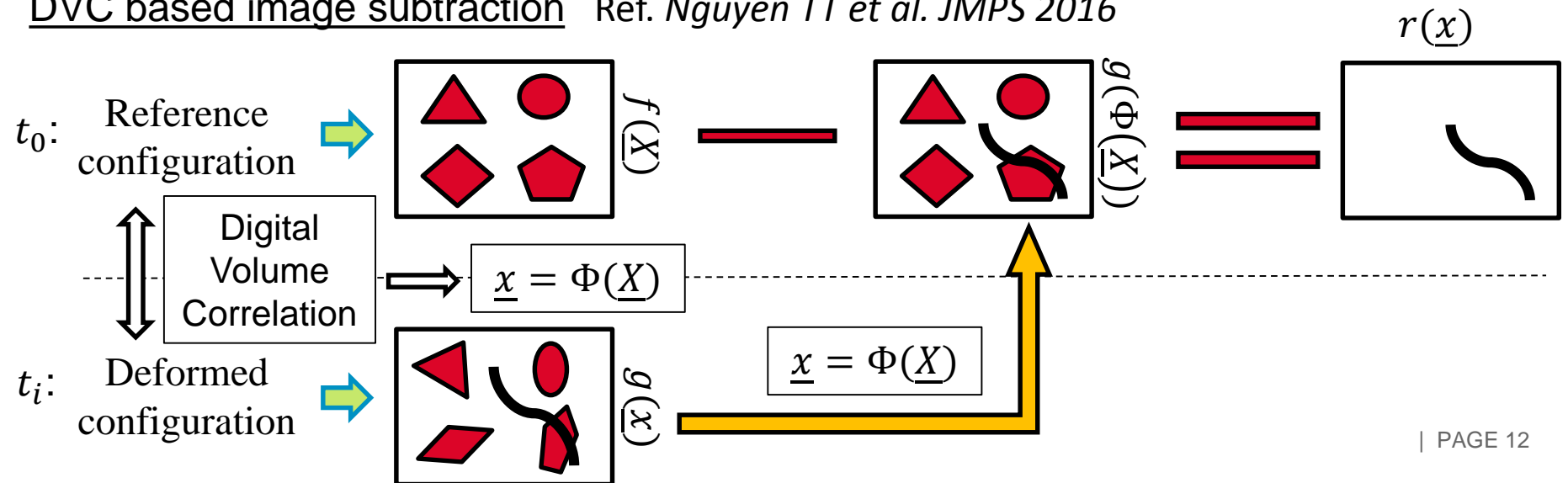


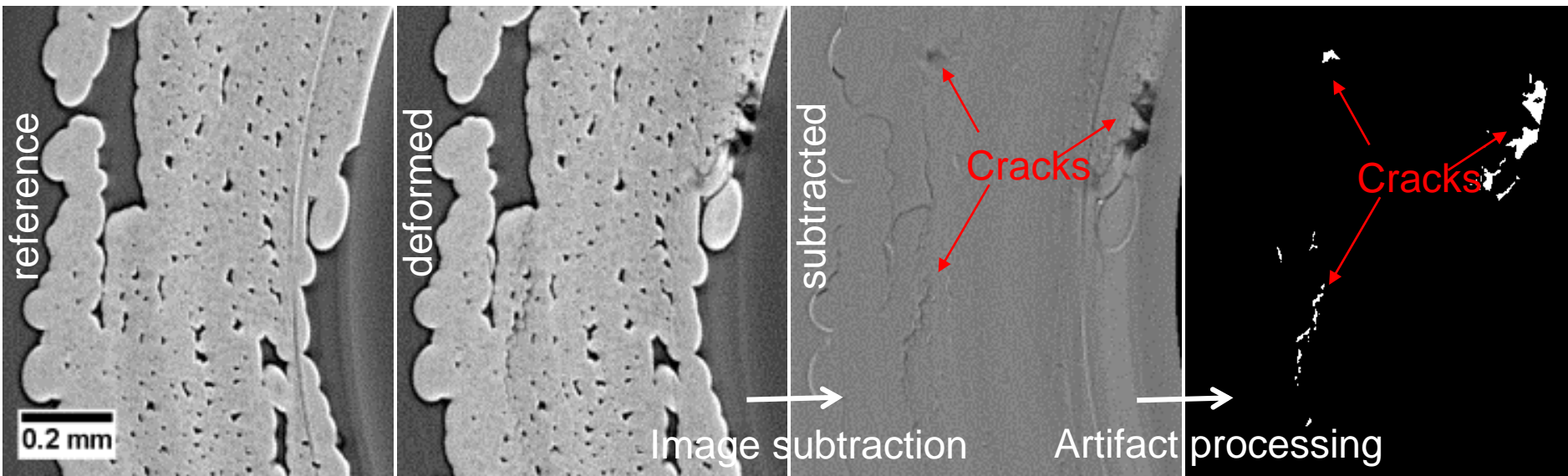
CRACK DETECTION





DVC based image subtraction Ref. Nguyen TT et al. JMPS 2016



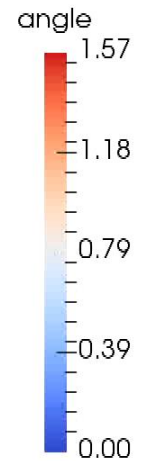
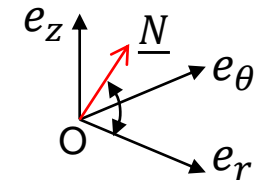
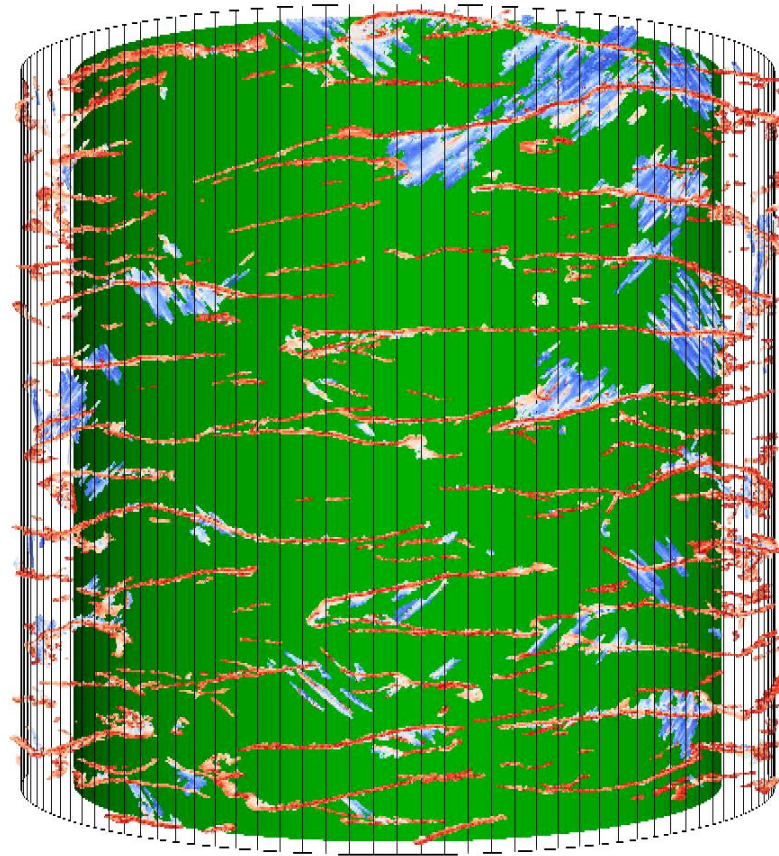
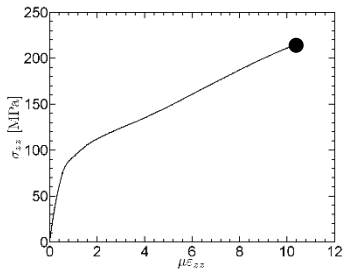


Remaining image artifacts:

- Over-contrasted pore-solid interfaces
- Ring artifacts
- Radial fluctuation of brightness

CRACK OBSERVATION 45°

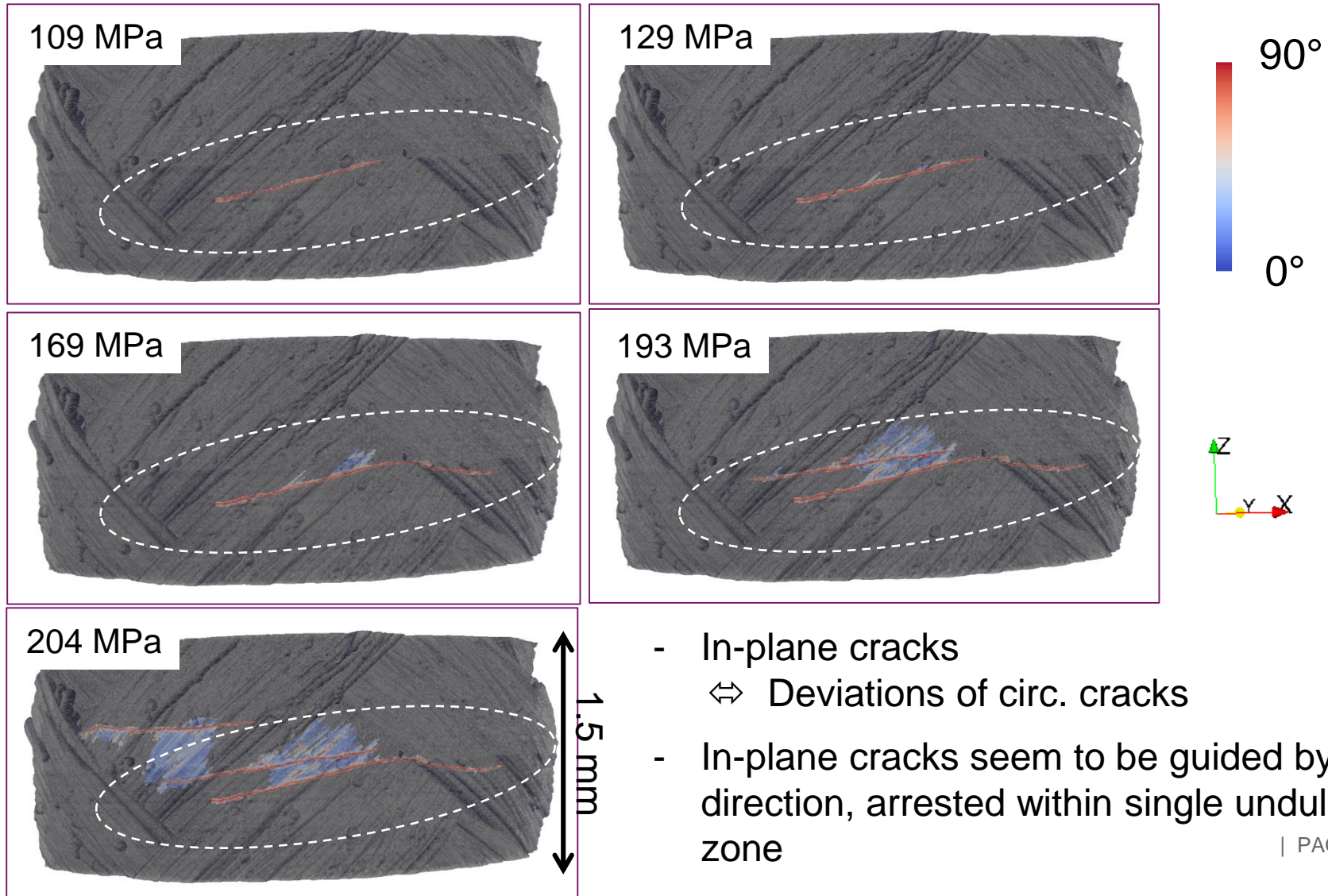
45°



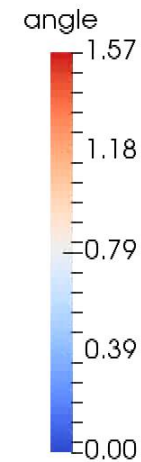
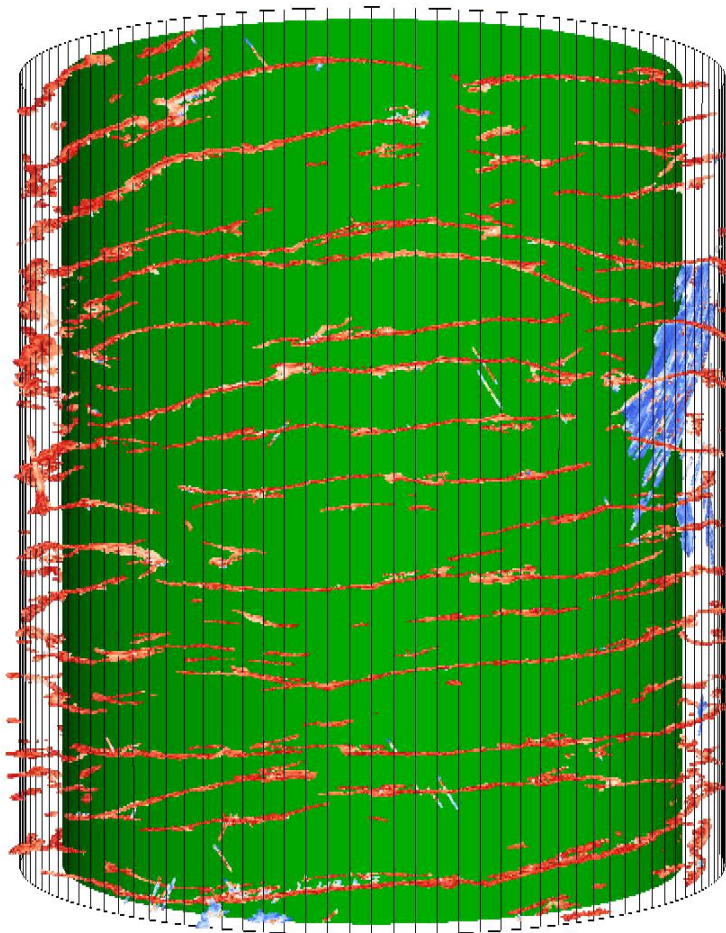
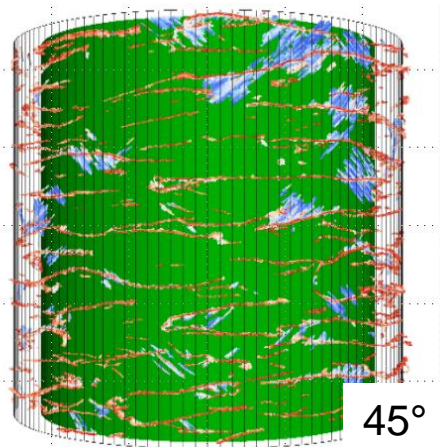
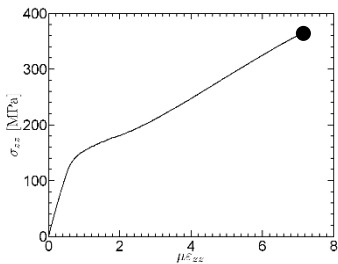
- TWO families of cracks: Circumferential (red) & In-plane (blue)
- $\perp \sigma_{zz}$
- $\parallel \sigma_{zz}$
- \parallel wall thickness

CRACK OBSERVATION 45°

A typical crack observed within 45° tube

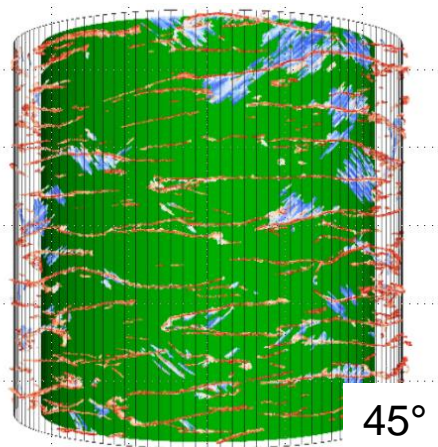
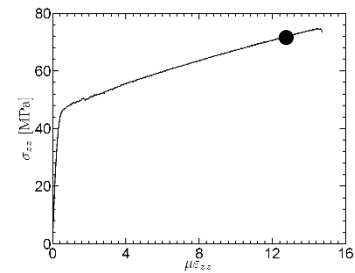


CRACK OBSERVATION 30°

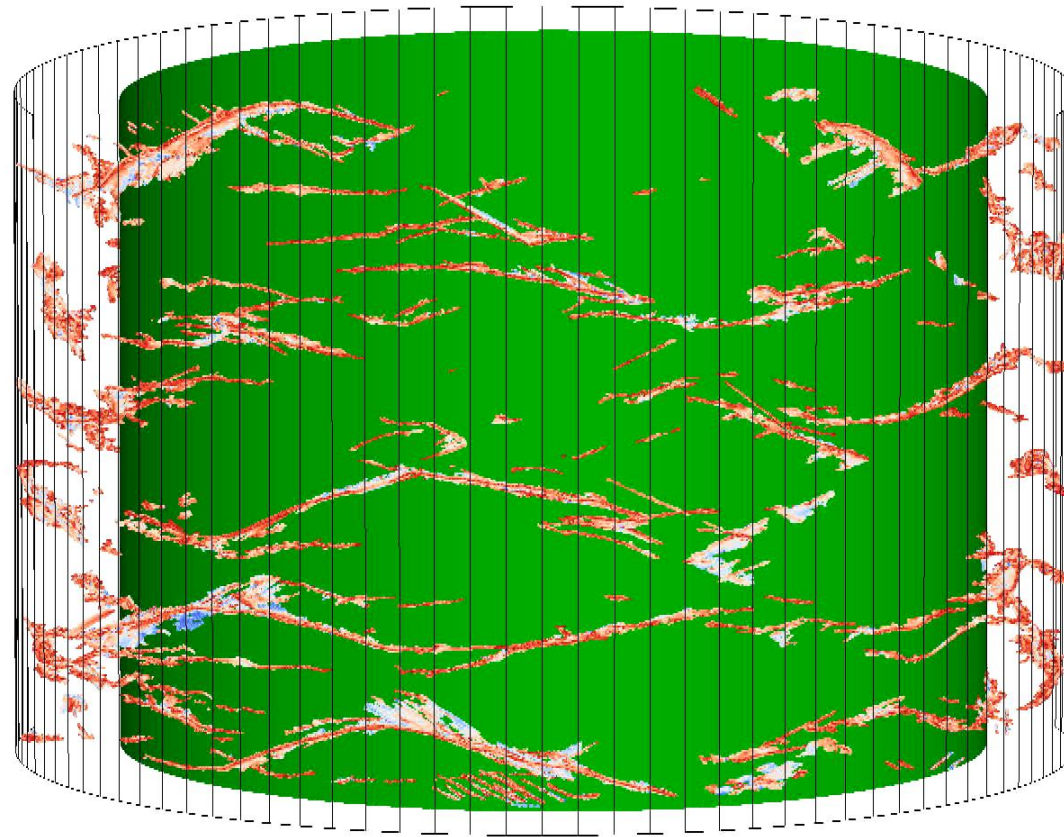


- Crack deviation (in-plane cracks):
 - Few initiation
 - Able to propagate far away

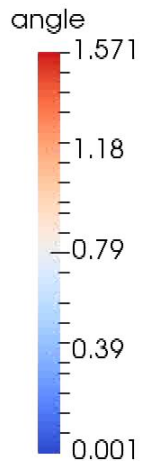
CRACK OBSERVATION 60°



45°

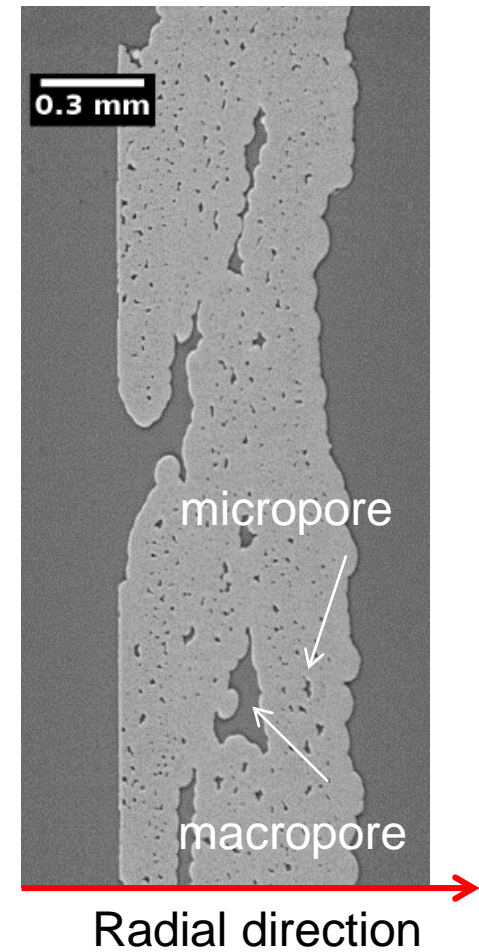
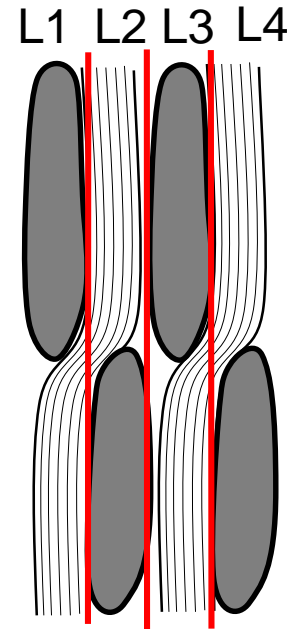
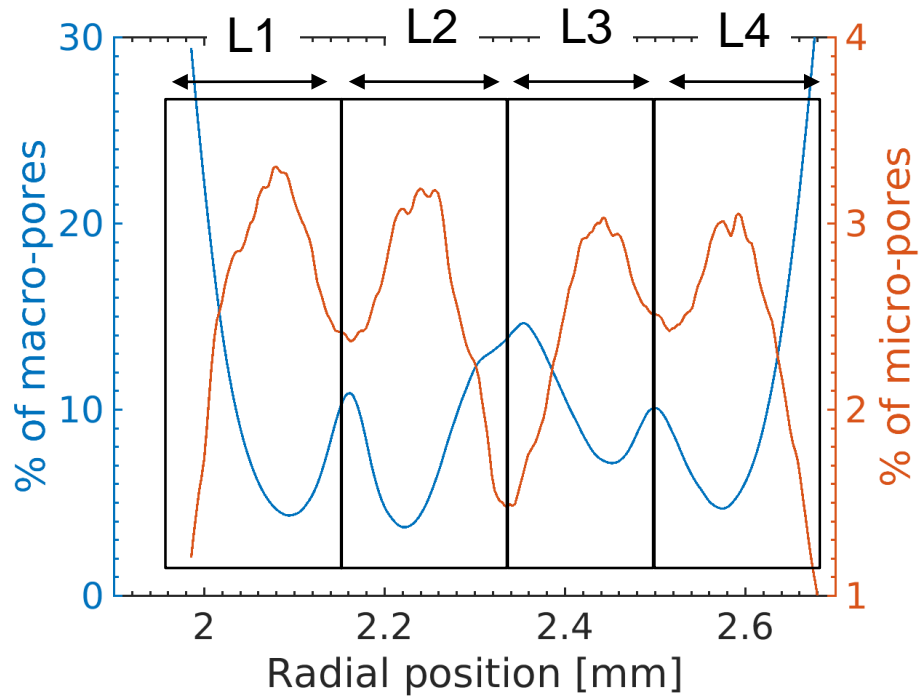


60°

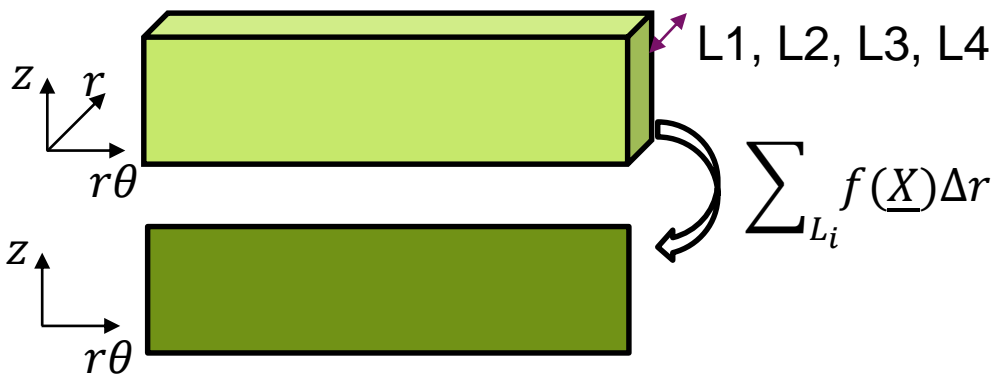
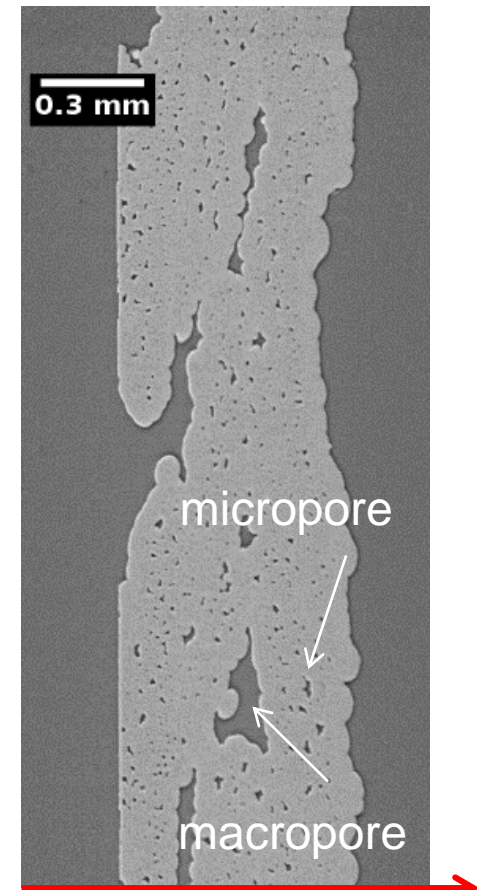
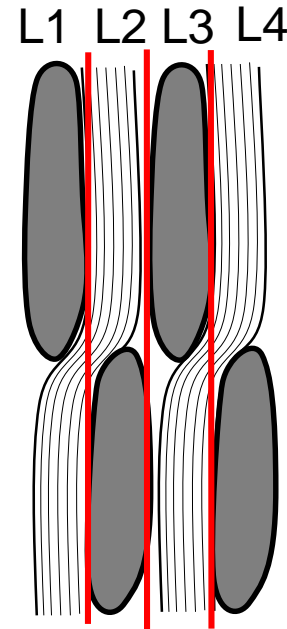
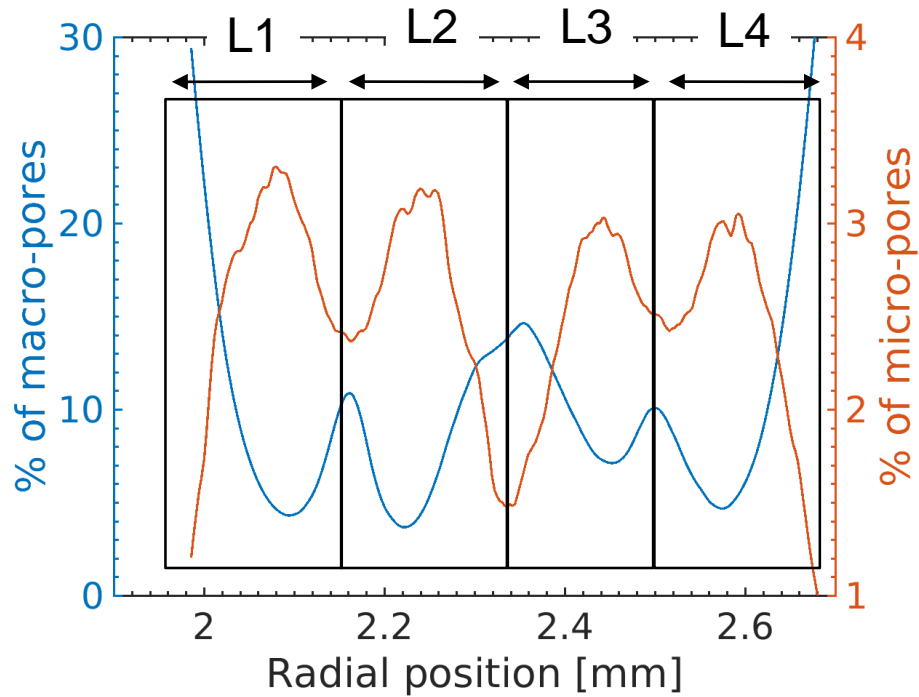


- Crack deviation (in-plane cracks):
 - Lots of initiation
 - Limited propagation
- The circ. cracks have more undulations (follow the braid undulation ?)

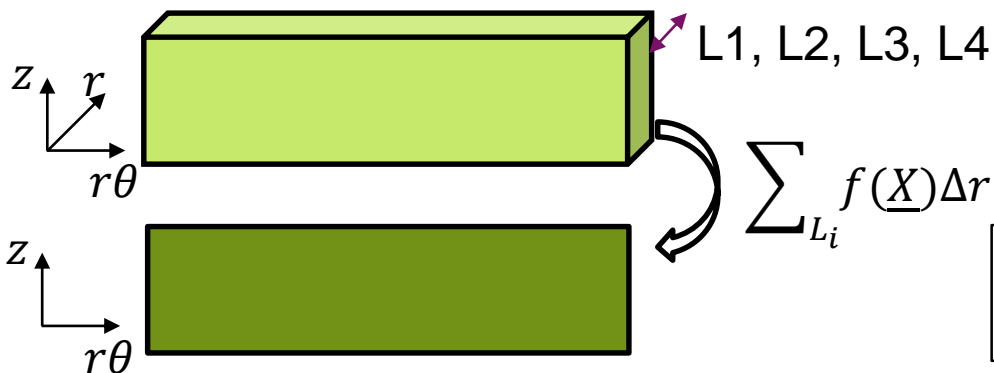
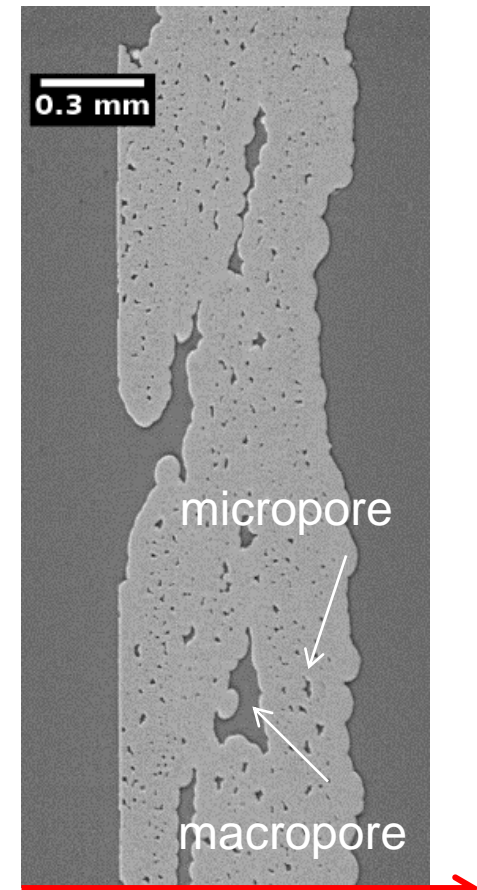
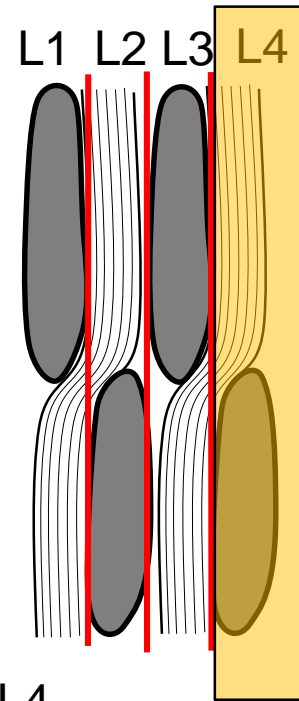
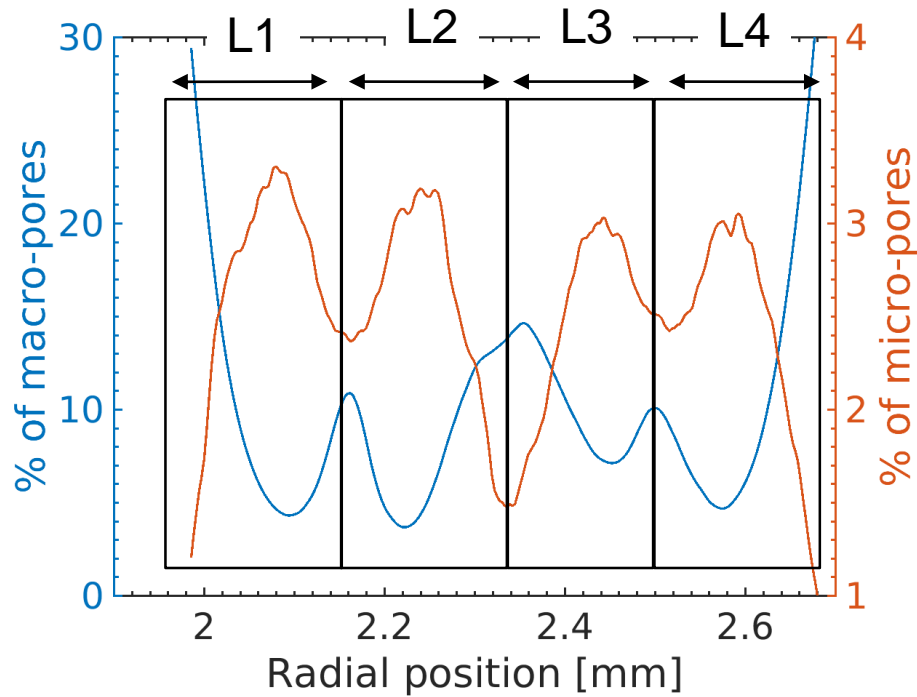
PROJECTION ALONG RADIAL DIRECTION



PROJECTION ALONG RADIAL DIRECTION



PROJECTION ALONG RADIAL DIRECTION

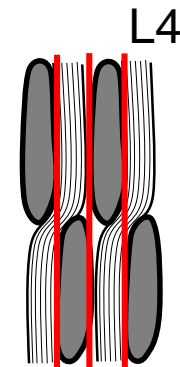
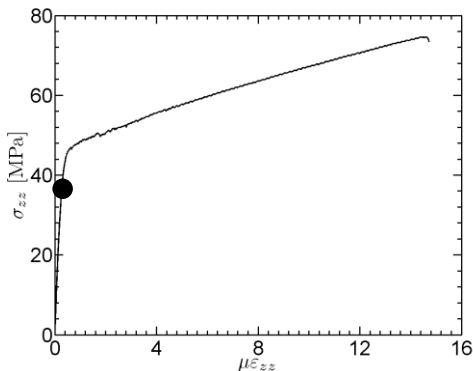
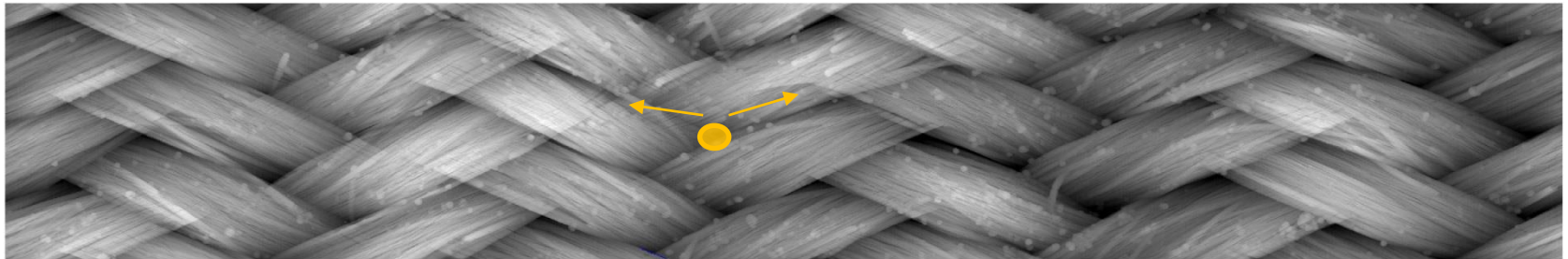
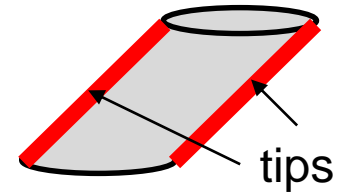


Effects on:
- circumferential cracks

CRACK AND BRAID 60°

Cracking within the 60° braided tube:

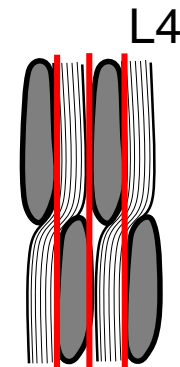
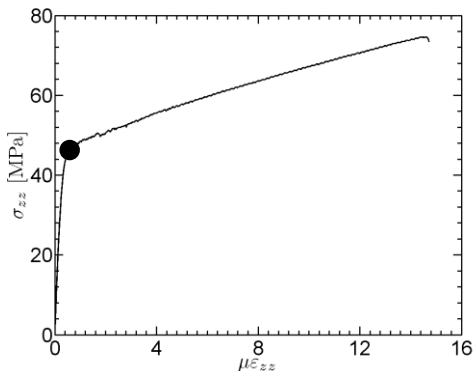
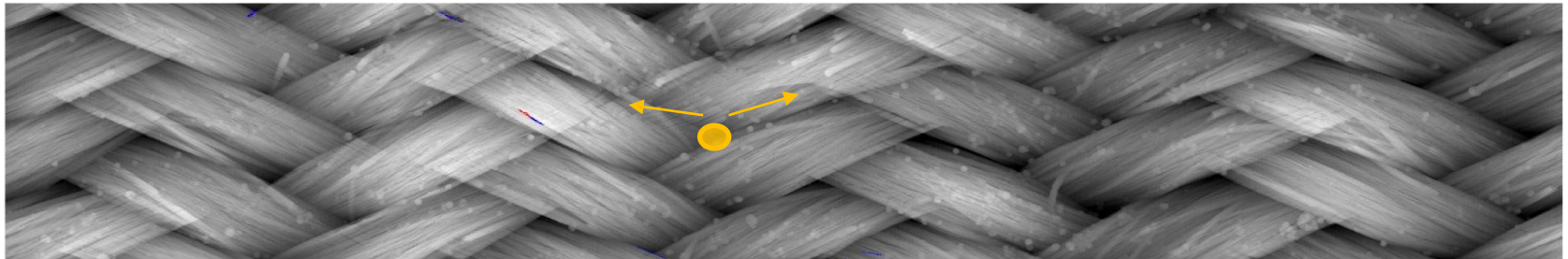
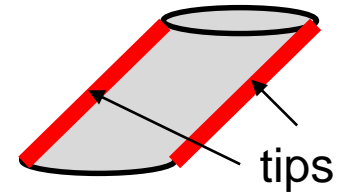
- Circumferential cracks:
 - Initiation at the “tips” of tows (?)
 - Orientation strongly influenced by fiber direction (inter-tow propagation)



CRACK AND BRAID 60°

Cracking within the 60° braided tube:

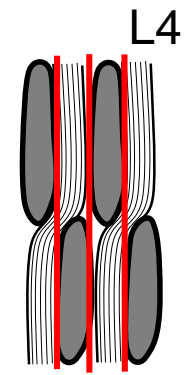
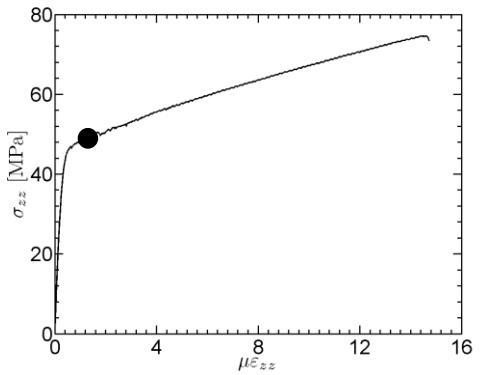
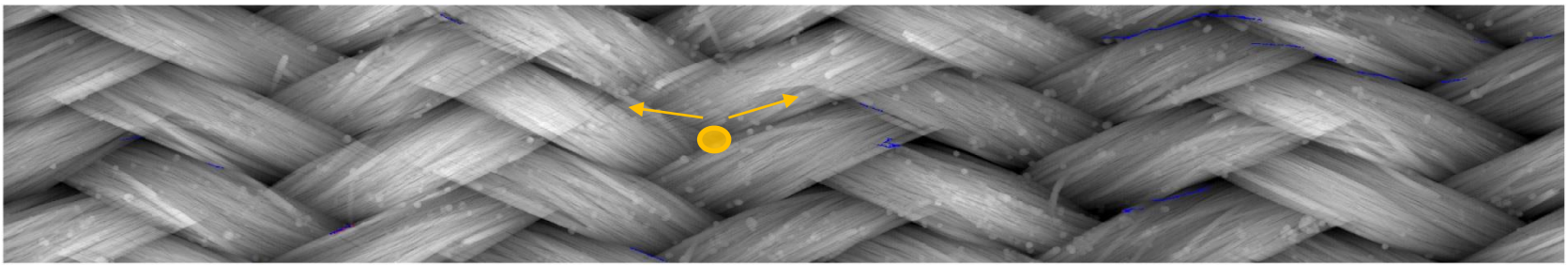
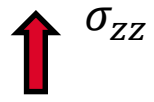
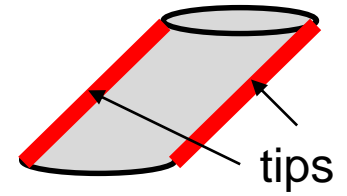
- Circumferential cracks:
 - Initiation at the “tips” of tows (?)
 - Orientation strongly influenced by fiber direction (inter-tow propagation)



CRACK AND BRAID 60°

Cracking within the 60° braided tube:

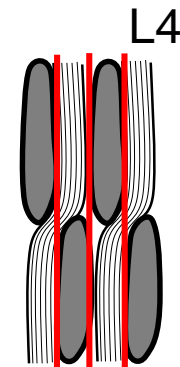
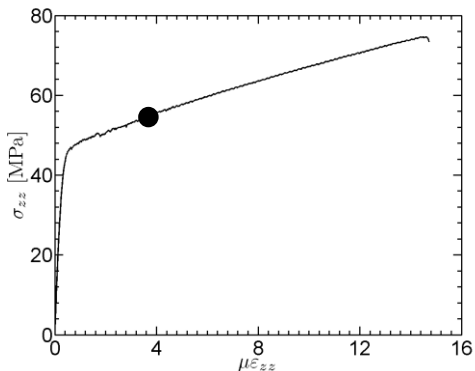
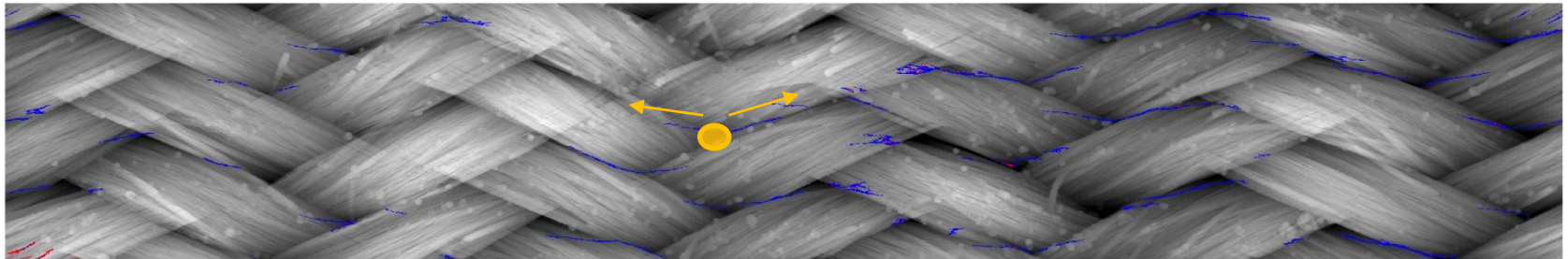
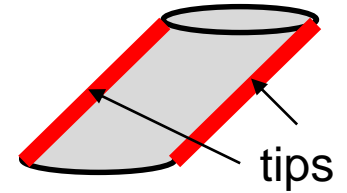
- Circumferential cracks:
 - Initiation at the “tips” of tows (?)
 - Orientation strongly influenced by fiber direction (inter-tow propagation)



CRACK AND BRAID 60°

Cracking within the 60° braided tube:

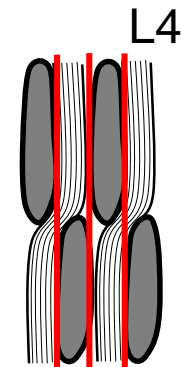
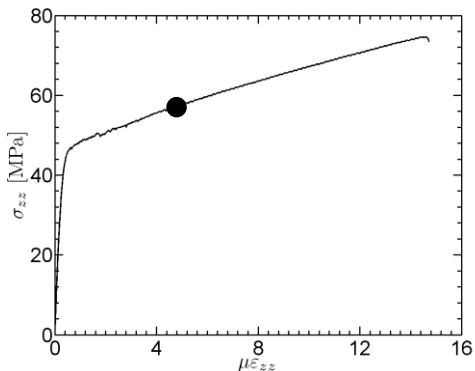
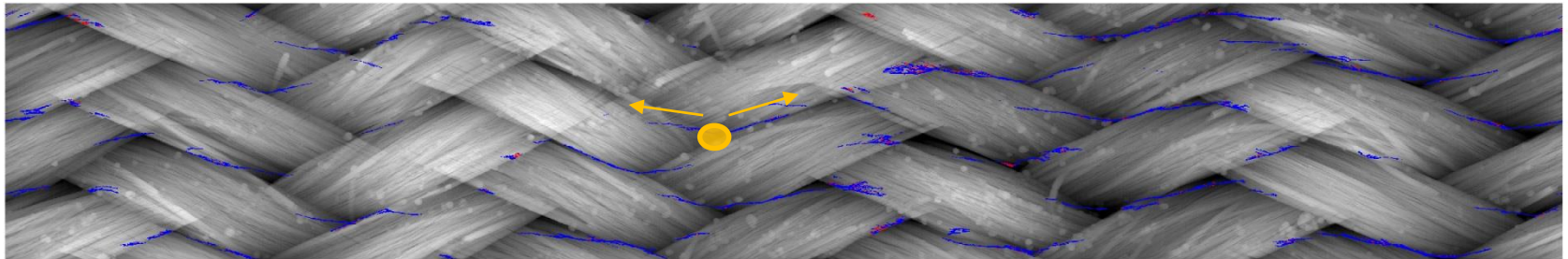
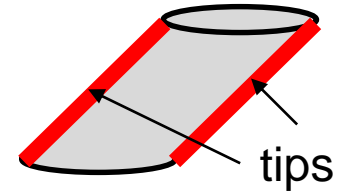
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CRACK AND BRAID 60°

Cracking within the 60° braided tube:

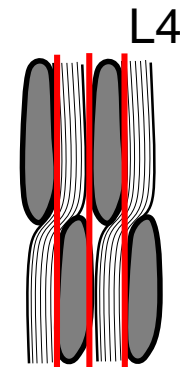
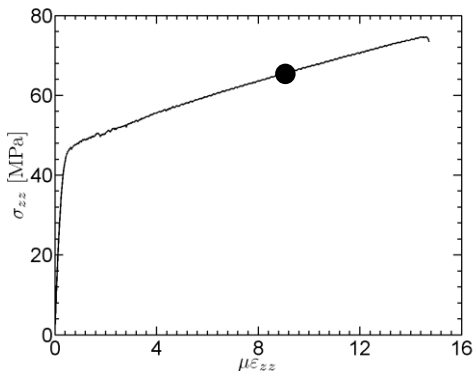
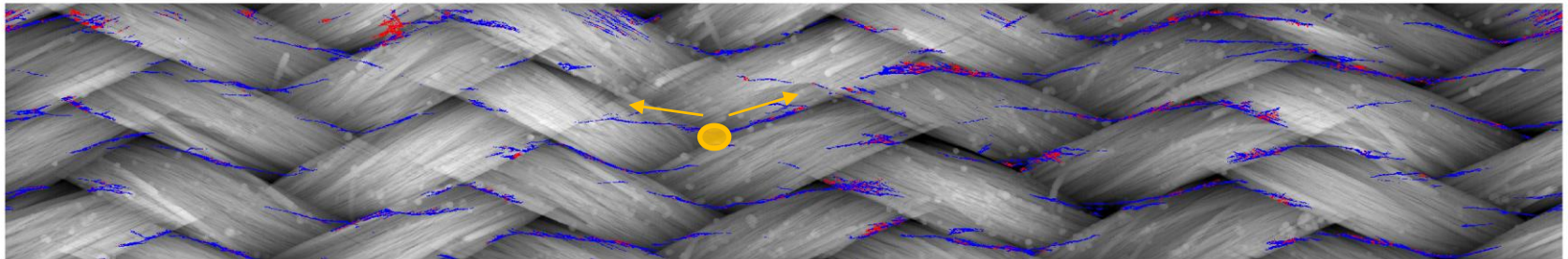
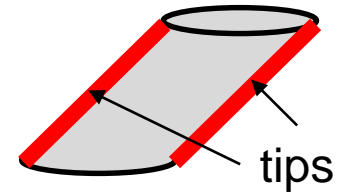
- Circumferential cracks:
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CRACK AND BRAID 60°

Cracking within the 60° braided tube:

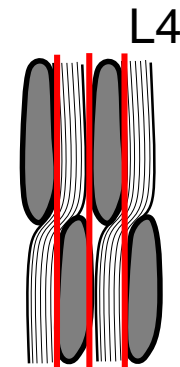
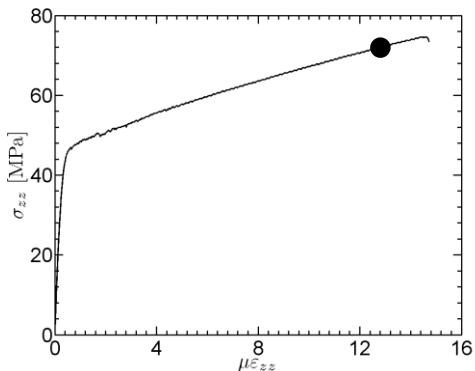
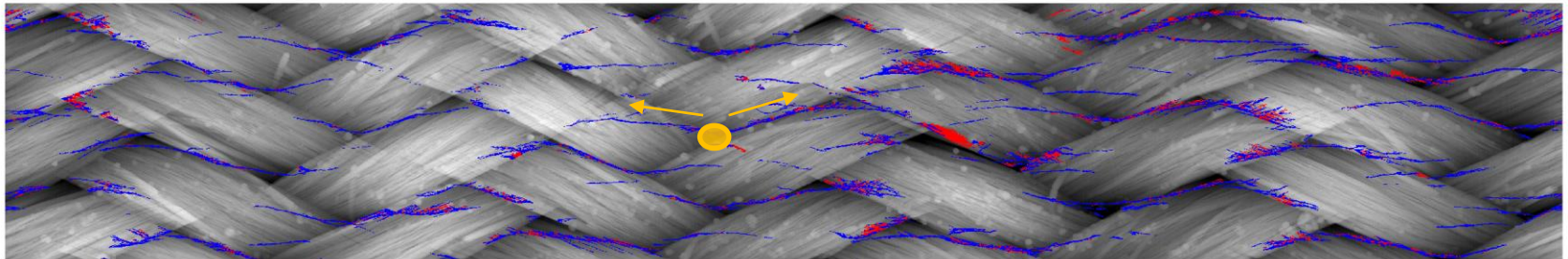
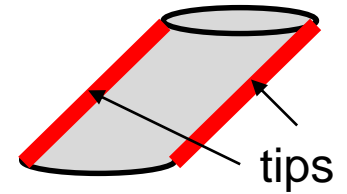
- Circumferential cracks:
 - Initiation at the “tips” of tows (?)
 - Orientation strongly influenced by fiber direction (inter-tow propagation)



CRACK AND BRAID 60°

Cracking within the 60° braided tube:

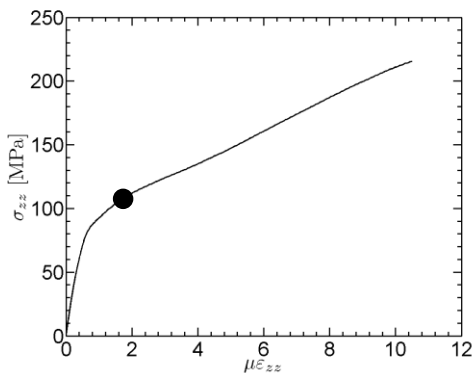
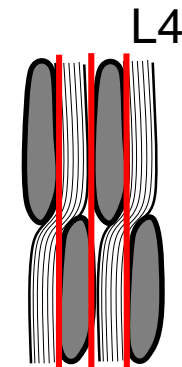
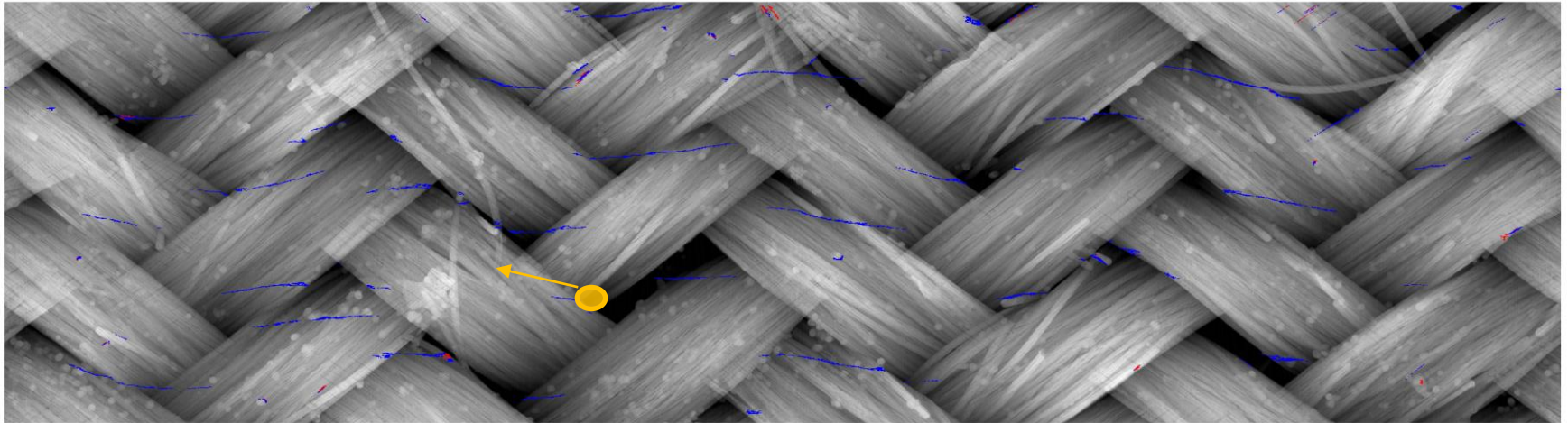
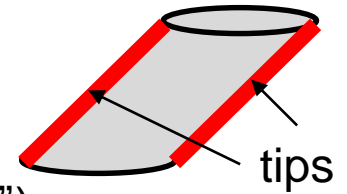
- Circumferential cracks:
 - Initiation at the “tips” of tows (?)
 - Orientation strongly influenced by fiber direction (inter-tow propagation)



CRACK AND BRAID 45°

Cracking within the 45° braided tube:

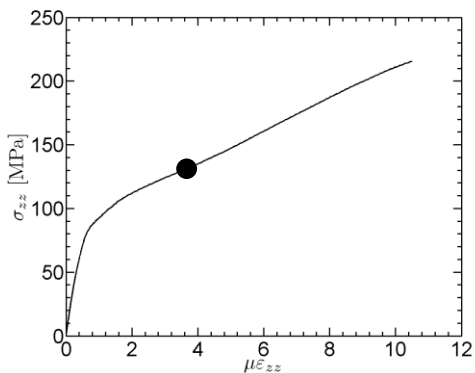
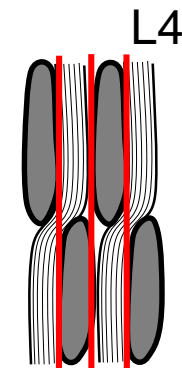
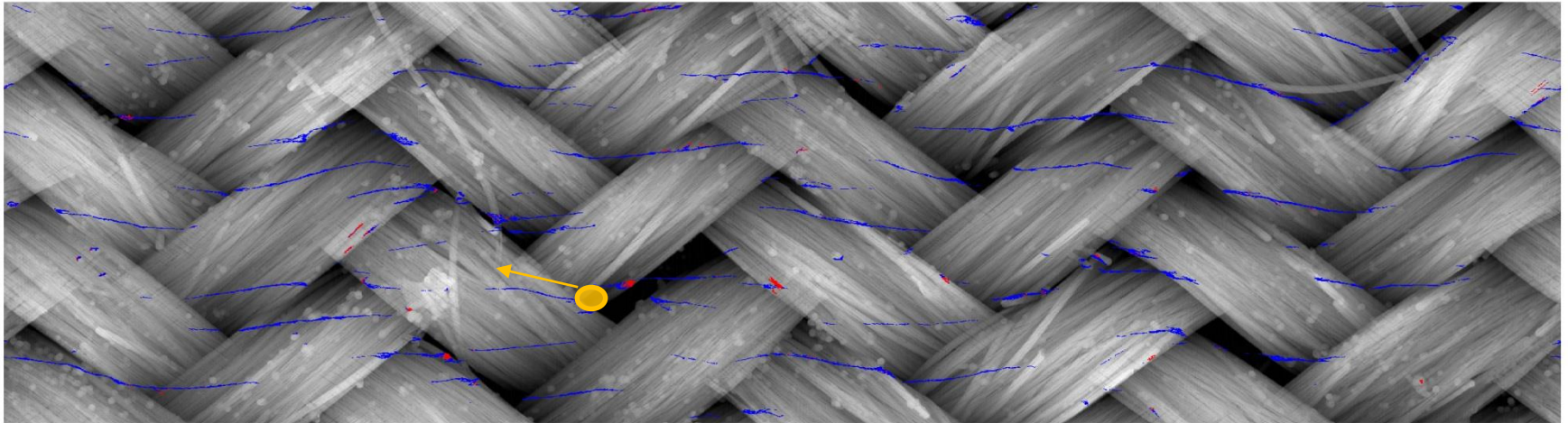
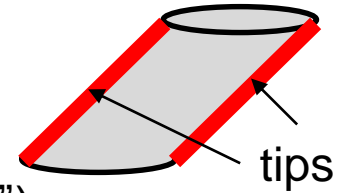
- Circumferential cracks:
 - Initiation at the “tips” of tows (?)
 - Orientation slightly influenced by fiber direction (near the “tips”)



CRACK AND BRAID 45°

Cracking within the 45° braided tube:

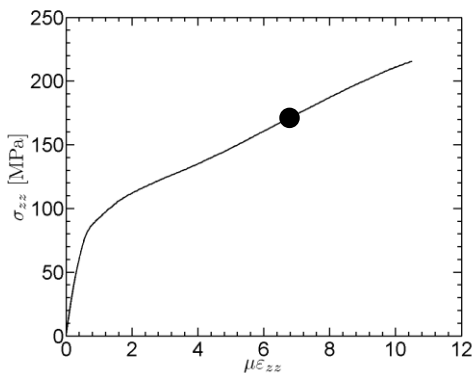
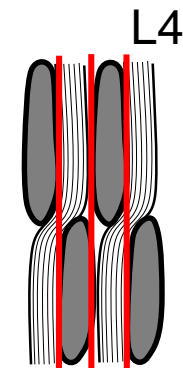
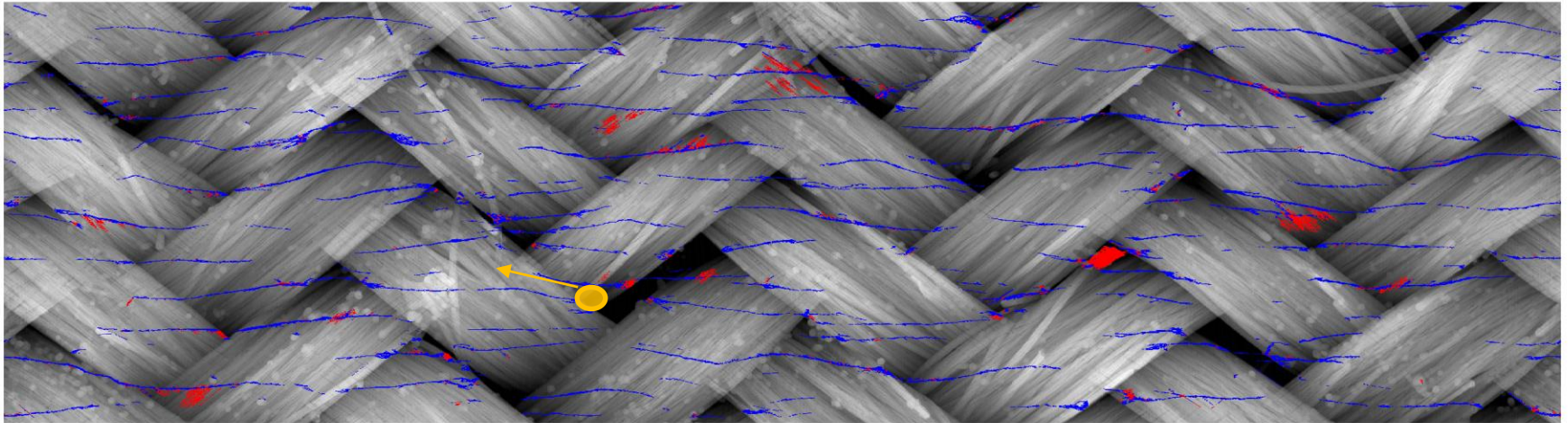
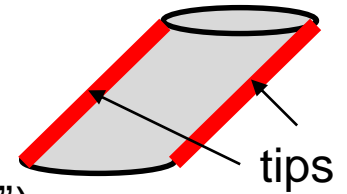
- Circumferential cracks:
 - Initiation at the “tips” of tows (?)
 - Orientation slightly influenced by fiber direction (near the “tips”)



CRACK AND BRAID 45°

Cracking within the 45° braided tube:

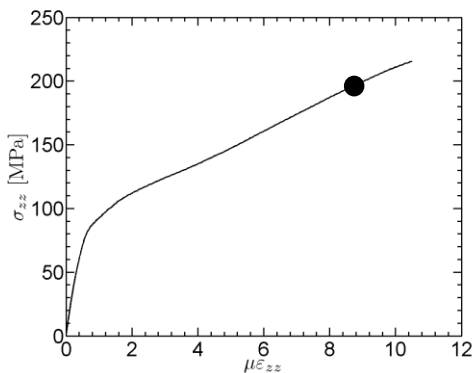
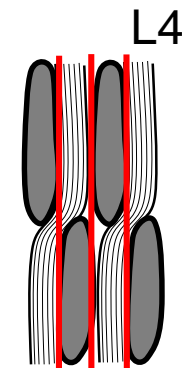
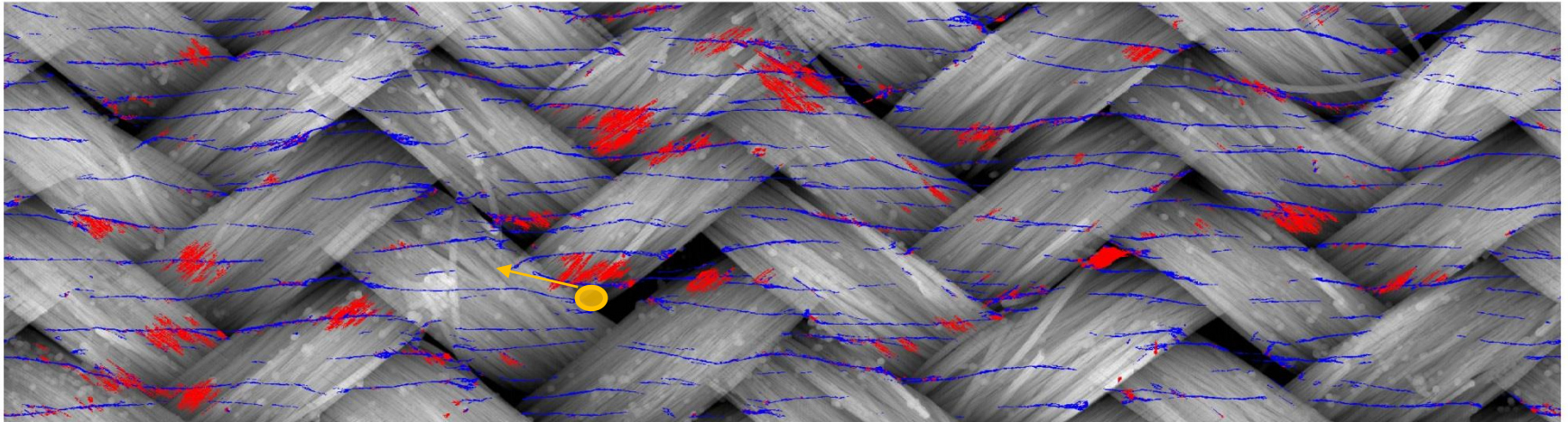
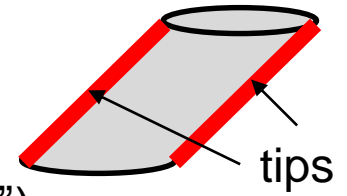
- Circumferential cracks:
 - Initiation at the “tips” of tows (?)
 - Orientation slightly influenced by fiber direction (near the “tips”)



CRACK AND BRAID 45°

Cracking within the 45° braided tube:

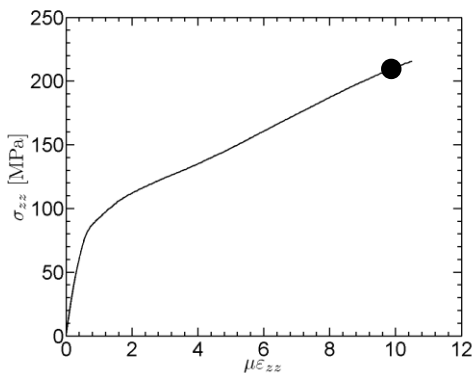
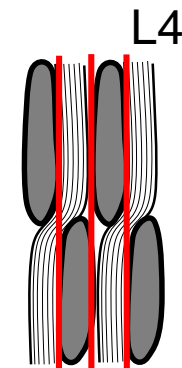
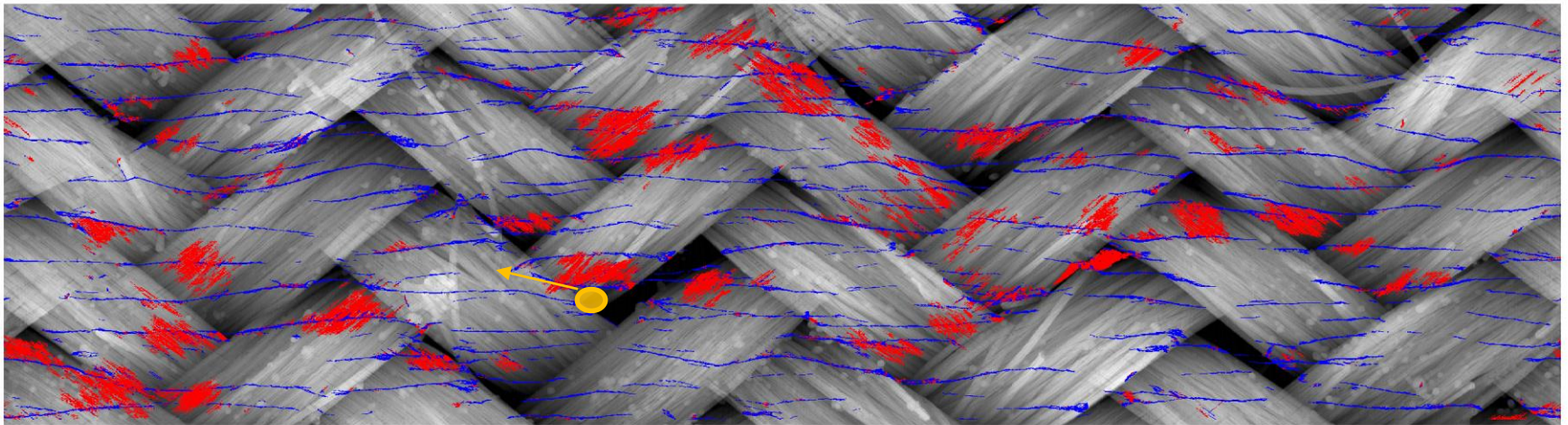
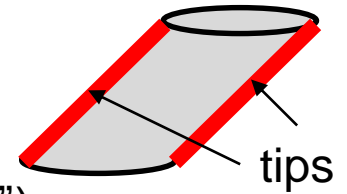
- Circumferential cracks:
 - Initiation at the “tips” of tows (?)
 - Orientation slightly influenced by fiber direction (near the “tips”)



CRACK AND BRAID 45°

Cracking within the 45° braided tube:

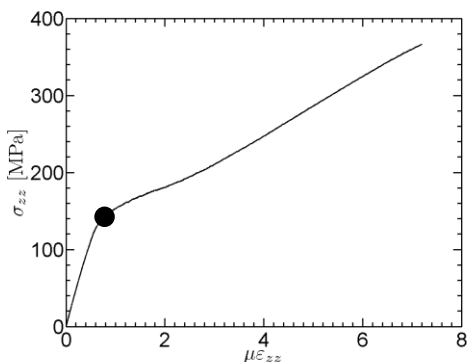
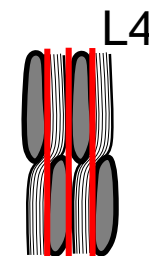
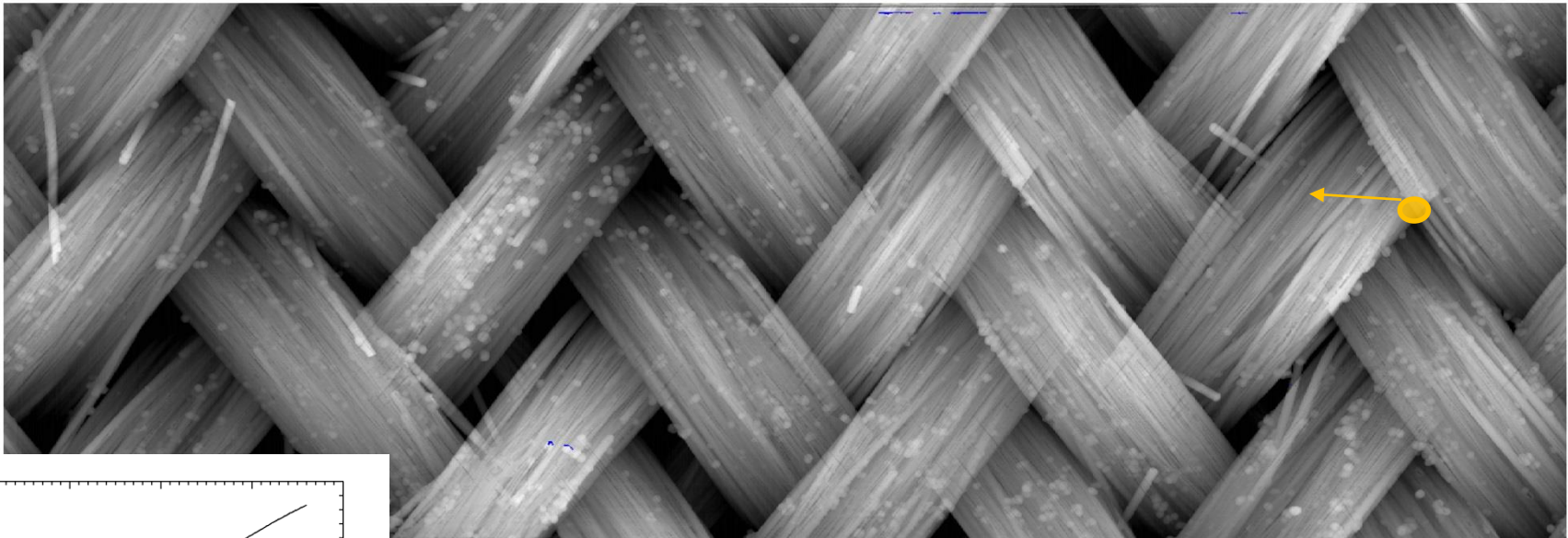
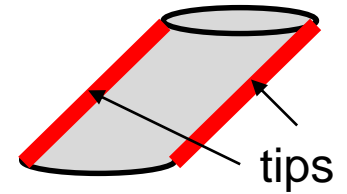
- Circumferential cracks:
 - Initiation at the “tips” of tows (?)
 - Orientation slightly influenced by fiber direction (near the “tips”)



CRACK AND BRAID 30°

Cracking within the 30° braided tube:

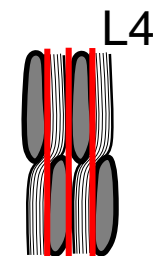
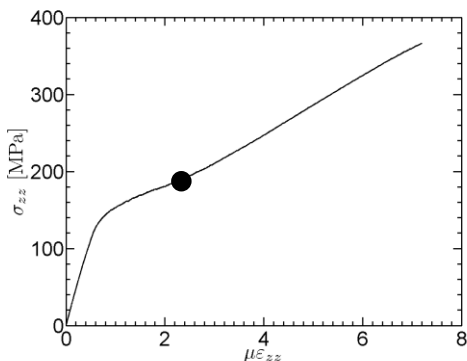
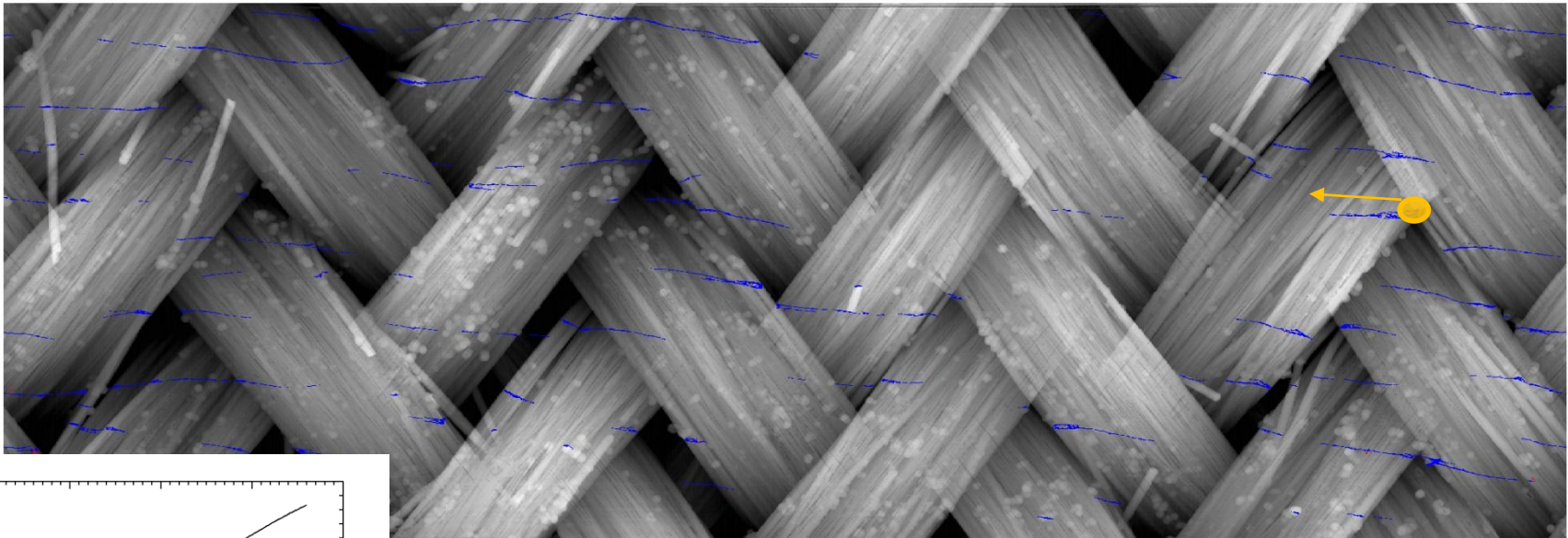
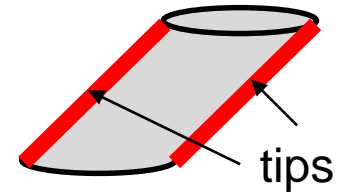
- Circumferential cracks :
 - Initiation at the “tips” of tows (?)
 - Orientation not influenced by fiber direction



CRACK AND BRAID 30°

Cracking within the 30° braided tube:

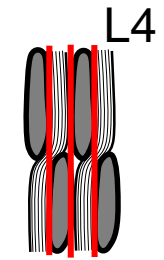
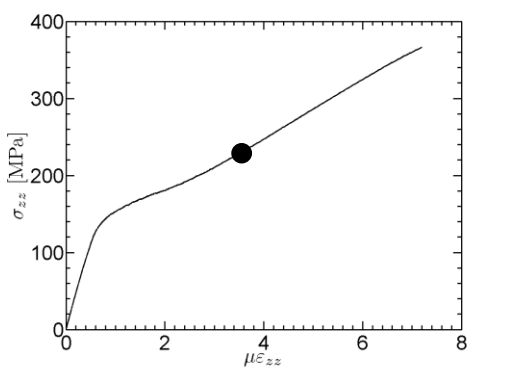
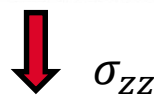
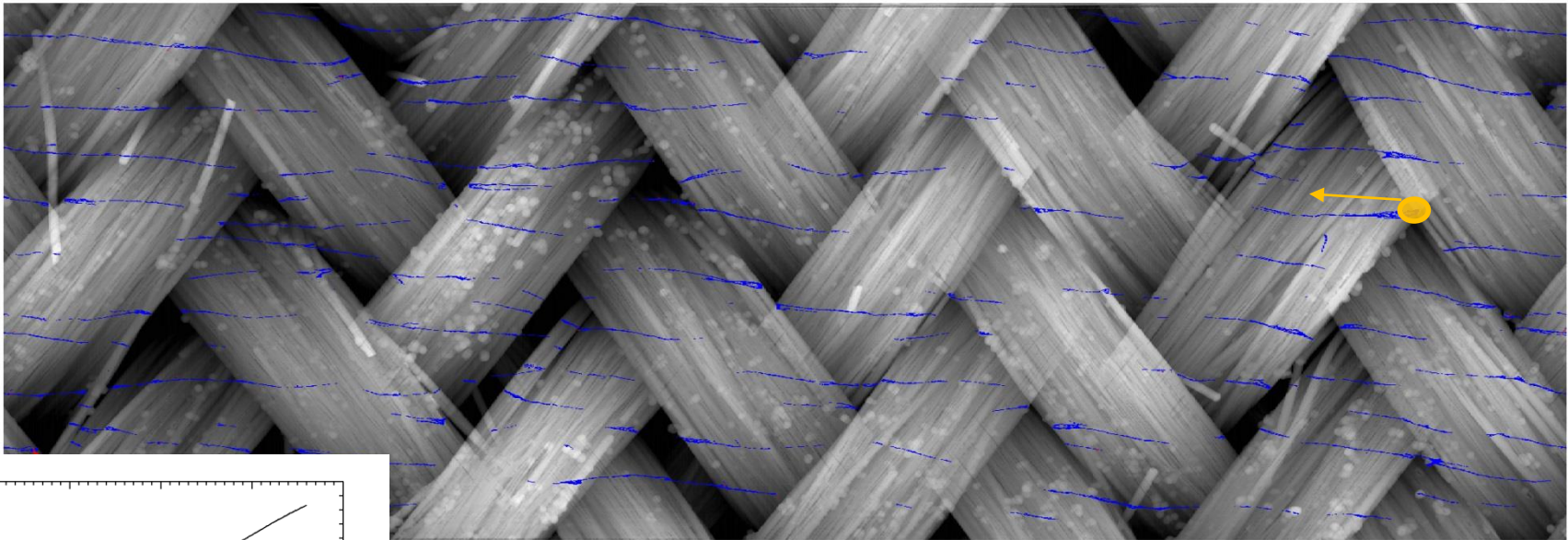
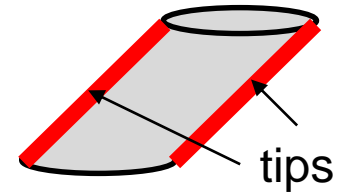
- Circumferential cracks :
 - Initiation at the “tips” of tows (?)
 - Orientation not influenced by fiber direction



CRACK AND BRAID 30°

Cracking within the 30° braided tube:

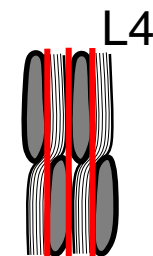
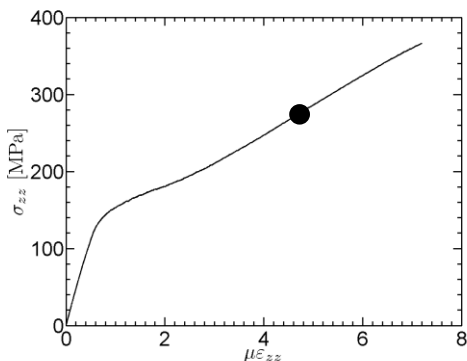
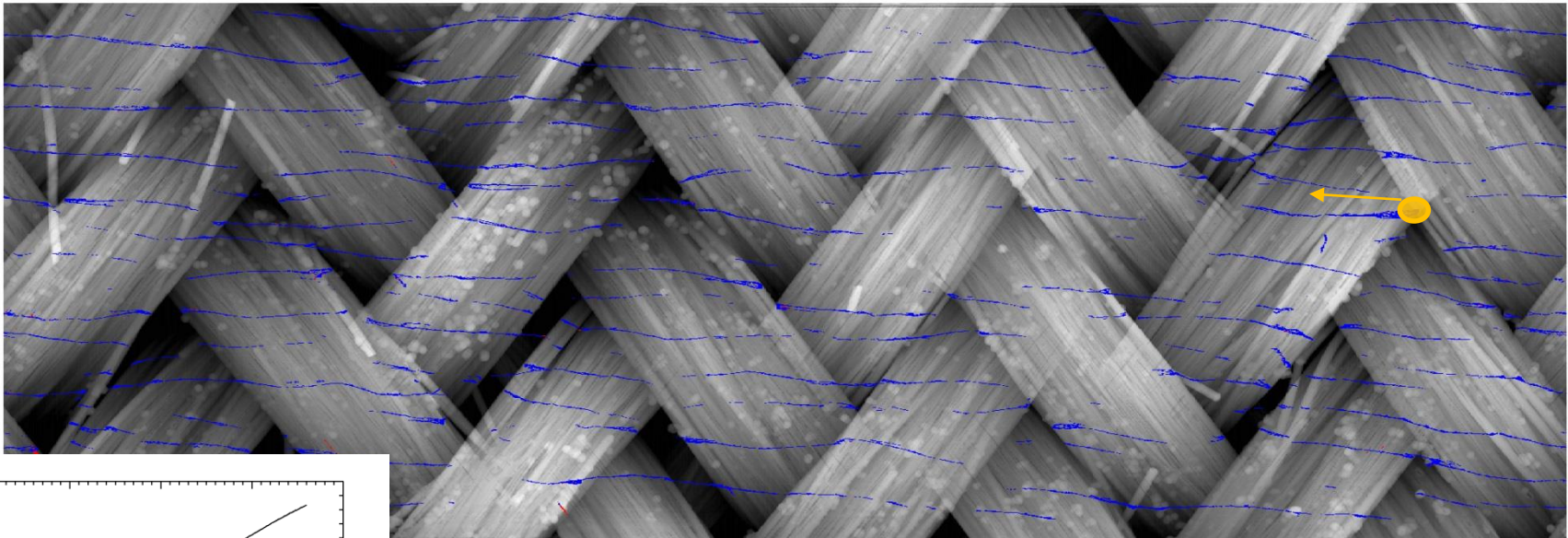
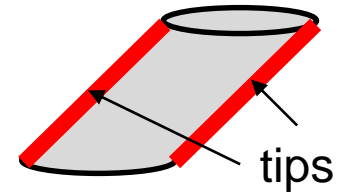
- Circumferential cracks :
 - Initiation at the “tips” of tows (?)
 - Orientation not influenced by fiber direction



CRACK AND BRAID 30°

Cracking within the 30° braided tube:

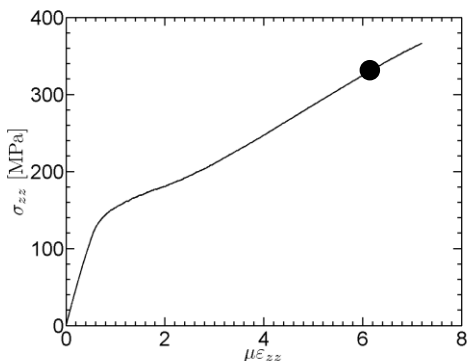
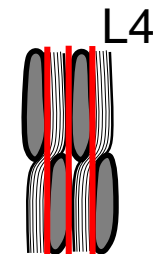
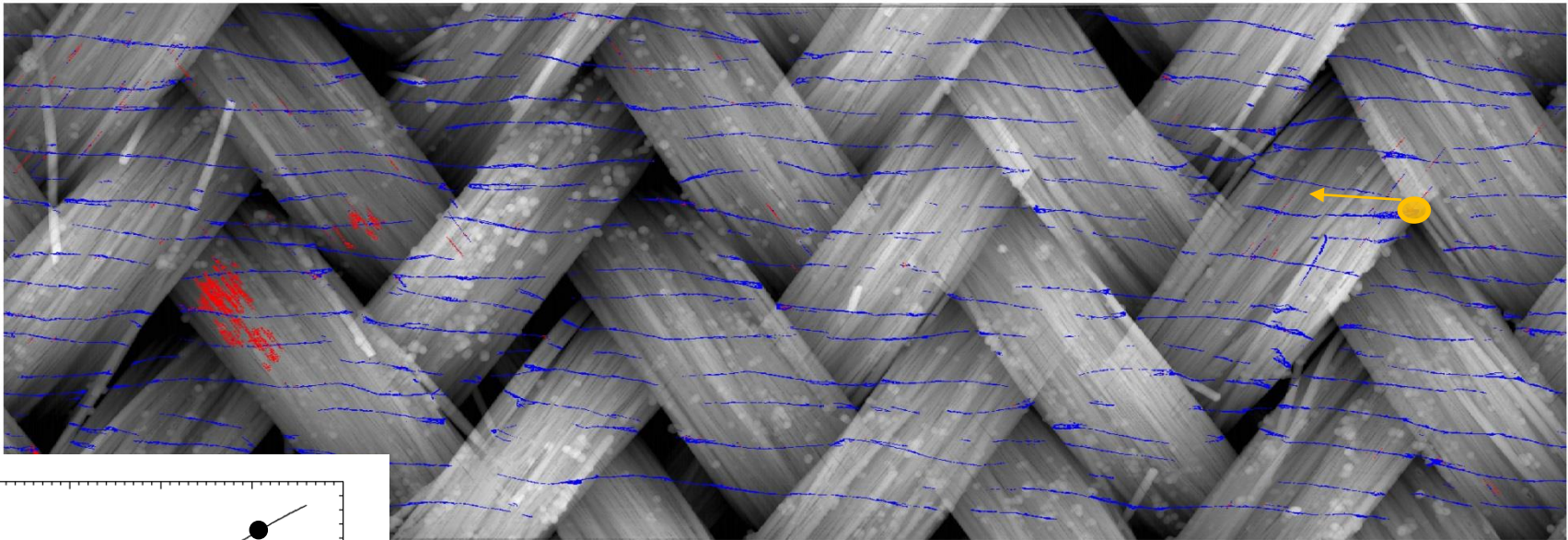
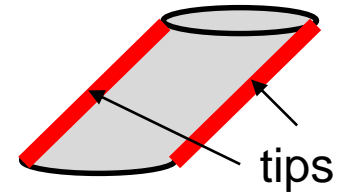
- Circumferential cracks :
 - Initiation at the “tips” of tows (?)
 - Orientation not influenced by fiber direction



CRACK AND BRAID 30°

Cracking within the 30° braided tube:

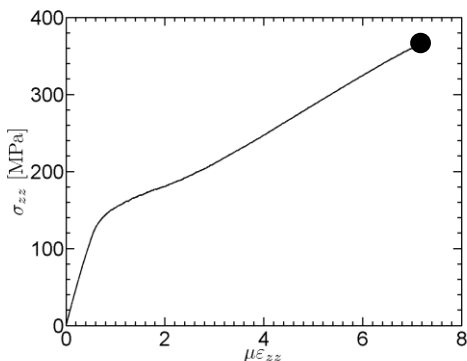
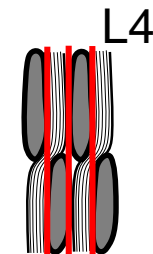
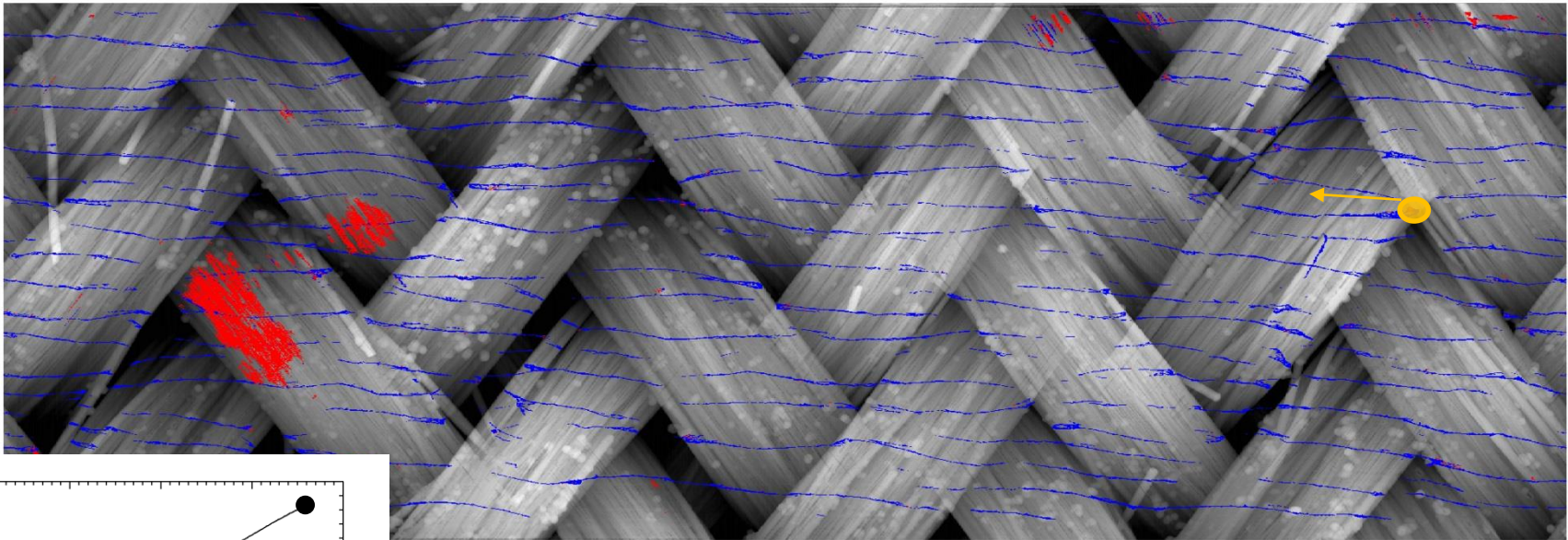
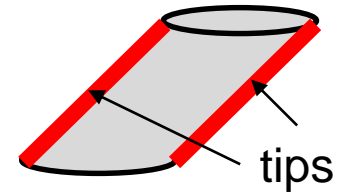
- Circumferential cracks :
 - Initiation at the “tips” of tows (?)
 - Orientation not influenced by fiber direction



CRACK AND BRAID 30°

Cracking within the 30° braided tube:

- Circumferential cracks :
 - Initiation at the “tips” of tows (?)
 - Orientation not influenced by fiber direction



Common points:

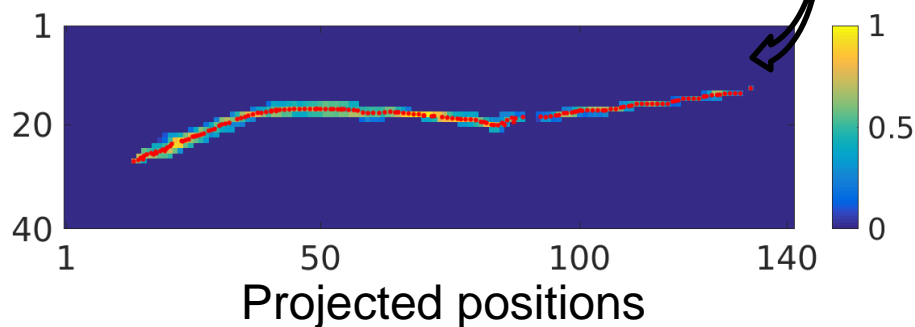
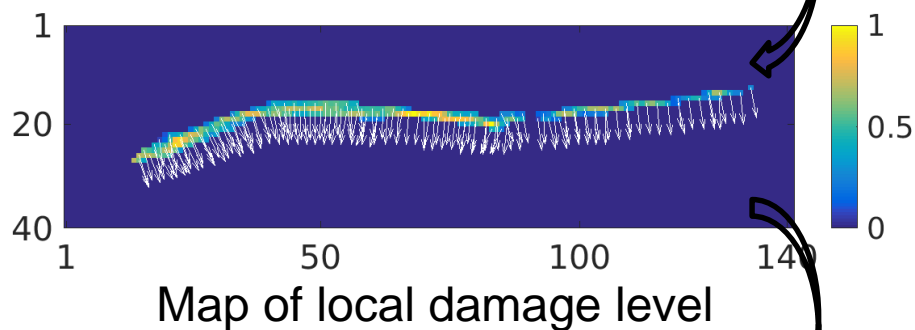
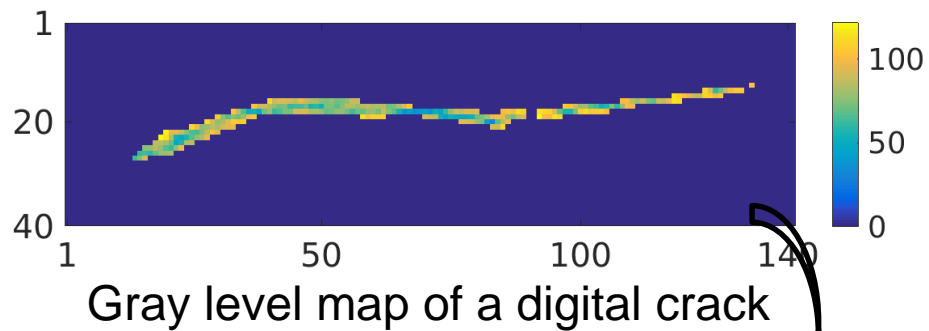
- Circumferential cracks initiate at the “tips” of tows (?)
- Circumferential cracks deviate to become in-plane cracks
- Propagation of in-plane cracks is guided by fiber direction

Uncommon points (braid angle effects):

- Circumferential cracks :
 - θ increases → crack orientation is more and more influenced by fiber direction
 - $\theta > \theta_c$ (60°), inter-tow propagation
- In-plane cracks :
 - θ increases → number of initiation becomes greater
 - propagation distance becomes smaller

CRACK QUANTIFICATION

- Quantitative measurement (opening, surface area) - method

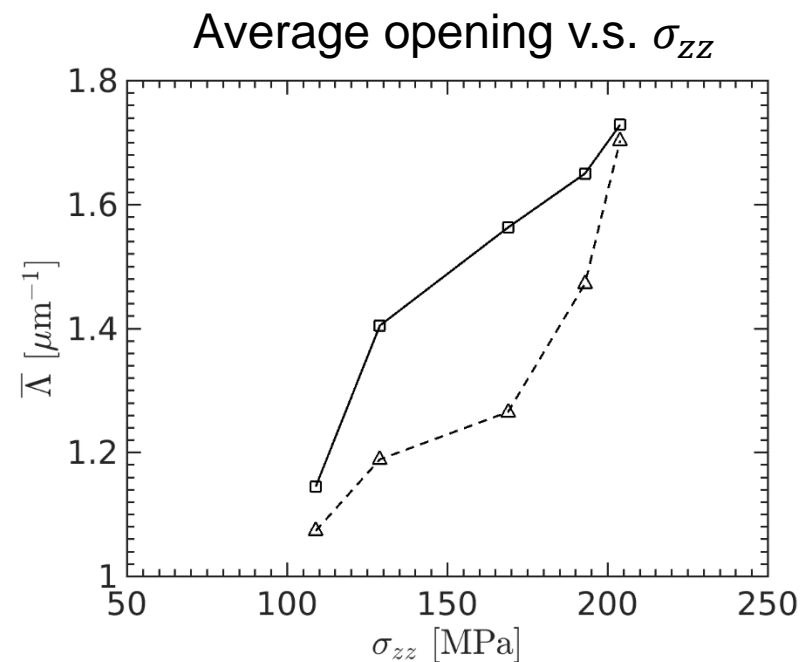
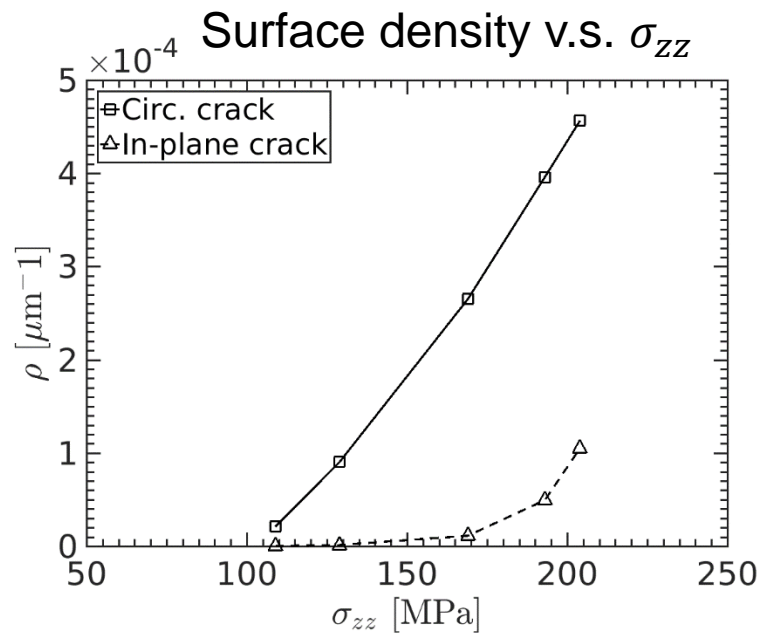


1- Evaluate a local damage level for each voxel
 ⇔ according to its gray level (in the subtracted image)

2- Project the voxelized damage information onto the median surface
 ⇔ by local orientation

- Average opening $\bar{\Lambda}$
- Surface area S
- surface density $\rho = S/V$

- Quantitative measurement (opening, surface area) - result



- Circ. \neq In-plane
- No saturation until fracture

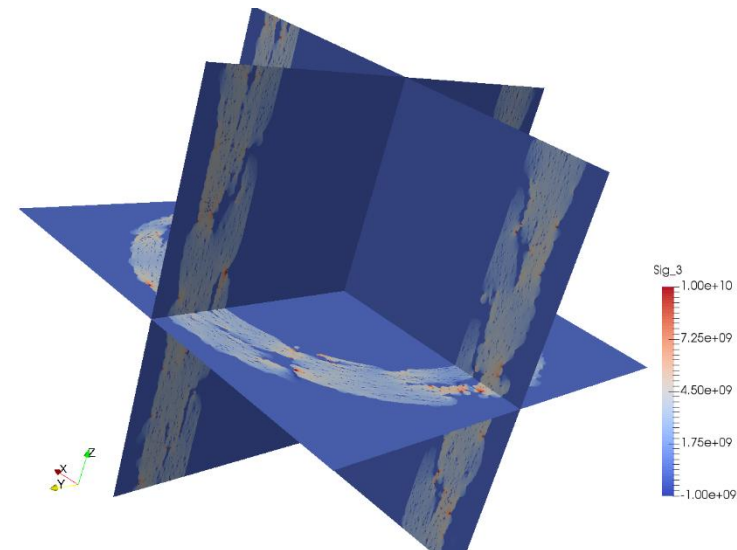
- Effects of braid angle on damage mechanisms:
 - circumferential cracks (initiation & orientation)
 - In-plane cracks (initiation and propagation distance)
- Method for quantifying geometry parameters (opening, surface area) of cracks

▪ Crack quantification for 30° and 60°

▪ Numerical simulation of real microstructures



Why the in-plane cracks open under tension load ?
What is the origin of such effects ?

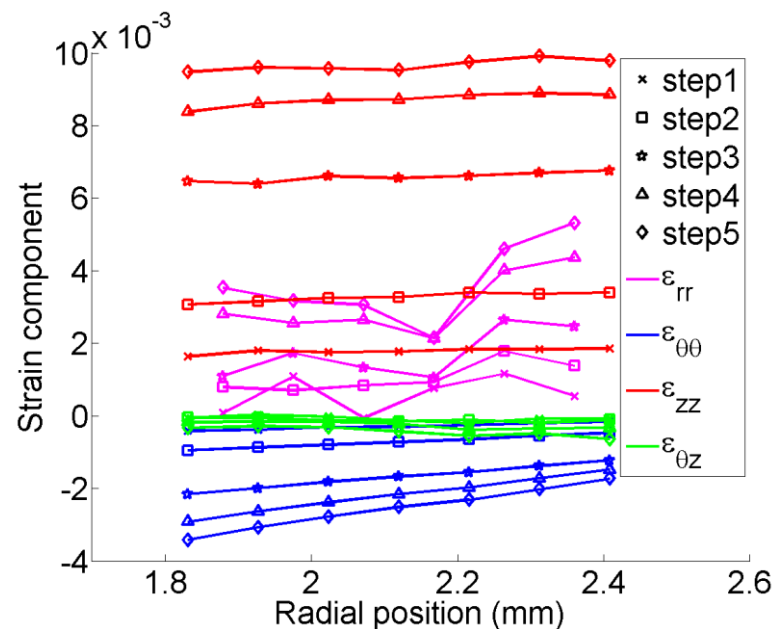
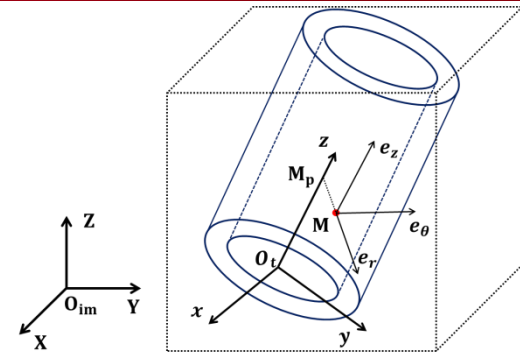


Thank you for your attention

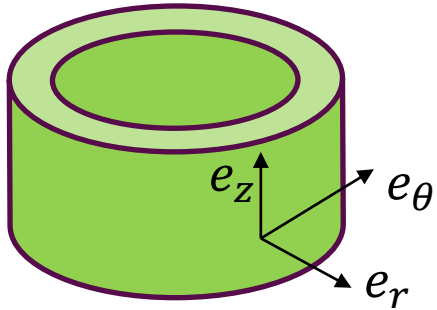
A small horizontal line, green on the left and yellow on the right, located at the bottom of the red section.

- Digital Volume Correlation (DVC)
 - Correlation grid adapted to the tube geometry
 - Correlation marker: pores

- Strain measurement
 - Average over each radial position
 - Method: kinematic optimization between a simulated displacement field and the DVC-measured one

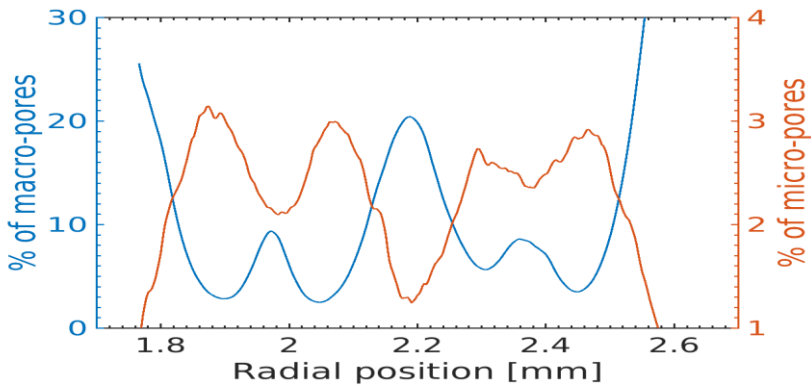
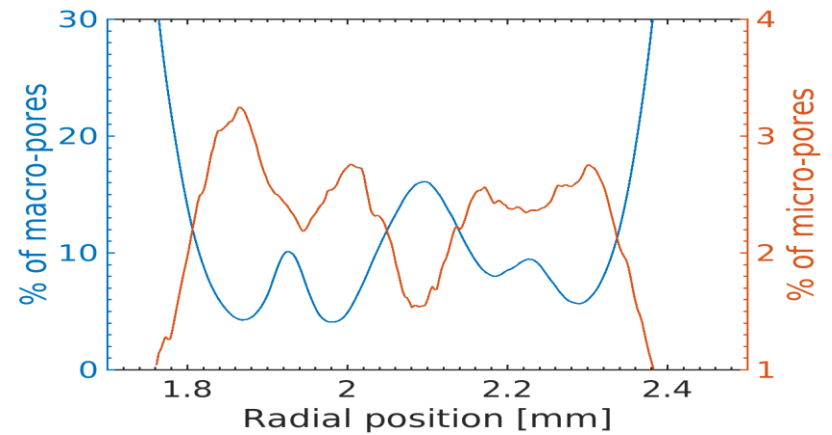
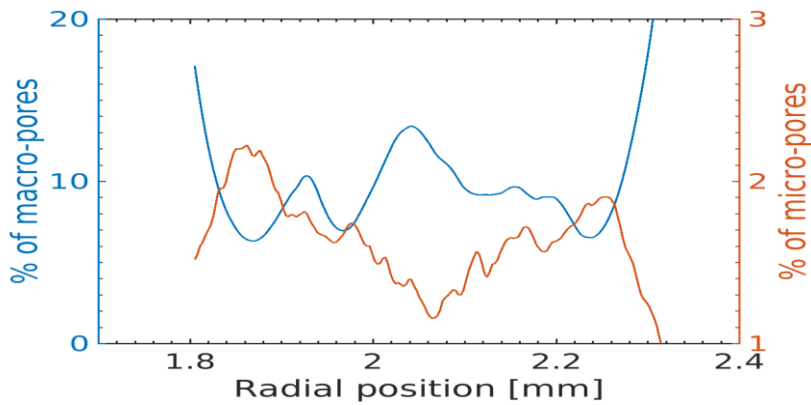


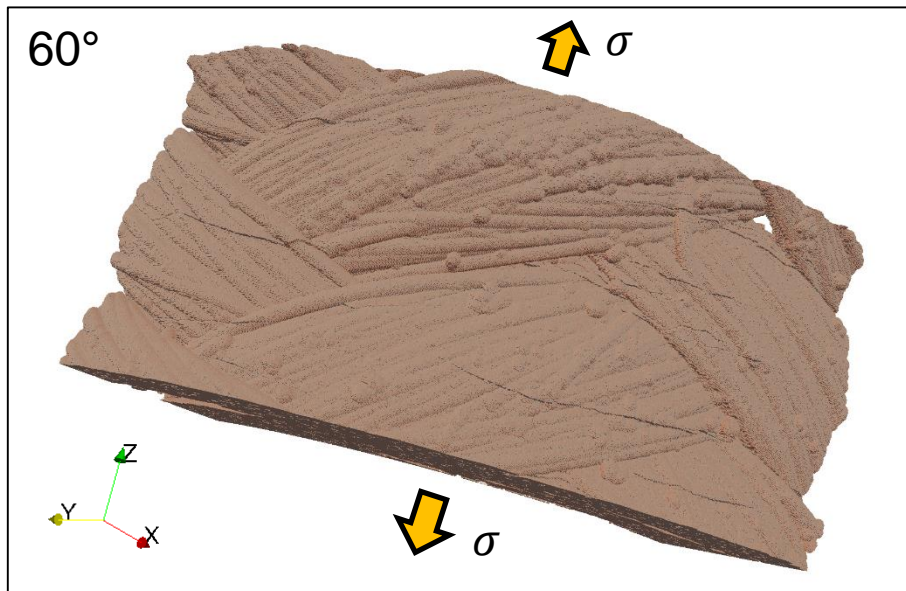
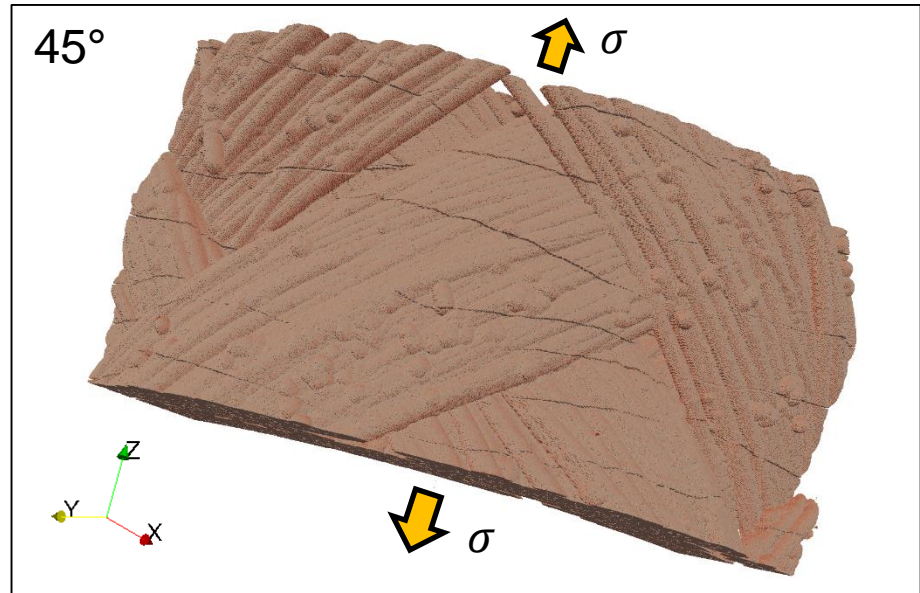
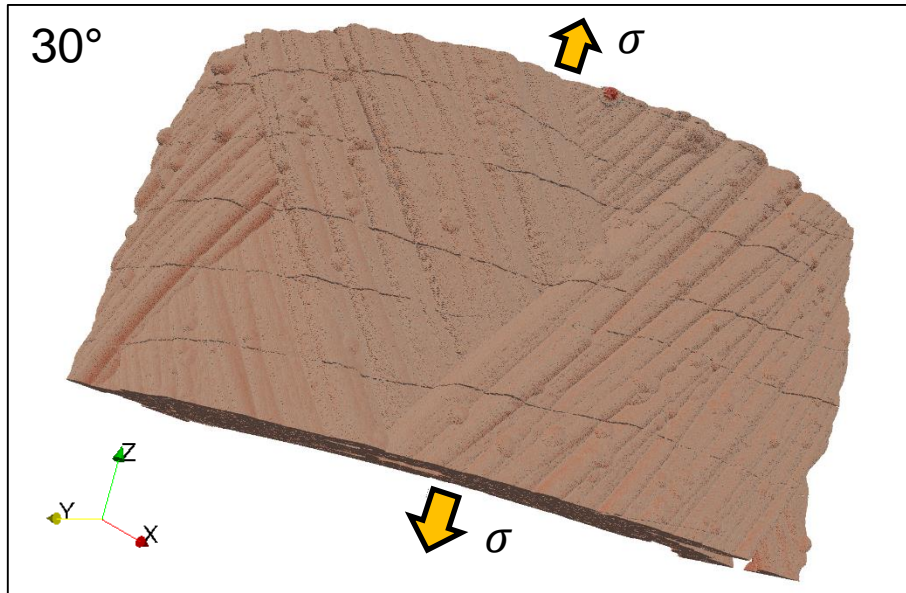
POROSITY DISTRIBUTION



Periodic in e_θ and e_z

Porosity evolution in e_r

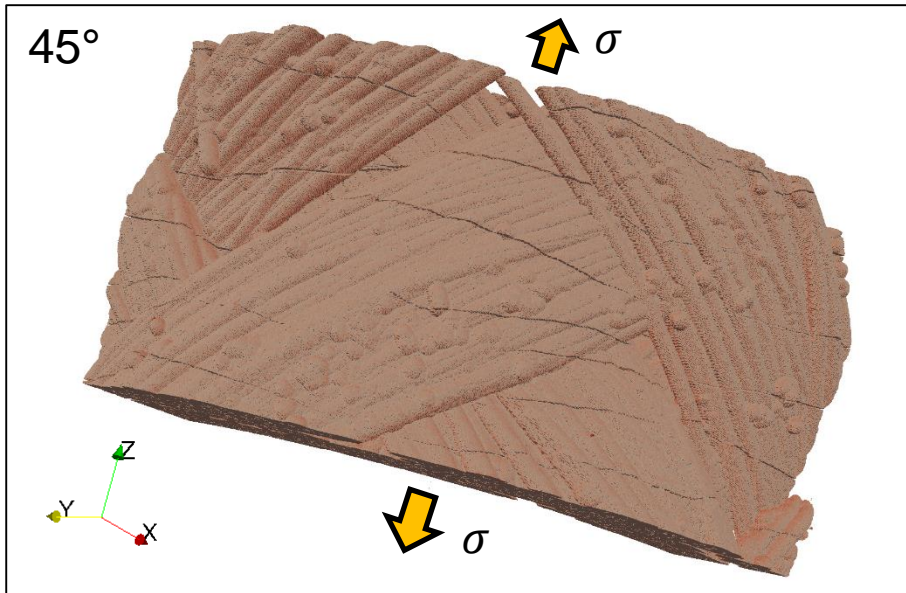




Information extracted from such images:

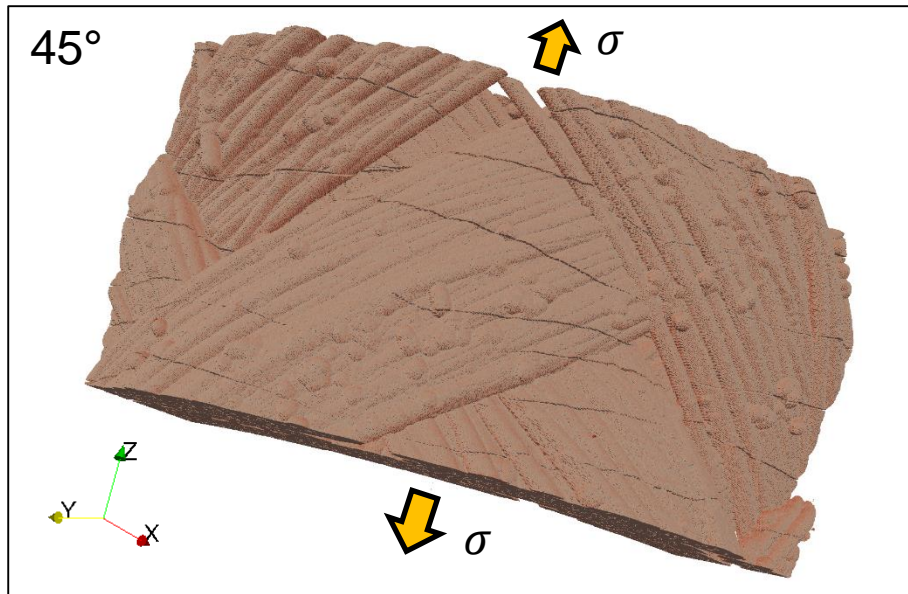
- Porosity distribution (undamaged tubes)
- Strain measurement (DVC)
- **Crack characterization**
(geometry, orientation, etc)

PROCESSING OF X-RAY TOMOGRAPHS

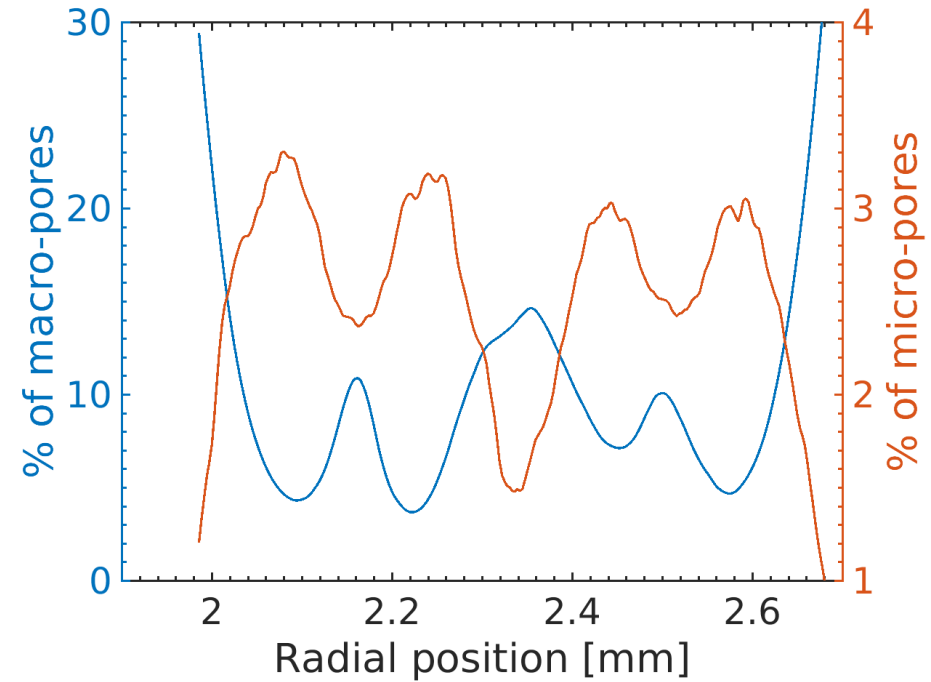


Porosity distribution (undamaged tube)

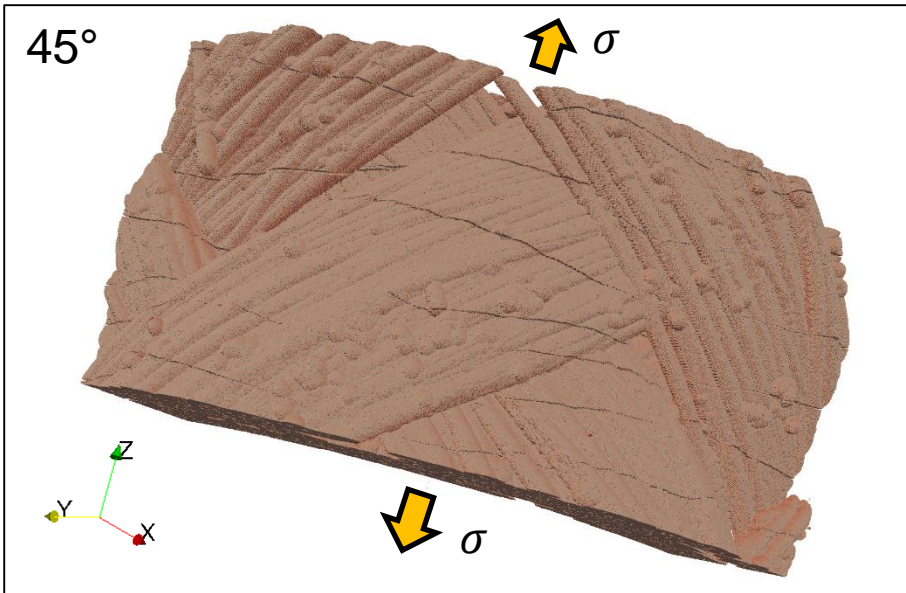
PROCESSING OF X-RAY TOMOGRAPHS



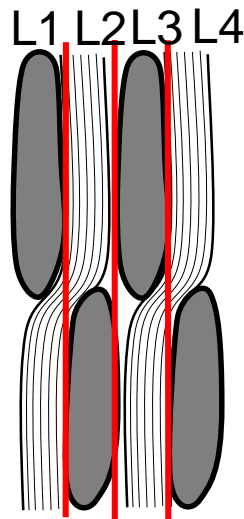
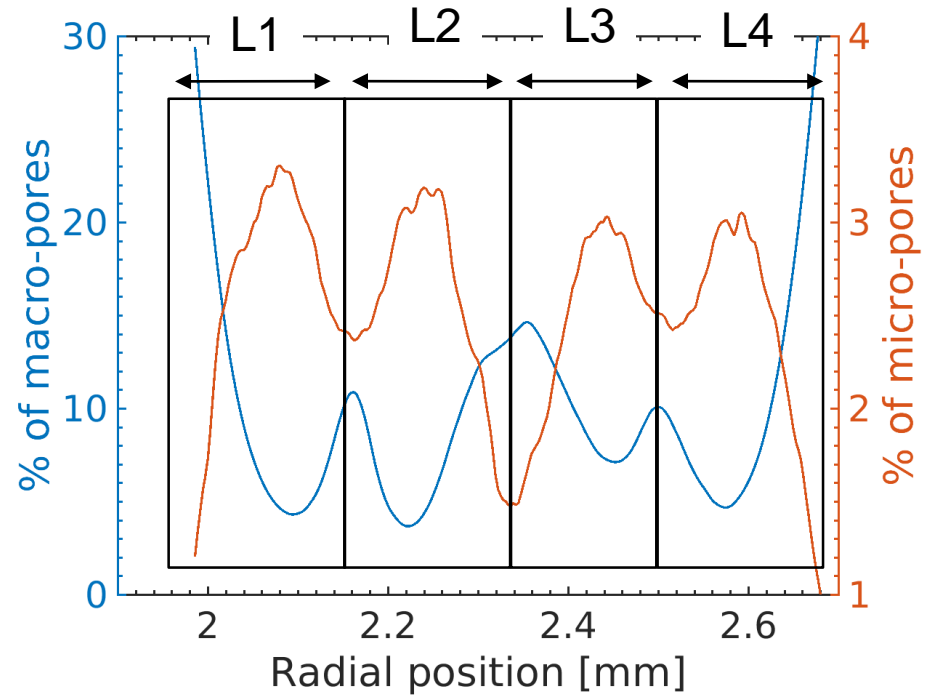
Porosity distribution (undamaged tube)



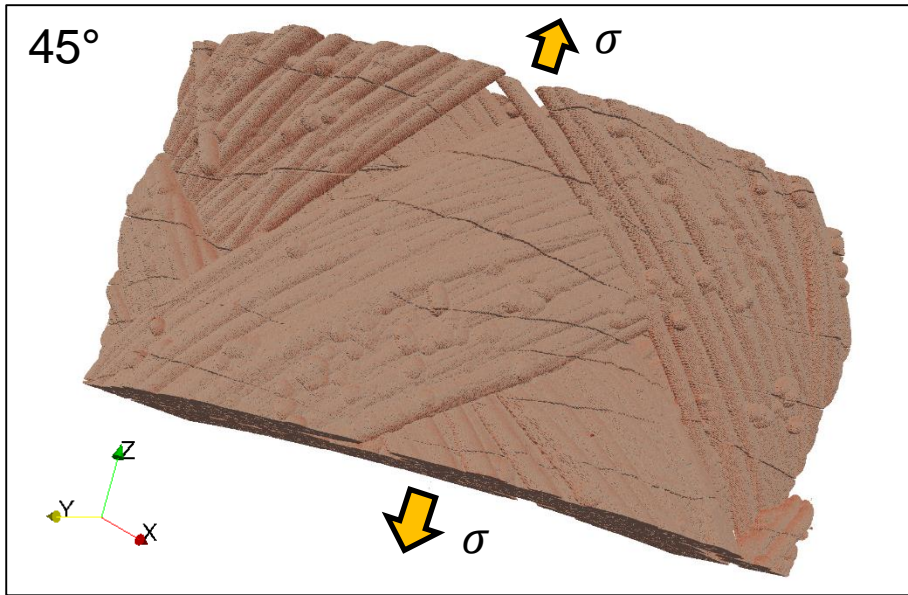
PROCESSING OF X-RAY TOMOGRAPHS



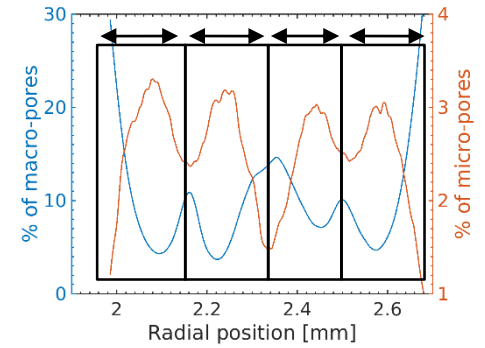
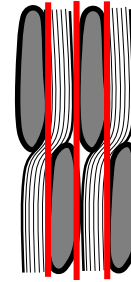
Porosity distribution (undamaged tube)



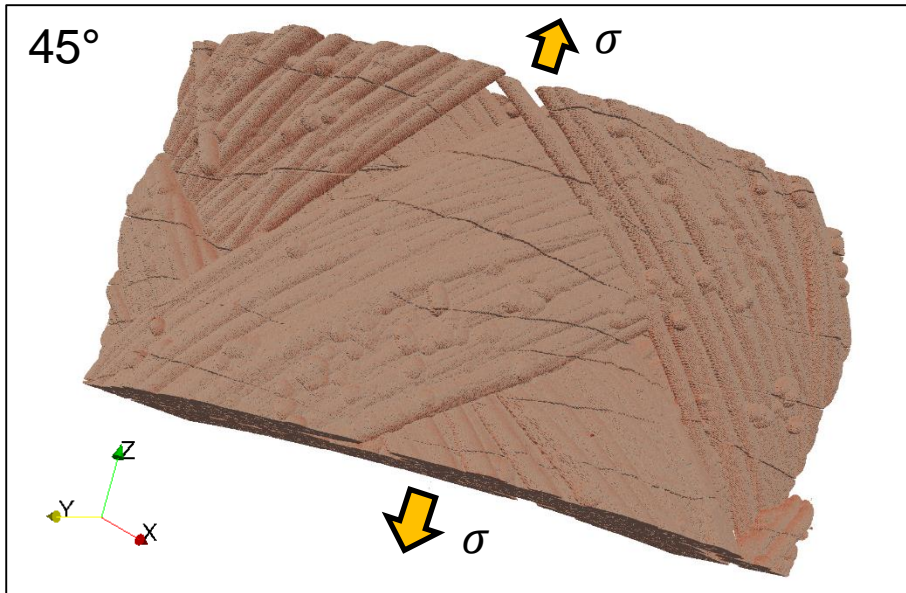
PROCESSING OF X-RAY TOMOGRAPHS



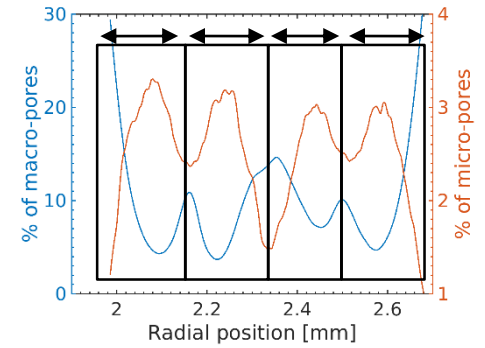
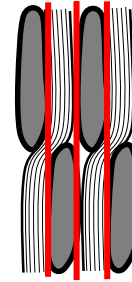
Porosity distribution (undamaged tube)



PROCESSING OF X-RAY TOMOGRAPHS

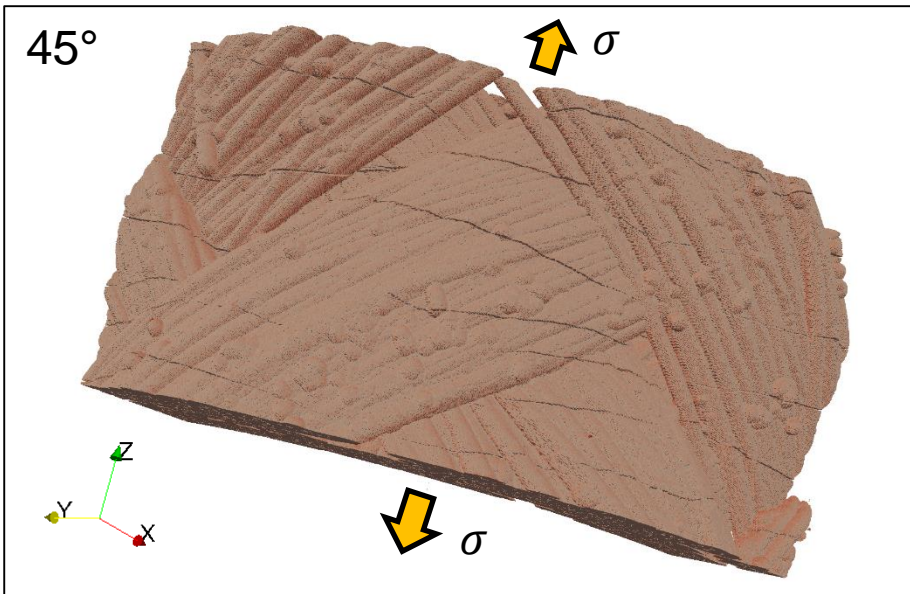


Porosity distribution (undamaged tube)

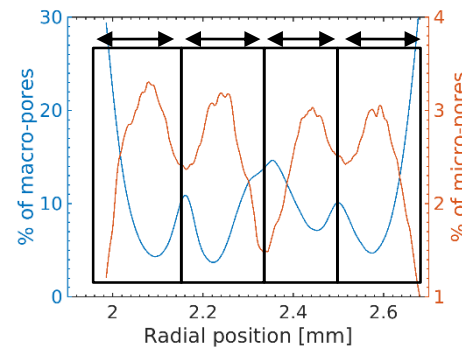
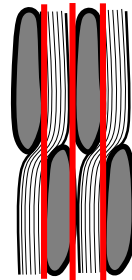


Strain measurement
(Digital Volume Correlation)

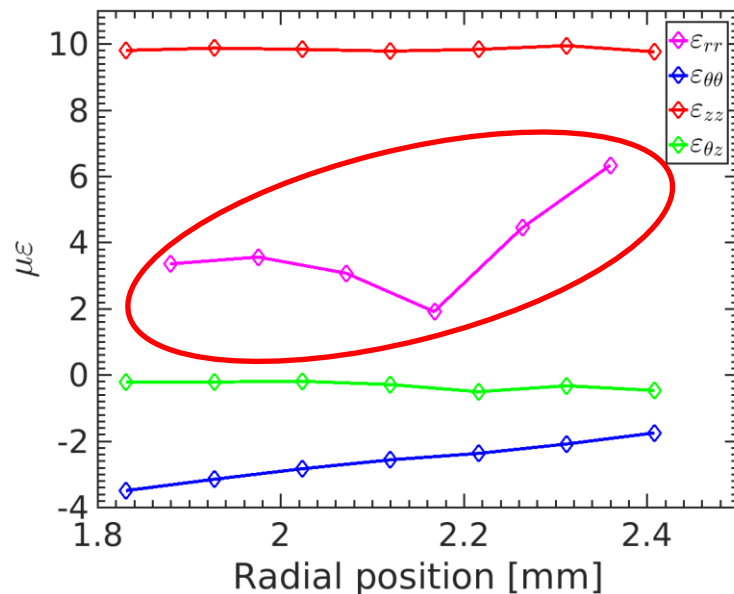
PROCESSING OF X-RAY TOMOGRAPHS



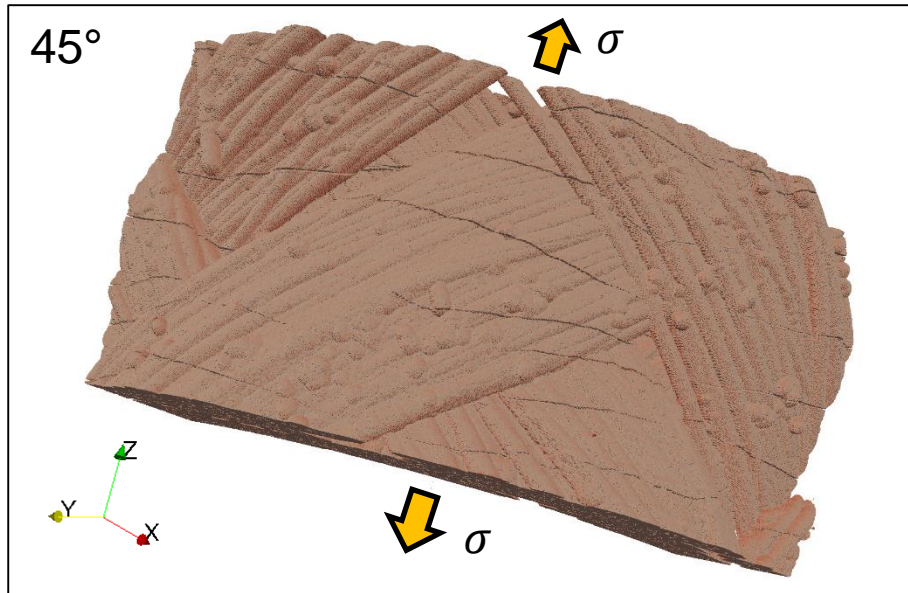
Porosity distribution (undamaged tube)



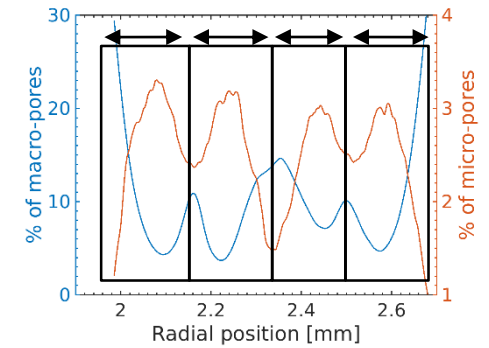
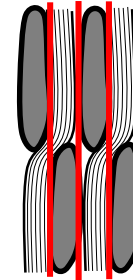
Strain measurement (Digital Volume Correlation)



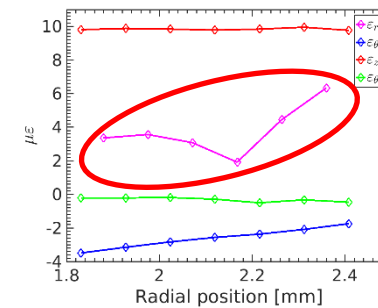
PROCESSING OF X-RAY TOMOGRAPHS



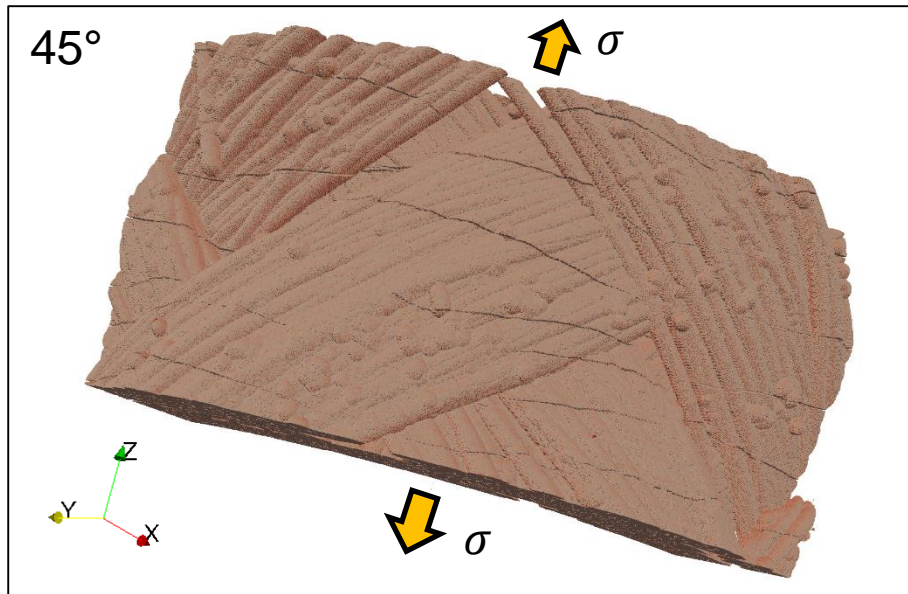
Porosity distribution (undamaged tube)



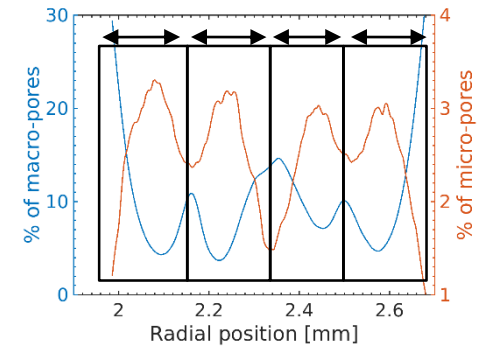
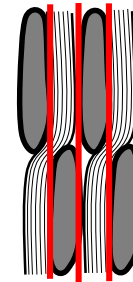
Strain measurement
(Digital Volume Correlation)



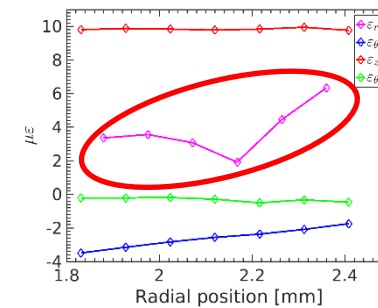
PROCESSING OF X-RAY TOMOGRAPHS



Porosity distribution (undamaged tube)

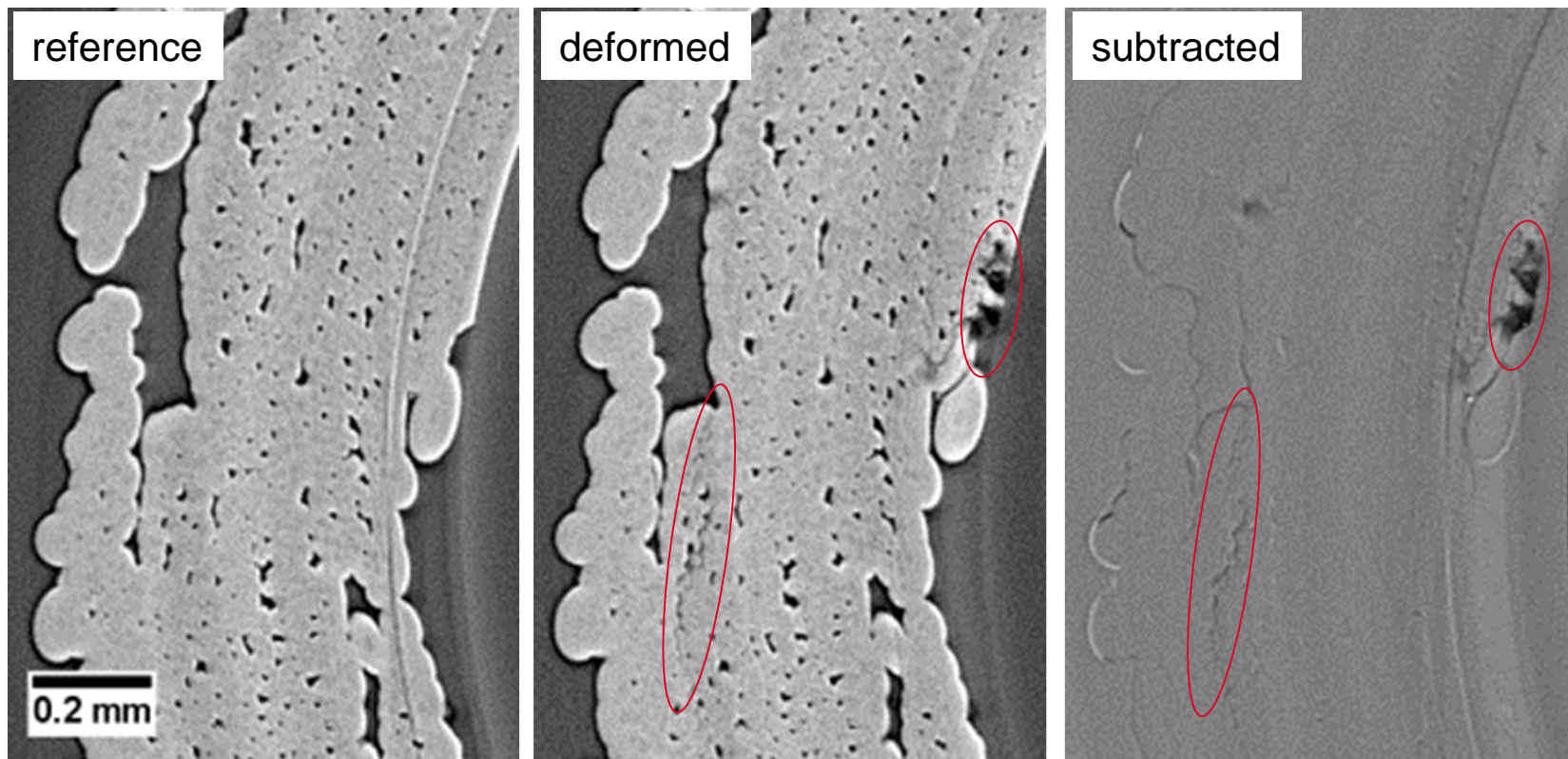


Strain measurement
(Digital Volume Correlation)



Crack characterization

CRACK DETECTION



- Subtracted image:
 - Contrast in the vicinity of 128
 - Artifacts remain



Artifact processing

- Artifact processing

- 1) Radial fluctuation of brightness

- ✓ For each circumference, subtract the average gray level :

$$V_{\text{red}}(r, \theta) = \frac{1}{2} [V_0(r, \theta) - V_{\text{av}}(r) + 255]$$

$$\text{with } V_{\text{av}}(r) = \frac{1}{N} \sum_i^N V_0(r, \theta^i)$$

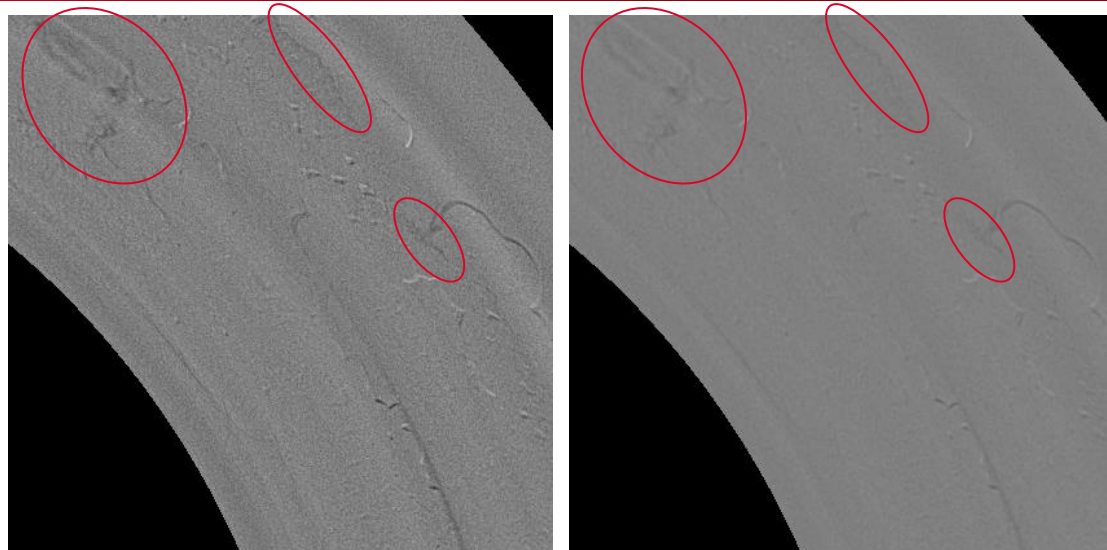
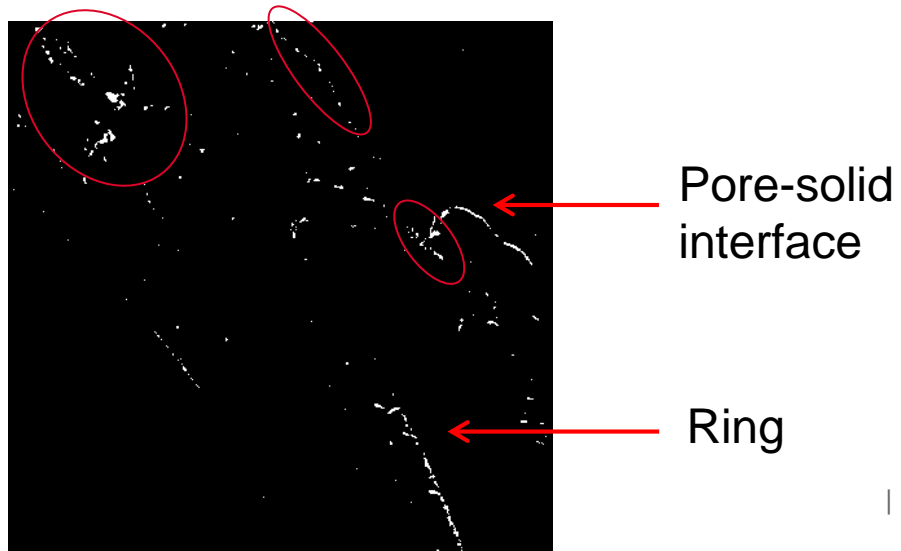


Fig. Avant & après la soustraction de luminosité

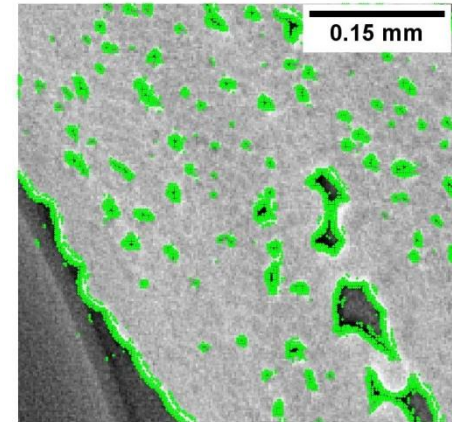
- 2) Image segmentation via a global threshold



- Artifact processing (continue)

3) Over amplitude pore/solid interface

- ✓ Identified in the reference image
⇔ Image gradient (Sobel operator)



Identified interfaces by Sobel operator

4) Ring

- ✓ Centered to image center
- ✓ Continuous in the circumferential direction



Interface reduction

Ring reduction

- Quantitative measurement (opening, surface area)

1- Compute the “voxelized” local damage level $d(\underline{X}_c)$

The gray level of one detected crack voxel:

$$g(\Phi(\underline{X}_c)) = [1 - \psi(\underline{X}_c)] \cdot f(\underline{X}_c) + \psi(\underline{X}_c) \cdot v_{air}$$

Volume fraction of air
in the voxel

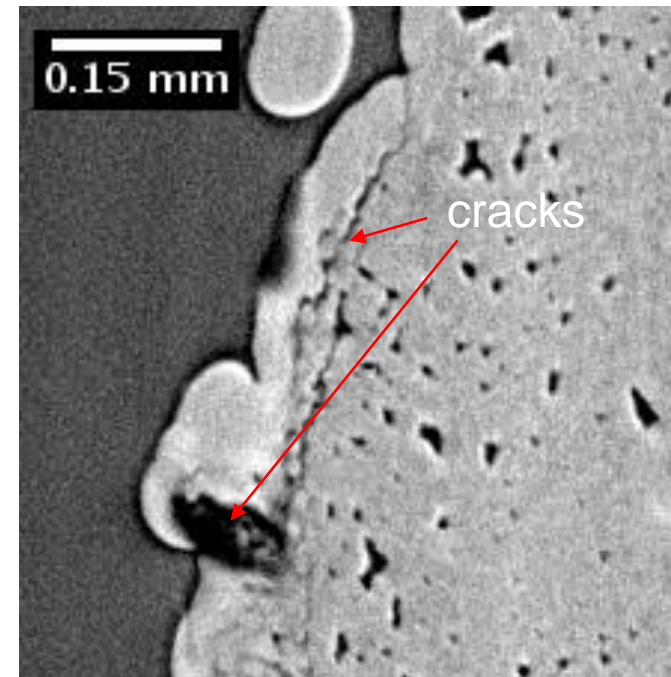
Gray level of an
air-voxel

$$r(\underline{X}) = \frac{1}{2} [g(\Phi(\underline{X})) - f(\underline{X}) + 255]$$

“Voxelized” damage level:

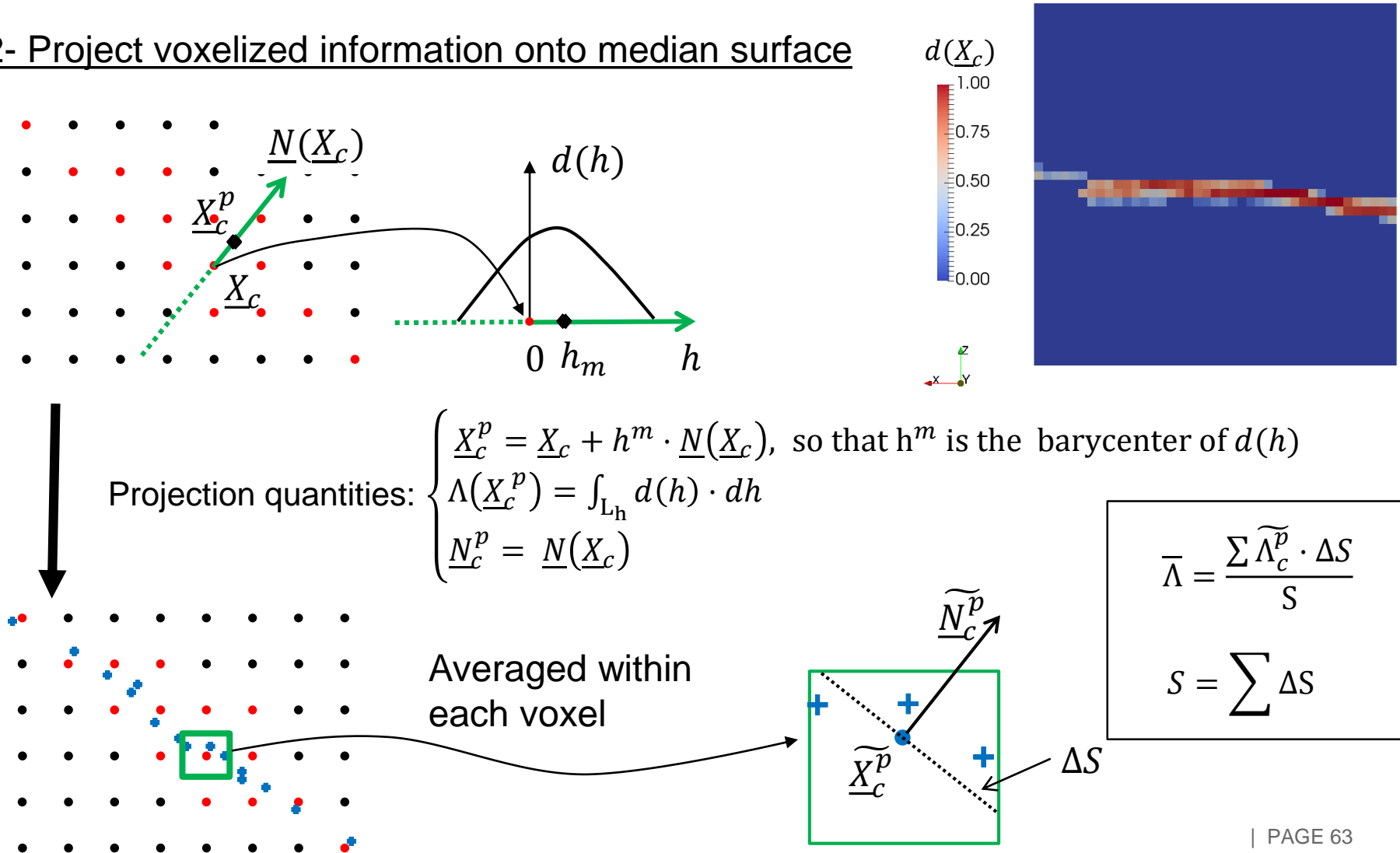
$$d(\underline{X}_c) := \psi(\underline{X}_c) = \frac{255 - 2 \cdot r(\underline{X}_c)}{f(\underline{X}_c) - v_{air}}$$

$$d(\underline{X}_c) \in [0,1]$$



- Quantitative measurement (opening, surface area) - continue

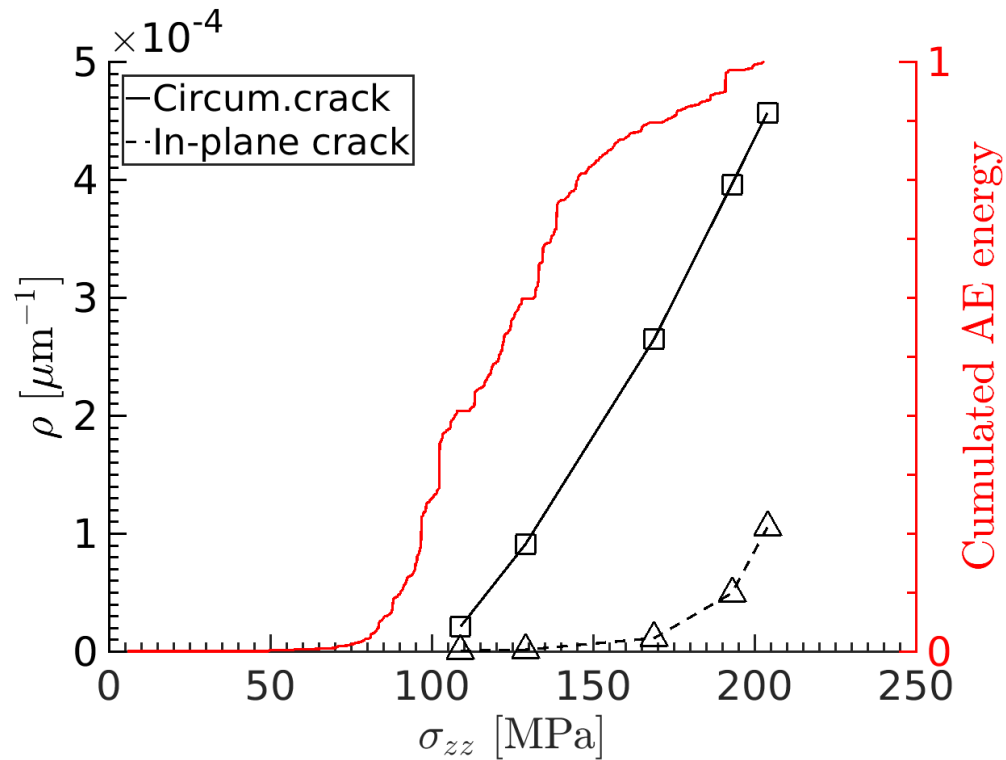
2- Project voxelized information onto median surface



CRACK QUANTIFICATION

- Quantitative measurement (opening, surface area) - results

Surface density : $\rho = S/V$



- Quantitative measurement (opening, surface area) - results

Average opening $\bar{\Lambda}$

