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Variation multi-échelle des composites textiles : modélisation basée sur l'image

Multi-scale variability of textile composites: image based modeling

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Maître de conférences (HDR)

CERI MP Nord Europe

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#IMTomorrow
#IMTNordEurope

05/11/2025 Charleville-Mézières
GdR FIBMAT (GdR CNRS 2139)

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Outline

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- Institute / Research team / Research topics

Part 1: Multi-scale nature of composites materials
- Different scales

Part 2: Multi-scale image based characterization
- Microscopy (Optical and SEM)
- Microcomputed tomography (rings, noise, small contrasts, edge effects etc)

Part 3: Image based modeling
- Supervised segmentation (TP activity, example of the 3D warp interlock composite with voids)
- Voxel based vs conformal model

Conclusions
- Current trends and challenges

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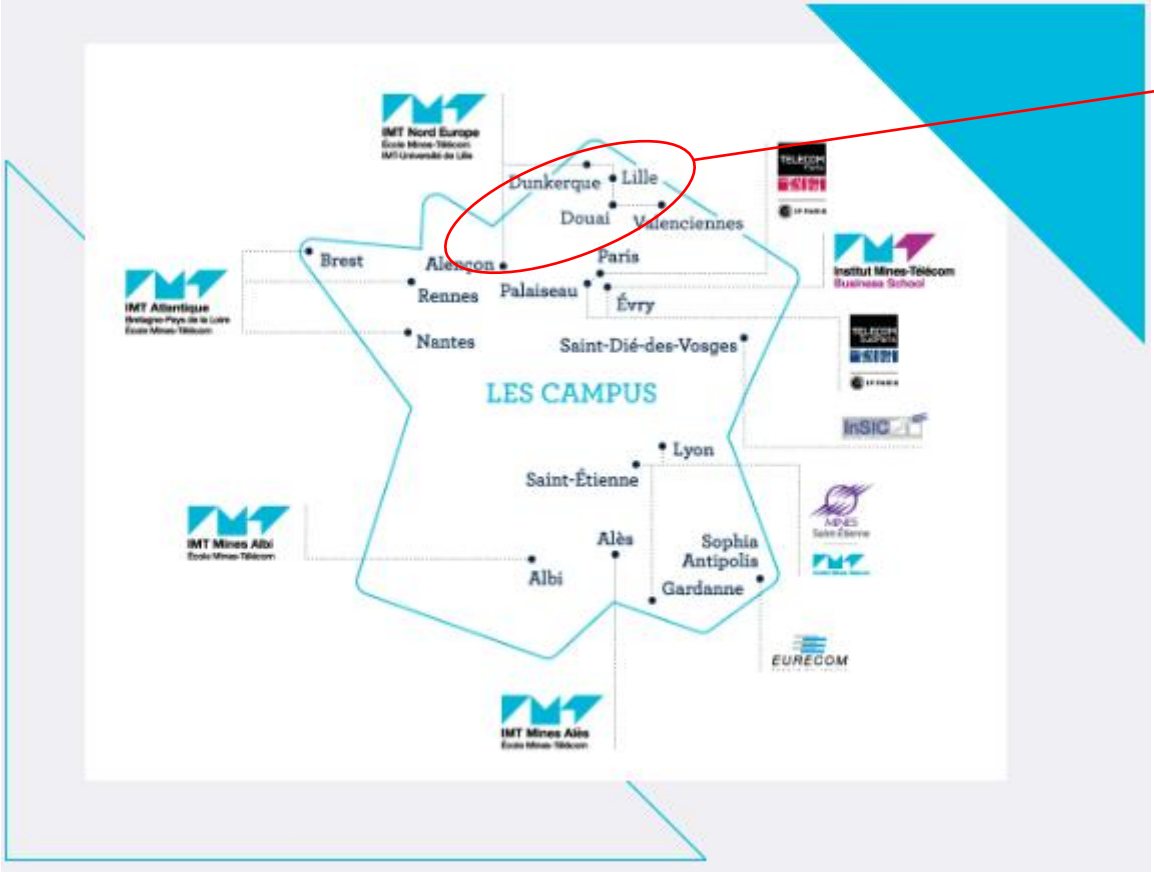

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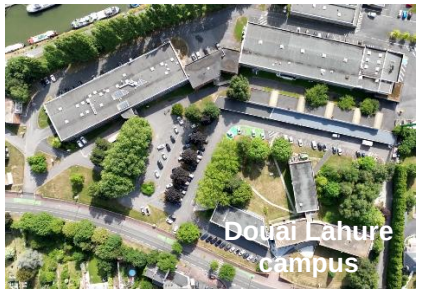

https://www.imt.fr/le-groupe-et-les-ecoles/nos-grandes-ecoles/

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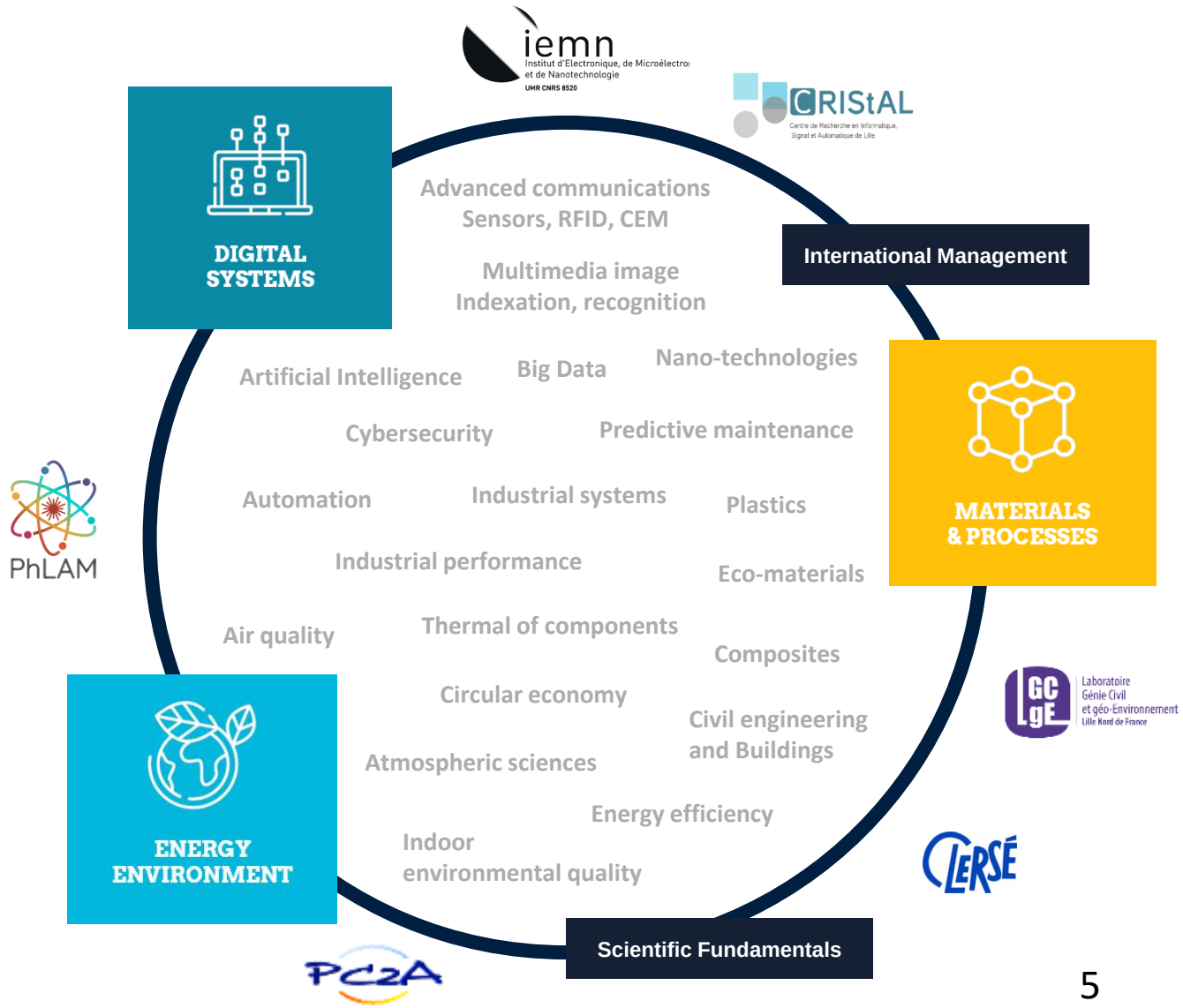
DIGITAL SYSTEMS

MATERIALS & PROCESSES

2 Departments

International Management

Scientific Fundamentals



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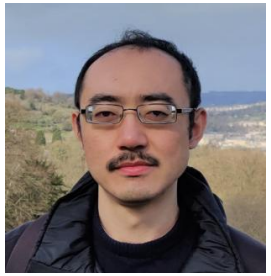
Y. Liu
PhD

I. Straumit
PhD



Y. Chen
Postdoc

X. Ma
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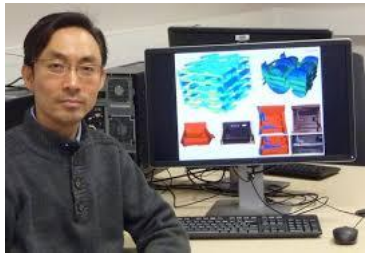
B. Wintiba
PhD

S. Lomov



C.H. Park

S. Panier

T.J. Massart

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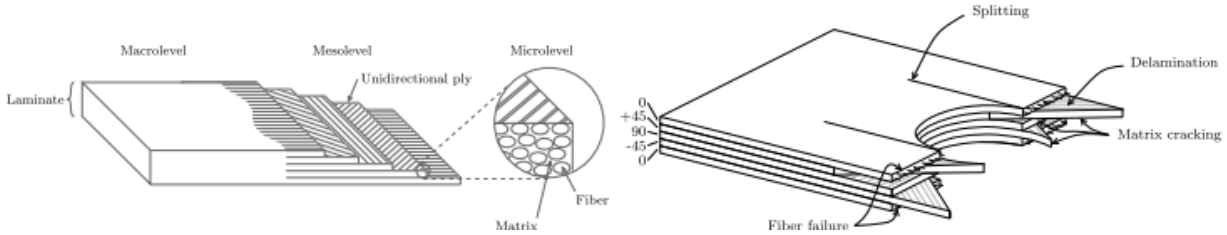
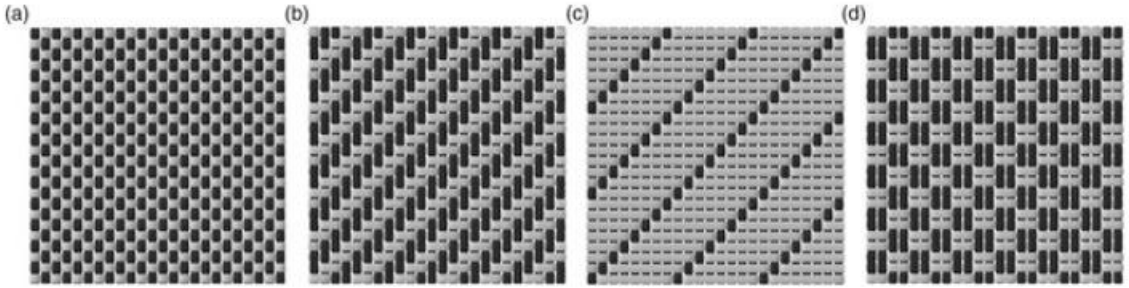
Multi-scale nature of composites materials

Laminates

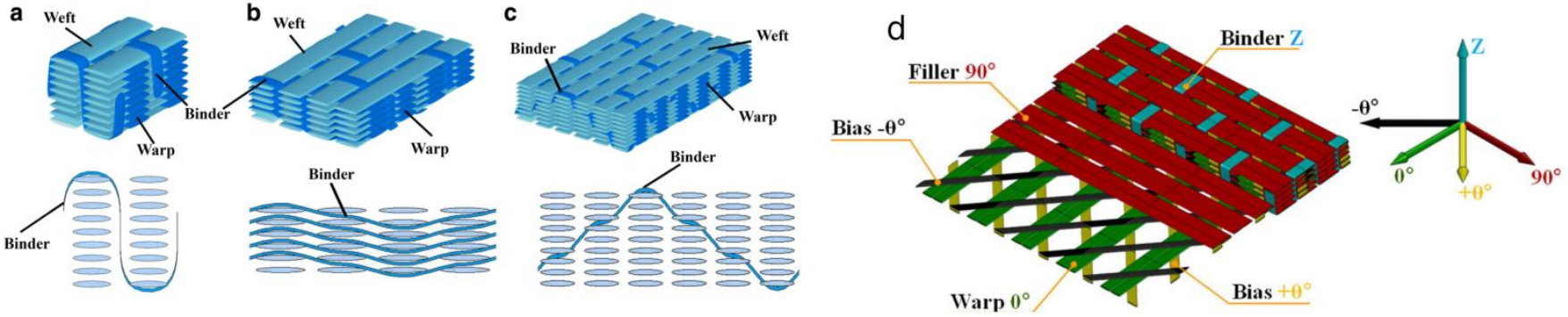


2D textile composites



Basic 2D weaves: (a) plain, (b) 2 × 2 twill, (c) 8-harness satin, and (d) basket.

3D textile composites



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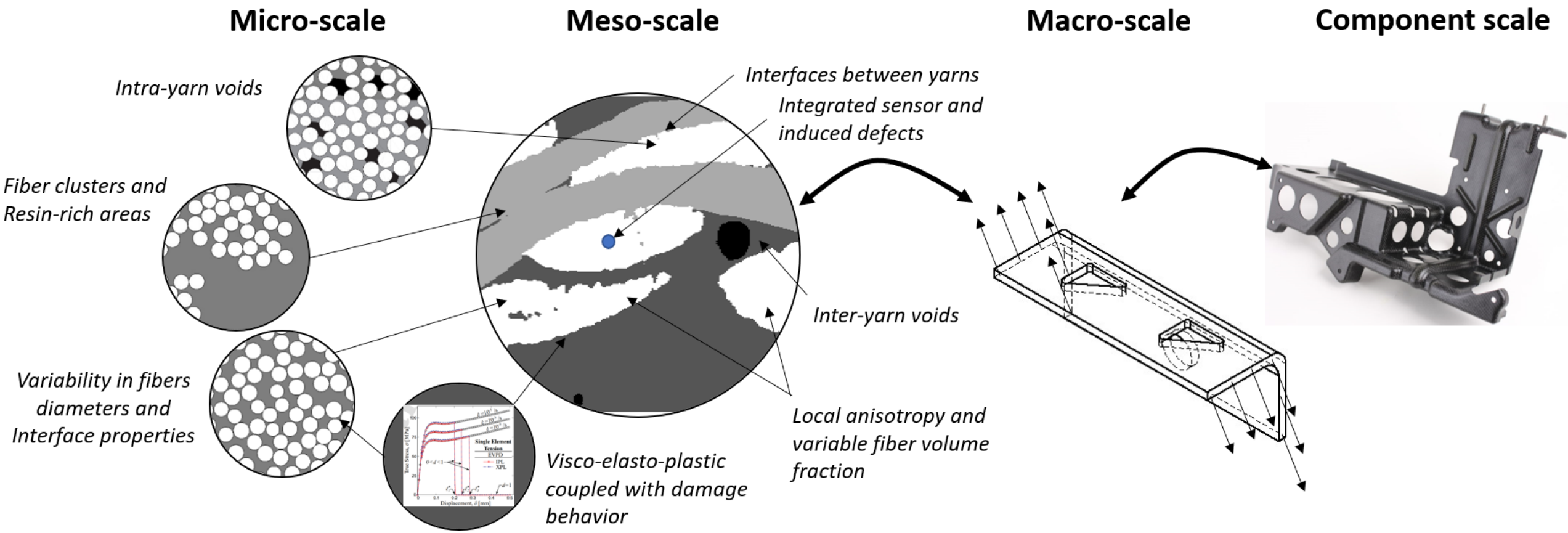
Multi-scale nature of composites materials



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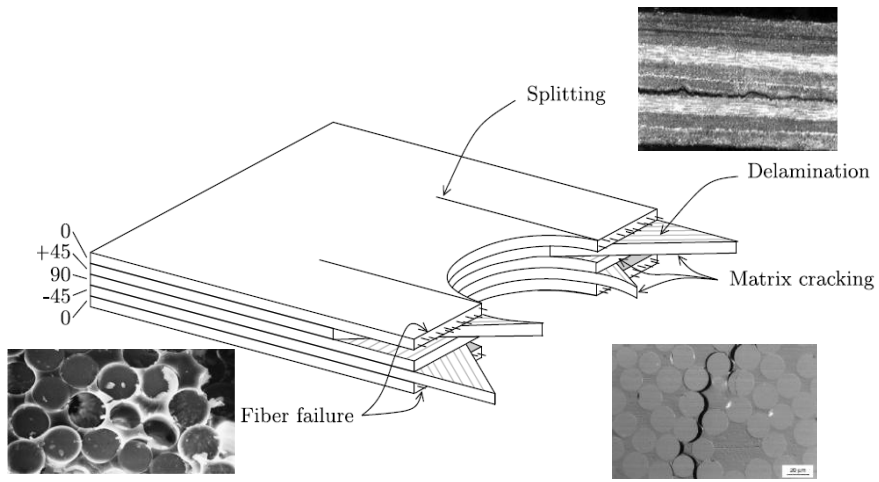
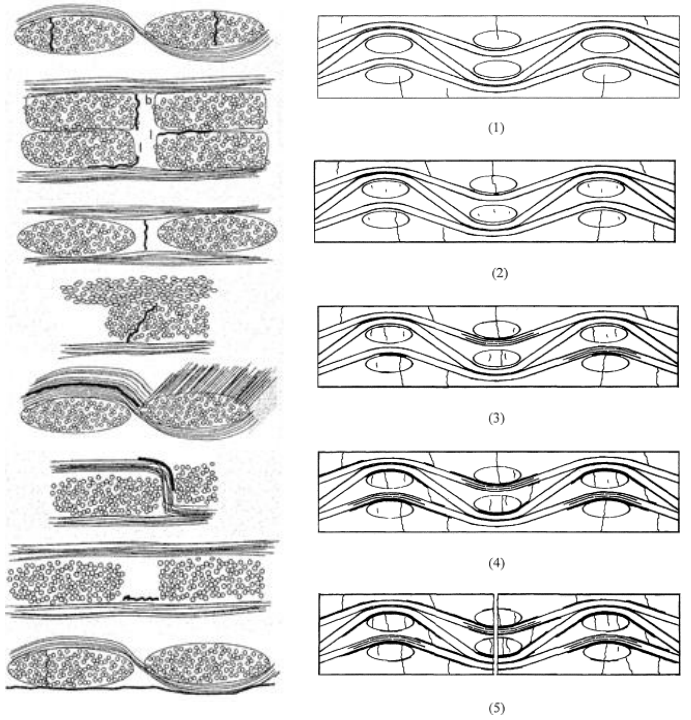
Constitutive behavior

- Behavior of constituent materials
- Reinforcement arrangement (short or continuous fibers, unidirectional or woven, etc.)
- Load-dependent response (simple or complex stress states; static or fatigue)
- Process induced defects
- Variety of damage mechanisms:
  - Fiber failure,
  - Matrix cracking (debonding, splitting), and
  - Delamination (e.g., in UD composites)
  - Crack propagation governed by yarn undulation (e.g., in textile composites)





L. Gorbatikh, S.V. Lomov. Damage accumulation in textile composites. In Modeling Damage, Fatigue and Failure of Composites materials. Eds. R. Talreja and J. Varna, 2016, pp. 41-59

K.-H Tsai C.-H Chiu T.-H Wu. Fatigue behavior of 3D multi-layer angle interlock woven composite plates. Composites Science and Technology, 60 (2000), 241-248.

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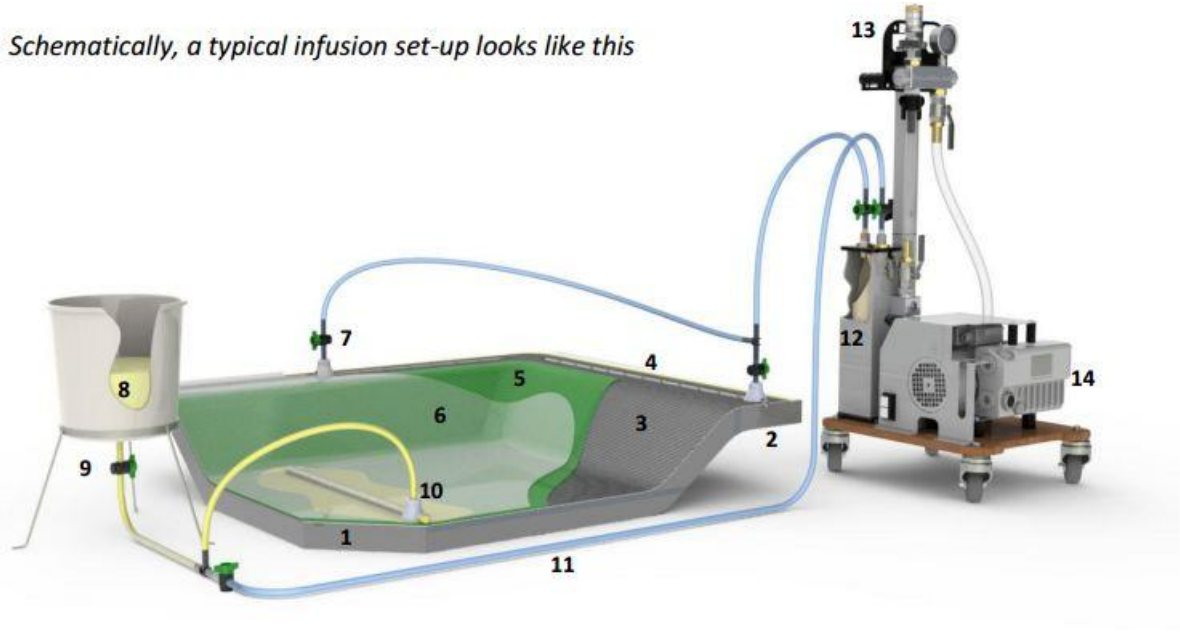
Manufacturing of composites



All composites were manufactured using LCM (vacuum infusion or RTM process).

Sources: https://www.composite-integration.co.uk/applications/rtm/
https://kbs-delivery.gr/en/content/7-vacuum-infusion-technique

Manufacturing of composites

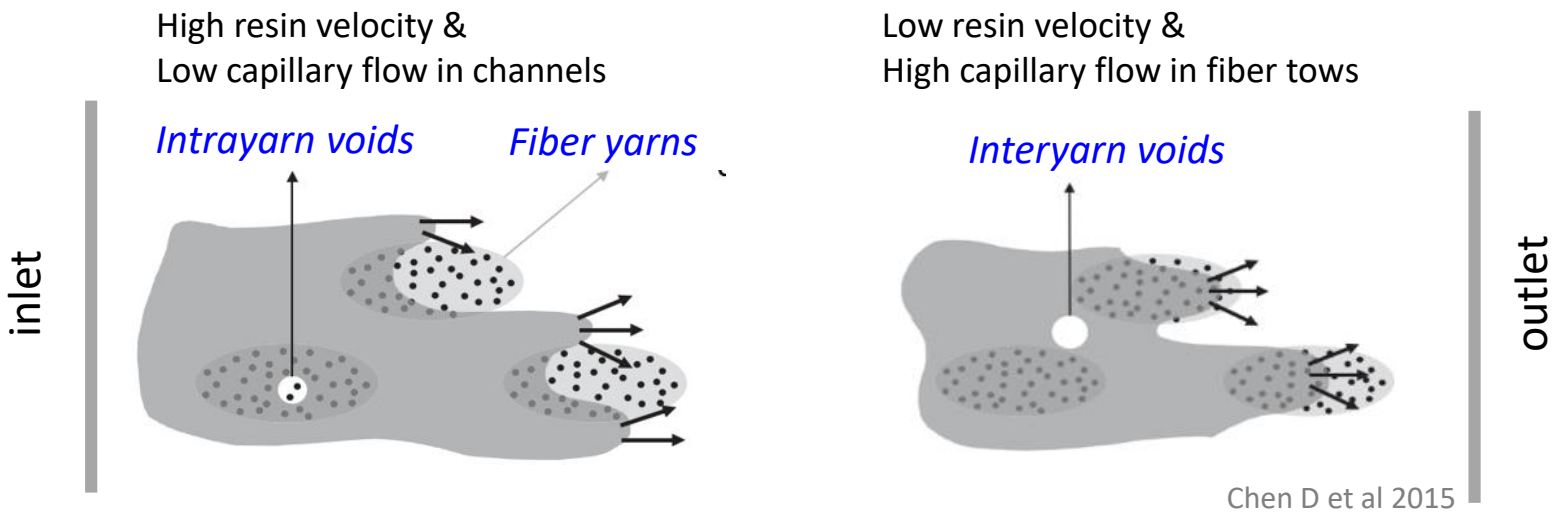
Resin transfer moulding

Preform | Injection of resin | Curing | De-mold

Voids formation during RTM

Main principle: Mechanical air entrapment by non-uniform resin flow at the flow front

Under a constant inlet pressure



Chen D et al 2015

Resin injection under ***constant pressure***: Control ***intra-yarn / inter-yarn voids***

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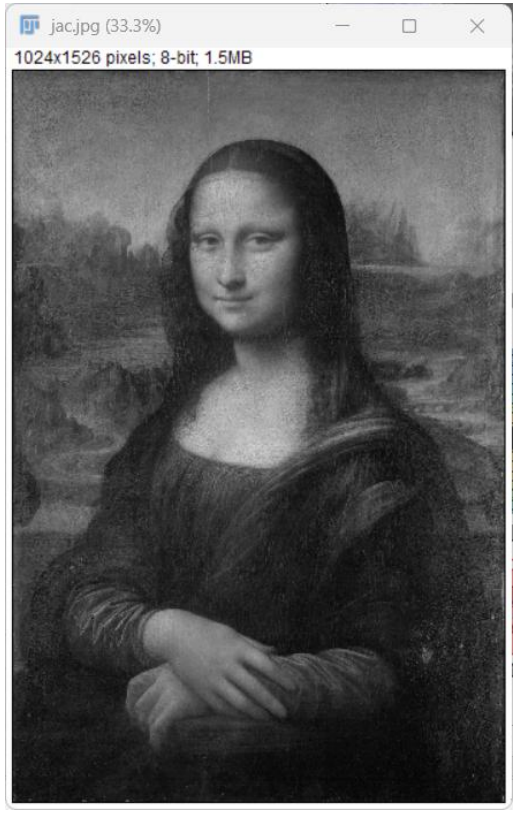
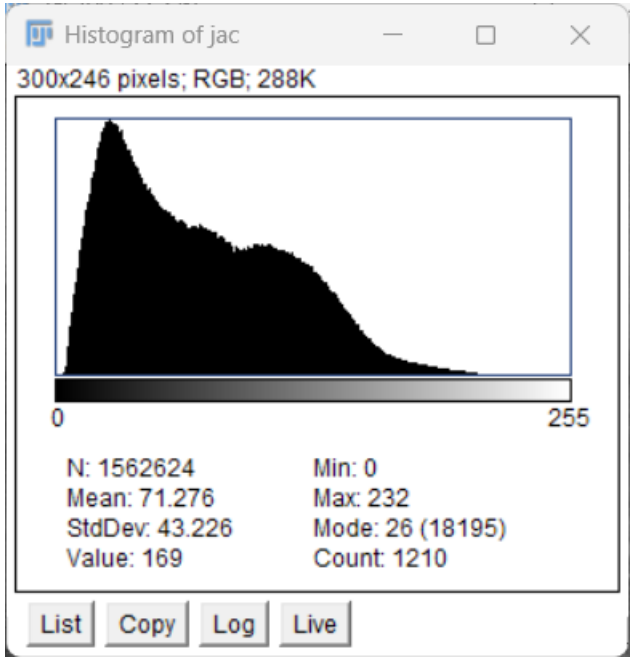
What does an image represent in our context?



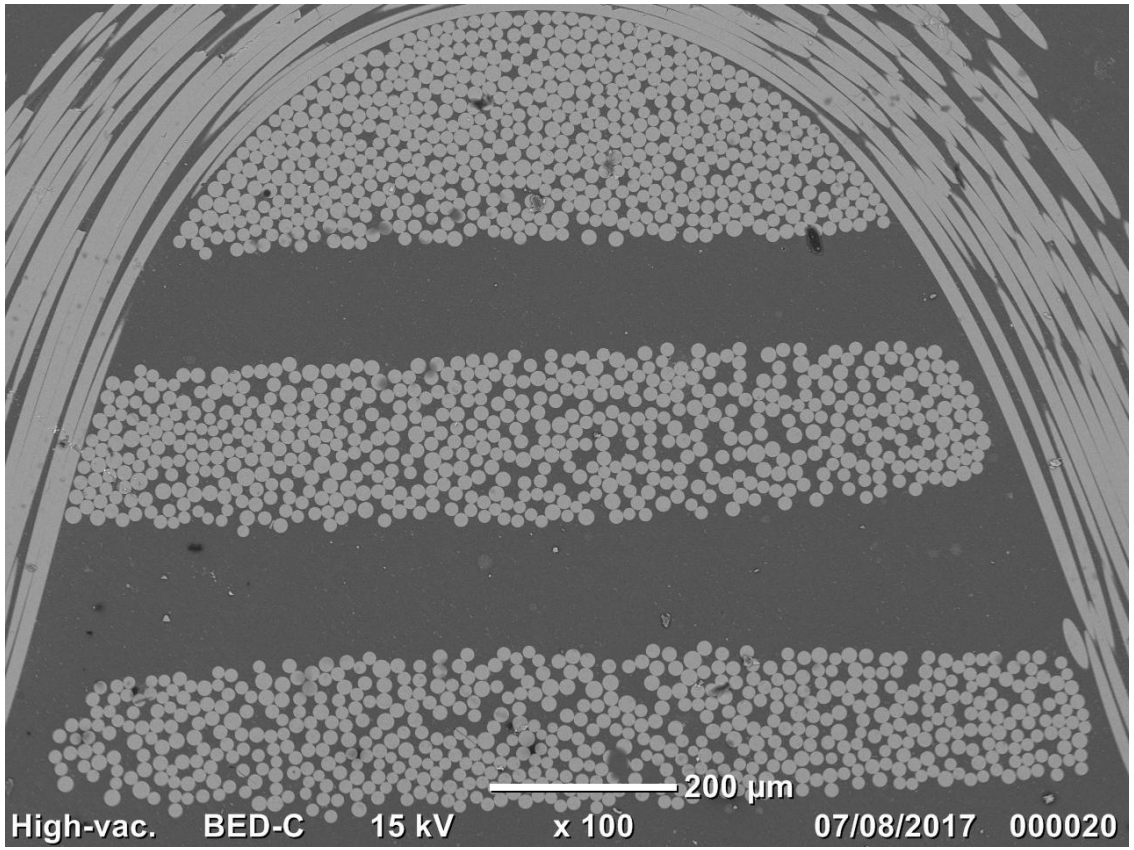


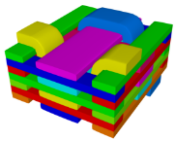
Léonard de Vinci
Entre 1503 et 1506 ou entre 1513 et 1516, peut-être jusqu'à 1517

Microscopy

SEM or optical:

- High resolution (µm or sub-µm scale)
- Can be automated
- 2D slices (or sequences of 2D slices)
- Preparing the sample for high-quality observation is not straightforward





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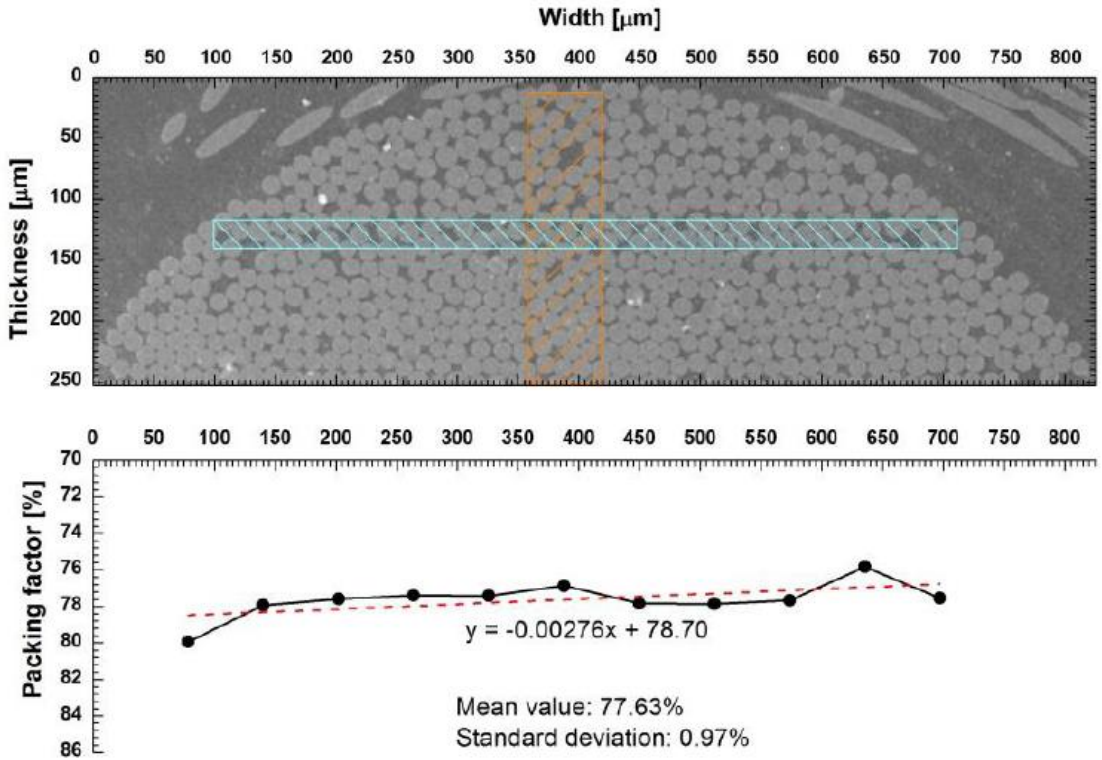
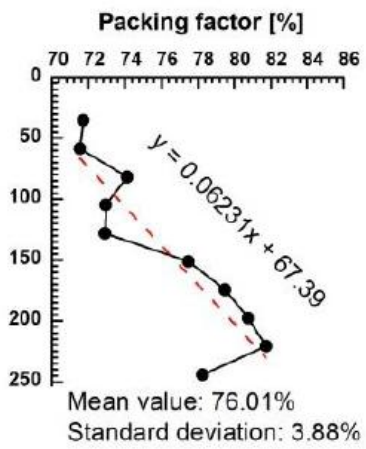
Microscopy

Observations:

- Gradients are governed by the meso-structure.
- Some regions are extremely dense.
- The image provides information about the current state (immediately after manufacturing).
- Numerical generation of RVEs is already possible using several codes available online.





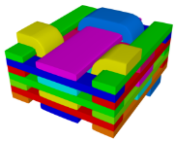


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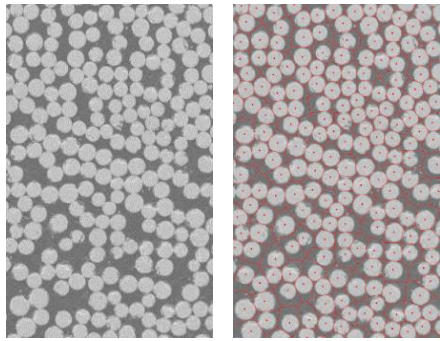
Image analysis

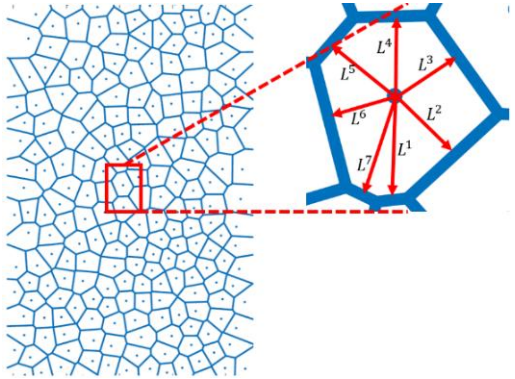
Information:

- Input information for the generation of microstructure
- Fiber radius distribution (R) & Inter fiber distance (IFD)

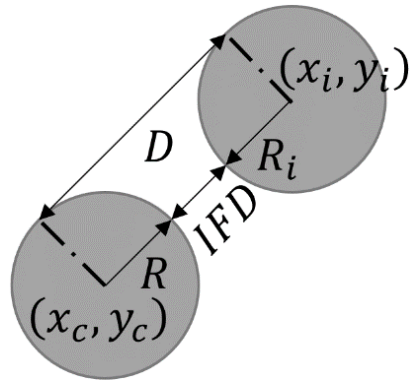


SEM

Identified fibers



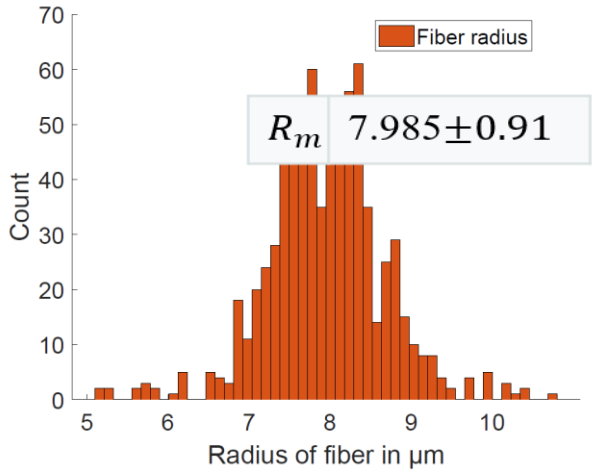
Voronoi Tessellation



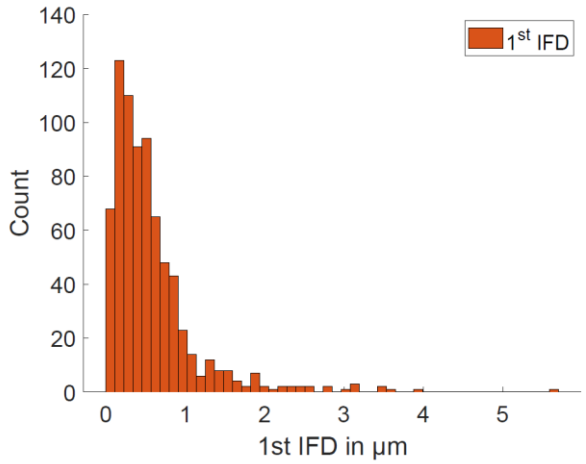
Definition of IFD

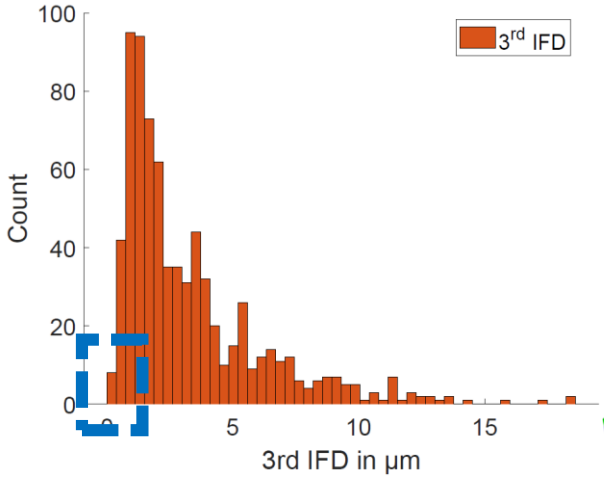
$R_i = min(\{L_i\})$

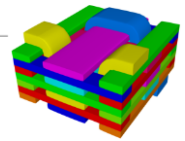
Fiber radius



IFD







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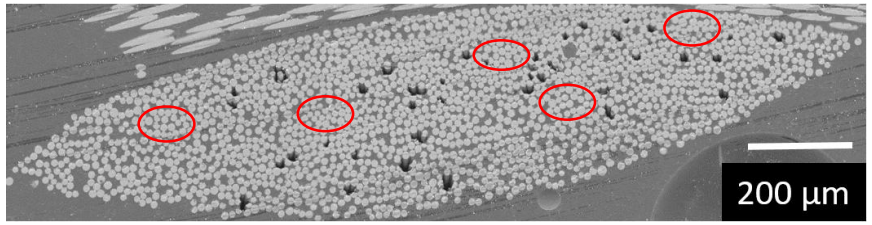
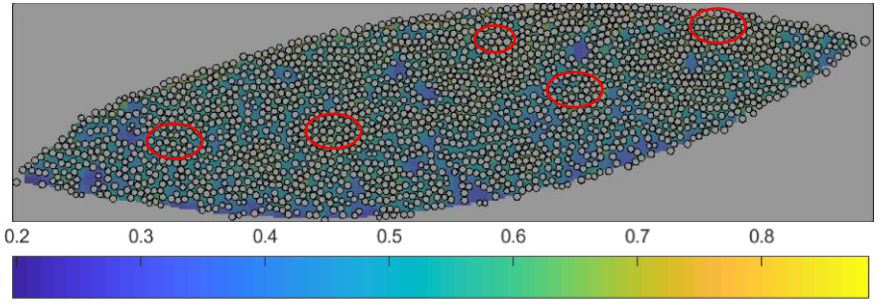
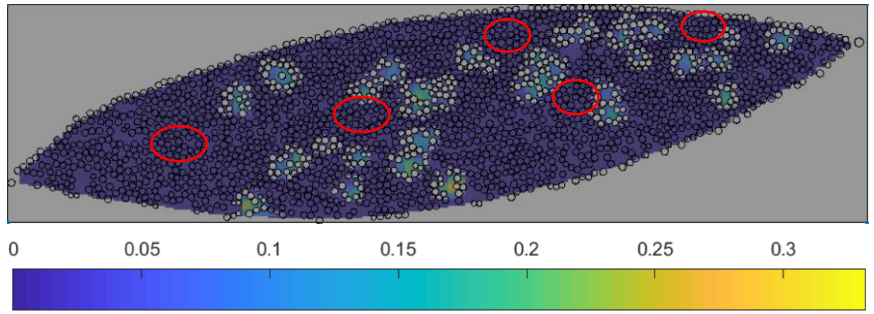


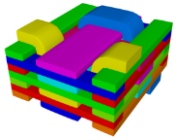
Local fiber packing



Matrix rich zone (MRV) Fiber rich zone (FRV)

Local void packing





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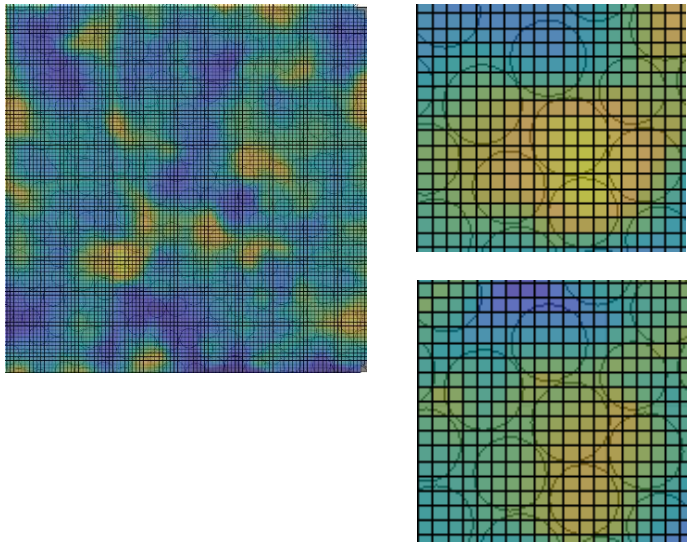
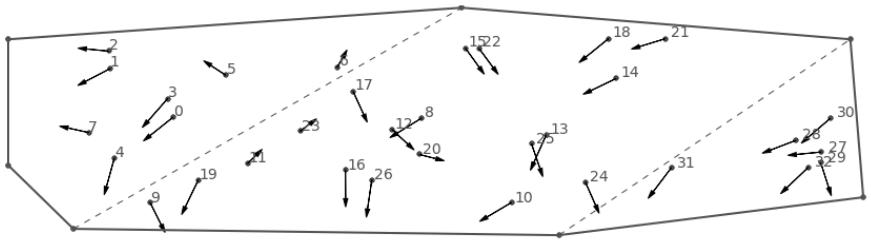
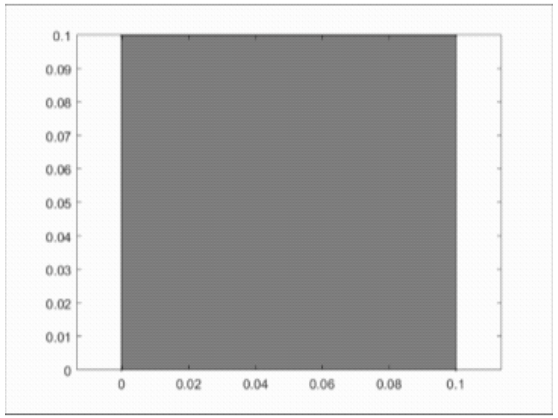
Microscopy based generators

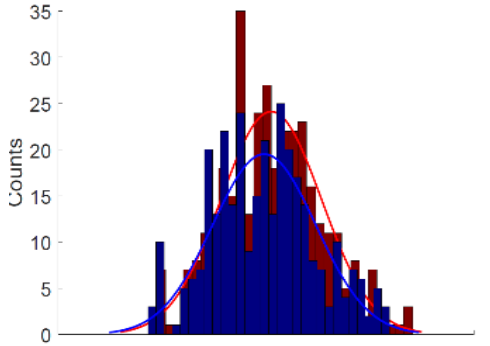
Information:

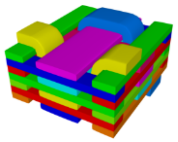
- Local fiber positioning
- Fiber clustering
- Defect characterization
- Correlations between fiber architecture and defects
- Incorporation of local measurements (such as local averaging)











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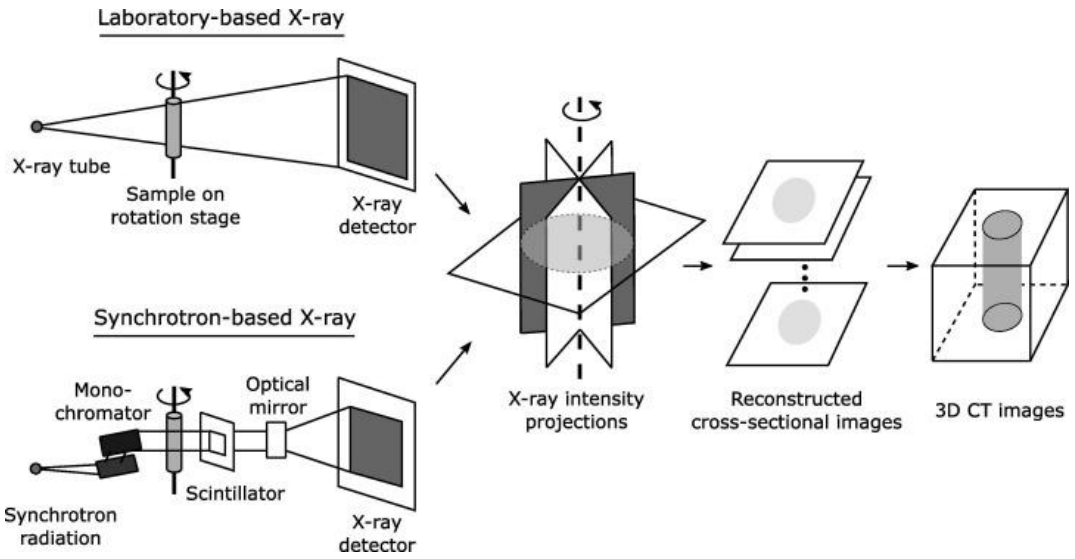
3D µCT

(almost non-destructive)

Working principle of µCT



ISIS4D platform (University of Lille)

$$I = I_0 \, e^{-\mu x}$$

I_0 = incident X-ray intensity
I = transmitted X-ray intensity (after passing through the material)
μ = linear attenuation coefficient (m^{-1}) — depends on material composition and X-ray energy
x = path length (thickness of the material, m)

$$\mu = \tau + \sigma + \kappa$$

τ = photoelectric absorption coefficient
σ = Compton scattering coefficient
κ = pair production coefficient (negligible for µCT energy ranges)

$$\mu(E) \propto \rho \, Z^n \, E^{-3}$$

ρ = density of the material
Z = atomic number
$n \approx 3$–4 (empirical, varies with energy range)

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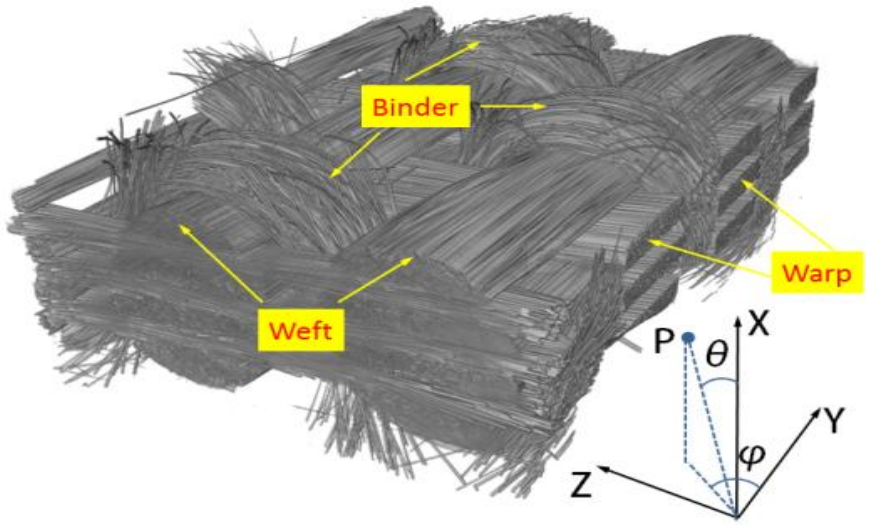
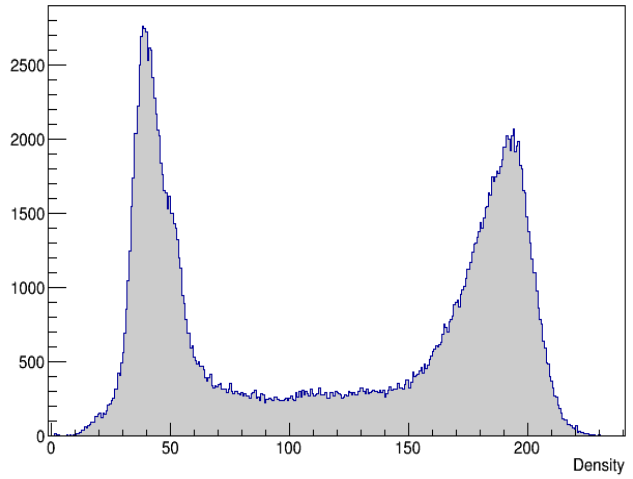
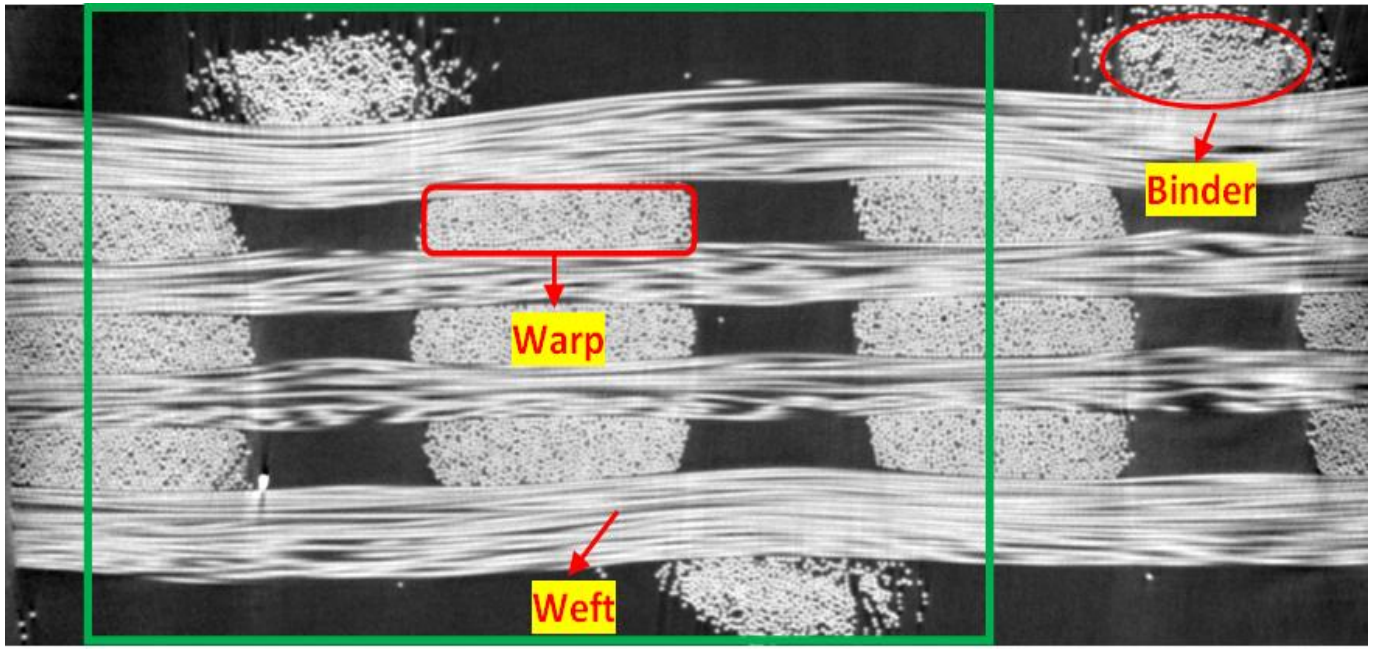
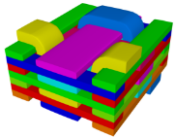
µCT for realistic reconstruction









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Outline

Introduction
- Institute / Research team / Research topics

Part 1: Multi-scale nature of composites materials
- Different scales

Part 2: Multi-scale image based characterization
- Microscopy (Optical and MEB)
- Microcomputed tomography (rings, noise, small contrasts, edge effects etc)

Part 3: Image based modeling
- Supervised segmentation (TP activity, example of the 3D warp interlock composite with voids)
- Voxel based vs conformal model

Conclusions
- Current trends and challenges

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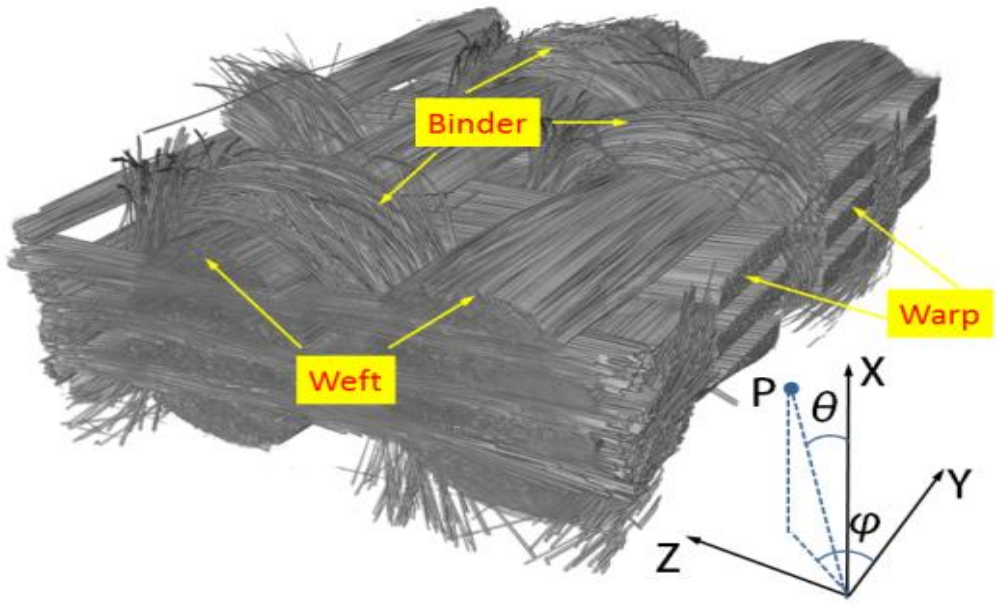
Preliminary image analysis

Why we cannot apply directly FEM or other solvers ?

- Reconstructed volume (mm^3): 13,71 x 3,14 x 9,99
- Voxel size 8,79 μm
- Total voxels = 1559 × 357 × 1137
- **Total voxels ~ 632.7 million** (free Abaqus license is limited to 1000 nodes, while the student version allows up to 250000 nodes.
- With the help of HPC and machine learning, these limits are being pushed further, but we are still only simulating about 300 mm^3 of material — far from a full structural scale.



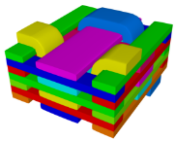


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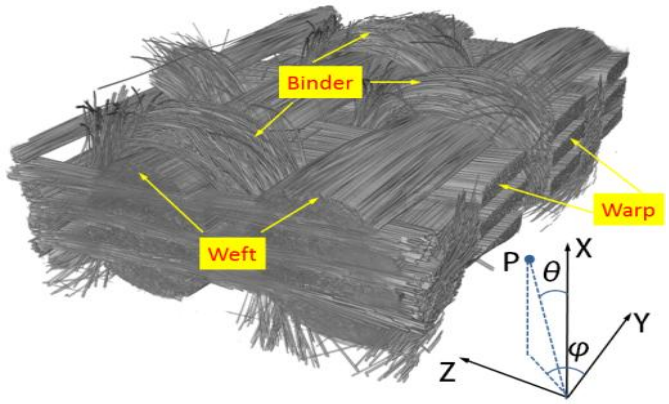
Image analysis

We started to look closer



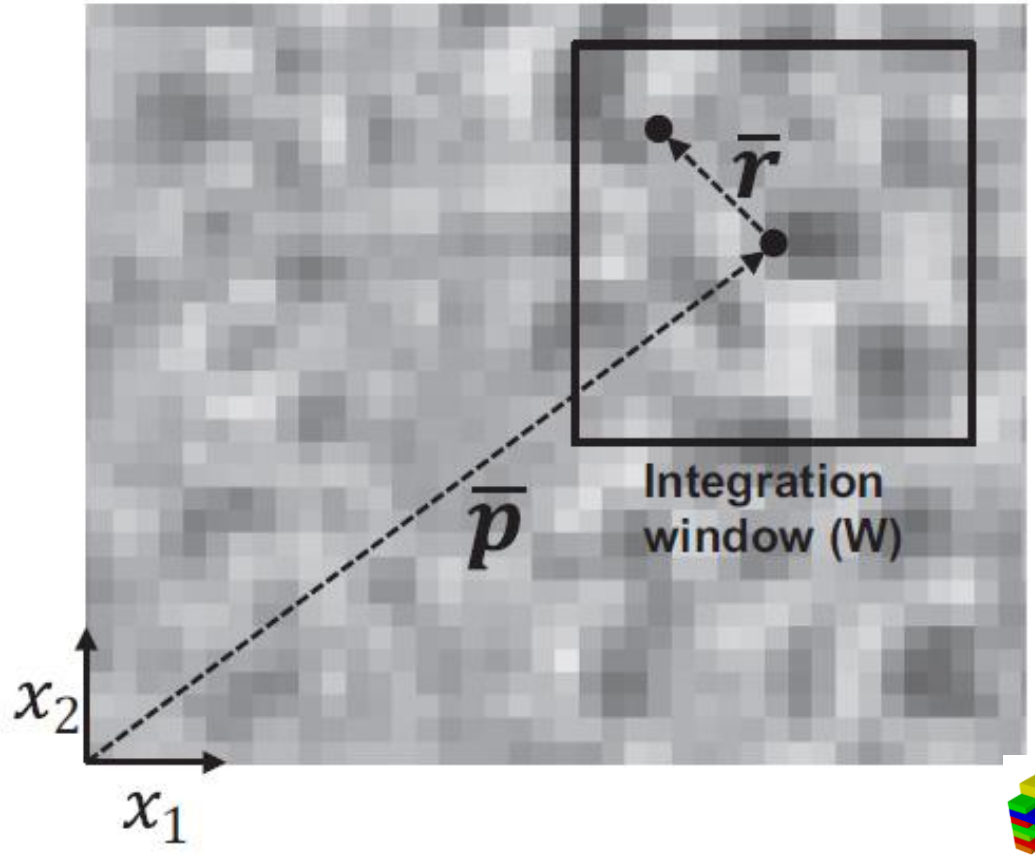


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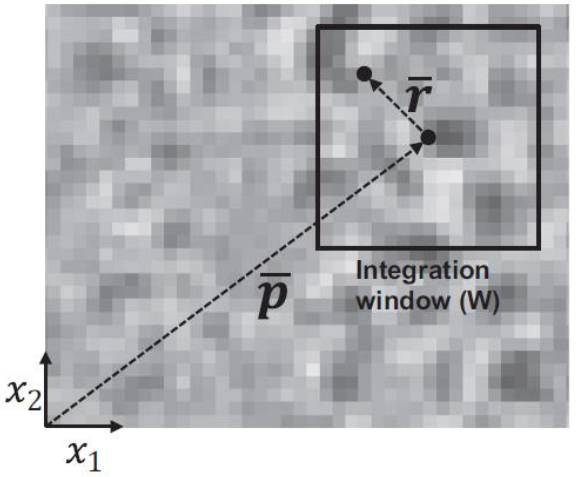
Image analysis

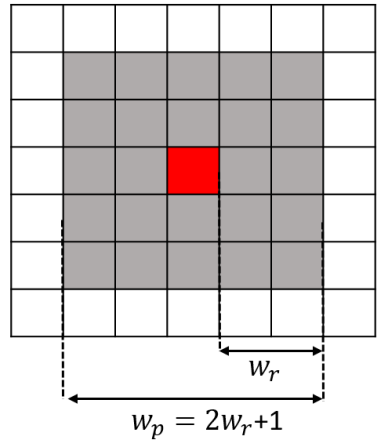
Structure tensor

$$S'(x_1, x_2, x_3) = \begin{bmatrix} \left(\frac{\partial I}{\partial x_1}\right)^2 & \frac{\partial I}{\partial x_1}\frac{\partial I}{\partial x_2} & \frac{\partial I}{\partial x_1}\frac{\partial I}{\partial x_3} \\ & \left(\frac{\partial I}{\partial x_2}\right)^2 & \frac{\partial I}{\partial x_2}\frac{\partial I}{\partial x_3} \\ sym & & \left(\frac{\partial I}{\partial x_3}\right)^2 \end{bmatrix}$$



Anisotropy

$$\beta = \begin{cases} 1 - \frac{\lambda_1}{\lambda_3} & \text{if } \lambda_3 > 0, \\ 0 & \text{if } \lambda_3 = 0. \end{cases}$$



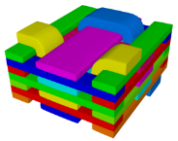


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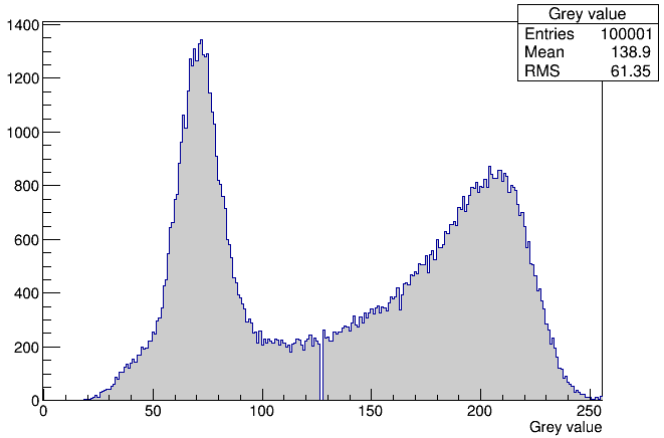
Image analysis

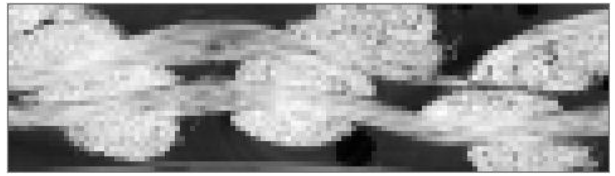
Three ingredients are indispensable for textile composites:

- Histogram (essentially the grayscale distribution)
- Selection of the averaging window (*r*)
- Averaged grayscale value
- Anisotropy, which is obtained from the structure tensor *S*

Histogram

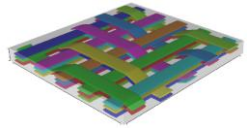


AVG



Anisotropy

KU LEUVEN



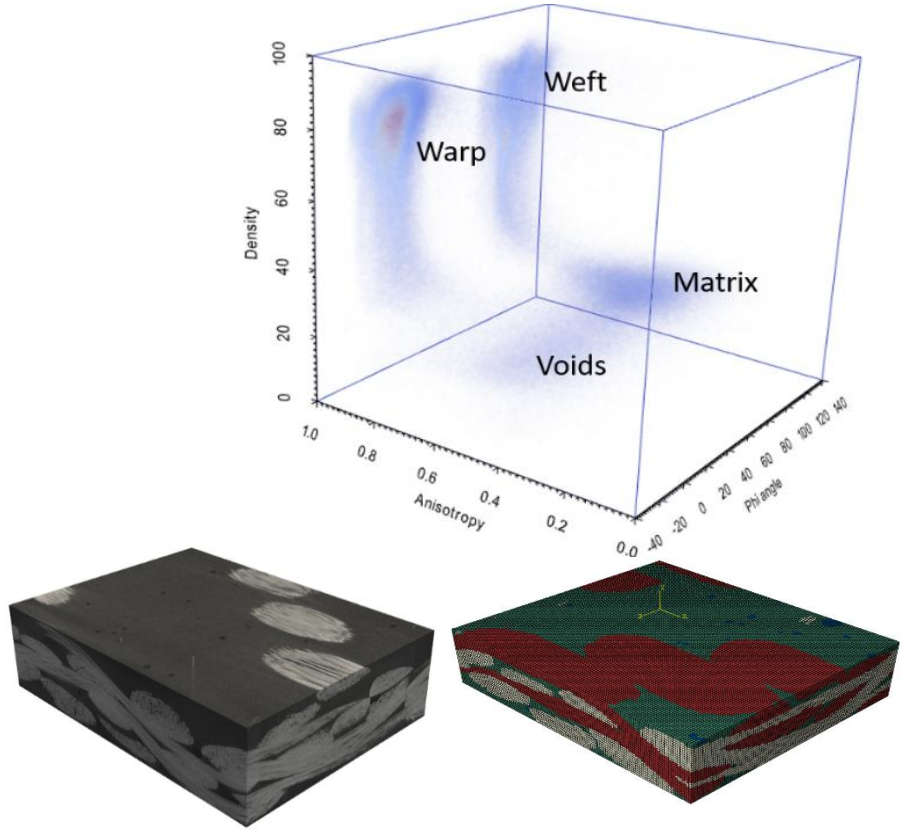
Reconstruction of micro-CT data

- Feature vector

Structure anisotropy $\beta = \begin{cases} 1 - \frac{\lambda_1}{\lambda_3}, & \lambda_3 > 0 \\ 0, & \lambda_3 = 0 \end{cases}$

Density $g(p) = \int_{w(p)} I(r)dr$

Azimuthal angle $\varphi = tan^{-1}\frac{v_x}{v_y}$



μCT data Segmented data

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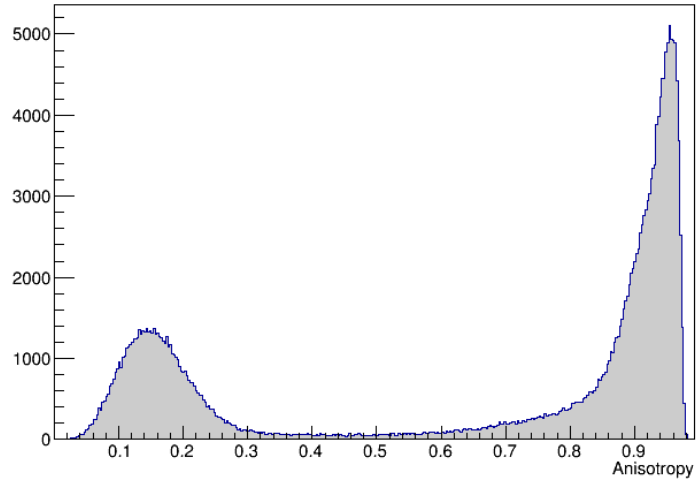
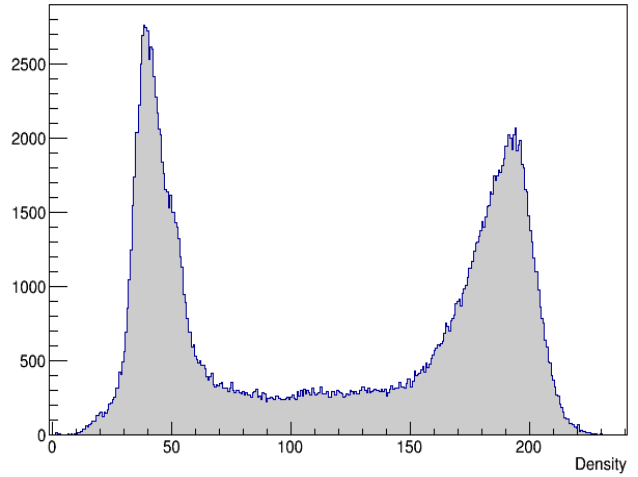
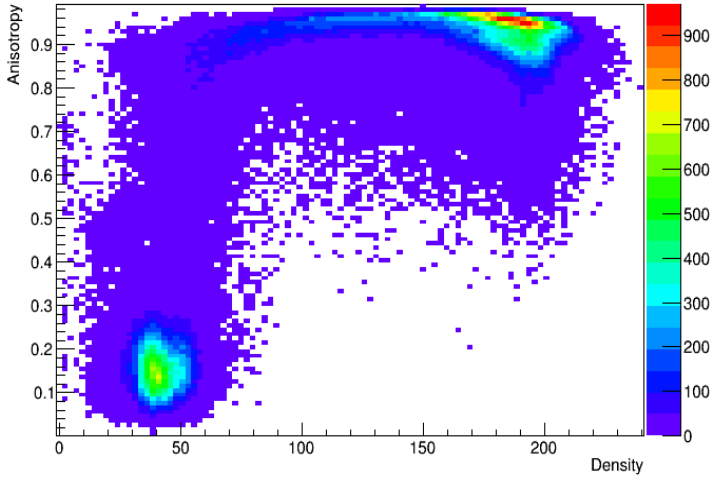
Image analysis



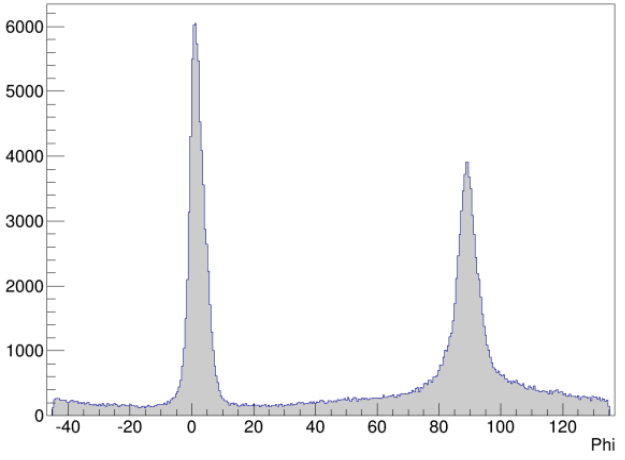
The histogram of degree of anisotropy



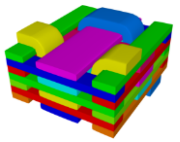
The histogram of grey value in the voxel model



The histogram of grey vs anisotropy



ϕ function in spherical coordinate



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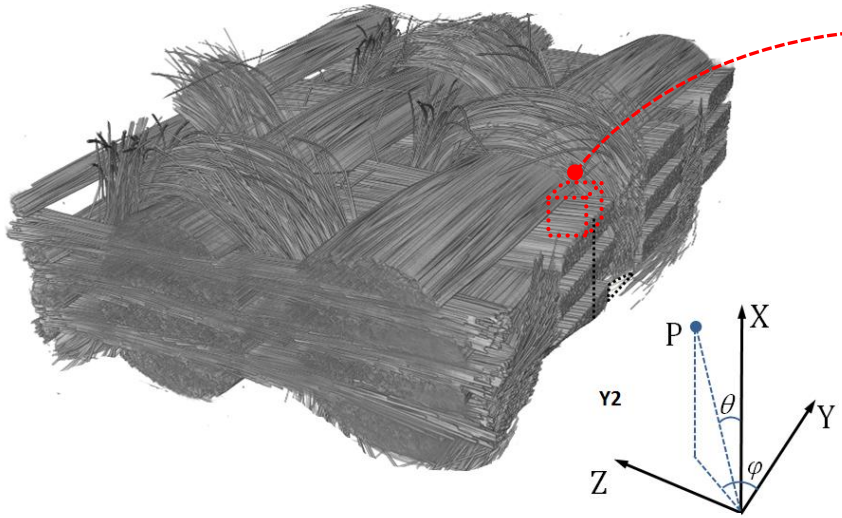
Summary for image analysis



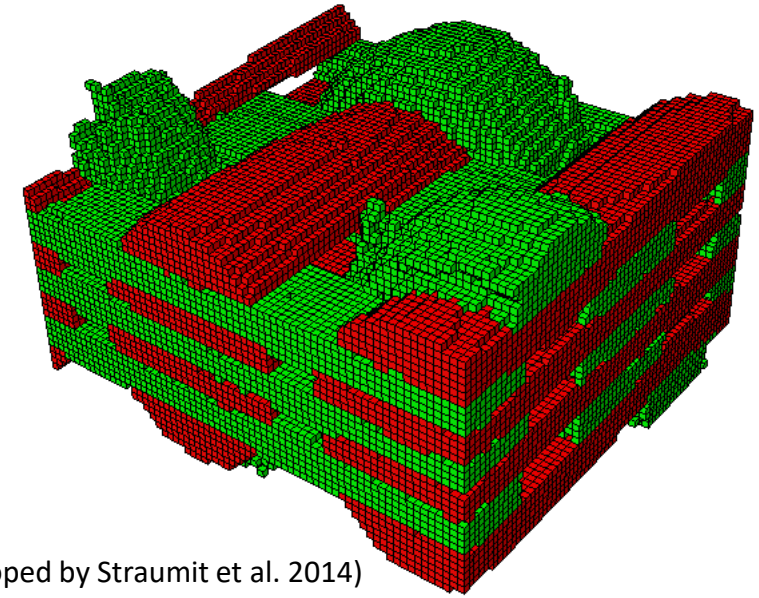
Averaged grey value (AGV)
Anisotropy
φ

Example-based supervised learning algorithm

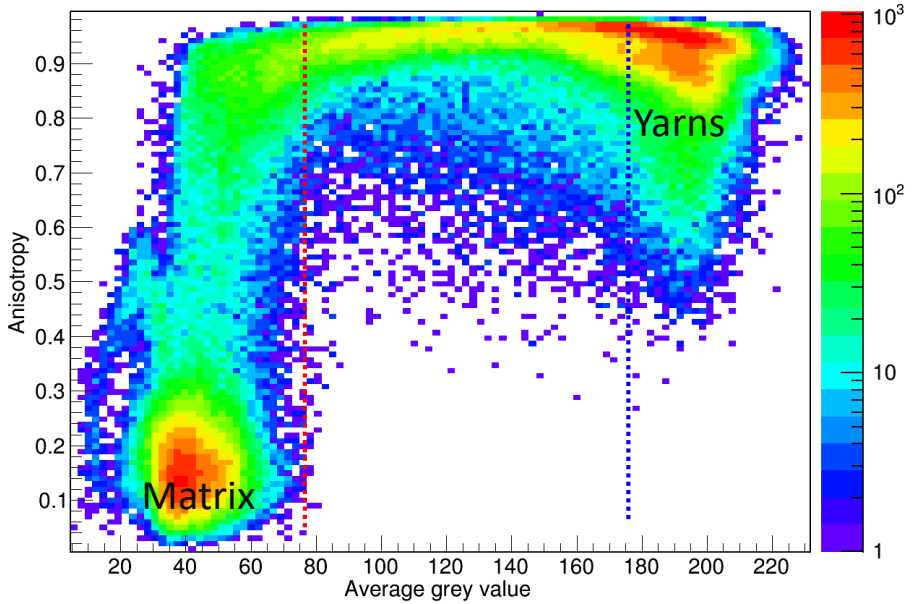
Matrix
$[AGV, Anisotropy, \varphi]_{matrix}$

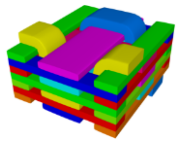
Warp
$[AGV, Anisotropy, \varphi]_{warp}$

Weft
$[AGV, Anisotropy, \varphi]_{weft}$



(VoxTex developed by Straumit et al. 2014)





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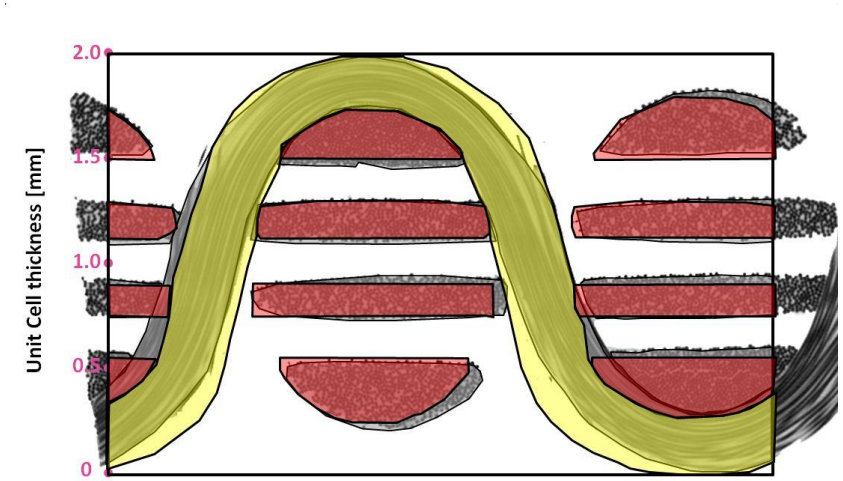
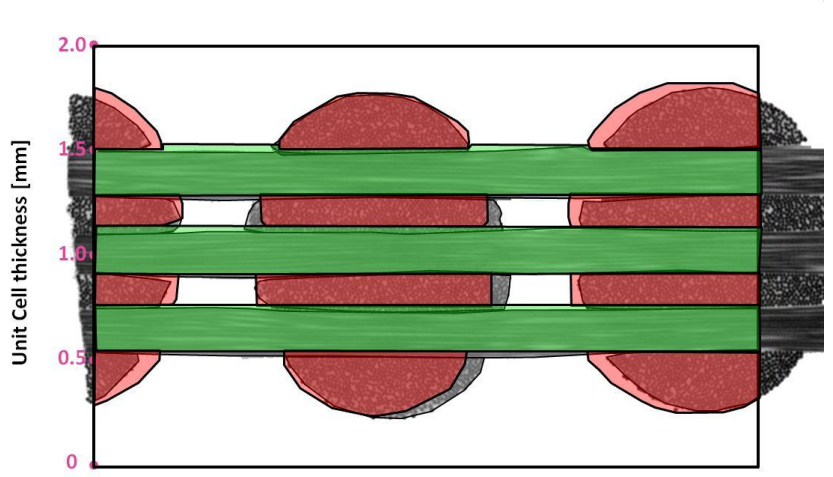
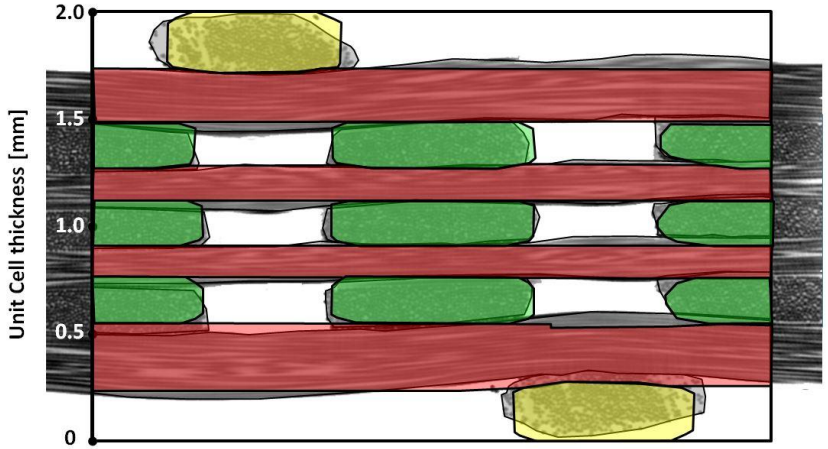
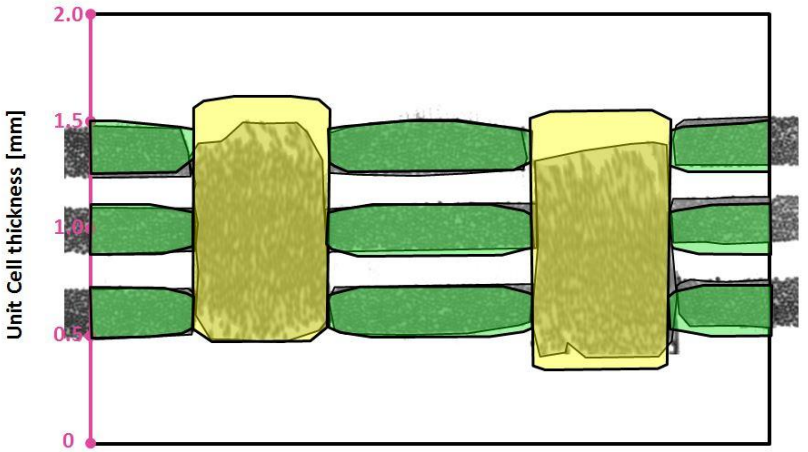
Geometry and FEA

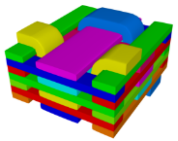








Grey regions: real yarns; colored regions: idealized yarn sections



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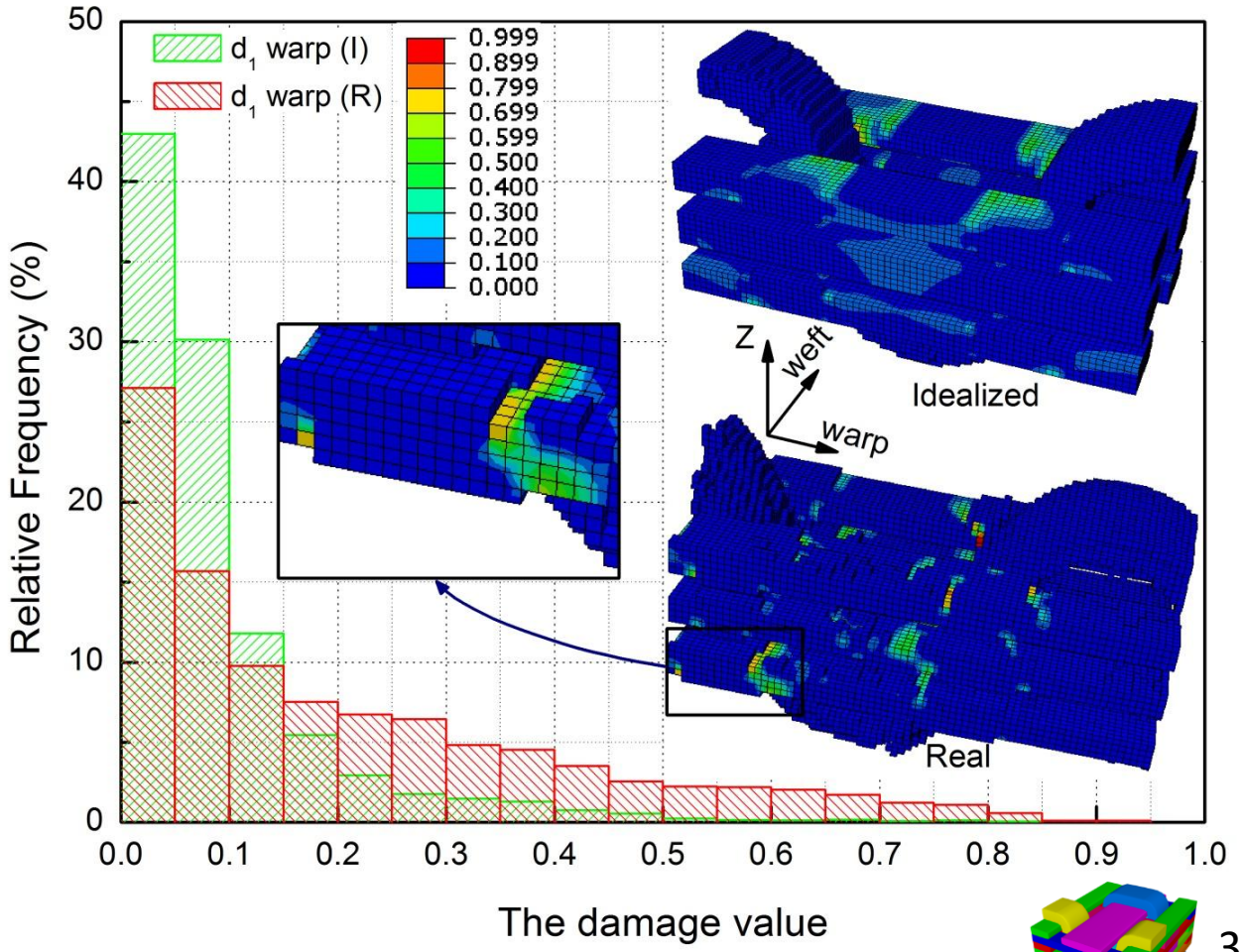
Damage modeling

- Realistic geometry changes the mechanisms and intensity of degradation.
- Be cautious when using voxel-type models.



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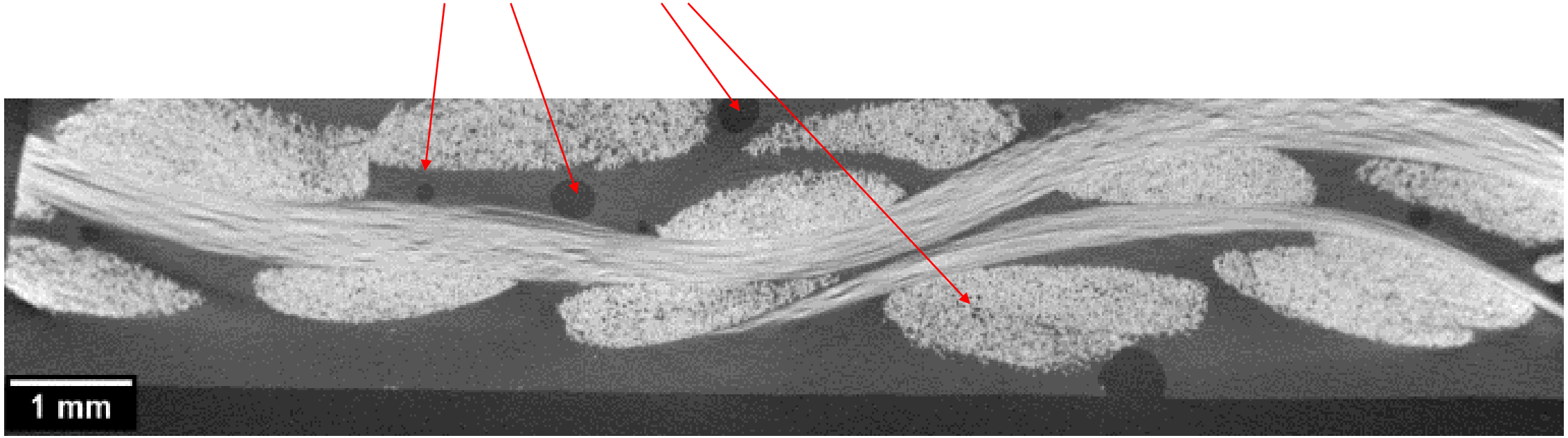
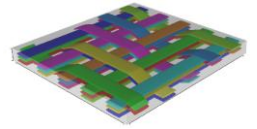
Textile with manufacturing defects

We added void type defects





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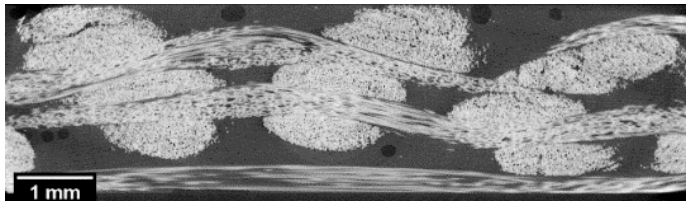
µCT with voids

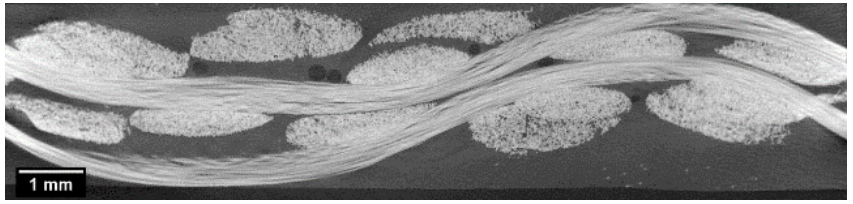
General description:

- 1440 projection images over a 360° rotation
- Projection image was the average of 6 frames
- Spot size of about 2 µm was chosen
- Two type of textiles (“satin” and “twill” in 3D)
- Voxel size 6,45 µm and 8,79 µm respectively
- Setups : tension 80 kV; current 124 µA (or 68 µA); frame rate 10 fps
- Reconstructed volume (mm^3): 9,96x3,06x7,17 or 13,71x3,14x9,99

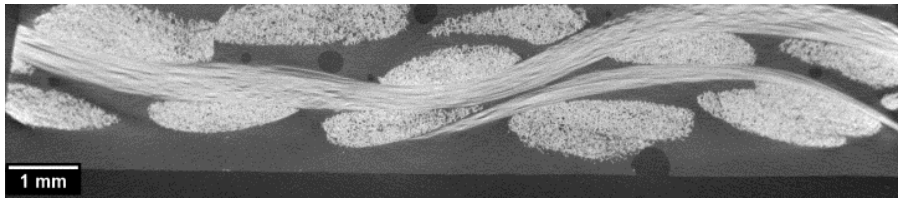
Reconstructed images:



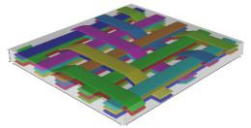
Satin3D Upper

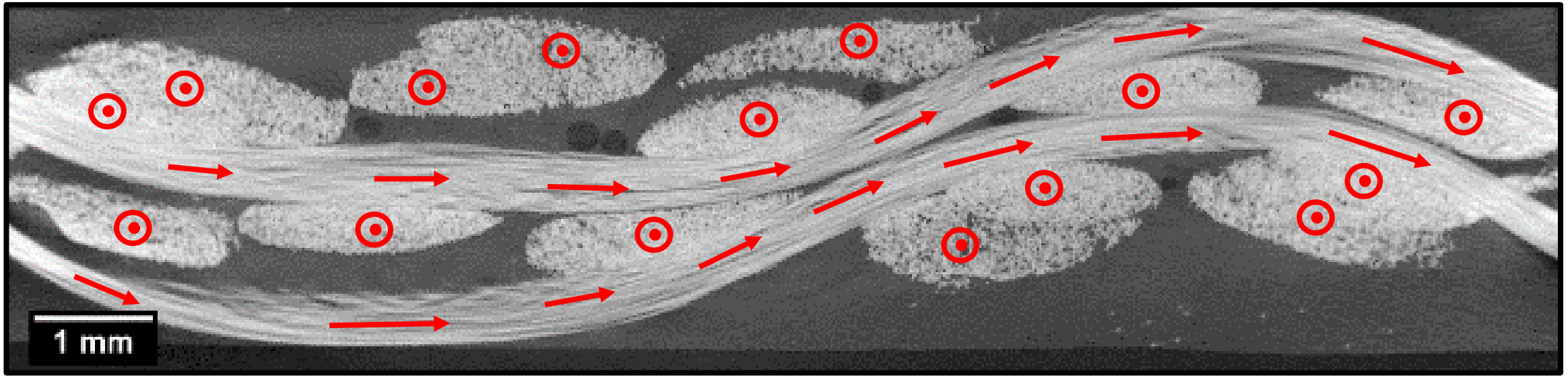


Twill3D Upper



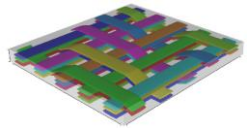
Twill3D Lower

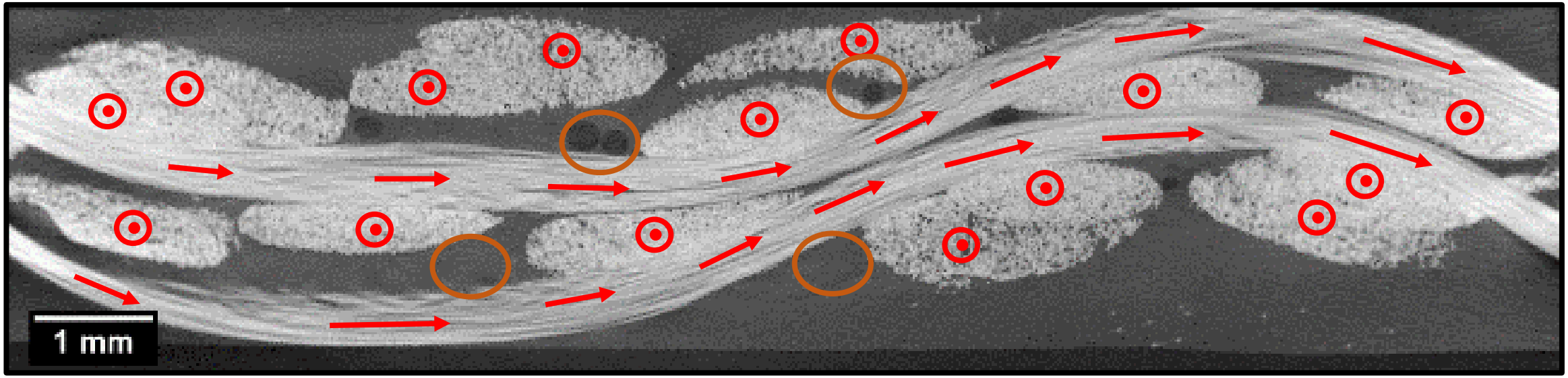




Challenges :

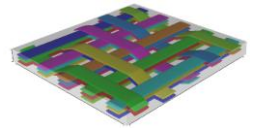
- Yarns are composite materials (anisotropic behavior)

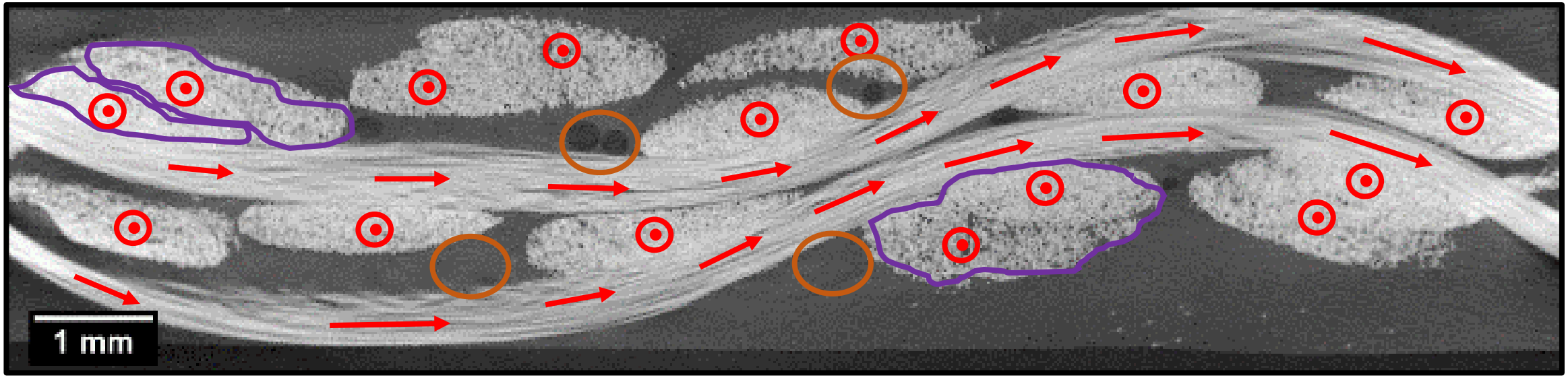




Challenges :

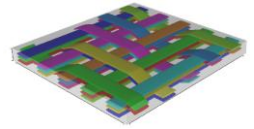
- Yarns are composite materials (anisotropic behavior)
- High level of noise due to several factors (e.g., textile size, high contrast between resin and fiber, low contrast between resin and voids)





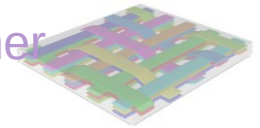
Challenges :

- Yarns are composite materials (anisotropic behavior)
- High level of noise due to several factors (e.g., textile size, high contrast between resin and fiber, low contrast between resin and voids)
- Mesoscale-driven architecture that continuously changes from one cross-section to another



Challenges :

- Yarns are composite
- High level of noise du nd fiber, low contrast between
- Mesoscale-driven arc



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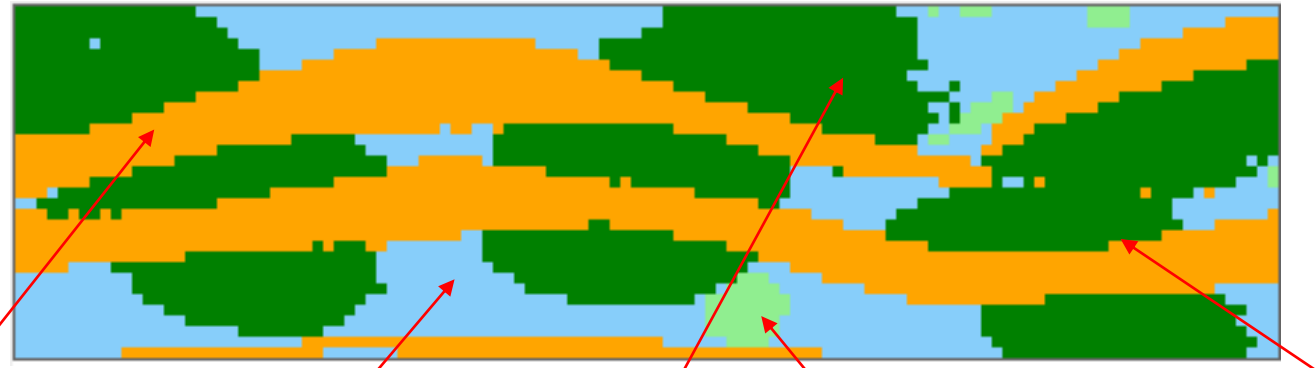
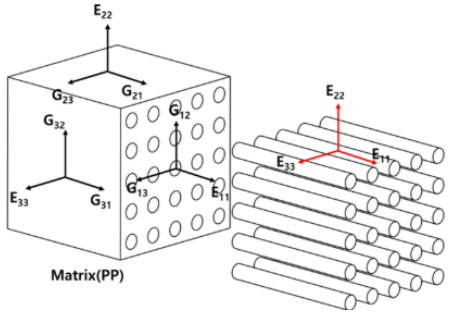
Segmentation results

Results of the supervised segmentation





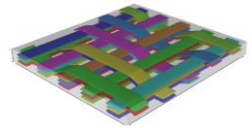
? warp yarns

? matrix

? weft yarns

? voids

? interfaces



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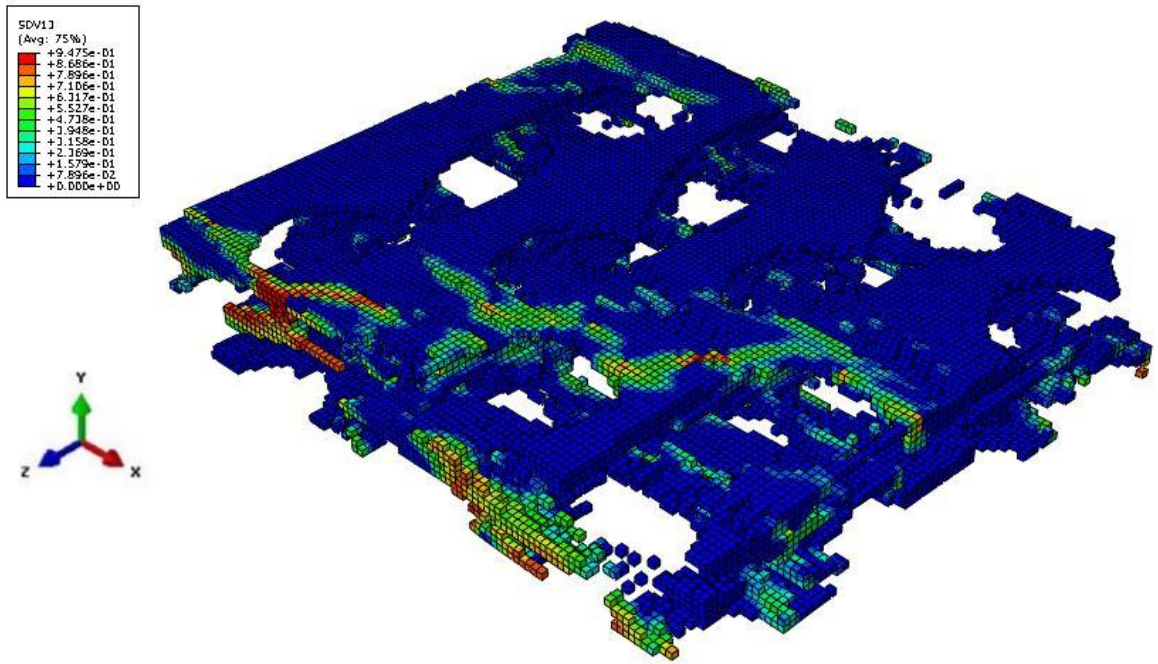
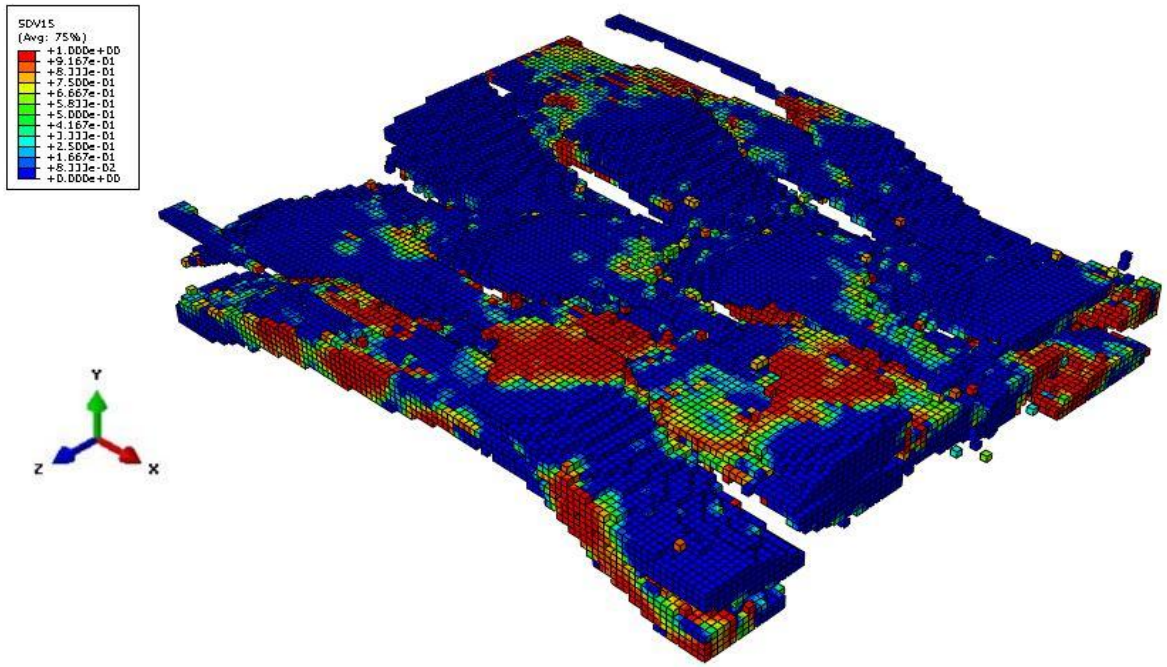
Voxel based mesh solution





N Naouar, D Vasiukov, CH Park, SV Lomov, P Boisse
Meso-FE modelling of textile composites and X-ray tomography Journal of Materials Science

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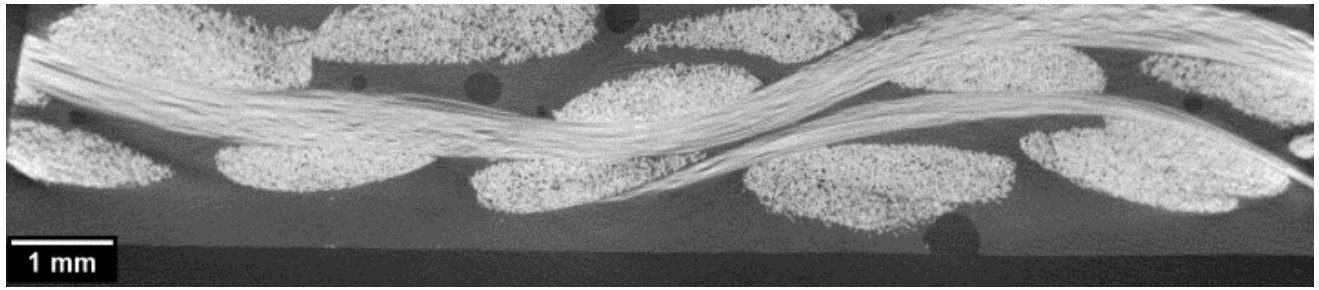
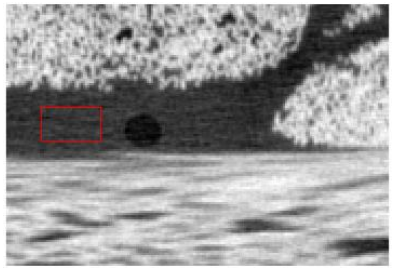
Segmentation activities

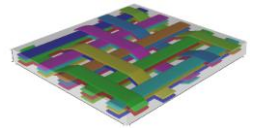
TP on supervised segmentation:

- Sample preparation (process conditions, phenomena to investigate)
- Image acquisition and preparation
- Parametric study
- Analysis
- Conclusions





https://github.com/yang-chen-2022/matlab-texcomp-segmentation



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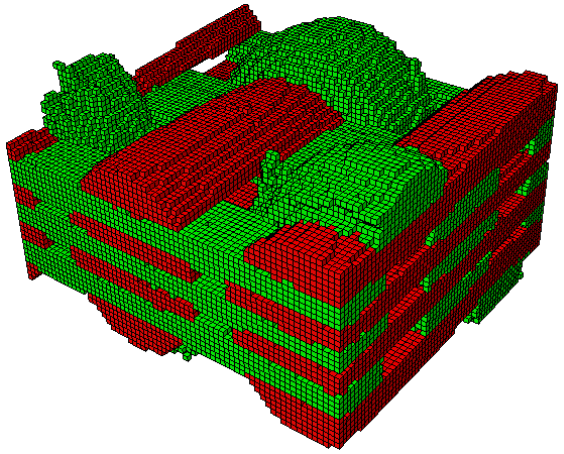
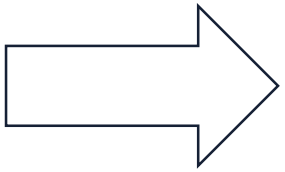
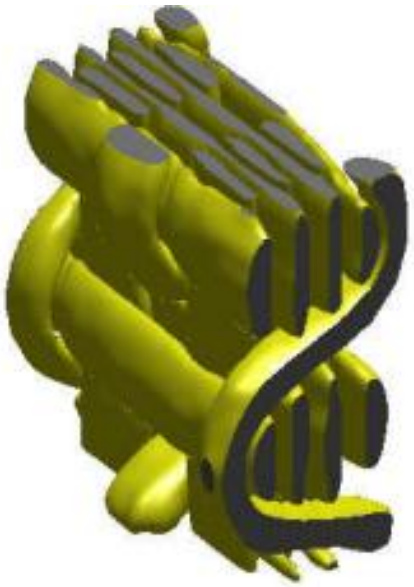
Conformal mesh







B Wintiba, D Vasiukov, S Panier, SV Lomov, KEM Kamel, TJ Massart
Automated reconstruction and conformal discretization of 3D woven composite CT scans with local fiber volume fraction control
Composite Structures 248, 112438

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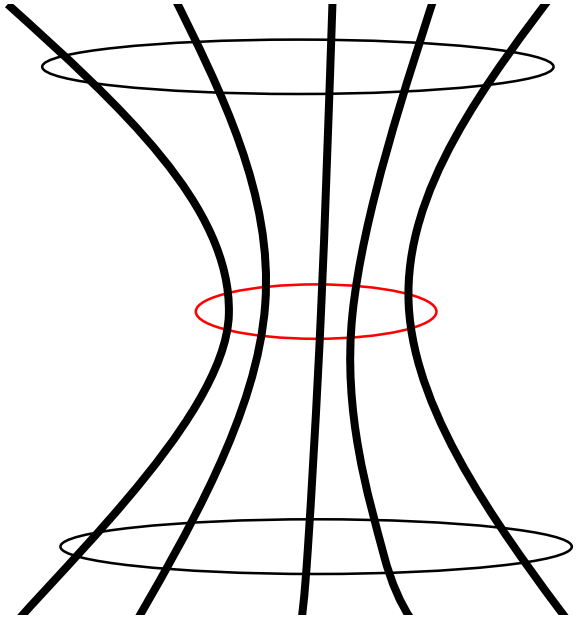
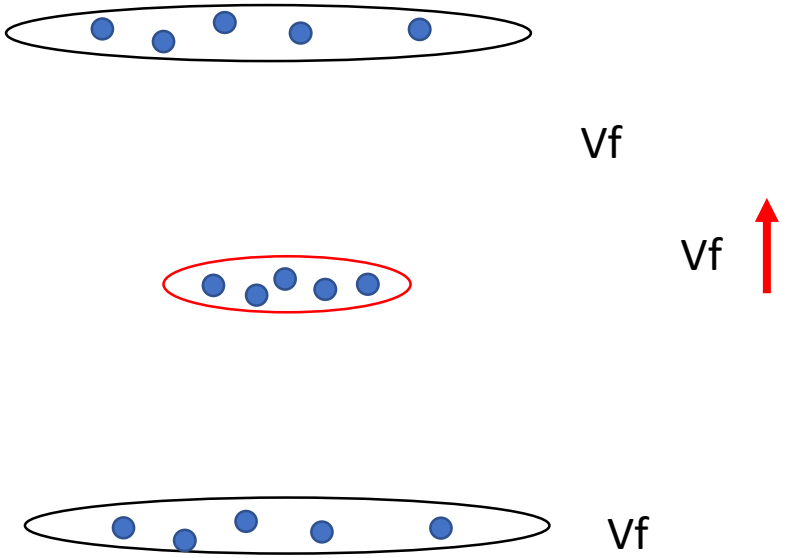
Fiber volume fraction (Vf) control

Variability in cross sections:

- Depends on the textile architecture
- Local material description based on the UD ply approximation (Chamis' or other)
- Gaps between yarns (generally can be modeled as resin material or cohesive elements)





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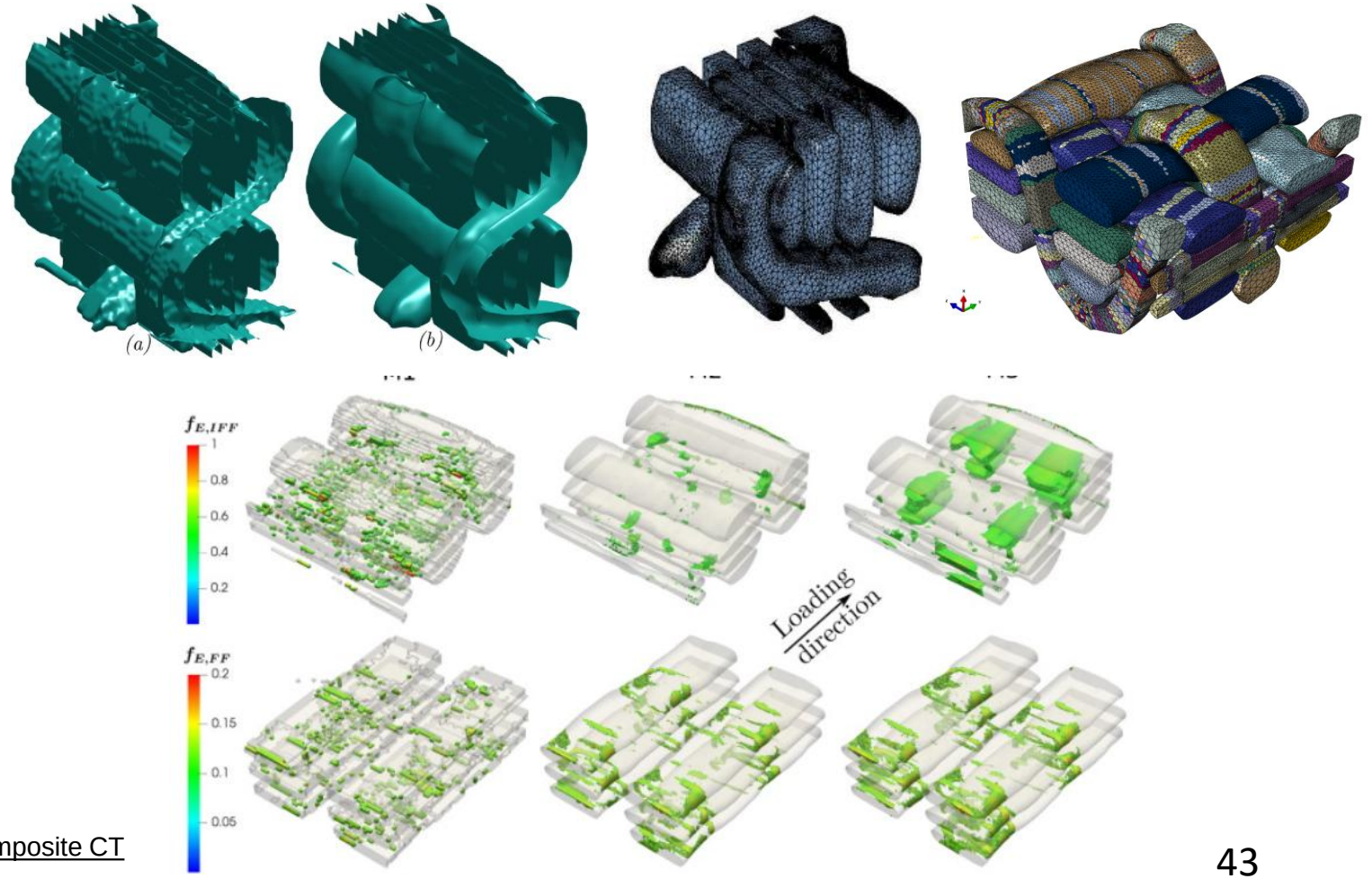
Conformal mesh

- Controlling Vf alters the degradation mechanisms and their intensity.
- Vf is assumed to be constant across the cross-section.
- The interfaces are challenging to approximate accurately.



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Outline

Introduction
- Institute / Research team / Research topics

Part 1: Multi-scale nature of composites materials
- Different scales

Part 2: Multi-scale image based characterization
- Microscopy (Optical and MEB)
- Microcomputed tomography (rings, noise, small contrasts, edge effects etc)

Part 3: Image based modeling
- Supervised segmentation (TP activity, example of the 3D warp interlock composite with voids)
- Voxel based vs conformal model

Conclusions
- Current trends and challenges

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Discussion

Advanced topics:

- Advanced characterization (synchrotron, in situ)
- Deep learning and machine learning (expert-annotated data)
- Process modeling and coupling with structural analysis
- Advanced material modeling (multiphysics, long-term behavior, bio-based or biodegradable materials)
- Advanced solvers (multiscale, computational acceleration)
- …

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Thank you!

Dmytro VASIUKOV

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