Fraunhofer ITWM

Research Institute in Civil Engineering and Mechanics

CENTRALE NANTES

Image Processing Applied to Multi-Scale Textile Reinforcements for Permeability Prediction

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Leibniz-Institut für Verbundwerkstoffe

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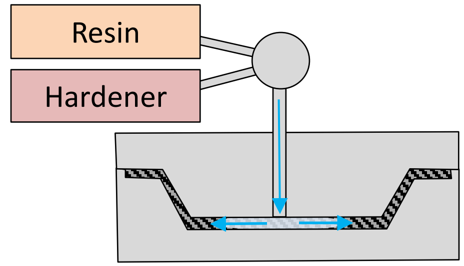
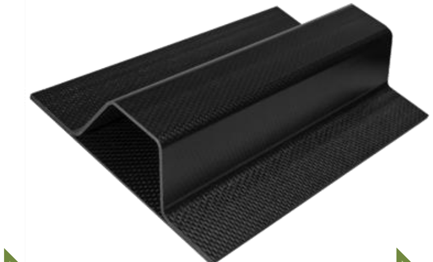
Introduction

Liquid Composite Molding Process





Textile → Preform → Liquid Composite Molding → Component

Darcy's law:

$$\mathbf{v} = -\frac{K}{\eta} \cdot \frac{\Delta P}{\Delta L}$$

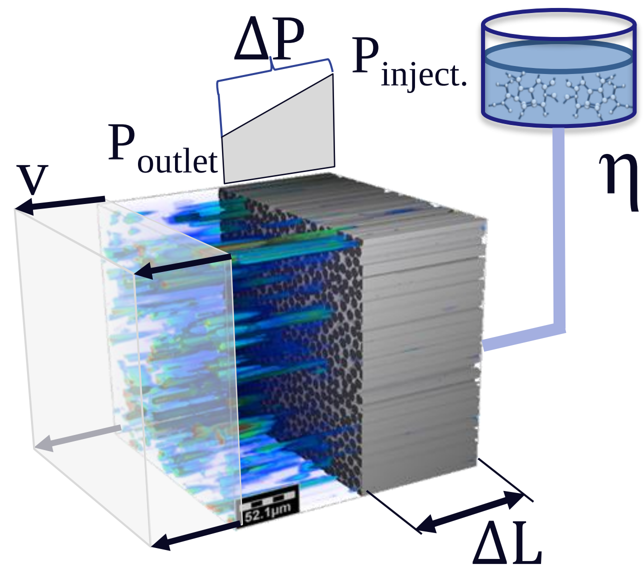
(volume-averaged) flow velocity: $\mathbf{v}$

Permeability: K

viscosity: η

pressure drop: ΔP

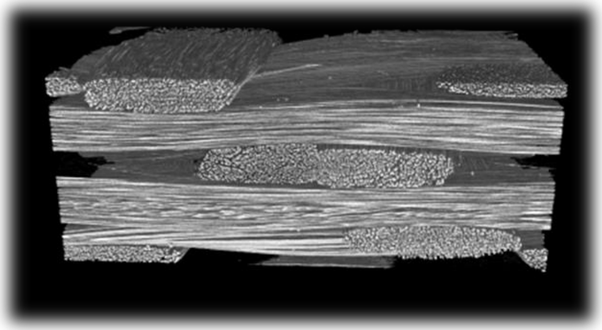
flow length: ΔL



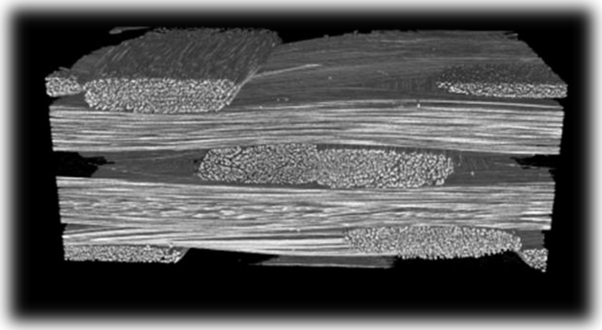
Motivation of benchmark

1. Fiber reinforcements in composites are special class of porous media:
   - *dual-scale porosity*,
   - *poor scale separation*,
   - *anisotropy*,
   - *variability*.

2. Very few commercial software to compute permeability of porous media. The majority – not designed to address multi-scale fibrous media.



Motivation of benchmark



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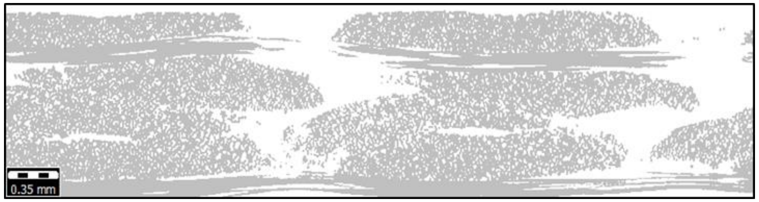
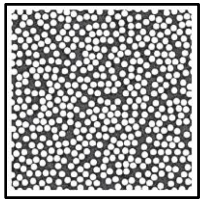
   - *anisotropy*,
   - *variability*.

2. Very few commercial software to compute permeability of porous media. The majority – not designed to address multi-scale fibrous media.

3. Benchmark of experimental measurements of permeability revealed high discrepancy of results – at least ~20% [*Vernet et al, 2014*].

4. Influence of material geometrical variability on permeability is difficult (impossible at micro-scale) to appreciate through a purely experimental effort.

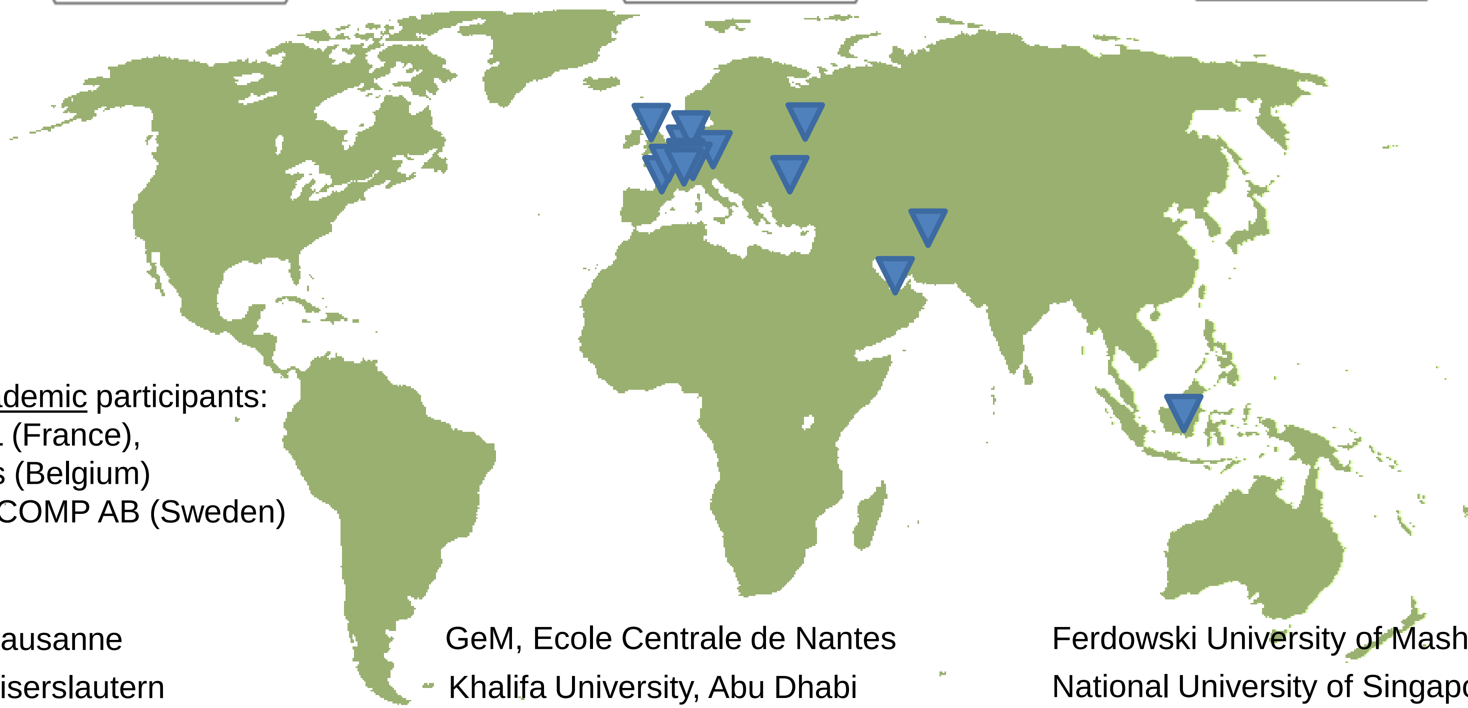




[*Bodaghi et al, 2016*]

<u>Virtual Permeability Benchmark</u> – first contribution to a real fibrous structure.

Benchmark organization



✓ 3 non-academic participants:
- TENSYL (France),
- Siemens (Belgium)
- RISE SICOMP AB (Sweden)

LPAC, Lausanne
IVW, Kaiserslautern
3SR Lab, Grenoble
ITWM, Kaiserslautern
ICI, Ecole Centrale de Nantes
TENSYL, Perigny

GeM, Ecole Centrale de Nantes
Khalifa University, Abu Dhabi
Universität Stuttgart
University of Nottingham
IMT Lille Douai
RISE, Göteborg

Ferdowski University of Mashdad
National University of Singapore
Skoltech, Moscow
École des Mines de Saint-Etienne
Siemens Industry Software, Leuven
KU Leuven

Benchmark organization

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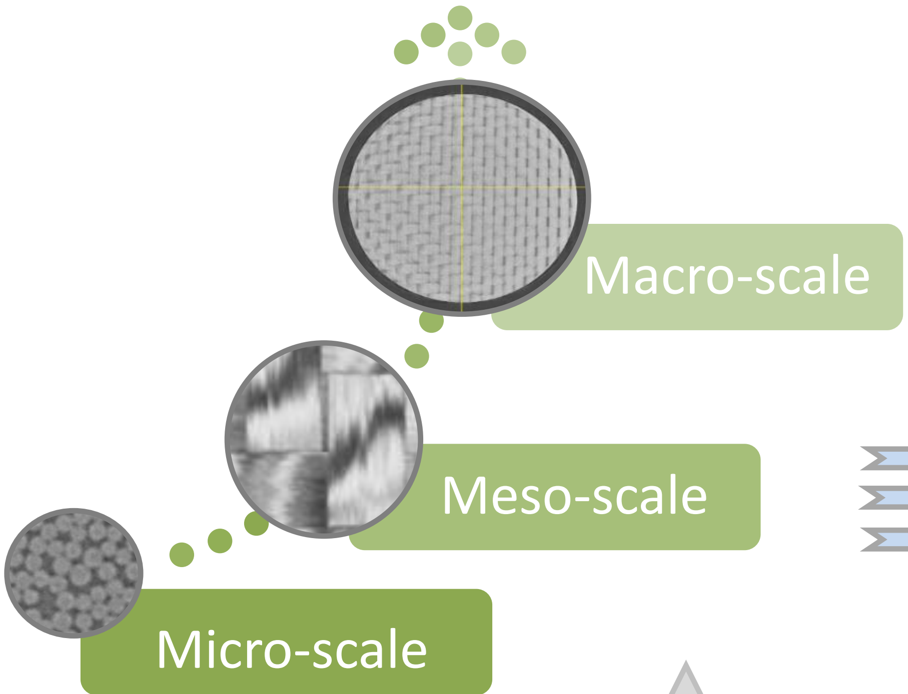
Objective: develop general guidelines for the image-based numerical prediction of permeability of engineering textiles

- To provide **pre-segmented** images to eliminate possible sources of variation.
- No fixed conditions (method, boundary conditions,…) for the calculations, except for the use of **pre-segmented** images.
- Samples with global fiber volume content (54%) with expected non-negligible flow at both scales.

two types of images/numerical samples

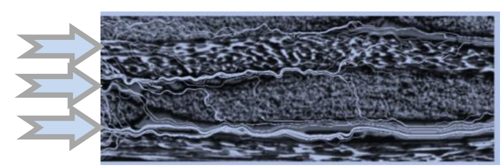
Benchmark approach

Final stage of the Virtual permeability benchmark



Macroscopic permeability tensor of twill 2/2 fabric

$$\mathbf{K} = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{xy} & K_{yy} & K_{yz} \\ K_{xz} & K_{yz} & K_{zz} \end{bmatrix}$$



First stage – microscopic predictions

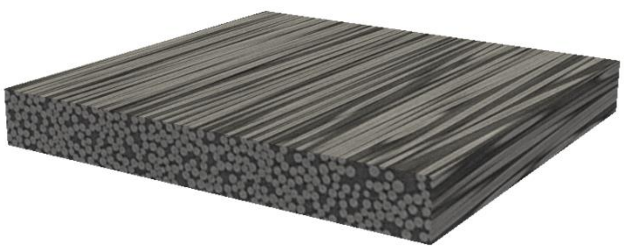
Single-scale flow → intra-tow permeability $\mathbf{K}_{tow}$

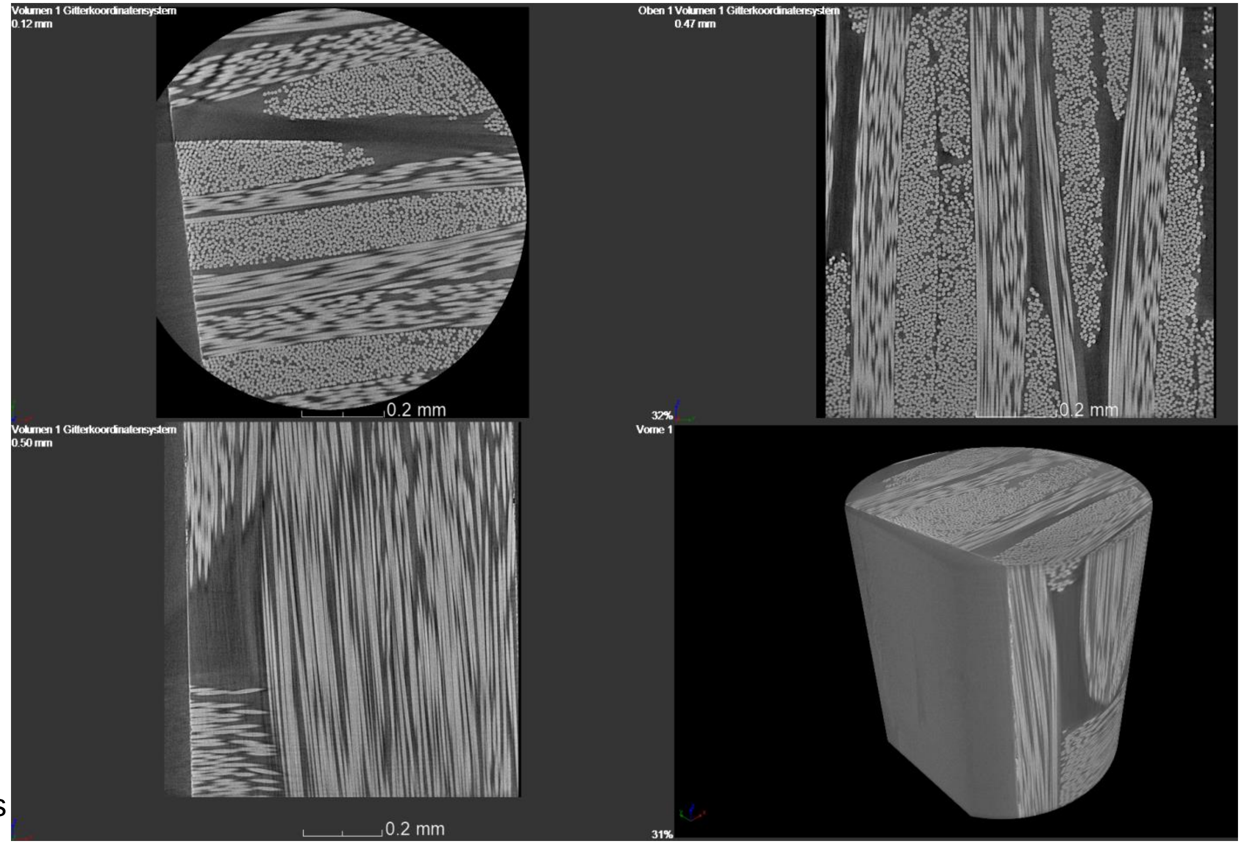
Micro-scale image processing

- Balanced twill 2/2 glass fabric (295 g/m^2) used in the experimental benchmark [*May et al, 2019*]
- 3 yarns twisted in a tow
- 40 twist/meter => 1 twist / 25 mm
- Fibre diameter: 7.5-9.3 µm (9 µm in data sheets)

3D X-Ray microscope scan prepared at IVW

Sample for calculation





<u>Sample volume:</u> tow thickness

~400 fibres in plane

507 µm fibres length

<u>Image voxel size:</u> 0.521^3 µm

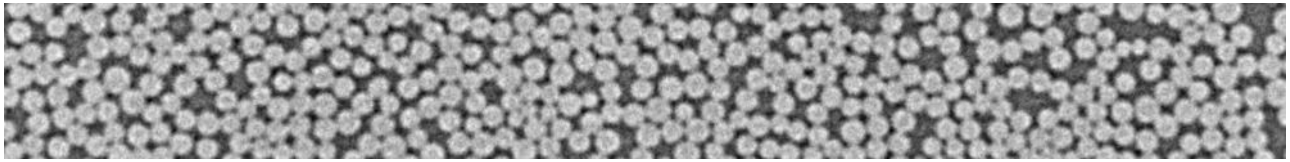
<u>Image dimensions:</u> 1003x124x973 voxels

Micro-scale image processing

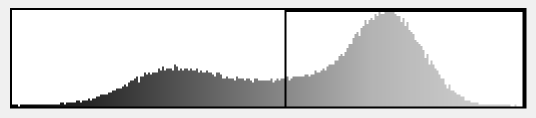
Segmentation of micro-scale images at CENTRALE NANTES

<u>Challenges:</u>

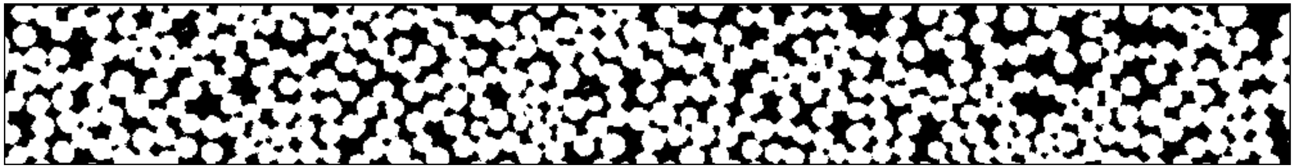
- scanner artefacts;
- fibres twisting;
- varying fibre diameter



Segmentation



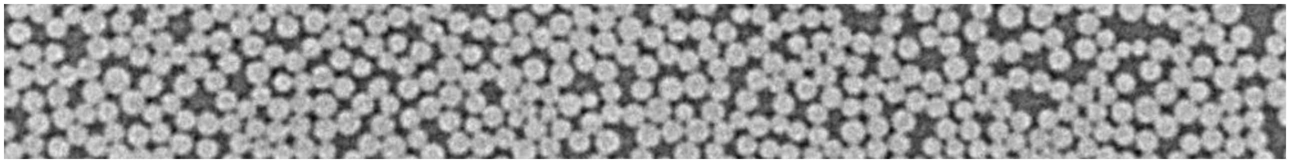
<u>Thresholding</u> techniques – presence of inter-fibre «bridges» that can block flow



– Traditional global/local <u>thresholding</u> techniques are hardly directly applicable

Micro-scale image processing

Segmentation of micro-scale images at CENTRALE NANTES

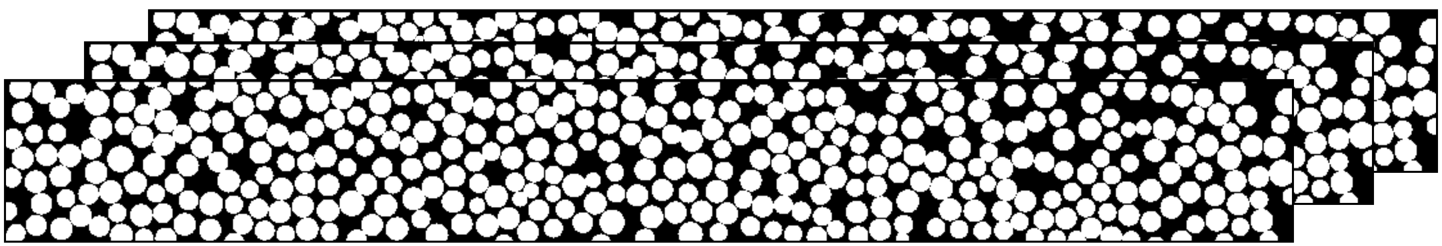


Segmentation

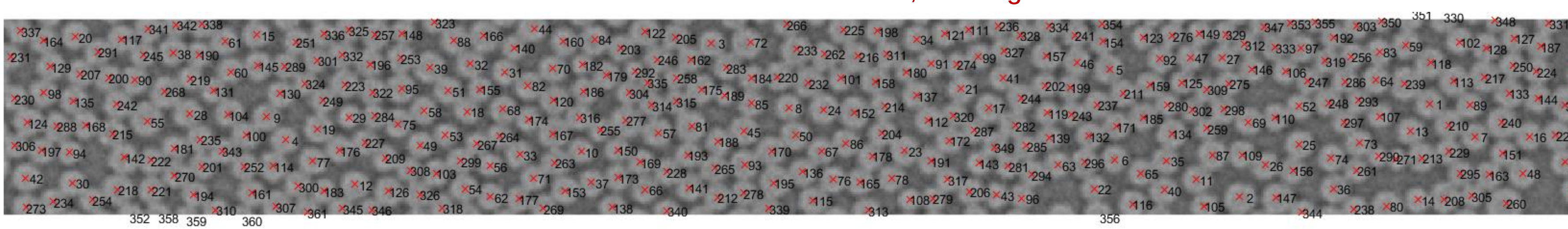
1/ Hough transform applied to 2D slices to detect fibres centres and circular cross-sections

2/ Tracking of fibre paths through slices and fibres labelling

3/ Smoothing of fibre paths



1/ Detection of fibres centers, labeling



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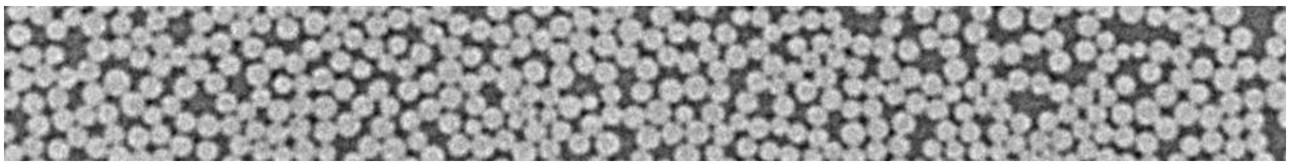

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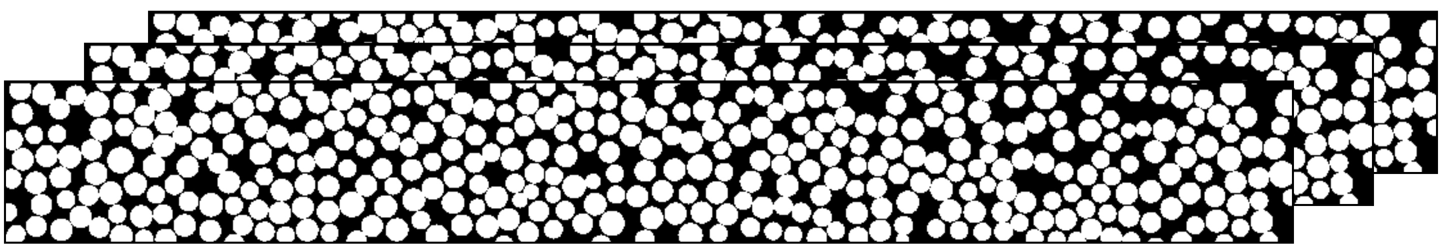
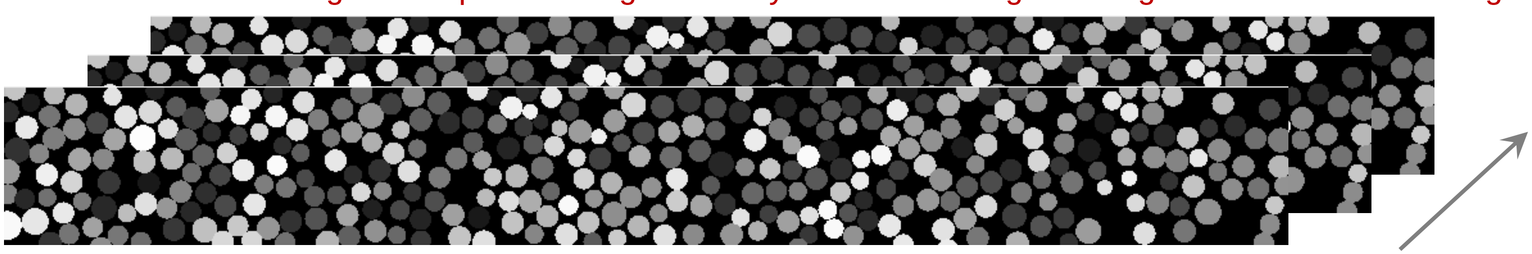


2/ Tracking of fibre paths through slices by the nearest neighbour algorithm and their labelling



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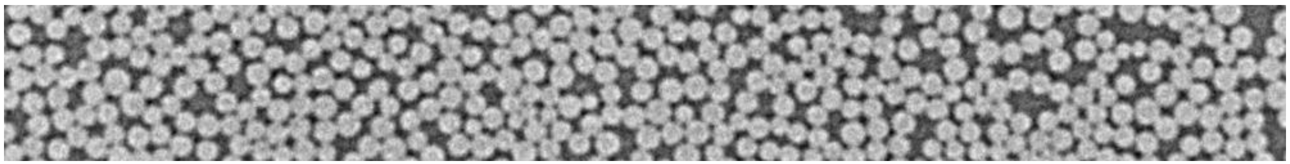

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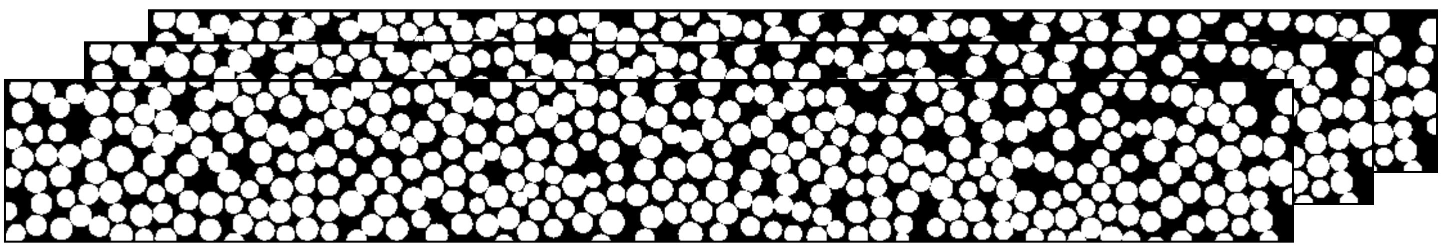
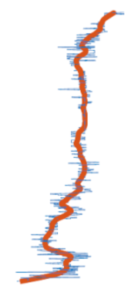
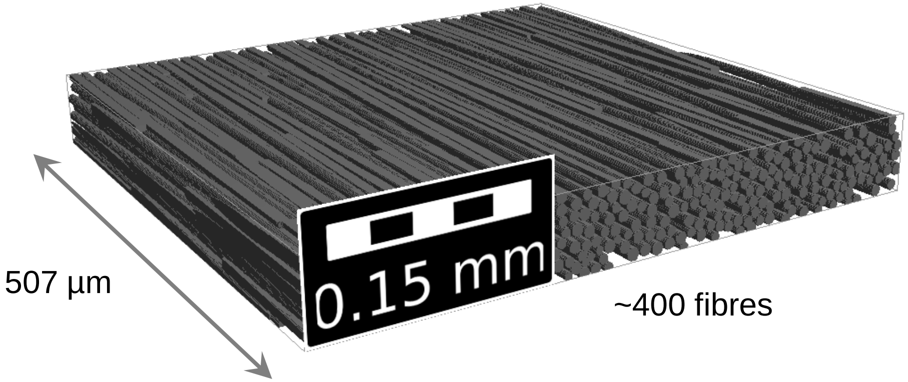


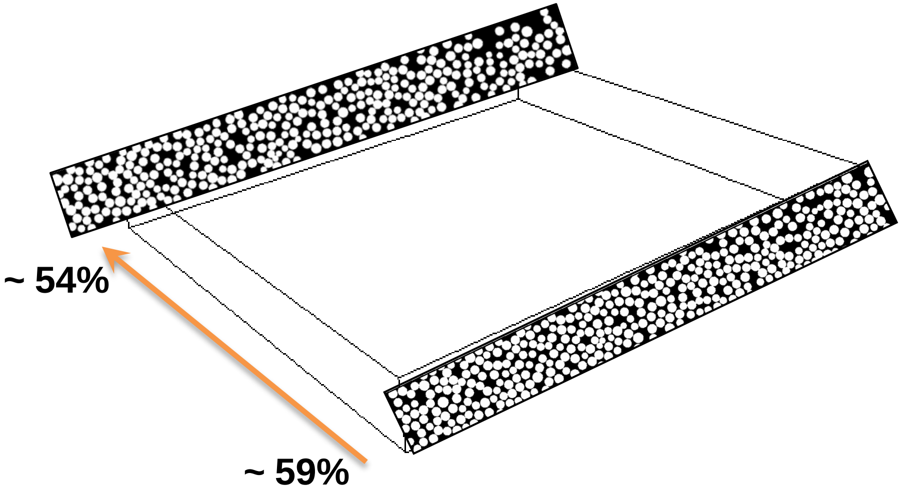


3/ 3D smoothing of fibre paths by local regression using weighted linear least squares and a 1st degree polynomial model:

Micro-scale image processing

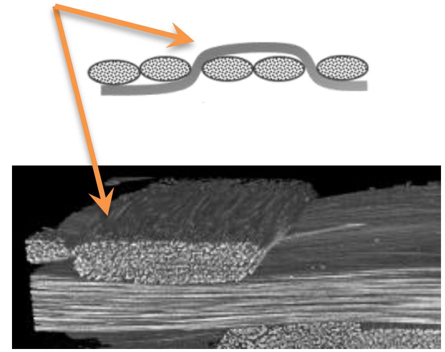
Provided segmented volume
with defined two phases





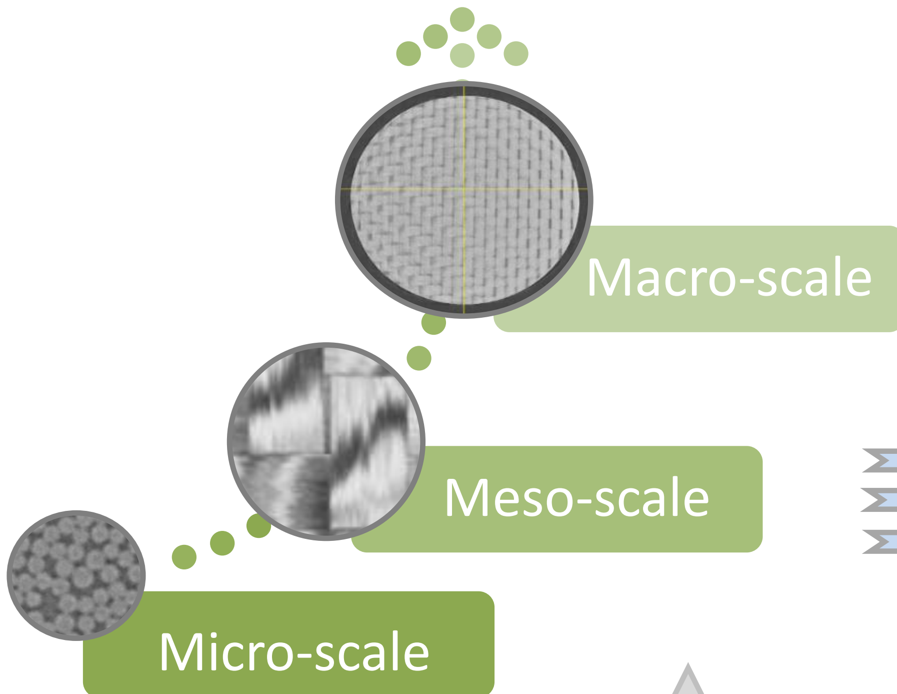
FVC = 54%-59%

Twill fabrics architecture with locally more or less compacted tows depending on their crossings:



locally varying within
the tow fibre volume
fraction FVC

Final stage of the Virtual permeability benchmark



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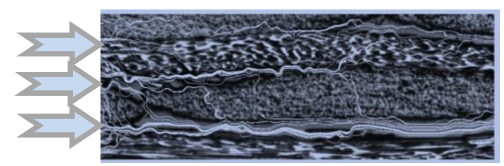

First stage – microscopic predictions

Single-scale flow

intra-tow permeability $\mathbf{K}_{tow}$

Meso-scale image processing

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Segmentation of meso-scale images at Fraunhofer ITWM

Several nested layers of twill fabric

Objectives:

- Segment tows and pore phases
- Separate tows based on direction (warp and weft)
- + Evaluate local orientation of tows

✓ Assure a proper fibre volume fraction

Challenges:

- highly compacted local contact areas;
- limited voxel size;
- slight variation in out-of-plane orientations

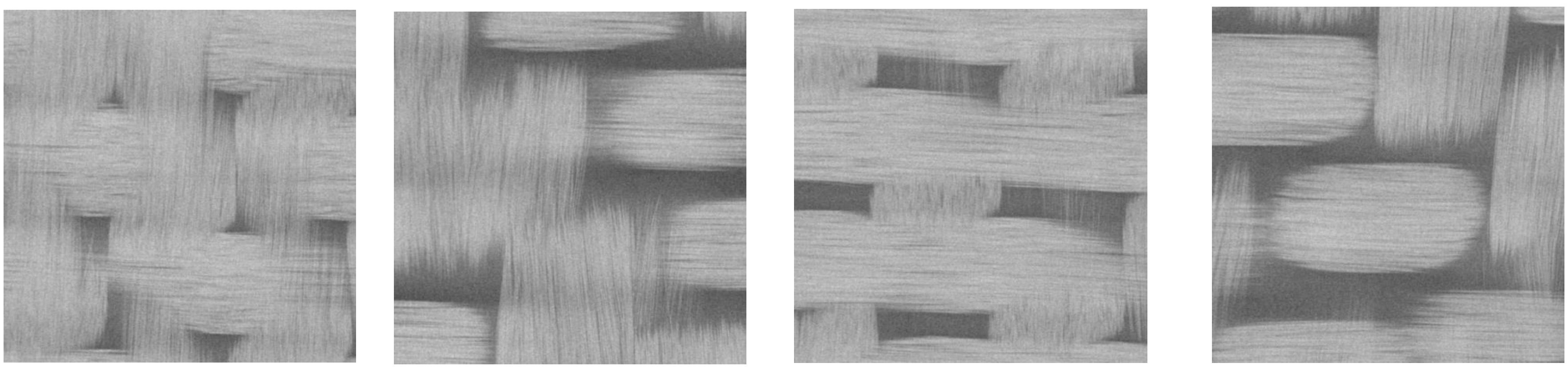
Segmentation of meso-scale images at Fraunhofer ITWM

➢ Apparent interpenetration

partial volume effect

strong X-ray absorption contrast

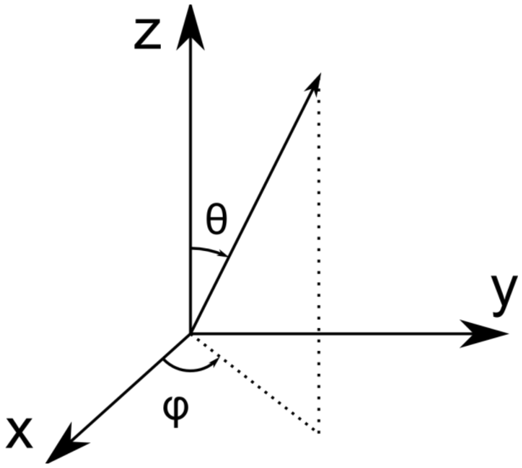
limited voxel size



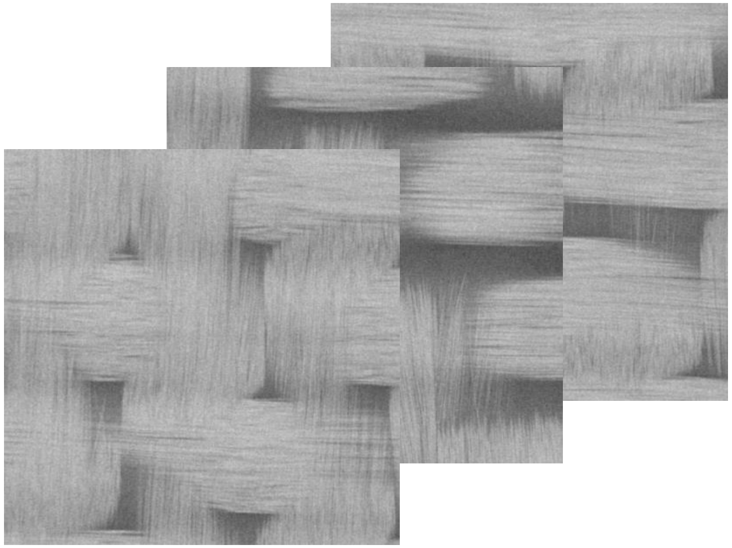
Examples of slices with the effect of “transparent” overlapping tows

– Orientations evaluation and directions separation cannot be performed by the direct use of a single 3D method.

- Orientation in spherical coordinates (θ, φ)
- Separate tows that differ by in-plane orientation
- φ to be estimated from XY-plane classification: 0 or $\pi/2$

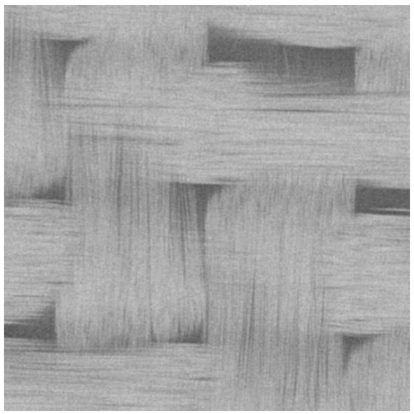


Several nested layers of twill fabric

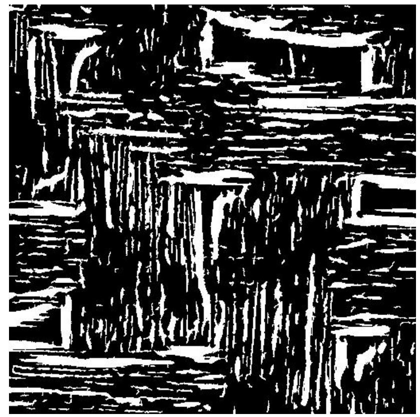


Meso-scale image processing

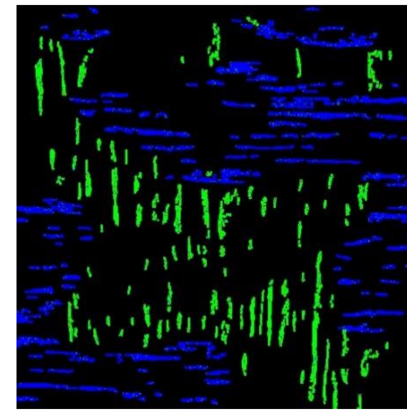
Segmentation of two in-plane directions



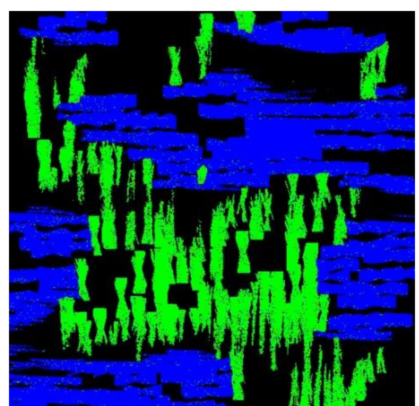
Tow segments identification by Frangi vesselness filter



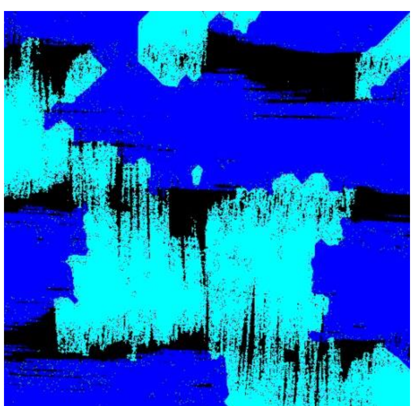
Tow segments classification based on orientation defined by Hessian approach



Tow segments reconstruction by directional dilation

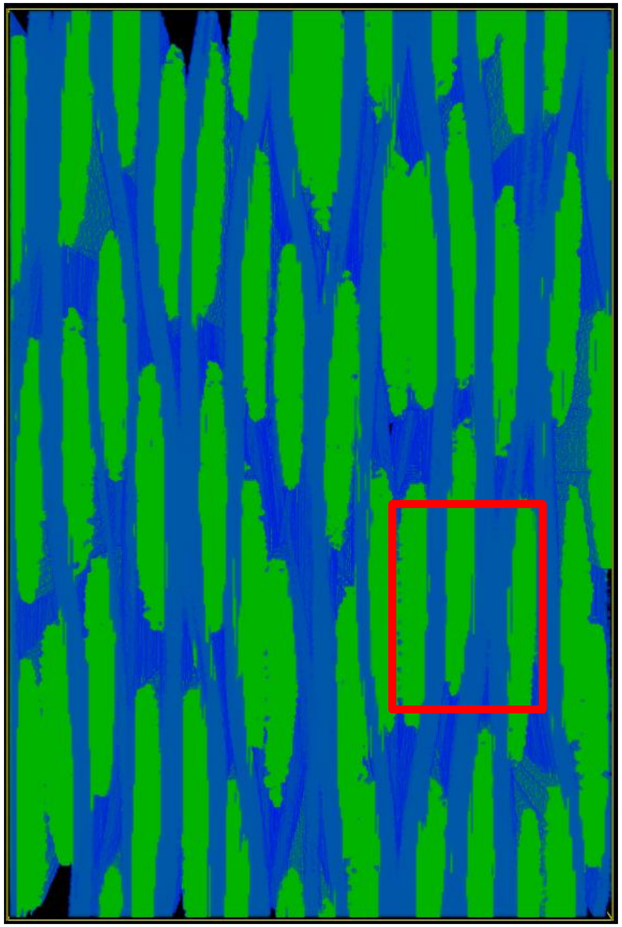


Full classification by the nearest neighbour algorithm

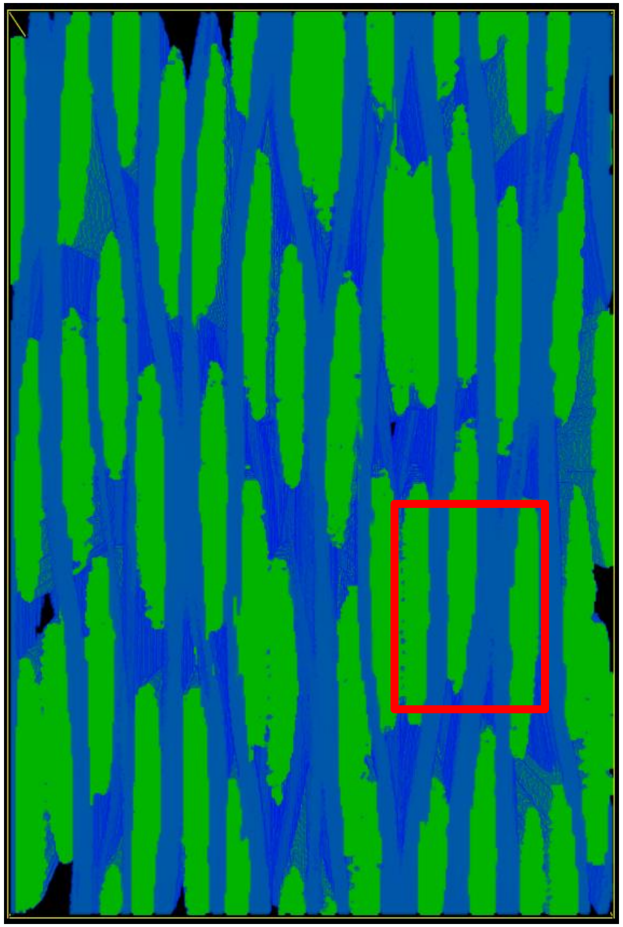


Meso-scale image processing

3D assembling: stacking of 2D slices



3D median filter for artefacts removal



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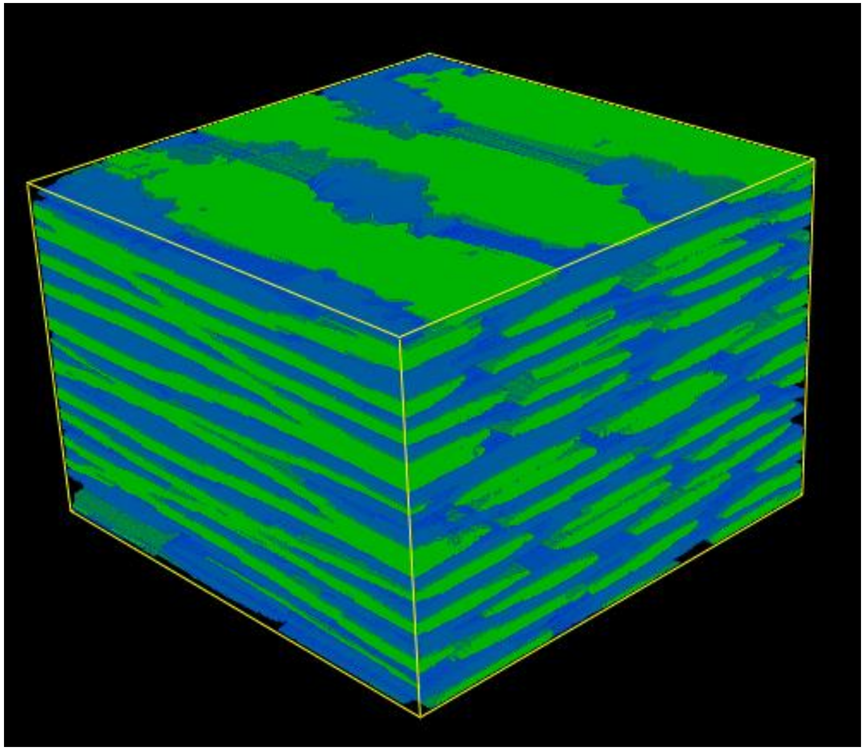
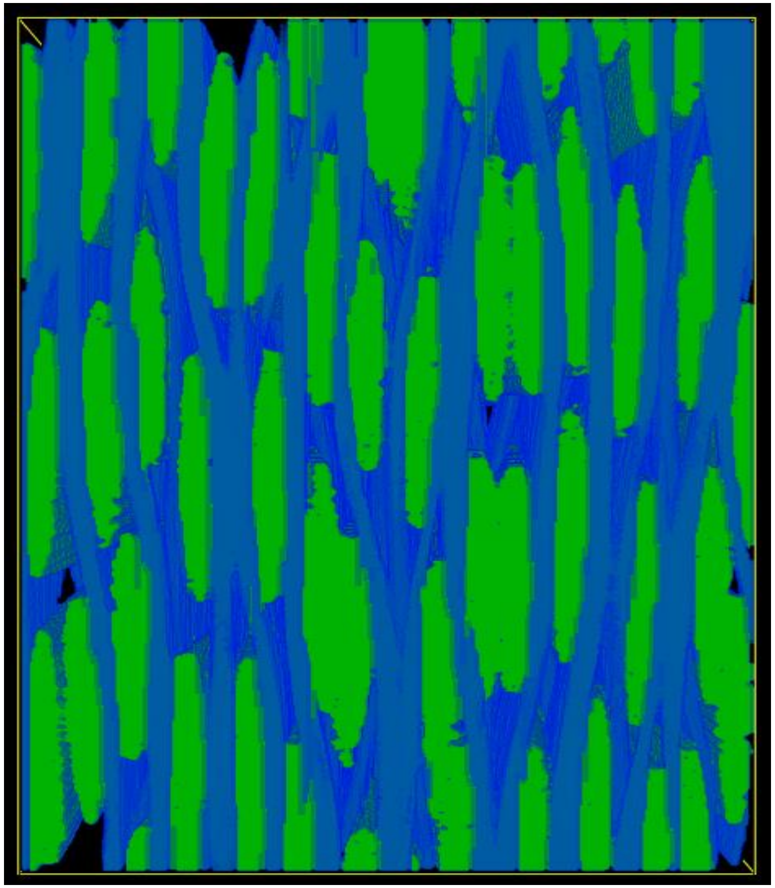
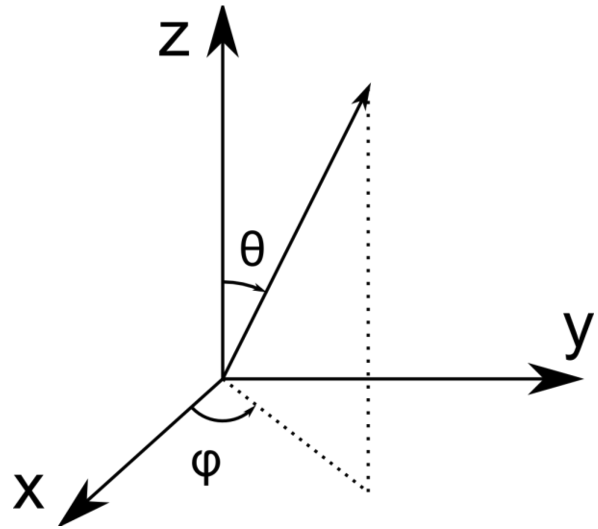
Results of segmentation

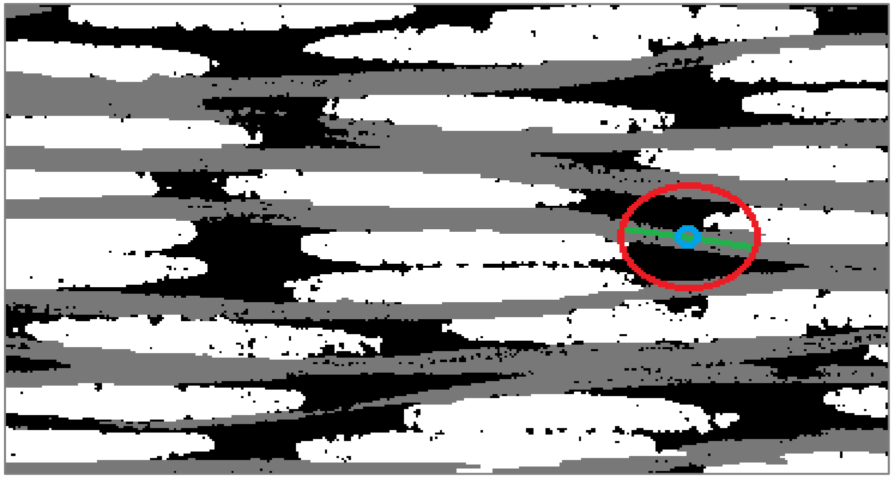




Local orientation estimation: out-of-plane orientation

- Orientation in spherical coordinates (θ, φ)
- φ estimated from XY-plane classification: 0 or $\pi/2$
- θ using anisotropic Gaussian filter in YZ and XZ planes



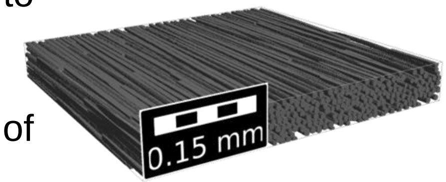


➢ For every point that belongs to the tow anisotropic filtering is performed on sampled orientations from a circle (red) choosing maximal filter response as θ.

Conclusions

Conclusions

- Appropriate image processing procedures have been successfully developed to apply at different scales of fibrous materials.



- Virtual permeability benchmark results large variation confirms the necessity of pre-segmentation of images as a source of additional discrepancies.

- Choice of methods to be applied to fibrous materials depends on a number of factors and their combination: image nominal resolution, variability of geometry, requirements for the speed of processing.

Way forward

- It would be interesting to benchmark separately the segmentation phase of fibrous reinforcements samples