Micromechanics of fibrous composites and permeability of fibrous media based on micro-CT images

Stepan V. Lomov[1], Oxana Shishkina[2], Jeroen Soete[1], Martine Wevers[1]

[1]*Department of Materials Engineering, KU Leuven, Belgium*

[2]*Siemens Digital Industries Software, Belgium*

www.composites-kuleuven.be

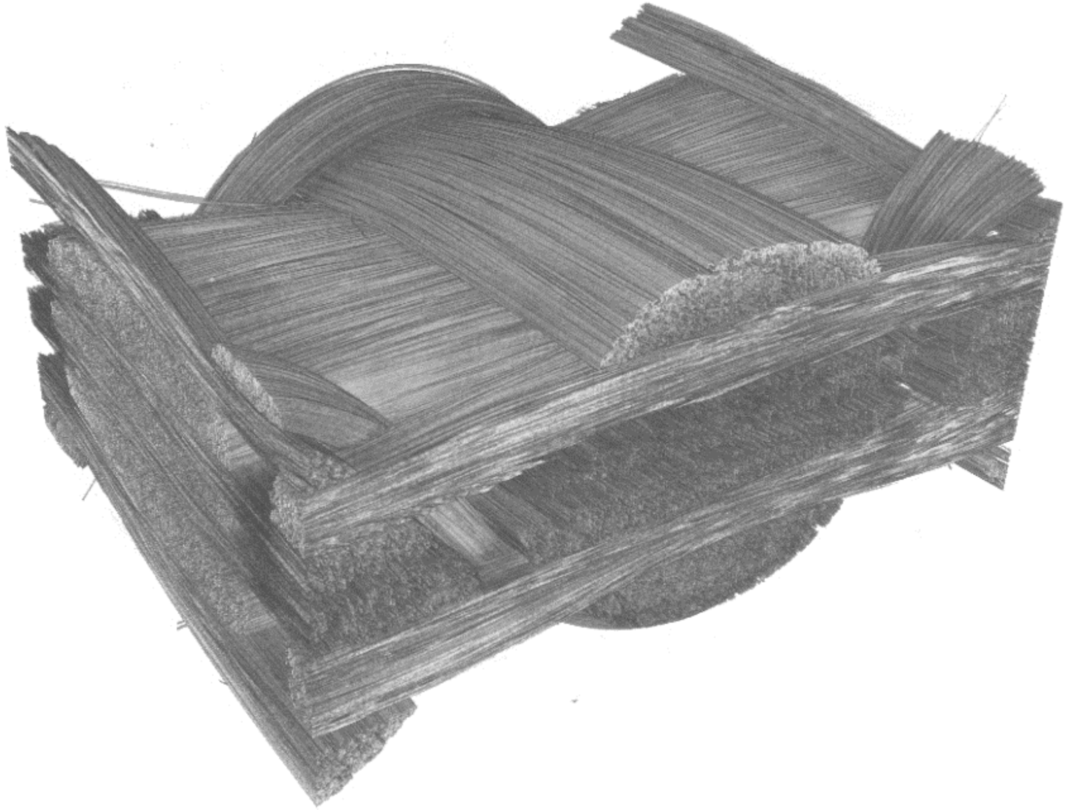
Through the µCT and what we found there

1. Introduction. Fibrous media: microstructural features and characteristics
2. Quantification of a µCT image of fibrous materials
3. Applications
   - Fibre orientations
   - Finite element models of deformation and damage
   - Permeability
4. Conclusions

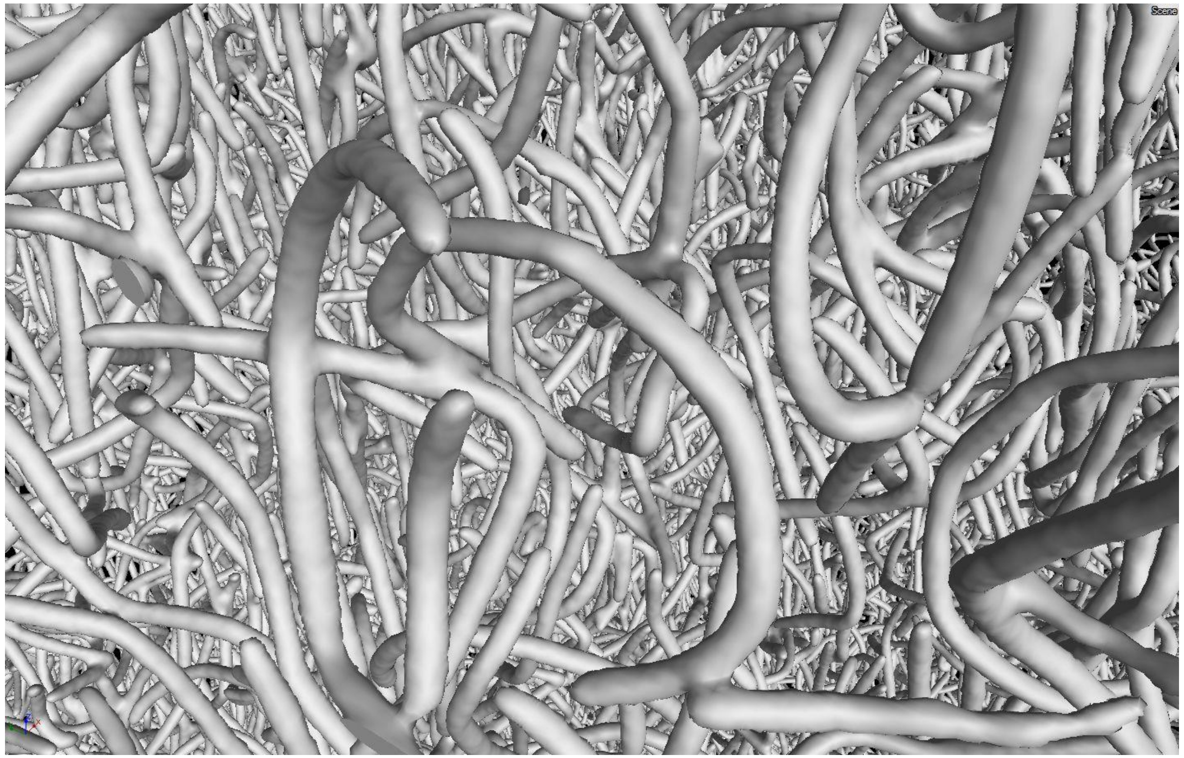
1. Introduction. Fibrous media: microstructural features and characteristics

2. Quantification of a µCT image of fibrous materials
3. Applications
    - Fibre orientations
    - Finite element models of deformation and damage
    - Permeability
4. Conclusions

Textiles and random fibre assemblies

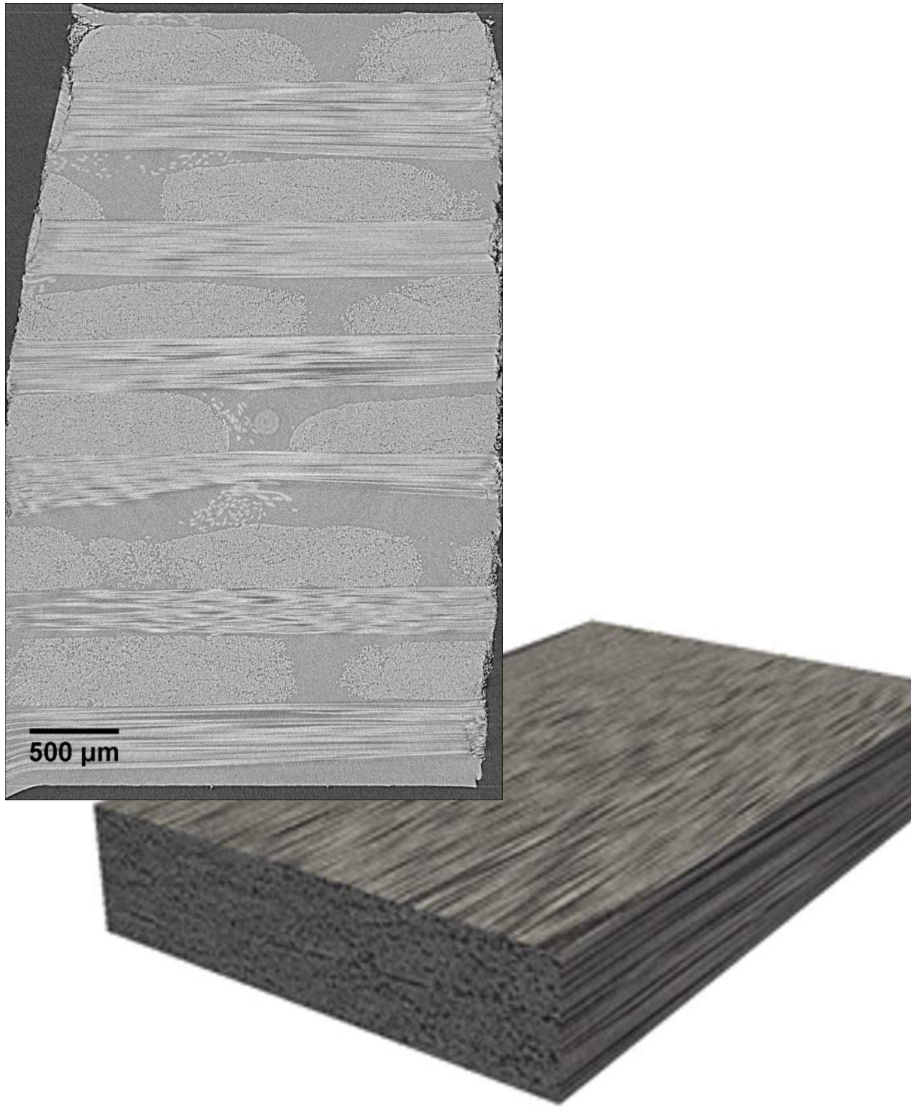


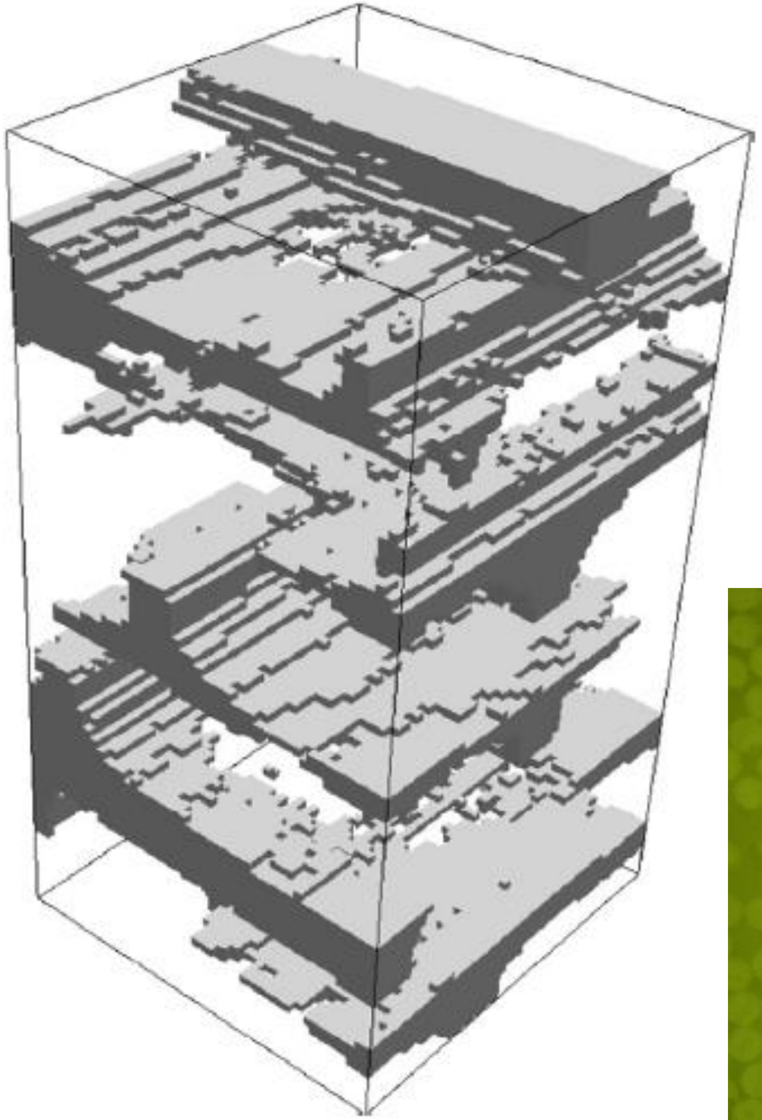
3D woven glass fibre textile



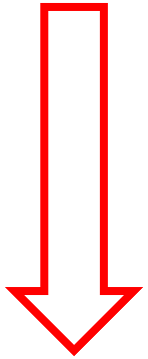
random steel fibre assembly

Textiles: Dual scale





yarn,
bundle &
pore size
~100 µm



fibre & pore
size ~10 µm

KU LEUVEN
MATERIALS ENGINEERING

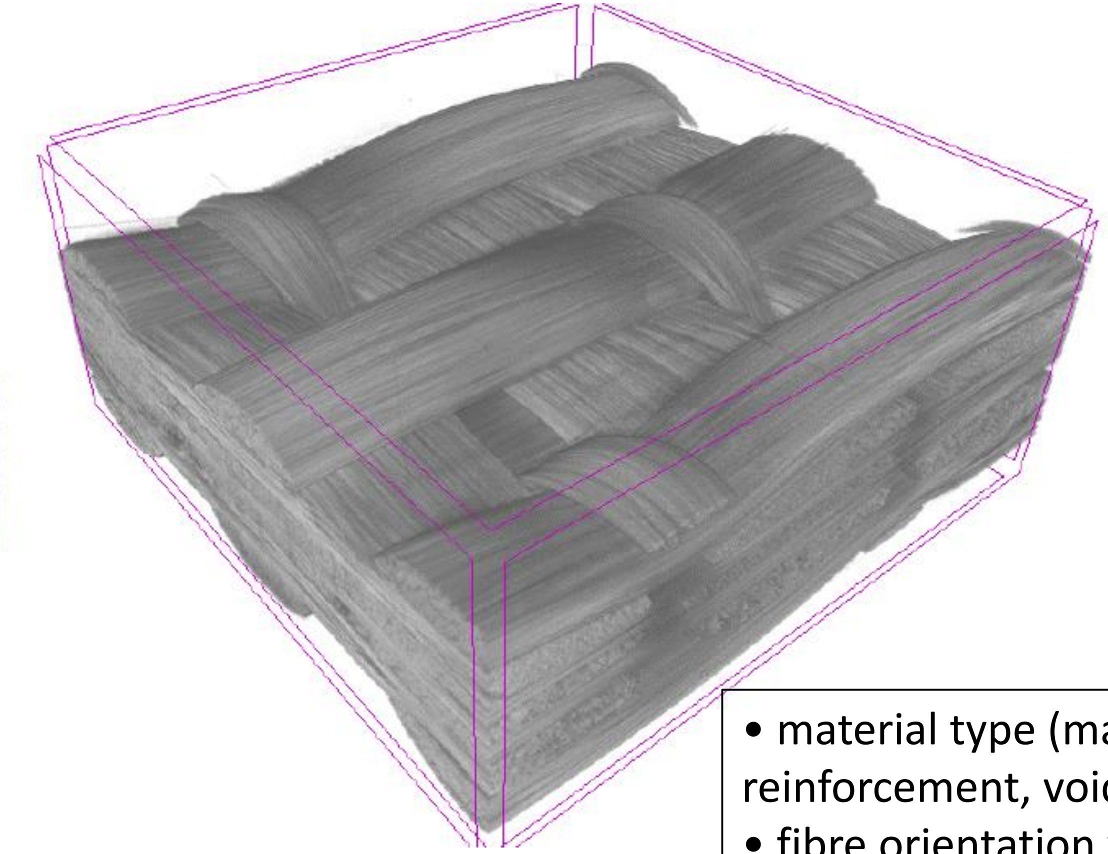
1. Introduction. Fibrous media: microstructural features and characteristics

2. Quantification of a µCT image of fibrous materials

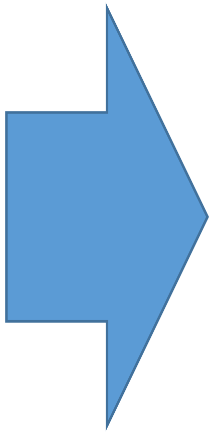
3. Applications
    - Fibre orientations
    - Finite element models of deformation and damage
    - Permeability
4. Conclusions

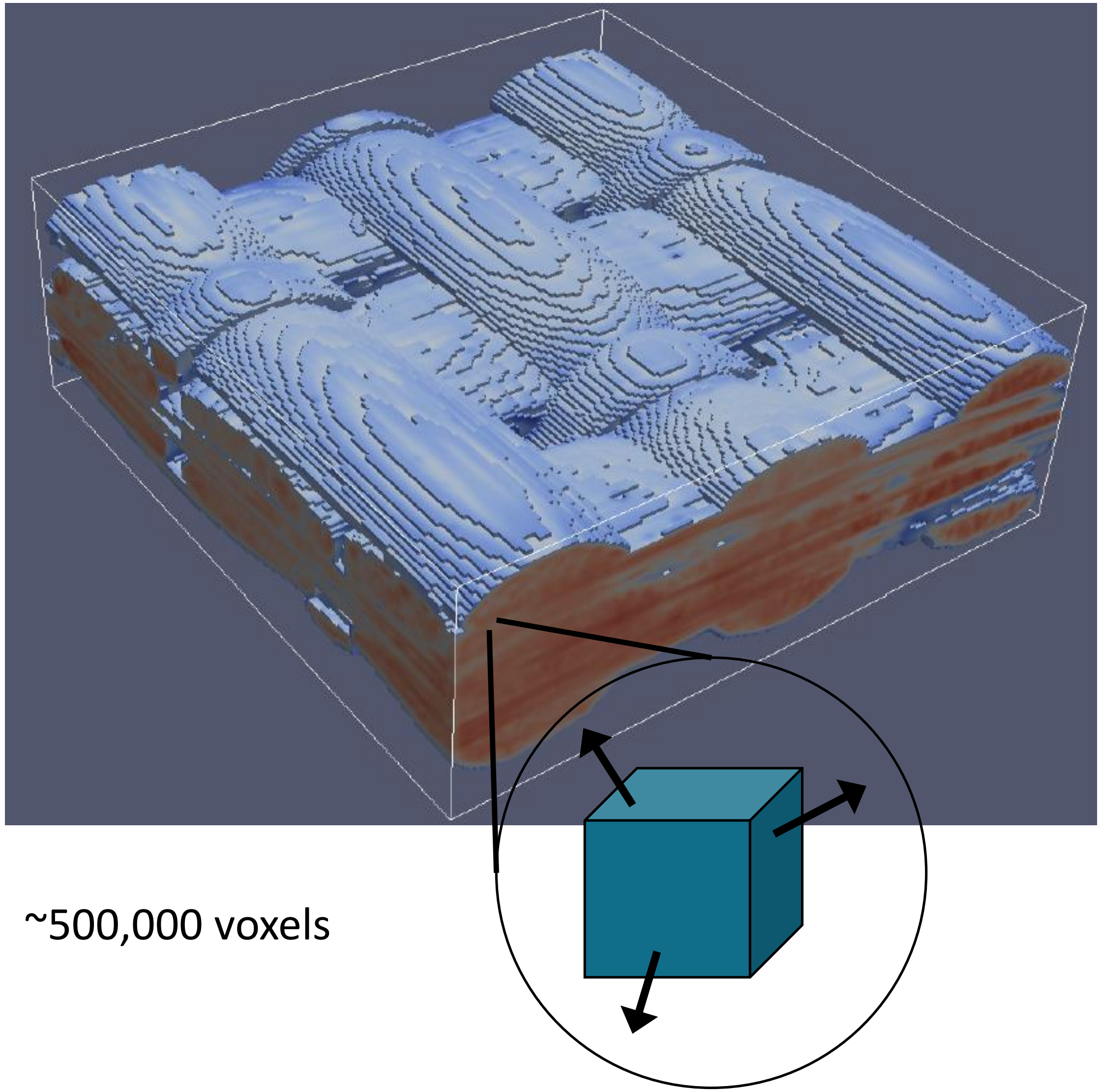
[Straumit, I., S. V. Lomov and M. Wevers (2015). Composites Part A 69: 150-158]

µCT image → voxel model



~100 mio pixels

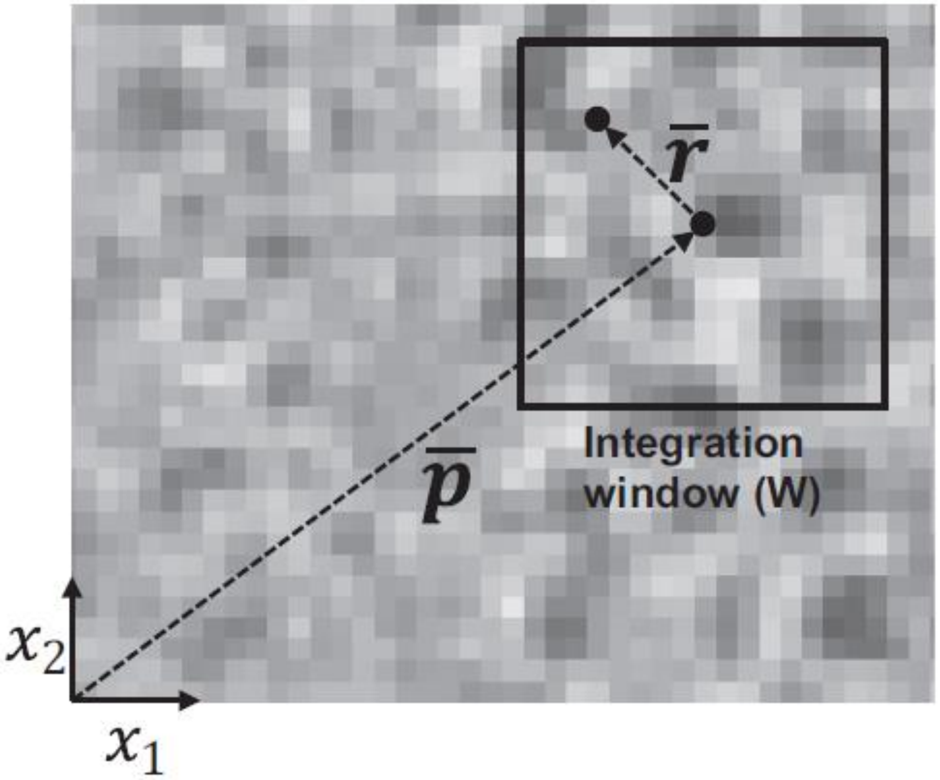




- material type (matrix, reinforcement, void);
- fibre orientation vector (for the reinforcement only);
- local fibre volume fraction (for the reinforcement only).

~500,000 voxels

Structure tensor and anisotropy

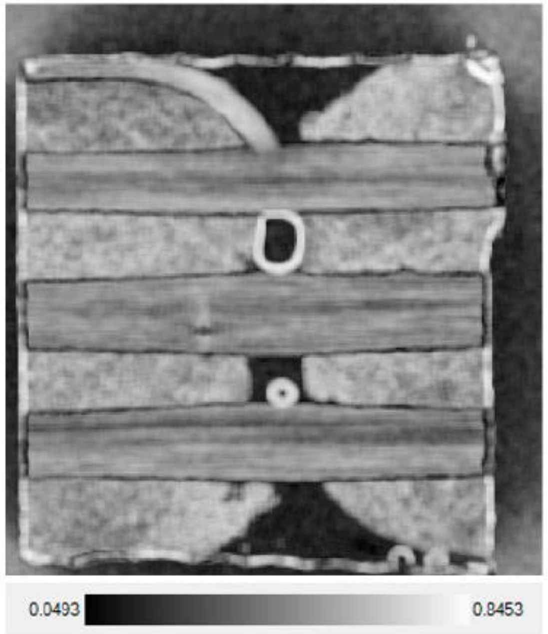


$$S'(x_1, x_2, x_3) = \begin{bmatrix} \left(\frac{\partial I}{\partial x_1}\right)^2 & \frac{\partial I}{\partial x_1}\frac{\partial I}{\partial x_2} & \frac{\partial I}{\partial x_1}\frac{\partial I}{\partial x_3} \\ & \left(\frac{\partial I}{\partial x_2}\right)^2 & \frac{\partial I}{\partial x_2}\frac{\partial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

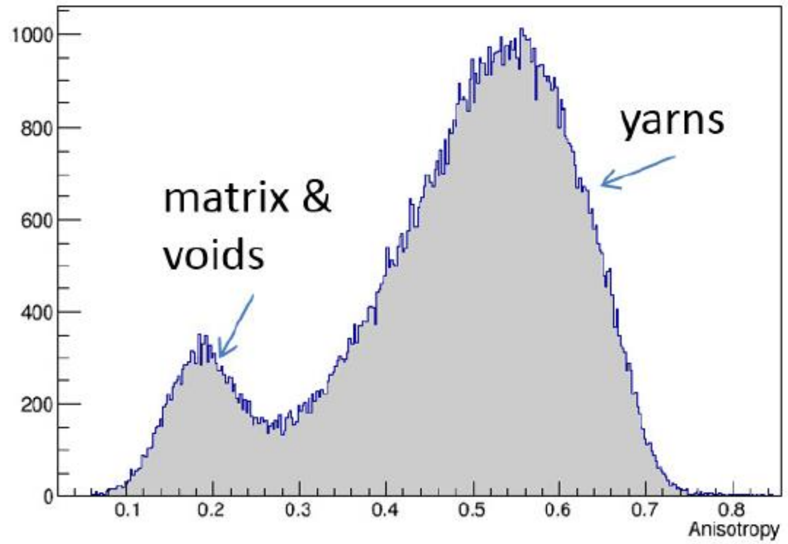
$$S(\boldsymbol{p}) = \int_{W(\boldsymbol{p})} S'(\boldsymbol{r})\, dr$$

Degree of anisotropy

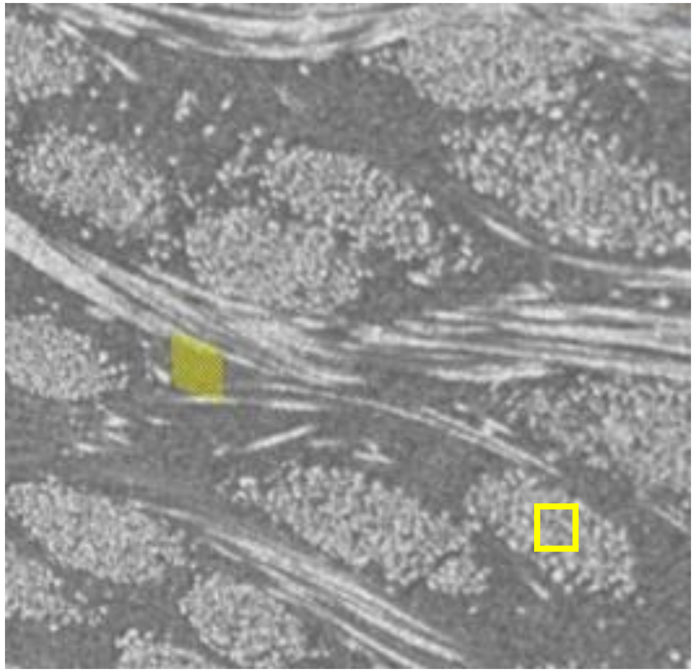
$$\beta = \begin{cases} 1 - \frac{\lambda_1}{\lambda_3} & \text{if } \lambda_3 > 0, \\ 0 & \text{if } \lambda_3 = 0. \end{cases}$$



3D woven carbon fibre/epoxy composite

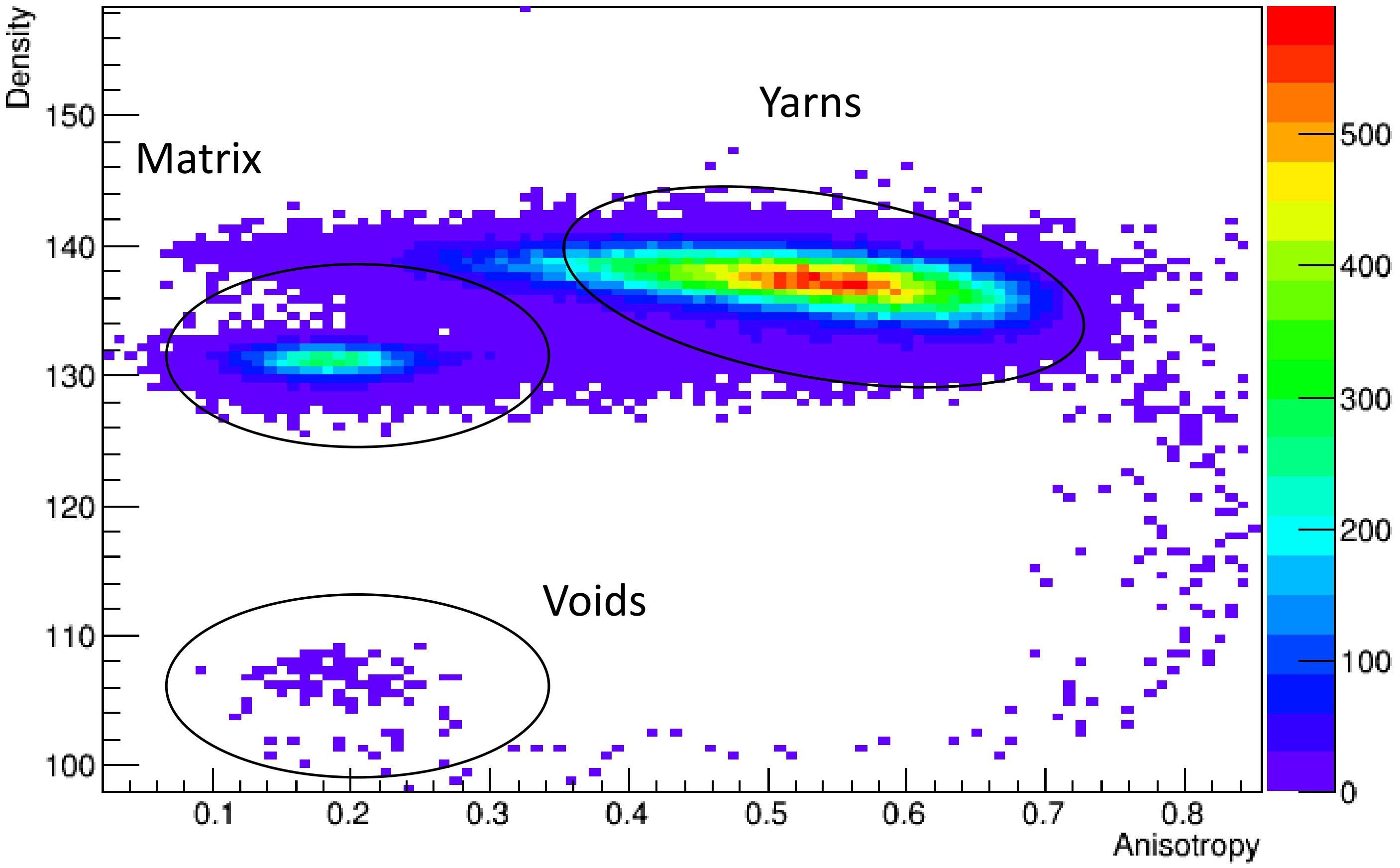


Segmentation



Methods of segmentation:

- Unsupervised (k-means)
- Supervised (Gaussian mixture model)

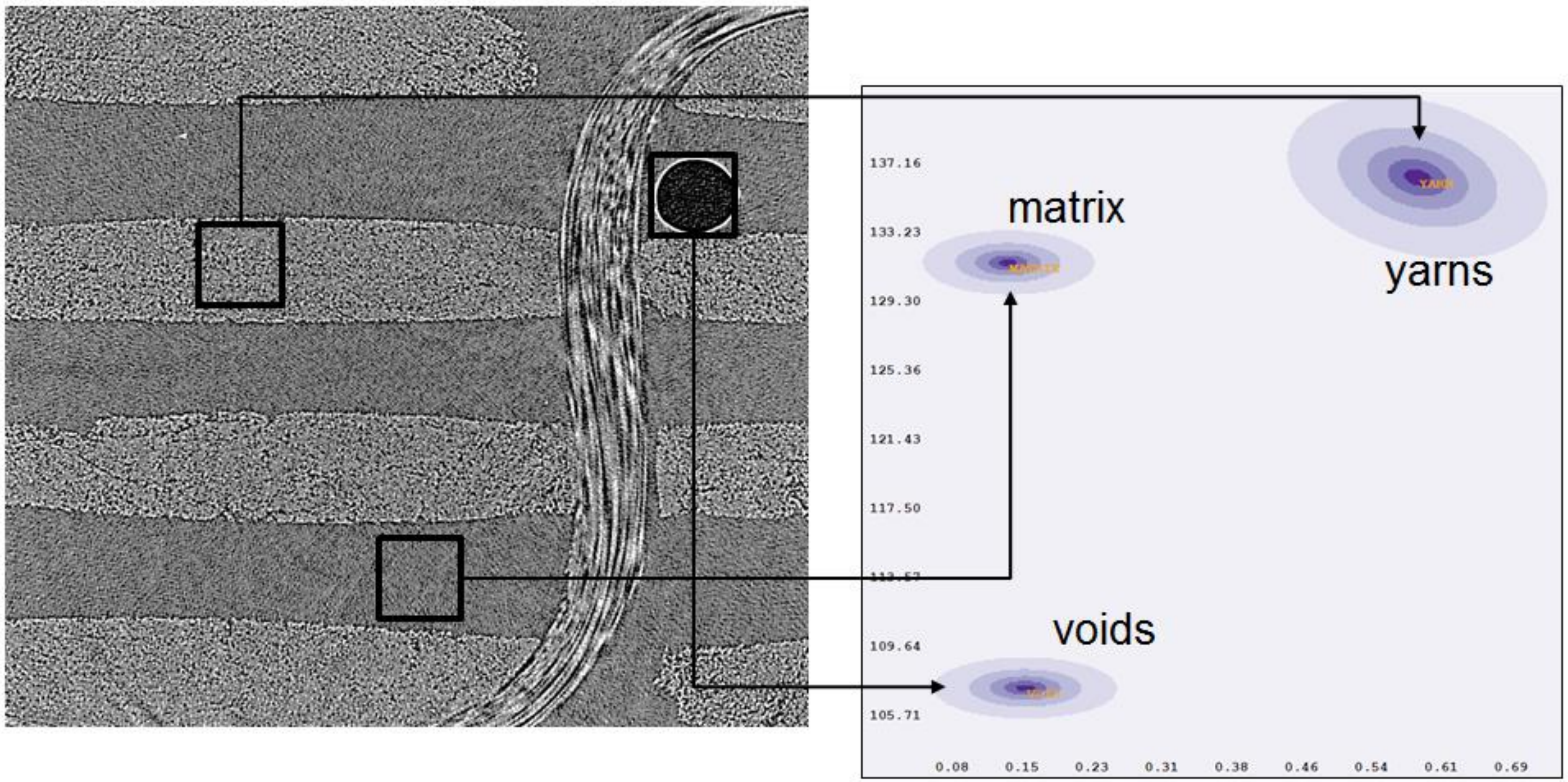


The variables, extracted from the image, reflect physical properties of the material:

- grey value – material attenuation
- structural anisotropy – material microstructure type

Supervised segmentation

Uses a training set: selected regions in the image with the class known a priori

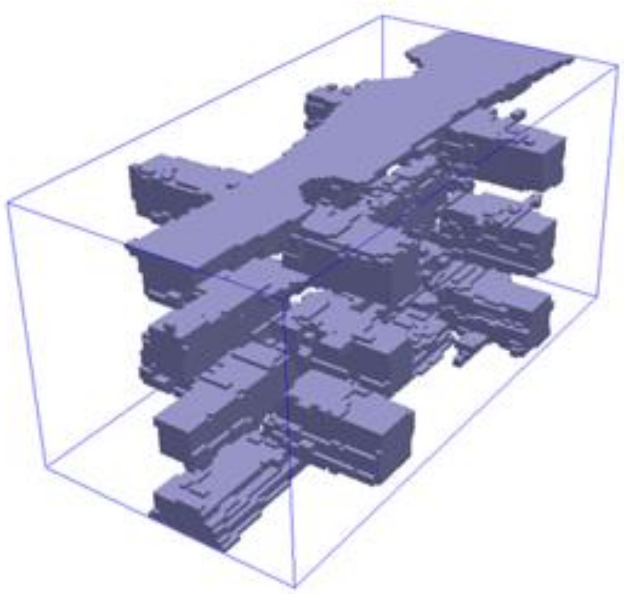


Components defined as Gaussian distributions:

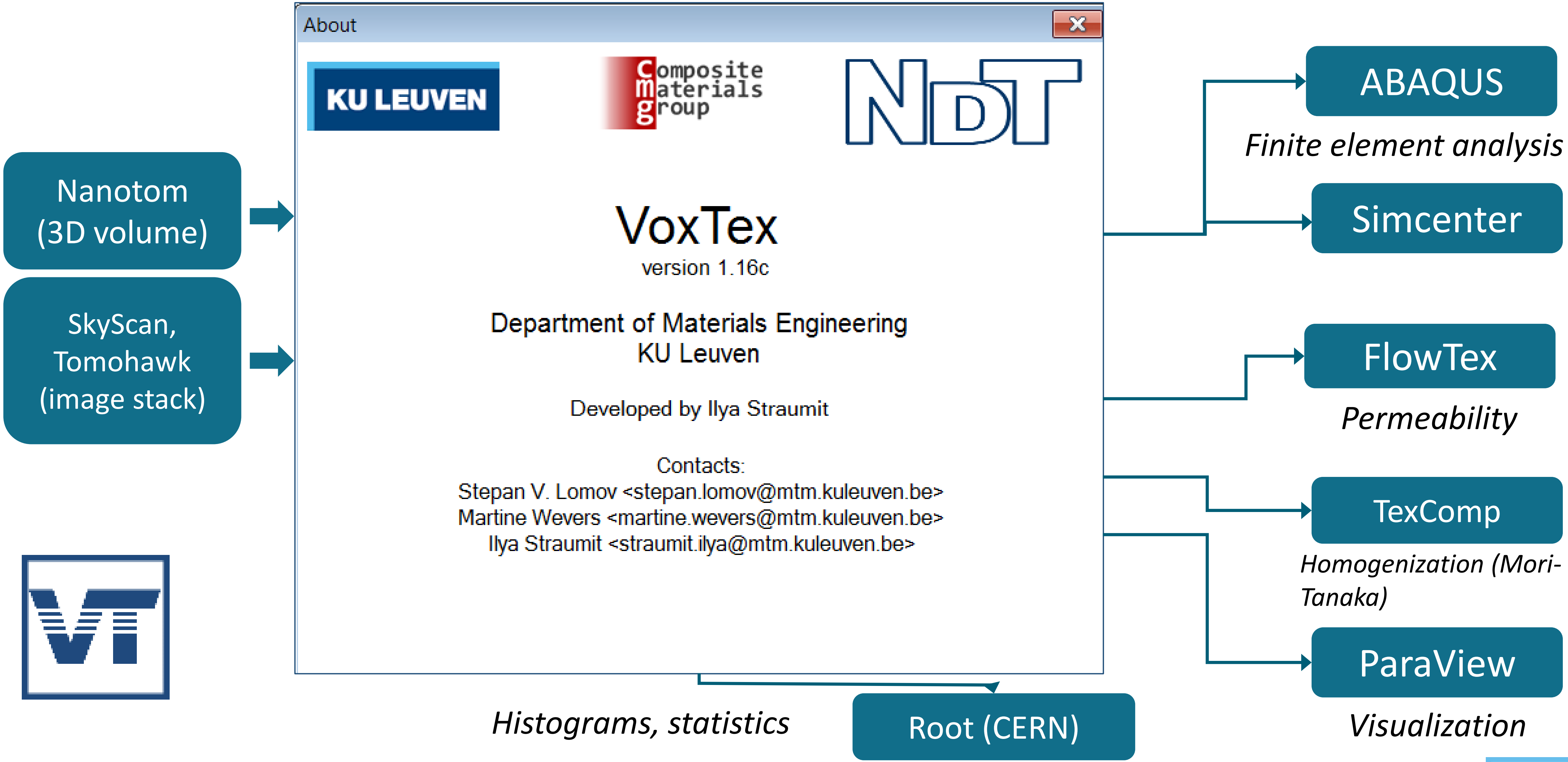
$$L_i(x) = \frac{1}{(2\pi)^{\frac{k}{2}}\sqrt{\boldsymbol{\Sigma}_i}} \exp\left(-\frac{(x-\boldsymbol{\mu}_i)^T \boldsymbol{\Sigma}_i (x-\boldsymbol{\mu}_i)}{2}\right)$$

Classification criterion:

$$C(x) = \underset{i}{\operatorname{argmax}}\, L_i(x)$$

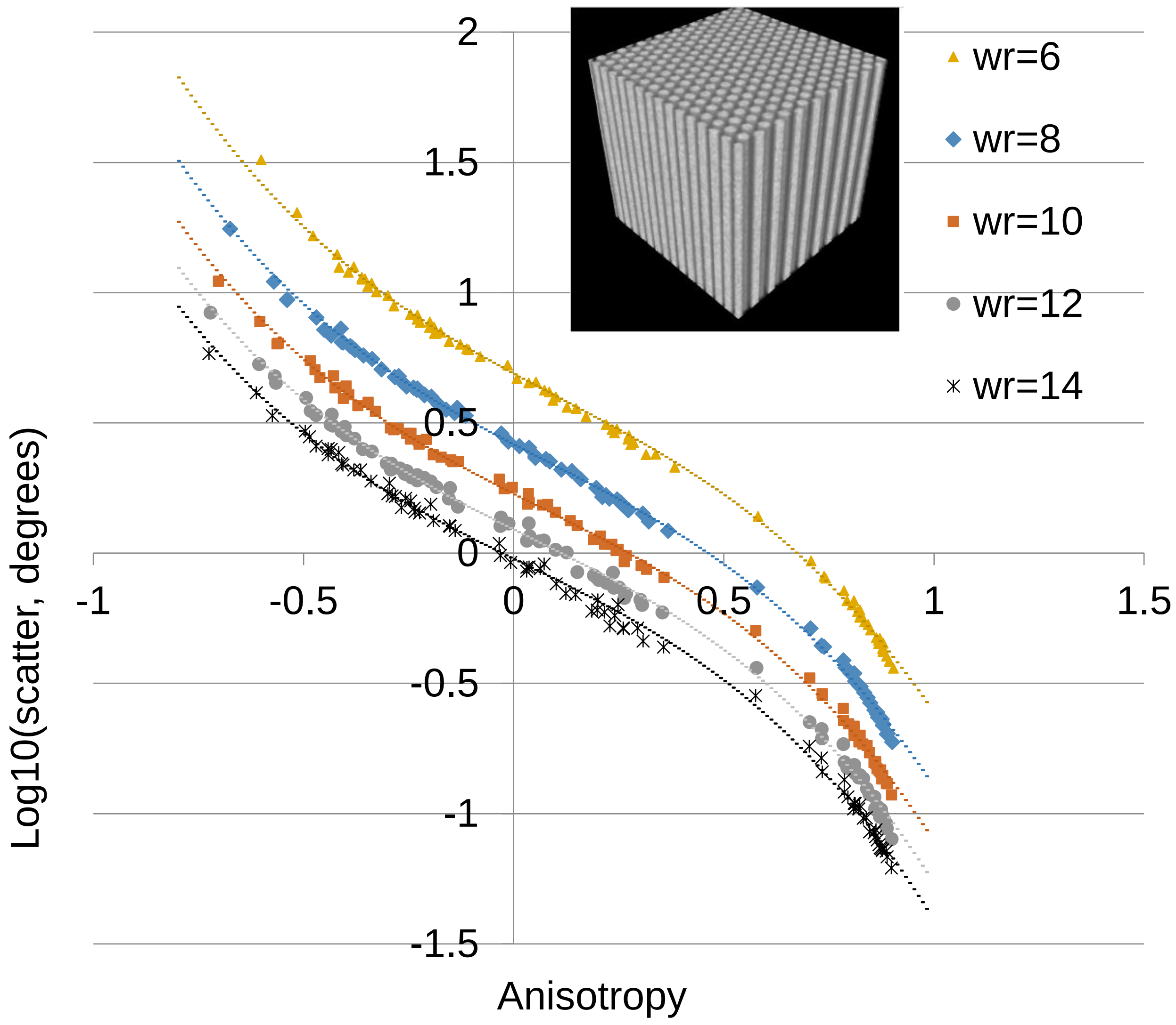


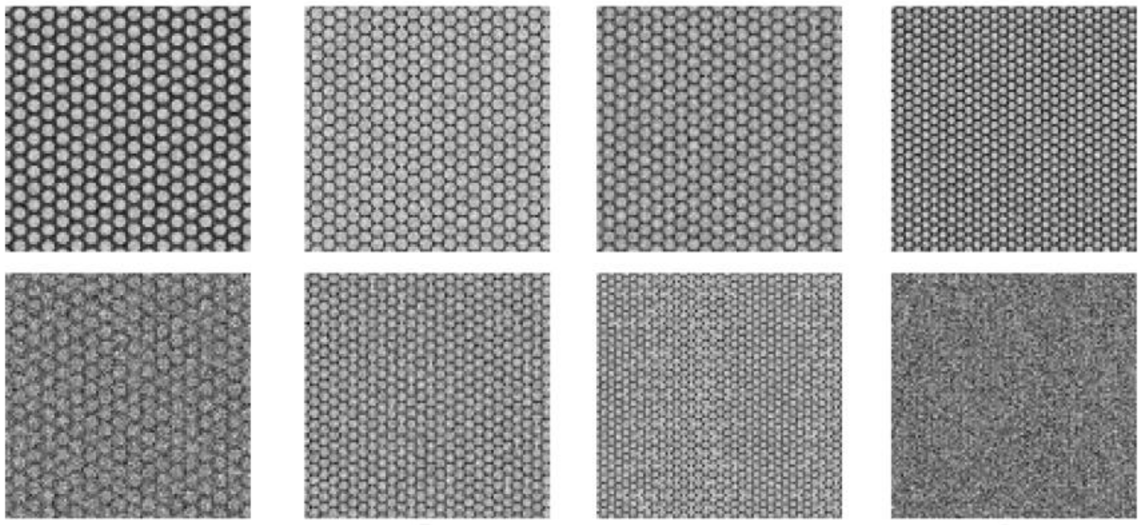
VoxTex software



1. Introduction. Fibrous media: microstructural features and characteristics
2. Quantification of a µCT image of fibrous materials
3. **Applications**
    - Fibre orientations
    - Finite element models of deformation and damage
    - Permeability
4. Conclusions

Estimation of precision and pixel size requirements





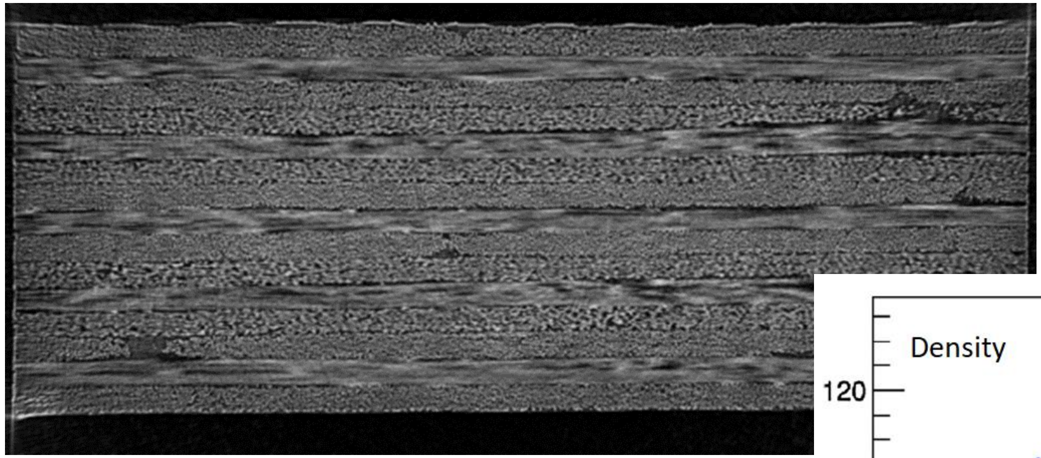
Recommended voxel size parameters

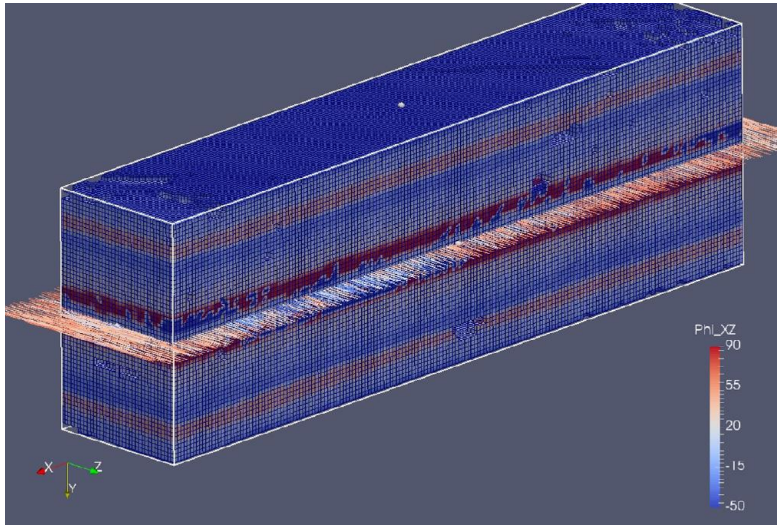
Material	Fibre diameter, µm	Pixel size, µm	Anisotropy	Scatter, degrees
Carbon	7	2.34	0.61	1.1
Flax	15…20	1.48	0.95	0.13
Steel	25	4.4	0.91	0.19
Glass	12	5.5	0.89	0.23

[Straumit, I., S. V. Lomov and M. Wevers (2015). Composites Part A 69: 150-158]

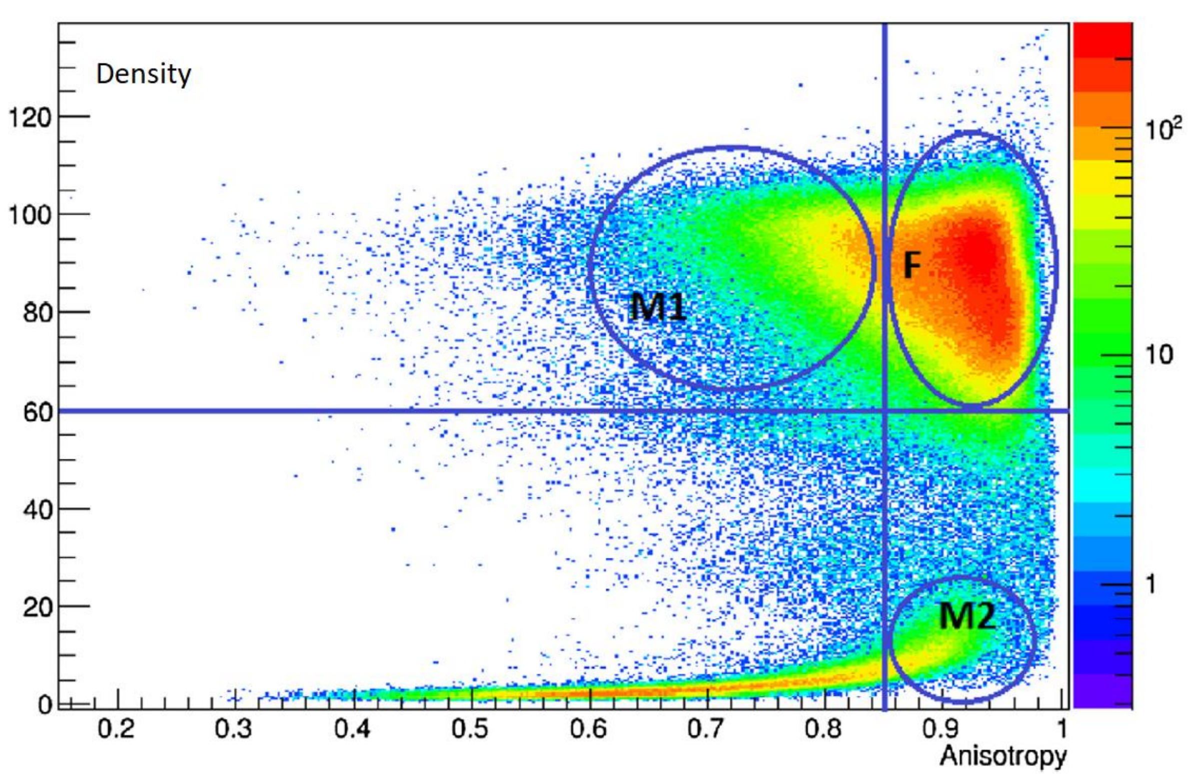
Dry Tape Laying

(-45/0/45/-20/0/20/90/0)$_{so}$ Produced at NLR, Coriolis machine Hexcel HiTape UD126 - AS7/V800E/QD2/6.35mm



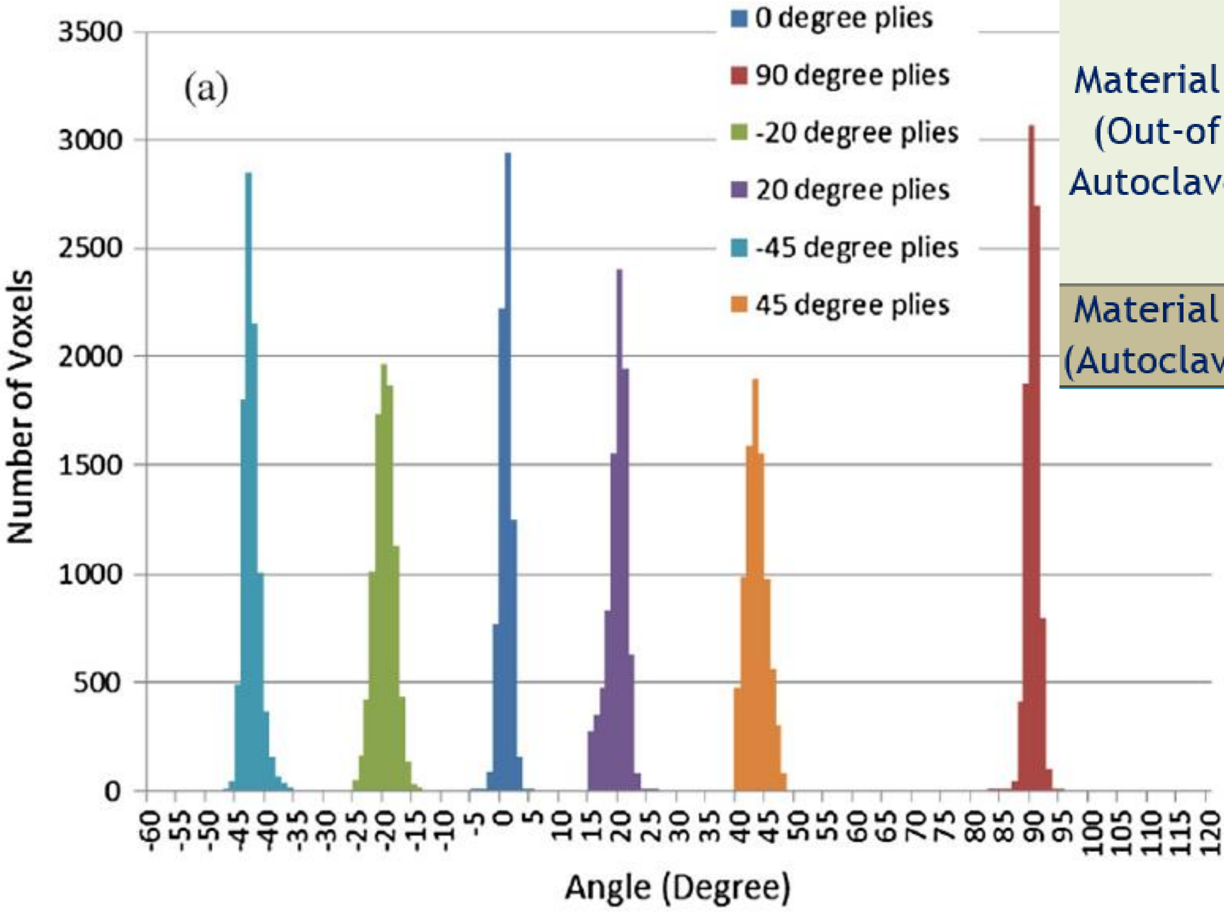


orientations output from the mid-plane of a ply



Nguyen, N., M. Mehdikhani, I. Straumit, L. Gorbatikh, L. Lessard, and S.V. Lomov, Composites Part A, 2018. **104**: 14-23

Fibre orientation: comparison in- and out-of-autoclave

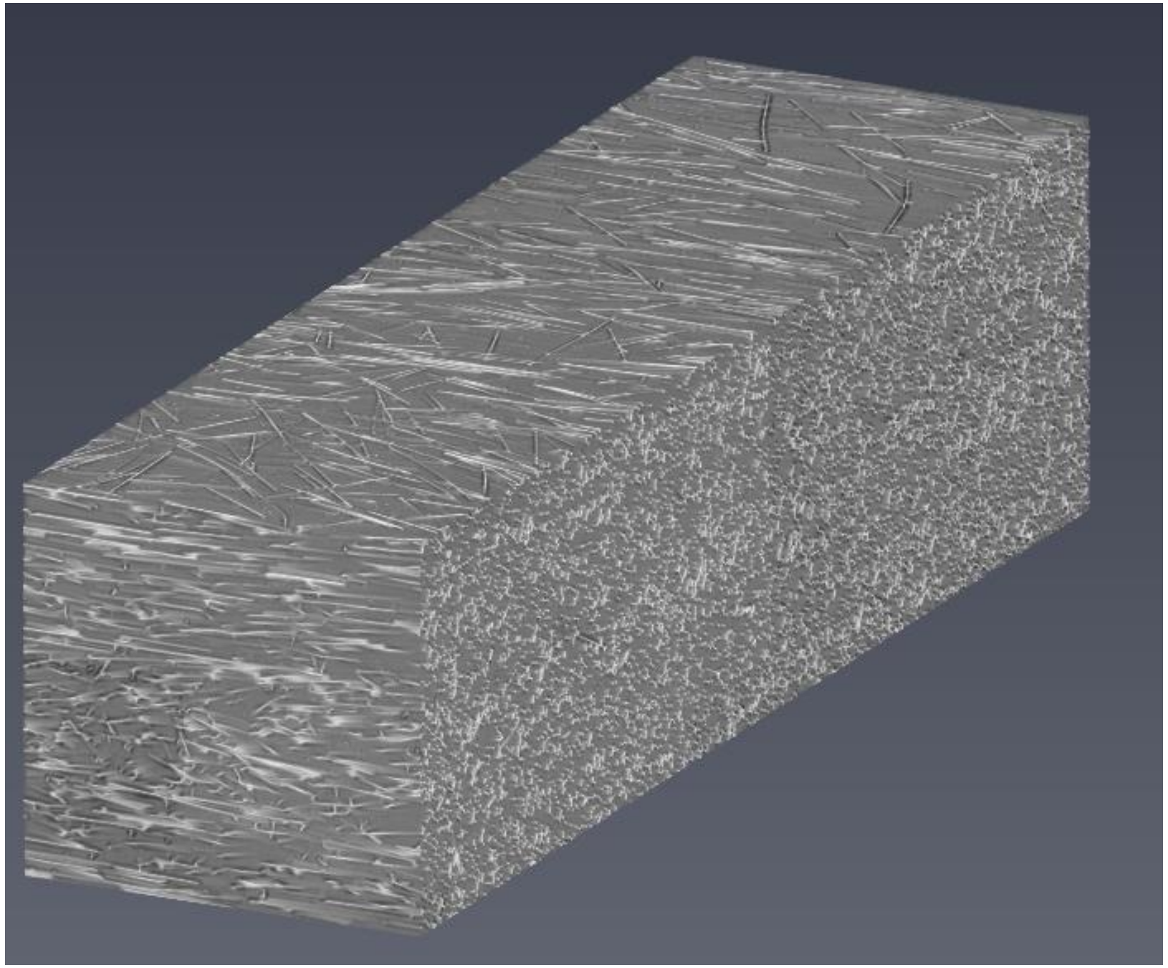


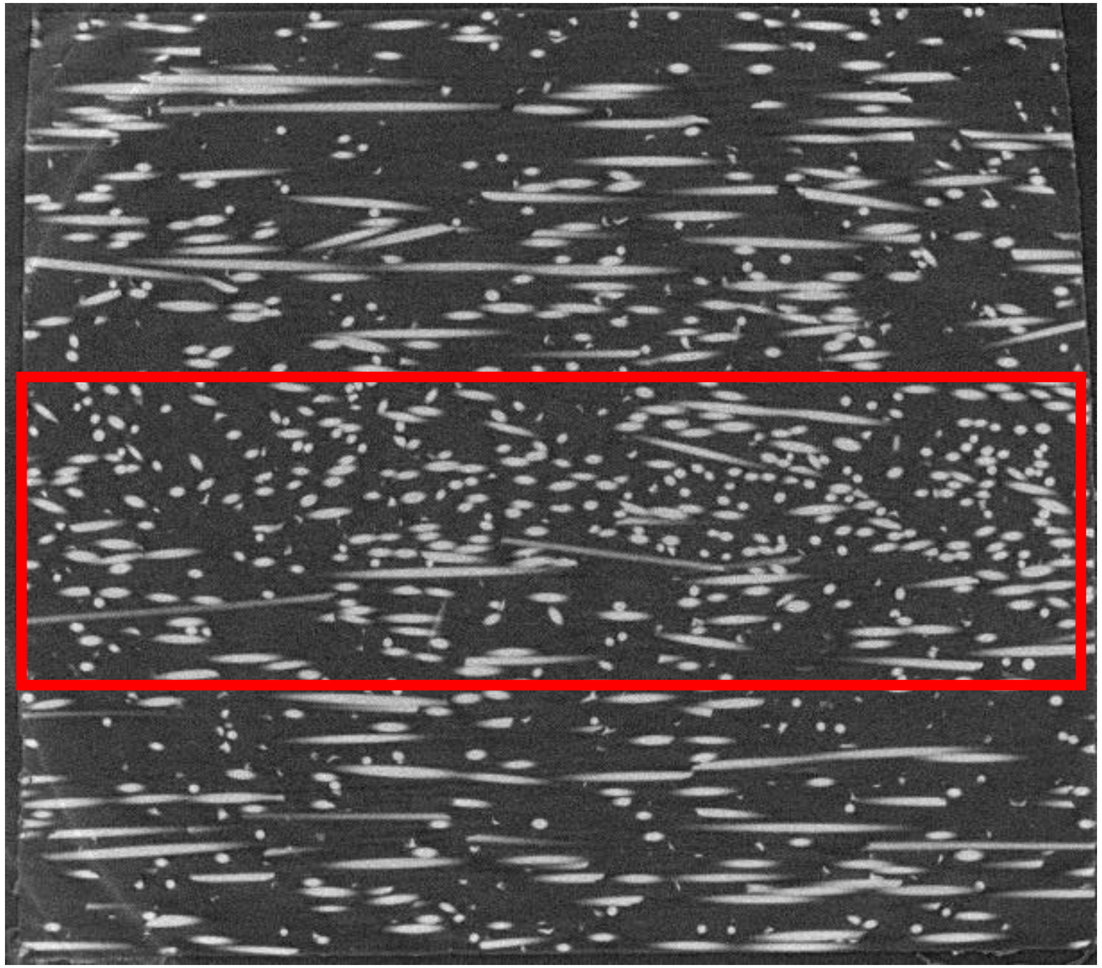
Material Type	In-plane			Out-of-plane
	Nominal Ply Angle α (Degree)	Ply Angle φ_t^α (Degree)	Fibres misalignment m_φ^α (Degree)	Fibres misalignment m_θ^α (Degree)
Material A (Out-of-Autoclave)	0	0.2	1.01	0.79
	20	19.0	1.70	1.34
	-20	-20.5	1.72	1.05
	45	44.0	1.80	2.4
	-45	-43.1	1.42	1.6
	90	90.3	1.11	0.84
Material B (Autoclave)	22.5	23.7	3.80	1.20
	67.5	66.7	2.16	1.25

Material A - automated dry fibre placement and subsequent vacuum-assisted resin transfer moulding
Material B - automated prepreg tape laying and subsequent autoclave curing

Difference in misalignment because of the high autoclave pressure

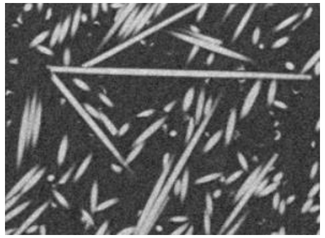
Random short fibre composites: glass/PP



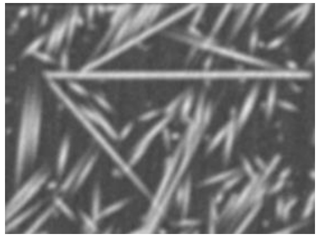


Validation of VoxTex vs ellipsometry (high-fidelity)

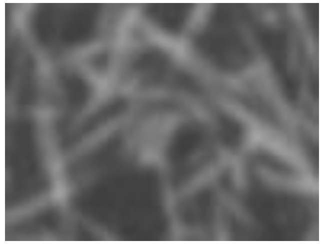
Glass fibre/PP composite, VF ~20%, d = 15 µm



1.4 µm/pix



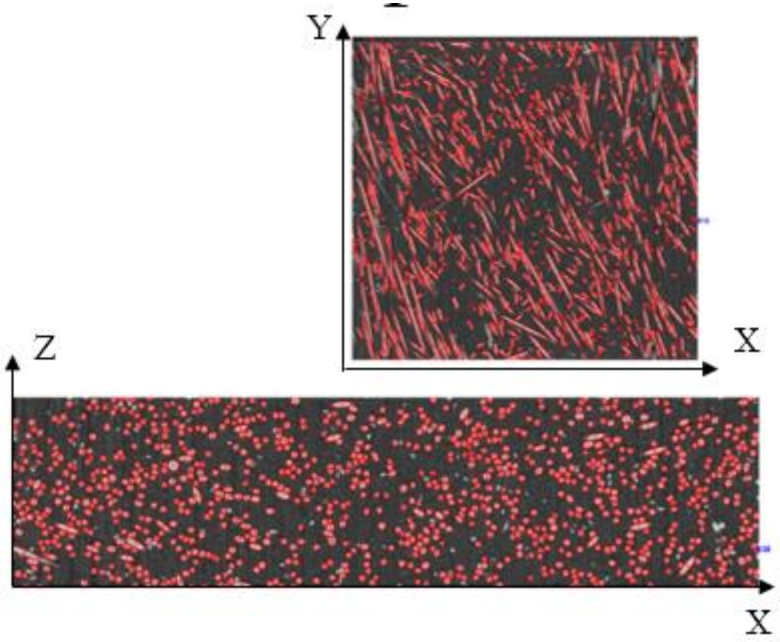
3.2 µm/pix

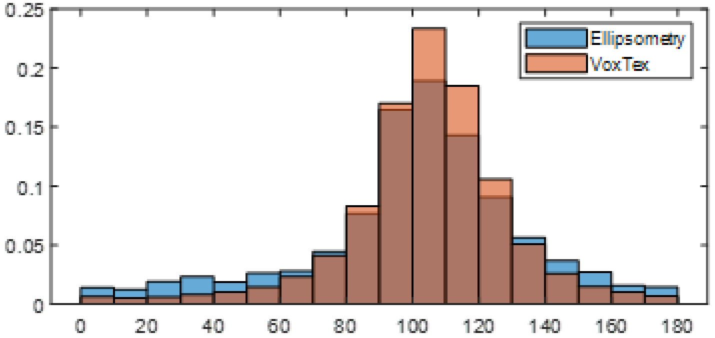


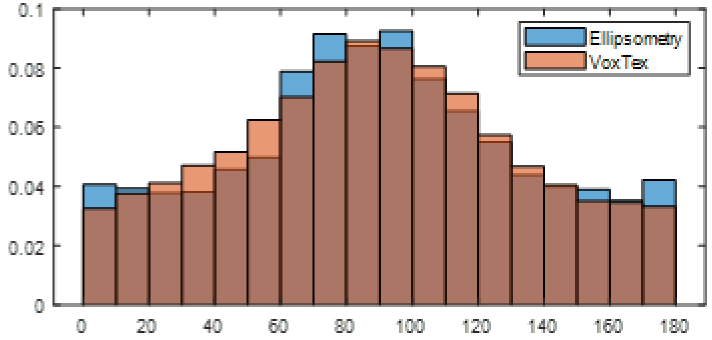
8 µm/pix

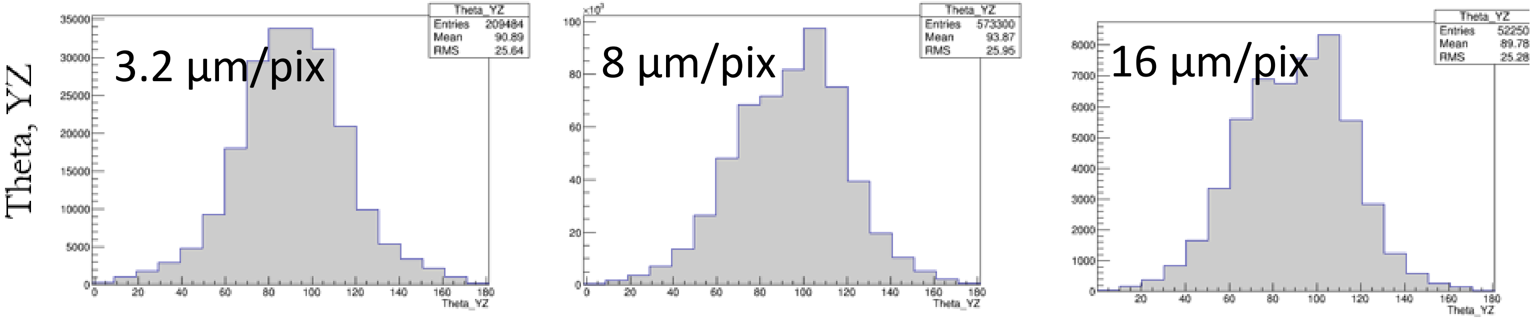
16 µm/pix

Ellipsometry @ **1.4 µm/pix** vs structure tensor @ **16 µm/pix**



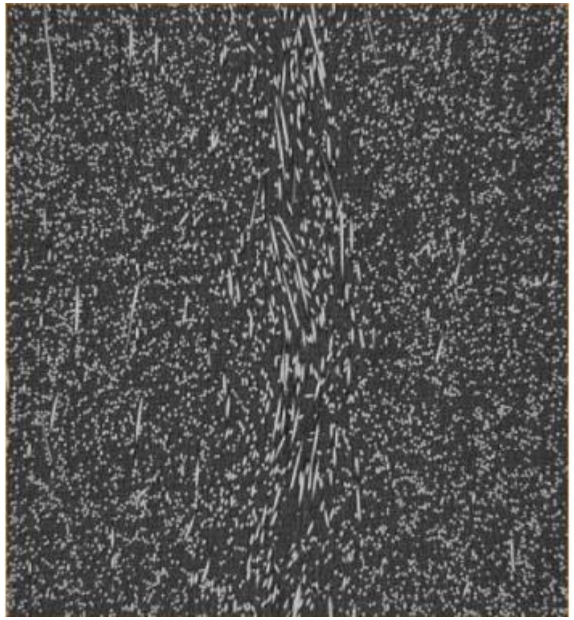


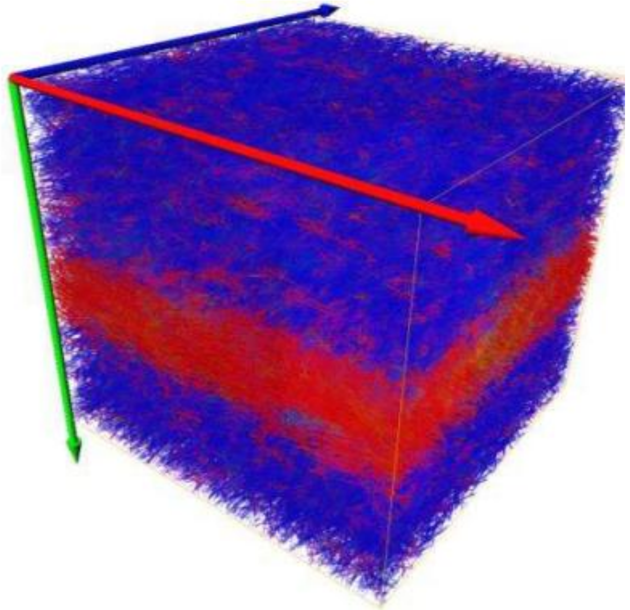




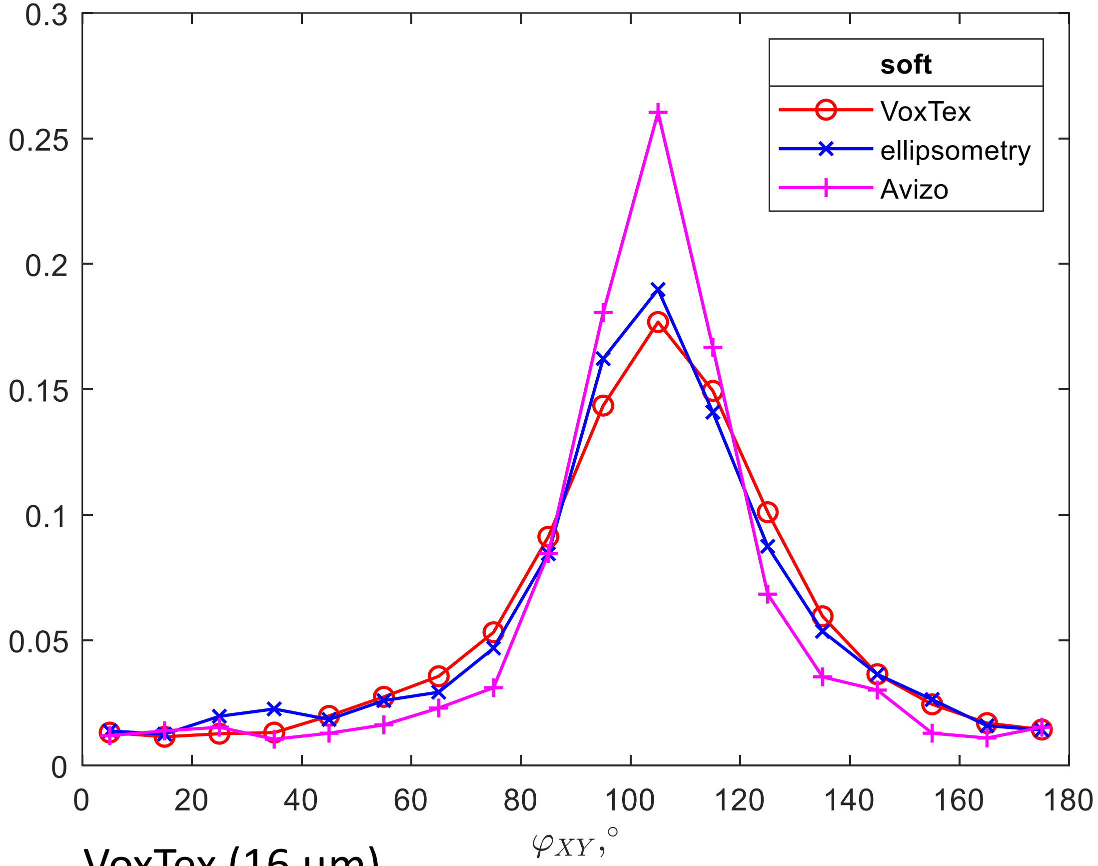
VoxTex, different image resolutions

Validation of VoxTex vs Avizo (high-fidelity)





AVIZO identification of the individual fibres



AVIZO (1.4 µm)

0.199	-0.151	0.006
-0.145	0.739	-0.009
0.006	-0.151	0.061

ellipsometry (1.4 µm)

0.182	-0.145	0.008
-0.145	0.693	-0.081
0.008	-0.081	0.125

VoxTex (16 µm)

0.194	-0.139	0.003
-0.182	0.652	0.02
0.003	0.02	0.154

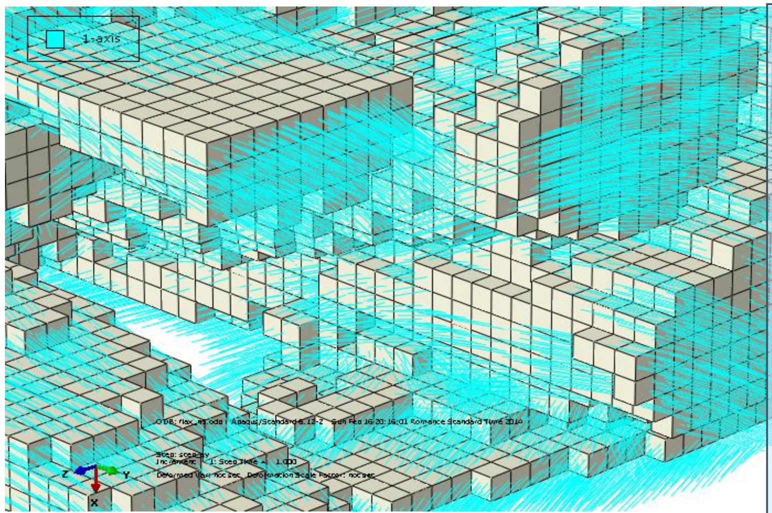
1. Introduction. Fibrous media: microstructural features and characteristics
2. Quantification of a µCT image of fibrous materials

3. Applications

- Fibre orientations
- **Finite element models of deformation and damage**
- Permeability

4. Conclusions

VoxTex → finite element voxel models



Geometric modeller — VoxTex creates a voxel model; after segmentation: identification of materials per voxel

Geo… corrector — no need for the geometrical corrections

Meshing — HEX elements = voxels

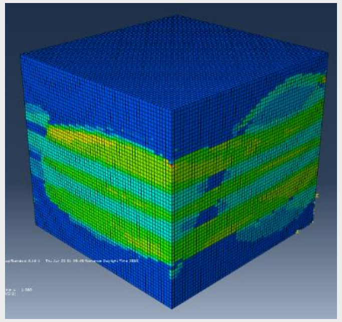
Assign material properties — fibre direction identification (structure tensor) and Chamis UD homogenisation

Boundary conditions — periodic boundary conditions NB: “weak” periodicity

FE solver, postprocessor

Homogenisation

Damage analysis



Abaqus
Simcenter

Impregnated fibre bundle test

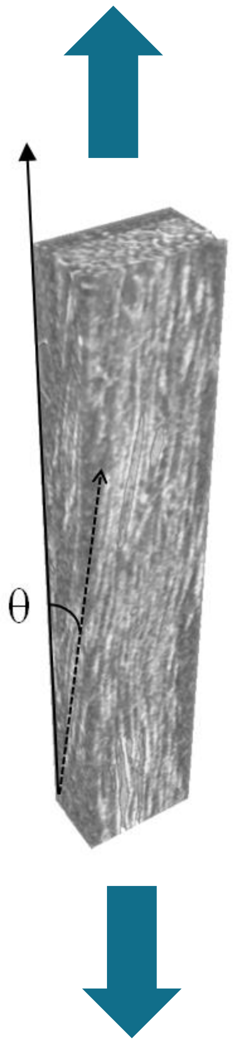
$$E_f = \frac{E_{UD} - E_m(1 - v_f)}{v_f}$$

Quasi-UD flax:
22.9±0.5 GPa -> flax **53.2** GPa

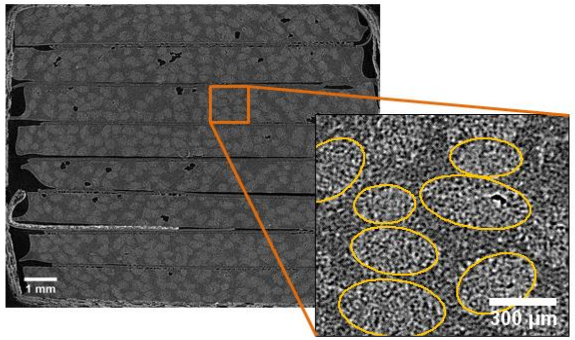
UD flax:
26.6±2.3 GPa -> flax **62.4** GPa

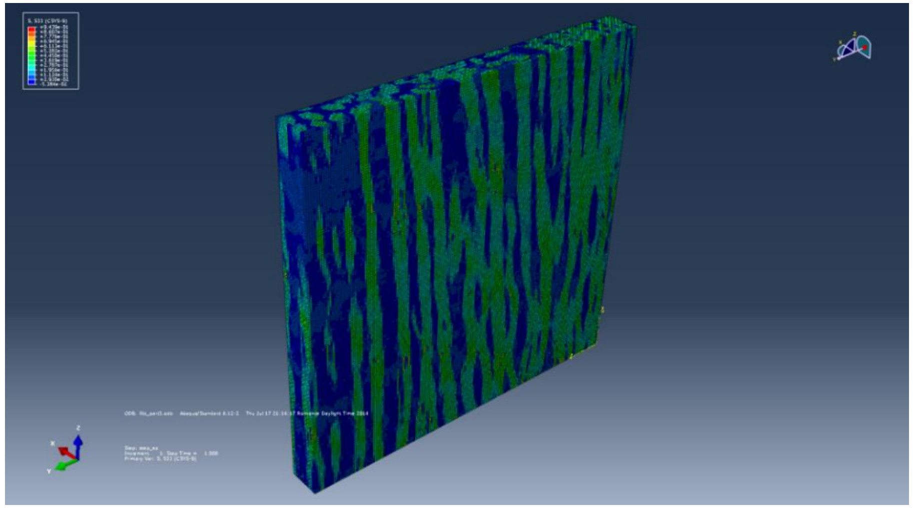
VF = 40%

How to obtain correct flax fibre modulus from quasi-UD tests?

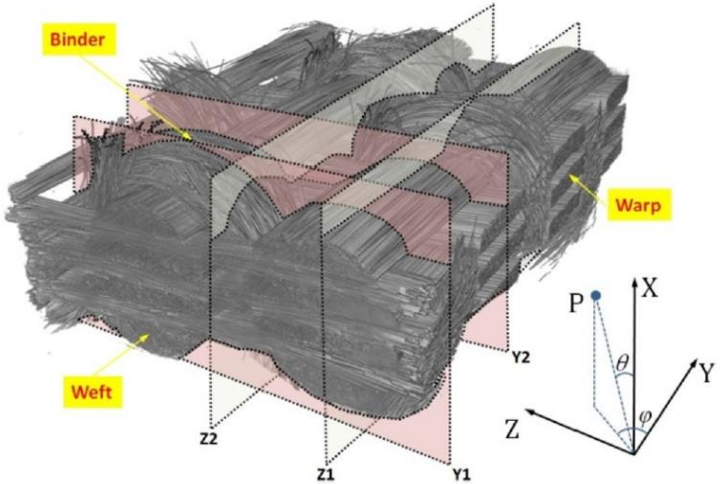


	Fibre volume fraction	Homogenised quasi-UD modulus from FE calculations		Fibre modulus, GPa
		with E_f = 58 GPa	with E_f = 85 GPa	
Sample #1	0.39	21.20	29.27	62.11
Sample #2	0.33	18.36	25.22	62.59
Sample #3	0.31	17.14	23.40	64.19
Sample #4	0.36	19.26	26.34	64.71
Sample #5	0.38	20.88	28.88	61.59
Mean				**63.04**
Std. Dev.				**1.35**
CVar				**2.1%**

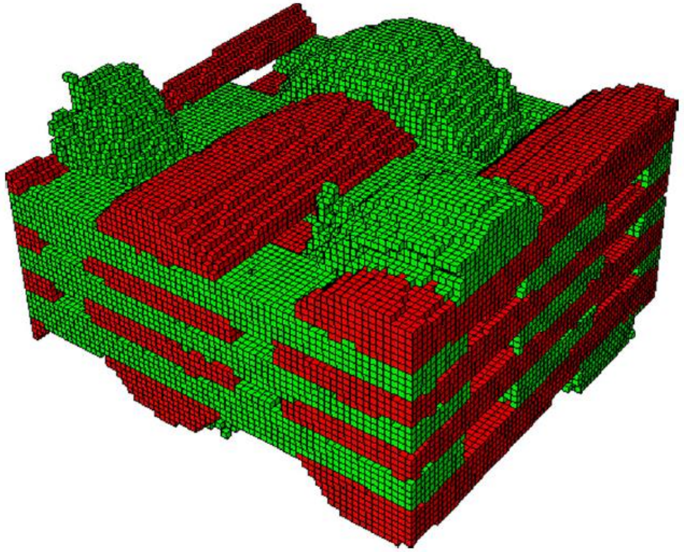


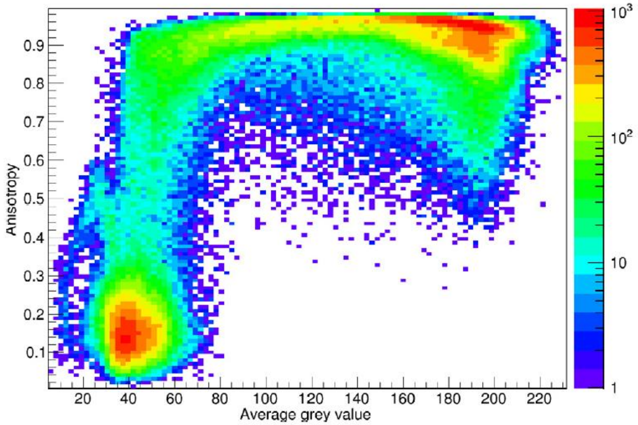


3D woven glass/epoxy composites



Properties	E-glass Fiber	Epolam 5015 Resin
Tensile modulus E_i^* (GPa)	72	3
Poisson's ratio ν_i	0.3	0.3
Tensile strength X_{iT} (MPa)	2000	80
Compressive strength X_{iC} (MPa)	1350	120
Density (g/cm^3)	2.6	1.1
Yarn linear density (tex)	300	–
Filament diameter (μm)	16	–
Number of fiber per yarn	600	–

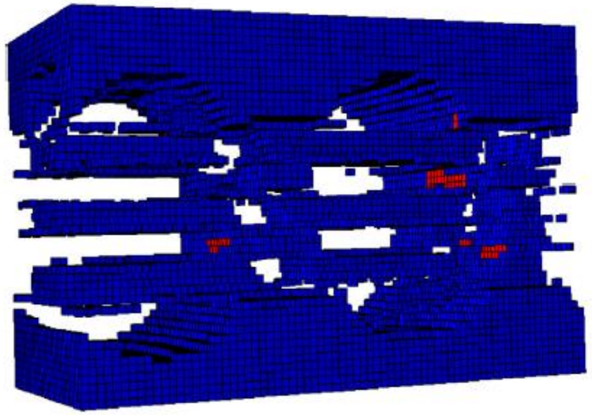




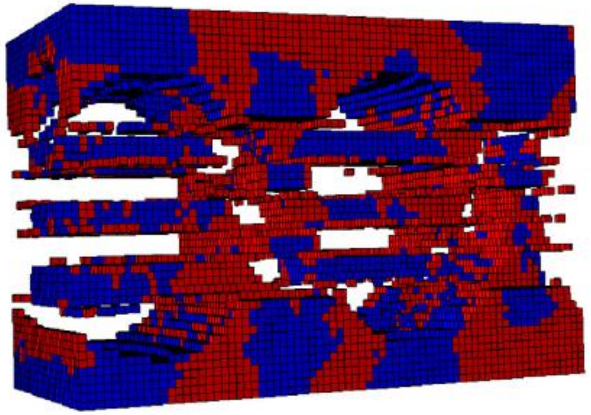
Tensile strength (MPa)	232.6
Tensile ultimate strain	0.0257

	Experiment
Tensile strength (MPa)	233.8 ± 1.7%
Tensile ultimate strain	0.0227 ± 4.6%

Damage maps



(a) damage initiation at tensile strain 0.27%



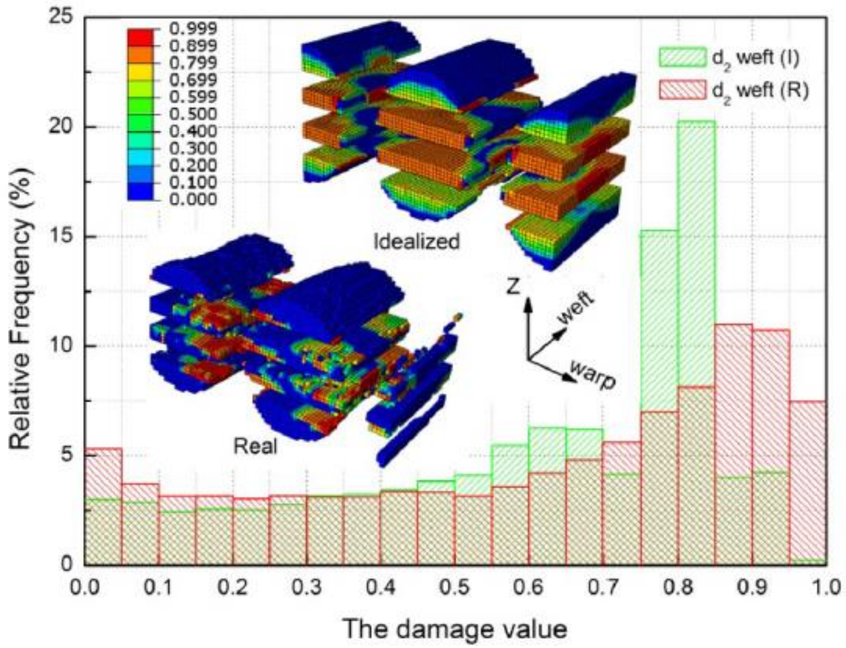
(b) damage evolution at tensile strain 0.68%

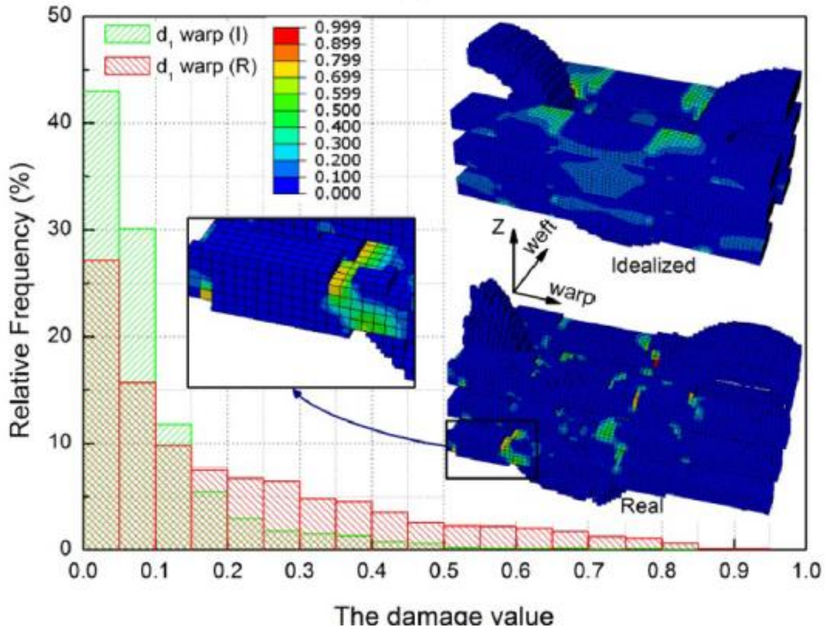
"I" = ideal yarn geometry (TexGen)
"R" = real yarn geometry (μCT + VoxTex)

damage in the matrix

fibre damage

transverse cracking in the weft





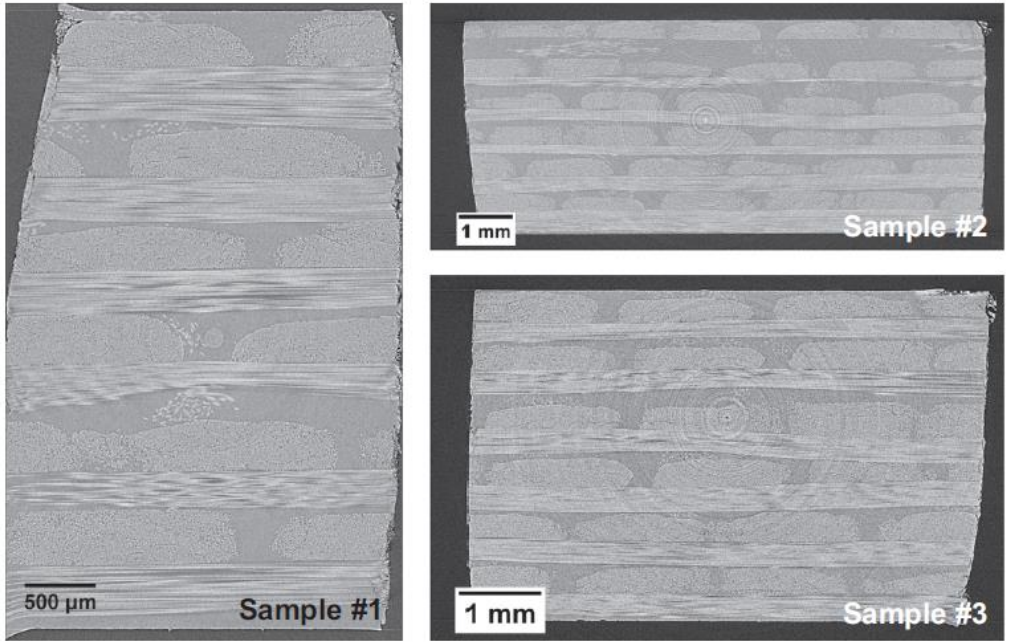
1. Introduction. Fibrous media: microstructural features and characteristics
2. Quantification of a µCT image of fibrous materials

3. Applications

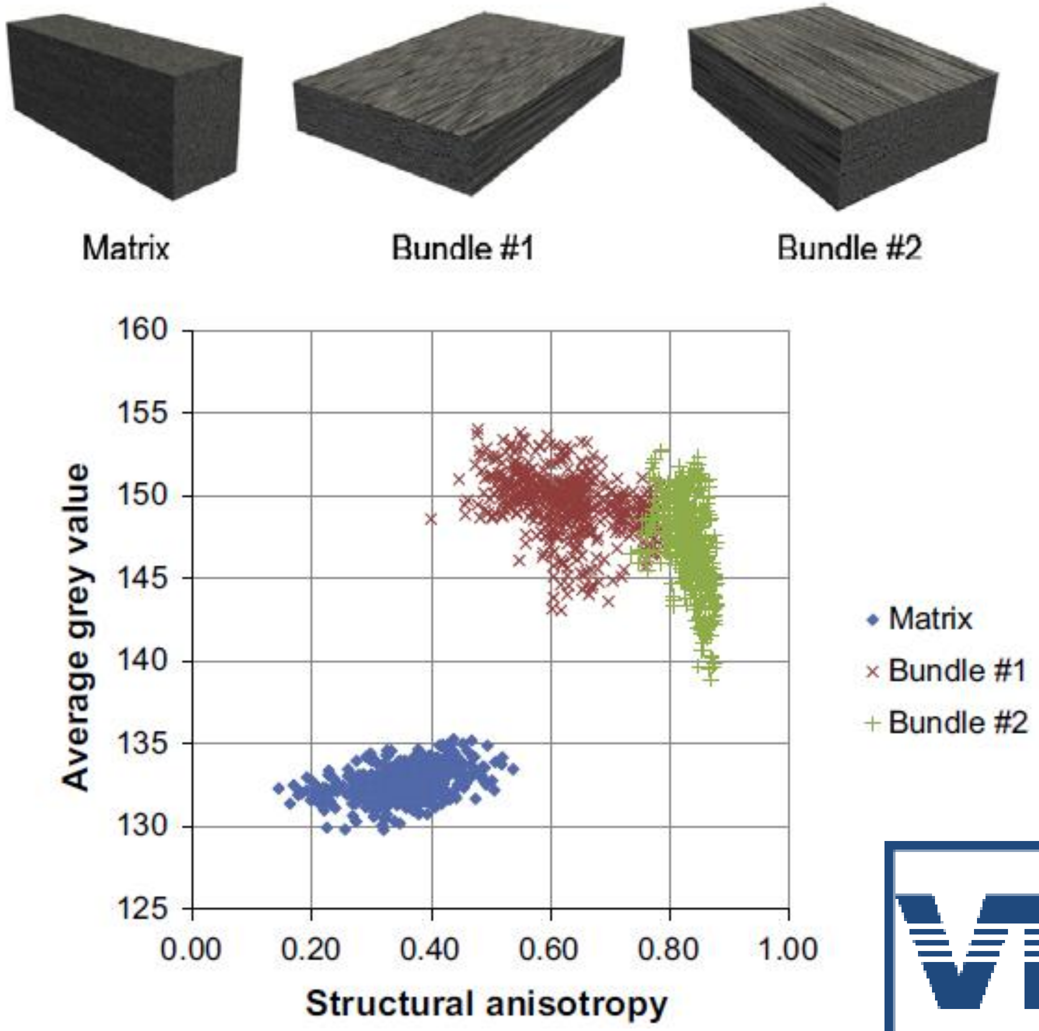
- Fibre orientations
- Finite element models of deformation and damage
- **Permeability**

4. Conclusions

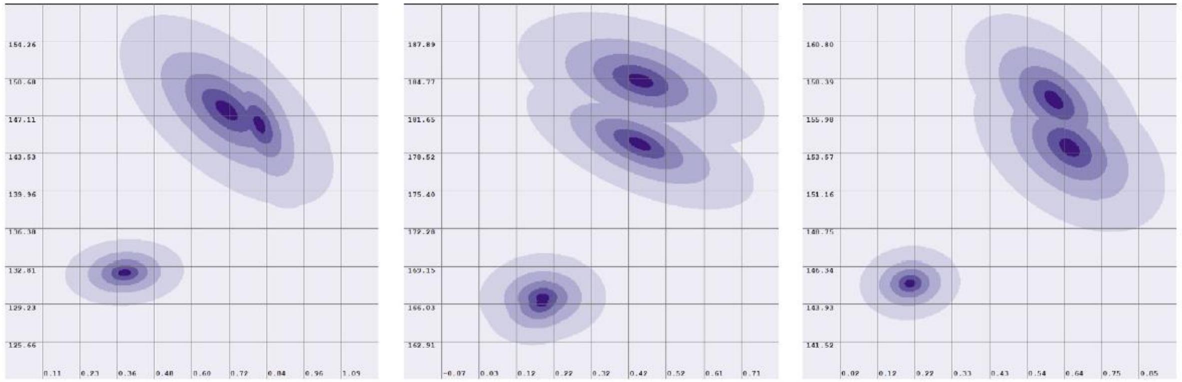
NCF composites: µCT images and processing



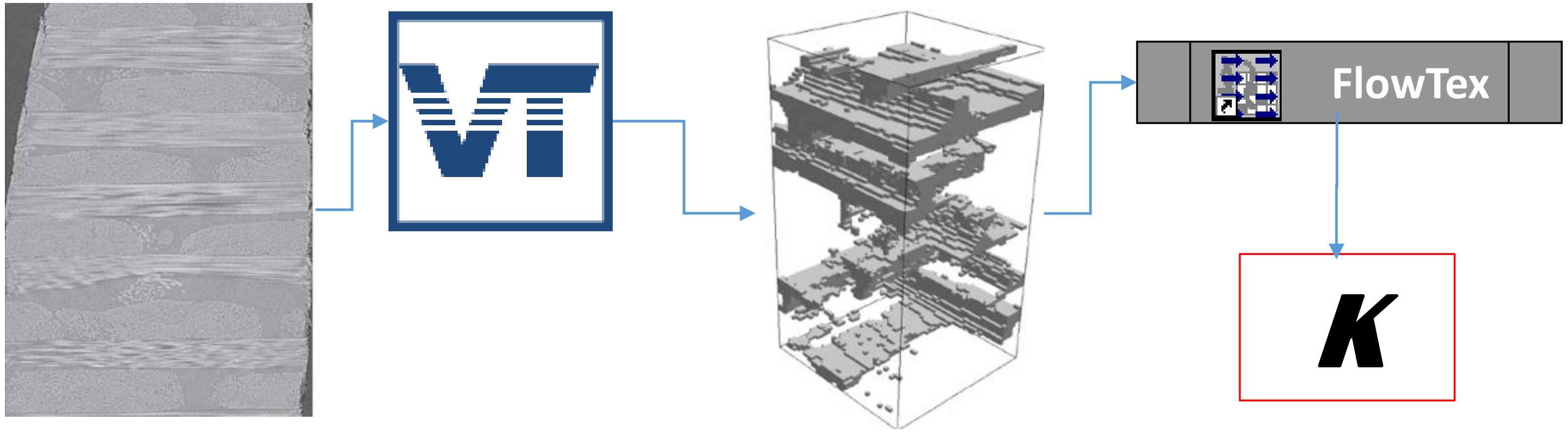
carbon NCF (Saertex) [+45°/-45°] tricot stitching, 540 g/m^2



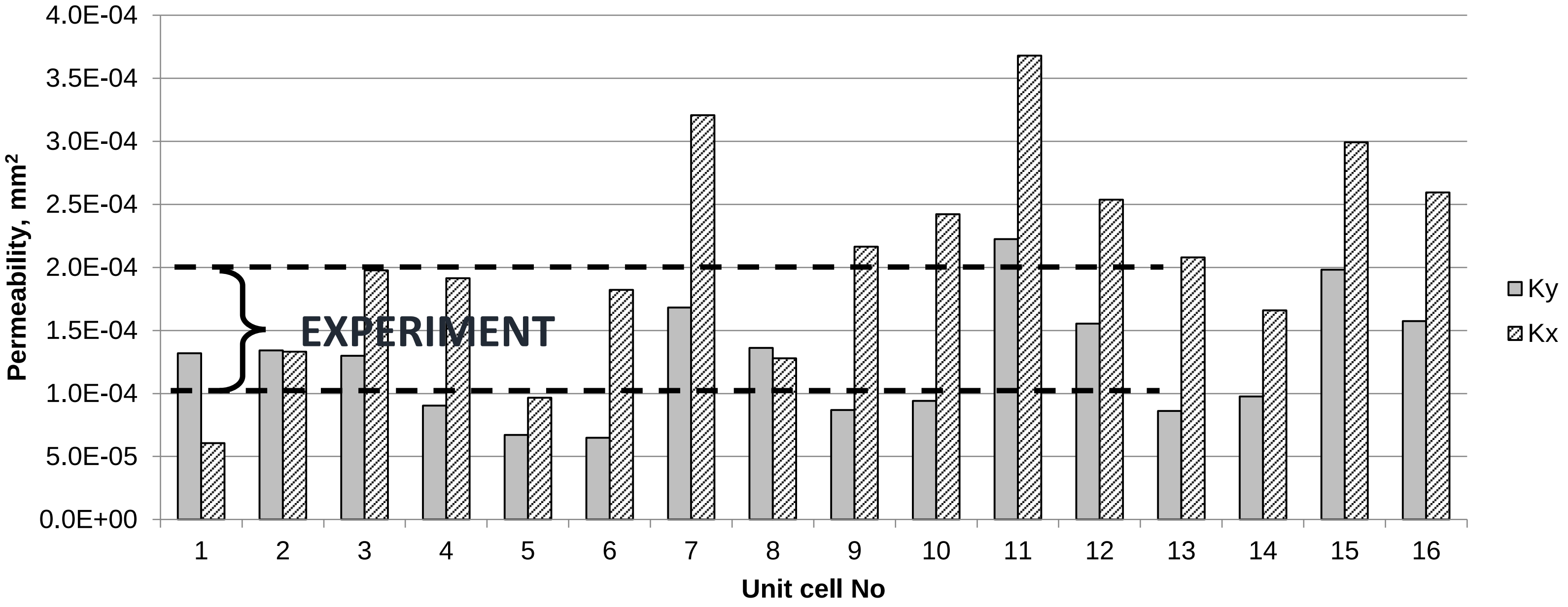
sample 1 sample 2 sample 3

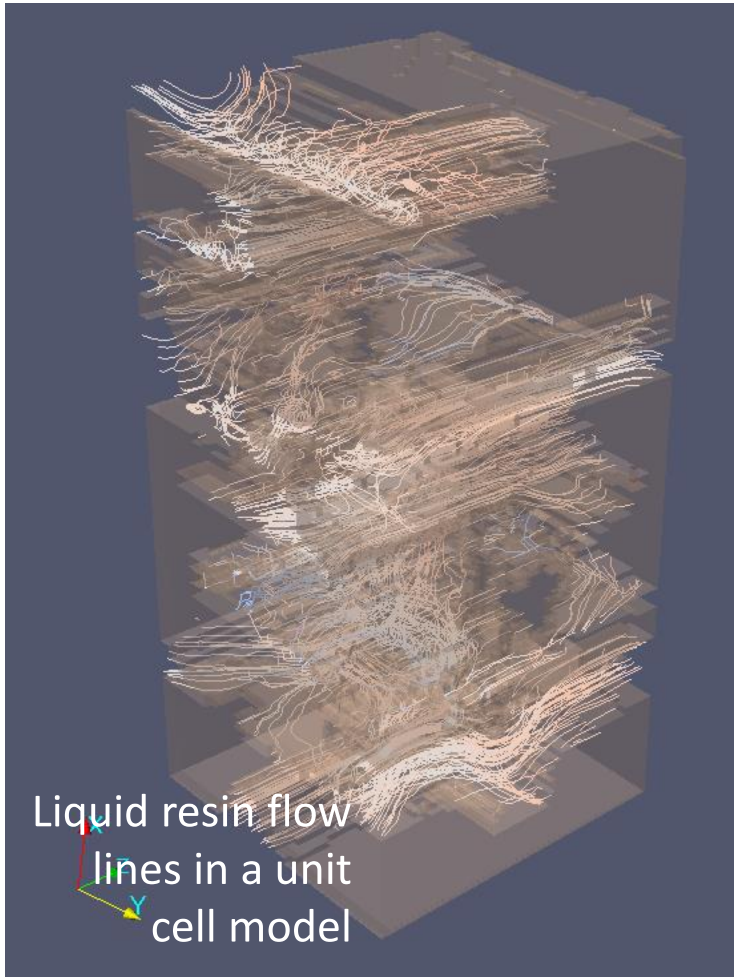


Permeability calculations



Results for 16 unit cells, resolution of the image 6 µm





1. Introduction. Fibrous media: microstructural features and characteristics
2. Quantification of a µCT image of fibrous materials
3. Applications
   - Fibre orientations
   - Finite element models of deformation and damage
   - Permeability

4. Conclusions

Conclusions

1. **Micro-computed X-Ray tomography is a state-of-the-art tool** for detailed investigation of internal structure of fibrous materials.

2. Lab-scale µCT allows **quantification of the fibrous structure and a seamless transfer of data to mechanical modelling software**, allowing calculation of:
   - homogenised stiffness
   - damage development and strength
   - permeability
   - effect of defects

VoxTex licences:

industry	4	★ (red)
university	7	★ (green)