Research Institute in Civil Engineering and Mechanics

Institut de Recherche en Génie Civil et Mécanique

Micro-Scale Results from the Benchmark Exercise on the Image-Based Permeability Prediction of Composite Reinforcements

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Image-Based Simulation for Industry - 2022

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Leibniz-Institut für Verbundwerkstoffe

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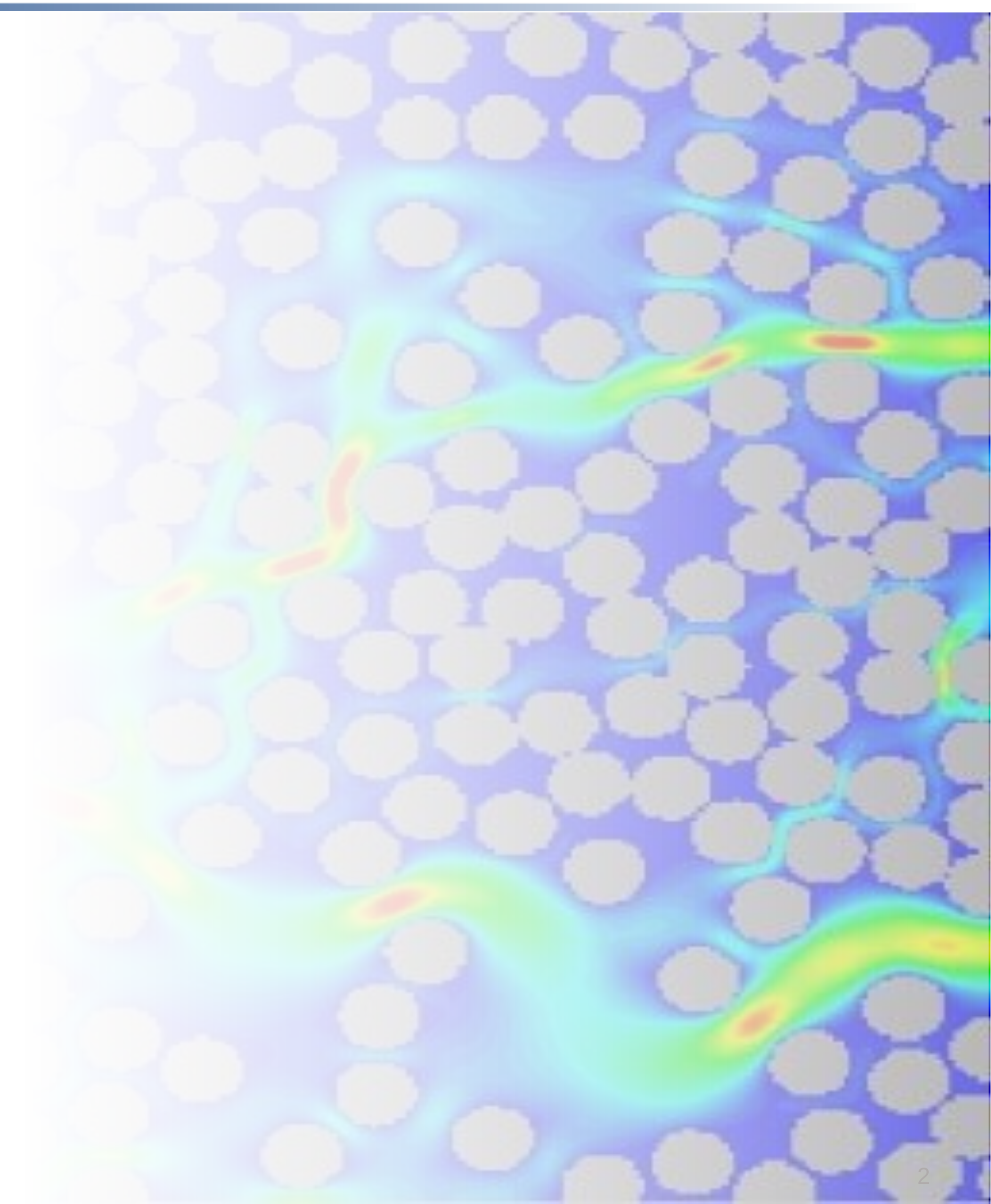
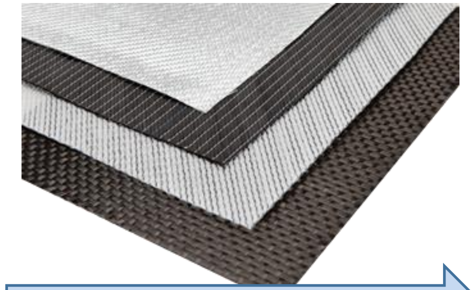
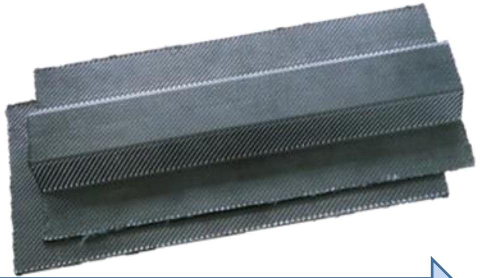
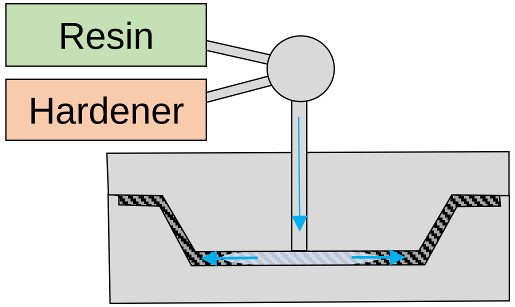


Context

Liquid Composite Moulding (LCM) Process





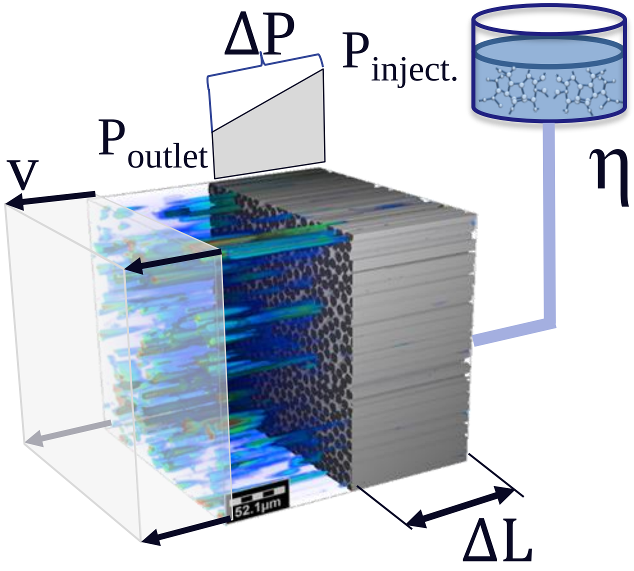


Textile → Preform → Liquid Composite Moulding (LCM) → Composite part

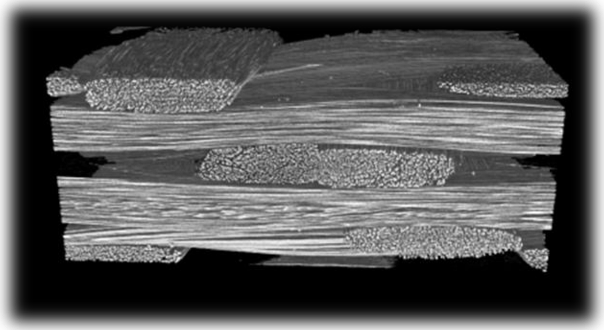
<u>Darcy‘s law:</u>

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

- v: volume-averaged flow velocity
- K: *Permeability*
- ΔP: pressure drop
- η: *viscosity*
- ΔL: flow length



Motivation of benchmark

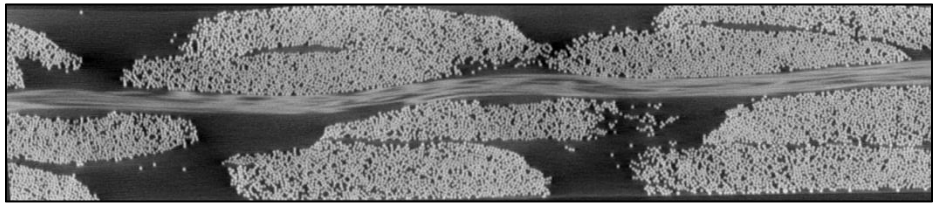


1. Fiber reinforcements in composites are special class of porous media:
   - *dual-scale porosity*,
   - *anisotropy*,
   - *variability*.

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

3. Benchmarks of experimental measurements of permeability of fibrous preforms revealed high discrepancy of results – at least ~20% [*N.Vernet et al, 2014*], [*D.May et al, 2019*], [*A.Yong et al, 2021*].

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



Virtual Permeability Benchmark – first contribution to a real fibrous structure.

Benchmark approach

ADVISORY BOARD

Dr. Luisa Silva

Dr. Elena Syerko
Prof.Christophe Binetruy
Main organizer

Prof. Stepan V. Lomov

Tim Schmidt
Dr.-Ing. David May
Main organizer

Prof. Suresh Advani

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

- Already **segmented** images of the material are provided to eliminate possible sources of variation.
- No fixed conditions (method, boundary conditions,…) for the calculations for the <u>first</u> stage of the benchmark.

Choice limited by the computational resources:

- discretization;
- 2D/3D formulation;
- subdivision into sub-volumes

Benchmark approach

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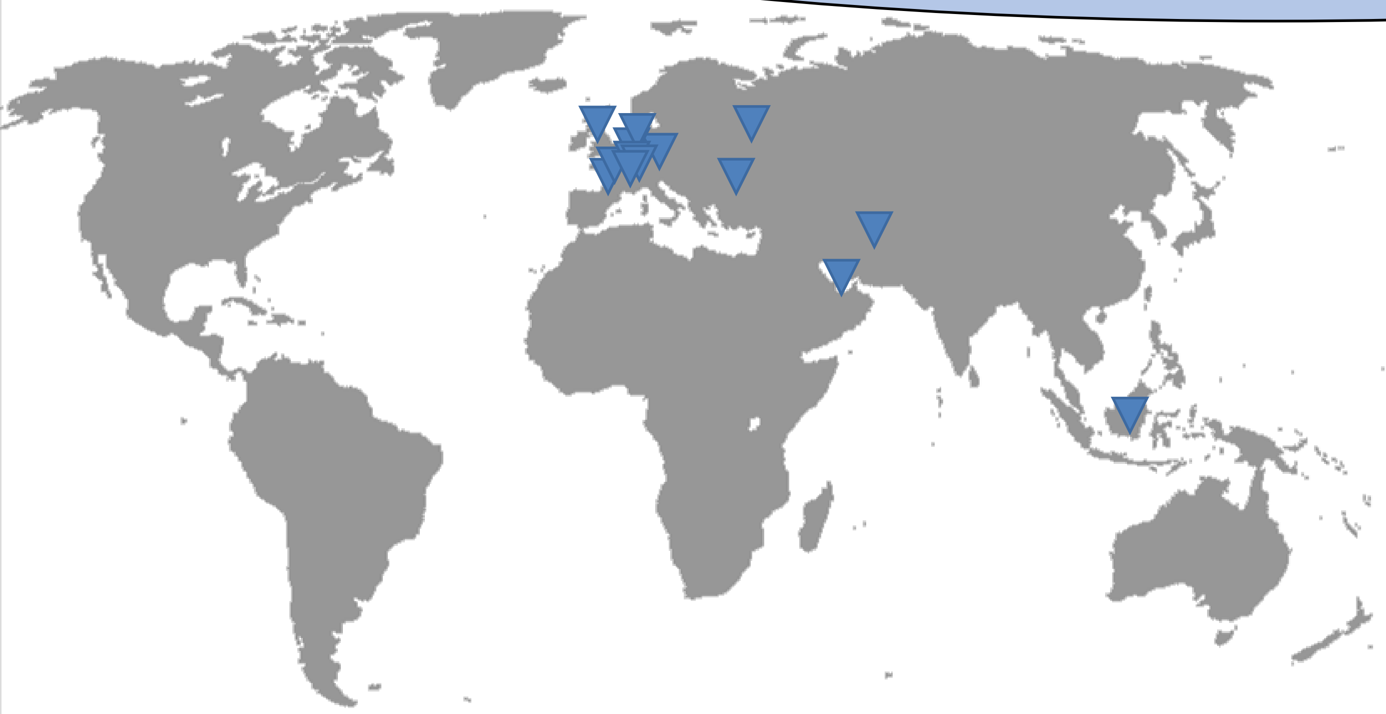
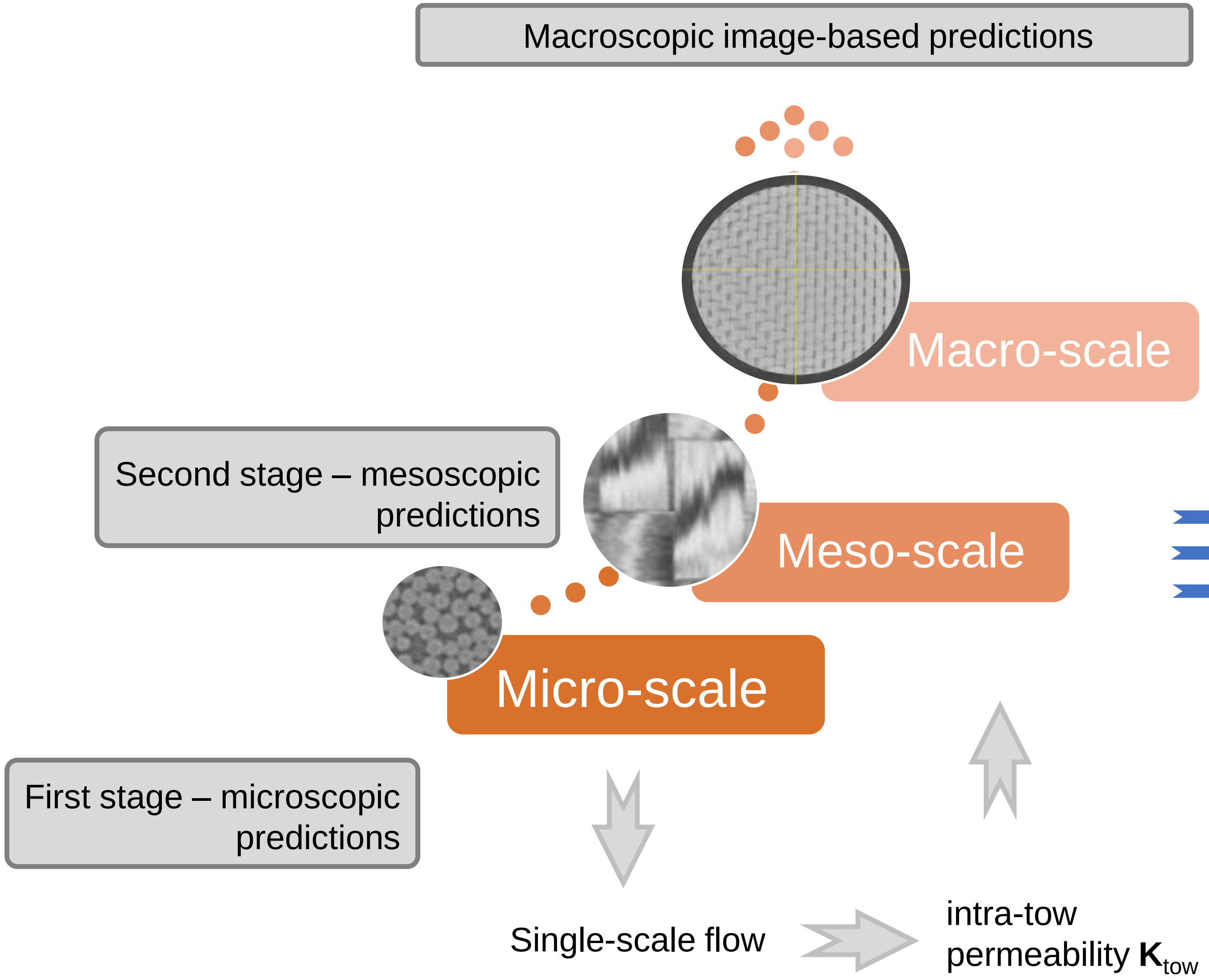


16 participants from 10 countries

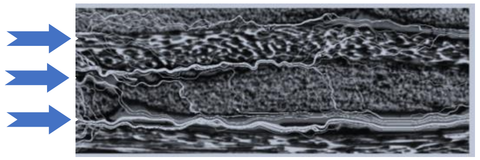
- LPAC, Lausanne
- IVW, Kaiserslautern
- 3SR Lab, Grenoble
- ITWM, Kaiserslautern
- ICI, Centrale Nantes
- TENSYL, Périgny
- GeM, Centrale Nantes
- KU Leuven
- Universität Stuttgart
- University of Nottingham
- IMT Lille Douai
- RISE, Göteborg
- Ferdowski University of Mashdad
- National University of Singapore
- Skoltech, Moscow
- Mines Saint-Etienne
- Siemens Industry Software, Leuven
- Khalifa University, Abu Dhabi

Benchmark approach



Mesoscopic permeability tensor of the twill woven textile

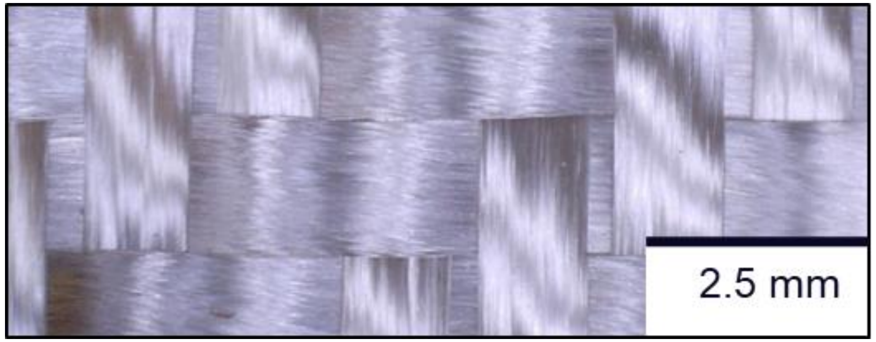
$$\mathbf{K} = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{xy} & K_{yy} & K_{yz} \\ K_{xz} & K_{yz} & K_{zz} \end{bmatrix}$$



Multi-scale flow

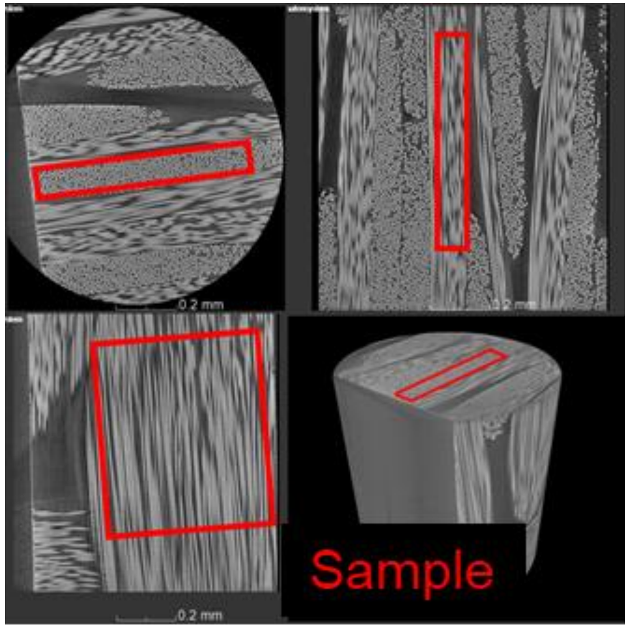
Input image data

Glass fibre woven fabric (295 g/m2)



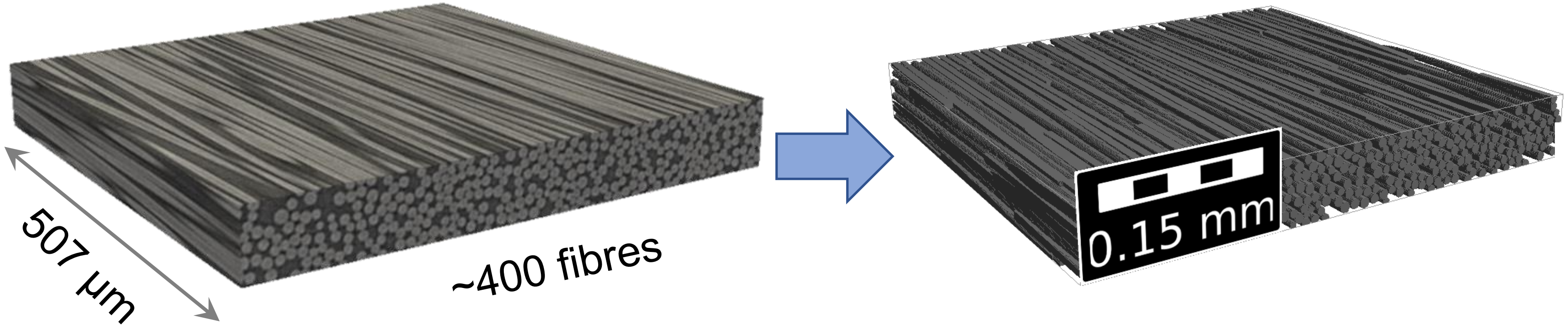
Tow specifications:

- 3 yarns twisted in a tow
- 40 twist/meter => 1 twist / 25 mm
- fibre diameter: 7.5-9.3 µm (data sheet: 9 µm)



Scan nominal resolution 0.52 µm³

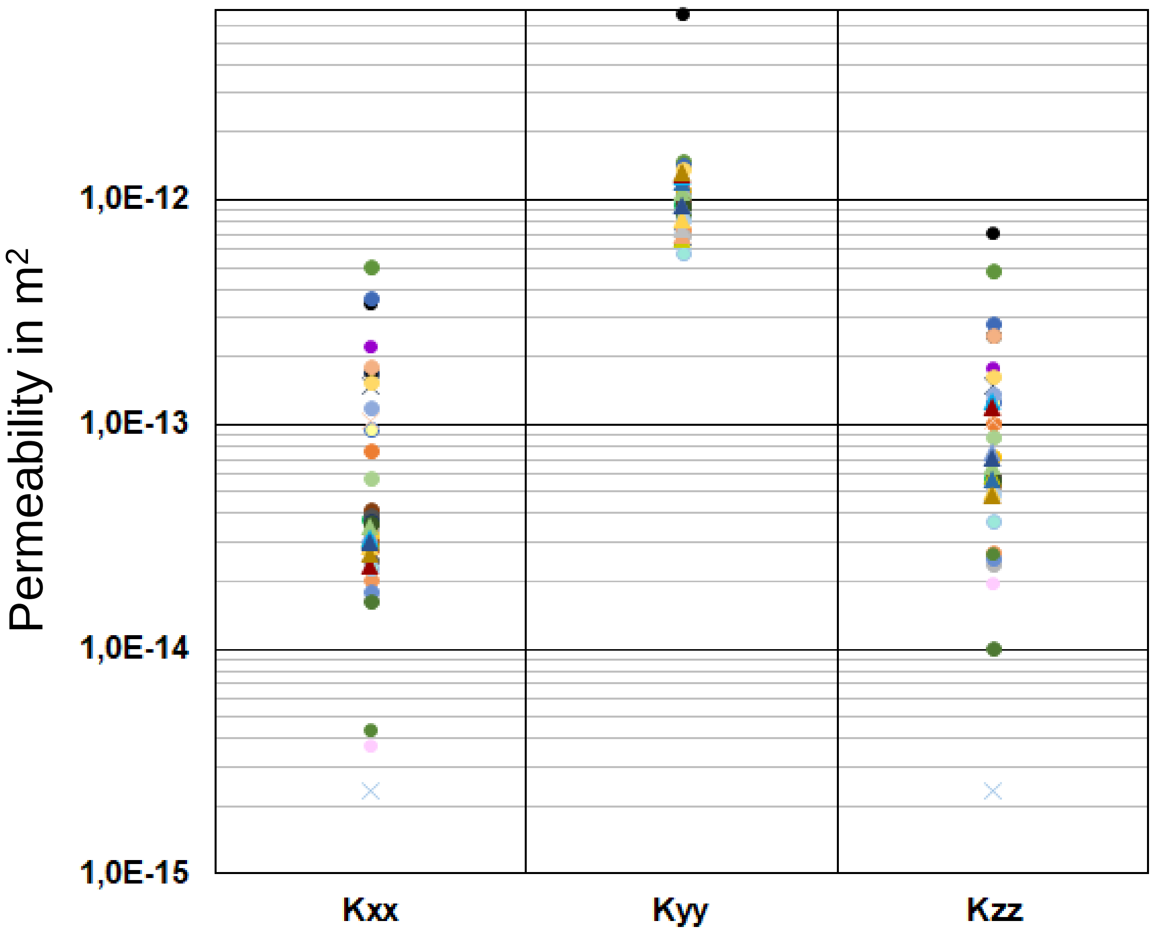
Provided <u>segmented</u> volume with defined two phases (~1000 x 120 x 1000 voxels)

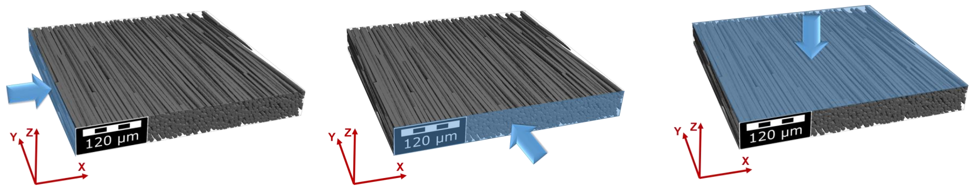


✓ Averaged over tow sample fibre volume content (FVC): 56.46%

Overview of micro-scale results

16 participants delivered 50 results in total





	K_{xx}, m^2	K_{yy}, m^2	K_{zz}, m^2
Mean	7.42E-14	1.11E-12	1.05E-13
STD	1.02E-13	8.97E-13	1.25E-13
CV	**137%**	**81%**	**119%**

- 3 participants provided results in **2D** (without axial permeability Kyy)
- Only two participants used the same method and settings

Overview of methods, models, and parameters used

Participant #	Numerical approximation	Discretization	Flow model	2D / 3D formulation	Physical variables formulation	Model size, voxels / Voxel size, μm^3	FVC, %
1	FVM	Voxel-based	Stokes	3D	SIMPLE	1003x973x124 / 0.521^3 μm^3	56.46
2	FEM	Geometry-based	Navier-Stokes	2D	mixed velocity-pressure	10 2D slices of ≈1003x124 / 0.521^3 μm^3	56.73 (55.06 – 59.54), 58.54 (57.08 – 61.39)
3	FVM	Voxel-based	Navier-Stokes	3D	mixed velocity-pressure	1800x180x200 / 0.2605 μm x 2.605 μm x 0.2605 μm	57.00
4	CVFEM	Voxel-based	Navier-Stokes	3D	mixed velocity-pressure	10 sub-volumes of ≈1003x100x124 for Kxx,Kzz 10 sub-volumes ≈100x973x124 for Kyy / 0.521^3 μm^3	56.46 (54.02 – 58.78), 56.46 (48.42 – 60.88)
5	FVM	Voxel-based / LIR	Stokes	3D	mixed velocity-pressure	1003x973x124 / 0.521^3 μm^3	56.46
6	FEM	Geometry-based	Stokes	2D	mixed velocity-pressure	973 2D slices of 1003x124 / 0.521^3 μm^3	55.87
7	FVM	Geometry-based	Navier-Stokes	3D	SIMPLE	1003x973x124 / 0.521^3 μm^3	59.87
8	FDM	Voxel-based	Stokes	3D	mixed velocity-pressure	972x972x108: 648 sub-volumes of 54x54x54 / 0.521^3 μm^3	57.16
9	FVM	Geometry-based	Stokes	3D	mixed velocity-pressure	16 sub-volumes of ≈251x243x124 / 0.521^3 μm^3	56.36 (46.96 – 60.84)
10	FEM	Voxel-based	Stokes	3D	pseudo-compressibility (penalization)	64 sub-volumes of ≈126x122x124 / 0.521^3 μm^3	56.46 (46.49 – 61.81)
11	FVM	Geometry-based	Navier-Stokes	3D	mixed velocity-pressure	1003x679x124 / ≈0.7368^3 μm^3	58.69
12	FVM	Voxel-based / LIR	Stokes	3D	SIMPLE mixed velocity-pressure	1003x973x124 / 0.521^3 μm^3	56.46
13	FVM	Geometry-based	Navier-Stokes	3D	mixed velocity-pressure	124x192x124 / 0.521^3 μm^3	59.54
14	FEM	Geometry-based	Stokes	2D	mixed velocity-pressure	973 2D slices of 1003x124 / 0.521^3 μm^3	56.46, 55.57
15	FEM	Geometry-based	Stokes	3D	mixed velocity-pressure	1003x973x124 / 0.521^3 μm^3	56.46, 51.00
16	FVM FDM	Voxel-based / LIR	Stokes	3D	SIMPLE mixed velocity-pressure	1003x973x124 / 0.521^3 μm^3 10 sub-volumes ≈1003x100x124 / 0.521^3 μm^3	56.46, 56.46 (54.02 – 58.78)

Influence of cropping into sub-domains

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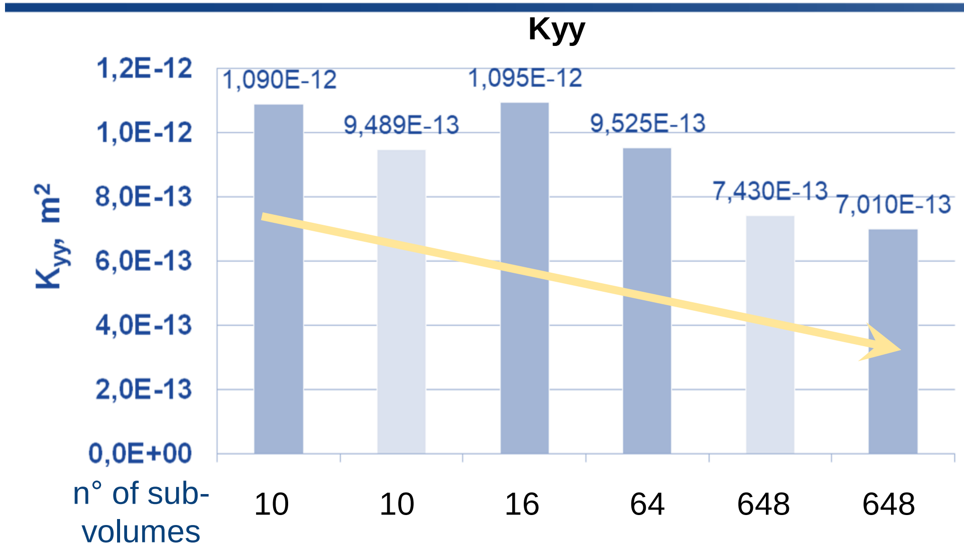
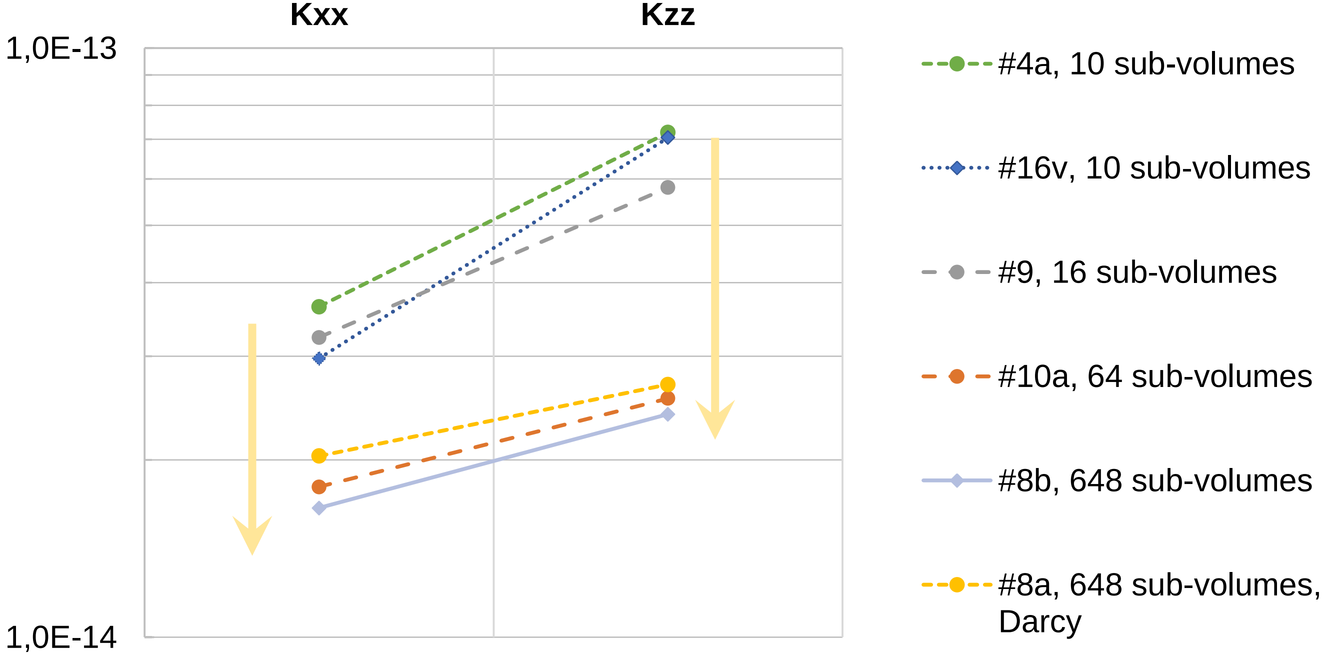
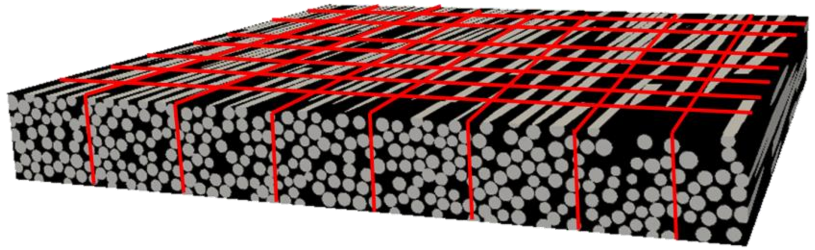
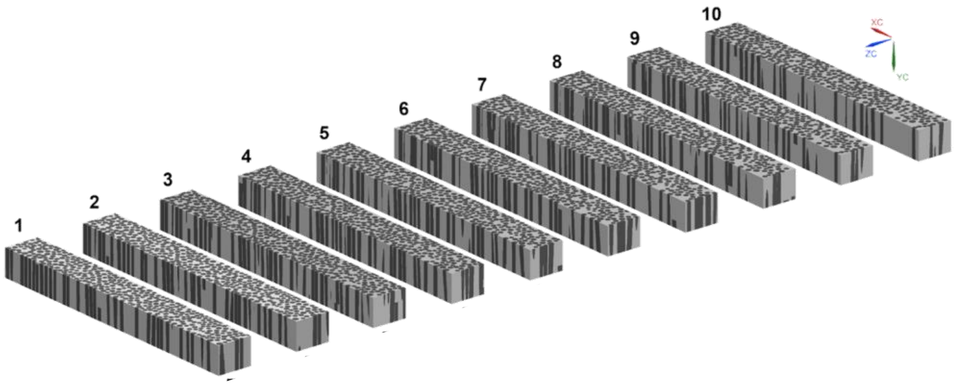


- **15% deviation from the main cluster mean value using 10 sub-volumes**



Arithmetic and harmonic means of values from sub-volumes

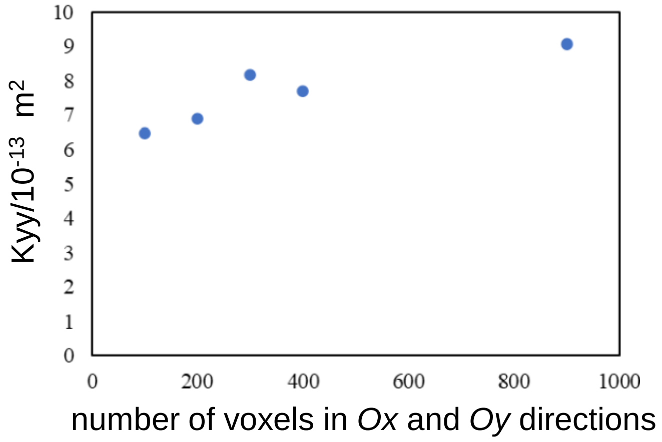


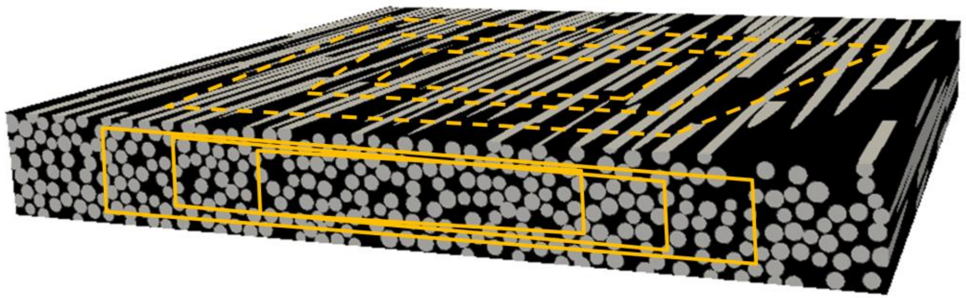


Influence of domain dimensions

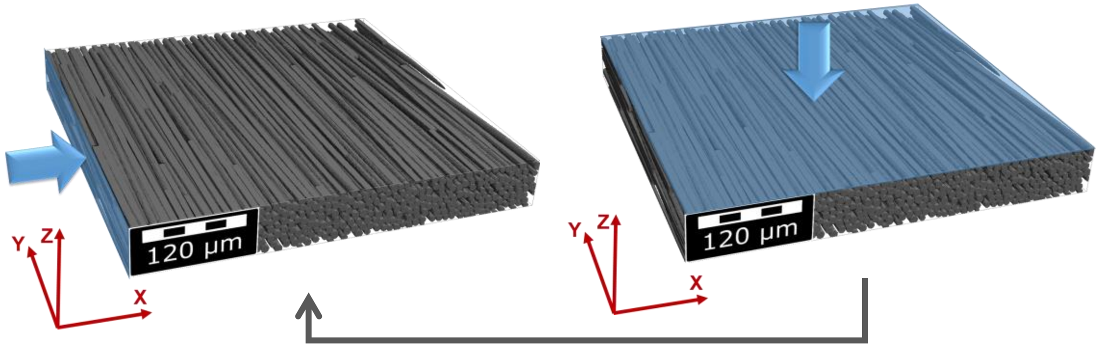
- No convergence of permeability with increasing domain size up to the entire sample volume:

Axial permeability with increasing domain size (#3)



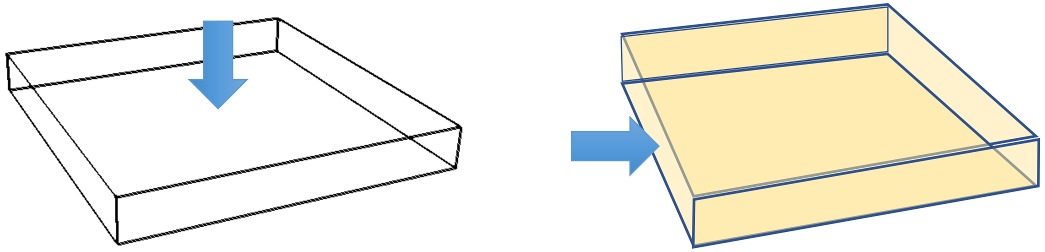


- Transverse Kzz is higher than transverse Kxx



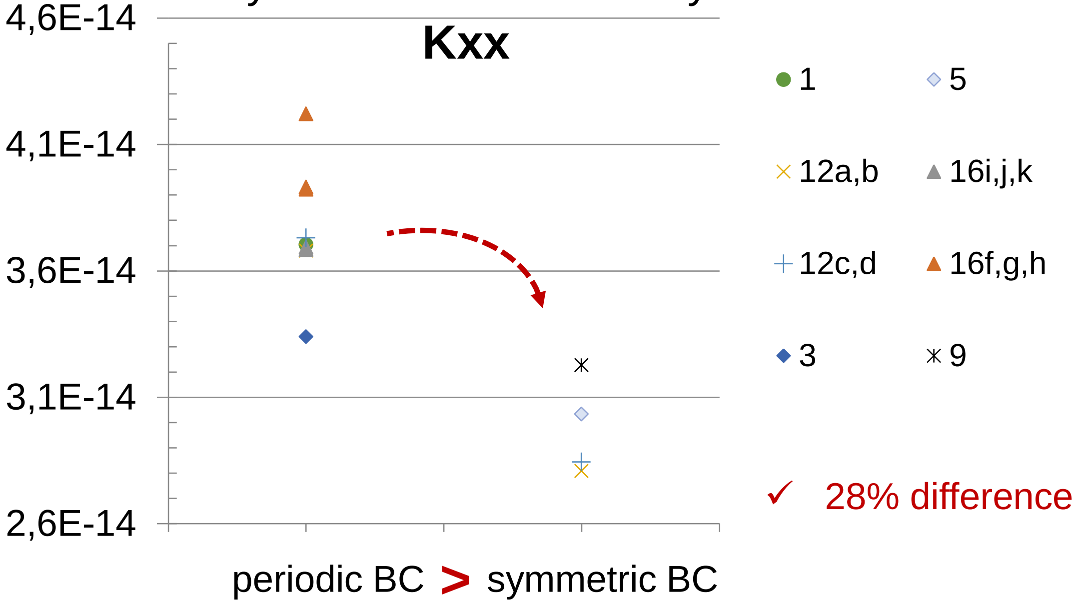
1/8th of in-plane dimensions, not statistically representative

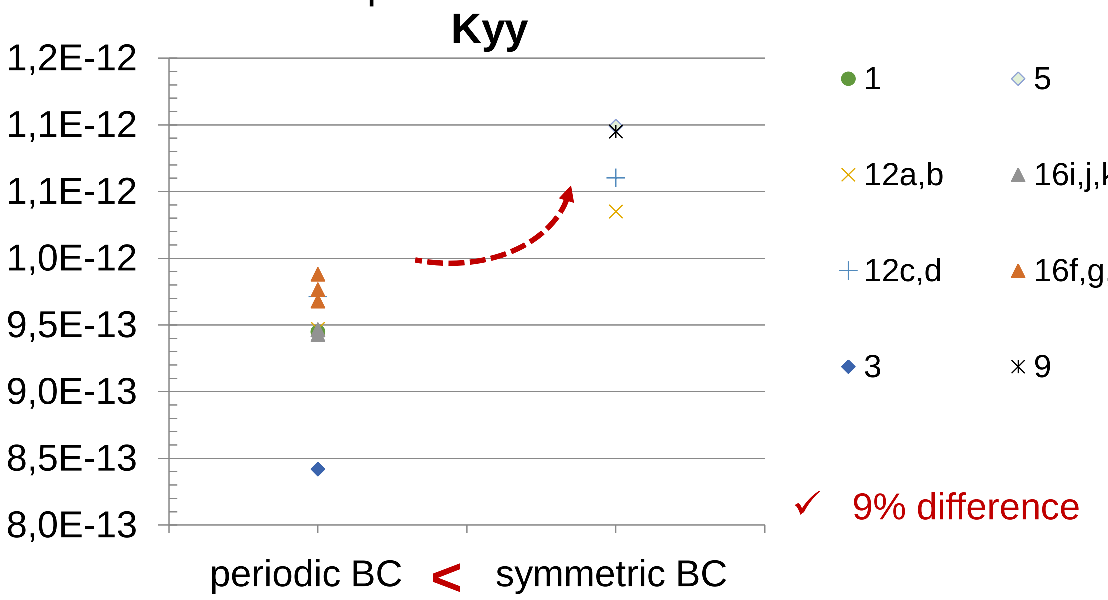
- Effect of BC in tangential direction for Kzz is minimized



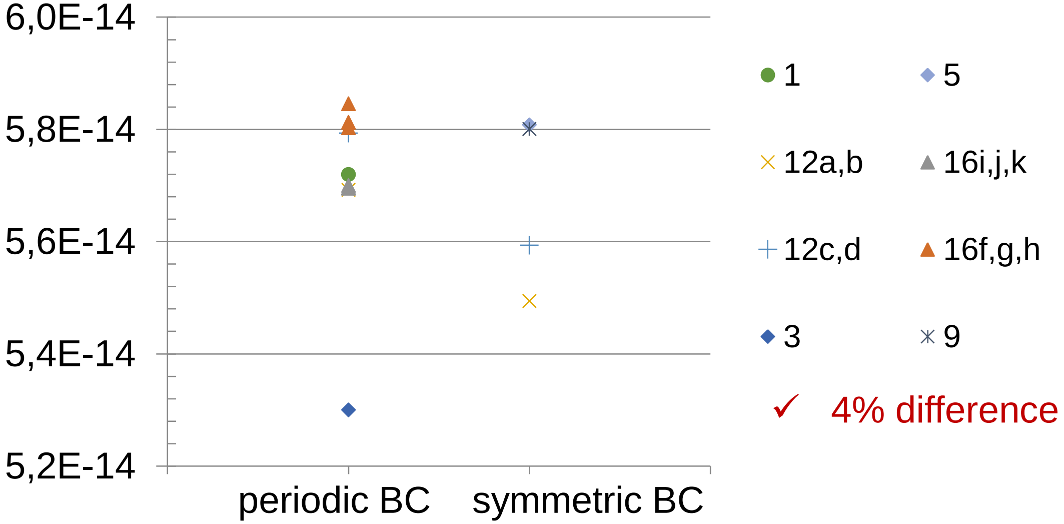
Influence of boundary conditions

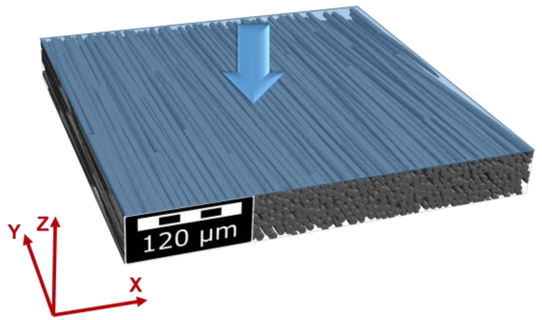
- When only the results obtained by the same methods and parameters are compared:





Through-thickness transverse component **Kzz**





Correlation with fiber volume content

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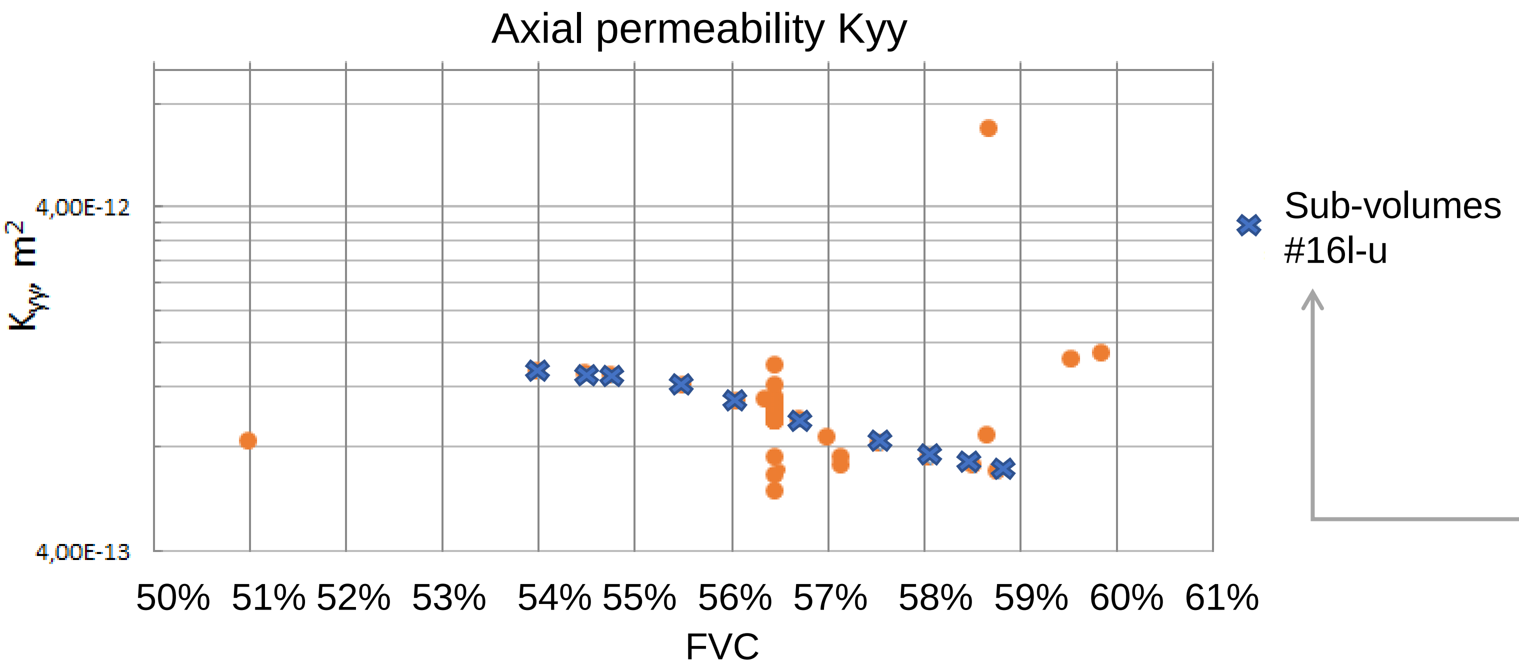
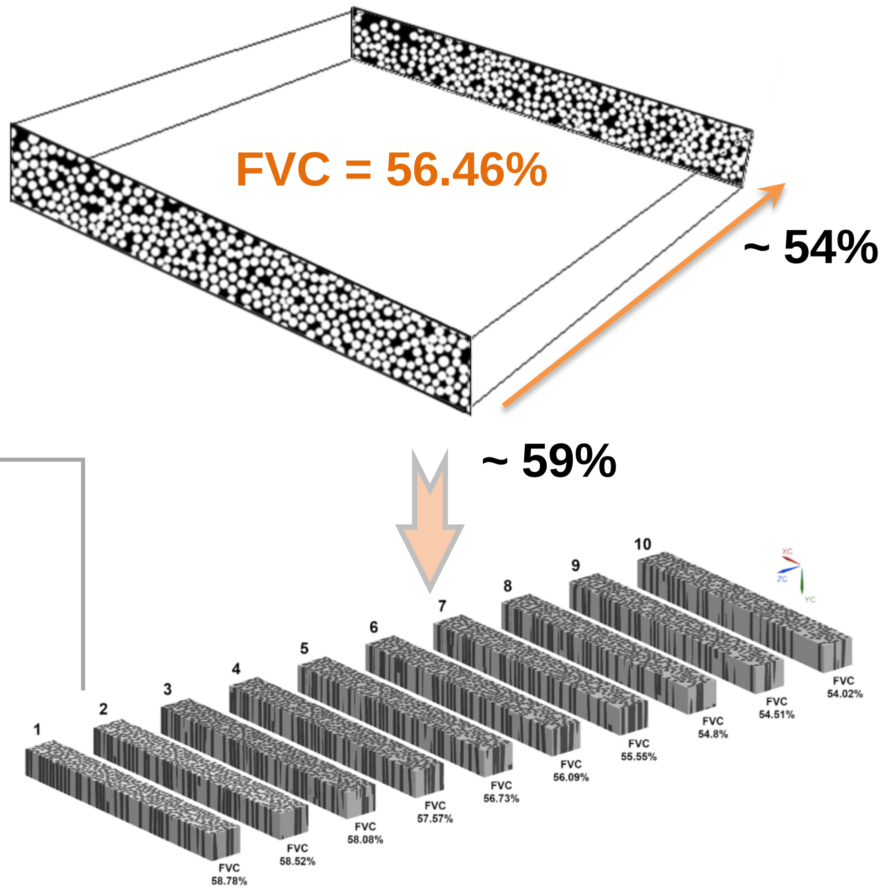
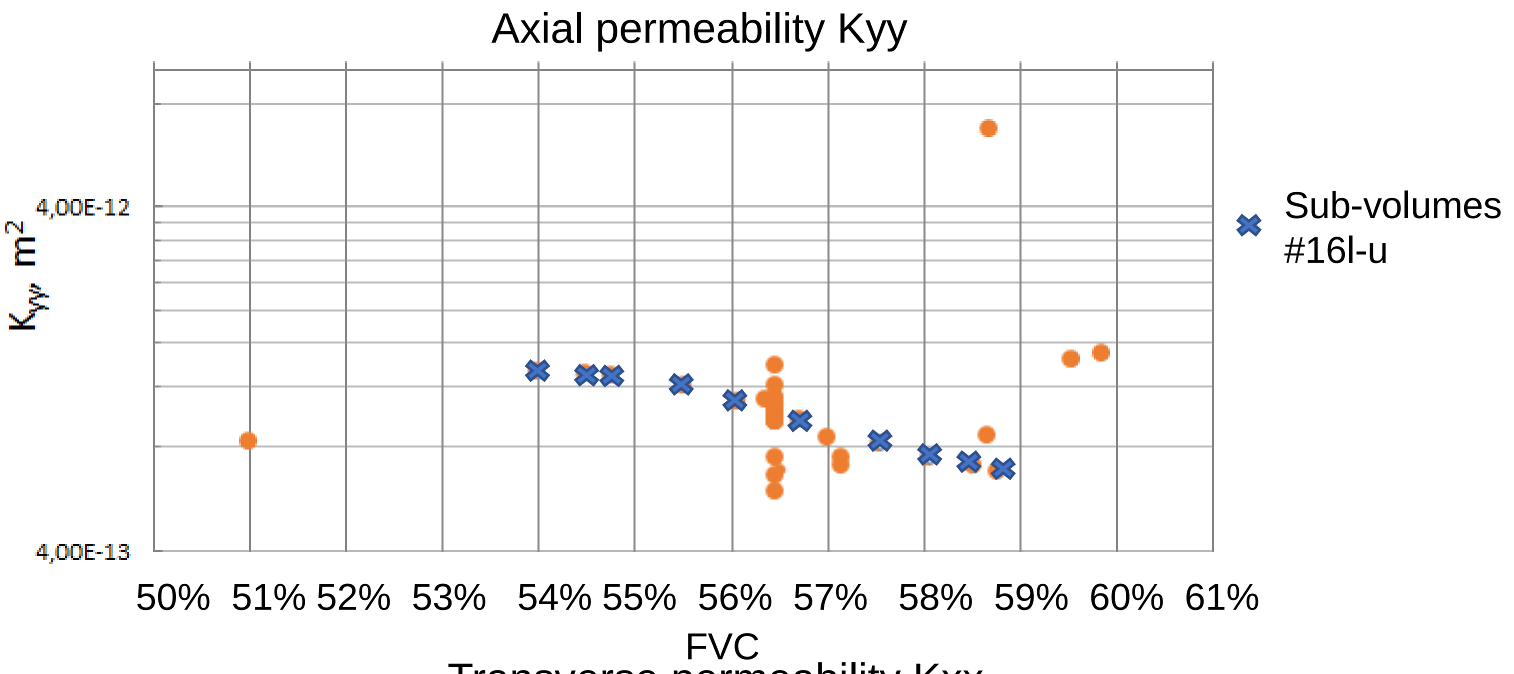


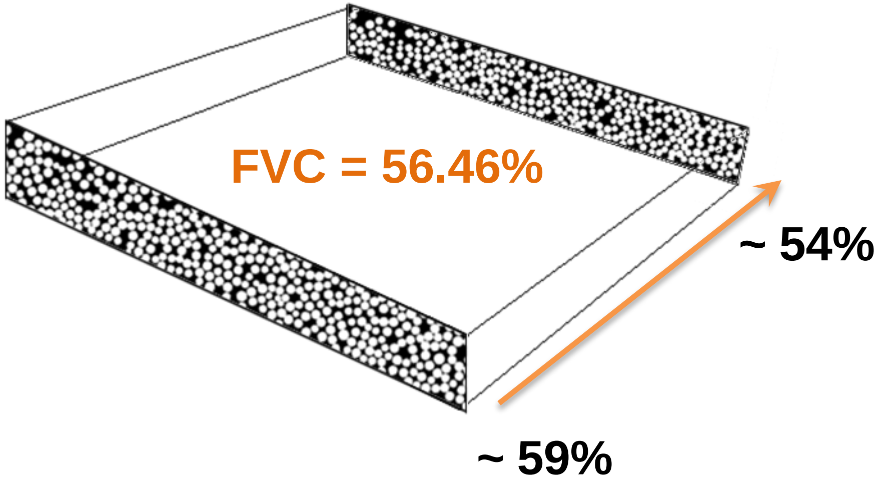


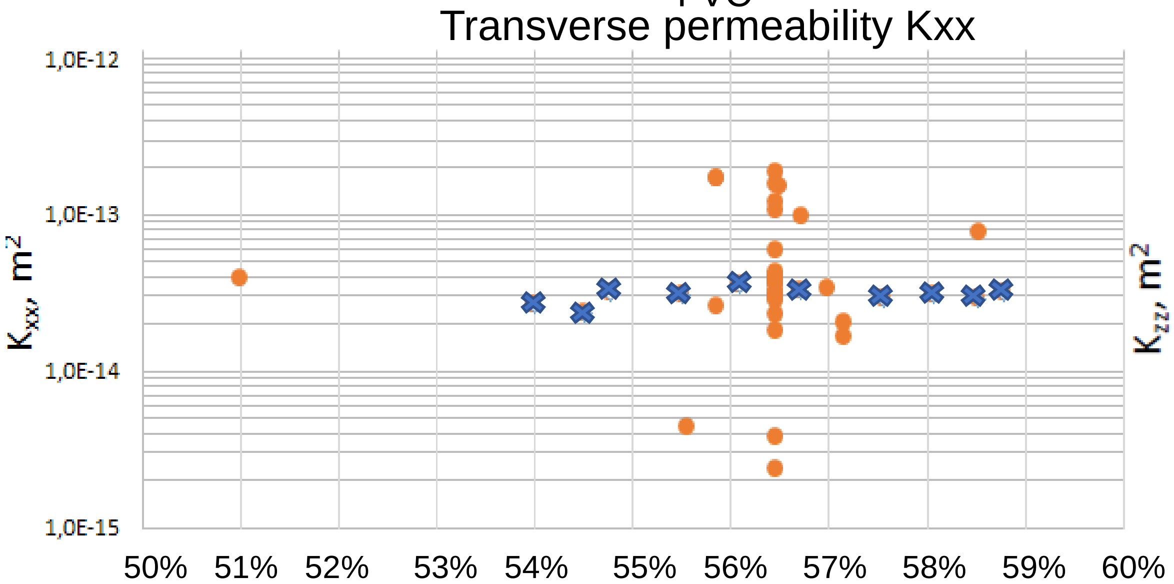
✓ Different FVC can result from: - different model sizes,
- cropping of edges,
- discretization of domain.

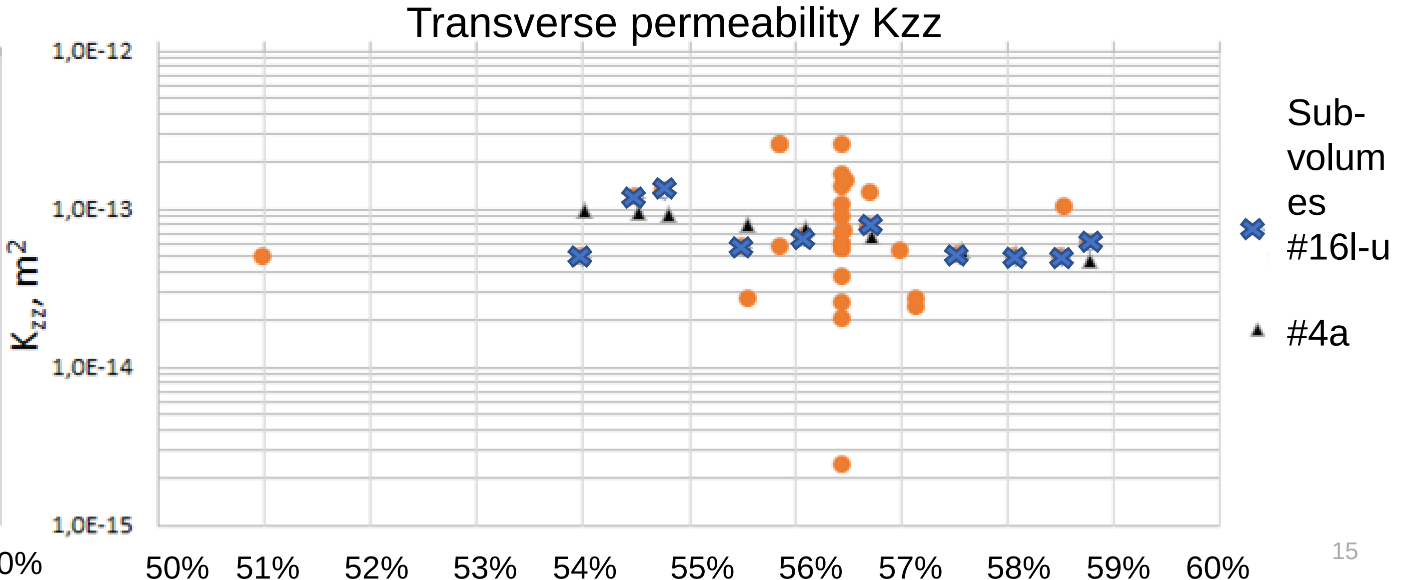
➢ Cluster of values at FVC = 56.46% has a CV of 16%.

Correlation with fiber volume content

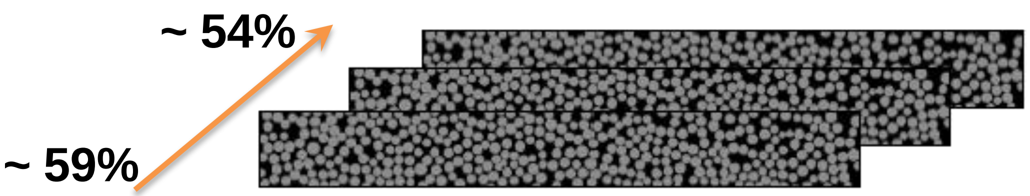


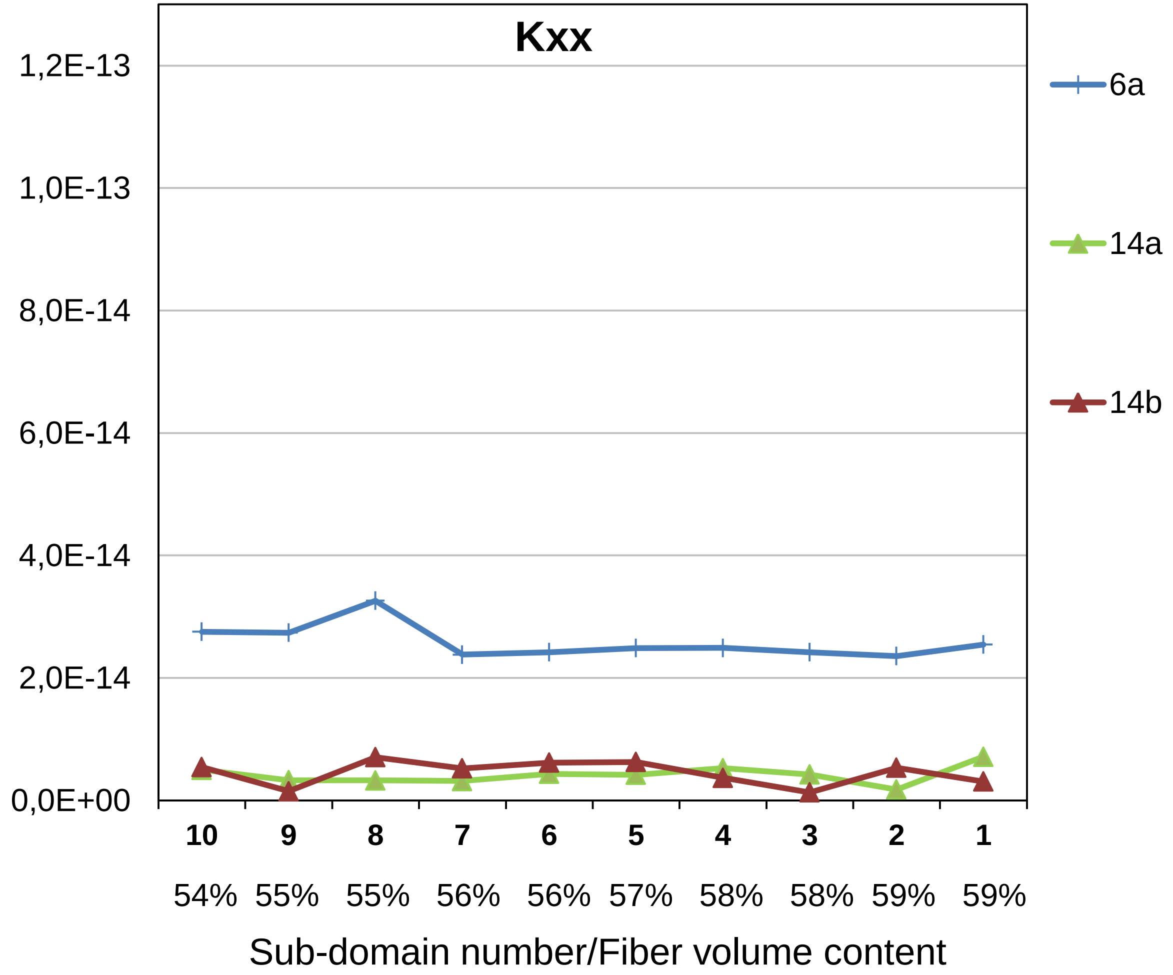


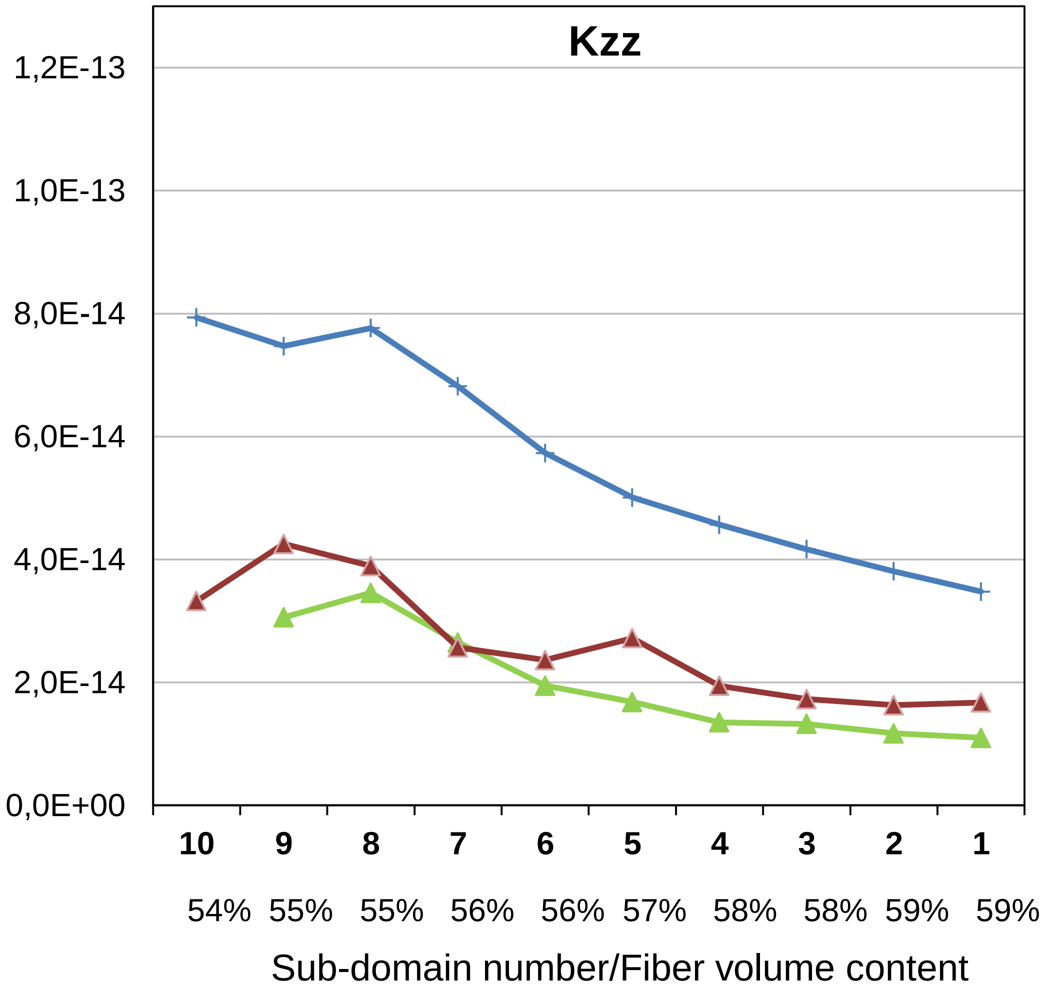




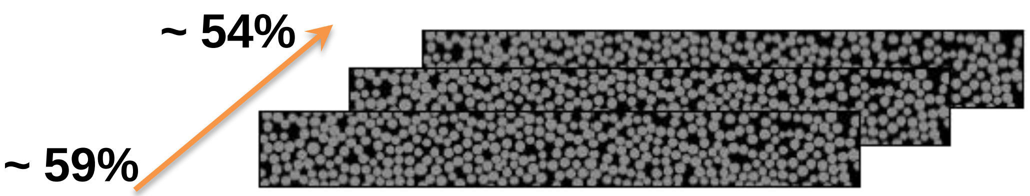
Correlation with fiber volume content: 2D/3D

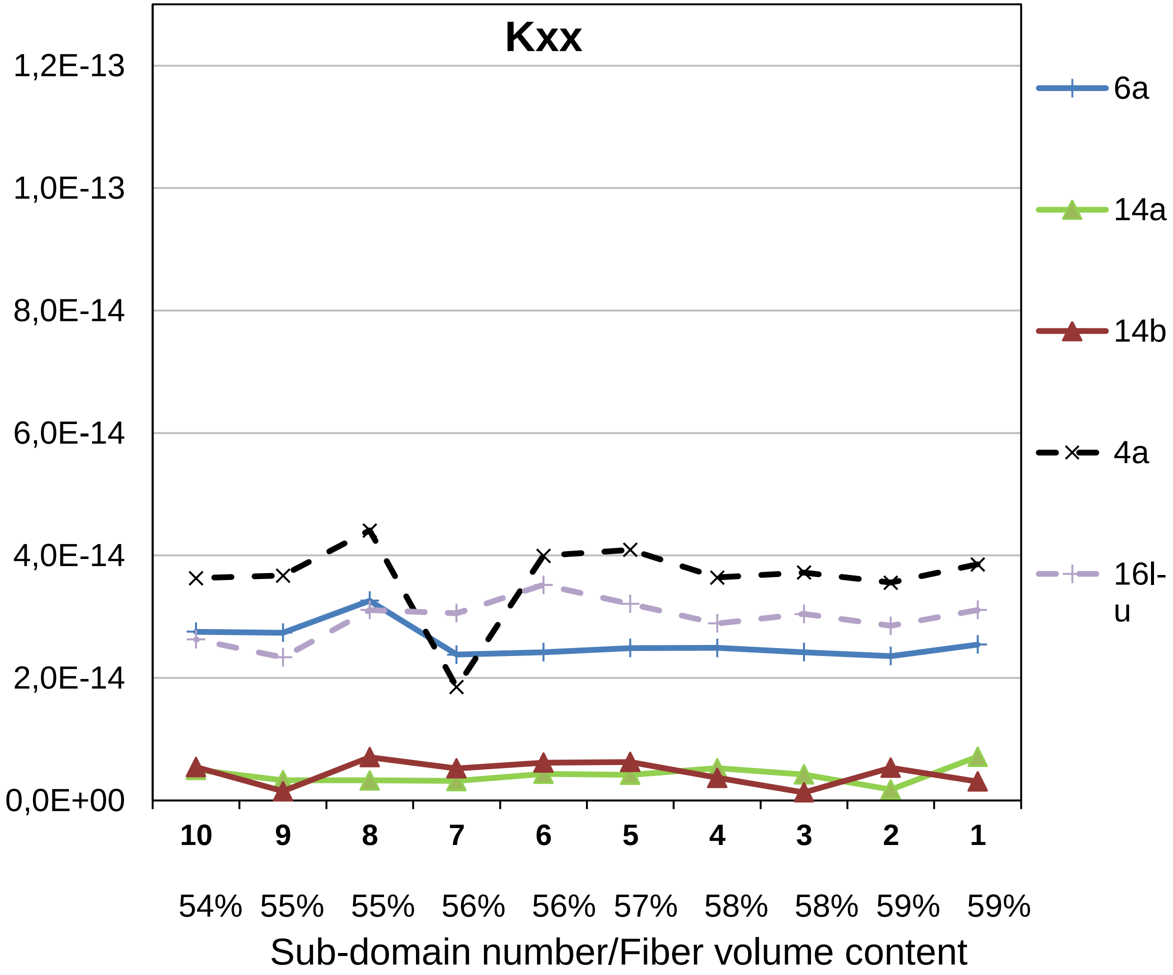


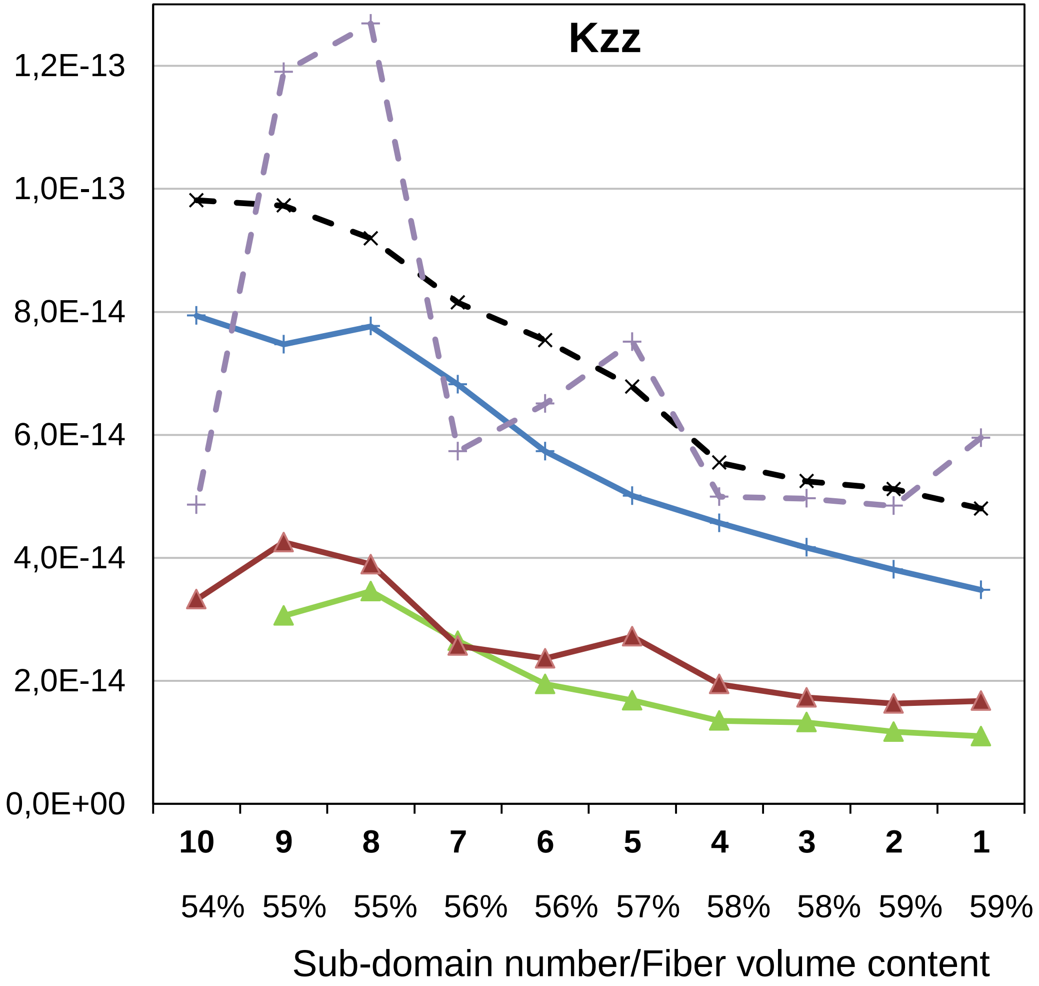




Correlation with fiber volume content: 2D/3D

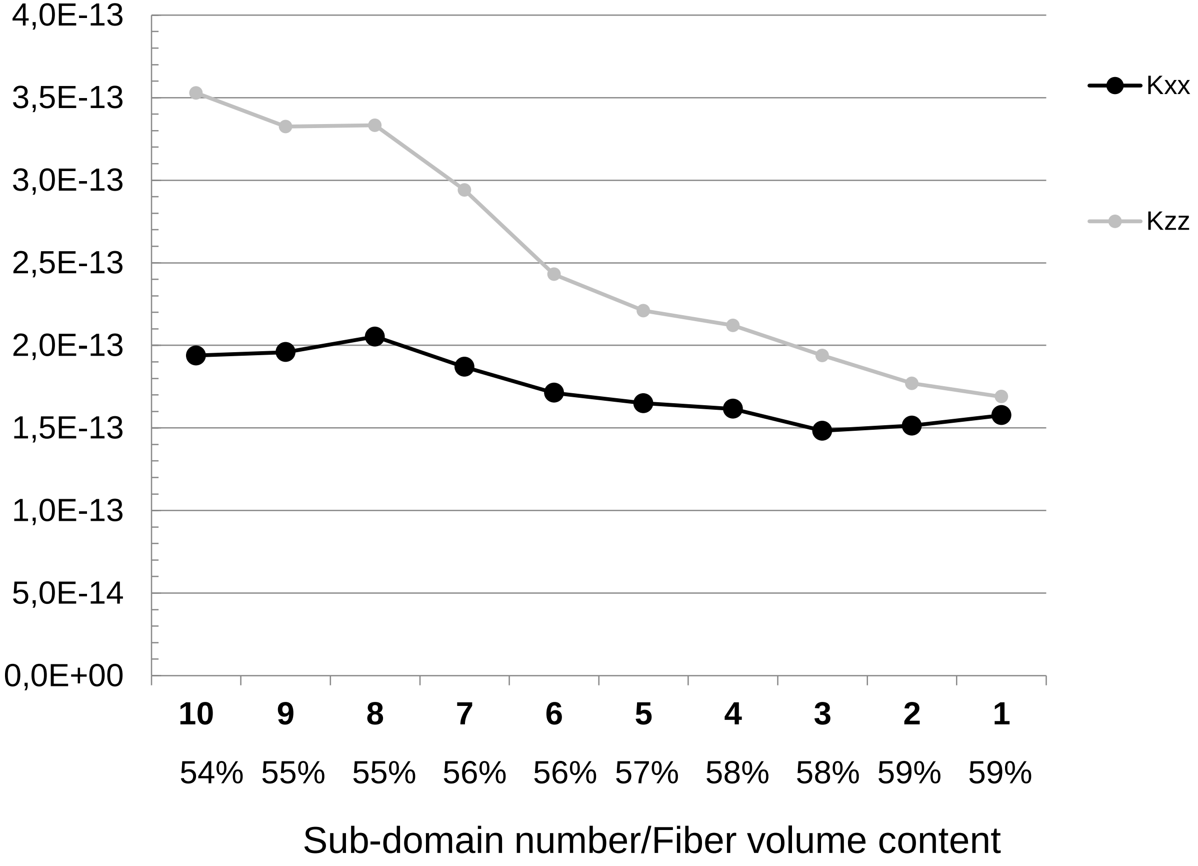


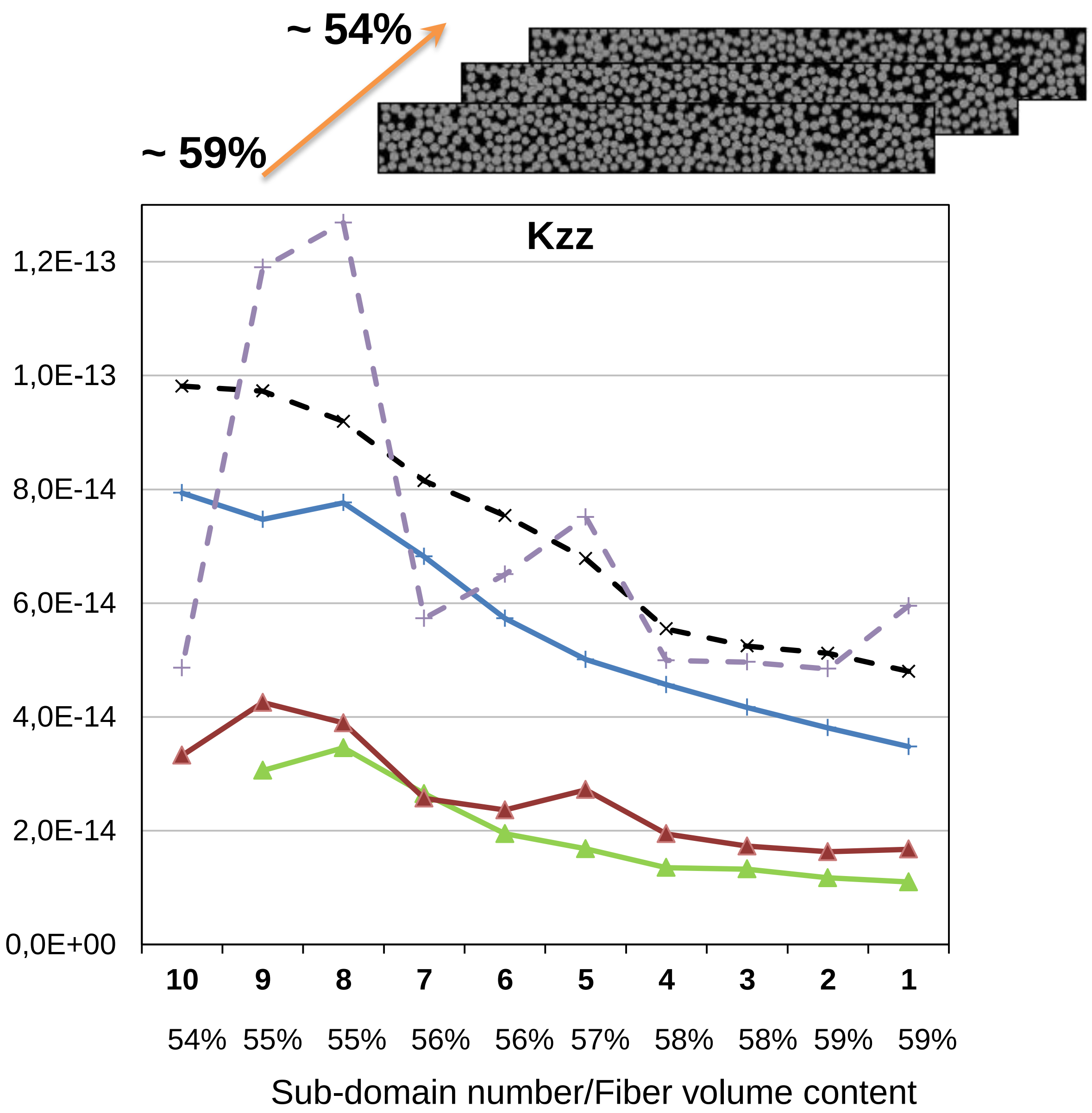




Correlation with fiber volume content: 2D/3D

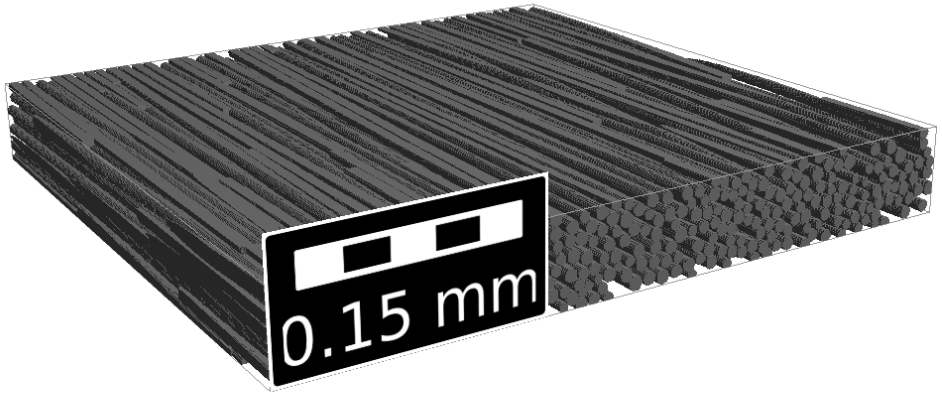
Transverse components of result #6b,c:
identification with Darcy's law accounting for the cross-flows





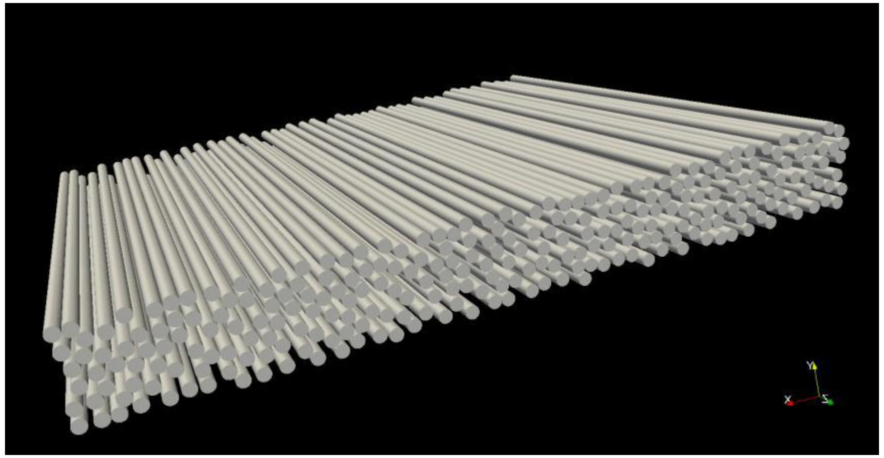
Computation on a real image vs. a digital twin

Real sample



Digital twin

(generated by random sequential addition method in #15b)



- Varying FVC 54-59% along the fibre direction
- Varying fibre diameter 7.5-9.3 µm

- Constant FVC 51% along the fibre direction
- Constant fibre diameter 9 µm

	K_{xx}, m^2	K_{yy}, m^2	K_{zz}, m^2
CV	**69%**	**40%**	**69%**

Correlation between results #15a (image) and #15b (digital twin) using the same method

Assumptions:

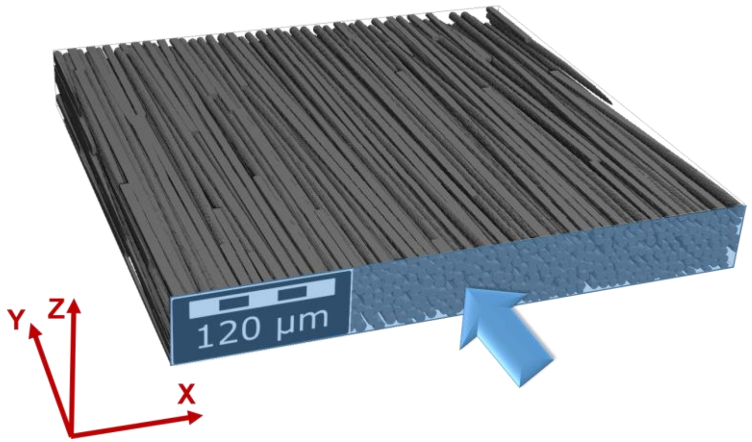
- fibres perfectly aligned
- constant fibre diameter
- no twist

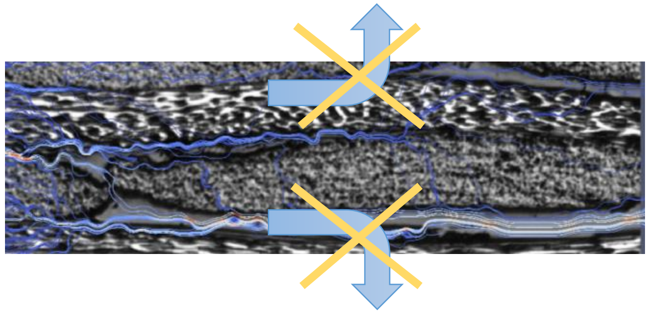
Summary and conclusions

Resulting cluster of permeability values

	K_{xx}, m^2	K_{yy}, m^2	K_{zz}, m^2
Mean	3.2E-14	9.4E-13	5.2E-14
CV	**24%**	**14%**	**25%**

- After detailed analysis of results => reduced coefficient of variation
- Importance of calculation of full permeability tensor, which is a symmetric positive definite second order tensor. Stokes equation to address the creeping flow condition.
- Dominant effect of:
  - permeability identification technique;
  - BC in tangential direction (compared to the BC in flow direction);
  - number of sub-domains used in renormalization technique.
- When principal directions of flow are unknown, no-slip and symmetric BC are not convenient.



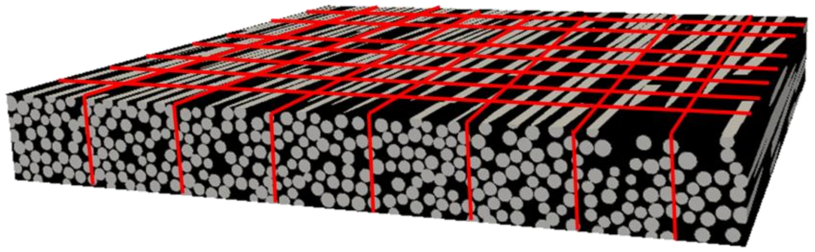


Summary and conclusions

- Subdivision into sub-domains with subsequent renormalization can be a reasonable solution, but highly dependent on:

  i) number of sub-domains;

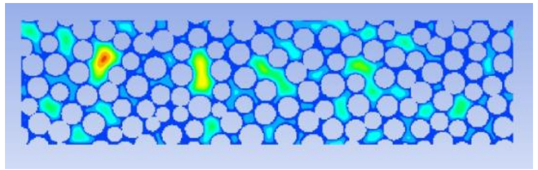
  ii) presence of transverse anisotropy effects in the microstructure.



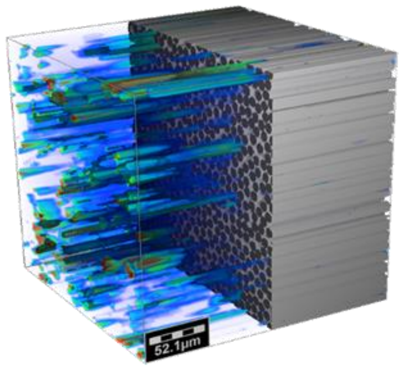
- No definite conclusion on the correlation of 2D/3D solutions based on the results of the benchmark for this type of microstructure.

Resulting cluster of permeability values

	K_{xx}, m^2	K_{yy}, m^2	K_{zz}, m^2
Mean	3.2E-14	9.4E-13	5.2E-14
CV	**24%**	**14%**	**25%**



From reporting #3

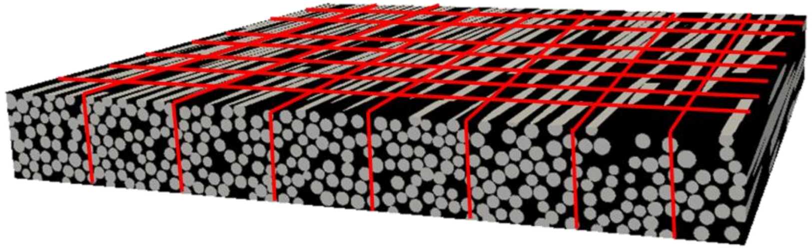


To access 3D image data of the first stage of the benchmark on the repository:

https://doi.org/10.5281/zenodo.6611926

Summary and conclusions

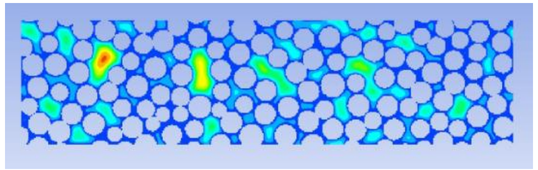
- ❑ Subdivision into sub-domains with subsequent renormalization can be a reasonable solution, but highly dependent on:
  i) number of sub-domains;
  ii) presence of transverse anisotropy effects in the microstructure.



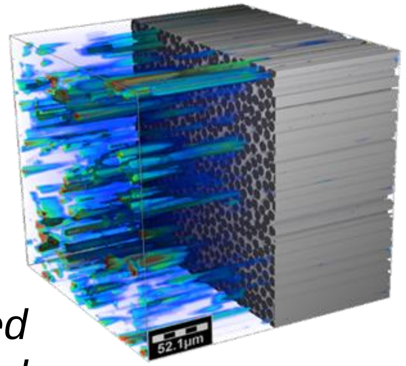
- ❑ No definite conclusion on the correlation of 2D/3D solutions based on the results of the benchmark for this type of microstructure.

Resulting cluster of permeability values

	K_{xx}, m^2	K_{yy}, m^2	K_{zz}, m^2
Mean	3.2E-14	9.4E-13	5.2E-14
CV	**24%**	**14%**	**25%**



From reporting #3

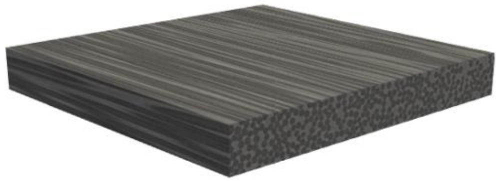


➢ *E. Syerko, T. Schmidt, D. May, C. Binetruy, S.G. Advani et al. Benchmark Exercise on Image-Based Permeability Determination of Engineering Textiles: Microscale Predictions // Composites Part A: Applied Science and Manufacturing 2022 (submitted).*

In-house developed solution PoroS

Institut de Recherche en Génie Civil et Mécanique

- Stokes / Brinkman solver;
- Pseudo-compressibility formulation;
- Homogenization technique for permeability tensor calculation based on the equivalence of dissipated at different scales powers.



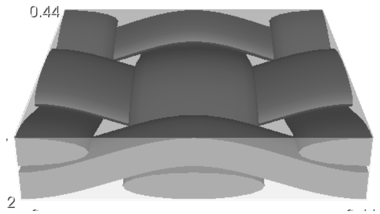
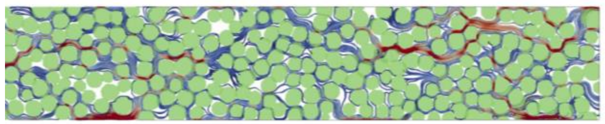


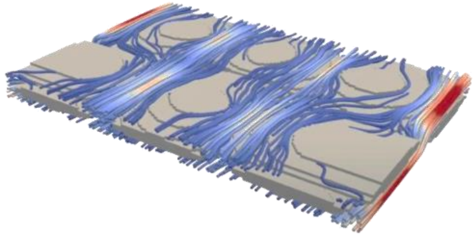
Image-Based Porous Medium Permeability Solver

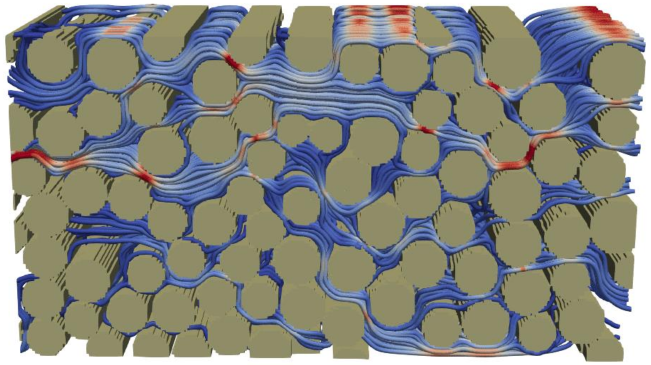
(IDDN.FR.001.400009.000.S.P.2022.000.20600)

PoroS

Calculation of local 3D flow and the permeability tensor







Flow calculated through the fibrous structure sample

- Values situated within the cluster of benchmark results.

Way forward

- **Second stage of the Virtual Permeability Benchmark** at meso-scale of the material is on-going until December 31st 2022.

For further questions on the Virtual Permeability Benchmark you can contact:

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