Optimisation of CT scanning for characterisation of carbon fibre pressure vessel microstructure

Shailee Upadhyay, Mahoor Mehdikhani, Stepan V. Lomov,
Dirk Vandepitte, Yentl Swolfs

ICCM 23
INTERNATIONAL CONFERENCE ON COMPOSITE MATERIALS
BELFAST 2023
30 JULY – 4 AUGUST

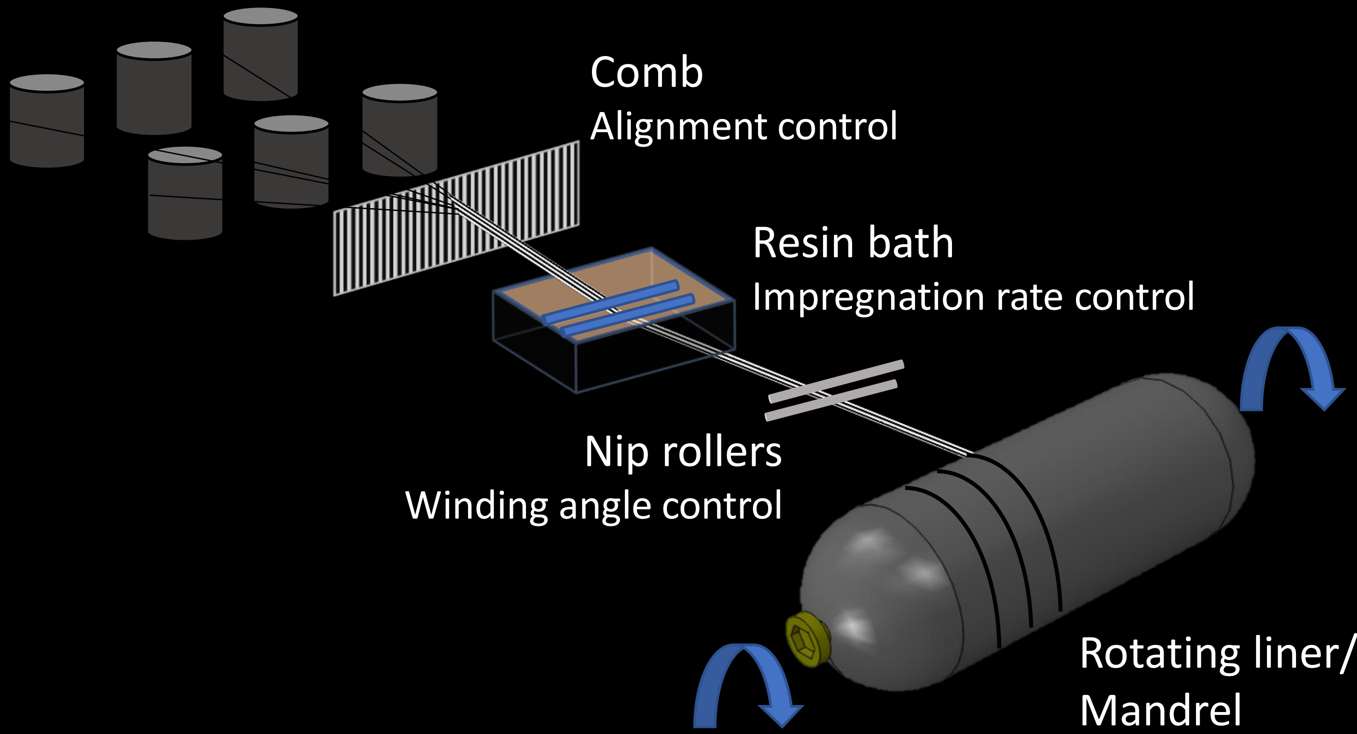
KU LEUVEN
MATERIALS ENGINEERING

Composite materials group

Composite pressure vessels

How are they made and what defects can they have?

Filament winding of composite pressure vessels



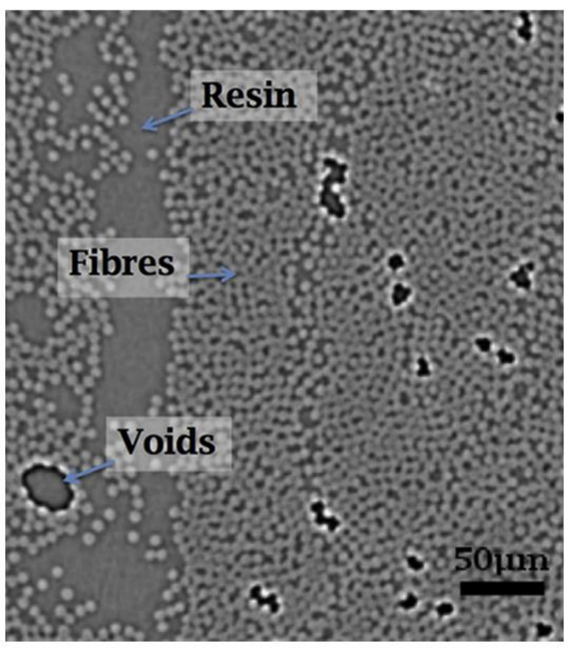
Low control of processing parameters

Microstructural variability /defects

Effect of variability on performance
Optimised design

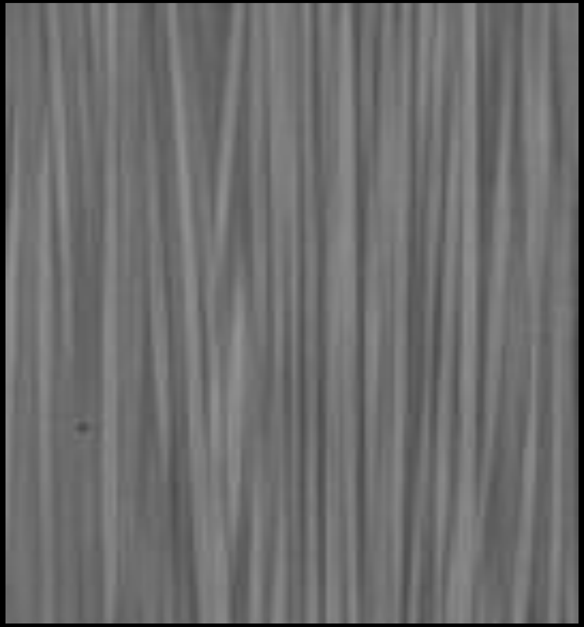
Microstructural variabilities and defects
Which parameters are of interest and why?

Voids



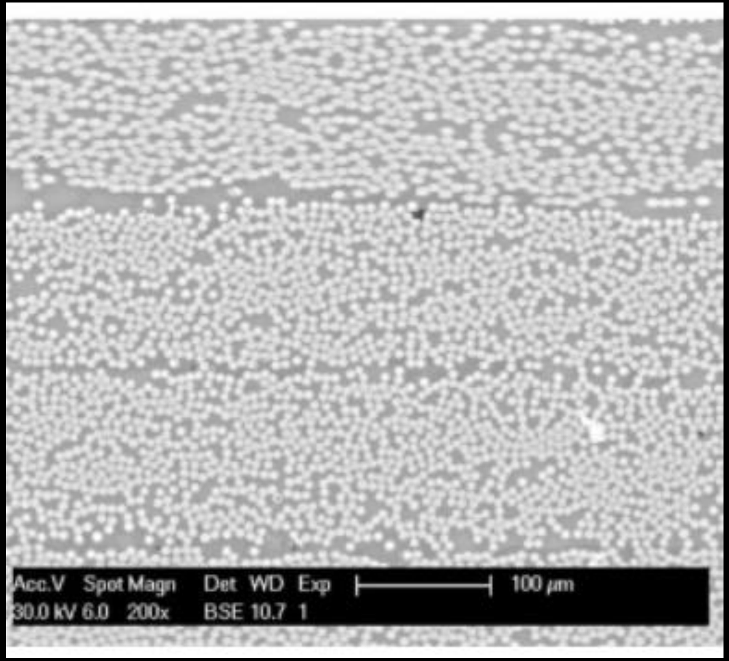
- Affect thermo-mechanical performance
- Act as crack initiation sites

Fibre misalignment



- Reduces tensile modulus
- Reduces load-carrying capacity

Fibre volume fraction variation



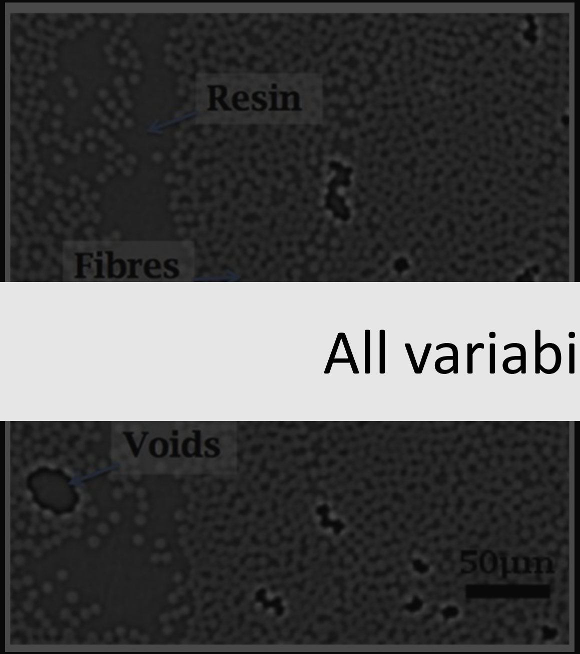
- Affects local and global strength
- Affects stress recovery length

Scott et al. (2014), Breite (2021), Mehdikhani et al. (2021)

Microstructural variabilities and defects

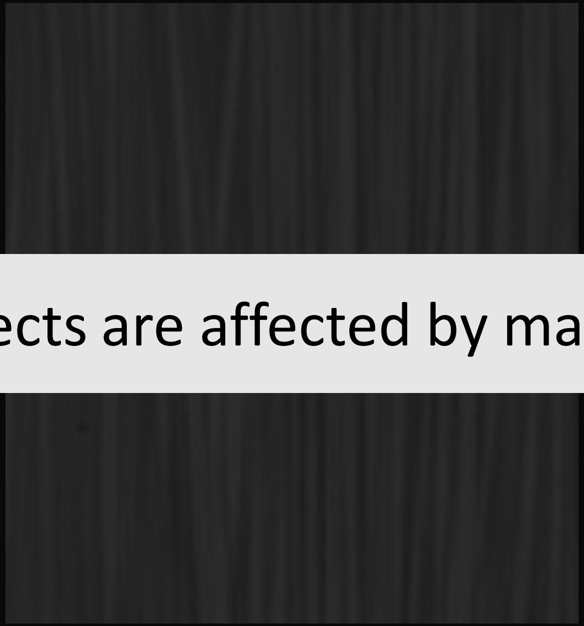
Which parameters are of interest and why?

Voids



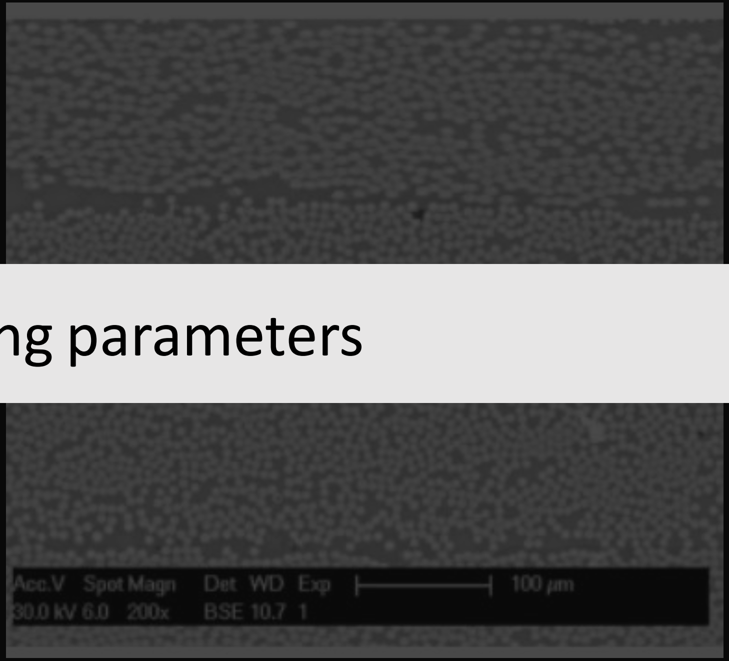
- Affect thermo-mechanical performance
- Act as crack initiation sites

Fibre misalignment



- Reduces tensile modulus
- Reduces load-carrying capacity

Fibre volume fraction variation



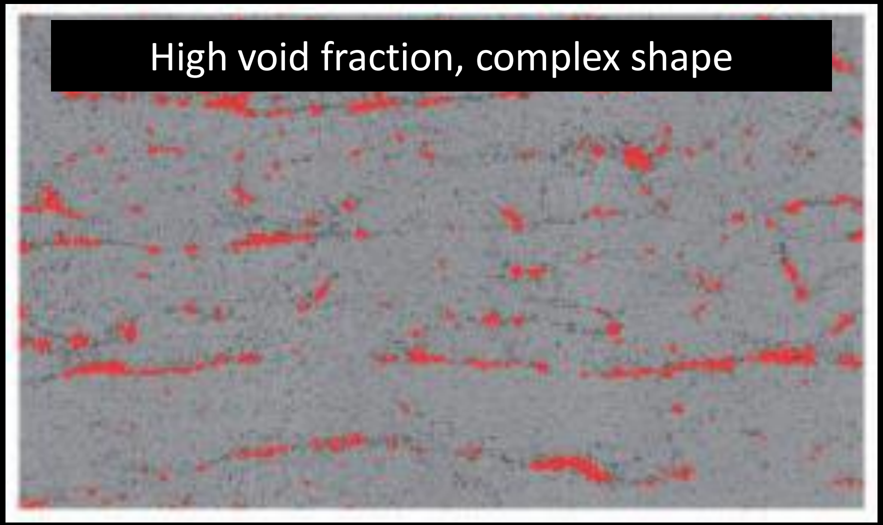
- Affects local and global strength
- Affects stress recovery length

All variabilities/defects are affected by manufacturing parameters

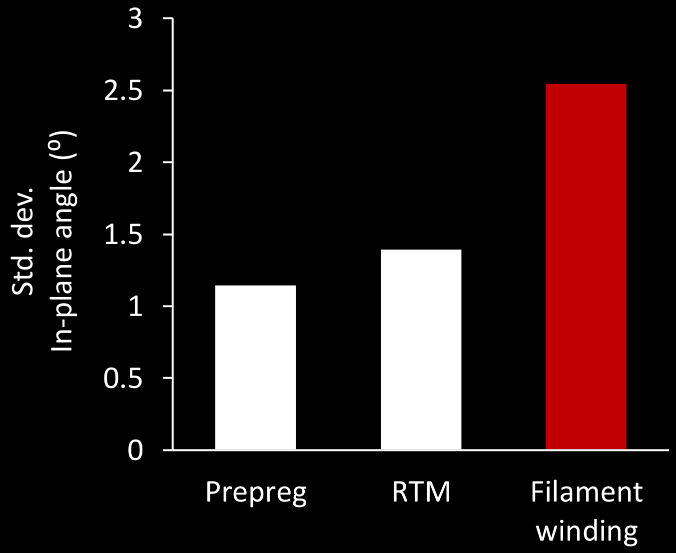
Scott et al. (2014), Breite (2021), Mehdikhani et al. (2021)

Microstructural variabilities in filament winding

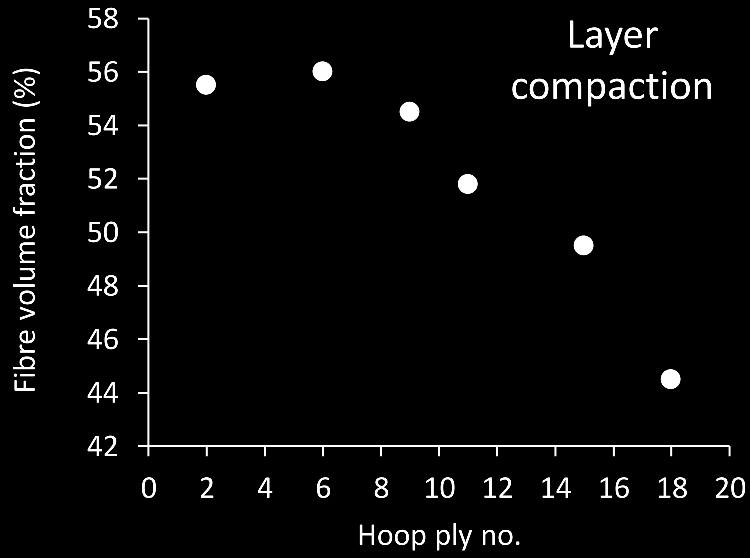
Voids



Fibre misalignment



Fibre volume fraction variation

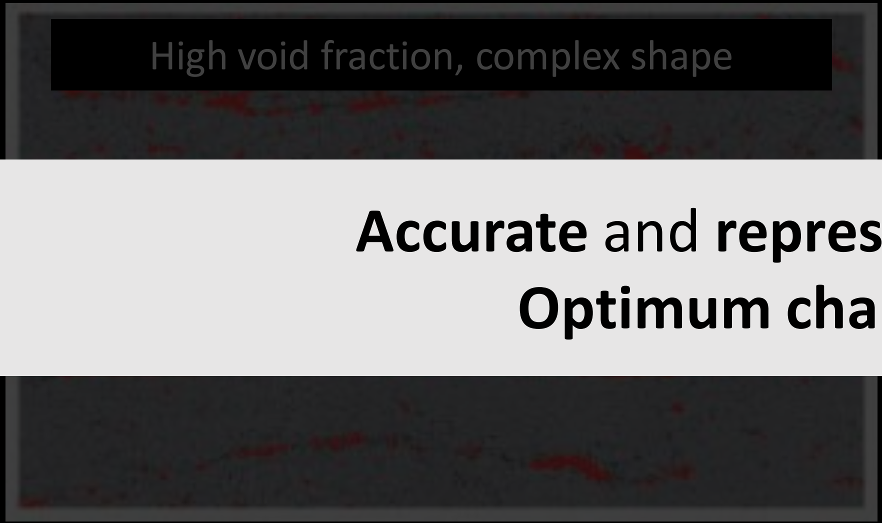


*** Most studies focus on hoop layers given their contribution to burst performance**

Lasn et al. (2020), Scott et al. (2014), Malgioglio (2021), Cohen et al. (2001), Rafiee et al. (2018)

Microstructural variabilities in filament winding

Voids



Fibre misalignment

Fibre volume fraction variation

Layer compaction

Accurate and **representative** microstructural characterisation is vital!

Optimum characterisation strategy needs to be defined

c

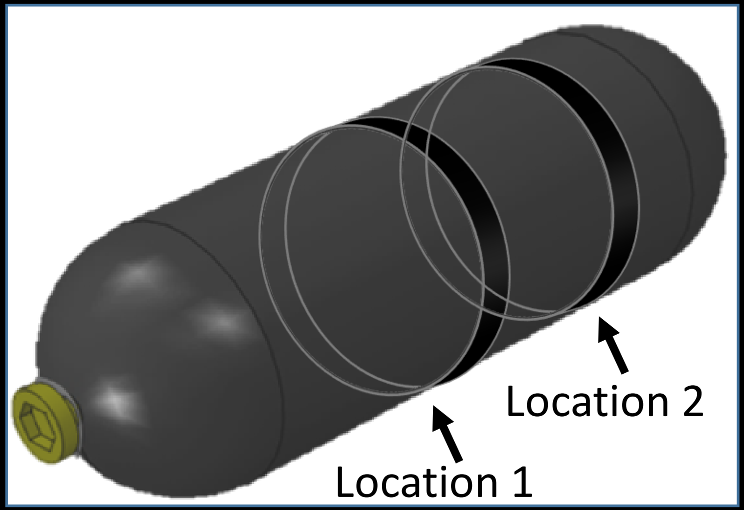
*** Most studies focus on hoop layers given their contribution to burst performance**

Lasn et al. (2020), Scott et al. (2014), Malgioglio (2021), Cohen et al. (2001), Rafiee et al. (2018)

Micro-CT for pressure vessel characterisation

Methodology, scan parameters and challenges

Micro-CT scan and preliminary observations

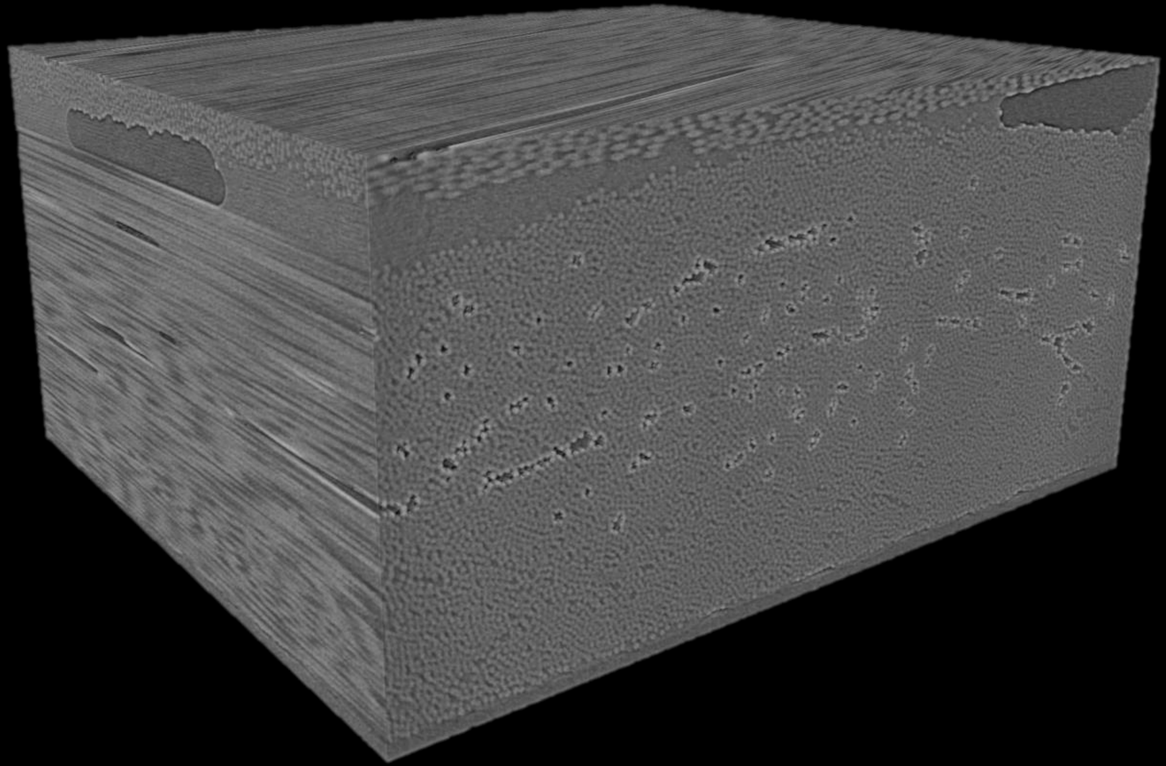


Outer end

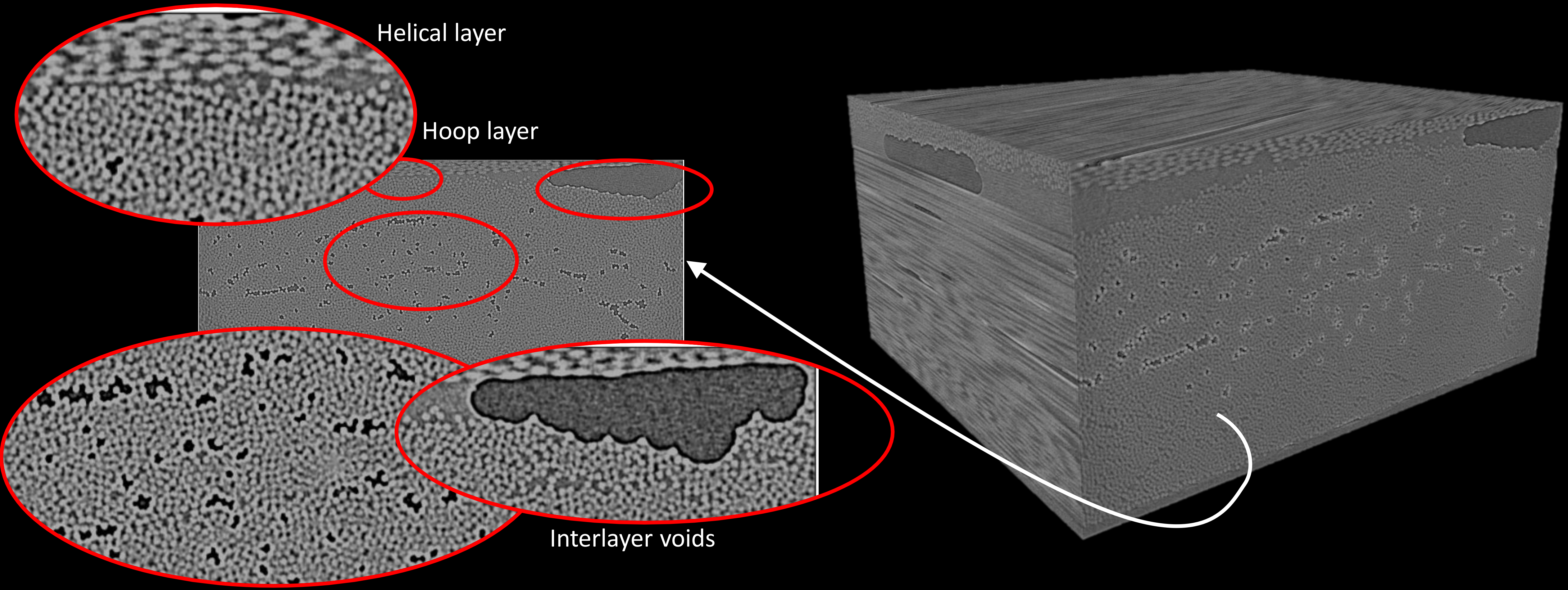
Liner end

Hoop layer

Micro-CT scan –
Tescan UniTom HR

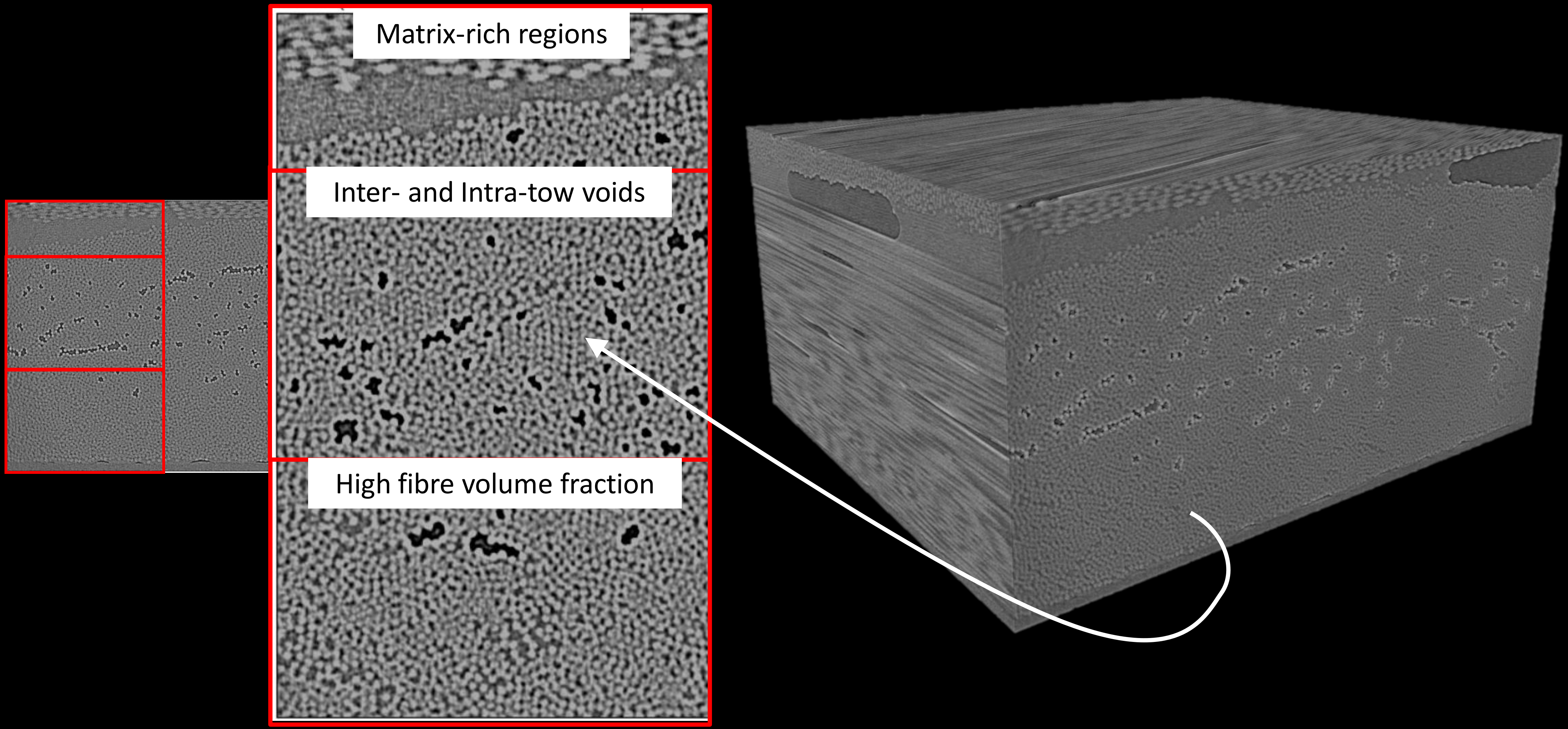


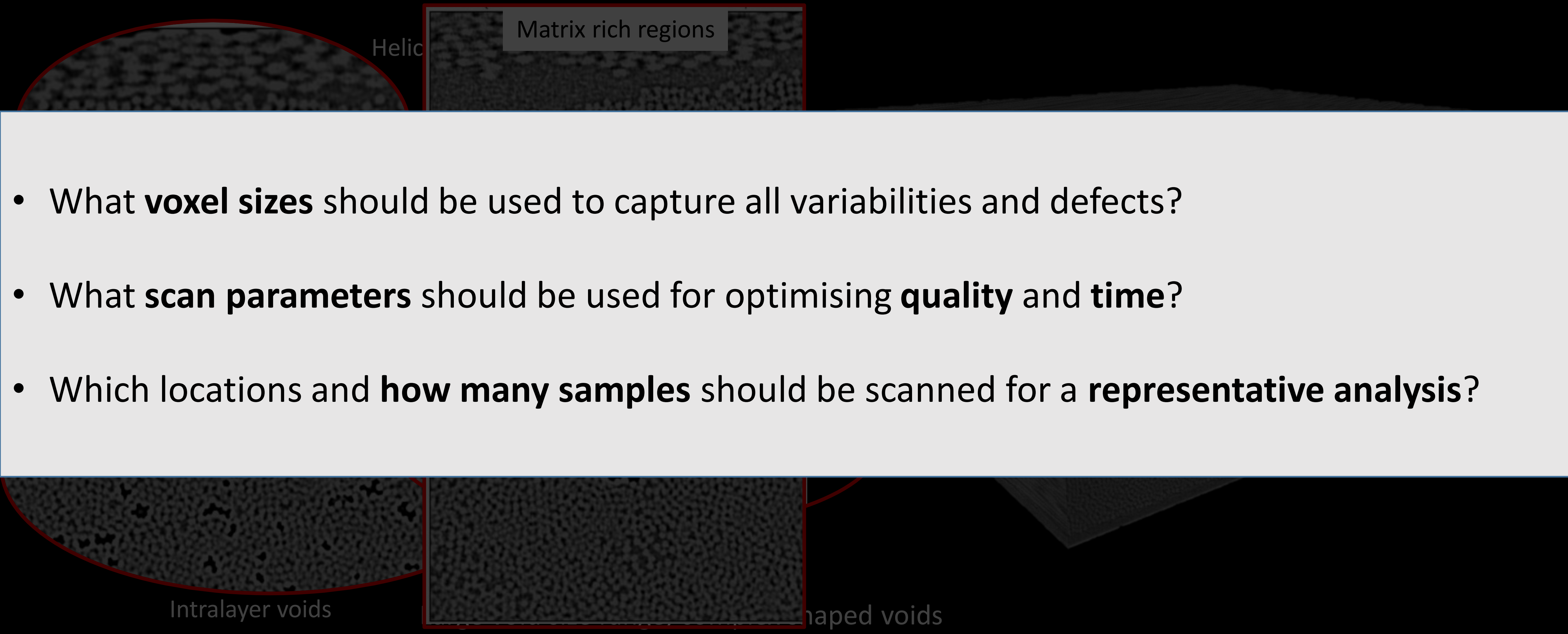
Qualitative observations - 1



Large void size range, complex shaped voids

Qualitative observations - 2





- What **voxel sizes** should be used to capture all variabilities and defects?
- What **scan parameters** should be used for optimising **quality** and **time**?
- Which locations and **how many samples** should be scanned for a **representative analysis**?

How can we get representative microstructure?

Representative microstructural analysis =

Optimum **scanning** parameters **+** Optimum **segmentation** strategy
(scale vs. time)

x

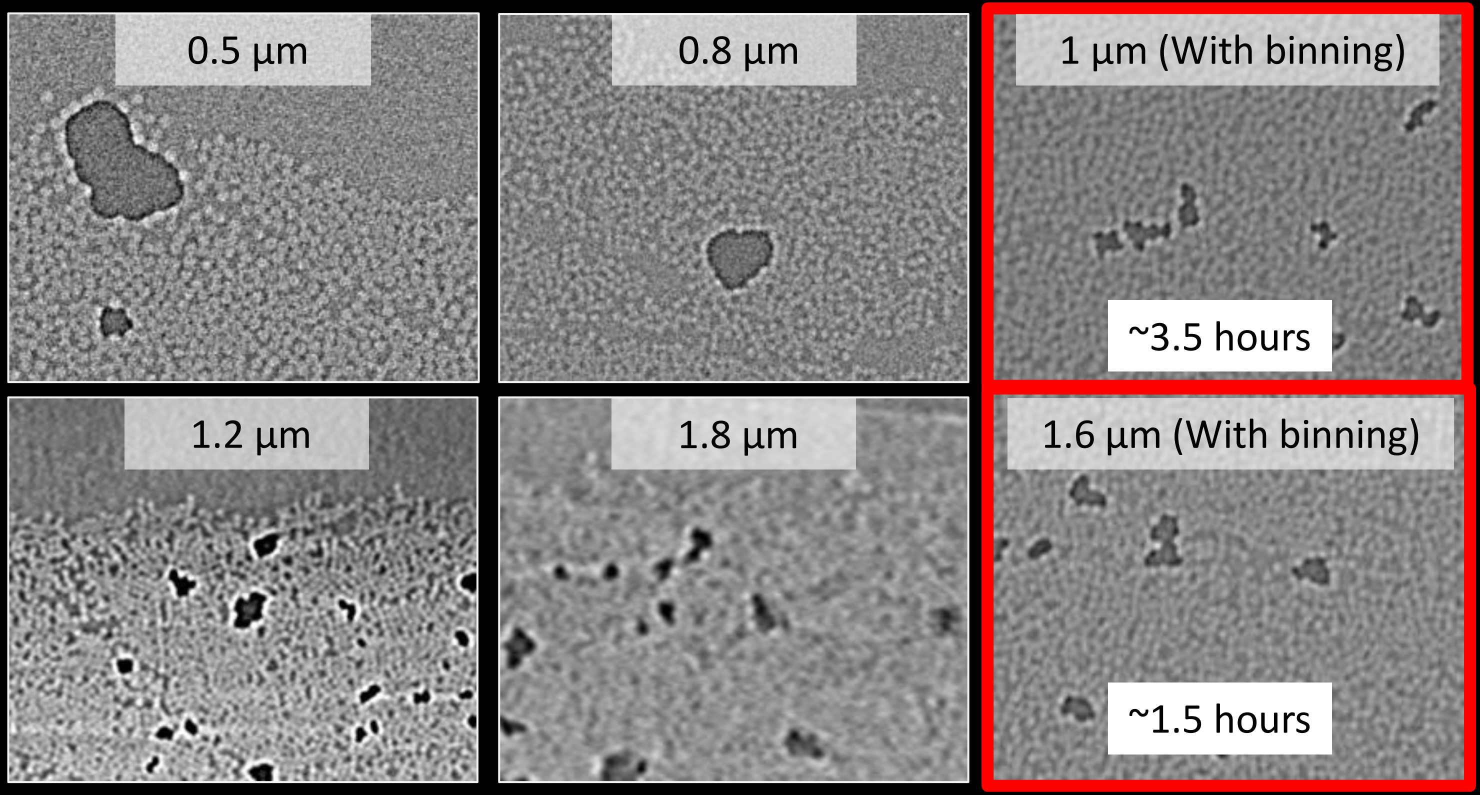
statistically **representative** samples
(location of sample, number of samples)

Scan parameter optimisation

Voxel size(s) and scanning modes

<u>Void and fibre visualisation</u>

- Voids (big, complex) → low resolution
- Fibre related variabilities → high resolution



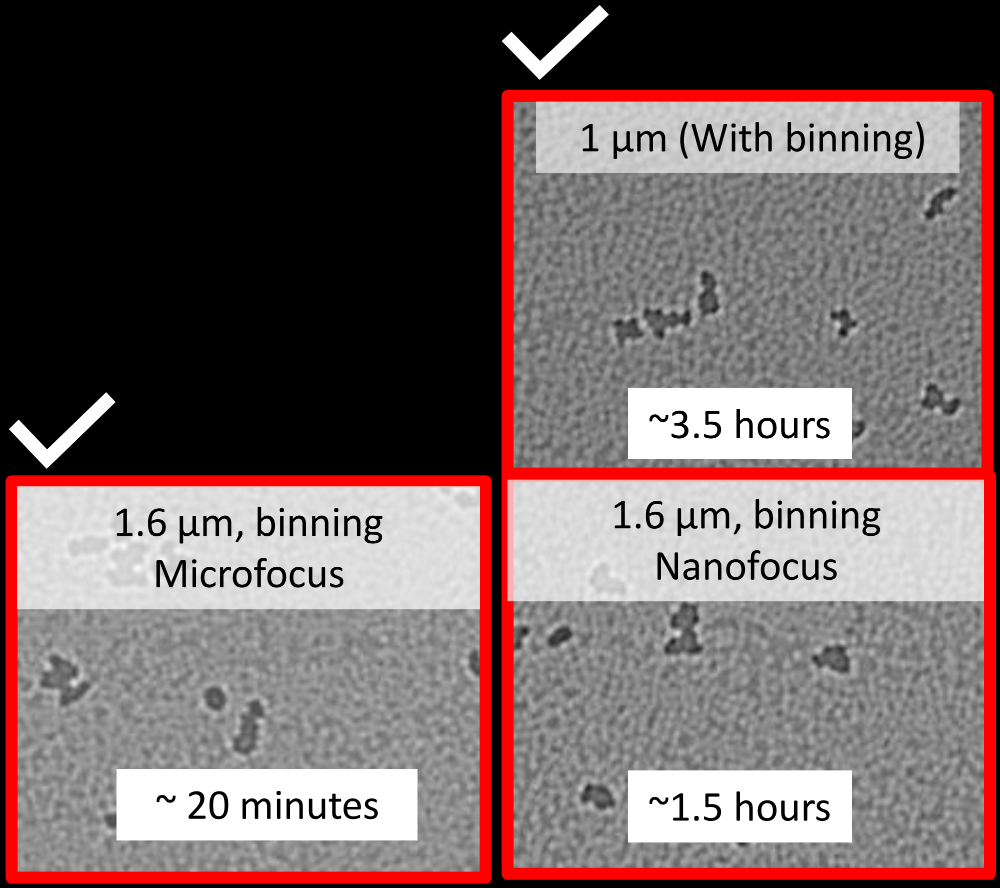
Voxel size(s) and scanning modes

<u>Focus mode</u>

For lower resolution (voids)

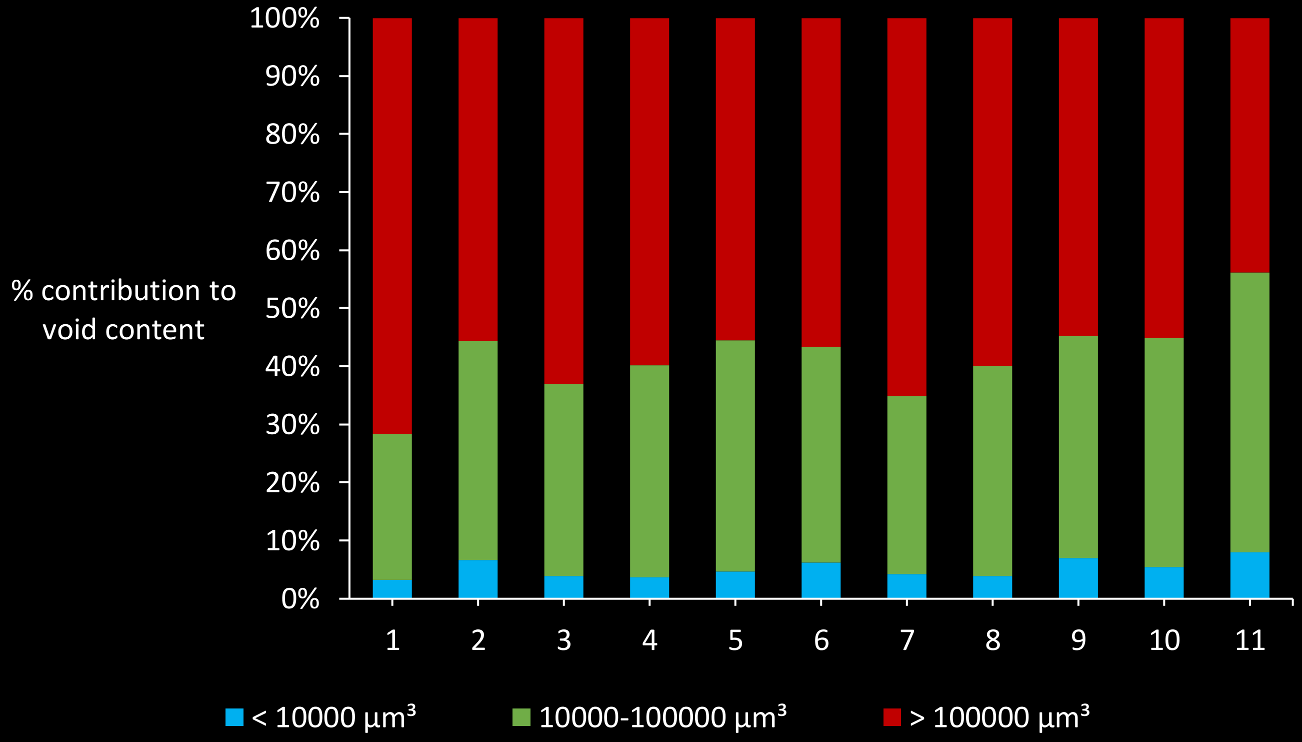
Scan time optimisation with sufficient image quality

1.6 µm with binning in microfocus mode



Voxel size modification based on observations

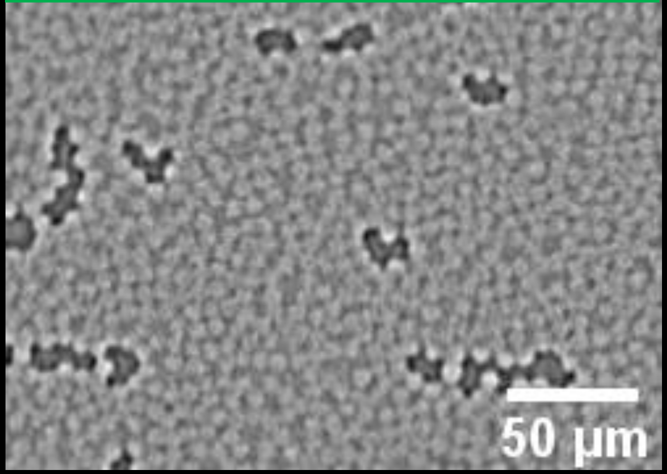
- ↑ Voxel size ➔ ↑ scanned volume ➔ more representative analysis
- Void size distribution for 11 pressure vessels
- Small voids (< 10000 μm³) contribute less than 10% to overall void content
  - voxel size increased to 2 or 2.5 μm with binning



Voxel size modification based on observations

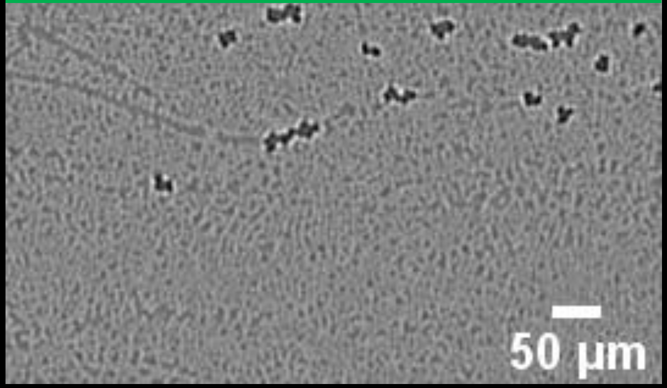
- ↑ Voxel size ➔ ↑ scanned volume ➔ more representative analysis
- Void size distribution for 11 pressure vessels
- Small voids (< 10000 µm³) contribute less than 10% to overall void content
  - voxel size increased to 2 or 2.5 µm with binning

1 µm (With binning)



Fibre visualisation

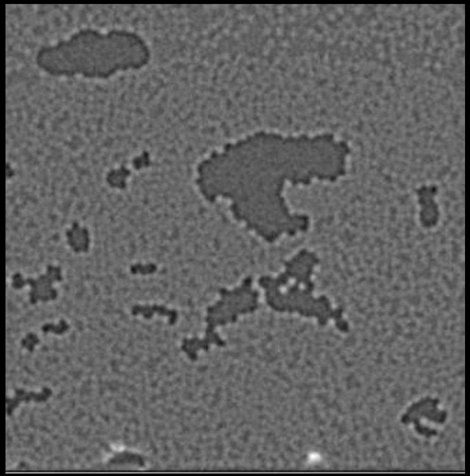
2/2.5 µm, binning
Microfocus

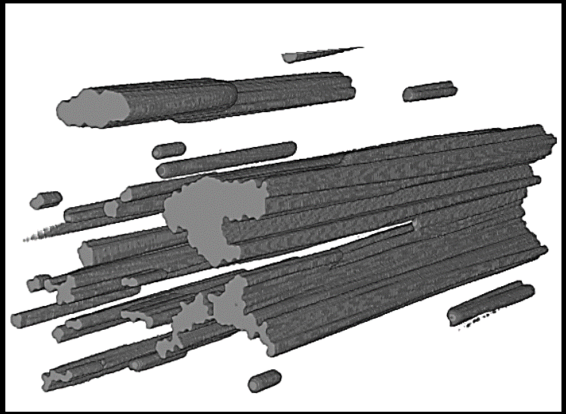


Void visualisation

Segmentation

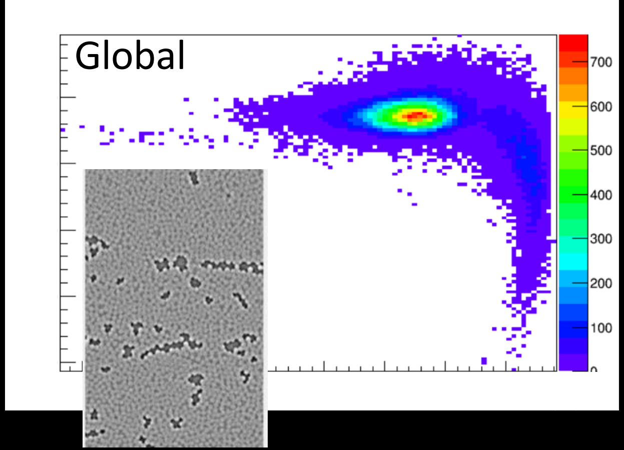
Voids

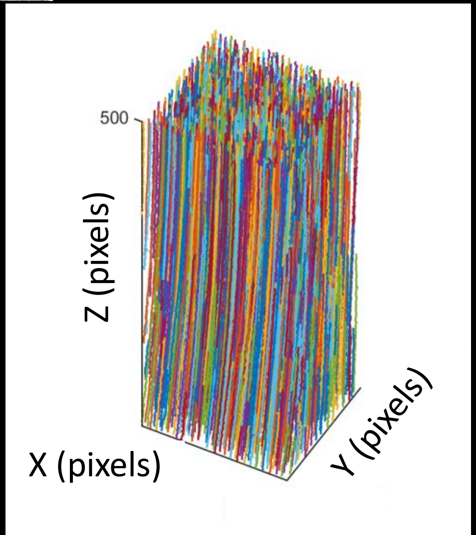




Deep-learning segmentation

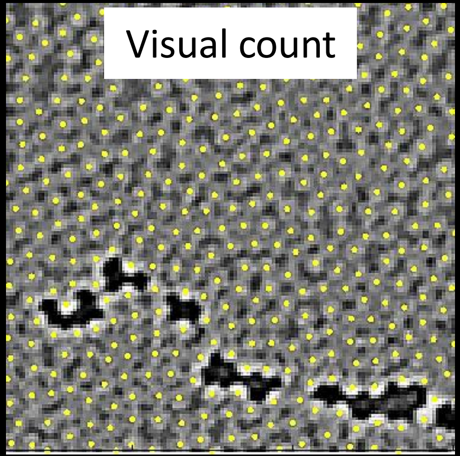
Fibre misalignment





Local (fibre tracking)

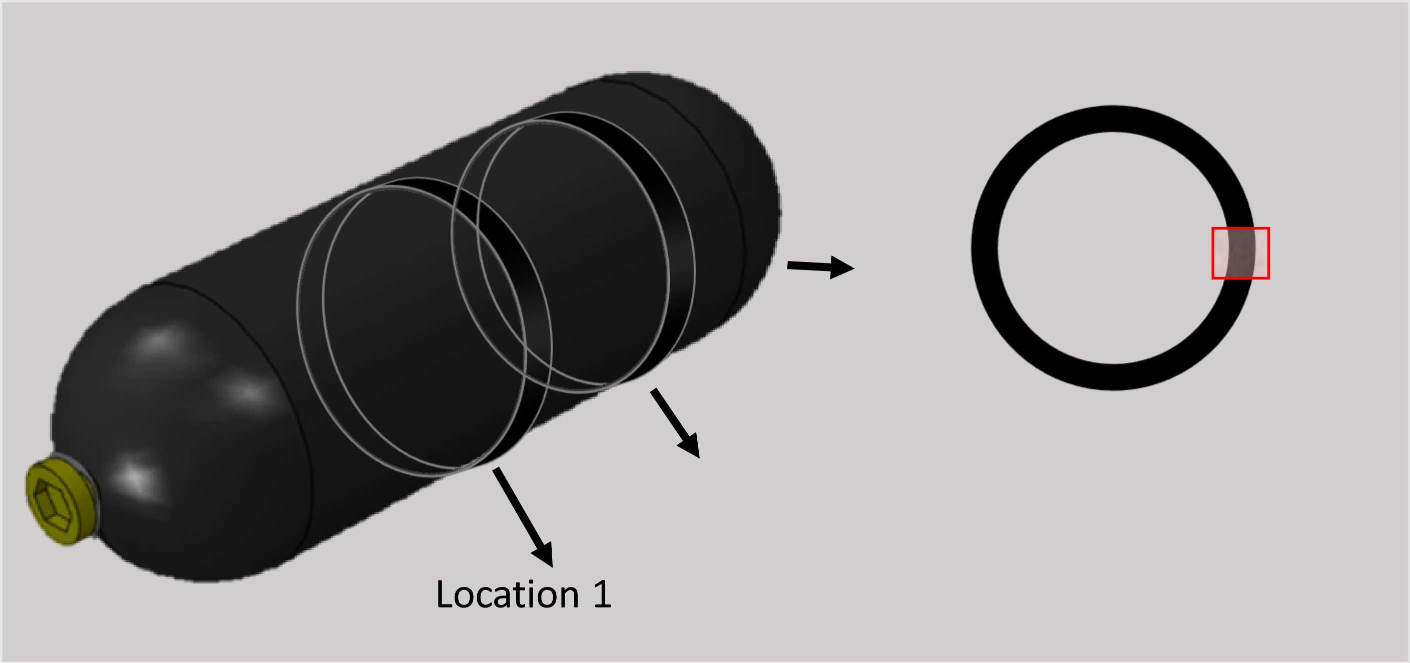
Fibre volume fraction (local)

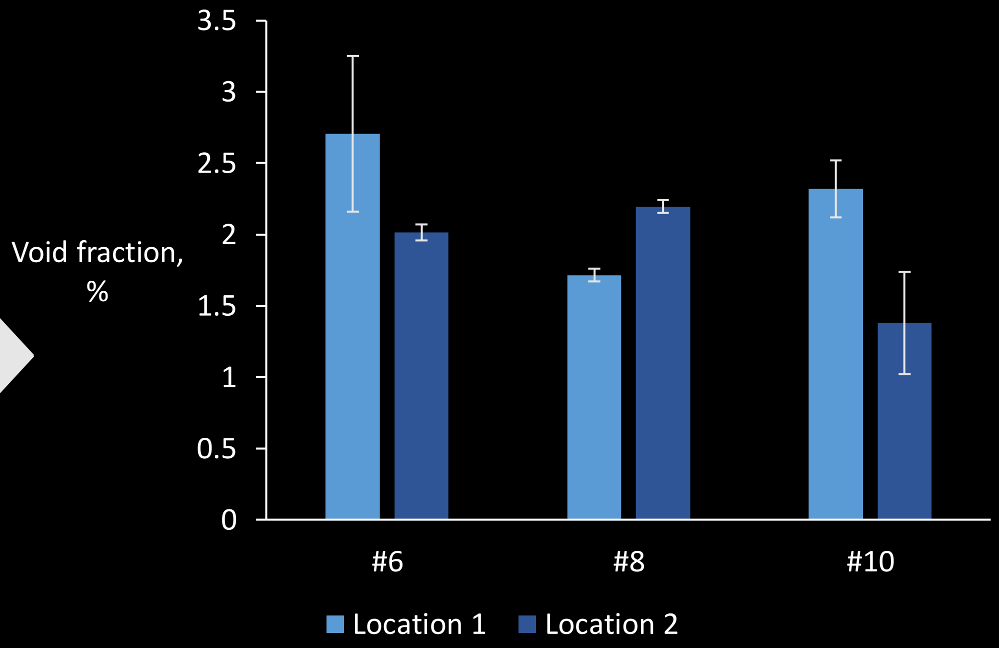


Smith et al. (2020), Straumit et al. (2015), Emerson et al. (2017), Schindelin et al.(2012)

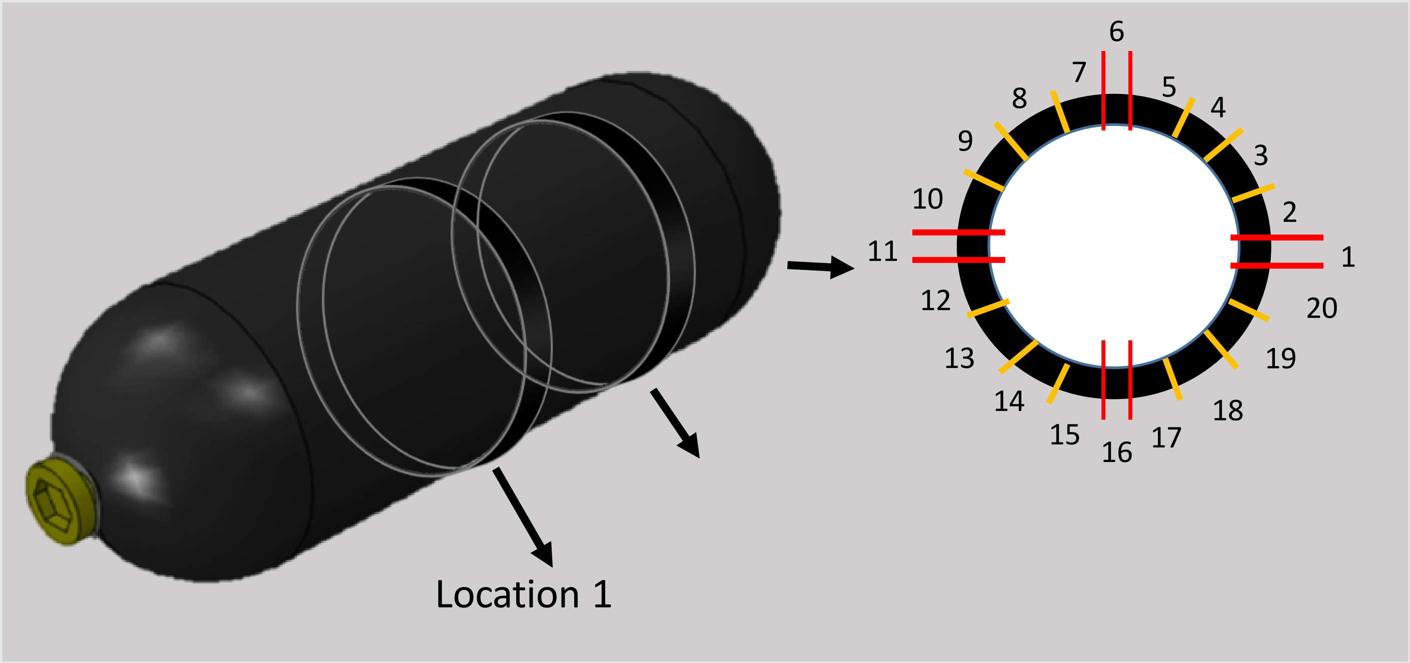
Smart selection of scan locations

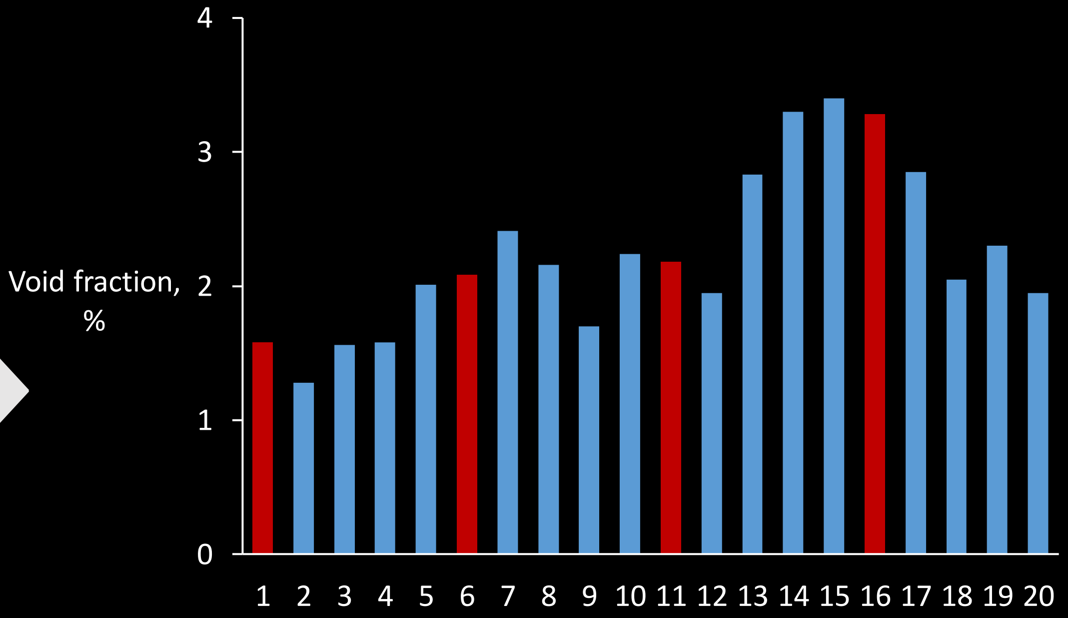
Representative analysis





Representative analysis

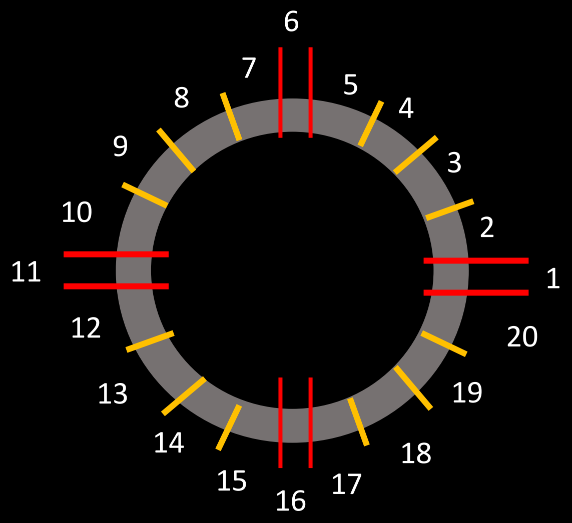




Circumferential position analysis

To determine number of samples to be scanned at the axial location

Method:



Scans at 2 micron

Probability distribution fitting

Spatial correlation – on average void fraction of each section

Cumulative mean analysis

Circumferential position analysis

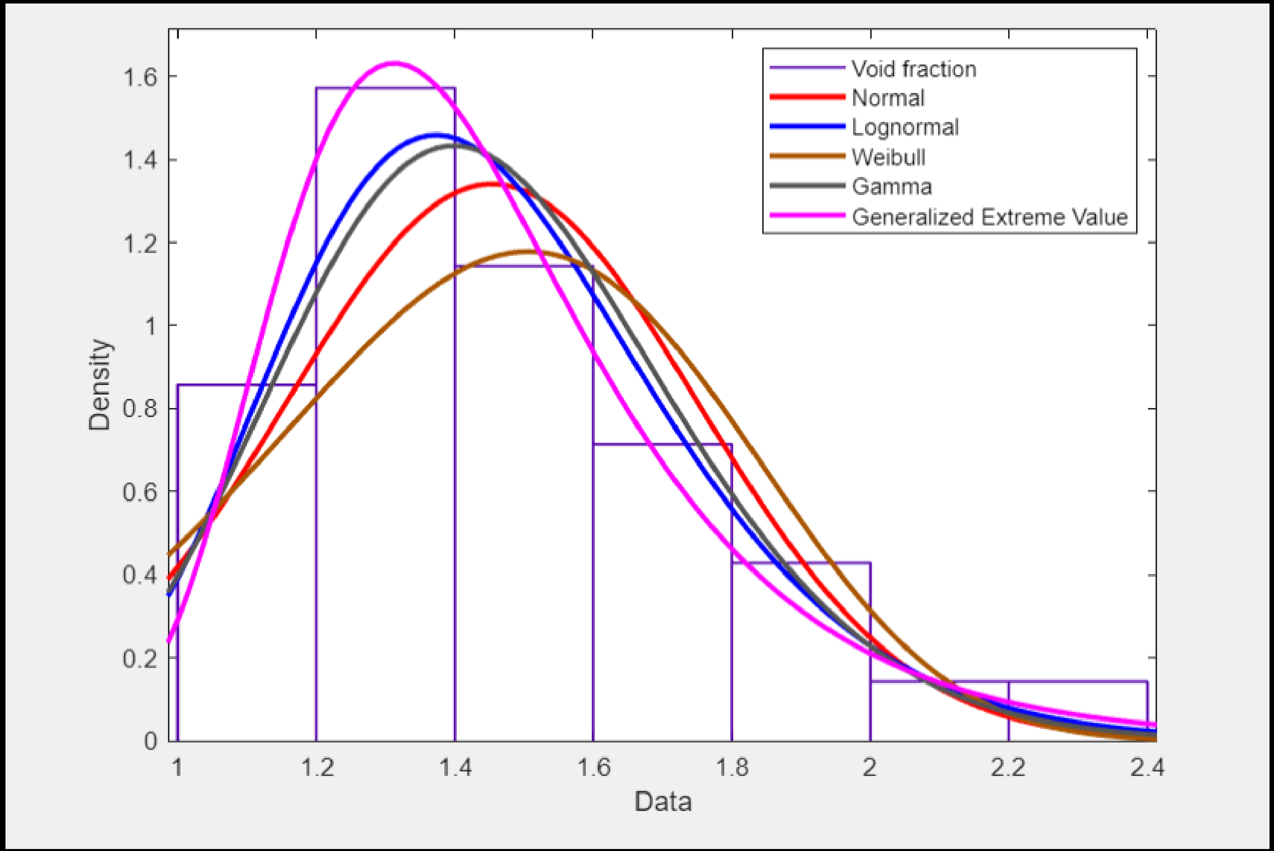
Distribution fitting

Following fits were tested:

- Normal
- Lognormal
- Weibull
- Gamma
- Generalised extreme value

Number of samples based on distributions:

- Within 10% of mean - Estimated N ~ 15/16
- Within 20% of mean - Estimated N ~ 8

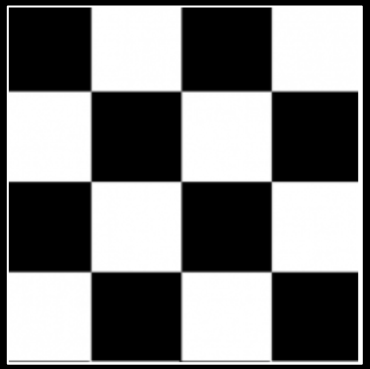


Circumferential position analysis
Spatial correlation

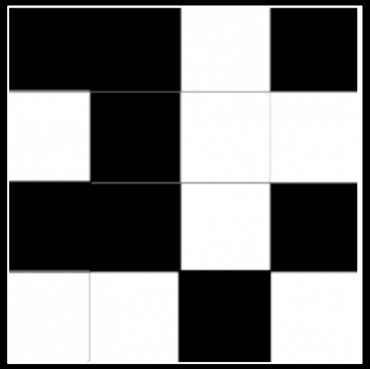
Spatial correlation computed using Contiguity matrix (weighting of neighbors) and Moran's I (MI)

No spatial correlation found

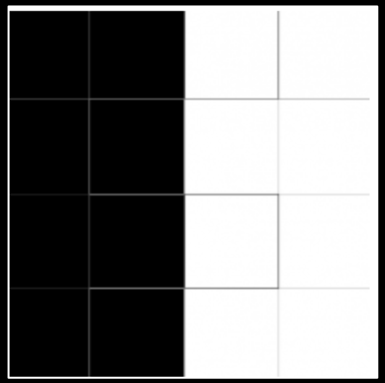
- With consideration of immediate neighbors only → weak negative correlation
- With consideration of weighted contribution from all neighbors → perfect randomness
- **Significance of autocorrelation → p-value not significant**



MI = -1 : Perfect dispersion
(Clustering of dissimilar values)



MI = 0: Perfect randomness



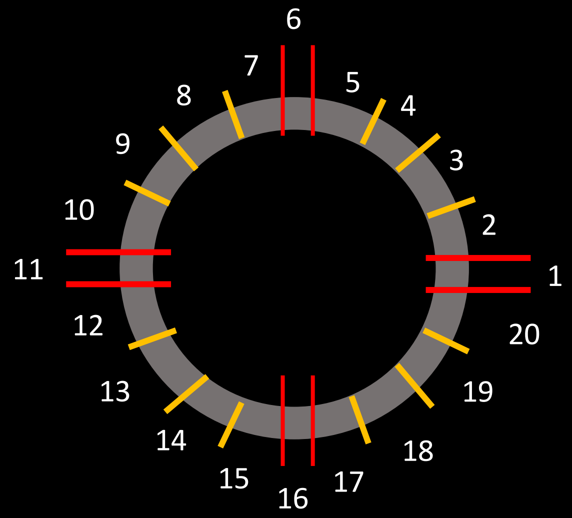
MI = 1 : Perfect clustering
(Clustering of similar values)

Circumferential position analysis
Cumulative mean analysis - method

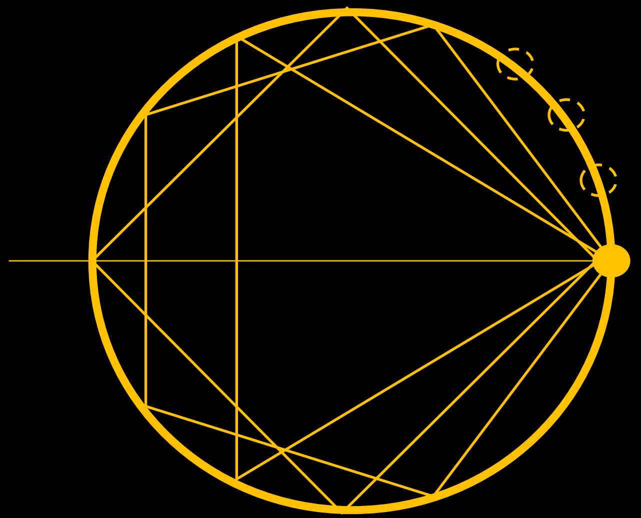
Methodology:

Mean with increasing number of samples

Observe when trend becomes stable → ideal # of samples



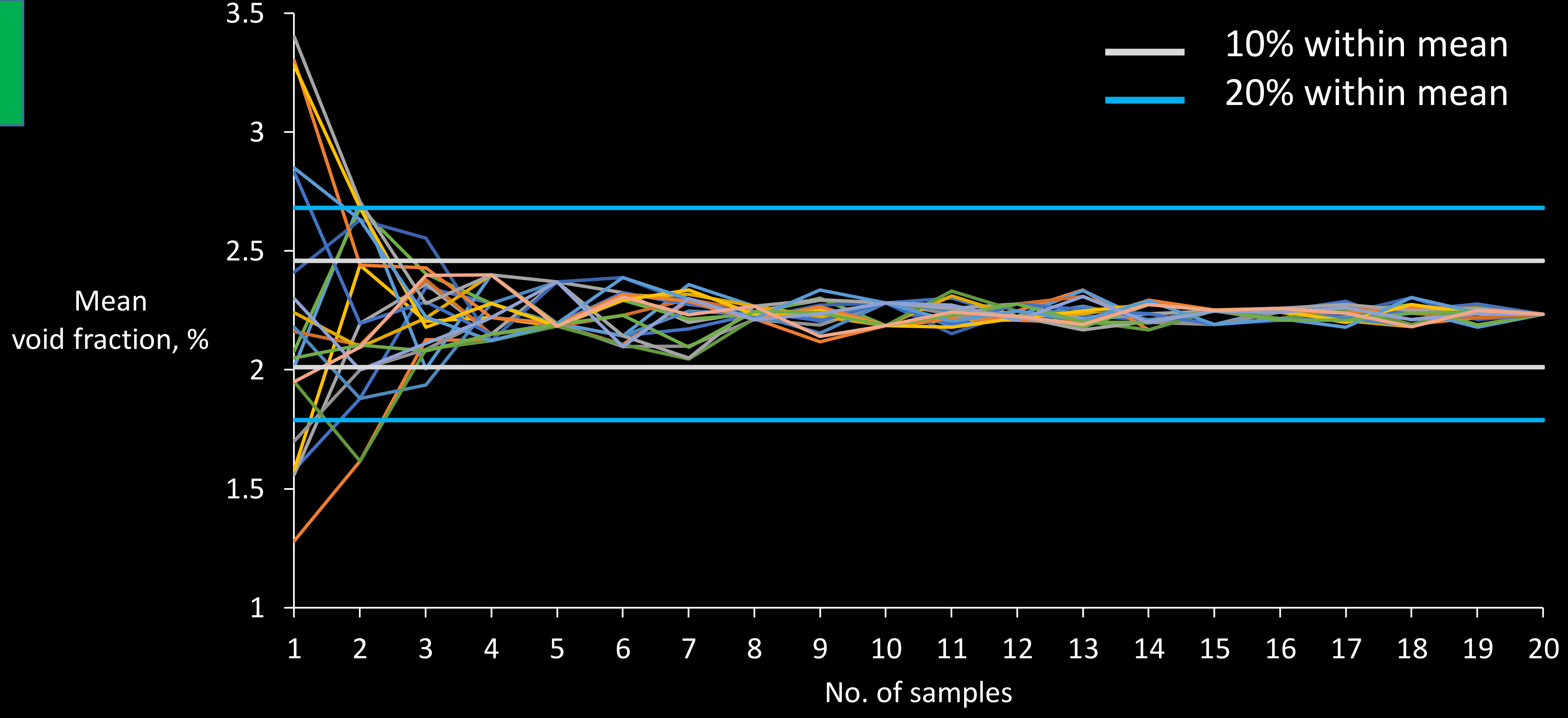
N-side polygon with selected origin
up to N = 19

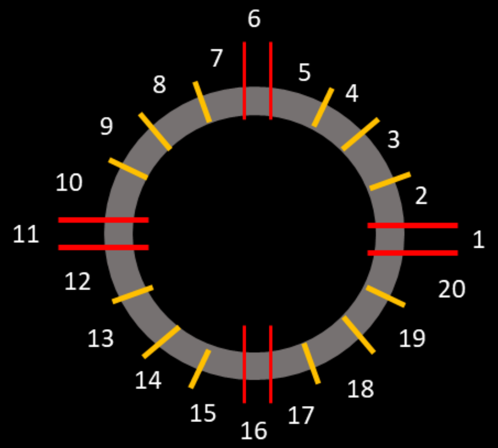


Circumferential position analysis
Cumulative mean analysis - results

Analysis with each location as origin

N = **4+ samples, well distributed**



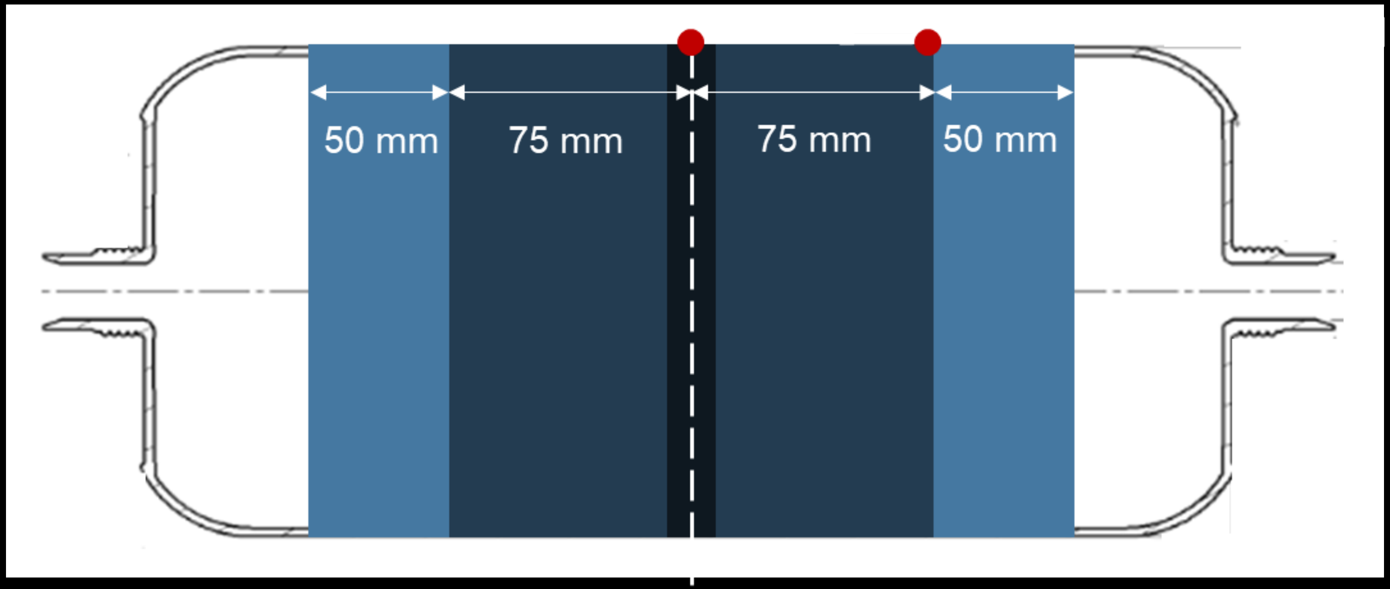


Axial position analysis

Failure observed mostly near centre of the pressure vessel

Simulation and literature → approximate zone of failure

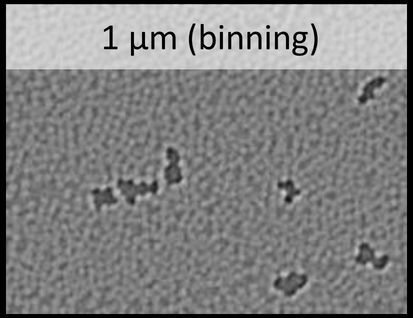
Further microstructure analysis for the below highlighted zone in progress

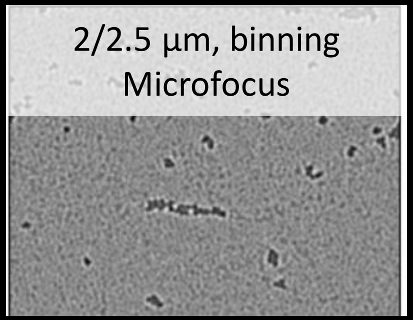


Conclusions

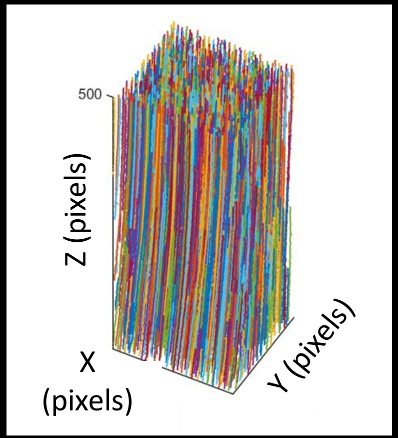
Optimised and **representative** microstructure analysis for composite pressure vessels

=

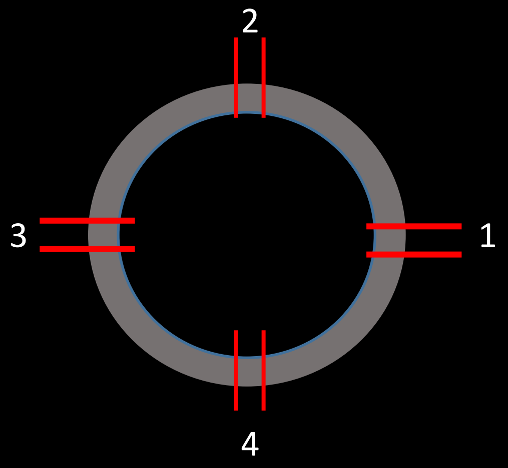




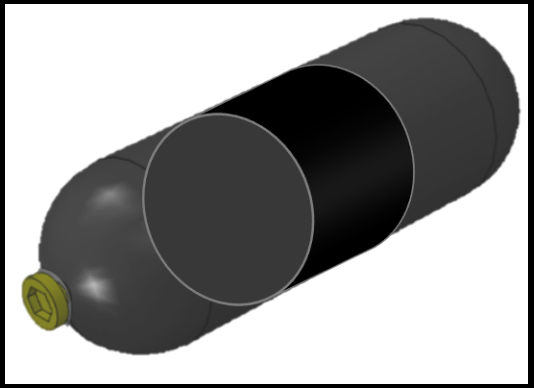
+



X



+



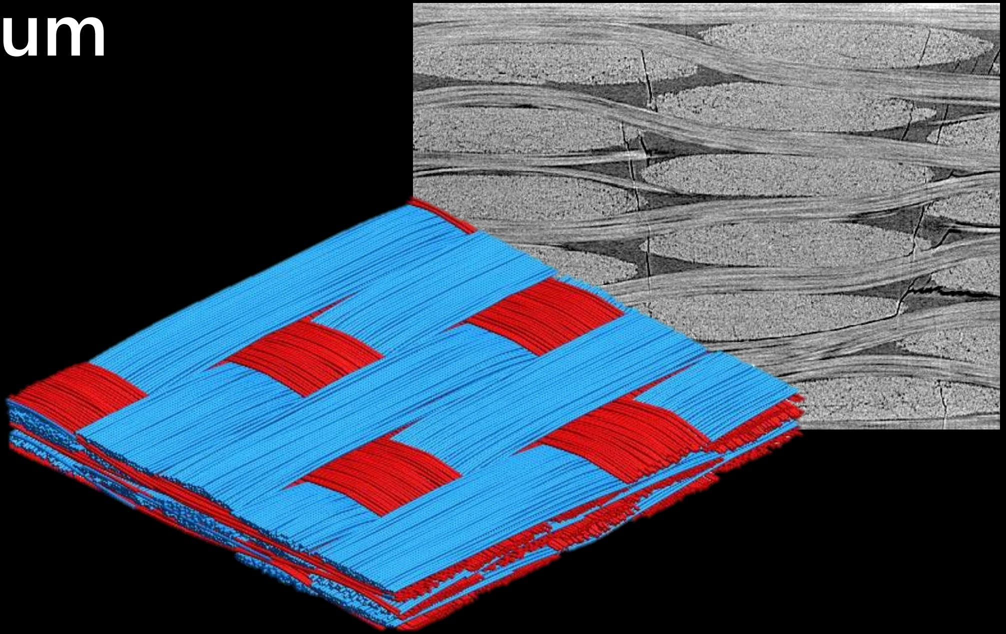
Acknowledgement

The authors gratefully acknowledge SIM (Strategic Initiative Materials in Flanders) and VLAIO (Flanders Agency for Innovation & Entrepreneurship) for their support of the ICON project OptiVaS, running in the Nanoforce Program. M. Mehdikhani would like to acknowledge his FWO Postdoc Fellowship, project ToughImage (1263421N).

TexComp-15 Conference: coming back home!

11-13 September 2024 | Leuven, Belgium

Abstract submission deadline 31 Mar 2024



www.tinyurl.com/texcomp15

TexComp15@gmail.com

Bibliography

Scott AE, Mavrogordato M, Wright P, Sinclair I, Spearing SM. In situ fibre fracture measurement in carbon-epoxy laminates using high resolution computed tomography. Compos Sci Technol 2011;71:1471–7.

Breite C. Aligning Fibre Break Models for Composites with the Observable Micro-Scale Material Behaviour. PhD Thesis 2021.

Mehdikhani M, Breite C, Swolfs Y, Wevers M, Lomov S V., Gorbatikh L. Combining digital image correlation with X-ray computed tomography for characterization of fiber orientation in unidirectional composites. Compos Part A Appl Sci Manuf 2021;142:106234.

Lasn K, Mulelid M. The effect of processing on the microstructure of hoop-wound composite cylinders. J Compos Mater 2020;54:3981–97.

Malgioglio F. Material variability across the scales in unidirectional composites longitudinal tension 2020.

Cohen D, Mantell SC, Zhao L. The effect of fiber volume fraction on filament wound composite pressure vessel strength. Compos Part BEngineering 2001;32:413–29.

Rafiee R, Torabi MA. Stochastic prediction of burst pressure in composite pressure vessels. Compos Struct 2018;185:573–83. https://doi.org/10.1016/j.compstruct.2017.11.068.

Smith AG, Han E, Petersen J, Olsen NAF, Giese C, Athmann M, et al. RootPainter: deep learning segmentation of biological images with corrective annotation. New Phytol 2022. https://doi.org/10.1111/nph.18387.

Straumit I, Lomov S V., Wevers M. Quantification of the internal structure and automatic generation of voxel models of textile composites from X-ray computed tomography data. Compos Part A Appl Sci Manuf 2015;69:150–8.

Emerson MJ, Jespersen KM, Dahl AB, Conradsen K, Mikkelsen LP. Individual fibre segmentation from 3D X-ray computed tomography for characterising the fibre orientation in unidirectional composite materials. Compos Part A Appl Sci Manuf 2017;97:83–92.

Schindelin J, Arganda-Carreras I, Frise E, Kaynig V, Longair M, Pietzsch T, et al. Fiji: An open-source platform for biological-image analysis. Nat Methods 2012;9:676–82. https://doi.org/10.1038/nmeth.2019.