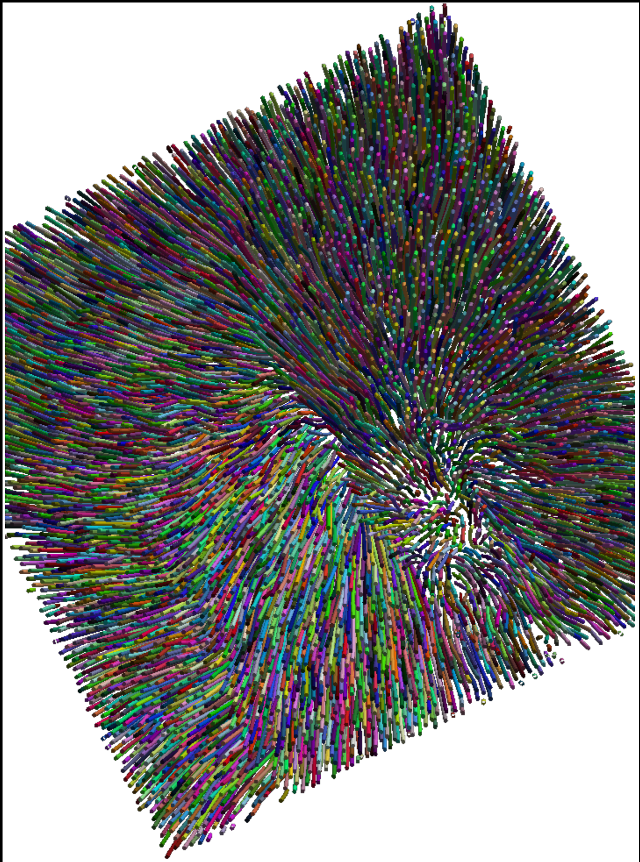


Monica Jane Emerson
monj@dtu.dk
DTU Compute
Department of Applied Mathematics and Computer Science

InSegt

A tool for interactive segmentation used for volumetric fibre segmentation

The CINEMA partners and my collaborators

The alliance for imaging and modelling of energy applications CINEMA

MAX IV

Academic partners:

University of Copenhagen, DTU, The University of Manchester, Northwestern University

Industrial partners:

Haldor Topsøe, Amminex, Rockwool, Xnovotech, LM Wind Power

DTU

Compute
Anders B. Dahl
Knut Conradsen
Vedrana A. Dahl
Camilla H. Trinderup

Wind Energy
Lars P. Mikkelsen
Kristine M. Jespersen

The University of Manchester

The School of Materials
Henry Moseley X-ray Imaging Facility
Ying Wang
Philip J. Withers

ESRF The European Synchrotron

ID19
Alexander Rack
Benoit Cordonnier
Vincent Fernandez

X-ray imaging combined with image analysis is a powerful tool for characterising materials

Synchrotron

Laboratory scanner

The alliance for imaging and modelling of energy applications

CINEMA

- AIM:
  - Develop methods to characterise the internal structure of complex materials used for energy technologies.
  - Correlate performance under realistic conditions to the microstructure and its changes.
- PURPOSE: Optimise materials to make devices
  - More efficient
  - Longer lasting
  - Lower in cost

Micro-structural characterisation of fibre composites

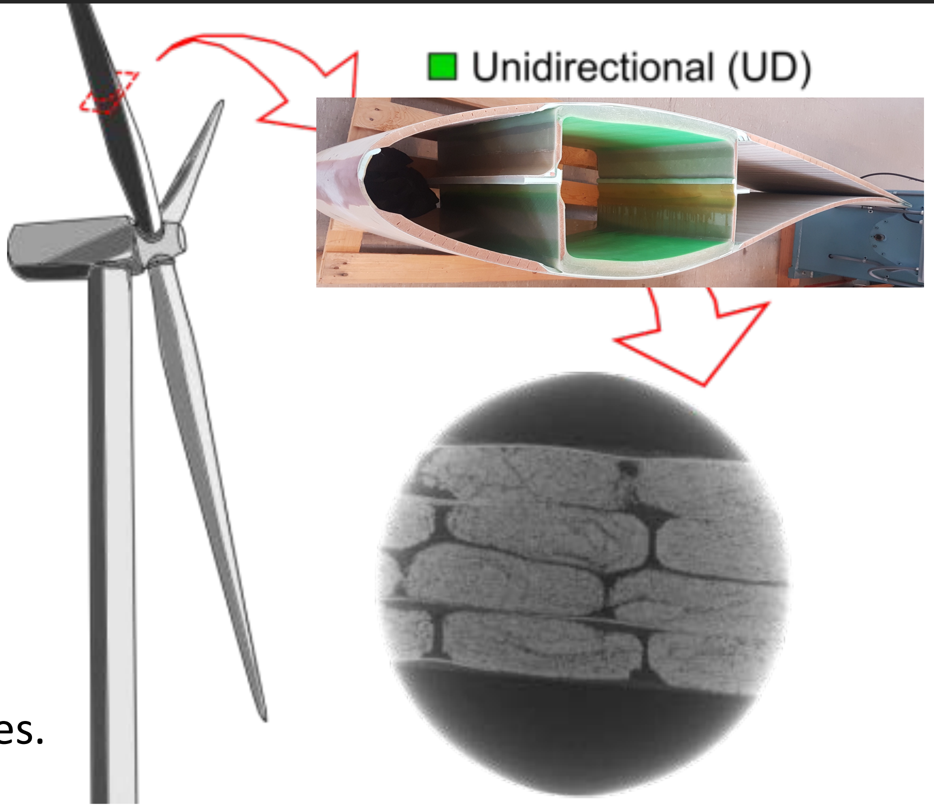
A 3D structural characterisation will accelerate understanding:

Micro-structure → mechanical properties

- Enable structural-life prognosis.
- Optimise material designs
- Discover ultra-resilient composites
- …

Micro-structure ← fibre and composite manufacturing

- Discover the effects of different manufacturing techniques.
- Improve the manufacturing process
- Quantify the uncertainties in the process
- …



Two material phases in fibre reinforced polymers:

- **Fibres**: glass, carbon, basalt… (diameter ~ 10 μm)
- **Polymer**: epoxy, polyester…

Image-based structural characterisation of materials

Sample preparation

3D scanning

Tomographic reconstruction

Segmentation of 3D Structures

FEM Simulations

Quantification

Manufacturing of a carbon fibre reinforced polymer

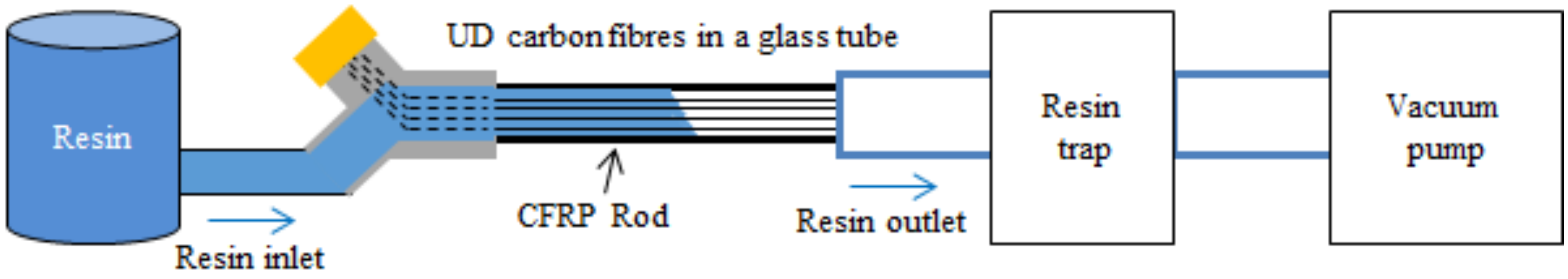


Image-based structural characterisation of materials

Sample preparation

3D scanning

Tomographic reconstruction

Segmentation of 3D Structures

FEM Simulations

Quantification

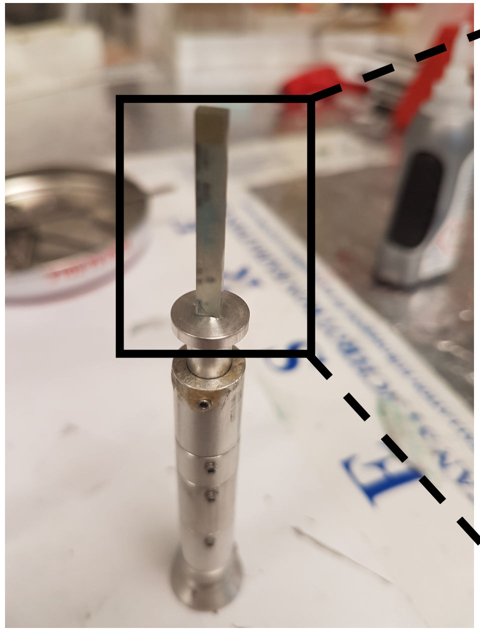


Image-based structural characterisation of materials

Sample preparation

3D scanning

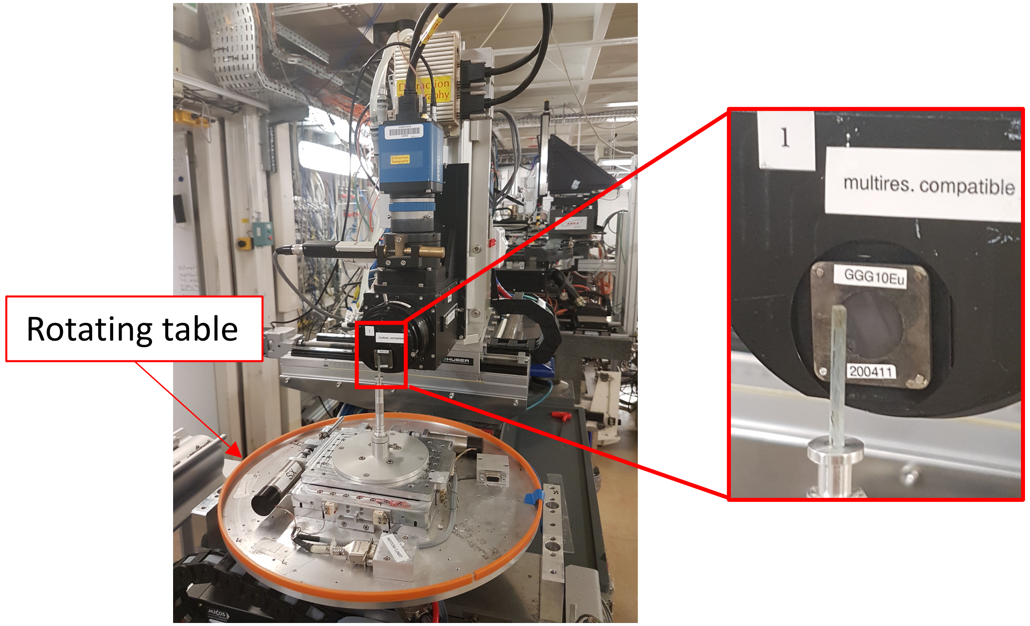
Tomographic reconstruction

Segmentation of 3D Structures

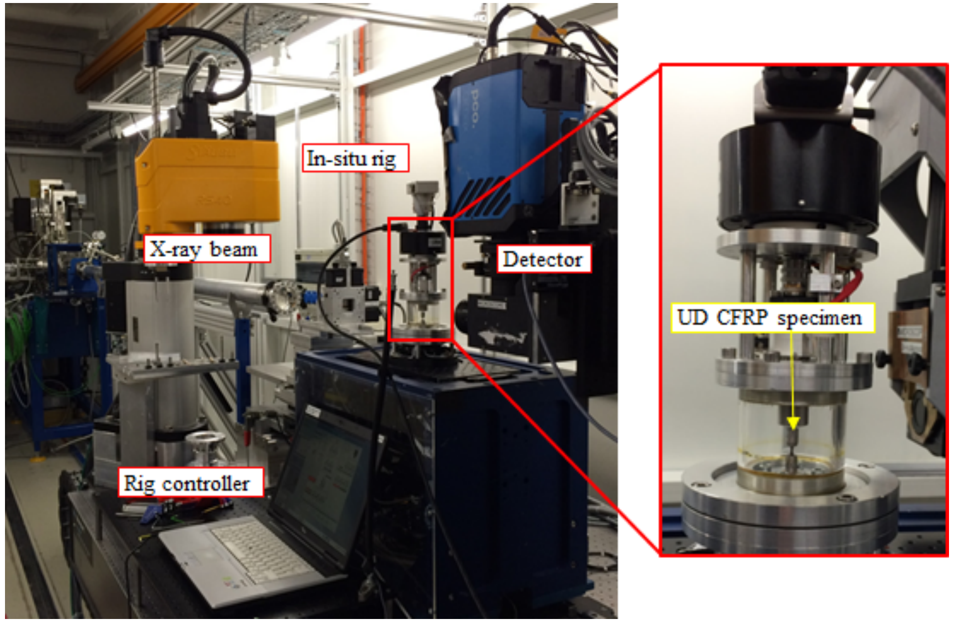
FEM Simulations

Quantification

Synchtron set-up for a **static scan**



Synchrotron set-up for **in-situ loading while scanning**



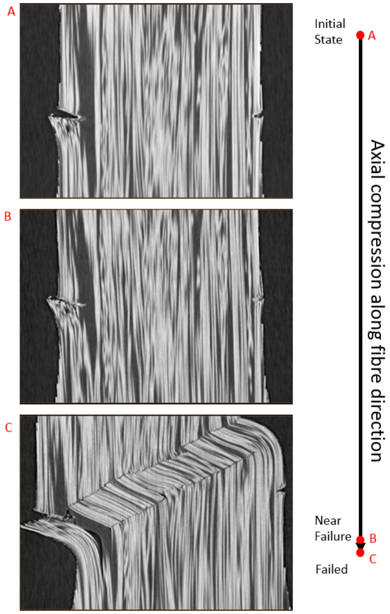


Image-based structural characterisation of materials

Sample preparation

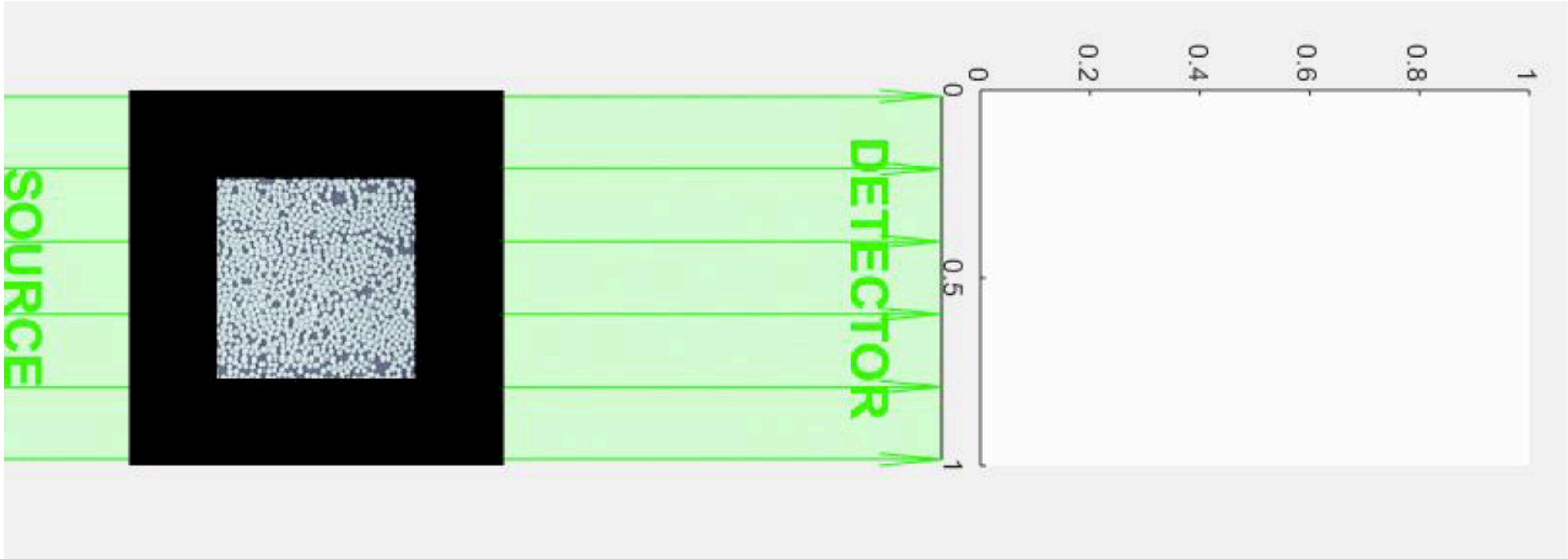
3D scanning

Tomographic reconstruction

Segmentation of 3D Structures

FEM Simulations

Quantification



Filtered Back Projection

Image-based structural characterisation of materials

Sample preparation

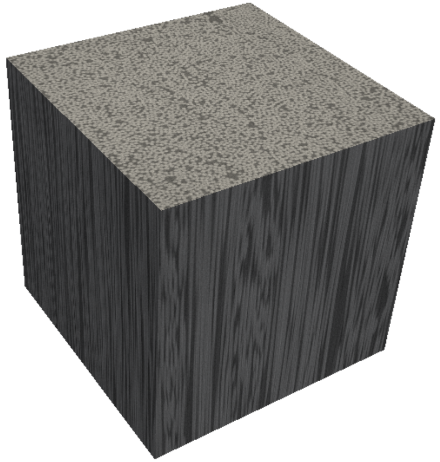
3D scanning

Tomographic reconstruction

Segmentation of 3D Structures

FEM Simulations

Quantification



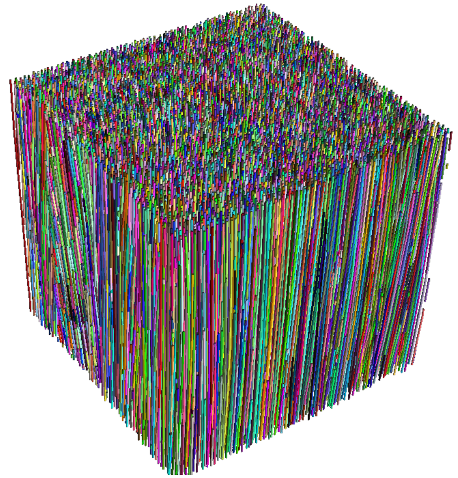


Image-based structural characterisation of materials

Sample preparation

3D scanning

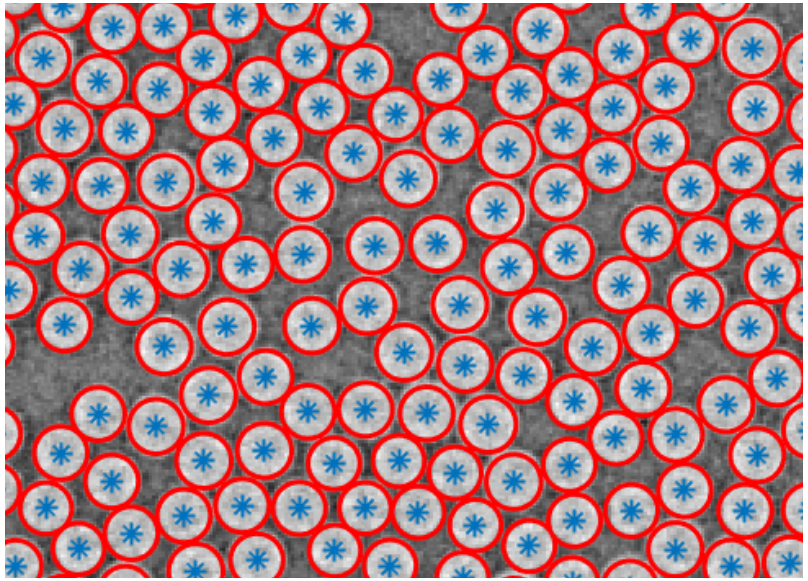
Tomographic reconstruction

Segmentation of 3D Structures

FEM Simulations

Quantification

Segmented fibre geometry



Micro-mechanical model

Stress under transverse loading

by Lars P. Mikkelsen (DTU Wind Energy)

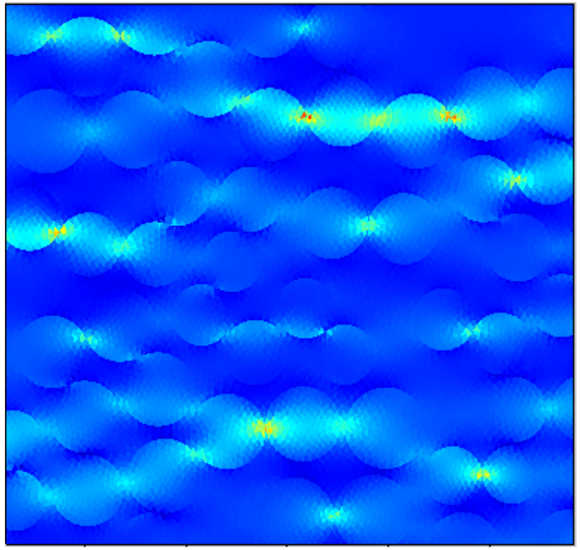


Image-based structural characterisation of materials

Sample preparation

3D scanning

Tomographic reconstruction

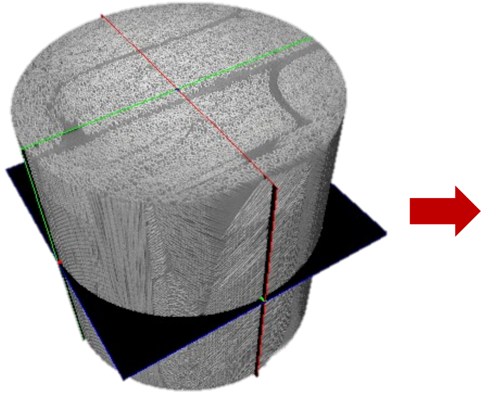
Segmentation of 3D Structures

FEM Simulations

Quantification

1. Static scan of a single sample

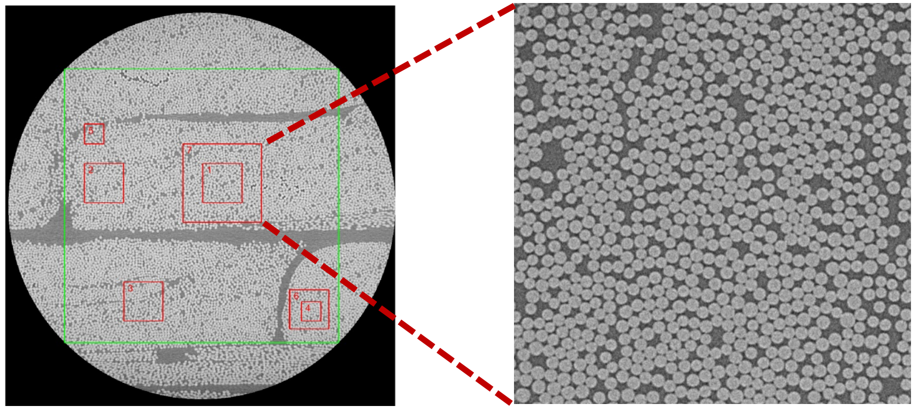
Tomogram



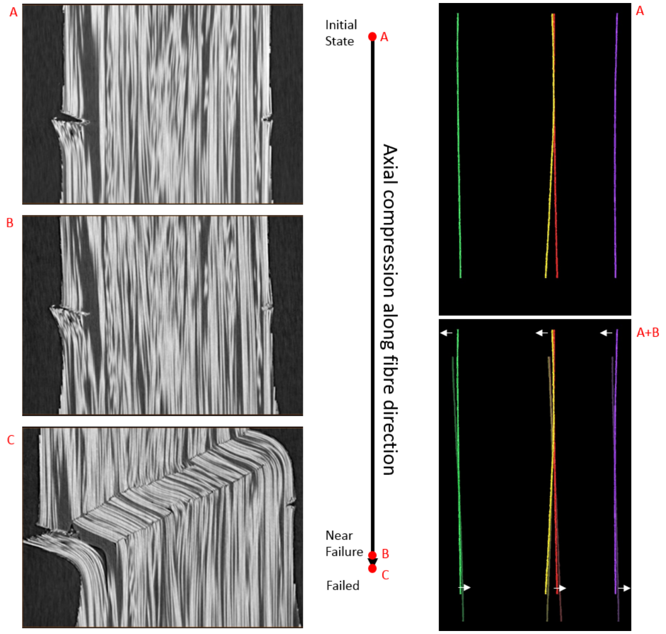
2.5 x 2.5 x 2.5mm

Cross-sectional slice

Zoom-in



2. Sequence of scans while loading a sample



Quantification: Characterisation of Real Structures

Sample design

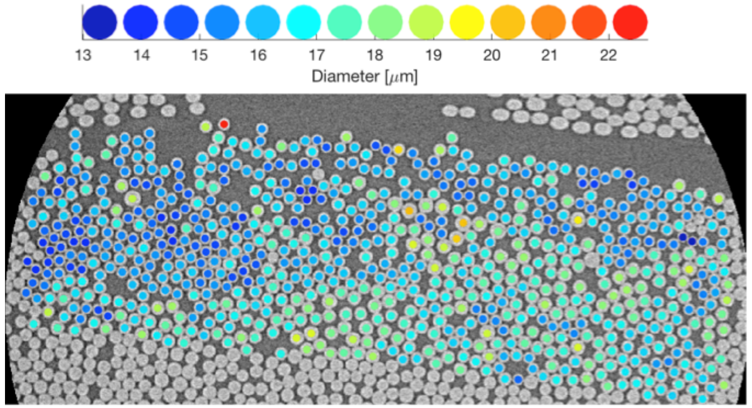
Fibre manufacturing
- Constant along fibre
- Variable across fibres

Constant diameters

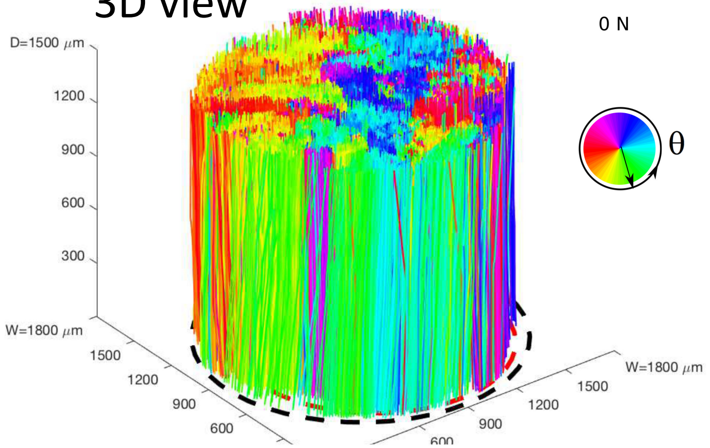
Composite manufacturing
- Fibre misalignment
- Fibre curvature

Aligned fibres

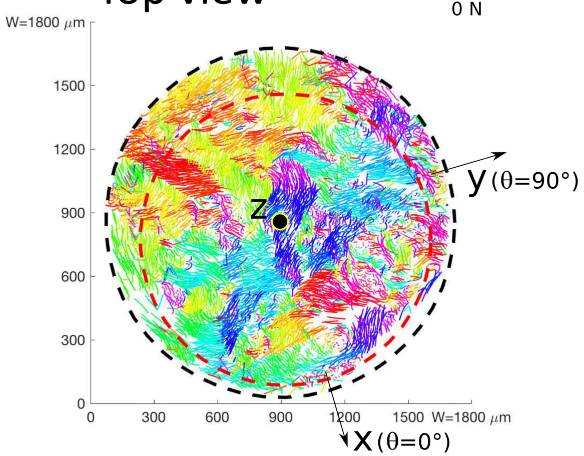
Real micro-structure



3D view



Top view



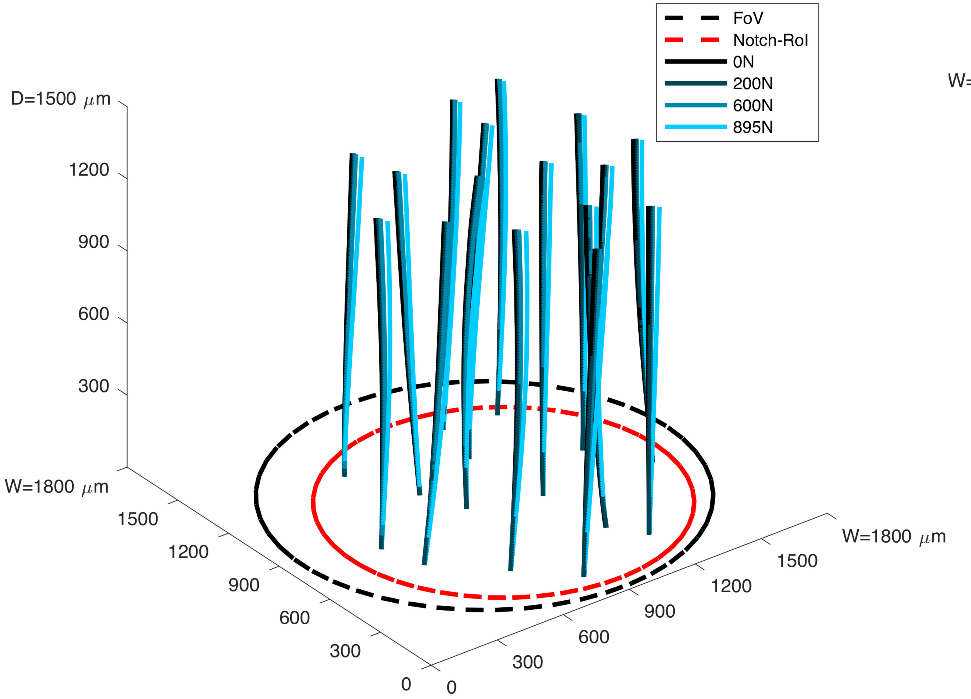
Mechanical properties

- **Compressive strength:**
(physical failure)
- **Stiffness:**
(functional failure)
- **Fatigue resistance:**
(fatigue failure)

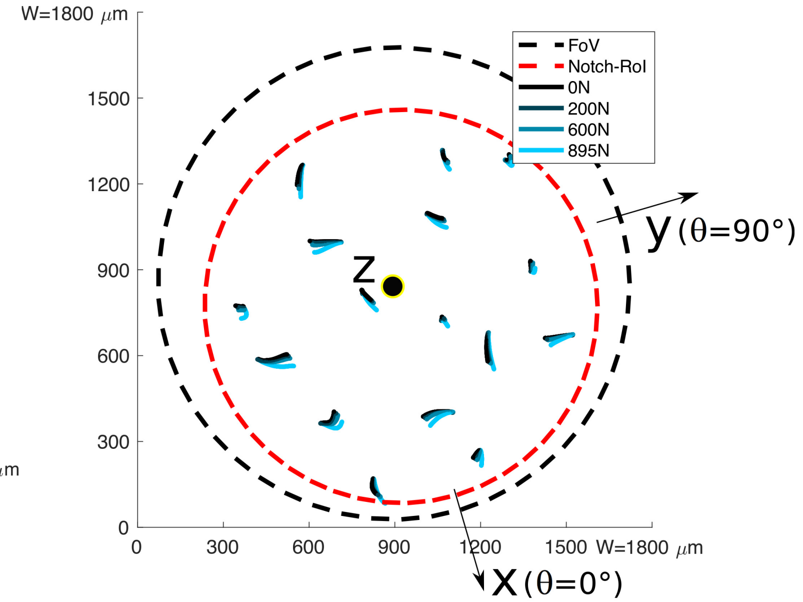
Quantification: Evolution of structures under load

Fibre trajectories under compression loading

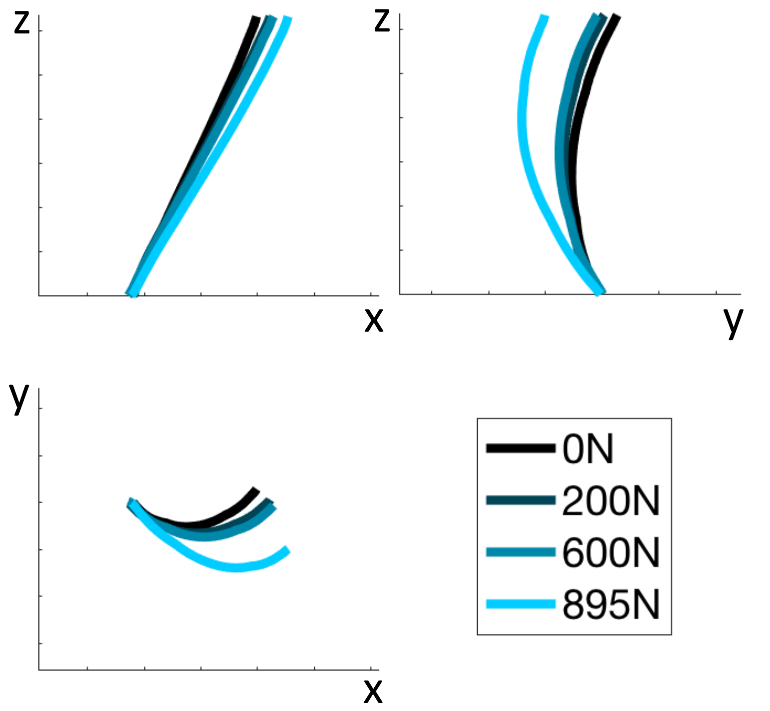
3D side view



Top view



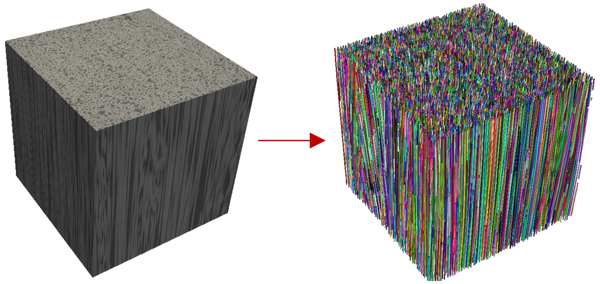
3 zoomed-in views of the evolution of one fibre



Contributions by topic

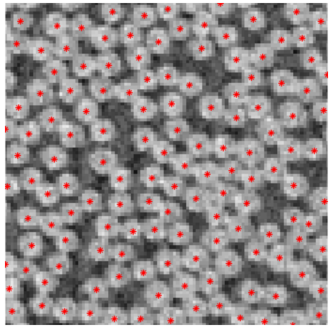
DEVELOPMENT

Fibre Geometry Extraction
via Individual Fibre Segmentation



1. Fibre cross-sections

2. Fibre trajectories



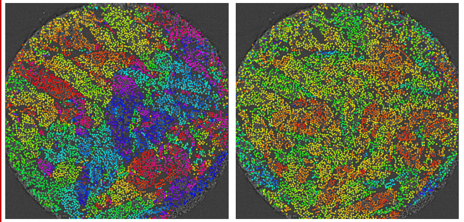
APPLICATIONS

1. Characterisation of Real Structures

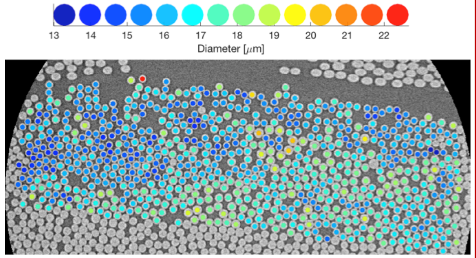
a) Fibre misalignment

Direction

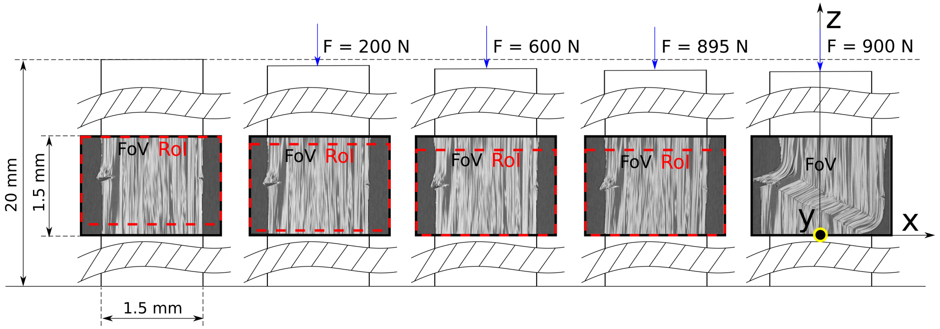
Magnitude



b) Fibre diameters

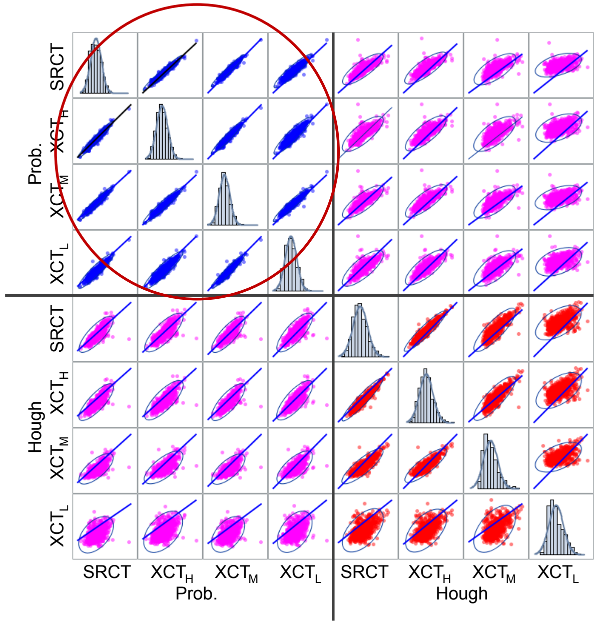


2. Evolution of Structures under Changing Load



VALIDATION

X-ray CT Imaging
+
Individual Fibre Segmentation



Individual fibre segmentation

- The challenges in our data
- The pipeline for individual fibre segmentation
- Previous work: *A literature review*
- 2D segmentation: The *Dictionary of Image Patches*
- 3D tracking

Challenges in our data

The data we analyse:

- A range of fibre materials (glass, carbon…)
- Representative volumes (full bundles)
- Fast scanning
  - At laboratory sources
  - For in-situ loading experiments

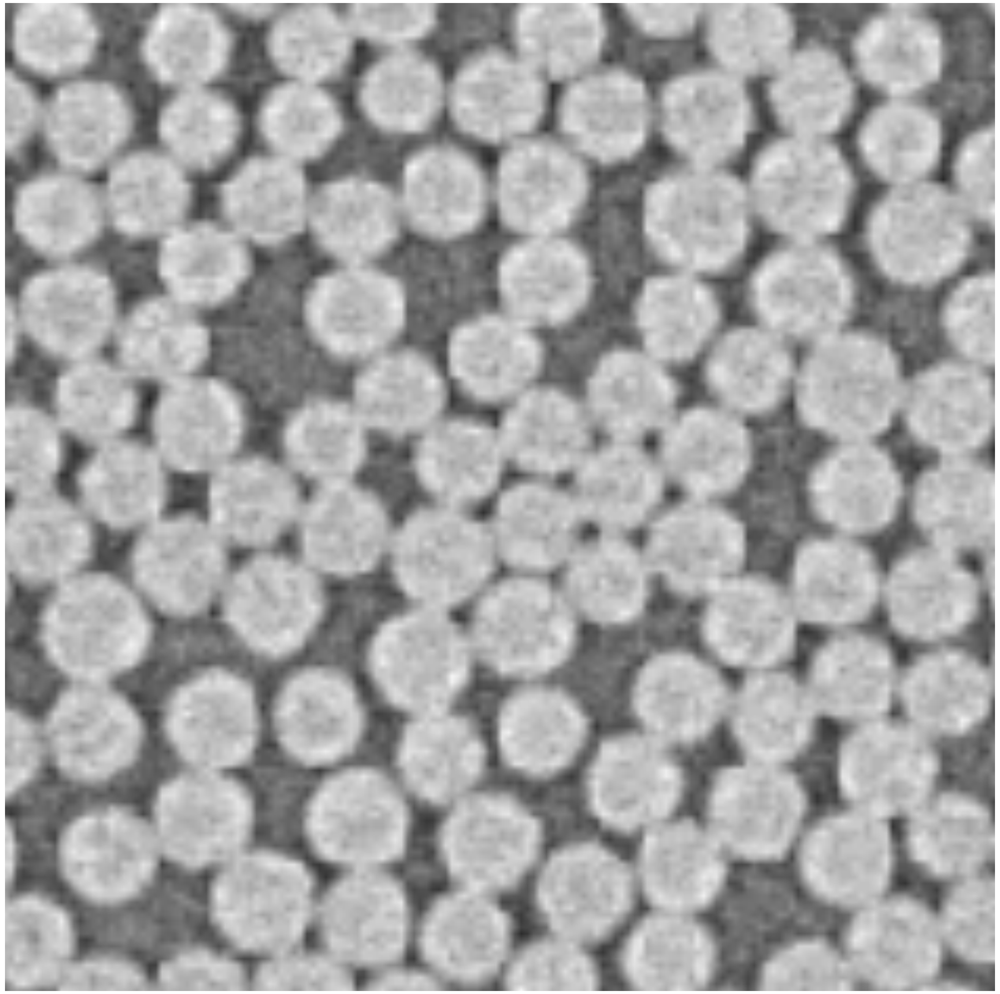
Challenges in our data

The data we analyse:

- A range of fibre materials (glass, carbon…)
- Representative volumes (full bundles)
- Fast scanning
  - At laboratory sources
  - For in-situ loading experiments

<u>Long scan in lab source glass fibres</u>

Main challenge
Closely packed fibres



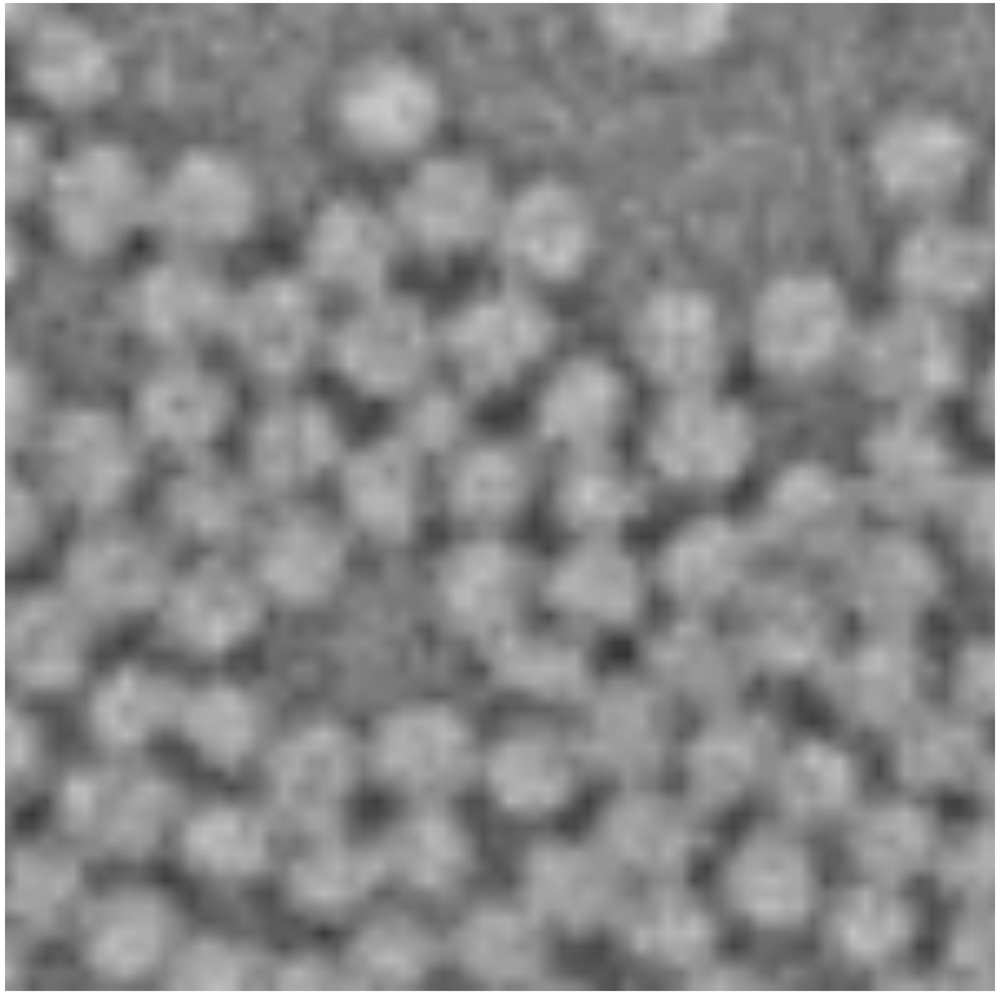
Challenges in our data

The data we analyse:

- **A range of fibre materials** (glass, carbon…)
- Representative volumes (full bundles)
- Fast scanning
  - At laboratory sources
  - For in-situ loading experiments

<u>Long scan in lab source</u>
<u>carbon fibres</u>

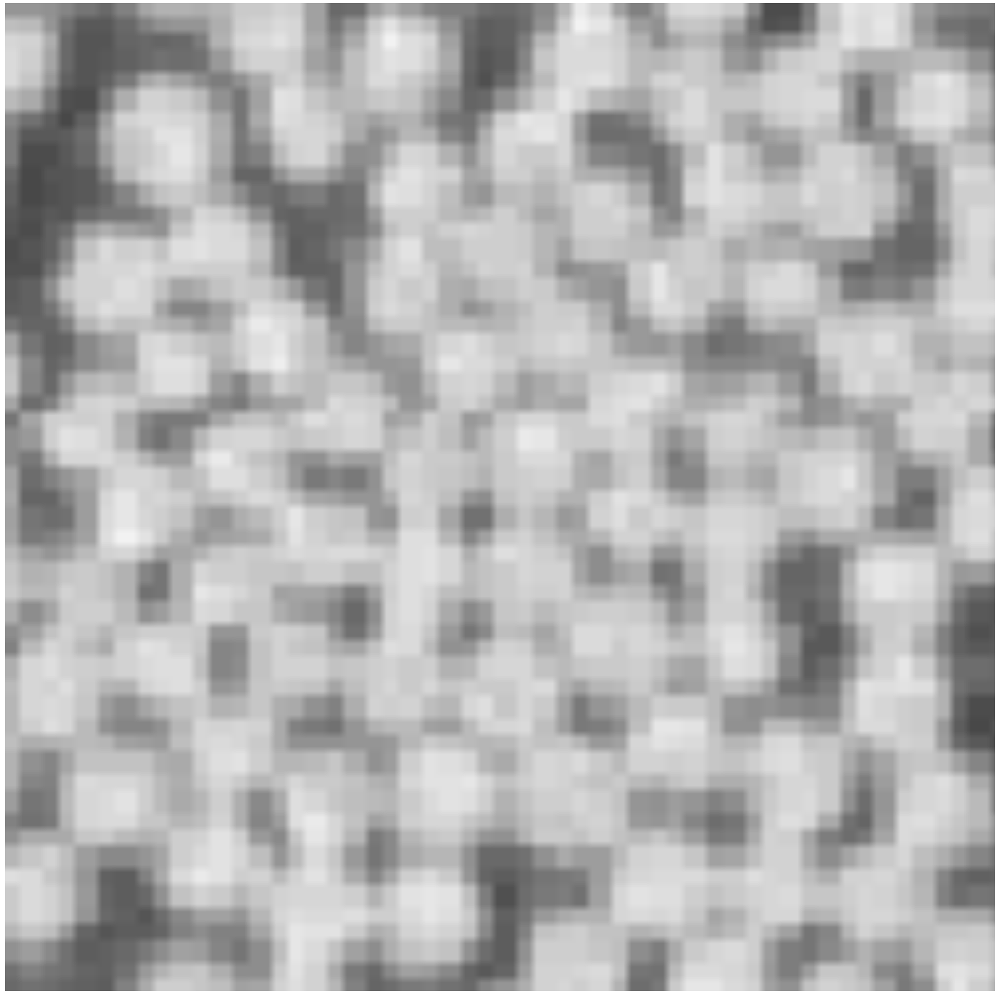
Main challenge
Limited contrast
between material phases



Challenges in our data

The data we analyse:

- A range of fibre materials (glass, carbon…)
- **Representative volumes** (full bundles)
- Fast scanning
  - At laboratory sources
  - For in-situ loading experiments



<u>Representative volume</u>
<u>glass fibres</u>

Main challenge
Limited spatial resolution
pixellated edges

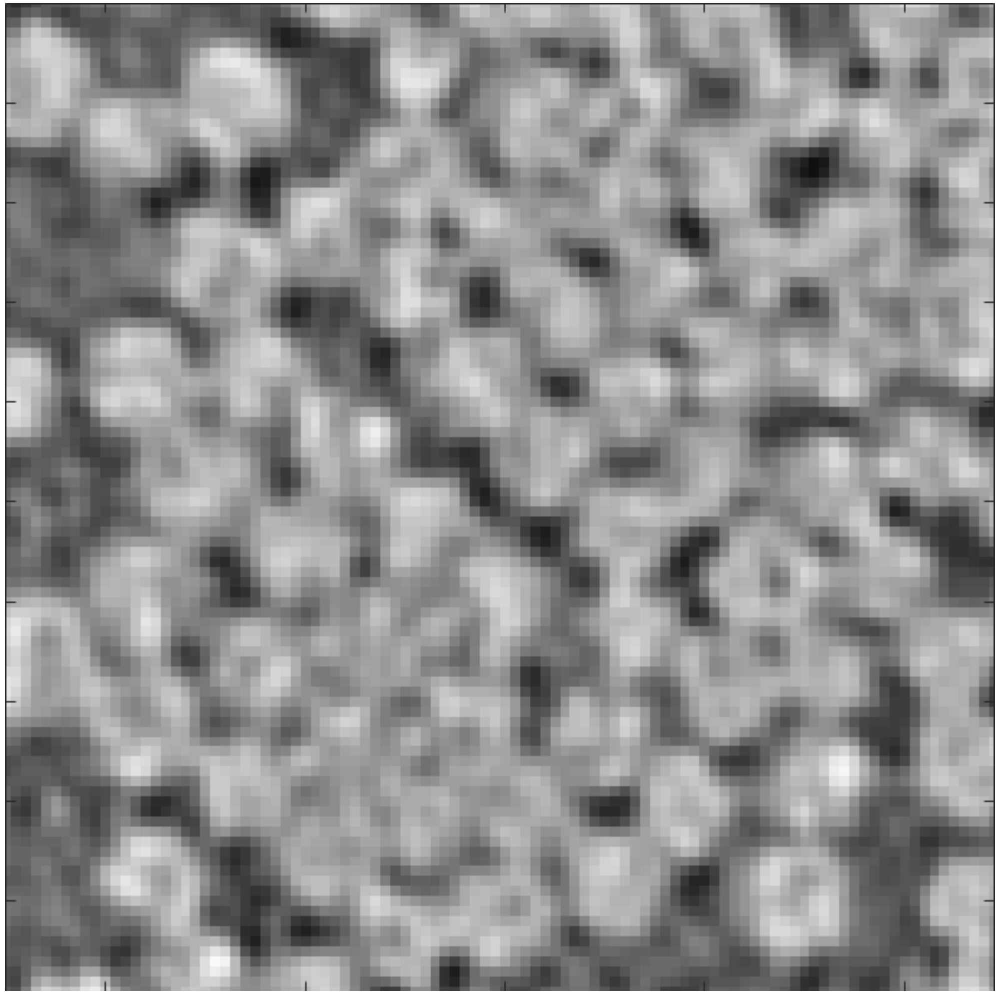
Challenges in our data

The data we analyse:

- A range of fibre materials (glass, carbon…)
- Representative volumes (full bundles)
- **Fast scanning**
  - At laboratory sources
  - For in-situ loading experiments

Fast scan (in-situ loading)
glass fibres

Main challenge
Limited spatial resolution
blurred edges



Challenges in our data

The data we analyse:

- A range of fibre materials (glass, carbon…)
- Representative volumes (full bundles)
- Fast scanning
  - At laboratory sources
  - For in-situ loading experiments

The challenges we encounter:

- Noise
- Limited contrast
- Blurriness
- Pixellation

Blurriness, Pixellation → Limited spatial resolution

We want to measure:

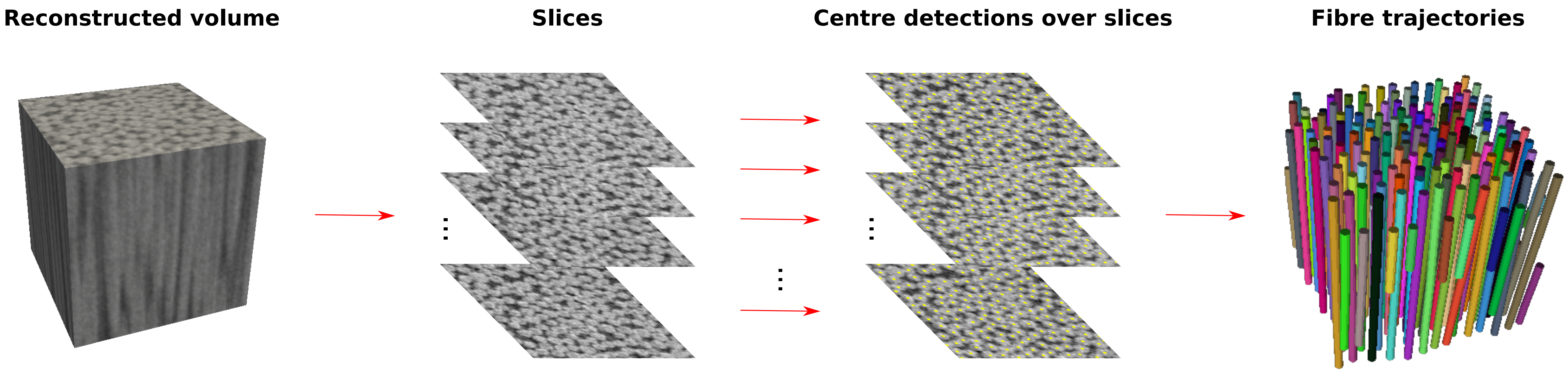
- Small curvature variations
- The start of the damage as early as possible
- The very small changes between loading steps

→ Very **PRECISE** centre lines

Individual fibre segmentation

- The challenges in our data
- The pipeline for individual fibre segmentation
- Previous work: *A literature review*
- 2D segmentation: The *Dictionary of Image Patches*
- 3D tracking

The pipeline for individual fibre segmentation



Individual fibre segmentation

- The challenges in our data
- The pipeline for individual fibre segmentation
- Previous work: *A literature review*
- 2D segmentation: The *Dictionary of Image Patches*
- 3D tracking

Segmentation of UD fibres: Literature review

Authors	Data (3D tomogram)	Pre-processing	2D Segmentation	Tracking	Post-processing
Requena et al. 2009	• **High quality** • FoV: 0.73 mm^2	None	**Grey value threshold**	Euclidean distance	Automatic
Czabaj et al. 2014	• Carbon fibres • FoV: 0.03 mm^2	None	Template matching (NCC)	Kalman filter	Automatic and **Manual** → **Small volumes**
Sencu et al. 2016 (Manchester)	• Blurred • FoV: 0.71 mm^2	Bank of filters	1. Local maxima 2. Ultimate eroding points	Bayesian inference (2 steps)	Automatic
Emerson et al. 2015-2018	• **Range of qualities** (Blurred, pixelised, carbon…) • FoV: 3 mm^2 → **Full bundles**	None	**Default parameters** Dictionary-based pixel classification	Euclidean distance	Automatic

Choices and parameters sensitive to image quality (Sencu et al.: Pre-processing, 2D Segmentation, Tracking)

Individual fibre segmentation

- The challenges in our data
- The pipeline for individual fibre segmentation
- Previous work: *A literature review*
- 2D segmentation: The *Dictionary of Image Patches*
- 3D tracking

What do we need?

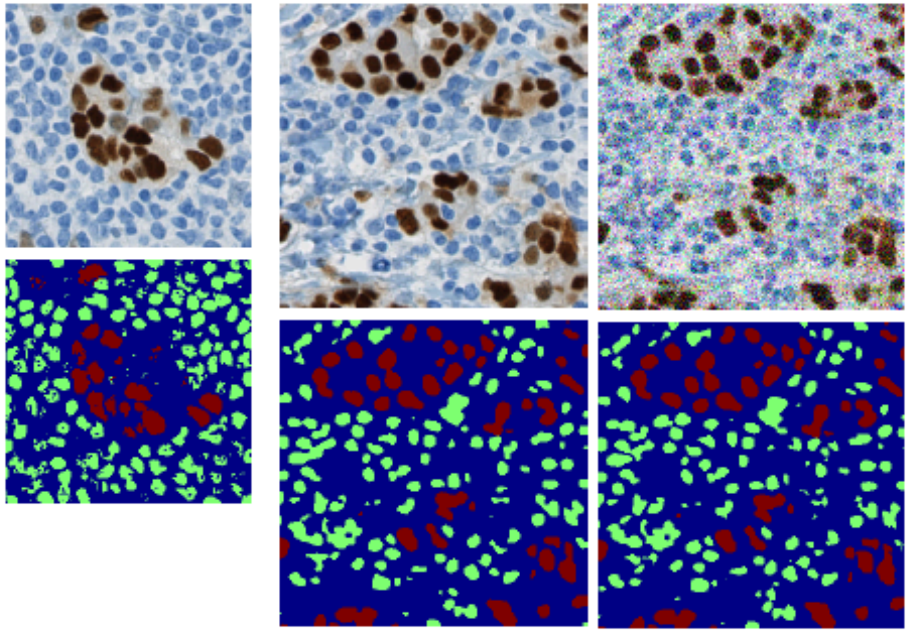
- A flexible method to handle
  - A range of image qualities
  - A range of materials
  - A range of fibre and pixel sizes
- Capture local differences at the fibre scale

(Compact) **Data model at the fibre scale**

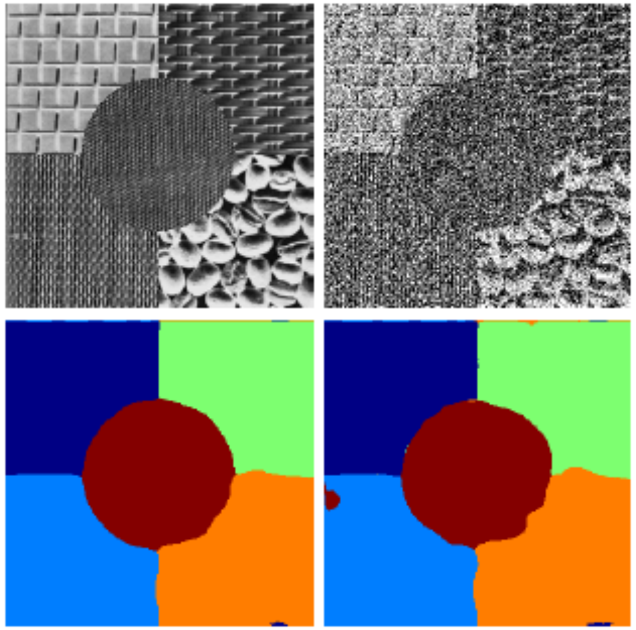
Why the dictionary of image patches?

- **Compact data model at a local scale**
- Successful in modelling repetitive image patterns and **cells**
- Robust to noise

Cells
with noise on the right



Segmentation of textures
with noise on the right



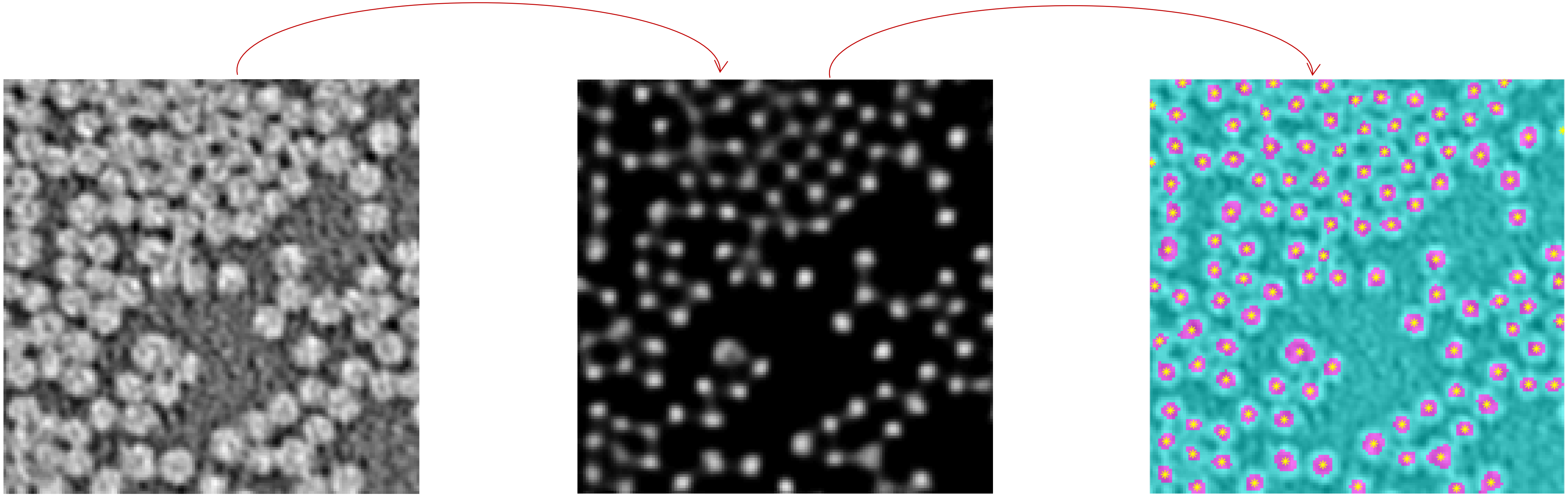
Dahl & Larsen 2011, BMVC

Detection of fibre cross-sections: Dictionary learning

Probabilistic segmentation of centre regions based on a dictionary of image patches

Probabilistic segmentation of centre regions

Thresholding and connected component analysis

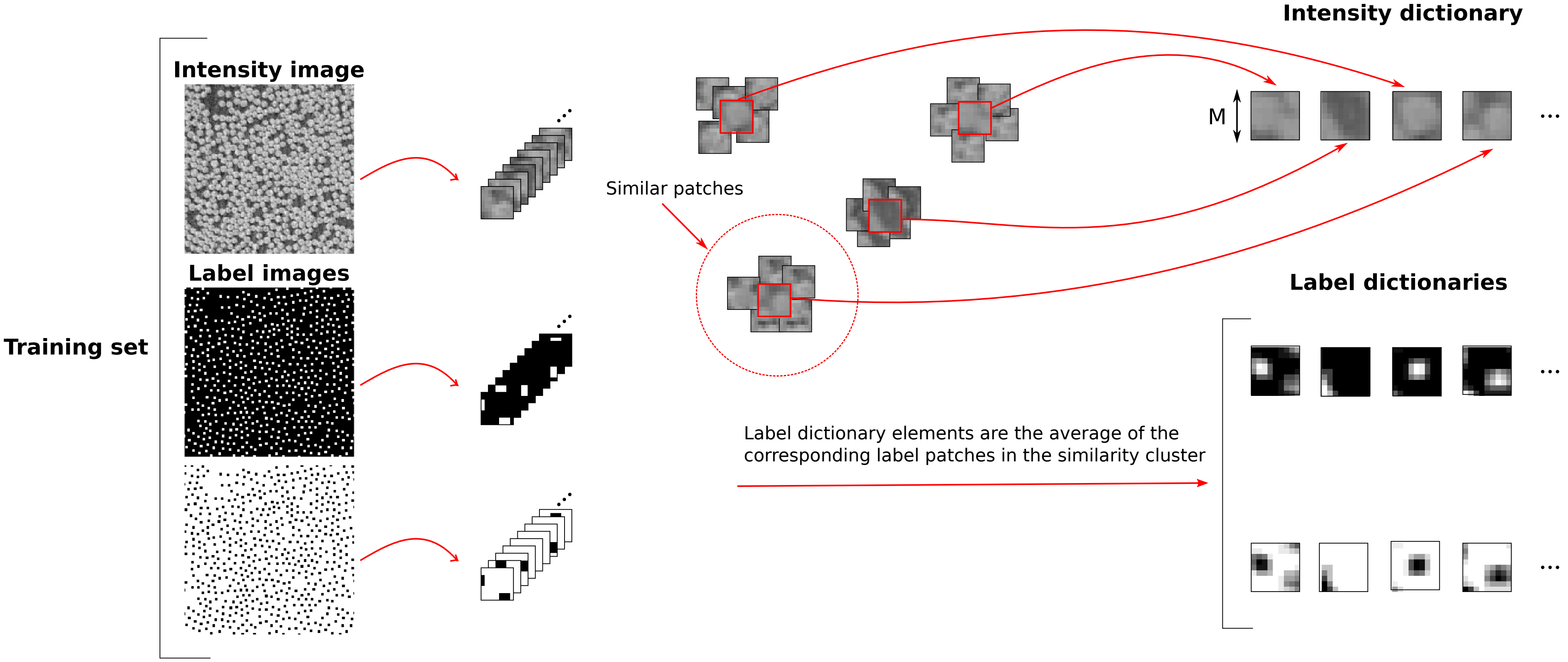


Training the dictionary of image patches

Step 1:
- Extract all image patches
- Randomly select a subset

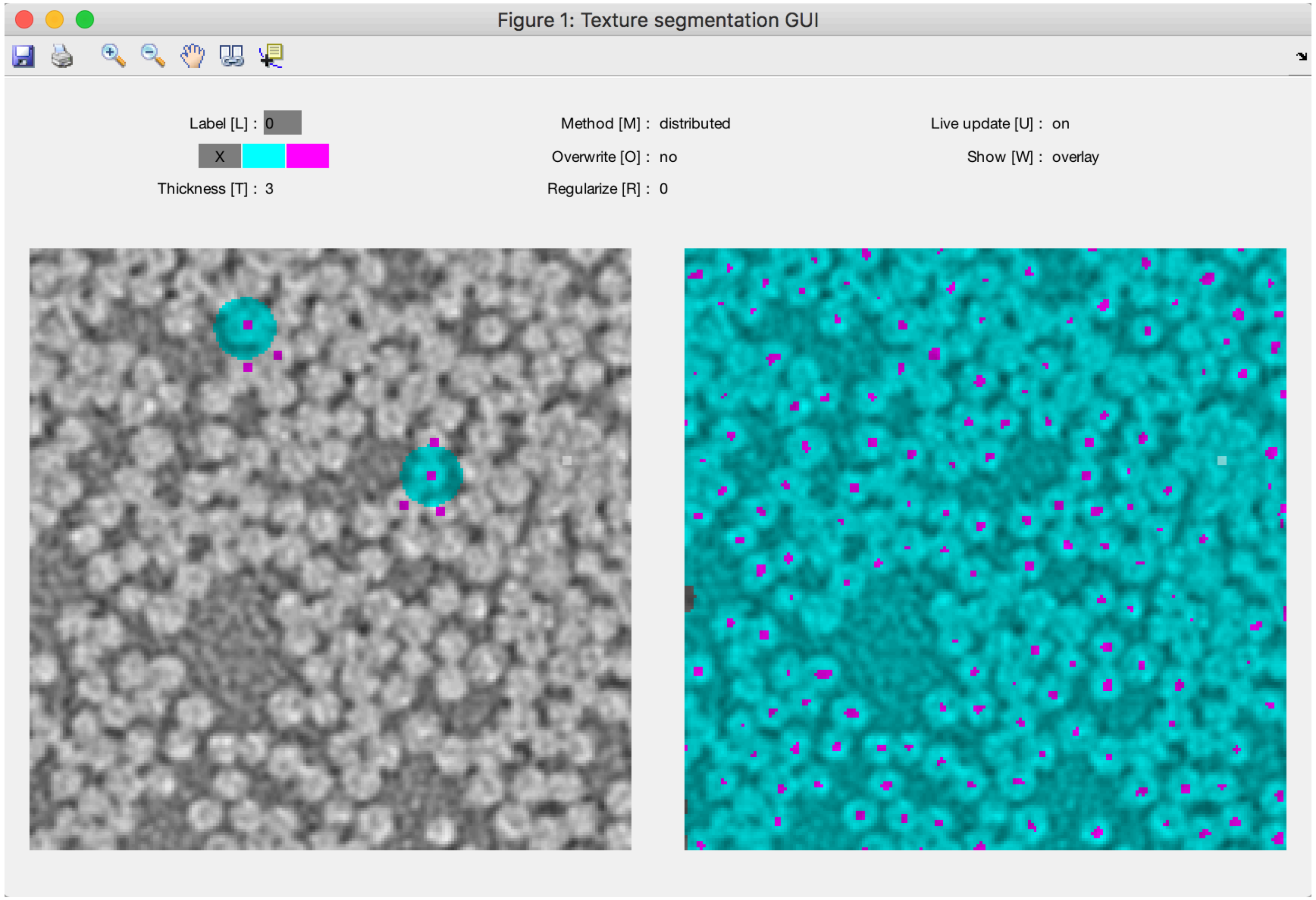
Step 2:
- Cluster similar intensity patches
- Calculate the centre for each cluster, that is, the intensity dictionary elements.

Step 3:
Establish dictionaries

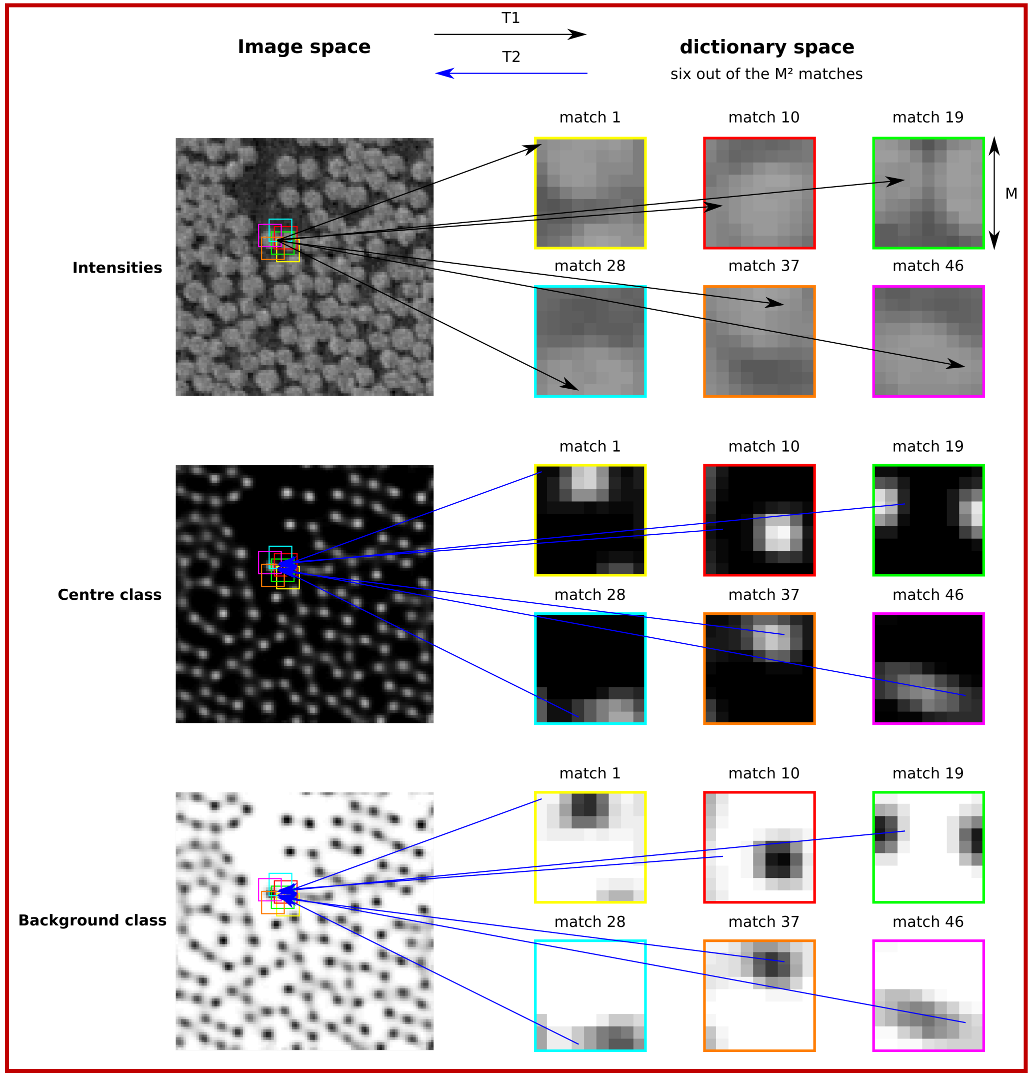


Training with the graphical user interface (GUI)

- User-friendly training
- Minimal user input
- Adaptable amount of manual input
- Immediate feedback



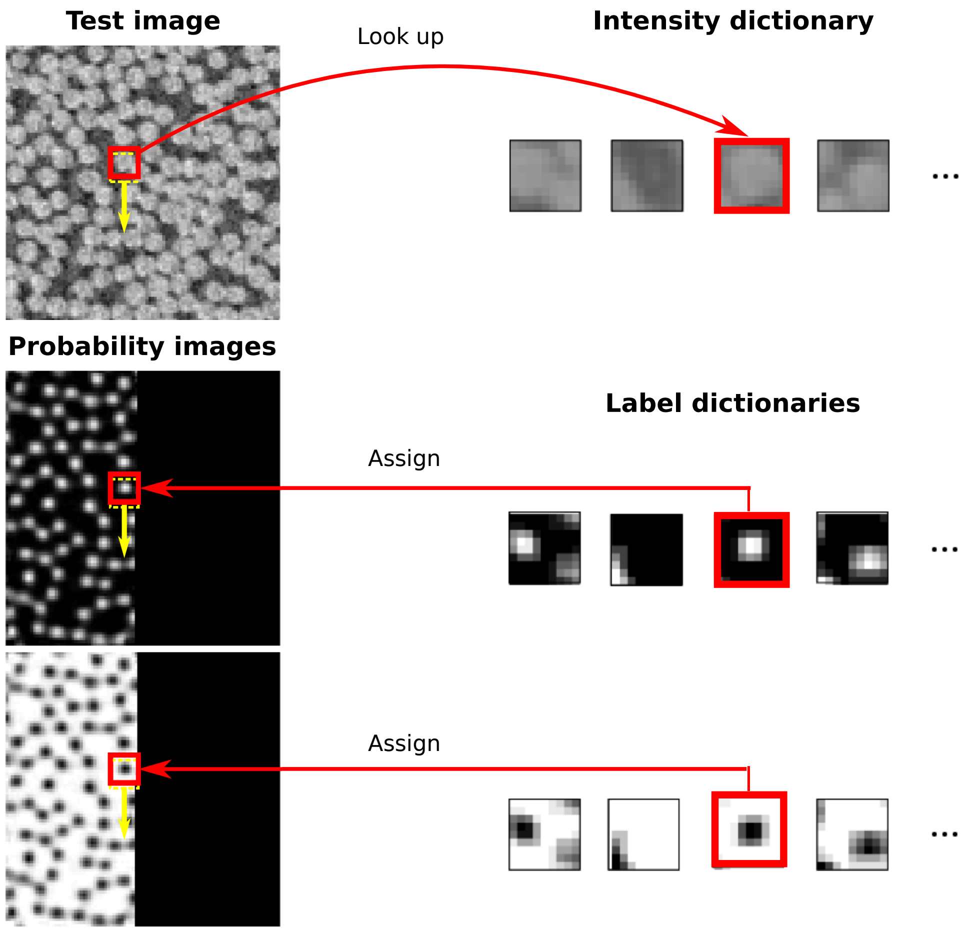
Training with the graphical user interface (GUI)



- Linear relationship between image and dictionary space
- A linear operation is a matrix multiplication
- Matlab® is fast at matrix multiplications
- Unlabelled pixels given equal probability for each class

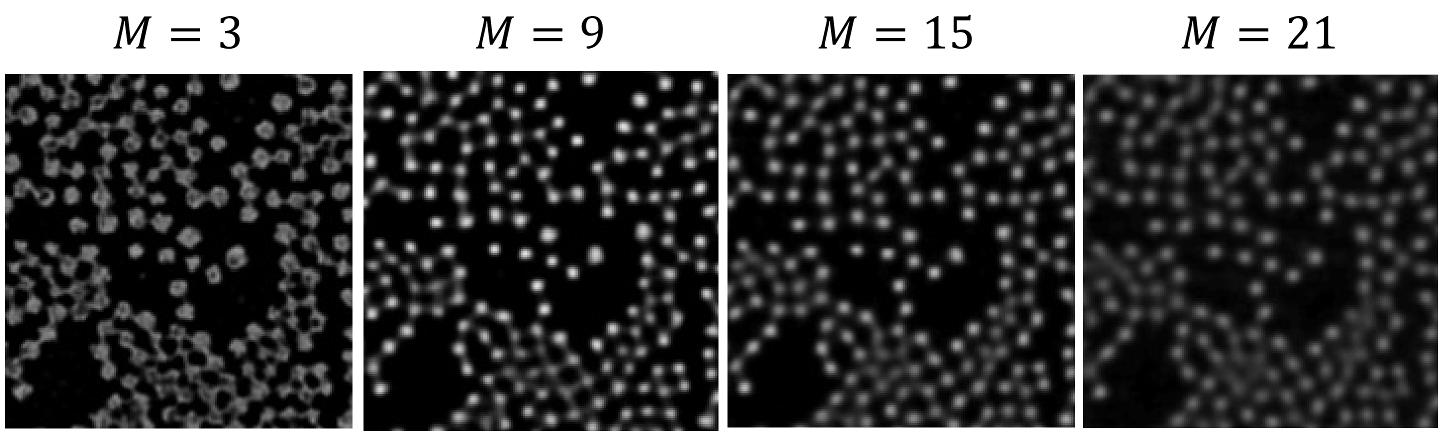
V.A. Dahl, C.H. Trinderup, M.J. Emerson , A.B. Dahl, Content-based Propagation of User Markings for Interactive Segmentation of Patterned Images, *IEEE Transactions on Image Processing*. (In submission)

Probabilistic labelling of an un-seen image



Tuning the parameters

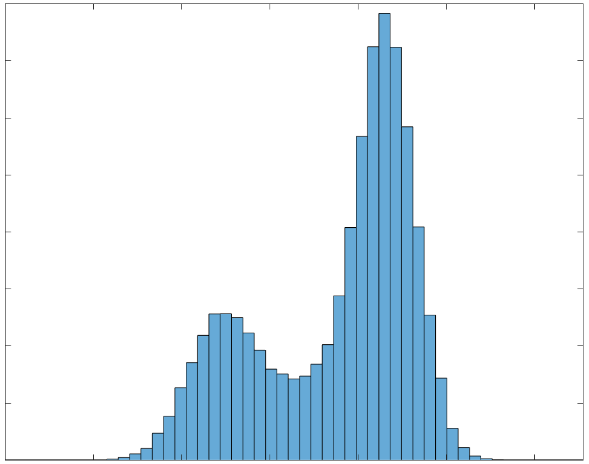
- Number of dictionary elements n
  - Fast search and small space in memory (compact)
  - Close enough matches (variety)
- Patch size M: scale of the texture



Detection of fibre cross-sections: Method comparison

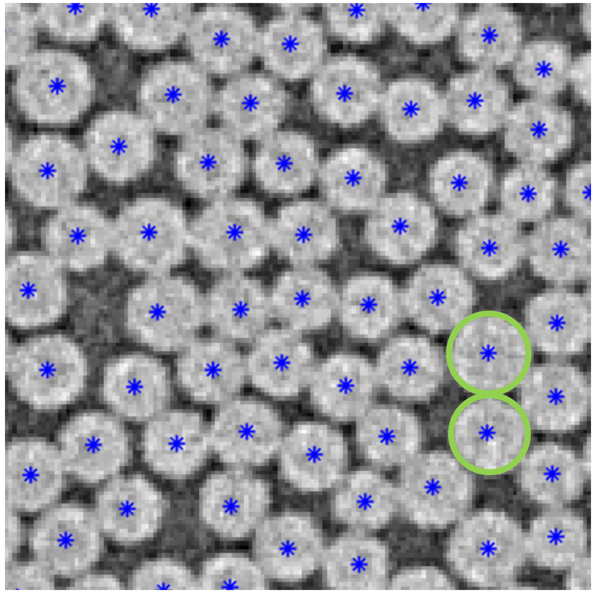
Long scan in lab source
glass fibres

Main challenge
Closely packed fibres



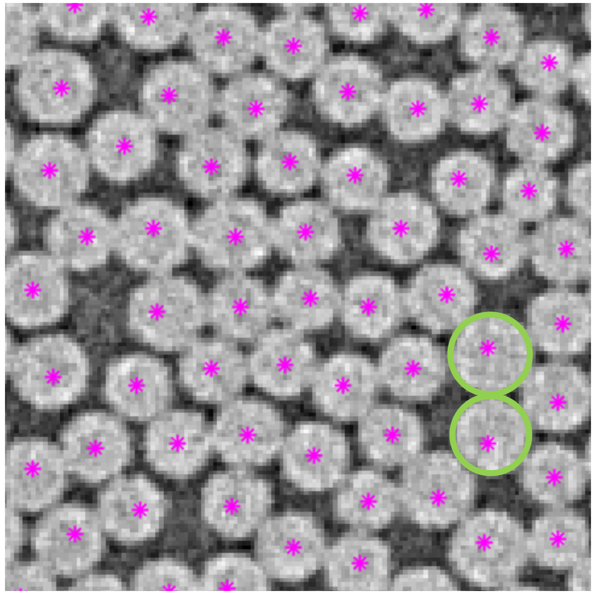
Histogram of intensities

Blob detection

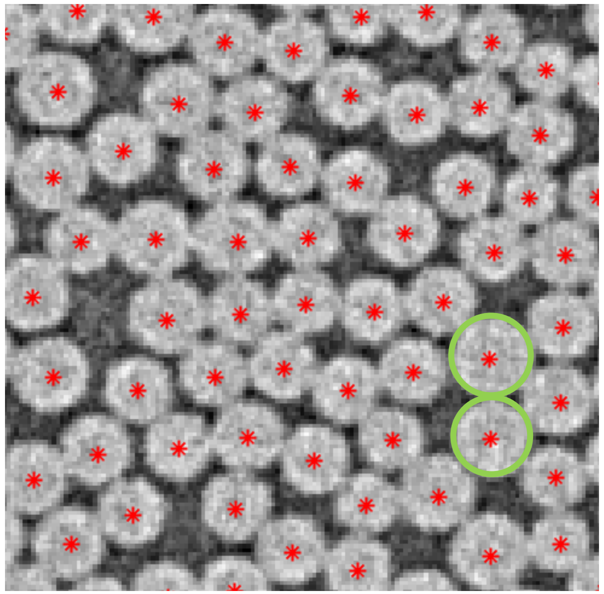


Pre-processed (smoothing)

Circular Hough Transform



Dictionary of image patches



Unprecise estimations

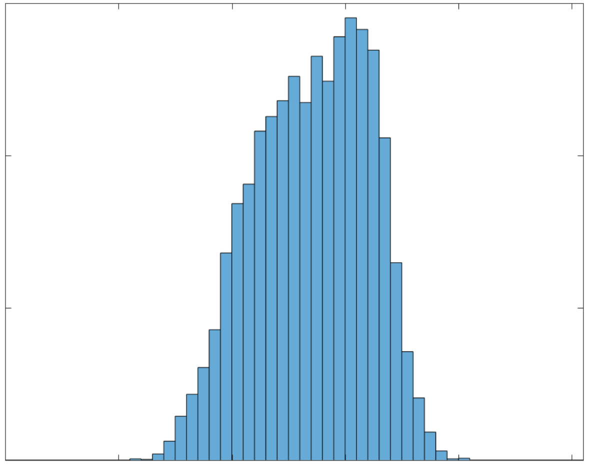
Detection of fibre cross-sections: Method comparison

Long scan in lab source carbon fibres

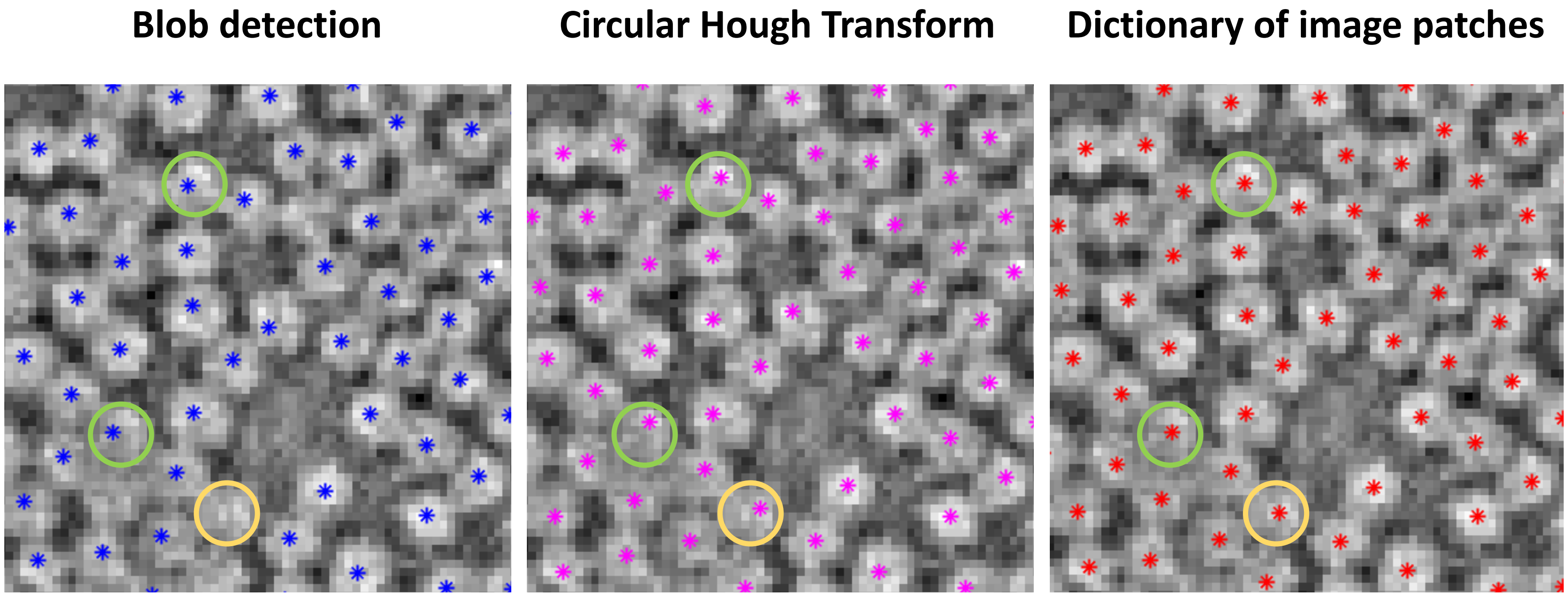
Main challenge

Limited contrast

between material phases



Histogram of intensities



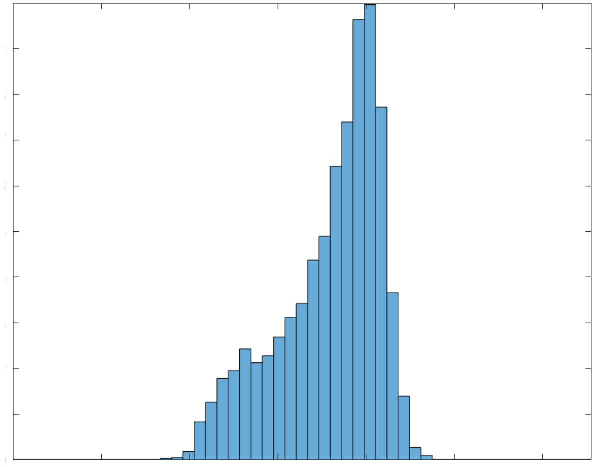
Unprecise estimations

Missed and unprecise estimation

Detection of fibre cross-sections: Method comparison

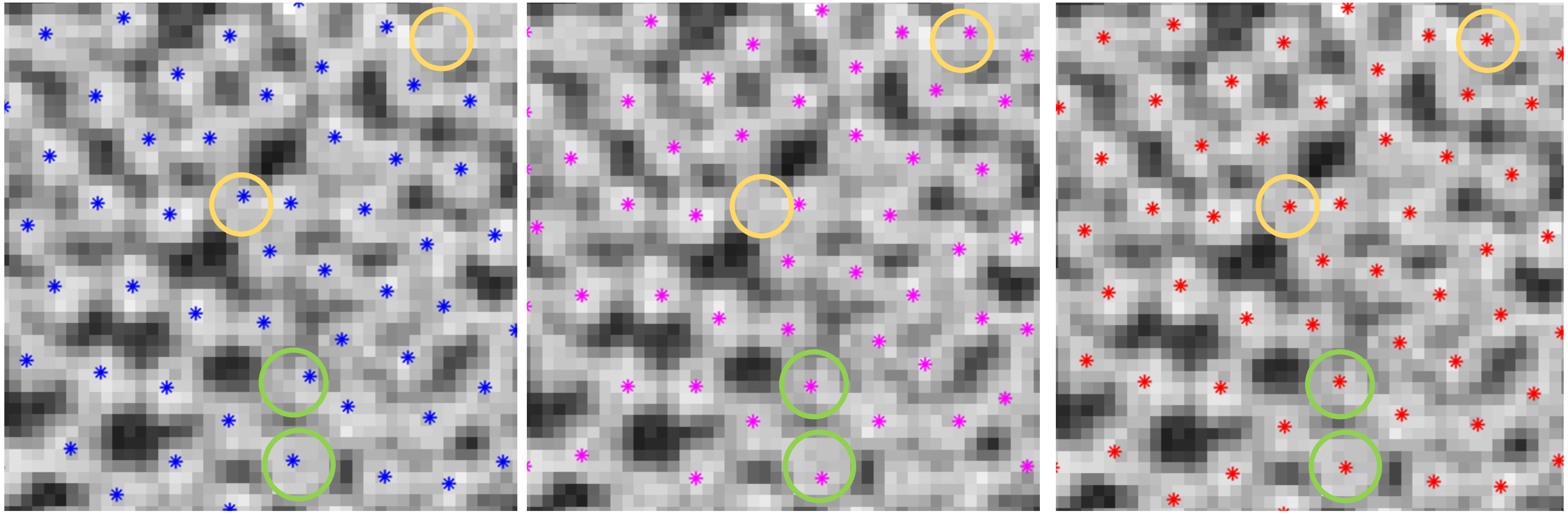
Representative volume
glass fibres

Main challenge
Limited spatial resolution
pixelised edges



Histogram of intensities

Blob detection | **Circular Hough Transform** | **Dictionary of image patches**

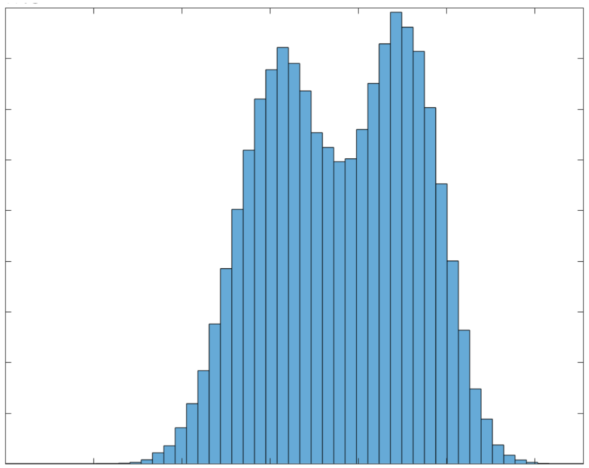


Unprecise estimations
Missed and unprecise estimations

Detection of fibre cross-sections: Method comparison

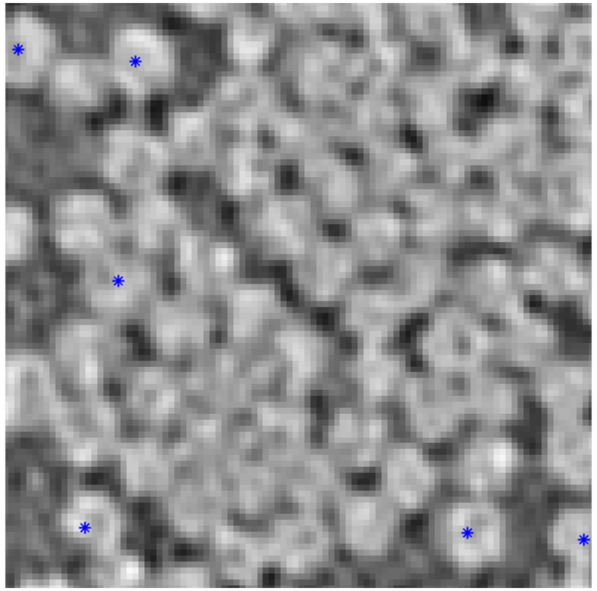
<u>Fast scan (in-situ loading)</u>

Main challenge:
Limited spatial resolution (blurred edges)

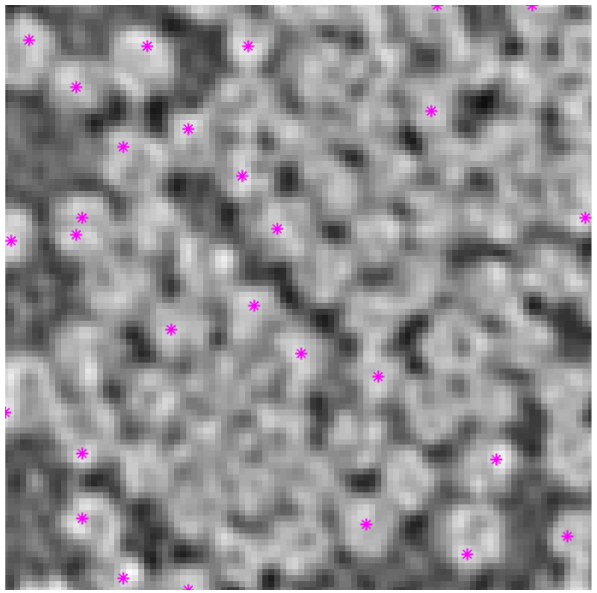


Histogram of intensities

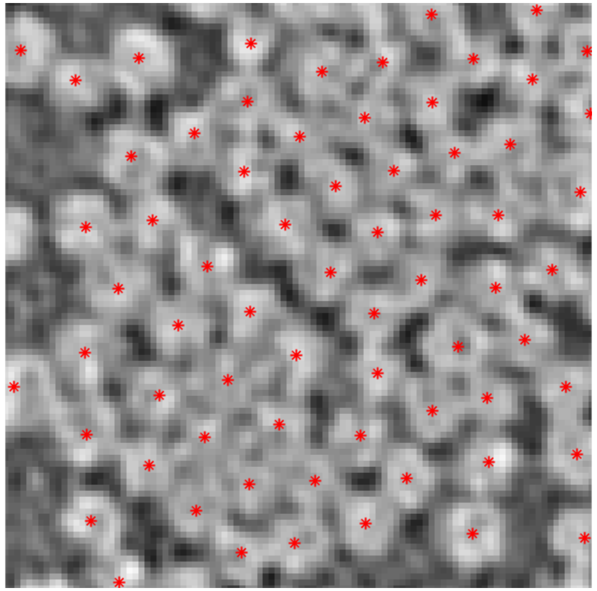
Blob detection



Circular Hough Transform



Dictionary of image patches



Individual fibre segmentation

- The challenges in our data
- The pipeline for individual fibre segmentation
- Previous work: *A literature review*
- 2D segmentation: The *Dictionary of Image Patches*
- 3D tracking

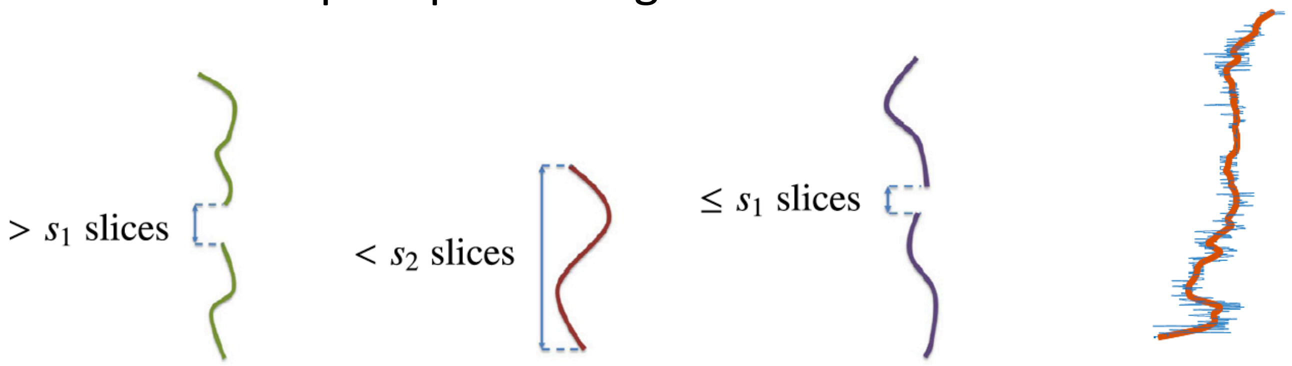
3D tracking: Literature review

Authors	Data (3D tomogram)	Pre-processing	2D Segmentation	Tracking	Post-processing
Requena et al. 2009	• High quality • FoV: 0.73 mm^2	None	Grey value threshold	Euclidean distance	Automatic
Czabaj et al. 2014	• Carbon fibres • FoV: 0.03 mm^2	None	Template matching (NCC)	**Kalman filter**	Automatic and Manual
Sencu et al. 2016 (Manchester)	• Blurred • FoV: 0.71 mm^2	Bank of filters	1. Local maxima 2. Ultimate eroding points	Bayesian inference (2 steps)	Automatic
Emerson et al. 2015-2018	• Range of qualities (Blurred, pixelised, carbon…) • FoV: 3 mm^2	None	Dictionary-based pixel classification	**Euclidean distance**	Automatic

3D tracking

First version (Paper Composites Part A): Unidirectional match of centres between slices

1. Closest match in cross-sectional plane (Euclidean)
2. Restrict matches to be under a certain distance
3. Automatic post-processing



(a) Split (b) Eliminate (c) Interpolate (d) Smooth

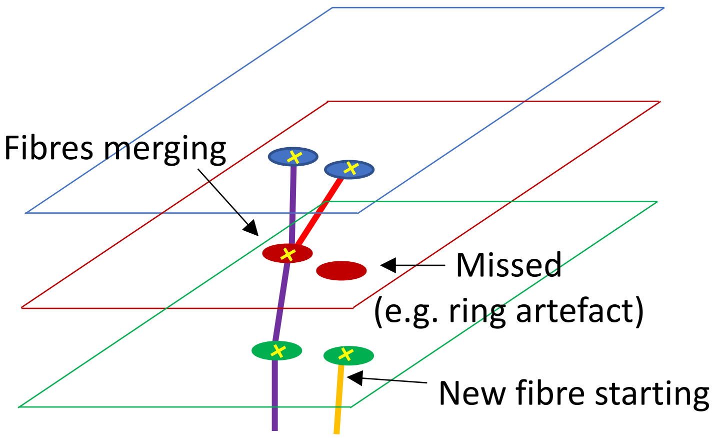
M.J. Emerson , K.M. Jespersen, A.B. Dahl, K. Conradsen, L.P. Mikkelsen, Individual fibre segmentation from 3D X-ray computed tomography for characterising the fibre orientation in unidirectional composite materials, Composites Part A: Applied Science and Manufacturing 97 (2017) 83-92.

3D tracking: Improvements

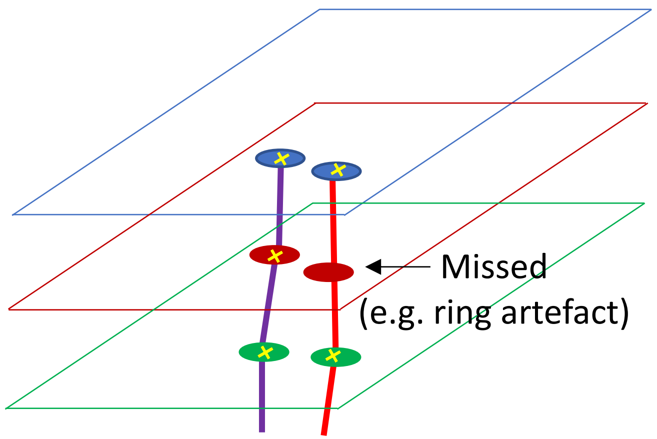
Second version (Papers CSTE)

1. Solves fibre merging

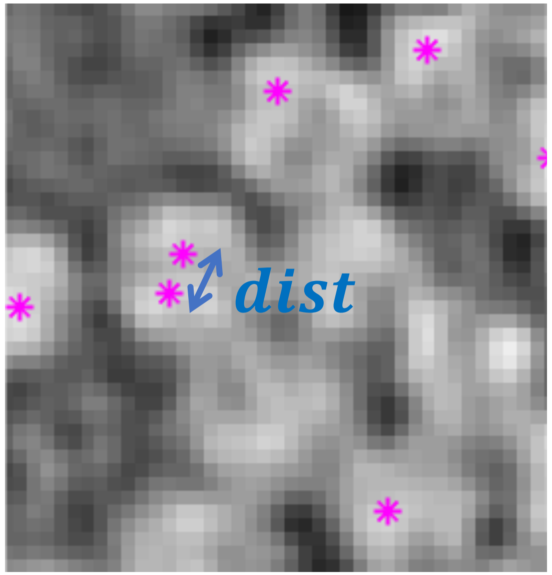
Unidirectional match



Bidirectional match



2. Handles double detections
   Merge detections when $dist < \text{th}$ where $\text{th} \in [d/2, d)$



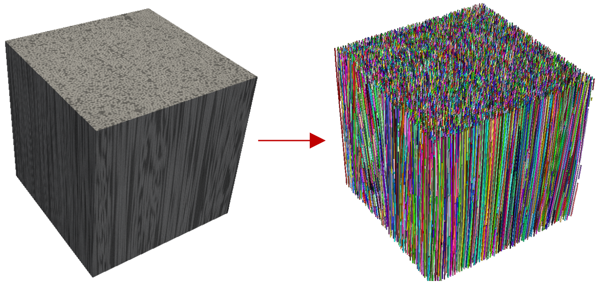
M.J. Emerson , Y. Wang, P.J. Withers, K. Conradsen, A.B. Dahl, V.A. Dahl, Quantifying Fibre Reorientation during Axial Compression of a Composite through Time-lapse X-ray Imaging and Individual Fibre Tracking, Composites Science and Technology. (Under review)

M.J. Emerson , V.A. Dahl, K. Conradsen, L.P. Mikkelsen, A.B. Dahl, Statistical validation of individual fibre segmentation from tomograms and microscopy, Composites Science and Technology 160 (2018) 208-215.

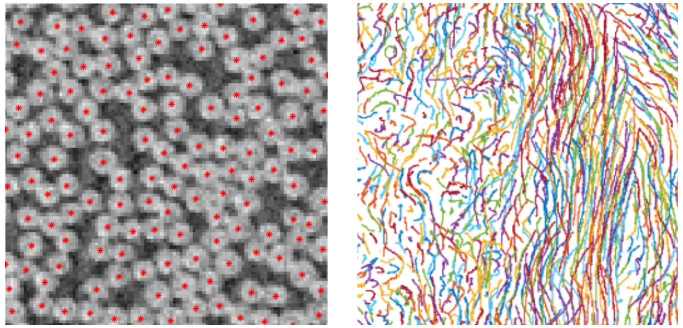
Contributions by topic

DEVELOPMENT

Fibre Geometry Extraction
via Individual Fibre Segmentation



1. Fibre cross-sections   2. Fibre trajectories

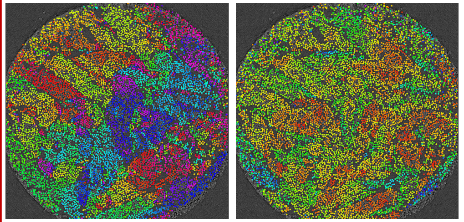


APPLICATIONS

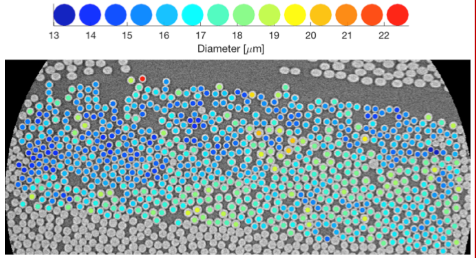
1. Characterisation of Real Structures

a) Fibre misalignment

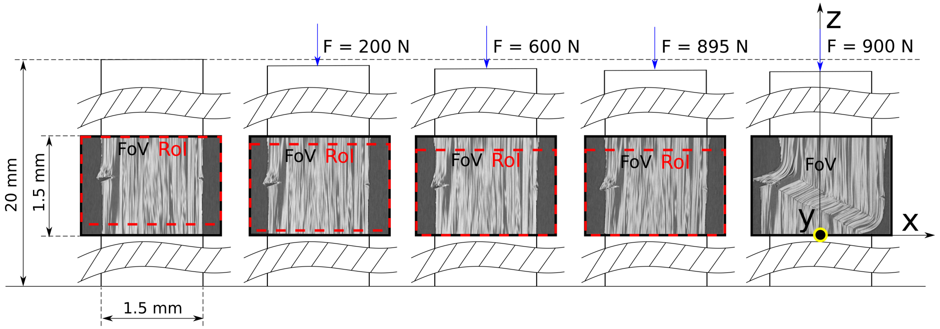
Direction   Magnitude



b) Fibre diameters

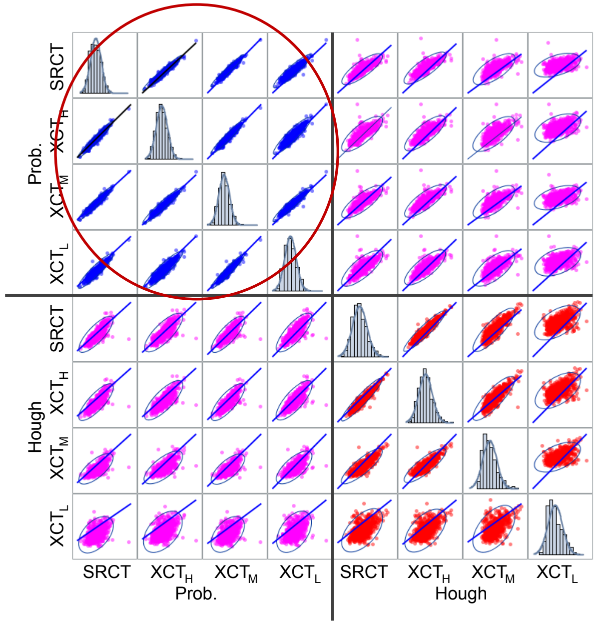


2. Evolution of Structures under Changing Load



VALIDATION

X-ray CT Imaging
+
Individual Fibre Segmentation



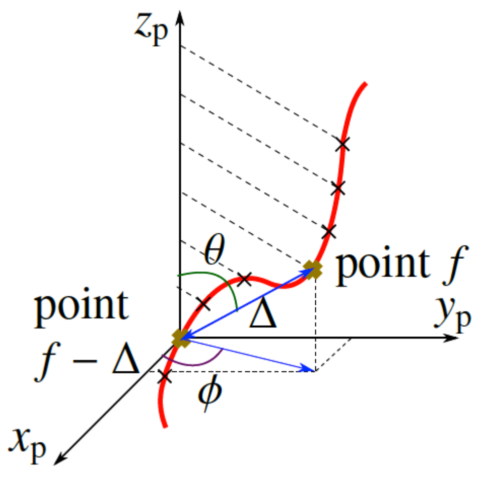
Individual fibre segmentation: Applications

1. Characterisation of real structures
    - Fibre orientations
    - Fibre diameters
2. Evolution of structures under changing load

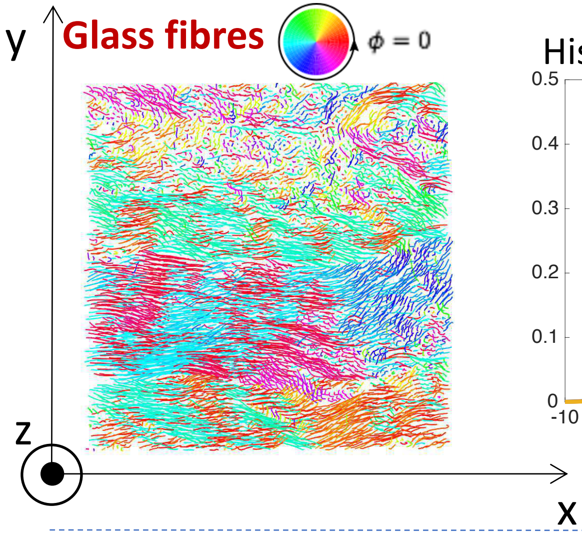
Characterisation of real structures: Orientations

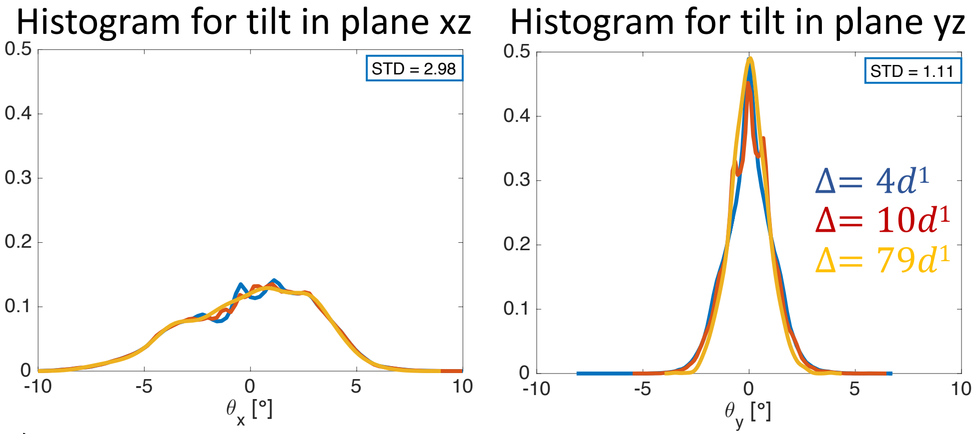
Findings Composites Part A

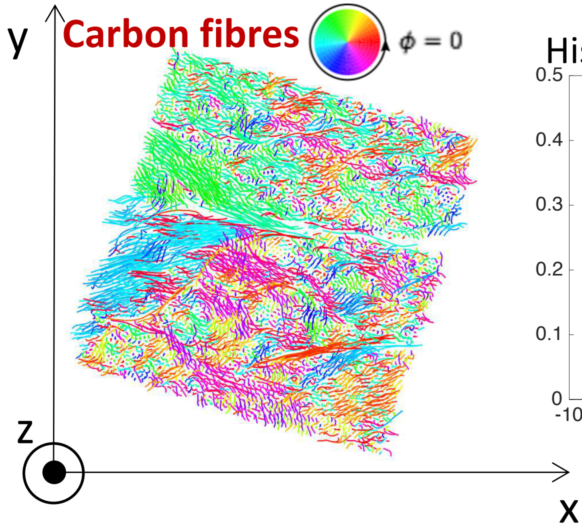
- Fibres are straight, as opposed to curved.
- Different distributions for glass and carbon, even though the manufacturing process was the same.

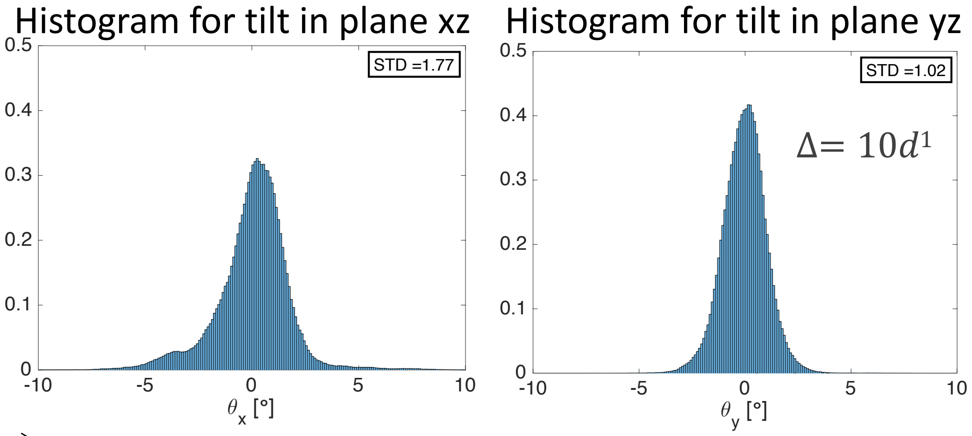


Local VS **global** misalignment (window Δ)
Direction: azimuth angle $\varphi \in [0,360)$
Tilt: inclination angle $\theta \in [0,90]$









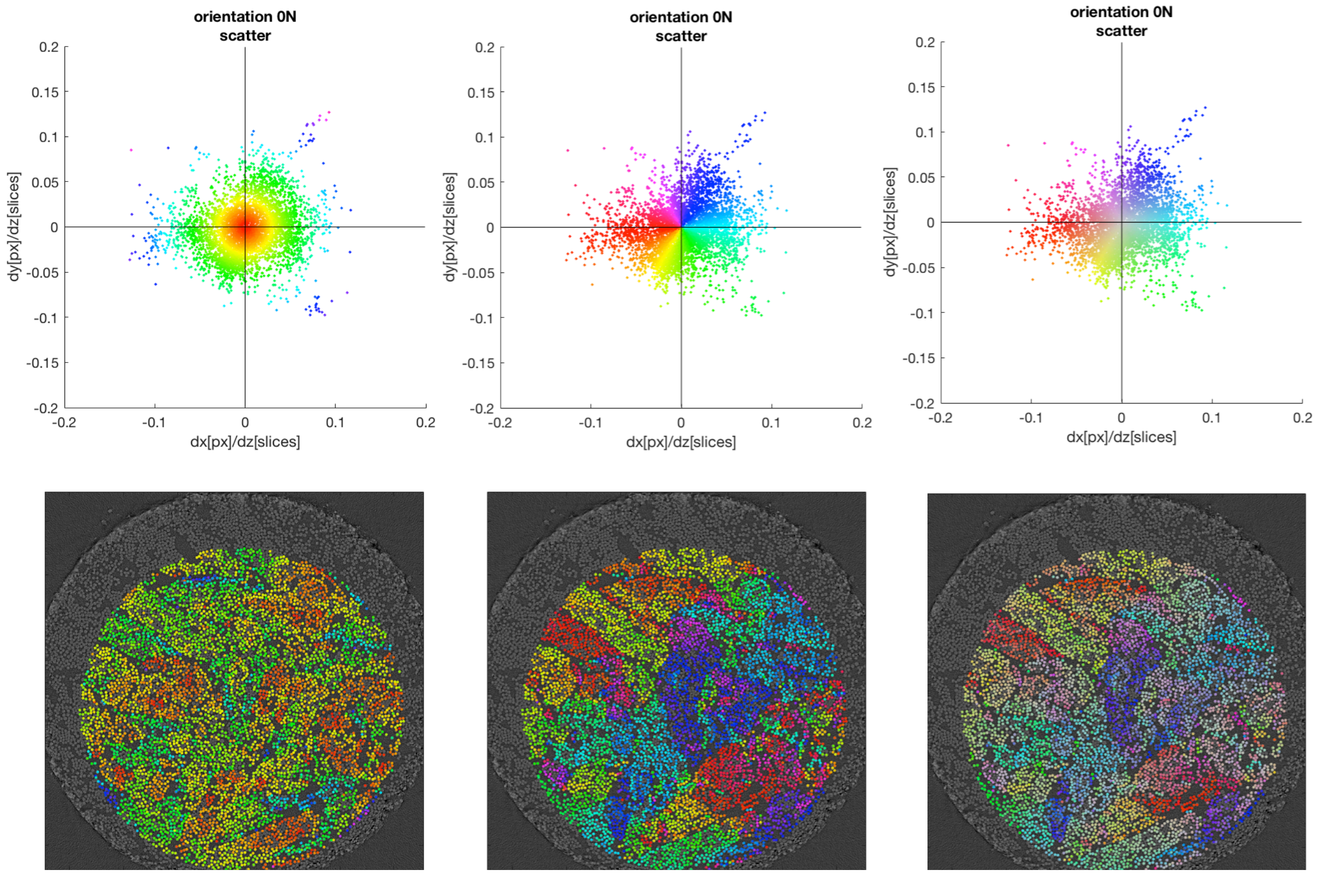
[1] $d \equiv$ fibre diameter

Characterisation of real structures: Orientations

Findings Paper CSTE with Manchester (Ying and Phil)

- The amount of misalignment clusters in space.
- The direction of misalignment clusters in space.
- The direction clusters are determined by fibre density.

Tilt θ | Direction φ | Direction θ weighed with tilt φ

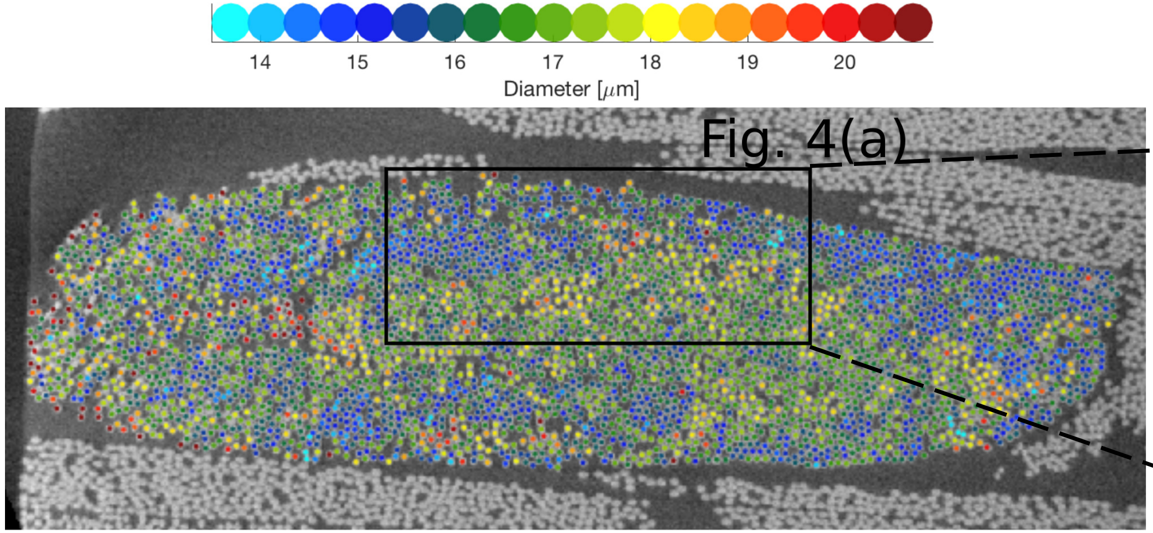


Tilt: inclination angle $\varphi \in [0,90]$
Direction: azimuth angle $\theta \in [0,360)$

Characterisation of real structures: Diameters

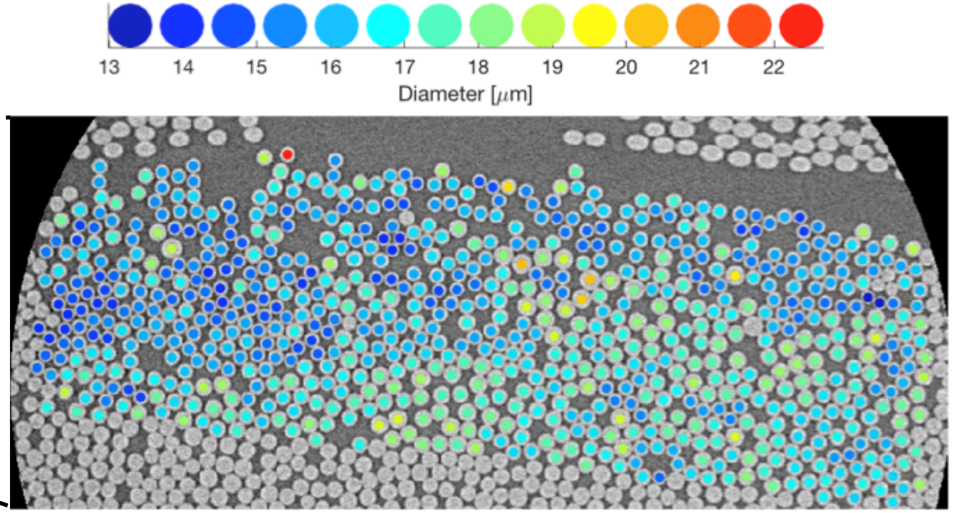
Conclusions Paper CSTE with DTU Wind Energy

- Low resolution quantification correlates with high resolution quantification (more later…)
- There is a trend in the diameters
- Analysing the spatial distribution of fibre diameters can provide insights about the fibre manufacturing process.



Low resolution quantification

analysed with dictionary from low resolution X-ray scan



High resolution quantification

analysed using different methods (imaging modality and analysis algorithm)

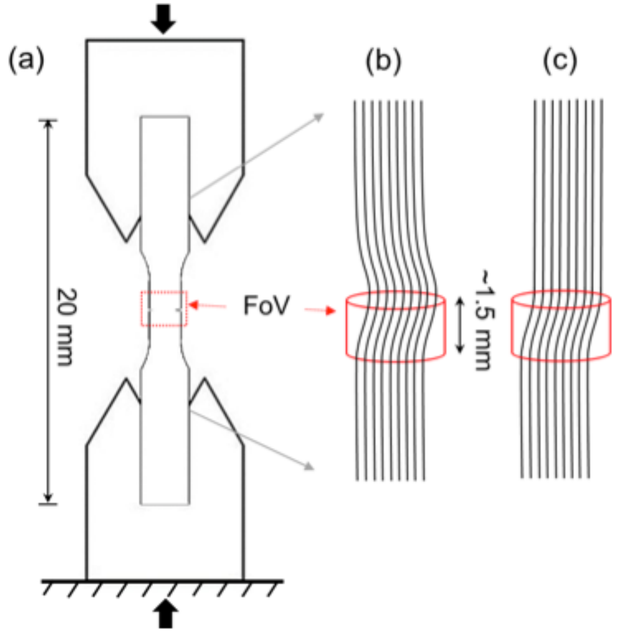
Individual fibre segmentation: Applications

1. Characterisation of real structures
    - Fibre orientations
    - Fibre diameters
2. Evolution of structures under changing load

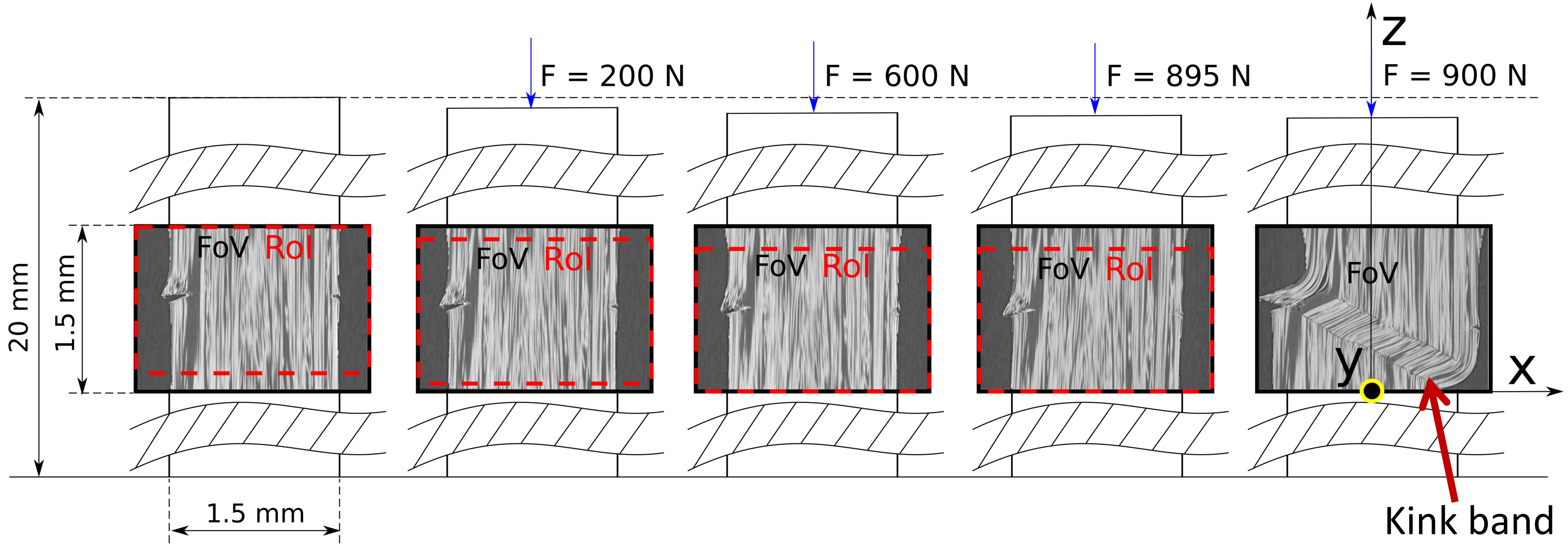
Evolution of structures under changing load

Paper with Ying and Phil: Ultra-fast imaging while compressing a composite in-situ

AIM: Investigate fibre micro-buckling and kink-band formation



Clamped sample (a) and fibre micro-buckling modes (b,c)



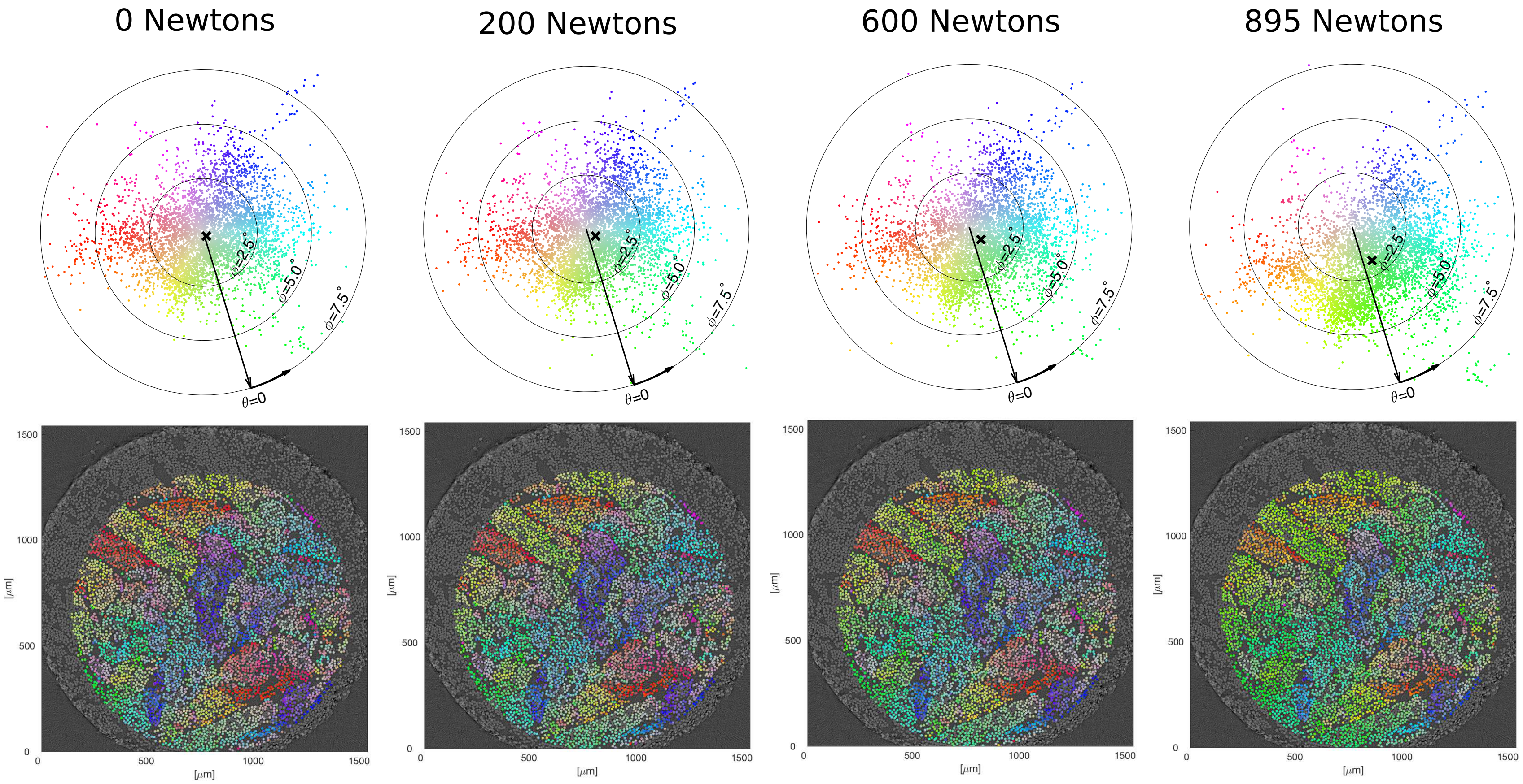
X-ray CT longitudinal slices in the direction of the kink-band plane. In **black** the field of view (FoV) and in **red** the common part of the sample (RoI) as it is vertically displaced.

Evolution of structures under changing load

Findings collaboration with Manchester

- At 25% of the failure load, fibres have started to tilt in approx. the kink direction
- Initially, there is a lack of fibres in the direction opposite to the kink

Tilt:
inclination angle $\varphi \in [0,90]$
Direction:
azimuth angle $\theta \in [0,360)$

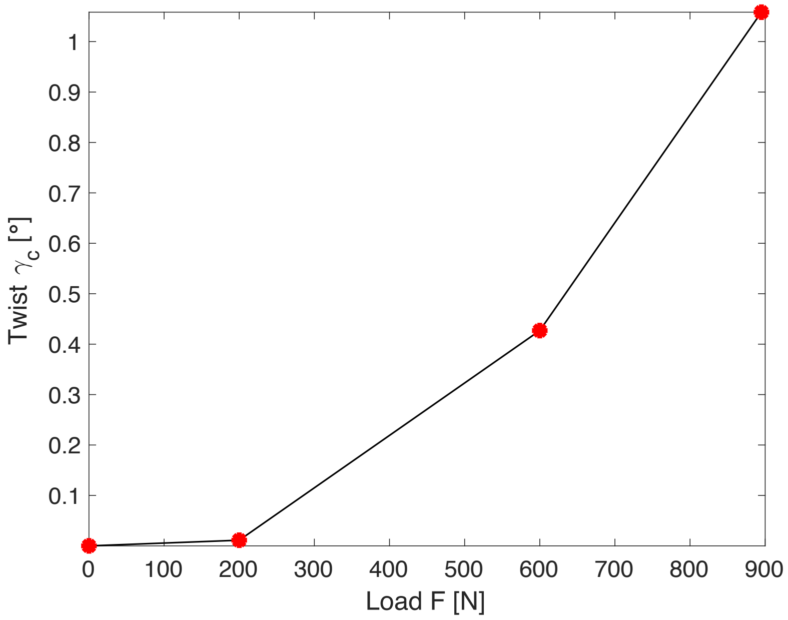


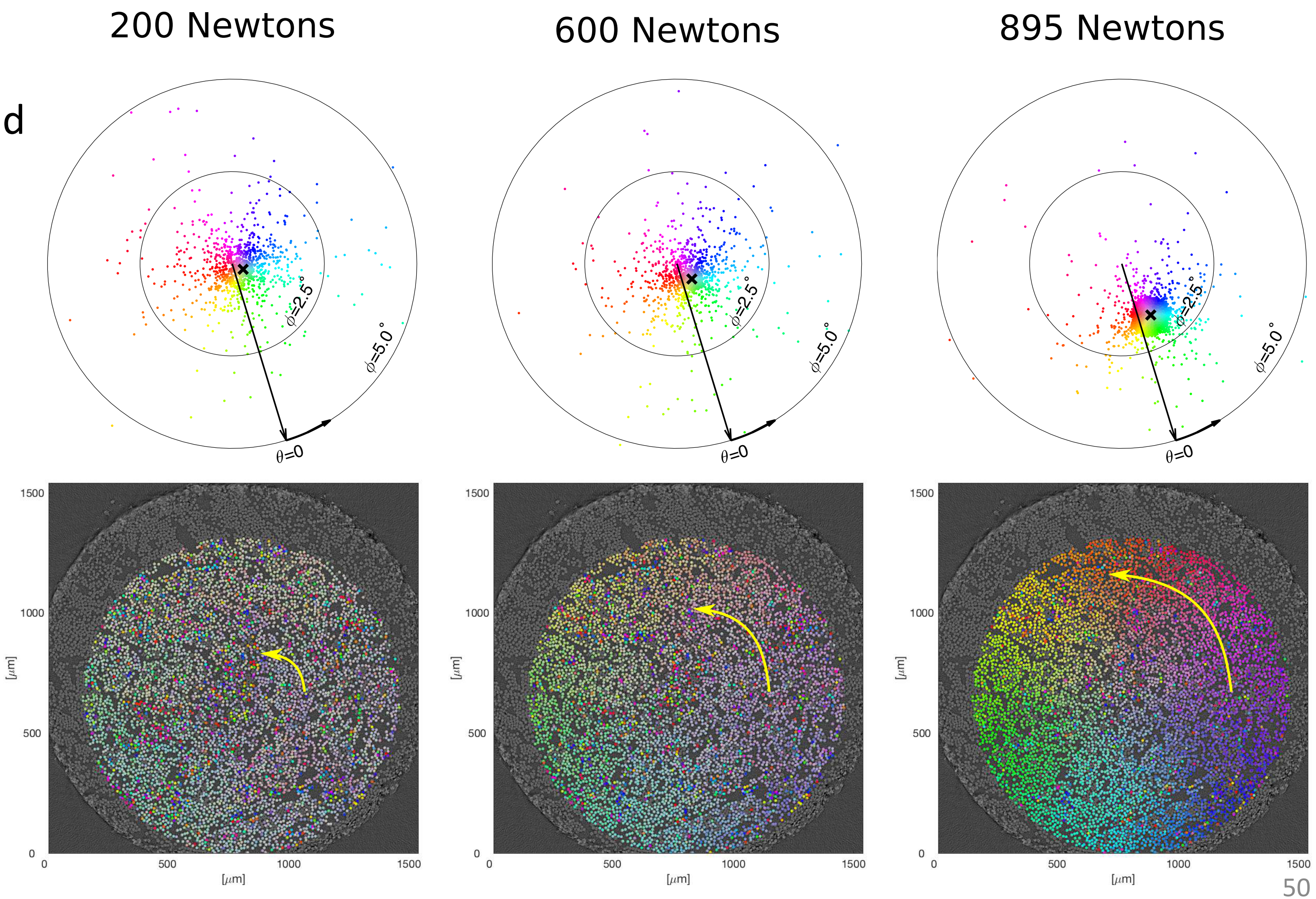
Evolution of structures under changing load

Findings with Manchester

The composite twists under increasing load

Inclination angle $\varphi \in [0,90]$
Azimuth angle $\theta \in [0,360)$

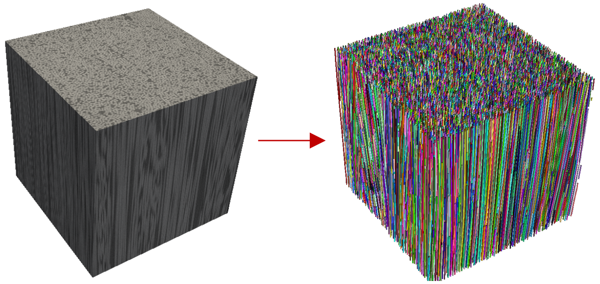




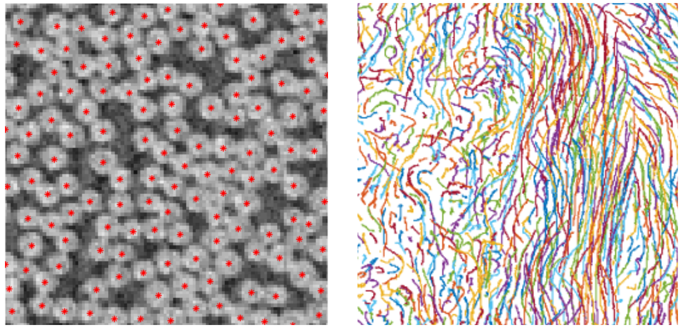
Contributions by topic

DEVELOPMENT

Fibre Geometry Extraction
via Individual Fibre Segmentation



1. Fibre cross-sections   2. Fibre trajectories

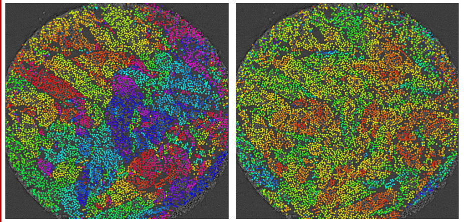


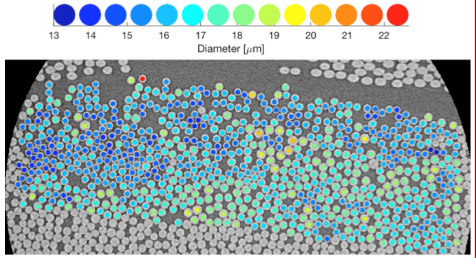
APPLICATIONS

1. Characterisation of Real Structures

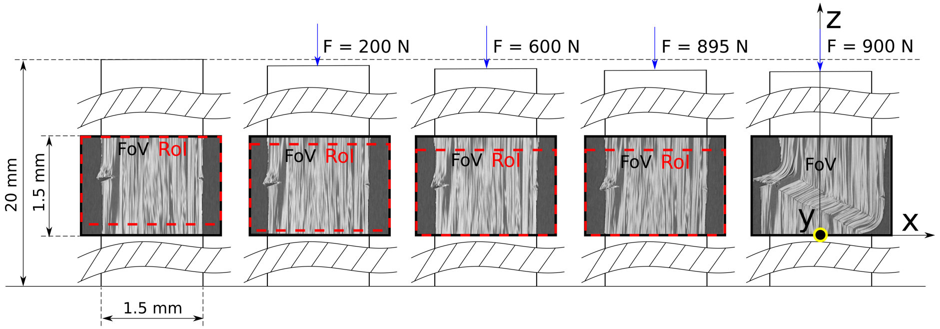
a) Fibre misalignment   b) Fibre diameters

Direction   Magnitude



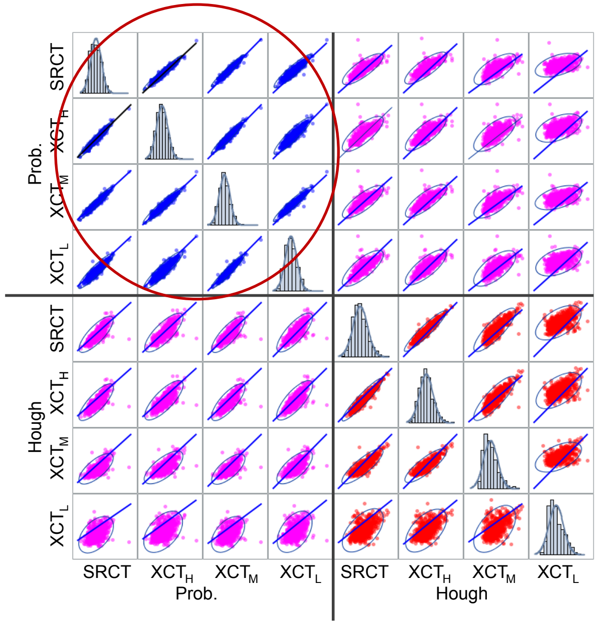


2. Evolution of Structures under Changing Load



VALIDATION

X-ray CT Imaging
+
Individual Fibre Segmentation



Validation: X-ray CT and dictionary segmentation

Method for measuring fibre geometry:

Mode
Imaging modality and resolution

→

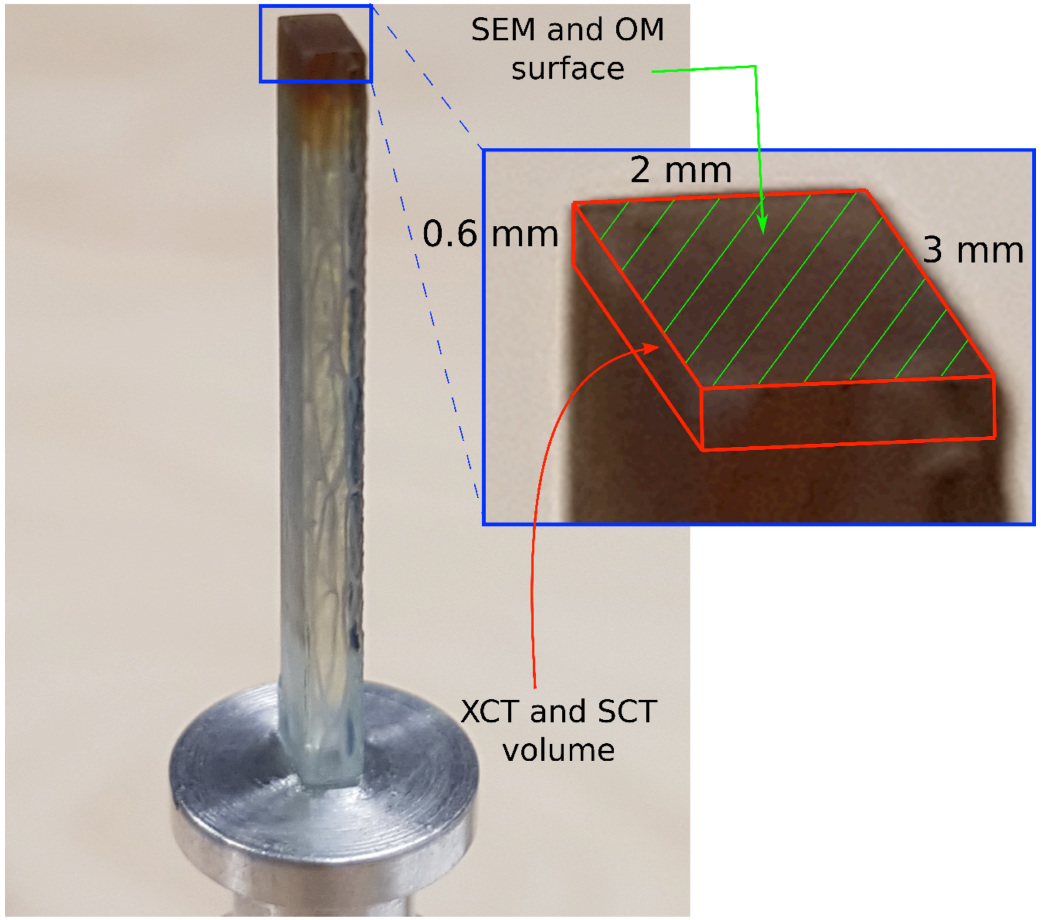
Algorithm

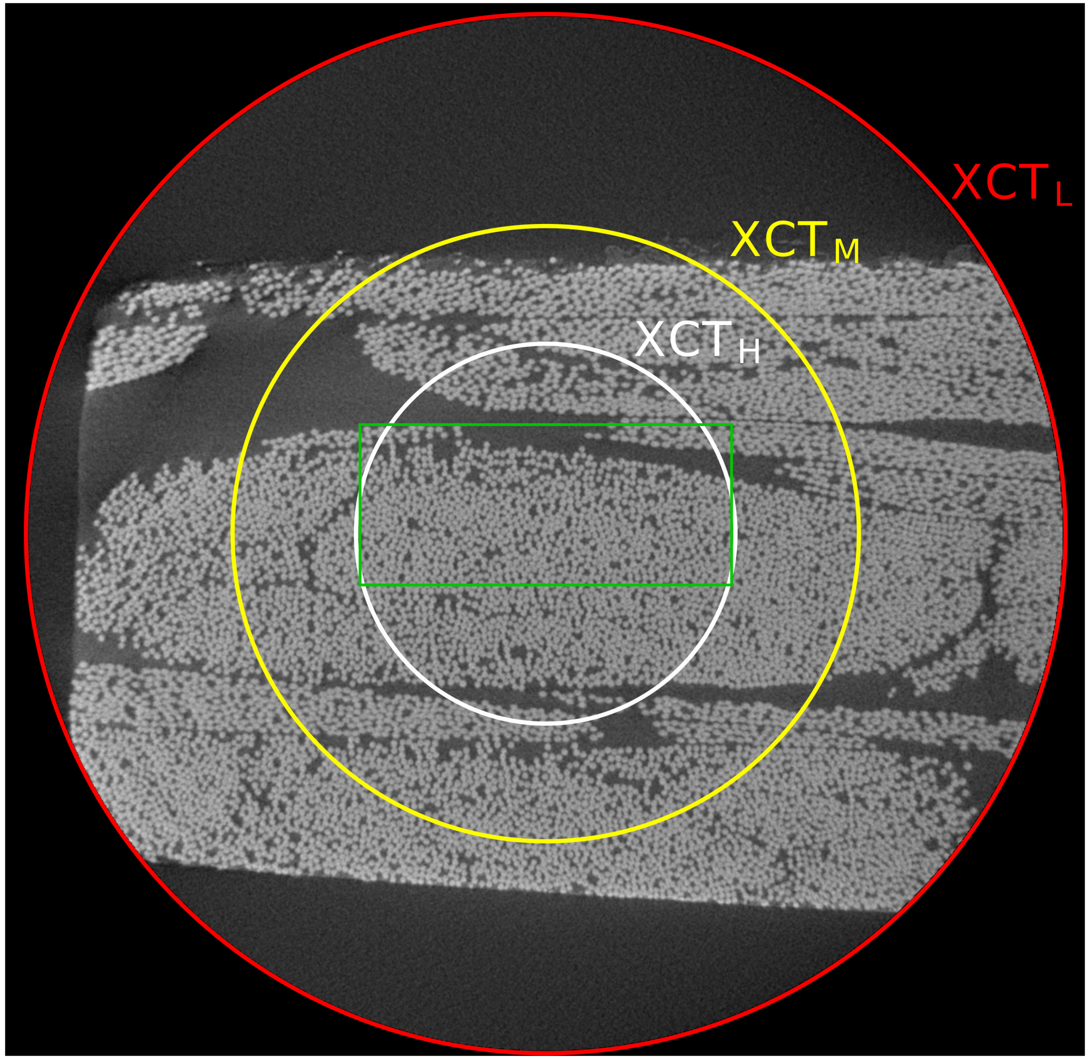
- Optical Microscopy (**OM**)
- Scanning Electron Microscopy (**SEM**)
- Synchrotron X-ray CT (**SRCT**)
- Laboratory X-ray CT
  - High resolution ($\mathbf{XCT_H}$)
  - Mid resolution ($\mathbf{XCT_M}$)
  - Low resolution ($\mathbf{XCT_L}$)

- Dictionary-based segmentation (**Prob**)
- Circular Hough transform (**Hough**)

Validation: X-ray CT and dictionary segmentation

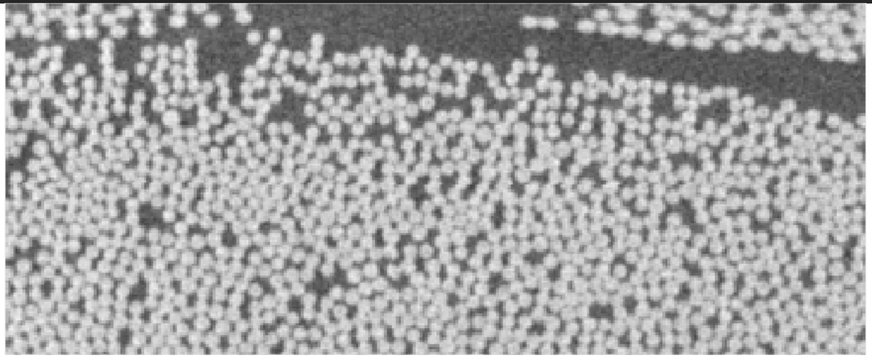
1st step: **Mode**



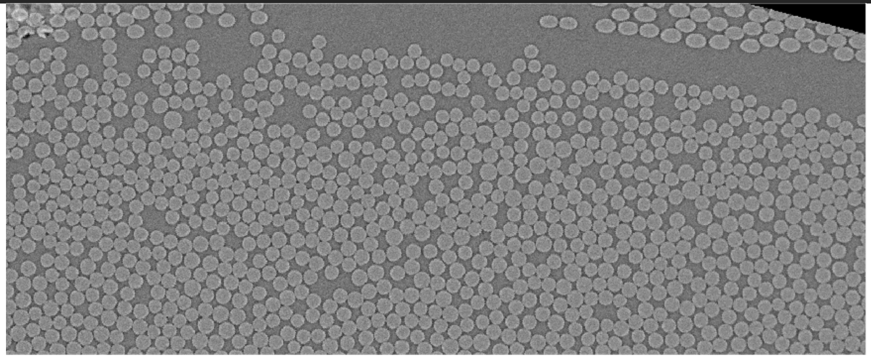


Validation: X-ray CT and dictionary segmentation

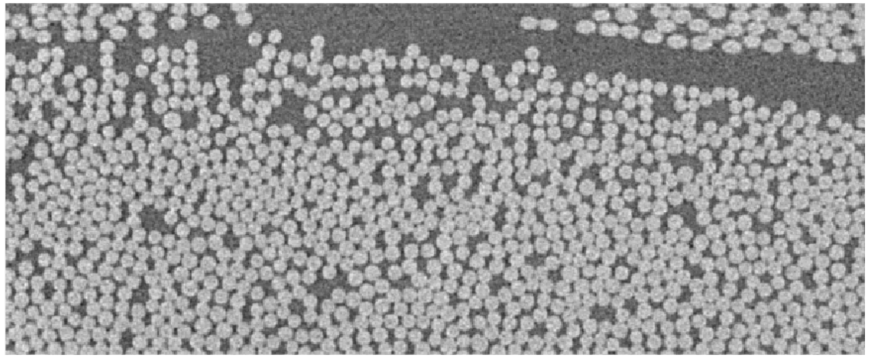
XCT_L
Pixel size = 2.81 µm



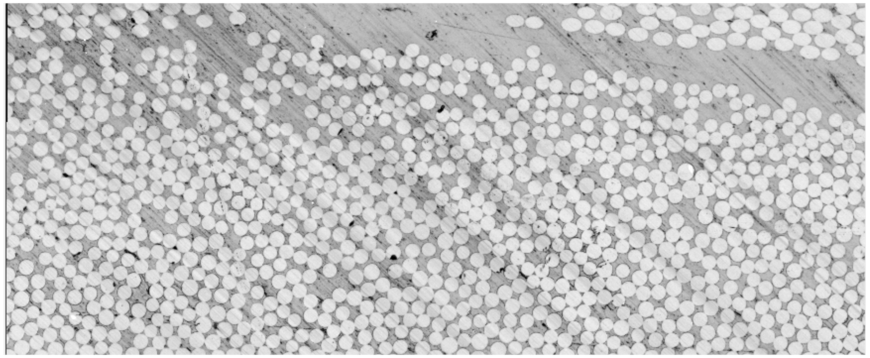
SRCT
Pixel size = 0.65 µm



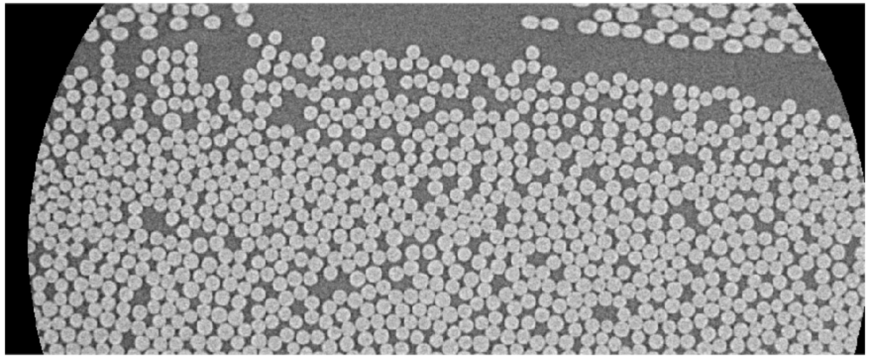
XCT_M
Pixel size = 1.69 µm



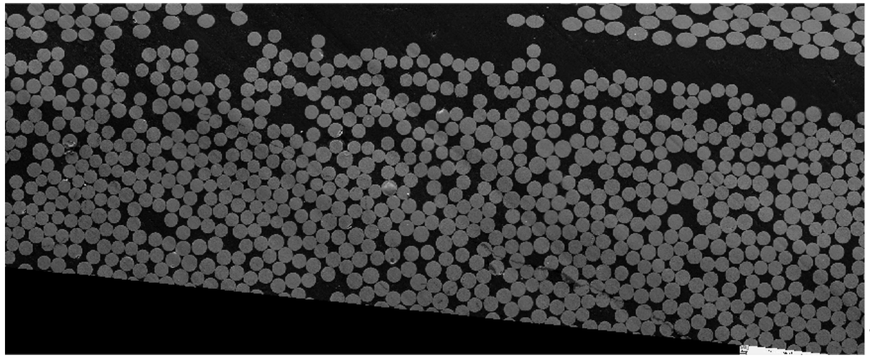
OM
Pixel size = 0.29 µm



XCT_H
Pixel size = 1.04 µm



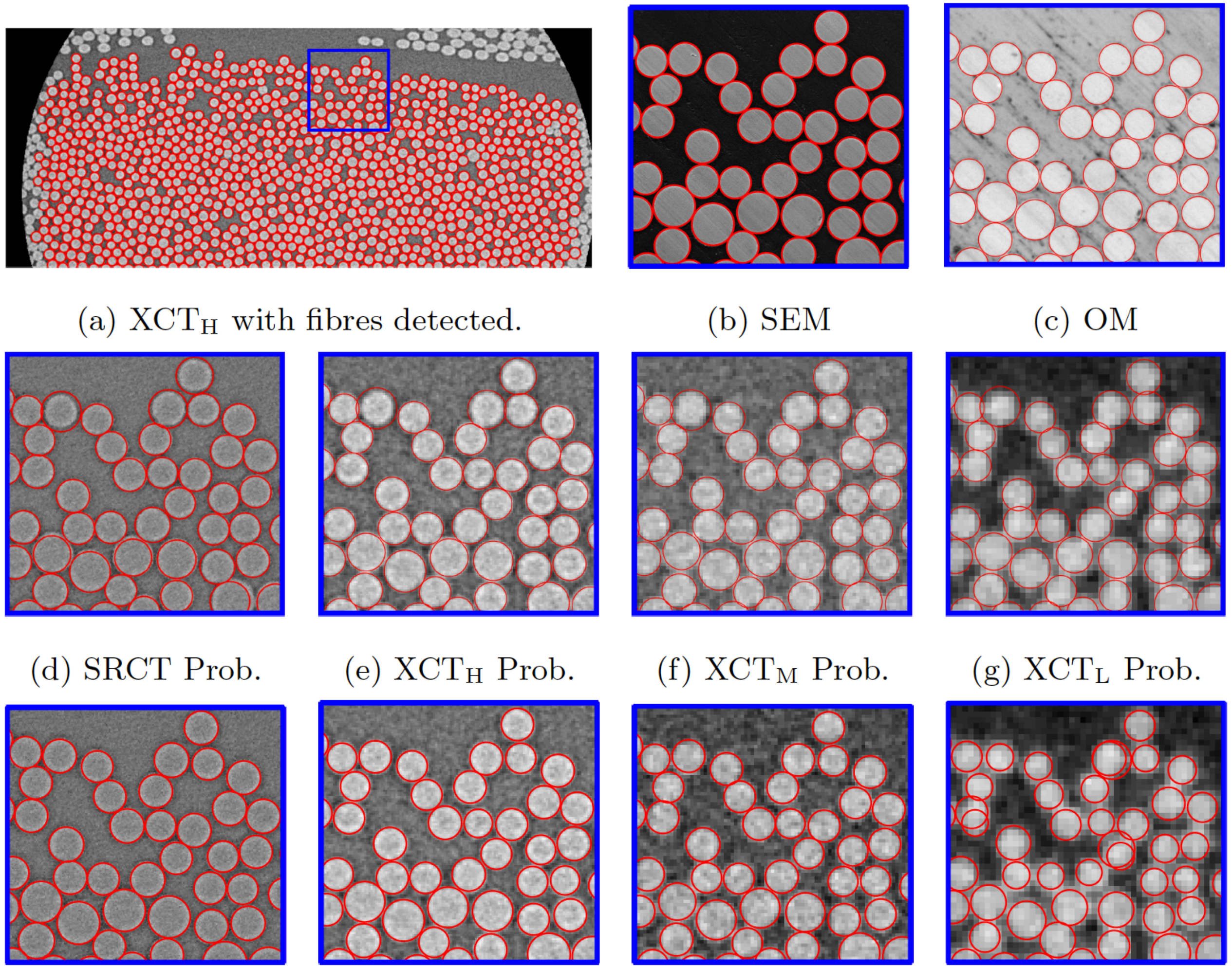
SEM
Pixel size = 0.19 µm



Validation: X-ray CT and dictionary segmentation

The 10 Methods under comparison

Abbrev.	Alg., $i = 1, 2$
SRCT	Prob.
XCT_H	Prob.
XCT_M	Prob.
XCT_L	Prob.
SRCT	Hough
XCT_H	Hough
XCT_M	Hough
XCT_L	Hough
OM	Hough
SEM	Hough



(a) XCT_H with fibres detected. (b) SEM (c) OM

(d) SRCT Prob. (e) XCT_H Prob. (f) XCT_M Prob. (g) XCT_L Prob.

(h) SRCT Hough (i) XCT_H Hough (j) XCT_M Hough (k) XCT_L Hough

Validation: X-ray CT and dictionary segmentation

Univariate approach

- Model I:
Three-way ANOVA to test the **effects** of **mode** and **algorithm**
- Model II:
Two-way ANOVA to test the **effect** of the **methods**
- Models A, B and C:
Reveal whether the spatial variation is **method** dependant

Multivariate approach

- Scatter plots:
Correlations between individual estimates across **methods**
- Principal Component Analysis (PCA):
Reveal the sources of **maximum variation**

Validation: X-ray CT and dictionary segmentation

Univariate approach

- Model I: Three-way ANOVA to test the effects of **mode** and **algorithm**

  Both mode and algorithm **have an effect** on the measured diameters

- Model II: Two-way ANOVA to test the effect of the **methods**

  The **method has an effect** on the measured diameters

- Models A, B, C: Reveal whether the spatial variation is **method** dependant

  All **methods** capture the same variation in the data, it is a variation in the physical diameters!

Validation: X-ray CT and dictionary segmentation

Univariate approach

- Model II: Two-way ANOVA to test the effect of the **methods**

$D_{\nu k} = \mu + \theta_\nu + \gamma_k + \epsilon_{\nu k}$, $\nu =\{1,\ldots 10\}$ and $k=1,\cdots,757$

Tukey grouping:

- In **blue** closest to production specification
- In **red** furthest away

Production specification for the diameter $d = 17\mu$m

Means with the same letter not significantly different (MODEL II)				
Method		Tukey Grouping		Means
Mode	Algorithm			
SRCT	Prob		A	17.1478
XCT_H	Prob	B	A	17.0573
SEM	Hough	B	A	17.0496
XCT_M	Prob	B	C	16.9608
SRCT	Hough		C	16.8633
XCT_L	Prob		D	16.5760
OM	Hough		D	16.5465
XCT_H	Hough		E	16.3196
XCT_M	Hough		E	16.2558
XCT_L	Hough		F	14.9572

Validation: X-ray CT and dictionary segmentation

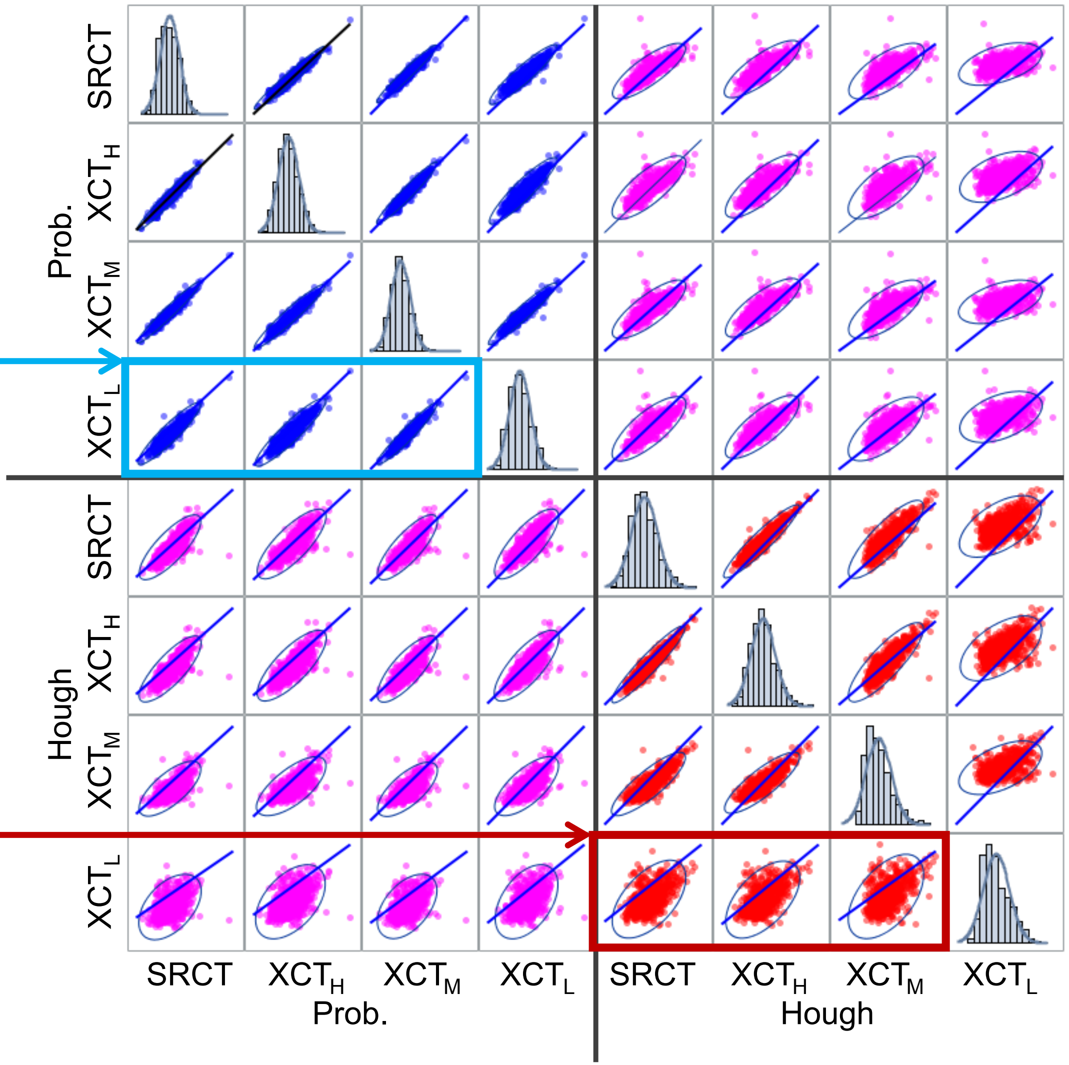
Multivariate approach

- Scatter plots:

Correlations between individual estimates across **methods**

Correlation ≃ 0.9

Correlation ≃ 0.5



Validation: X-ray CT and dictionary segmentation

Multivariate approach

- Principal Component Analysis

✓ **PC1:** Variation in the sample

✓ **PC2:** Variation due to the chosen algorithm

✓ **XCT_L** mode analysed with **Hough** algorithm **deviates**

High-resolution modes

Alg.	Hough				Prob.	
Mode	OM	SEM	SRCT	XCT_H	SRCT	XCT_H
PC1	0.4139	0.4178	0.4186	0.4130	0.3955	0.3898
PC2	-0.2977	-0.2827	-0.2825	-0.2461	0.5649	0.6099

CT modes

Alg.	Prob.				Hough			
Mode	SRCT	XCT_H	XCT_M	XCT_L	SRCT	XCT_H	XCT_M	XCT_L
PC1	0.3777	0.3742	0.3777	0.3686	0.3650	0.3647	0.3352	0.2452
PC2	-0.2589	-0.2642	-0.2825	-0.2999	0.1932	0.1910	0.2777	0.7365

Conclusions by topic: Development

Individual Fibre Segmentation in 3D

- Densely packed unidirectional (UD) fibres
- Robust to noise, contrast and spatial resolution.
- A range of fibre materials
- Fast scanning
  1. Short scans at lab set-ups
  2. Ultra-fast imaging while in-situ loading
- Precise segmentation of representative volumes

Interactive training with minimal user input

- User-friendly and efficient training
- Immediate feedback
- Input is minimal and adaptable to the data-set
- Flexible and thus applicable to other materials

Conclusions by topic: Applications

Characterisation of real structures

- Non-destructive investigation of real fibre arrangements in 3D
  (orientations, diameters,…)
- Understanding influence of real fibre arrangements over the mechanical properties
  (e.g. Finite Element Models)
- Revealing the effects of the manufacturing over the micro-structure and ultimately the real material properties

Evolution of structures under load

- Accurately quantify micro-structural changes fibre by fibre, using ultra-fast imaging and in-situ loading.
- Understanding damage mechanisms and their precursors
  (e.g. compression loading, fibre micro-buckling and kink-band formation)
- Accelerate the discovery of new stochastic- and physics-based damage models

Conclusions by topic: Validation

X-ray CT coupled with our segmentation algorithm:

- Quantitative proof of the precision in our approach for characterising UD fibre composites.
- Highly precise measurements under limited spatial resolutions
- Representative characterisation of fibre geometry at the micro-scale

Conclusions: Big picture achievements

- Statistical image analysis tools for charactering the 3D micro-structure of UD fibres representatively.
- Contributed to the CINEMA pipeline in the segmentation and the quantification steps.
- Demonstrated that measuring real fibre geometry opens up numerous possibilities.

X-ray imaging combined with image analysis is a powerful tool for characterising materials

MANCHESTER 1824
The University of Manchester
Phil Withers
Ying Wang

DTU
Lars P Mikkelsen
Kristine M Jespersen
Knut Conradsen
Anders B Dahl
Vedrana A Dahl

Thanks!

Monica Jane Emerson
monj@dtu.dk