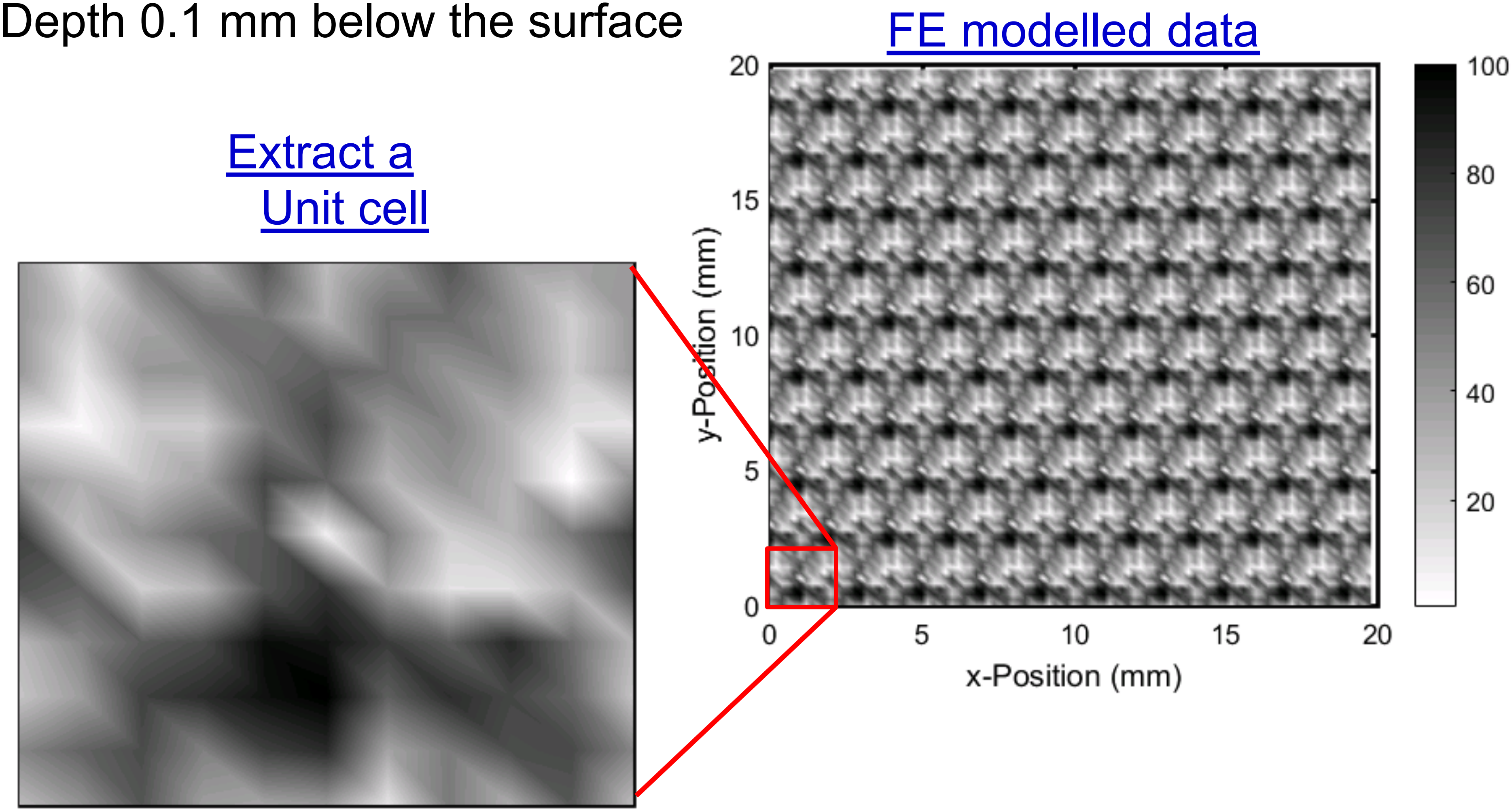
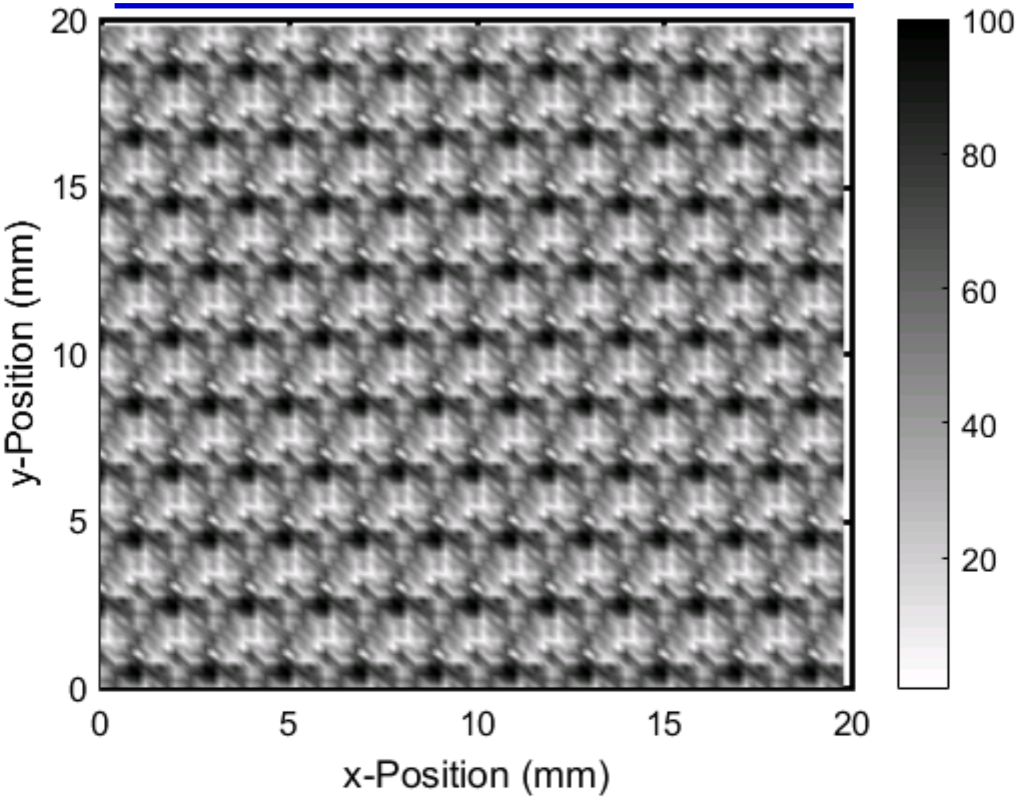
3D-woven composite - Defect detection

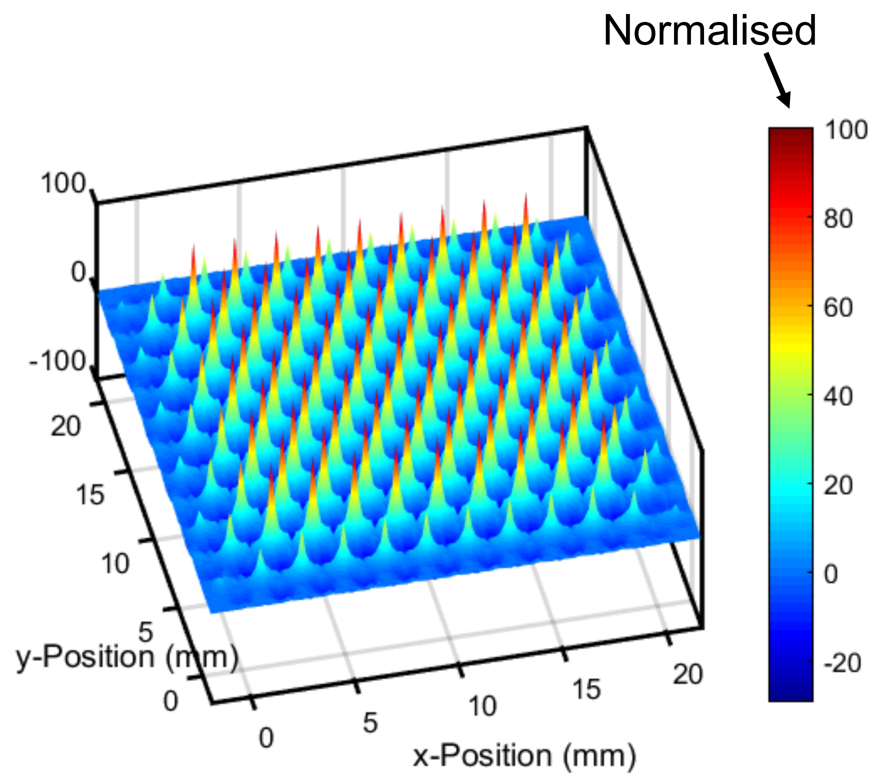
Depth 0.1 mm below the surface



3D-woven composite - Defect detection

Cross-correlate with unit cell

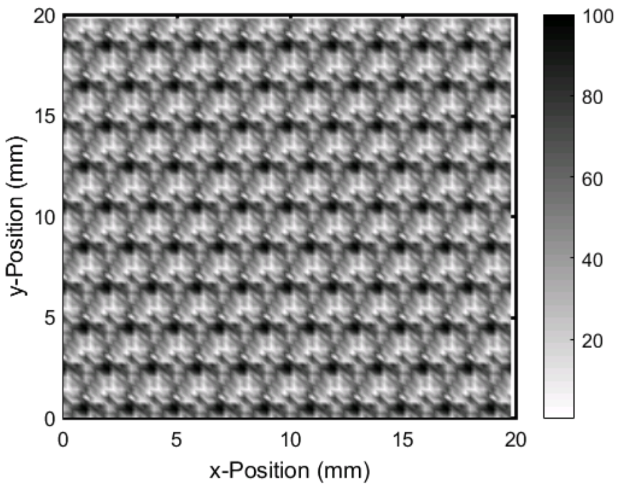




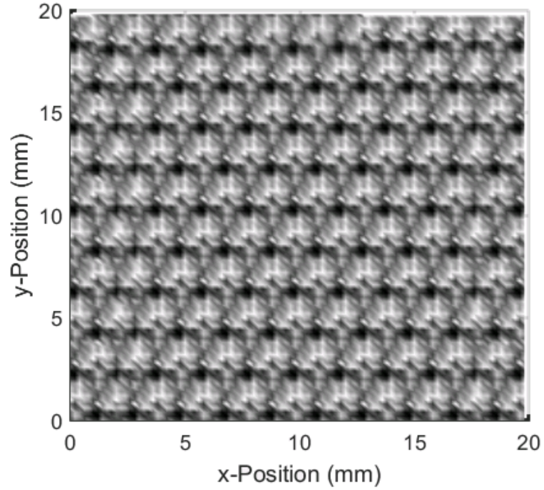
Maximum of the cross-correlation (red) corresponds to the centre location of the unit cells.

3D-woven composite - Defect detection

Create benchmark scan using a unit cell at each peak in the cross-correlation…

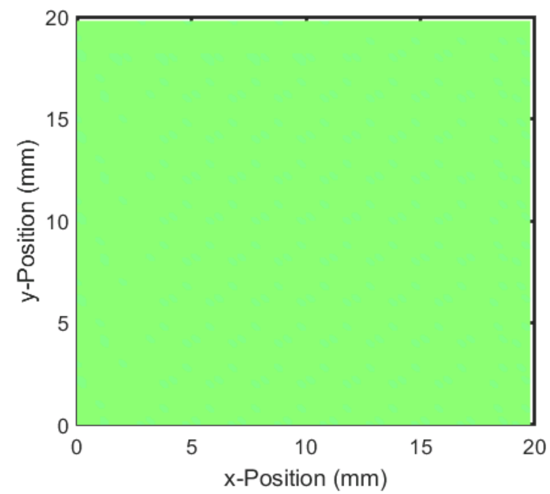


Original scan



Benchmark scan

Then subtract benchmark scan from measured scan…

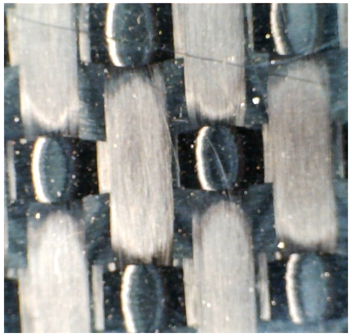


Subtraction result

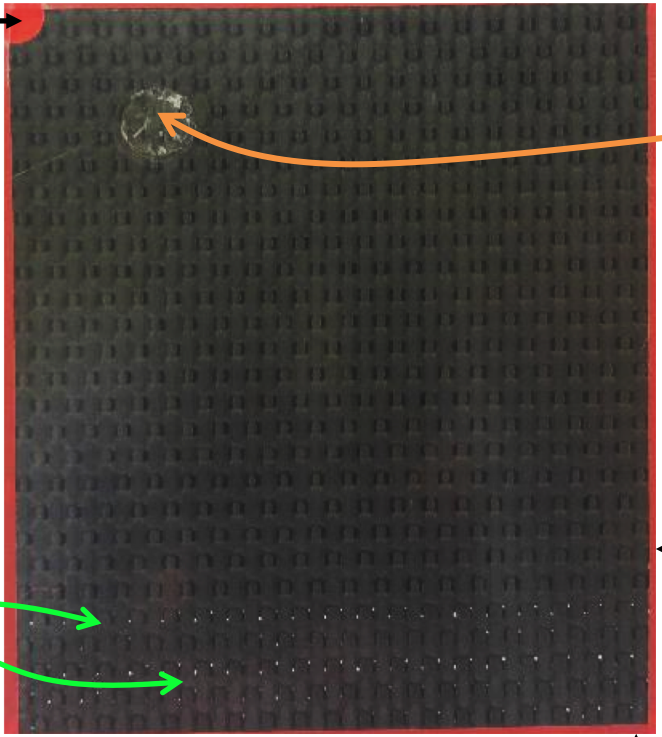
3D-woven composite - Defect detection

Real specimen: 1.7 mm thick (5-layers). FVF≈50%

Sticker placed to check orientation of sample



Orthogonal ⇨



Resin block from infusion

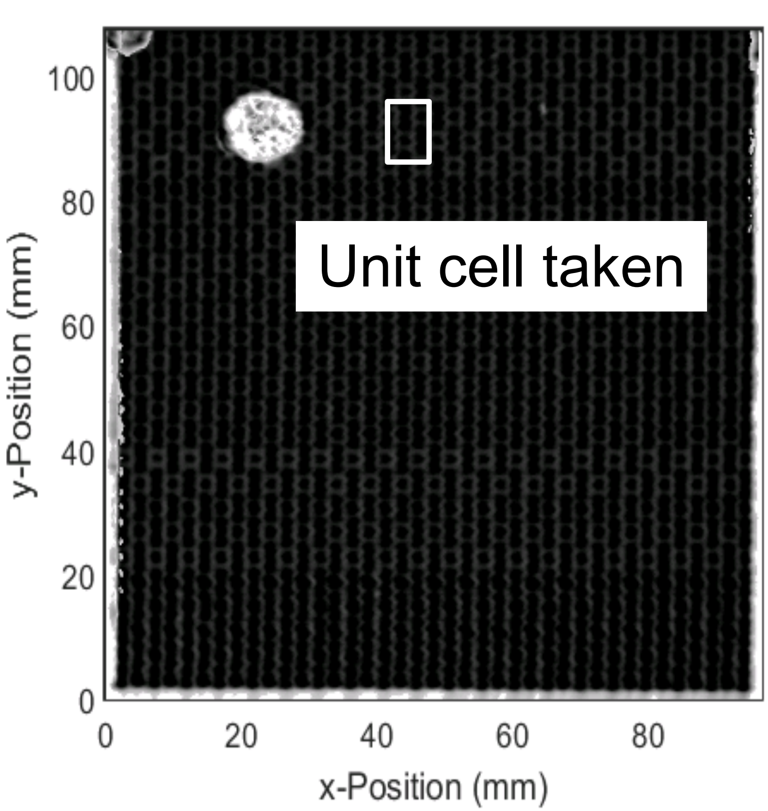
Resin columns allowing light through

Tape around the edges showing delimitation of the scanned regions

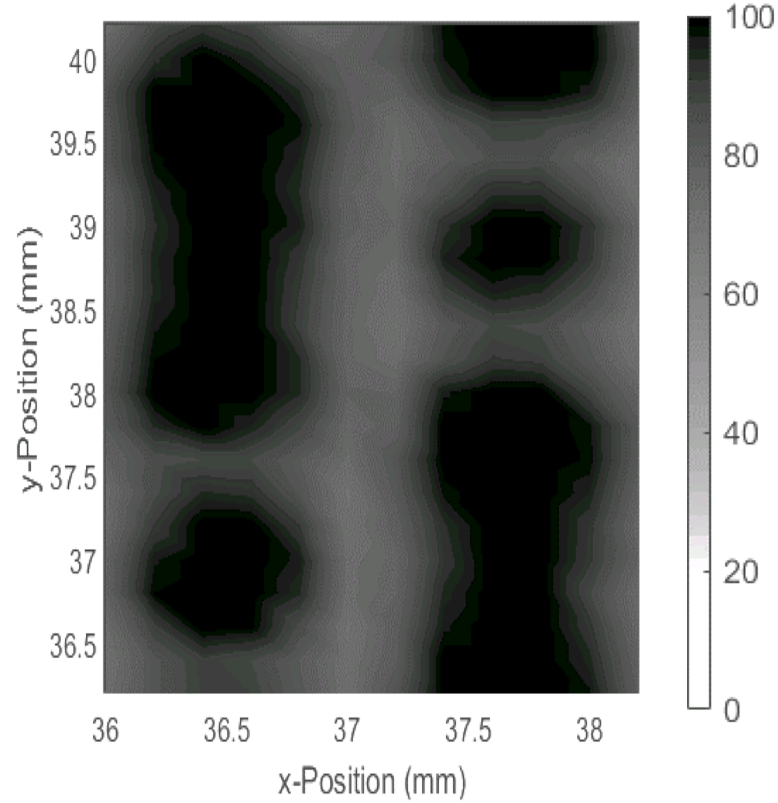
[Real specimen top view (and back-lit)]

3D-woven composite - Defect detection

Single unit cell extraction



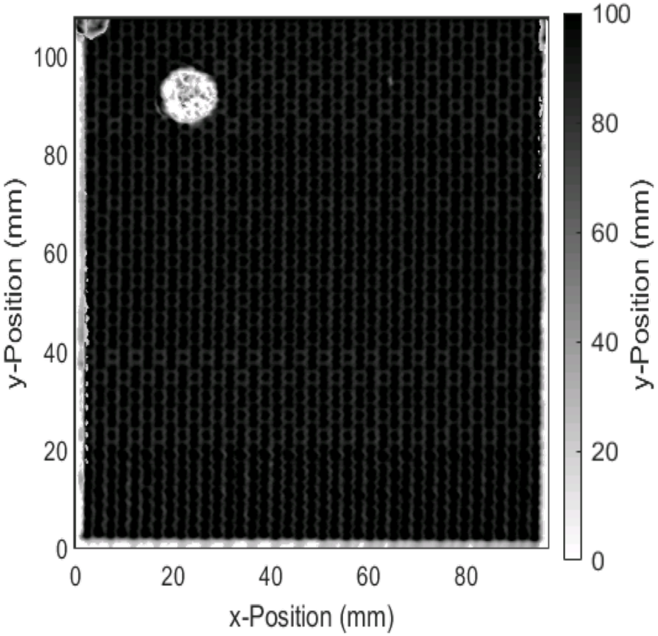
C-Scan 0.1mm below the surface
(showing the unit cell chosen)



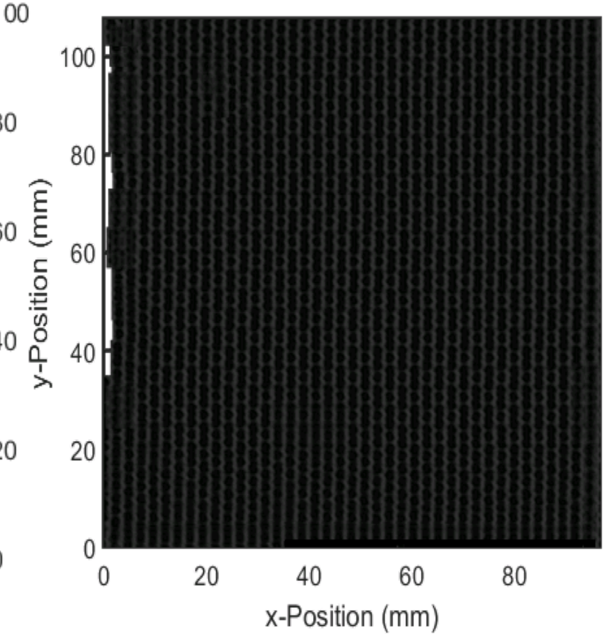
Unit cell dimension

3D-woven composite - Defect detection

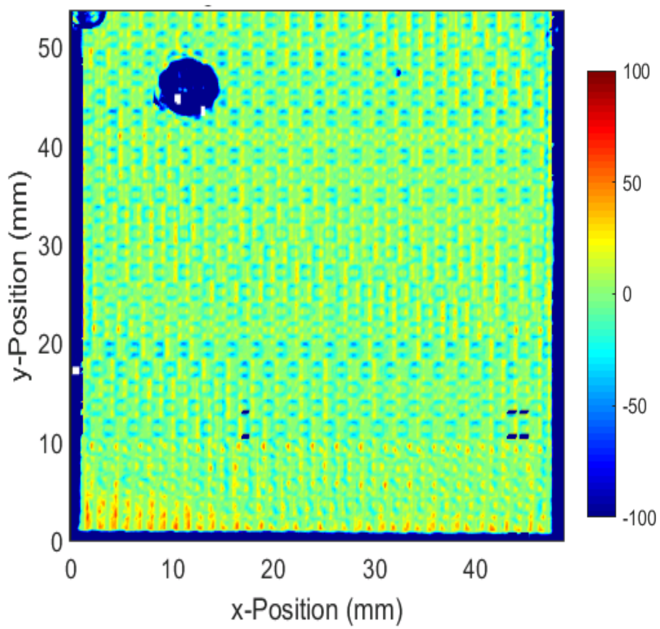
Benchmark scan vs Original scan



Original scan



Benchmark scan

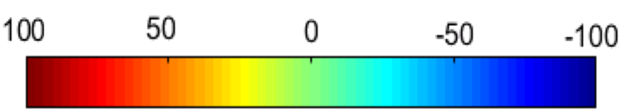


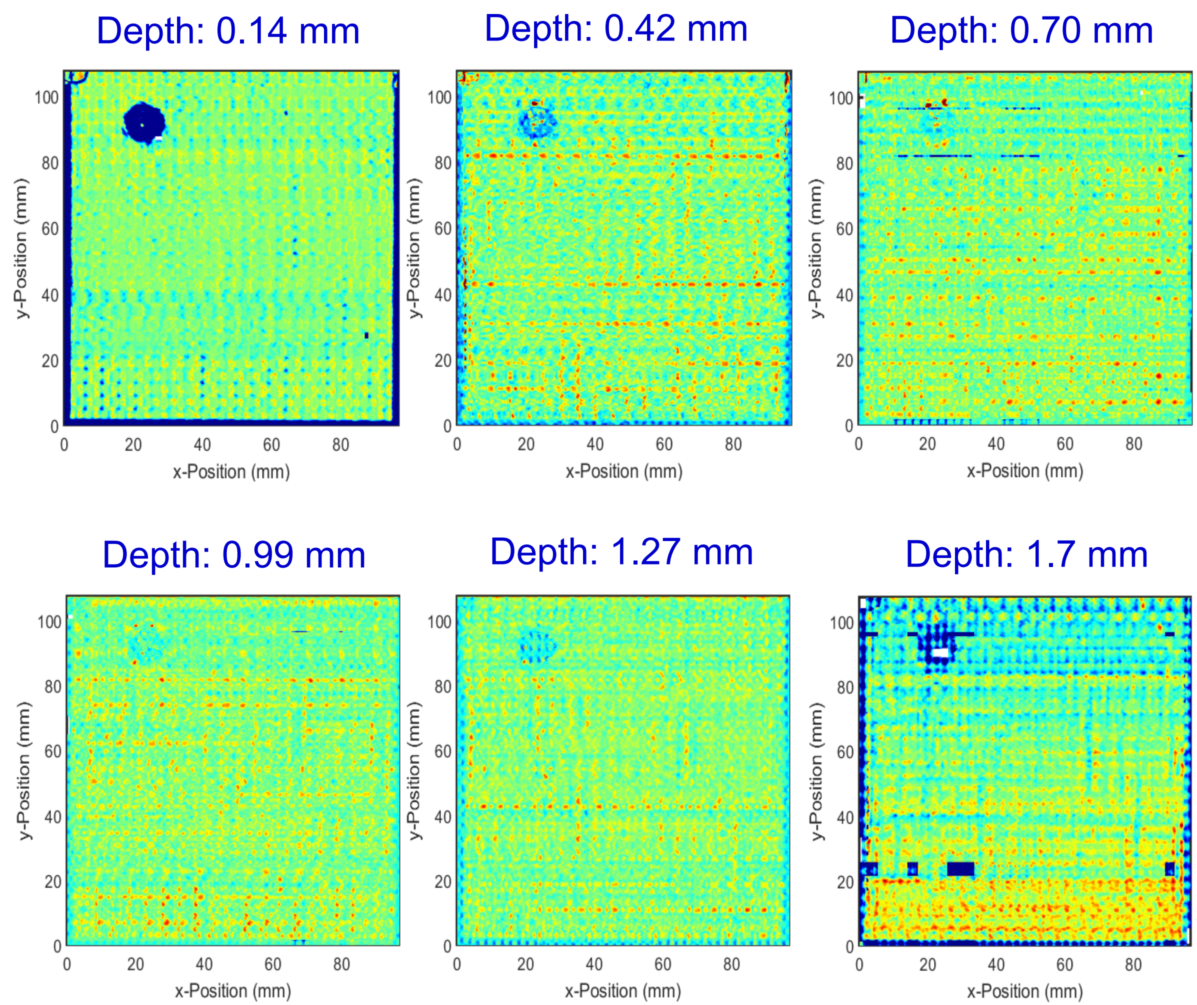
Subtraction result

Then subtract benchmark scan from measured scan…

3D-woven composite - Defect detection

- Extension to 3D
  - Same process performed for each in-plane layer in the 3D data.
  - Six different depths below surface…

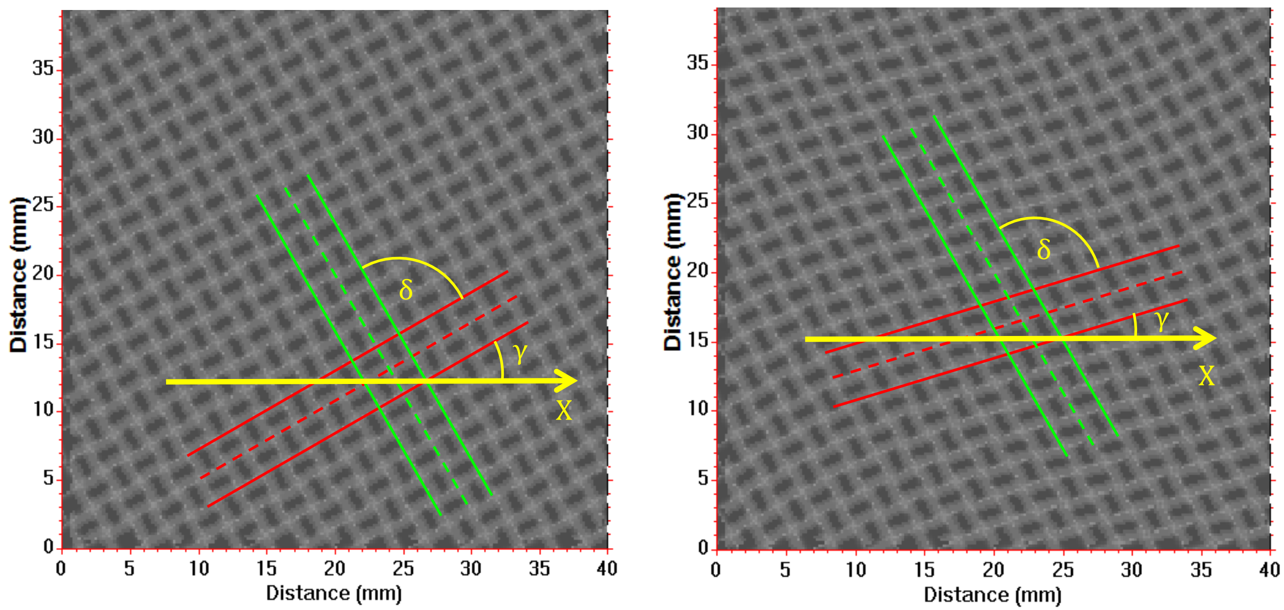




2D Woven Composites

Warp and Weft yarn measurement

- Warp and Weft angles and spacing – plain weave

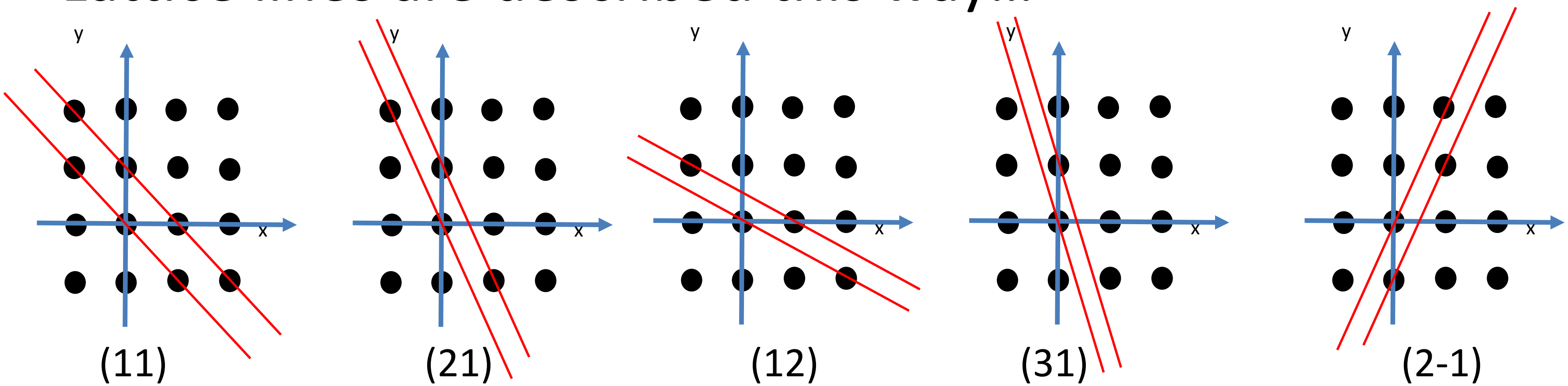


These lines have Miller indices (01) and (10) (indistinguishable)

But also truly identical ‘pattern’ lines at twice this spacing (0½)

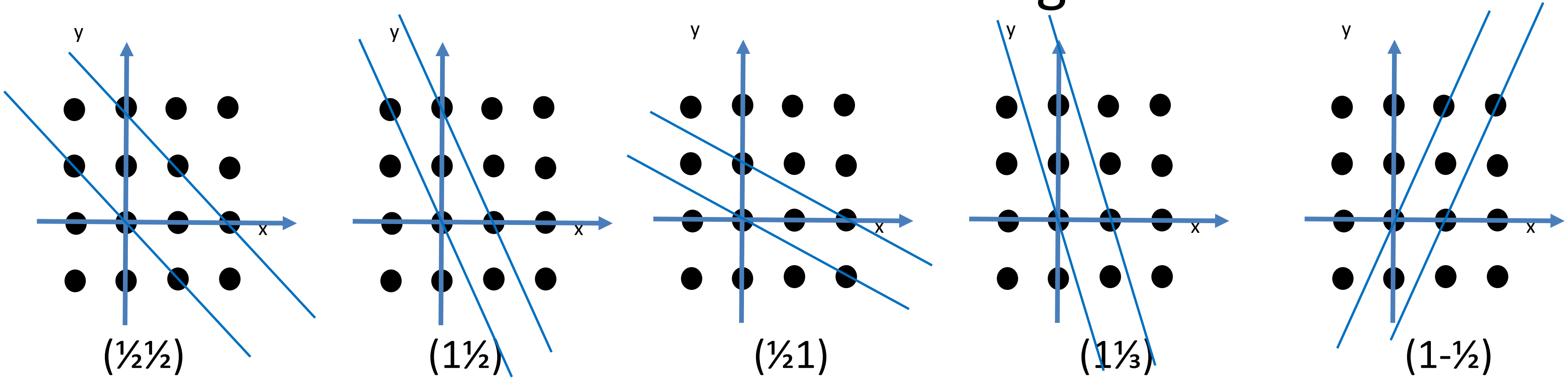
Miller indices

- Lattice lines are described this way…



(11) (21) (12) (31) (2-1)

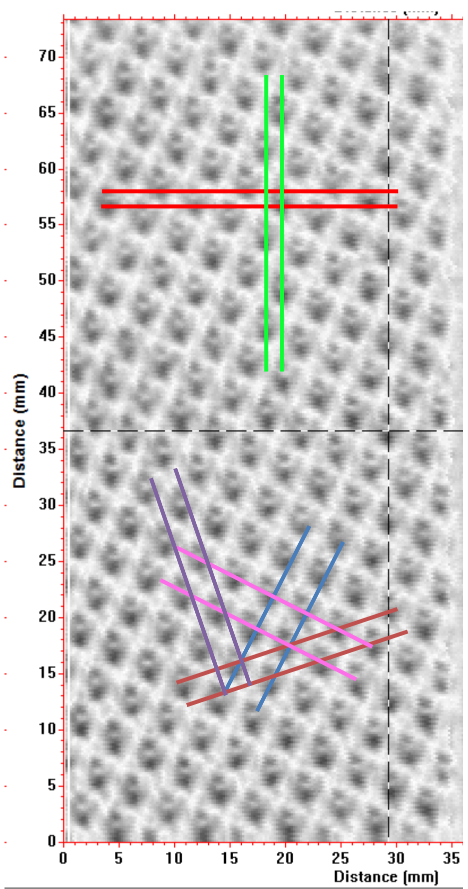
- …and weave-characteristic lines using fractional indices

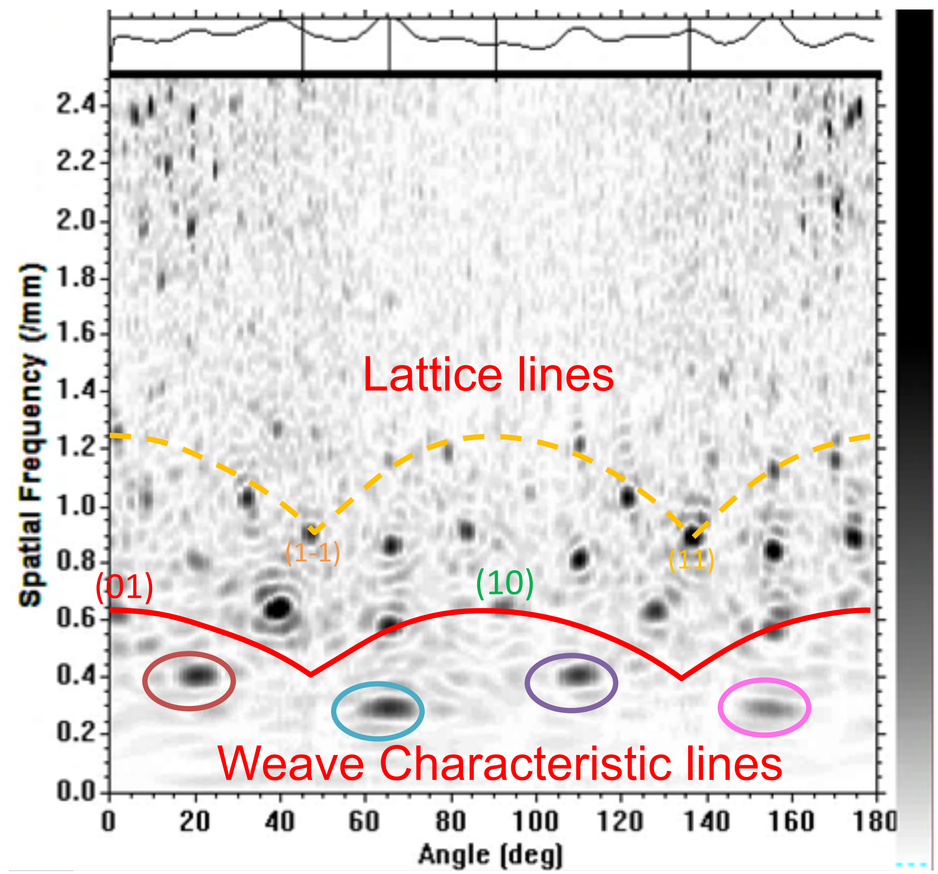


(½½) (1½) (½1) (1⅓) (1-½)

Image Transformation

- Radon Transform & FFT gives: spatial-frequency vs angle

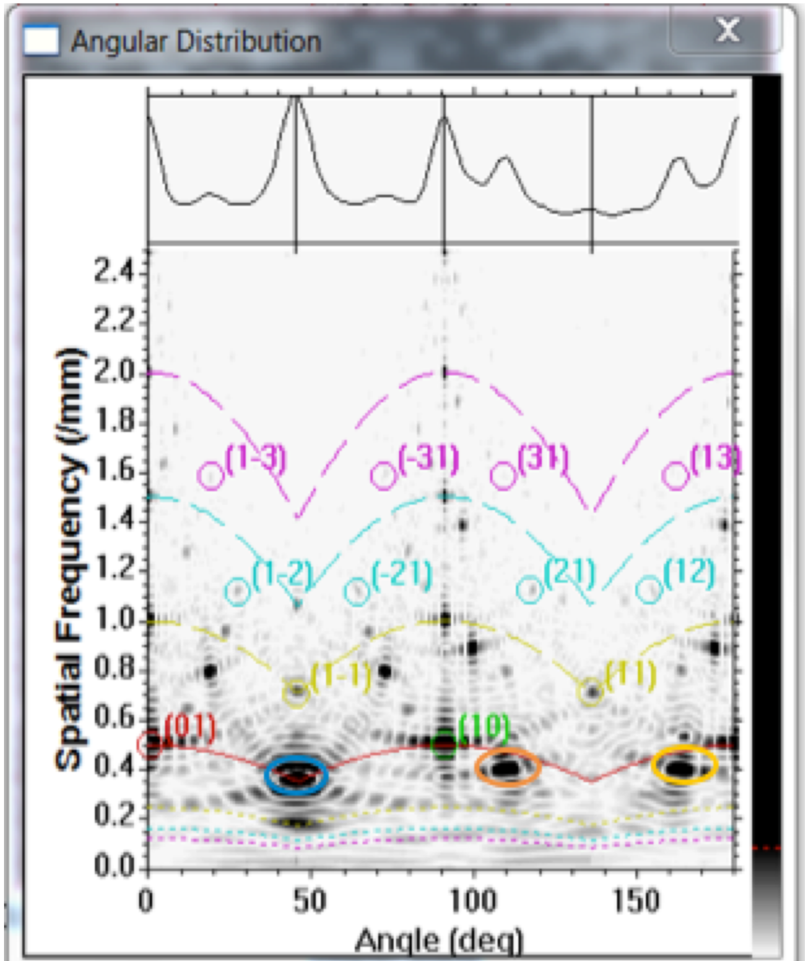


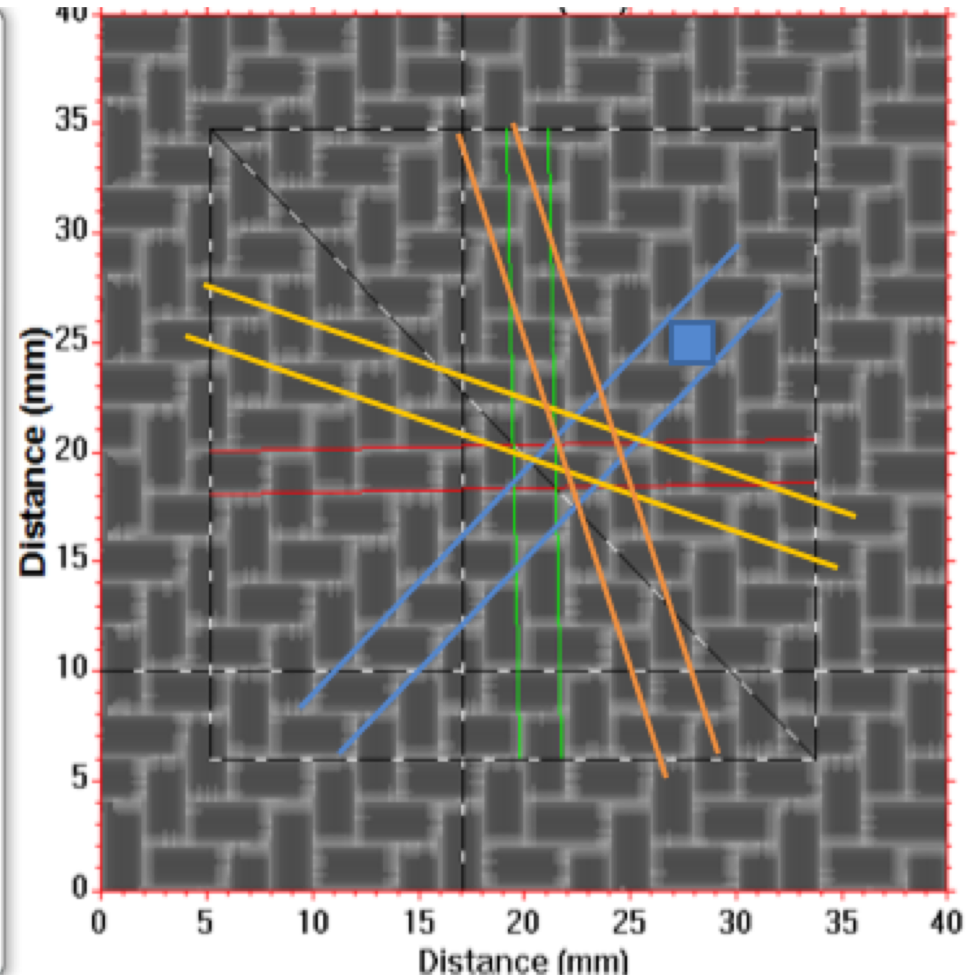


(⅕-⅗) (⅖-⅕) (⅗⅕) (⅕⅖)

N=5 for 5-harness satin weave

Weave Classification

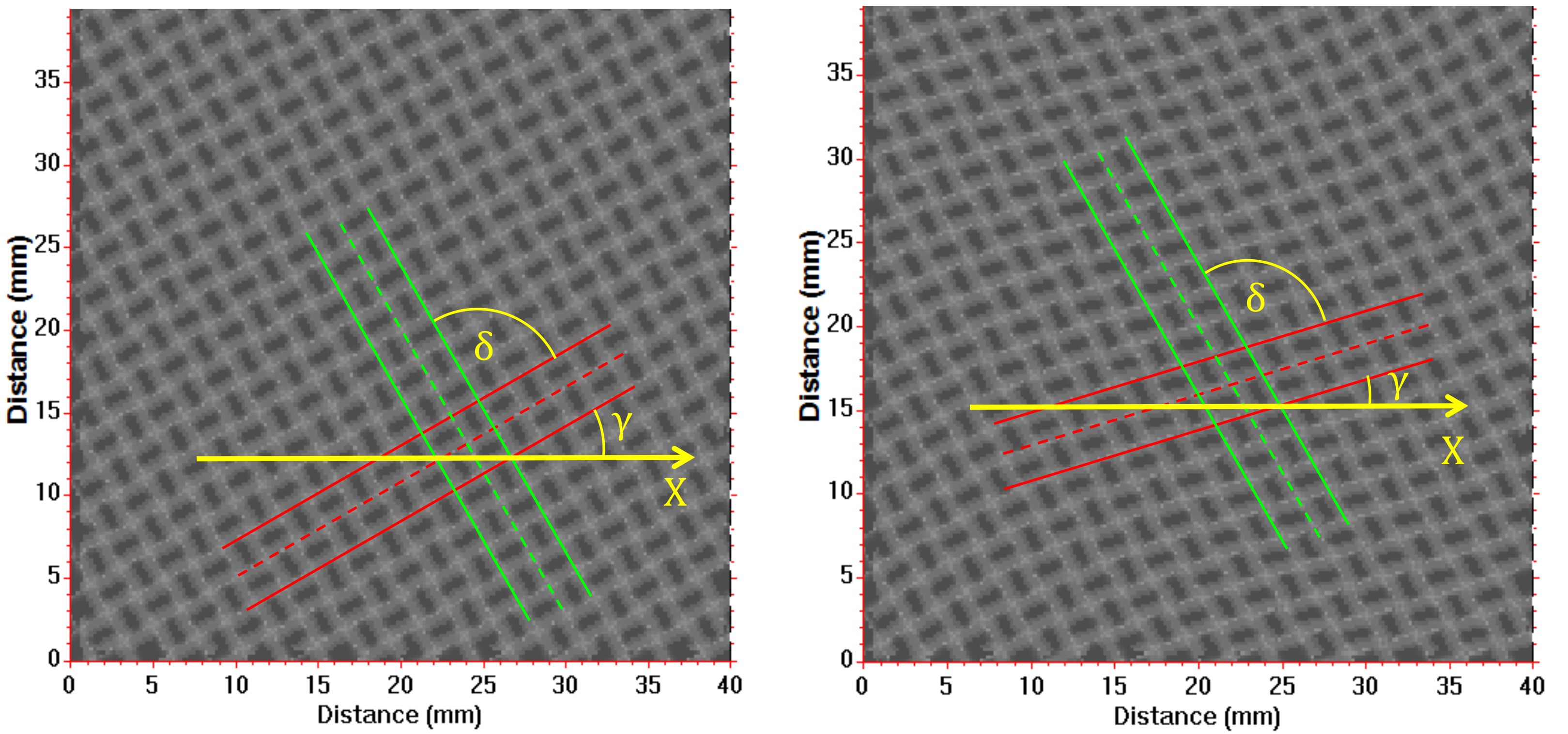




(½ -½) (1⅓) (⅓1)

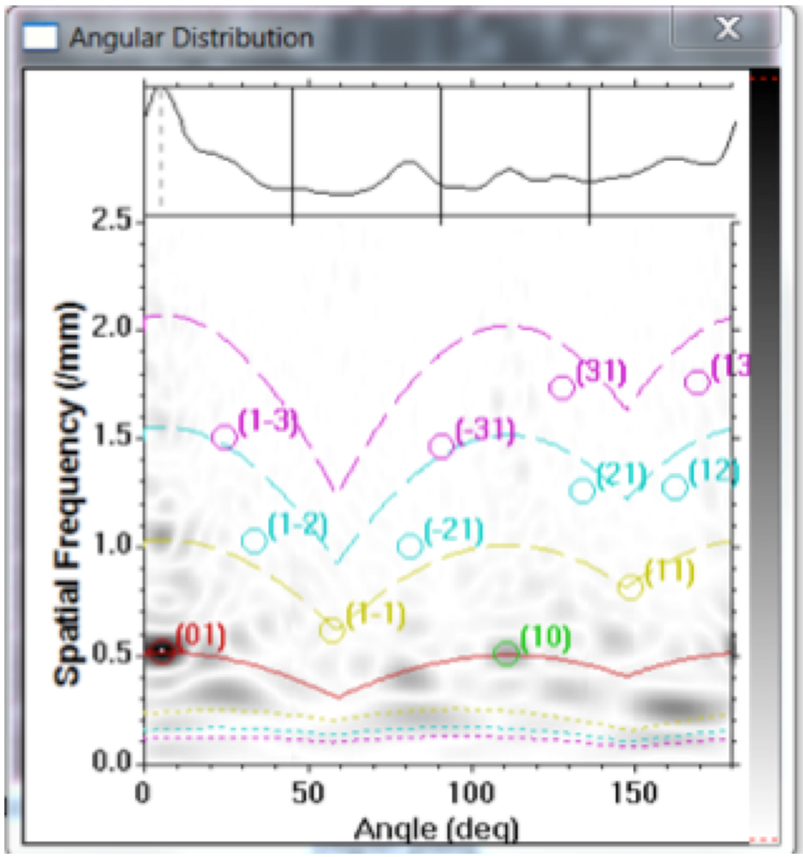
Mapping distortion

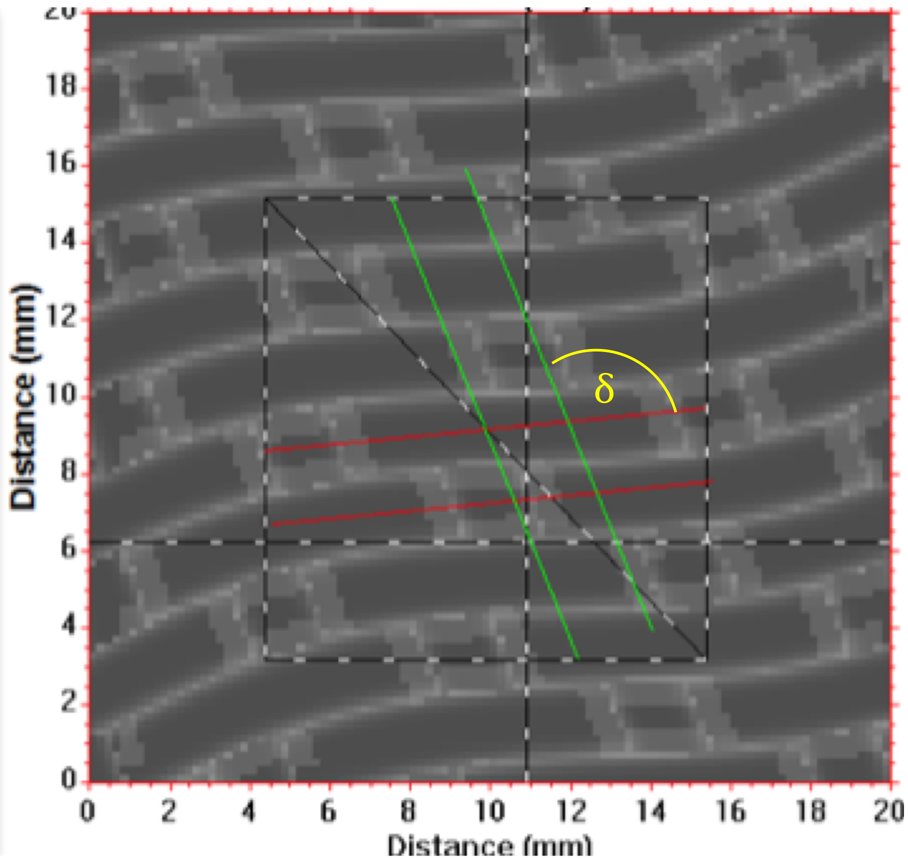
- Map δ - the angle between warp and weft



Mapping distortion – 5-harness satin

- In this case, δ=110° between warp and weft



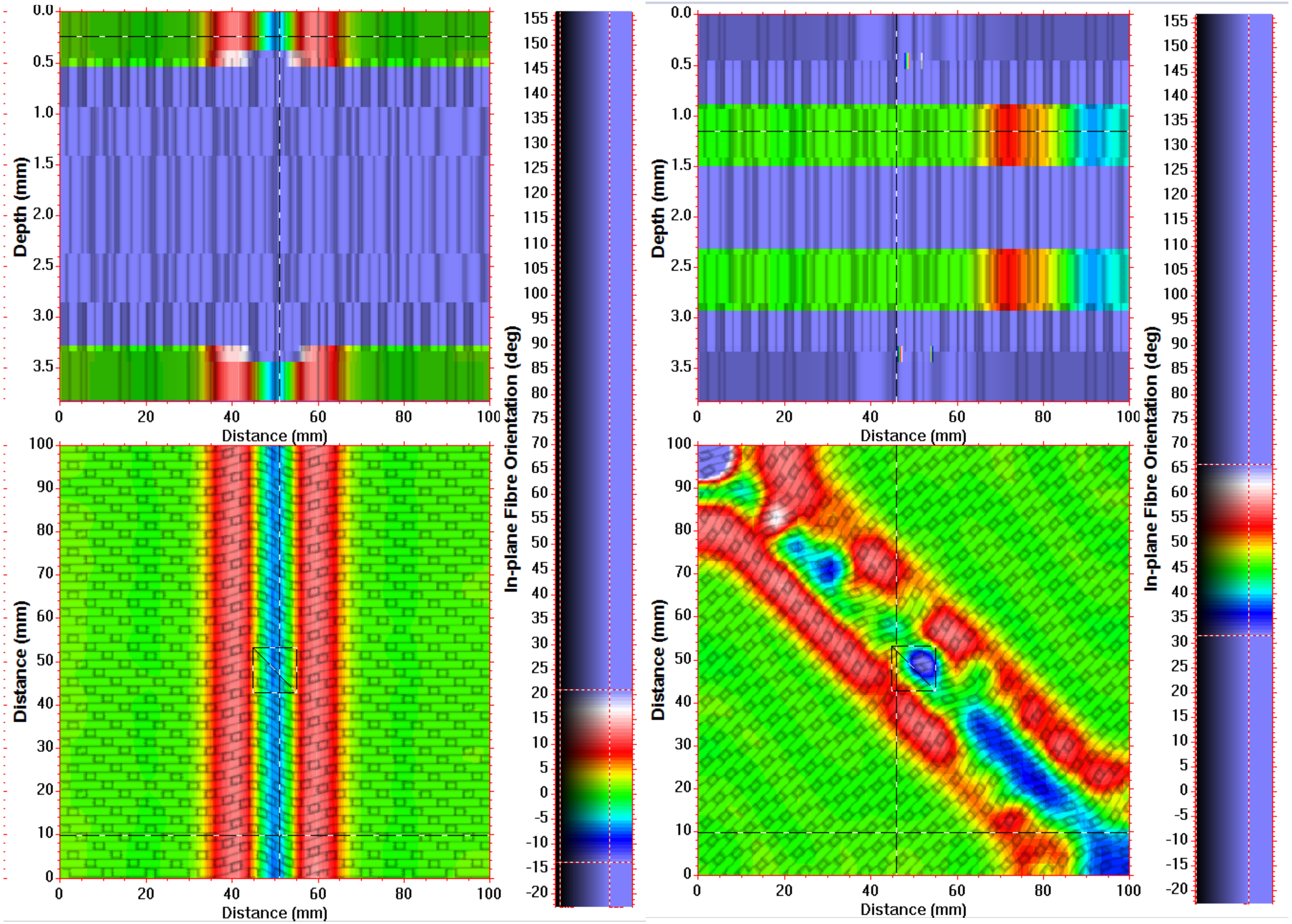


Mapping distortion – 5-harness satin

Simulated 5-harness satin weave with sine-wave in-plane waviness.

0/90 and +45/-45 plies are shown.

Colour is shear angle measurement

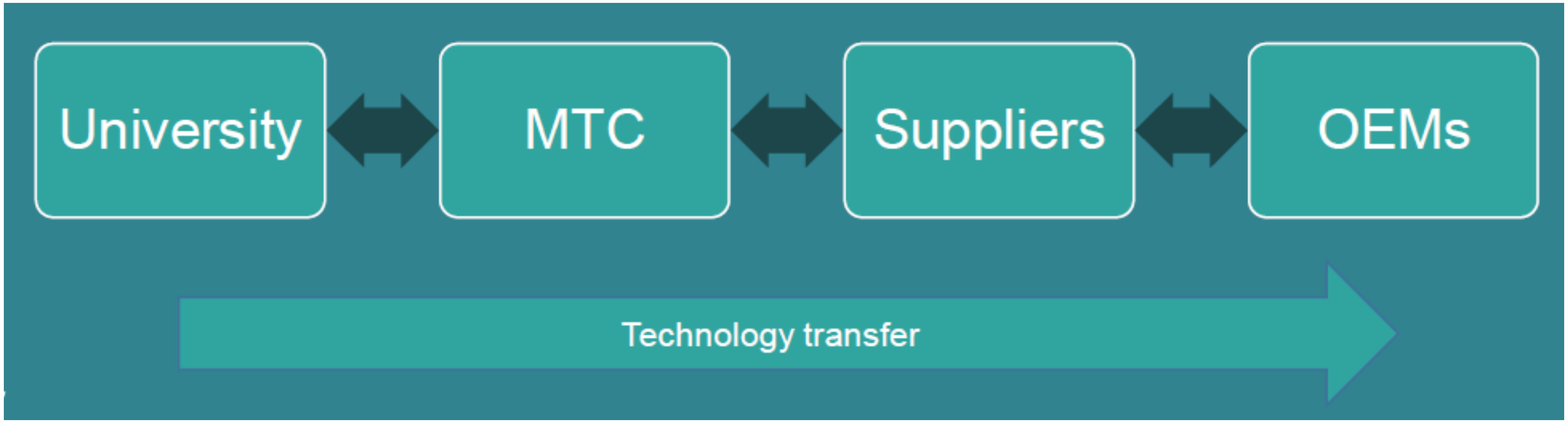


Transitioning academic algorithms to multiple supply-chain partners

- Transition software-engineering documents, not actual software.
- Allows customisation within pre-existing commercial software packages.

Multiple suppliers

- Manufacturing Technology Centre (MTC), UK
  - New programme to ease transition of academic public-domain algorithms into industry
- Algorithm Deployment Support Service (ADSS)



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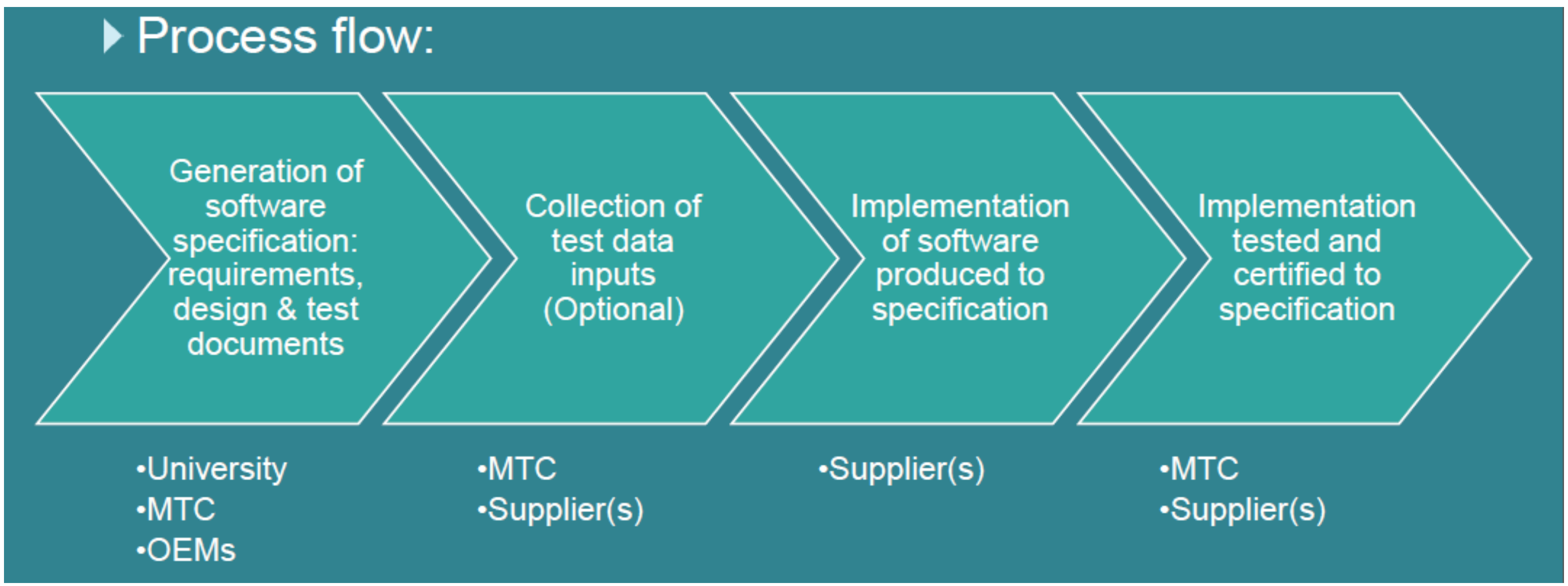

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Multiple suppliers

- Some industries insist on multiple suppliers
  - A new design strategy based on NDT requires confidence in long-term support
  - Sole-supplier is often unable to provide that.
- Publish science, algorithms, validation
- Enable implementation with multiple suppliers
  - University prepares software engineering documents
  - Supports implementation
  - BUT end-users require confidence in implementation

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Pilot scheme - NDT Algorithms

- Ultrasonic 3D imaging of composites
  - EPSRC Fellowship in Manufacturing 2013-2018
  - End-user-funded collaborative project (9 partners)…

Academic Research	End users	NDT Supply Chain
University of Bristol	Rolls Royce	Ultrasonic Sciences Ltd
	BAE Systems	DolphiTech
Software engineering & testing	Dstl (MoD)	Wavelength NDT / UTEX
Manufacturing Technology Centre	GKN/Fokker Aerospace	+ 1 other
	Wind turbine company	

- Deployment of novel algorithms in industry (MTC)
  - Algorithm Deployment Support Service
    - Software-engineering document generation
    - Validation tests

Ultrasonic 3D imaging of composites

- Ultimate aim is to underpin lighter designs:
  - Full 3D inversion of material properties and defects
  - NDT-based performance prediction of as-manufactured, or damaged components

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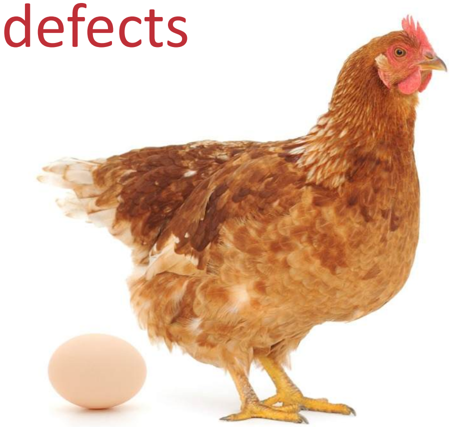

- ‘Chicken and Egg’ problem
  - NDT implementation requires ‘pull’ from OEMs
  - Aircraft design ‘pull’ requires *established* NDT technology.
- Preliminary phase: solve a current problem
  - Better-informed concessions – enhanced ‘imaging’

Advantages of MTC approach

- Offers traceability of requirements to implementation
- Offers 3D perspective to documentation
- HTML enables documents to be easily transferred and hosted on site
- Offers an intuitive way that a user can control the level of information they want to see

Progress Chart and Planner

	Requirements Document	Design Document	Test Document	User Manual
Development and testing of Software Engineering Documents				
Stage 1	Nov 2018	Jan 2019	Mar 2019	Apr 2019
Stage 2	Mar 2019	Apr 2019	Apr 2019	May 2019
Stage 3	Apr 2019	May 2019	May 2019	Jun 2019
1st Supplier implementation				
Stage 1	Apr 2019	May 2019	Jun 2019	Aug 2019
Stage 2	May 2019	Jun 2019	Aug 2019	Sep 2019
Stage 3	Jul 2019	Aug 2019	Sep 2019	Oct 2019
2nd Supplier implementation				
Stage 1	Aug 2019	Sep 2019	Oct 2019	Nov 2019
Stage 2	Sep 2019	Oct 2019	Nov 2019	Dec 2019
Stage 3	Oct 2019	Nov 2019	Dec 2019	Jan 2020

Conclusions

- Analytic Signal formulation separates phase (ply spacing) effects from amplitude (resin layer thickness).
- Ply tracking uses phase to track resin layers.
- Out-of-plane wrinkles can be measured using structure tensor applied to phase data.
- In-plane waviness measured using Radon transform on amplitude data.
- 3D weaves characterised and defects detected using cross-correlation of amplitude data vs benchmark.
- 2D weaves classified using image transformation of amplitude data, Miller indices, and distortions mapped.

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Publications (presentation code: 44999)

Analytic signals and ply tracking:

- R A Smith, et al, "Ultrasonic Analytic-Signal Responses from Polymer-Matrix Composite Laminates." IEEE UFFC, Vol 65(2), pp 231-243. doi: 10.1109/TUFFC.2017.2774776, 2018
- R A Smith et al, "Ultrasonic Tracking of Ply Drops in Composite Laminates." Proc. QNDE, AIP Conf. Proceedings 1706, 050006 (2016); doi: 10.1063/1.4940505, 2016.

Out-of-plane ply orientation and wrinkle measurement:

- L J Nelson, "Ply-orientation measurements in composites using structure-tensor analysis of volumetric ultrasonic data." Composites A, Vol 104, pp 108-119, doi: 10.1016/j.compositesa.2017.10.027, 2018.
- B Larrañaga-valsero, et al. "Wrinkle measurement in glass-carbon hybrid laminates comparing ultrasonic techniques: A case Study." Composites A, Vol. 114, pp. 225-240, doi: 10.1016/j.compositesa.2018.08.014, 2018.

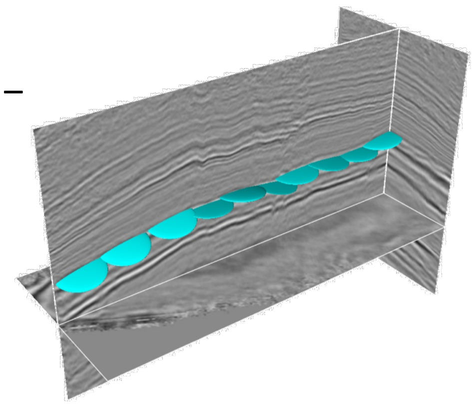
In-plane fibre direction and stacking sequence:

- L J Nelson & R A Smith, "Fibre direction and stacking sequence measurement in carbon fibre composites using Radon transforms of ultrasonic data", Composites A, Vol. 118, pp. 1-8, doi: 10.1016/j.compositesa.2018.12.009, 2019.

Ply Wrinkle Measurement

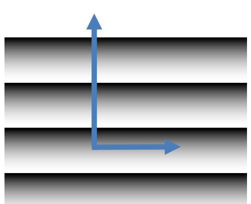
- Structure-tensor method
  - 2D or 3D gradients in data

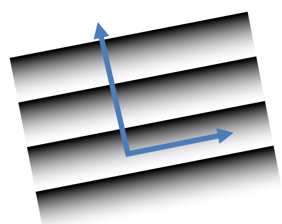
Rock strata imaging – Geological sciences



$$S = \begin{bmatrix} I_x^2 & I_xI_y \\ I_xI_y & I_y^2 \end{bmatrix}$$

Eigen*vectors* of the tensor indicate orientation at that pixel location.





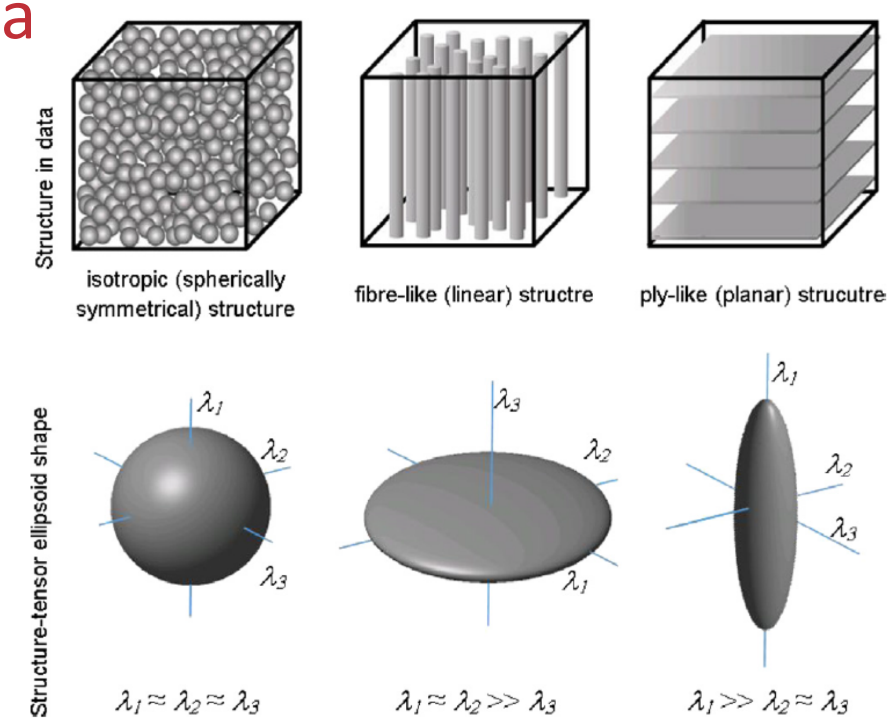
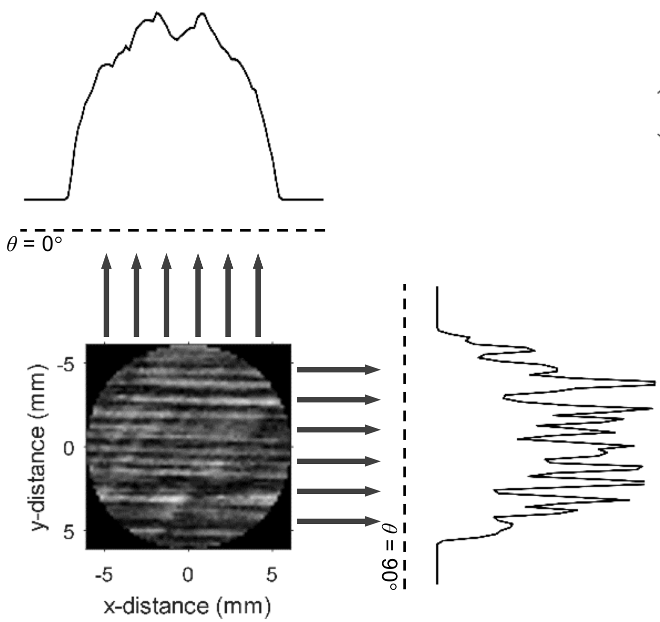


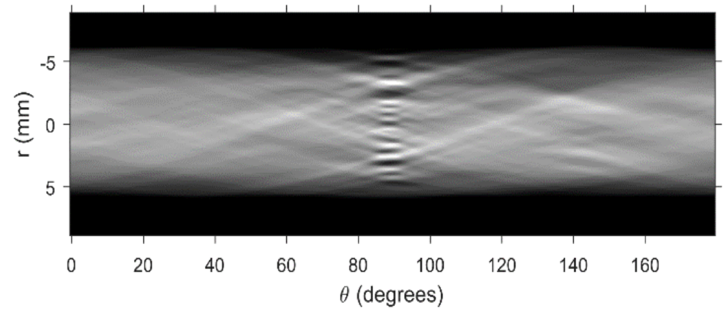
Fig. 3. Examples of three classes of structure in 3D data (above) and the corresponding structure-tensor shape when viewed as an ellipsoid (below). (For

In-plane fibre orientation

- Fibre angle measurement: Radon Transform

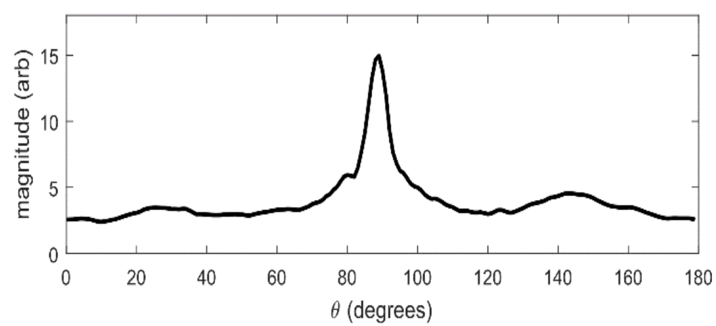


Radon Transform example projections at 0° and 90°



Radon Transform from 0° to 179°

Measure of contrast at each projection angle



Angular distribution from 0° to 179°