Overview of potential for NDT of Automotive Composites.

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Engineering and Physical Sciences Research Council

Acknowledgements

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- EPSRC Fellowship in Manufacturing
- EPSRC Impact Acceleration Project

Content

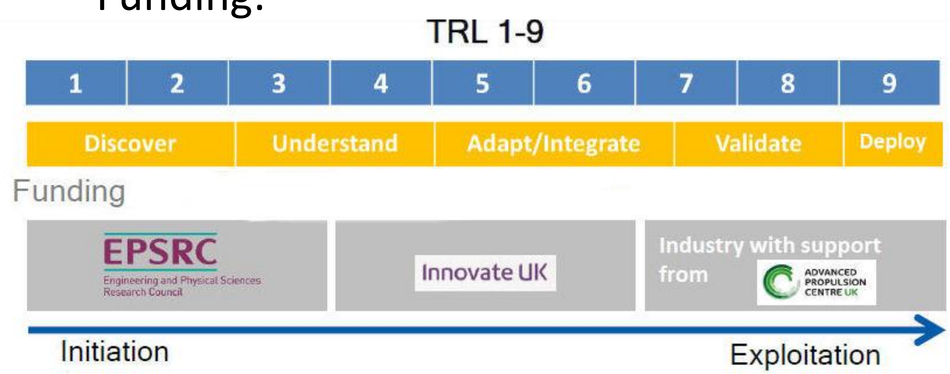
- Introduction
  - Automotive Composites in the UK Composites Strategy
- NDT of Composites Overview
- Using NDT to characterise 3D material properties & model performance
  - 3D non-destructive characterisation
  - FE Materials Modelling

Aerospace

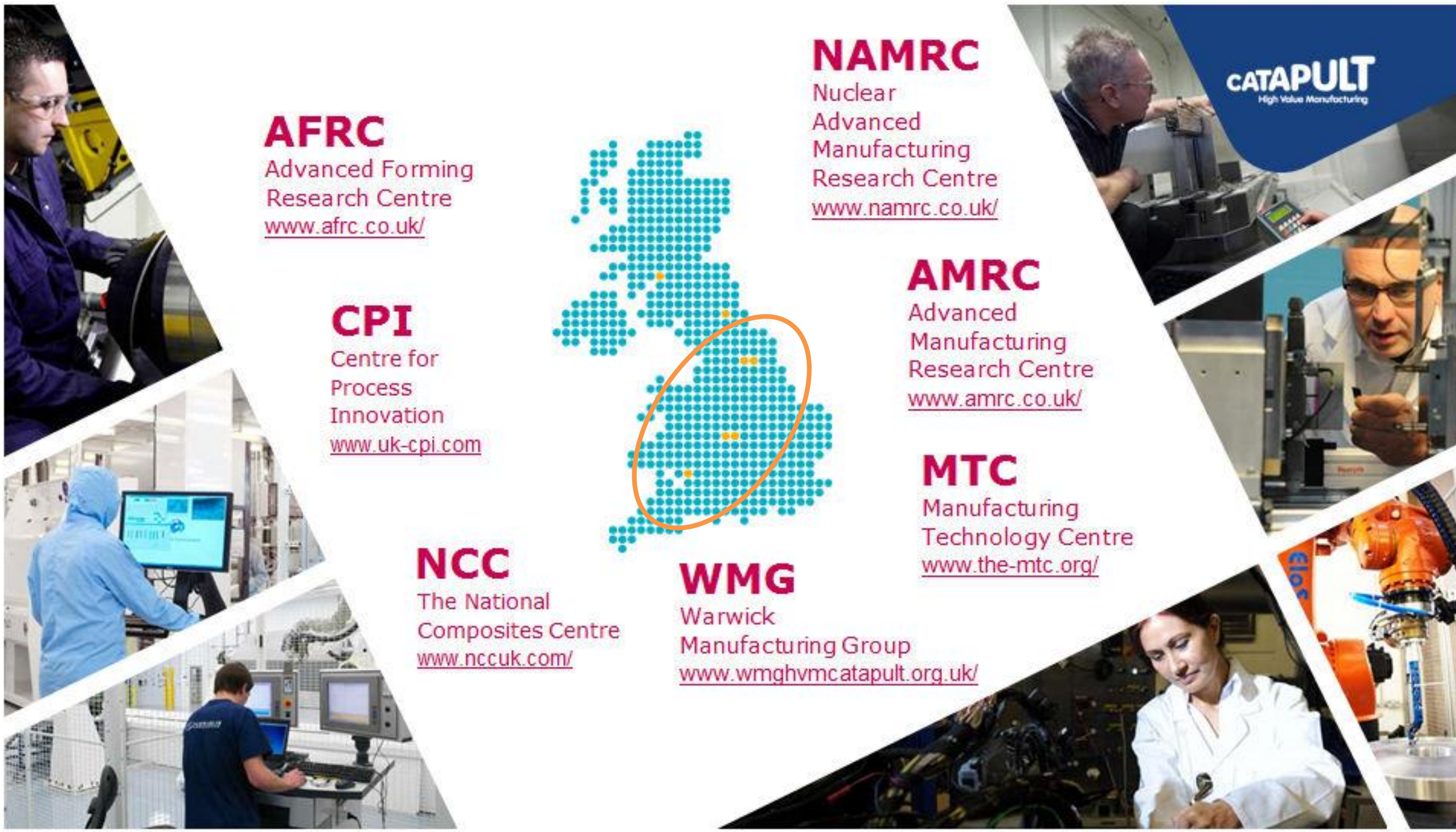
- Strategy led by Aerospace Growth Partnership http://www.theagp.aero/
- Technology led by Aerospace Technology Institute http://www.ati.org.uk/
- Have Specialist Advisory Groups
- Refreshing roadmaps.

Automotive

- Led by Automotive Council http://www.automotivecouncil.co.uk/
- 5 Technology Workstreams:
  - Internal Combustion Engines
  - Electric Machines & Power Electronics
  - Lightweight Vehicle & Power Train
  - Energy Storage & Management
  - Intelligent Mobility
- Funding:



HVM Catapult Overview



UK Composites Strategy 2016

UK Composites – Market Opportunities

	AEROSPACE	DEFENCE	AUTOMOTIVE	RAIL	CONSTRUCTION	MARINE	OIL & GAS	RENEWABLES	UK Total
2030 Opportunity	UPPER £3,590m 17% LOWER £1,250m	UPPER £1,146m 7% LOWER £909m	UPPER £3,490m 15% LOWER £1,430m	UPPER £155m 7% LOWER £125m	UPPER £1520m 8% LOWER £1235m	UPPER £370m 3% LOWER £320m	UPPER £1,100m 31% LOWER £315m	UPPER £1,100m 4% LOWER £878m	UPPER £12.48bn 11.97%
2020 Forecast	UPPER £1,155m 33% LOWER £1,040m	UPPER £952m 16% LOWER £924m	UPPER £530m 4% LOWER £475m	UPPER £98m 10% LOWER £75m	UPPER £640m 14% LOWER £510m	UPPER £270m 3% LOWER £240m	UPPER £337m 68% LOWER £82m	UPPER £685m 3% LOWER £646m	UPPER £4.67bn 15.32%
2015 Baseline	£273m	£383m	£380m	£55m	£362m	£220m	£15m	£601m	£2.29bn

Ultrasonics and NDT Group

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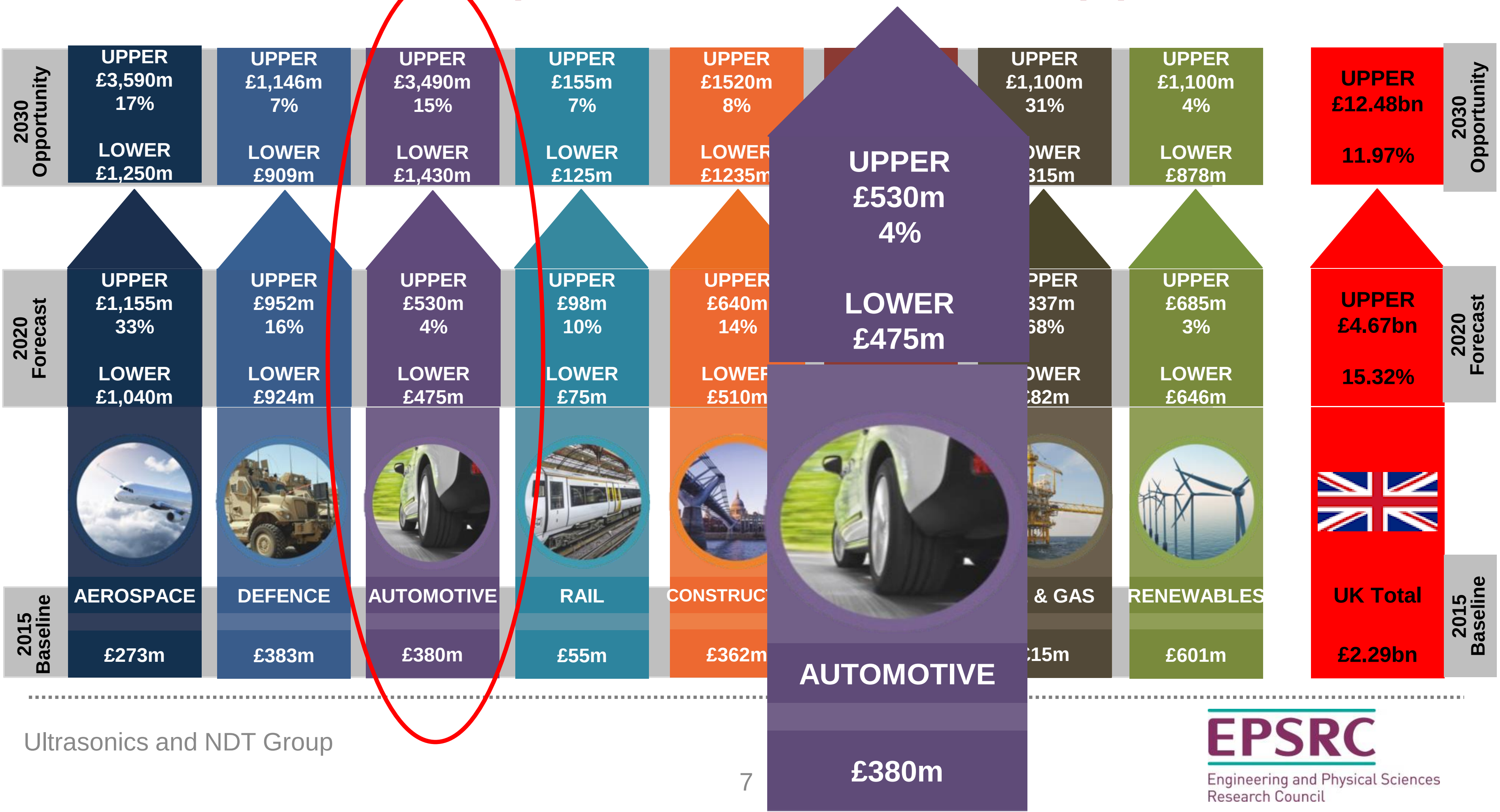
UK Com… Strategy 2016

UK Composites – … Opportunities



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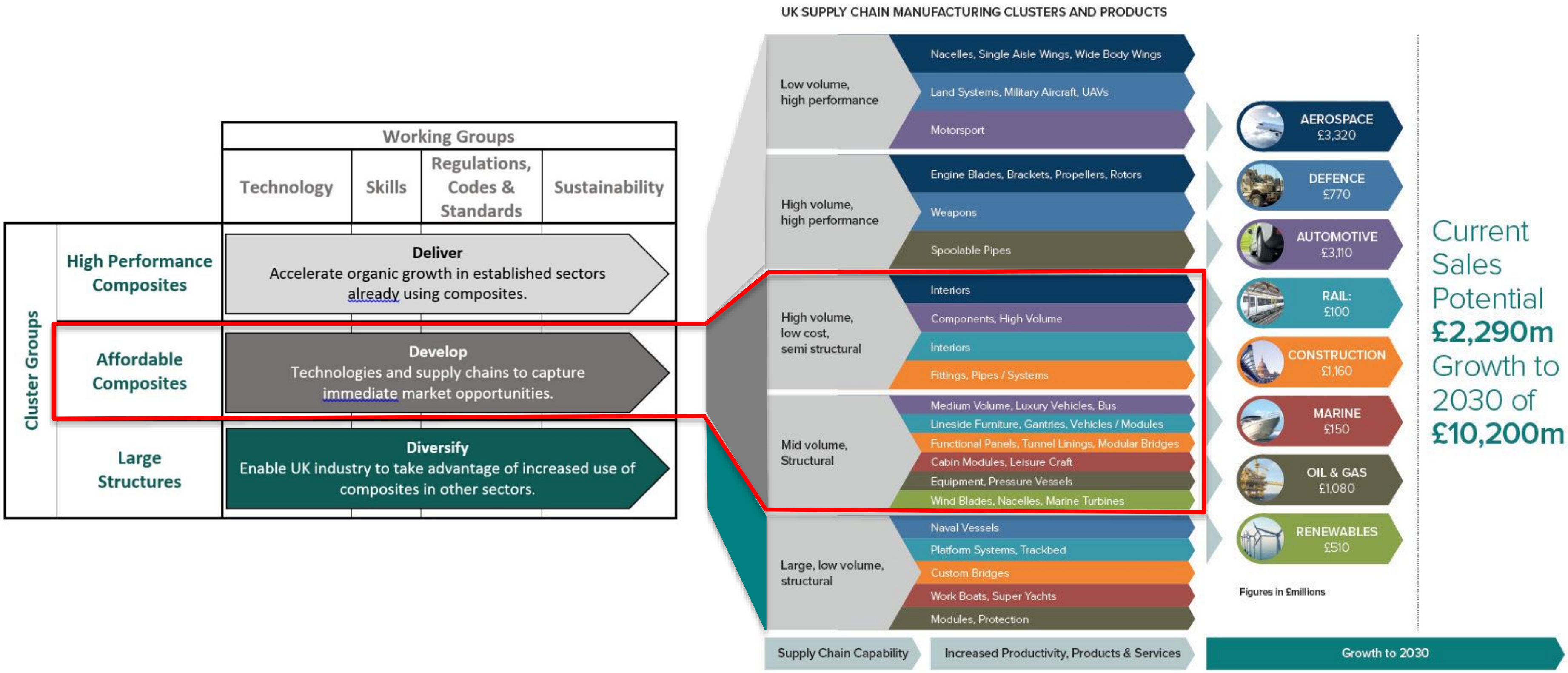
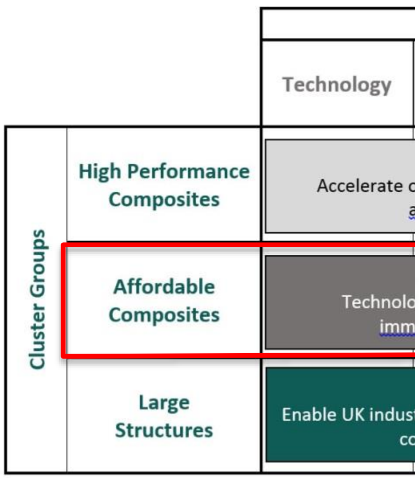
UK Composites Strategy 2016

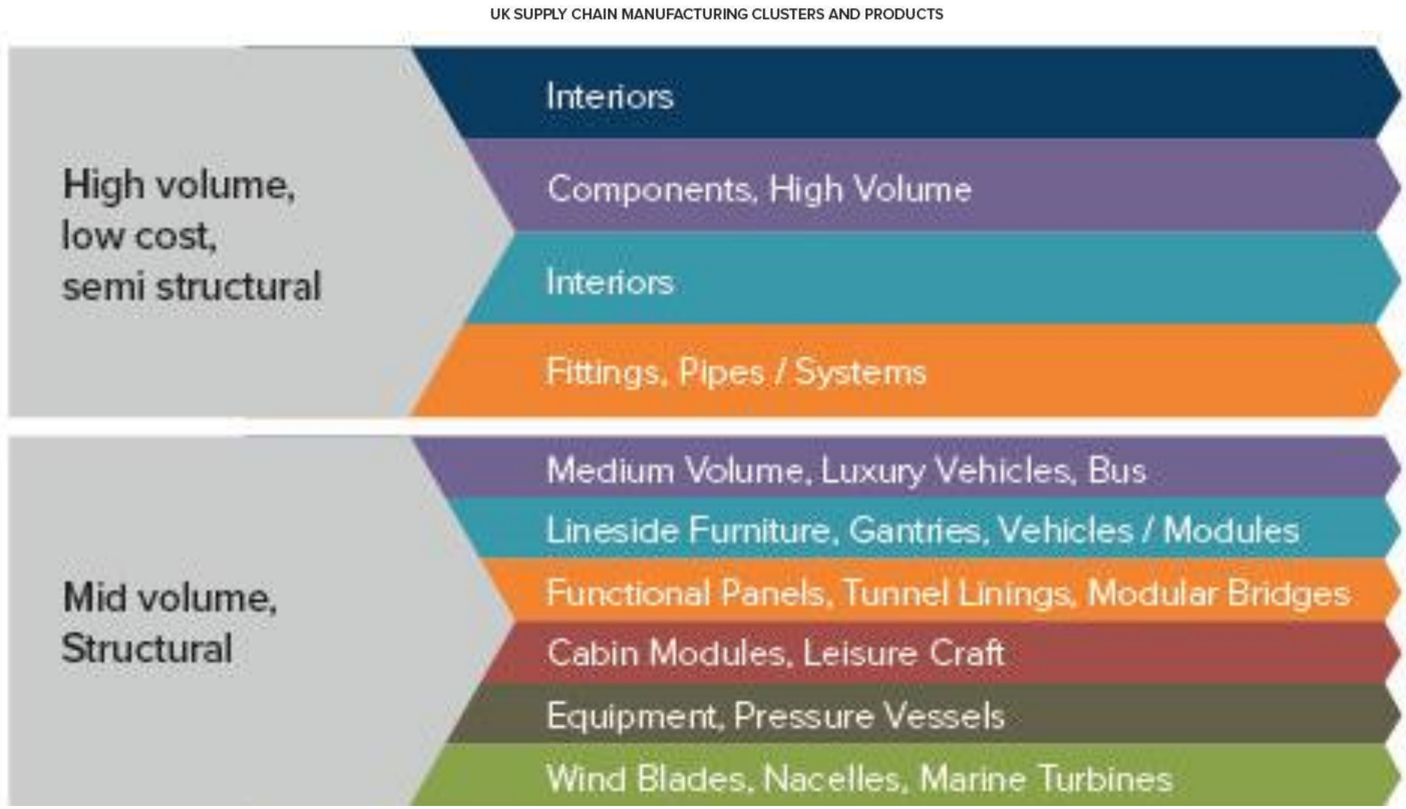
CLF Strategy Delivery



UK Composites Strategy 2016

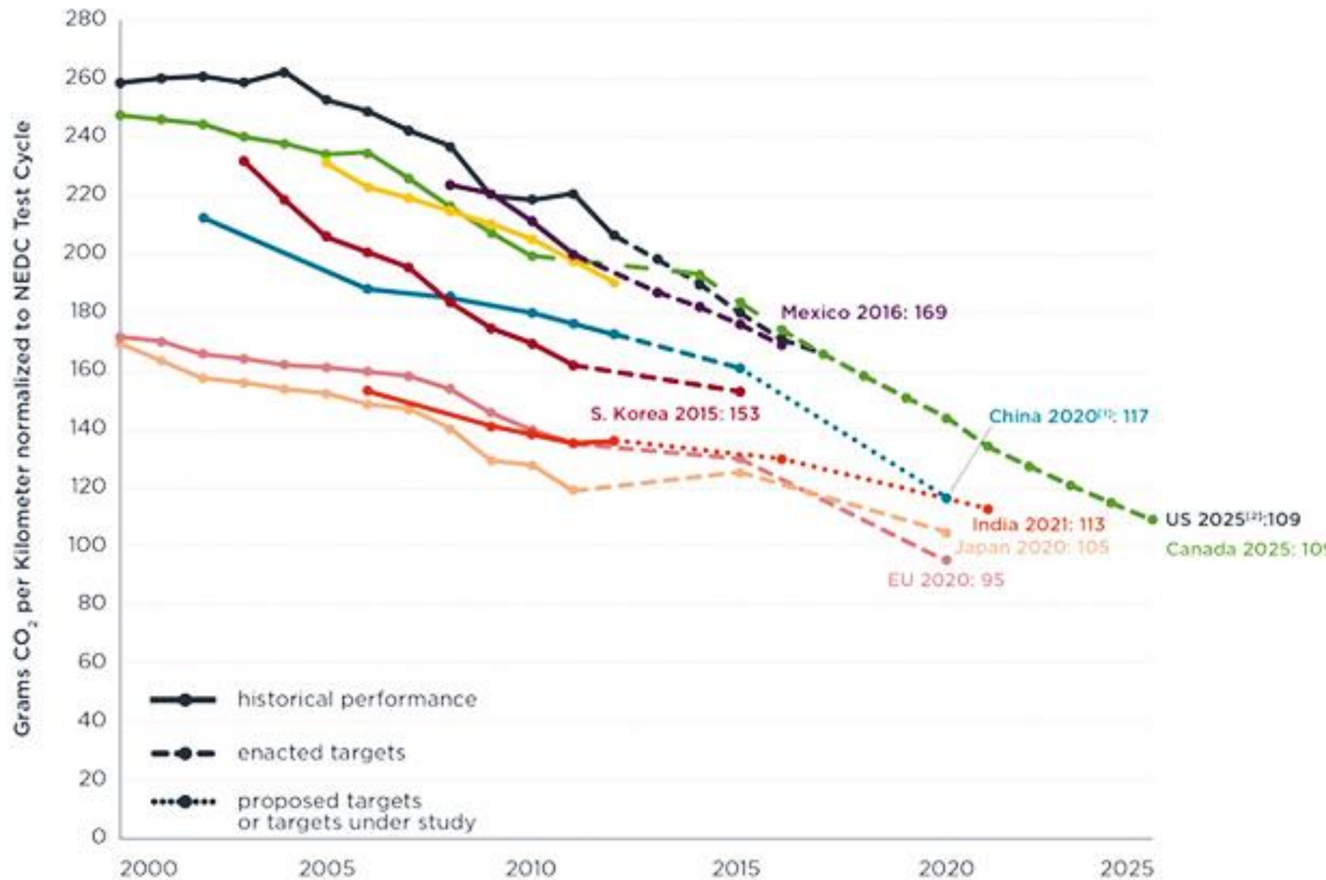
CLF Strategy Delivery





Global Picture – Key Growth Market

Global emission targets are driving growth in use of composites in higher volume automotive.



[1] China's target reflects gasoline vehicles only. The target may be higher after new energy vehicles are considered.
[2] US, Canada, and Mexico light-duty vehicles include light-commercial vehicles.
[3] Supporting data can be found at: http://www.theicct.org/info-tools/global-passenger-vehicle-standards

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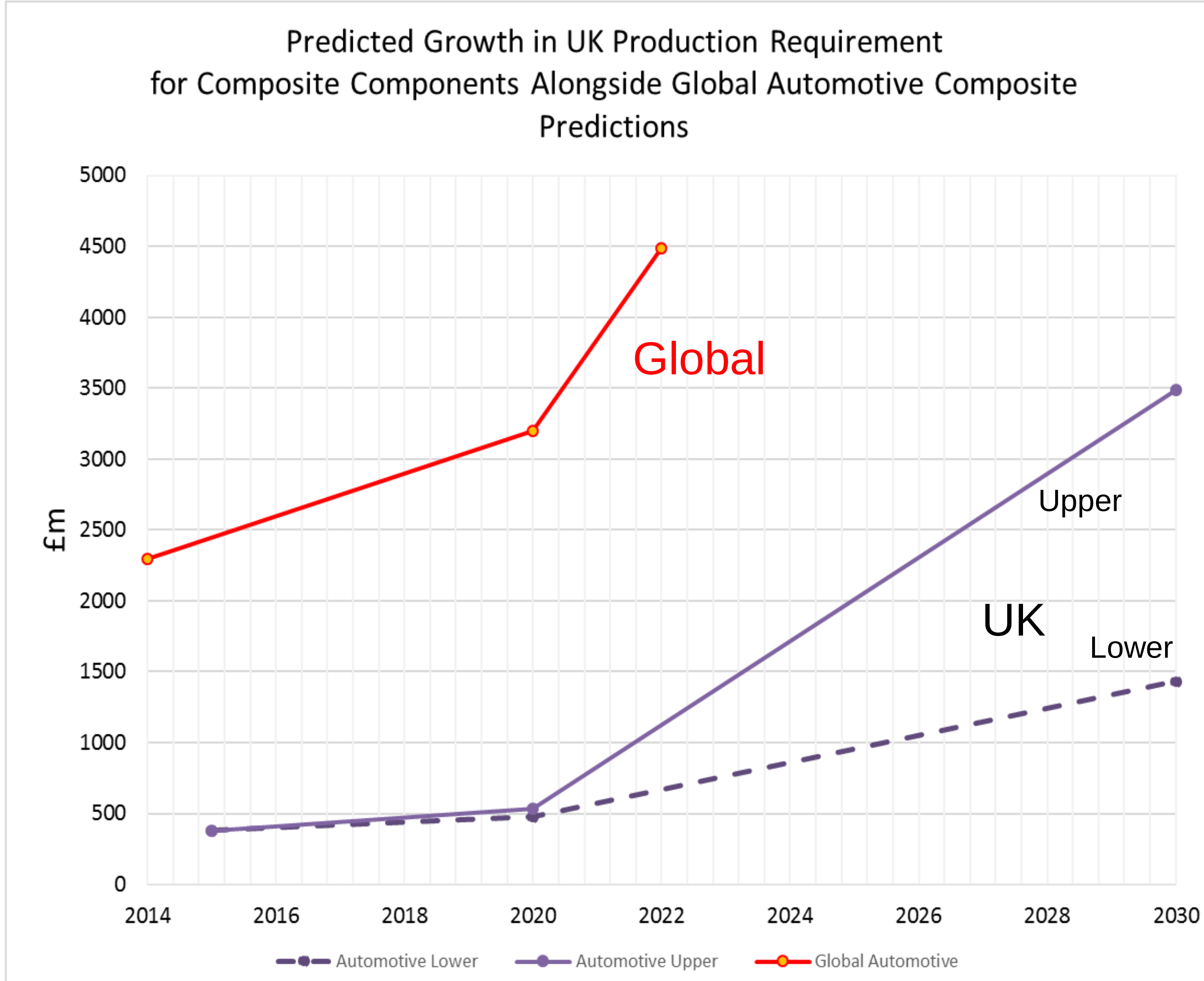
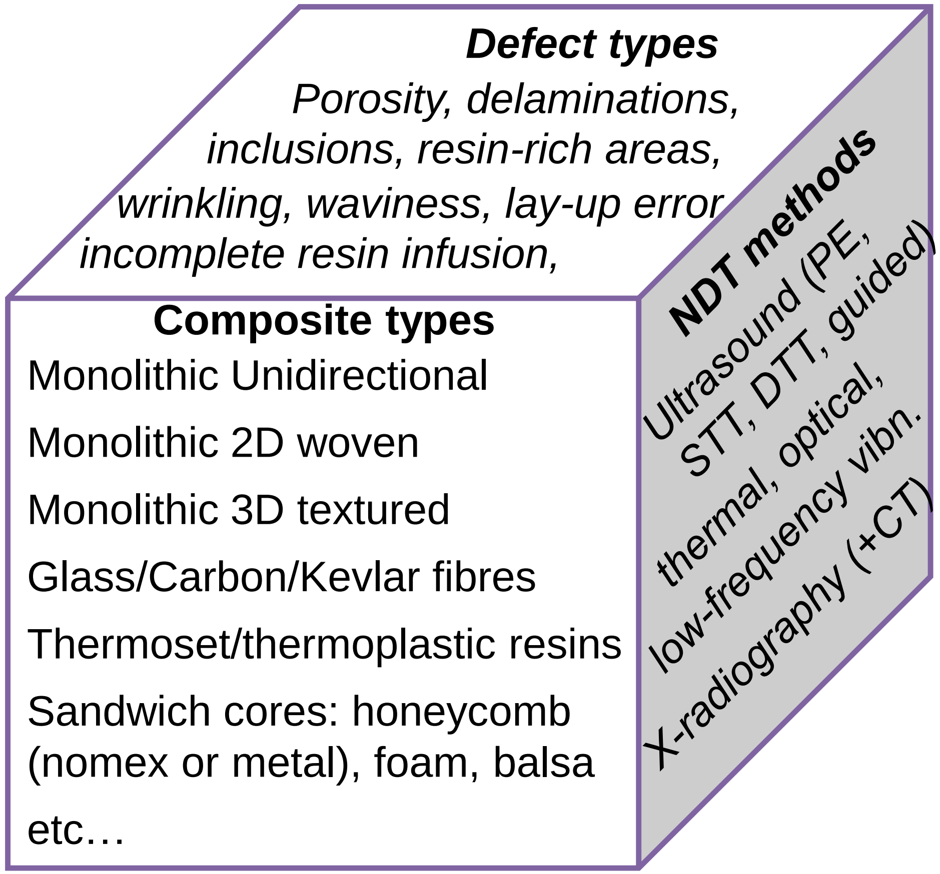
Global Picture – Key Growth Market

Light-weight drivers mean that global growth is predicted at a 10-fold increase in composite parts in auto by 2030!



NDT of Composites Overview

NDT of Composites Overview

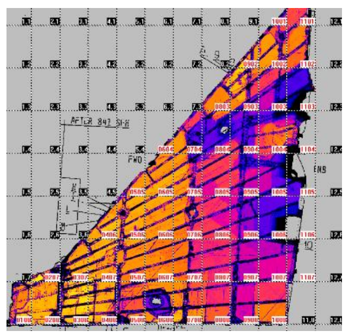


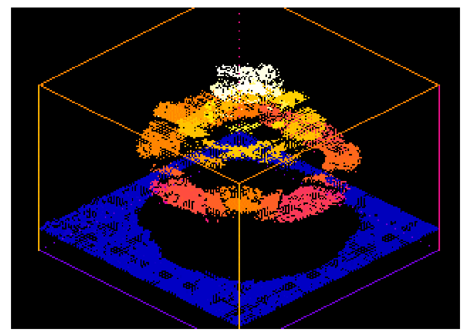
- Refer to reviews, books, training courses!

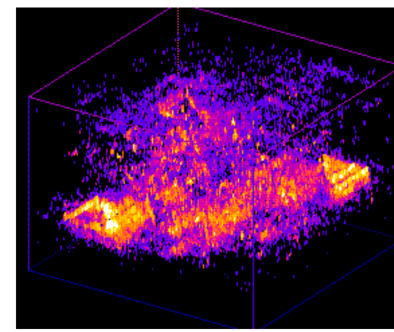
NDT of Composites Overview

	Defect detection	Defect characterisation	Material characterisation
>95% Universal	Ultrasound X-ray CT	Ultrasound X-ray CT	Ultrasound X-ray CT
Specific	The rest	The rest	The rest

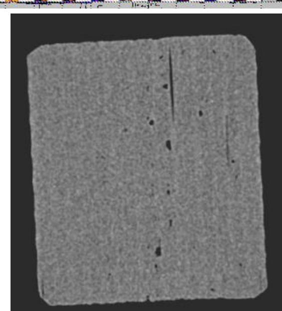
Ultrasound:

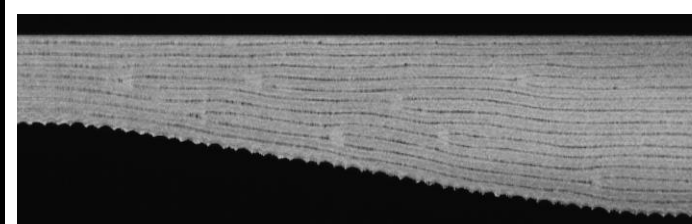






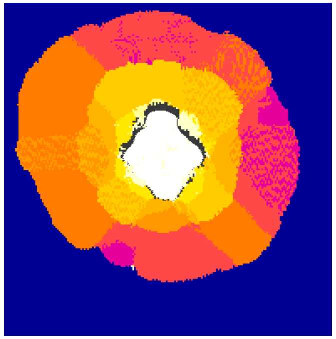
X-ray CT:



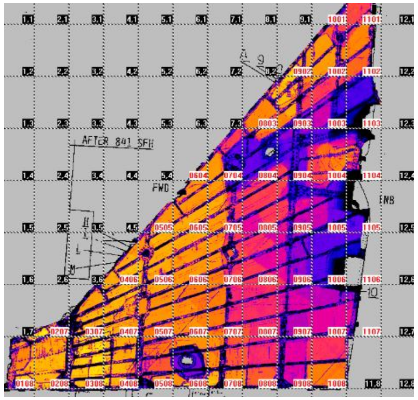


NDT of Composites Overview

- Ultrasound – reason for success
  - Wavelengths ~ply spacing and < defect size
  - Beam size ≤ defect size
  - Amplitude and phase contain different information



- Ultrasound – Limitations
  - Scanning speed limits area of coverage
  - Accessibility
  - Coupling into surface
  - Depth of penetration in thick attenuative structures



NDT of Composites Overview

- X-ray CT – reasons for success
  - Responds to mass density (actually electron density)
  - Contrast between different materials in composite
  - Resolution < defect size and ≤ ply spacing
- X-ray CT – limitations
  - Limited component size and shape
  - Radiation containment - Usually requires a cabinet
  - Trade-off between component size and resolution
  - Scanning time

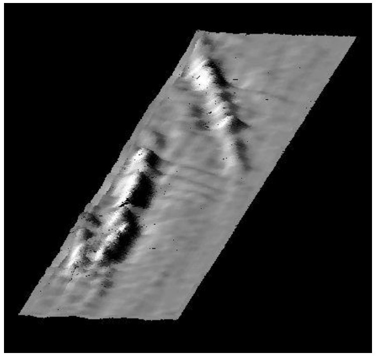
Using NDT to characterise 3D material properties & model performance

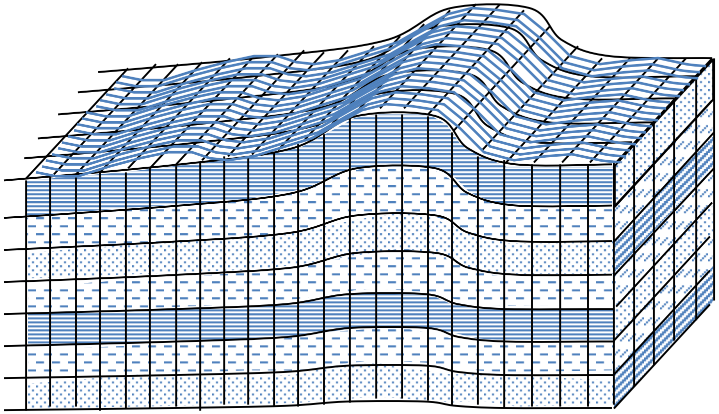
3D non-destructive characterisation

FE Materials Modelling

3D non-destructive characterisation

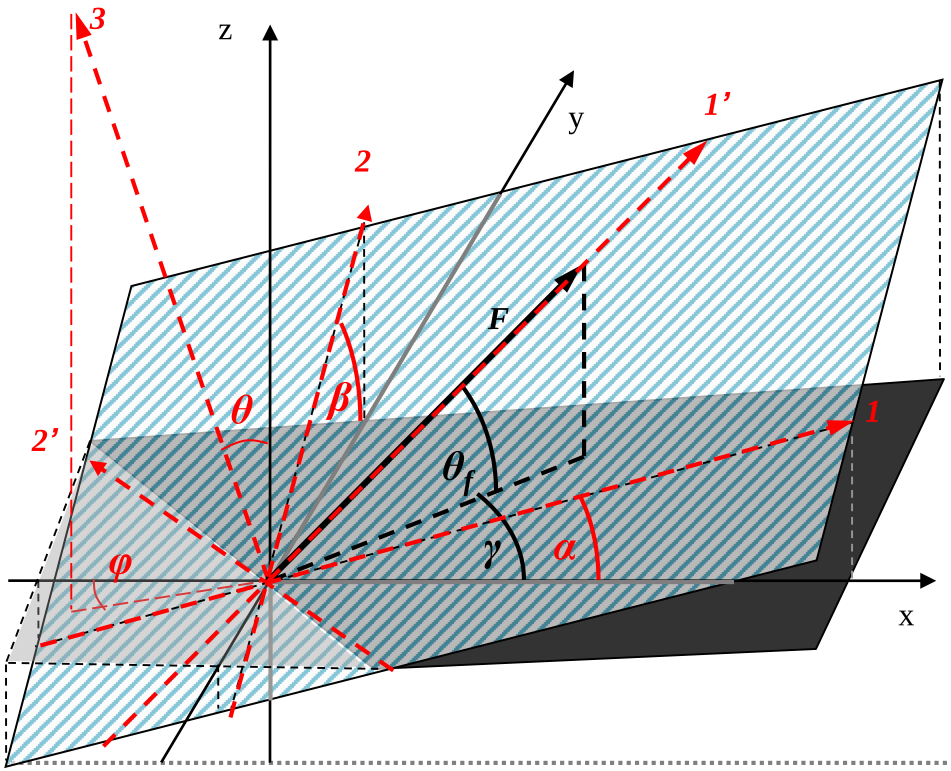
- Predict performance of as-manufactured component.
  - Materials model with actual 3D NDT data inputs
- Finite-element mesh created from NDT ply-wrinkling data.

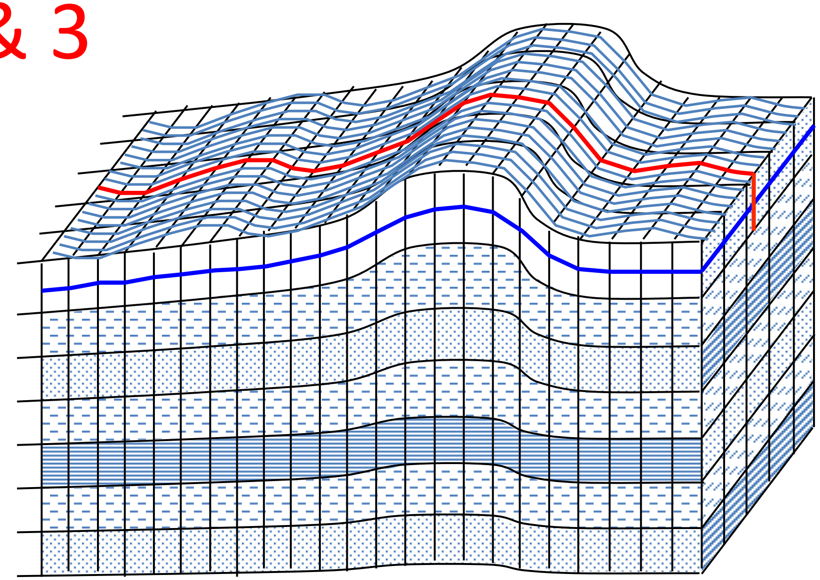




Materials Modelling

- Populate cells with 3D Fibre Angle (α,β,γ), vector field, stiffness axes 1′, 2′ & 3





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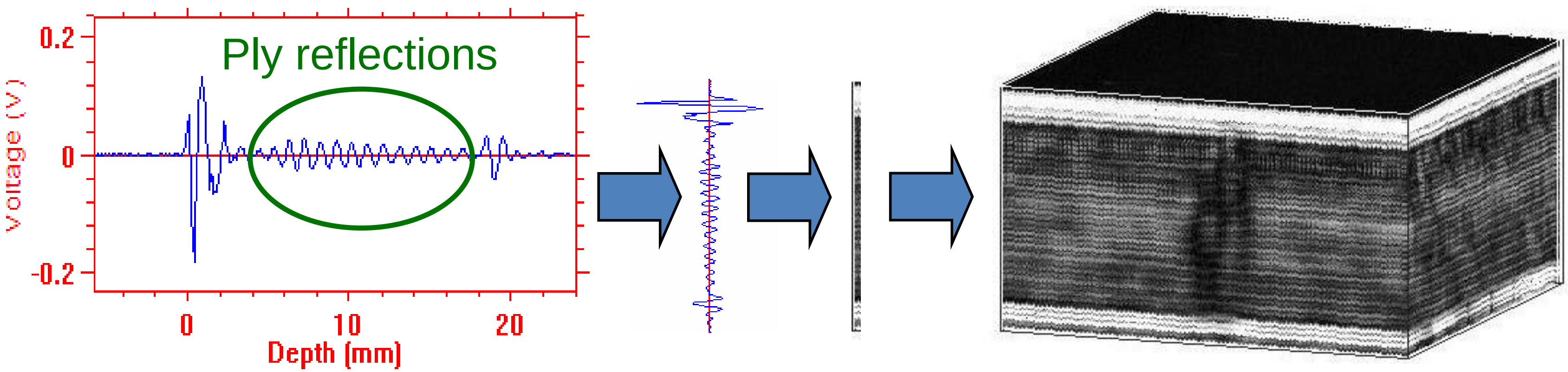
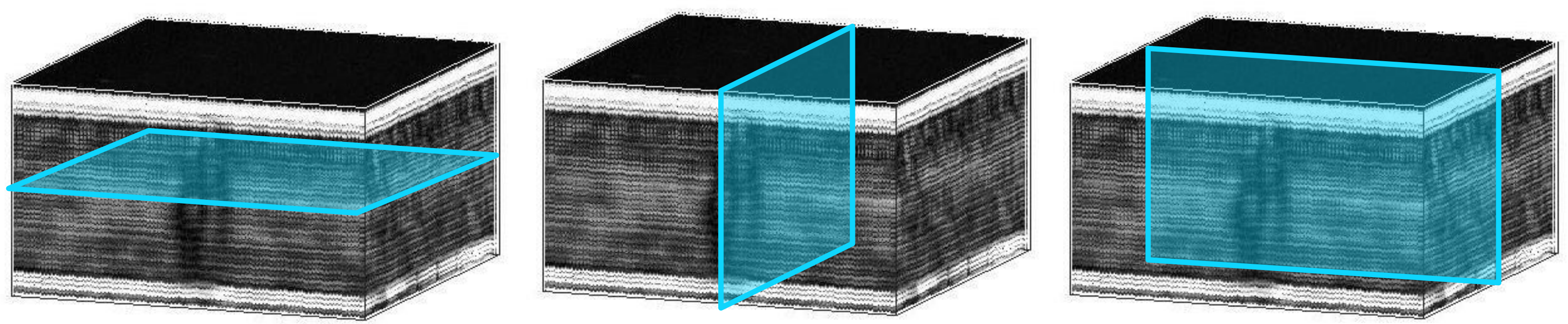
3D non-destructive characterisation

Ultrasound

- Grey level can be amplitude or phase response





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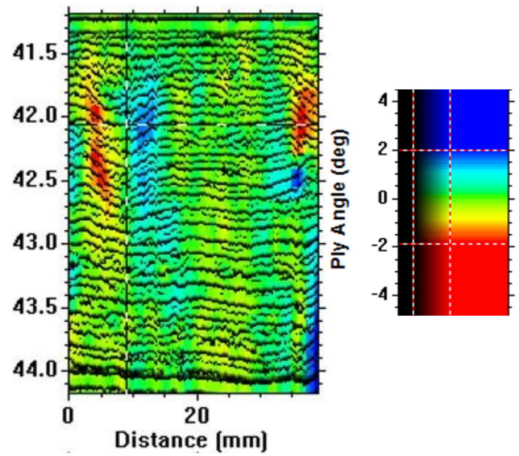
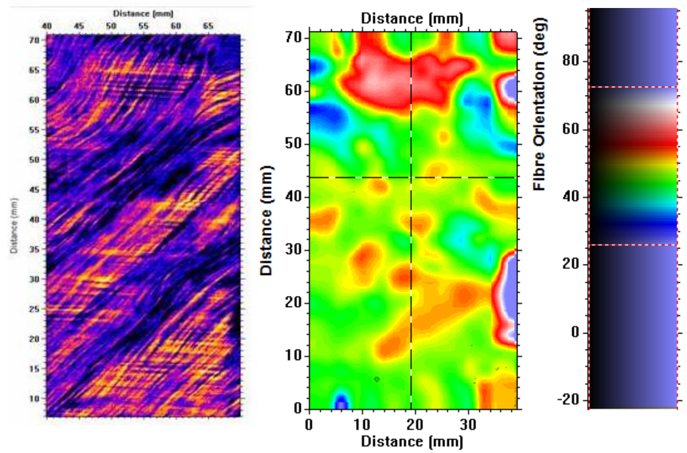
3D non-destructive characterisation

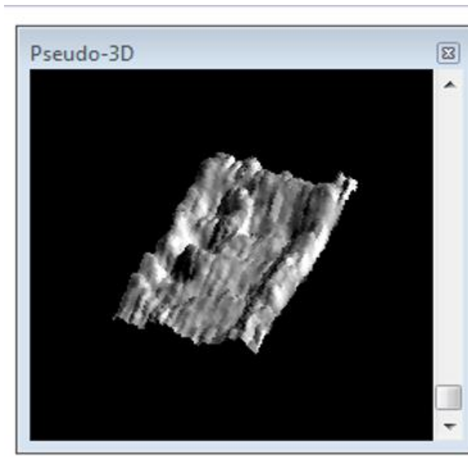
- Quantitative 3D fibre orientation ‘inversion’

B-scan



C-scan

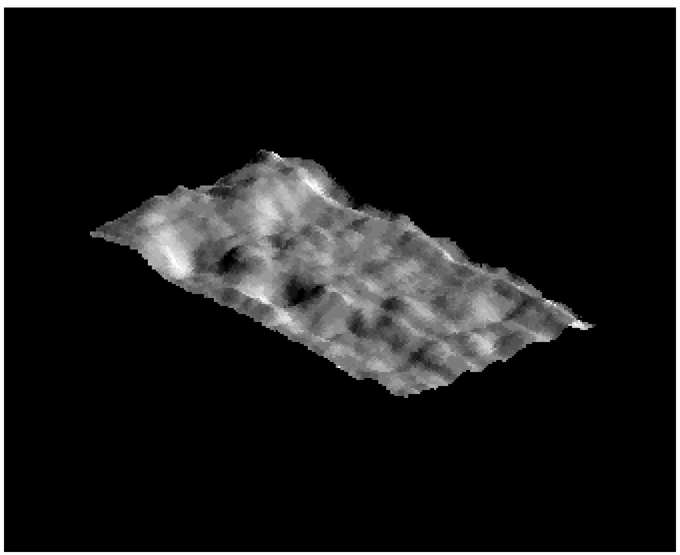


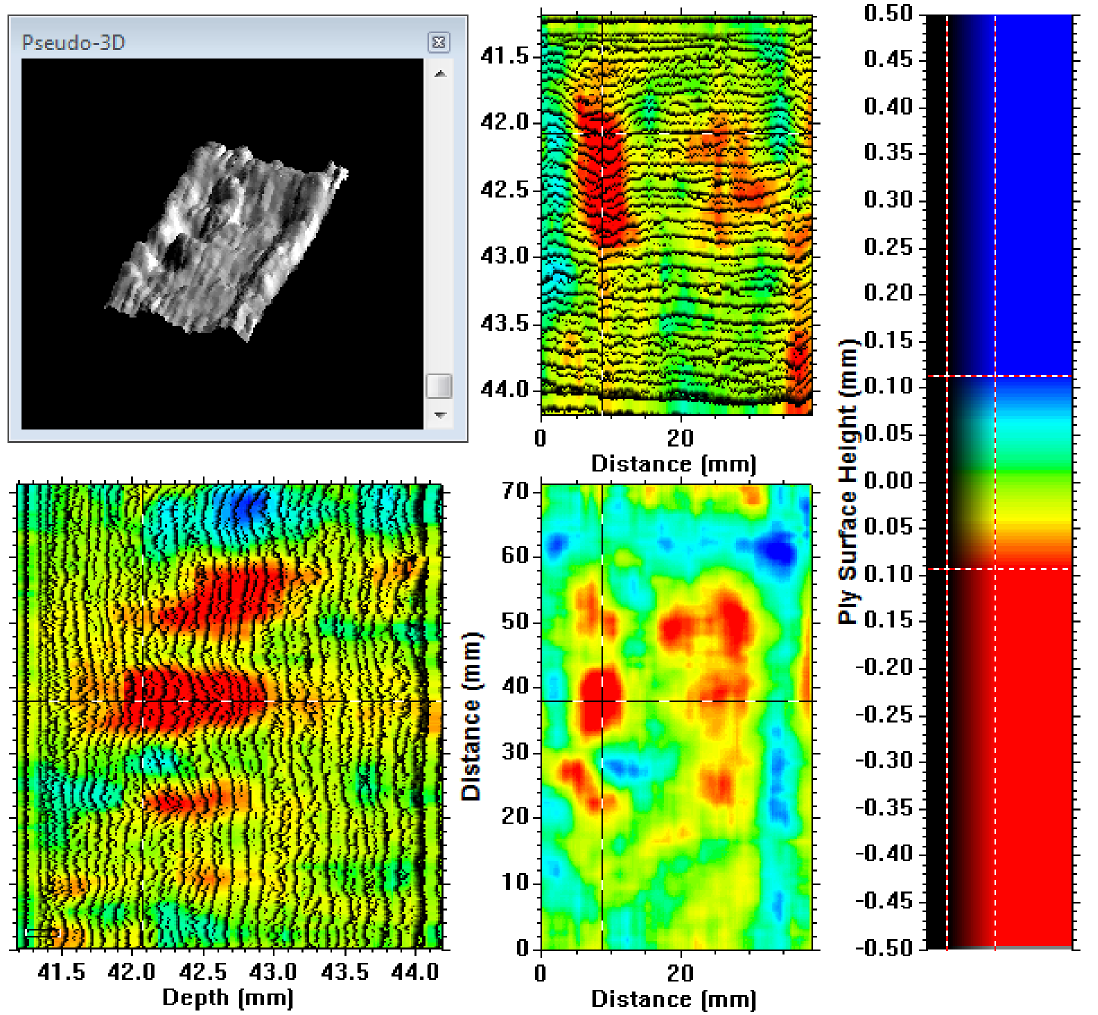


α, β – out-of-plane fibre angle + γ – in-plane fibre angle → Surface Heights

3D non-destructive characterisation

- Quantitative ply surface height…





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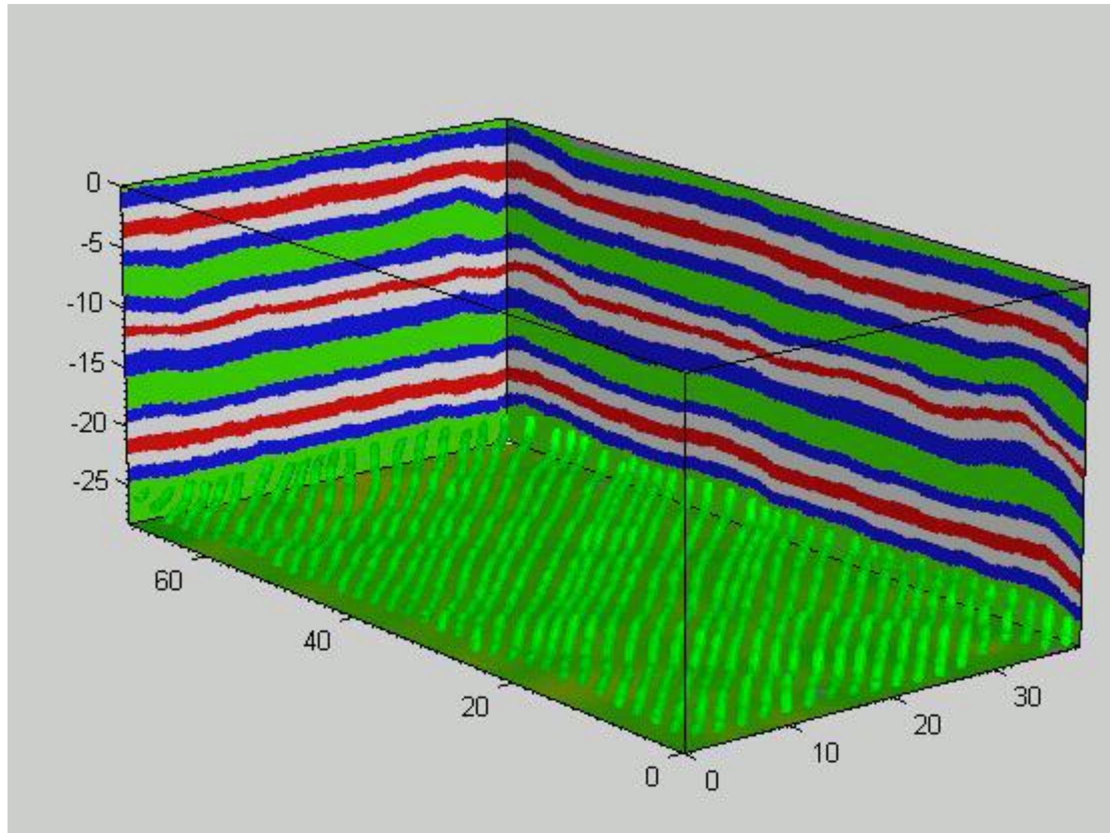
3D Vector Map of Fibre-tow orientation

- Vector Field
  - Fibre-tow maps of ‘streamlines’ (analogy with fluid dynamics), vectors, $\boldsymbol{F}$



0.125 mm thick plies.
$[45°, 0°, -45°, 90°, -45°, 0°, 45°]_3$

Ply tracking

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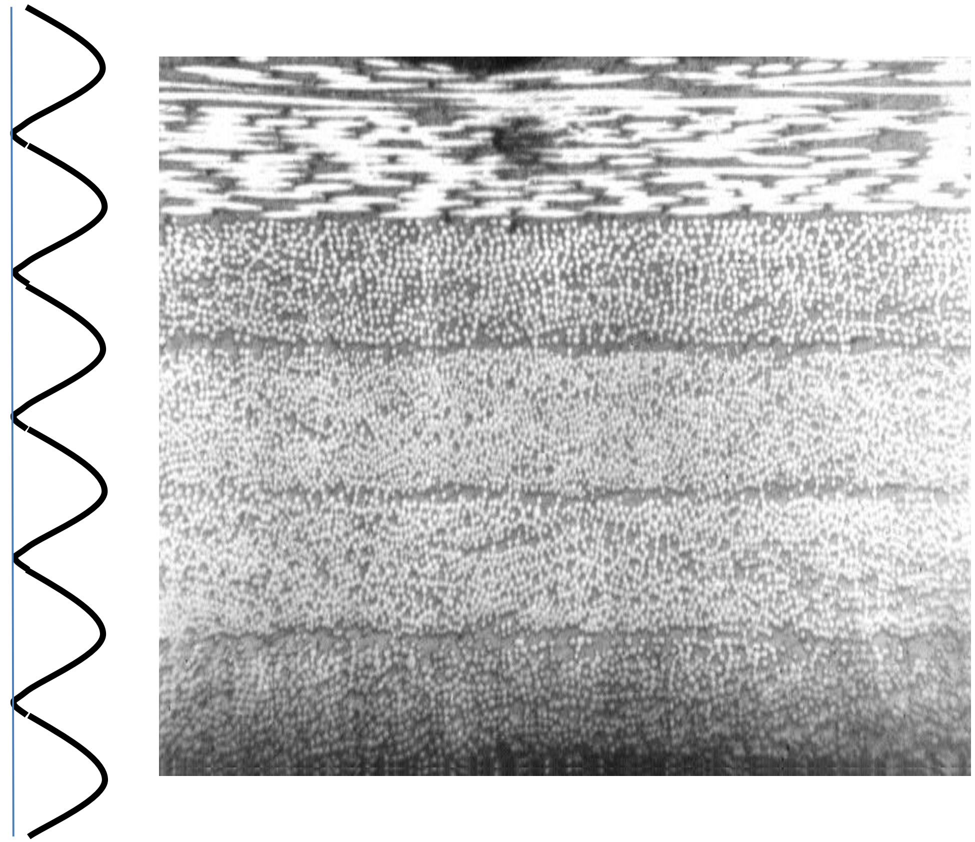
Ultrasonic Propagation in CFRP

- CFRP
  - Ultrasonic propagation is complex
  - Interfering reflections from resin layers
  - Weak resonances
    - 6 MHz for 0.25 mm plies
  - Resonances disrupted
    - Ply thickness variations
    - Material property variations
  - Localised response

Low Reflection Coefficients (R). R peaks at resin layers - thin, so thickness-dependent R.



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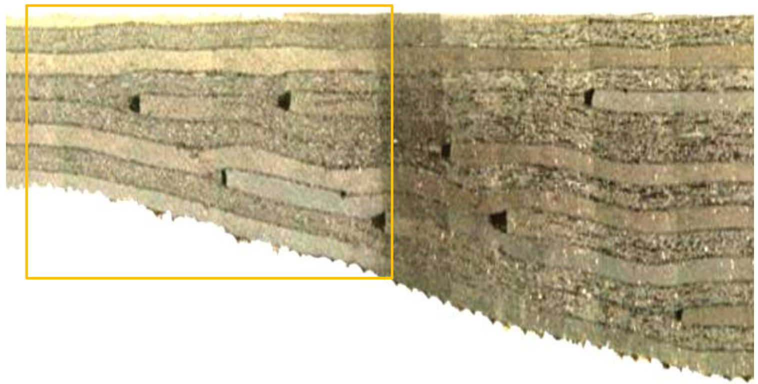
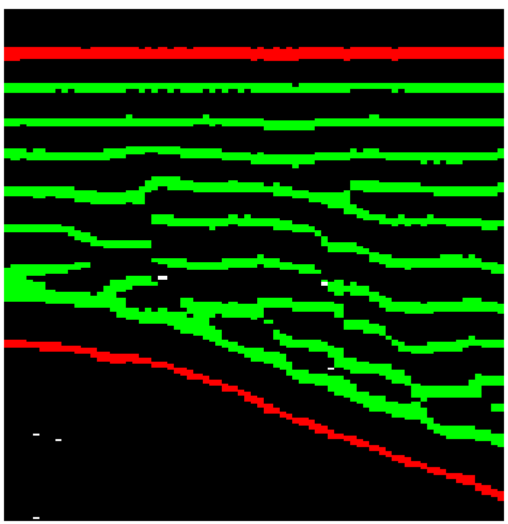
Ply-drop specimen

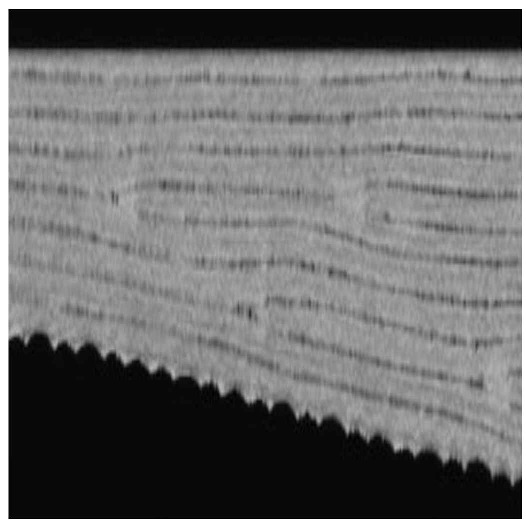


Optical Micrograph

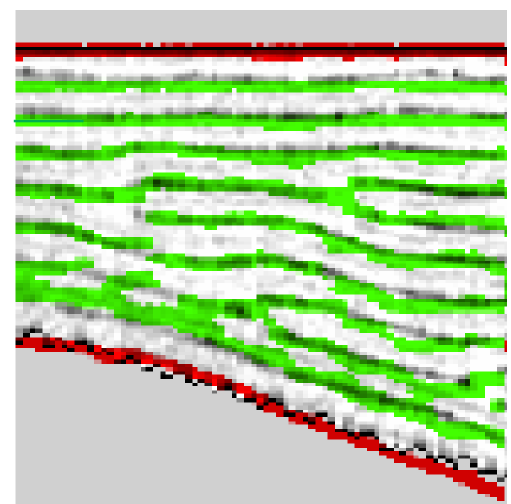
Analytic-signal



X-ray CT



Overlaid



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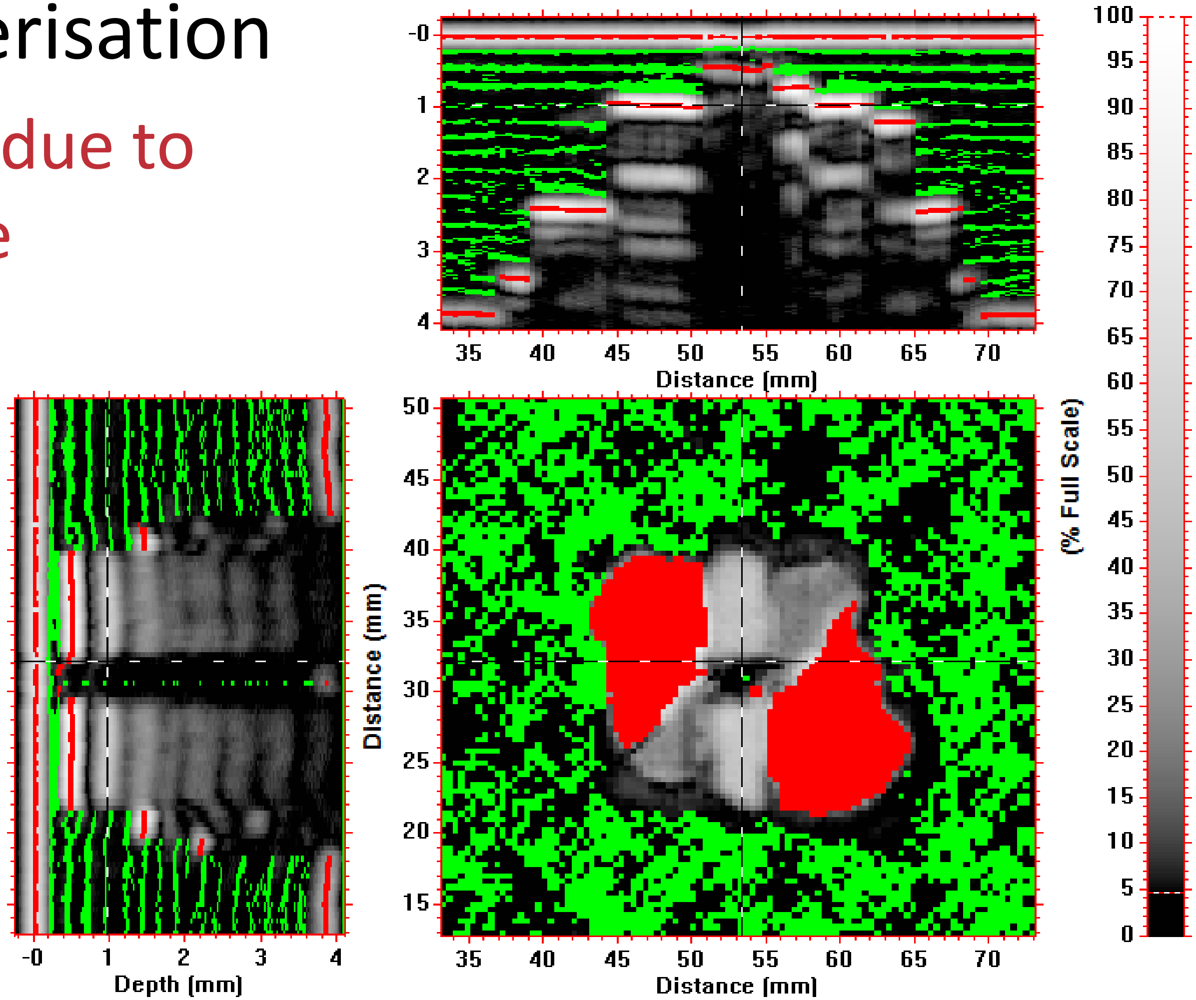
Impact Damage - delaminations

- Defect Characterisation
  - Delaminations due to impact damage



- Instantaneous amplitude with Ply tracking…

Green: Resin layer.   Red: front, back or delamination.

Note: multiple reflections are not colour coded

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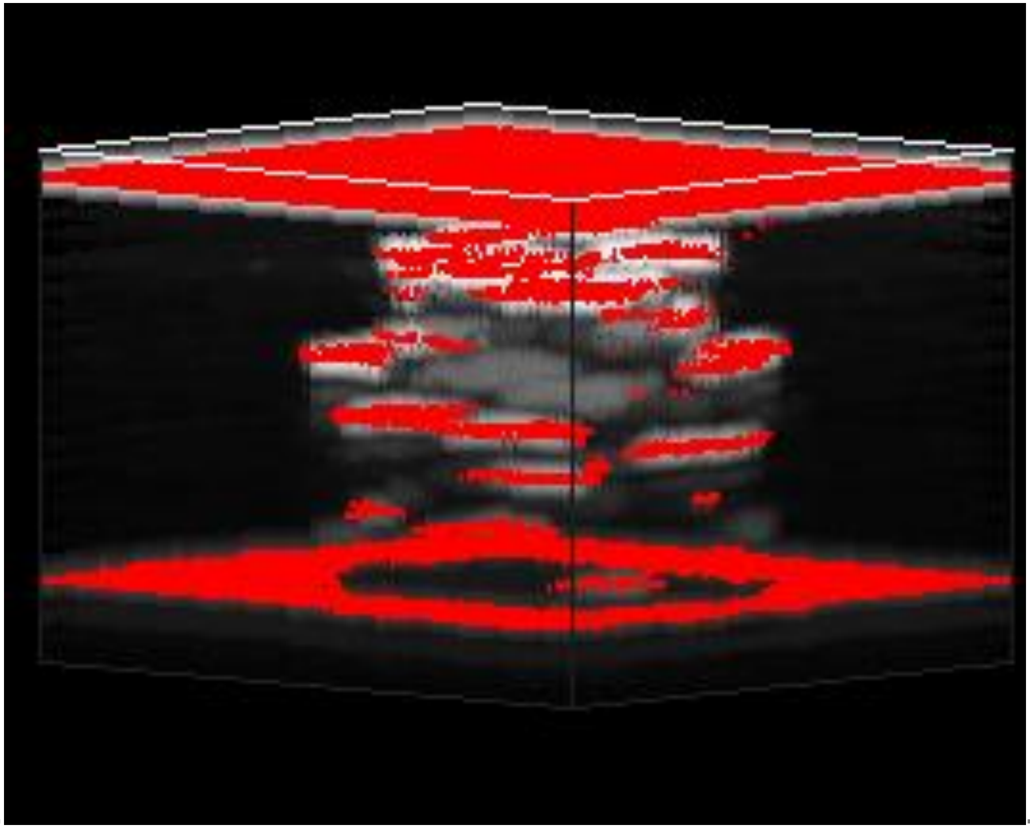
Impact damage - delaminations

- Defect Characterisation
  - Delaminations due to impact damage

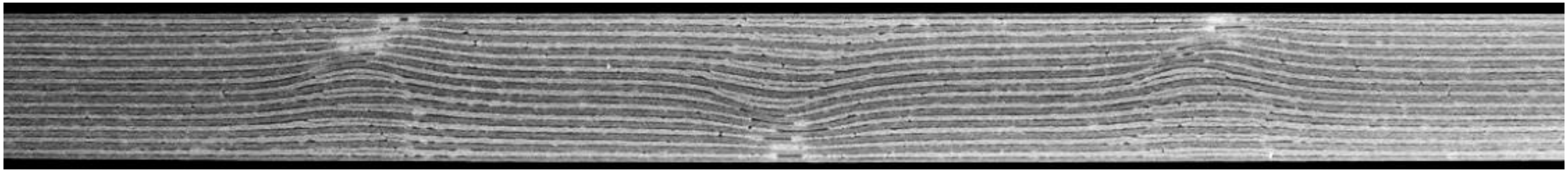


- Instantaneous amplitude with Ply tracking…

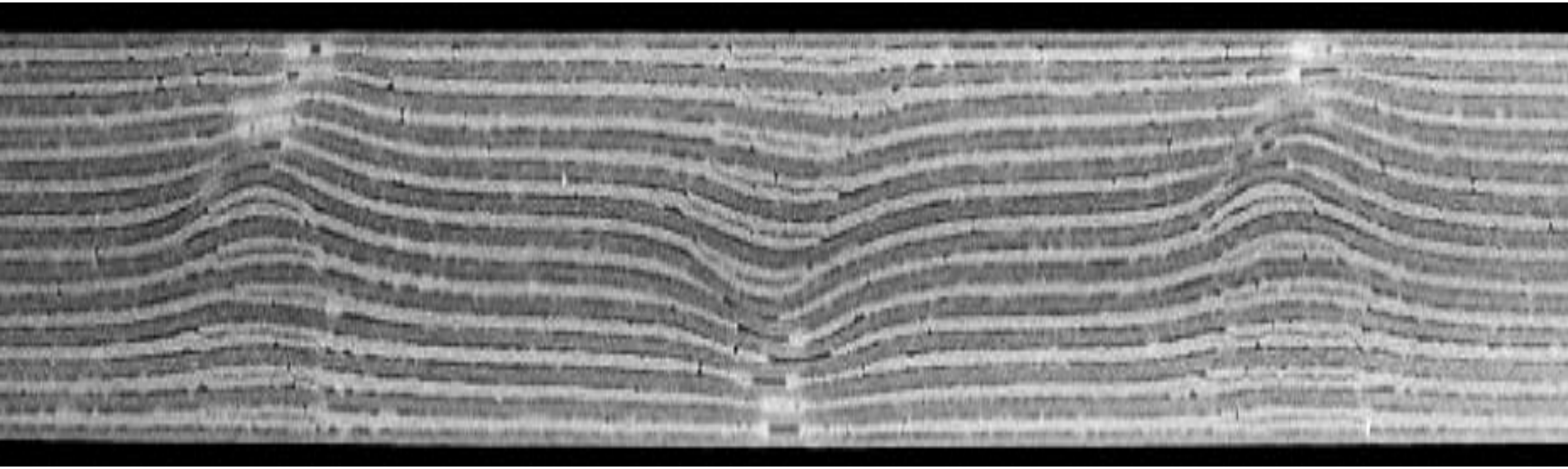
Red: front, back or delamination.
Note: multiple reflections are not colour coded

Tape gaps, overlaps, wrinkling

- Tape gaps and overlaps can cause wrinkling



X-ray CT data



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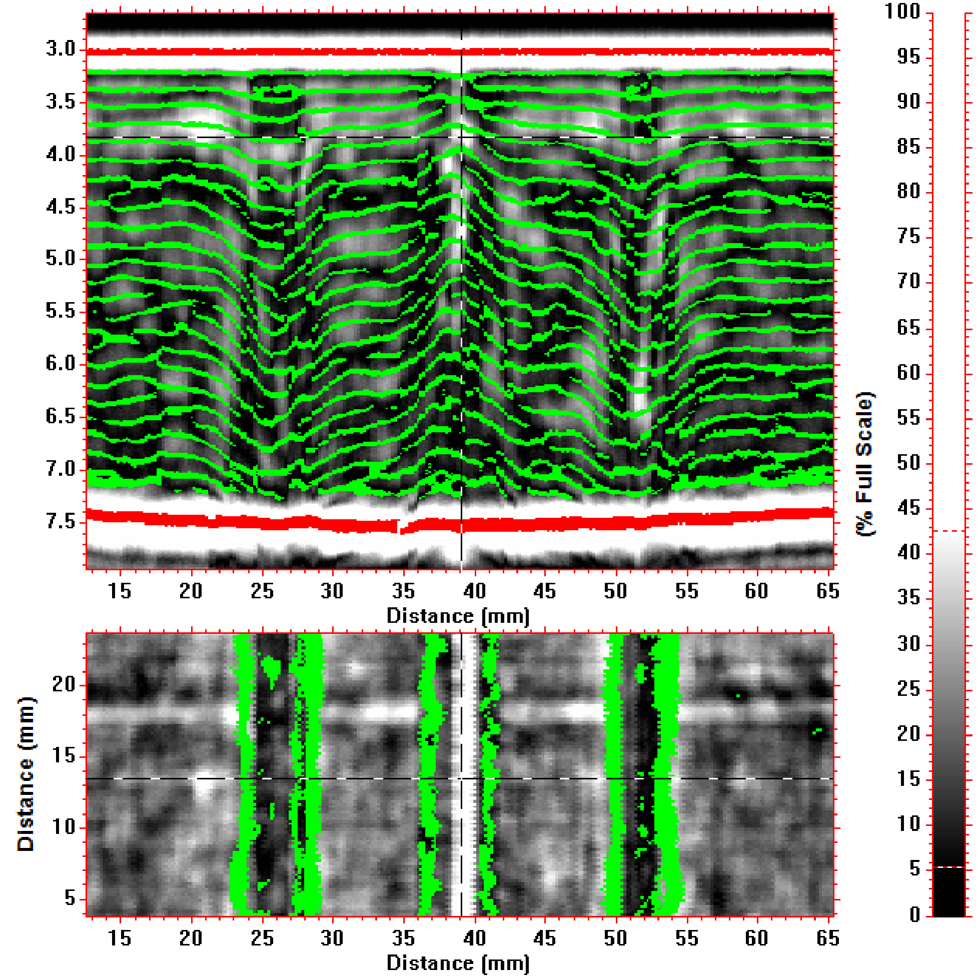
Tape gaps, overlaps, wrinkling

Front-wall, back-wall, ply-drops

- Instantaneous amplitude with resin layers, FWE, BWE
- Note white line at peak amplitude



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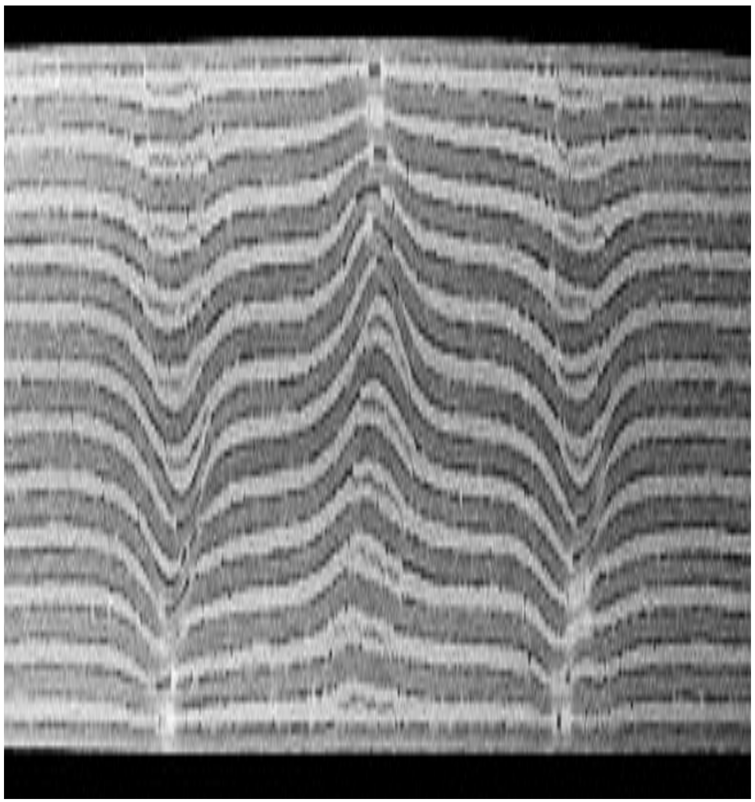
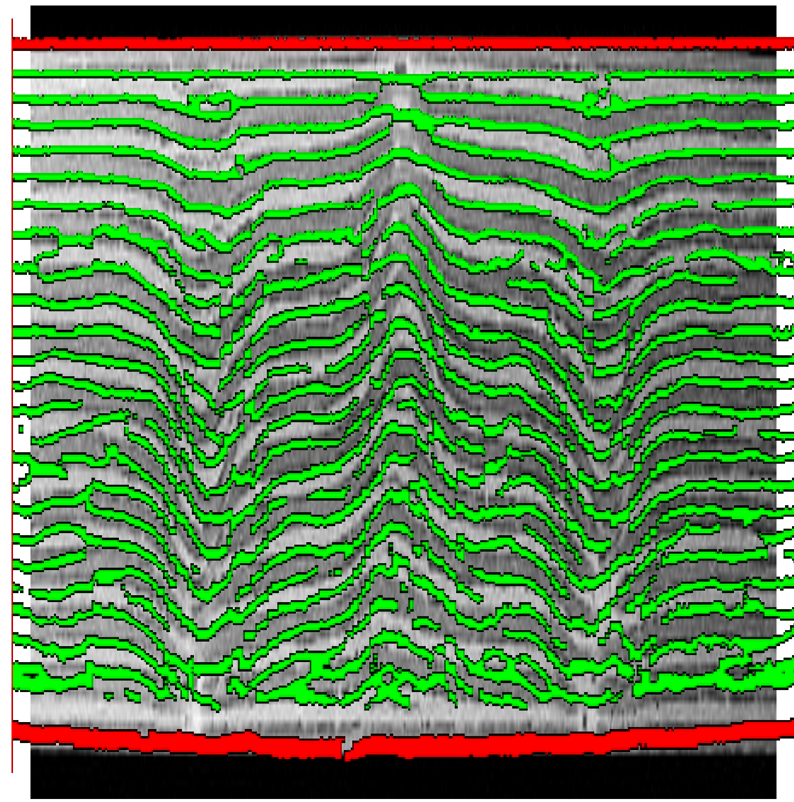
Tape gaps, overlaps, wrinkling

X-ray CT scan

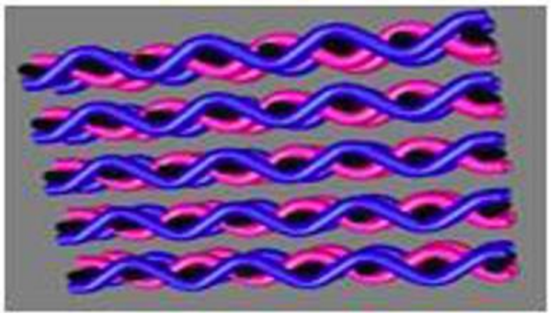


With analytic-signal overlay

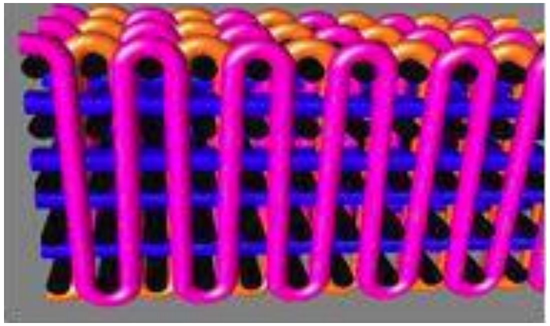


Woven Composites

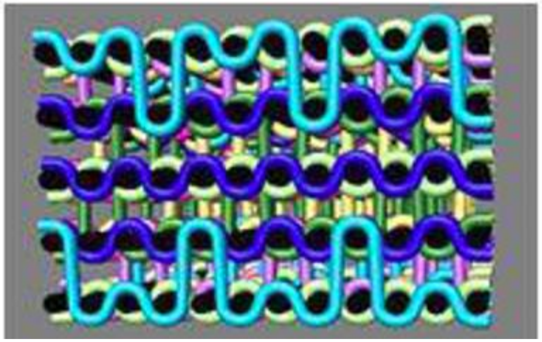
2D woven… & 3D textile



Plain weave



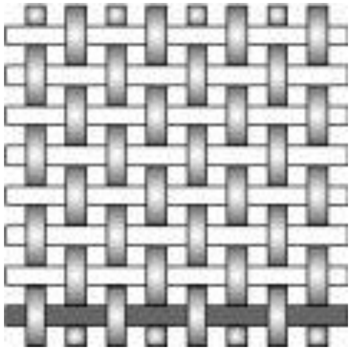
Orthogonal



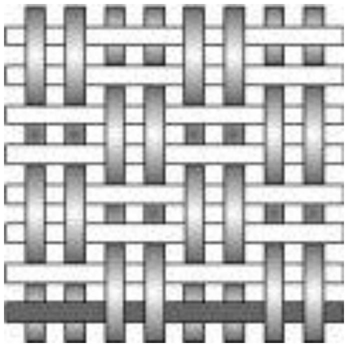
Multilayer 3D

Ply Fingerprinting for woven fabrics

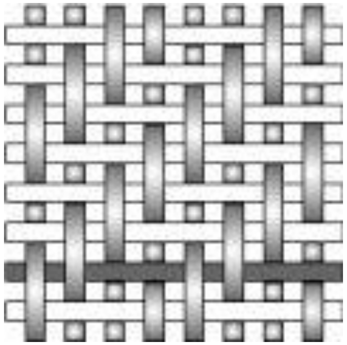
- Multiple peaks in:
  - Angular distribution, and
  - Spatial frequency distribution
- But each weave has a characteristic *Ply Fingerprint*



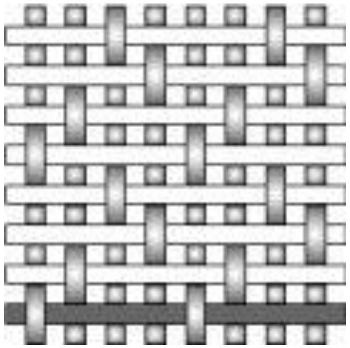
Plain



Basket 2*x*2



Twill 2*x*2



4-harness satin with ‘crow’s-foot’ [1,2,3,2] repeat

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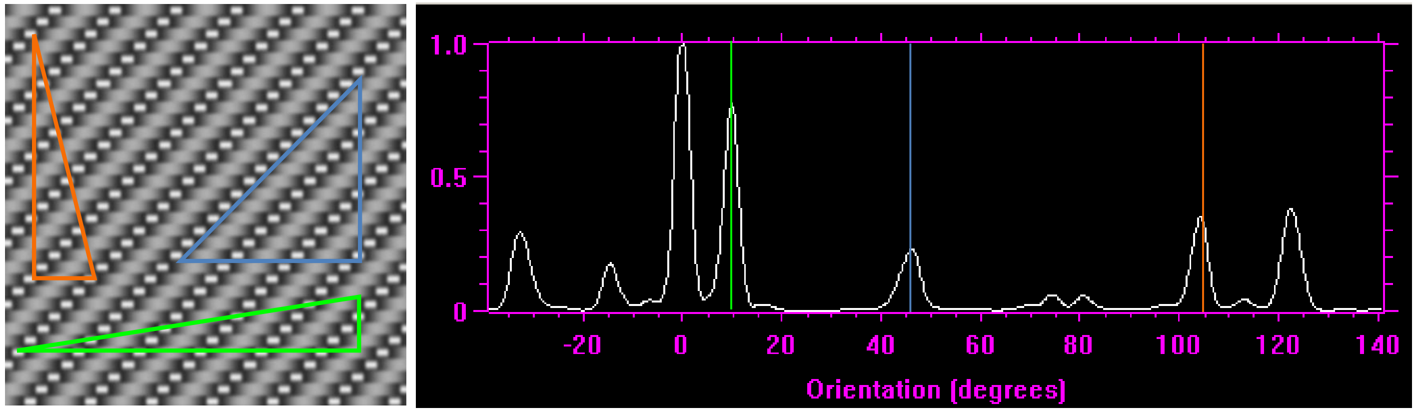
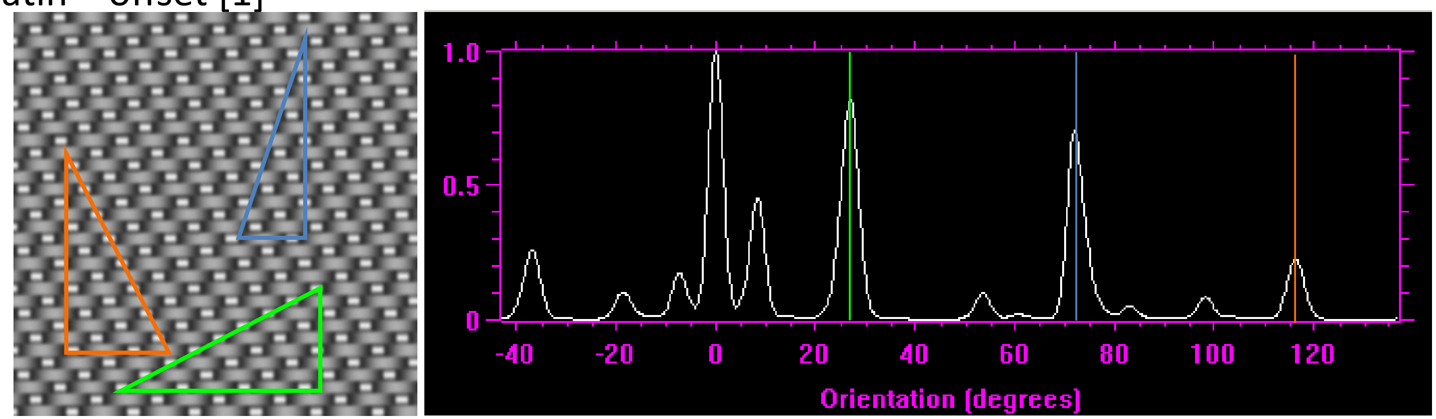
Ply Fingerprinting for woven fabrics



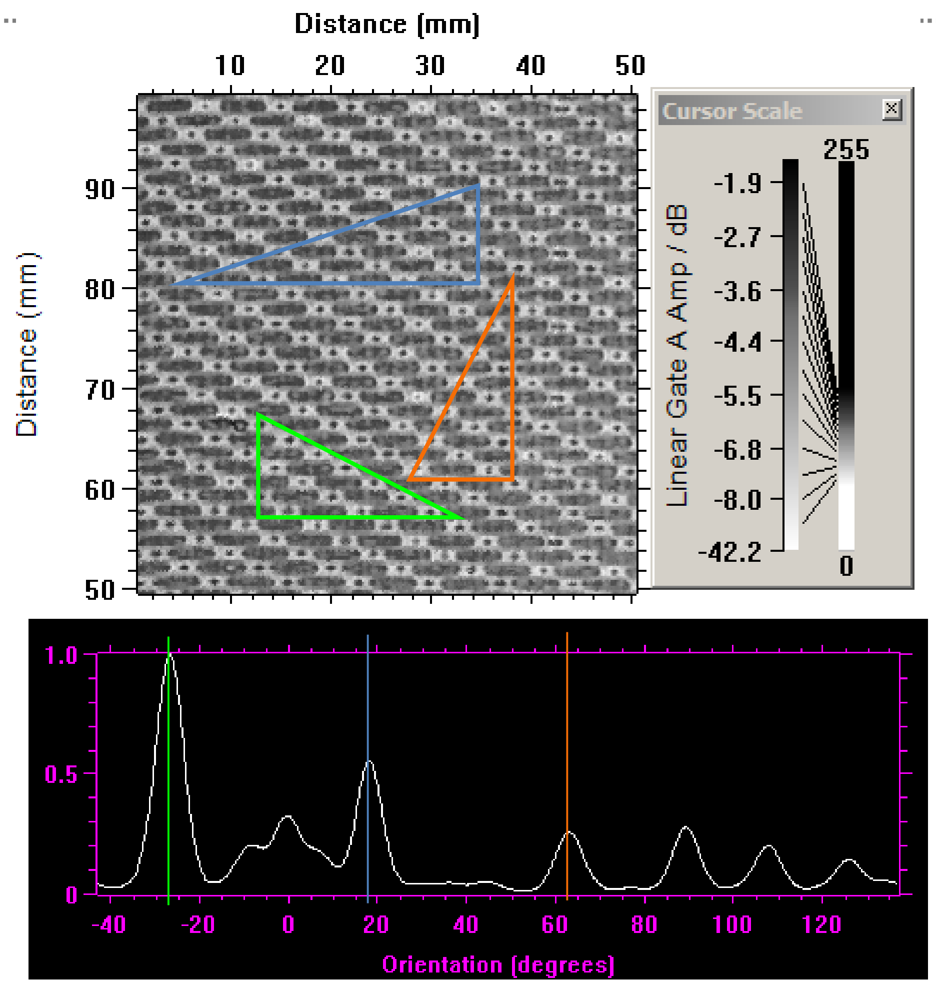
- 5-harness satin – offset [1]



- 5-harness satin – offset [2]

Ply Fingerprinting for woven fabrics

- Ultrasonic data
- 5-harness satin weave offset [2]



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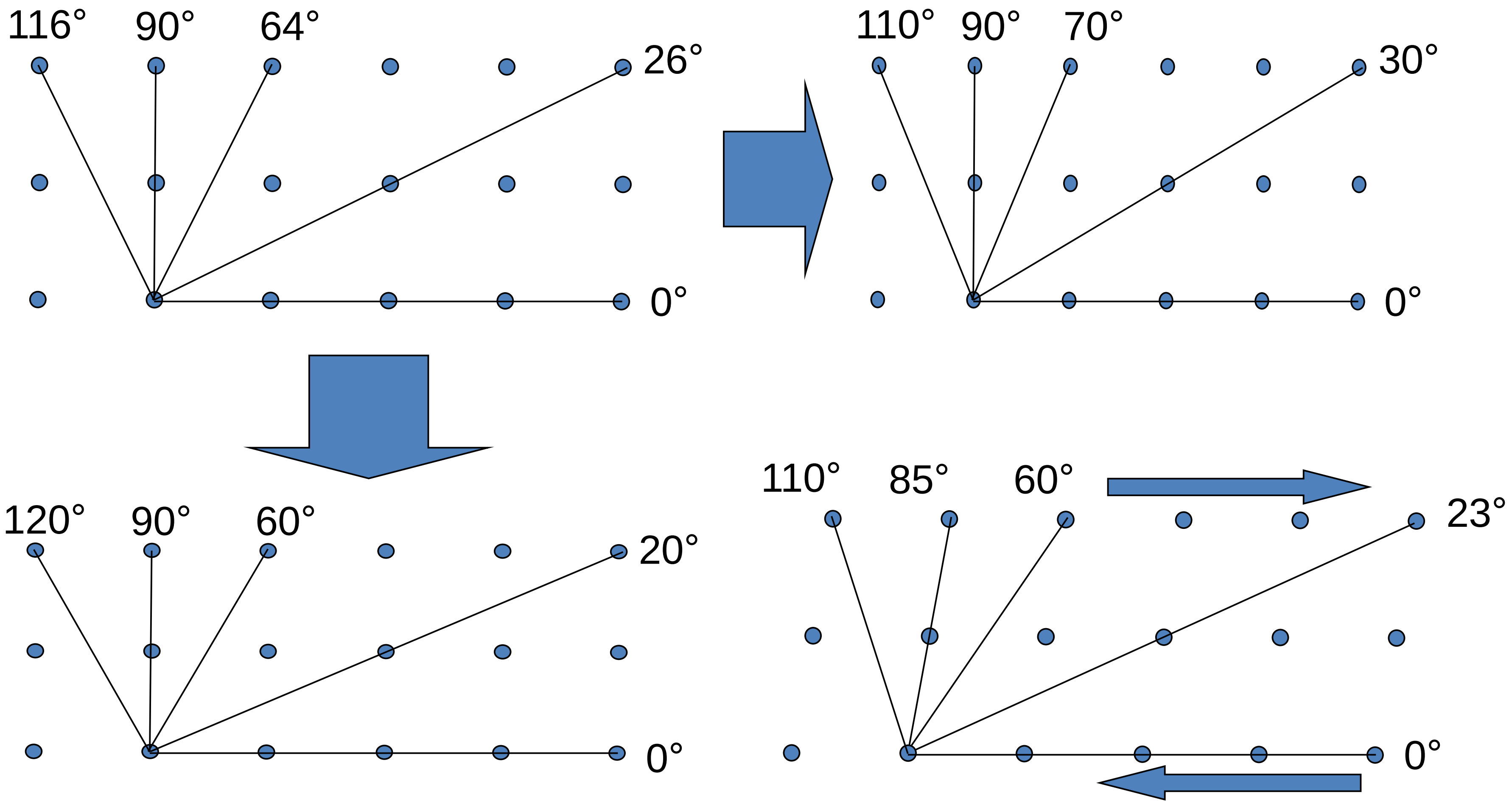
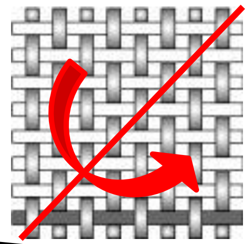
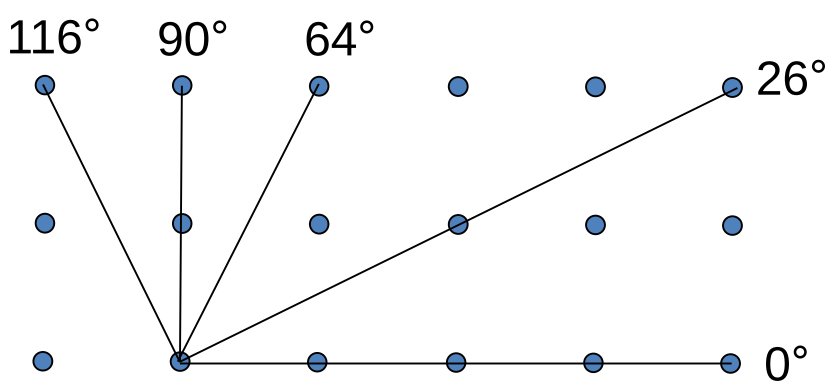
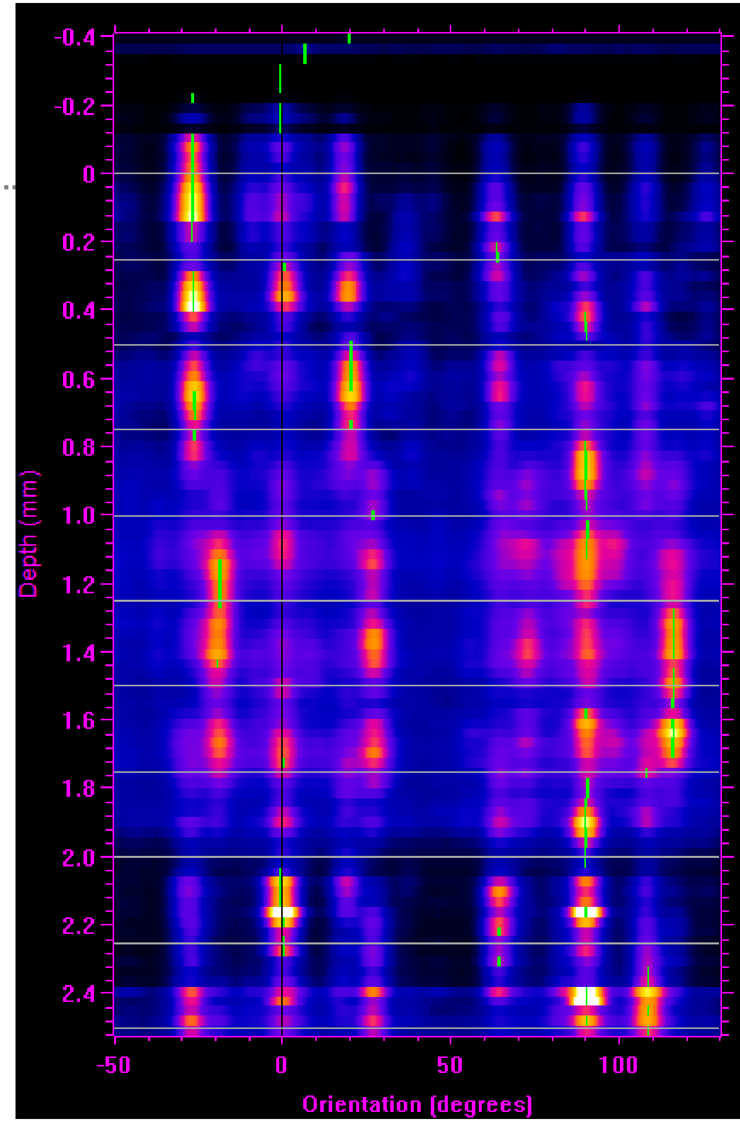
Woven fabrics – distortion/shear



- ‘Fingerprint’ obtained for each ply
- Top half:
  - -26° 0° 20° 64° 90° 110°
- Bottom half:
  - -20° 0° 26° 70° 90° 116°
- One strong angle from a square array of dots is at ±26.5°







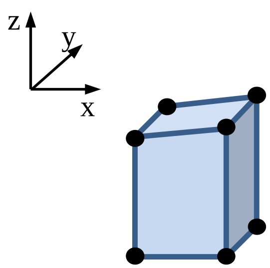
FE Materials Modelling

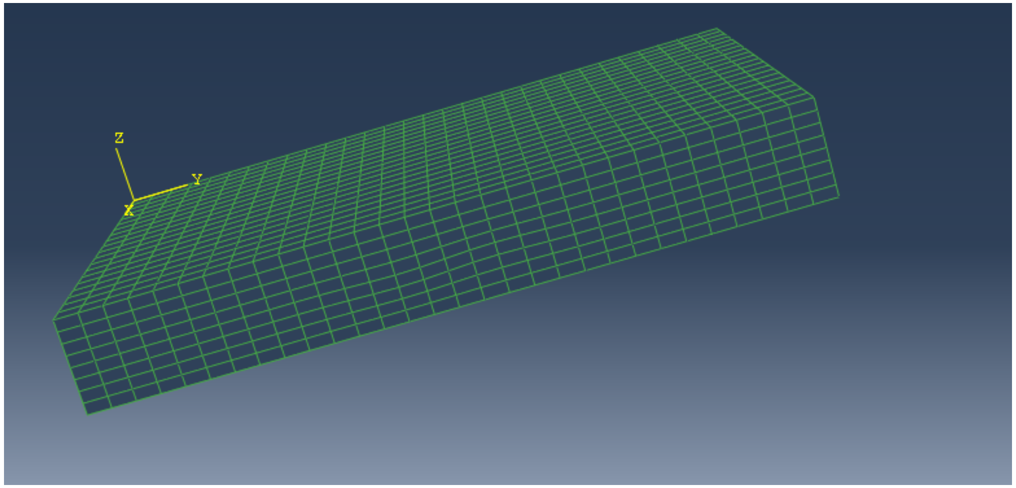
Mechanical properties of ‘as-manufactured’ component

Better-informed concession decisions

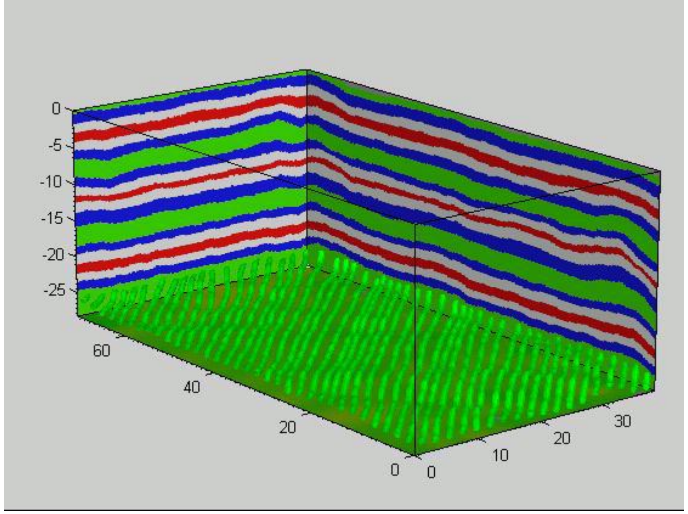
FE Materials Modelling

- Predict performance of component.
  - Materials model with actual 3D NDT data inputs
  - Create FE mesh using ply interface heights
  - Population with stiffness axes from fibre directions



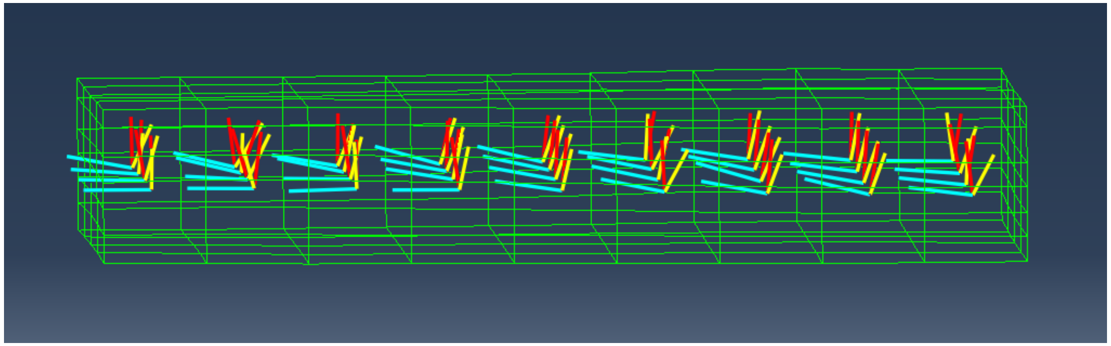


- Populate cells with 3D Fibre Angle (α,β,γ), vector field, stiffness axes 1’, 2’ & 3



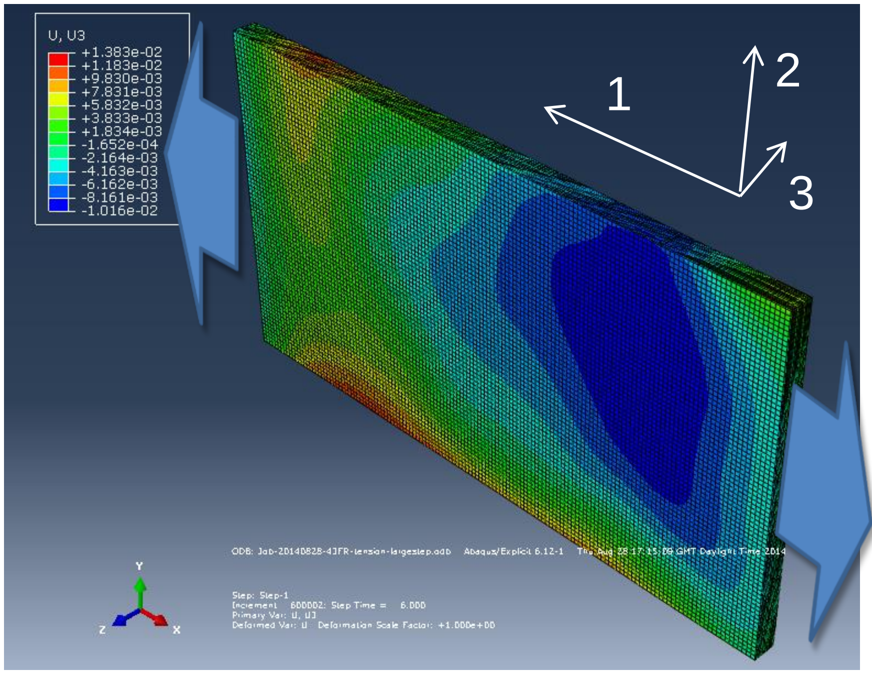
Fibre-tow vector field

FE mesh populated with fibre-tow vector field



FE Materials Modelling

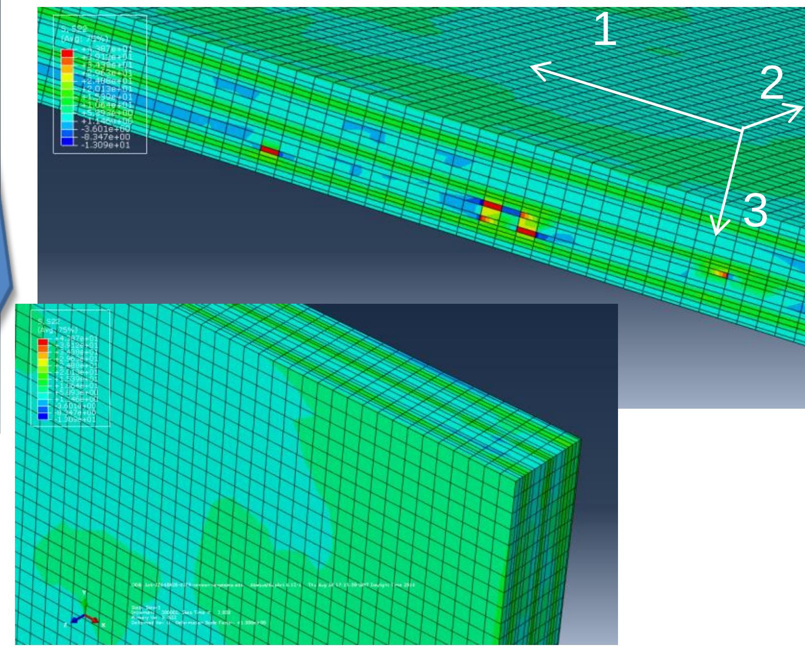
- Modelling of real specimen from NDT data



U$_3$ displacement (out-of-plane)

Tensile loading

S_{22} stress (parallel to 90^o fibres)



0.125 mm thick plies.

$[45^o, 0^o, -45^o, 90^o, -45^o, 0^o, 45^o]_3$

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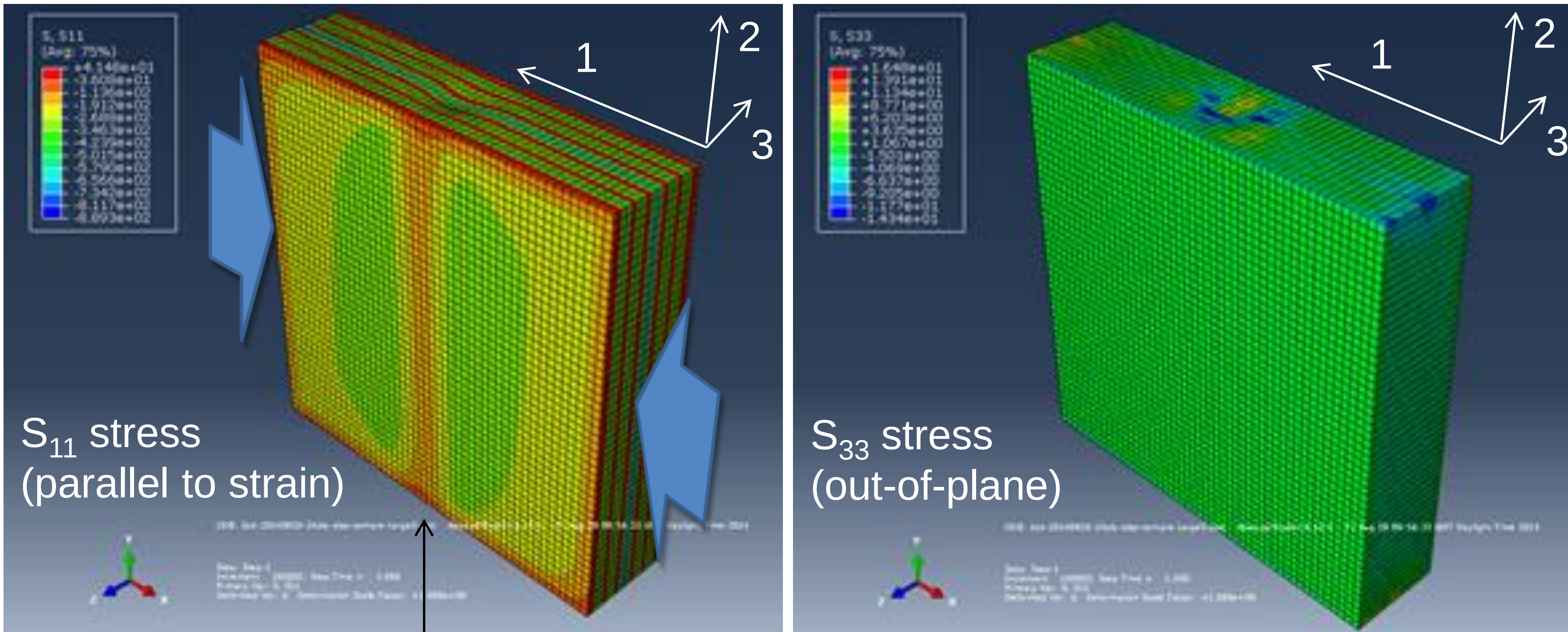
FE Materials Modelling

- Simulated 24-ply specimen – compressive loading

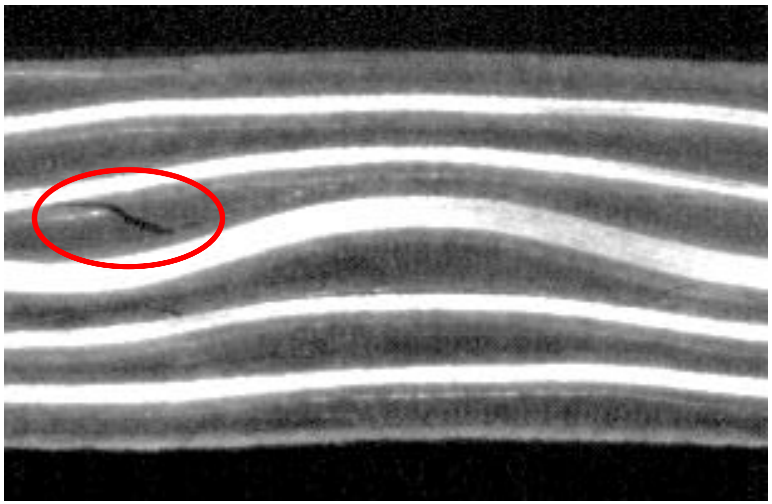


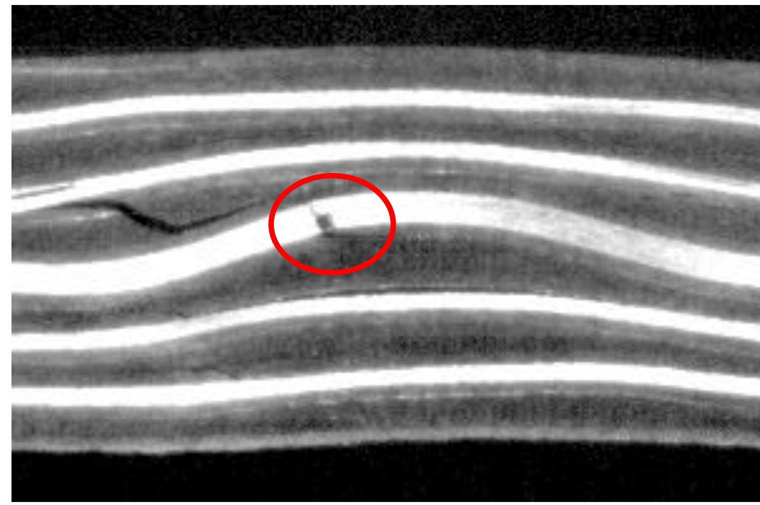
Simulated with a wrinkle

0.25 mm thick plies.
$[+45 / 90 / -45 / 0]_{3S}$

FE Materials Modelling

- Failure-mode Modelling





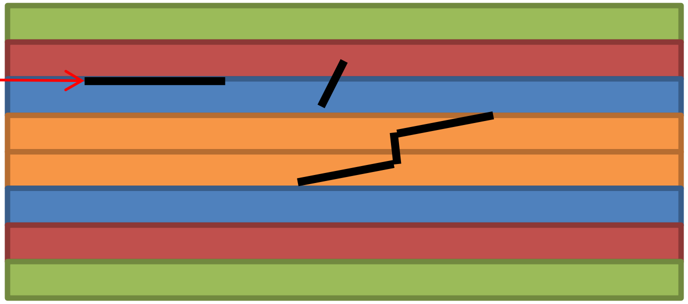
(Experimental results from earlier work by Mukhopadhyay et al, 2013)

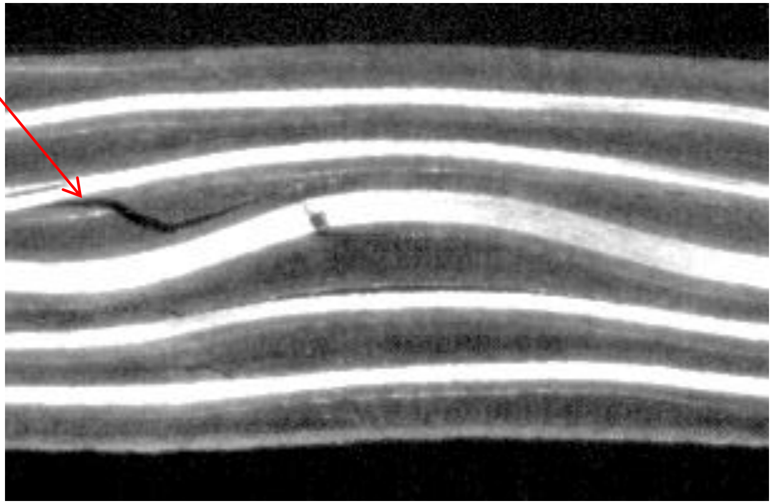
- Compression-loading. Development of:
  - matrix crack and delamination (left), and
  - post failure fibre kinking in axial plies (right).

NDT-based prediction of strength

Modelled failure modes

- Delaminations





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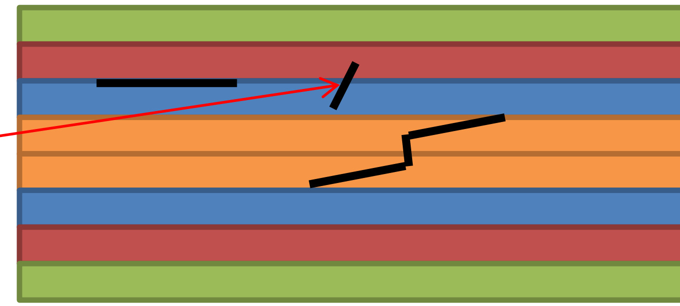
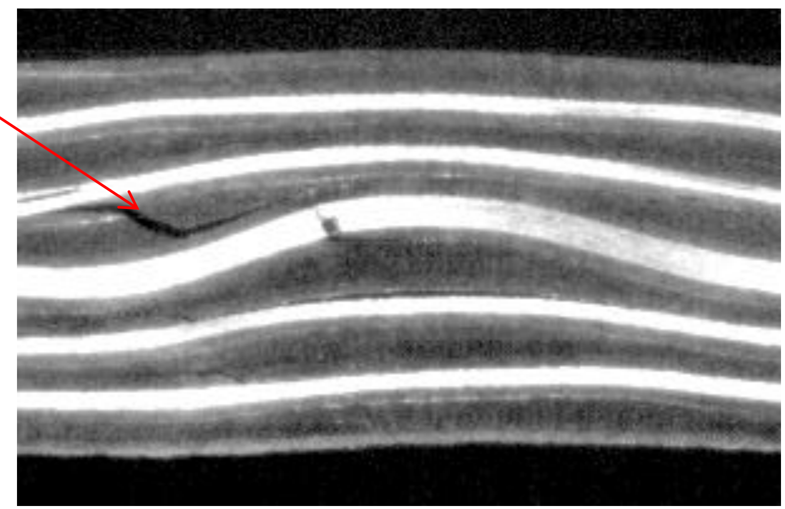
NDT-based prediction of strength

Modelled failure modes

- Delaminations
- Matrix crack





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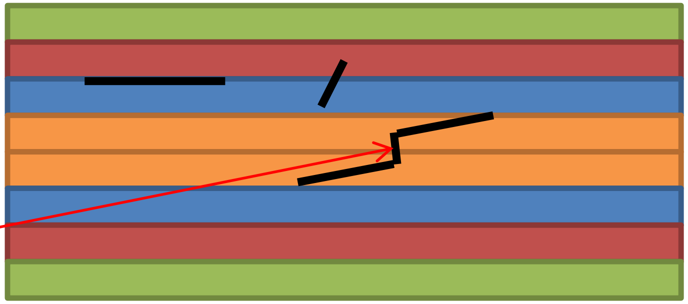
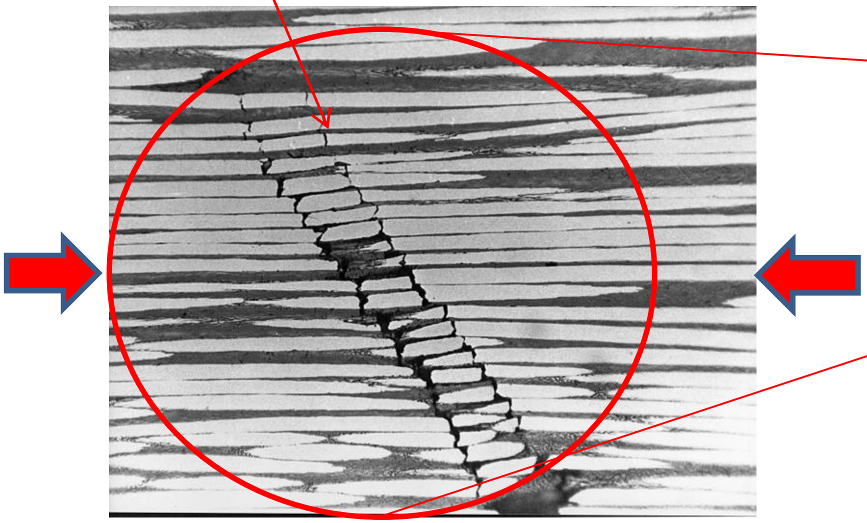
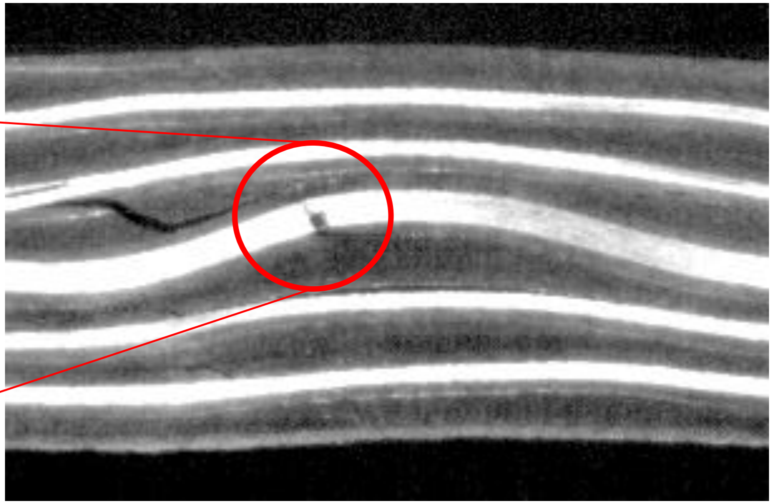
NDT-based prediction of strength

Modelled failure modes

- Delaminations
- Matrix crack
- Fibre kink

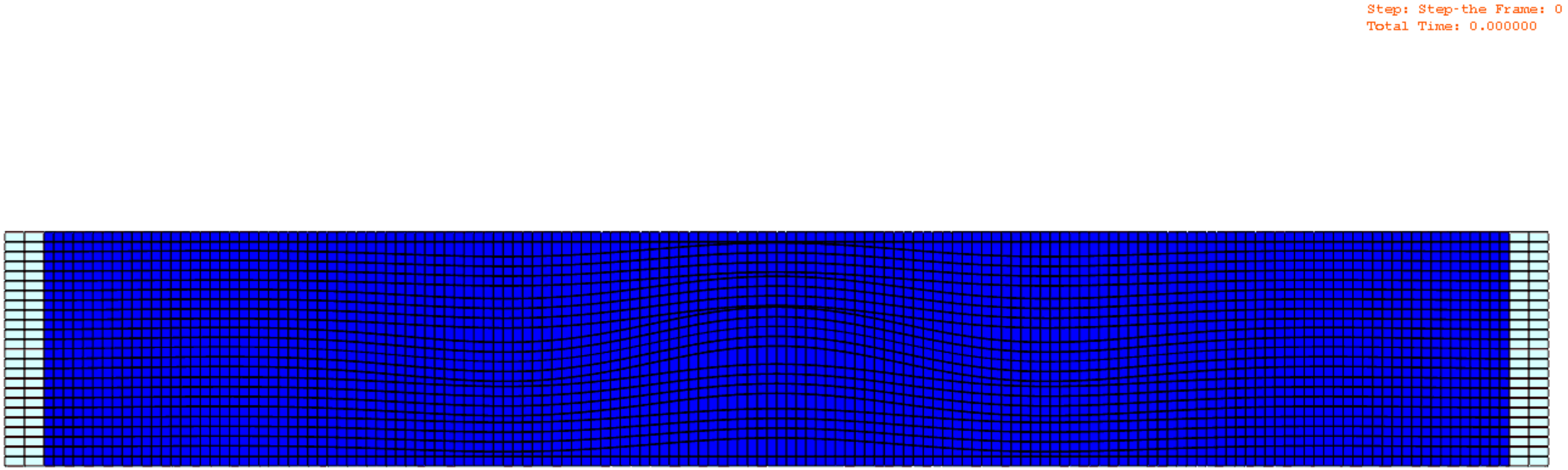


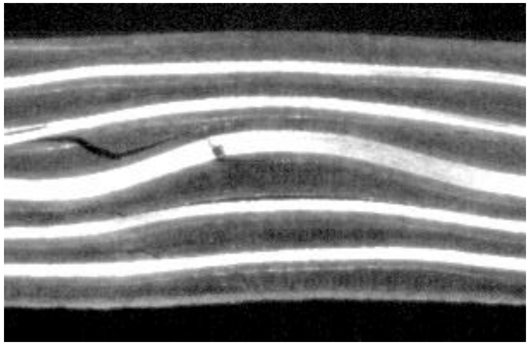




Engineering and Physical Sciences Research Council

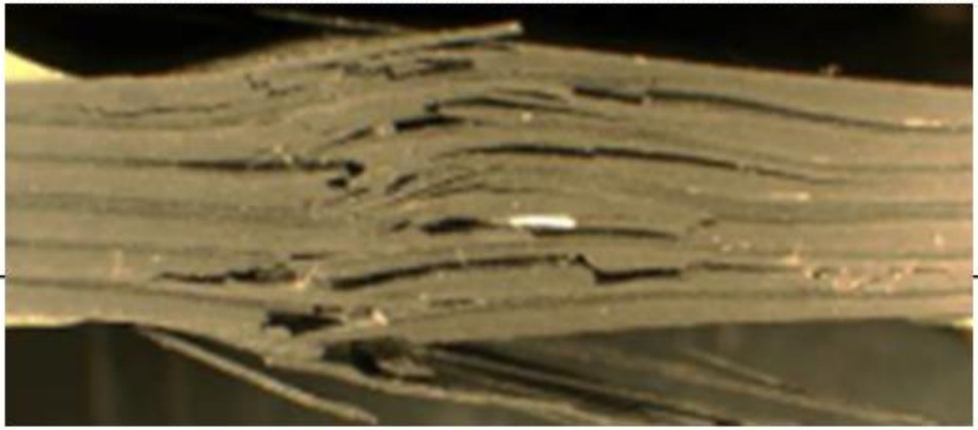
NDT-based prediction of strength

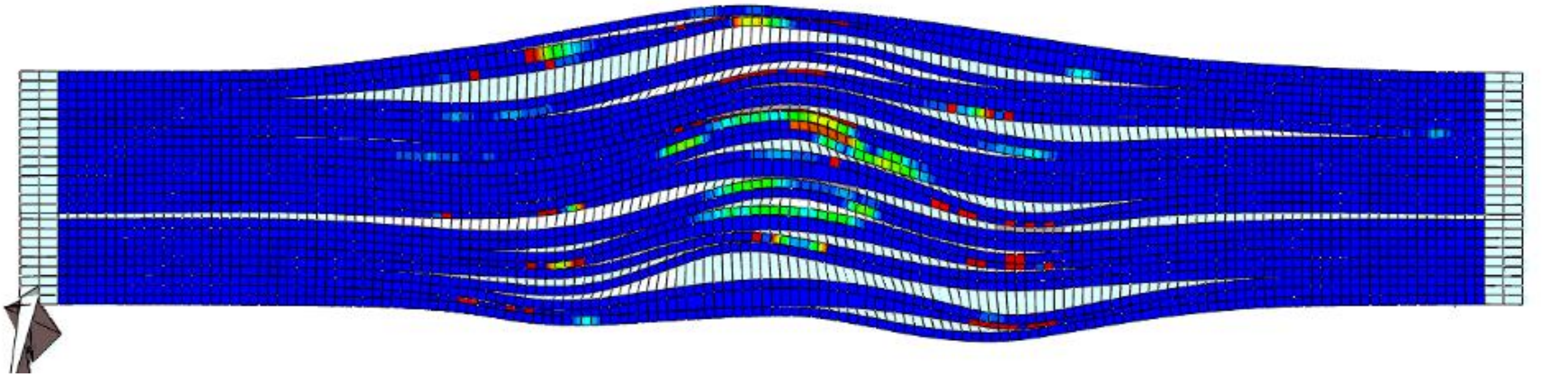




Miss Ningbo Xie, PhD student

Simulation and modelling





Miss Ningbo Xie, PhD student

Conclusions

- Ultrasound and X-ray CT offer:
  - 3D characterisation
  - Inversion to map 3D material properties
  - Automated creation of FE materials models
  - Prediction of performance
- But only ultrasound can do this for large components.
- NDT-based FE Materials modelling offers potential benefits