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Current 3D characterisation of composites and importance of metrics

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Ningbo Xie and Stephen Hallett

University of Bristol

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Content

- Introduction
- Ultrasonic 3D imaging of composites
  - Analytic signal
  - Ply drops, tape gaps, tape overlaps
  - Delaminations
  - Wrinkles, waviness, etc
- Fibre-orientation mapping
- NDT-based FE performance modelling
- Importance of metrics

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Introduction

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

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Introduction

- Ultrasonic 3D imaging of composites (Fellowship)
  - EPSRC Fellowship in Manufacturing 2013-2018
  - Seeking partners:
    - End-users to demonstrate the algorithms
    - Supply-chain for embedding the algorithms in software
- Impact acceleration project:
  - Algorithm Deployment Support Service at MTC
    - Software-engineering document generation
    - Validation tests

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Ultrasonic 3D imaging of composites

Reference:

R.A. Smith, L.J. Nelson, M.J. Mienczakowski and P. D. Wilcox,

“Ultrasonic tracking of ply drops in composite laminates.”

AIP Conf. Proc. 1706, 050006 (2016);
http://dx.doi.org/10.1063/1.4940505

QNDE conference date: 26–31 July 2015, Minneapolis.

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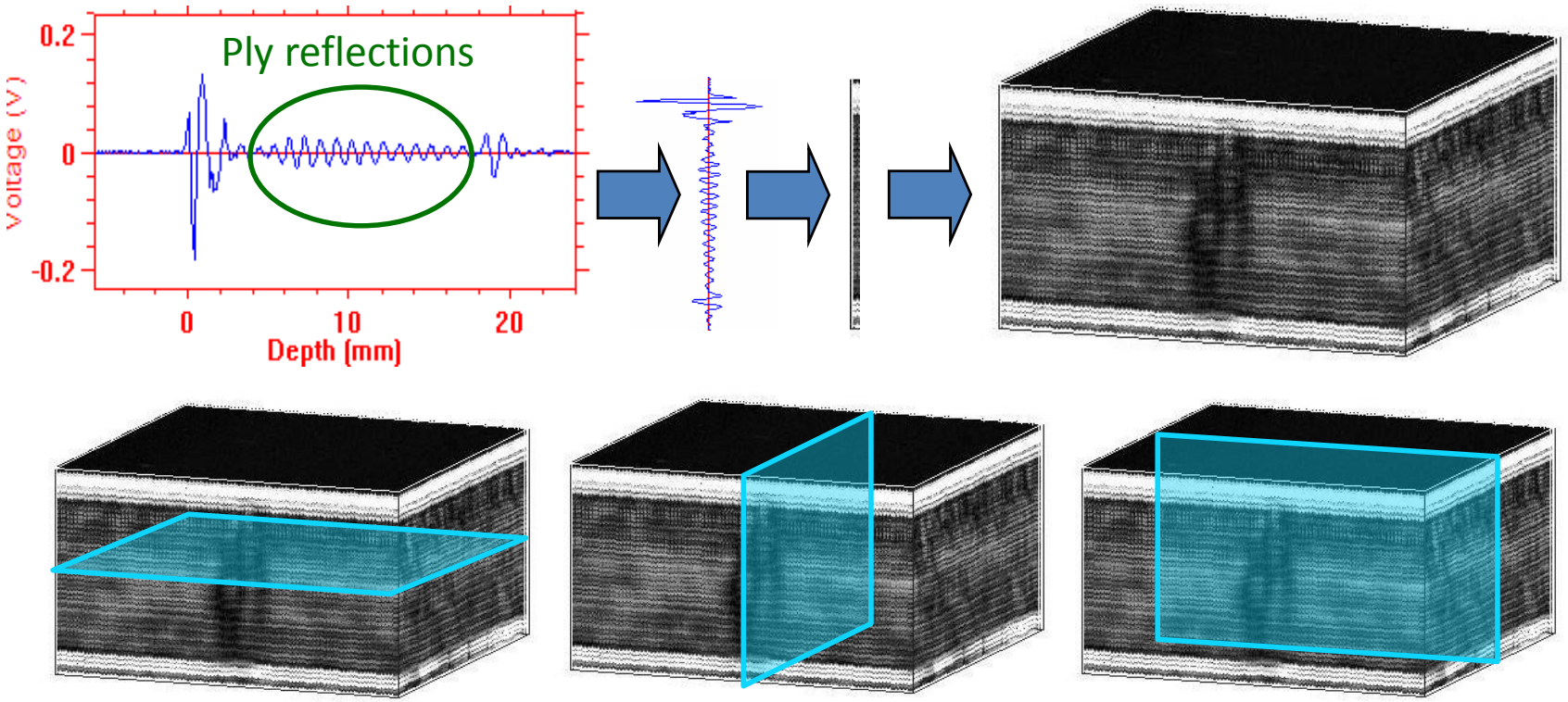
Ultrasonic 3D imaging of composites

Full-waveform data acquisition…



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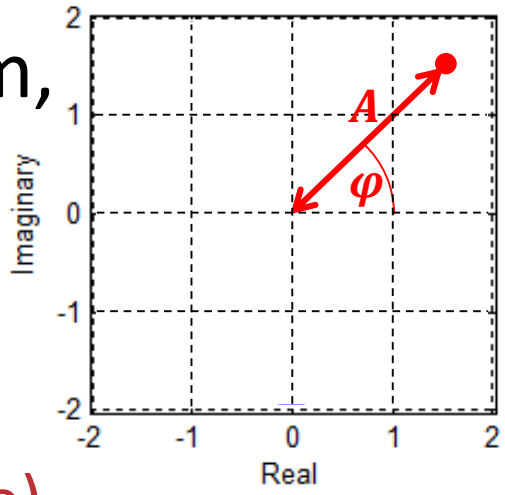
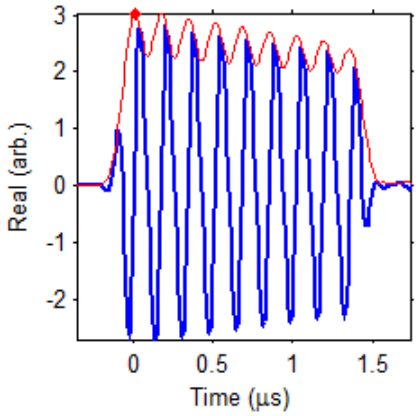
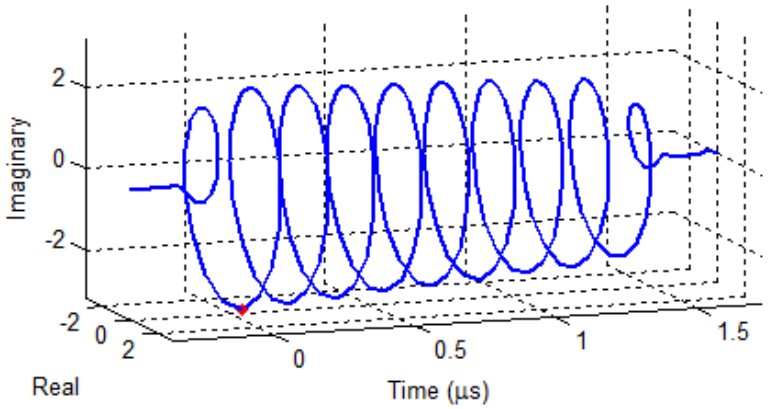
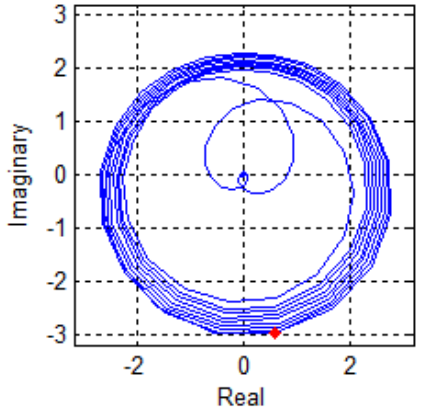
Ultrasonic 3D imaging of composites

- Analytic signal conversion algorithm, giving:
  - Instantaneous Amplitude (envelope)
  - Instantaneous Phase
  - Instantaneous Frequency (Phase/time)









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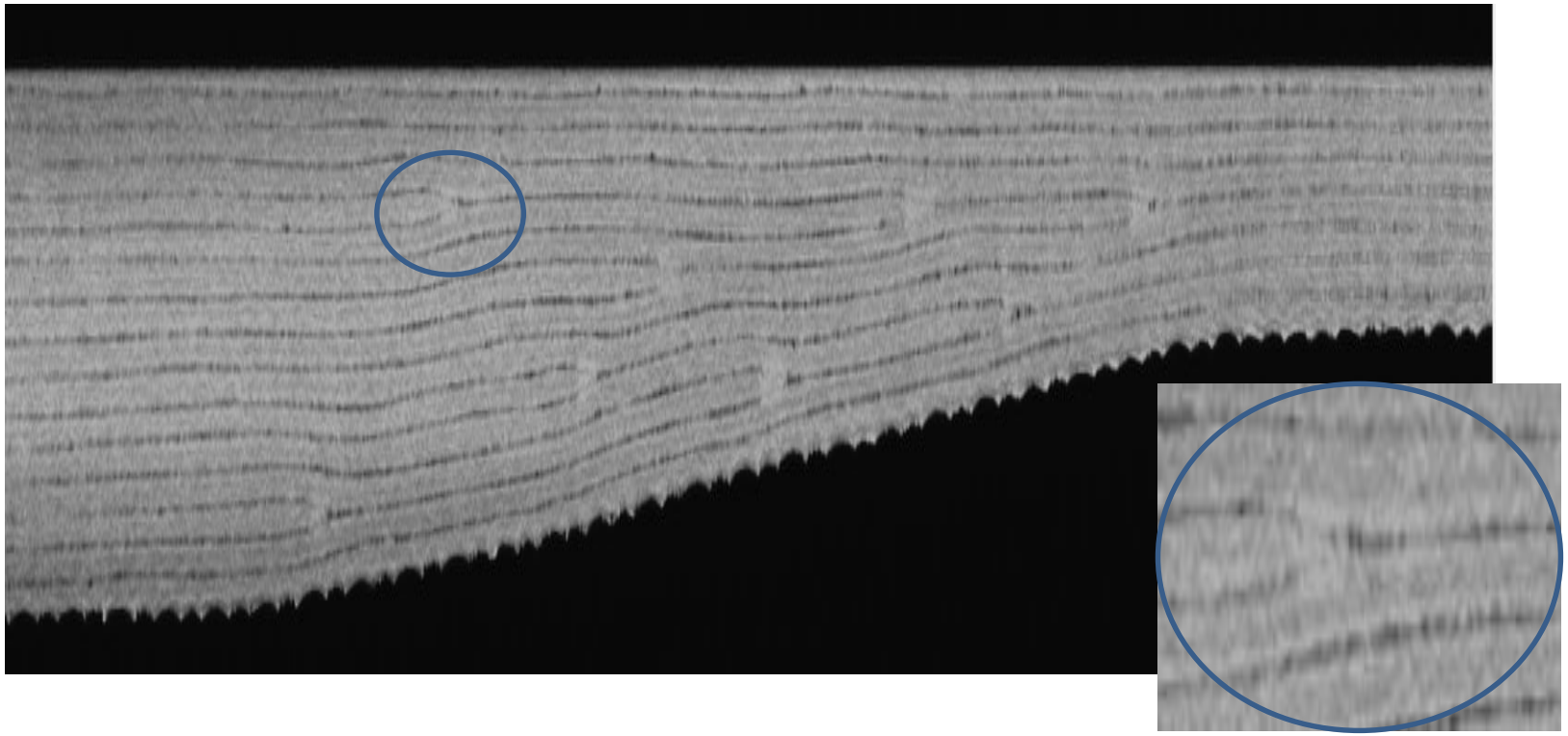
3D tracking of resin inter-ply layers

- Ply-drop coupons
- X-ray CT: 49 kV, 20 µm voxel size, 4 shots



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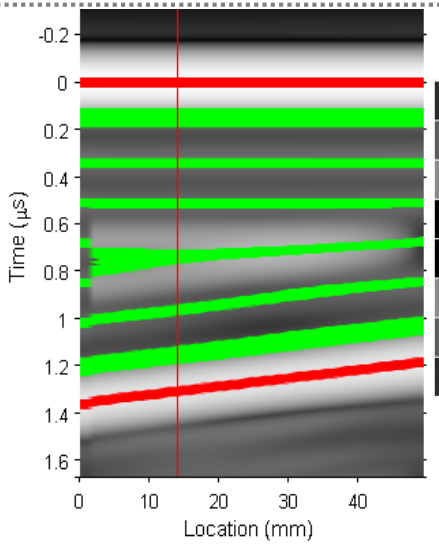
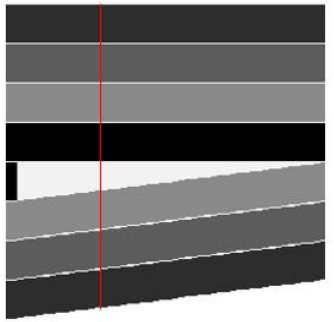
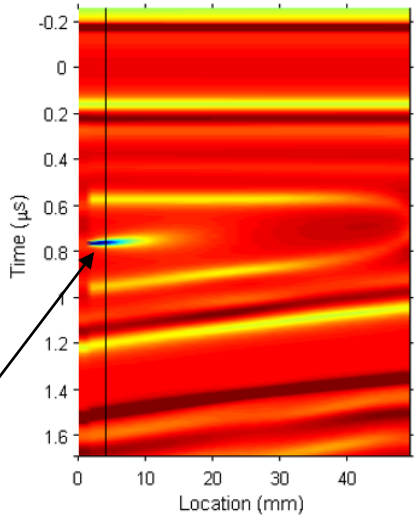
Ultrasonic 3D imaging of composites

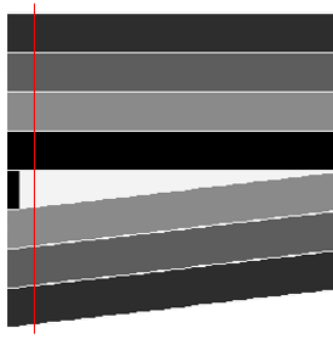
- Ply tracking – simulated data
  - Uses Instantaneous Amplitude, phase & frequency
  - Superimposes FWE, BWE (red) and resin layers (green)
  - Identification, classification and tracking of ply drops, tape gaps and tape overlaps





Instantaneous amplitude with ply tracking





Instantaneous frequency

Deep reduction in instantaneous frequency

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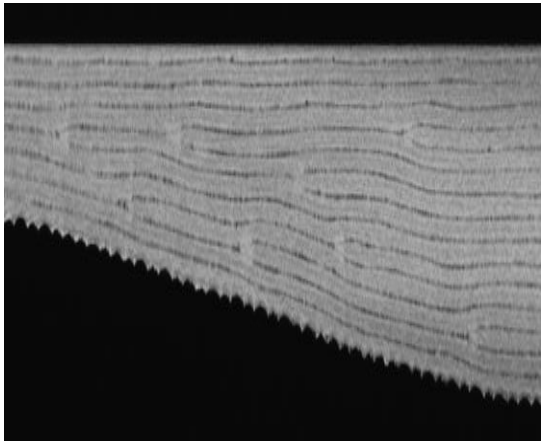
Ply Tracking

- Real data, wedge specimen
  - 0.189 mm ply spacing
  - 0.050 mm resin layers



49 kV, 4-shots per projection,
20 µm voxel size

- X-ray CT scan…

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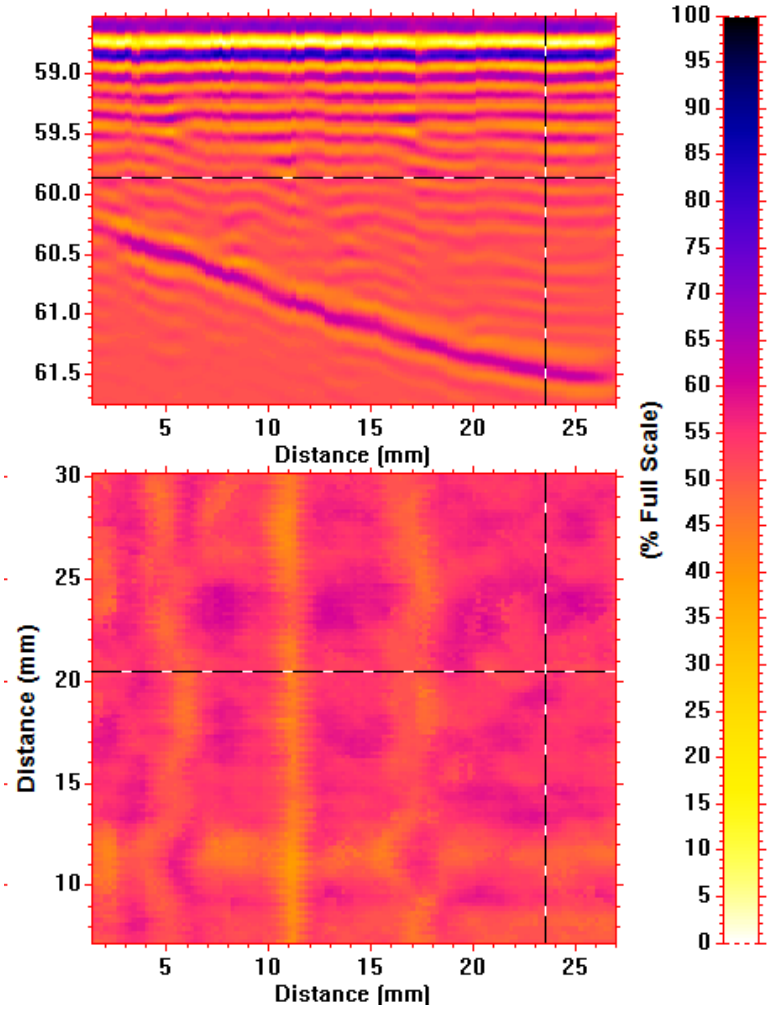
Ply Tracking

- Real data, wedge specimen
  - 0.189 mm ply spacing
  - 0.050 mm resin layers
- Resonant frequency ~8 MHz
  - 7.5 MHz Centre Frequency
  - 7.5 MHz bandwidth
- Conventional B-scan…



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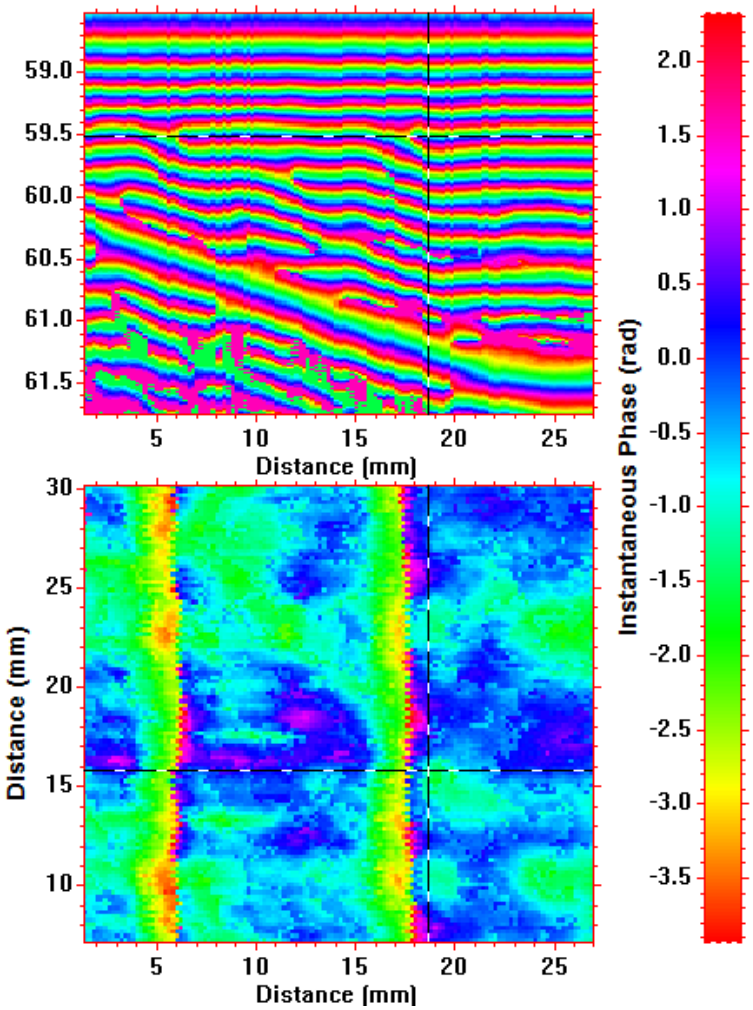
Ply Tracking

- Real data, wedge specimen
  - 0.189 mm ply spacing
  - 0.050 mm resin layers
- Resonant frequency ~8 MHz
  - 7.5 MHz Centre Frequency
  - 7.5 MHz bandwidth
- Instantaneous phase…



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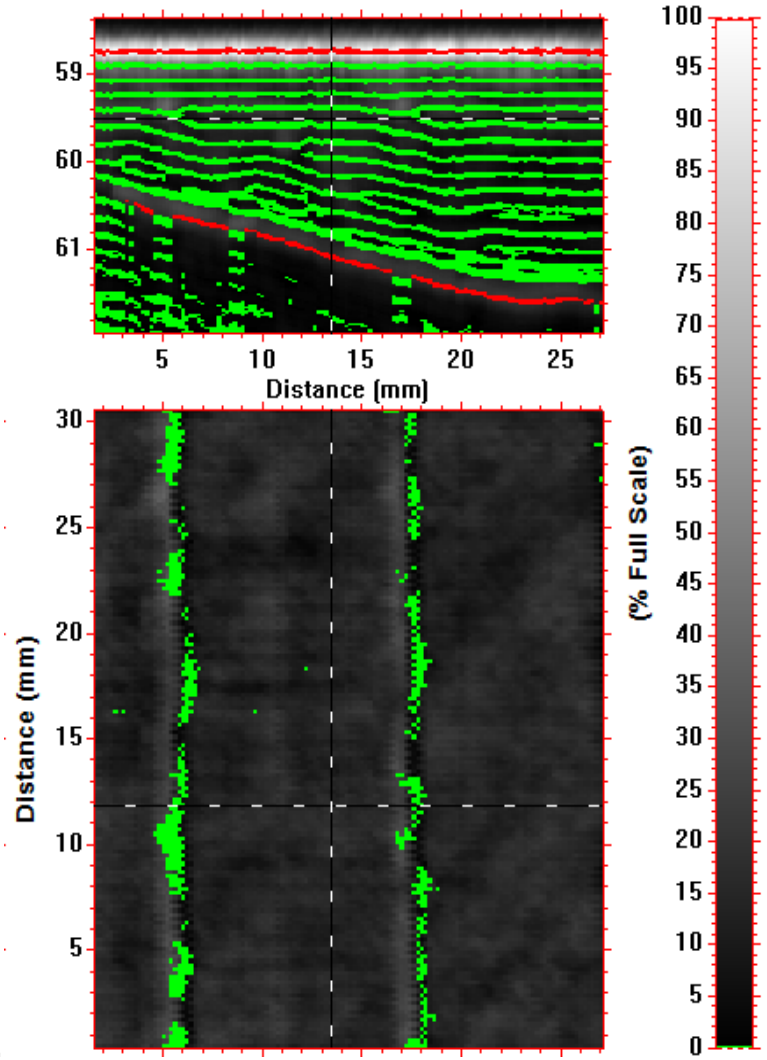
Ply Tracking

- Real data, wedge specimen
  - 0.189 mm ply spacing
  - 0.050 mm resin layers
- Resonant frequency ~8 MHz
  - 7.5 MHz Centre Frequency
  - 7.5 MHz bandwidth
- Ply tracking from Phase
- Instantaneous Amplitude with ply tracking…



Greyscale: amplitude. Green: Resin layer. Red: front or back surface.

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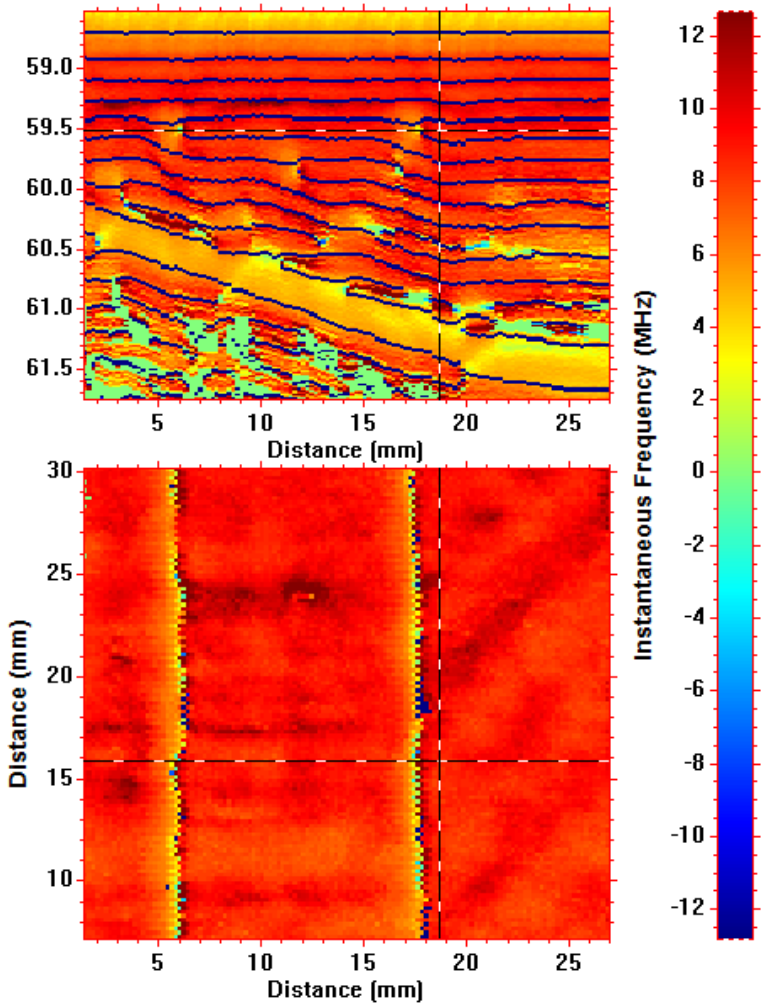
Ply Tracking

- Real data, wedge specimen
  - 0.189 mm ply spacing
  - 0.050 mm resin layers
- Resonant frequency ~8 MHz
  - 7.5 MHz Centre Frequency
  - 7.5 MHz bandwidth
- Instantaneous Frequency…
  - Drops at end of a ply
  - Drops in 1st and last ply



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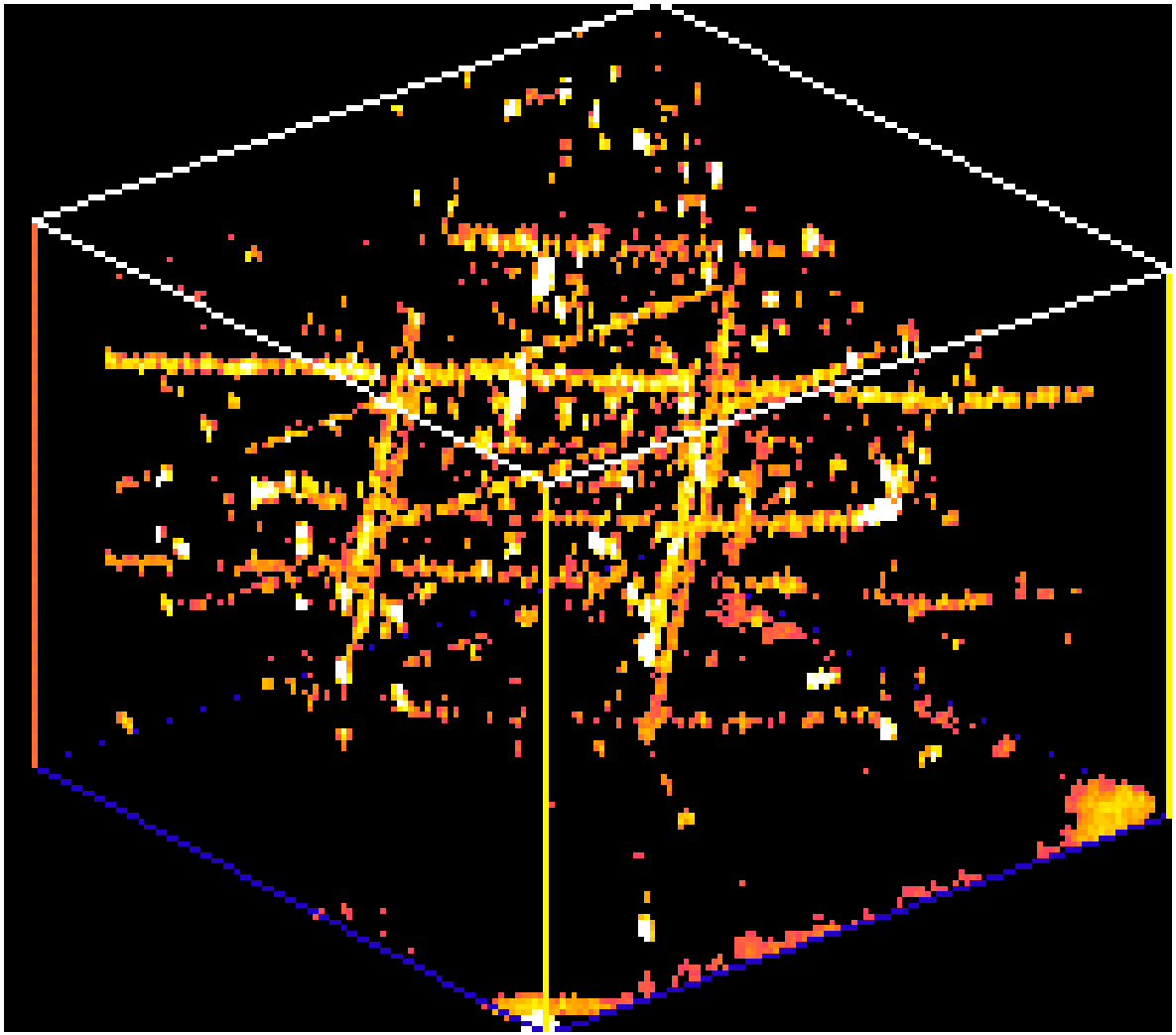
Tape gaps and overlaps



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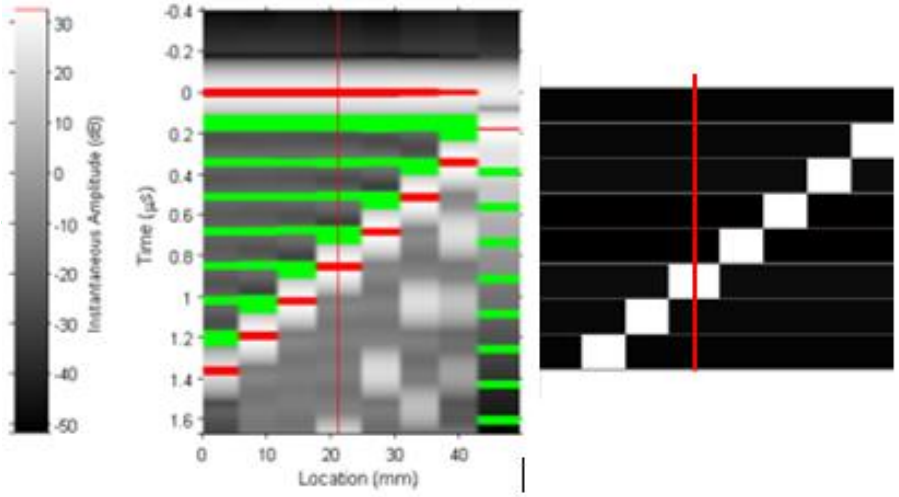
Ultrasonic 3D imaging of composites

- Defect Characterisation
- Simulated delamination
  - Identification of delaminations as air-backed BWE



Simulated data for delaminations in an 8-ply composite
Green: Resin layer. Red: front, back or delamination.
Note: multiple reflections are not colour coded

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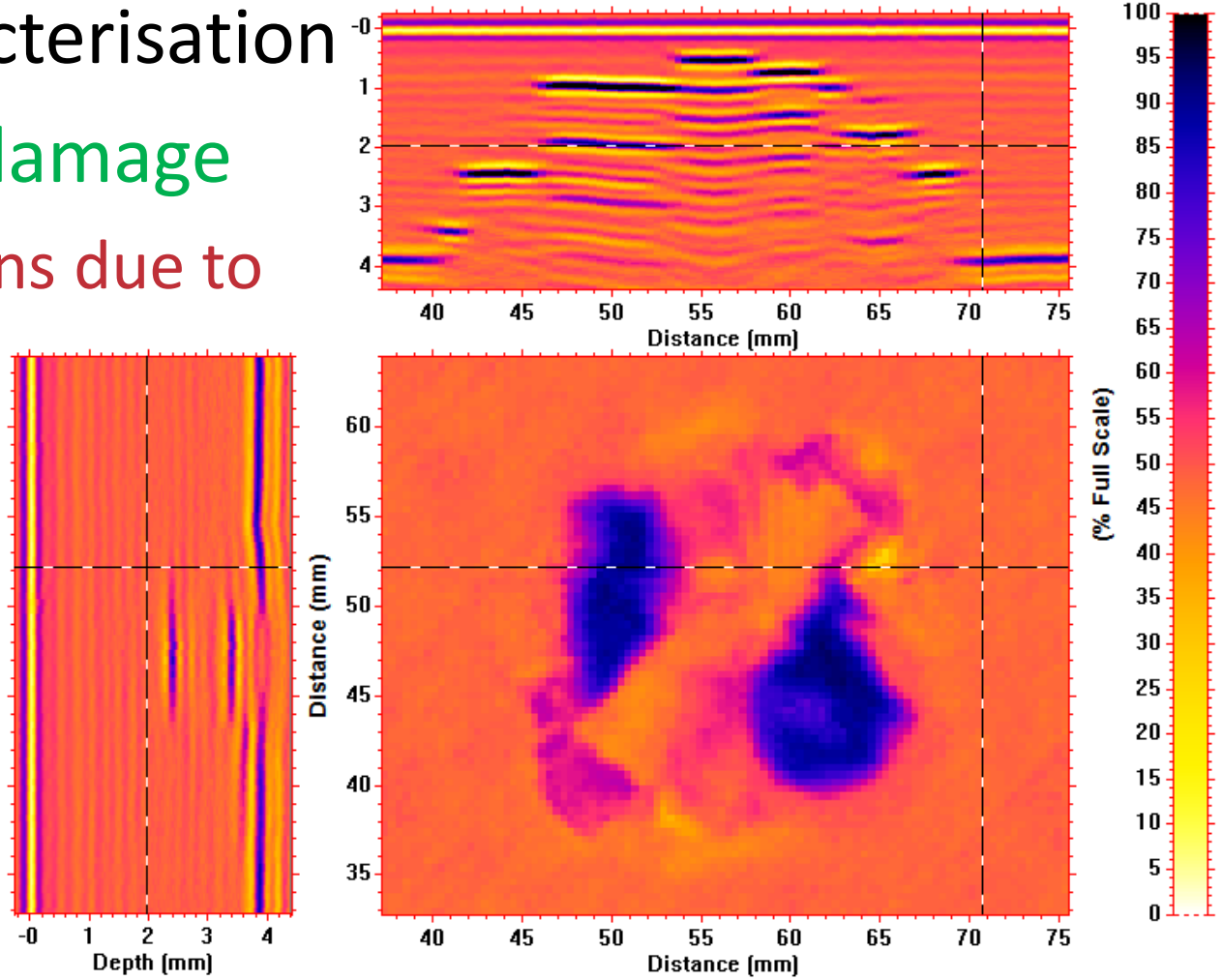
Ultrasonic 3D imaging of composites

- Defect Characterisation
- Real impact damage
  - Delaminations due to impact
- Conventional B-scan…



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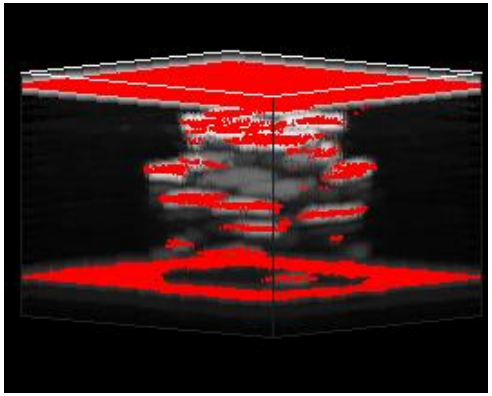
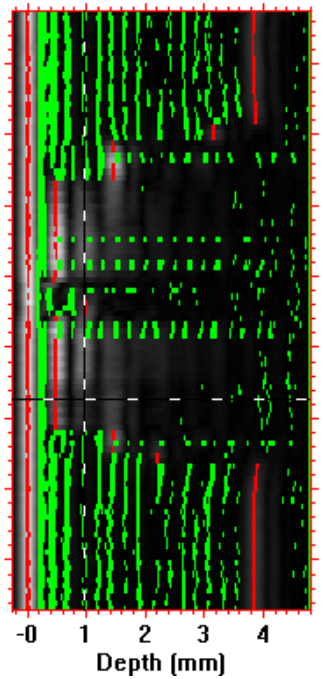
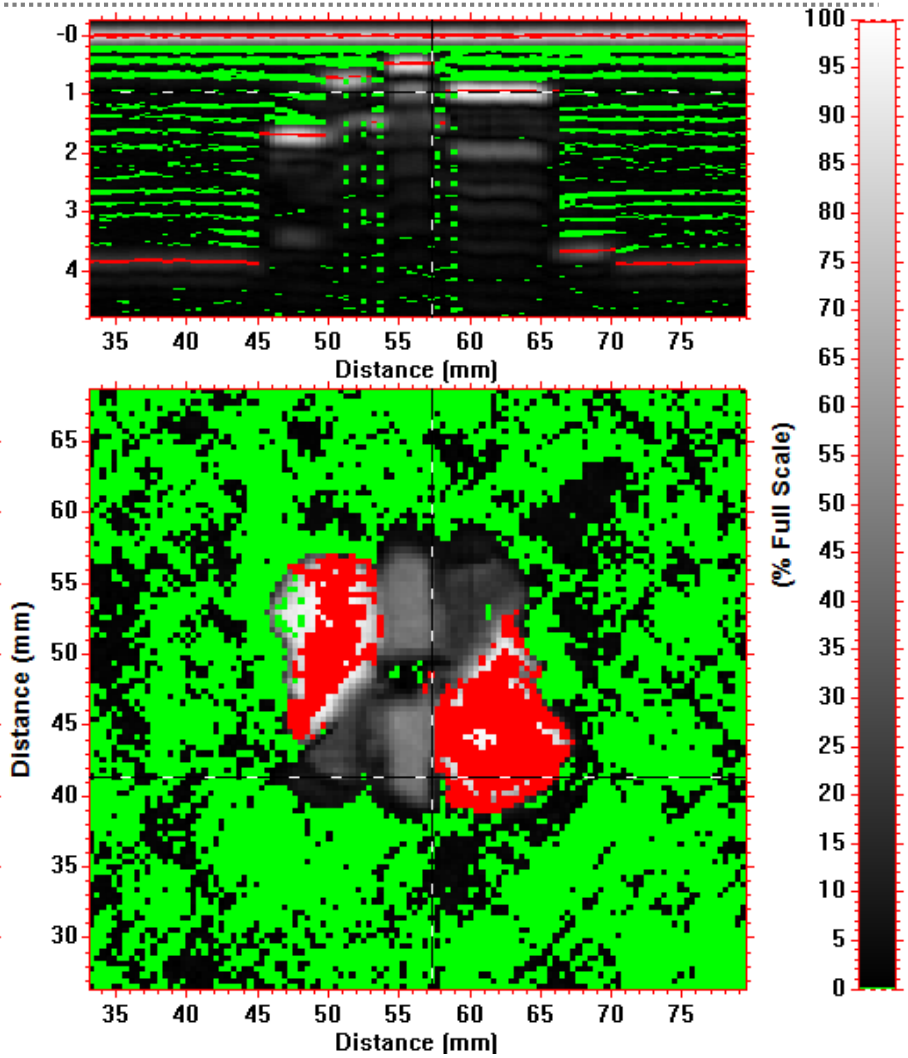
Ultrasonic 3D imaging of composites

- 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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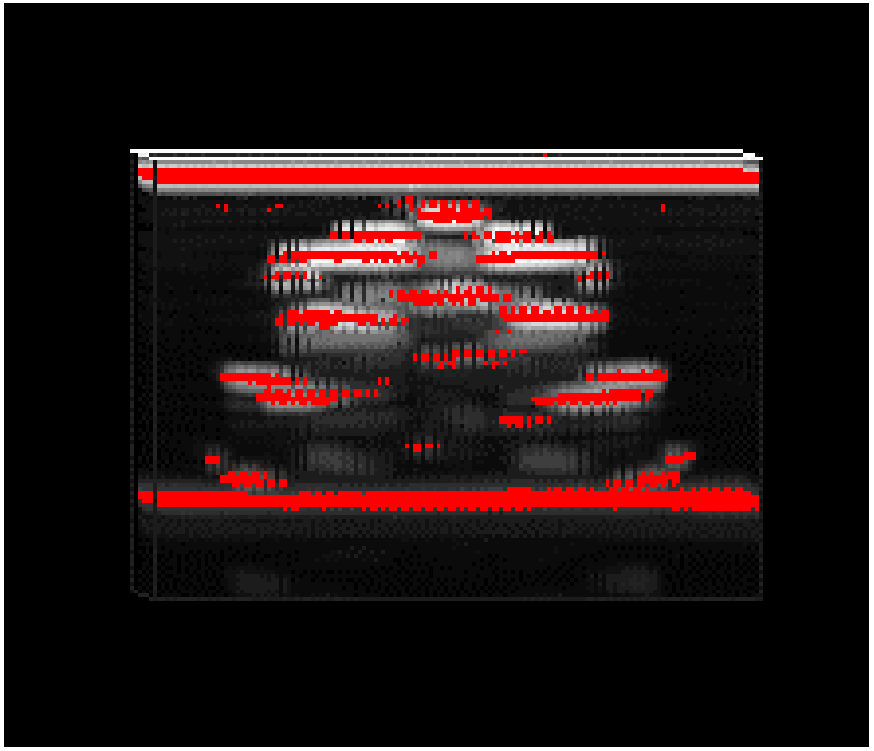
Ultrasonic 3D imaging of composites

- Defect Characterisation
  - Delaminations due to impact damage

Video:



- Instantaneous amplitude with Ply tracking…

Red: front, back or delamination.

Note: multiple reflections are not colour coded

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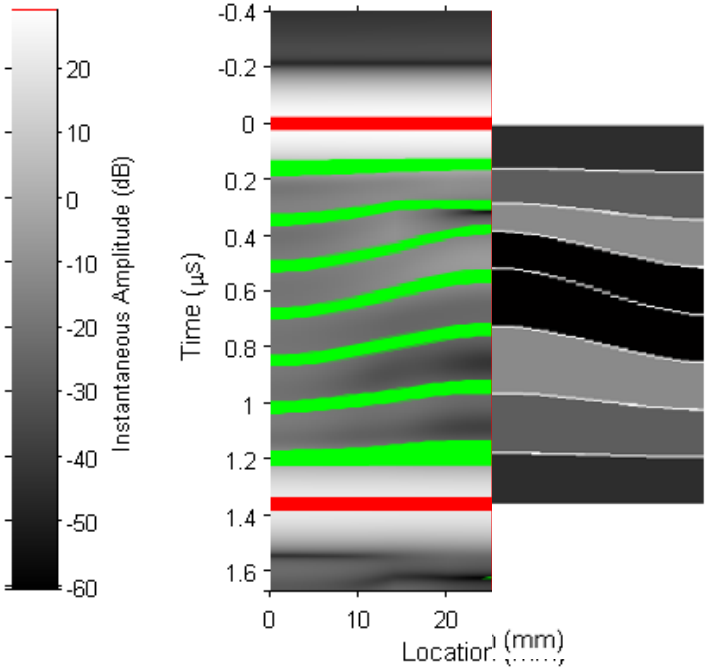
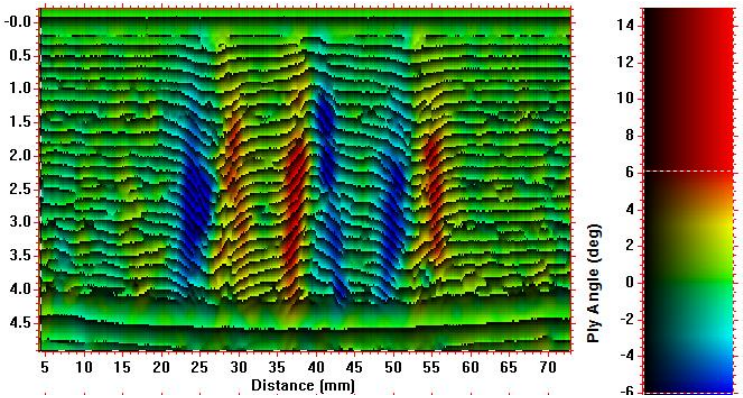
Ultrasonic 3D imaging of composites

- Defect Characterisation
  - Mapping of out-of-plane wrinkles
    - Quantification of the wrinkle properties recently shown to be important for strength



Simulated wrinkle with mapping of resin layers (green).



Real component with mapping of ply angle through wrinkles.

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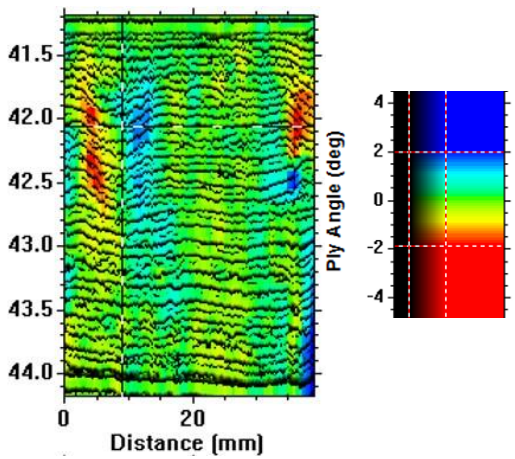
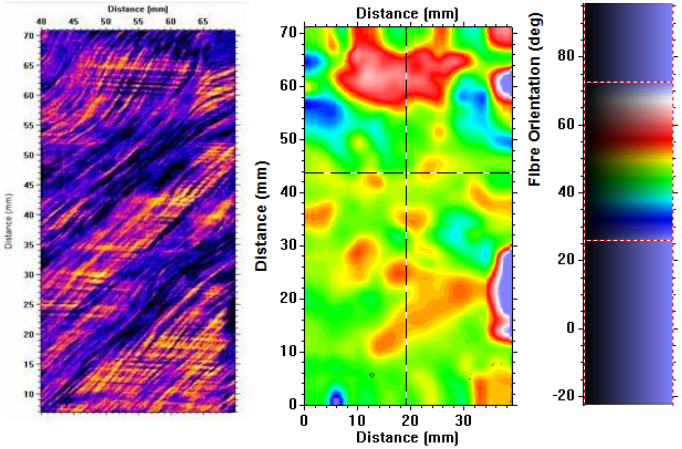
3D non-destructive characterisation

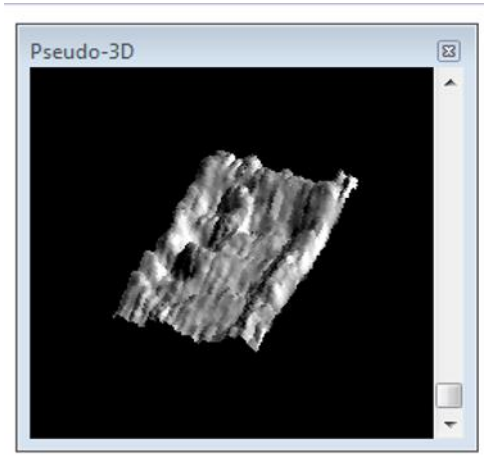
- Quantitative 3D fibre orientation ‘inversion’

B-scan



C-scan

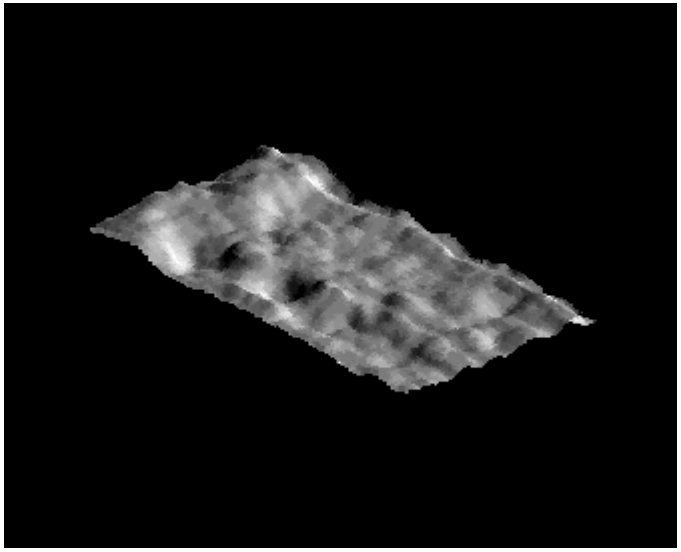


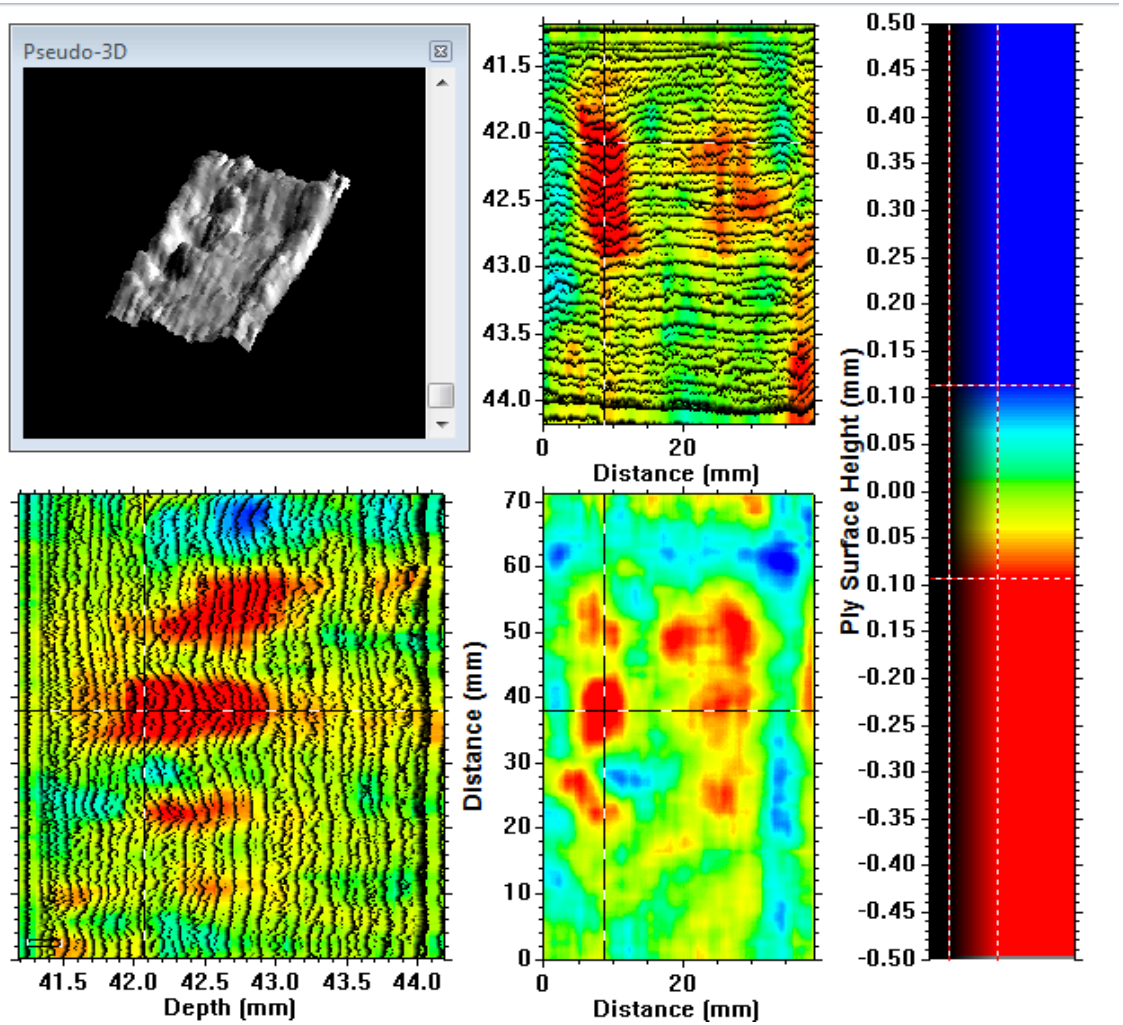


α,β – out-of-plane fibre angle + γ – in-plane fibre angle → Surface Heights

3D non-destructive characterisation

- Quantitative ply surface height…





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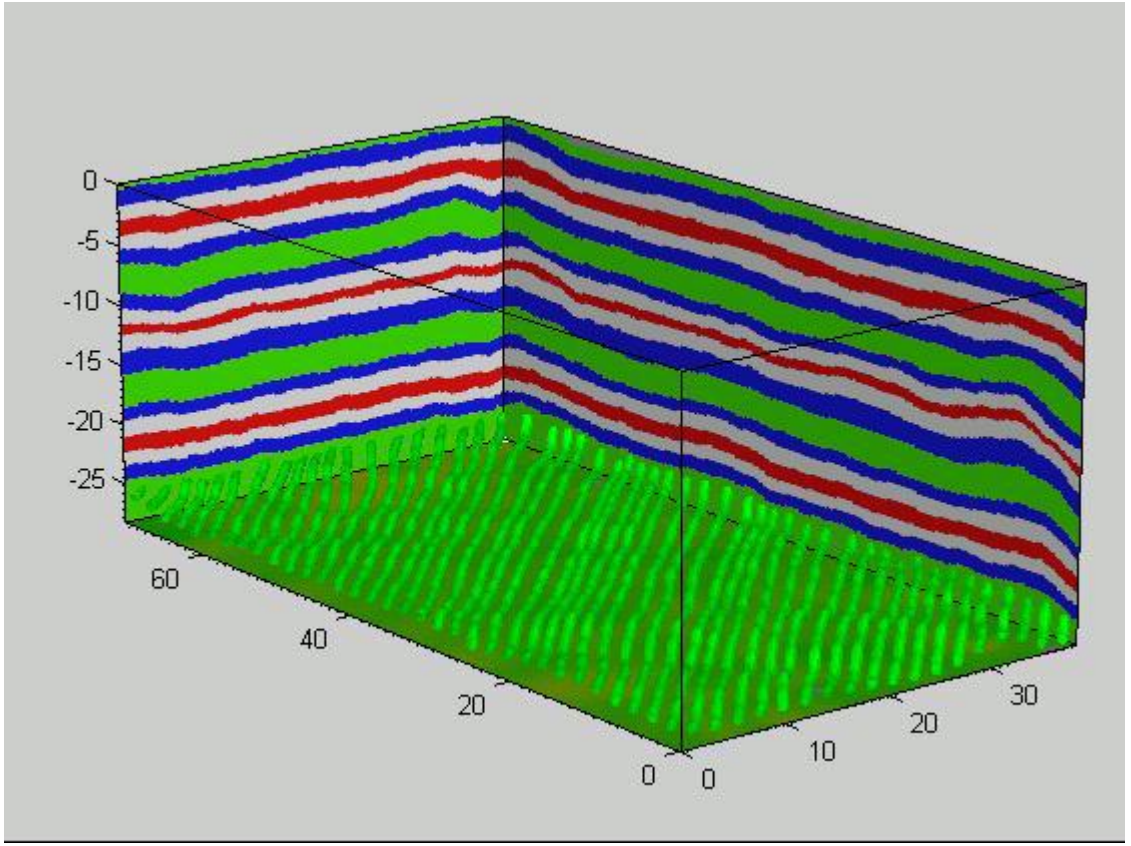
3D Vector Map of Fibre-tow orientation

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



0.125 mm thick plies.

$[45^{\circ}, 0^{\circ}, -45^{\circ}, 90^{\circ}, -45^{\circ}, 0^{\circ}, 45^{\circ}]_3$

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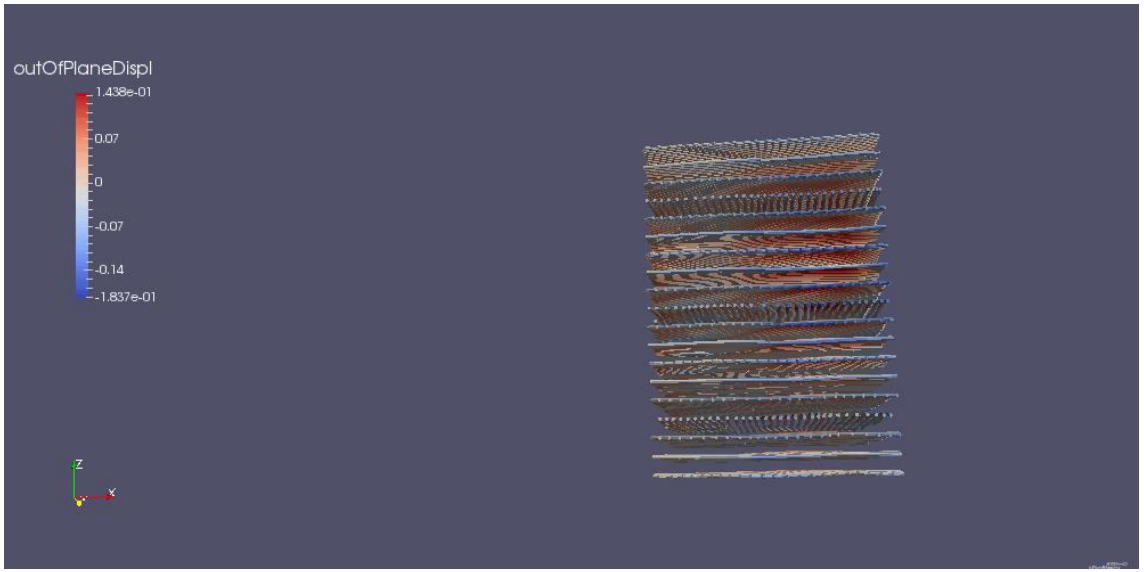
3D Vector Map of Fibre-tow orientation

- 3D map of
- Fibre tows
- 3D orientation



Dr Luke Nelson, Research Associate

0.125 mm thick plies.

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

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Importance of metrics

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Importance of metrics

- NDT-based performance modelling

- Example: Out-of-plane Wrinkling
  - Ningbo Xie, Supratik Mukhopadhyay and Stephen Hallett, University of Bristol:

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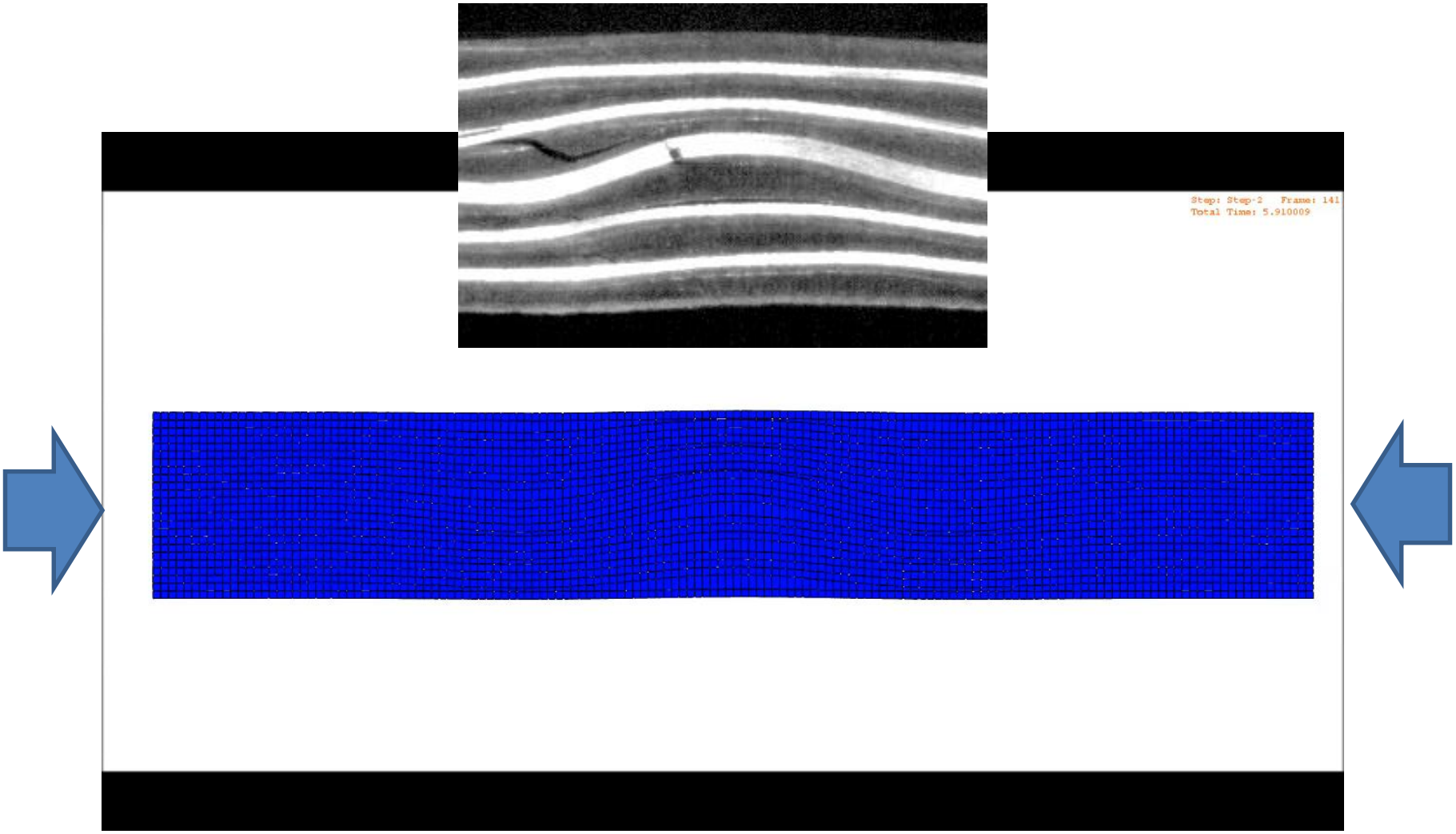
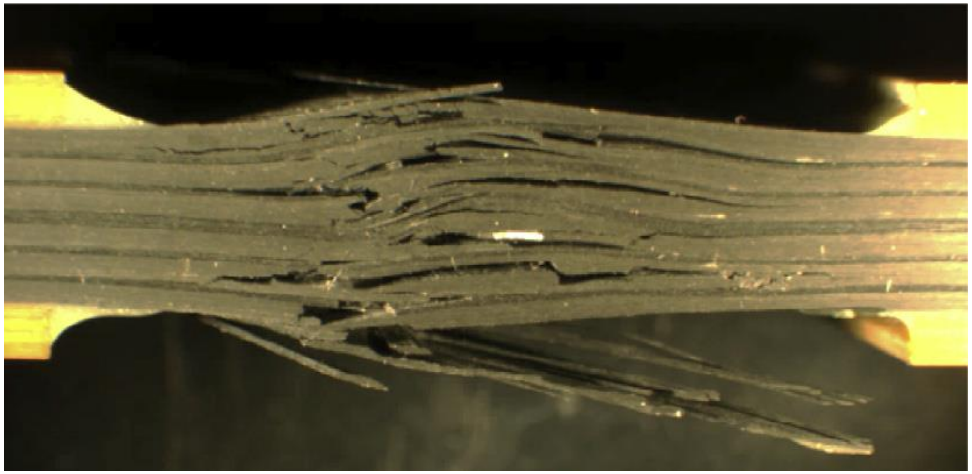
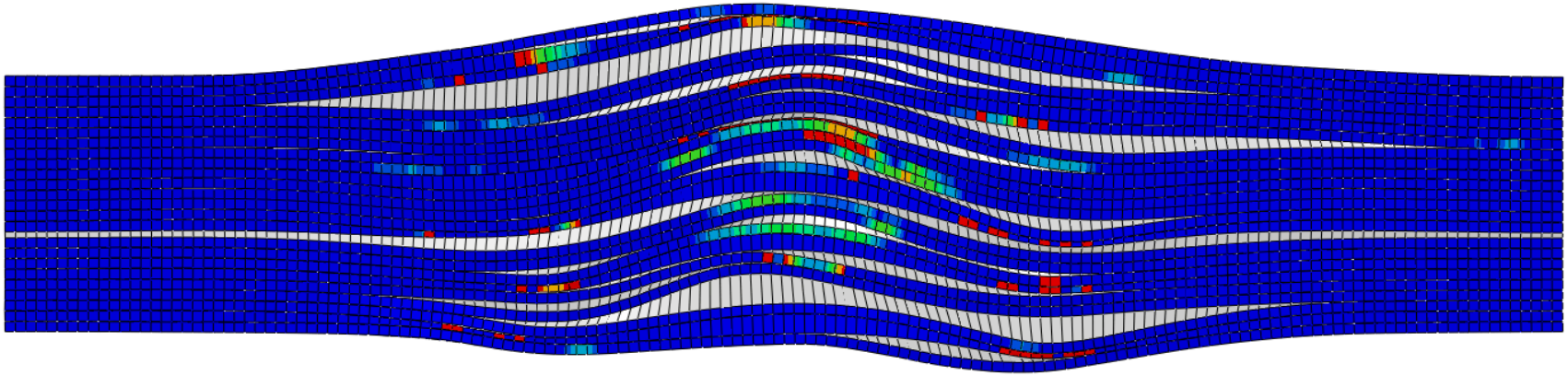
NDT-based prediction of strength



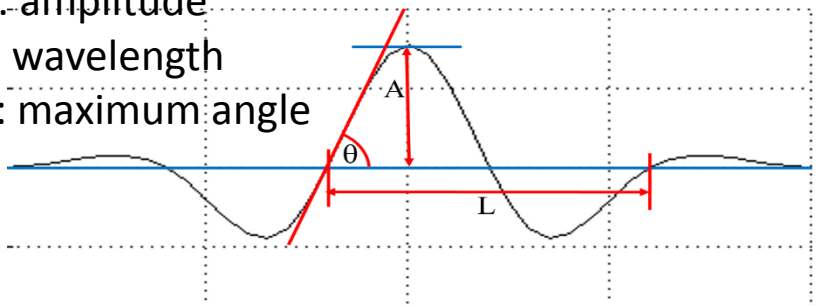
NDT-based prediction of strength

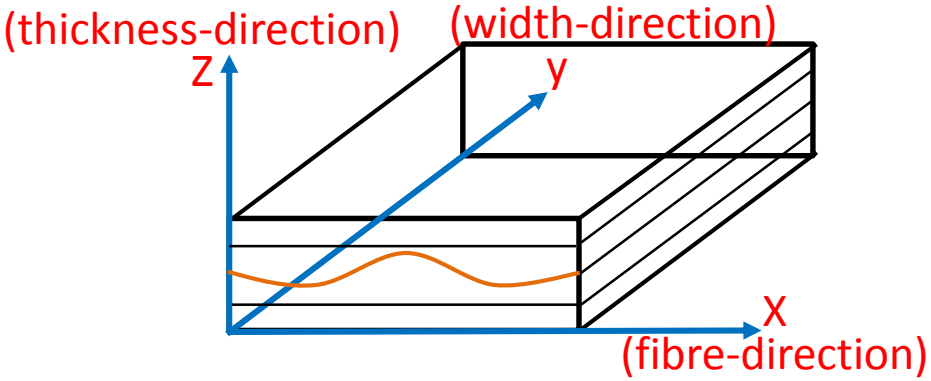




Wrinkle Shape Parameters Analysis

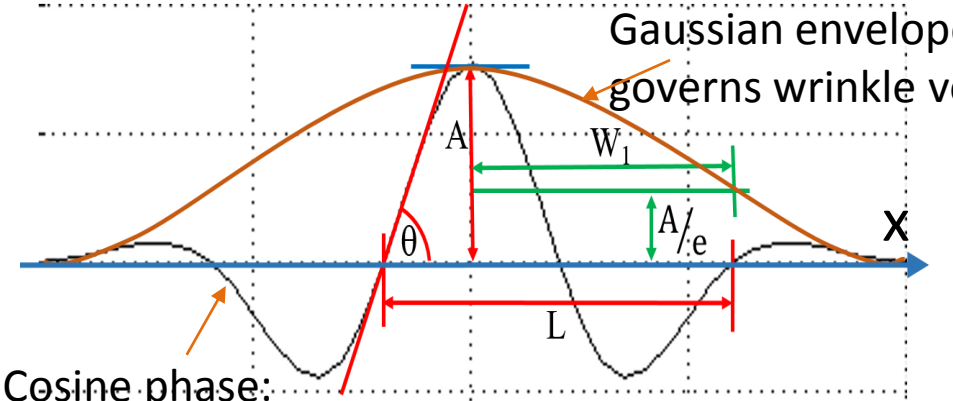
A: amplitude
L: wavelength
θ: maximum angle





Wrinkle shape along x-direction:

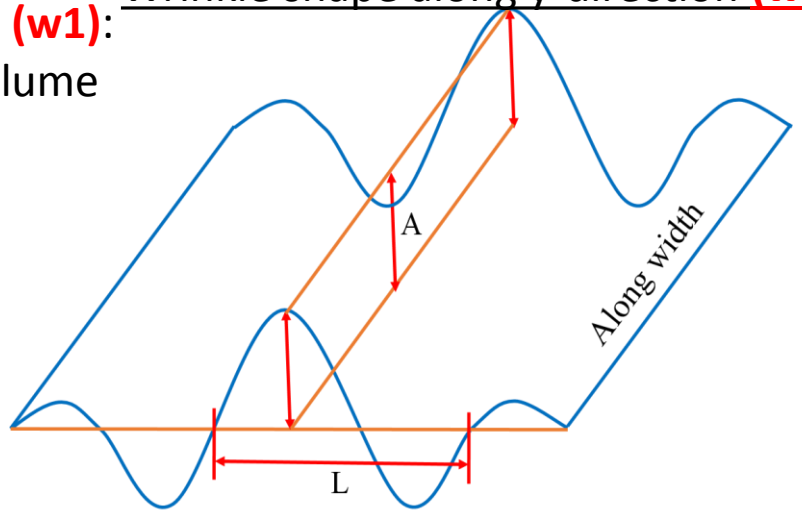
Gaussian envelope **(w1)**: governs wrinkle volume



Cosine phase: defines wrinkle shape

$$Displacement = Ae^{-x^2/W_1^2}\cos\left(\frac{2\pi x}{L}\right)$$

Wrinkle shape along y-direction **(w2)**:



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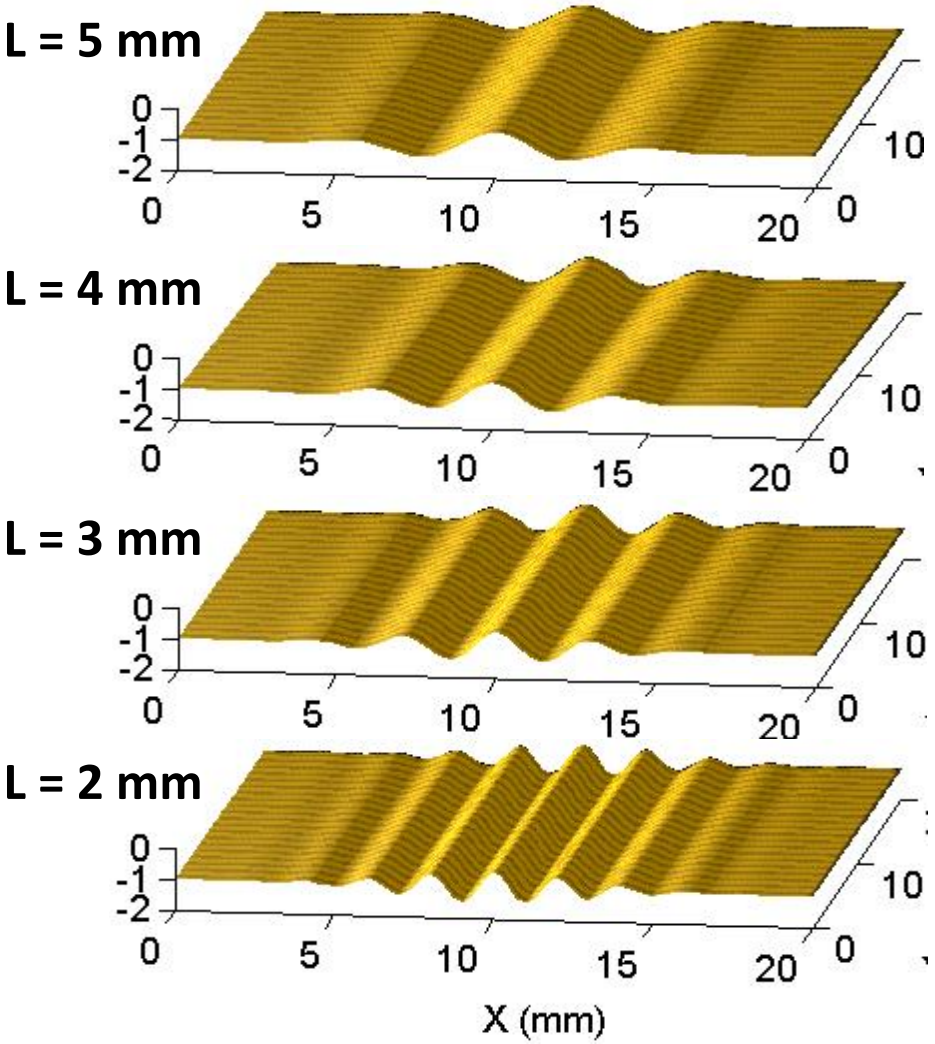
Importance of metrics

- Constant volume
- Effect of shape of wrinkle
  - Wavelength, L
  - Amplitude, A=0.5 mm
  - Maximum angle, ϕ



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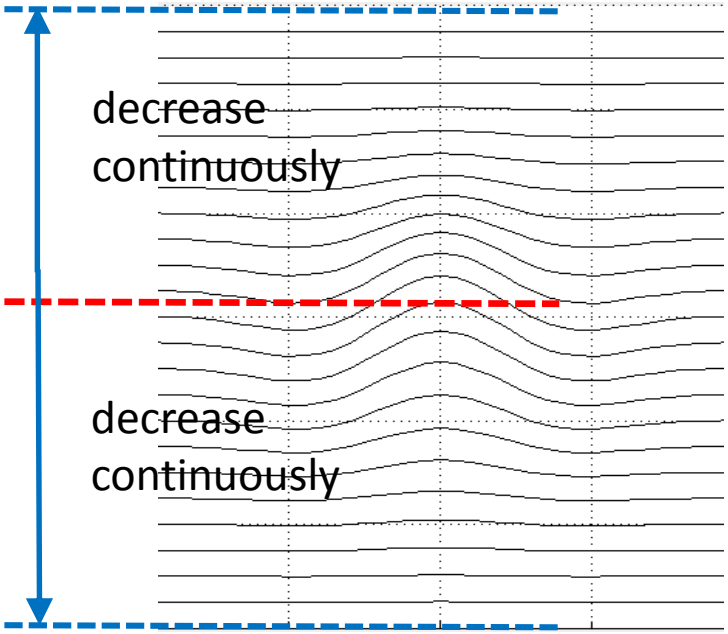
Wrinkle Shape Parameters Analysis

The depiction of Gaussian amplitude distributions:

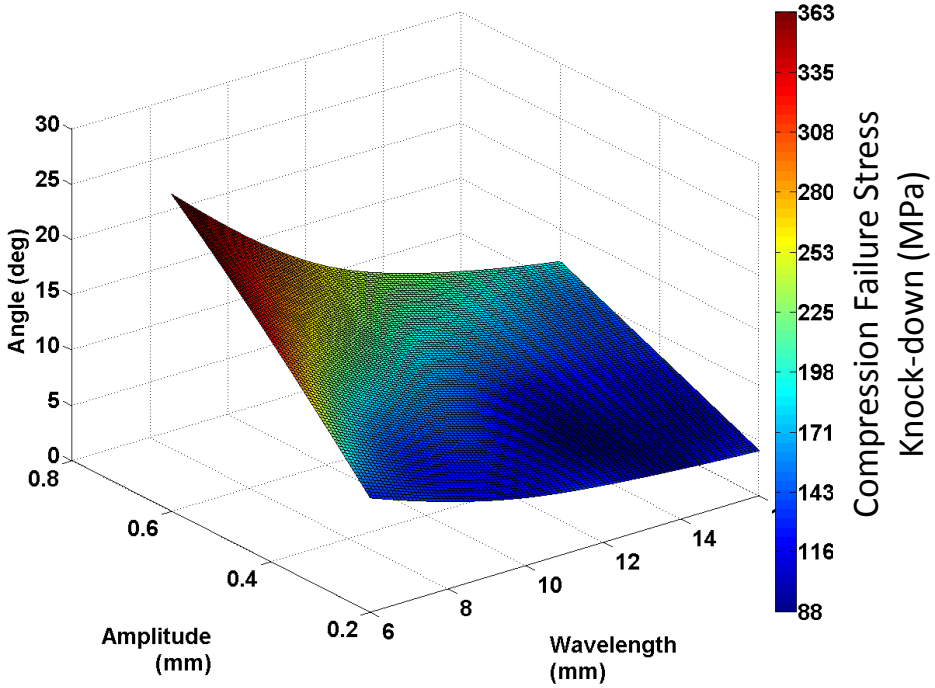
Gaussian reduction:

$$A_i = Ae^{-(i-i_{mid})^2/n^2}$$



Knock-down of failure stress:

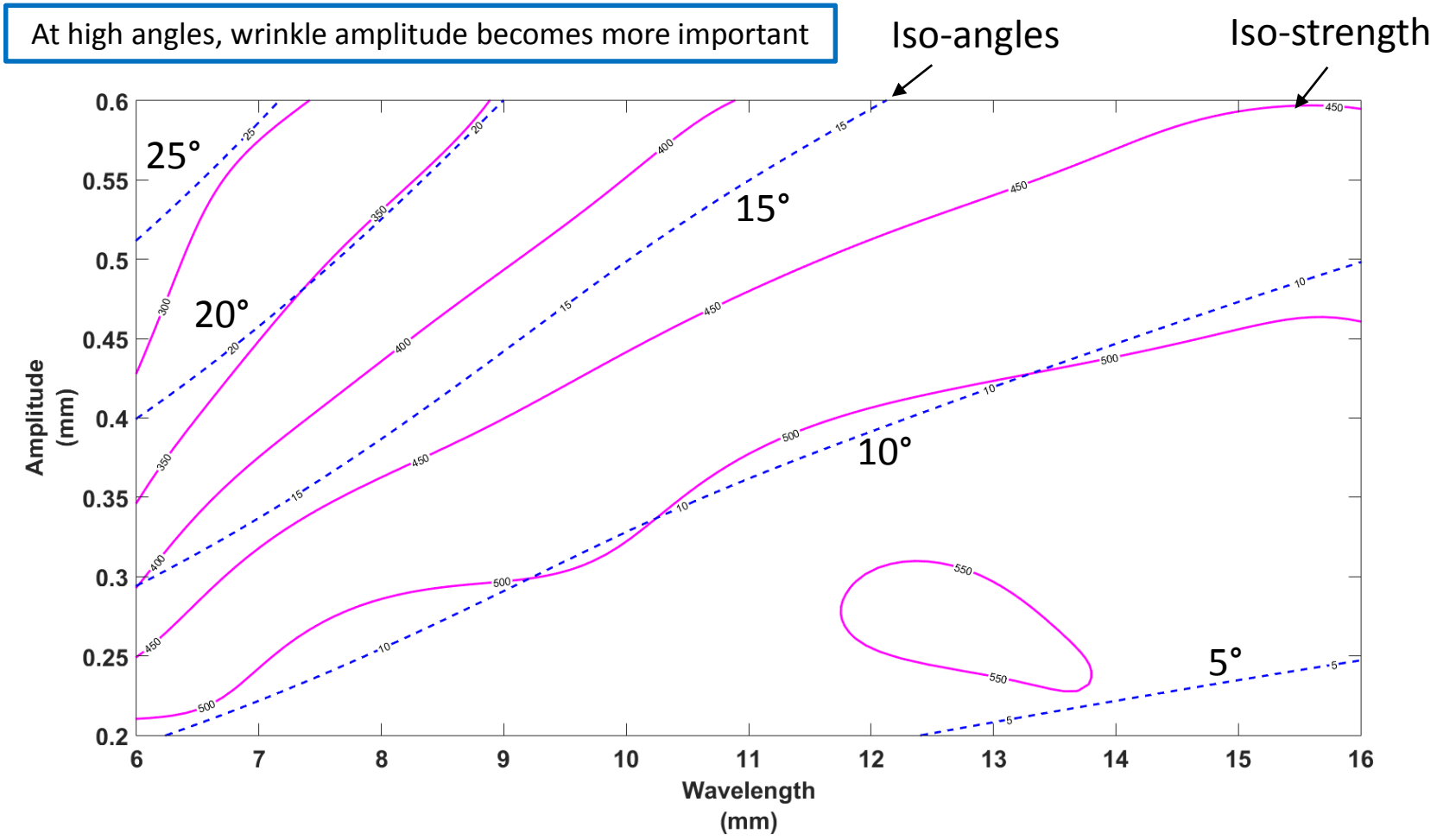
For a wrinkle region with fixed volume, maximum angle is the major parameter for determining compression strength.



Knock-down = tested pristine value (643.5 MPa) - model value

Fixed Wrinkle Volume

At high angles, wrinkle amplitude becomes more important

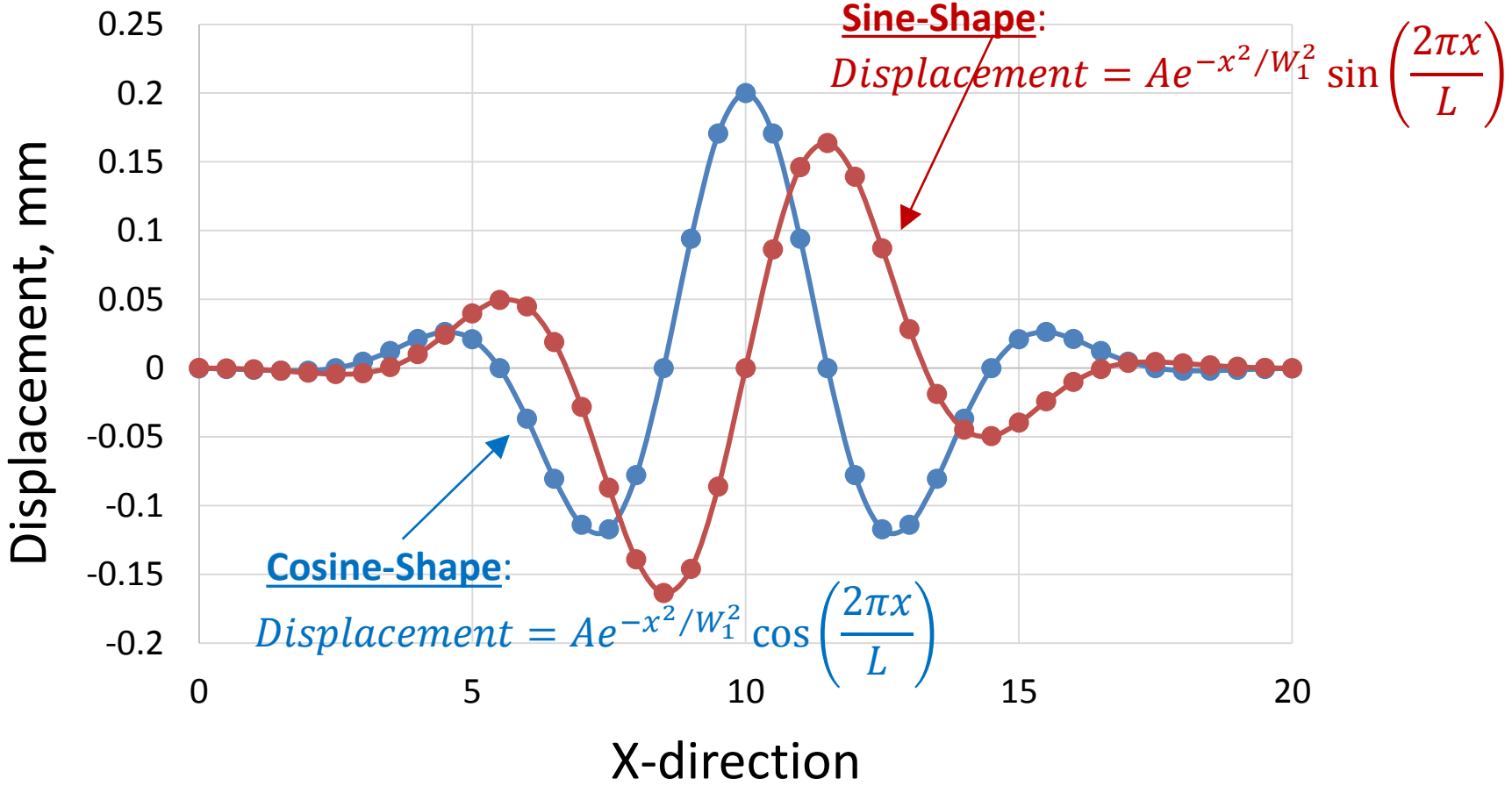


Sine and Cosine Shape

- Fixed Wrinkle Volume – effect of amplitude, wavelength and angle
- Comparison of Sine and Cosine Shape
- Fixed Maximum Angle, effect of length, width and height of wrinkle.

Sine and Cosine Shape

- Cosine Shape & Sine Shape with Fixed Angle



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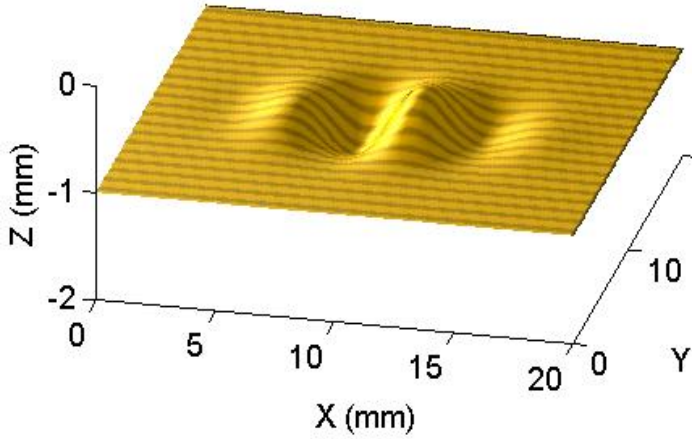
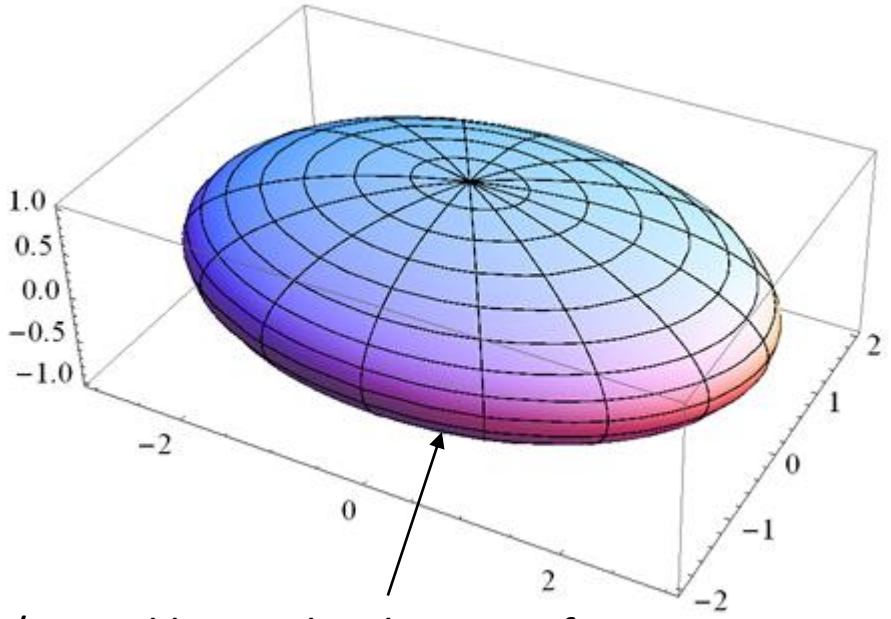
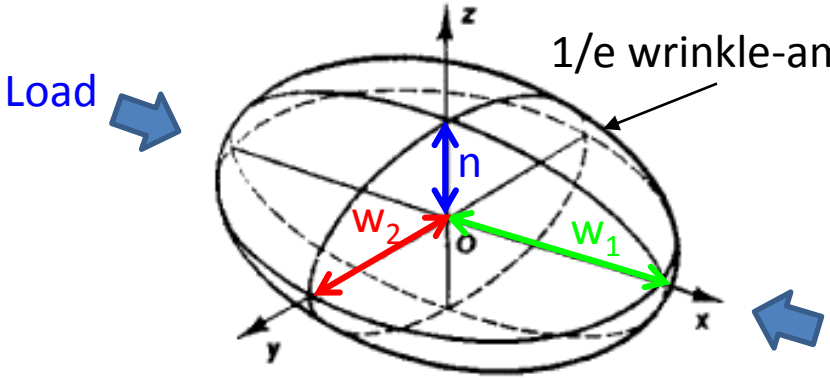
Importance of metrics

- Volume of wrinkle





1/e wrinkle-amplitude iso-surface



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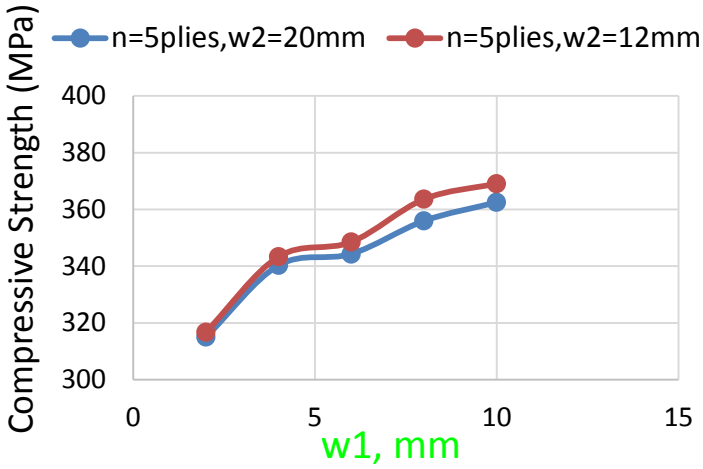
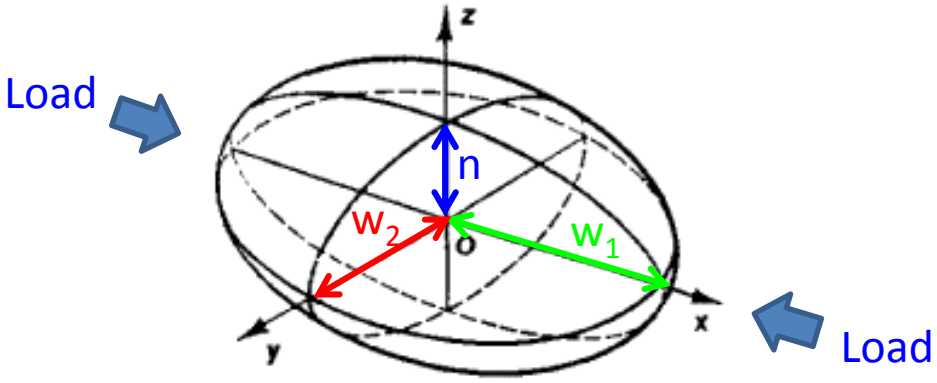
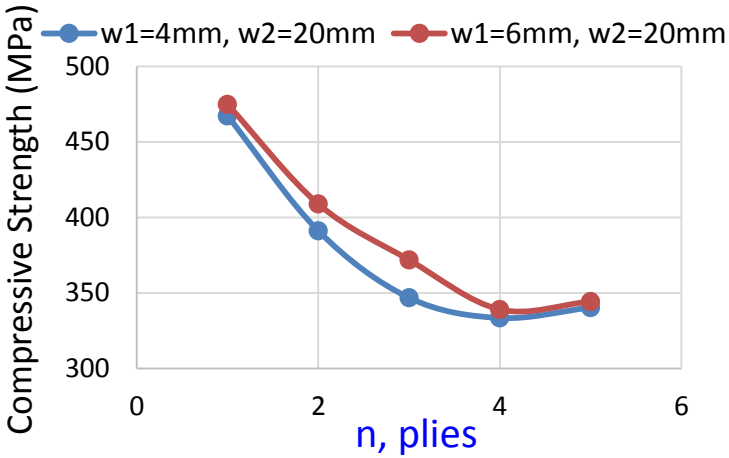
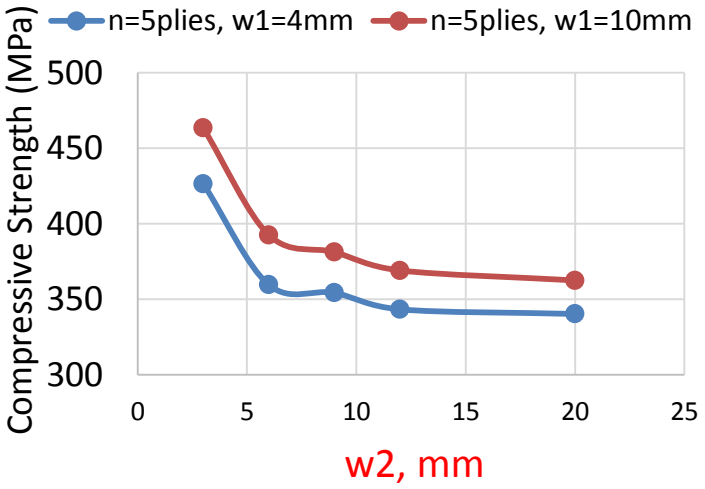
Importance of metrics

- Volume of wrinkle









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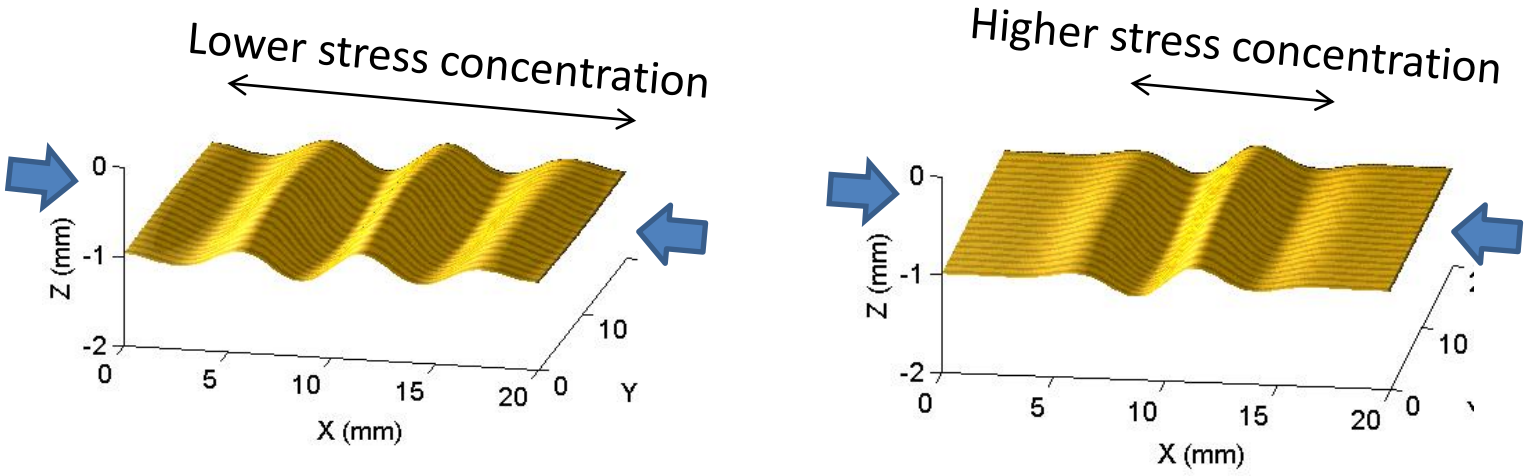
Importance of metrics

- Volume of wrinkle
- Two different effects. Strength reduced more by:
  - Shorter wrinkle volume in load direction



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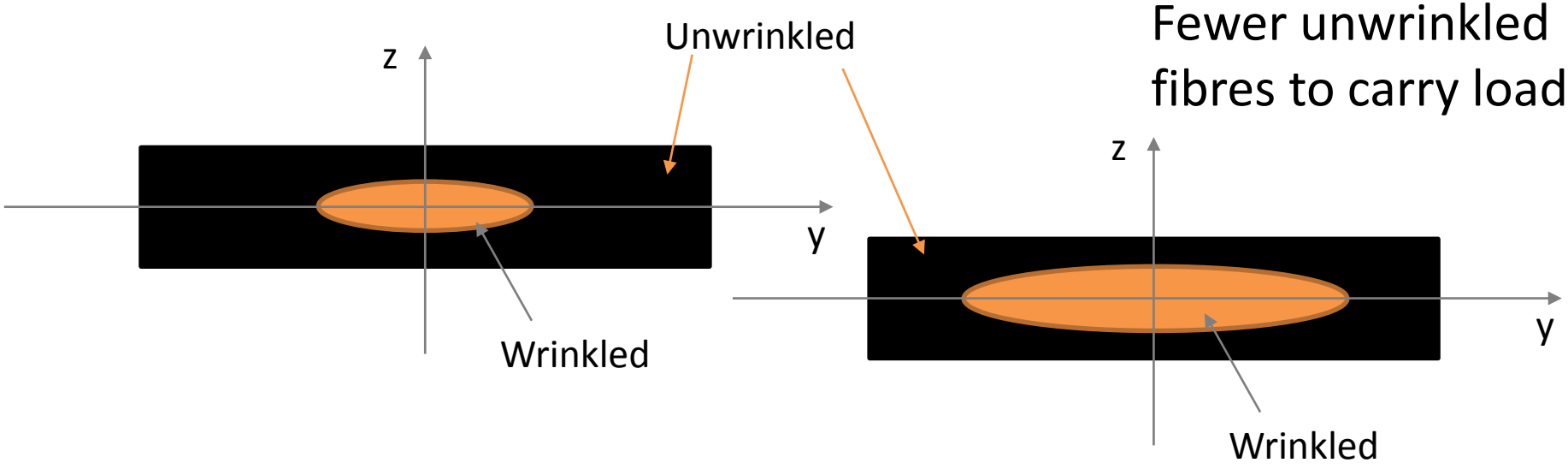
Importance of metrics

- Volume of wrinkle
- Two different effects. Strength reduced more by:
  - Shorter wrinkle volume in load direction
  - Larger wrinkle cross-section perpendicular to load.



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Summary

- New ultrasonic methods are being developed.
- 3D characterisation of material properties is possible.
- FE material models can be created from NDT data – still need to prove this end-to-end.
- Models can tell us about the most important metrics. For out-of-plane wrinkles, worst case:
  - Short wrinkle in load direction
  - Large wrinkle area perpendicular to load

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