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Multi-scale CT for imaging and testing of composites

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1st International Symposium on Multi-Scale Experimental Mechanics

Acknowledgements

- Researchers & collaborators:
  - Mark Mavrogordato, Neil O'Brien, Pete Wright, Anna Scott, Daniel Bull, Serafina Garcea, Sebastian Rosini, Stephen Wilby
  - Mark Spearing, Ian Sinclair, Tony Bunsell, Alain Thionnet, Brian Cox, Qingda Yang, Warren Hepples, Kingsley Ho
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- Royal Society Wolfson Research Merit Award (Spearing)
- European Synchrotron Radiation Facility (ID19) and Swiss Light Source (TOMCAT)

Overview

- Computed Tomography
- Through process performance
- Specimen considerations
- Particle-toughening micro-mechanisms
- Loading rig considerations
- Quasi-destructive CT
- Future opportunities/challenges
- Summary

Computed Tomography

Is a non-destructive technique in which penetrating-radiation measurements of the X-Ray opacity of an object along many X-Ray paths

- to compute a cross-sectional map of the linear attenuation coefficients of the object

Performance factors

Scan quality dependent upon:

1. how finely the object is sampled
2. how accurately the individual measurements are made, and
3. how precisely each measurement can be related to an absolute frame of reference

*ASTM E 1441-00

Why use CT…

- Meso & microstructural visualisation & quantification
  - Defect analysis
- Through process/time series analysis
  - Fabrication
  - Performance
- Failure analysis
  - Visualisation of mechanisms
  - Model initialisation, calibration, validation
- NDE/NDT
  - Correlative imaging
  - Engineering applications

GFRP infiltration

Through-process analysis

- Thorough, time-resolved analysis via various CT & CL tests
  - ➔ Micro-mechanical & macro-mechanical insight

Material

- •Unidirectional CFRP
- •Thick (150x100x4.5mm)
- •Rubber particle toughened
- •Non-toughened

Drop Tower Impact & QSI (SRCL)

C-Scan

3D Imaging

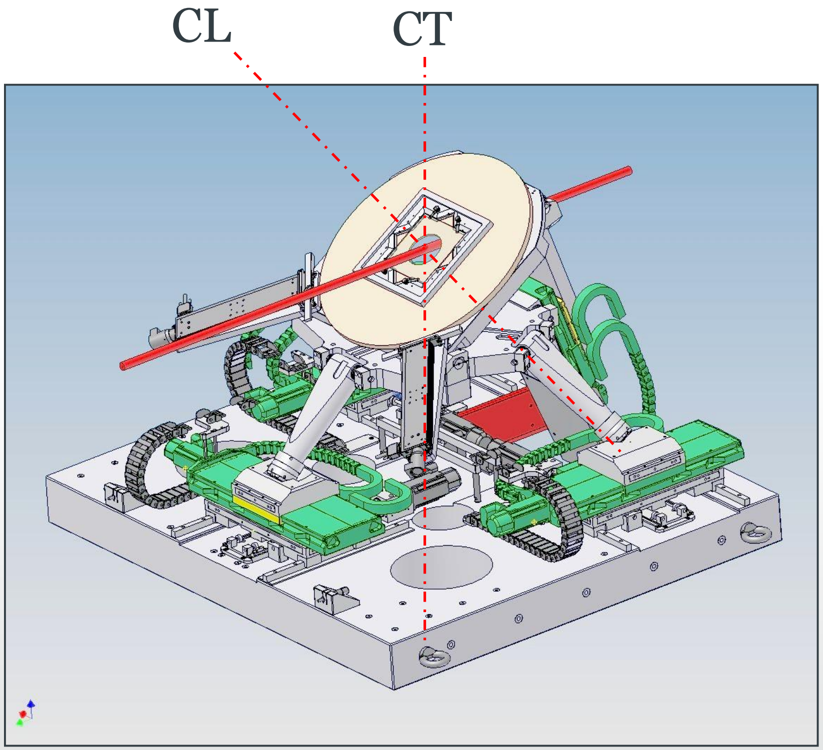
- MicroCT
- Synchrotron CT
- Synchrotron computed laminography (CL)

Image Analysis

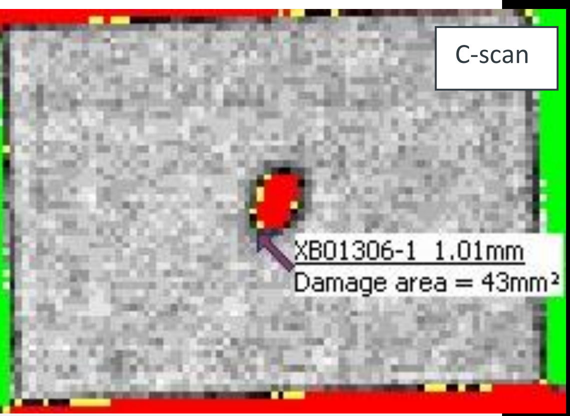
- Qualitative inspection
- Damage and feature segmentation
- Quantify damage

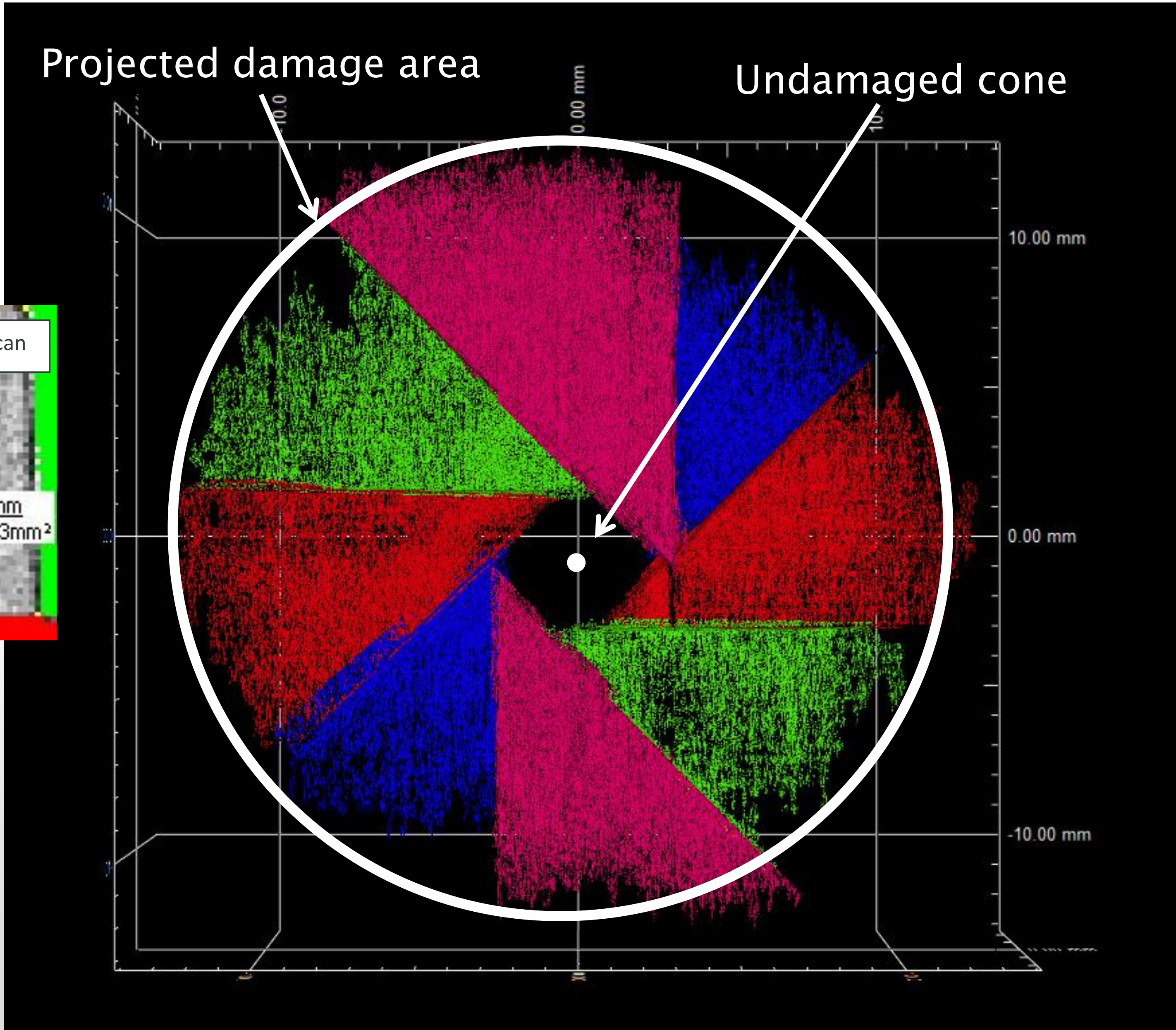
Compression test

- Conventional testing
- *In situ* (µCT)
- Bulk FEA simulation



Impact damage mapping

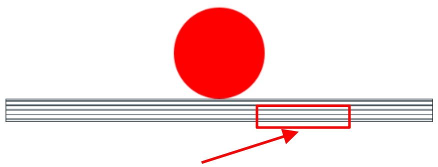




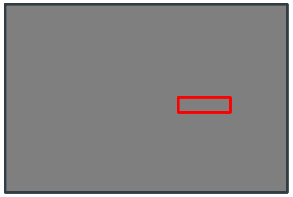
Bull, Sinclair & Spearing, Comp, Sci Tech, 2014

Quasi-static indentation (SRCL)

Time-series (~4D CL *ex situ* scan)
150 x 100 x 4.5 mm panels

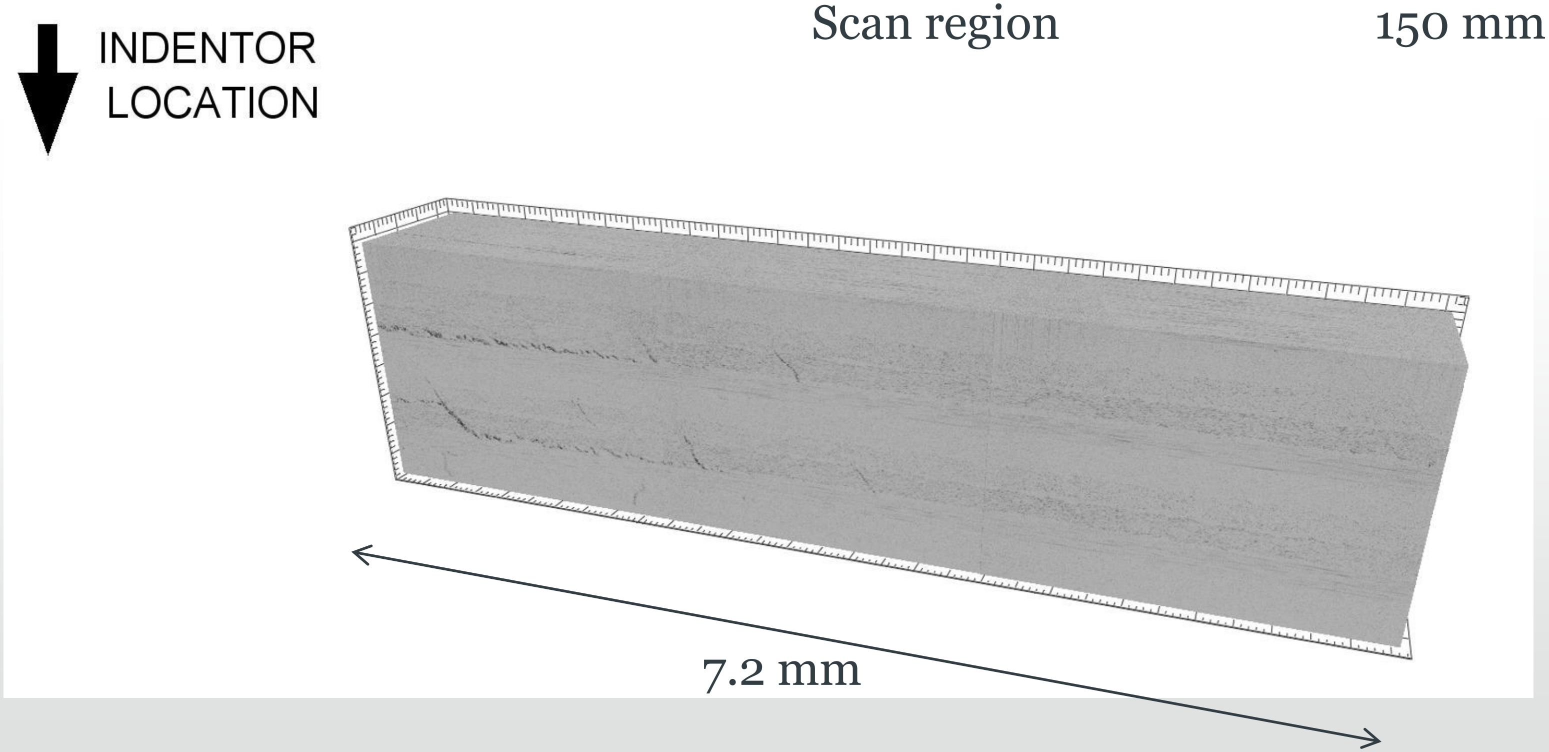


Scan region

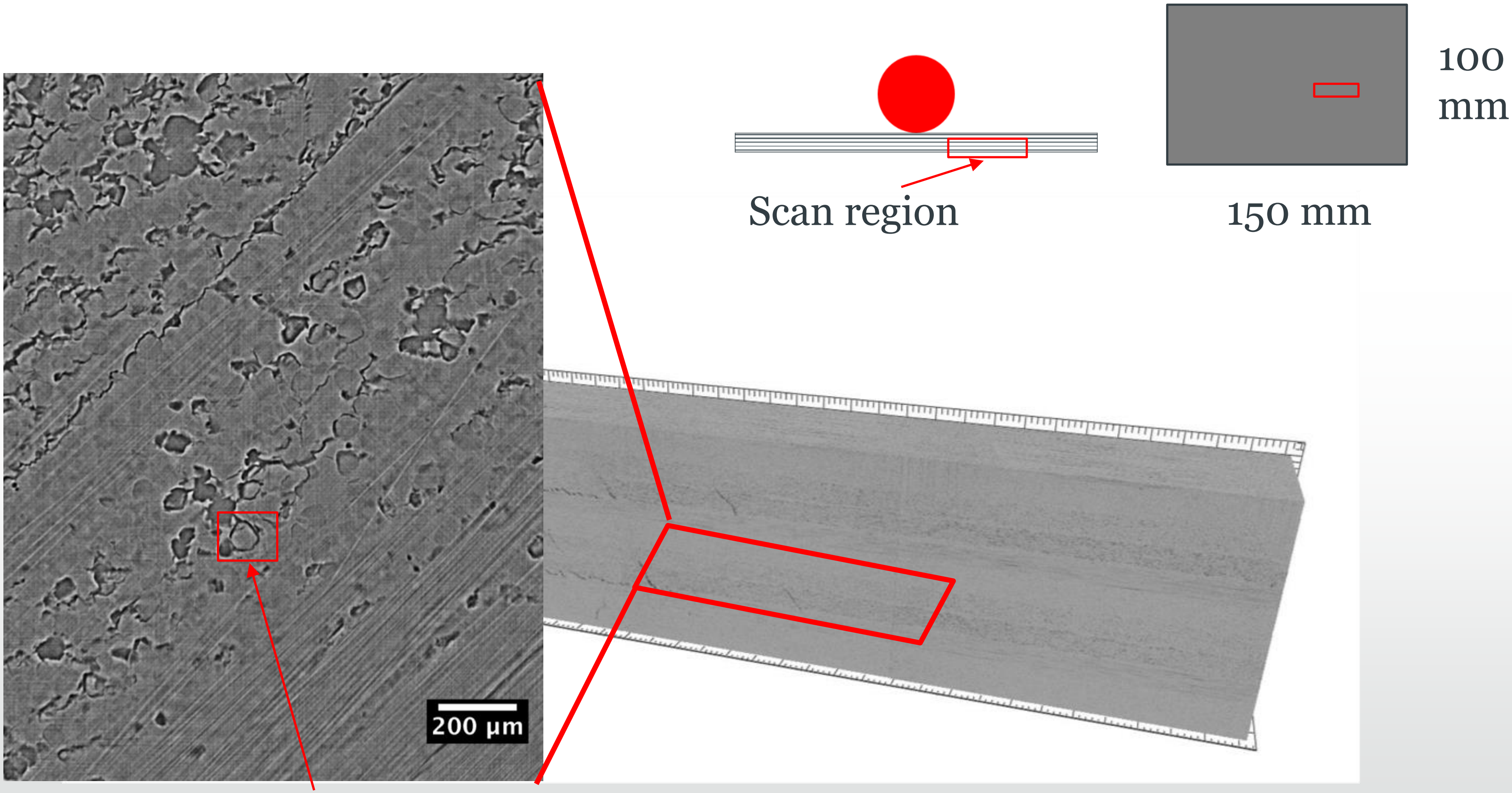


100 mm

150 mm



Quasi-static indentation (SRCL)



Particle de-bonding events

Toughened interlayer comparison

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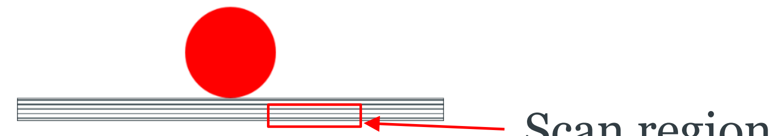
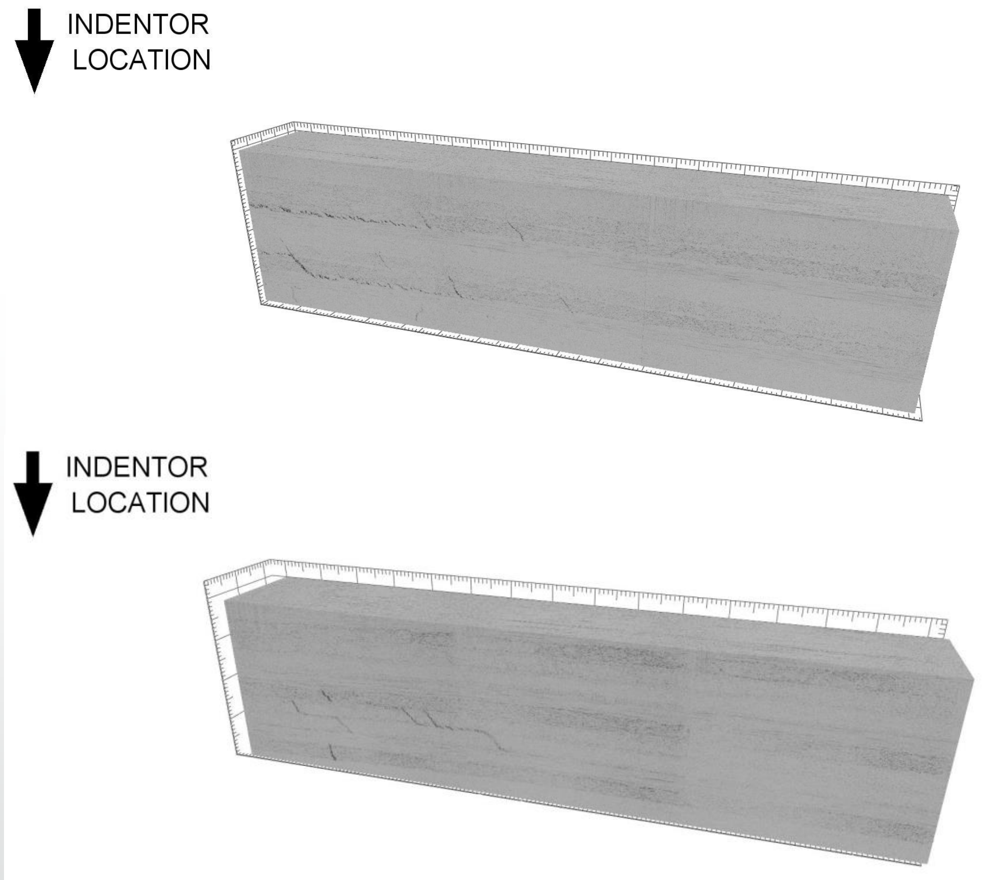


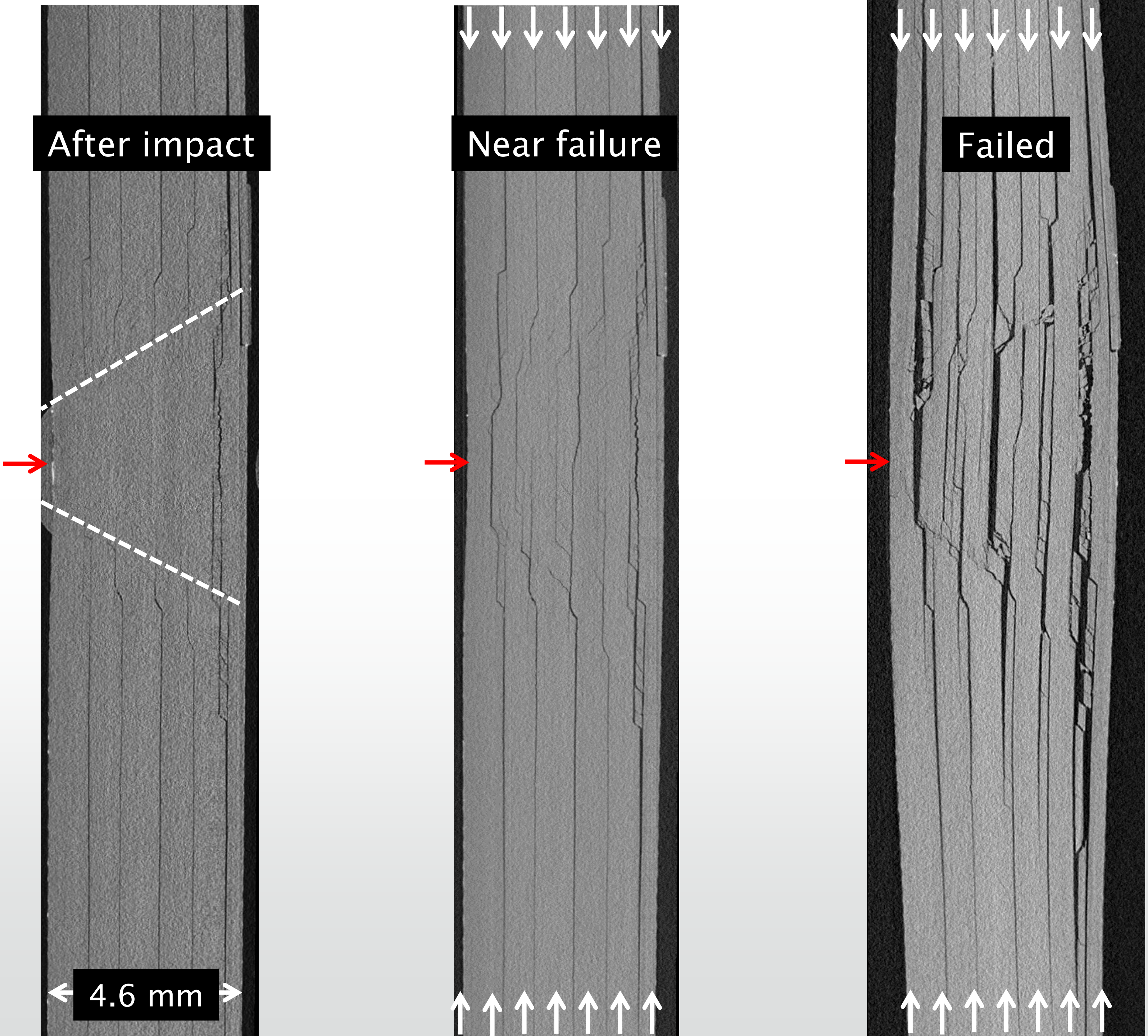
Time-series (~4D CL *ex situ* scan)
150 x 100 x 4.5 mm panels



Low G_{IIC} laminate
- Delaminations are not effectively suppressed
- Poor CAI performance

High G_{IIC} laminate
- delaminations are better suppressed
- More matrix cracking present
- Good CAI performance

Only the particle type has changed – all other variables consistent



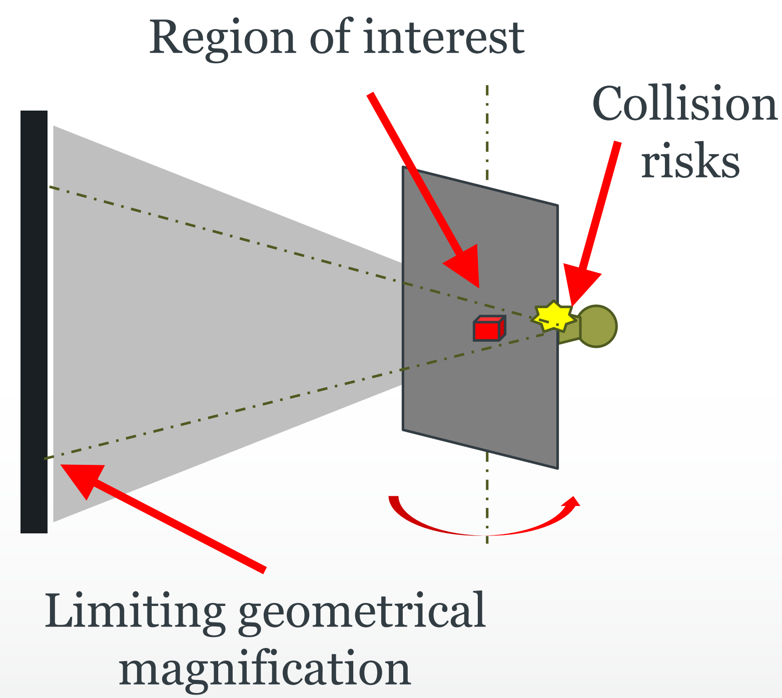
After impact
4.6 mm
Near failure
Failed

Specimen: Dimensions

Large aspect ratio panels

- Limit magnification
  - Sample-source distance

- Artifacts in the reconstructions
  - Photon starvation at the longest path length



Affecting spatial resolution, i.e. how finely the object is sampled

Specimen considerations

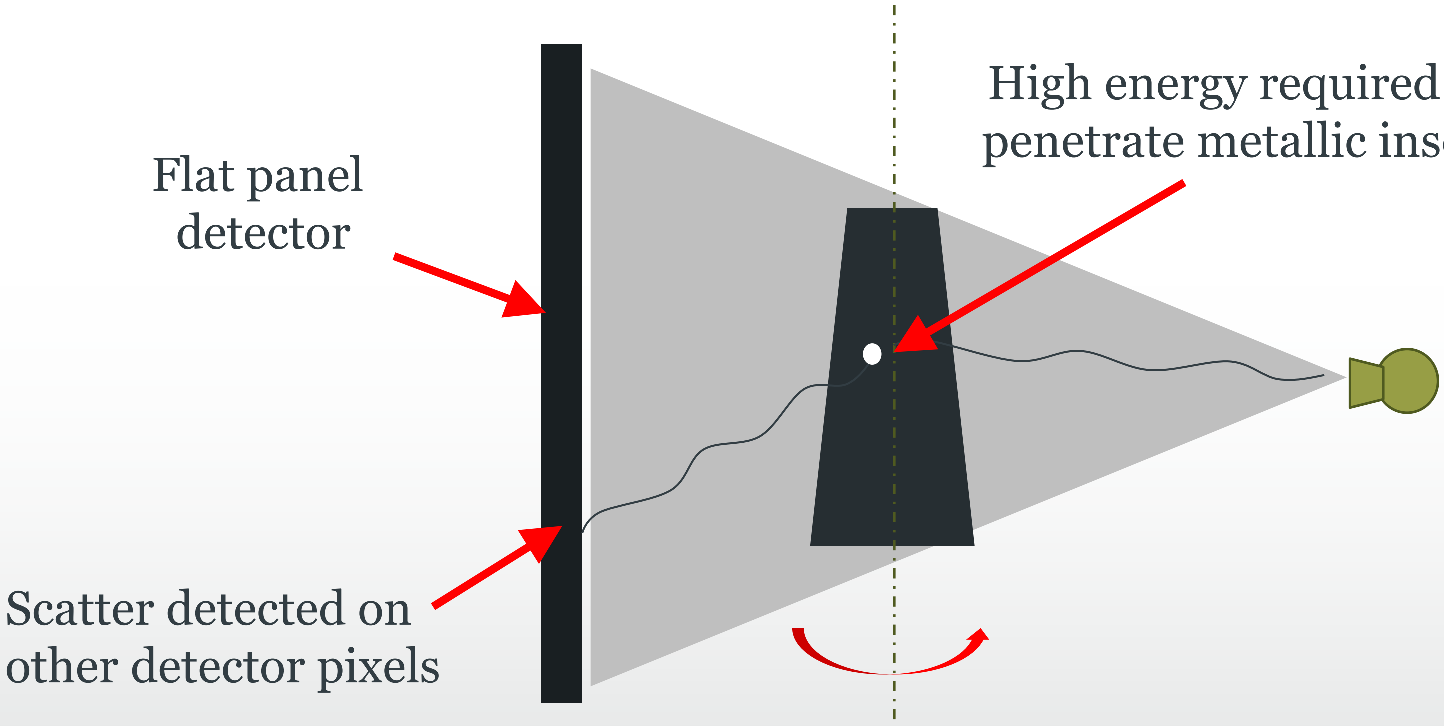
Specimen size:

- Aspect ratio, size and weight.
  - Limitations (physical and resolution)

Composition:

- X-ray transparency/density
  - X-ray energy, filters, flux, etc.

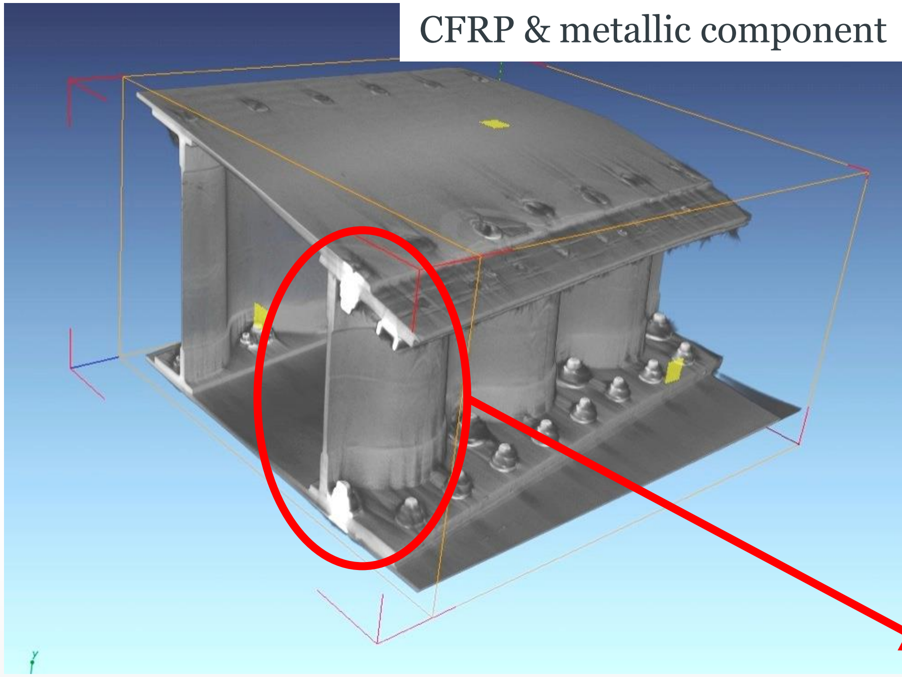
Challenging specimens

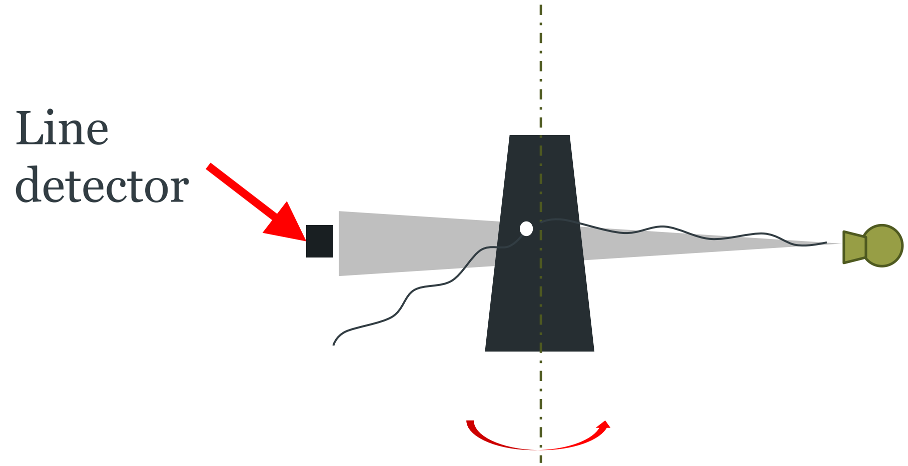


Affects accuracy of each individual measurement

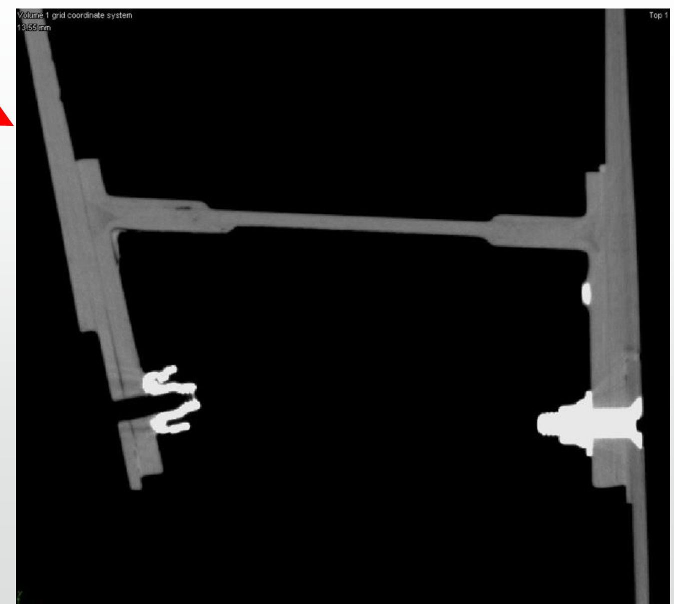
Multi-material components

CFRP & metallic component





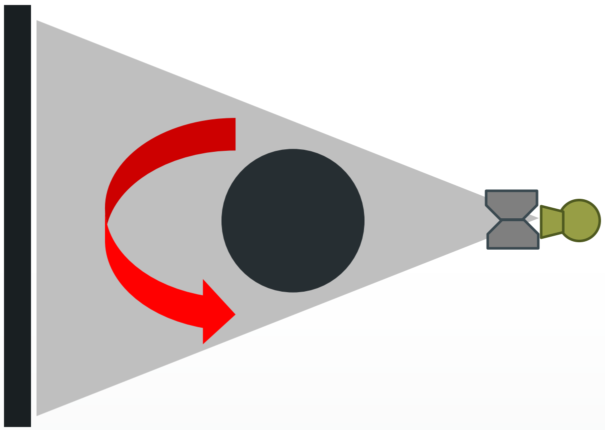
Higher degree of collimation



Using the line detector array is **time consuming**
-> do a normal scan and use the line detector only at regions of interests

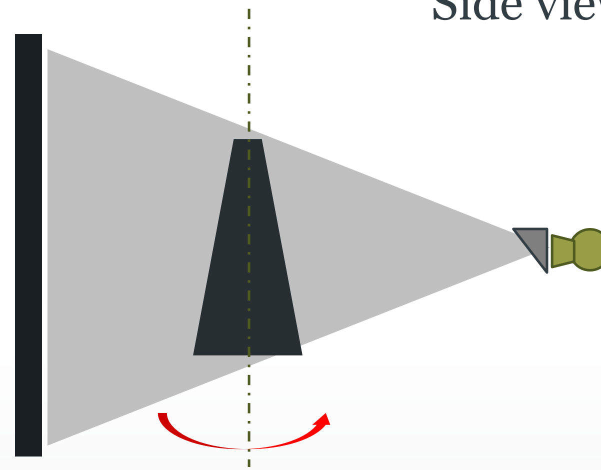
Compensation filters

Top-down view

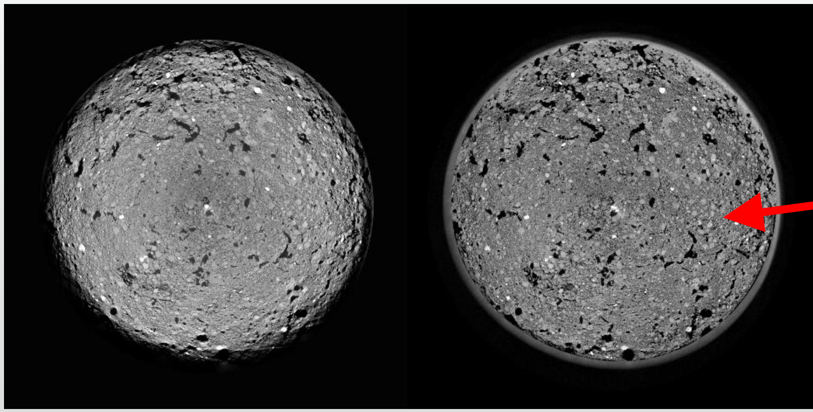


Bowtie filter

Side view



Wedge filter



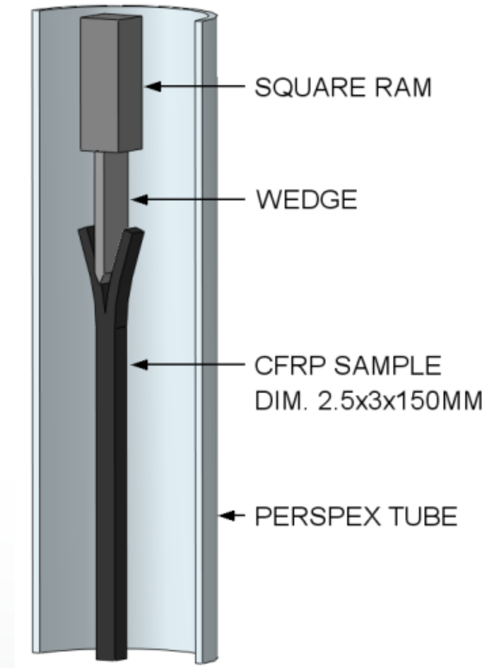
More uniform distribution of attenuation coefficients radially

μ-VIS – soil, bowtie filter

Understanding particle-toughened interlayers

In situ experiments

- CFRP materials
  - Interlayer particle volume fraction = 13%
  - ~5 µm intermediate modulus carbon fibres
  - 16 ply uni-directional layup



- Synchrotron Radiation Computed Tomography
  - Swiss Light Source, Paul Scherrer Institut
  - 0.325 µm voxel resolution

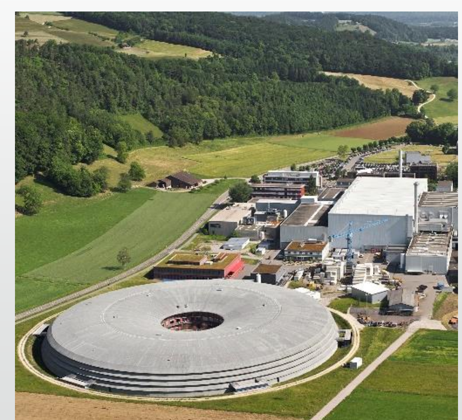


Photo: M. Fischer, <http://www.psi.ch/media/research-using-synchrotron-light>

Particle Type – Micro-mechanisms

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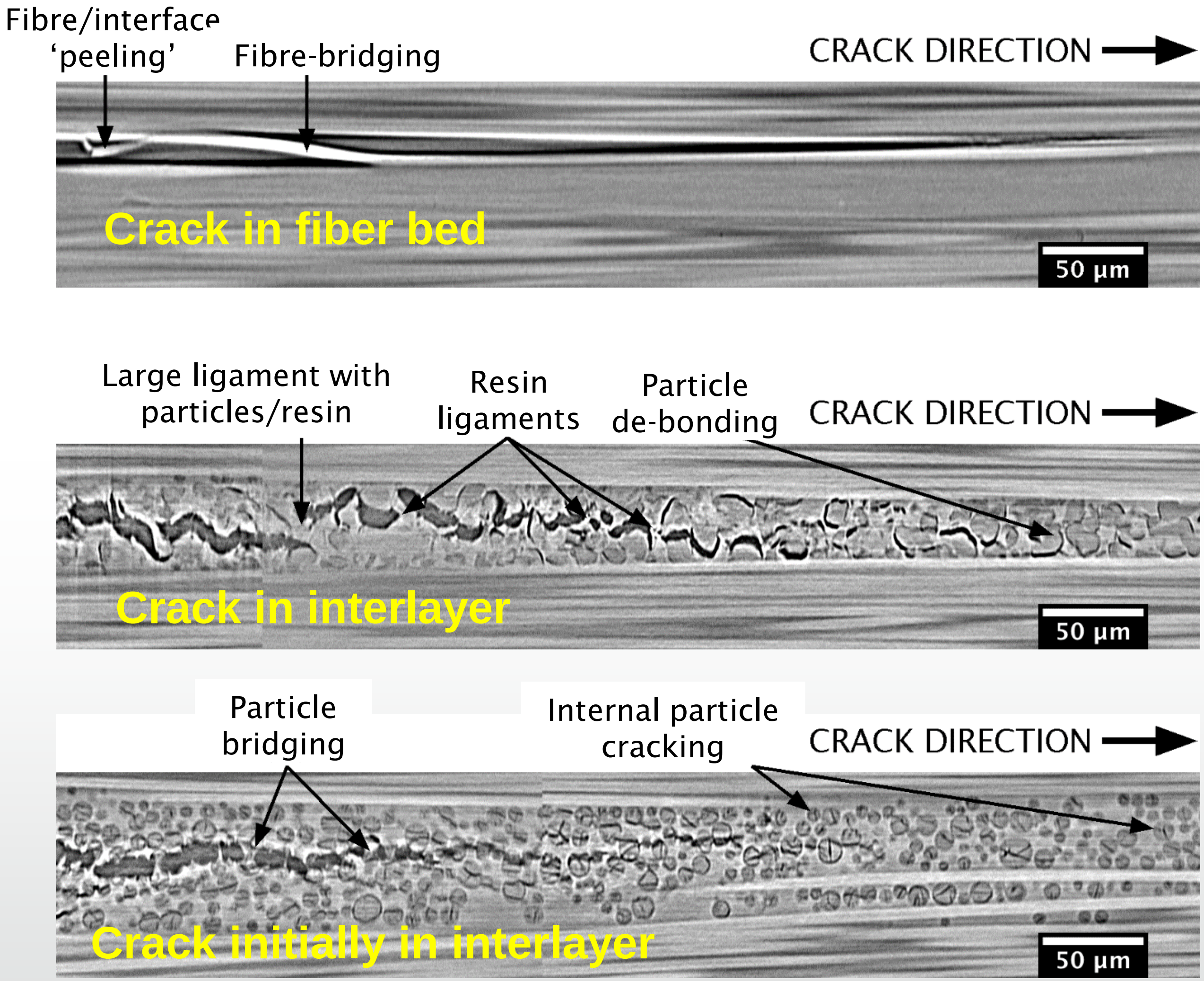
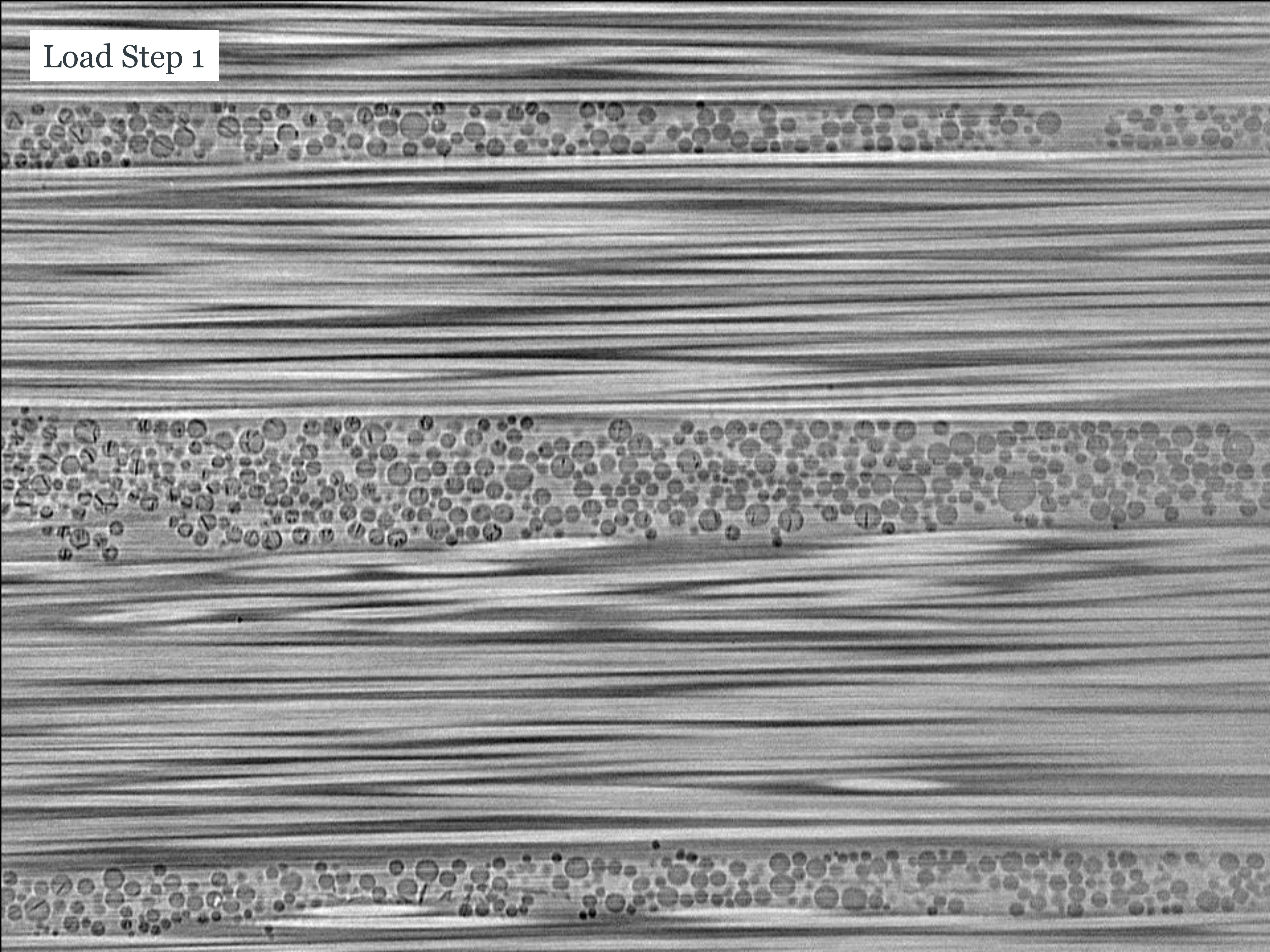
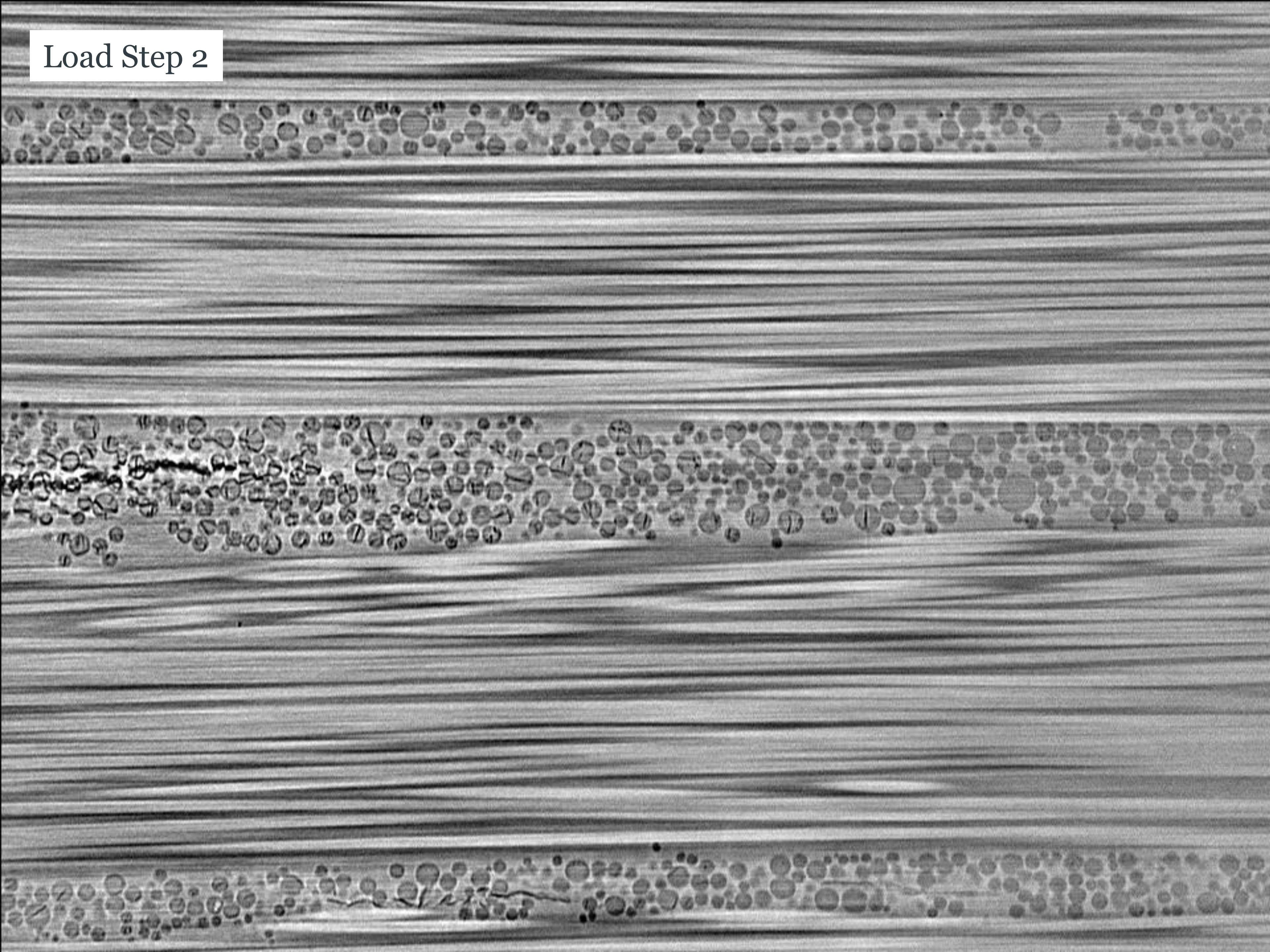


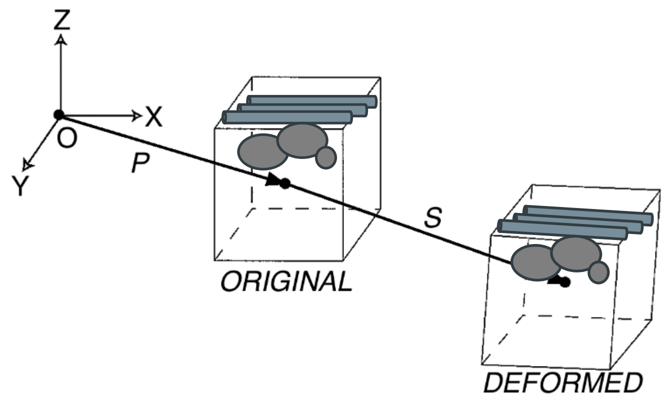
Base resin, Fibre and Particle Loading consistent


Load Step 1

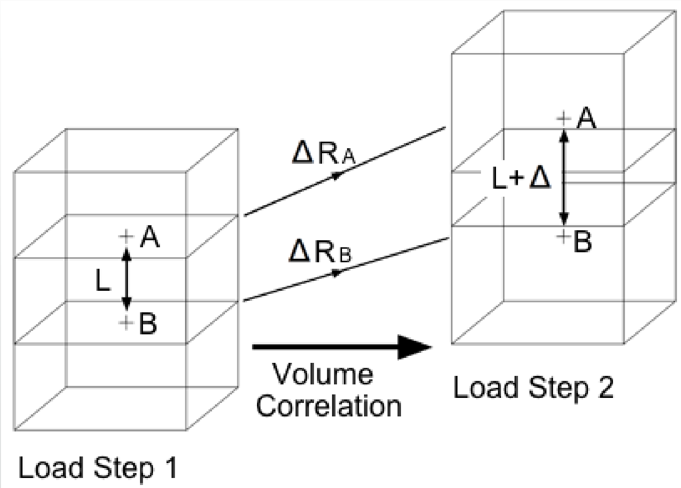

Load Step 2

Digital Volume Correlation

*B.K. Bay et. al. Expt. Mech. **39**(3) pp. 217-226, 1999.

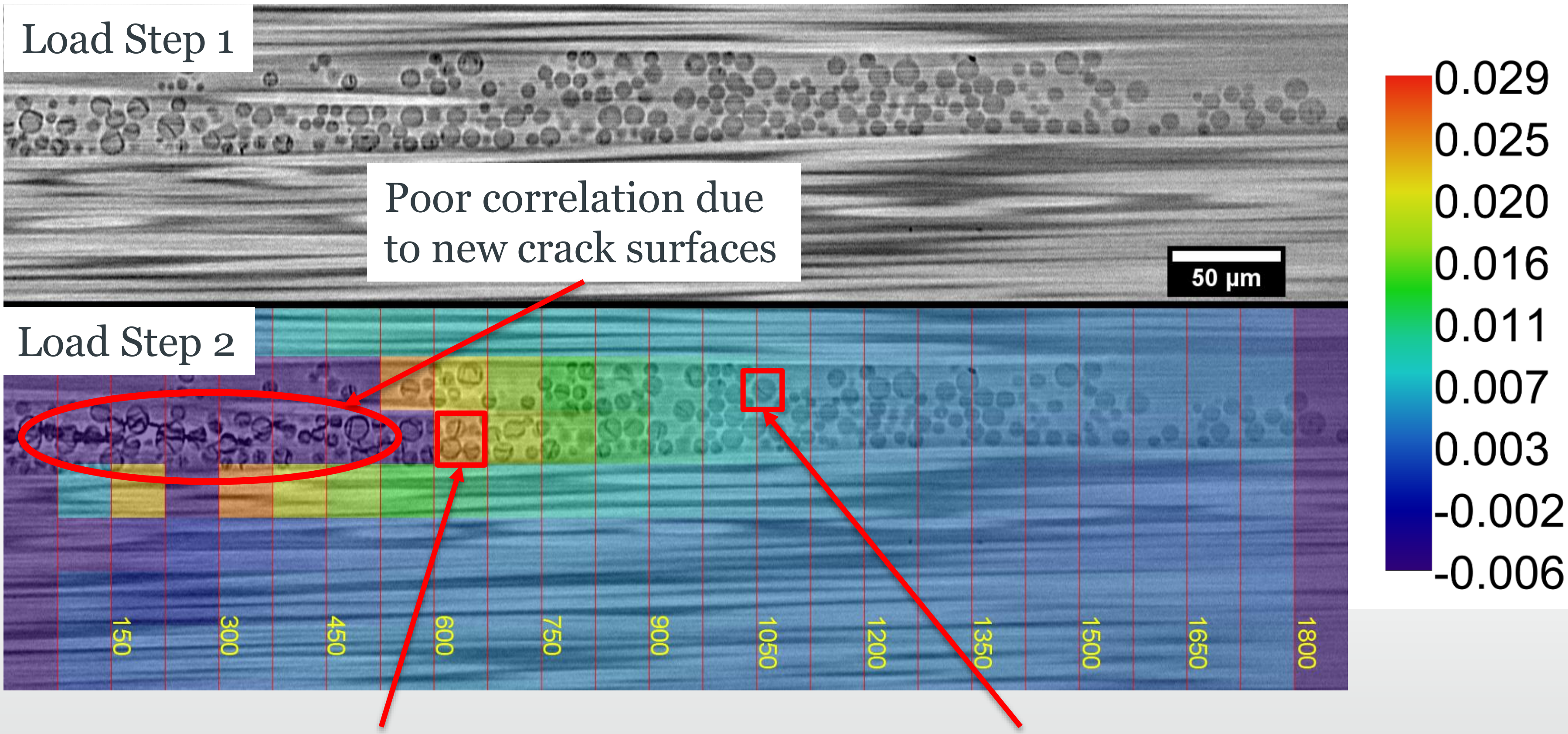


- Placement of the sub-volume between load steps
  - Dependent upon
    - Quality of the scans (noise & res.)
    - Material micro-structure
    - Size of the sub-volume
    - Amount of deformation/new features
- Calculation of the strains
  - Determined by the relative change distance between neighbouring sub-volumes



*G. Borstnar *et al.*, *Acta Mat*. Vol. 103, 2016

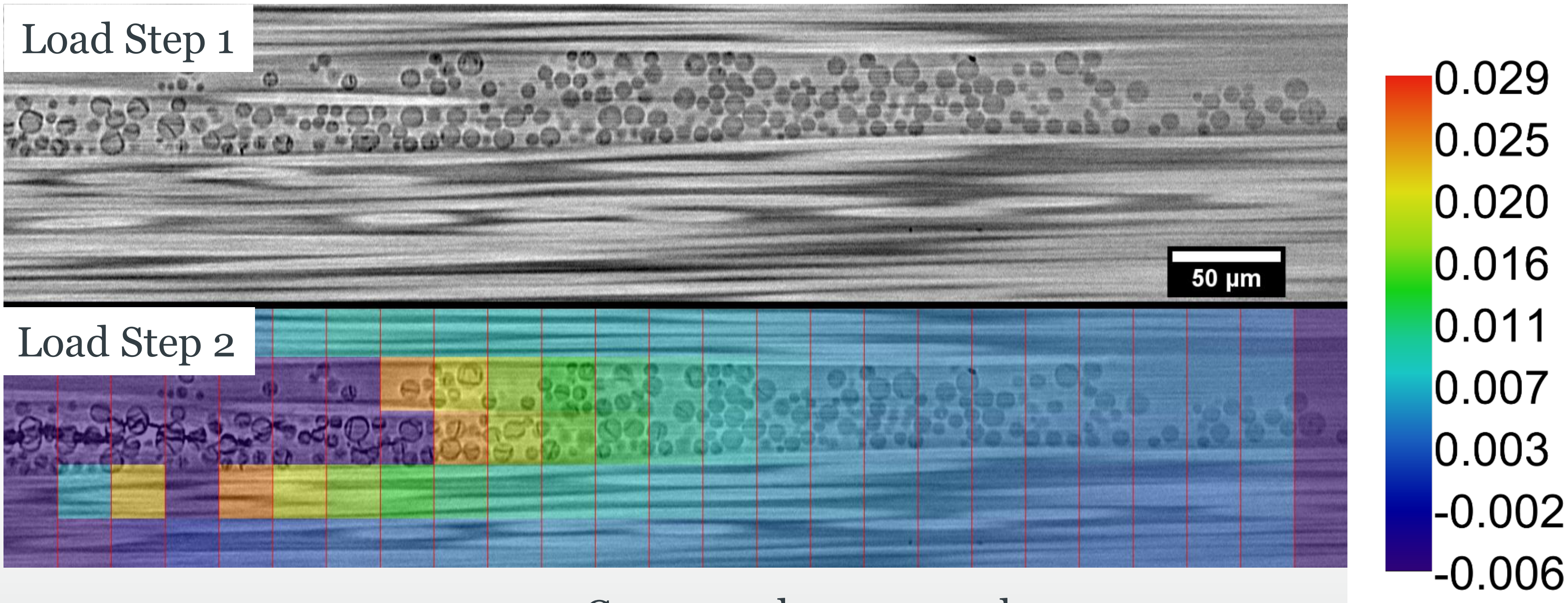
Tensile opening strains in Mat. A



Micro-mechanical observations of Mat. A particles de-bonding at average local tensile strains of > 2%

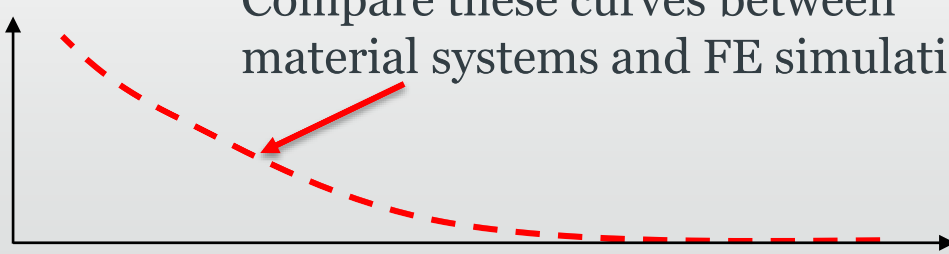
Observations of internal particle fracture occurring at strains as low as 0.5%

Tensile opening strains in Mat. A



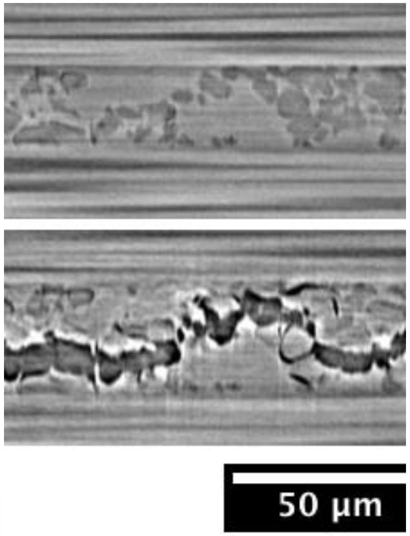
Tensile opening strains/ nodal displacement

Compare these curves between material systems and FE simulations



Position along the crack tip process zone

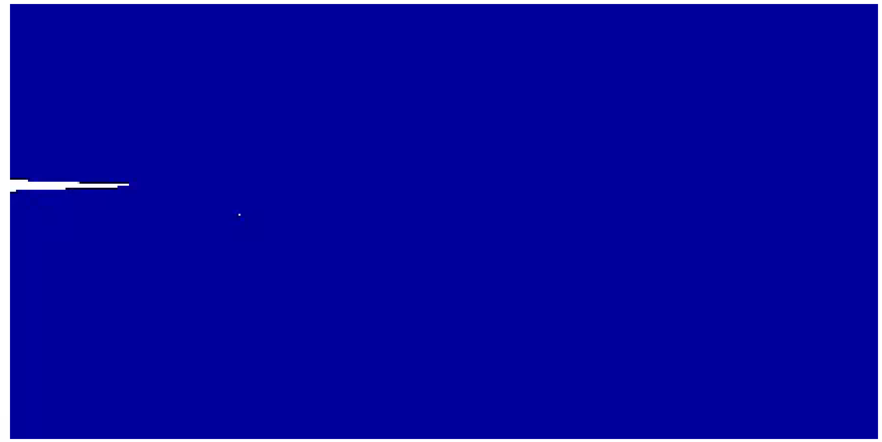
Crack path modelling



Microstructure

Validation

2D FE micromechanical simulation

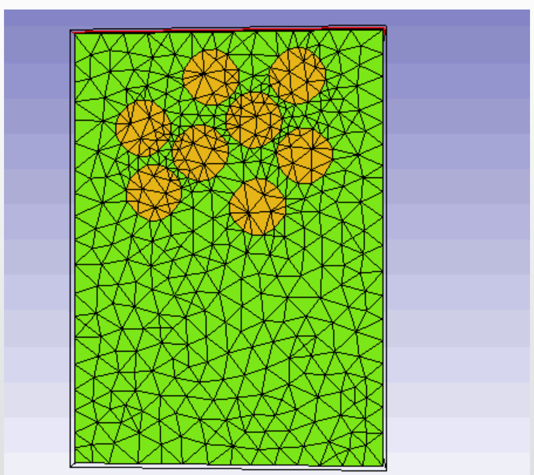


Matrix & particle

Fibre interface

Particle interface

How do we get these input properties?



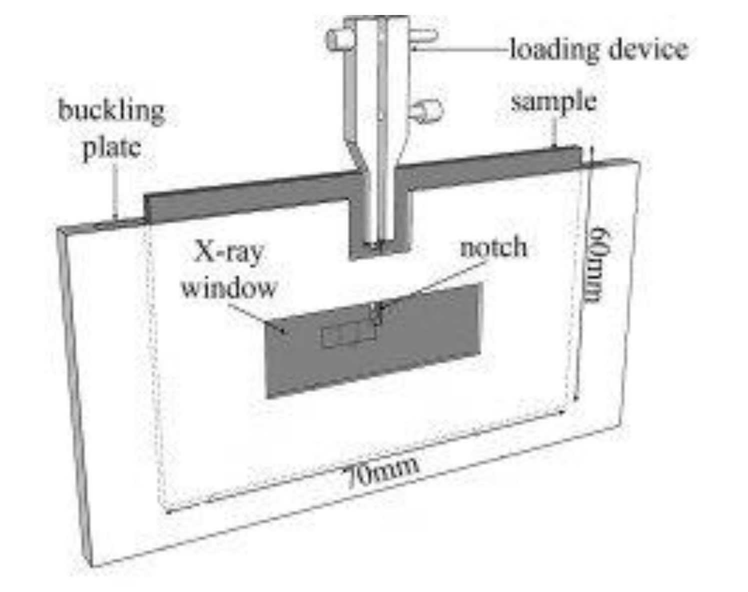
FUTURE – realise this in 3D

In situ rig considerations

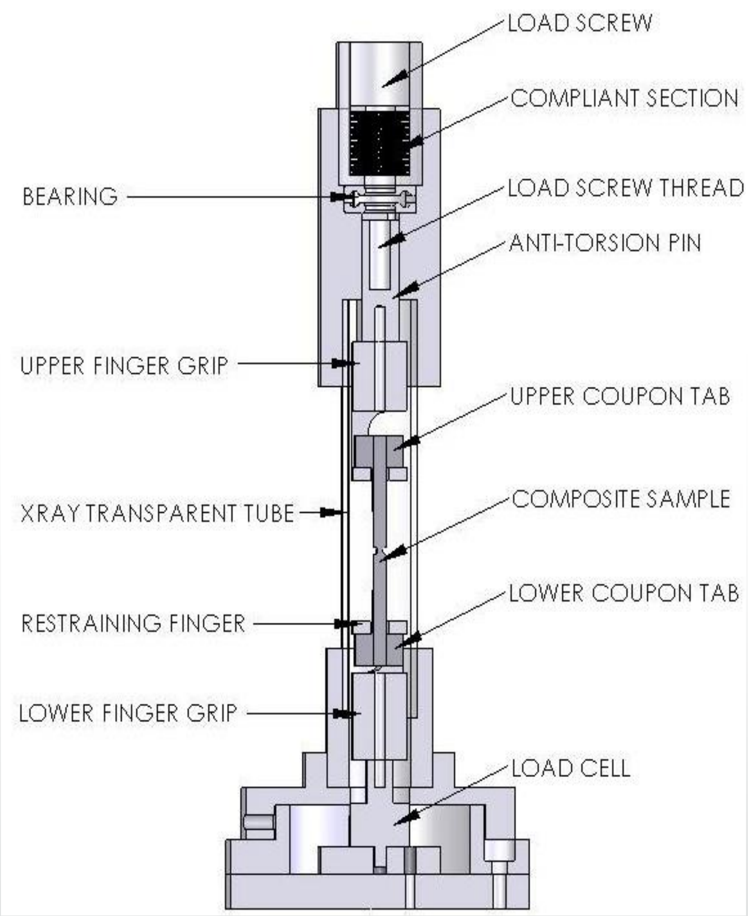
In situ loading rigs

Computed Tomography

Computed Laminography



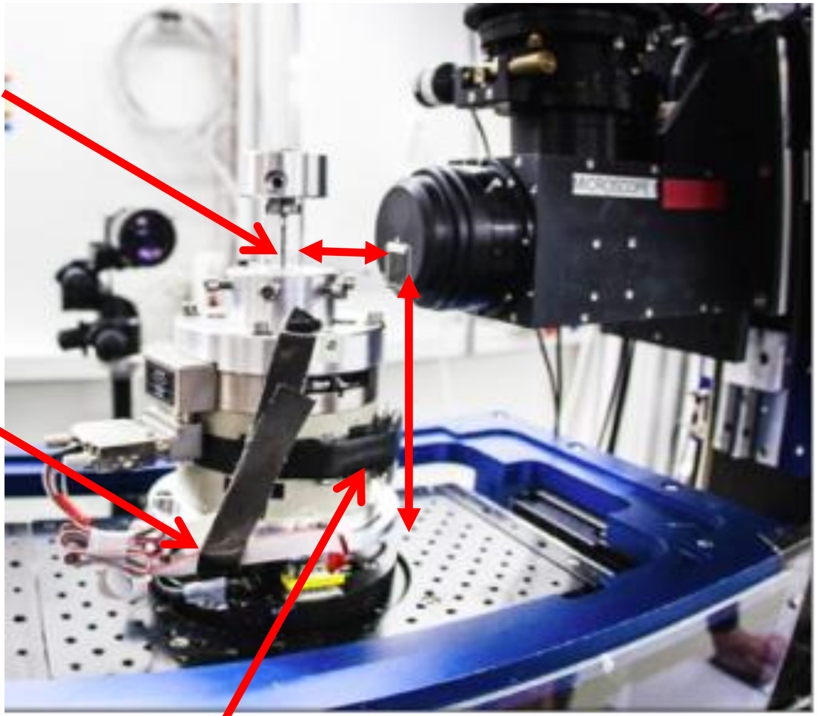
A.J. Moffat et. al., Scr. Mat., 62(2), pp 97-100, 2010.



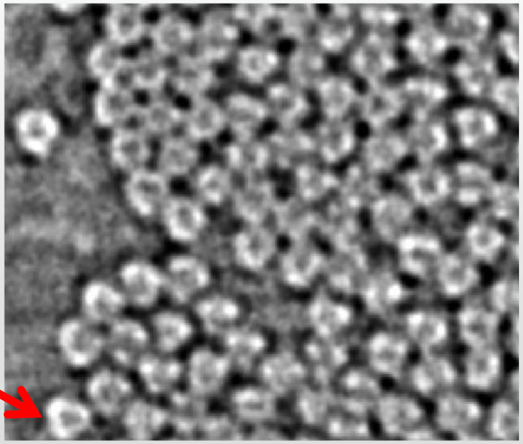
P. Wright et. al., Compos. Sci. Tech. 70(10) pp 1444-1452, 2010.

Rig considerations

- X-ray transparency
- Weight restriction
- Beam height restriction
- Rig slenderness – phase (SRCT) or magnification (lab)
- Cable drag
- Off-axis weight



Movement artifact - Carbon fibres (~5 µm) appear like triangles



In situ testing at synchrotrons

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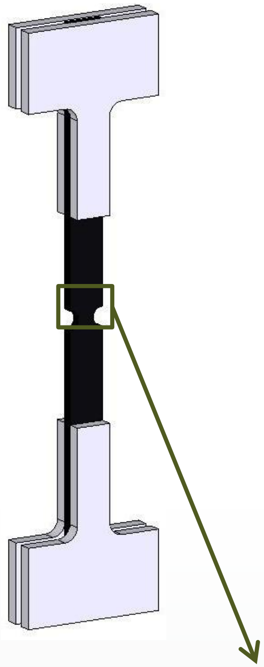
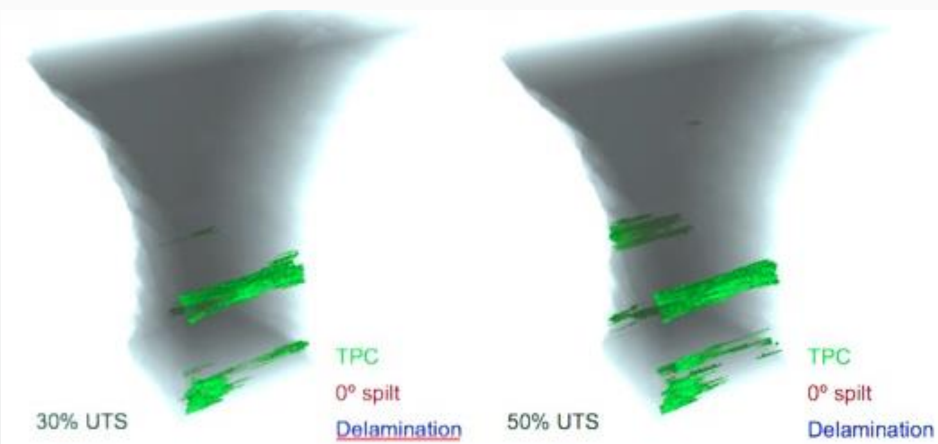


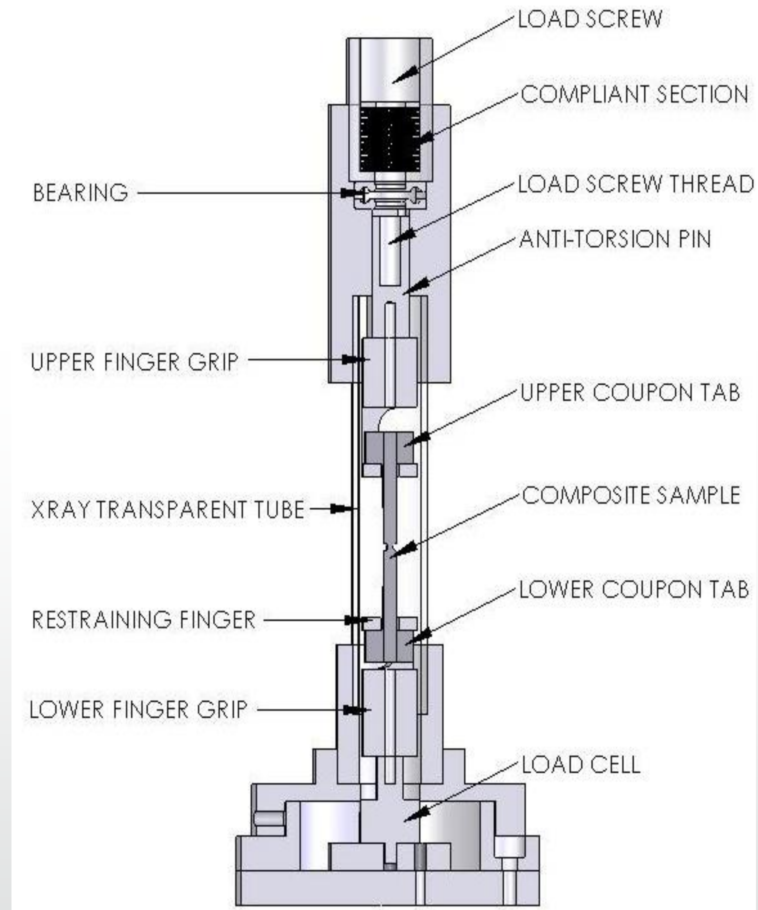
Damage progression in cross-ply CFRP sample

- Transverse ply cracks



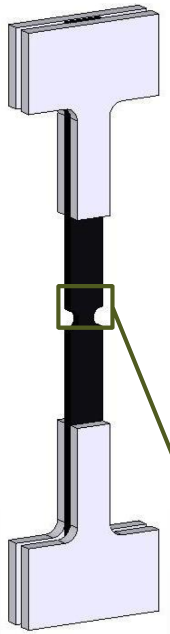
Beamlines: ESRF/ID19

Computed Tomography



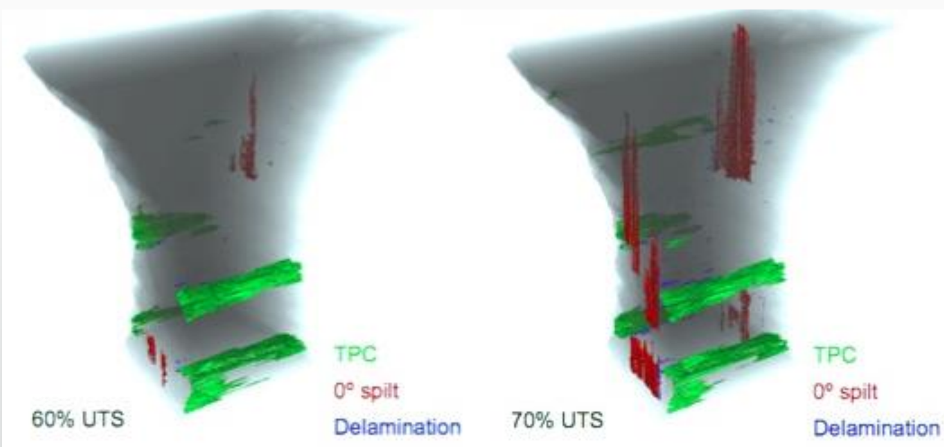
P. Wright et. al., Compos. Sci. Tech. 70(10) pp1444-1452, 2010.

In situ testing at synchrotrons



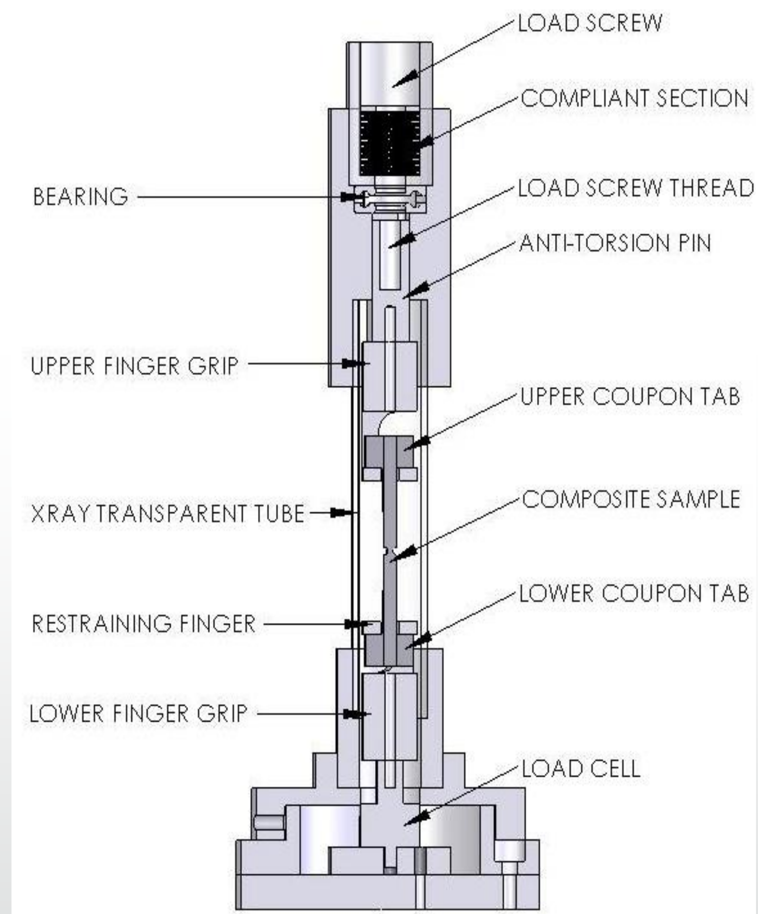
Damage progression in cross-ply CFRP sample

- Transverse ply cracks
- 0° split



Beamlines: ESRF/ID19

Computed Tomography



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In situ testing at synchrotrons

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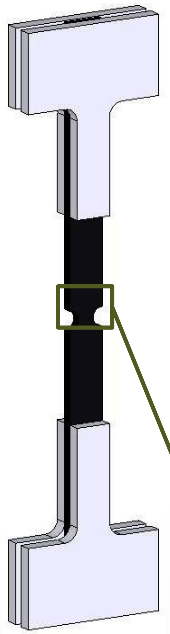
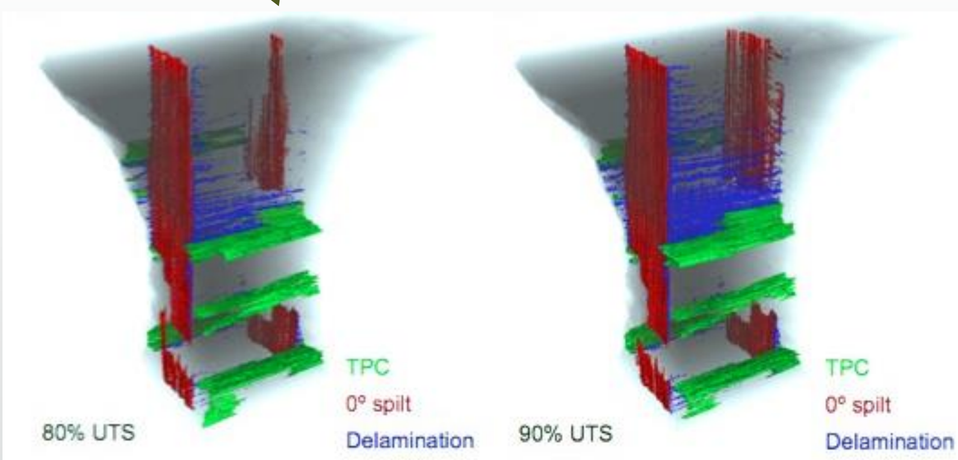


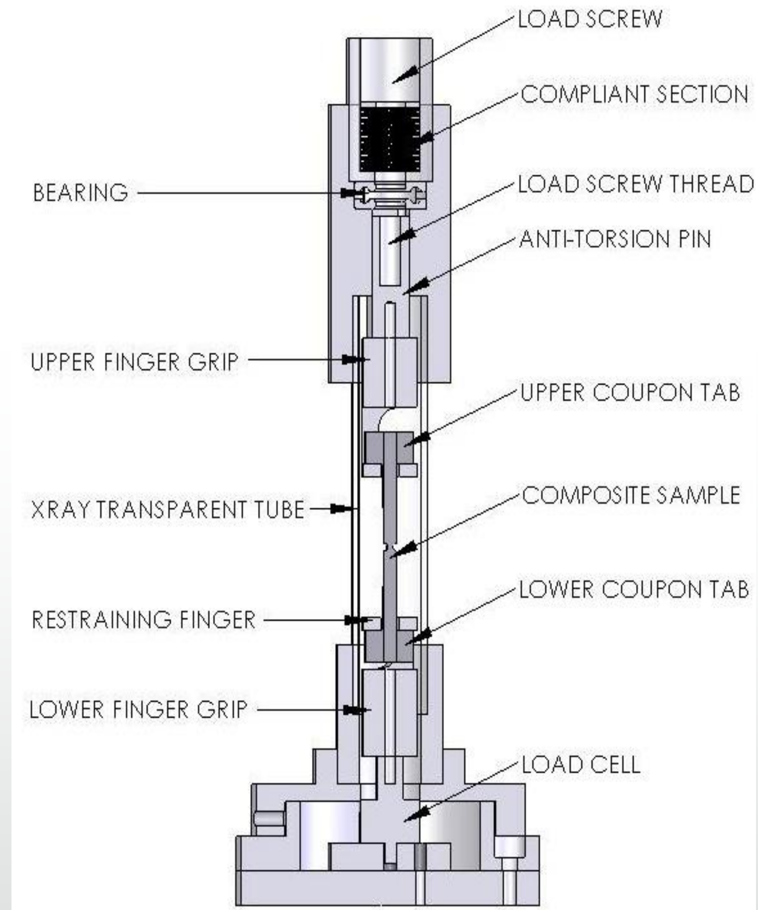
Damage progression in cross-ply CFRP sample

- Transverse ply cracks
- 0° split
- Delamination



Beamlines: ESRF/ID19

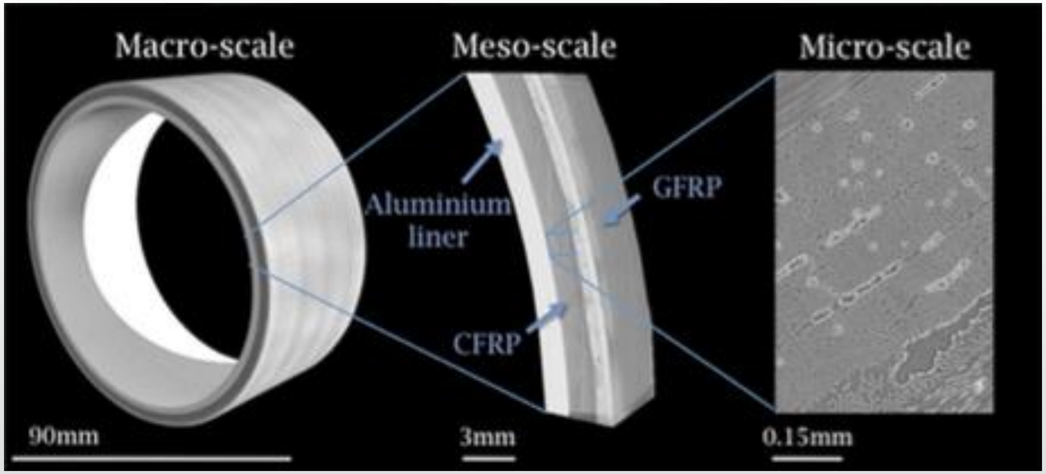
Computed Tomography



P. Wright et. al., Compos. Sci. Tech. 70(10) pp1444-1452, 2010.

Complementary techniques

- Beyond match-stick testing…
- Large scale structural performance related to micro-scale mechanisms
- Need to assess 'fibre breaks' in non-ideal/real microstructures



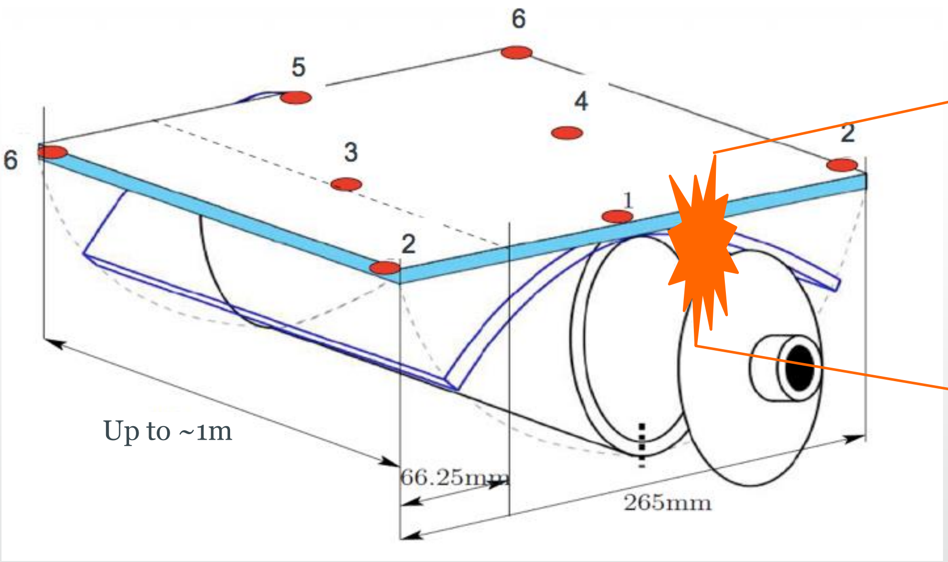
Vox. Res. 75 µm 15 µm 1.4 µm

Hybrid Composite Metallic Structure

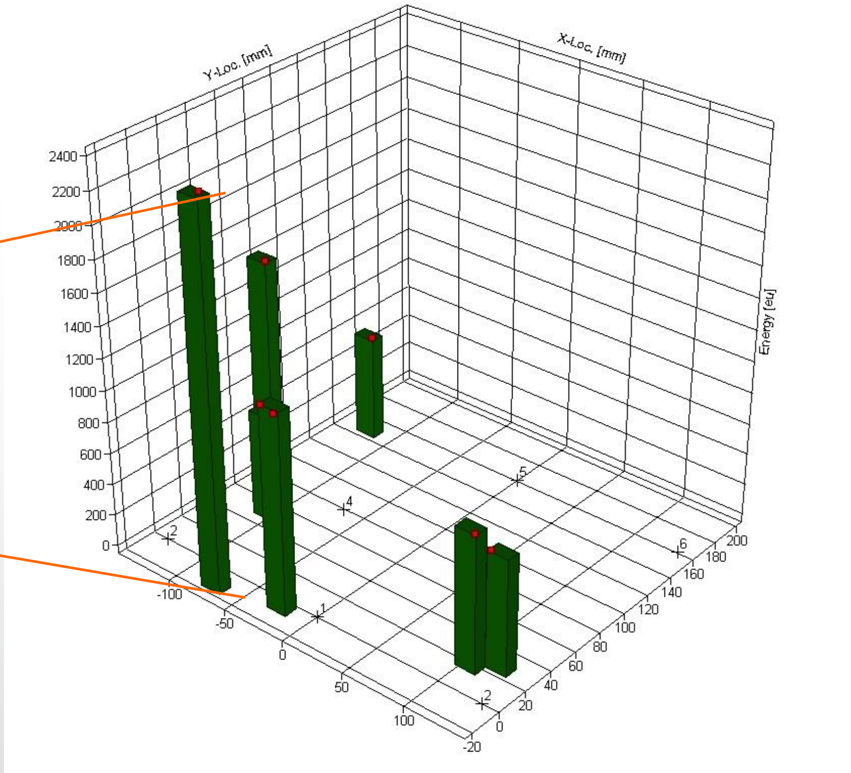
Hydrostatically loaded composite circumferential structure

-Specimens extracted at near-failure, informed by Acoustic Emission

-Al-alloy/CFRP

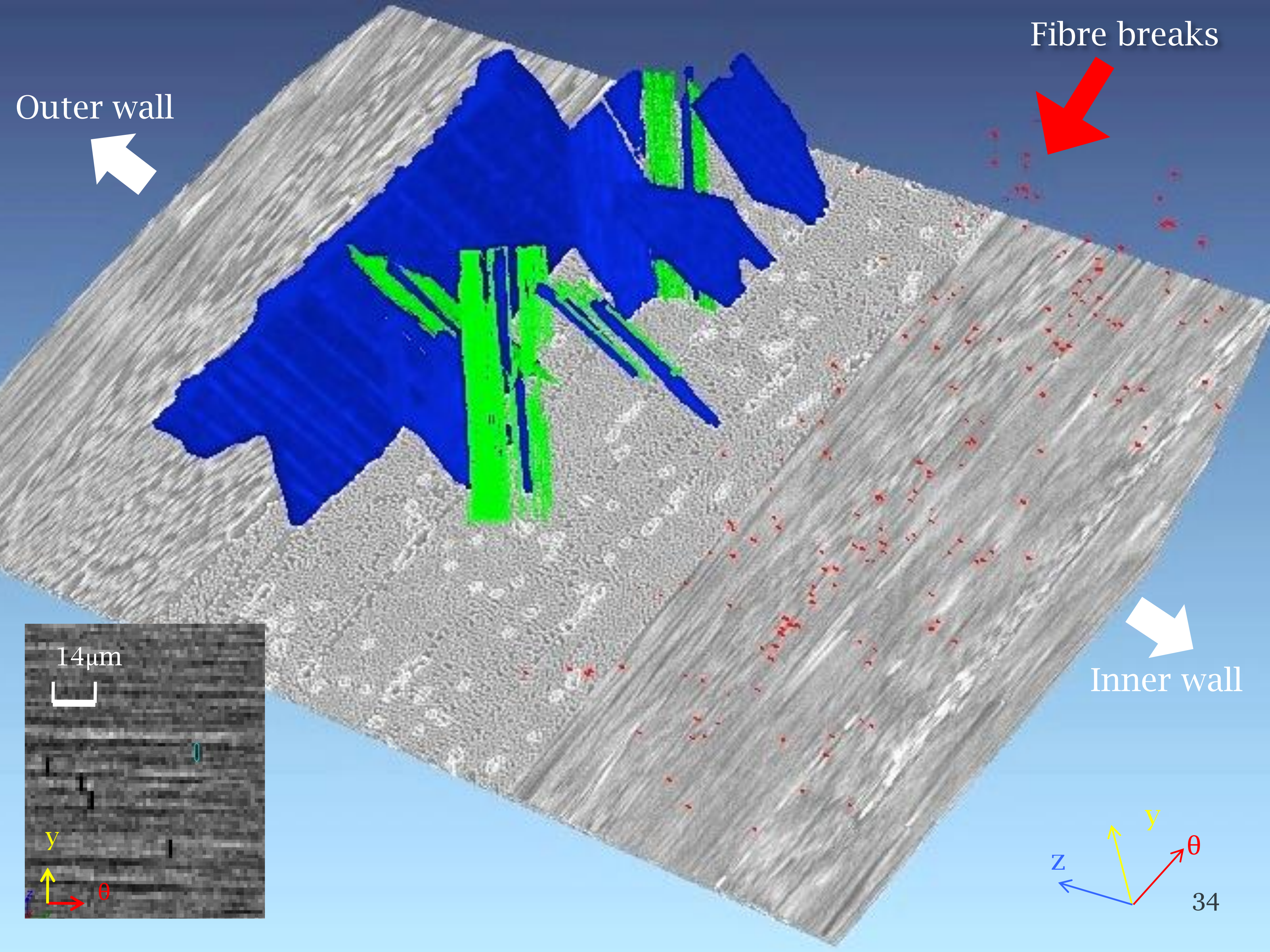


Sensor locations on the structure



High energy locations

*A.E. Scott et. al., Compos. Sci. Tech. 90, 2014


Fibre breaks
Outer wall
Inner wall
14µm
y
θ
z
y
θ

Void-fibre break mapping

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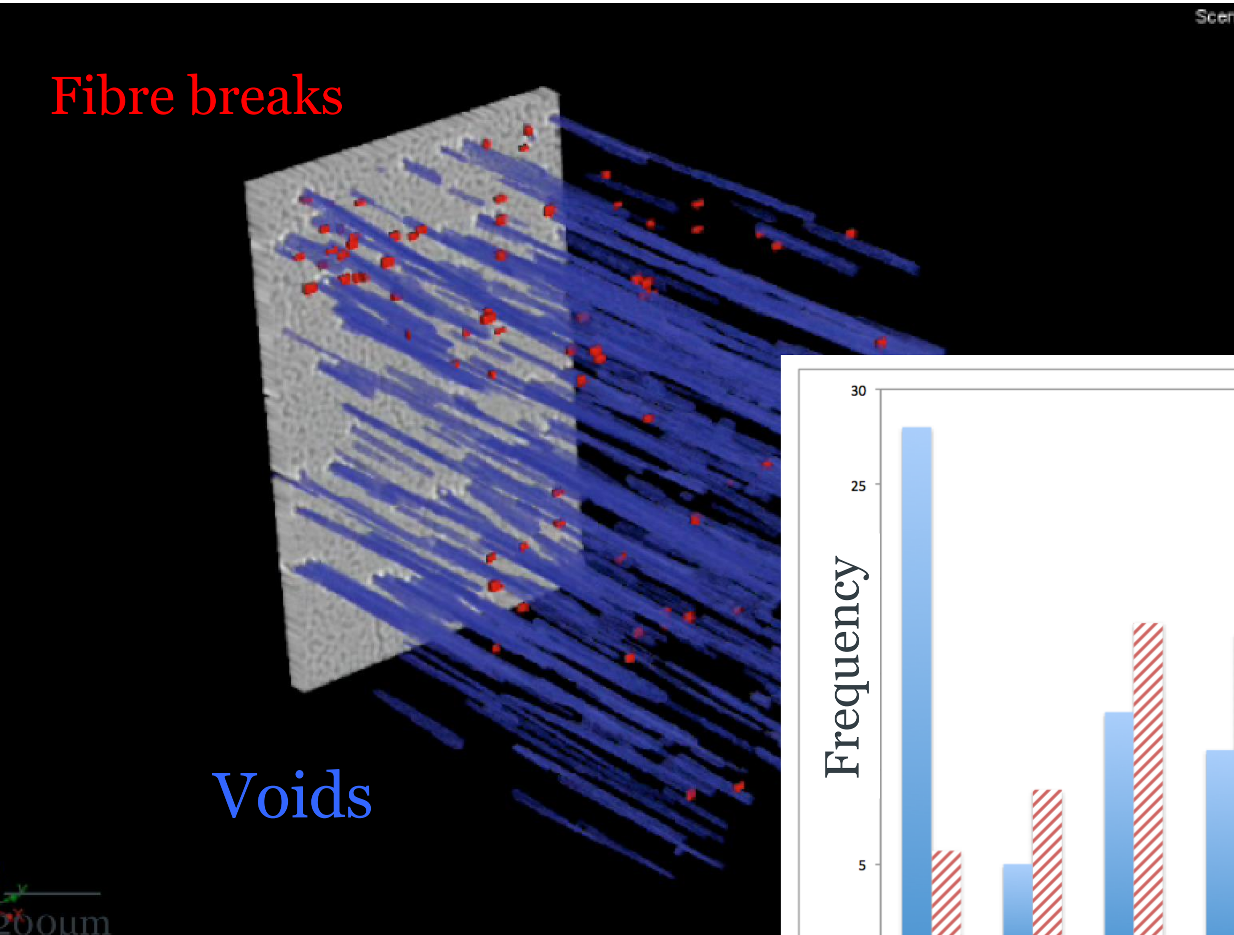
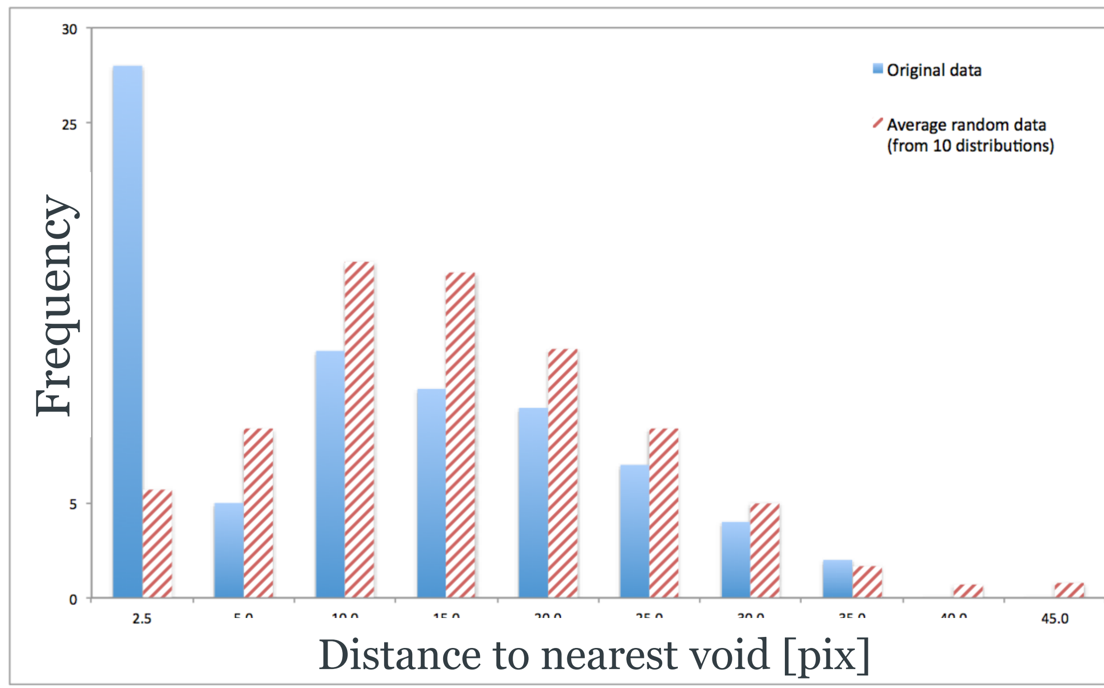
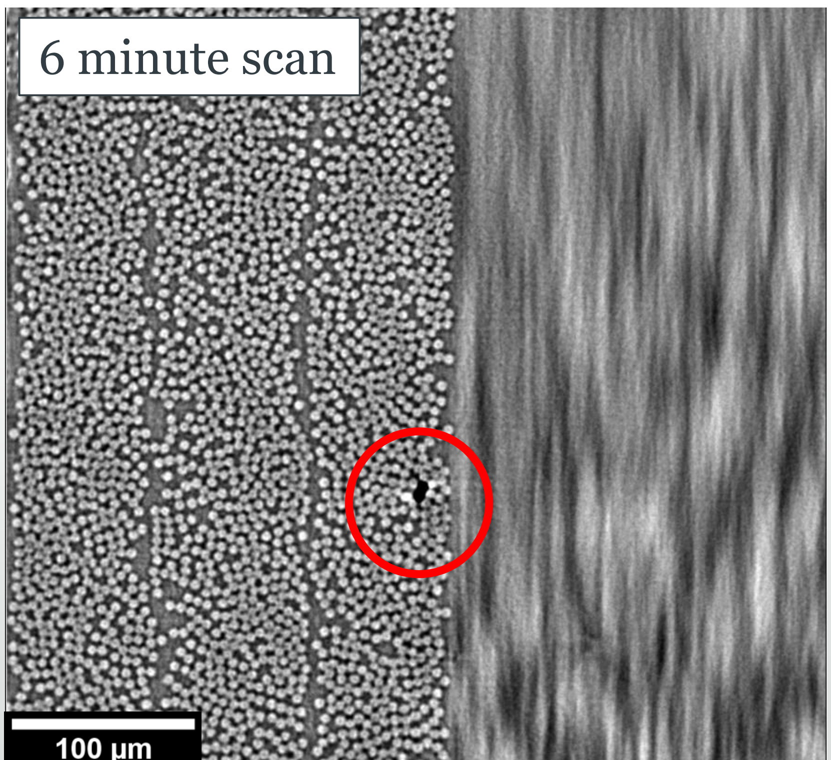
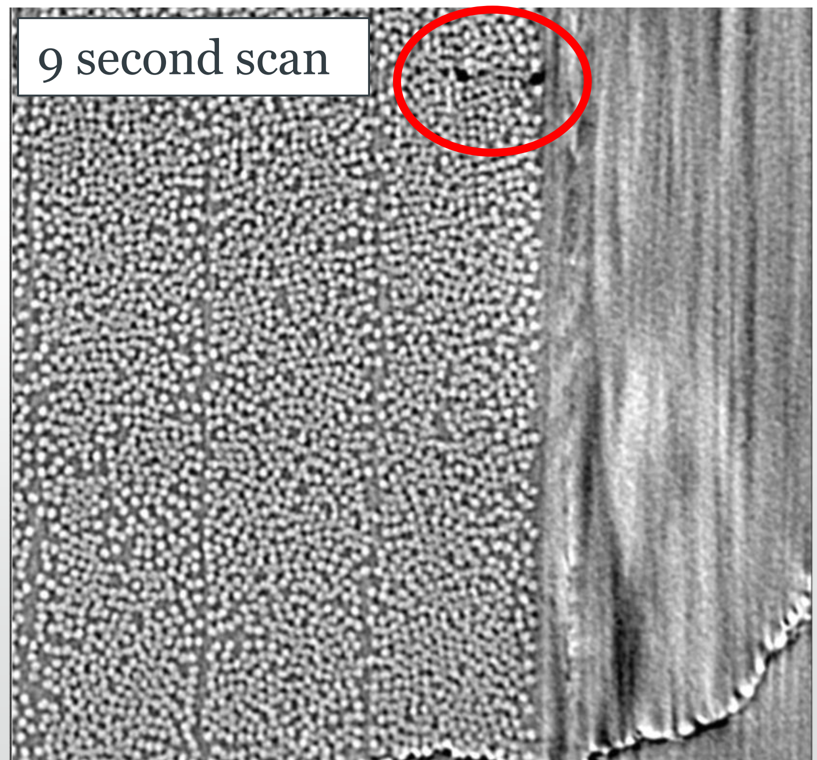




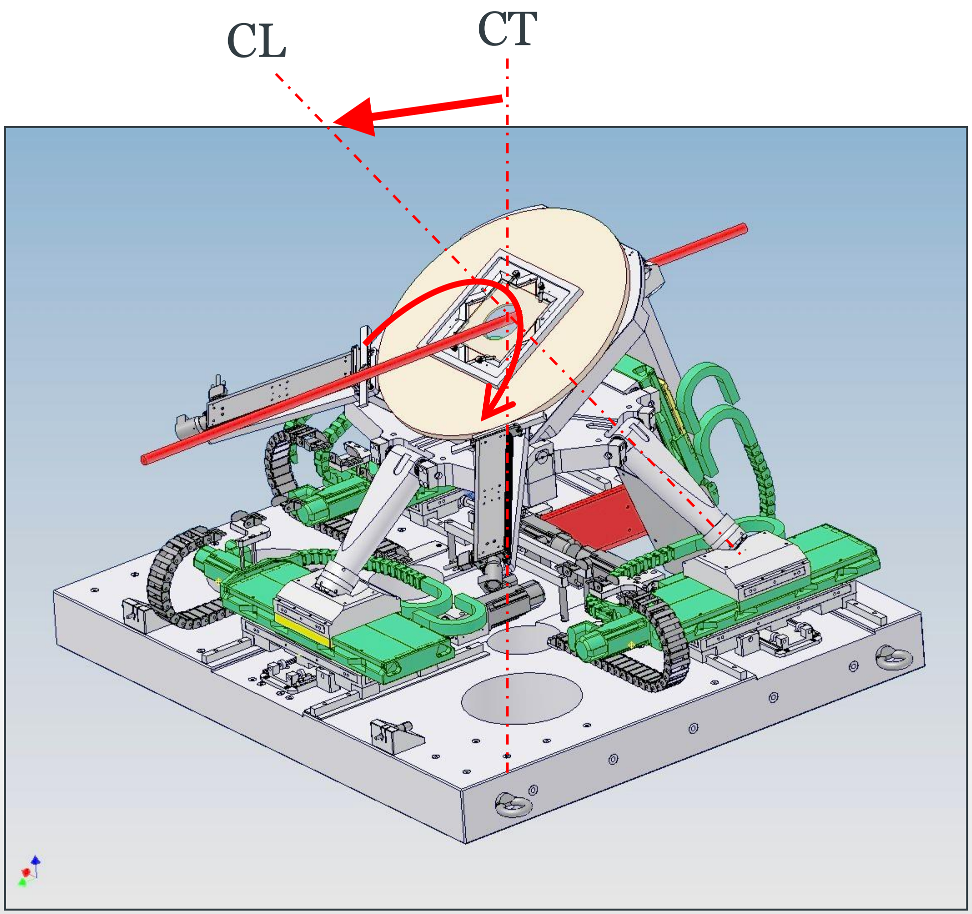
Future developments/opportunities

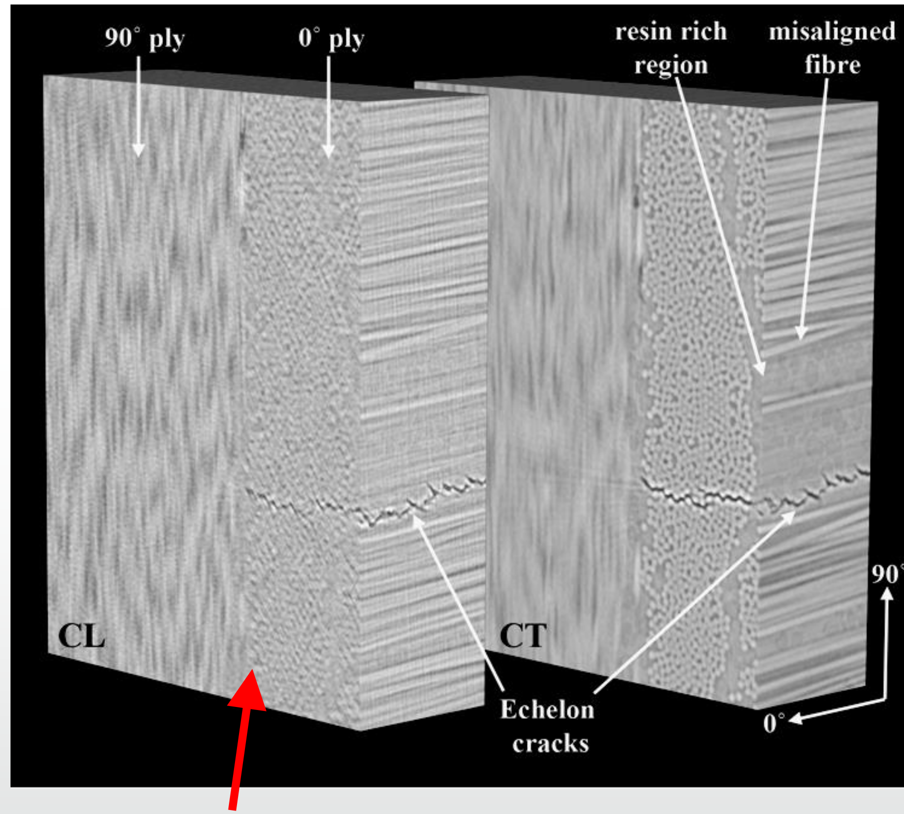
- **Fast scanning** is a key development relevant for *in situ* tests
- **Limited angle CT** and associated **iterative reconstruction** methods for large structures and complex testing rigs





Laminography: ESRF (ID19)



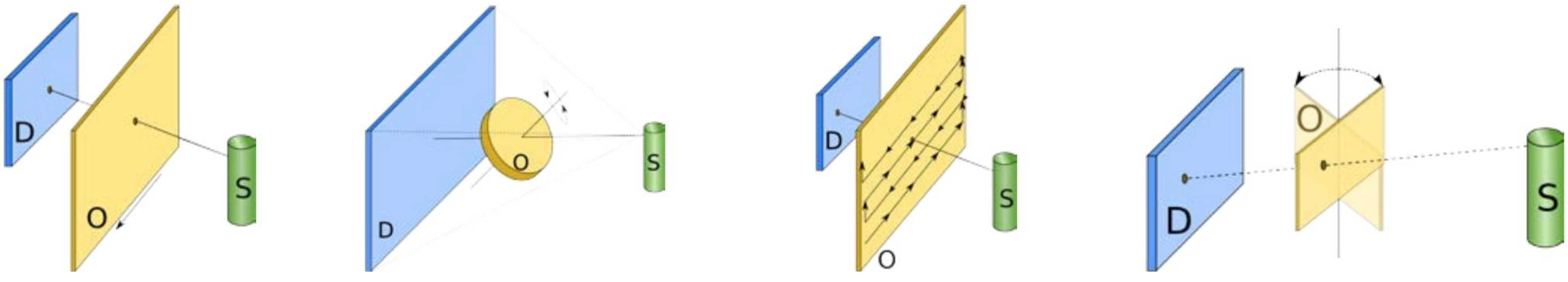


Courtesy: Lukas Helfen

Micron/sub-micron resolution is possible in larger panels

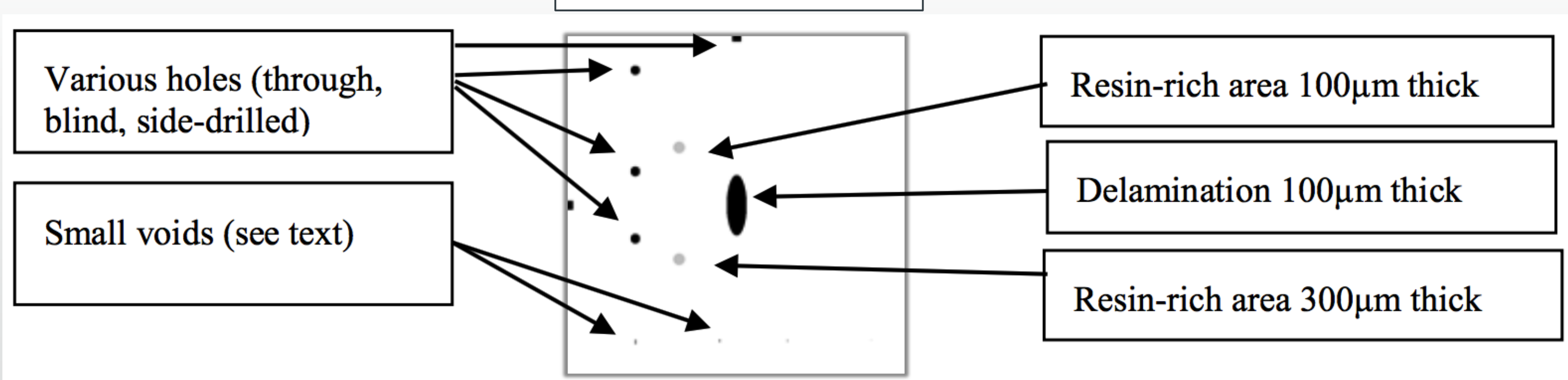
μ-VIS: Arbitrary X-Ray path methods

- Breaking limitations of size/axisymmetry



Linear | Rotary | Raster | Swing (1 axis)

Test Phantom



O'Brien *et al.*, (2016), iCT

μ-VIS: Arbitrary X-Ray path methods

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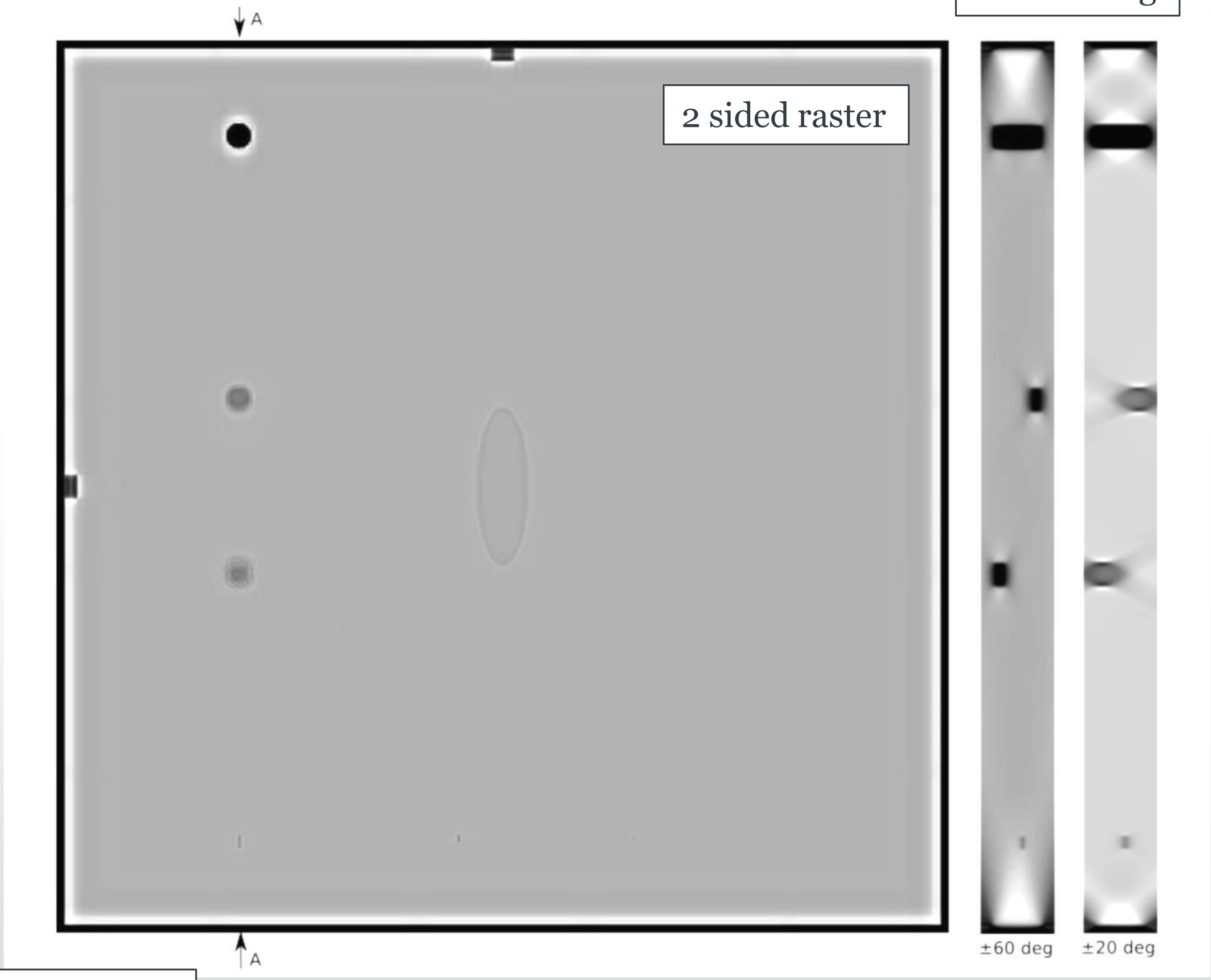
15 iteration SIRT reconstructions

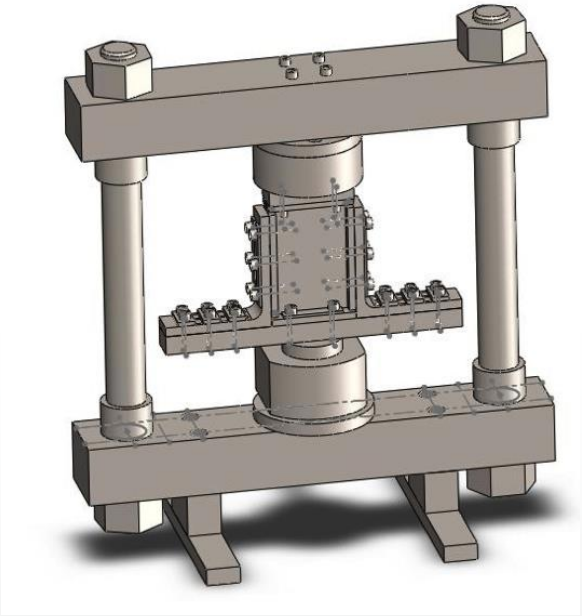
2 axis swing



O'Brien *et al.*, (2016), iCT

Challenges

- Industrial applications – large and arbitrary shapes
- Automatic segmentation to make morphological measurements
- Curating the data – making it available and storing it
- Traceability of the measurements – No standard for metrology



In situ compression rig

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Summary

- Opportunity for understanding material behaviour from microns to meters
- Big opportunity to conduct ‘time-consuming’ experiments:
  - Wealth of data obtained -> Data Rich Mechanics
  - Informed by models, to inform models

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Thank you for listening

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μ-VIS X-Ray Imaging Centre

CYTEC SOLVAY GROUP

PAUL SCHERRER INSTITUT PSI

TOMCAT beamline

EPSRC Engineering and Physical Sciences Research Council

Impact acceleration account

ESRF The European Synchrotron

ID 19 beamline

Luxfer Gas Cylinders