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Data-Rich Composite Mechanics Using Multi-scale Computed Tomography

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Introduction

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- High Resolution Computed Tomography - a new opportunity
  - The need for multi-scale imaging approaches
- Examples of application to three composite damage mechanisms
  - Transverse ply cracking
  - Splitting from notches
  - Fibre failure
- Concluding Remarks

Synchrotron Radiation Computed Tomography (SRCT)

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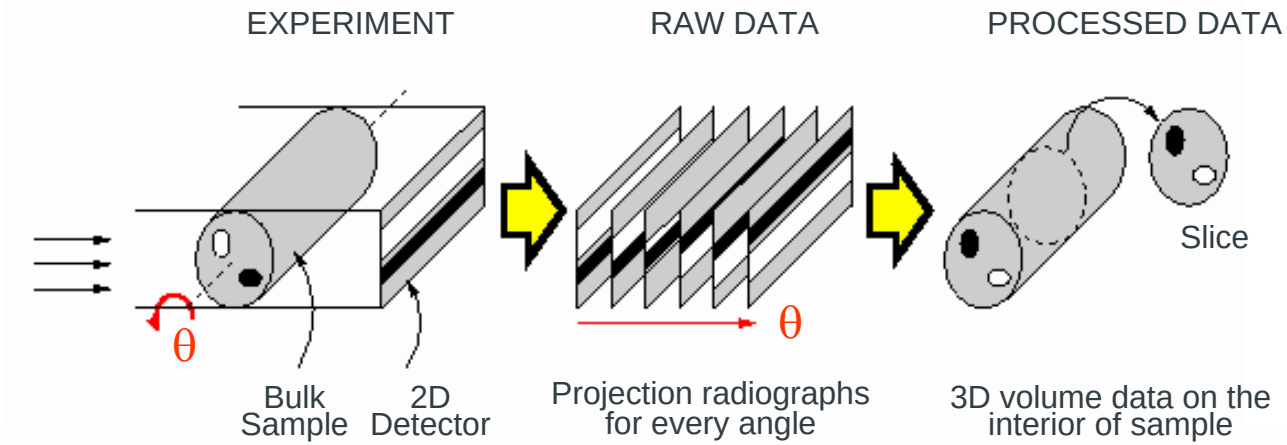

- High fidelity 3D imaging resolution from 0.3 µm,
- Coherent, monochromatic beam for absorption and phase contrast imaging
- Avoids cutting/polishing/ surface artefacts of microscopy

Lab-Scale CT Imaging@ Southampton

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• *Complete support* for the processes of 3D imaging:

- Experiment design, through data analysis, to validated, publishable measurements.
- World class collaboration in *High resolution CT imaging*, *HPC* & e*Science*, *computer vision*, *multi-user facilities management*

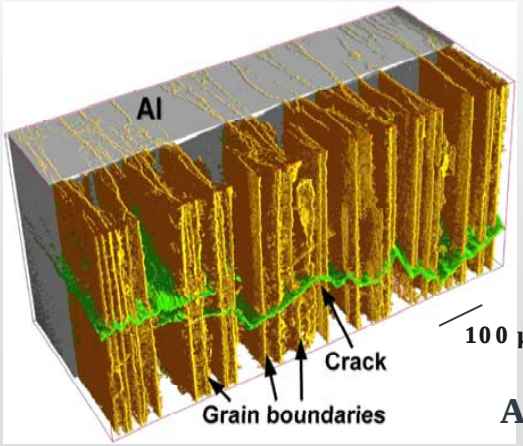
• £2.2M extension of current CT activities (both lab and synchrotron): custom designed, dual beam-line computed tomography lab and visualisation/analysis suite:

(1) 225kV high resolution/high throughput system: Nikon/Metris HMX-ST

- 20-225kV operating range, 1µm resolutions, Robotic sample exchange, Samples to ~300mm diameter/50kg

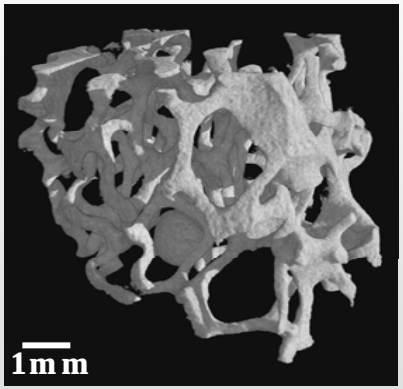
(2) 225/450kV Custom Bay

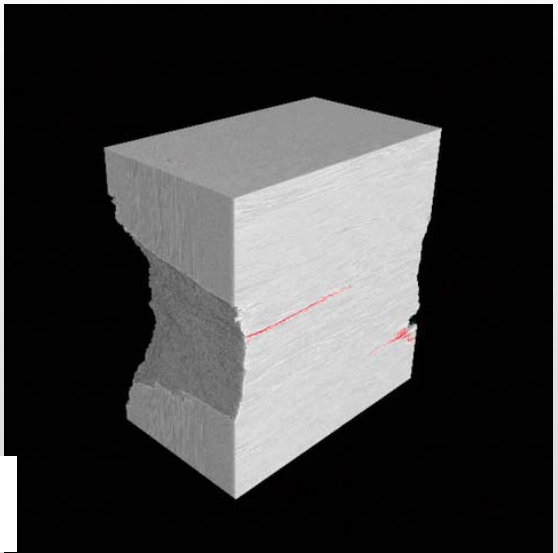
- 20-225kV and 100-450kV sources, resolutions: ~3µm low kV, 50µm at 450kV
- 1 x 1 x 1.5m imaging volume, 100kg manipulator rating



Al fatigue crack

Open-cell Al-alloy foam





CFRP static fracture

SRCT: Toughening Mechanisms

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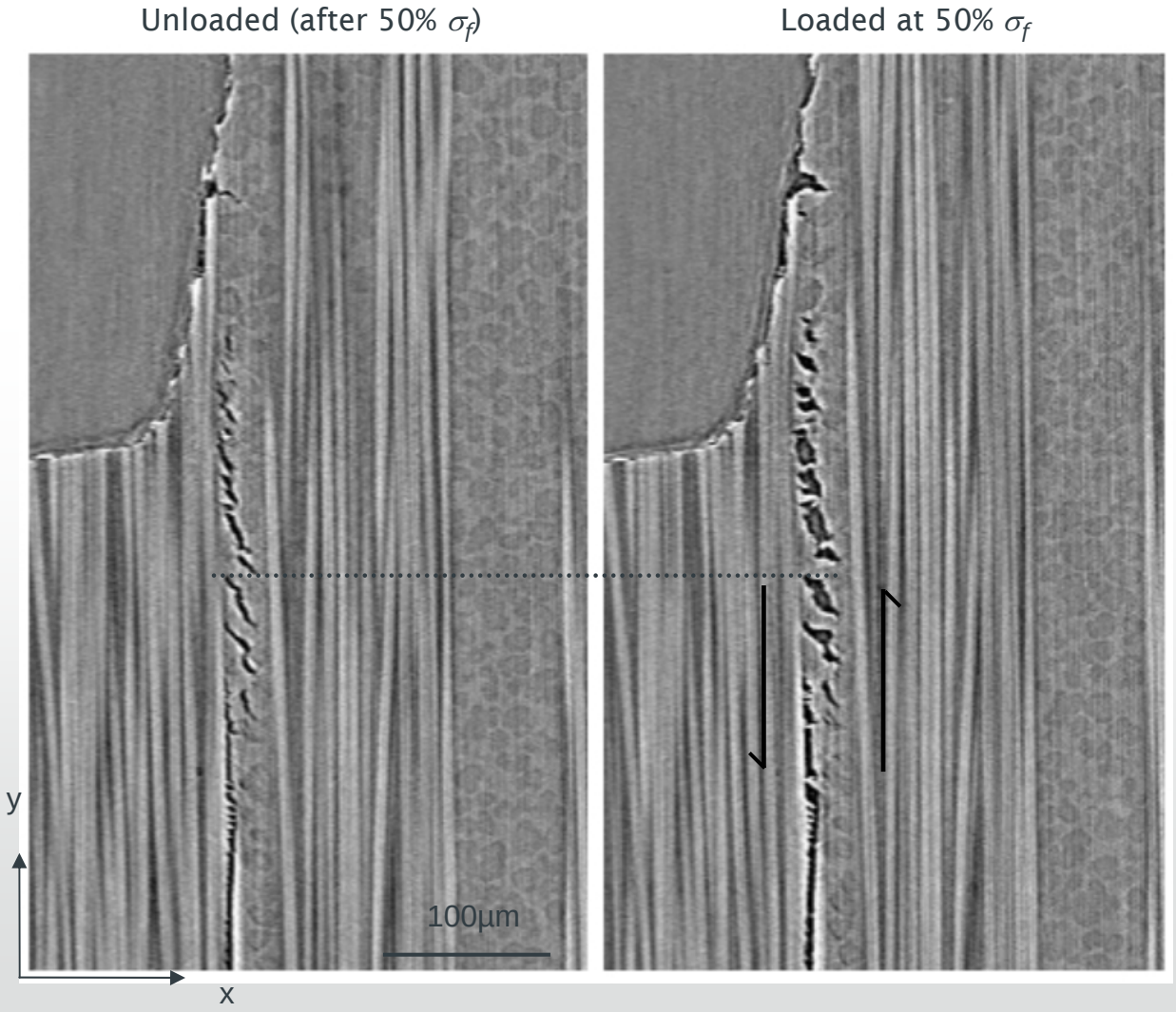

- Echelon cracks in the resin rich region
- Opening indicates shear displacement upon loading
- Particles form in the resin rich regions - rubber toughening

SRCT: Delamination

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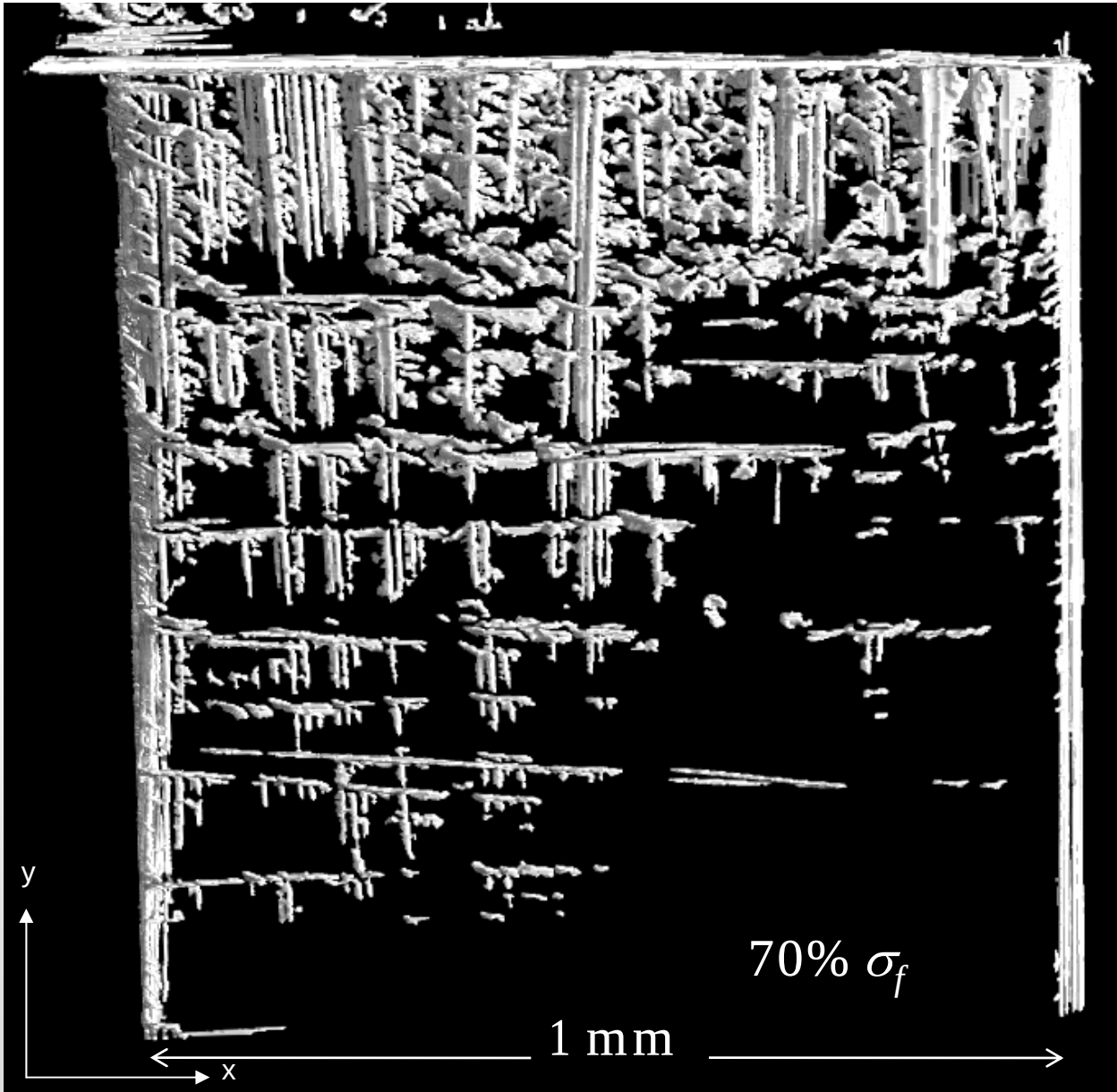
- Damage grows and coalesces
- Cross-hatched pattern of damage exists
- Bridging across the ply interface until high stresses
- Delamination is 3D, discontinuous and consisting of multiple mechanisms



SRCT: Limited Field of View -
Need for Multiscale Approach

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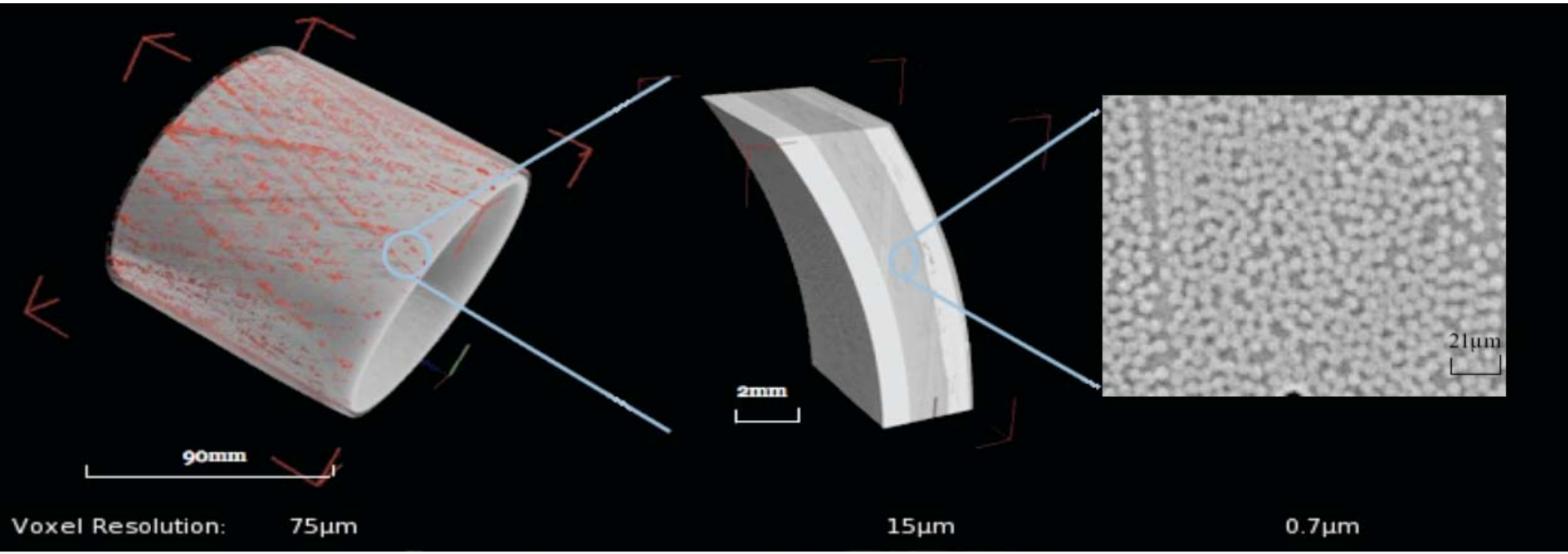

Macro-structure

Whole cylinder scans

Meso-structure

Regions extracted from whole cylinder.

Micro-structure

Sub-regions extracted from meso-structure.

Lab Scale CT: Southampton
Up to 1m diameter

SRCT: ESRF
4mm diameter[7]

In Situ Tensile Loading

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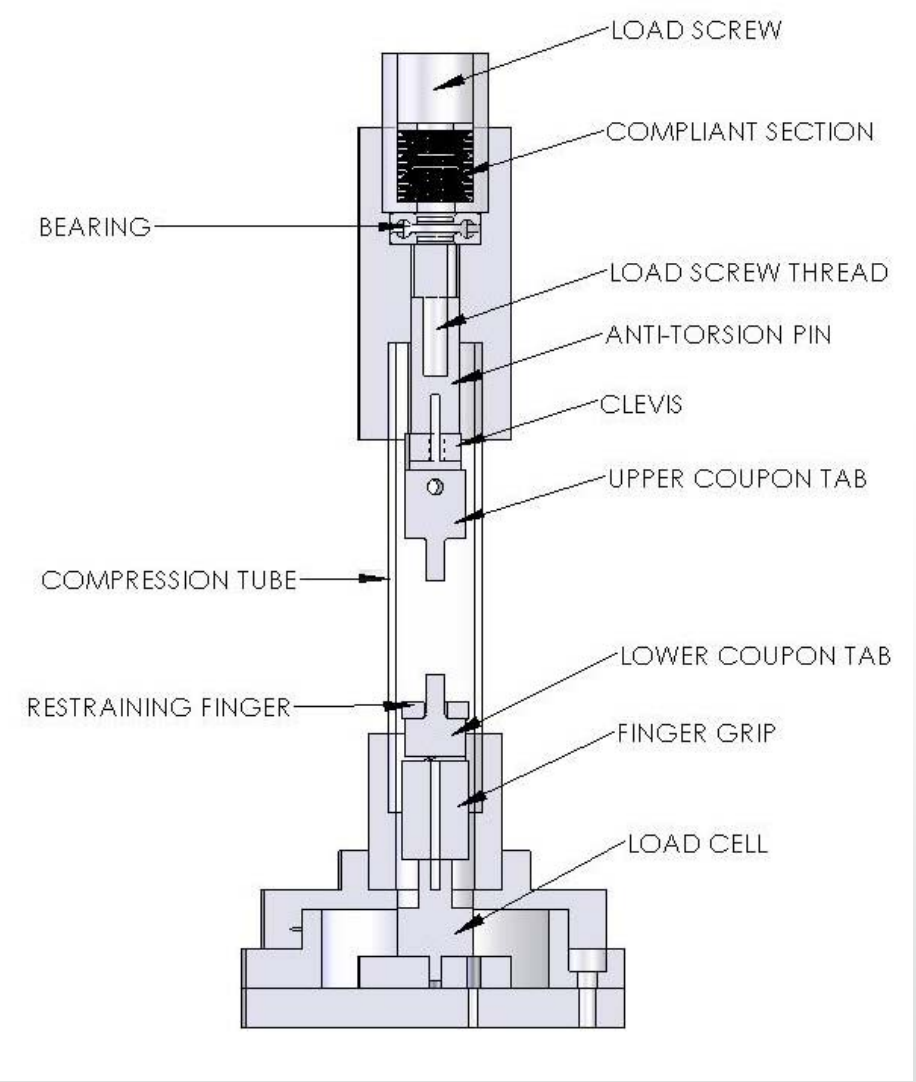

- Manually loaded rig.
- 1 kN load capacity
- Minimal load drift over imaging duration (3-10 min)
- 1-4 mm wide samples bonded between Al tabs - jig for tab and sample alignment
- Allows for *in situ* damage growth observations and comparison of deformations at multiple load levels

Transverse Ply Cracking

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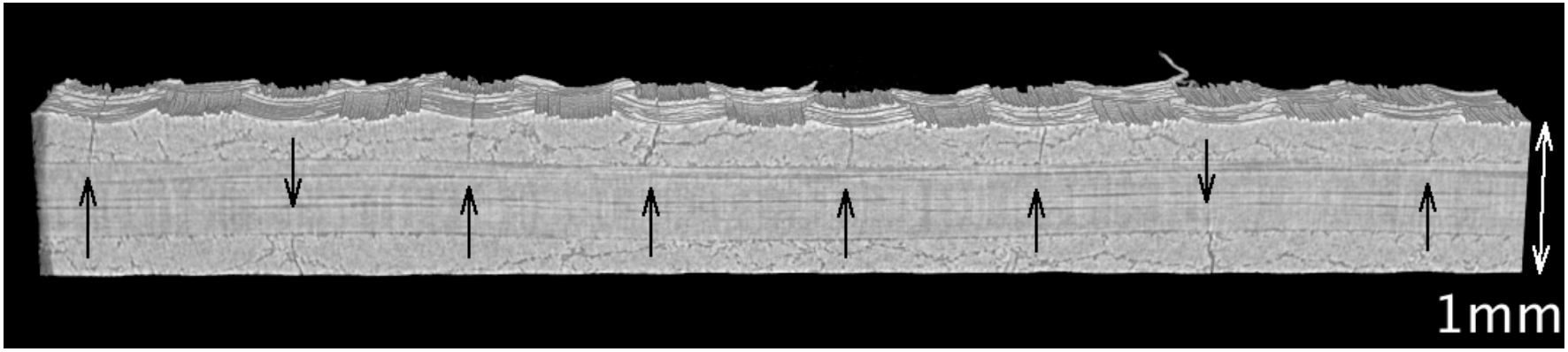

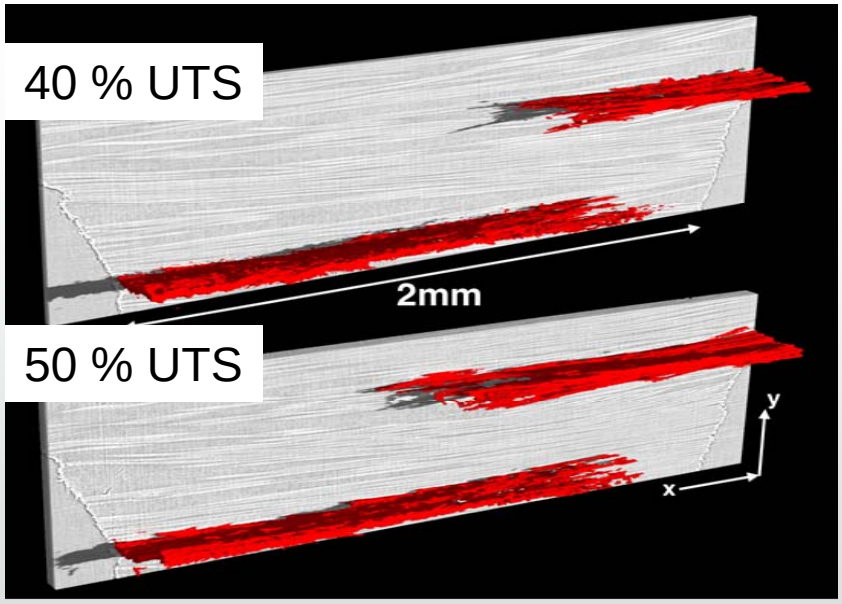

- Lab CT images arrays of TPC's observed
- Possible correlation with surface texture
- Rapid growth across specimen width - steady state cracking
- Some evidence of crack shielding

TPC's at High Resolution

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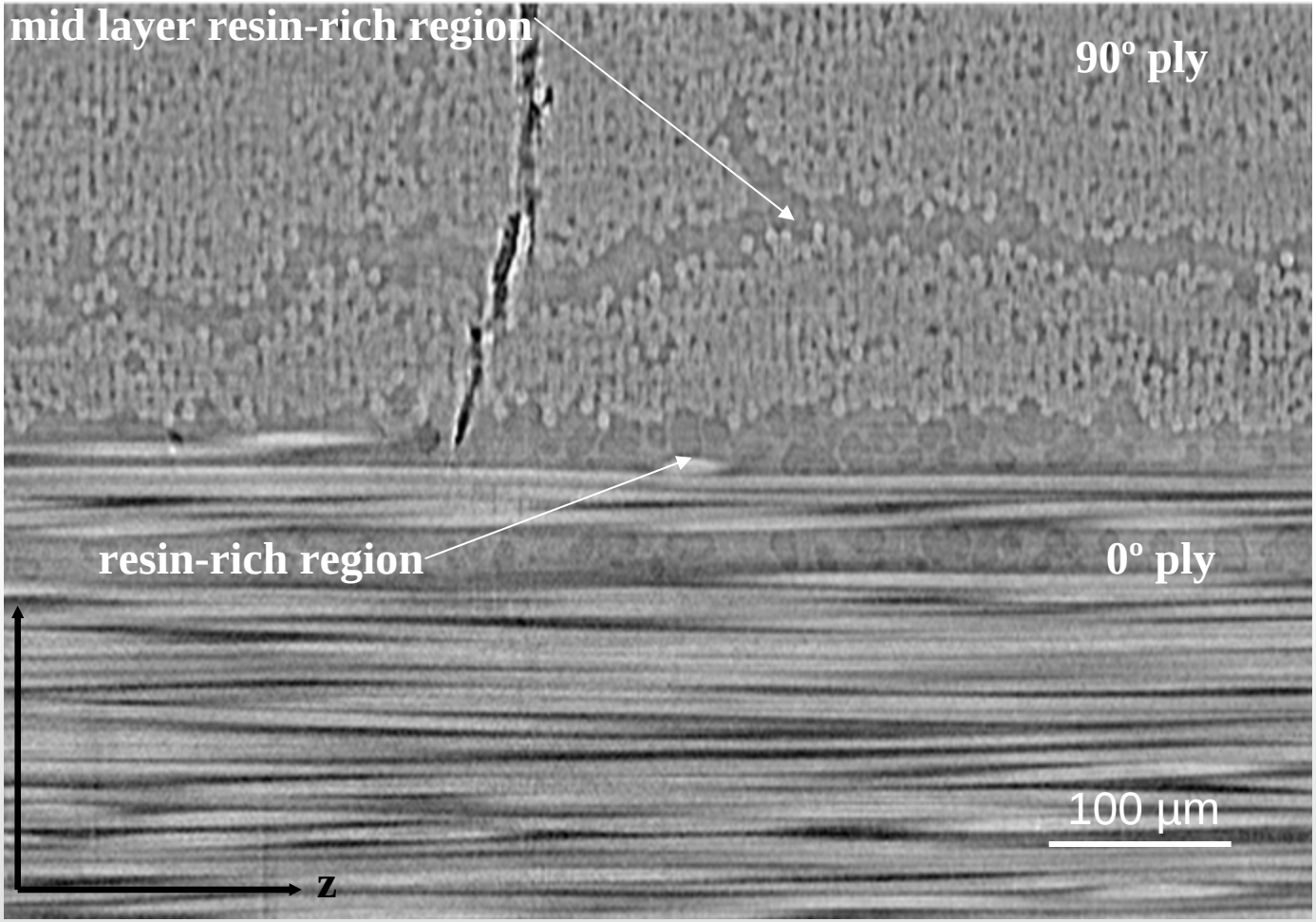

Toughening particles result in resin rich regions at interfaces

TPC Opening Profiles

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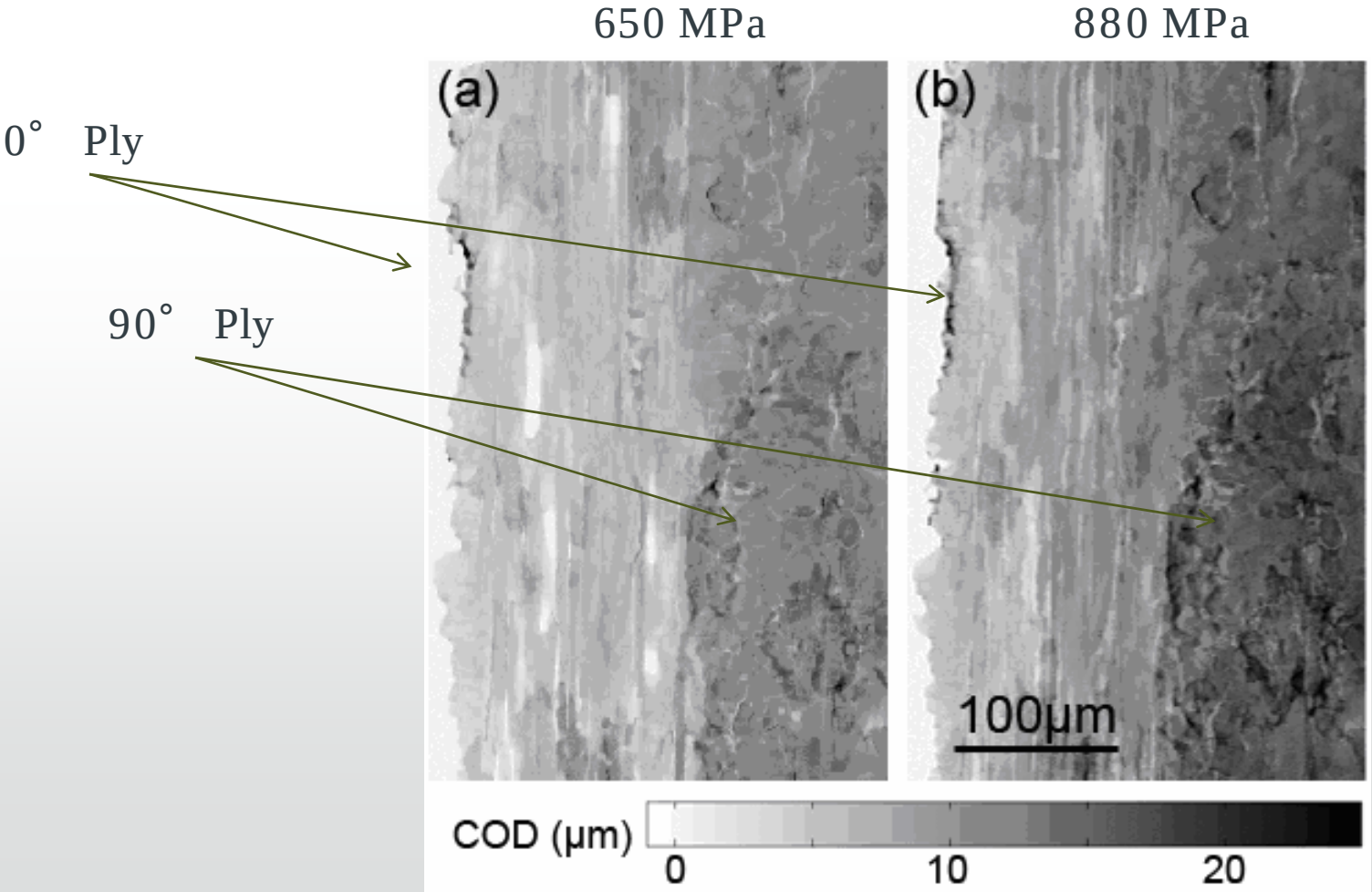
- 3-D quantitative data on displacements can be obtained with sub-micro resolution



Model - Experimental Comparison

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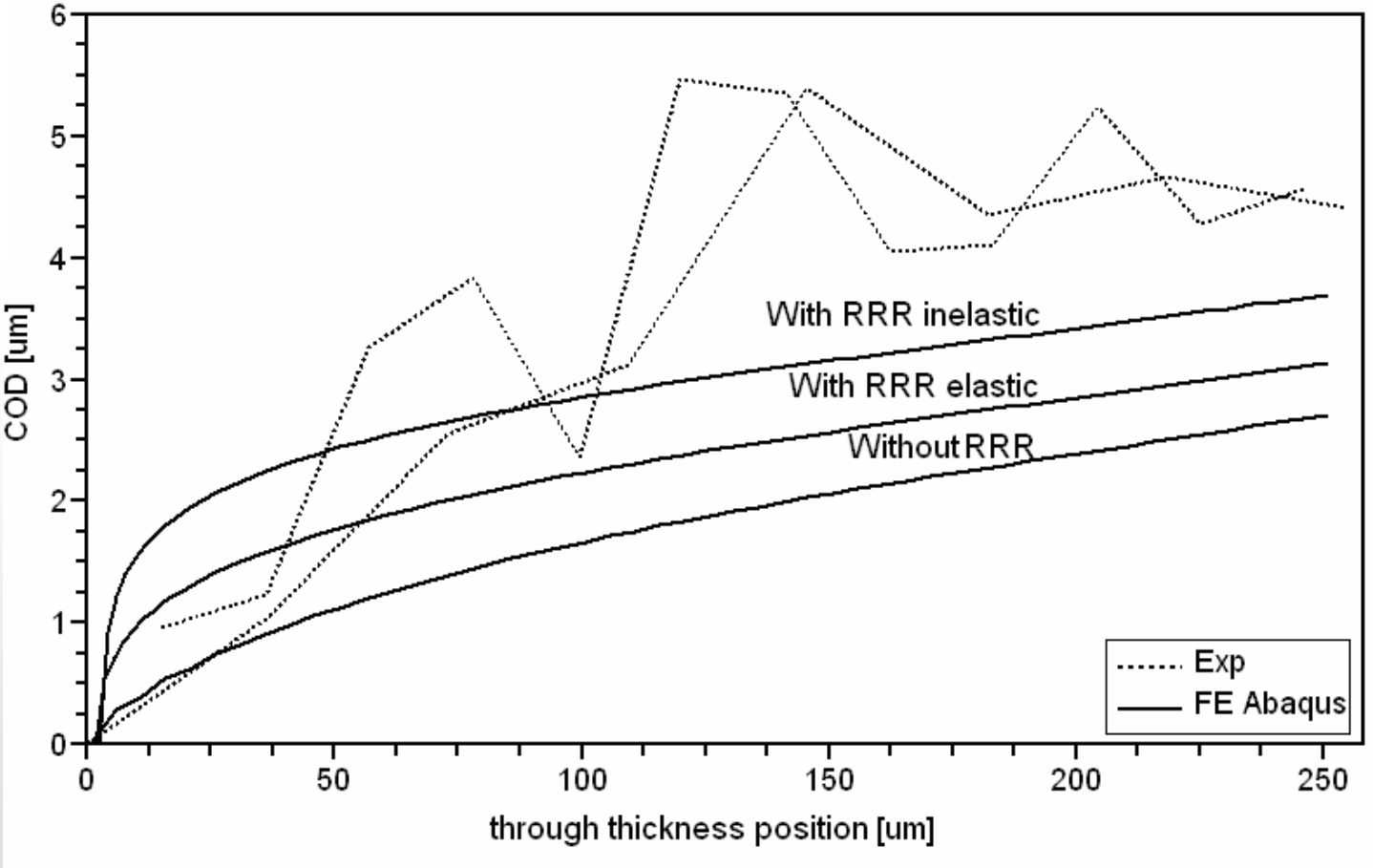
- Quantitative data allows comparison with analytical and numerical models



Suggests importance of modeling resin rich regions

Split Growth from Notches

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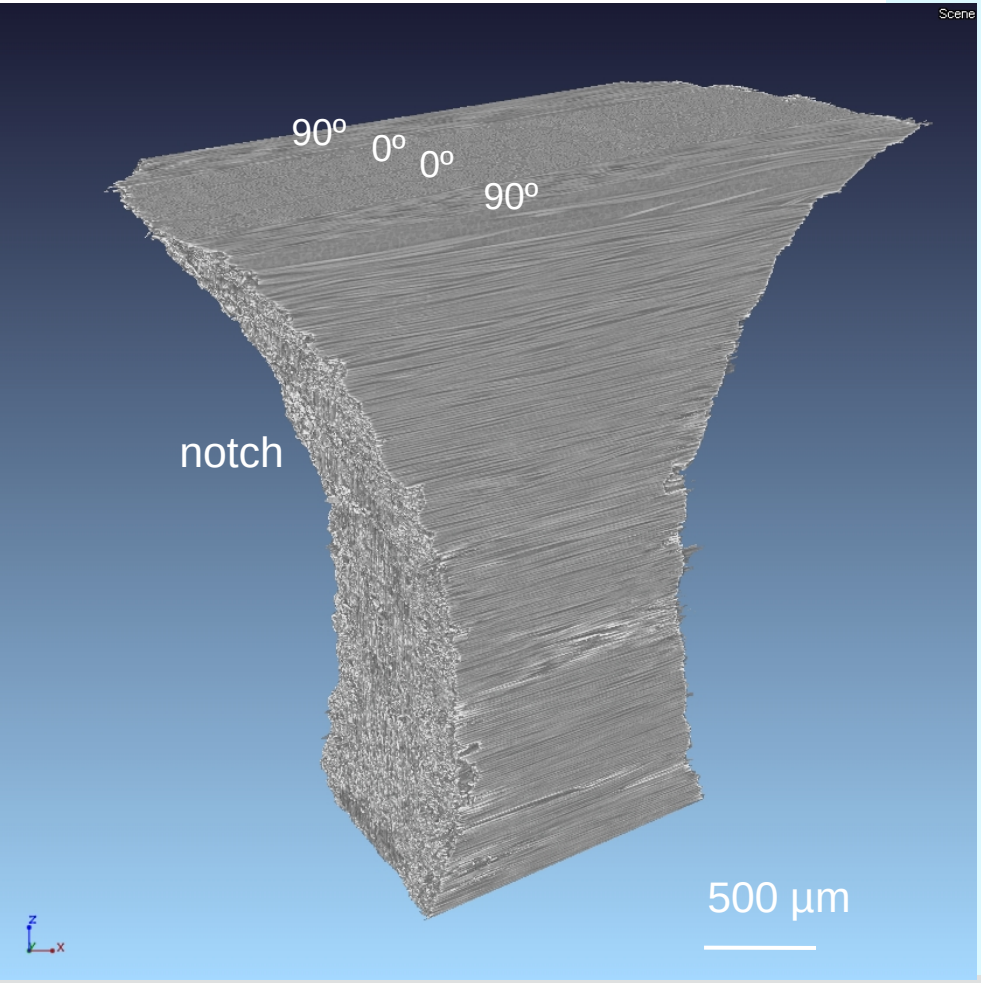

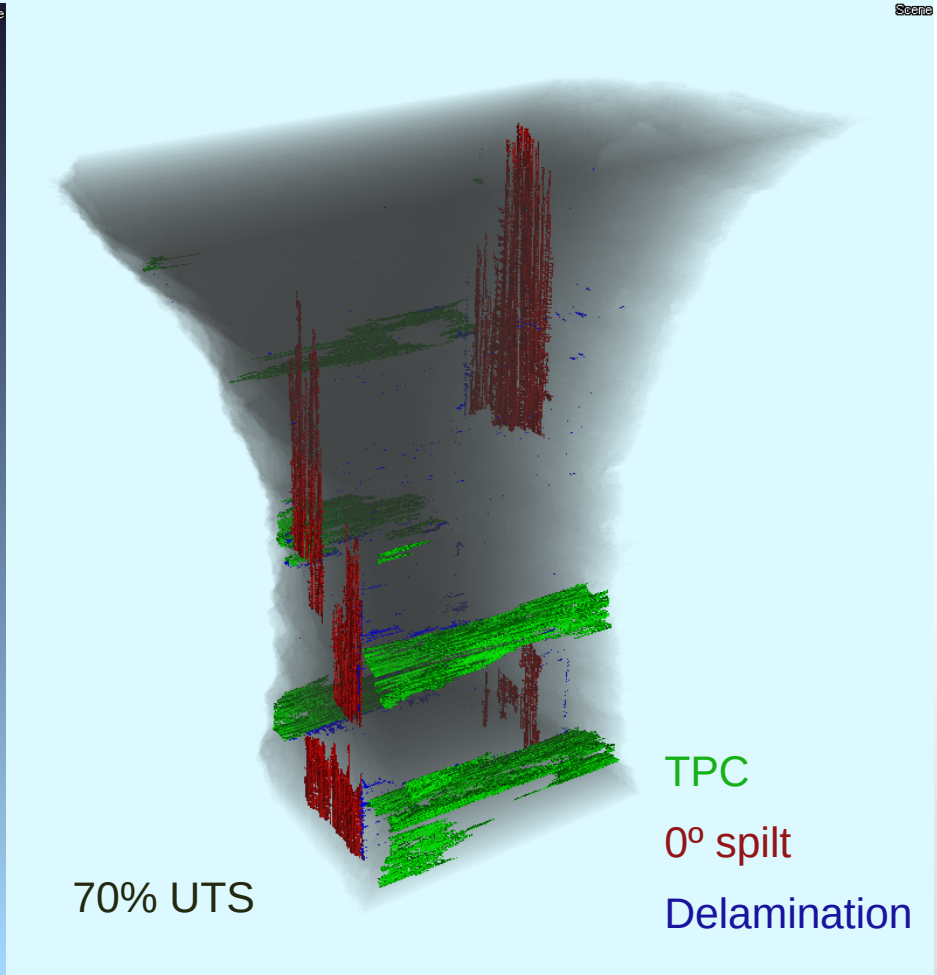

Damage Propagation
$[90/0]_S$ 80% UTS (nominal)

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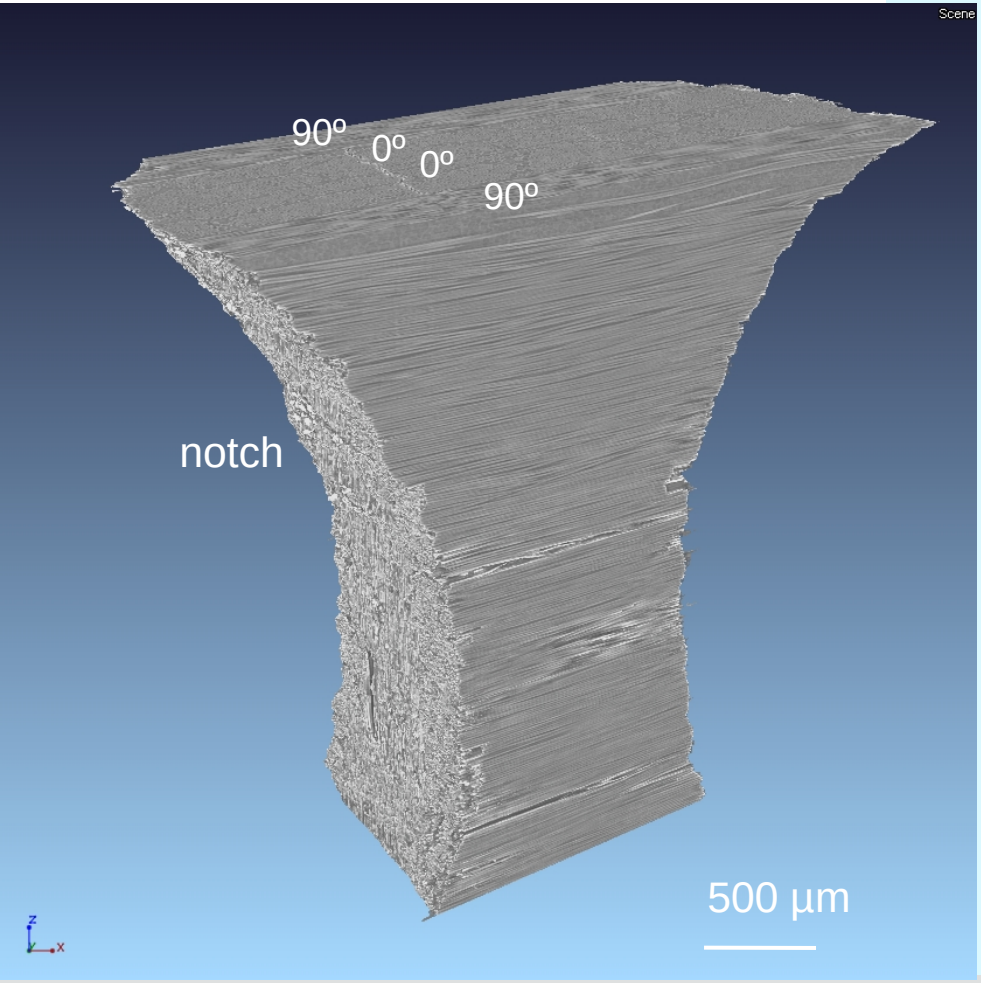

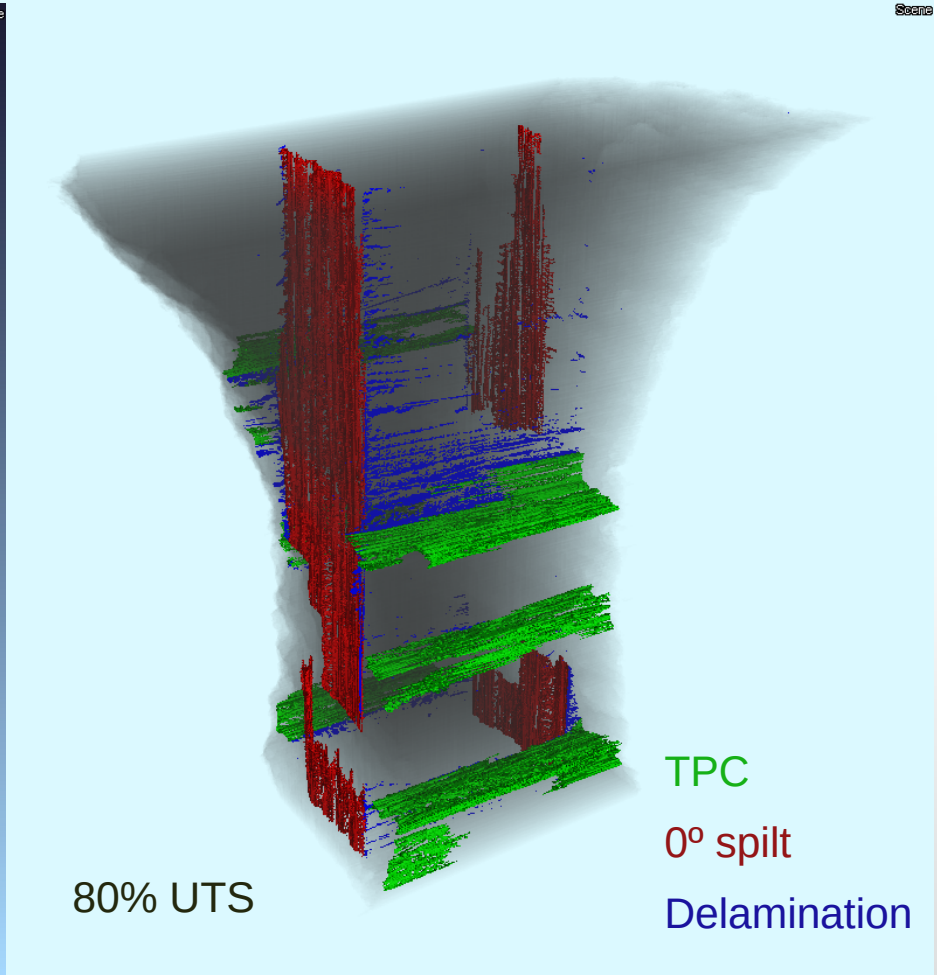

3D FE Modeling of Splits

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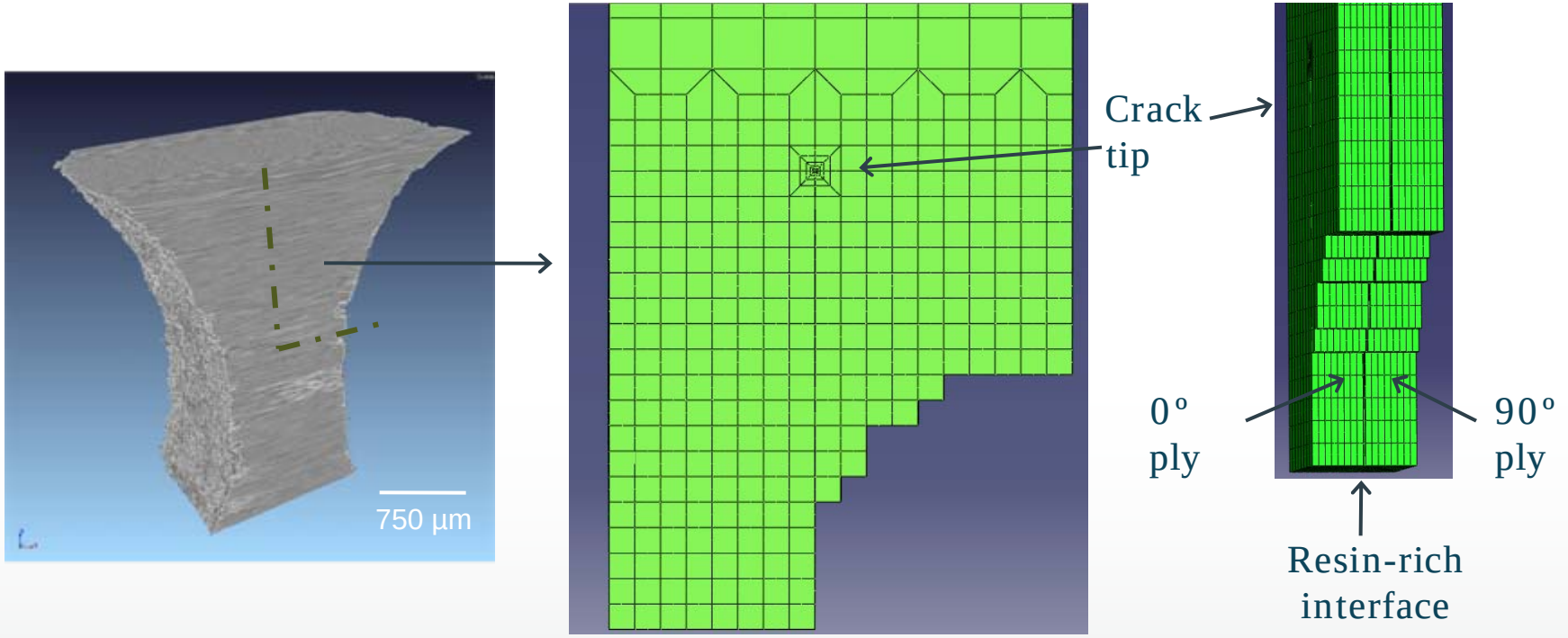

- 20 node, 3D, solid continuum elements, 1/8th geometry (3 symmetry planes)
- 0º split modelled as adjacent elements with independent nodes along split path
- Mesh refinement analysis carried out
- Thermally induced residual stress
- Cohesive elements introduced between crack surfaces

Experiment vs. Model

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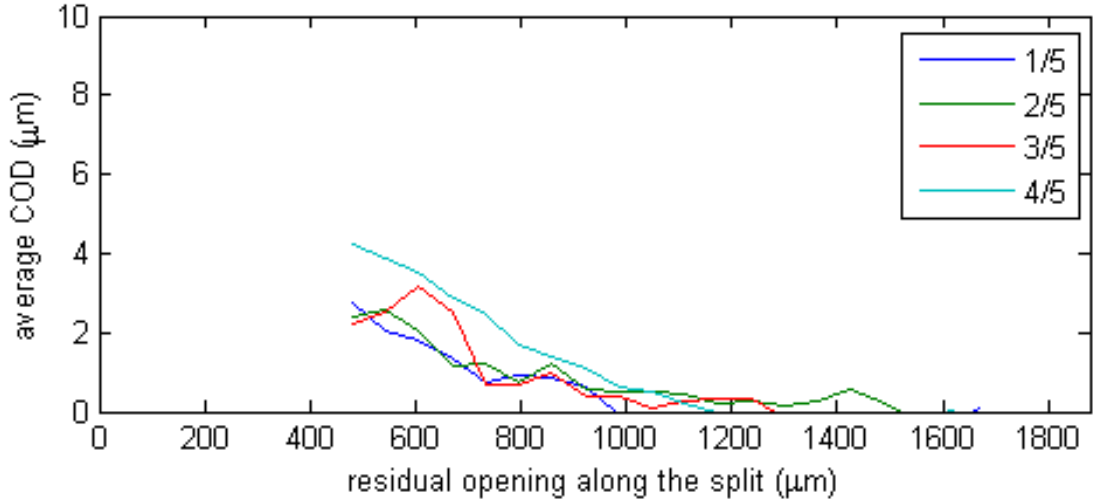
Experiment:

COD along the 0º split calculated at four positions through the laminate thickness at 40% UTS

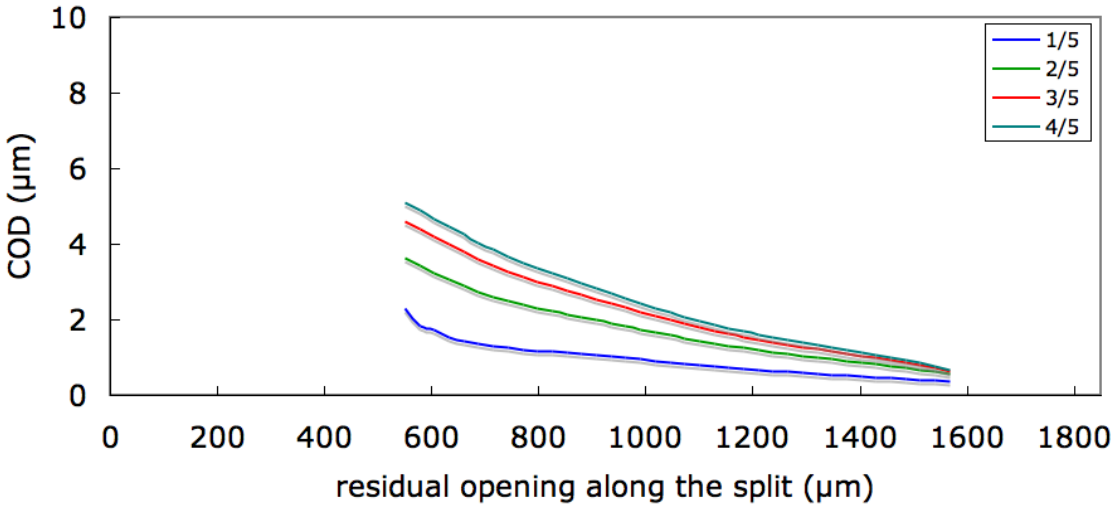
Experiment



Model:

COD prediction follows trend and shows reasonable correlation with absolute values at 40% UTS

Model



Full Volume Displacement/Strain Mapping

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- Full volume resolution of deformation/strain fields during damage propagation would enable calibration and validation of physically based damage models

- Two independent approaches employed:
  - Individual fiducial marker tracking: ~ 4μm aluminium particles distributed sparsely at the ply interfaces (<0.005% vf)
  - True 3D, feature based digital image correlation: "Digital image correlation (DIC)" ➔ "Digital volume correlation (DVC)"

Image Correlation

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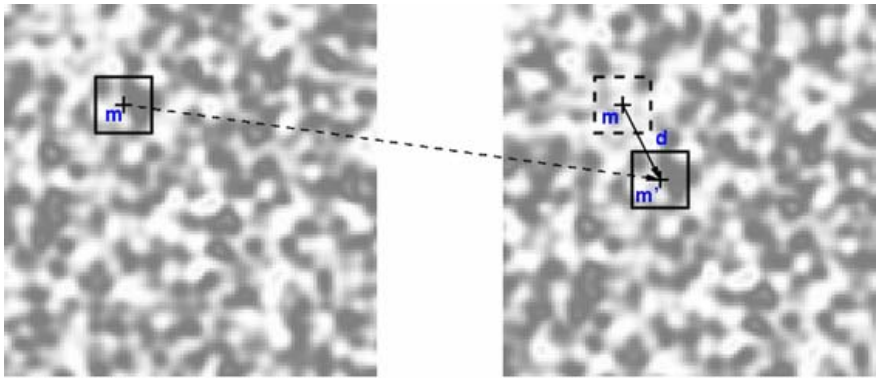
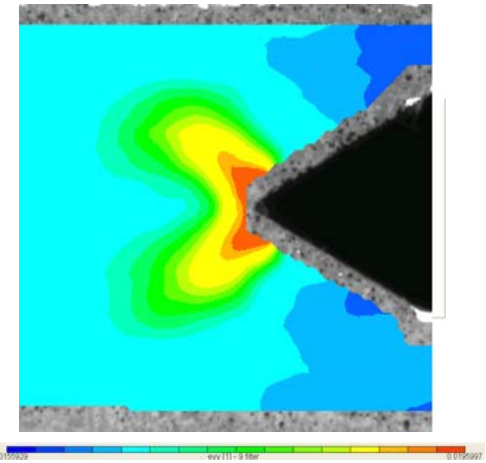
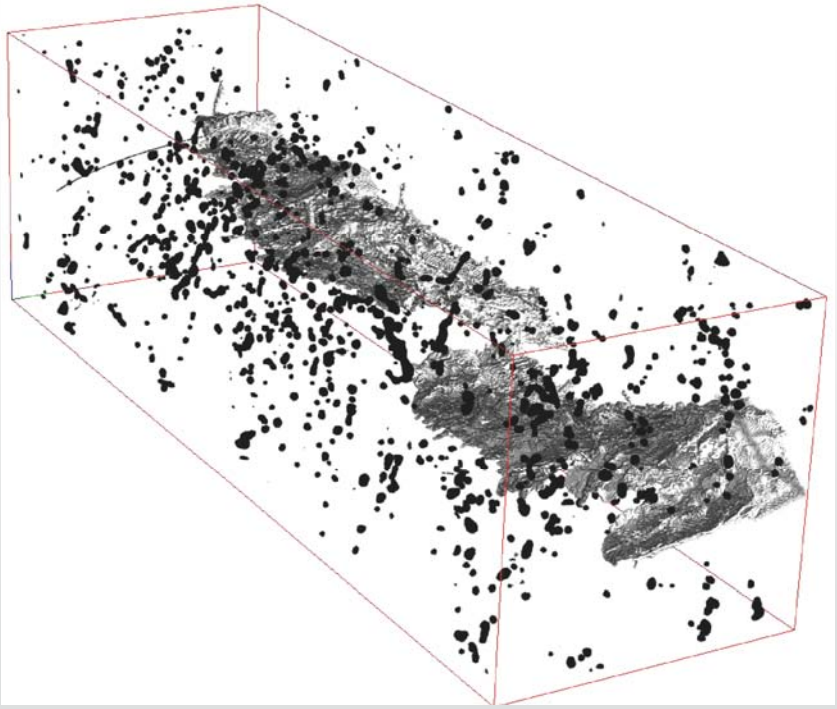
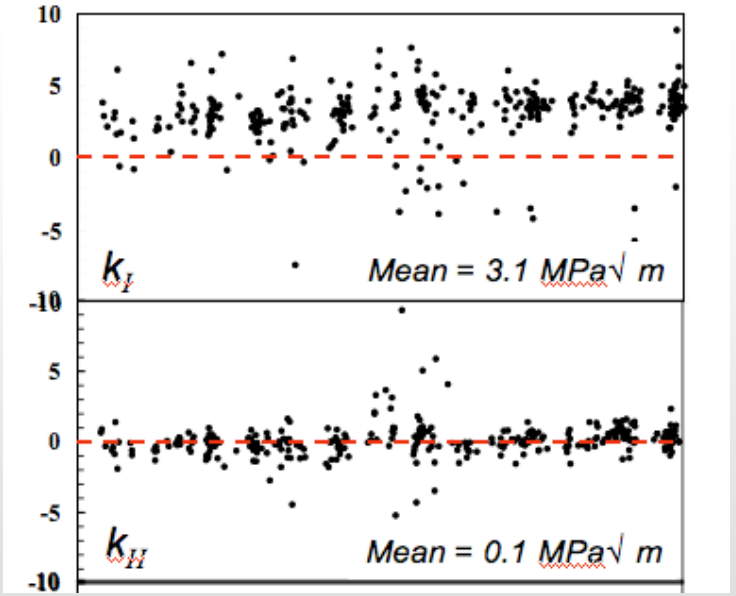


2D surface correlation





3D volume correlation



H. Toda, I. Sinclair *et. al.* (Univ. of Southampton)
Acta Materialia 52 (2004) 1305–1317

Feature Tracking for Displacement Fields

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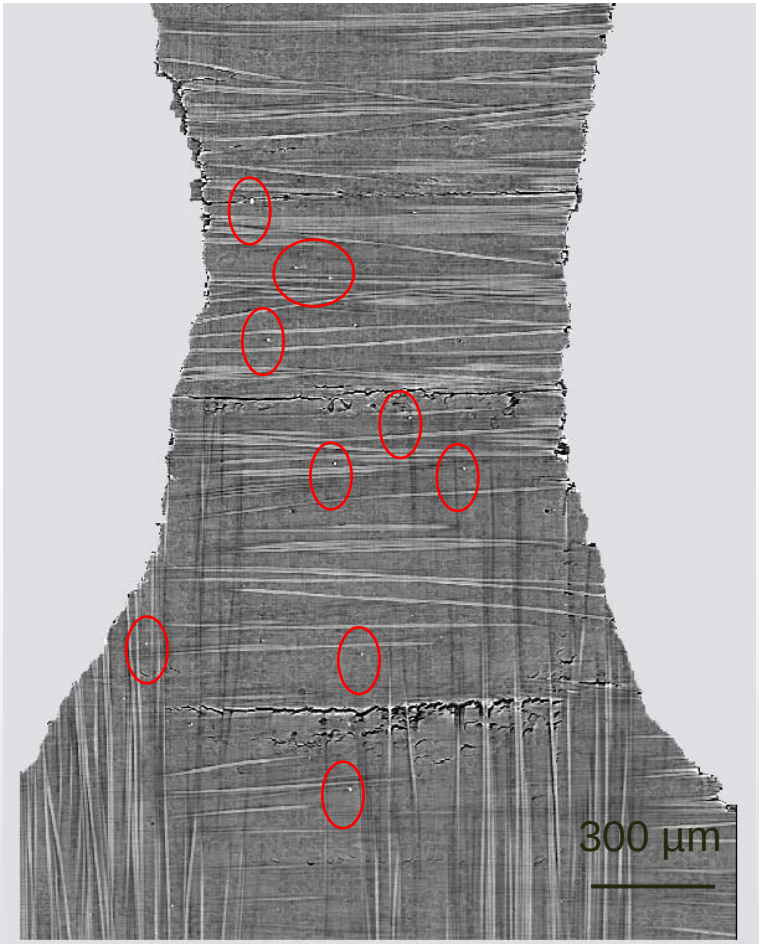

Particles identified at 0º/90º ply interfaces

- Sparse distribution of aluminium particles
- Presence does not affect damage micro-mechanisms or macroscopic properties
- Bright features can be readily identified and tracked between SRCT images

Digital Volume Correlation (DVC)

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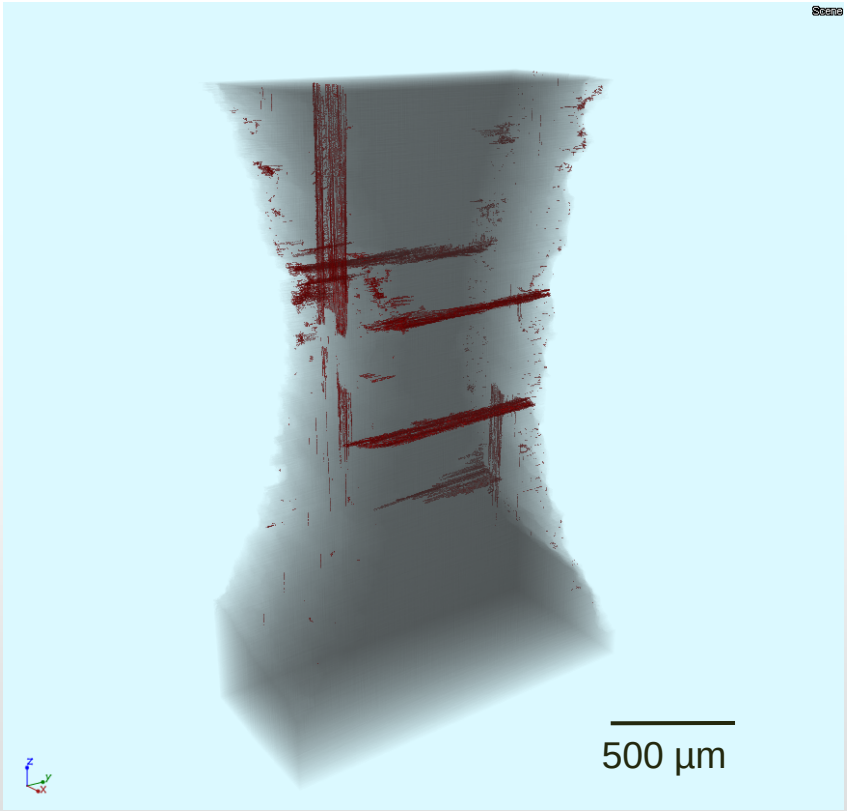
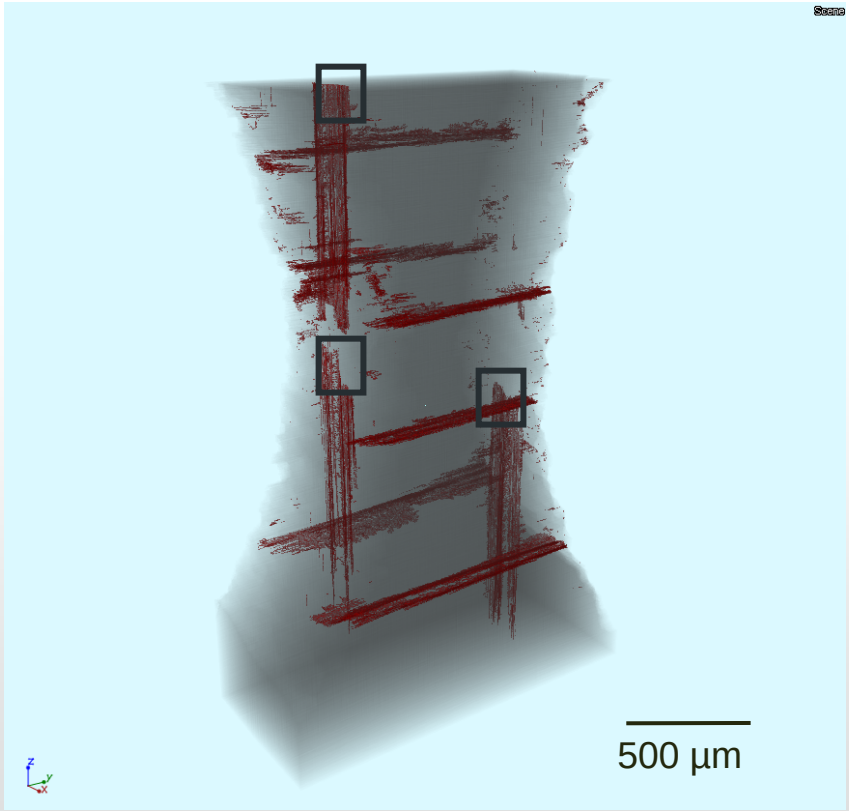
- Strains calculated from a displacement comparison of two SRCT volumes:



$[90/0/90]_T$ - 40% UTS



$[90/0/90]_T$ - 50% UTS

DVC Results

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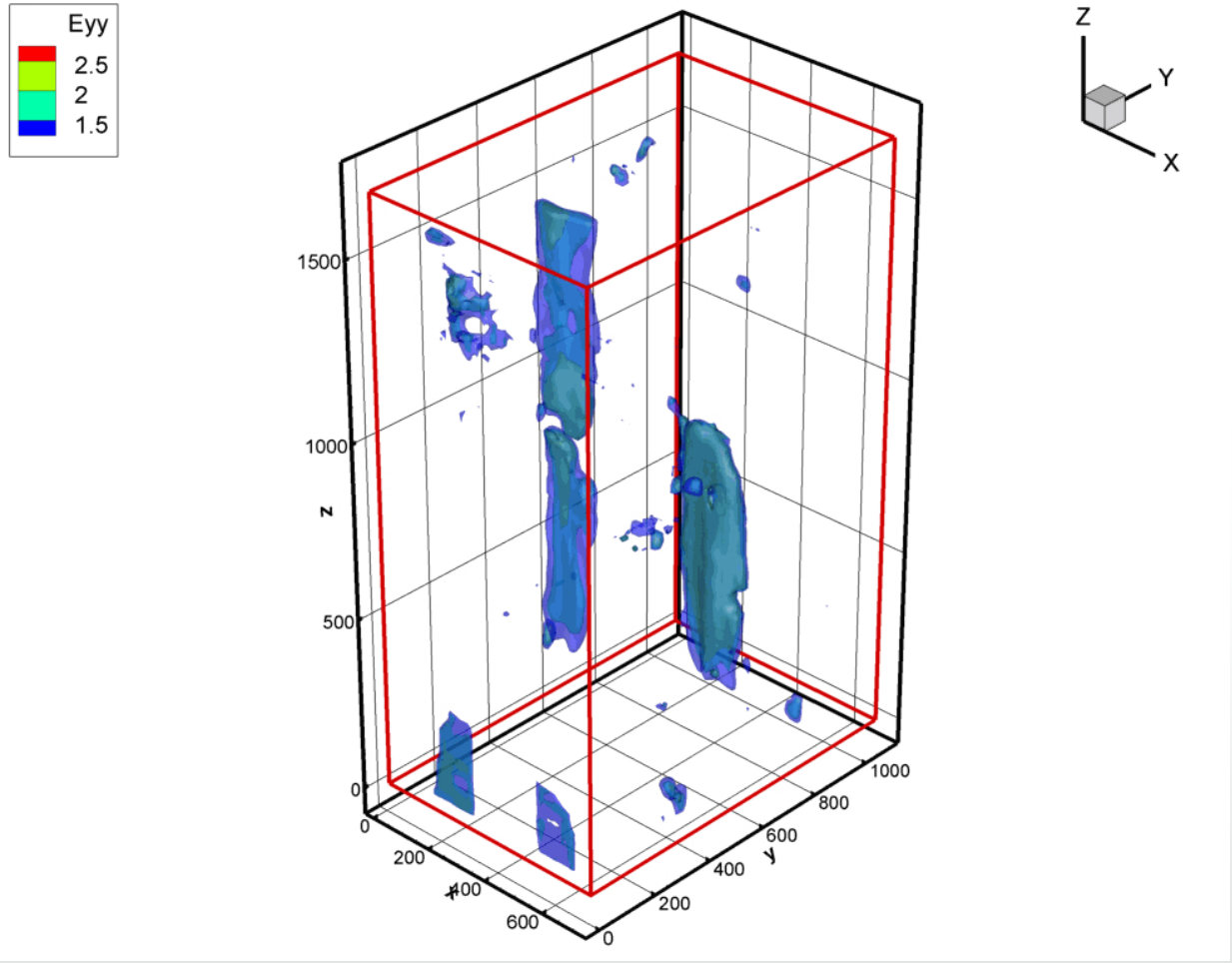

Produced in collaboration with LaVision

Fibre Fracture -new work - modeling in progress

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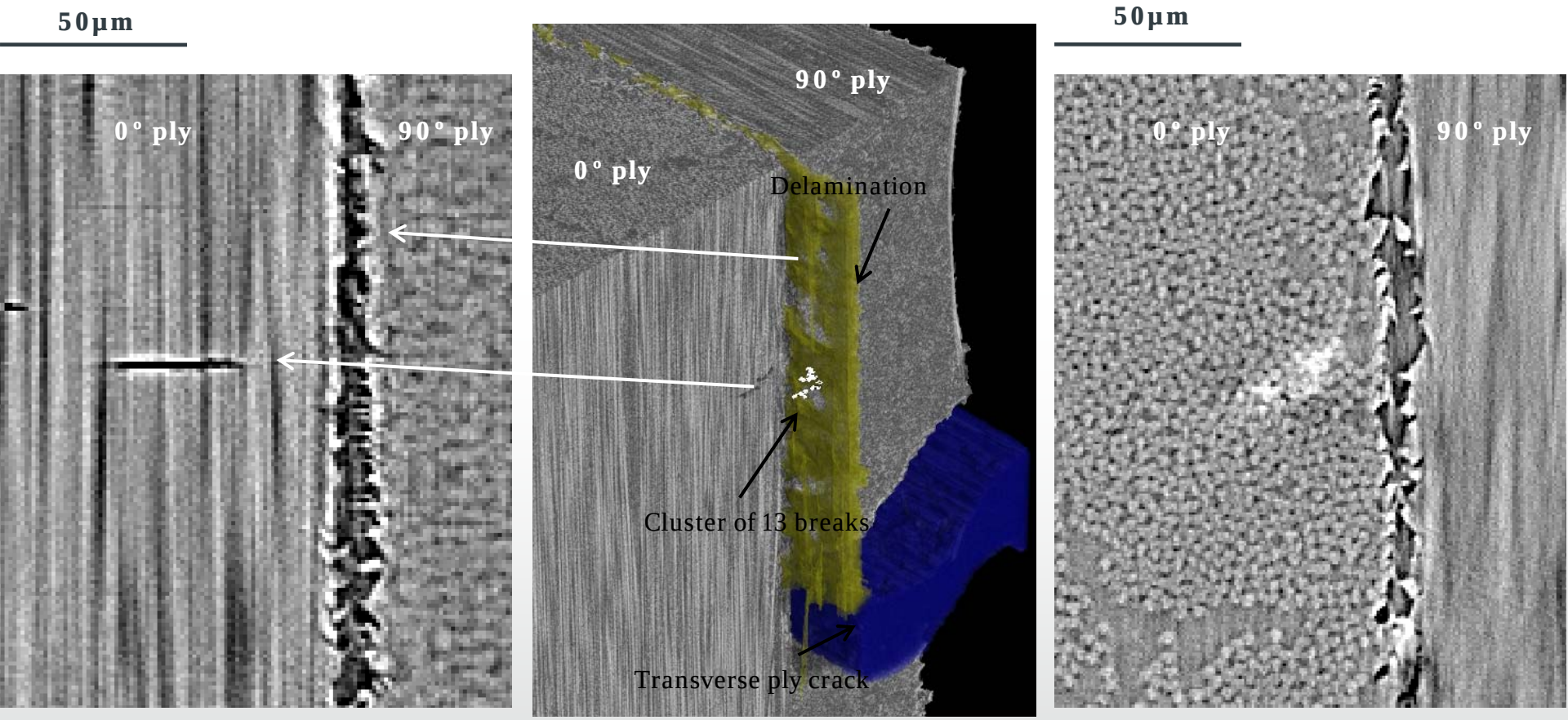
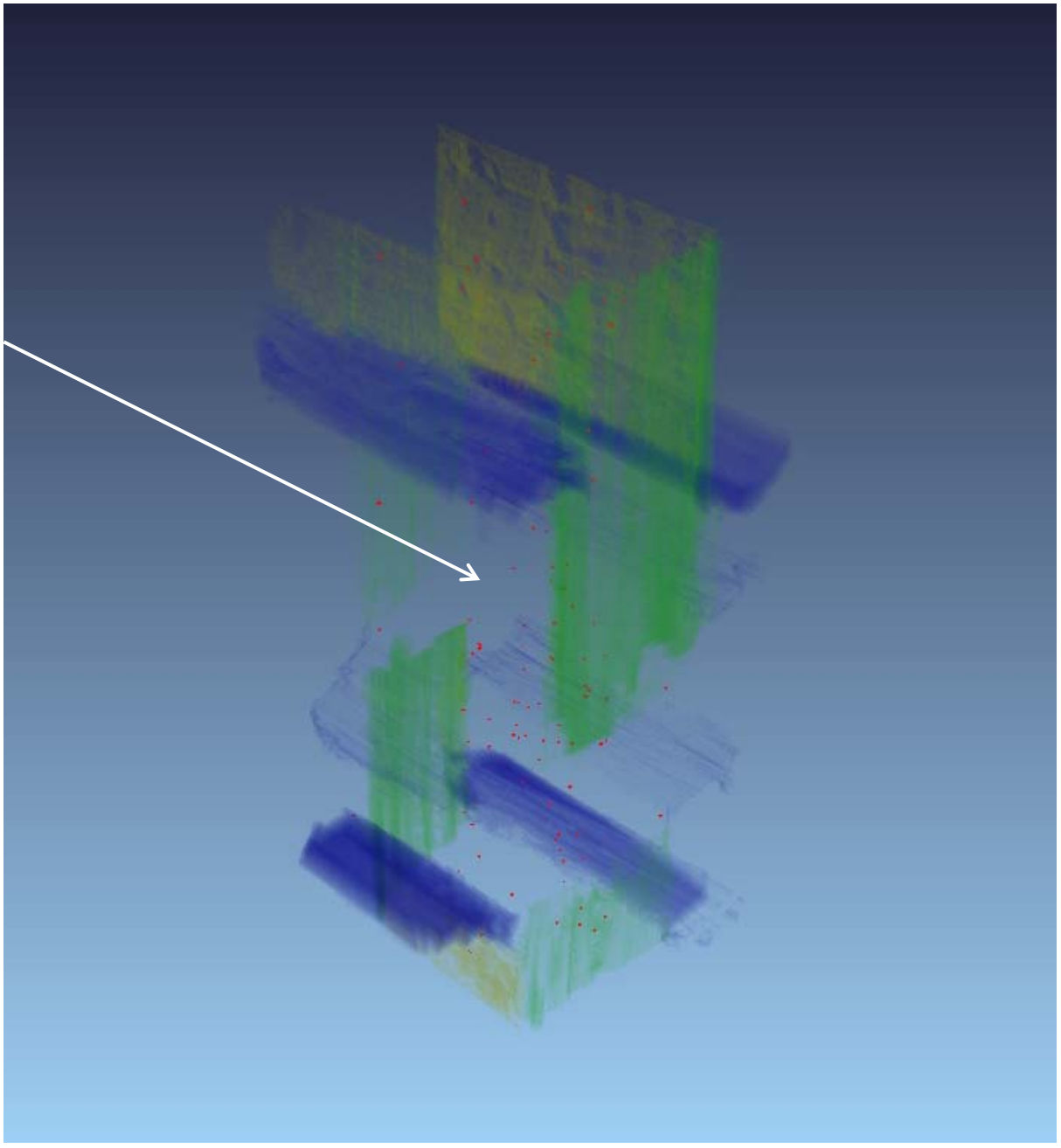
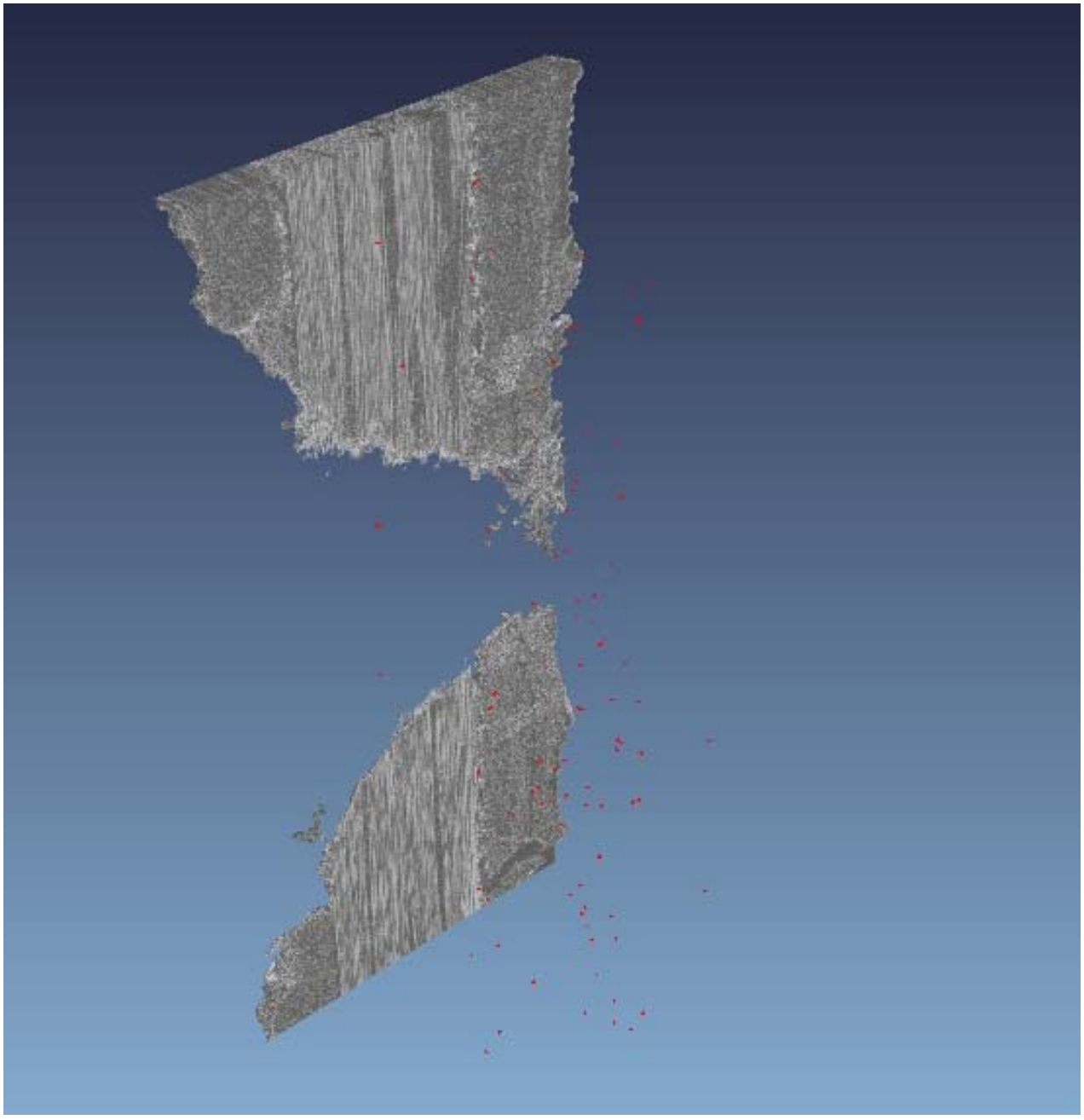


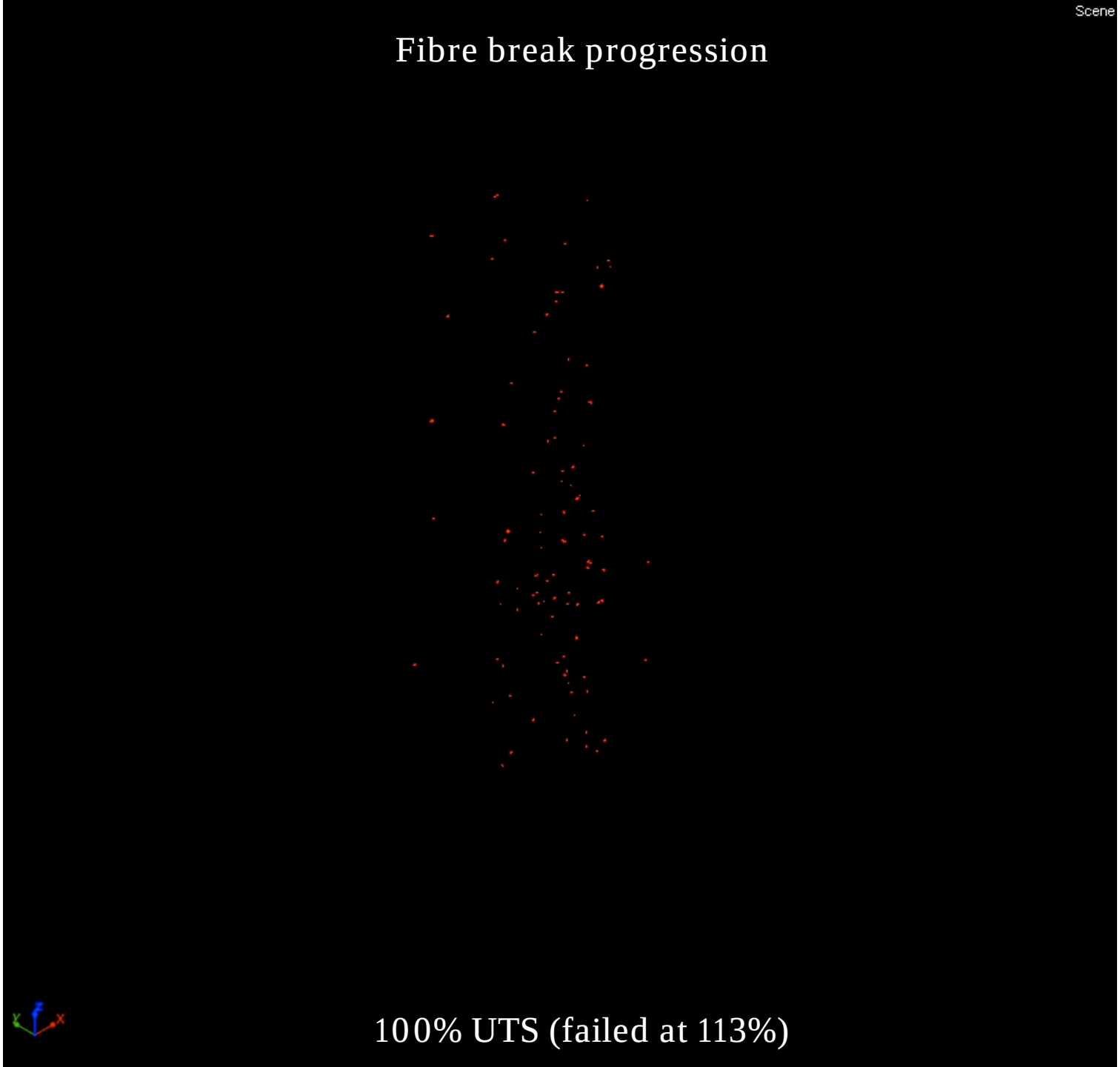
100% UTS (failed at 113%)

Fibre breaks



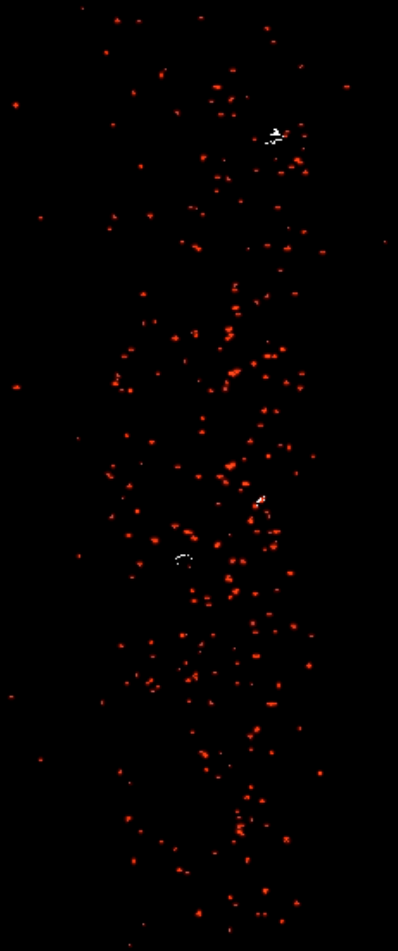
100% UTS (failed at 113%)




Scene
Fibre break progression
100% UTS (failed at 113%)

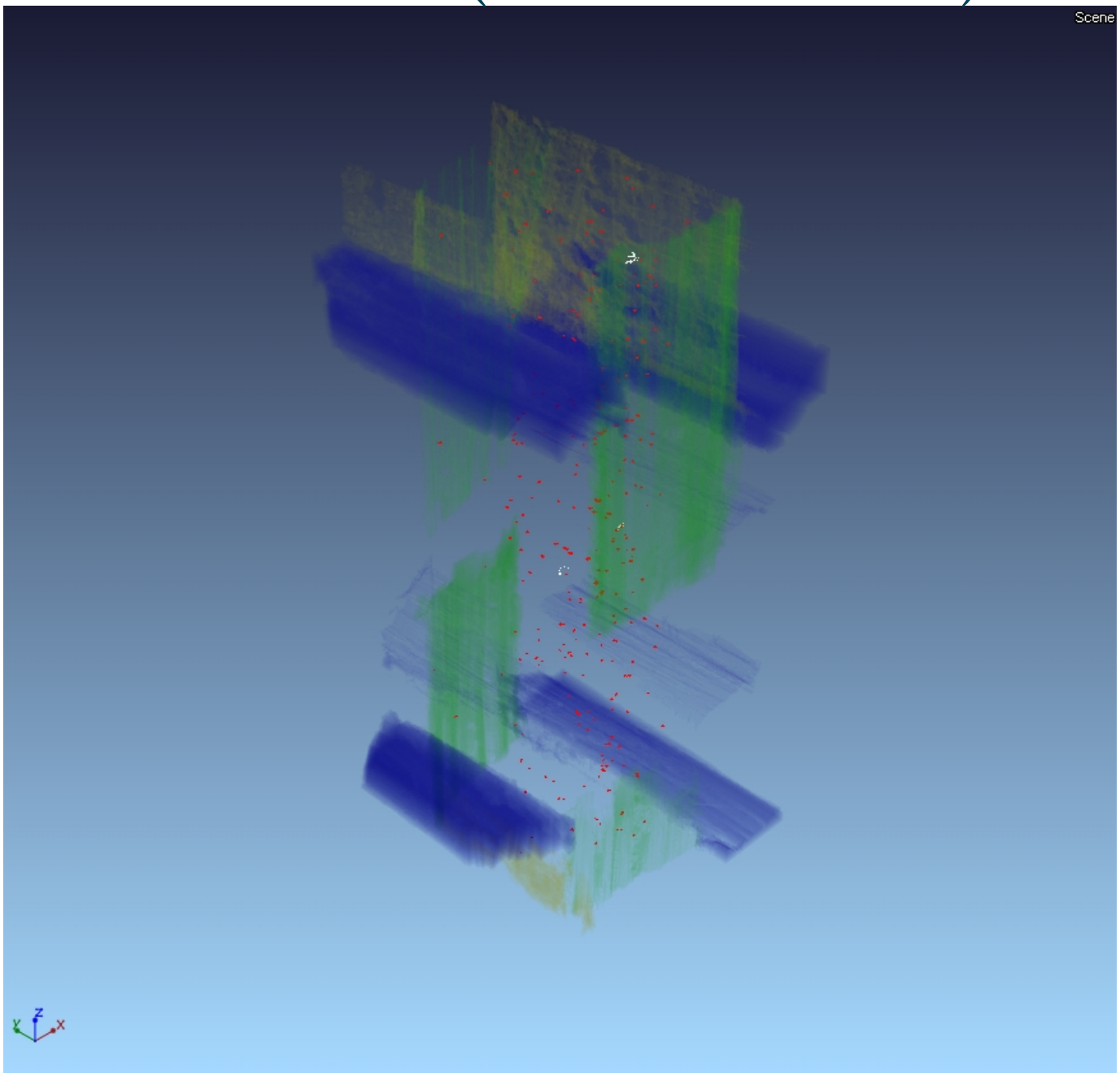
Scene

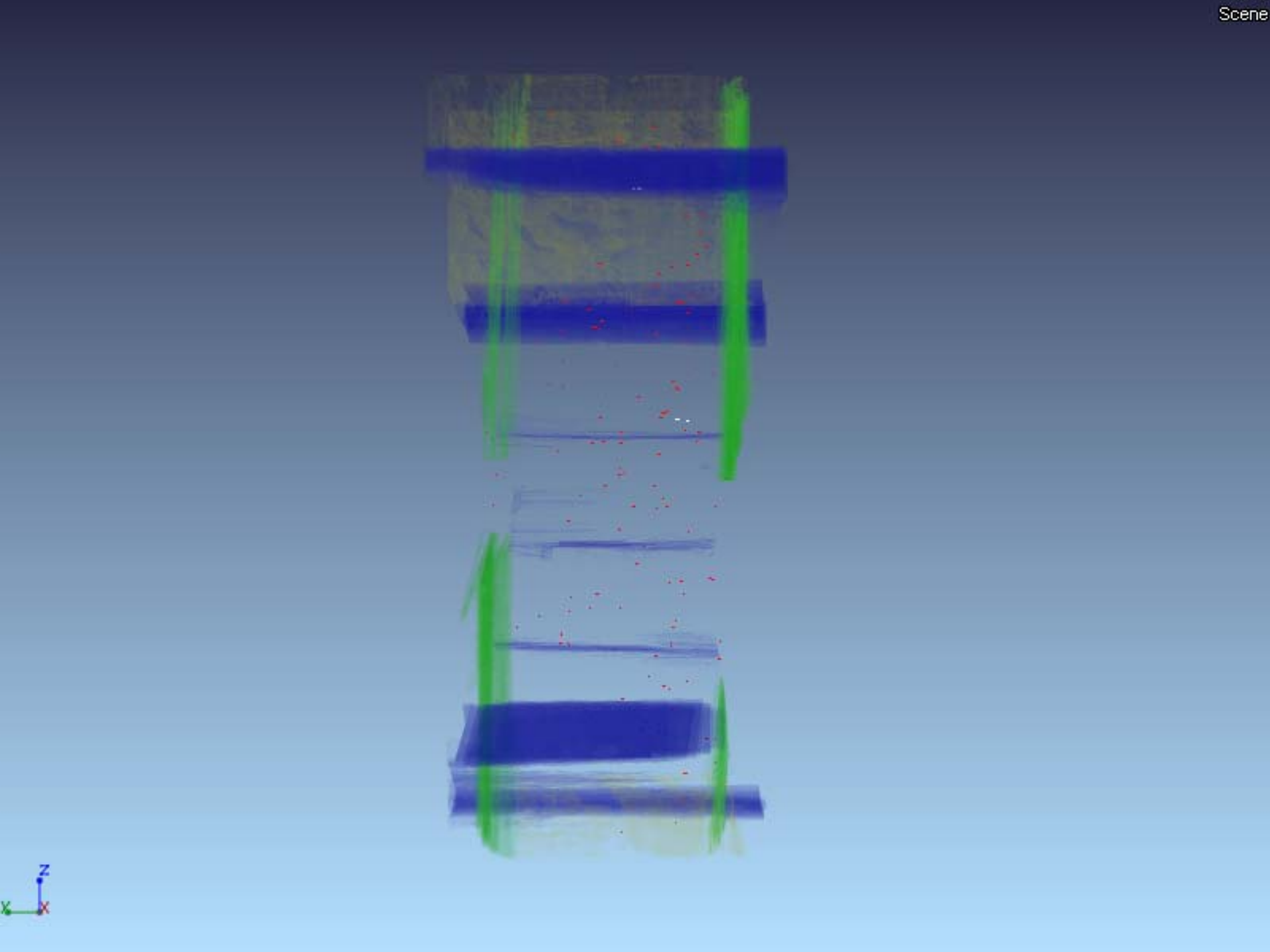
Fibre break progression



110% UTS (failed at 113%)

110% UTS (failed at 113%)




Scene
Z
X

The Data Rich Mechanics Opportunity

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- High resolution CT allows comprehensive data sets to be obtained for damage and resulting local displacements and strains
- Used to inform and validate mechanism based-models for most aspects of composite damage, failure and durability
- Offers new opportunity to understand fundamental mechanisms to inform material development
- This represents a real opportunity to move beyond current empirical approaches to composite design

The Challenges

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- To bridge the lengthscales adequately, so as to ensure that observations made at high resolution are representative of large scale structures
- The development of more sophisticated feature recognition algorithms to speed up data reduction process
- The development of better approaches to data handling to allow for storage and manipulation of large data-sets and to make them available to the community
- The development of methods to compare 3-D data to models, including statistical aspects

Conclusions

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- *in situ* fracture tests carried out using multi-scale computed tomography imaging
- Key failure modes mapped in three dimensions under load - new insights achieved
- Comparison of micro-scale displacements with physically-based model predictions; strains also possible
- Great opportunities for improving predictive modelling capability for composite mechanics
- Challenges remain, but the opportunities are great

Acknowledgements

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Questions?