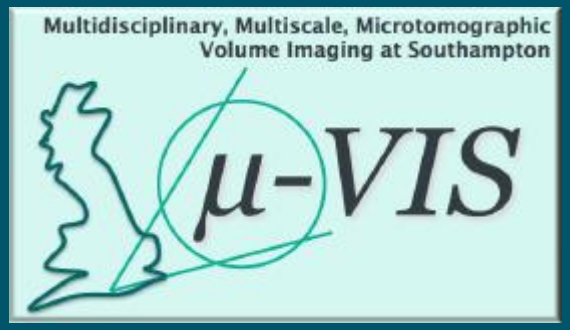

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Faculty of Engineering and the Environment

Damage analysis in polymer matrix composites

I. Sinclair

i.sinclair@soton.ac.uk

BSSM Workshop:

Challenges in X-ray computed tomography for materials behaviour assessment

Acknowledgements

- *Huge thanks to Lyon MATEIS group (Buffiére, Maire…)*
- Southampton collaborators on this work:
  - Prof. Mark Spearing, Dr Mark Mavrogardato, Pete Wright, Anna Scott, Daniel Bull
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- Brian Cox (Teledyne), Qingda Yang (U. Miami)
- Tony Bunsell (Mines, ParisTech) & Alain Thionnet (U. Bourgogne)
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- Royal Society Wolfson Research Merit Award (SMS)

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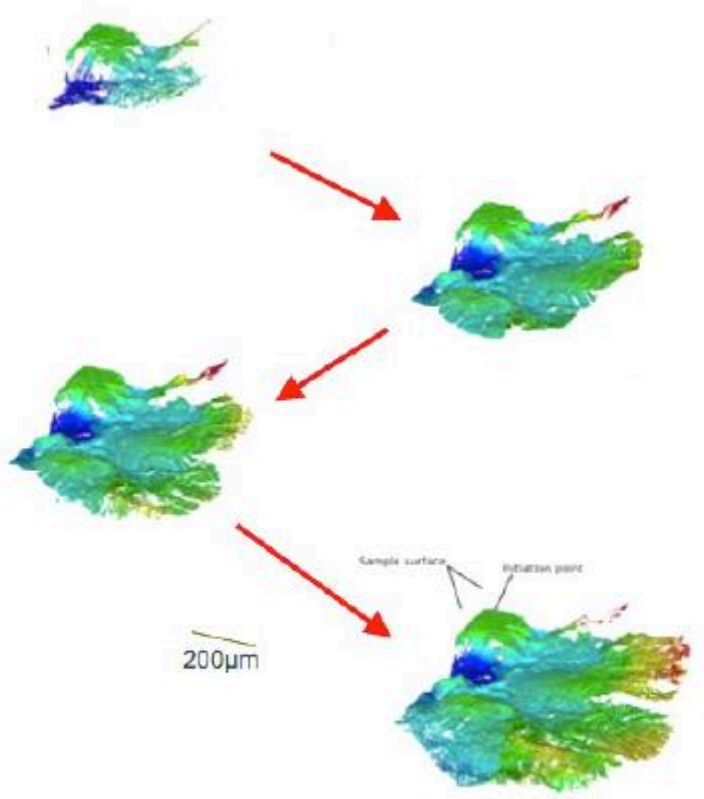
- Introduction
- CFRP notched tensile
  - *In situ* CT
  - Intra- & inter-laminar failure
  - Fibre breaks
- Larger structures
  - Hybrid hoop structures
  - Compression after impact
  - Laminography
- Summary



Fatigue crack growth in nanostructured Al alloy

Introduction

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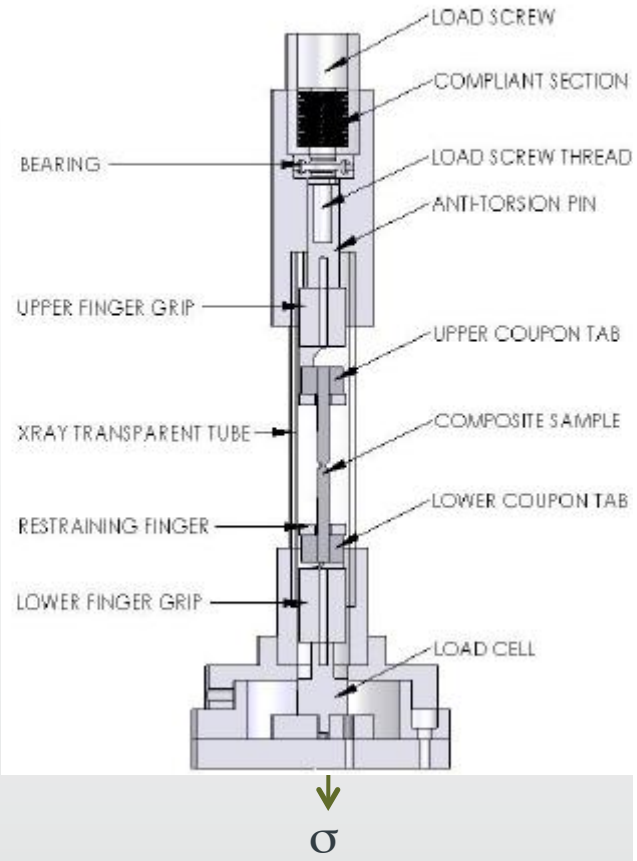
- Composites, particularly continuous carbon fibre materials have come a long way since 1965!
  - Large primary structures now commonplace
- Yet we still do not have a usable understanding of many aspects of strength, toughness, durability
  - Design remains generally conservative
  - We do not push the limits of the materials' capability
- *DATA RICH MECHANICS*
  - Dramatic evolution in availability and resolution of various full-field and/or volumetric ('full volume'?) sensing modalities, *e.g.* CT
  - ➢ Model initialisation and validation at various lengths scales to inform physically-based engineering simulation
  - ➢ Realise a predictive *'virtual testing'* approach, reducing cycle times, design/certification costs, whilst improving efficiency and expanding the effective design envelope

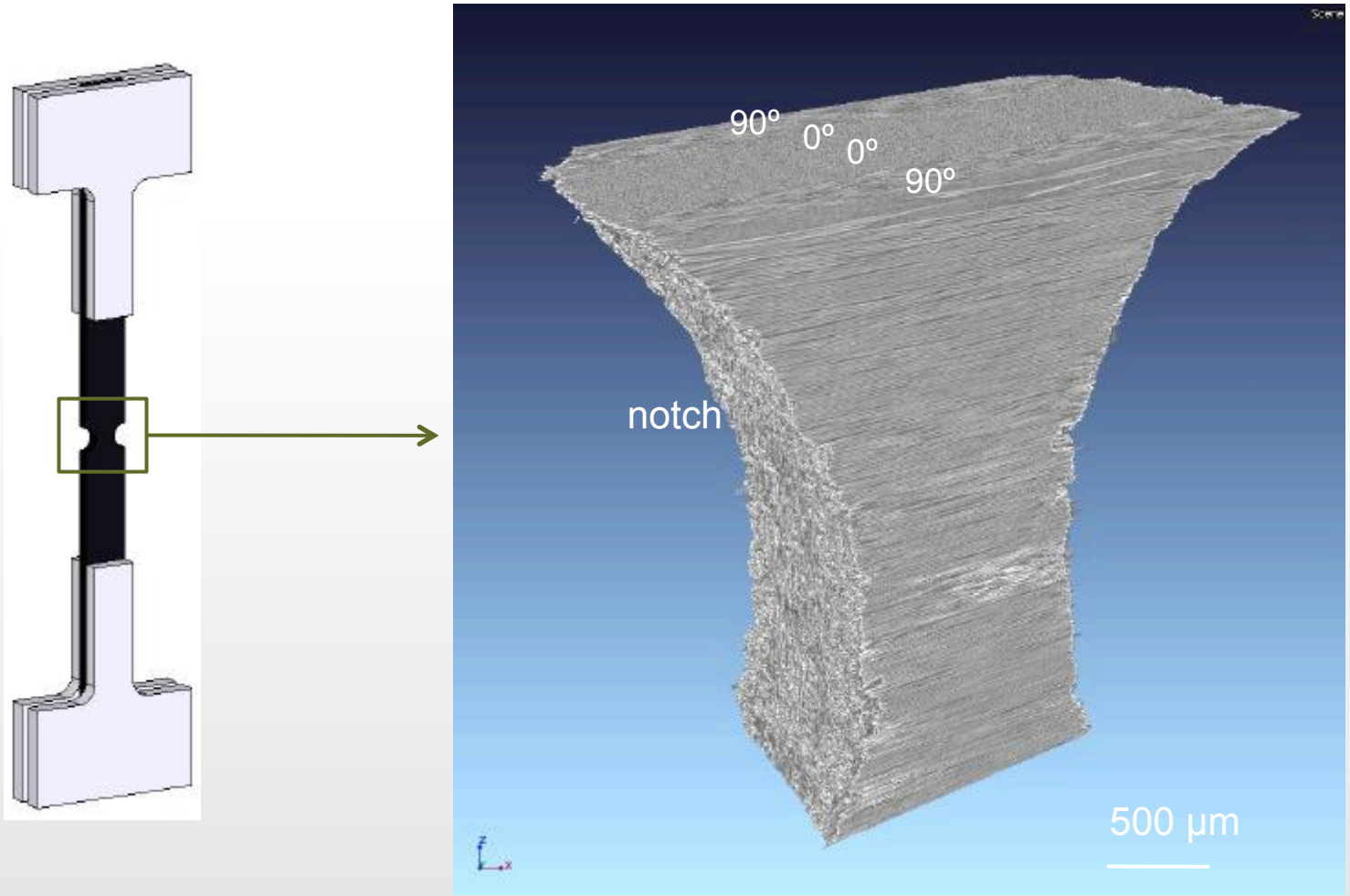
CFRP laminate testing

- Notched tensile failure
- **$[90/0]_S$**, $[0/90]_S$, $[90/+45/-45/0]_S$, $[90/0/90]_T$ CFRP laminates
  - Alternative matrix toughness levels
  - Al particulate (~ 4µm) fiducial markers
- Double edge notch samples produced using abrasive waterjet machining
  - Width = 4mm, notched radius = 1mm
  - Thickness = 0.25mm per ply
  - 10 and 25mm wide samples also compared
- Imaging at ESRF/ID19, 1.4µm voxels, 20kV, 100ms exp., D = 35mm

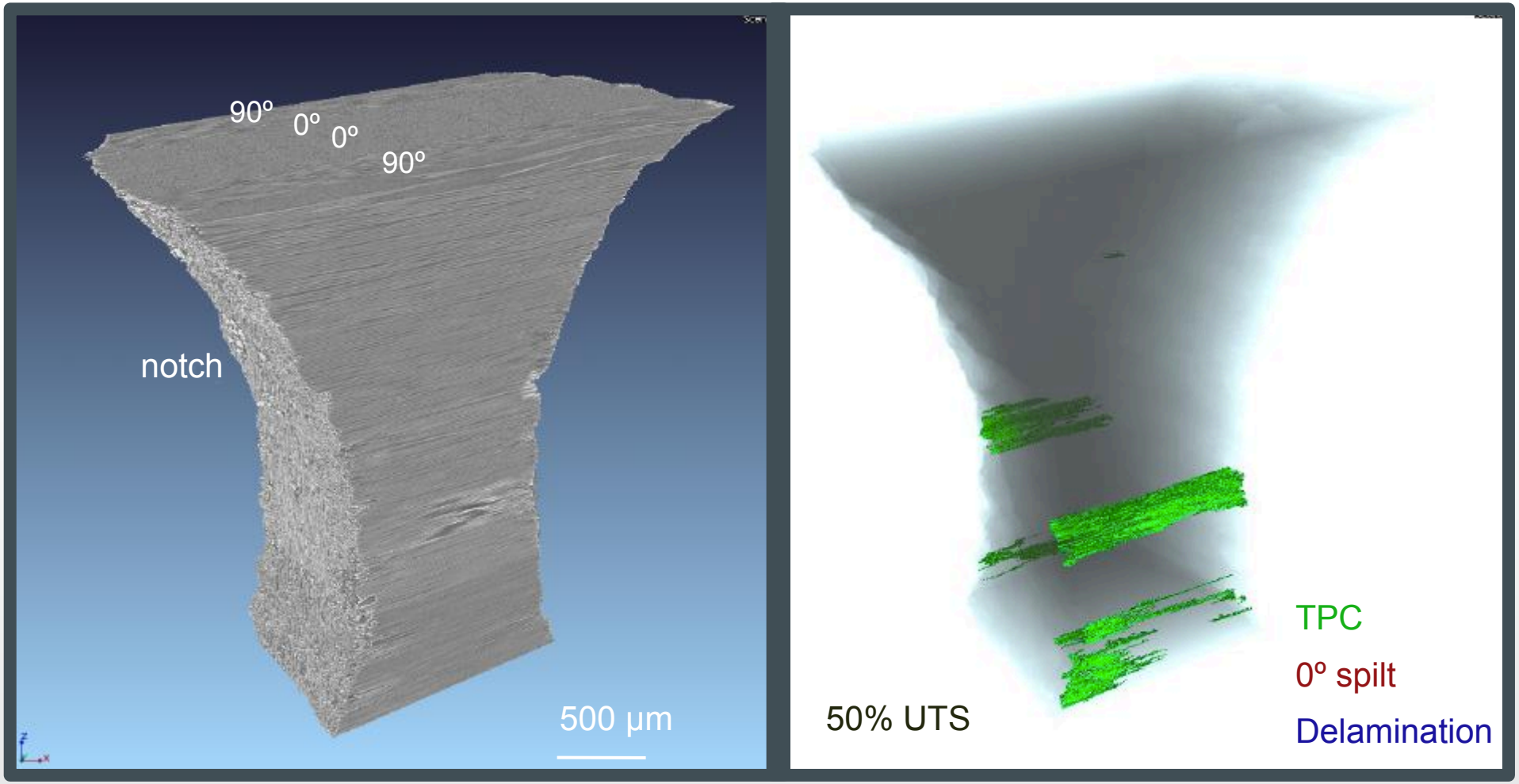


Results

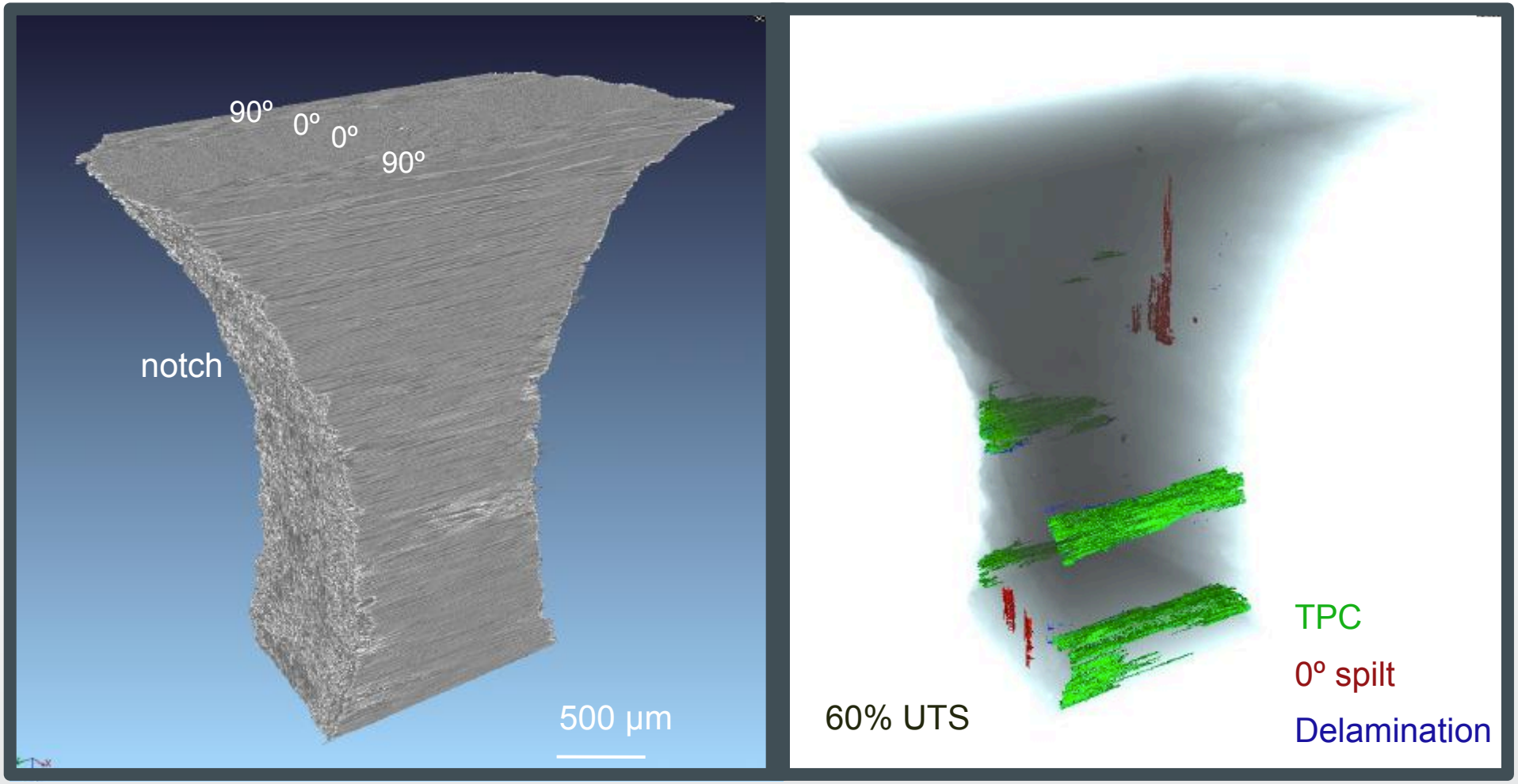
- 3D view of notched region



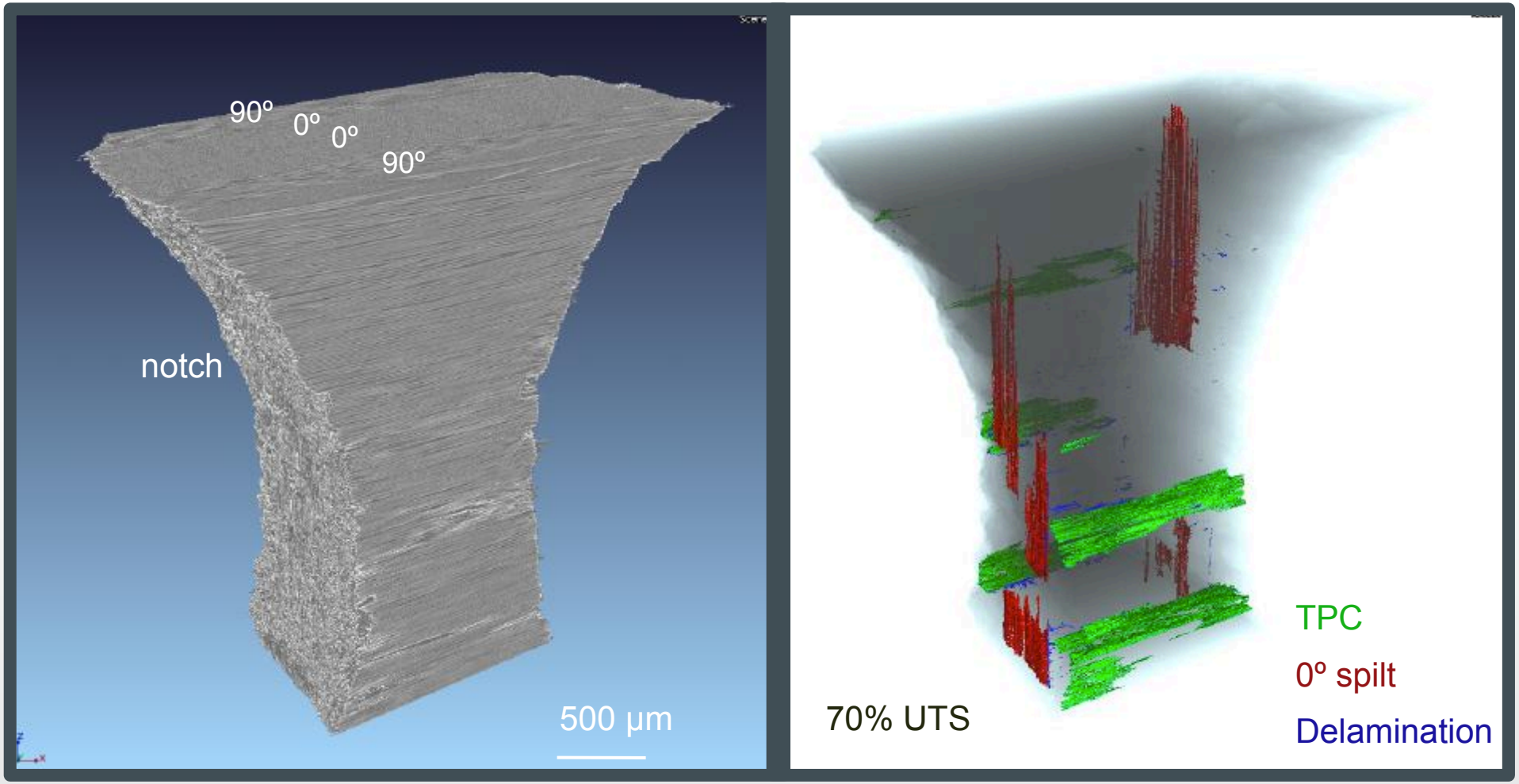
Damage Propagation
$[90/0]_S$ 50% UTS (nominal)



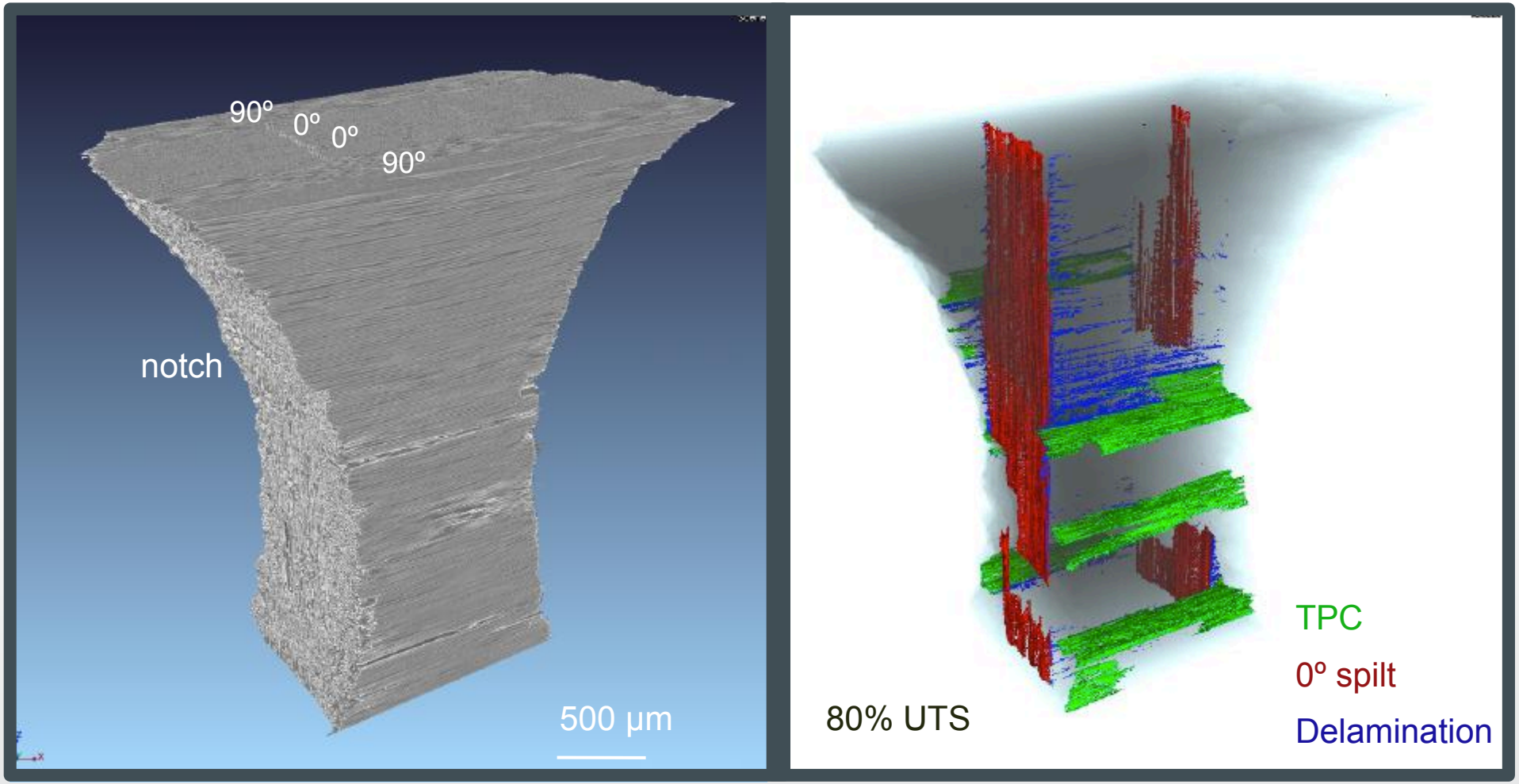
Damage Propagation
$[90/0]_S$ 60% UTS (nominal)



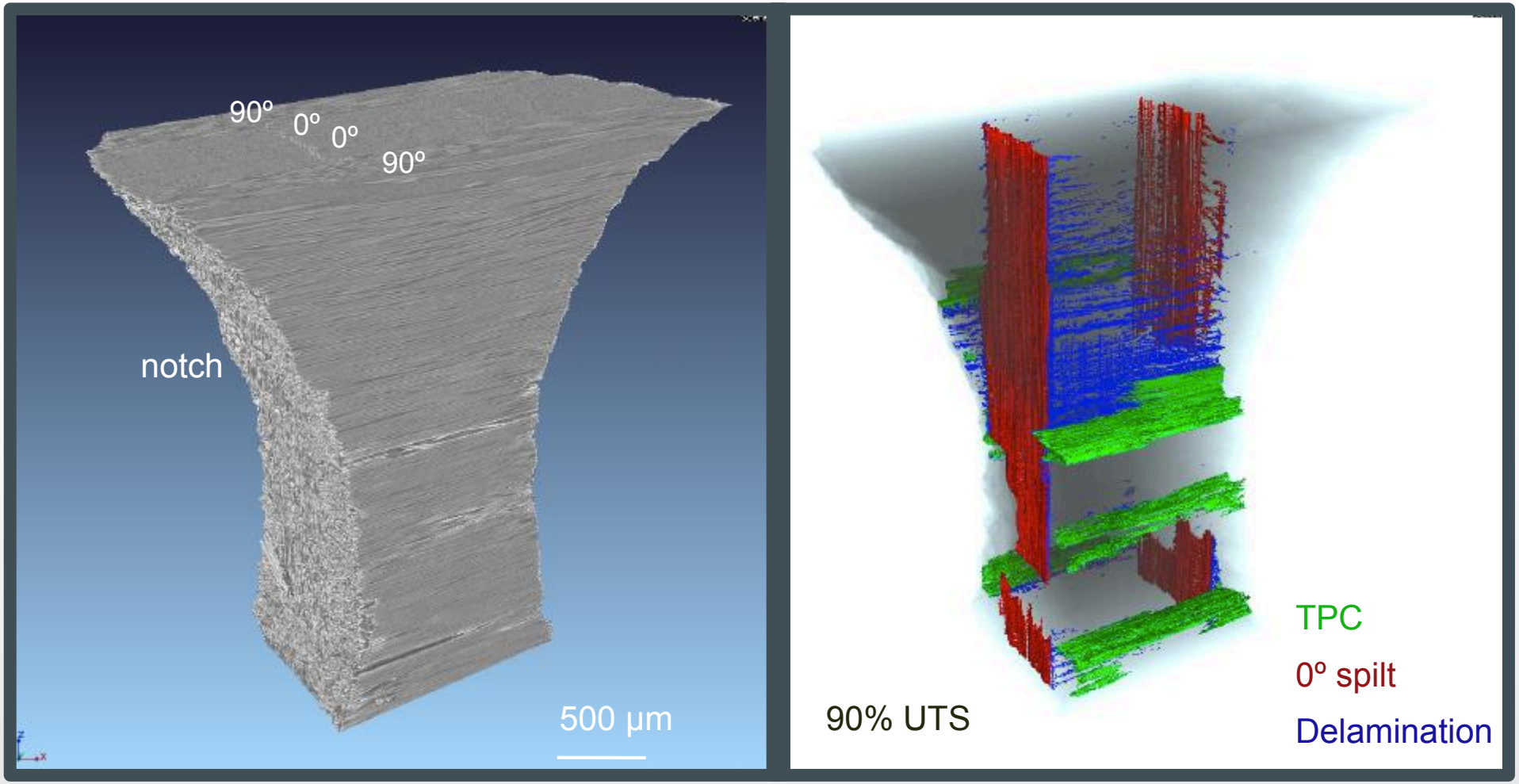
Damage Propagation
$[90/0]_S$ 70% UTS (nominal)



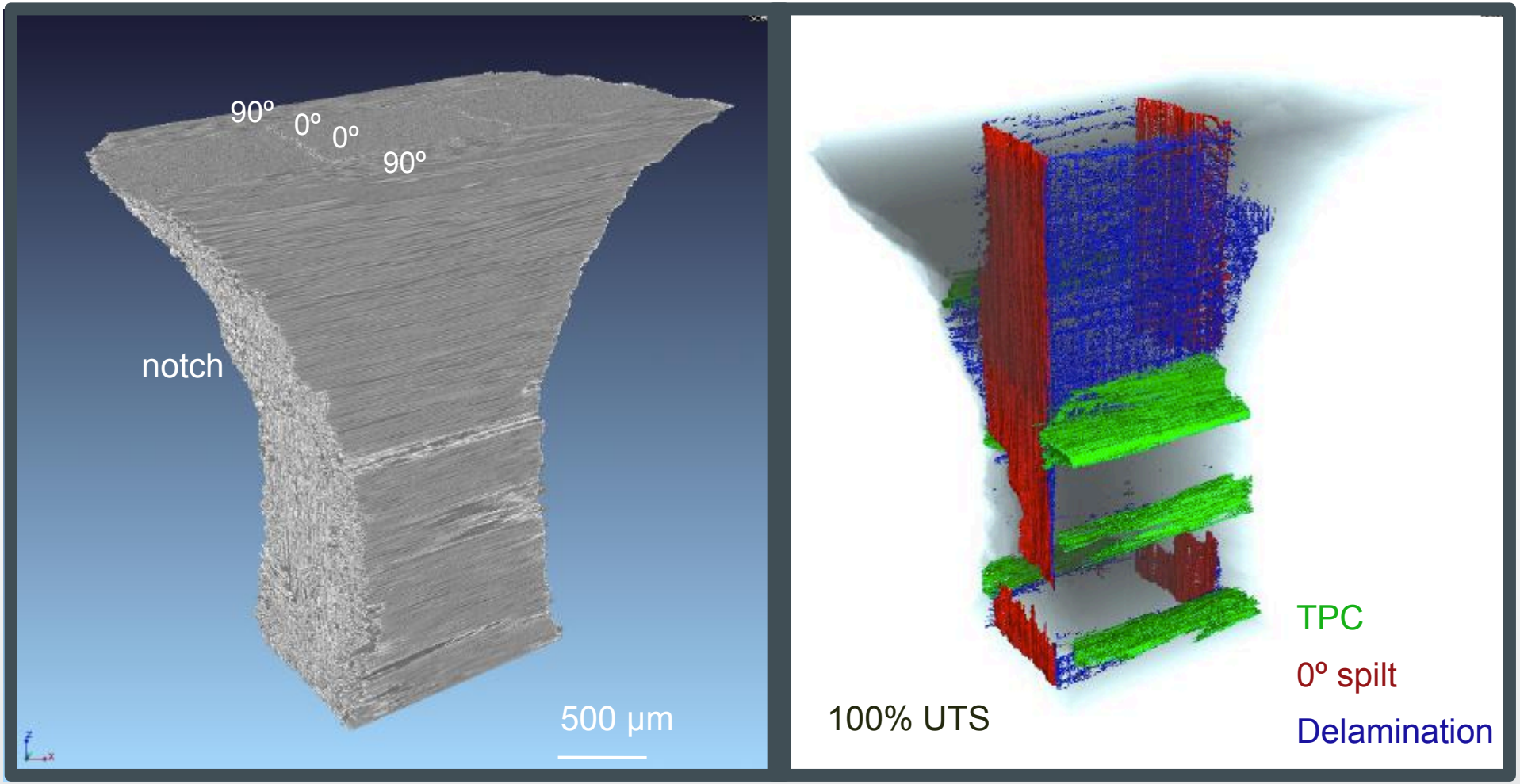
Damage Propagation
$[90/0]_S$ 80% UTS (nominal)



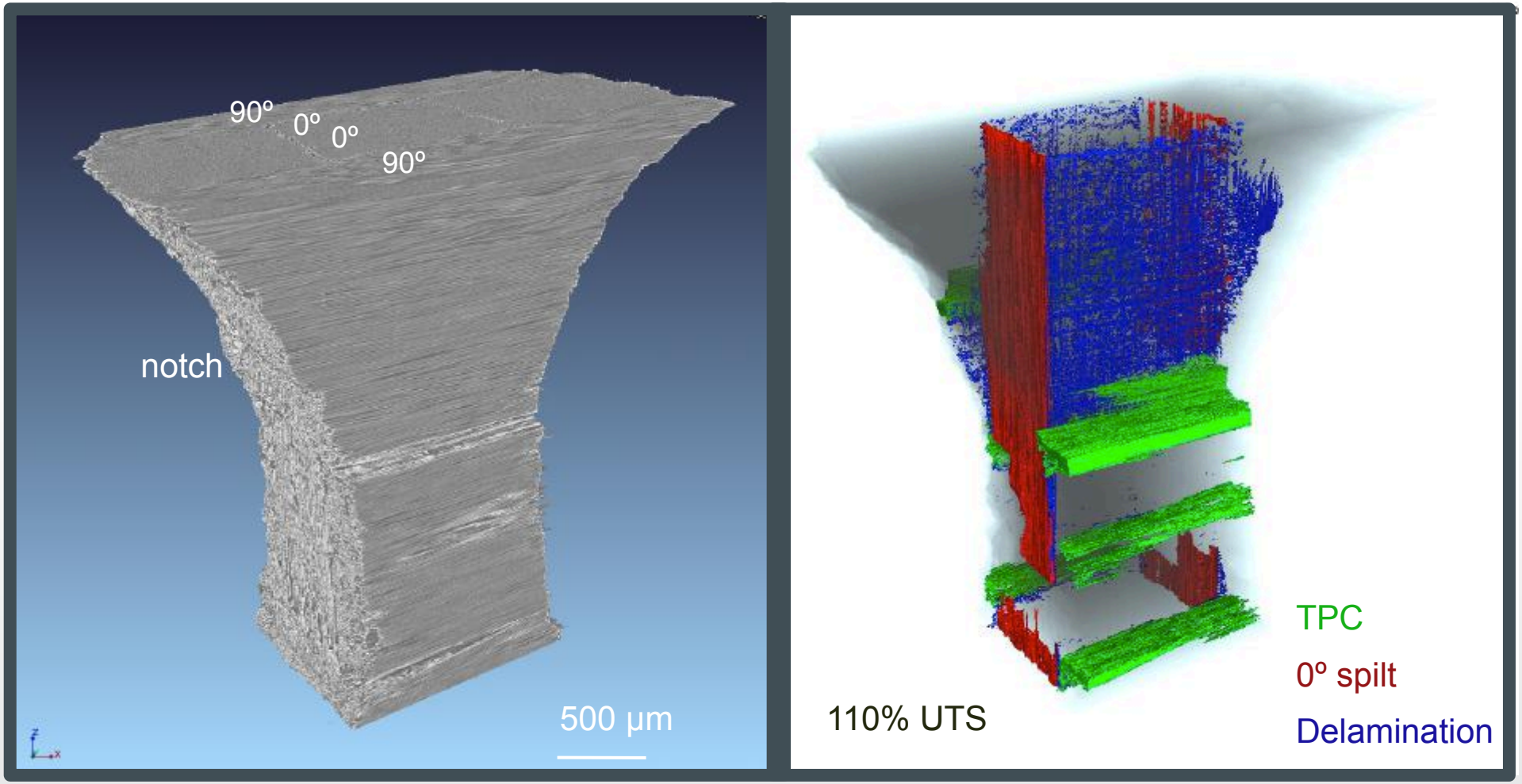
Damage Propagation
$[90/0]_S$ 90% UTS (nominal)



Damage Propagation
$[90/0]_S$ 100% UTS (nominal)

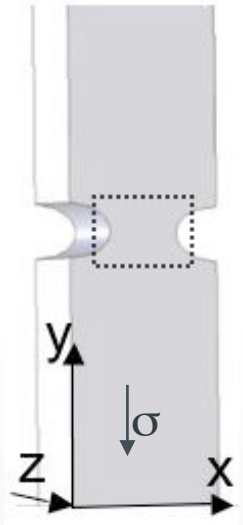


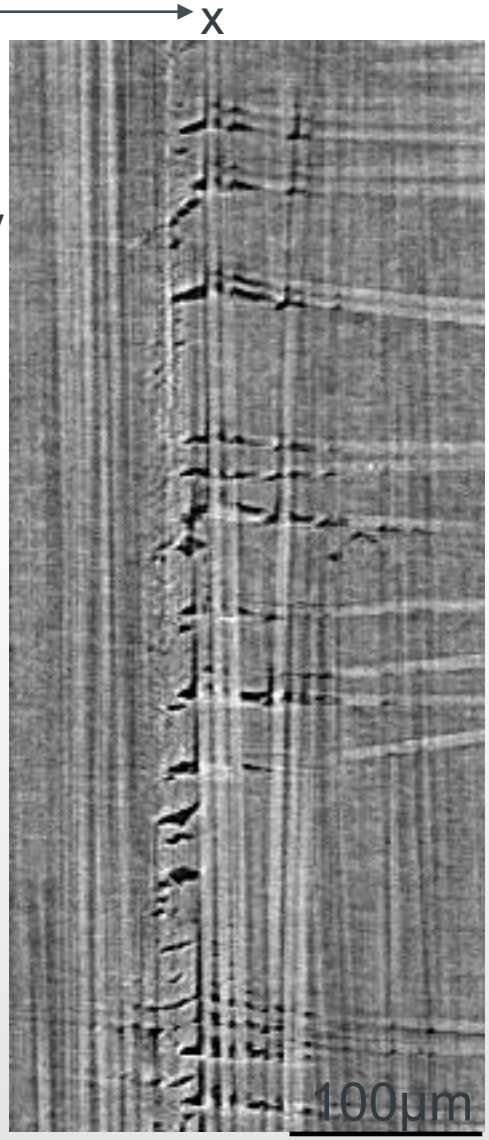
Damage Propagation
$[90/0]_S$ 110% UTS (nominal)

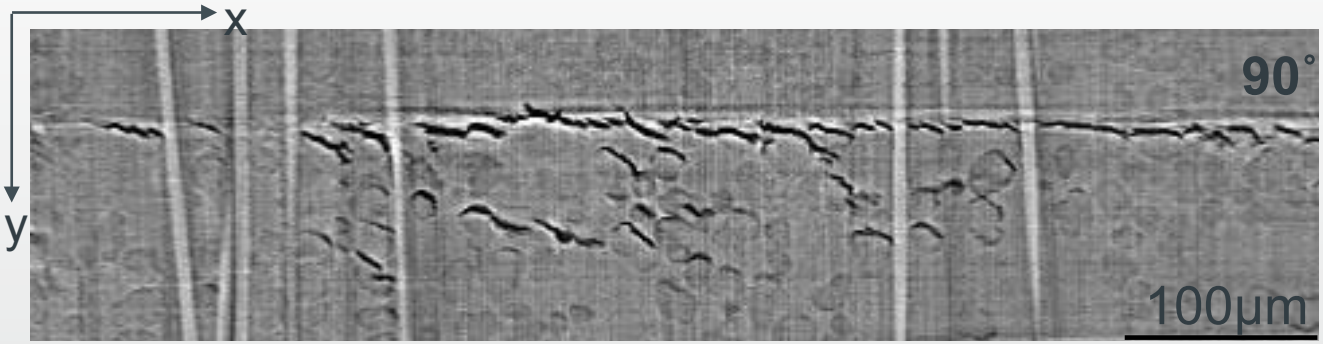


Notched PMCs: Mechanisms

- Delamination evolves discontinuously from both toughening particles and fibres
  - 3D, multi-mechanistic failure mode

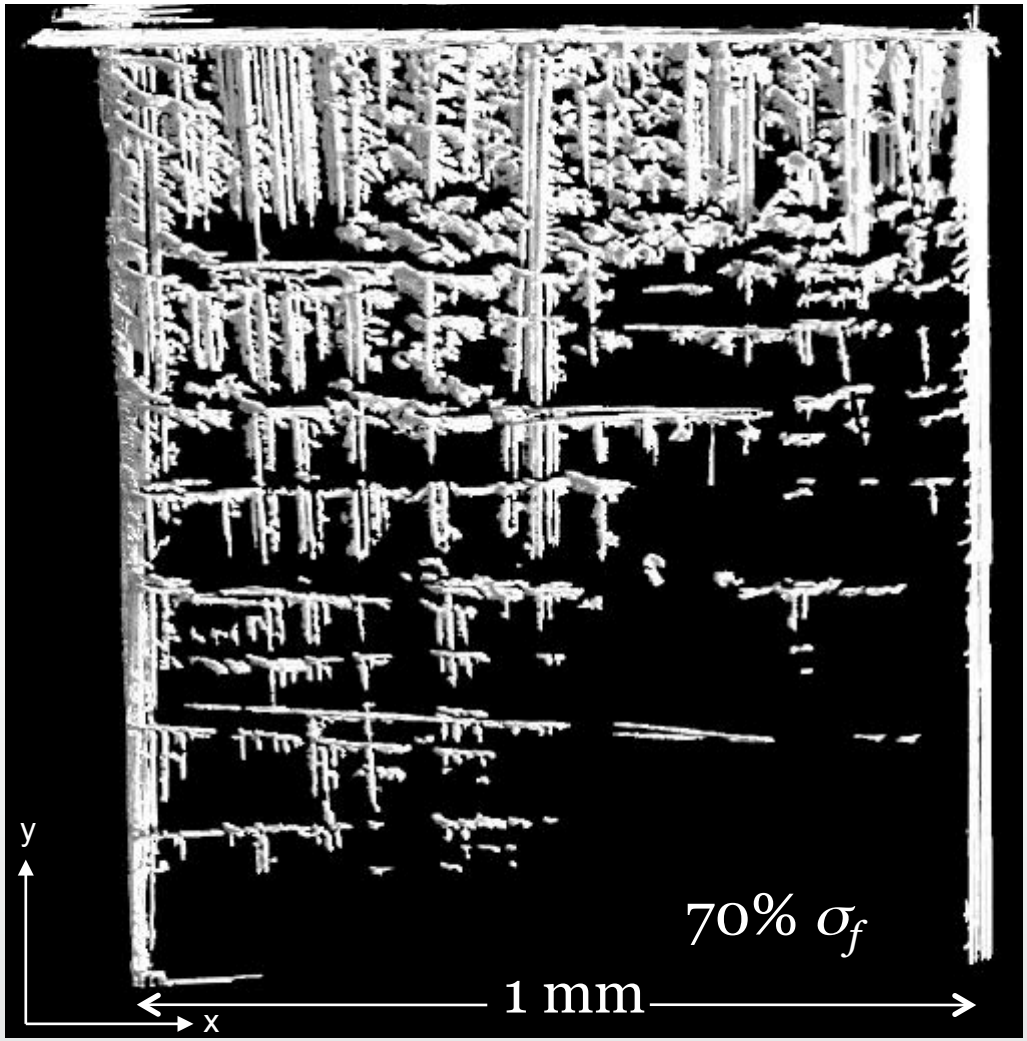




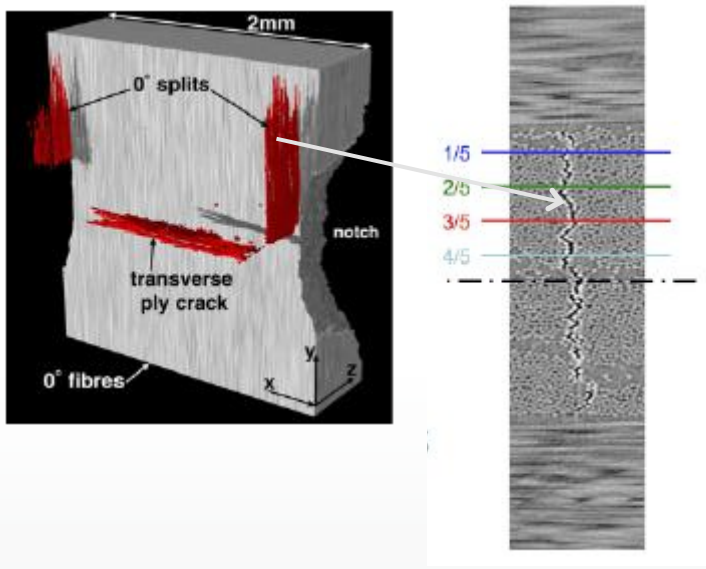


Notched PMCs: Mechanisms

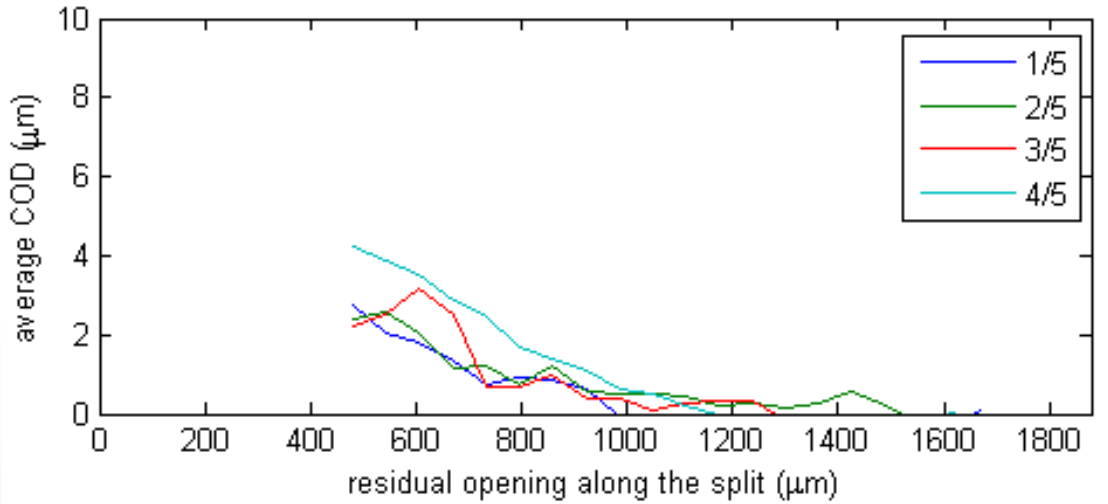
- Semi-cohesive 3D failure zone at interface in toughened systems

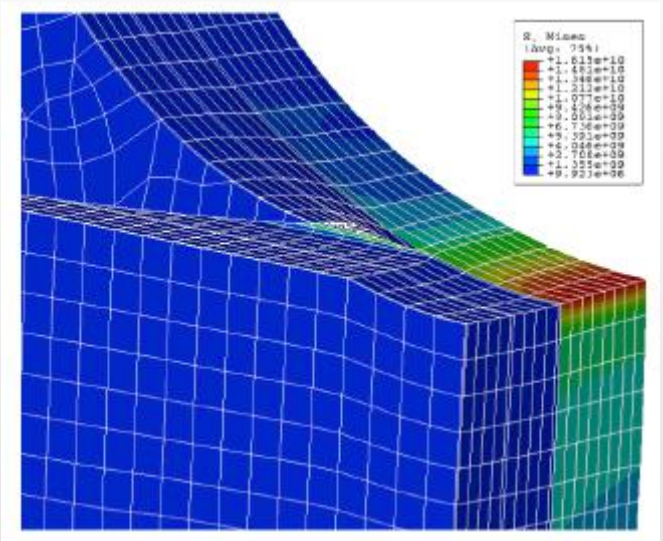


Notched PMCs: Simulation

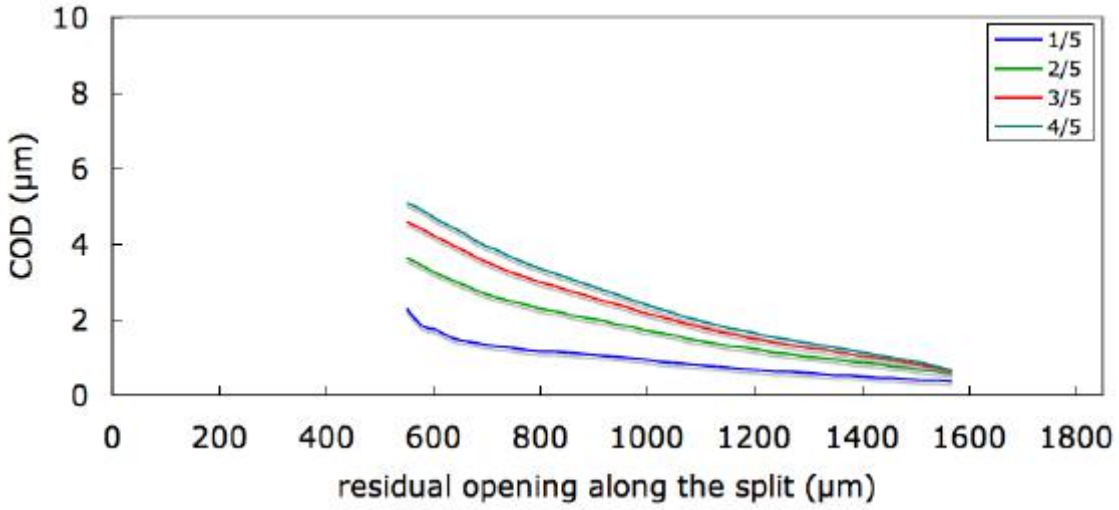


Experiment





Model



Notched PMCs: Simulation

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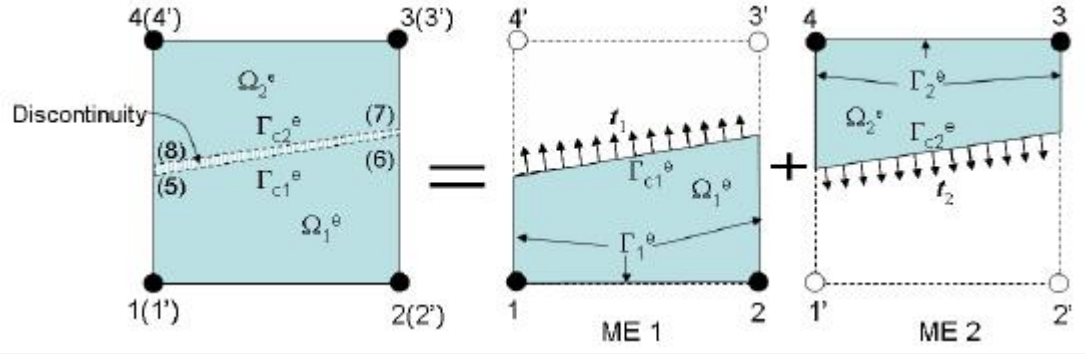
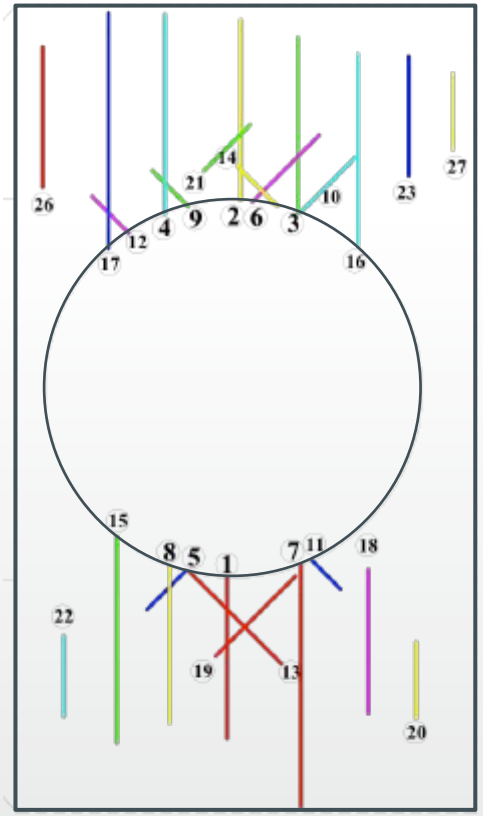
A-FEM (augmented finite element method)
Hansbo and Hansbo, 2004
Yang *et al.*, 2008

- **Ghost elements** add extra crack displacement
- Local – can set up as ABAQUS user element

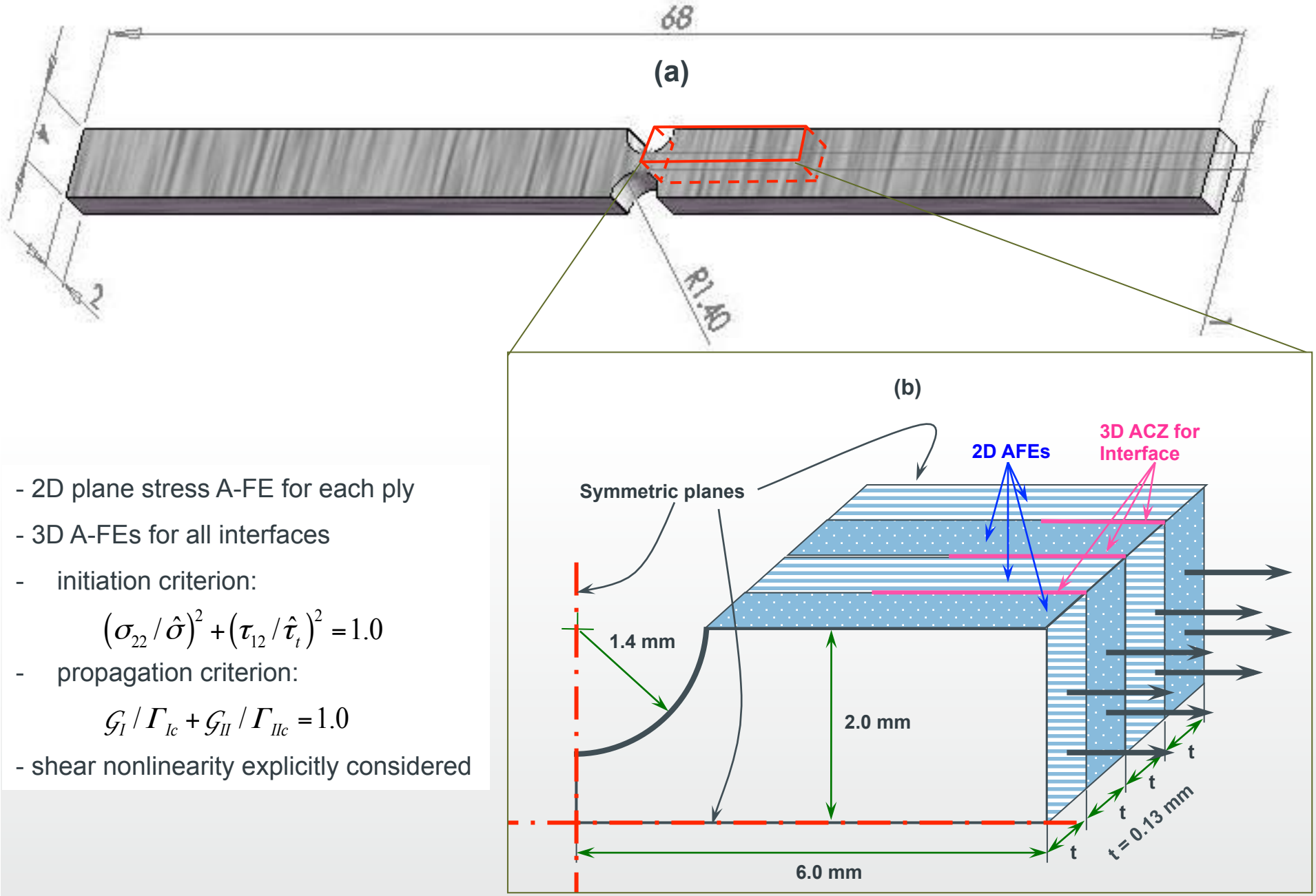


Ling, Yang & Cox, 2008



Round hole cracking, multiple plies

- Incorporate CZM
- Arbitrary crack initiation
- Stochastic processes



- 2D plane stress A-FE for each ply
- 3D A-FEs for all interfaces
- initiation criterion:

$$\left(\sigma_{22}/\hat{\sigma}\right)^2+\left(\tau_{12}/\hat{\tau}_t\right)^2=1.0$$

- propagation criterion:

$$\mathcal{G}_I/\Gamma_{Ic}+\mathcal{G}_{II}/\Gamma_{IIc}=1.0$$

- shear nonlinearity explicitly considered

A-FEM Parametric comparison

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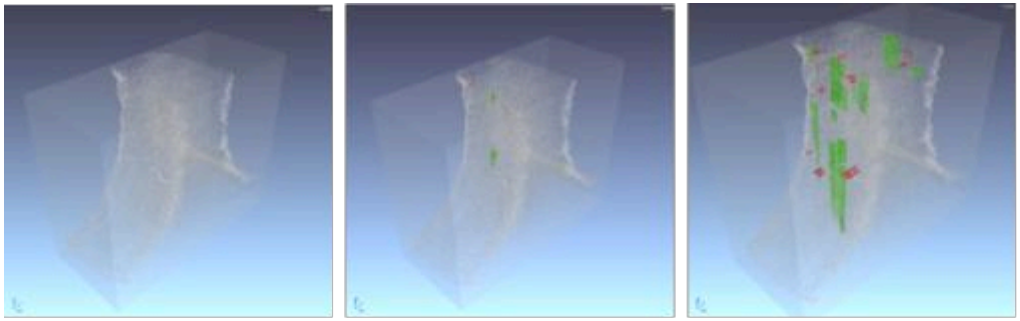
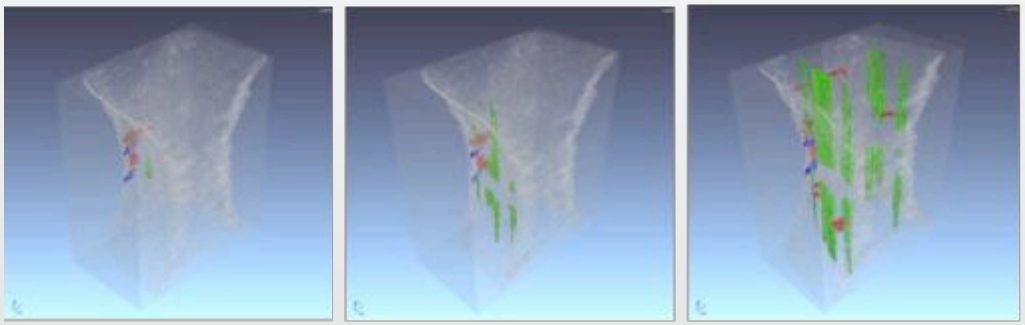
Matrix A



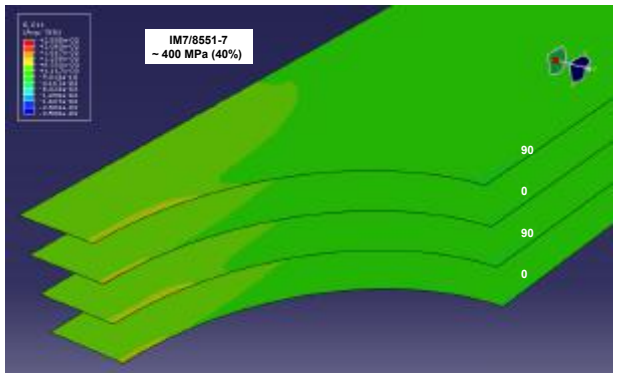
Matrix B

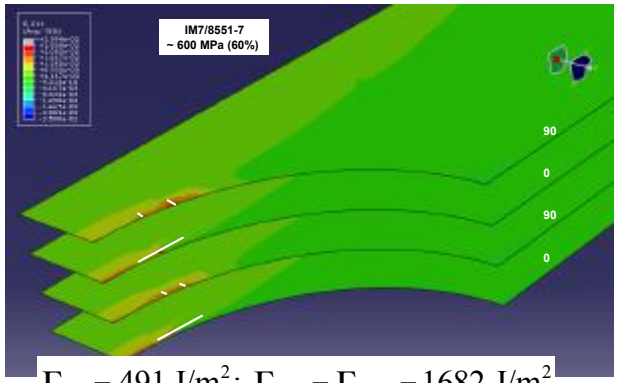
Matrix C

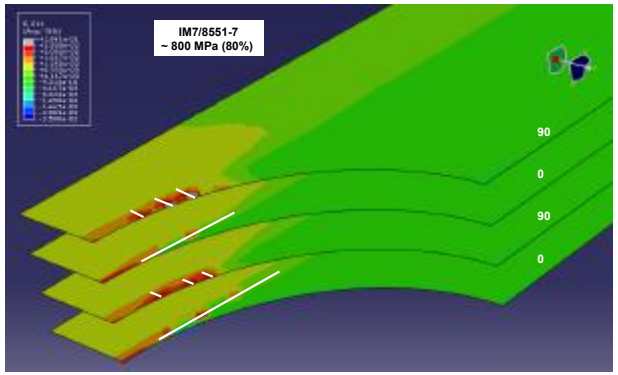


40% UTS 60% UTS 80% UTS

A-FEM Parametric comparison

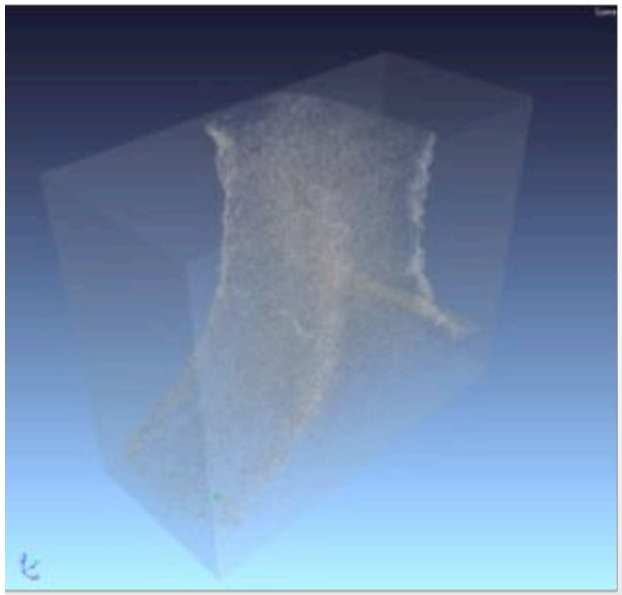


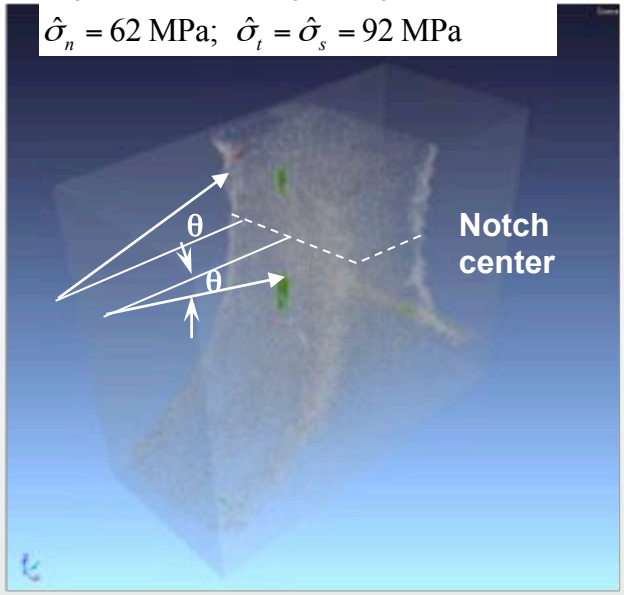


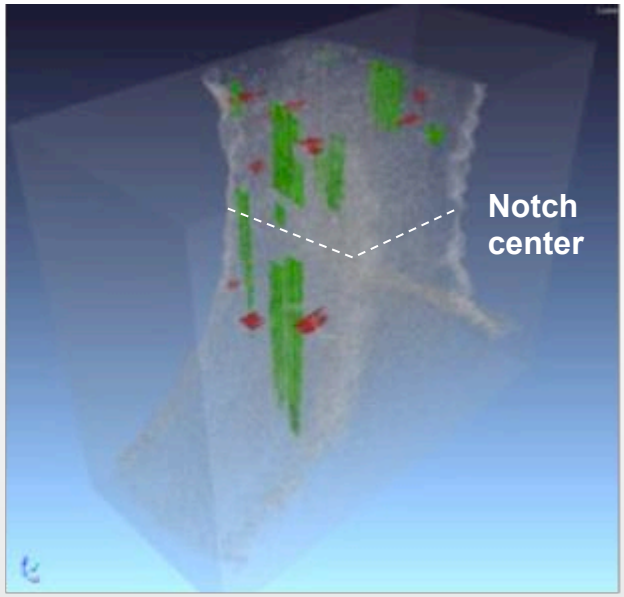


$\Gamma_{IC} = 491$ J/m^2; $\Gamma_{IIC} = \Gamma_{IIIC} = 1682$ J/m^2

$\hat{\sigma}_n = 62$ MPa; $\hat{\sigma}_t = \hat{\sigma}_s = 92$ MPa

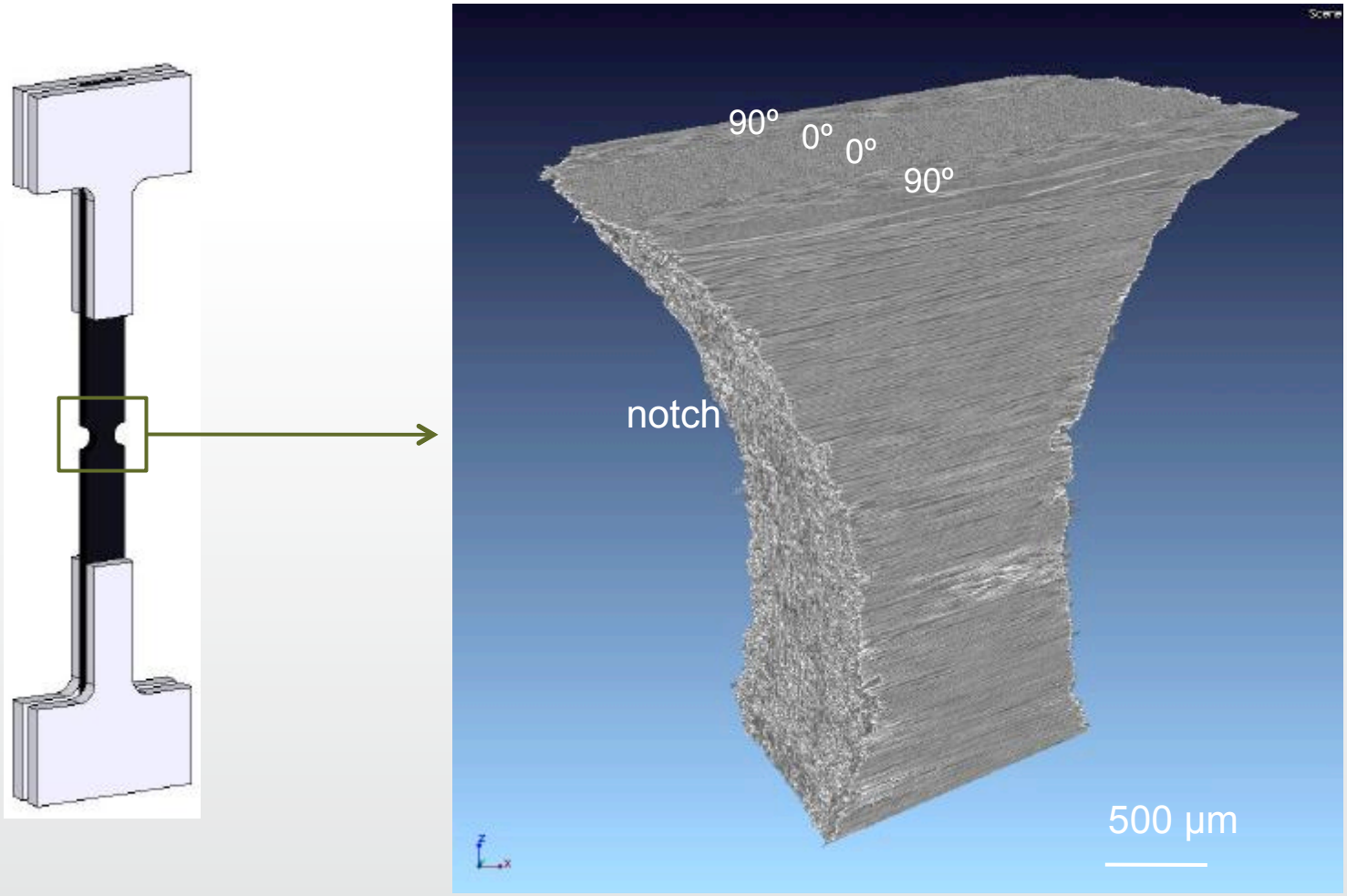


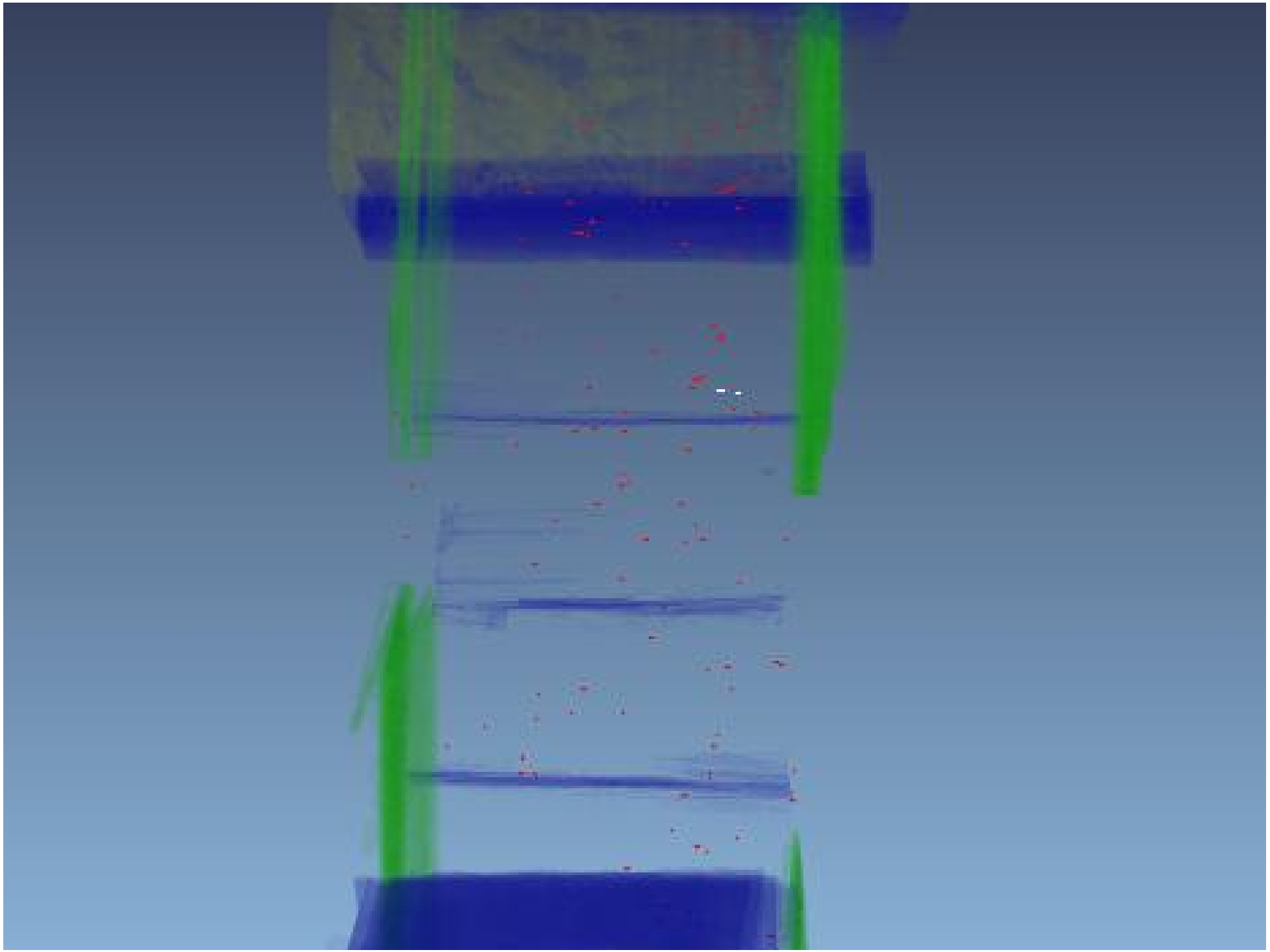




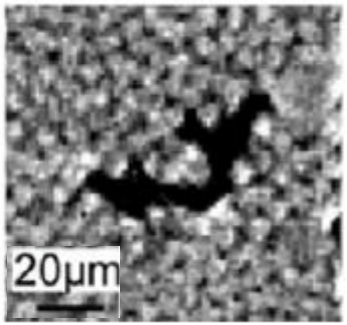
Results

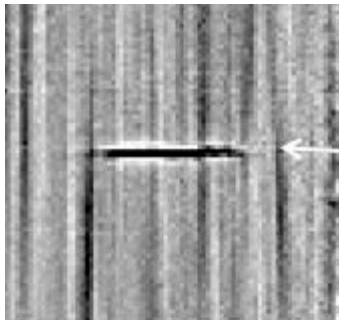
- 3D view of notched region

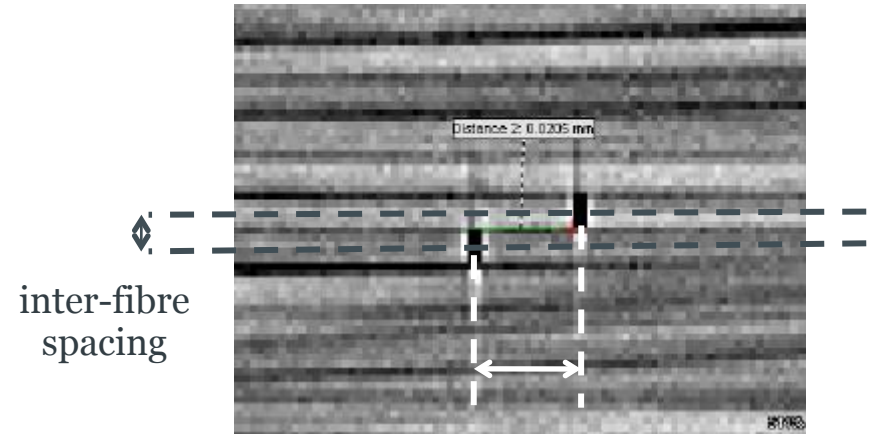




Fibre break analysis

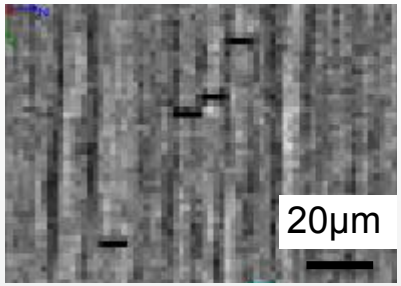






< minimum δ

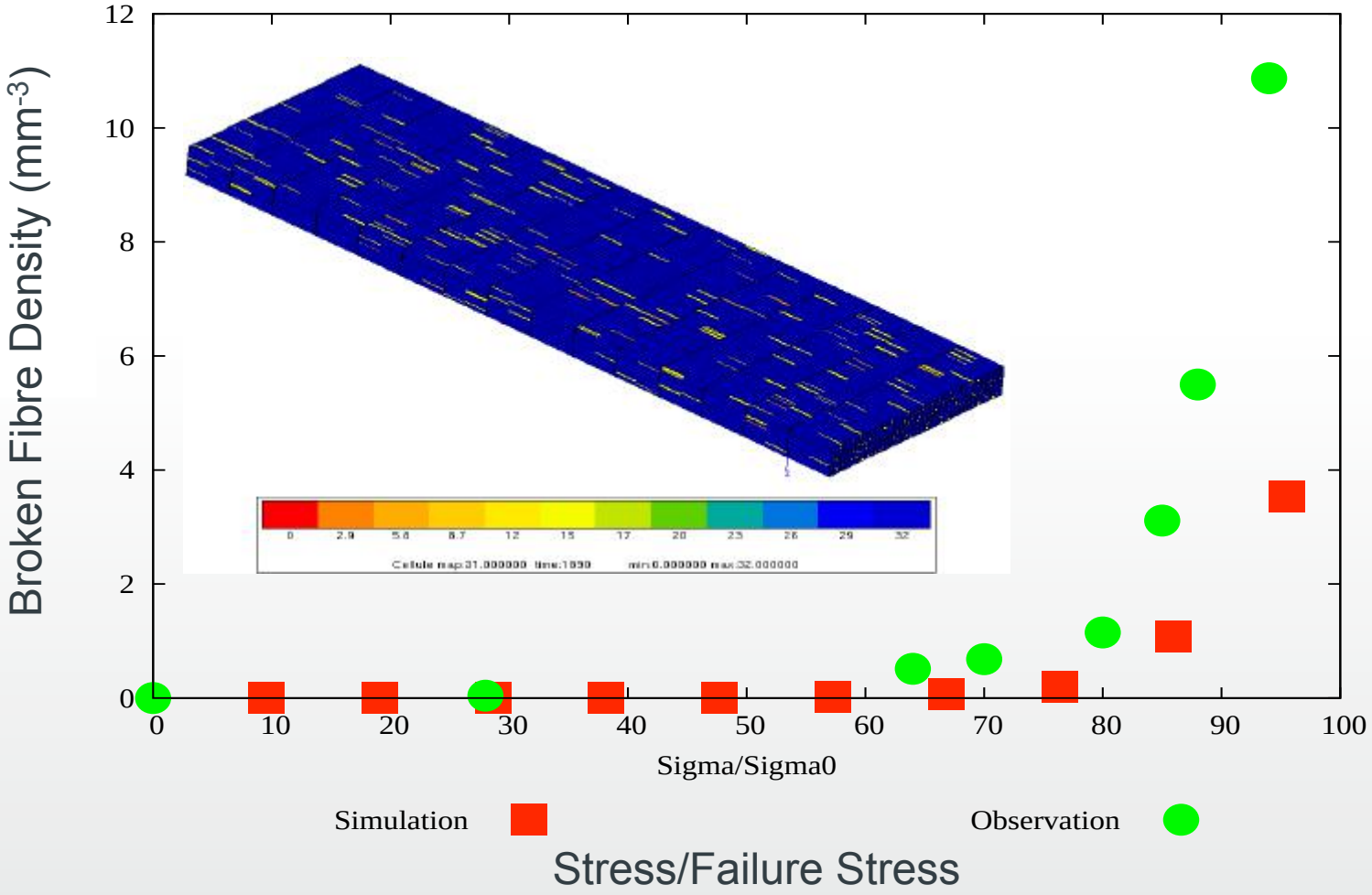
Pre-preg laminate: large co-planar clusters (max = 12plet)



Filament wound: smaller, dispersed clusters

% of Ultimate Failure	28	64	70	80	85	88	94
1plet	1	5	12	22	92	100	144
2plet		3	5	6	7	18	29
3plet					3	1	11
4plet						1	3
5plet							1
6plet							1
7plet							1
11plet							1
14plet							1

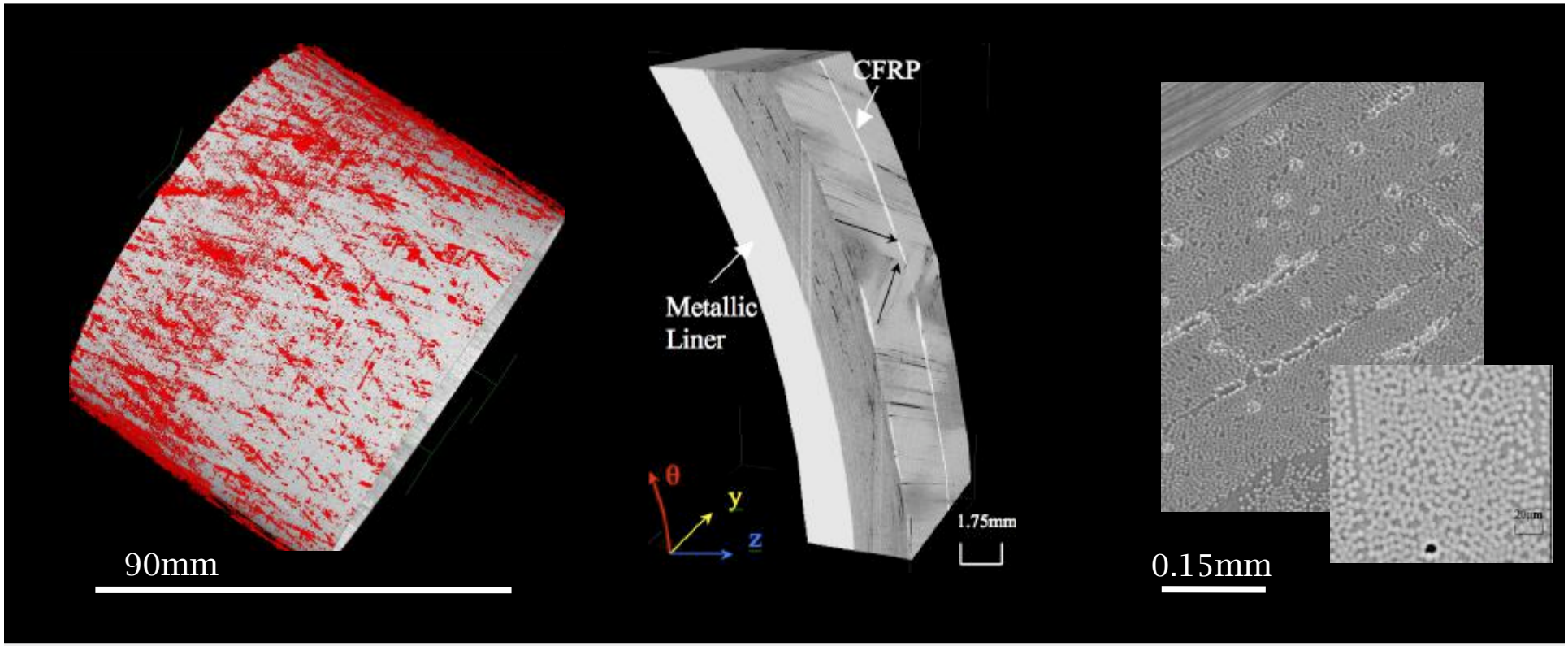
Initial Model and Experimental comparison



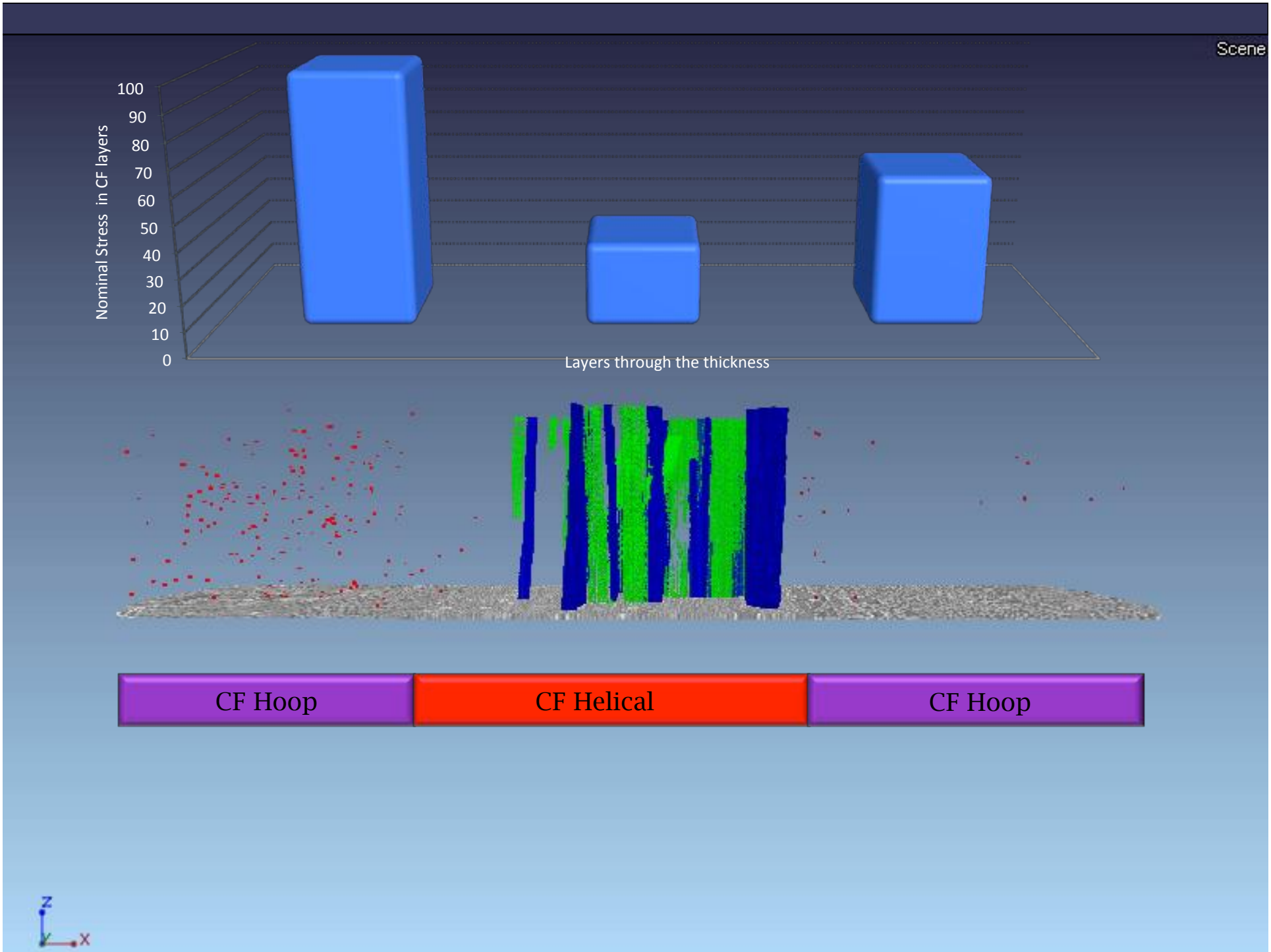
- RVE simulation, with Weibull fibre failure, debonding & load transfer to neighbours *[AfterA.E. Scott, I. Sinclair, S.M. Spearing, A. R. Bunsell, A. Thionnet. Submitted to Composites A]*

Multi-scale/built-up structures

Hybrid Al-alloy/CFRP/GFRP tube



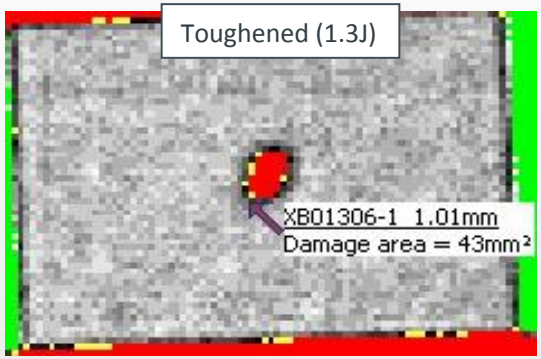
Voxel Resolution: 75μm	15μm	1.4μm
Macro-structure	Meso-structure	Micro-structure
μCT	μCT	SRCT


Scene
Nominal Stress in CF layers
100
90
80
70
60
50
40
30
20
10
0
Layers through the thickness
CF Hoop
CF Helical
CF Hoop
Z
X

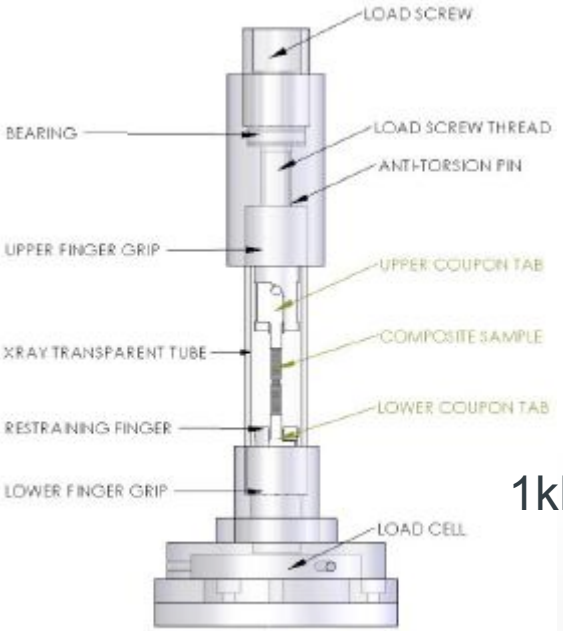
Laminography & CAI

- Compression after impact (CAI)
  - Materials & structure dependent ➔ length scales
  - Imaging post-impact, and *in situ* (compression)

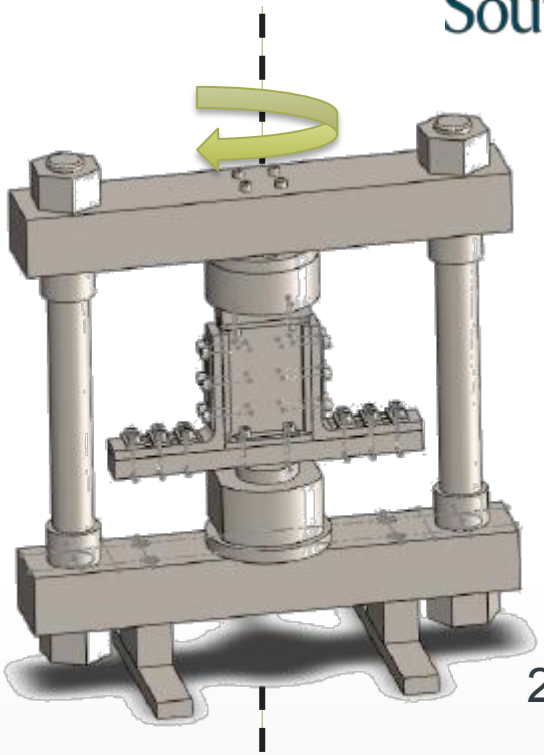
  ➔ Micromechanical toughening & macroscopic deformation



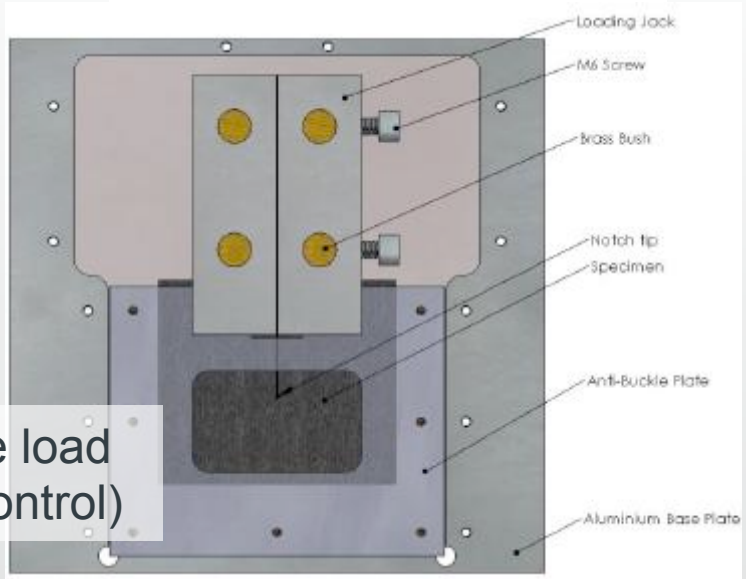
Loading devices



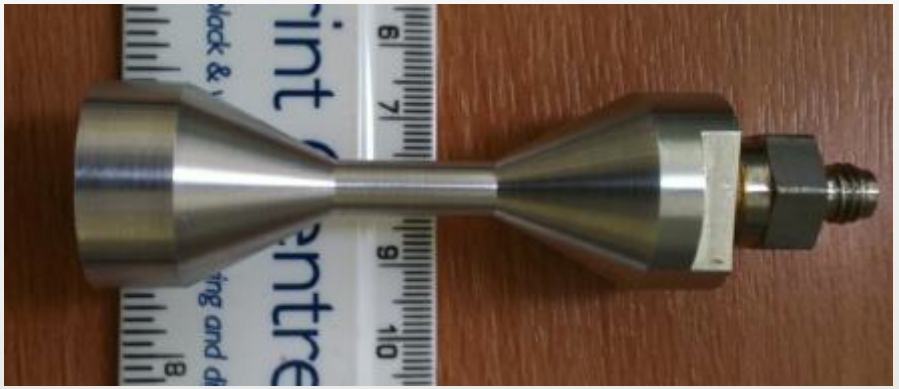
1kN



200kN



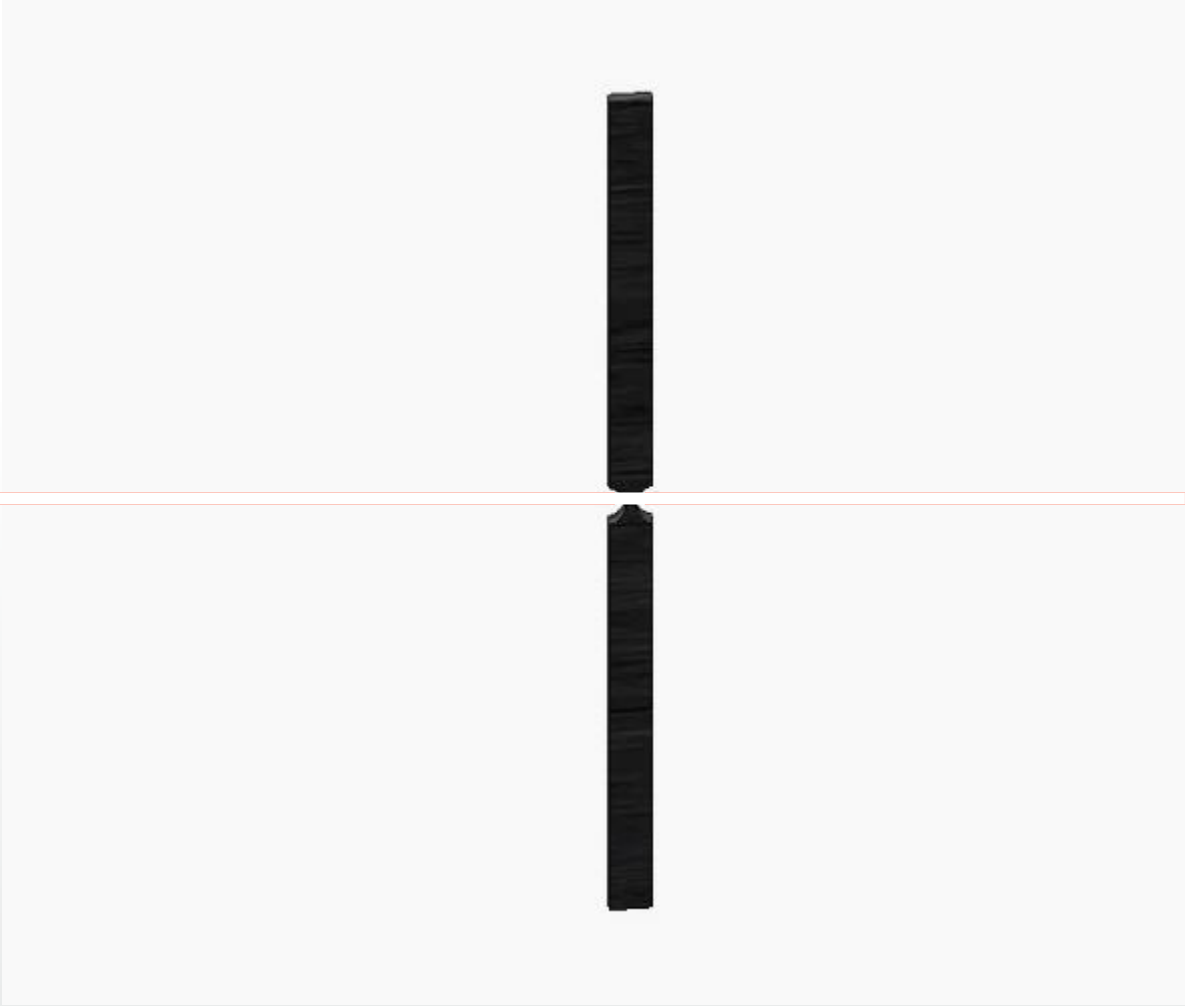
Wedge load
(disp control)



14MPa hydrostatic pressure/4 ˚C

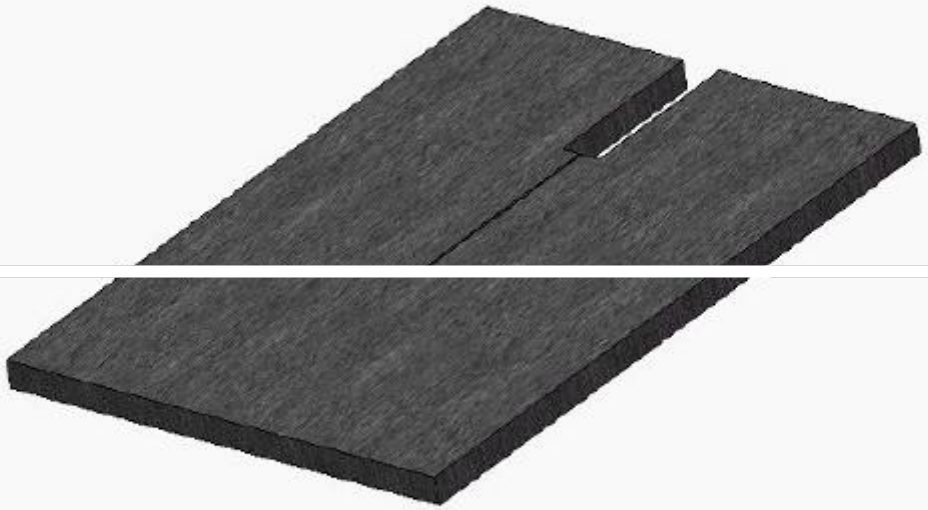
Laminography

SRCT

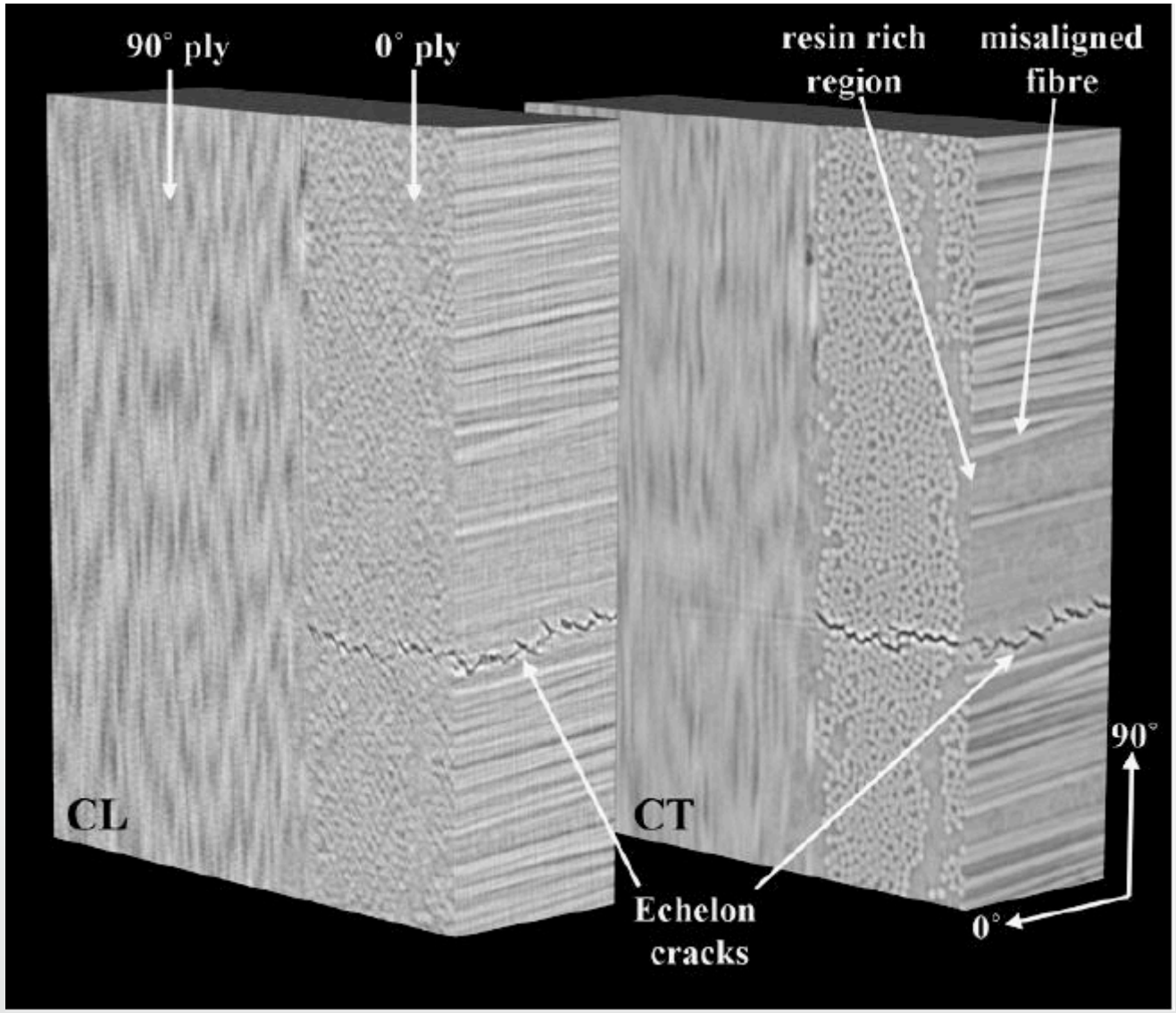


Laminography

SRCL



CT & CL: Direct comparison



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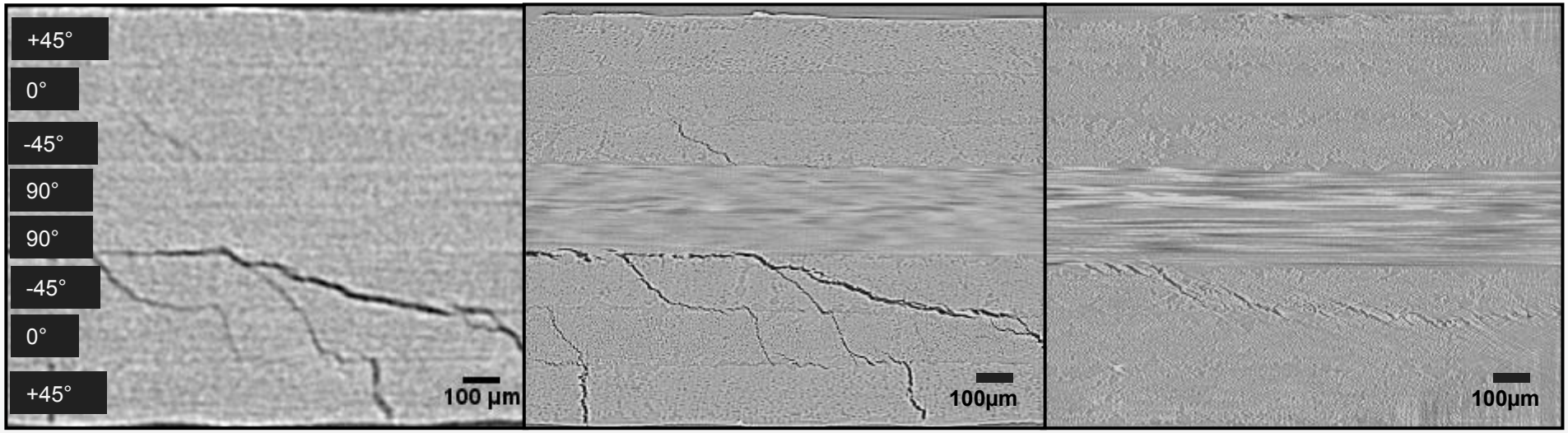
μCT
4.3μm resolution

SRCT
1.4μm resolution

SR Laminography
0.7μm resolution



Showing same sample at similar location

Showing different sample
with similar damage

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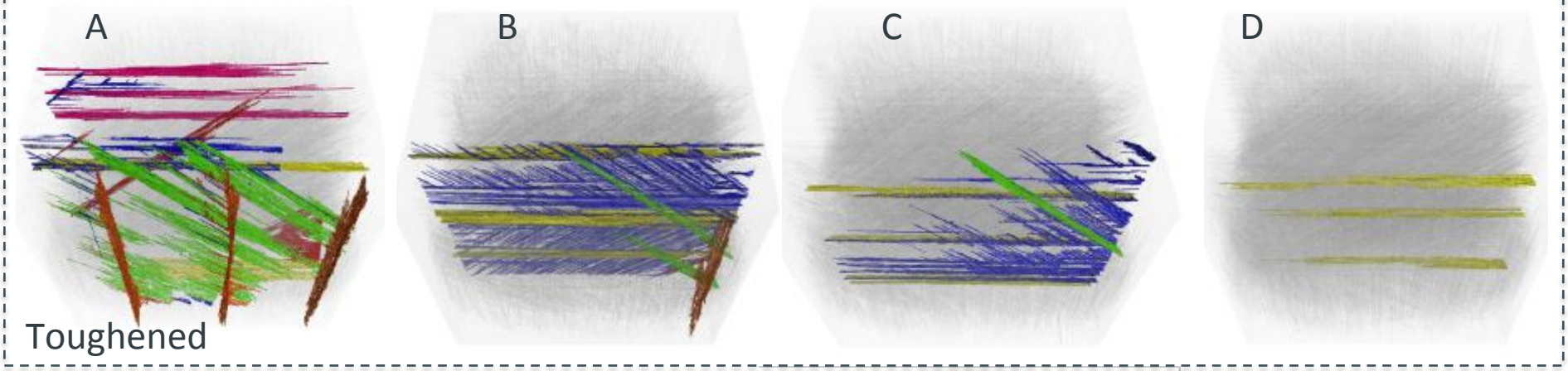

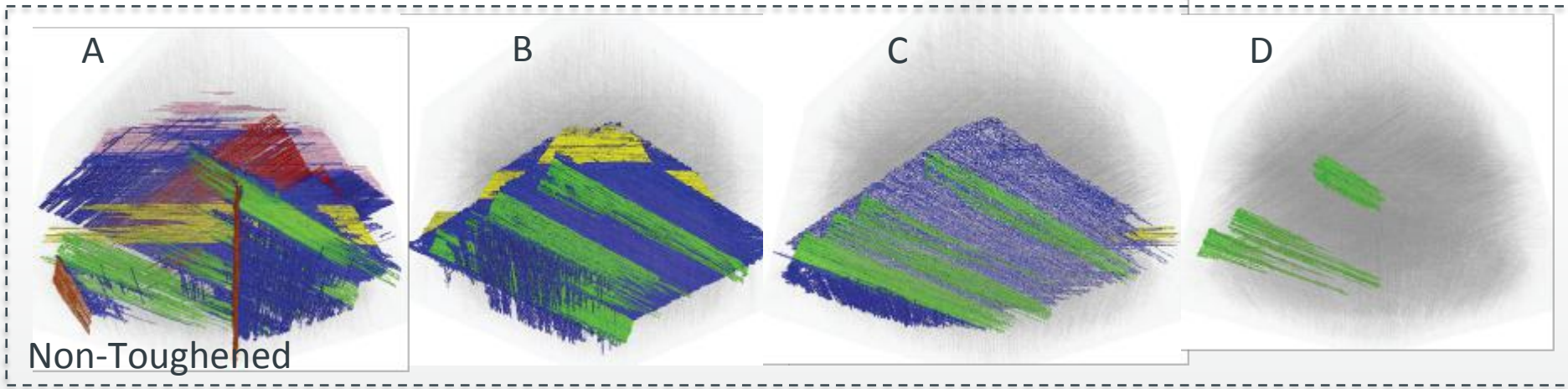

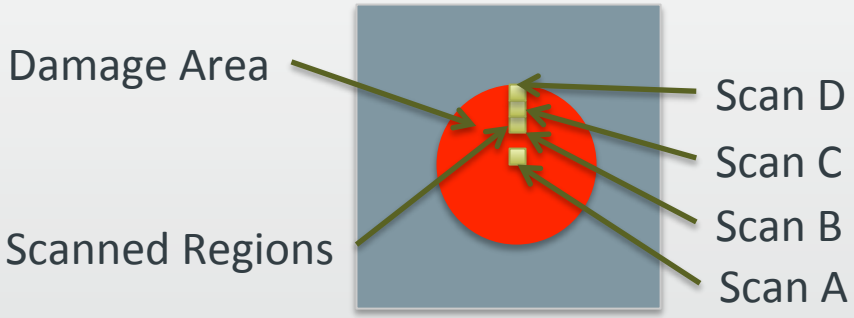

- Matrix Crack 2nd Ply 90°
- Matrix Crack 3rd Ply -45°
- Matrix Crack 4th-5th Ply 0°
- Matrix Crack 6th Ply -45°
- Matrix Crack 7th Ply 90°
- Matrix Crack 8th Ply +45°
- Delamination

Summary

- CT and related methods provide considerable opportunities in composite failure analysis
  - Material geometry, failure processes and simulation requirements conducive to CT assessment
  - Key failure processes visualised and quantified at fibre, lamina and laminate scale as a function of load
  - Larger samples/structures assessed by a combination of methods
- An exemplar of contemporary '*data rich mechanics*' approach?
  - Last 10 years has seen an shift in both experimental and computational capacity in relation to micromechanics of failure
  - Novel experimental fidelity for model initialisation and validation, at scales that can inform engineering simulation
  - Aim: replacing extensive, relatively uninformative test programs with highly informative strategic investigations and integrated simulation strategy
  - Support 'Virtual testing' approach

Multidisciplinary, Multiscale, Microtomographic Volume Imaging at Southampton

μ-VIS

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An interdisciplinary CT imaging centre for engineering, biomedical, environmental and archaeological sciences