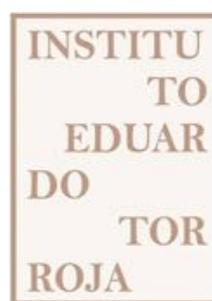




JAMES MARTIN 21ST CENTURY SCHOOL



In situ 3D observation of mechanical damage within SiC–SiC ceramic matrix composites for nuclear fuel clad

James Marrow^a, Shixiang Zhao^a, Luis Saucedo Mora^b, Biao Cai^c,
Tristan Lowe^c, Christine Reinhard^d, Peter D. Lee^c and Paul Mummery^e

^a Department of Materials, University of Oxford, UK

^b Institute Eduardo Torroja for Construction Sciences, Madrid, Spain

^c School of Materials, The University of Manchester, UK

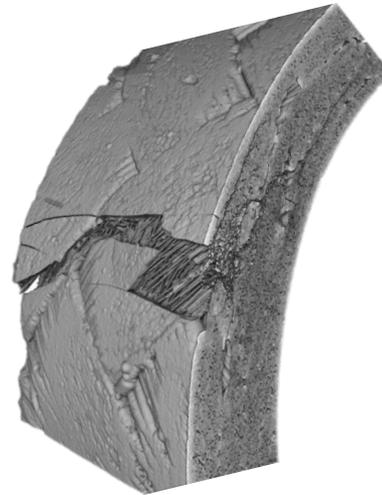
^d Diamond Light Source, UK

^e School of Mechanical, Civil and Aerospace Engineering, The University of Manchester, UK

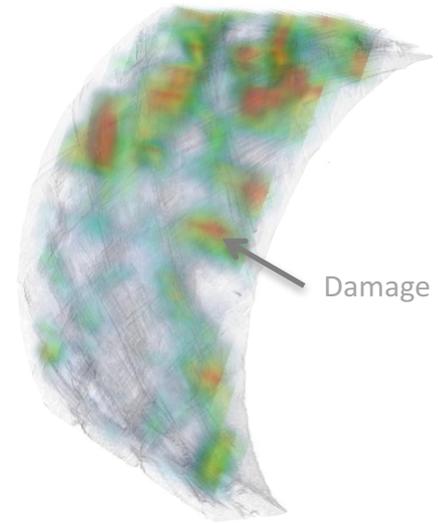


Overview

- Key techniques
 - Computed Tomography
 - Digital Volume Correlation
- The Engineering Problem
 - SiC-SiC_{fibre} composite fuel cladding
- Strain and Damage
 - Experimental observations of damage development
- Modelling of deformation and damage
 - Finite Element Meshfree Microstructure model



Tomography

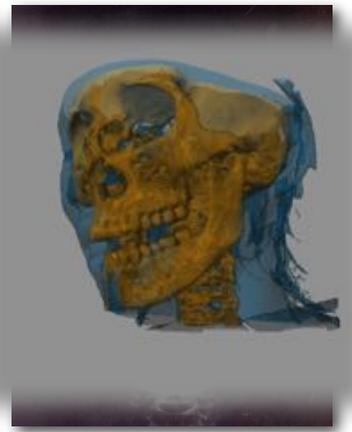


Tomography and
Digital Volume Correlation

Visualizing in 3D

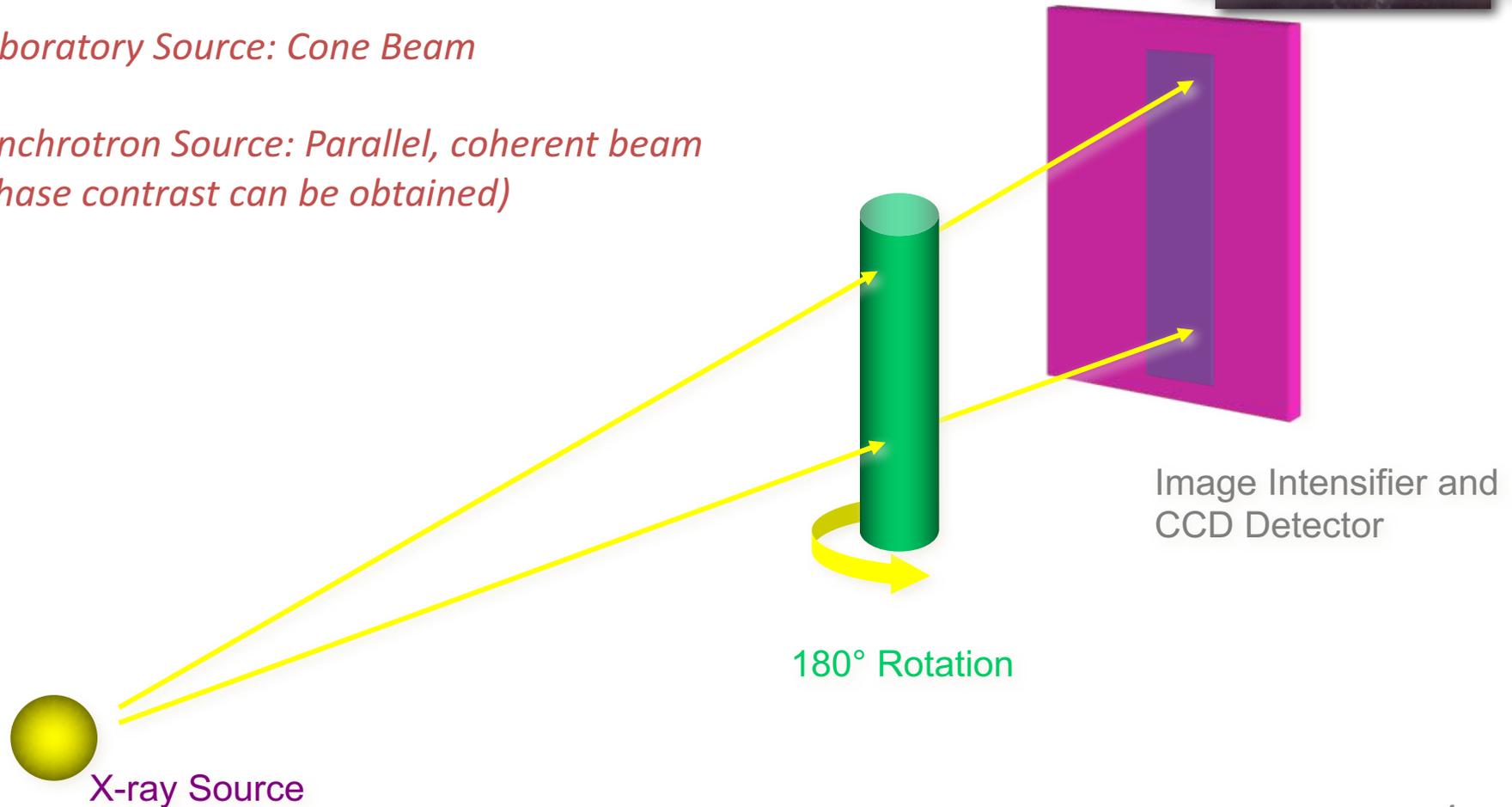
X-RAY TOMOGRAPHY

Computed X-ray Tomography: Principles

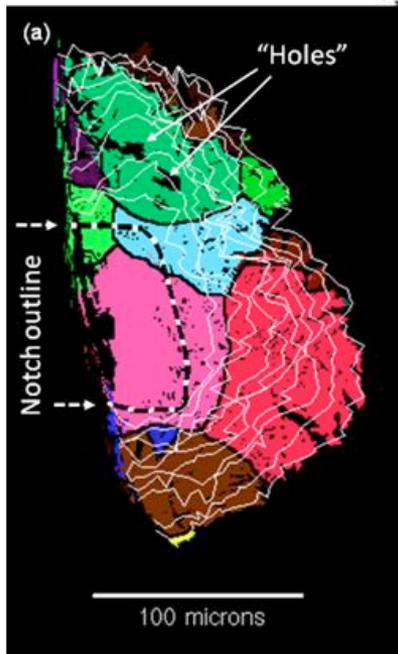
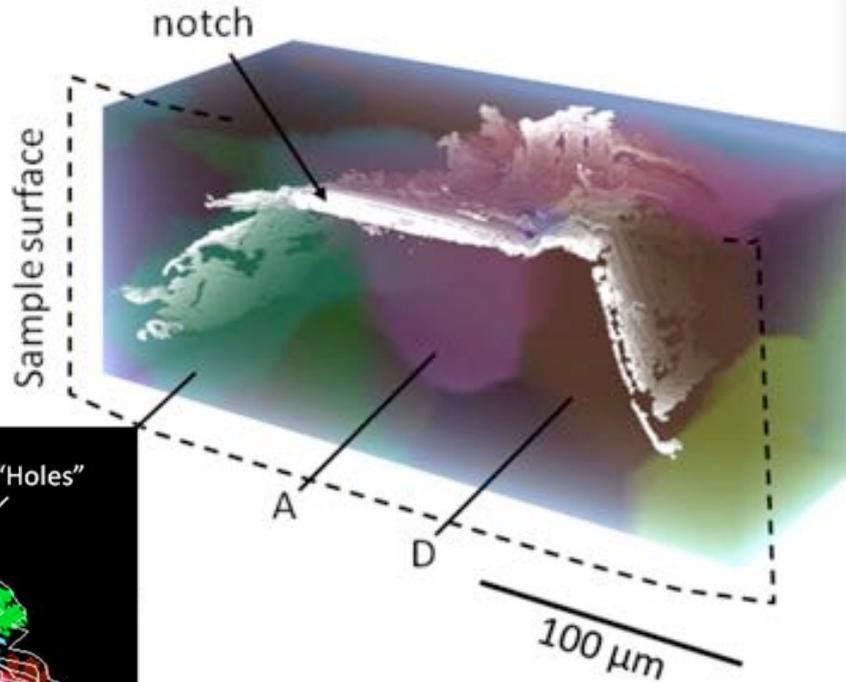


Laboratory Source: Cone Beam

*Synchrotron Source: Parallel, coherent beam
(phase contrast can be obtained)*

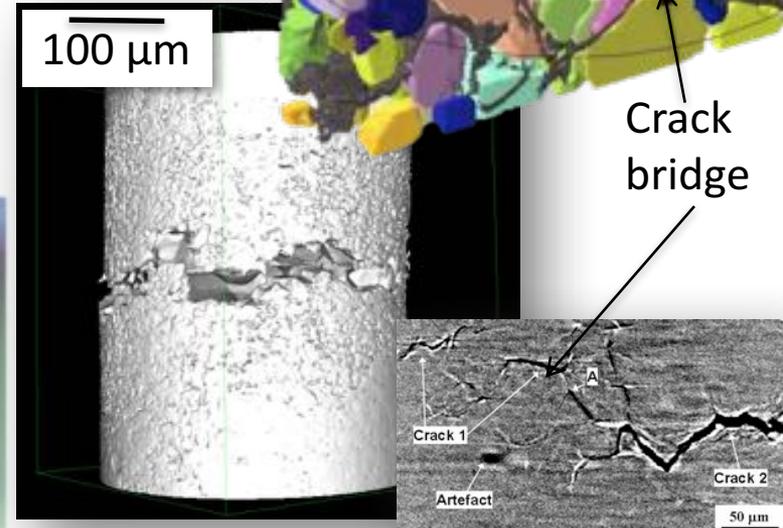


Computed X-ray Tomography: Examples



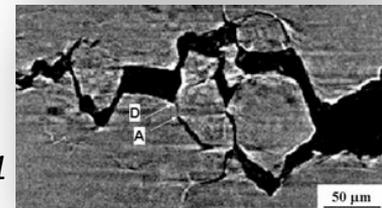
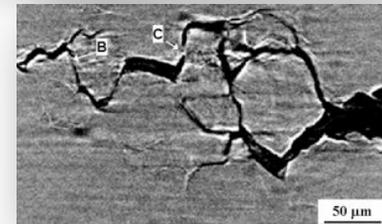
Short fatigue cracks in Magnesium alloy

doi: 10.1016/j.actamat.2011.07.034
 Acta Materialia, 59, (2011), 6761–6771



Intergranular stress corrosion cracking in sensitised austenitic stainless steel

doi: 10.1126/science.1156211
 Science, 321, (2008), 382–385



doi: 10.1016/j.jnucmat.2006.02.042
 Journal of Nuclear Materials, 352, (2006), 62–74

Mapping Deformation

DIGITAL IMAGE CORRELATION

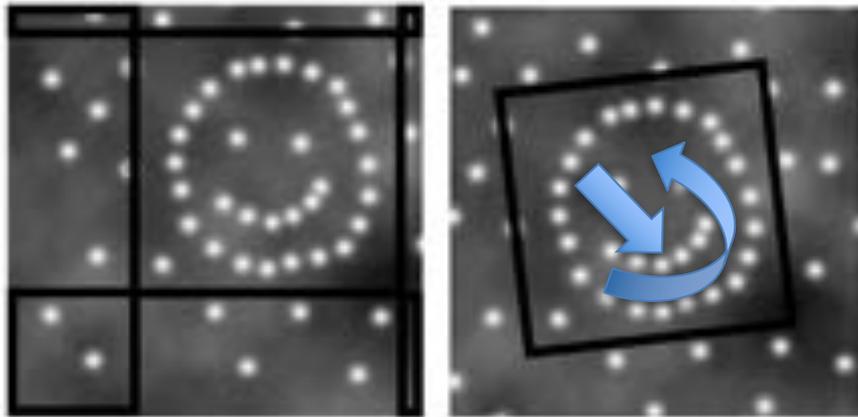
Digital Image Correlation (DIC)

The correlation function between arrays of pixels between images is *minimised* to obtain their relative translations, rotations (and deformations)

Simple in concept: computationally intensive

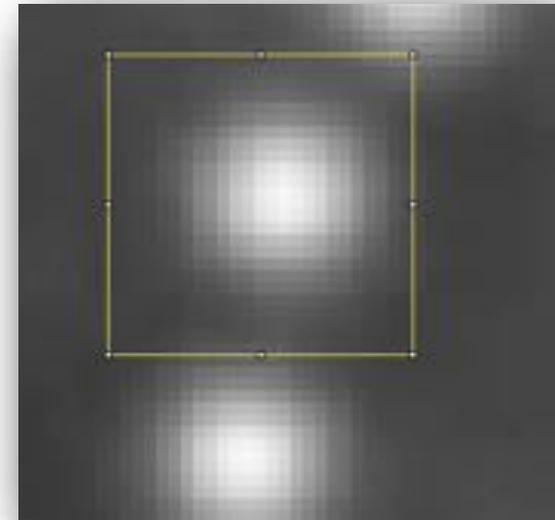
The Output is a Field of Displacement Vectors

Digital Volume Correlation (DVC) uses 3D arrays of voxels: “sub-volumes”



Reference Image

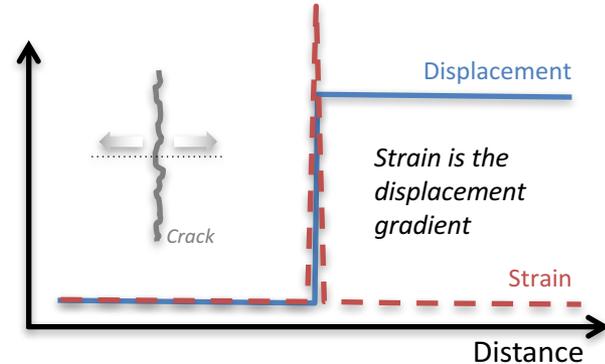
Displaced Image



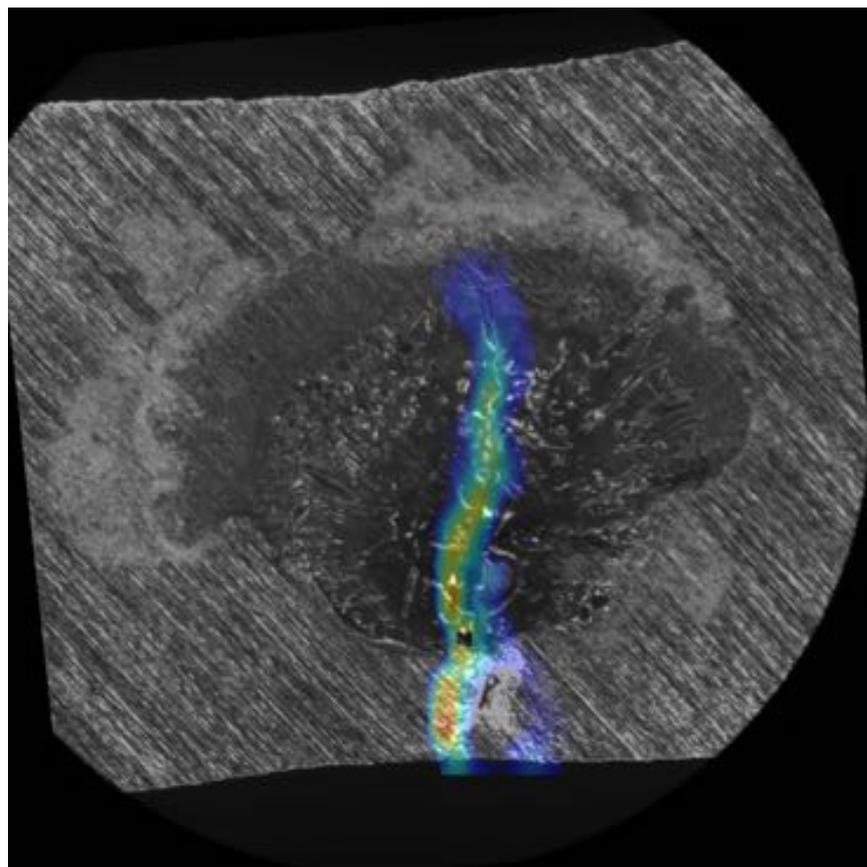
Increasing the array size increases precision (exponentially) to sub-pixel levels

In practice, image quality and artefacts can reduce this

Digital Image Correlation: Example application



Detection of stress corrosion crack nucleation, under salt films, in austenitic stainless steels in long-term, controlled humidity experiments

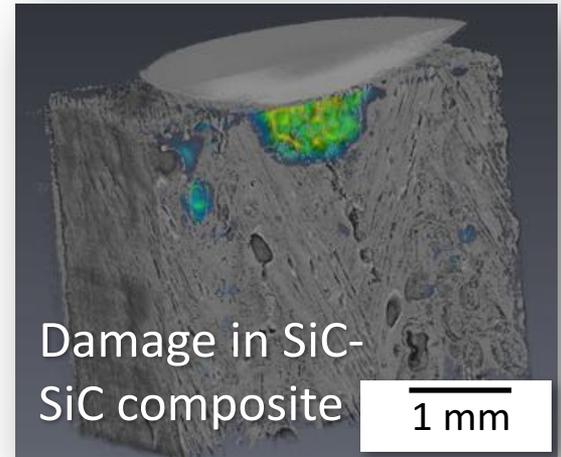
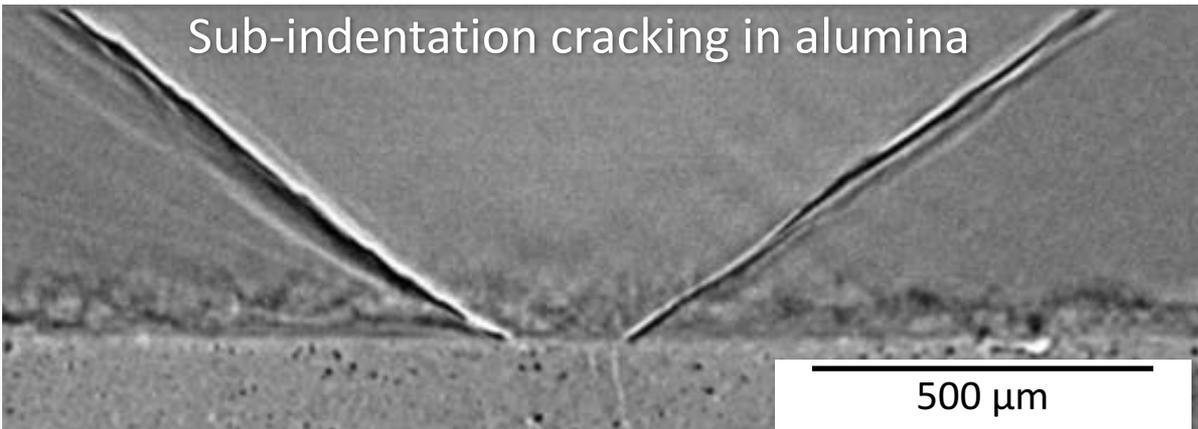


Observing and Measuring in 3D

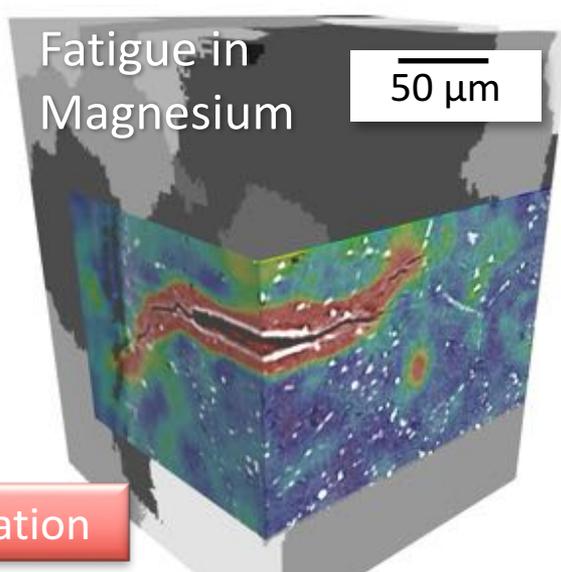
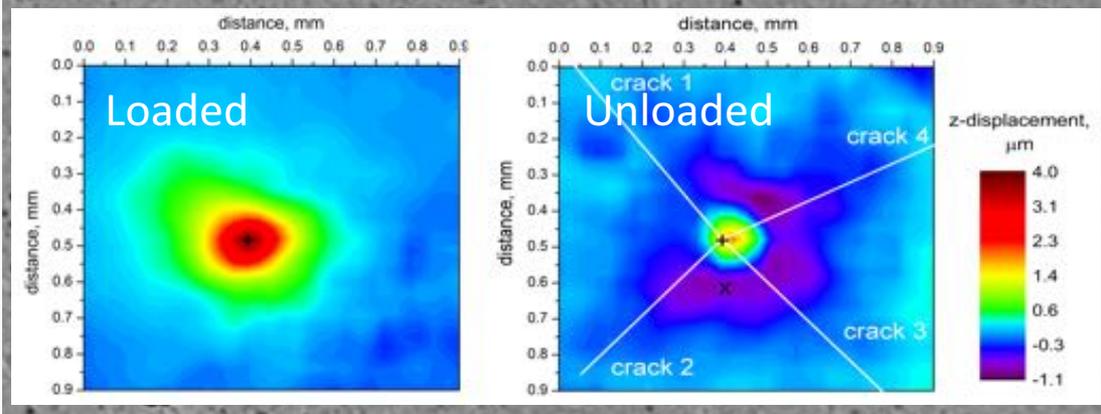
COMBINED TOMOGRAPHY AND DIGITAL VOLUME CORRELATION

Example Applications

Sub-indentation cracking in alumina



Vertical Displacement Maps



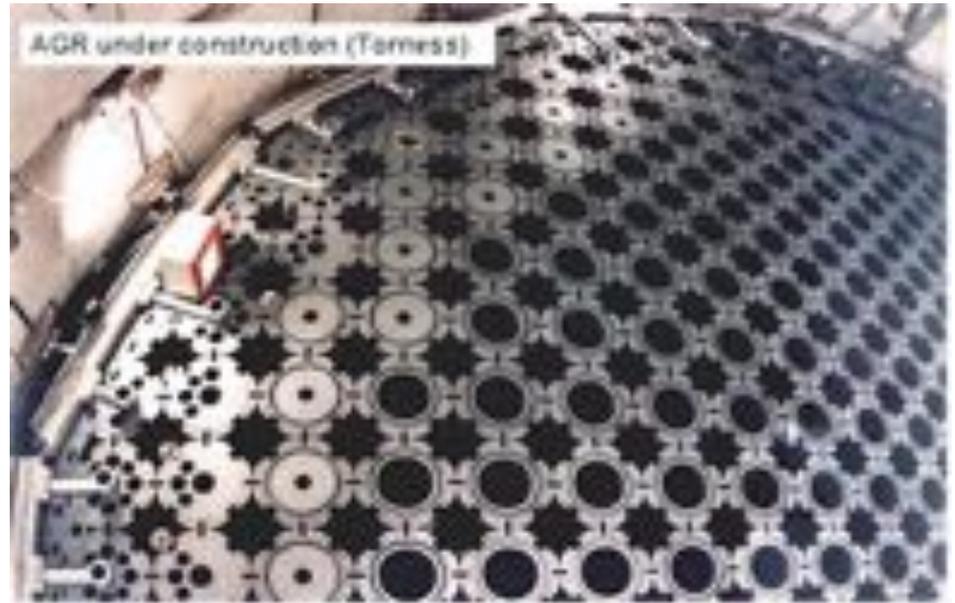
3D deformation mapping provides insights into materials deformation

doi: 10.1016/j.ijfatigue.2014.04.003
Int. J. Fatigue, 66, (2014), 183-193

doi: 10.1016/j.jeurceramsoc.2014.04.002
J. Eur. Ceram. Soc., 34, (2014), 3127-3232

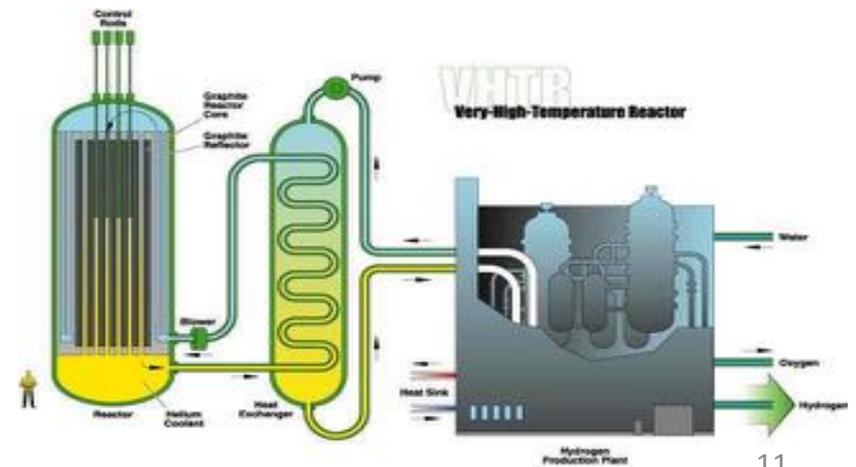
doi: 10.1016/j.finel.2015.11.003
Finite Elem. Anal. Des., 110 (2016), 11-19

An example of the quantitative use of tomography and digital volume correlation



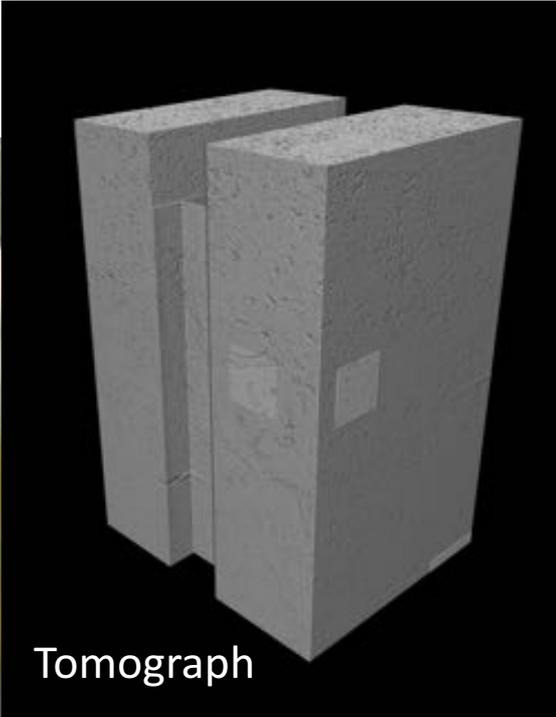
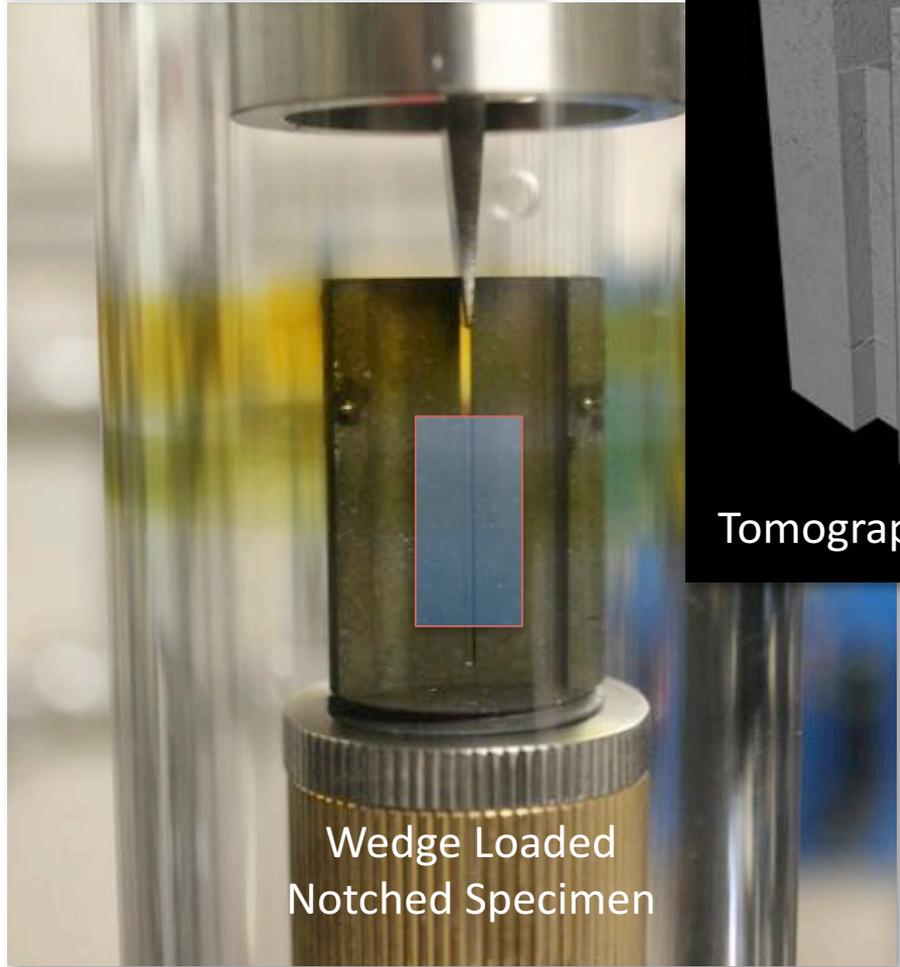
Collaborative work with EDF Energy Ltd

GRAPHITE



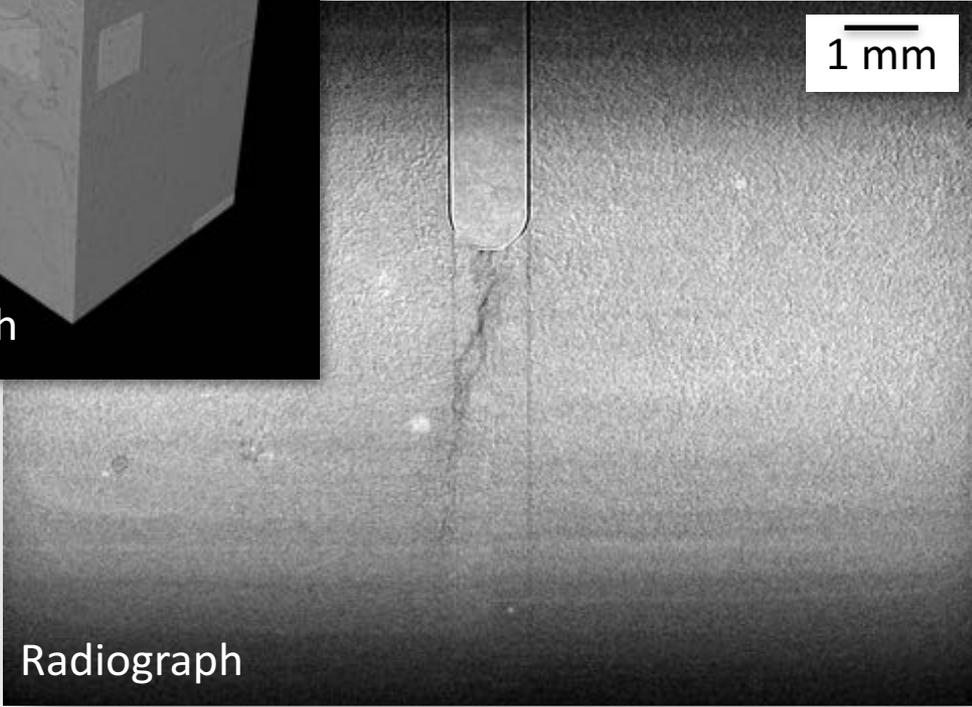
Inside the Fracture Process Zone..

Wedge-loaded specimen with straight notch

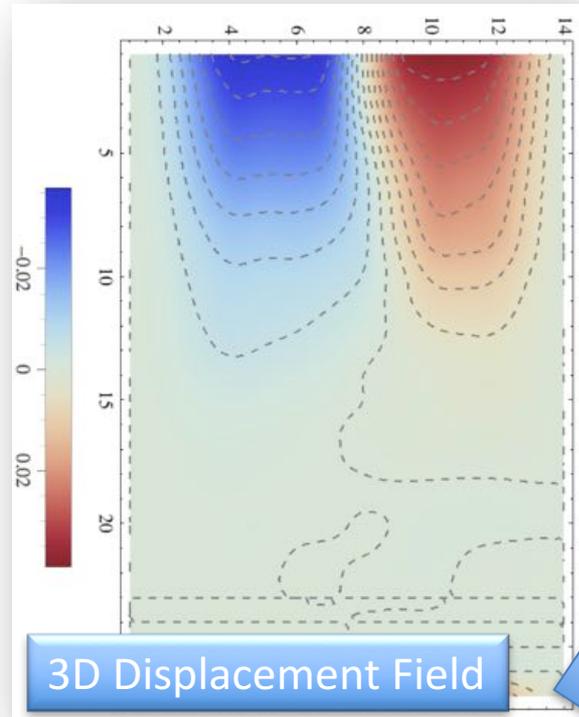


Crack propagation from notch with periodic tomography and diffraction mapping

IM1-24 Gilsocarbon (GCMB grade)



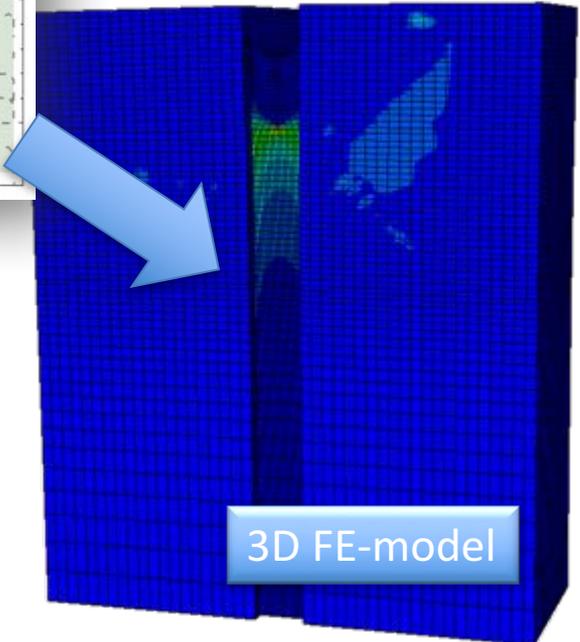
Crack Driving Force



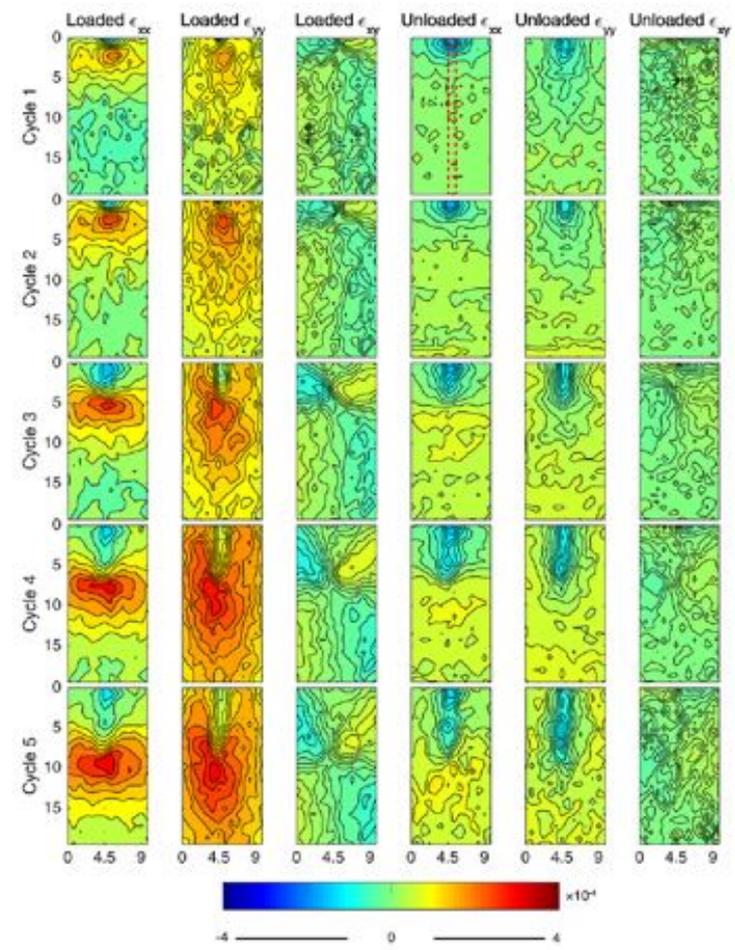
3D Displacement Field

The DVC measured displacement field is used to calculate the elastic strain energy release rate (J-integral)

Wedge-loaded specimen:
Applied load is NOT used

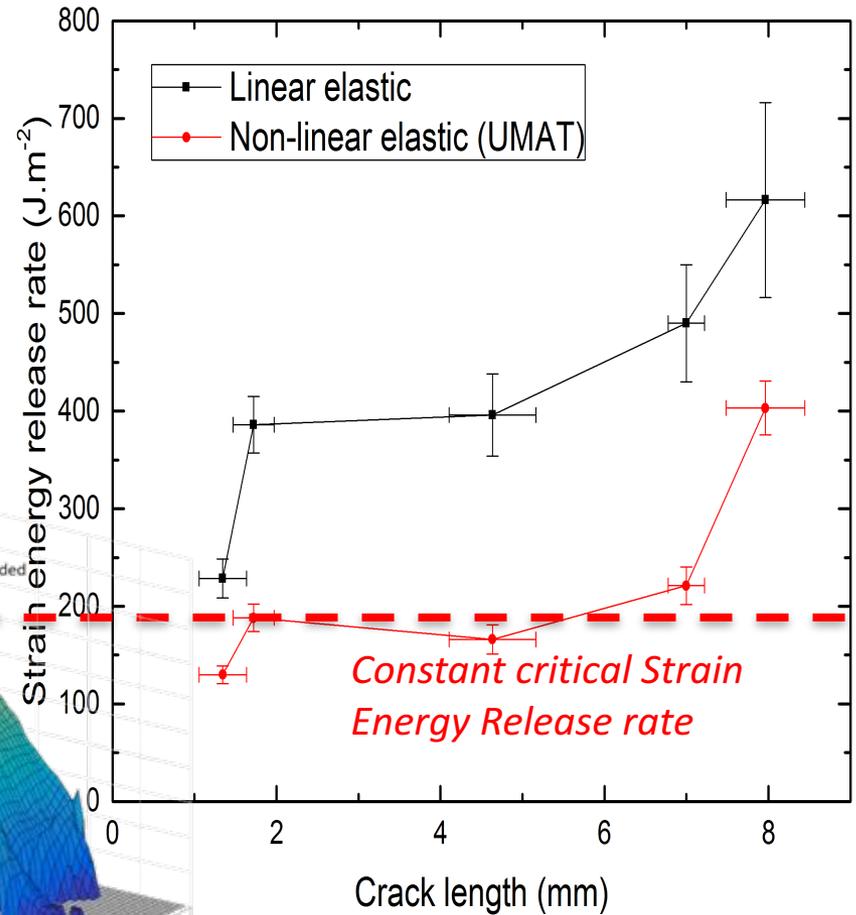
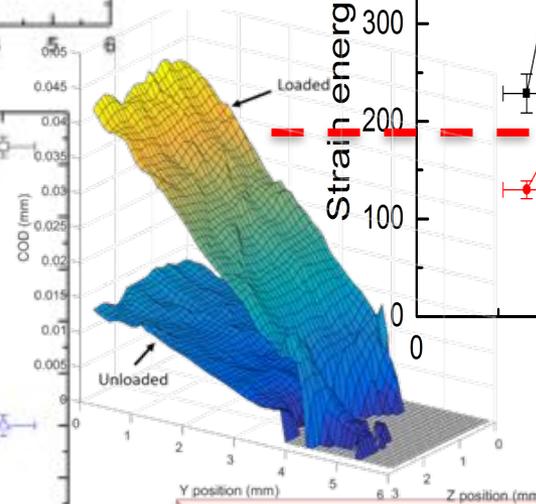
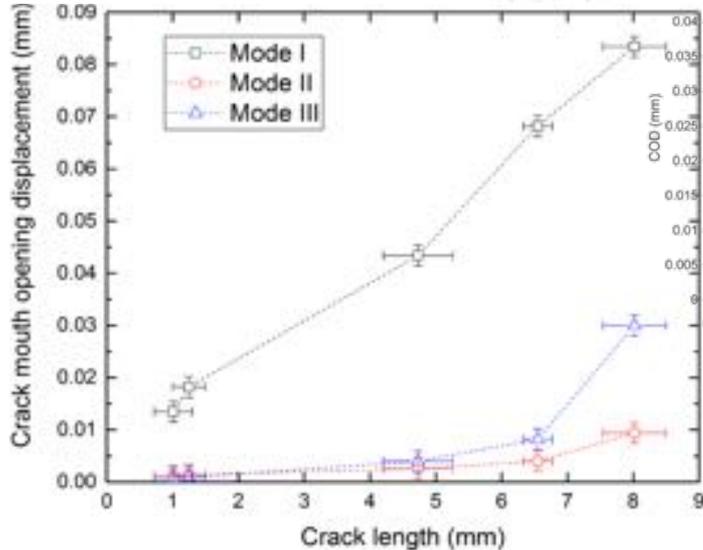
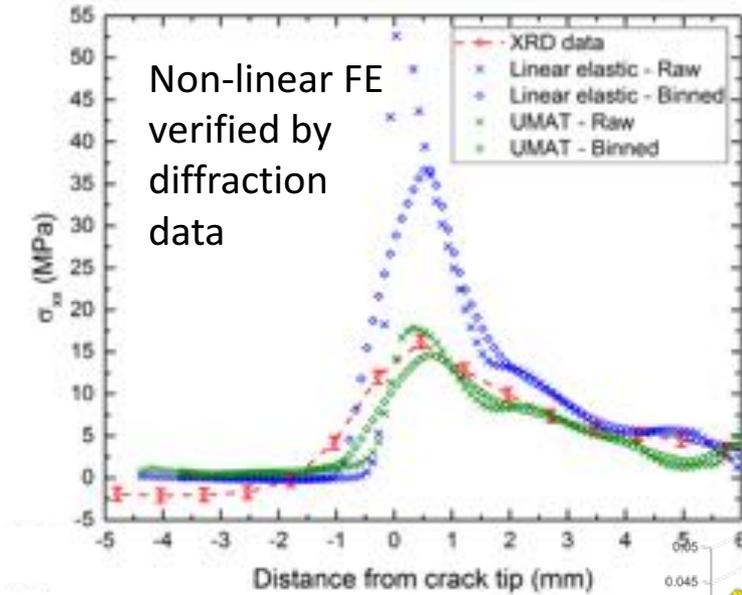


3D FE-model



Diffraction Mapping of Strain Field

Mode and Work of Fracture



Work of fracture (mode I) evaluated from Tomo/DVC displacement field and non-linear FE

The engineering problem

SIC-SIC FUEL CLAD FOR GEN IV HIGH TEMPERATURE REACTORS

SiC-SiC_{fibre} Nuclear Fuel Clad

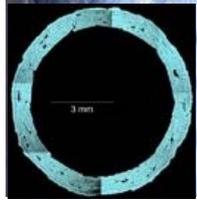
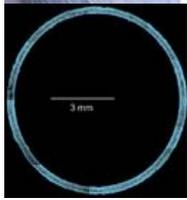


SiC-SiC_{fibre} composites

wound

2D braid

3D braid



$d \geq 2.7$

$d \sim 2.9$

$d \sim 2.3$

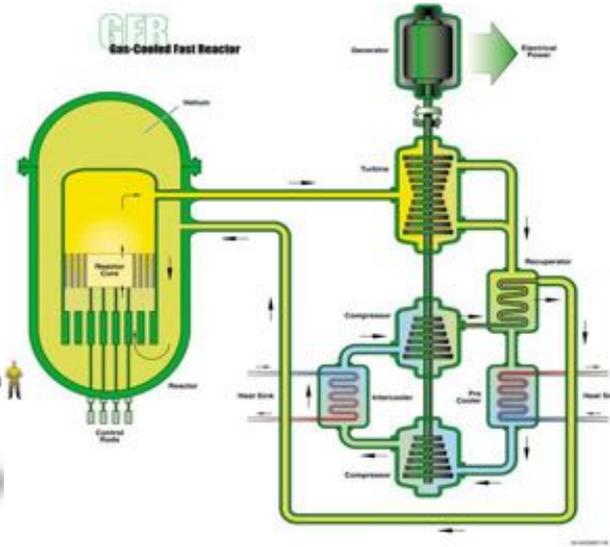
porosity ~ 10%

porosity ~ 5%

porosity ~ 30%

High cost process

Low cost processes

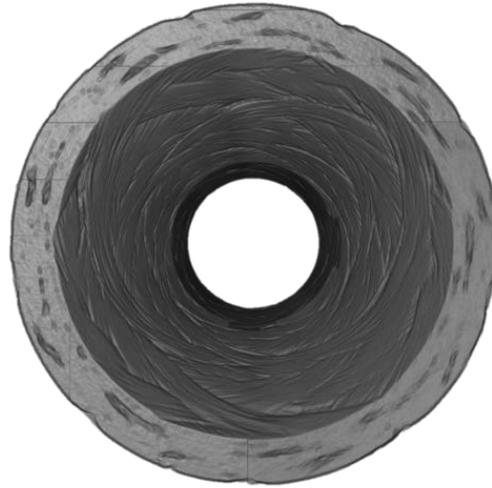


Fuel Clad Operating Parameters (Gas Cooled Fast Reactor)

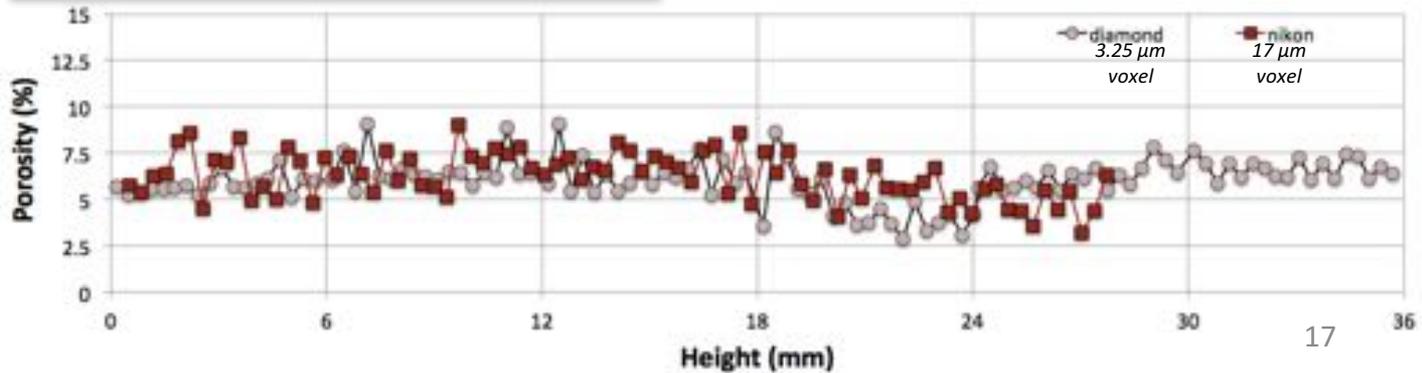
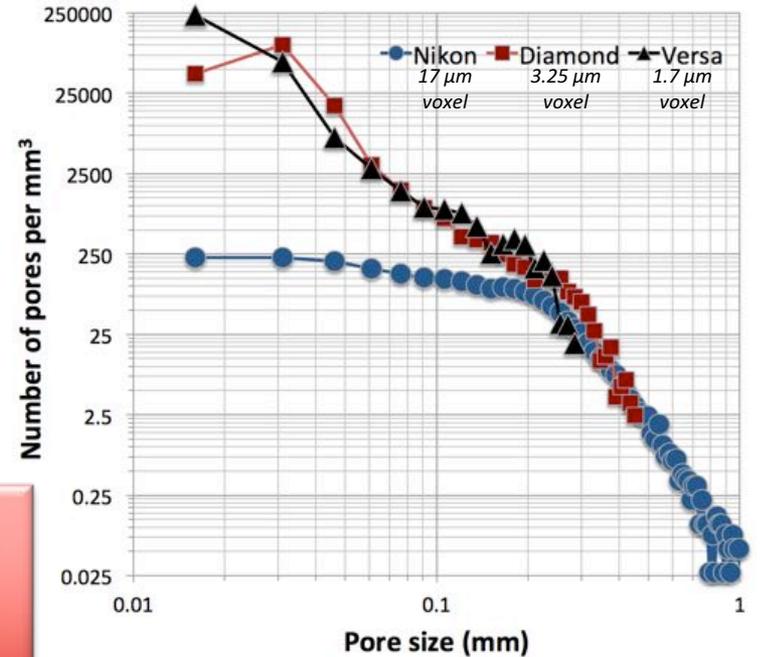
- Temperature
 - Normal operation: 900-1100°C
 - Accident: 1600°C (few hours) and 2000°C (<1 hour)
- Fast Neutron Dose
 - >60 to 80 dpa (displacements per atom)
- Mechanical
 - Coolant pressure (7 MPa)
 - Fuel swelling, fission gas release, thermal gradients
- Chemical/Erosion
 - Impure flowing He, accidental air ingress, carbide actinides

The problem: predicting risk of damage development, and design of test methods to evaluate materials

Microstructure Characterisation



Computed X-ray Tomography can observe and quantify porosity



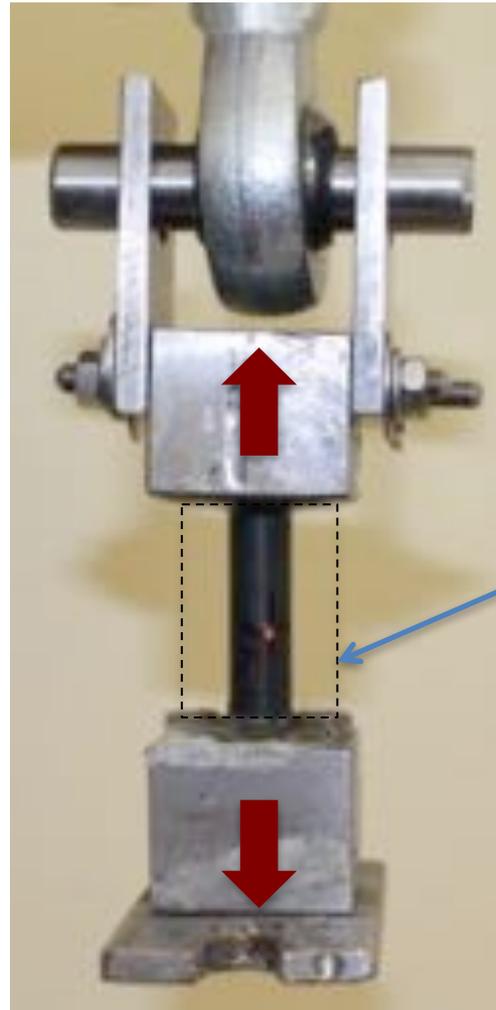
Experiments with tomography and digital volume correlation

IN SITU OBSERVATIONS OF DAMAGE DEVELOPMENT

Axial Tensile Loading

Objective: to observe damage development, in situ

Radiograph



*Imaged at
0, 17, and 35 MPa
tensile stress*

*(Tensile strength
~ 100 MPa)*

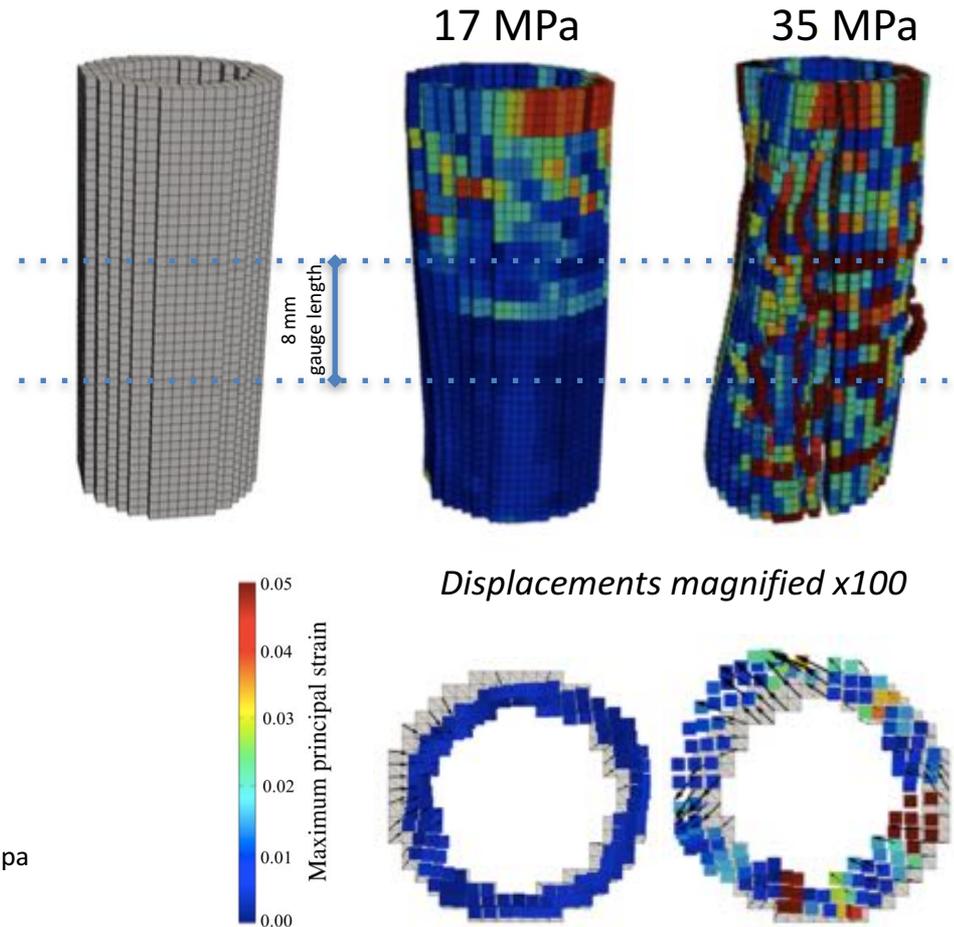
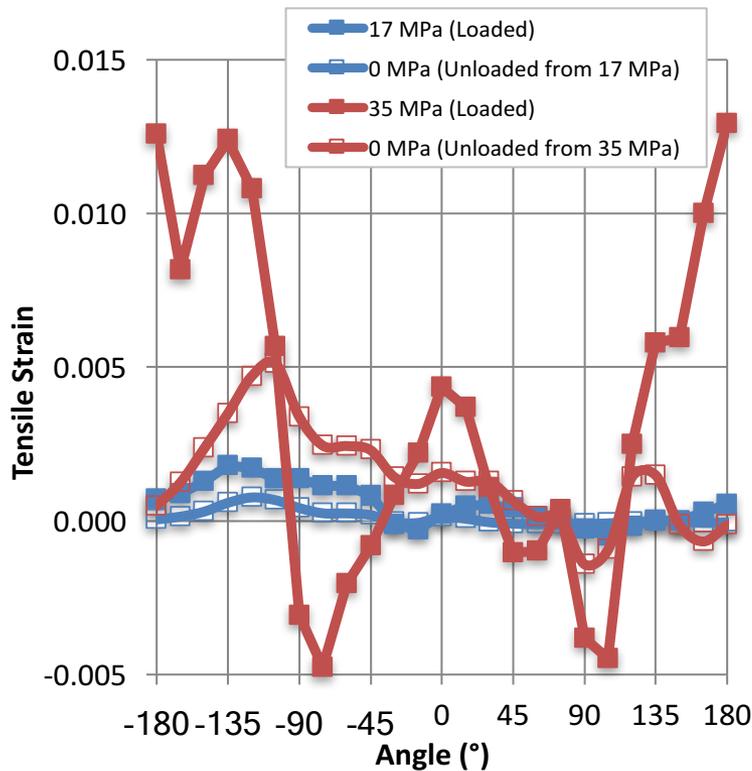
Scanned
volume

20 mm

*Nikon Custom Bay (80 keV, 17 μ m voxel)
~ 3 hours per scan*

3D Displacement Measurement

Effect of fibre weave on local deformation can be measured



Tensile elastic modulus from average strain: 35 GPa at 17 MPa, 14 GPa at 35 MPa
Expected tensile elastic modulus: 250 GPa

Digital Volume Correlation: 128x128x256 voxels (elongated dimension of the subset aligned parallel to the tube axis). 75% subset overlap, with 2 passes

This damage cannot be resolved in the tomographs

Mapping of Damage

Increasing Peak Load

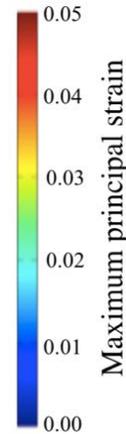
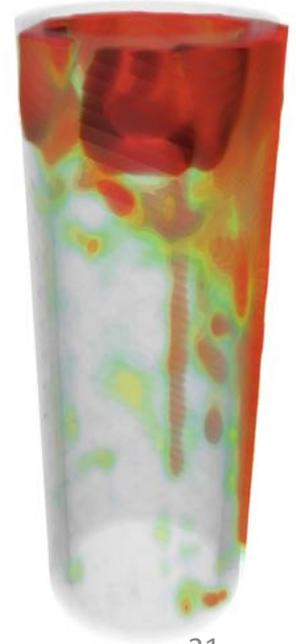
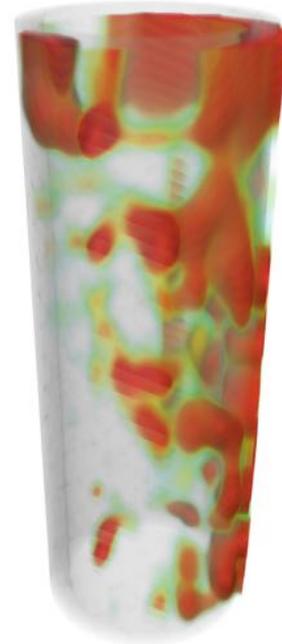
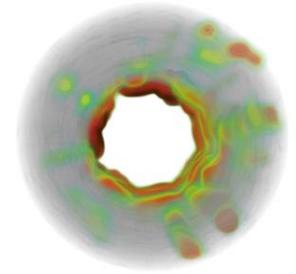
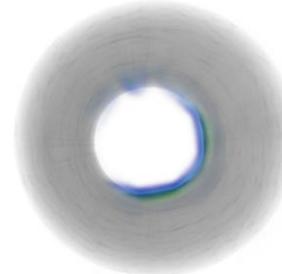
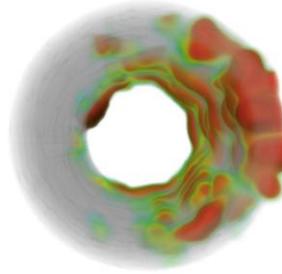
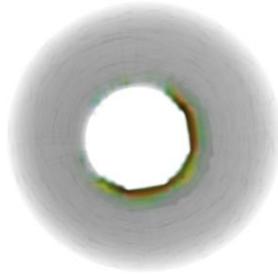


17 MPa

35 MPa

Unloaded from
17 MPa

Unloaded from
35 MPa

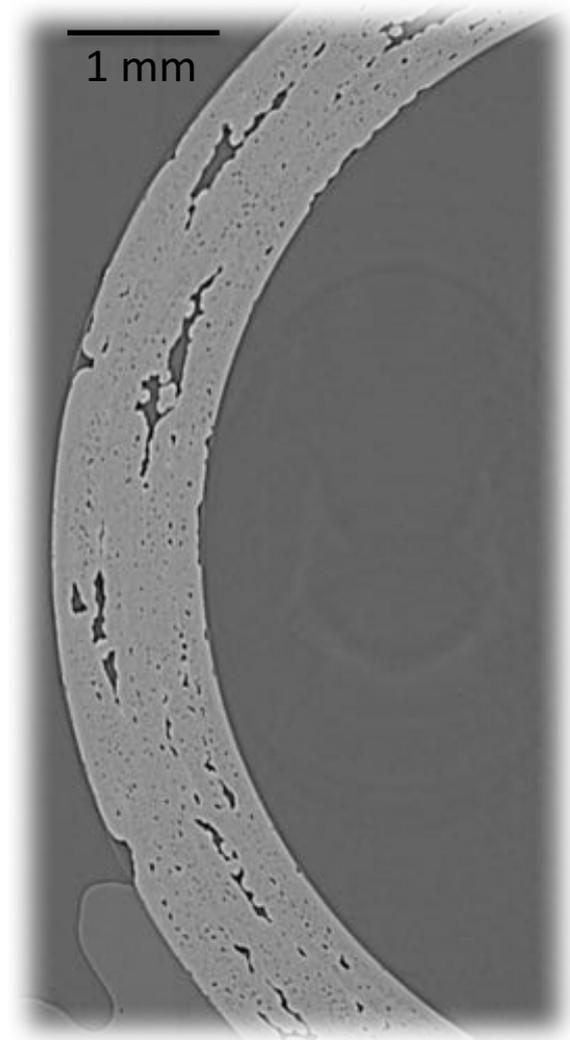
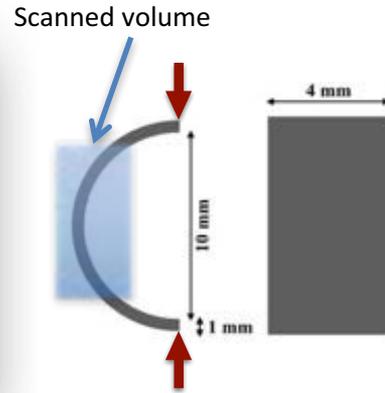


Loaded

Unloaded

C-Ring Test (Tomography)

Objective: to observe damage development, in situ

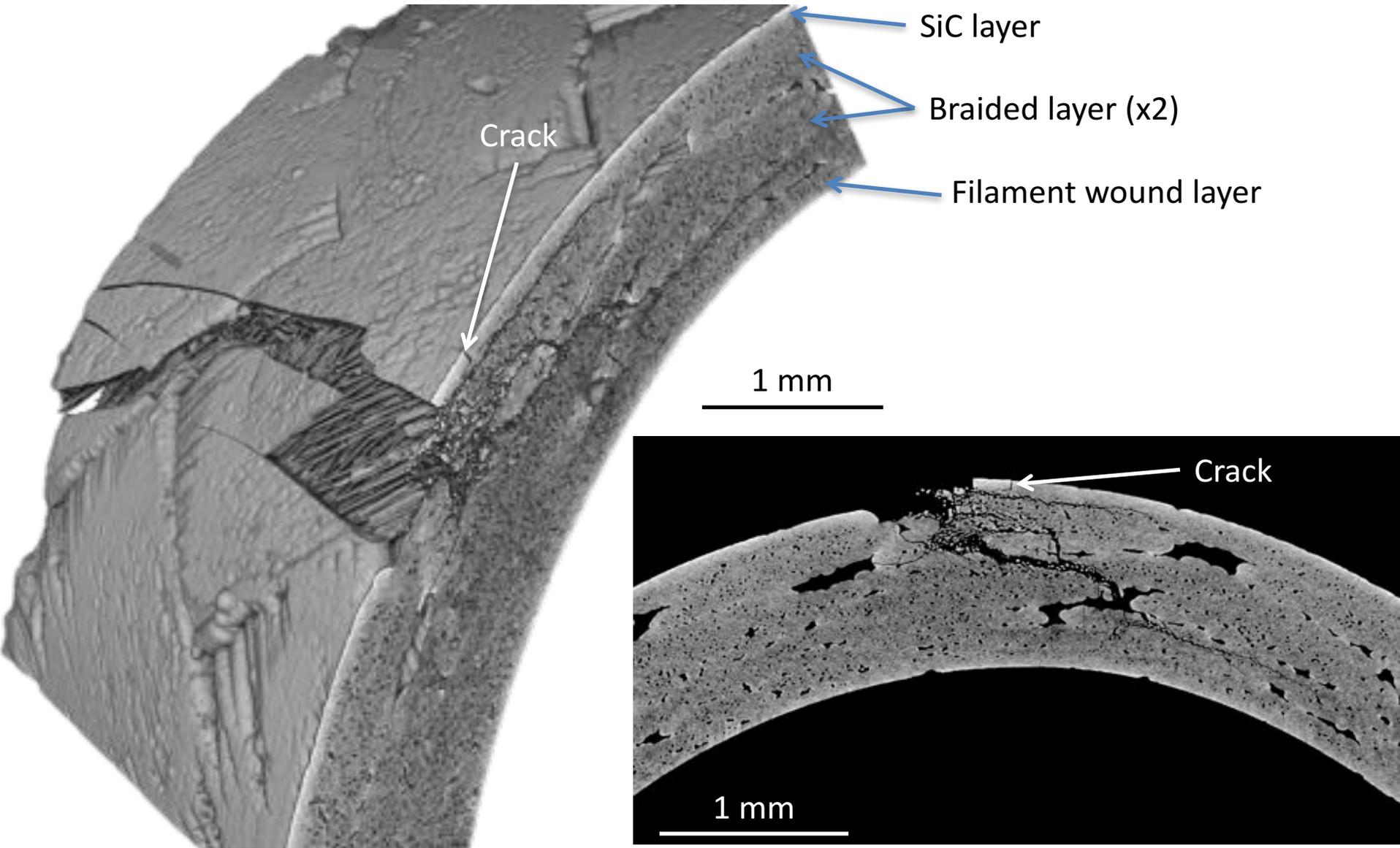


In situ mechanical compression rig

Beamline I12 (JEEP) (56 keV, 3.25 μm voxel)
~ 10 minutes per scan

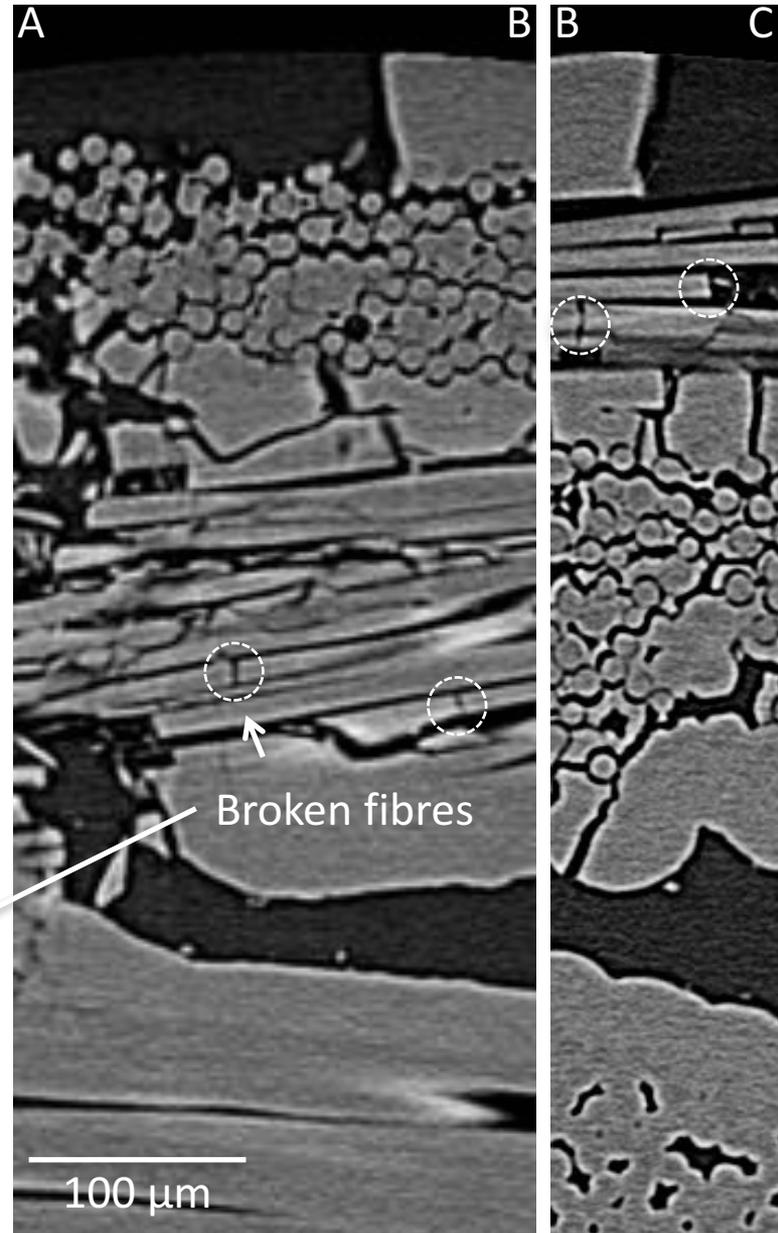
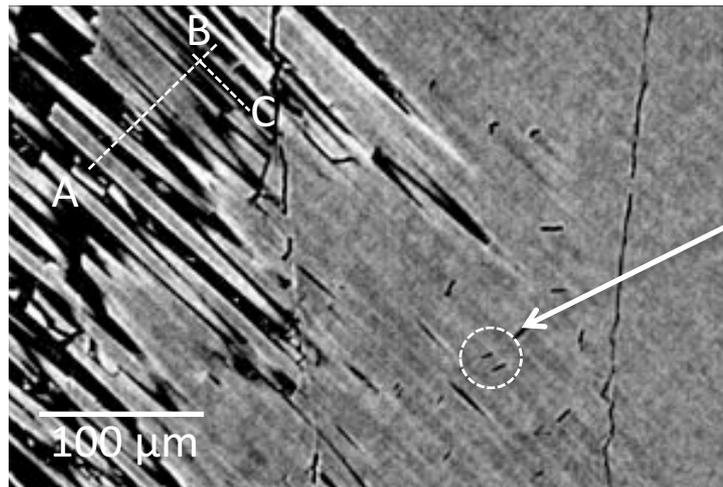
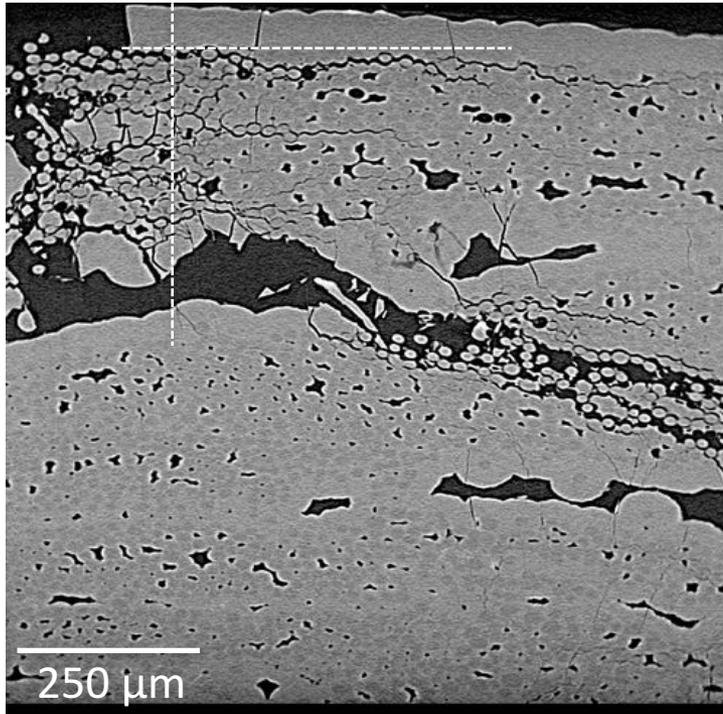
Post-Test Tomography

North Star Instruments
X5000, 60 keV 3.5 μm
voxel, 2 hour scan

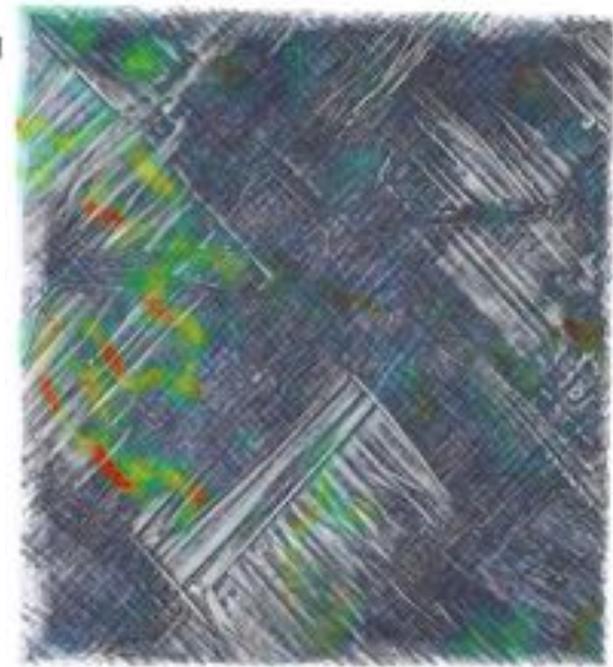
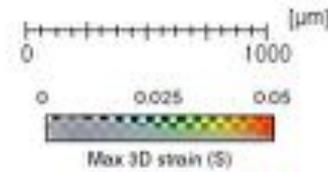


Post-Test Tomography

Zeiss Xradia Versa 520
60 keV, 1 μm voxel, 10 hour scan

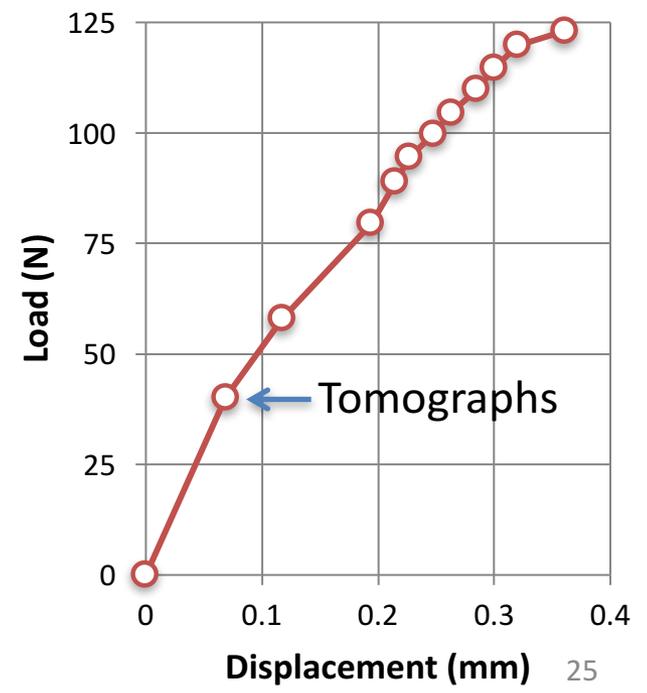
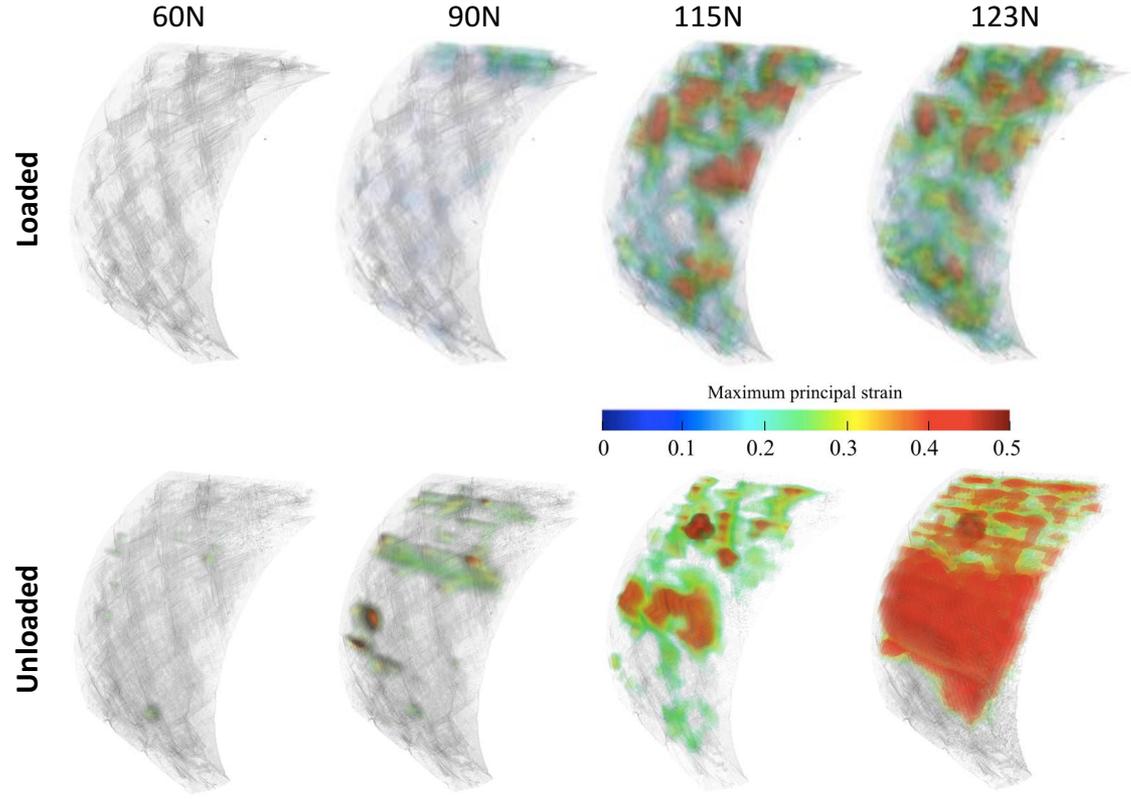


C-Ring Test (DVC)

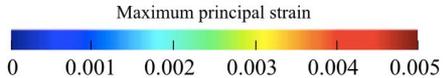


Deformation can be mapped, in situ and in 3D

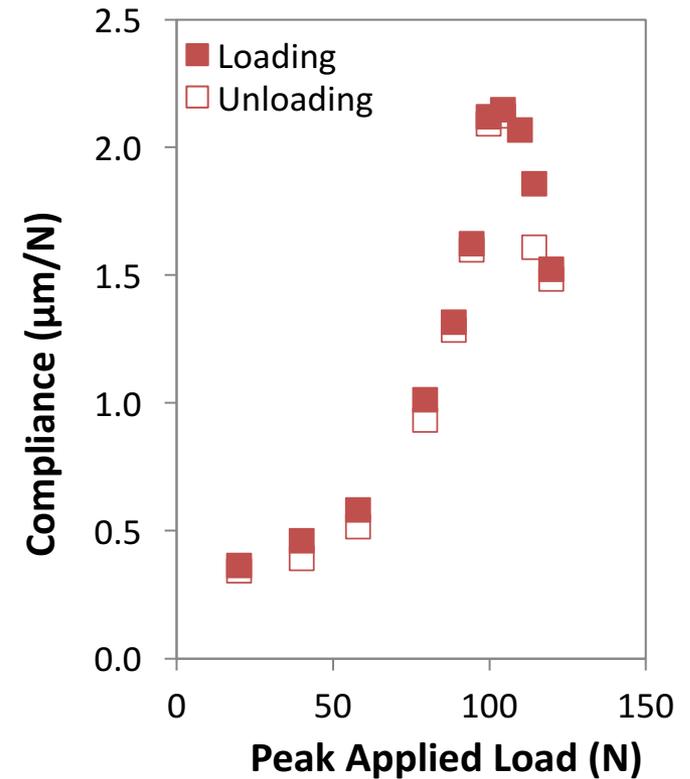
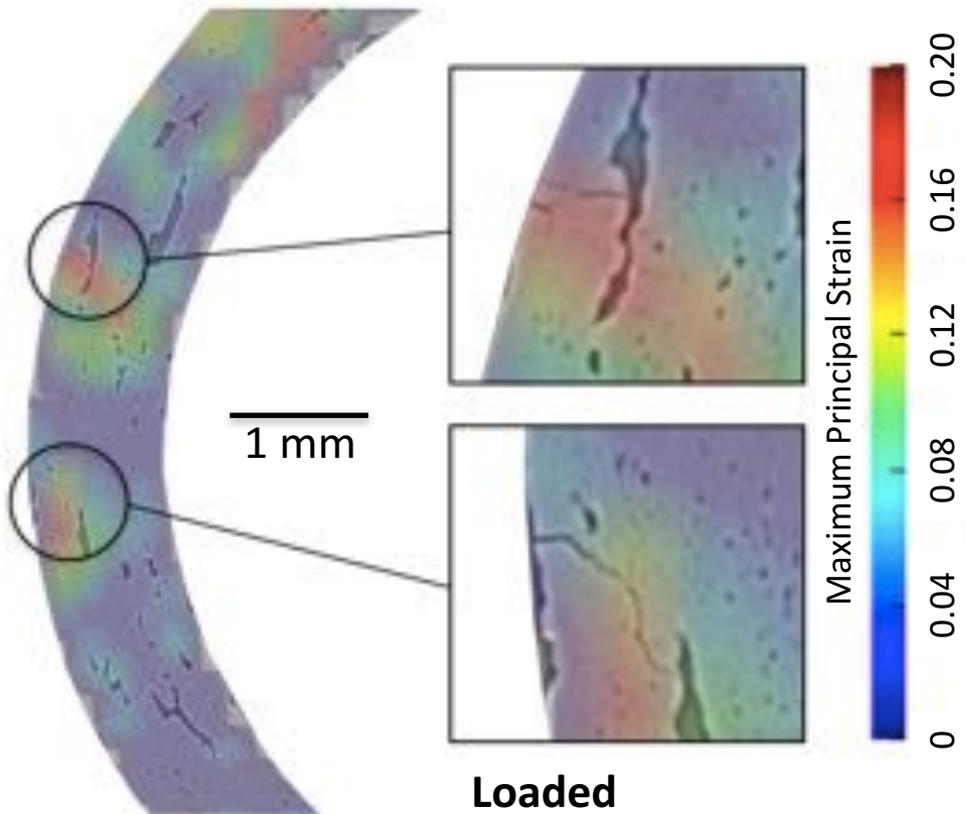
Increasing Peak Load



Digital Volume Correlation: 128x128x128 voxels, 50% subset overlap with 2 passes



C-Ring Test (Digital Volume Correlation)



Local strains correspond to cracking

Cracking increases the compliance

Over a vertical gauge distance of 5.4 mm

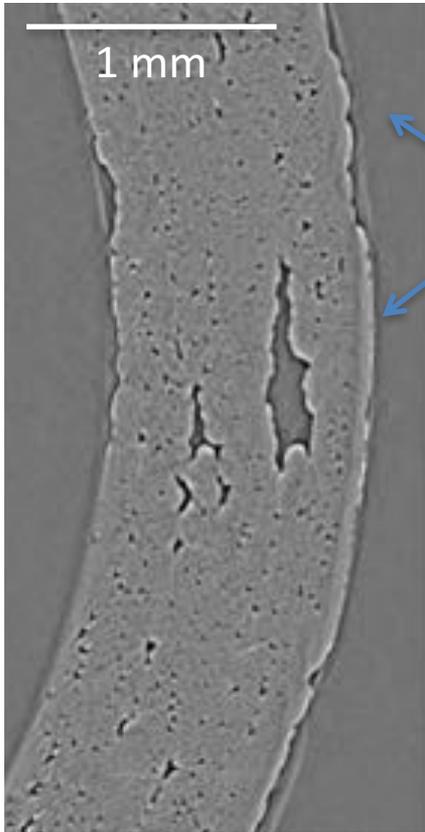
Tomography at 900°C (and 1100°C)

C-ring Test Specimen



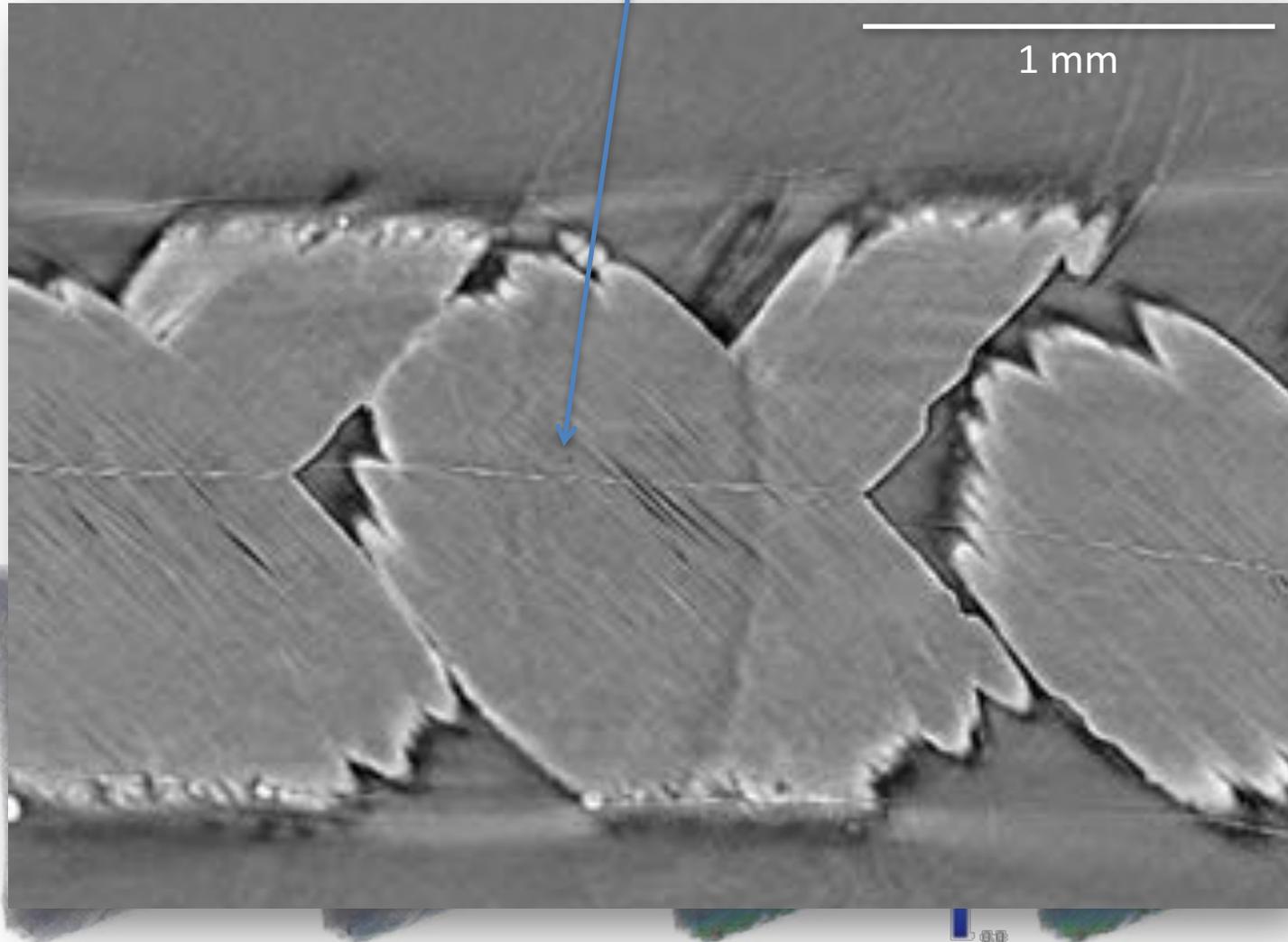
P2R Tomography Rig and Furnace

Continuous Tomography at 900°C



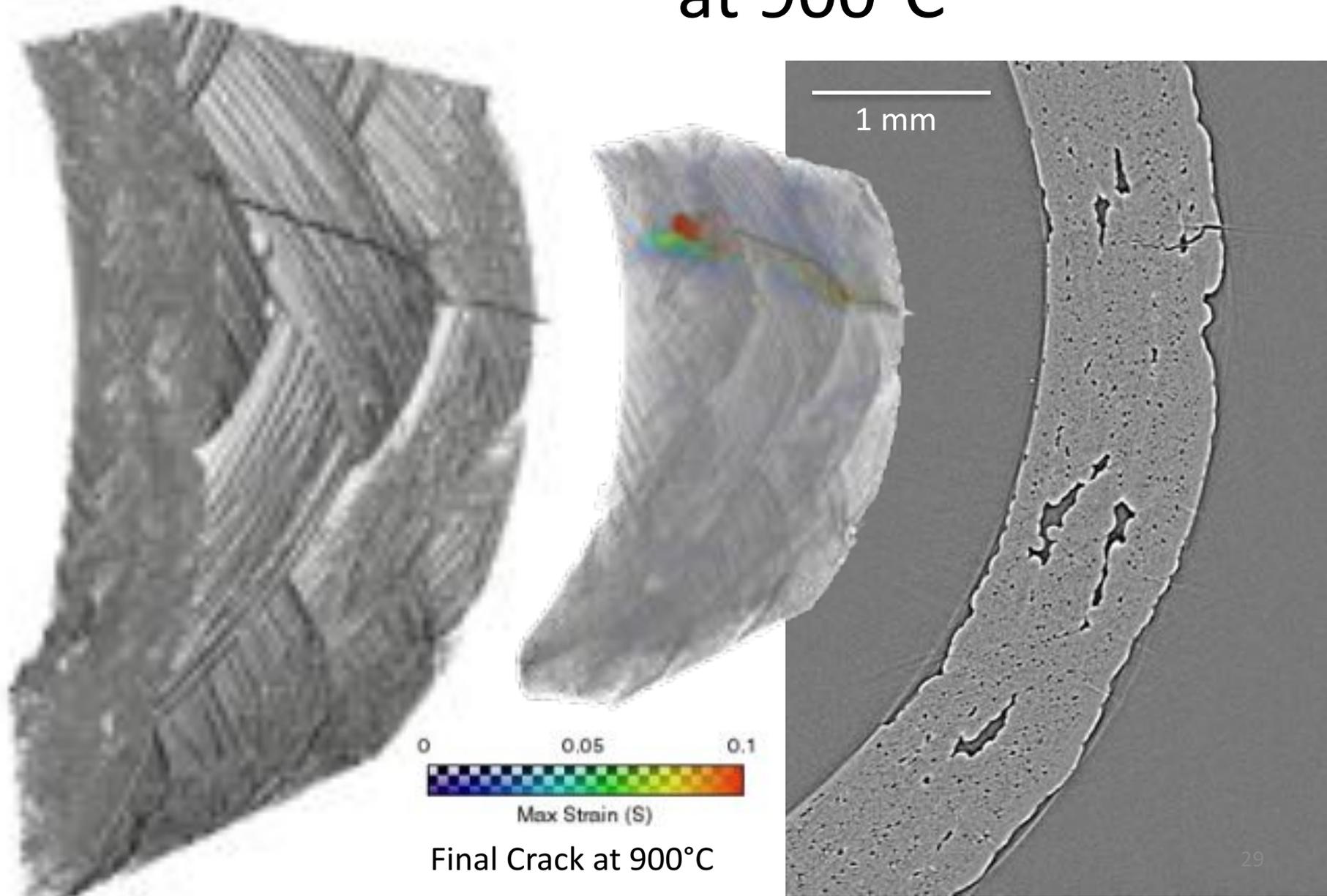
Main crack (~80 N)

Fibre crack (~30 N), then fibre fracture (~50 N)



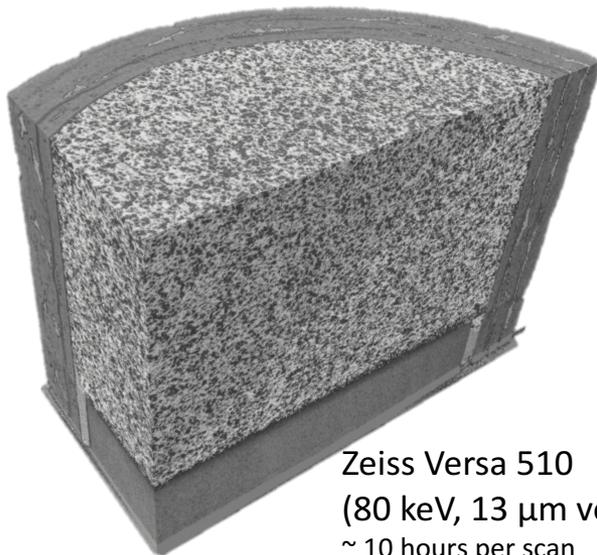
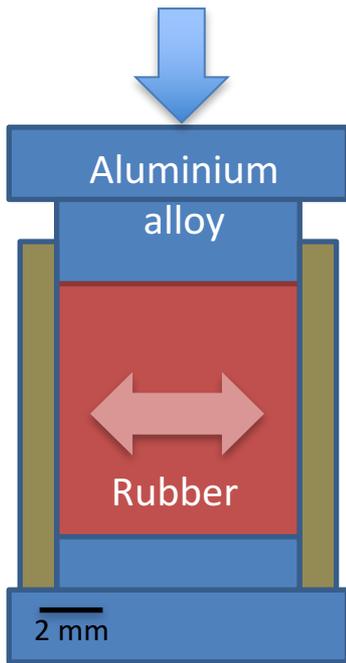
0 N

Continuous Tomography at 900°C

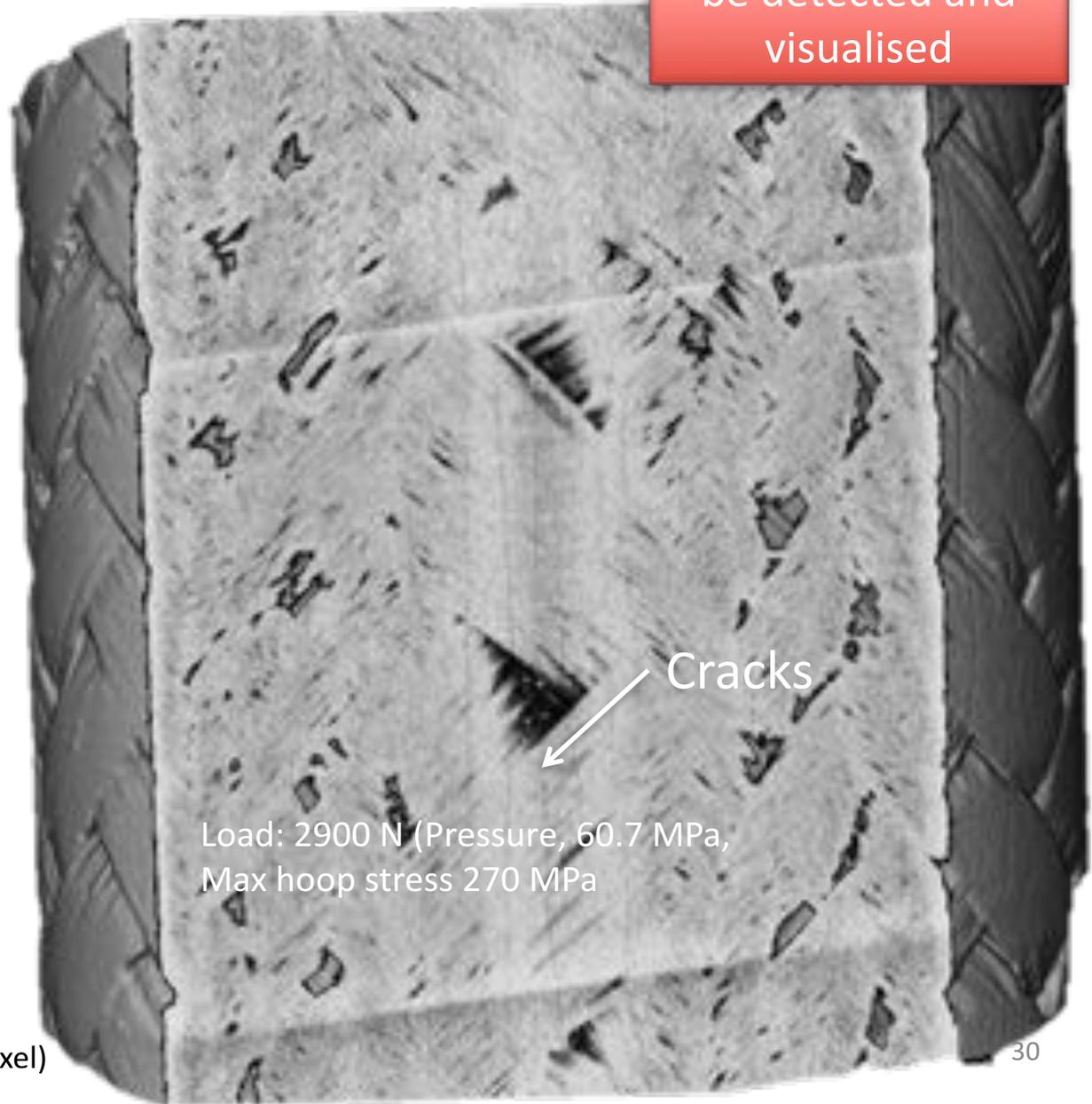


Hoop Pressurisation

Matrix cracking can be detected and visualised

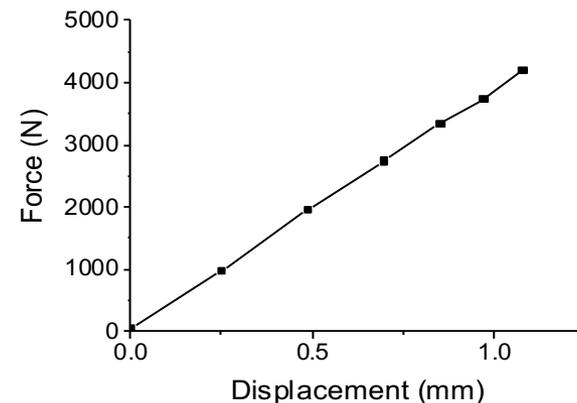
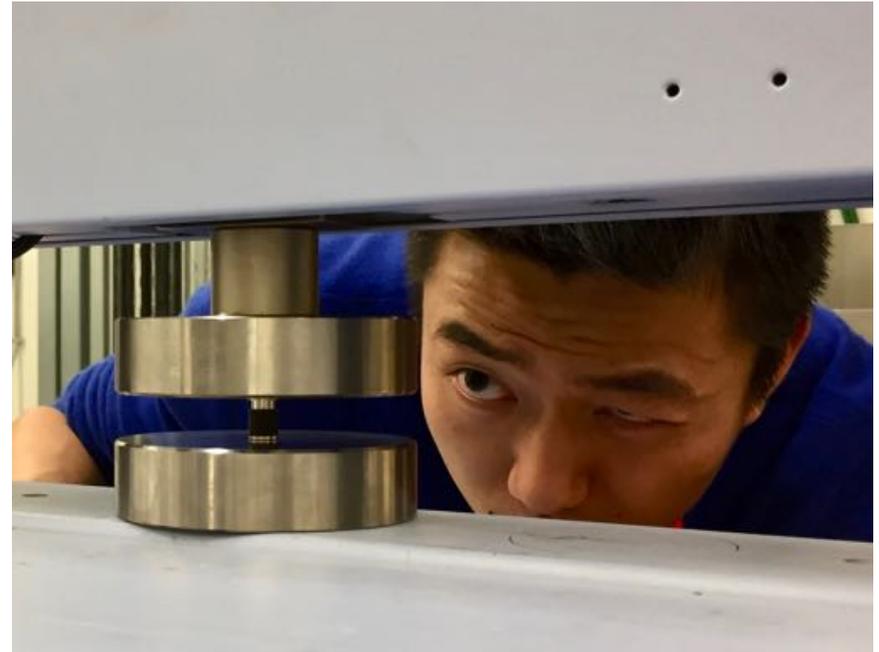


Zeiss Versa 510
(80 keV, 13 μm voxel)
~ 10 hours per scan



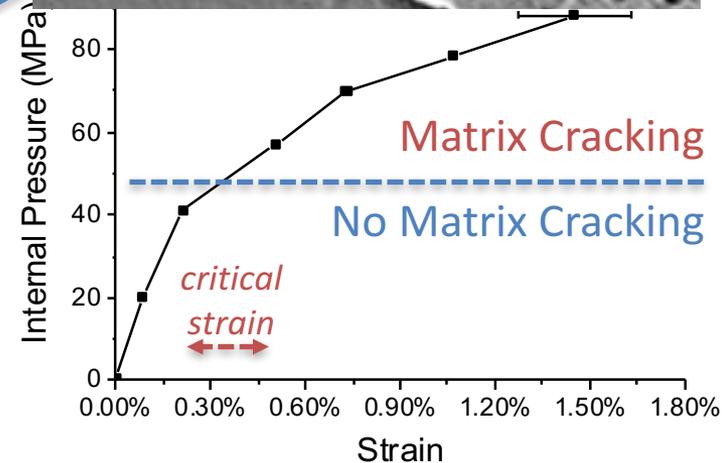
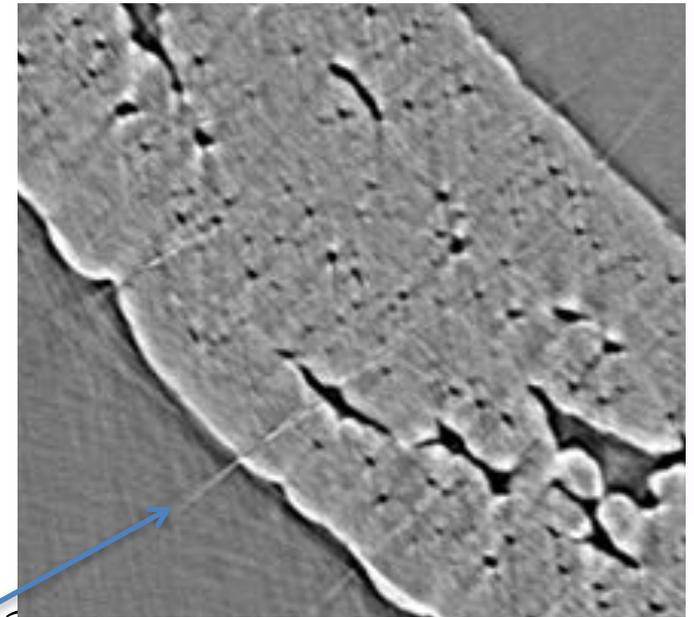
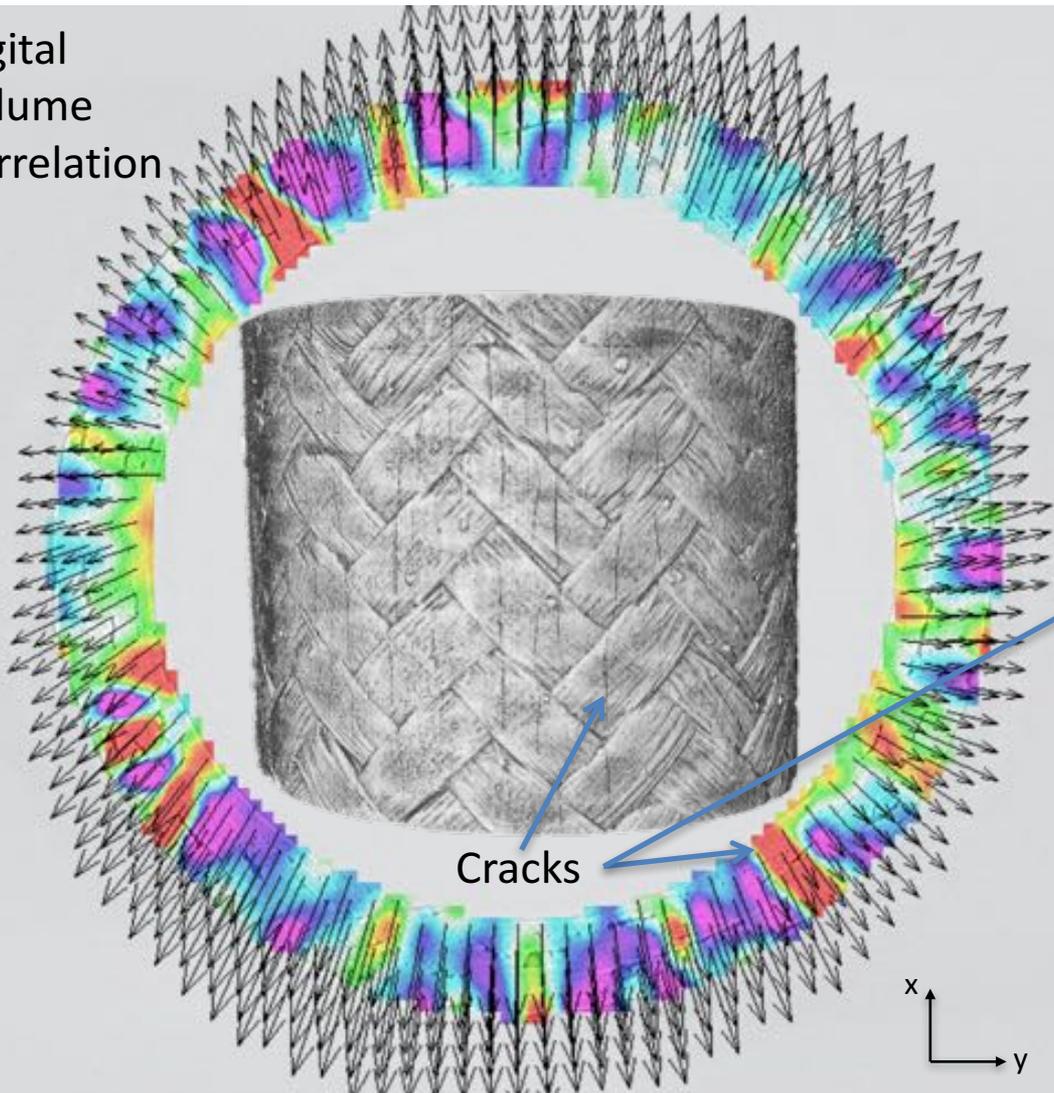
Load: 2900 N (Pressure, 60.7 MPa,
Max hoop stress 270 MPa)

Limited Angle Synchrotron X-ray Tomography with in situ loading



Limited Angle Synchrotron X-ray Tomography with in situ loading

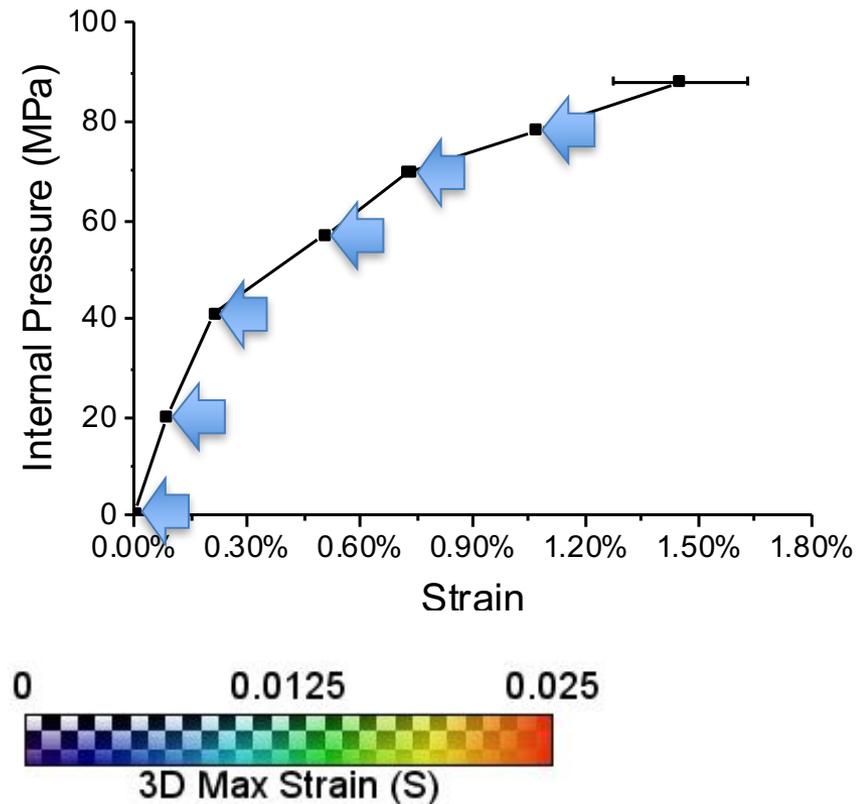
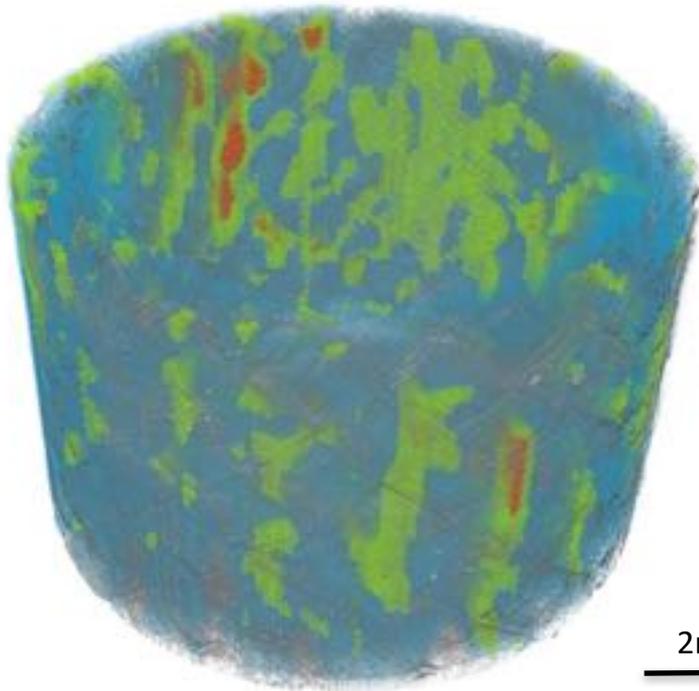
Digital Volume Correlation



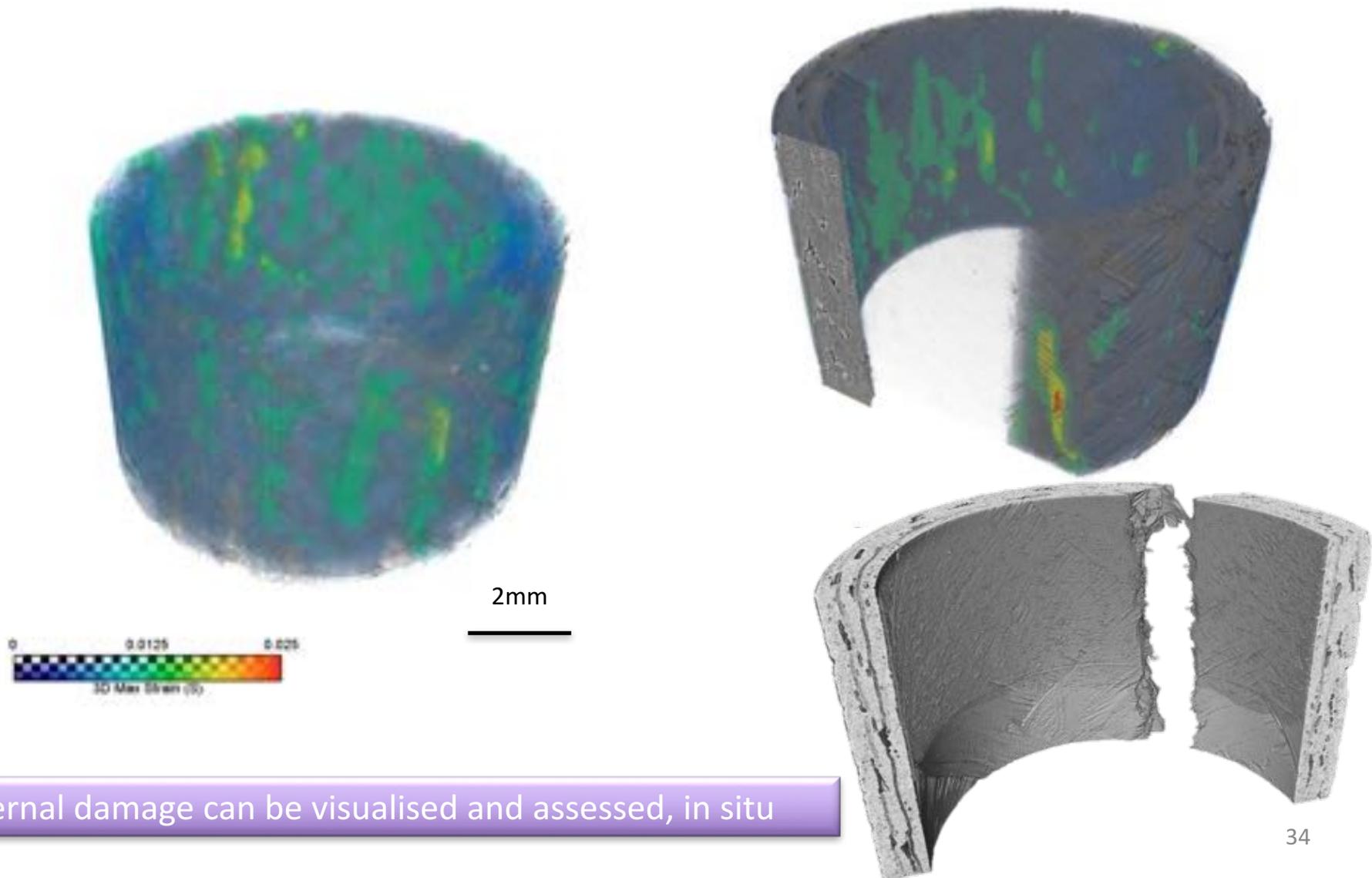
Limited Angle Synchrotron X-ray Tomography with in situ loading

Development of damage with applied pressure

(6)



Limited Angle Synchrotron X-ray Tomography with in situ loading



Internal damage can be visualised and assessed, in situ

Experimental Observations

- X-ray Computed Tomography
 - 3D description of microstructure and porosity
- Digital Volume Correlation
 - Measures deformation
 - Can detect and quantify damage
 - Critical strains to initiate and propagate cracking

Questions:

- *Can modeling simulate these experiments?*
- *Can these experiments be used to test and calibrate models?*
- *Can models be used to predict the performance of engineering components in different experimental conditions?*

Required: Macroscopic models with high fidelity to microstructure

Application of FEMME model

SIMULATION OF DAMAGE IN SIC-SIC COMPOSITE

Porosity

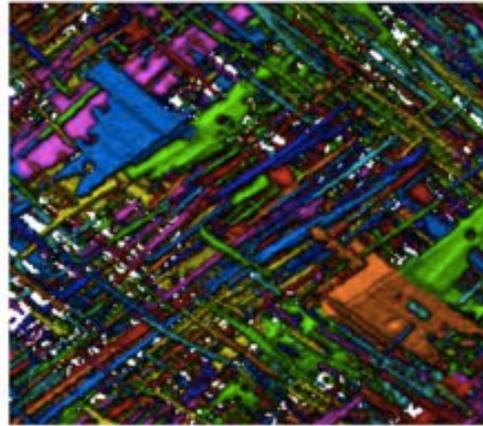
Segmentation to quantify the pore population



DATA



Small pores



0.5 mm

DATA

Large pores

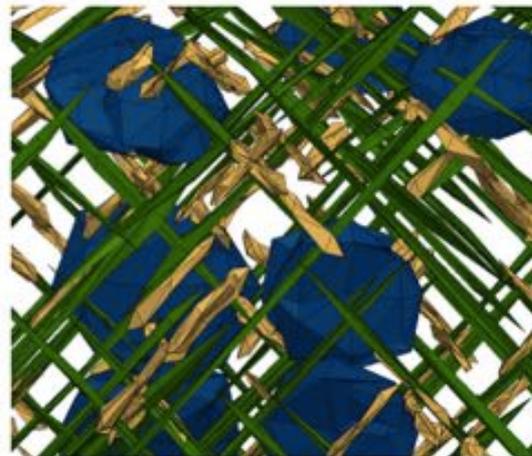


5 mm

Flat pores at intersections between the fibre tows.

Longitudinal pores (long and short) along the fibres.

Model reproduces the observed total porosity and pore types



Flat pores



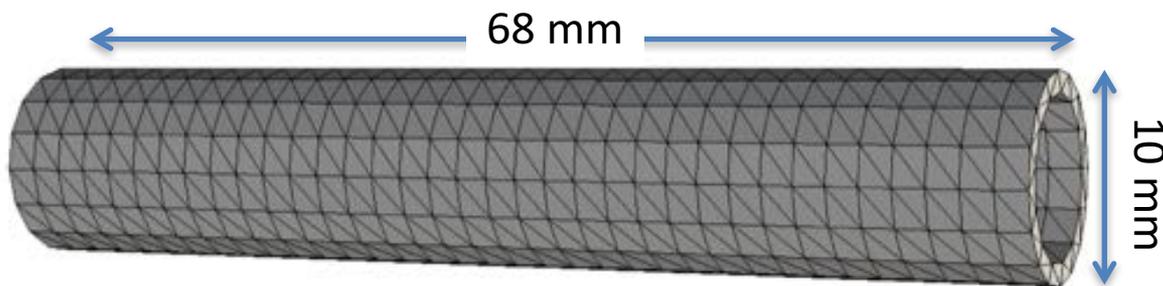
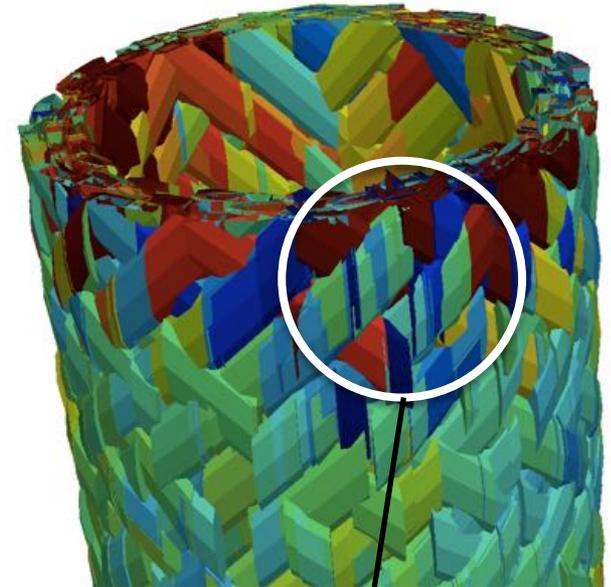
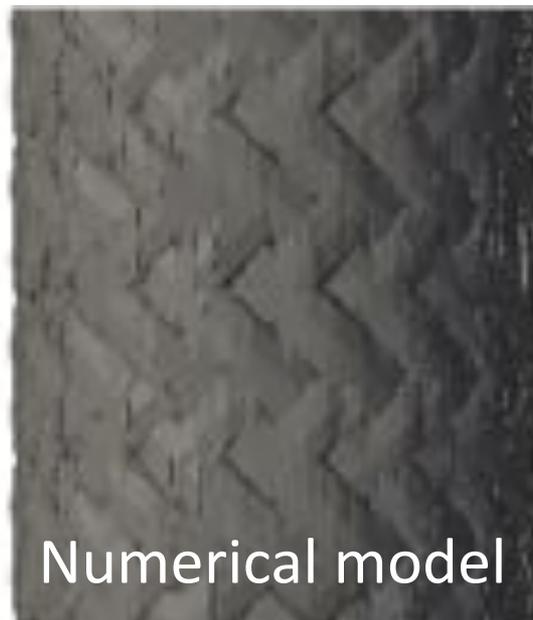
Short longitudinal pores



Long longitudinal pores



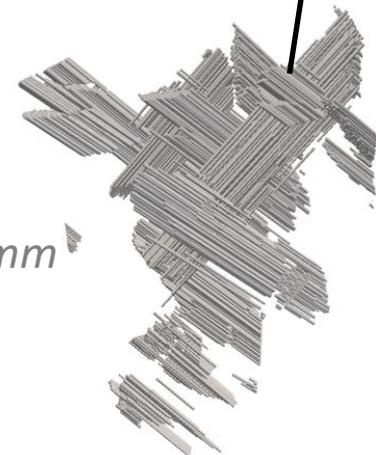
Fibres and Weave



3228 tetrahedral elements

FE mesh

Element size: 1.5 mm
Cell size: 50 μm
($\sim 2 \times 10^7$ cells)

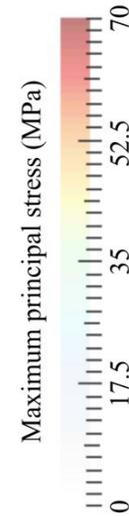
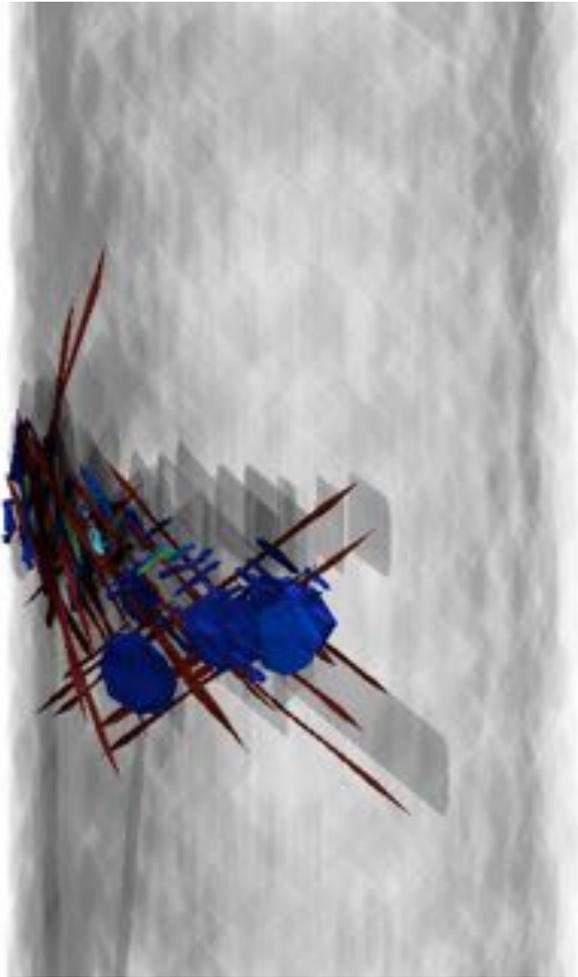


Properties (fitted):

Fibre: E_{fibre} : 400 GPa, critical strain: 0.000125

Matrix: E_{matrix} : 100 GPa, critical strain: 0.00025, Poisson Ratio: 0.26

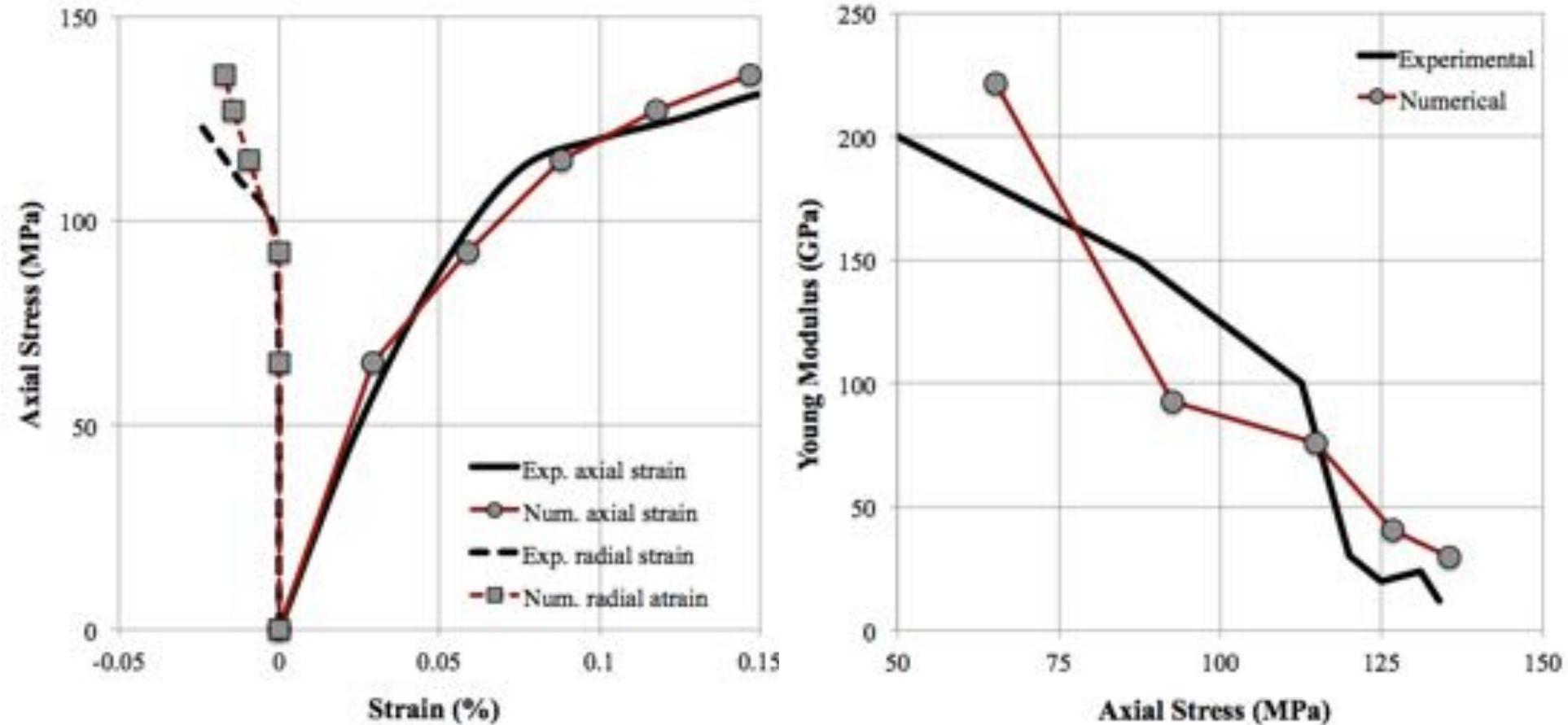
Damage Development



Progressive damage development and stress redistribution

Simulation time: 8 hours (serial desktop workstation)

Mechanical Properties



Fibre and matrix properties obtained by fitting numerical model to experiment

Data: Bernachy-Barbe, et al., Anisotropic damage behavior of SiC/SiC composite tubes: Multiaxial testing and damage characterization, Compos. Part A Appl. Sci. Manuf. 76 (2015) 281–288.

doi:10.1016/j.compositesa.2015.04.022.

C-Ring Simulation



FE mesh



Cellular Layer

Mesh creation as for tube model



C-Ring Simulation

23.3 N



44.2 N

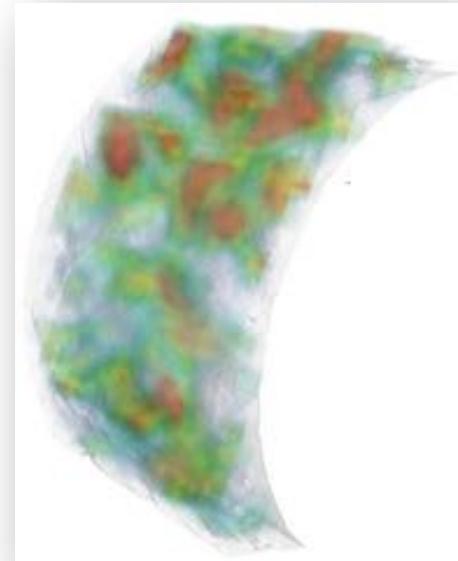


66.1 N



Expected patterns of damage are obtained

123 N (Experiment)



85.5 N



102.5 N



112.8 N



120.9 N



Maximum principal strain

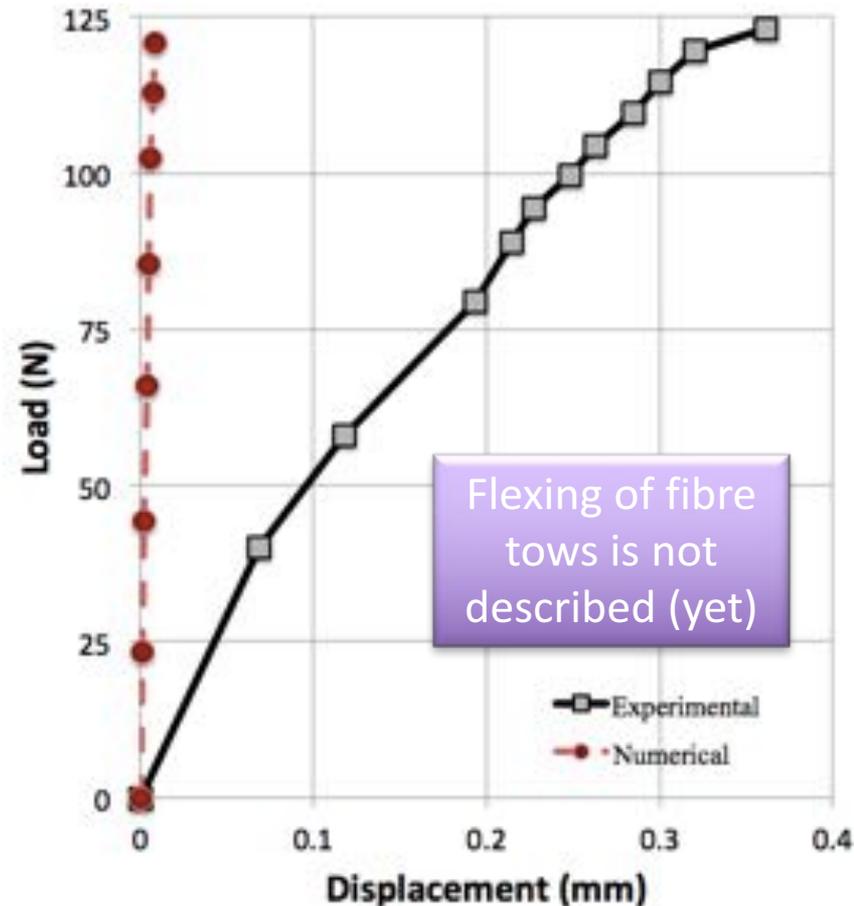
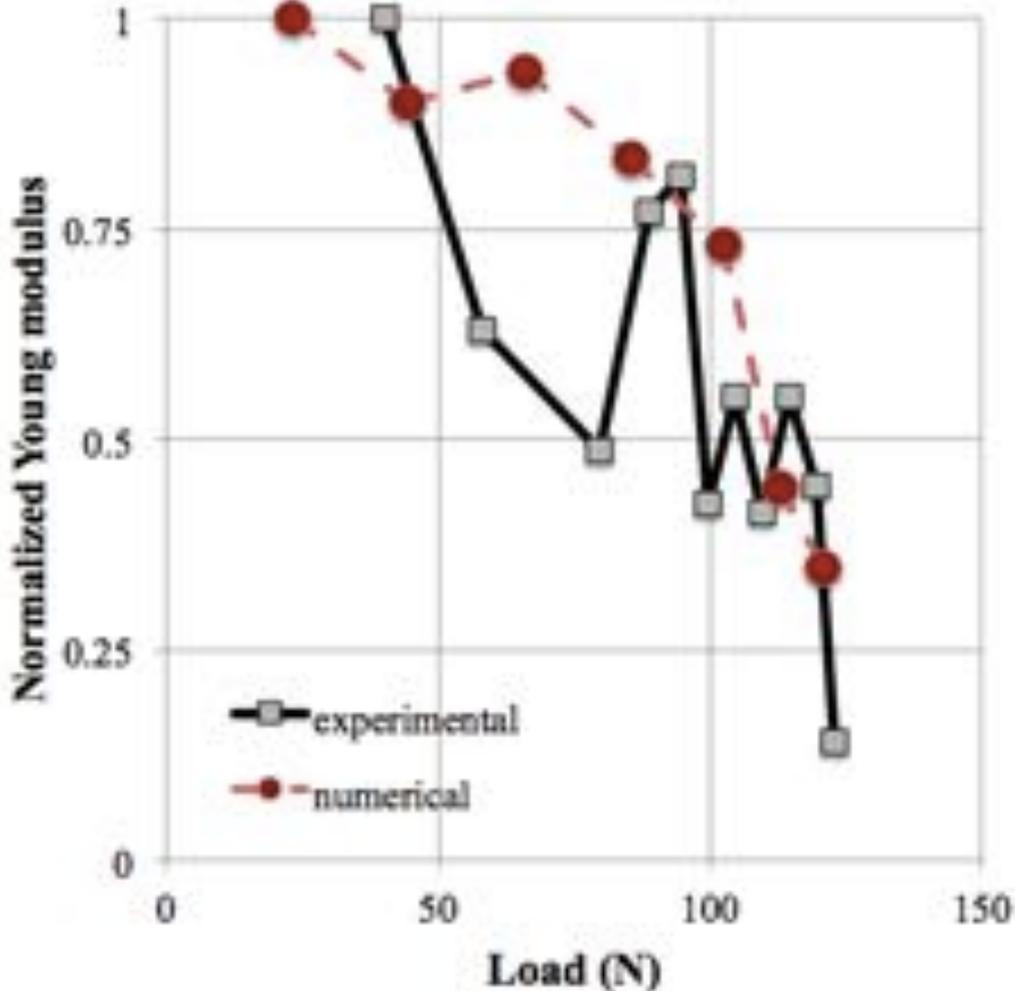


Broken cells

Damage observed as high nominal strain in experiment

C-Ring Simulation

Effect of damage on stiffness is reproduced, but stiffness is over-predicted



Flexing of fibre tows is not described (yet)

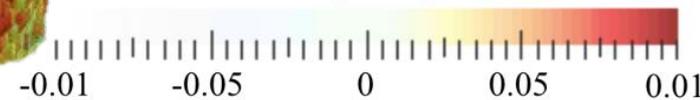
Internal Pressurisation

Internal pressure



Variations in stress state and effects of microstructure can be simulated

Maximum principal strain



Summary

- Observation and numerical simulation of damage development in ceramic composite
 - Qualitative agreement of simulations with observed damage patterns
 - Quantitative agreement of models with experiment
 - Tuning of material parameters required
- Large simulations achieved in reasonable time with high microstructure fidelity

Future applications:

Stochastic effects of defective weaves and manufacturing

Design of specimen geometries for qualification of irradiation and oxidation effects...

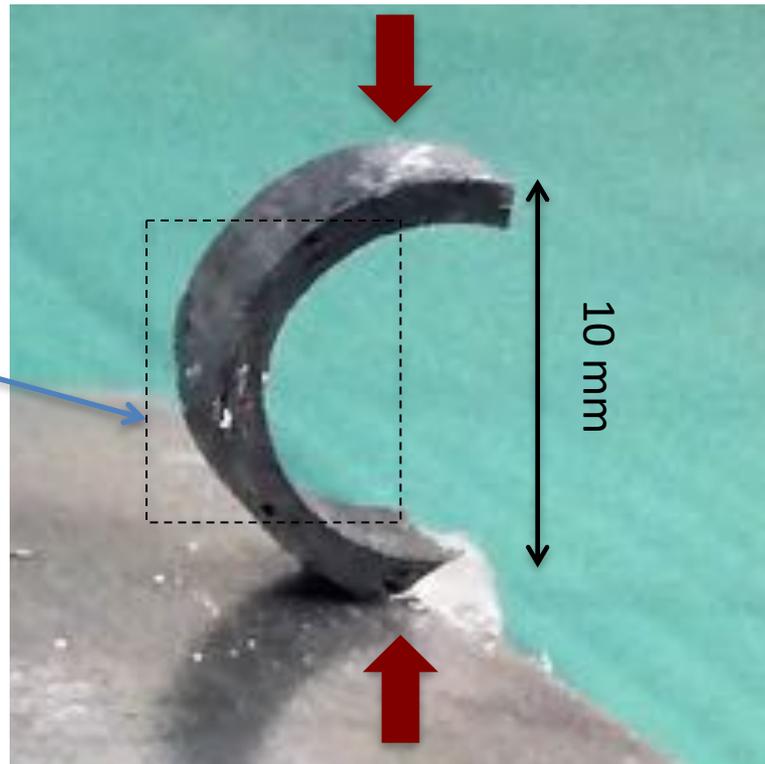
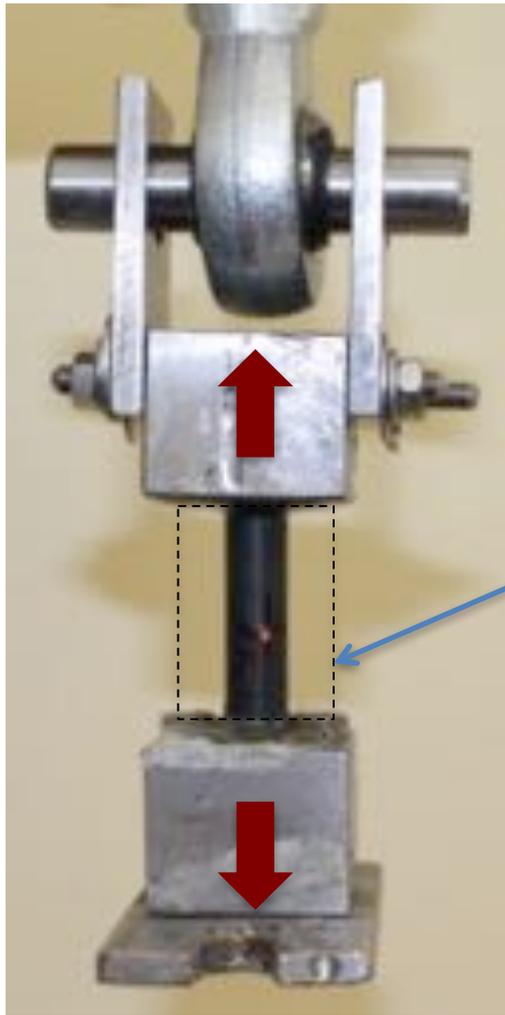
Acknowledgements

Dr James Martin (1933-2013)
Founder of the Oxford Martin School



Also:
Mahmoud Mostafavi

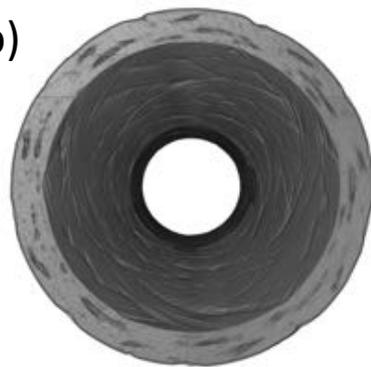




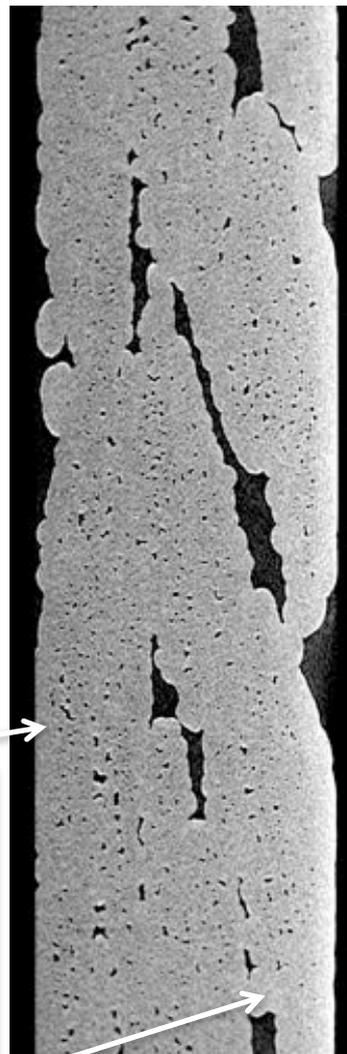
a)



b)



d)



e)



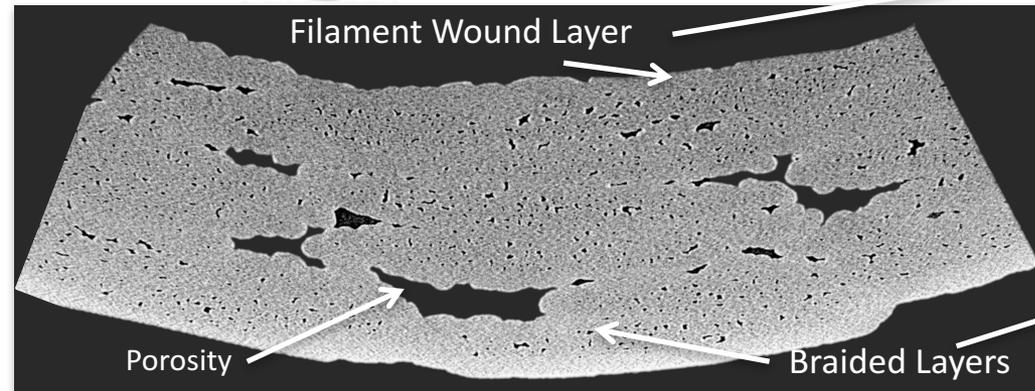
Filament Wound Layer

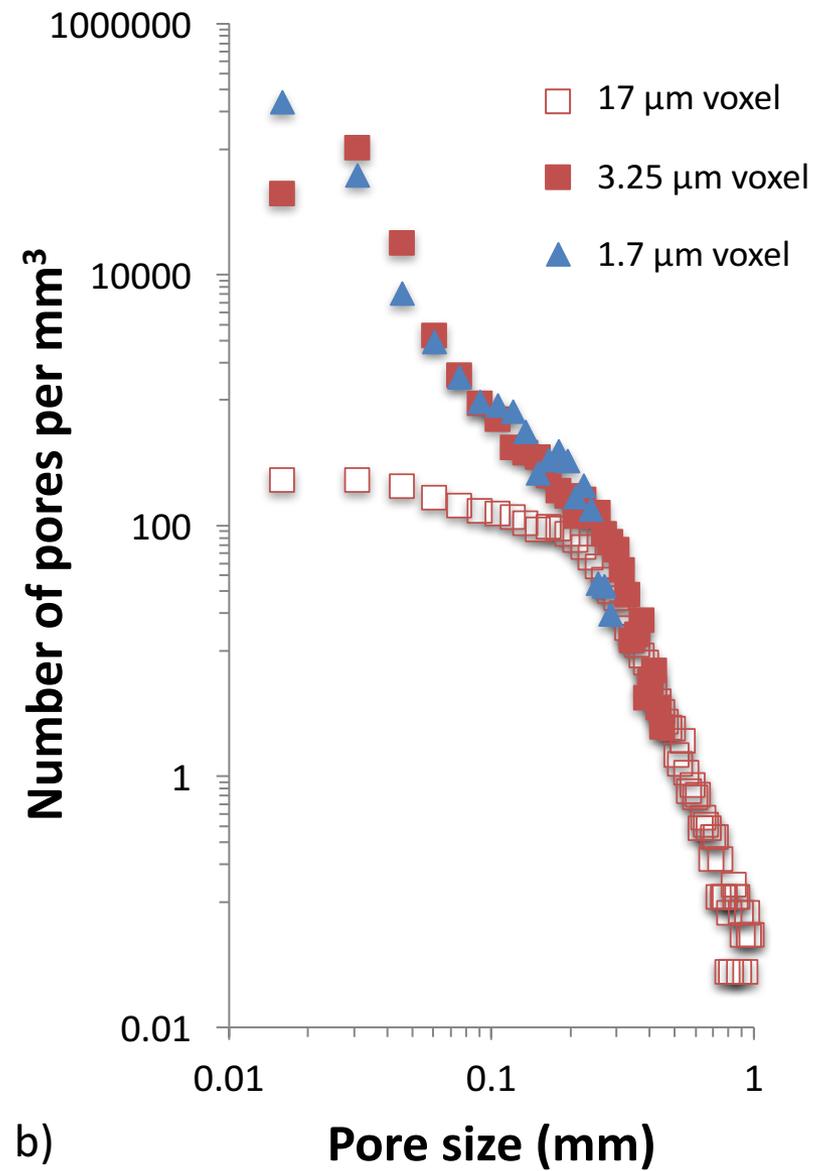
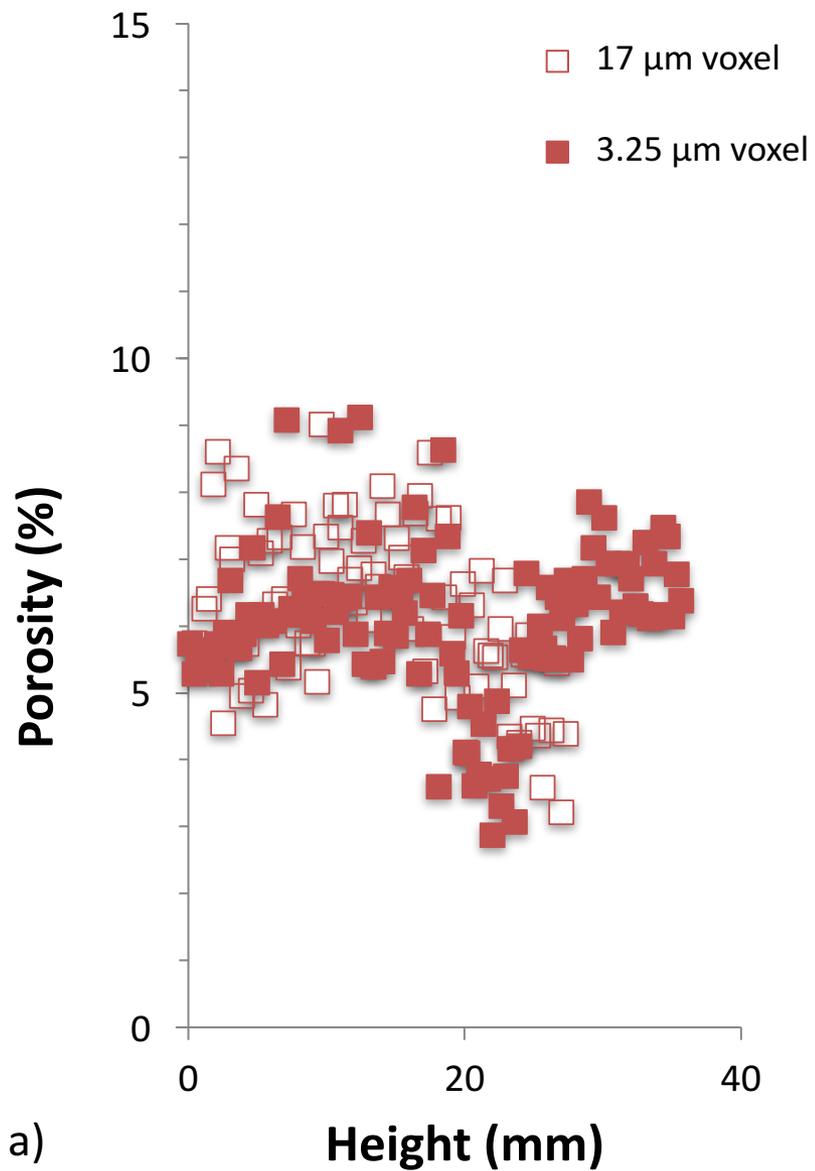
Porosity

Braided Layers

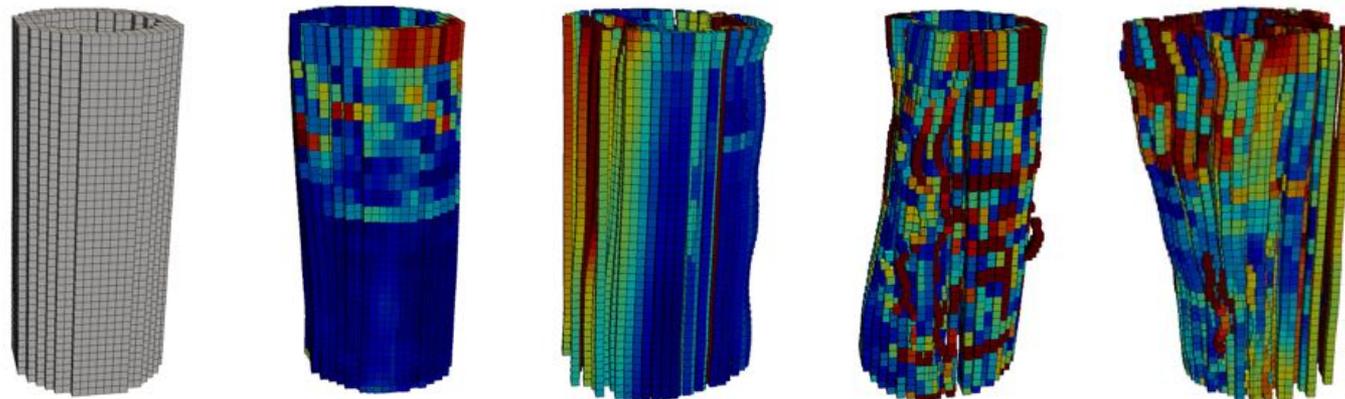
c)

1 mm





a)



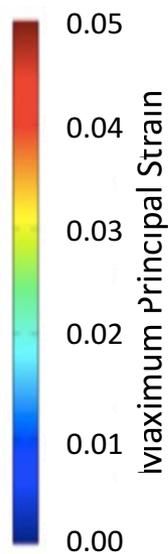
400 N

20 N
(after 400 N)

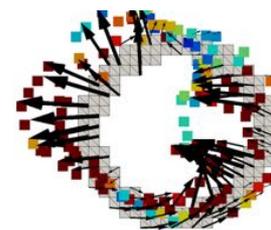
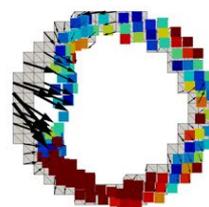
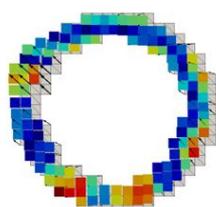
800 N

20 N
(after 800 N)

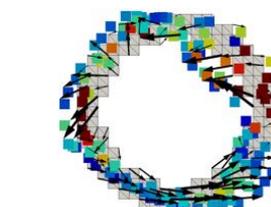
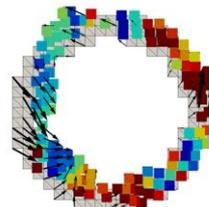
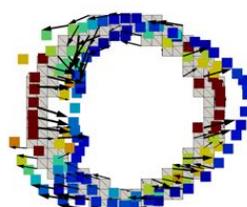
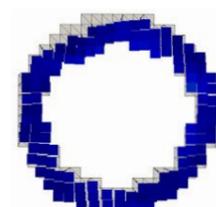
b)



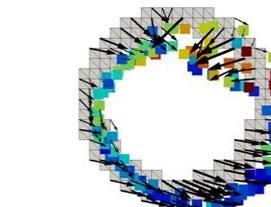
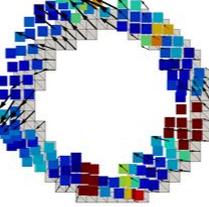
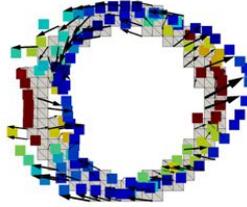
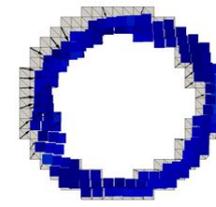
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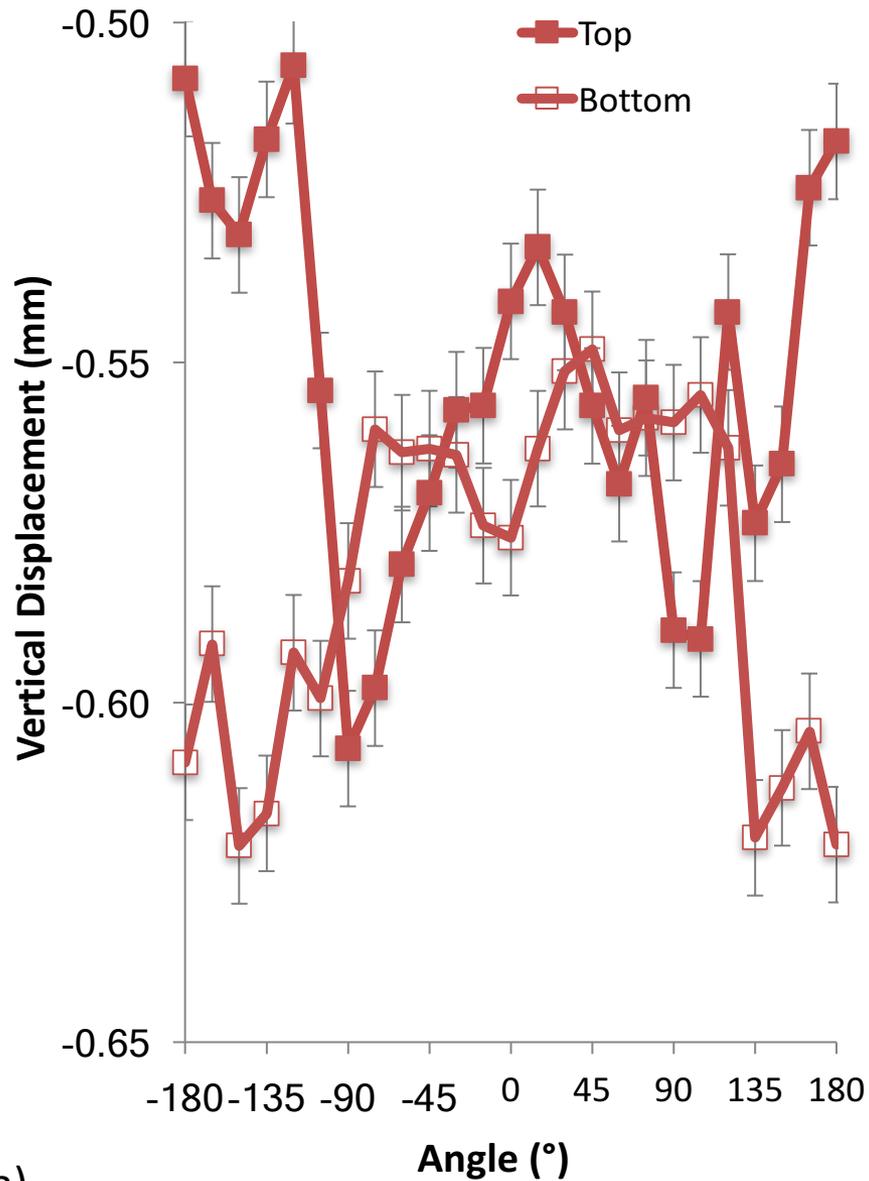


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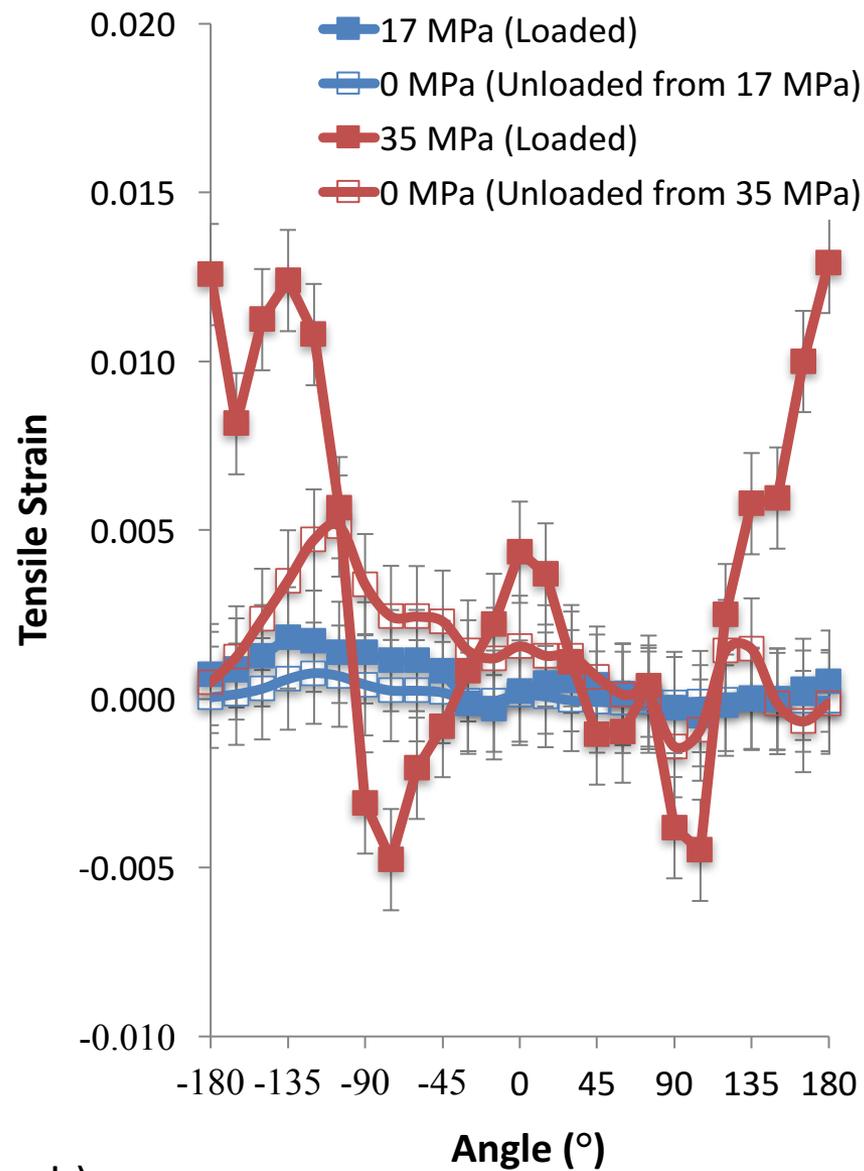


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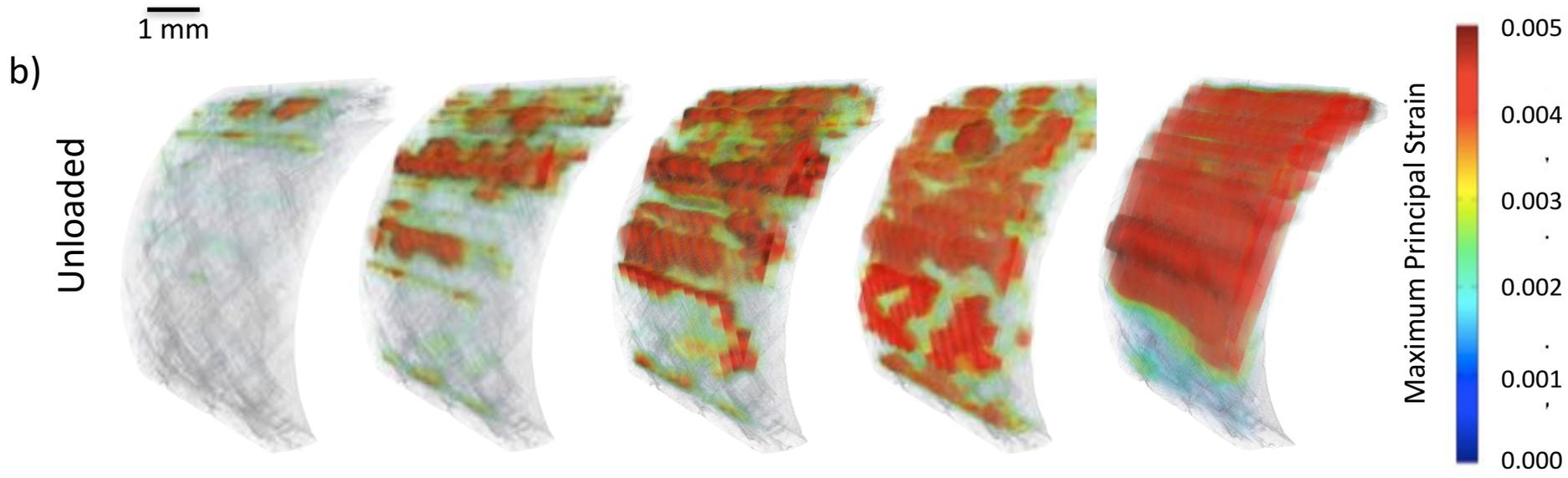
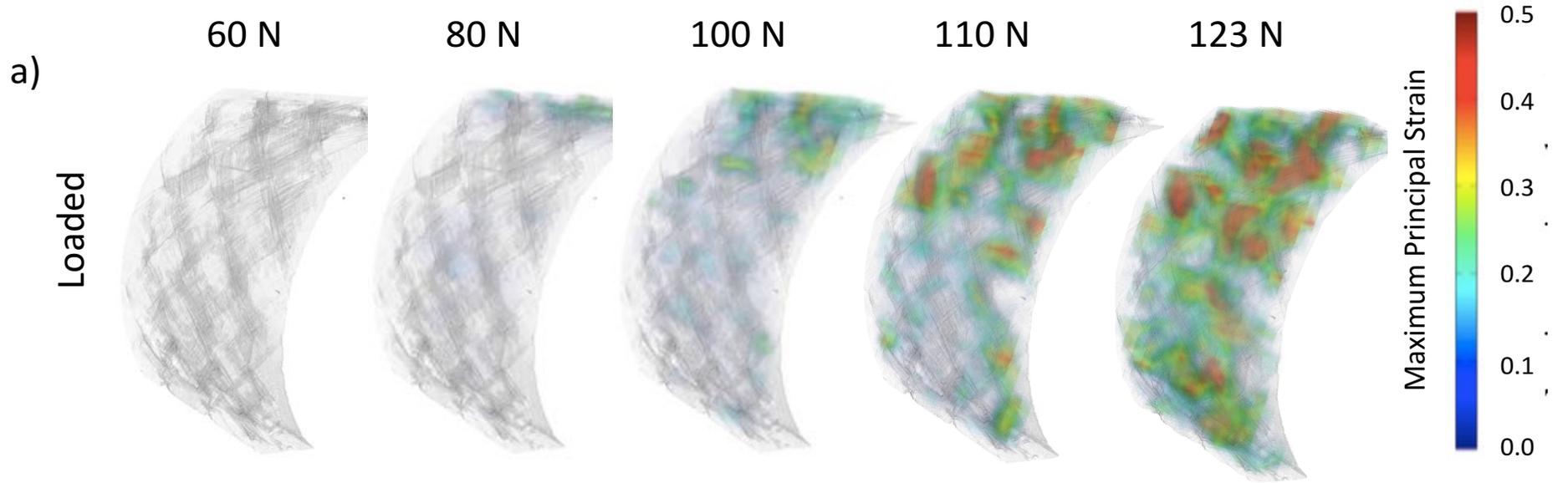




a)

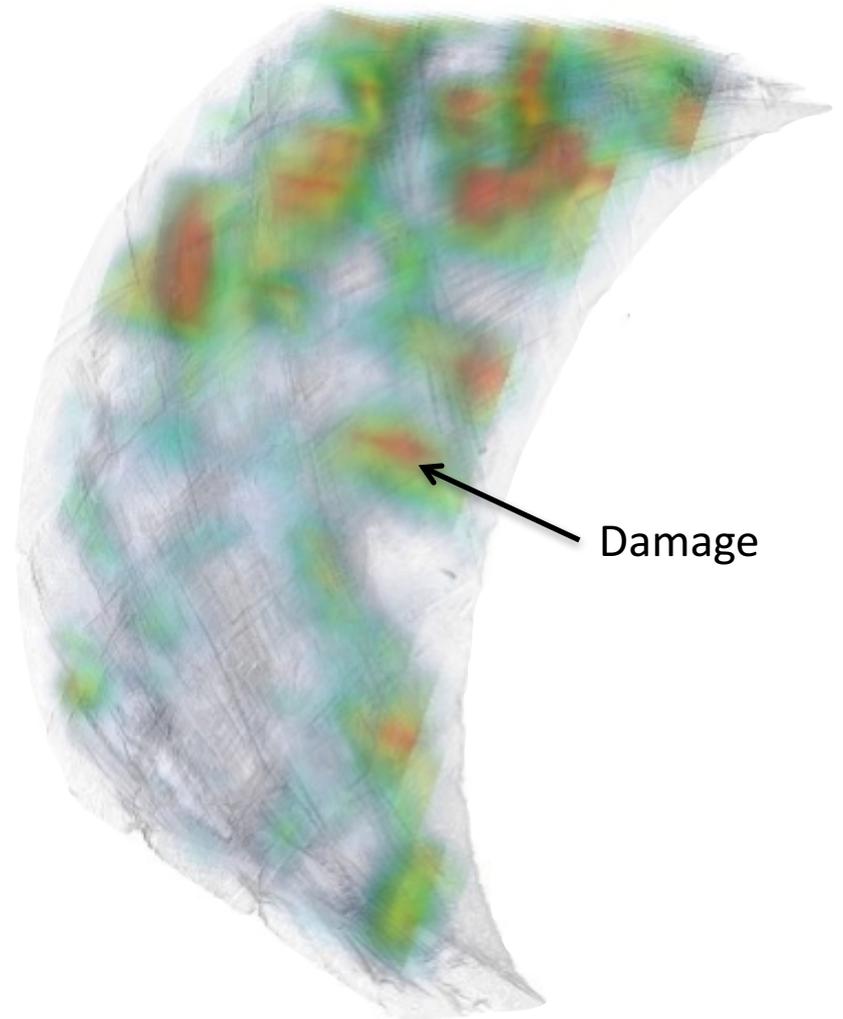


b)



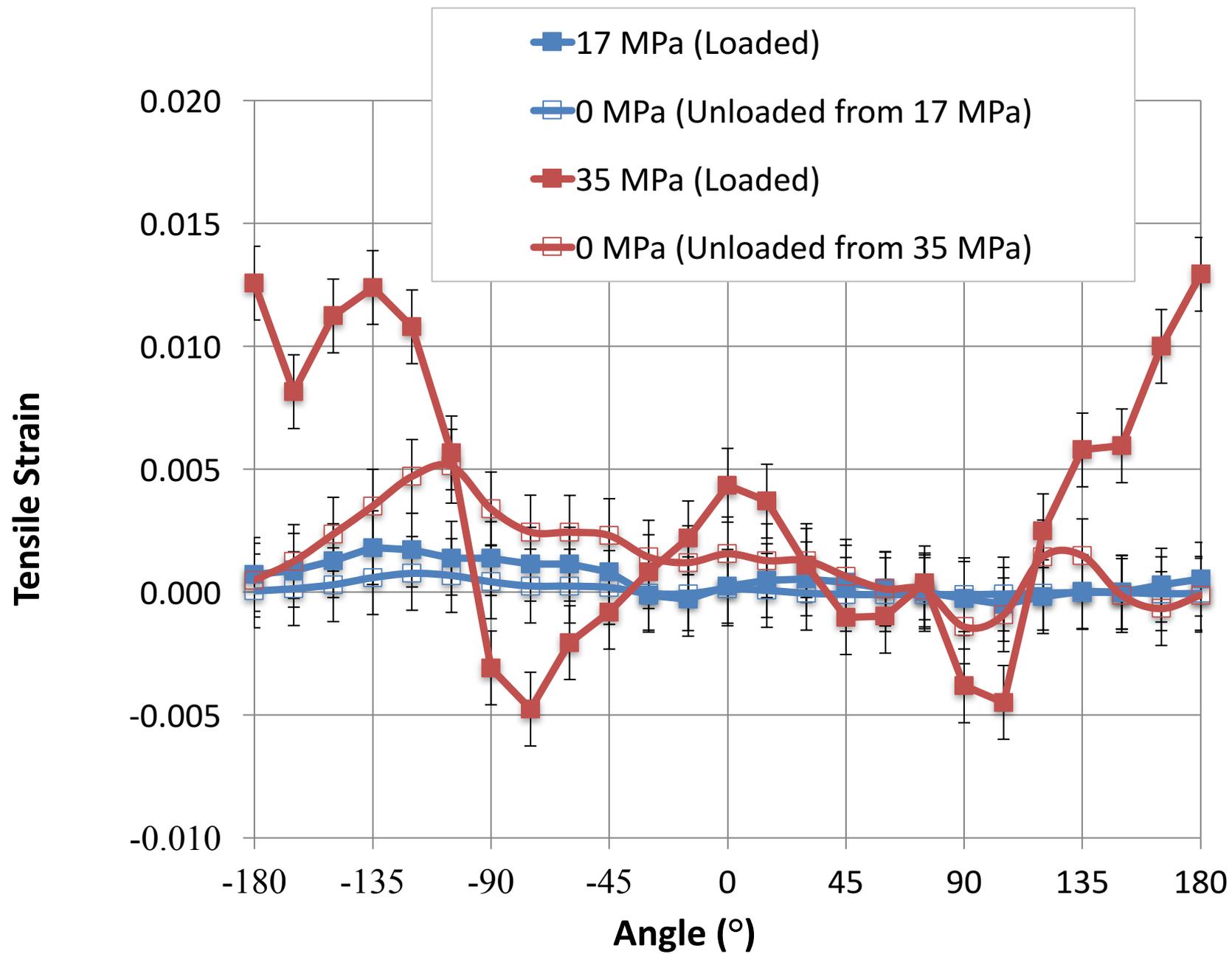


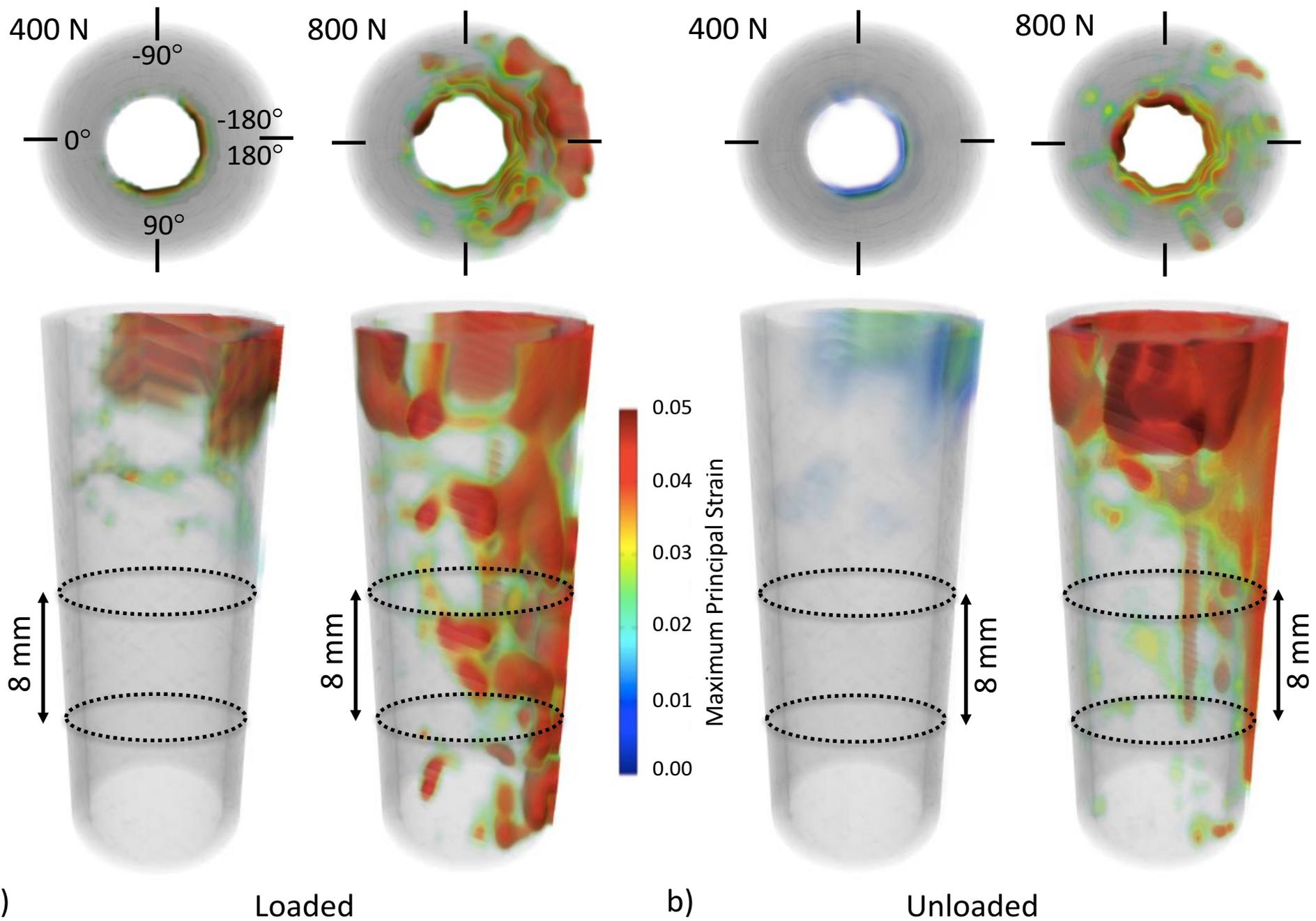
Tomography

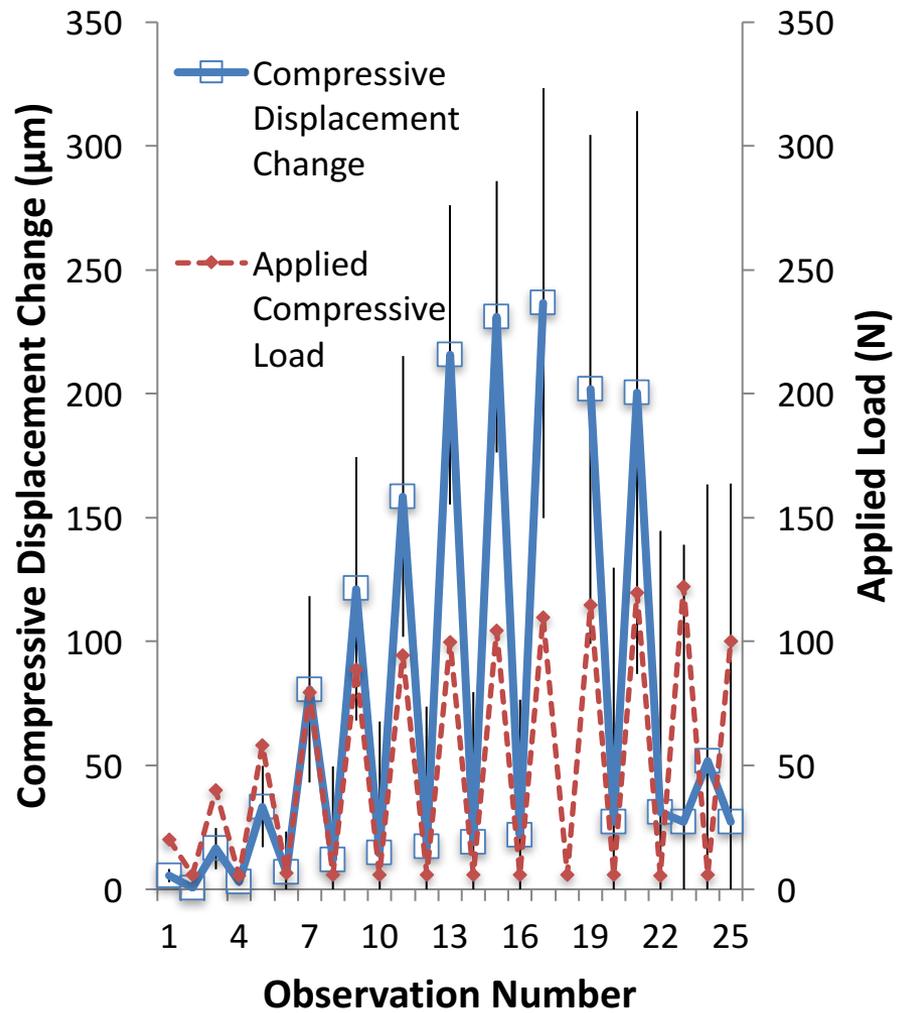


Damage

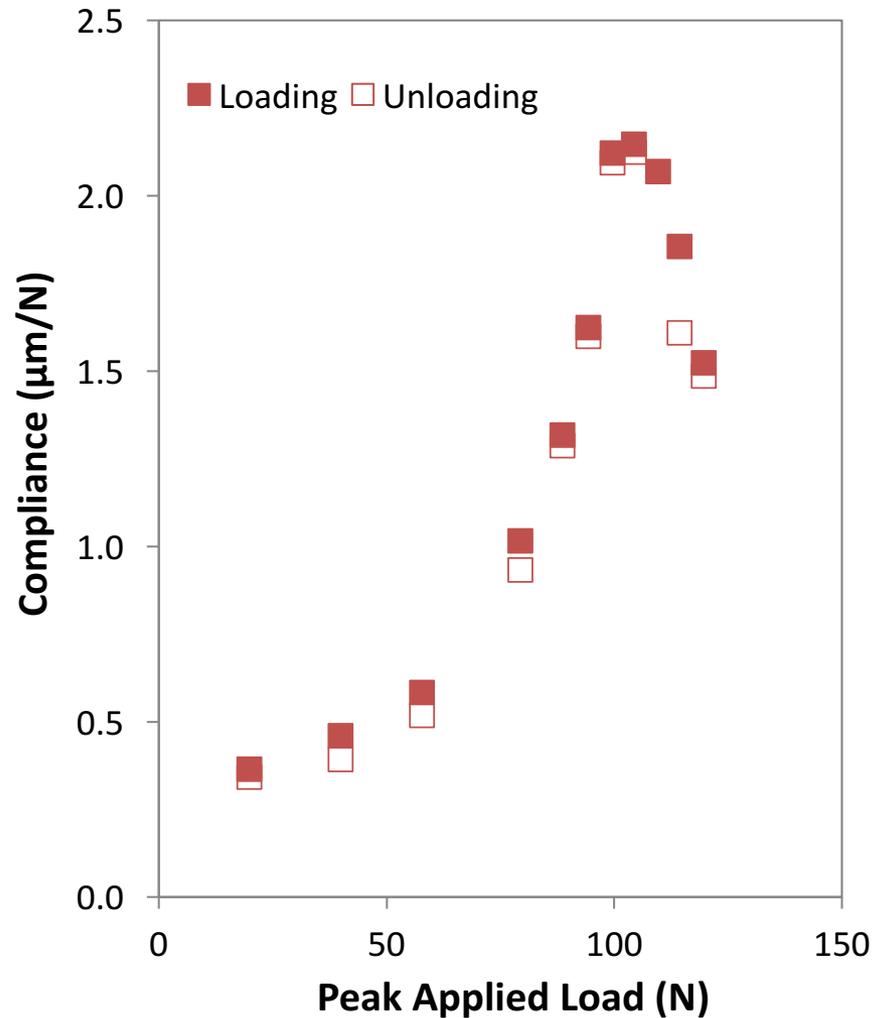
Tomography and Digital Volume Correlation







a)



b)

The displacement field of the SiC/SiC tubes from the DVC

- The result is relative to the average rigid body motion (loading at 600N)

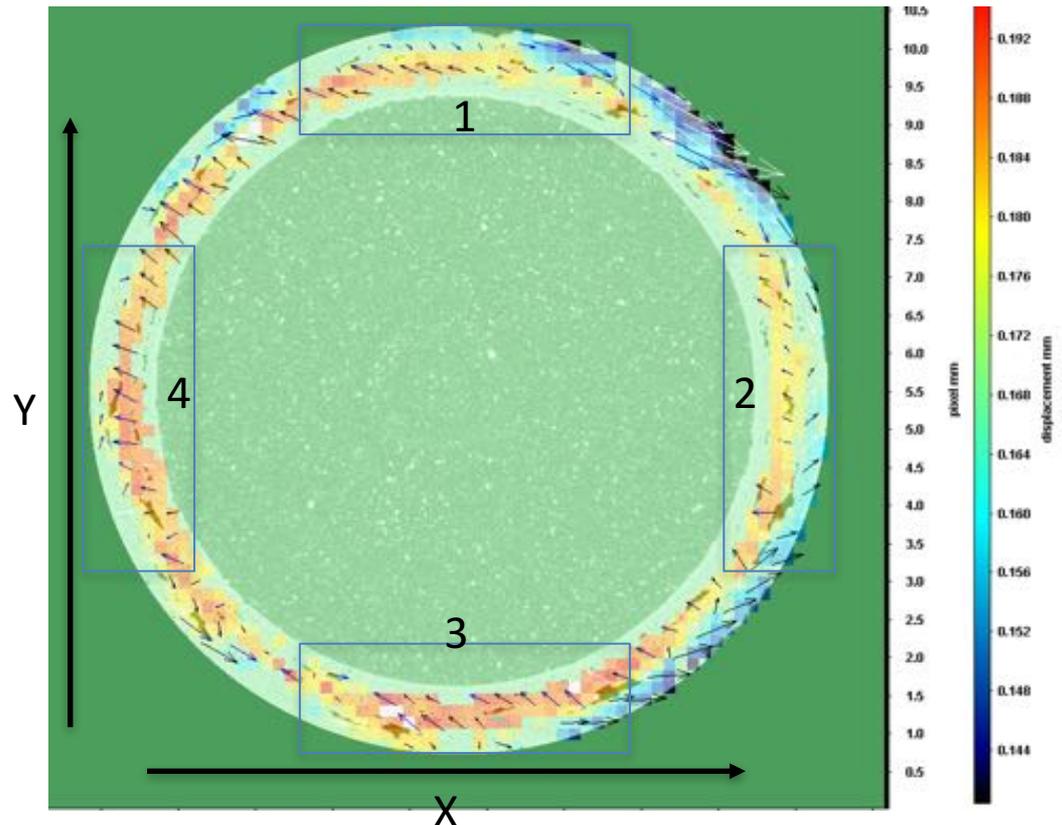
- The statistic displacement difference between 1 and 3 is (V3-V1 in mm)

$$\Delta Y = 0.00509, \Delta X = 0.001247$$

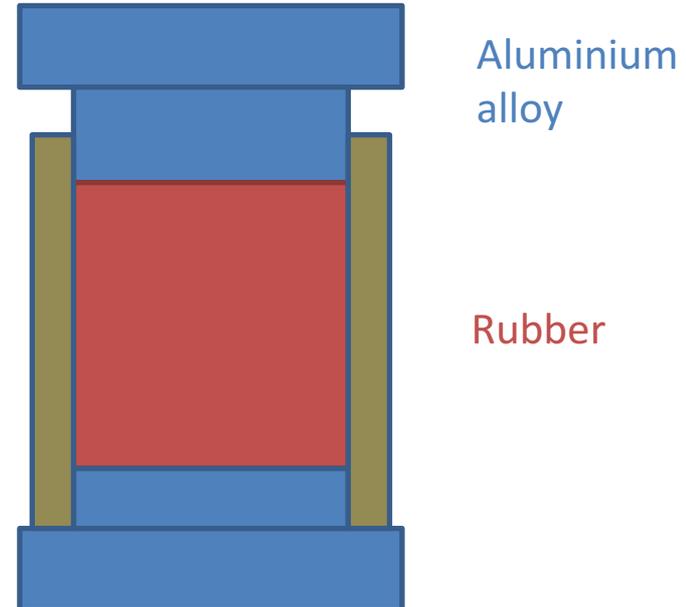
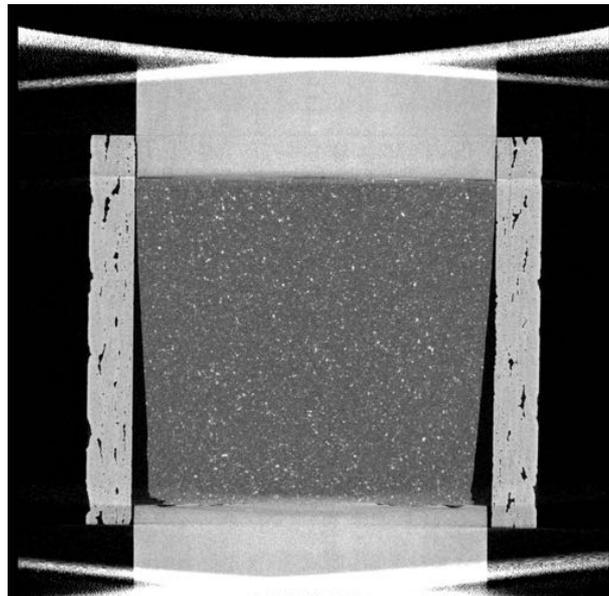
- between 2 and 4 is (V4-V2 in mm)

$$\Delta X = -0.00644, \Delta Y = 0.001263$$

- The Tube is expanding in X and Y direction

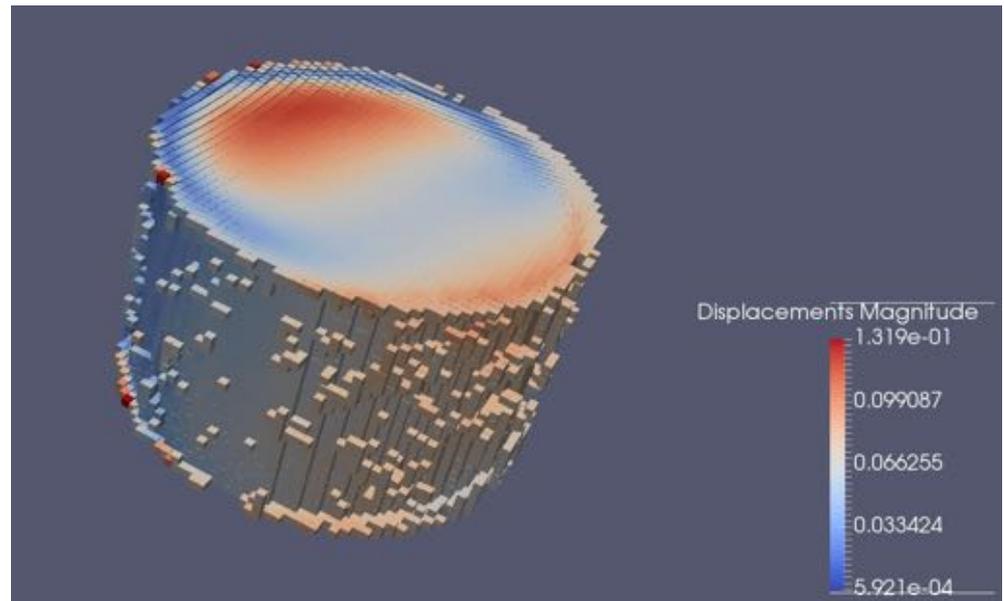


X-Ray Tomography



The deformation of the rubber

- The displacement field of the rubber after rigid body motion and rotation correction



Current limitations..

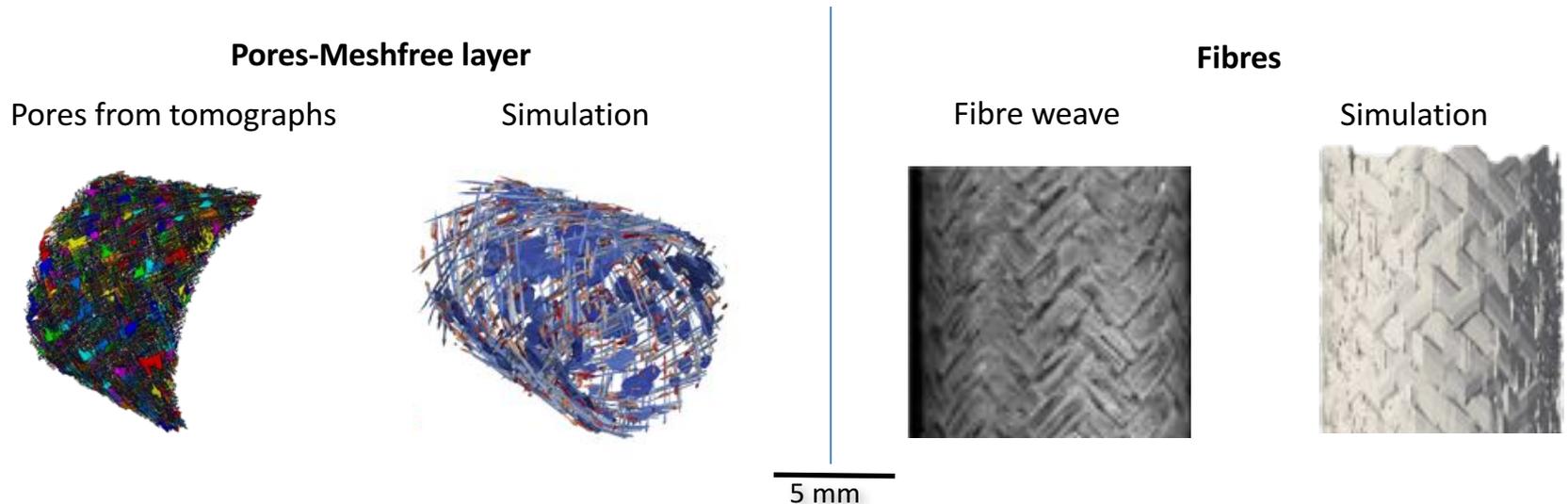
- FEMME model designed for brittle porous microstructures
- It does not (yet) account for..
 - Anisotropic elastic properties and flexure behaviour of fibre tows
 - Mechanistically correct re-distribution of stress with fibre/matrix interface failure

These factors can be accounted for through modification of the intra-layer communication in the model

FEMME model

a Finite-Element Microstructure Meshfree model

- It uses finite-element and cellular automata layers, connected by a meshfree layer
- Reproduce the microstructure and address the important aspects of the microstructure into a larger scale model of the component.
- 2-3 orders of magnitude faster than the FEA with similar details



FEMME model

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