University of BRISTOL

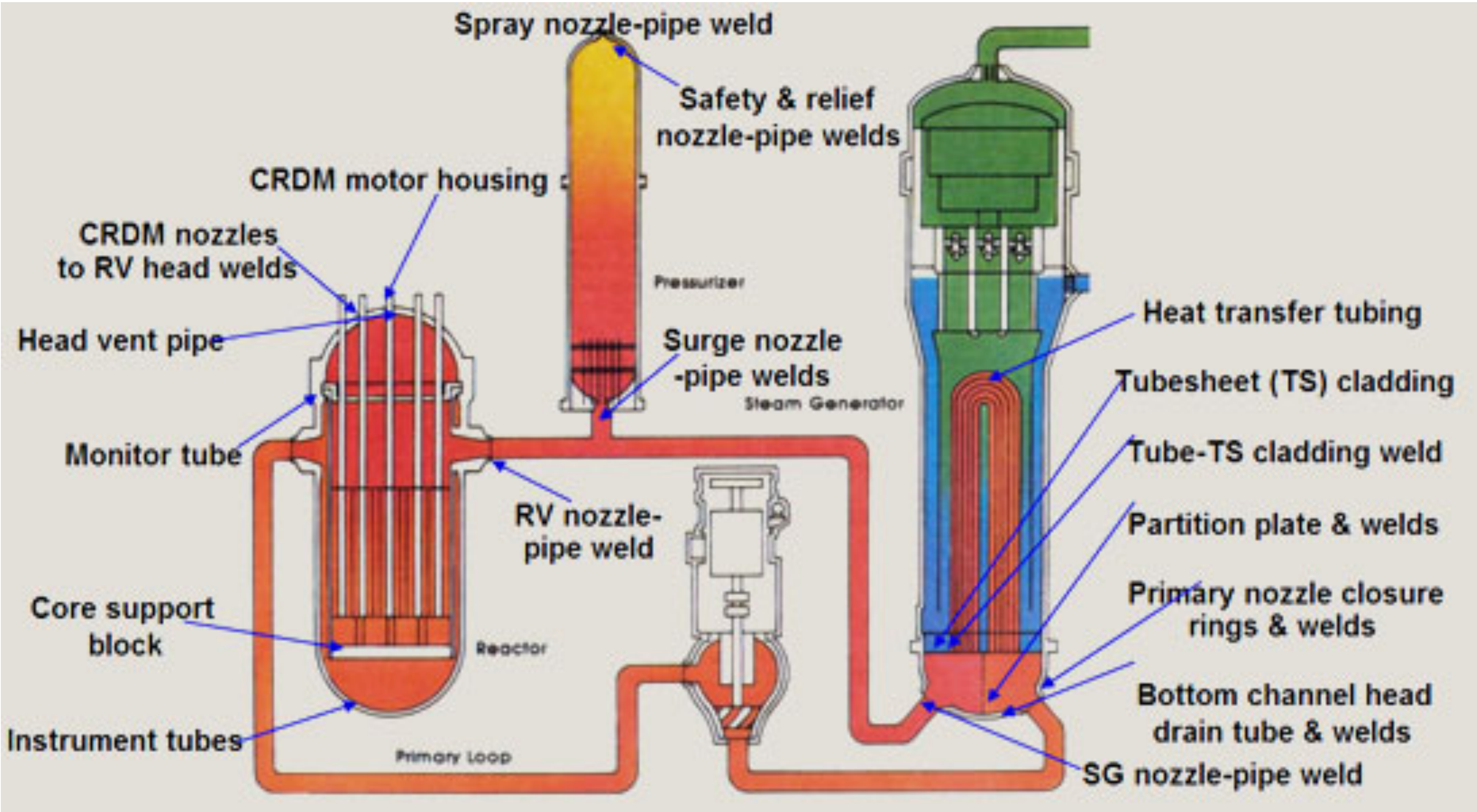
Validating 3D two-parameter fracture mechanics for structural integrity assessments

C. A. Simpson, S. Tonge, A. Cinar, C. Reinhard, T. J. Marrow, M. Mostafavi

Solid Mechanics Research Group

University of BRISTOL

Why do we do this?

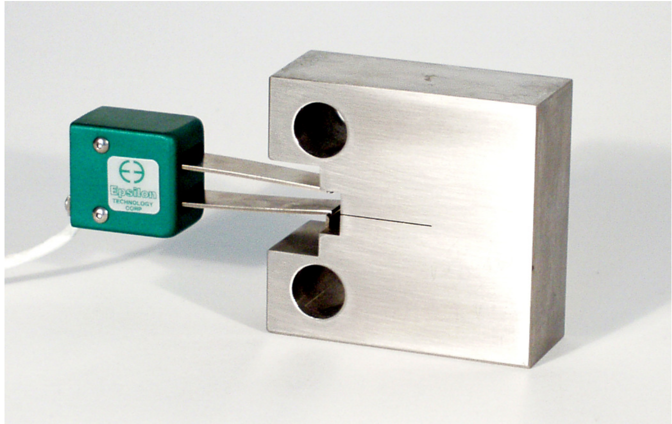


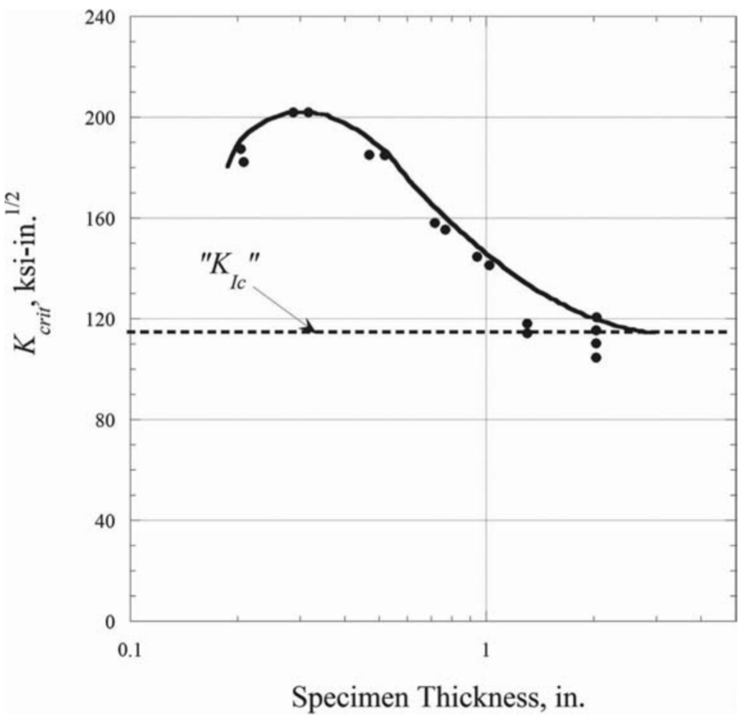
Solid Mechanics Research Group

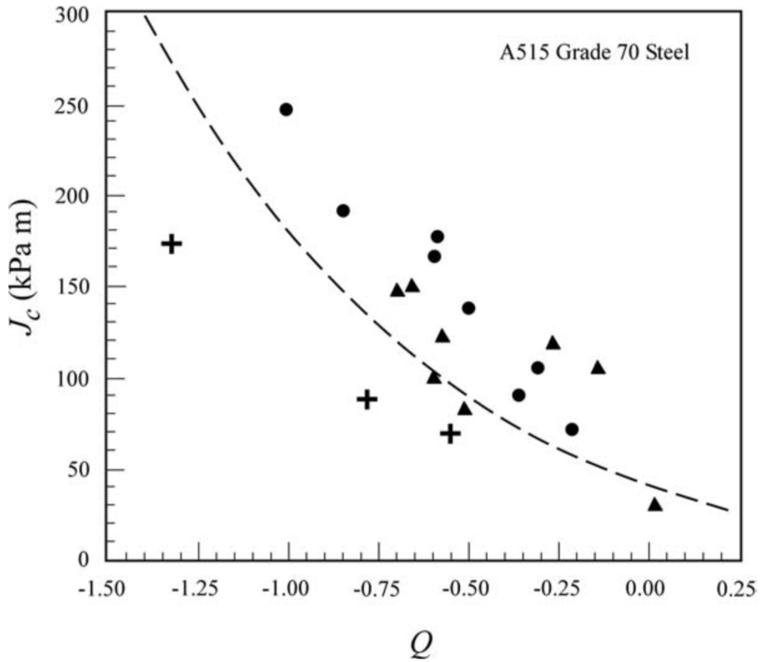
University of BRISTOL

How do we test against fracture?

- » Long crack
- » Thick sample
- » Minimum fracture energy





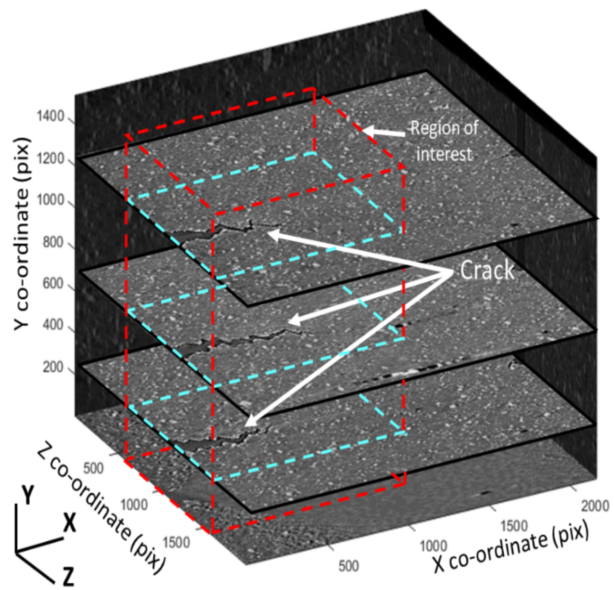


What was our aim?

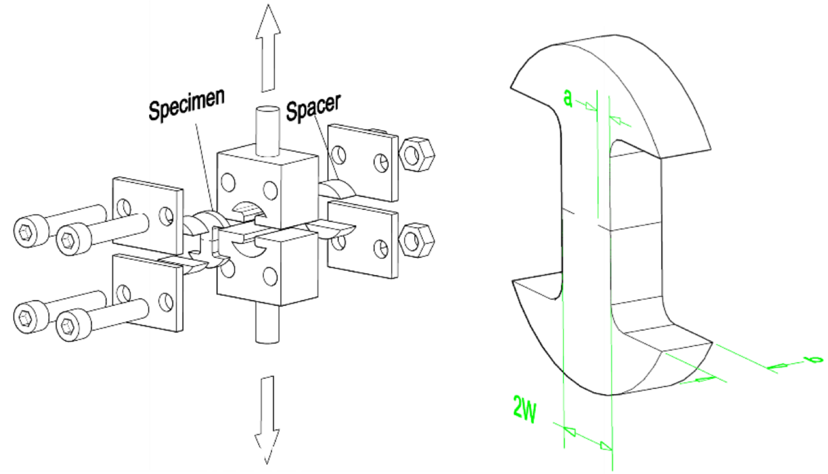
» In structural integrity assessment, we talk about T, Q (in-plane) and Tz (out-of-plane).
  - *Either* in-plane or out-of-plane constraint

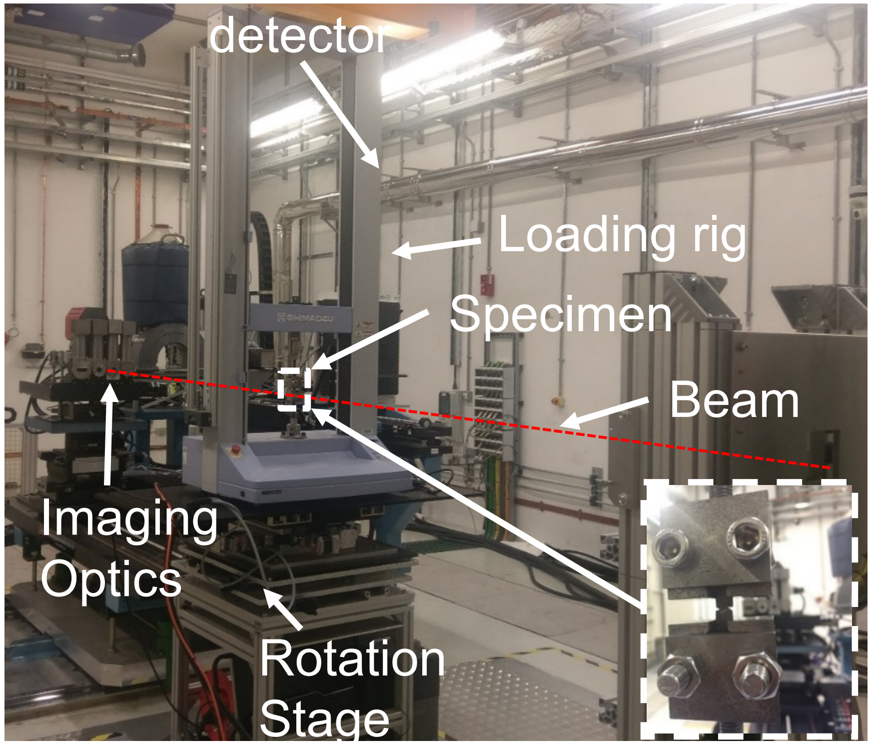
» New approaches are being developed that assess the amount of plasticity around the crack-tip.
  - More understanding and validation is still needed!

» Aim to develop that understanding and provide additional, fundamental detail to underpin these calculations
  - Find plastic zone.
  - Separate J_{total} into plastic/elastic component
  - Through thickness variation in J



Experiment Overview





- Al-Ti Double-edge notch tension samples (DENT)
- Varying the amount of 2D plastic constraint
  - a/W = 0.1, 0.5
  - b = 5mm, 20mm
  - *One combination covered here*
- Work carried out at the DLS
  - I12:JEEP beamline
- 2 part experiment
  - Monochromatic XRD (elastic)
  - XCT/DVC (elastic + plastic)

Solid Mechanics Research Group

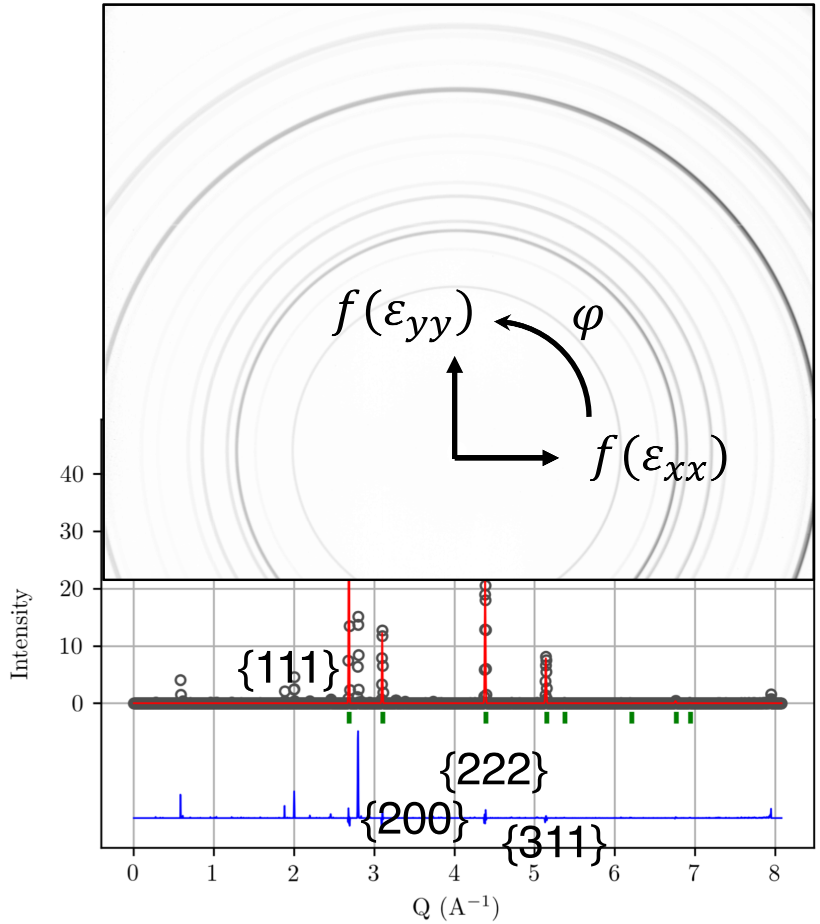
University of BRISTOL

X-ray Diffraction (XRD)

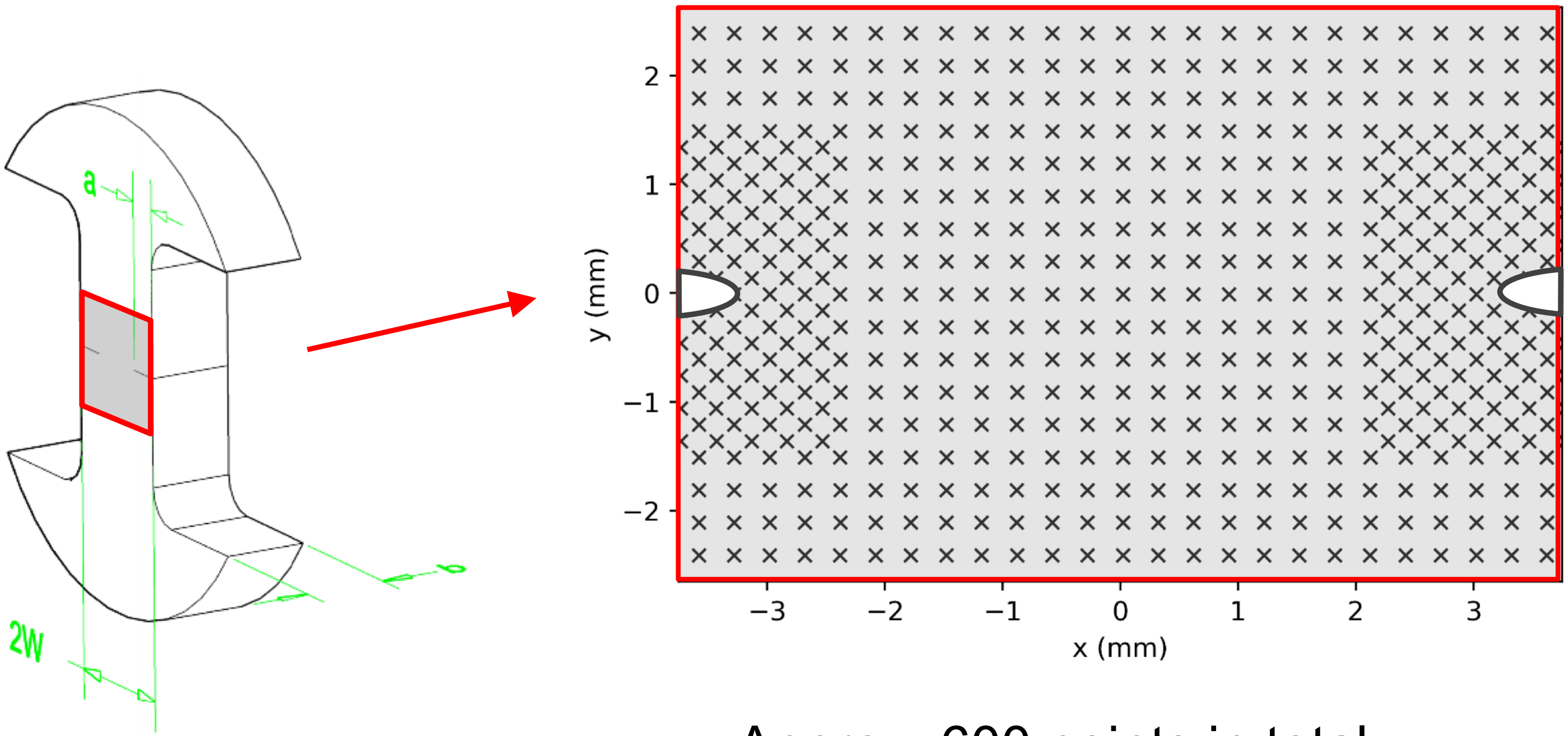
» Monochromatic 2D diffraction
  - Energy = 60 keV
  - Caking: $\Delta\varphi = 10°$
  - d, a calculated according to Bragg's Law:
  - $\varepsilon = \Delta d / d_0$

» 600 measurements made across a 2D grid…

» Looking to quantify 2D elastic strain and $J_{elastic}$



2D XRD Strain Maps

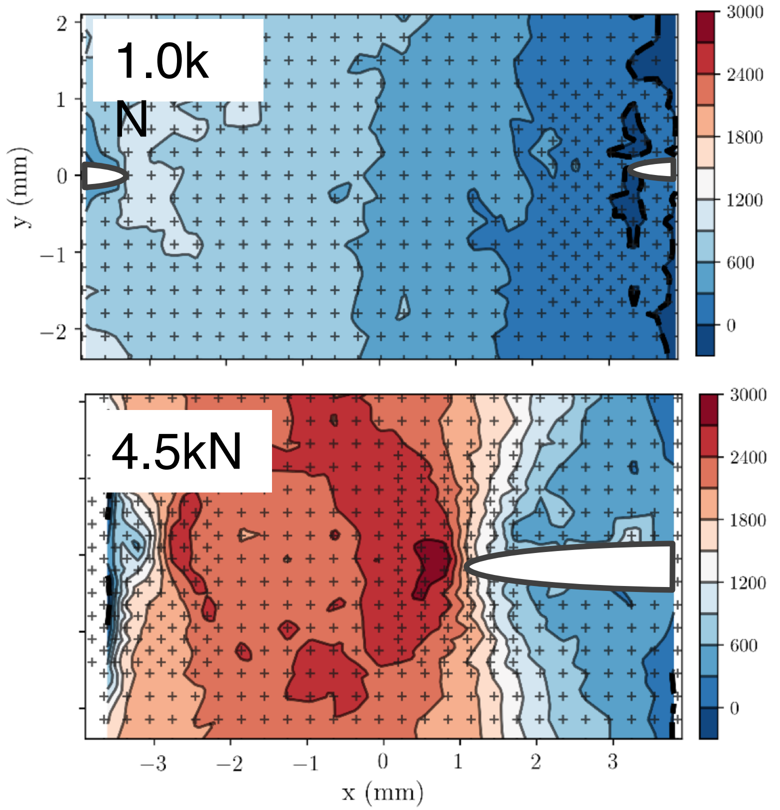


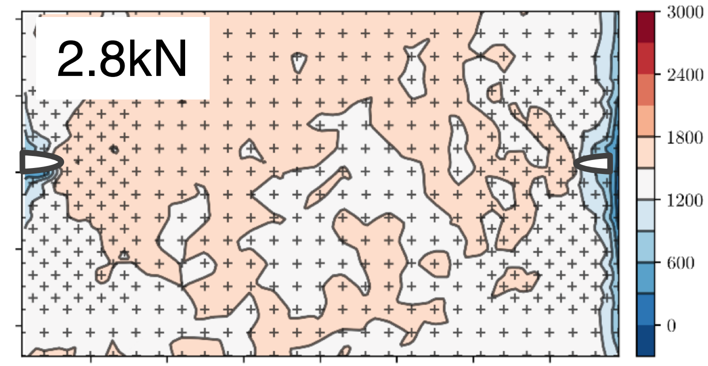
» Approx. 600 points in total
» High point density at around notch (high strain gradient)

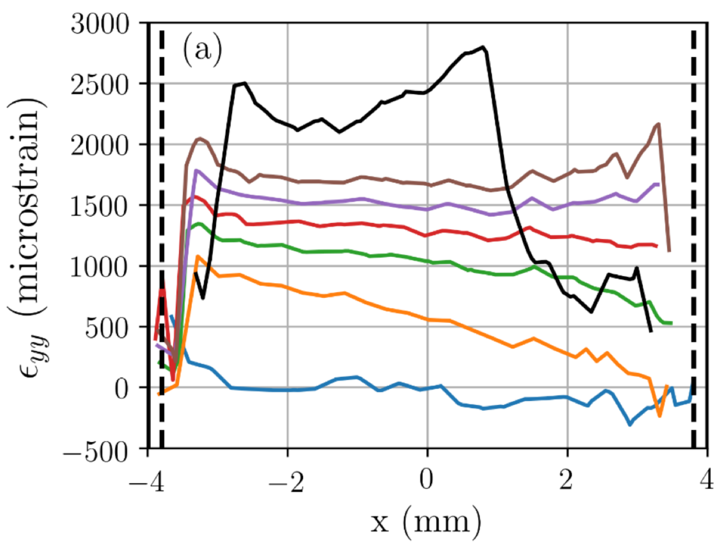
Solid Mechanics Research Group

University of BRISTOL

2D XRD Strain Maps (ε_{yy}): b = 5mm, a/W = 0.1







» Next step -> use 2D elastic strain to calculate $J_{elastic}$ [1]

[1] Barhli, S. M. e al. (2016). Obtaining the J-integral by diffraction-based crack-field strain mapping. Procedia Structural Integrity, 2, 2519–2526.

Solid Mechanics Research Group

University of BRISTOL

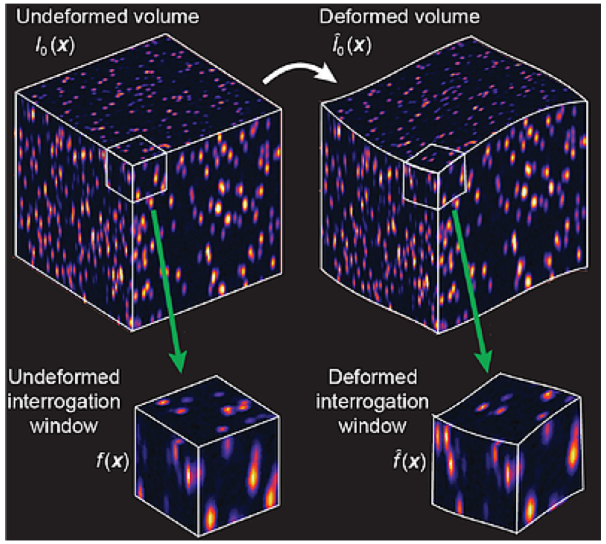
Digital Volume Correlation

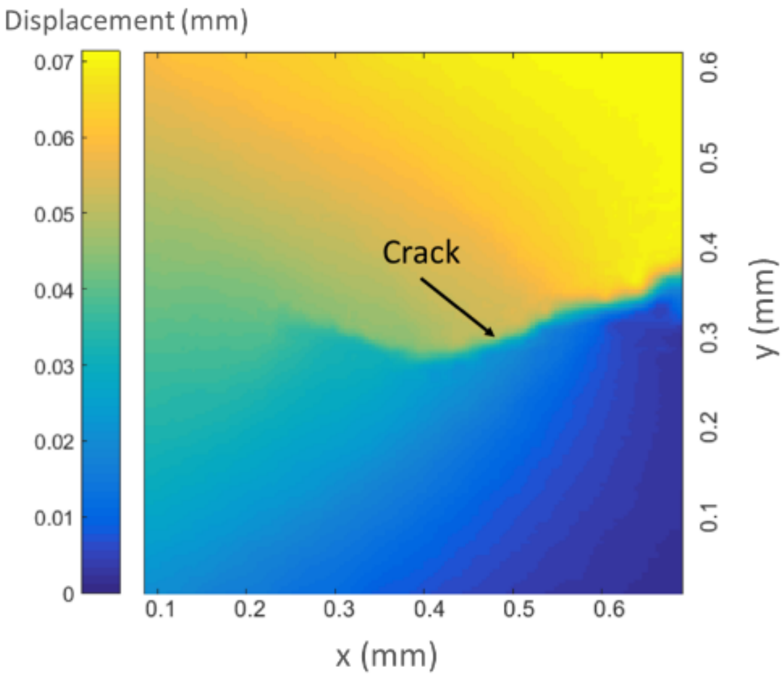
» 3D equivalent to digital image correlation

» Used to determine displacement and strain fields in 3D volumes

» Tomogram is divided into overlapping sub-volumes

- Sub-volume size of 16 voxels
- 80% Overlap





Solid Mechanics Research Group

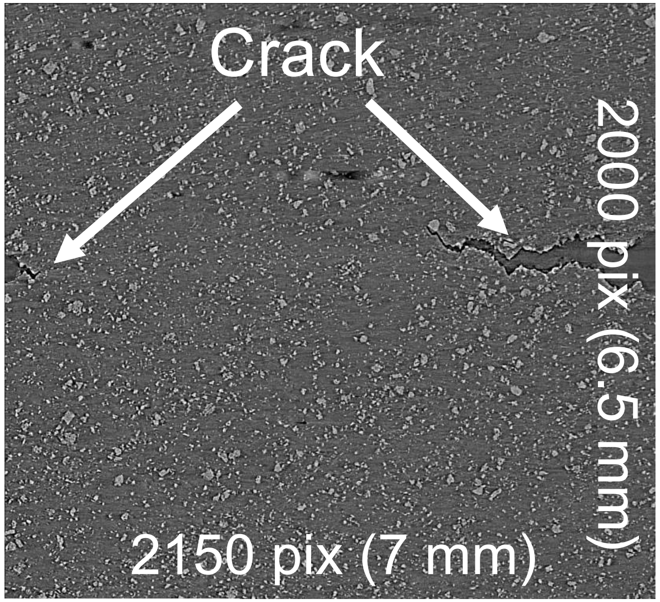
University of BRISTOL

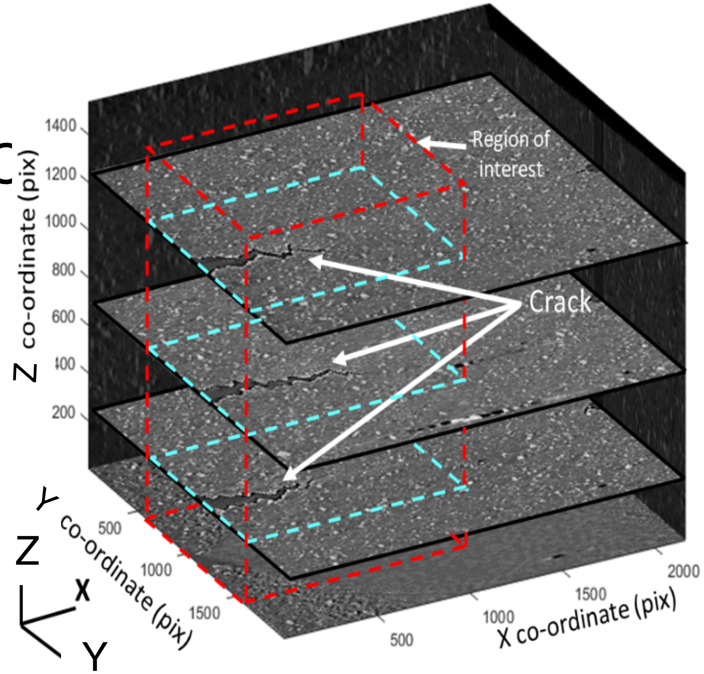
X-ray CT: b = 5mm, a/W = 0.1

- Limited angle X-ray computed tomography
  - 145°
  - 60 keV, 2501 projections
  - Voxel size ~4um

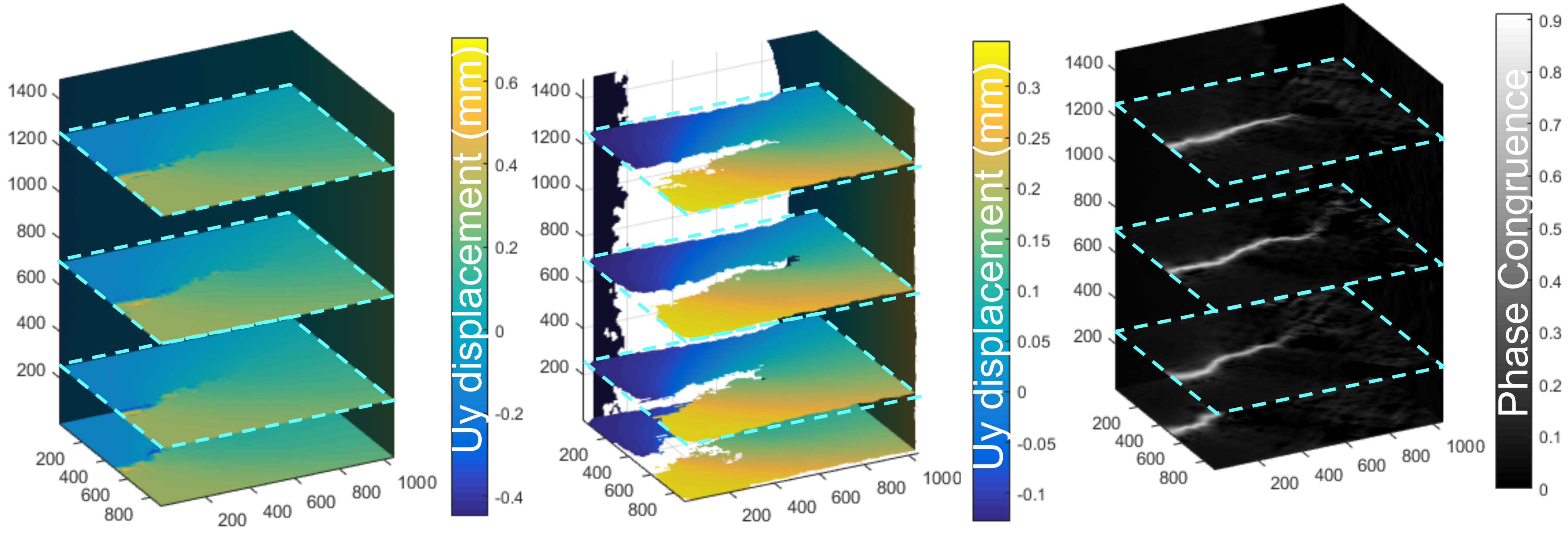
- Al-Ti selected for its inherent speckle
  - Provides contrast for DVC

- Aim is to evaluate COD, total strain and J_{total}





DVC/Phase Congruency Workflow



Raw Uy displacement

Outlier deletion and extrapolation

Volumetric Phase congruency

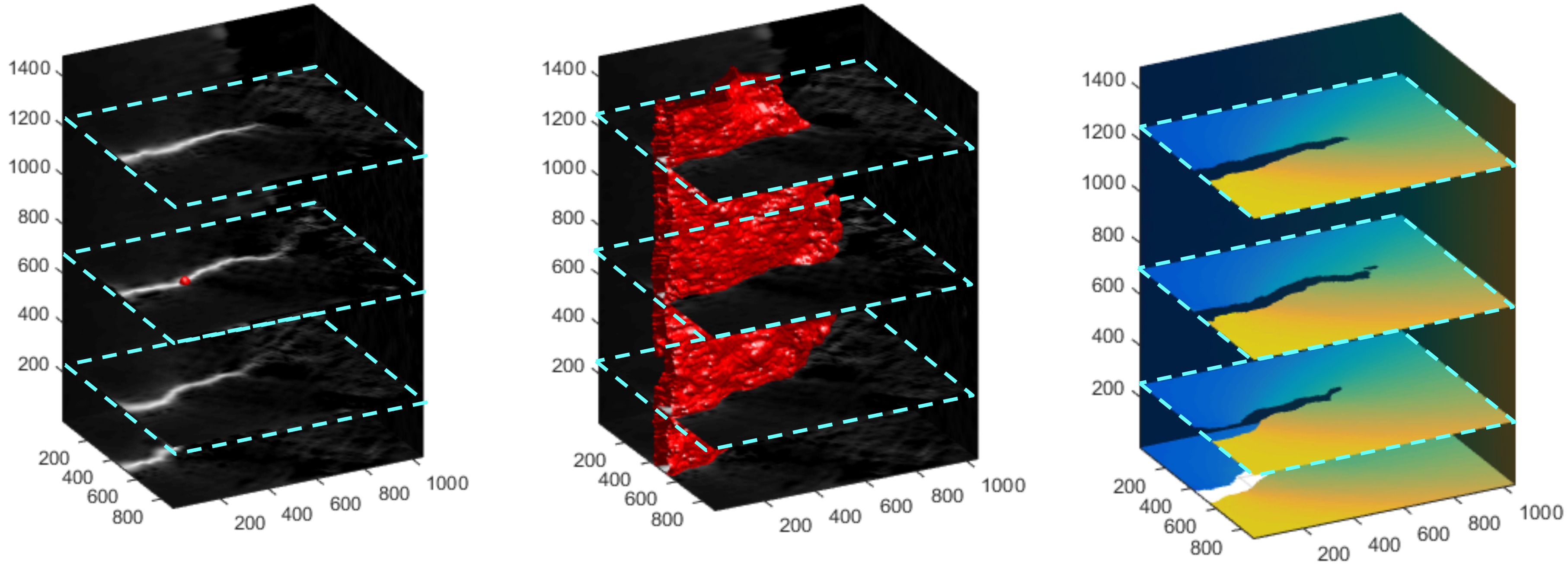
[1]

Cinar, A. F. et al. (2017). An autonomous surface discontinuity detection and quantification method by digital image correlation and phase congruency. Optics and Lasers in Engineering, 96, 94–106.

Solid Mechanics Research Group

University of BRISTOL

Crack Segmentation Workflow



Seeding point Selection

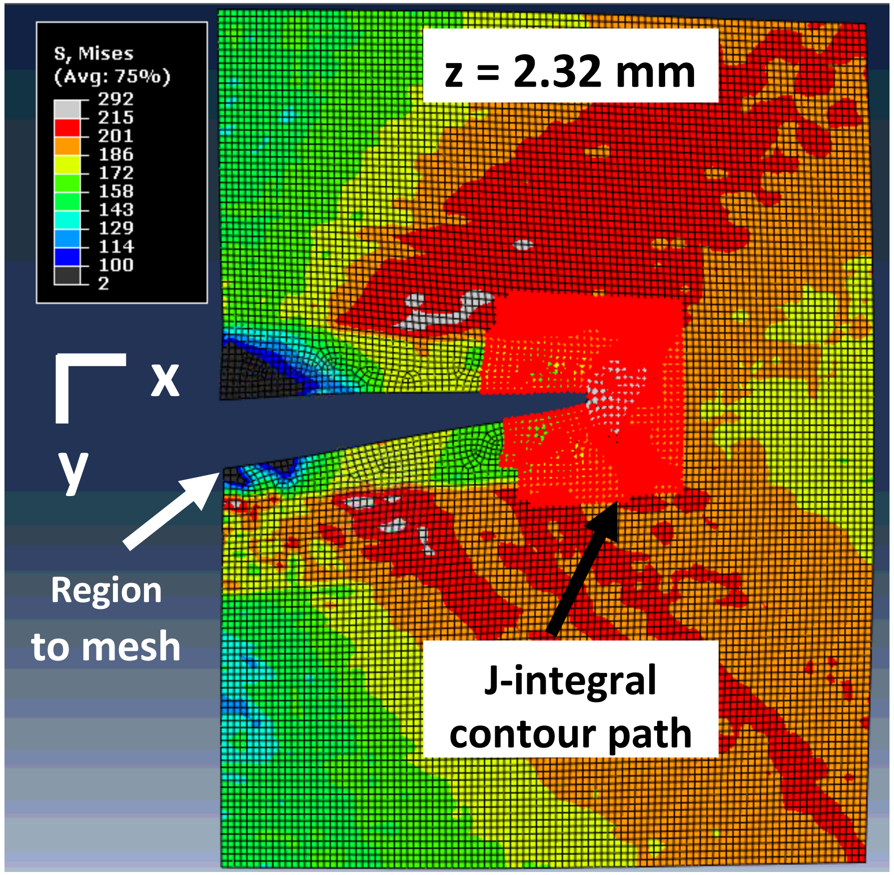
Segmentation

Segmentation boundary identification

[1]

J-integral Calculation (OUR-OMA)

- Import displacement fields into Abaqus
- Segment crack path (using VPC-CD derived values)
- Automatic FE meshing of region around crack path
- Contour integral around crack evaluated by FE solver (domain integral method)



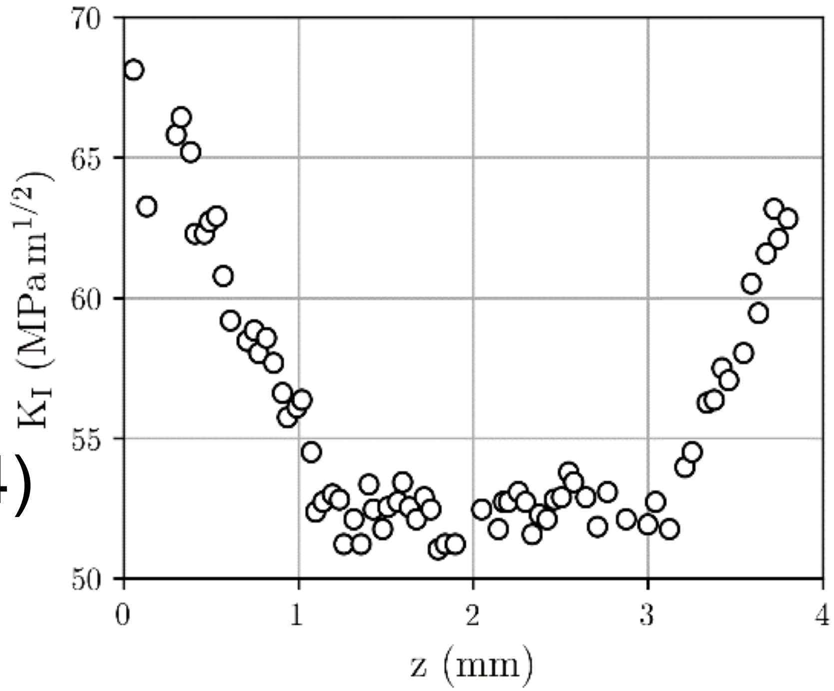
Barhli, S. M. et al. (2017). J-Integral Calculation by Finite Element Processing of Measured Full-Field Surface Displacements. Experimental Mechanics, 57(6), 997–1009.

Solid Mechanics Research Group

University of BRISTOL

Initial Results - J_{total}

- J_{total} converted to K:
    - $K_I = \sqrt{J E}$
- Minimum value of $52 MPam^{1/2}$ reached at the sample centre
- Results not in agreement with analysis by Petit and Dodds (2004)
    - Increased plasticity at sample surface?
    - Error in 2D slice-by-slice approach?



Solid Mechanics Research Group

University of BRISTOL

Conclusions and Where Next?

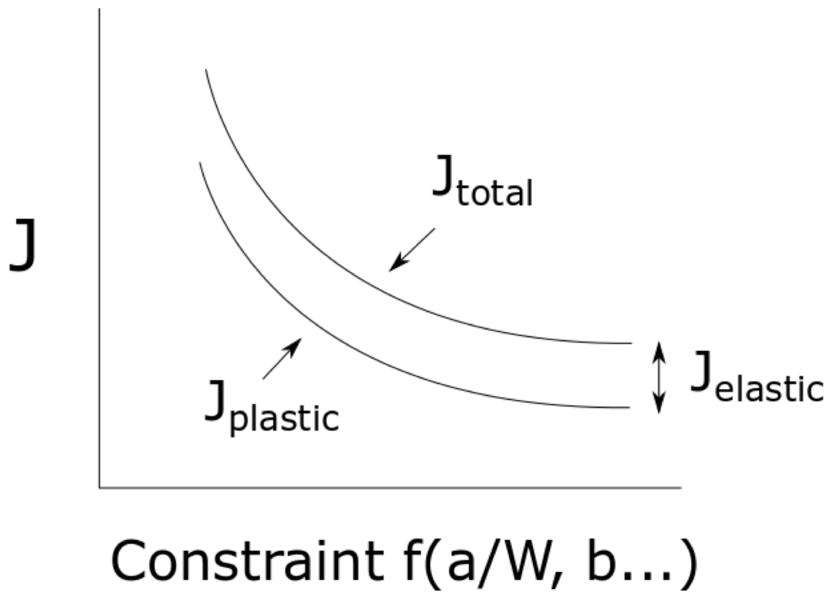
» Sophisticated set of tools developed to tackle this problem

1. VPC-CD (crack detection)
2. OUR-OMA (J from DVC)
3. JMAN-S (J from XRD strain)
4. pyXe (XRD analysis)

» Efforts are beginning to yield quantitative information!

» Next steps are to:

1. Calculate $J_{elastic}$ from code (JMAN-S)
2. Separate of $J_{elastic}$ and $J_{plastic}$ from J_{total}
3. Look at the variation in $J_{elastic}$ wrt 2D plastic constraint
   - ***Does this remain constant?***

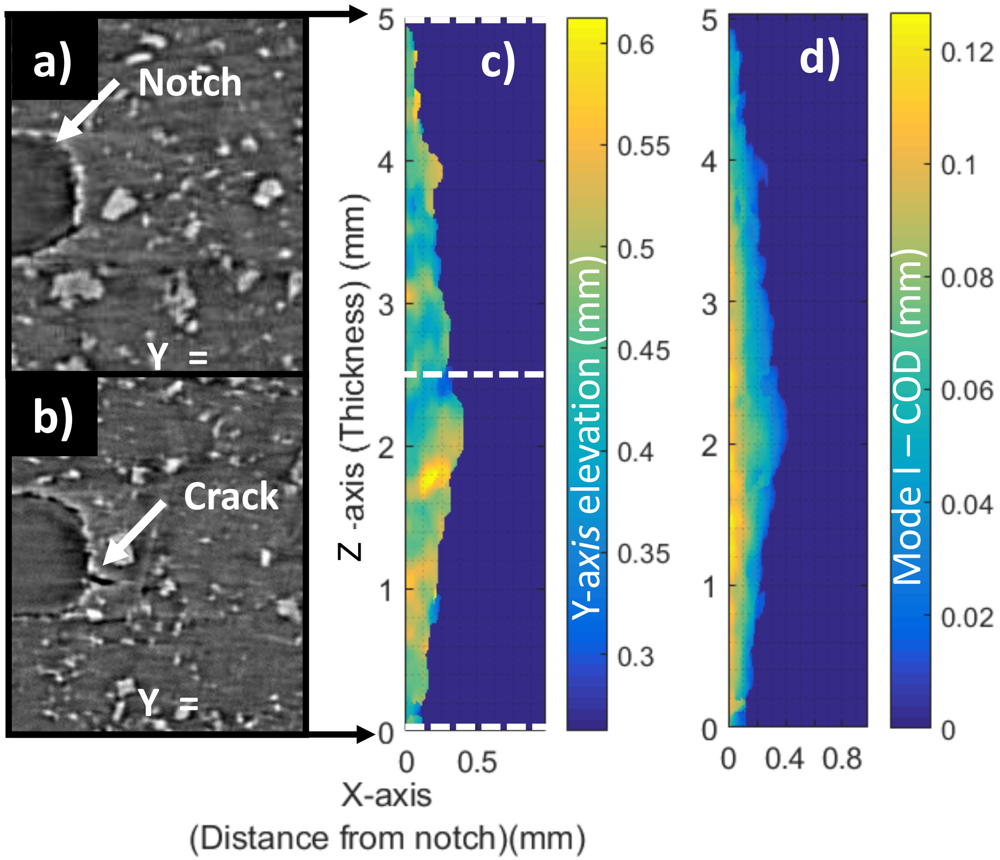


Solid Mechanics Research Group

University of BRISTOL

Crack Opening Displacement (COD)

- Thin sample, long notch
  - B = 5mm, a/W = 0.1
- Through thickness crack elevation (crack tortuosity)
  - Interesting to capture the 3D crack path!
- Associated crack opening displacements wrt. through thickness position also interrogated.



Conclusions

- Image based damage mechanics can help calculate parameter that were not measurable before
- Combination of 3D finite element and digital volume correlation can provide accurate boundary conditions
- DVC and XRD can be used to separate elastic and plastic strains
- Work of fracture through the thickness of specimens was calculated in this work