University of BRISTOL

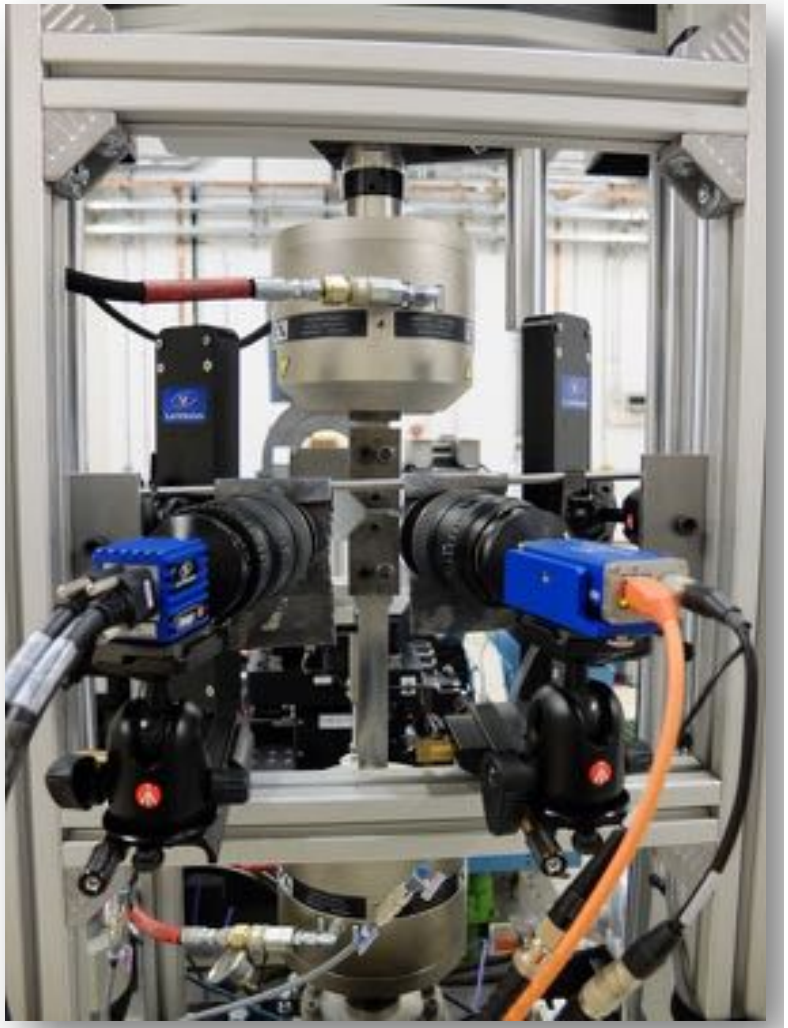
Integrated image correlation and finite element simulation

Blurring the line between experiment and modelling

Mahmoud Mostafavi

Overview

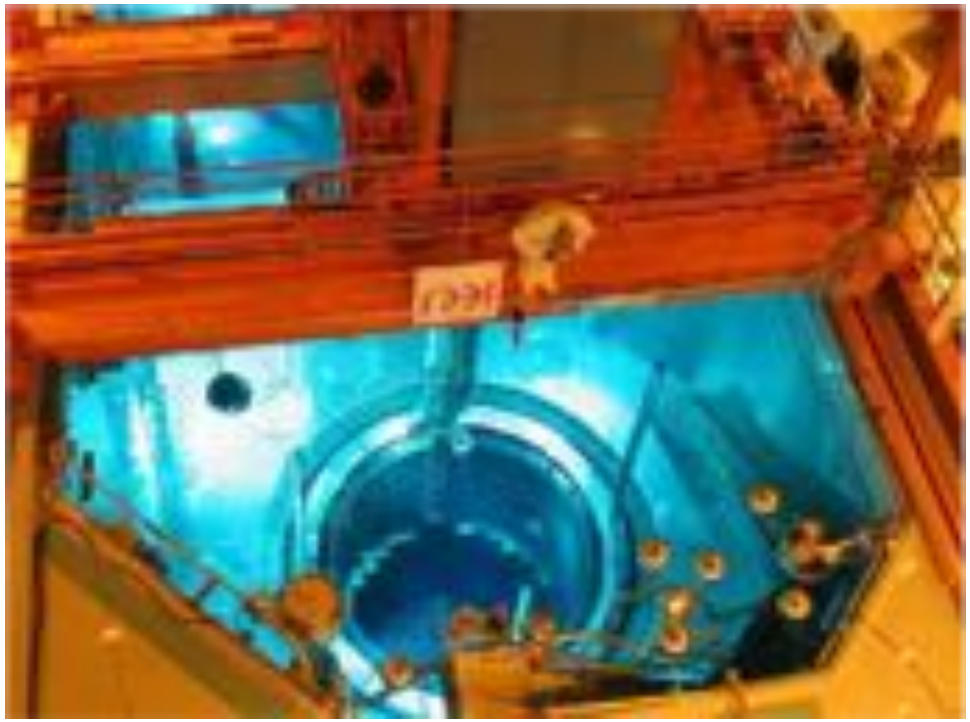
- Past: How structural integrity assessments were developed
- Present: What techniques are available and how we can use them
- Future: What future structural integrity assessments will look like



Stereo digital image correlation and energy dispersive X-ray diffraction of a fatigue experiment

*With Professor P.J. Withers, University of Manchester

Shippingport during construction



World Nuclear News

Past and Present

Engineering context

Circumferential welding of a reactor vessel by submerged arc welding

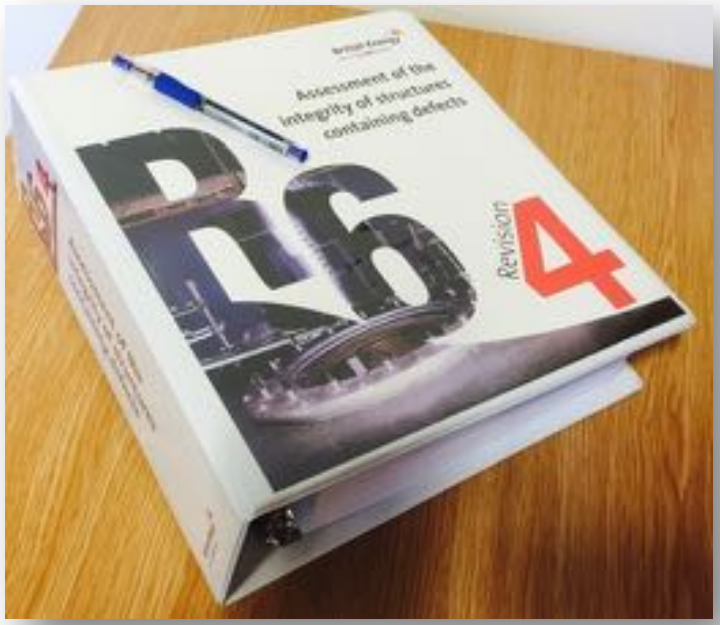
Cracked welded pipe knee joint

Operator has to submit a safety case to the regulator to renew its license

Structural Integrity Assessment

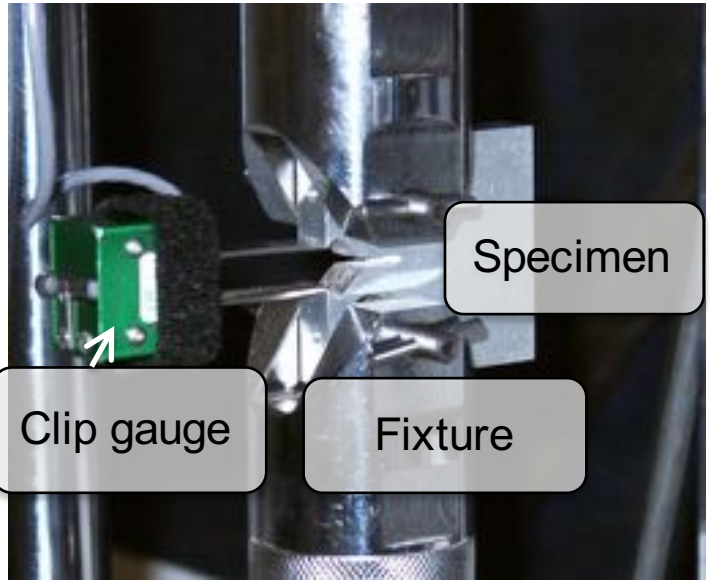
- R6 in the UK (also BS7910)
- EPRI in the USA
- RSE-M in France (EDF – ARIVA)

Products of 1980's
They have served us well

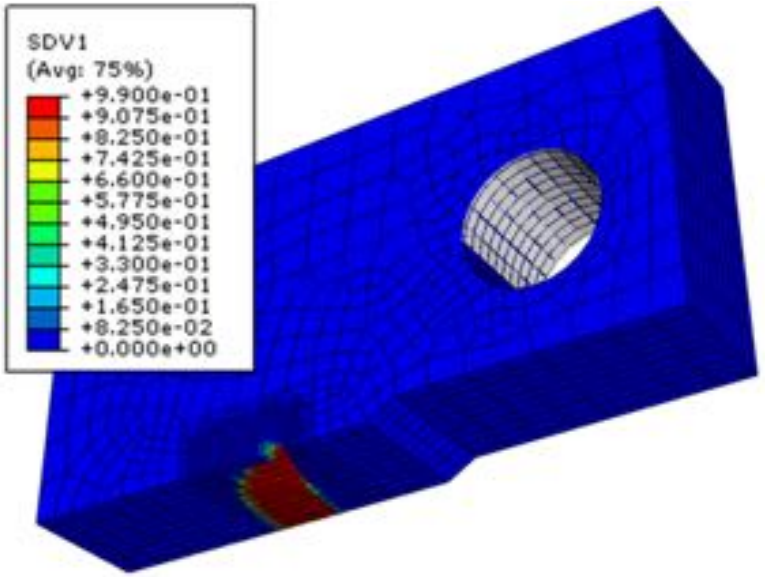


How is it done?

Material properties



Fracture behaviour



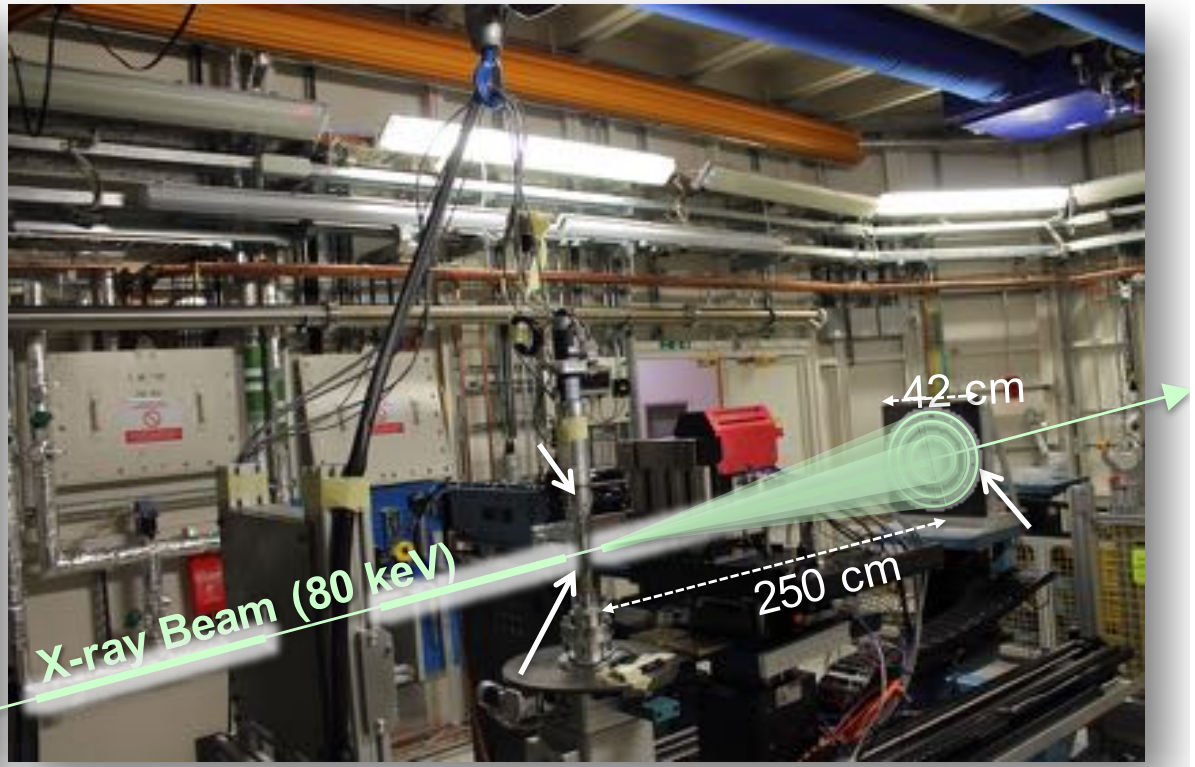
Finite element simulation

FE model is validated using measurement on *one point: crack opening displacement*

And how much does it cost?

- Option 1: In-house ~£250
  - No FE, No material property is needed, residual stress estimated at one point)
- Option 2: In-house ~£3000
  - No FE, material properties are needed, residual stress estimated at one point
- Option 3: External consultancy ~£250k
  - Elastic-plastic FE, materials properties and residual stress measured at >10000 points

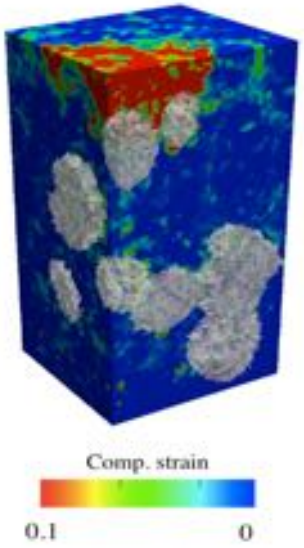
Exchange rate:
£1=$1.53



Future

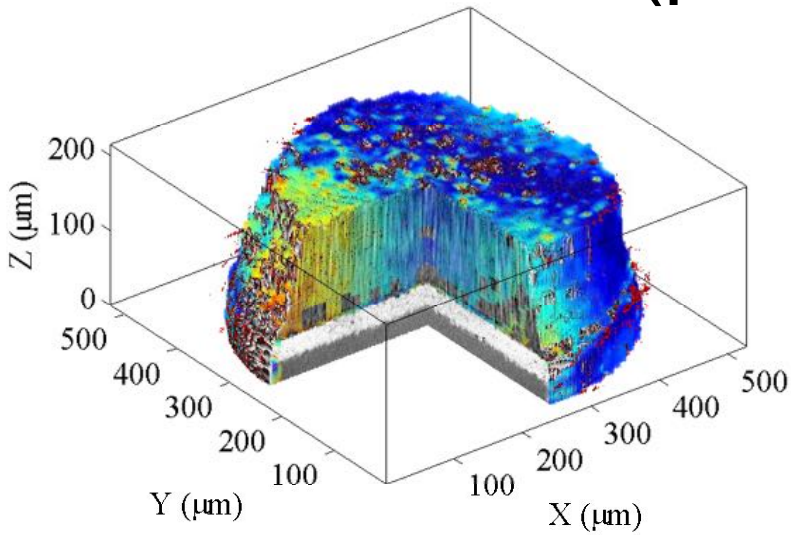
What toys do we have!

- Digital image correlation
- X-ray Computed tomography
  - Lab sources
  - Synchrotron sources
- Digital volume correlation
- X-ray Diffraction
- Microstructurally-faithful finite element simulation



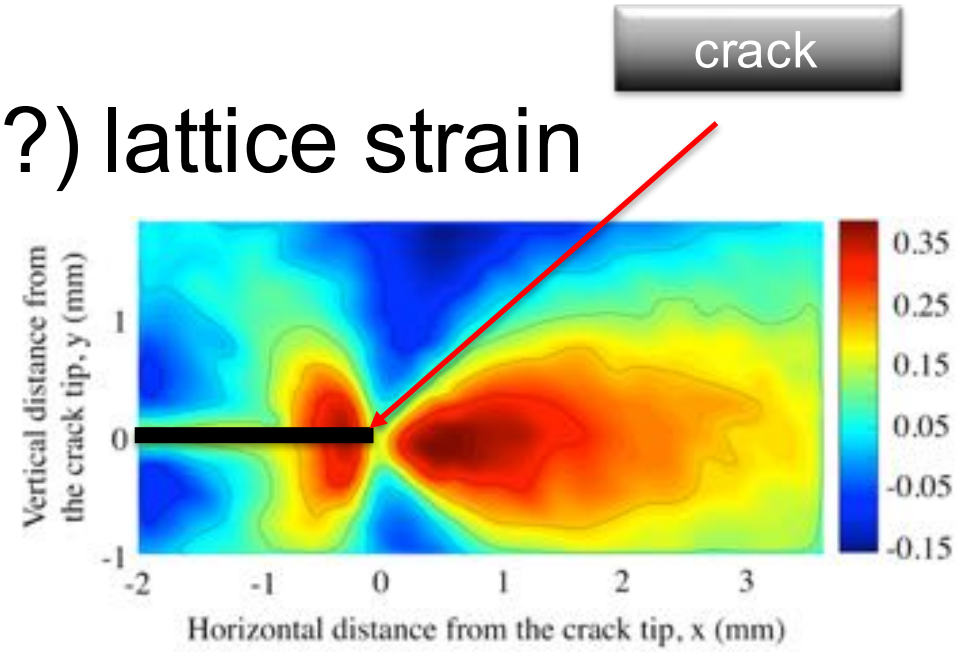
What information do we have?

- Full-field displacement field
- Full-field microstructure
- Full-field elastic (plastic?) lattice strain



Total displacement field in a thermal barrier coating subject to 20 hours thermal loading*

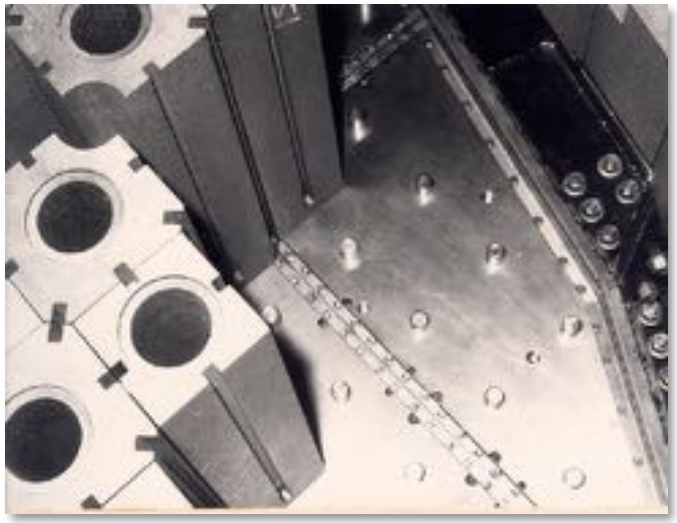
* With Dr B.Connolly, University of Birmingham



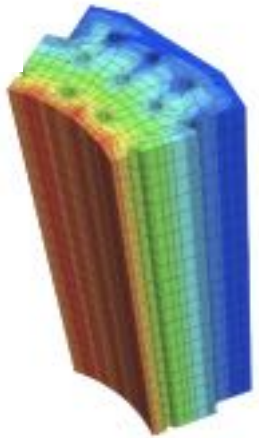
Elastic strain field mapped around a fatigue crack tip

* With Prof P. J. Withers, University of Manchester

Heysham 2 (during construction)



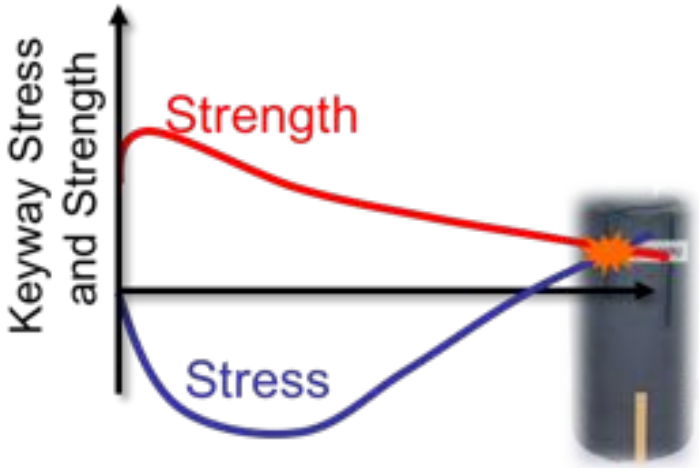
Graphite bricks in the core

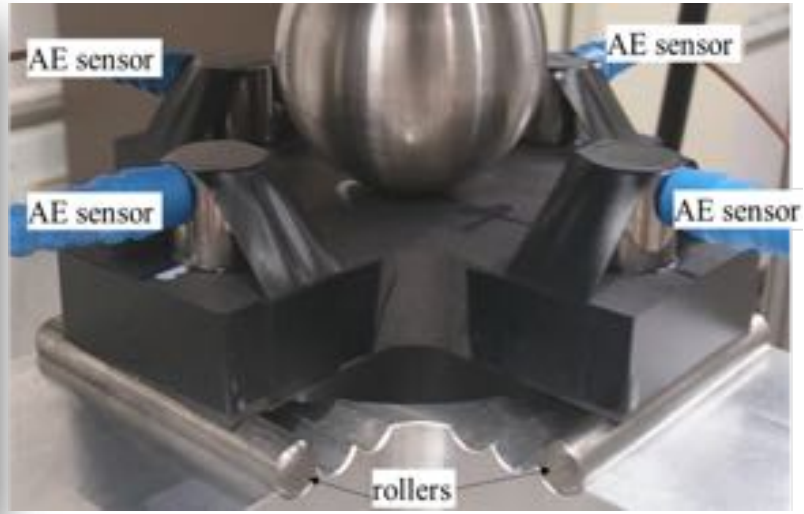


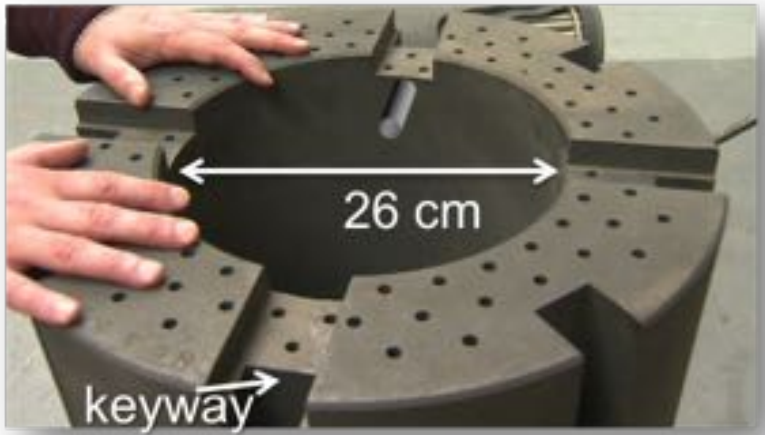
FE simulation

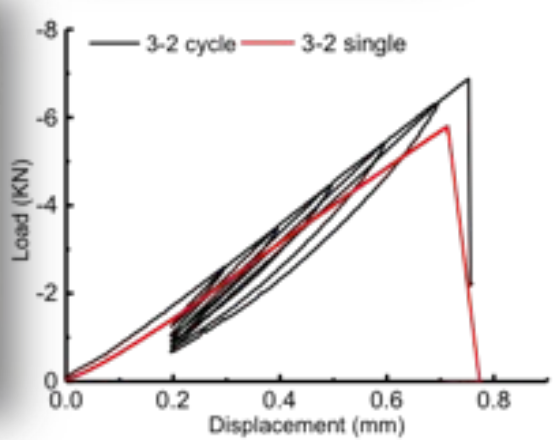
Fracture of nuclear graphite

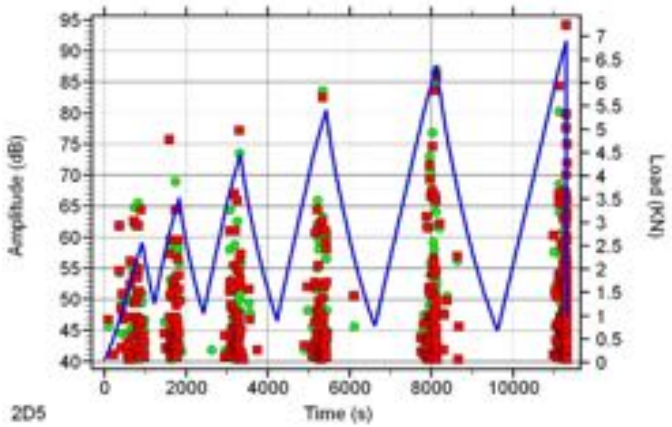
Why graphite?





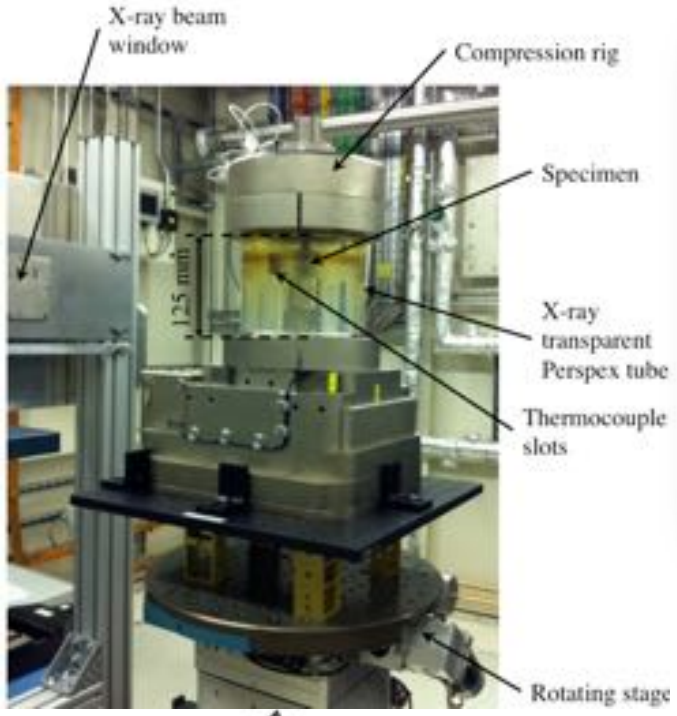


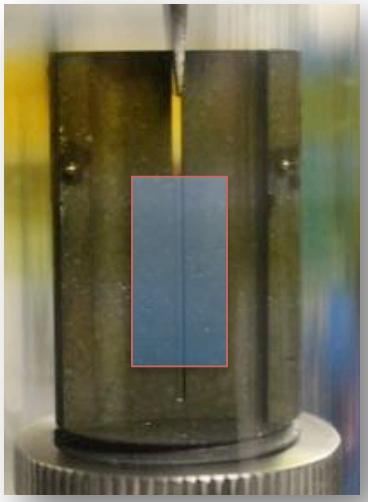


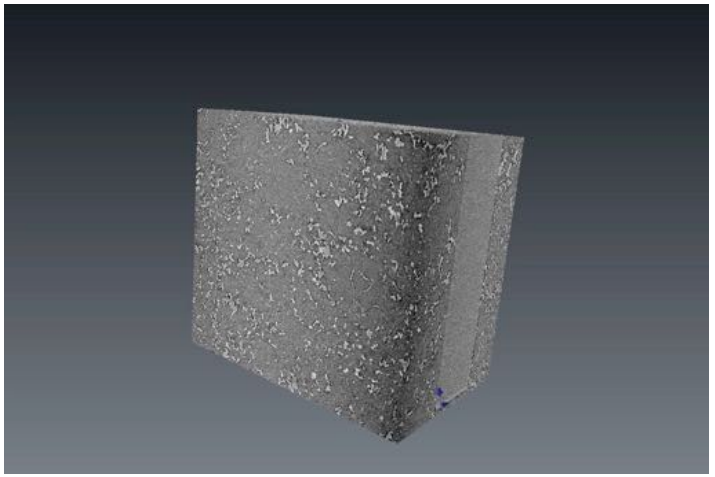


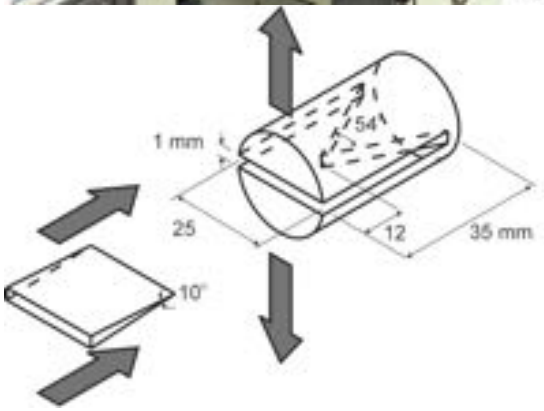
* With Professor P. E. J. Flewiit, University of Bristol

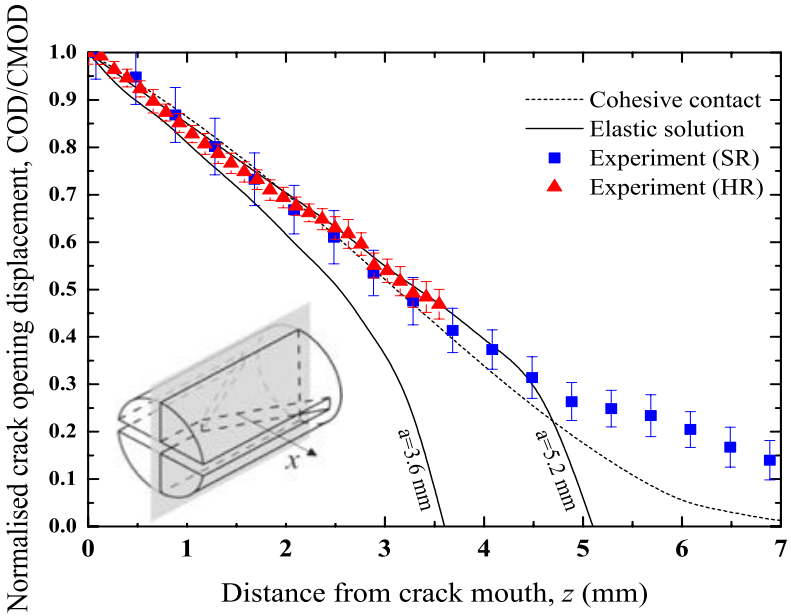
Is crack tip real?





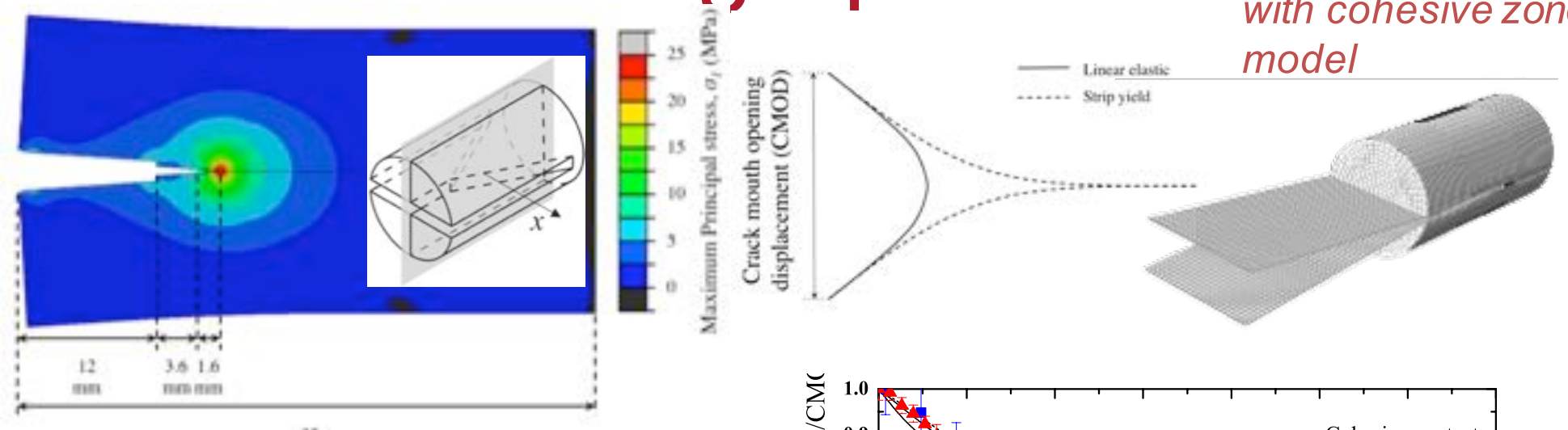




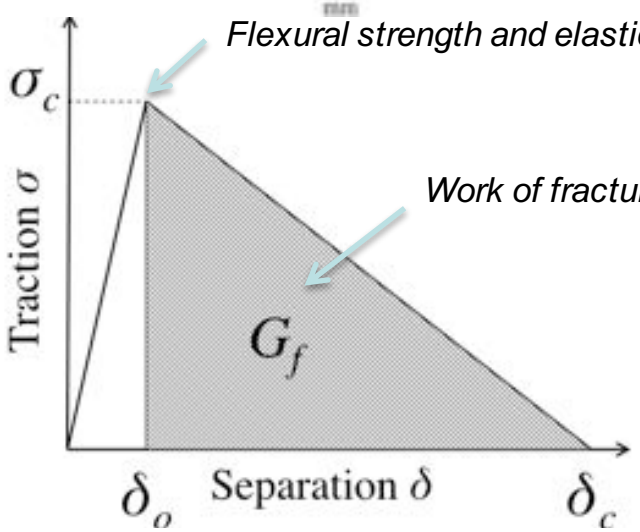


How to model graphite?

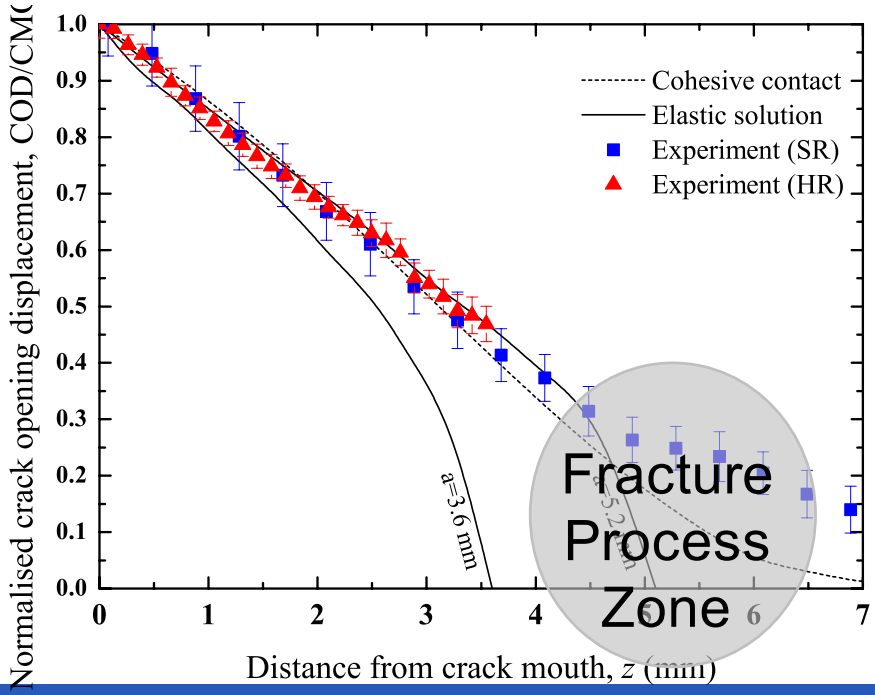
3D FE simulation with cohesive zone model



Flexural strength and elastic modulus

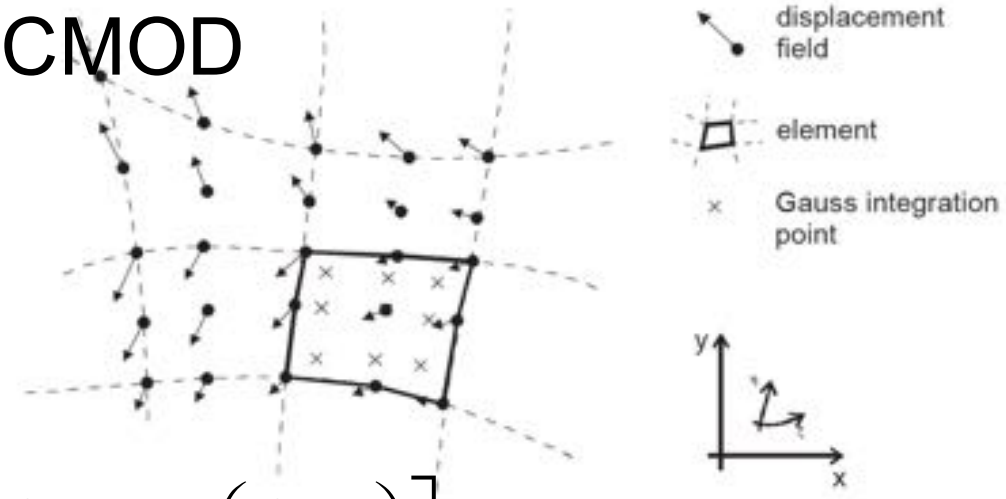


* With Professor J. Marrow, University of Oxford



Combining DIC and FE

- After Jim Rice J-integral
- Usually is calculated from CMOD



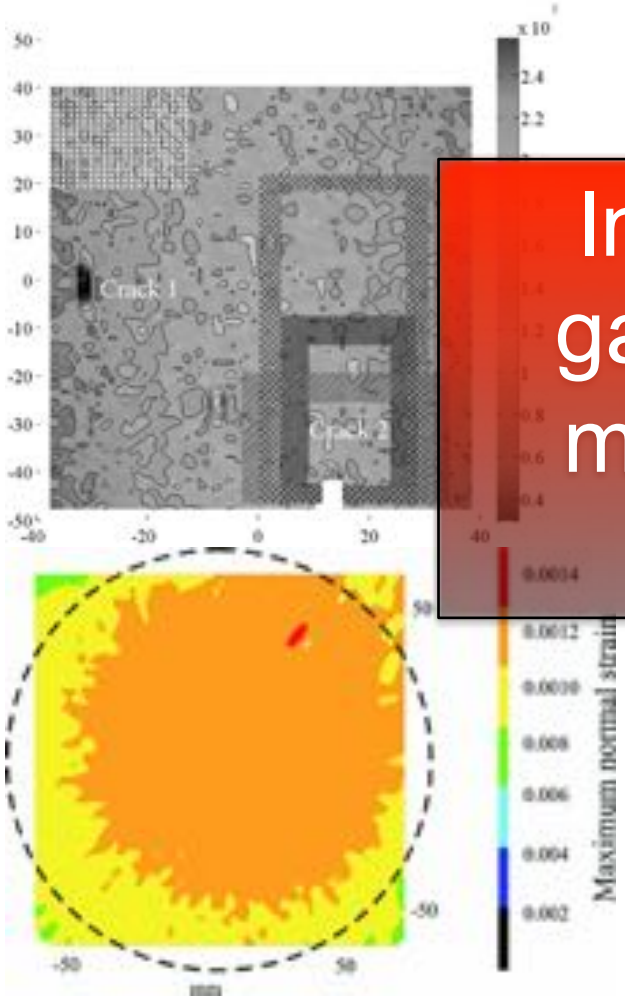
$$J = \int_{\Gamma} \left(\frac{\partial w}{\partial x} dy - T_i \frac{\partial u_i}{\partial x} ds \right)$$

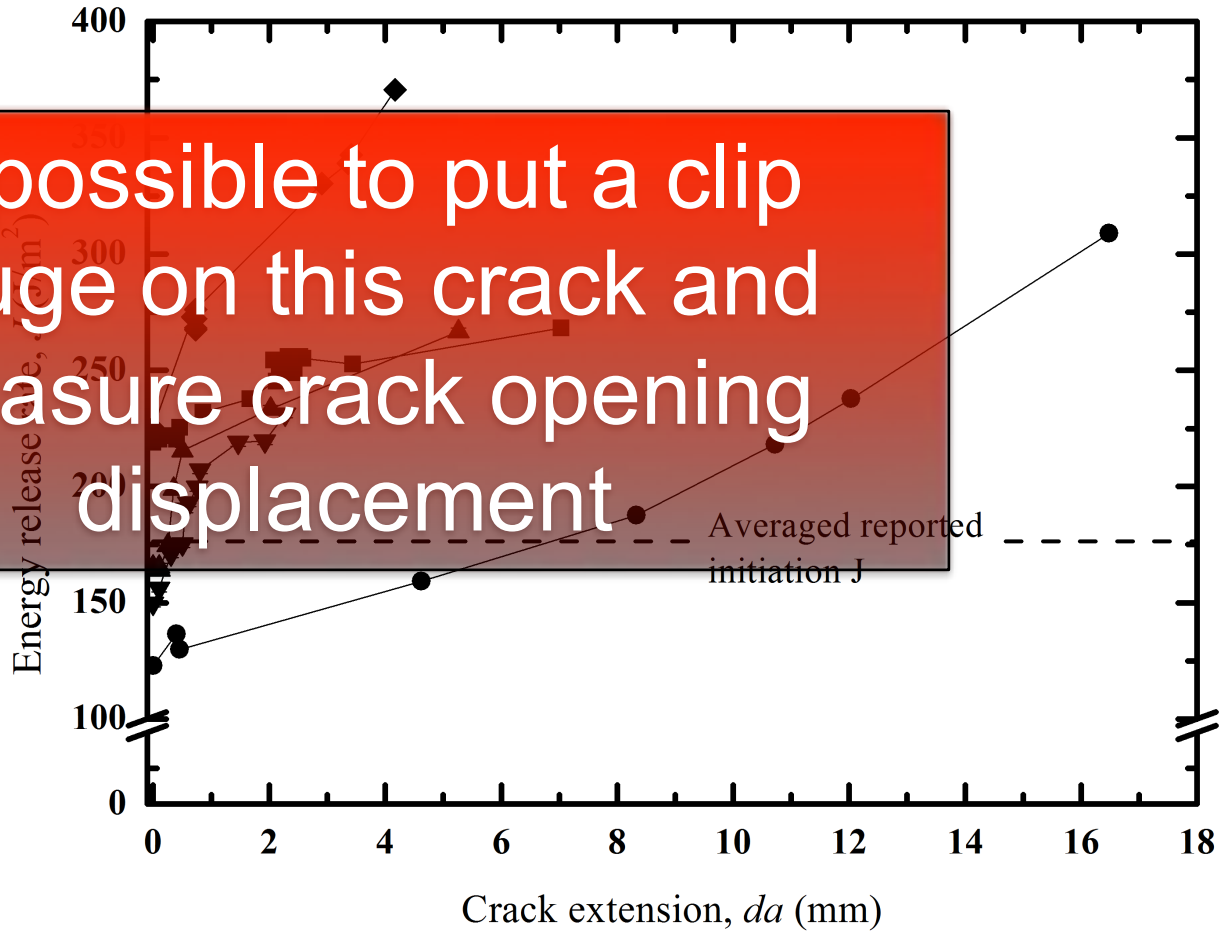
$$J = \sum_{Elements} \sum_{p=1}^{GP} \left[\left(\sigma_{ij} \frac{\partial u_i}{\partial x_1} - \bar{W} \delta_{1j} \right) \times \frac{\partial q_1}{\partial x_1} \det \left(\frac{\partial x_k}{\partial \eta_k} \right) \right]_p w_p$$

- J-integral in the presence of residual stress (JEDI)

* With Dr T Becker, University of Stellenbosch

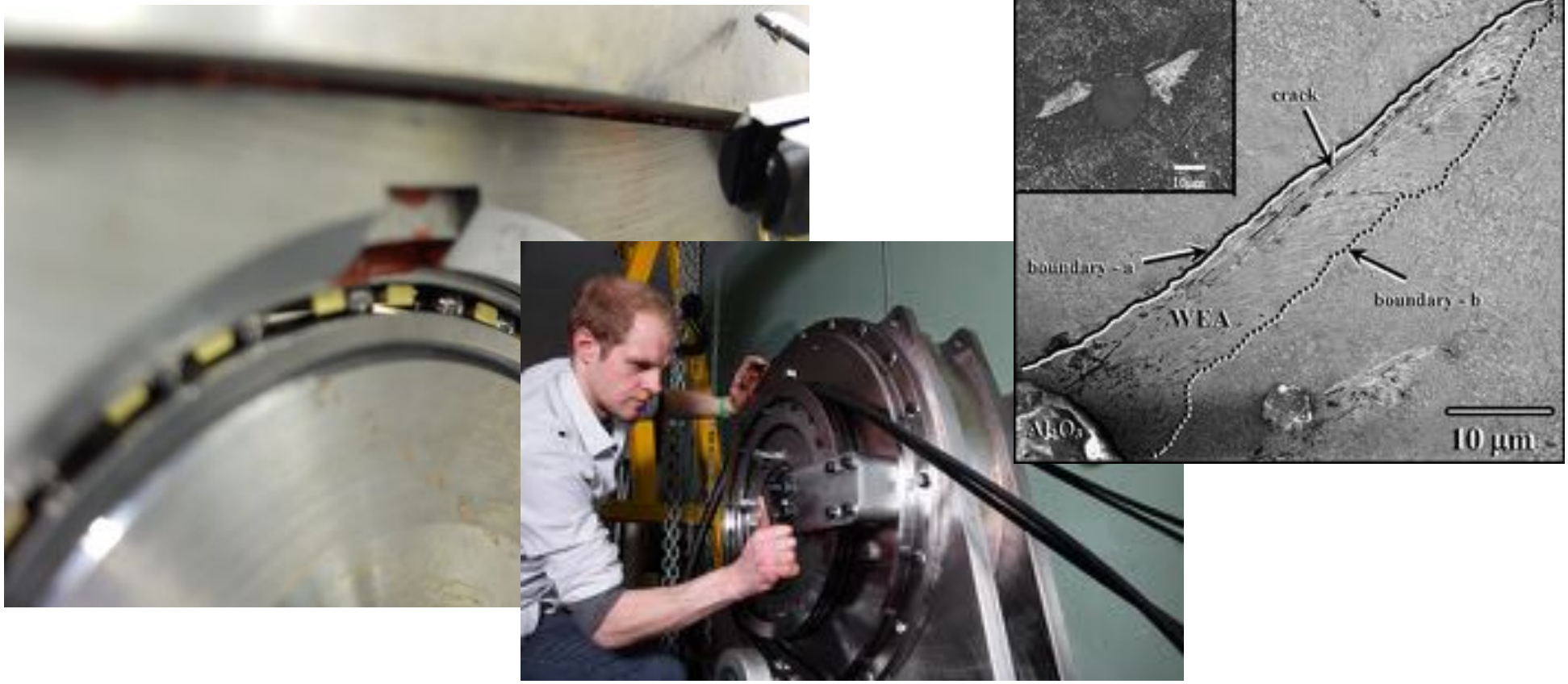
Direct elastic J Measurement





Impossible to put a clip gauge on this crack and measure crack opening displacement

* With Professor T. J. Marrow, University of Oxford

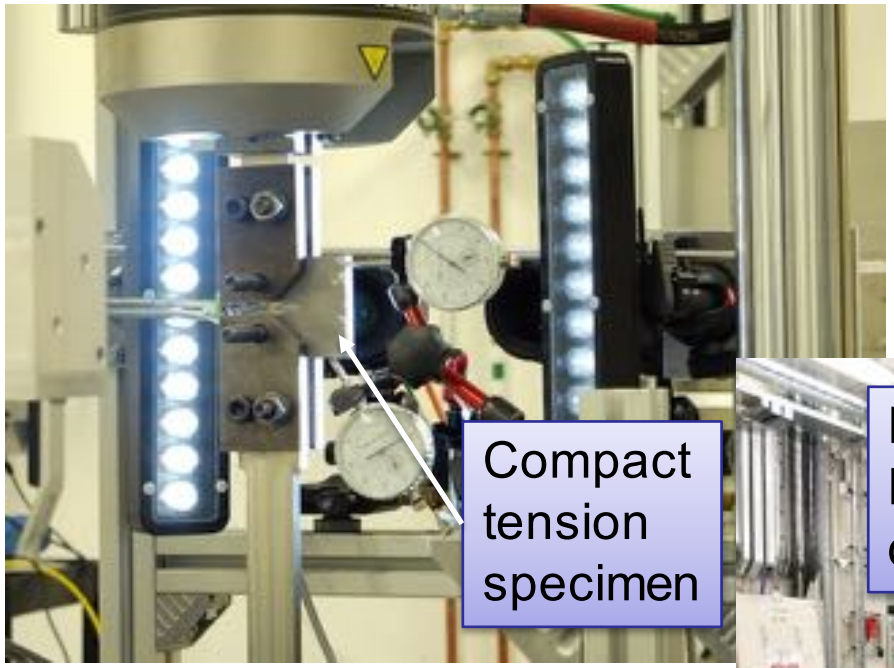


*

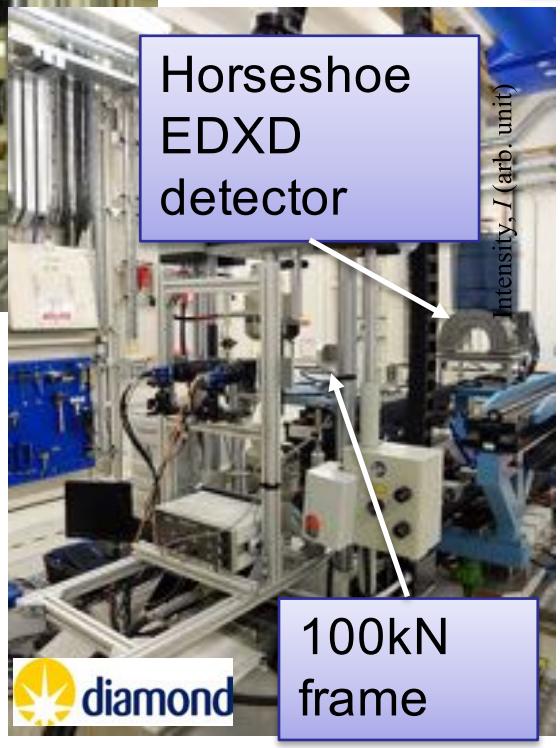
Fatigue of bainitic steel

* Grabulov, A., R. Petrov, and H.W. Zandbergen. INTERNATIONAL JOURNAL OF FATIGUE, 2010. **32**: p. 576-583

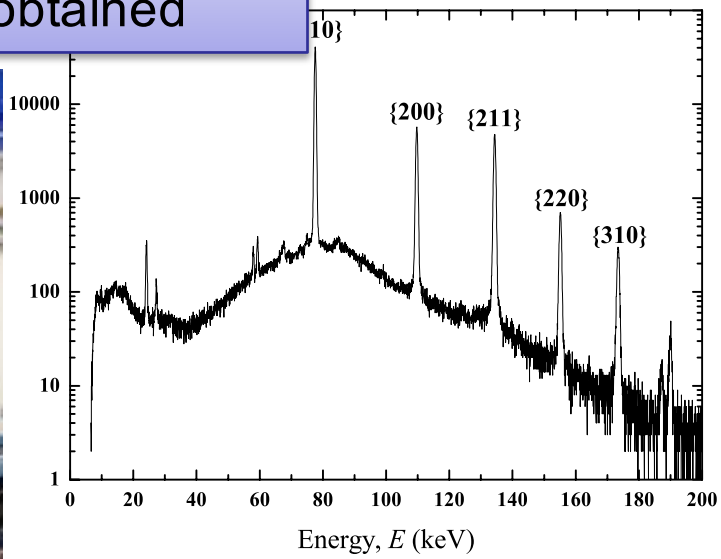
DIC and synchrotron



Effect of overload (crack tip blunting and residual stress) was investigated



23 diffraction peaks are obtained



diamond

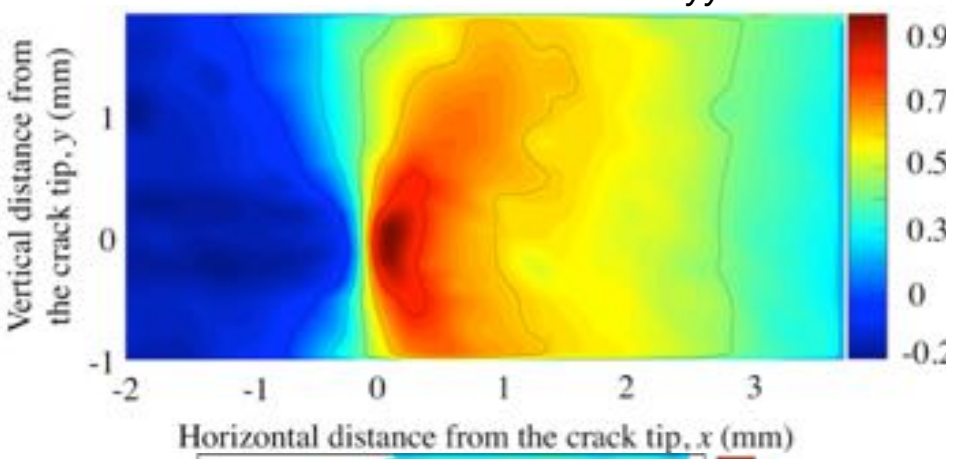
* With Prof P. J. Withers, University of Manchester

DIC and XRD

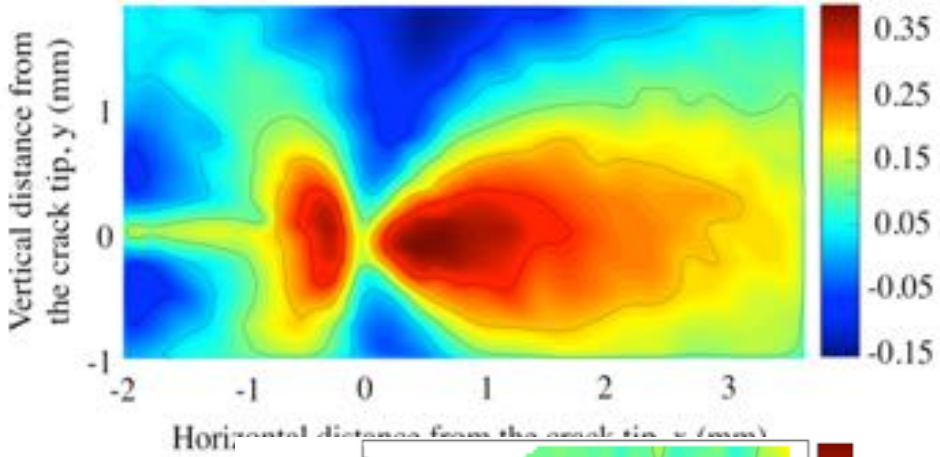
XRD

Lattice strain – elastic

In the loading direction e_{yy} (%)

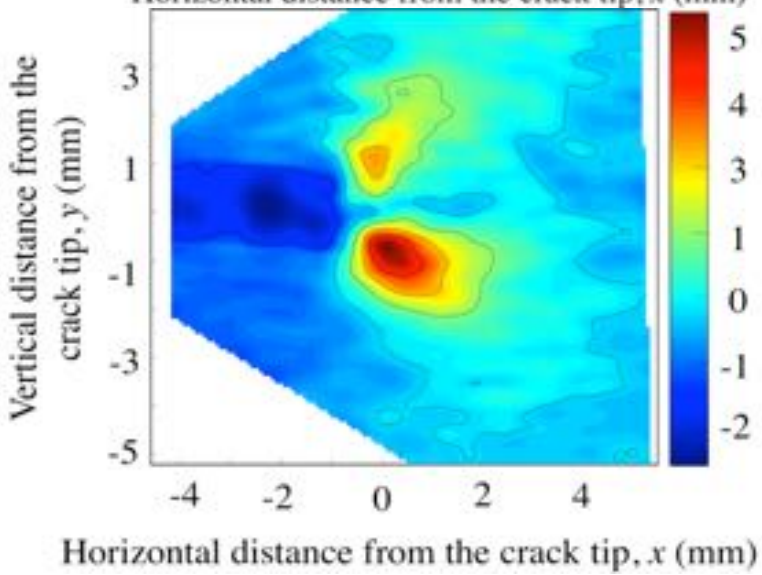


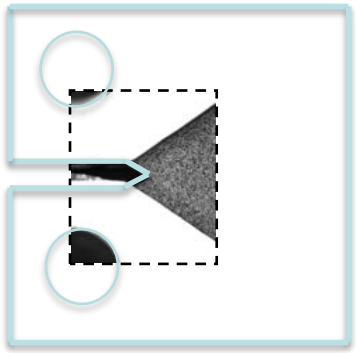
parallel to the crack growth direction e_{xx} (%)

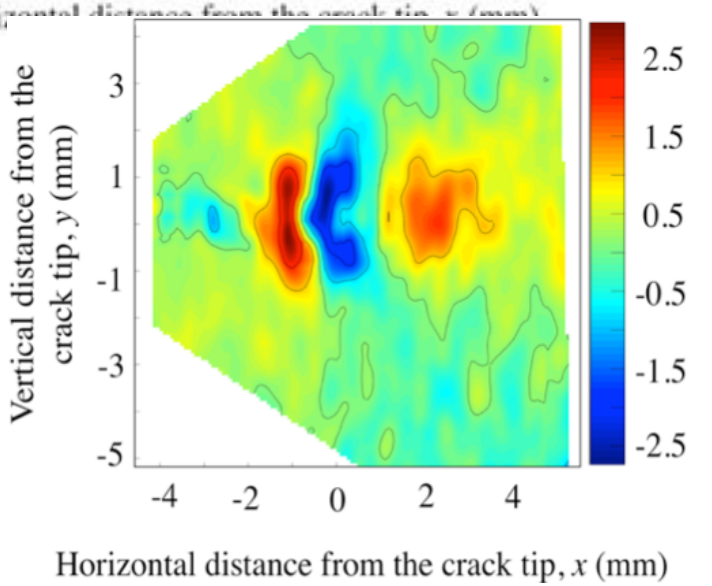


DIC

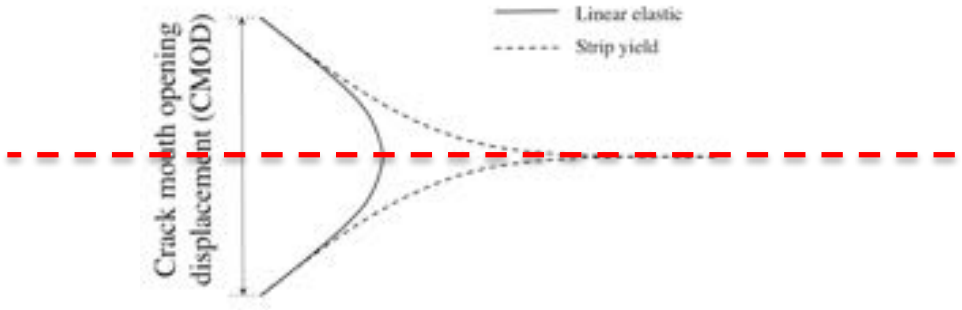
Surface strain – total



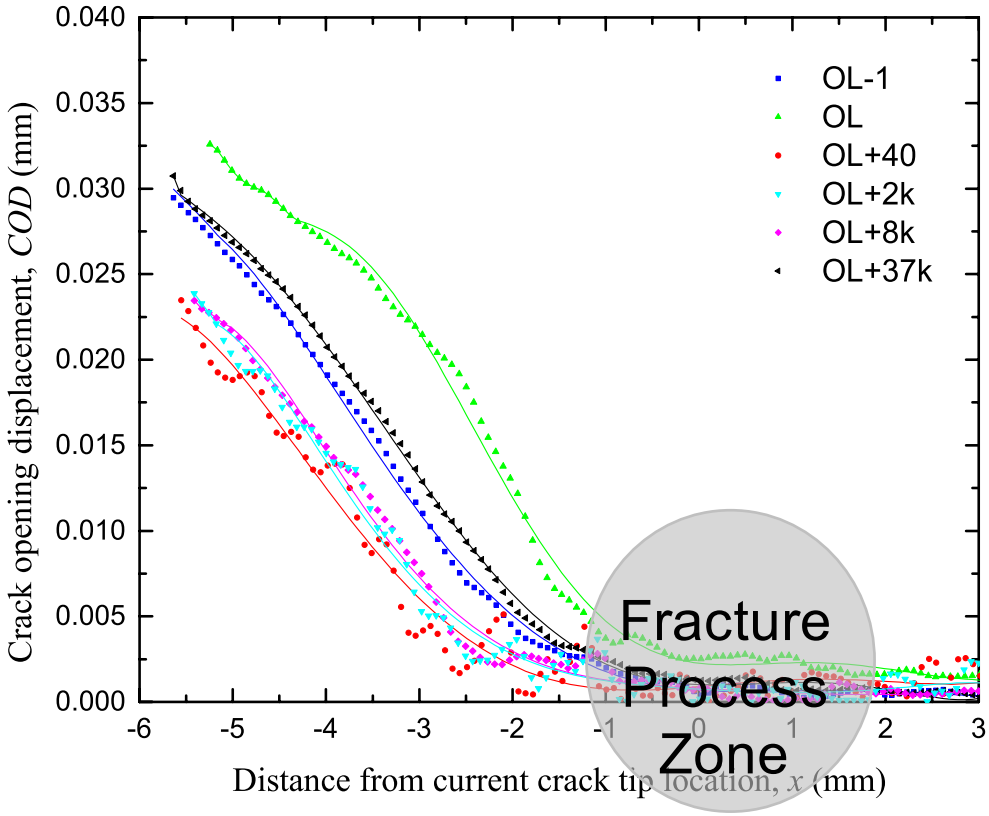




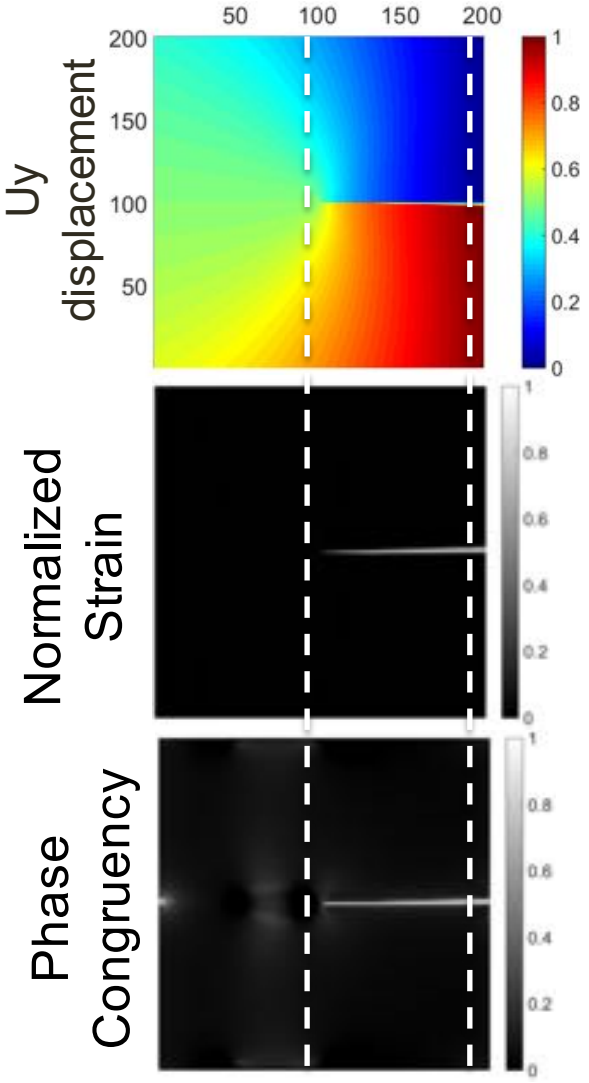
Crack opening

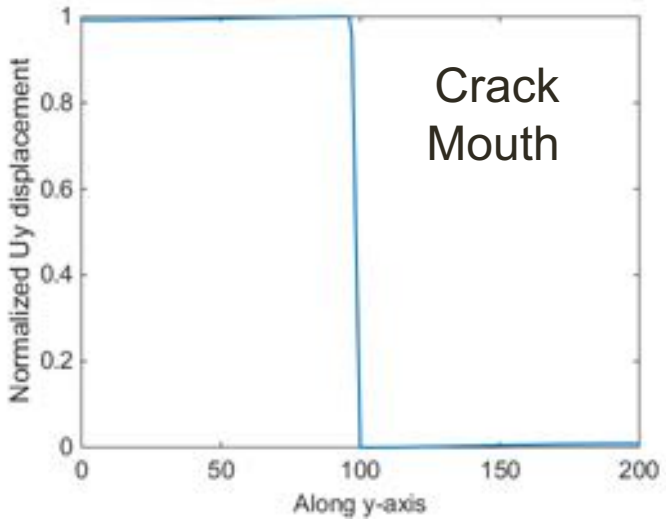


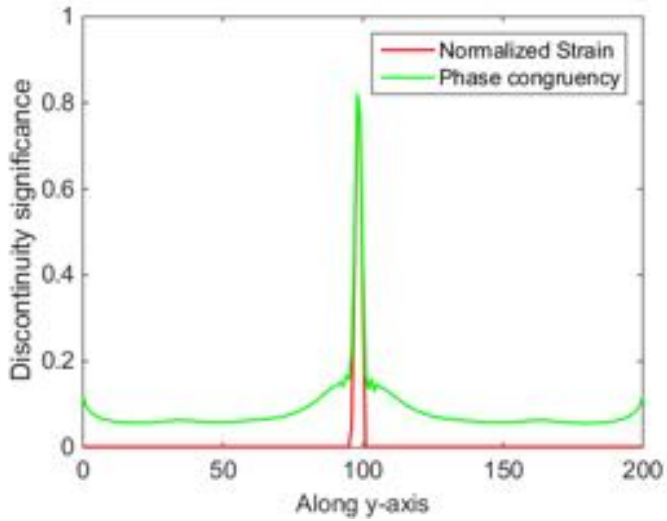
- Crack is identified
- Opening displacement profile was extracted
- The far field opening profiles are affected by the local residual stress field

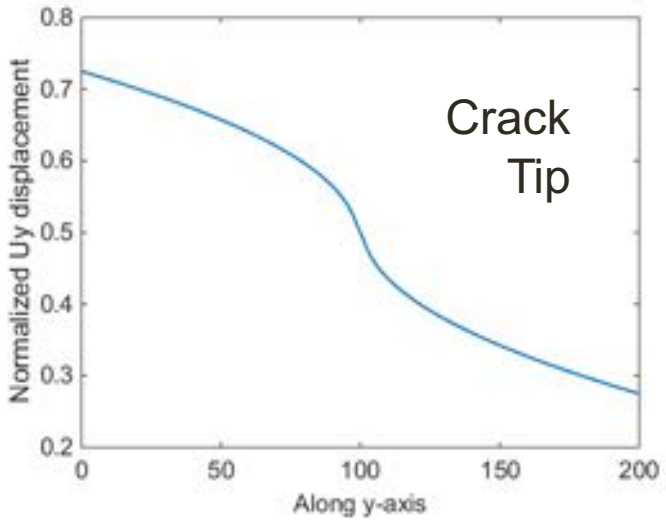


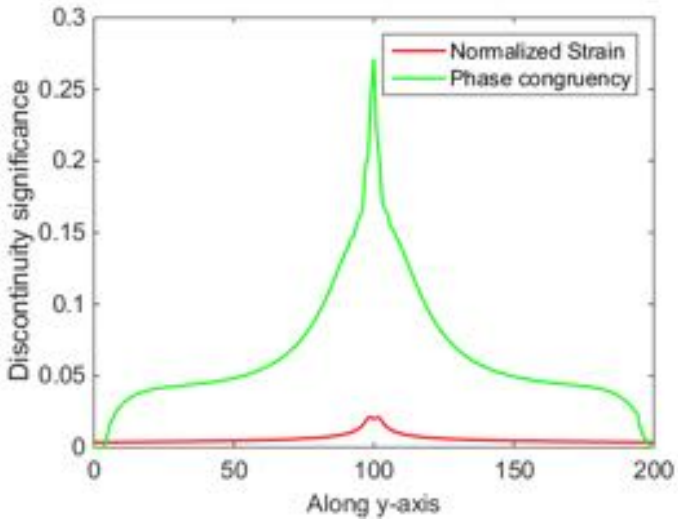
How to find a crack



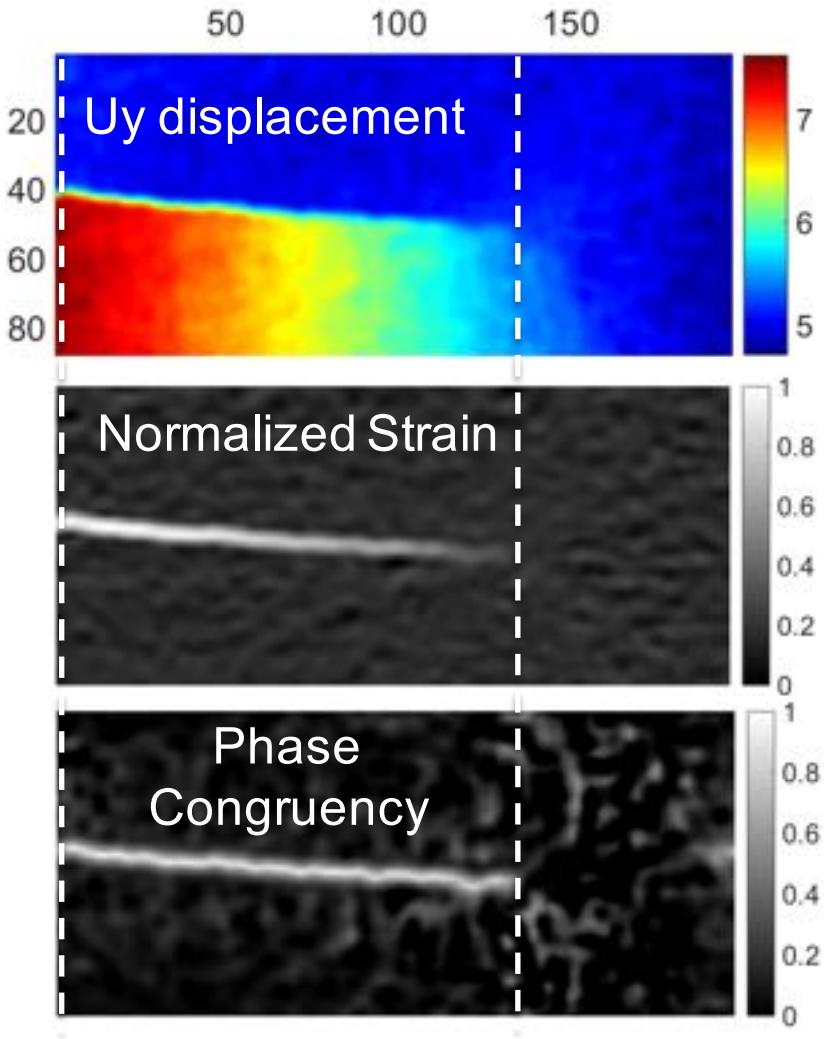


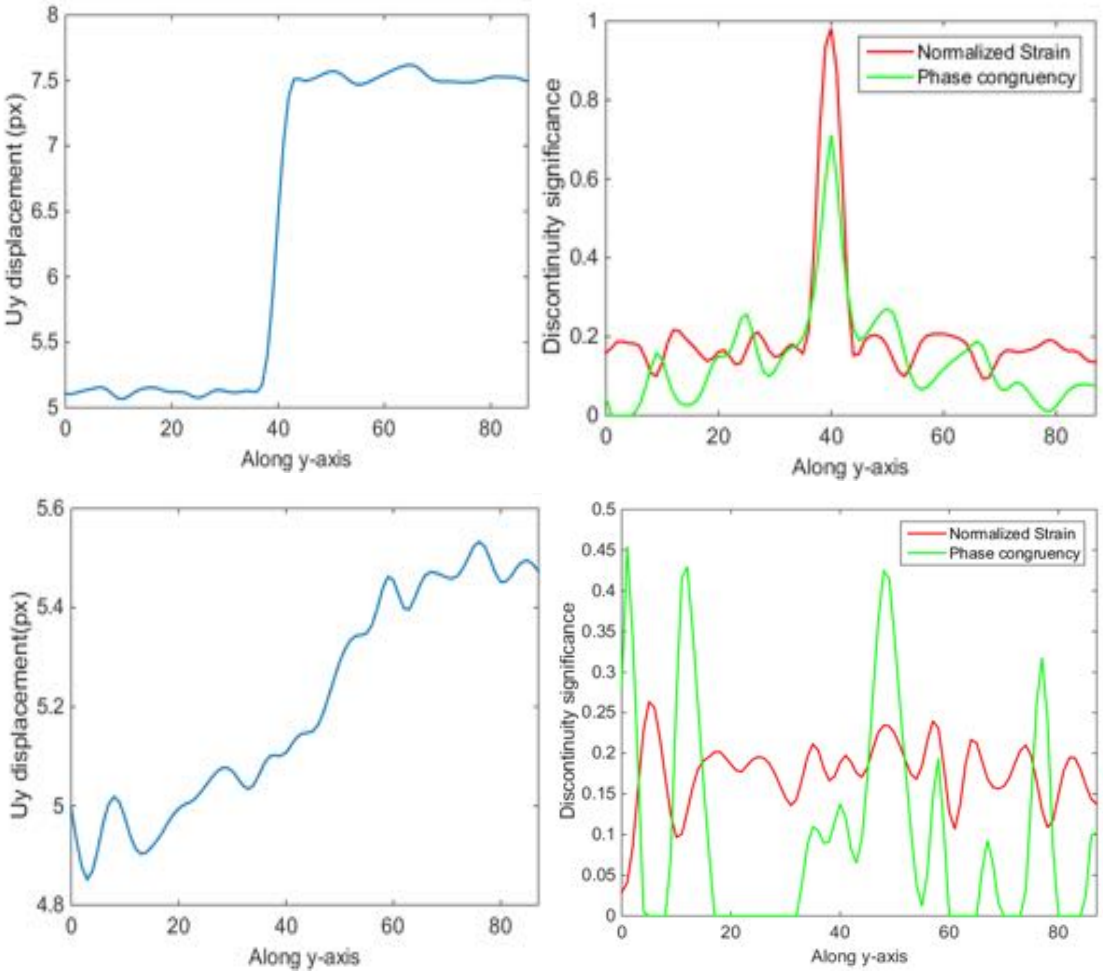




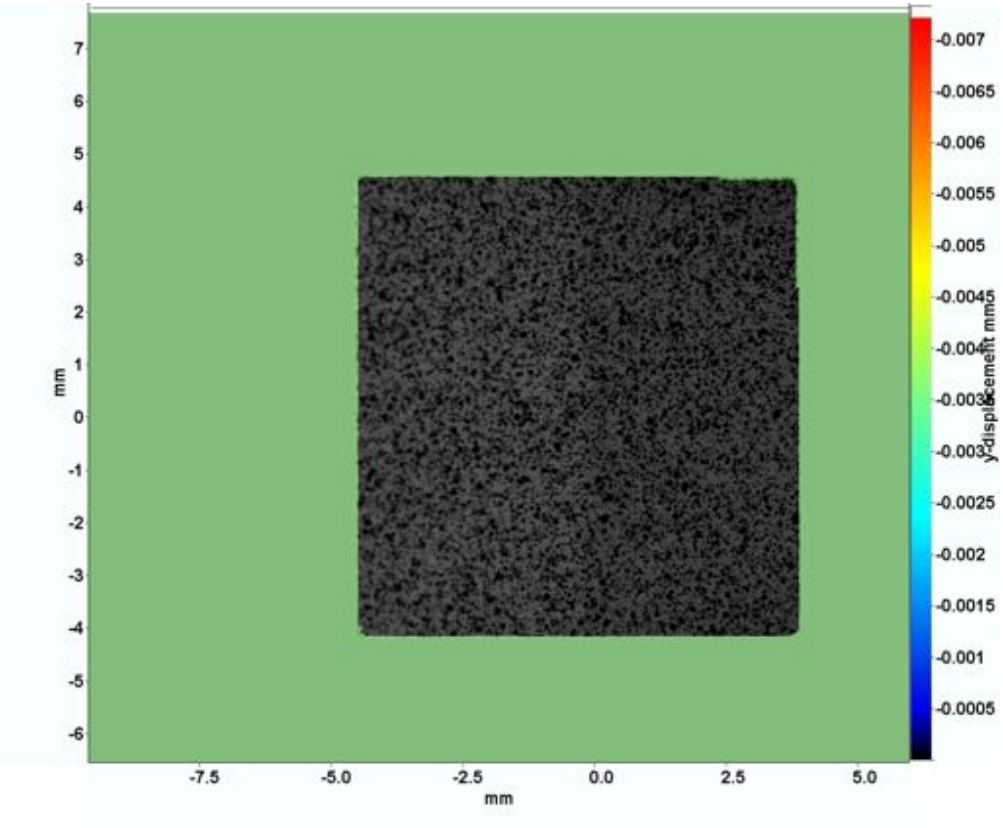


Phase Congruency



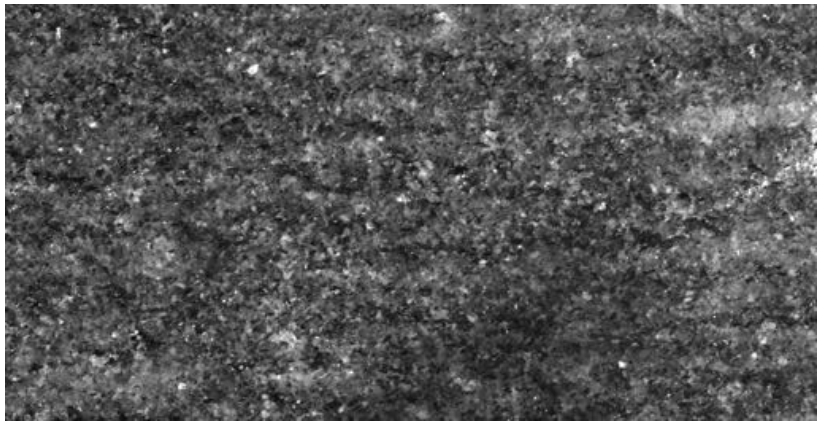


Crack detection

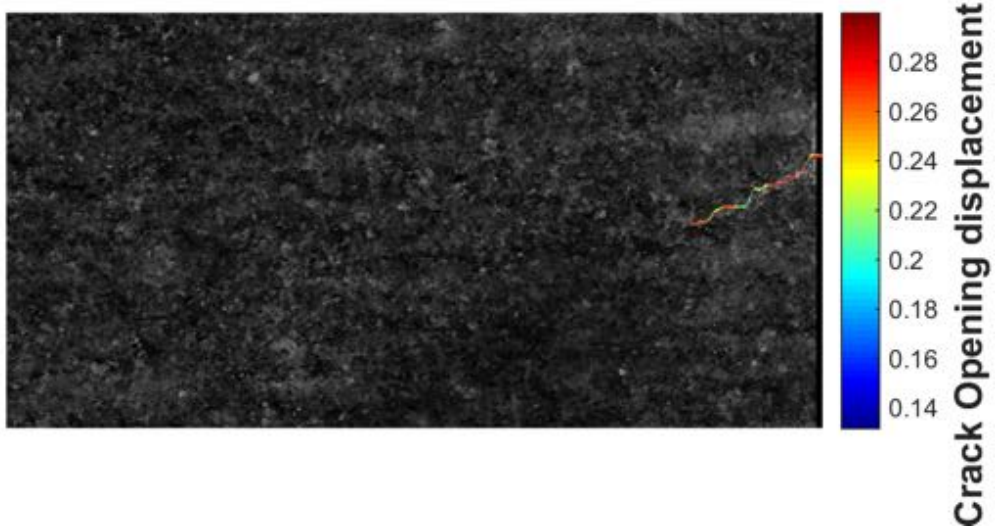


Directly from DIC analysis (bainite steel)

Original images



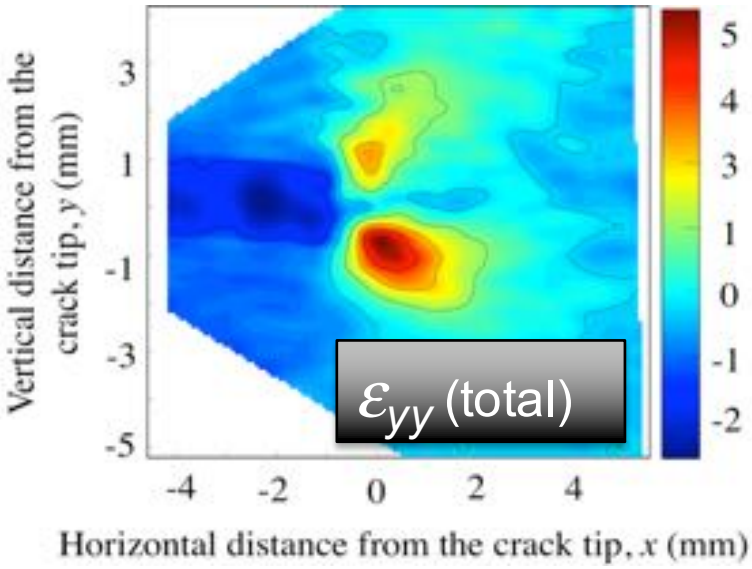
Atomatic crack detection and quantification

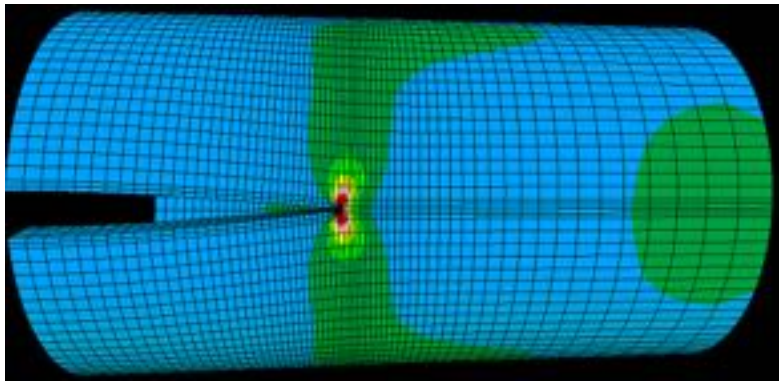


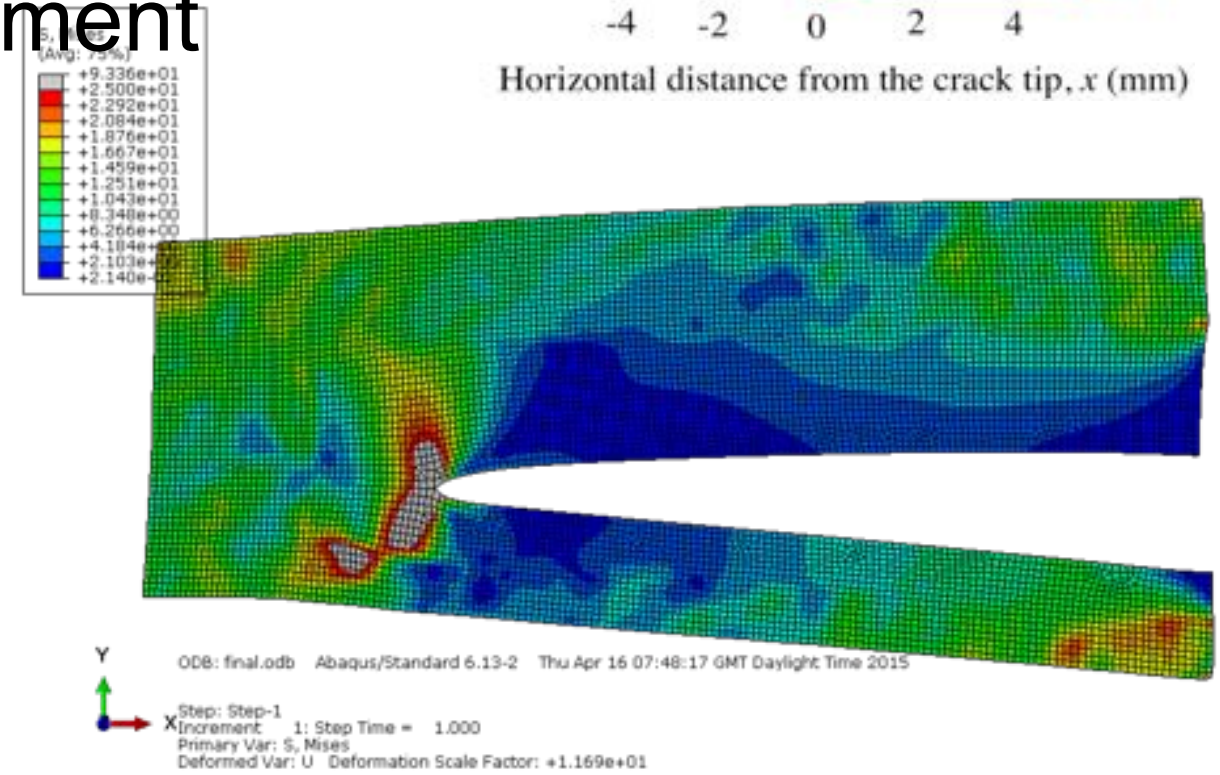
* With Dr T. Sjögren and Dr M. Johansson

DIC informed FE

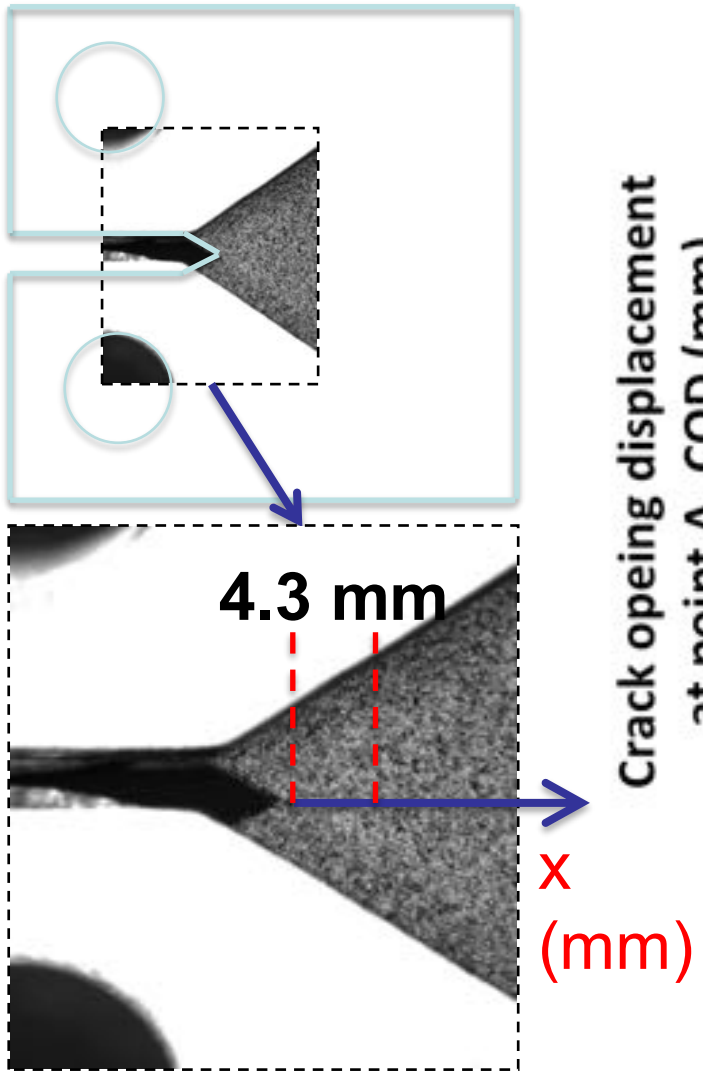
- One point verification and validation
- Full-field measurement

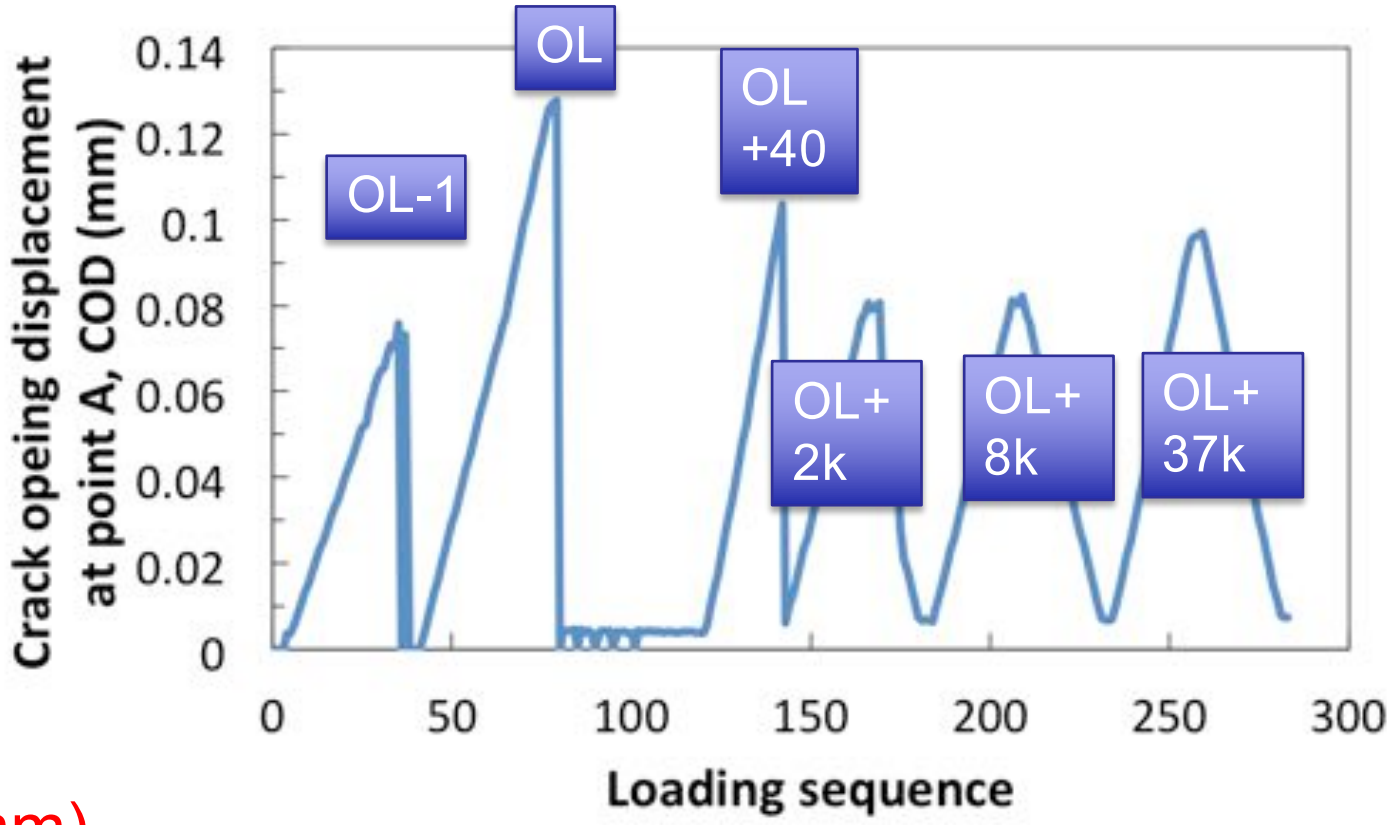






CMOD evolution

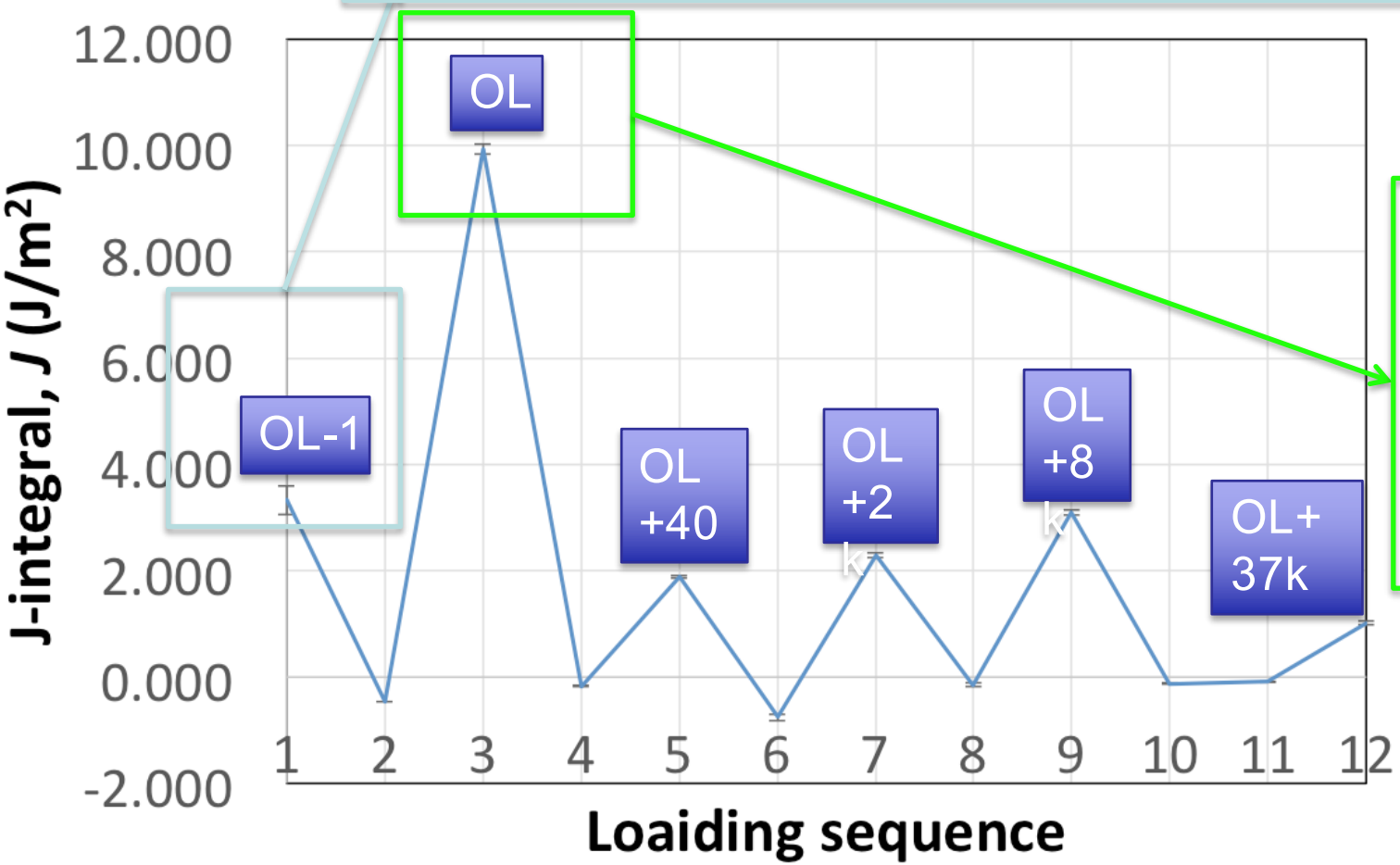




Direct *J*-calculation

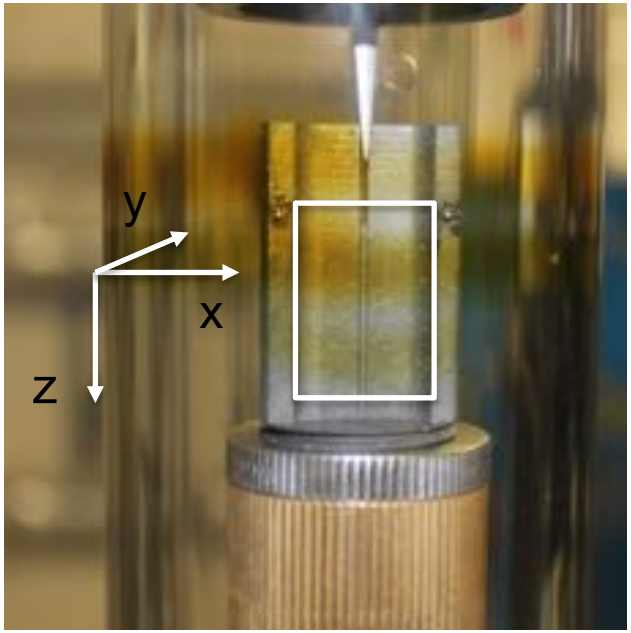
J=3.329 J/m^2
i.e. K_{OL-1}=27.72 MPa.m$^{0.5}$

From applied load: K_{OL-1}=35 MPa.m$^{0.5}$
(21% difference)

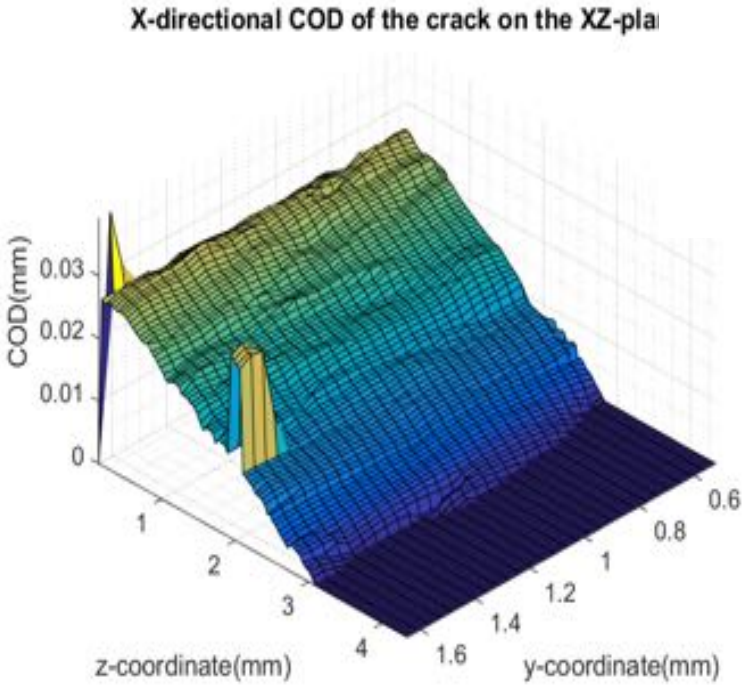


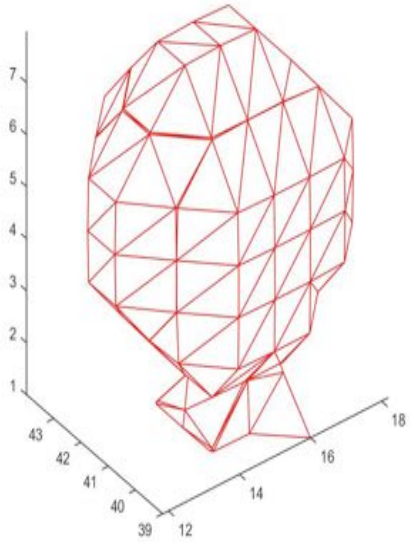
J=9.930 J/m^2
i.e. K_{OL}=47.87 MPa.m$^{0.5}$
=1.7K_{OL-1}
(21% difference)

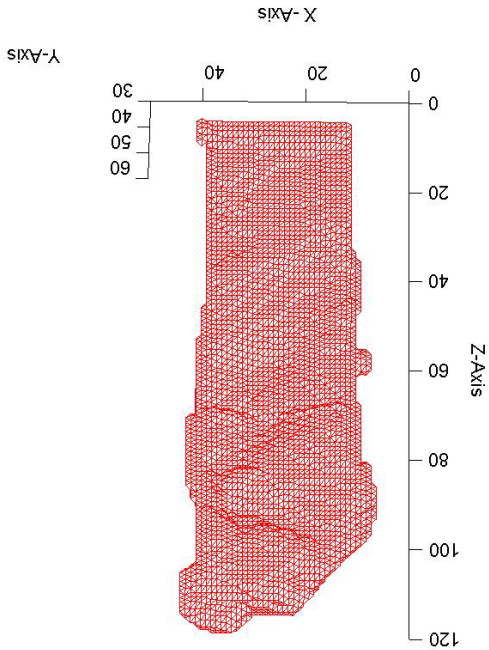
3D Crack Detection

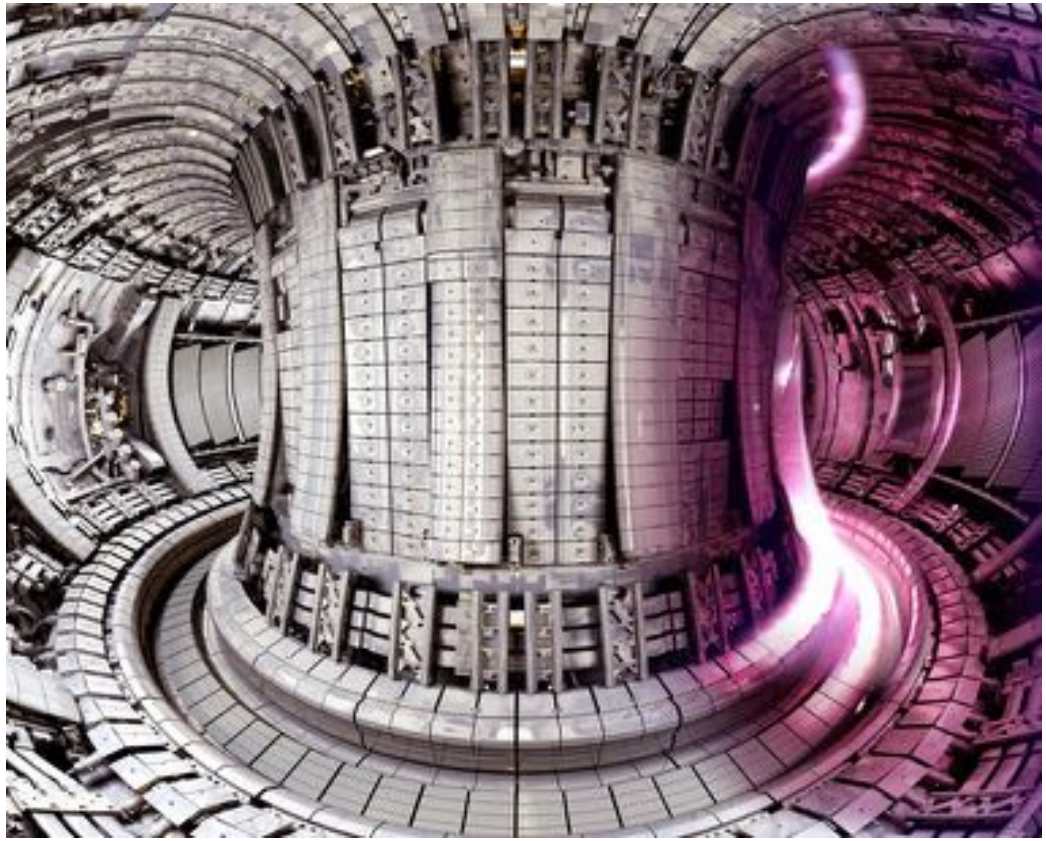


- X-ray tomography
- 2000 x 2000 x 4500 pix
- DVC analysis:
  Voxel size: 128x128x128
  Overlap: 75%



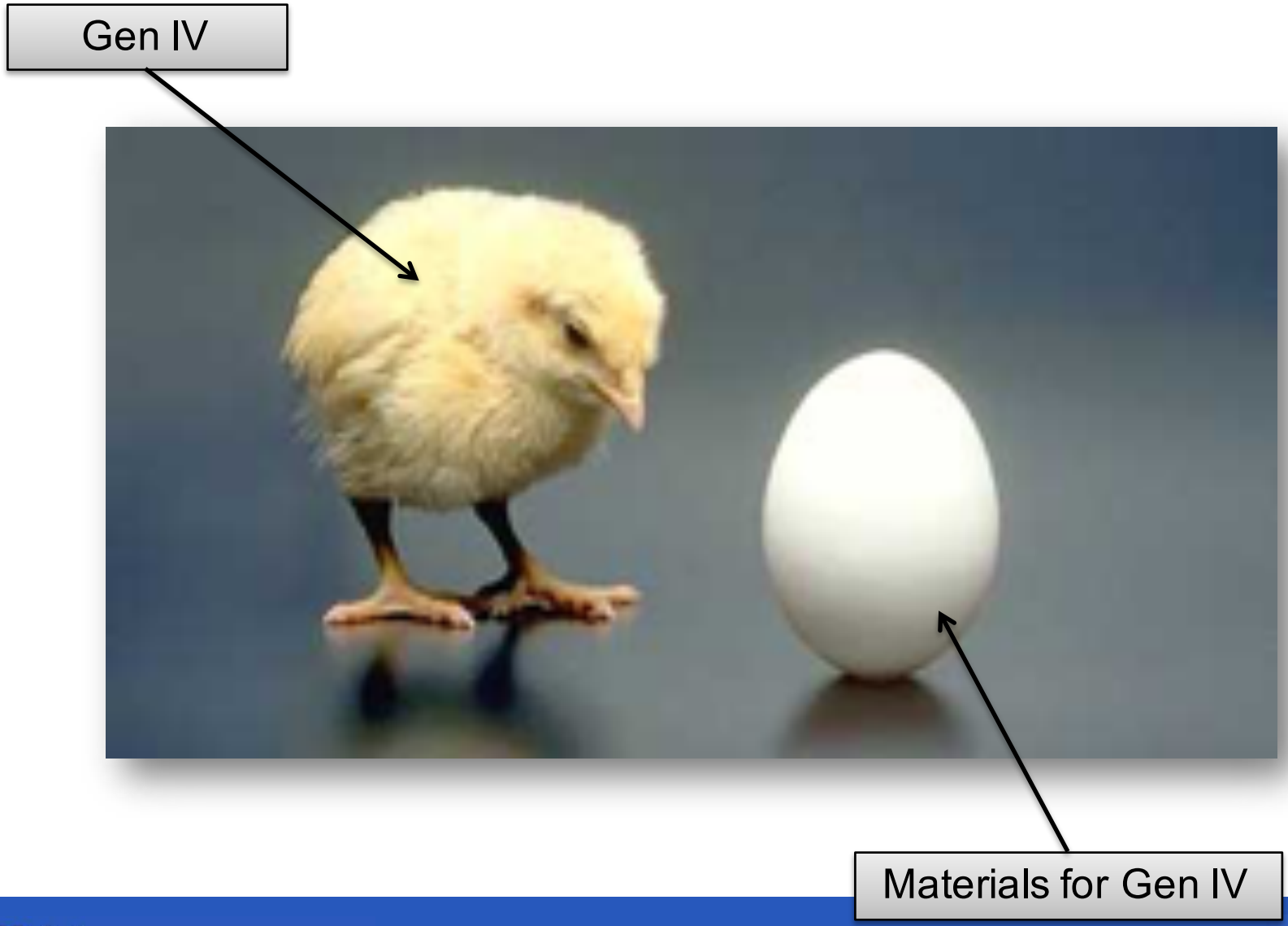




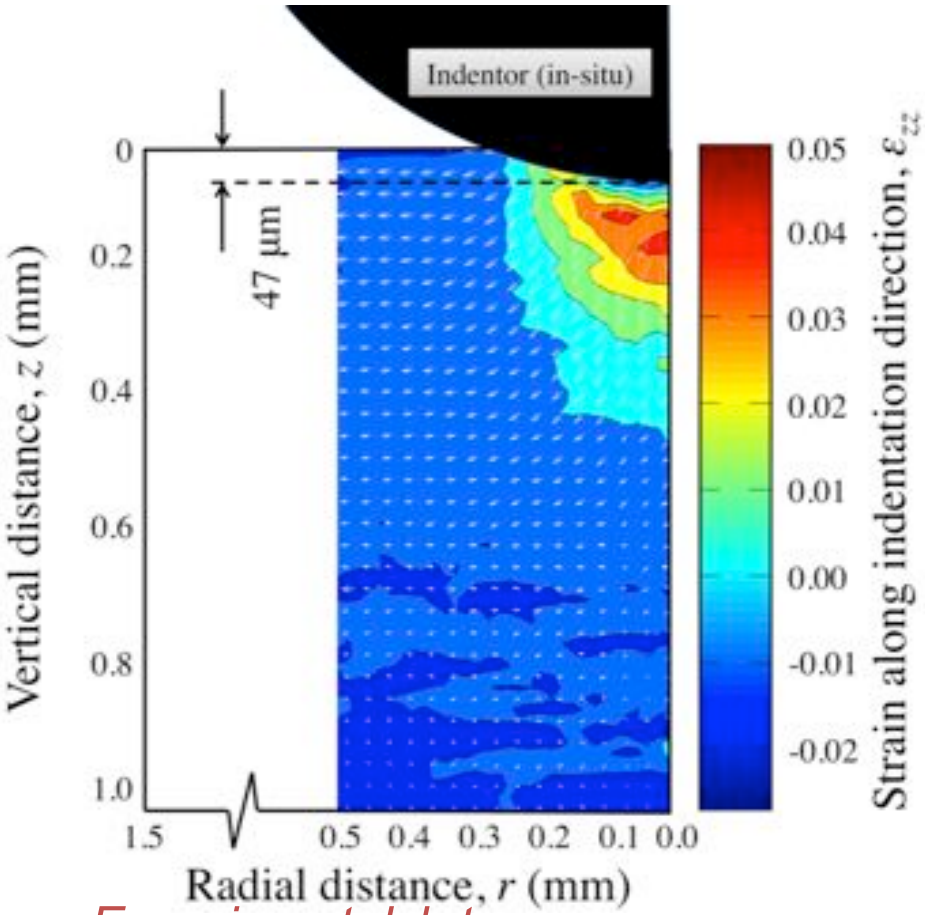


- Oxide dispersion-strengthened alloy

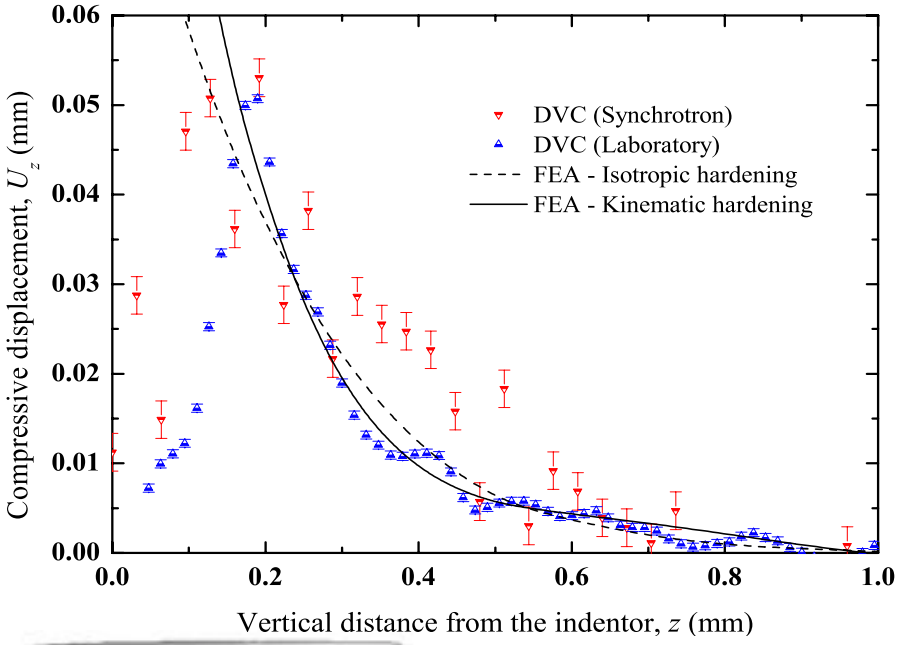
Gen IV Nuclear Power Plants



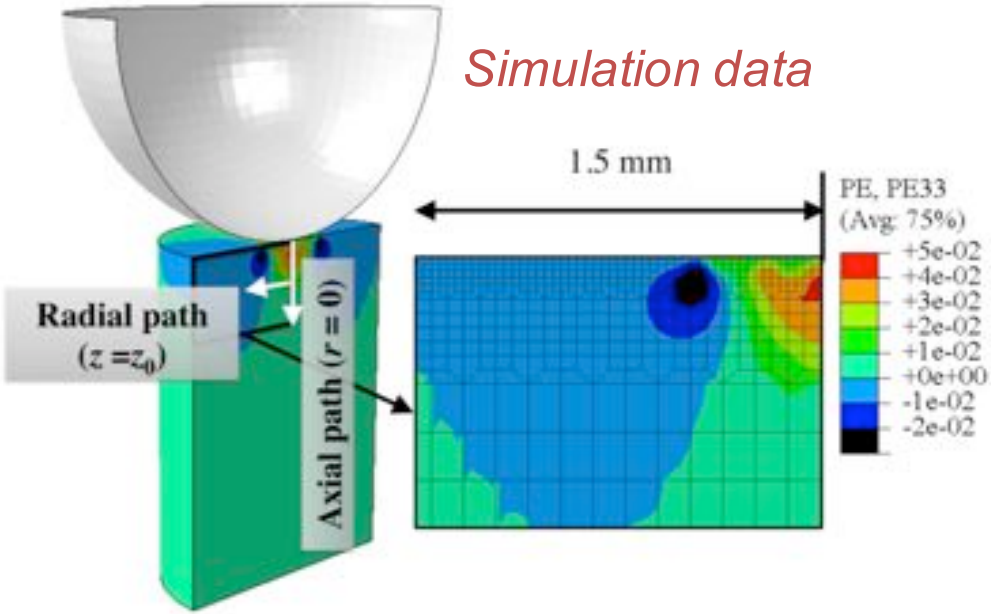
FE-DVC



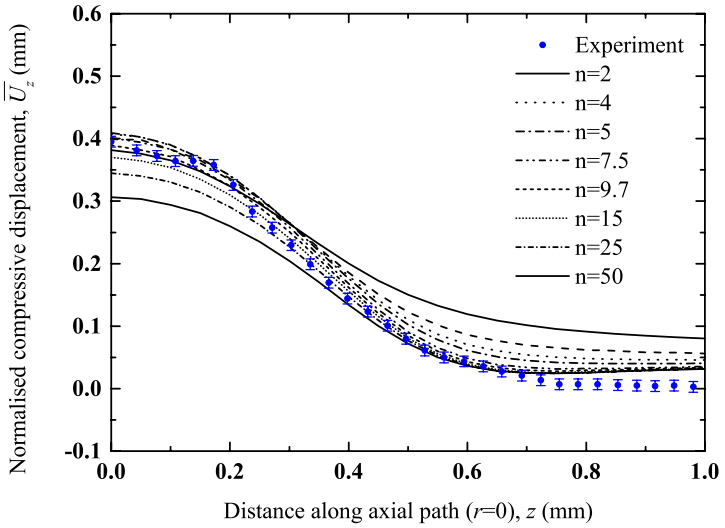
Experimental data

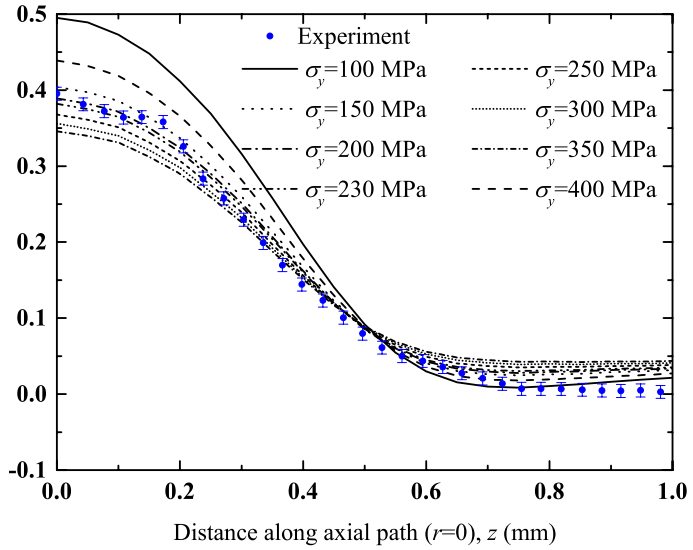


Simulation data

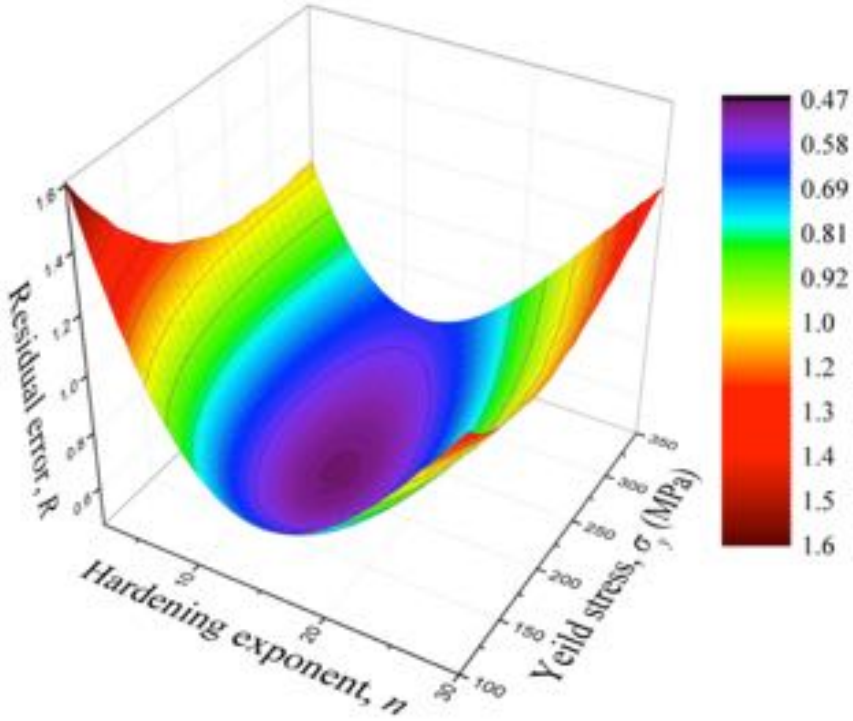


Reverse engineering





"Reverse Engineering" can be used to obtain material properties

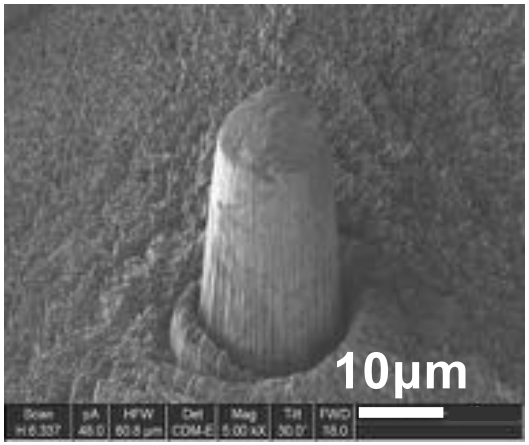


Residue

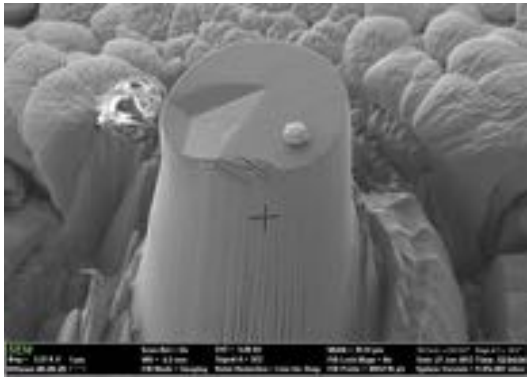
$$R_{ij} = \sqrt{\sum_{k=1}^{N} \left(M_{ijk}^{FE} - M_{ijk}^{Exp} \right)^2}$$

Nano tompgraphy

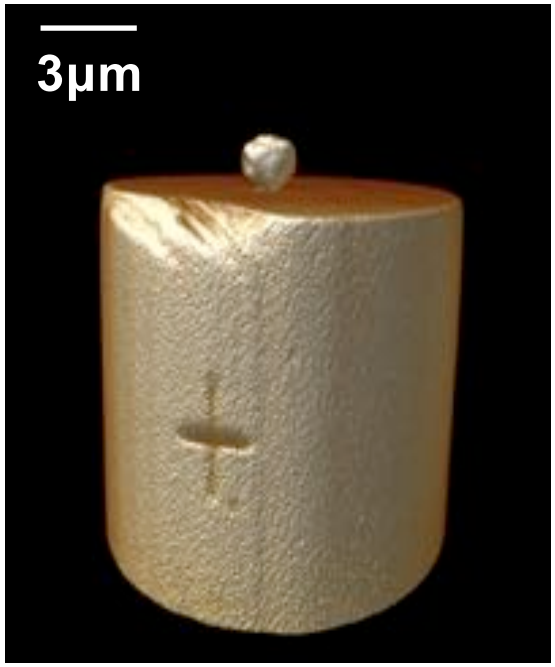
Before



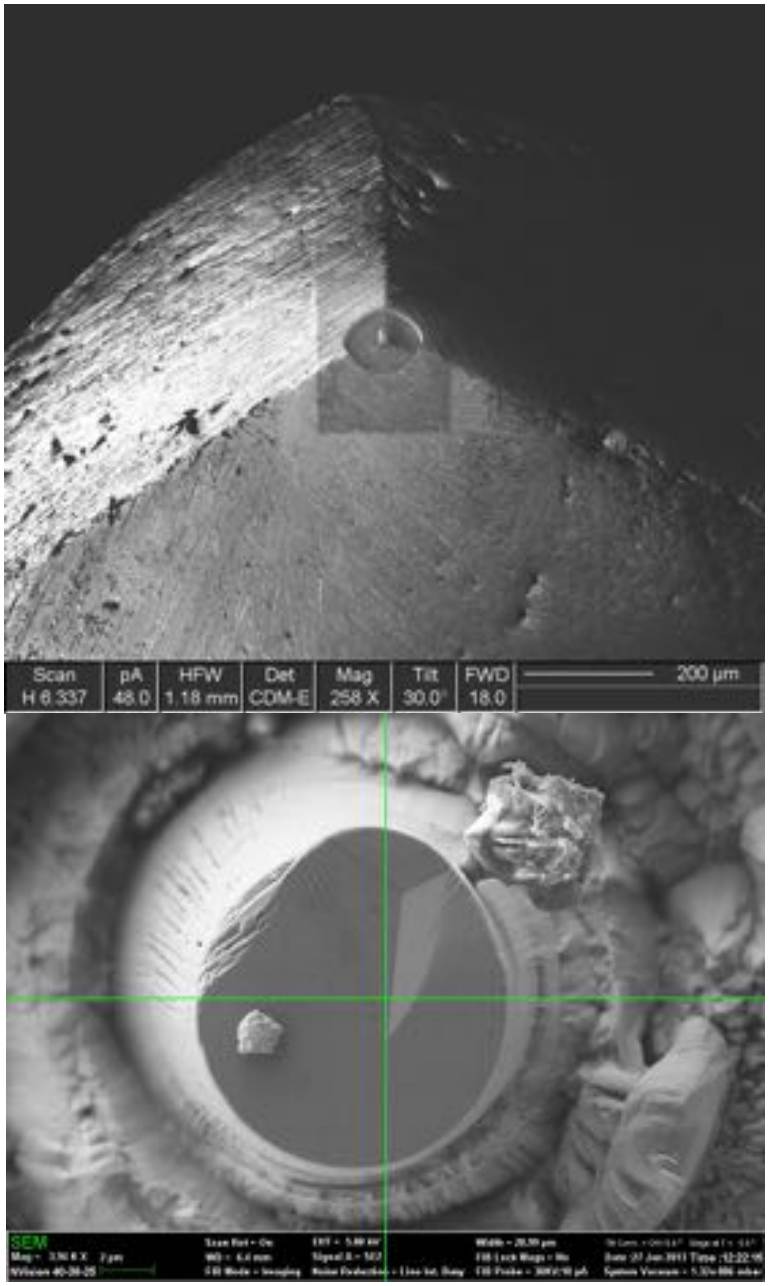
After



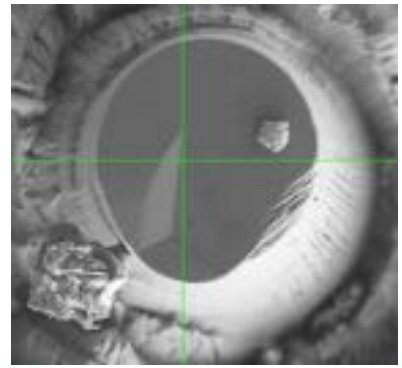
Nano-tomography
(resolution 35nm)

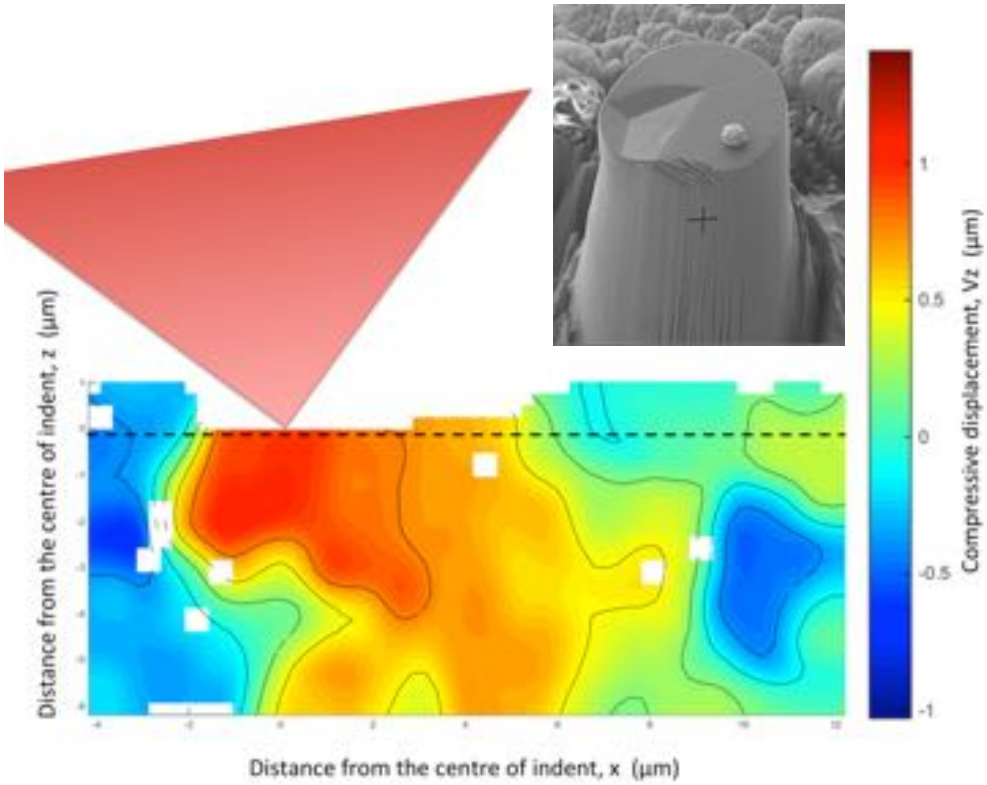


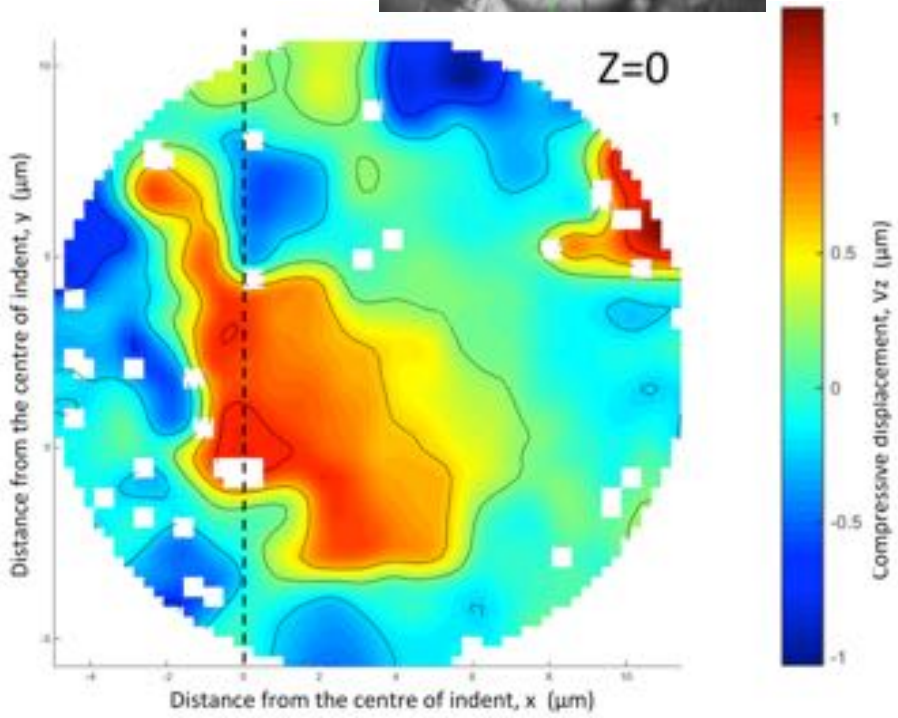
Material property extraction from nano-tomography, in-situ nano-indentation, and digital volume correlation



Displacement field





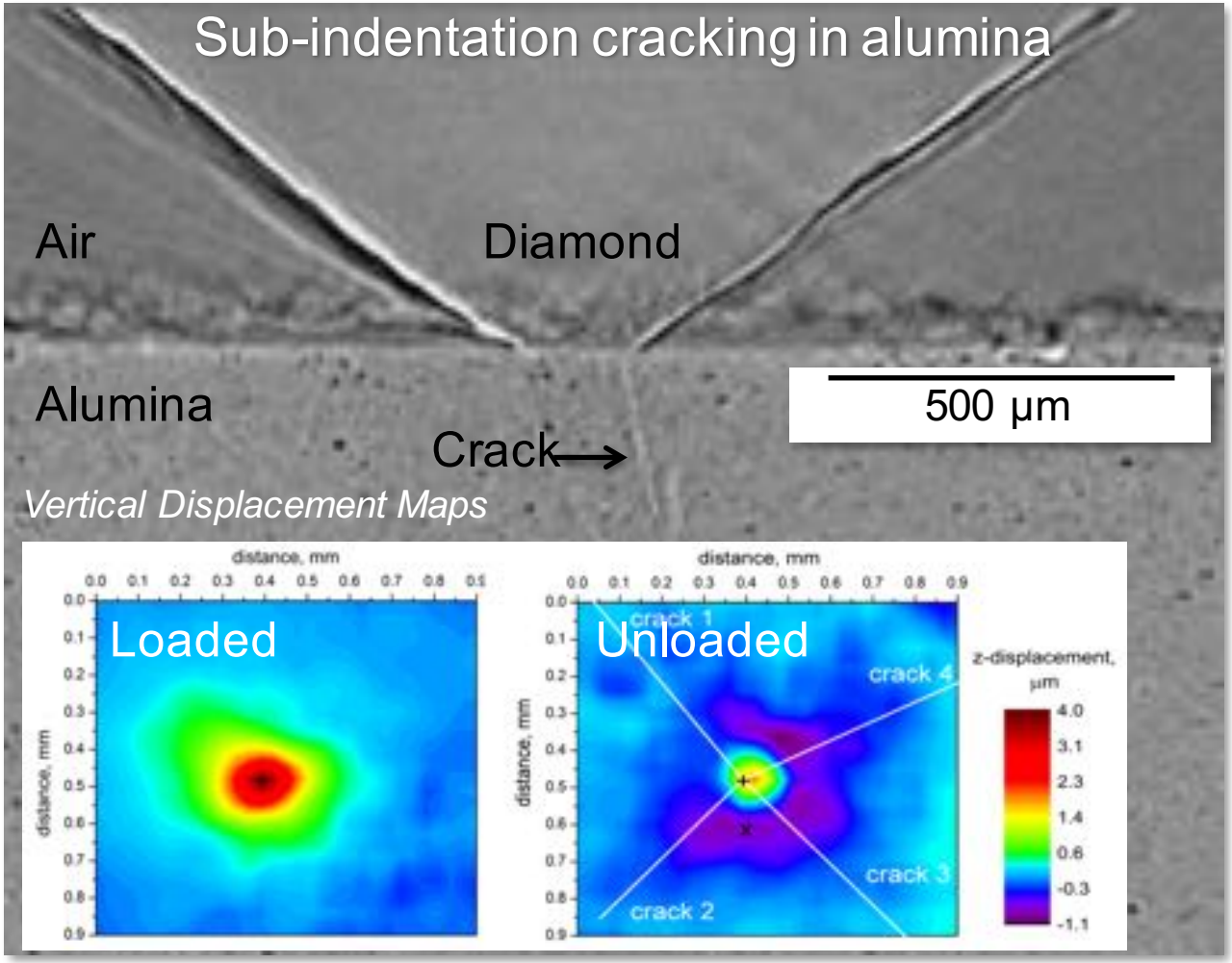


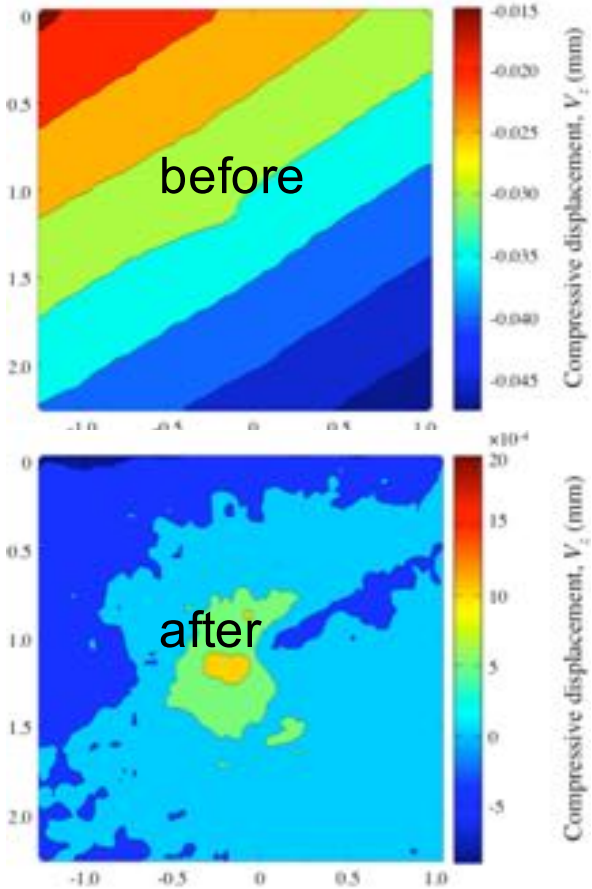
We are still analyzing the data!

Other examples

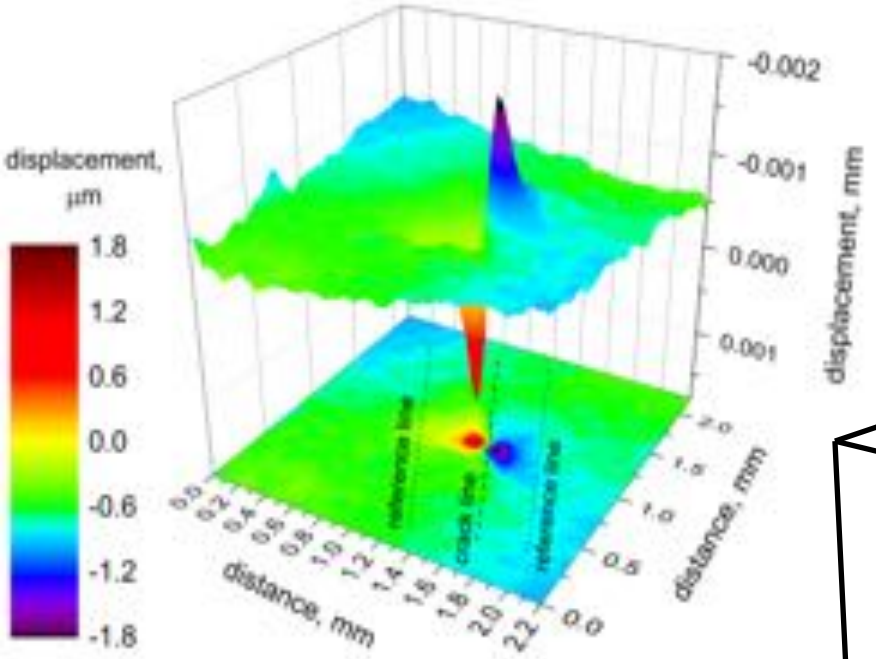
Ceramic indentation

Seemingly simple problems e.g rigid body rotation during the experiment can become a big issue when the aim is to resolve small displacements



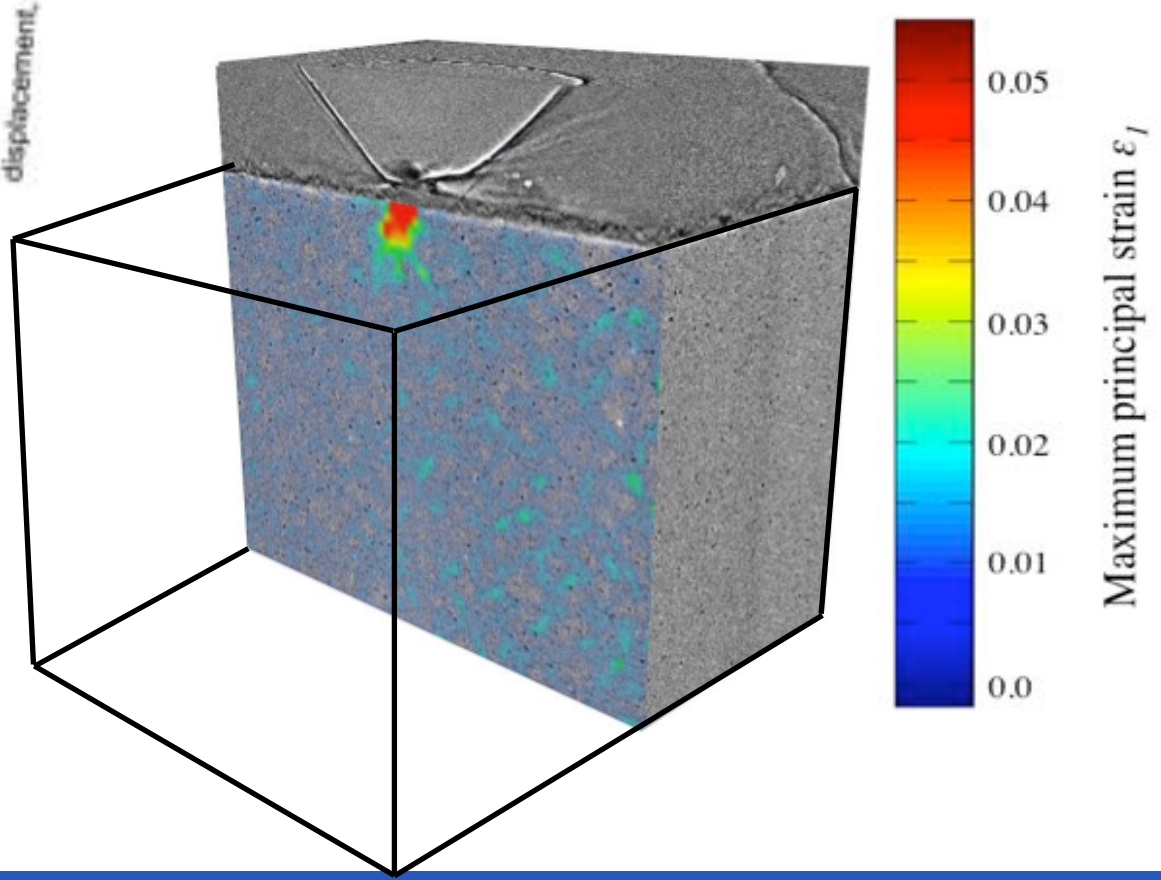


Strain visualization: alumina



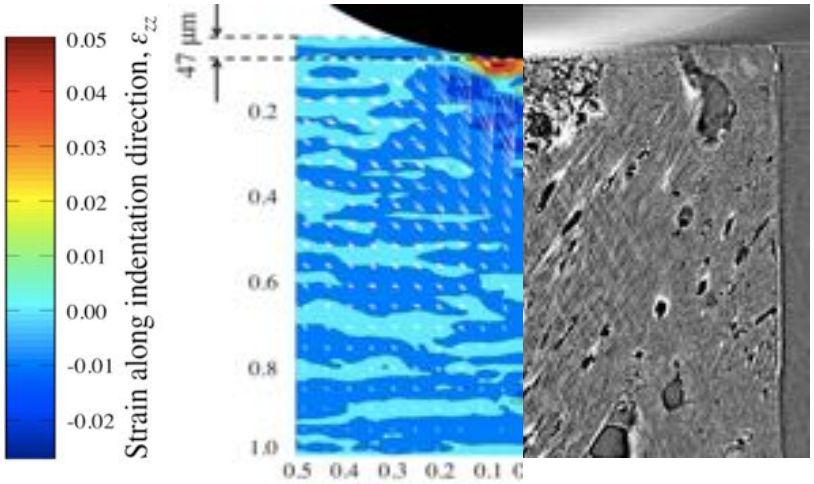
The displacement component perpendicular to a trace through the indenter

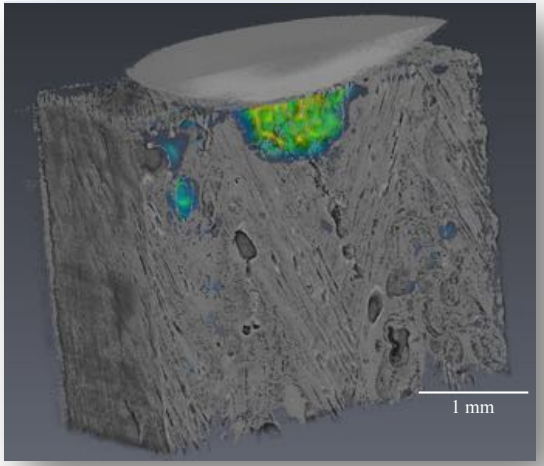
DVC detects damage at the indentation point, but quantification is difficult



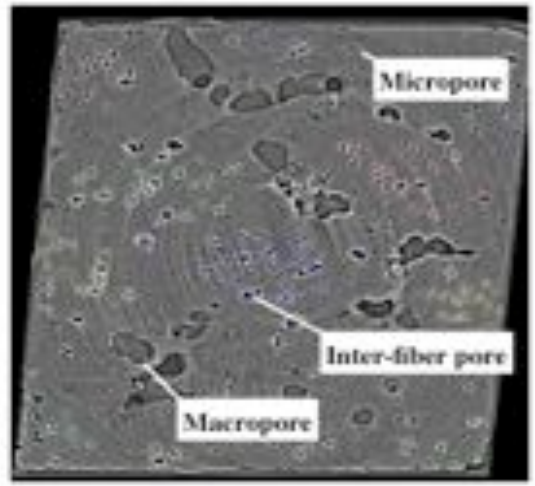
The crack openings show a mixed mode I (opening) and mode II (in-plane sliding)

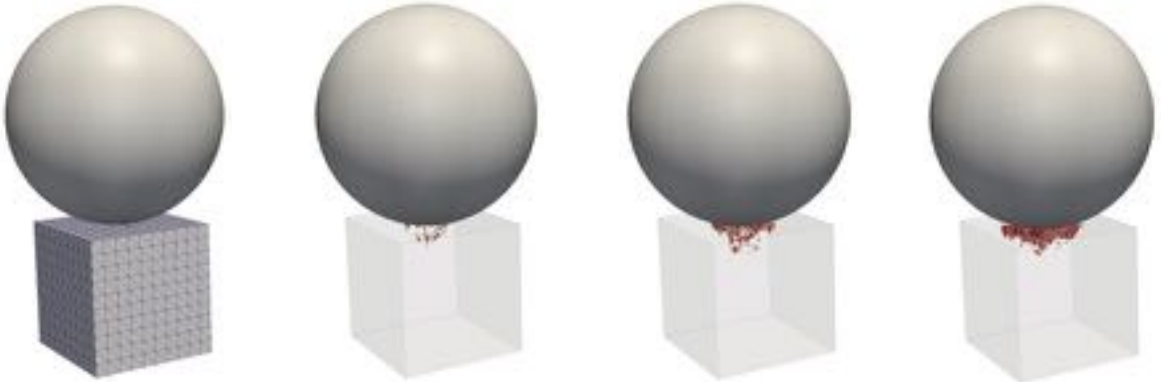
Damage in SiCSiC$_{fibre}$



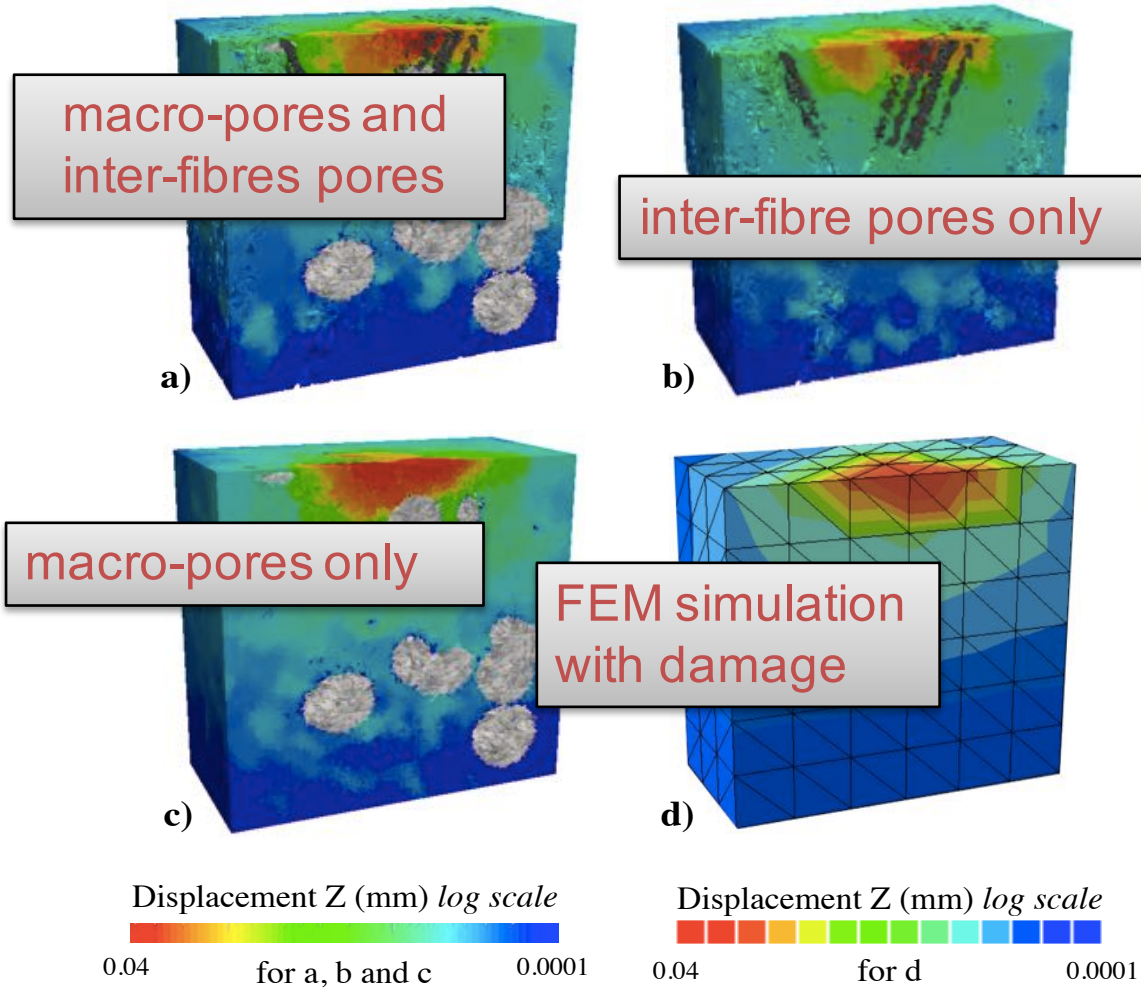


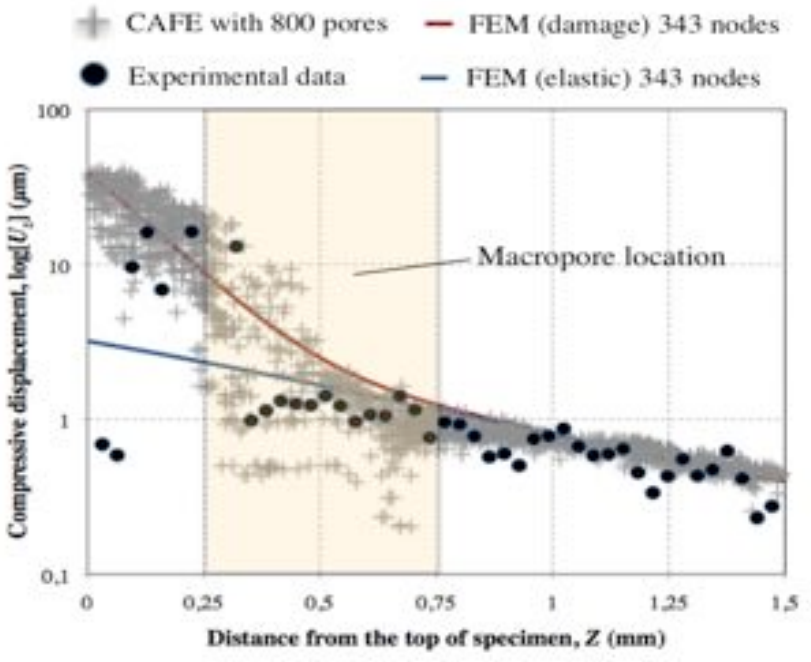
Zone of damage observed under the indentation





CAFÉ modelling

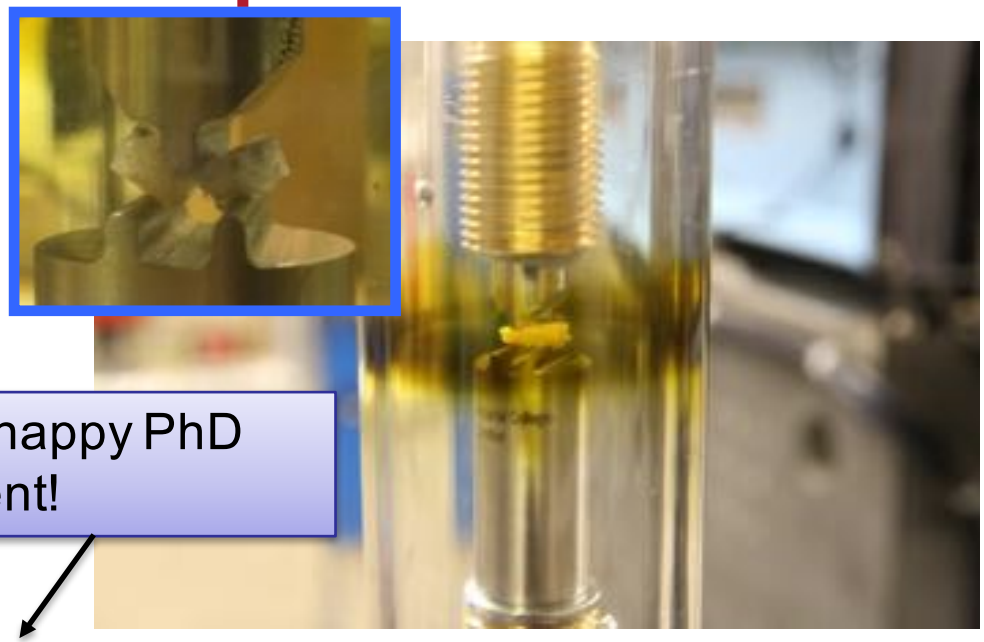




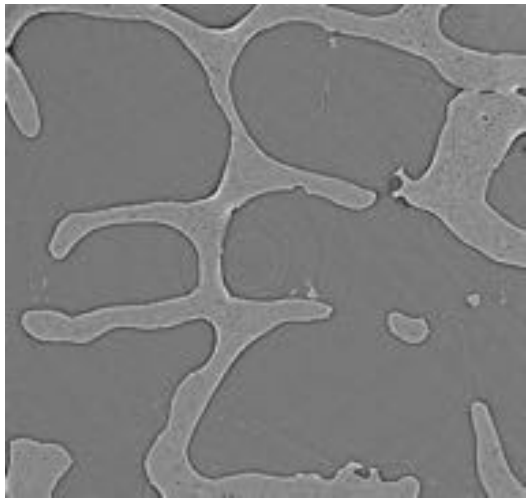
Influence of the pores and fibres on the compressive displacement field; CAFE simulation with

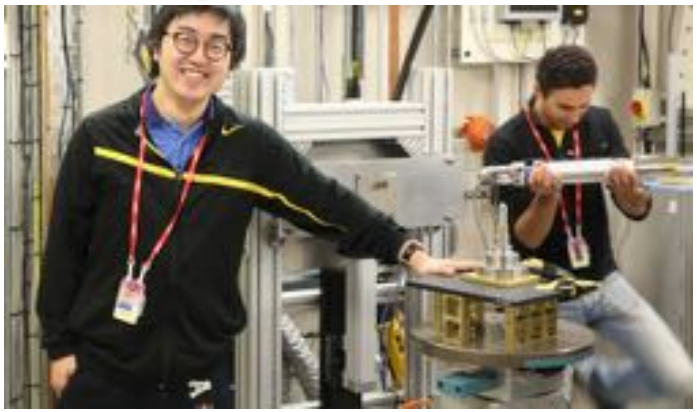
Osteoporosis

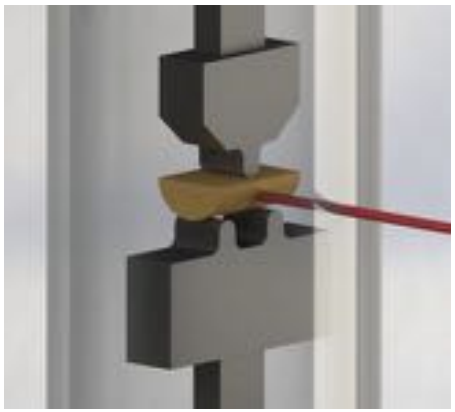
Tubercular HUMAN bone!

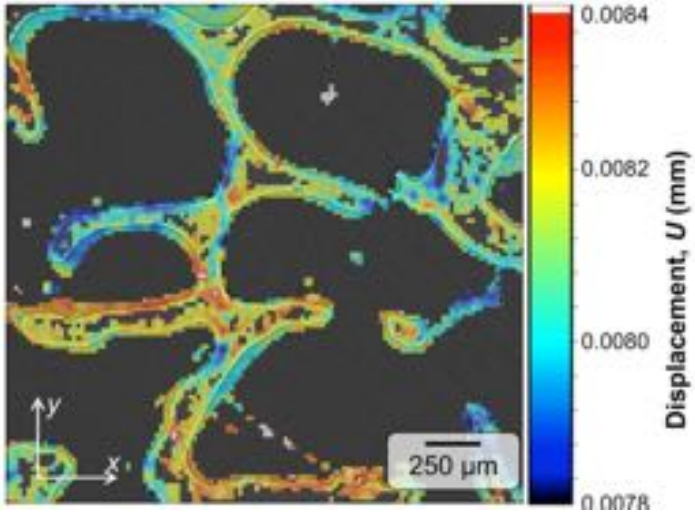


Very happy PhD student!



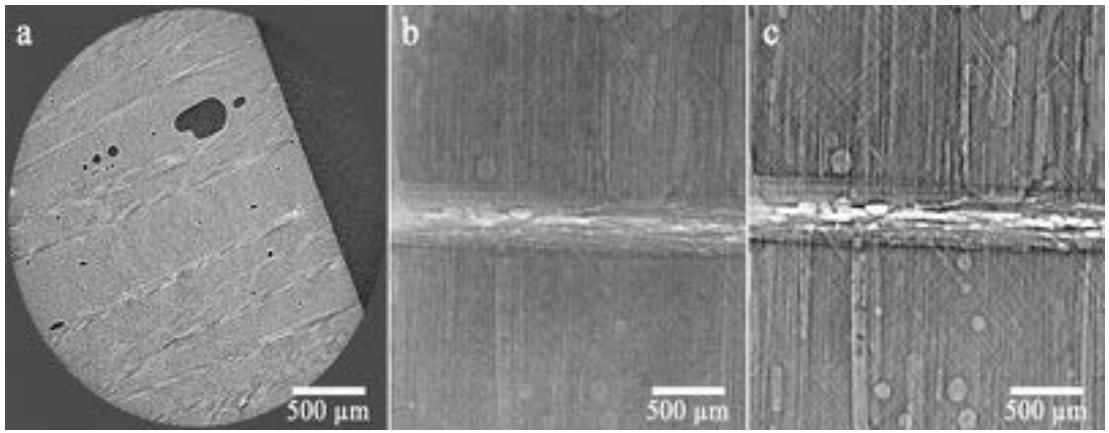






* With Dr R. Abel, Imperial College London

Composites at low temperature



XCT scans of a representative carbon fibre composite: (a) a reconstructed slice (b) trial projection without phase contrast (c) same as (b) with phase contrast

AirLander 50: the lighter than air hybrid airship, originally designed for the United States Army as Long Endurance Multi-intelligence Vehicle (LEMV)

* With Dr J. Meredith, University of Sheffield

Conclusion

- Digital image/volume correlation is a powerful technique but the analysis that comes after measurement is as important
- We can not only find cracks in 2D and 3D but quantify them (COD, J, …)
- Combined with other full-field techniques (e.g. XRD) they can give us an insight into why materials behave the way they do.
- Their application spans from nuclear to aerospace and biomechanics
- Combining them with modelling techniques (such as finite element analysis can give us even more information

Acknowledgment

- Professor T.J. Marrow (University of Oxford)
- Professor P.J. Withers (University of Manchester)
- Professor P.M. Mummery (University of Manchester)
- Professor P.E.J. Flewitt (University of Bristol)
- Dr B. Connolly (University of Birmingham)
- Dr R. Abel (Imperial College London)
- Dr J. Meredith (University of Sheffield)
- Dr L. Sacedo-Mora (University of Oxford)
- Dr D. Armstrong (University of Oxford)
- Dr P. Wilson (University of Sheffield)
- Dr R. Bradly (University of Manchester)
- Dr C. Simpson (University of Manchester)
- Dr C. Reinhard (Diamond Light Source - JEEP)
- Dr T. Connolley (Diamond Light Source – JEEP)
- Dr D Hollis (LaVision UK)
- Dr D Liu (University of Bristol)
- Ahmet Cinar (University of Sheffield)
- Shaocheng Ma (Imperial College London)
- Selim Barhli (University of Oxford)
- Dan Khoskou (University of Birmingham)

If you are interested to know more

- Mostafavi M, Baimpas N, Tarleton E, Atwood RC, McDonald SA, Korsunsky AM, Marrow TJ. Three-dimensional crack observation, quantification and simulation in a quasi-brittle material. Acta Mater. 2013;61:6276-89.
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- Mostafavi M, McDonald SA, Çetinel H, Mummery PM, Marrow TJ. Flexural strength and defect behaviour of polygranular graphite under different states of stress. Carbon. 2013;59:325-36.
- Mostafavi M, McDonald SA, Mummery PM, Marrow TJ. Observation and quantification of three-dimensional crack propagation in poly-granular graphite. Eng Fract Mech. 2013;110:410-20.
- Mostafavi M, Vertyagina Y, Reinhard C, Bradley R, Jiang XG, Galano M, Marrow TJ. 3D studies of indentation by combined X-ray tomography and digital volume correlation. Key Eng Mater. 2014;592-593:14-21.
- Saucedo Mora L, Mostafavi M, Khoshkhou D, Reinhard C, Atwood RC, Zhao S, Connolly BJ, Marrow TJ. 3D cellular automata finite element (CAFE) modelling and experimental observation of damage in quasi-brittle nuclear materials: Indentation of a SiC-SiC fibre ceramic matrix composite. SMINS-3, International Workshop on Structural Materials for Innovative Nuclear Systems. Idaho, USA2013.
- Vertyagina Y, Mostafavi M, Reinhard C, Atwood RC, Marrow TJ. In situ quantitative three-dimensional characterisation of sub-indentation cracking in polycrystalline alumina. J Eur Ceram Soc. 2014;34:3127-32.