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Using neutron diffraction for the solution of engineering problems: a perspective from academia and industry in the UK

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Neutron strain measurement in the UK

- Long tradition of using international sources
  - ILL, LLB, France; HMI, Germany; Risø, Denmark; Chalk River, Canada
- Measurements performed using conventional powder diffractometers, ‘adapted’ for strain analysis
- ENGIN instrument developed at the UK ISIS pulsed neutron source in the early 1990s
- ENGIN-X built on a dedicated beamline, with new sample environment, in ~2000-4

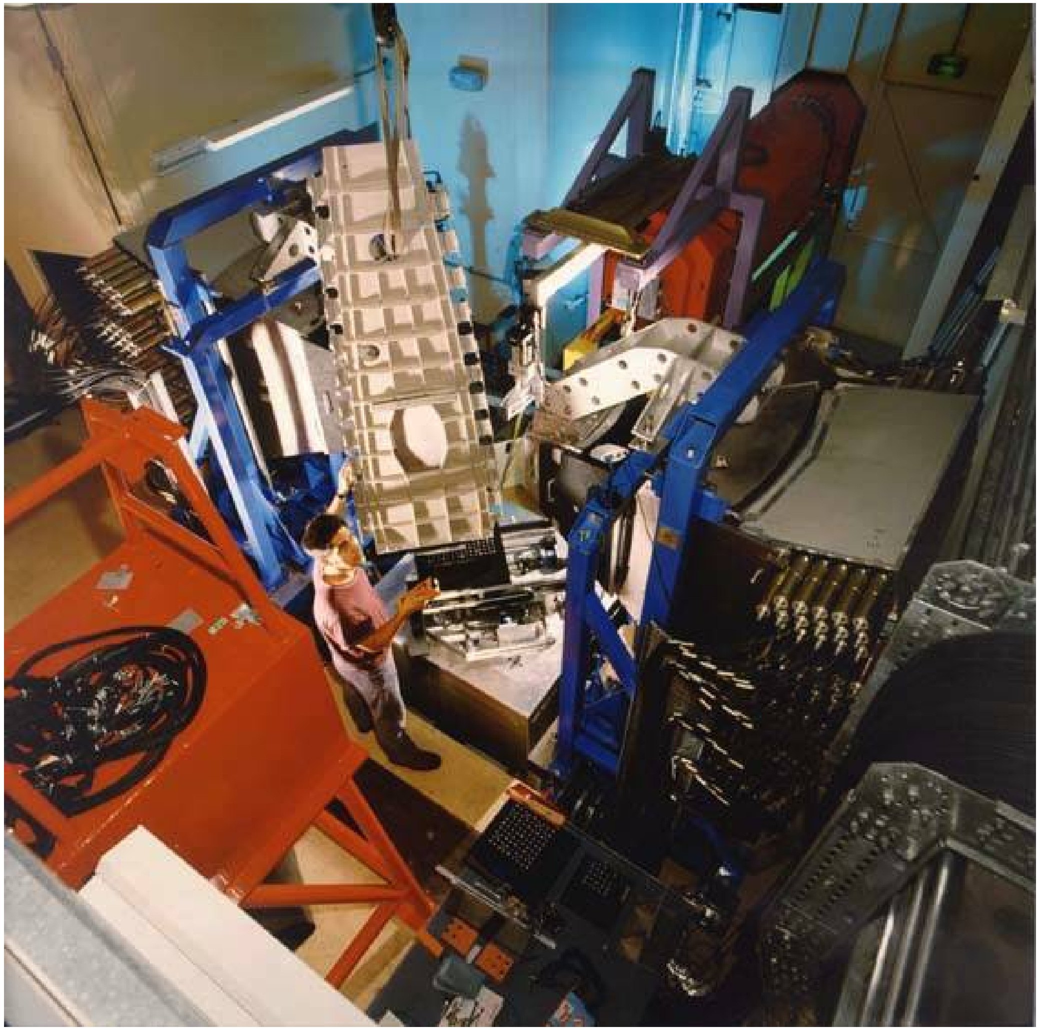
Neutron strain measurement in the UK

- UK is a partner in the ILL reactor neutron source
- SALSA diffractometer developed as a dedicated strain measurement instrument in 2001-5

- Advances also in the use of synchrotron X-rays for engineering measurements, with the development of a joint Facility for Materials Engineering (FaME38) at the ILL and ESRF sources in Grenoble, France

ENGIN-X

- User operation since 2003
- 218 experiments
- 515 user days
- 2.3 times oversubscribed
- XYZω positioner
- 1500 kg capacity
- xyz accurate to 5μm (500 mm travel)
- ω accurate to 0.002° (full 360°+ rotation)
- Standard “VAMAS” baseplates with pre-drilled holes for sample location

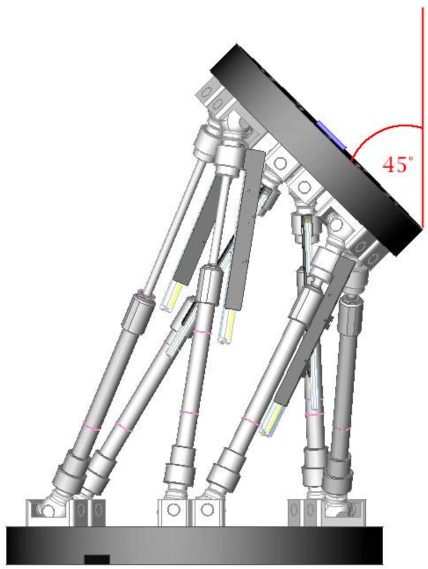


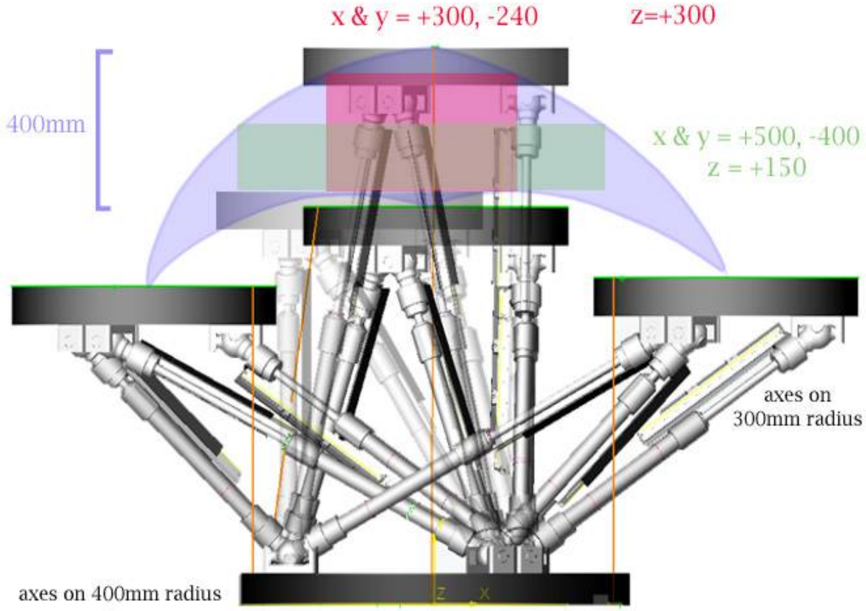
ENGIN-X ancillary equipment

- 100 kN servohydraulic stress rig for in-situ loading, cycling and fatigue experiments
- Radiant furnace allows heating and thermal cycling of samples mounted on the stress rig
- Cryo-cooler for experiments at LN2 temperatures or lower
- Because ISIS is a pulsed source, pulses can be timed and summed cumulatively for high-frequency experiments
- Co-ordinate measuring machine (CMM) for offline determination of sample geometry to ease experimental set-up, including laser scanning arm
- Software system for experimental design, measurement point definition, and sample alignment

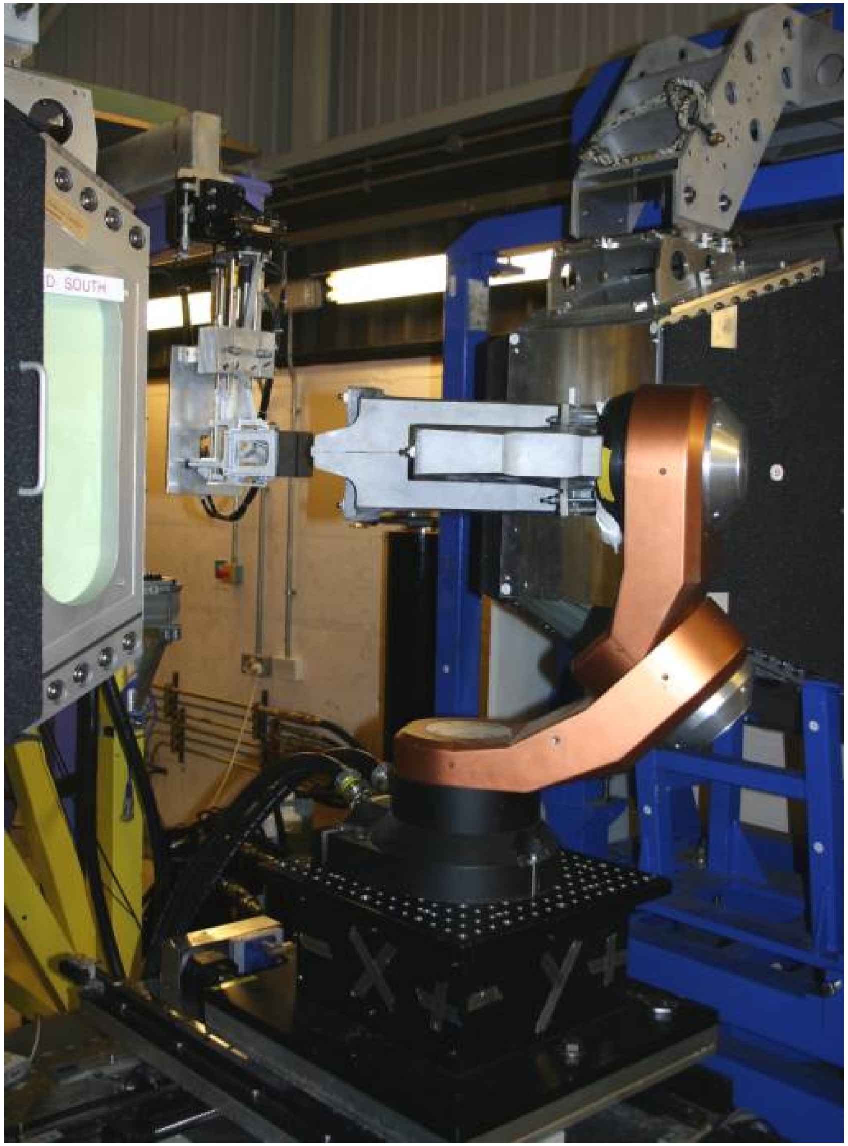
SALSA

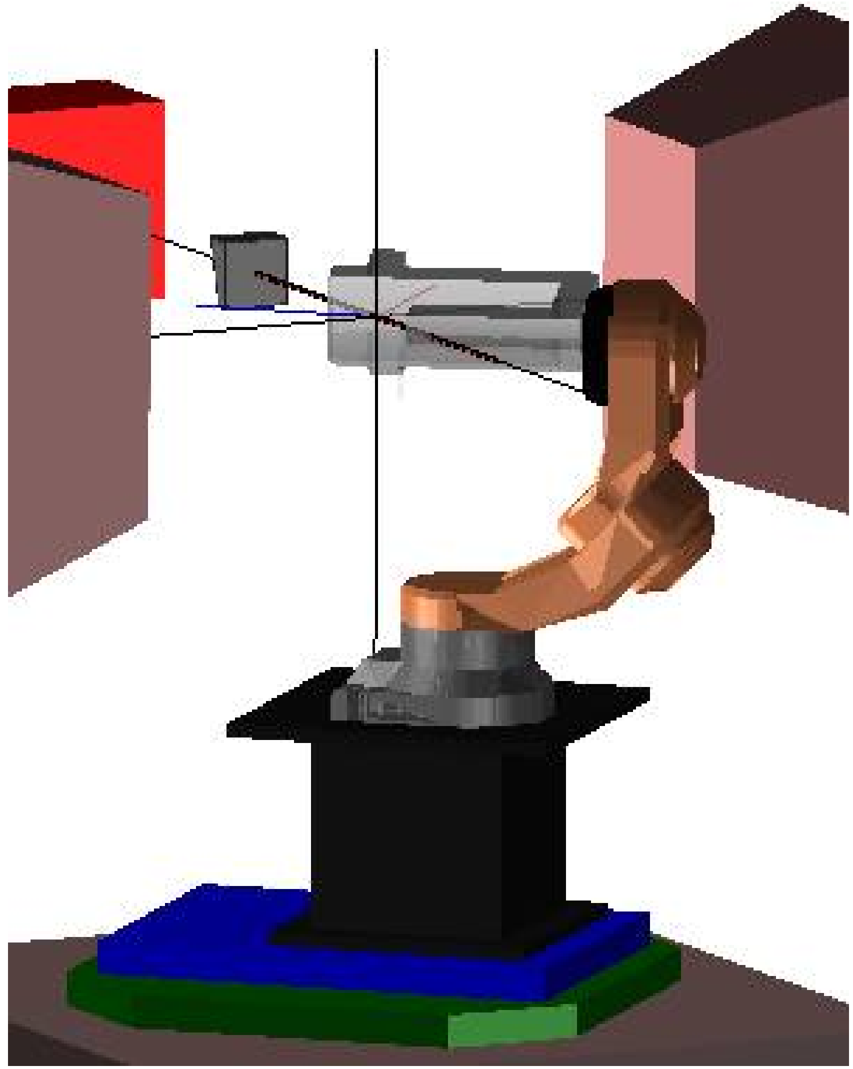
- Positioning using a ‘hexapod’ (Stewart platform)
- Can tilt sample as well as translate/rotate
- 500 kg capacity
- xyz accurate to <10μm within a ±200mm workspace





Robotic positioning





Industrially-relevant experiments

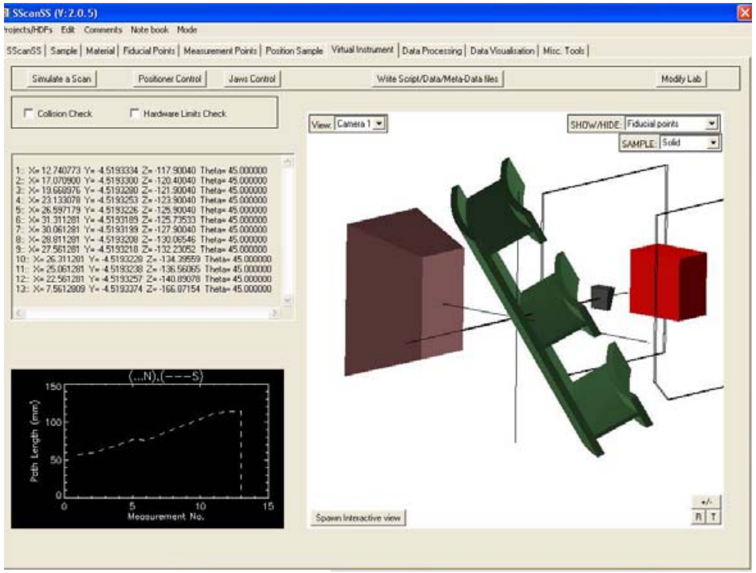
- Experiments that have direct industrial relevance are encouraged
  - Should be clear ‘engineering science’ content
  - Results must be publishable in order for standard direct access to apply
- Projects must be led by a university-based researcher

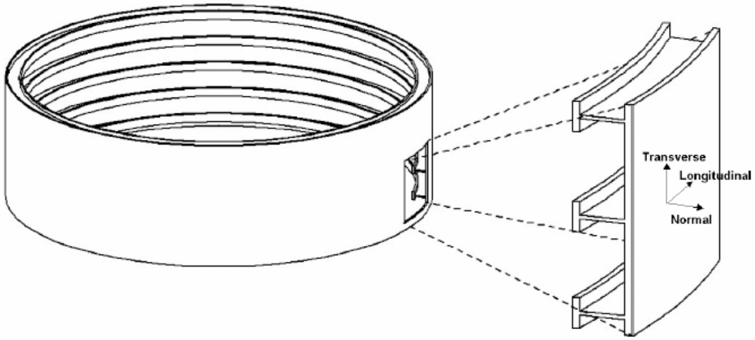
Examples

- Nuclear industry
  - Residual stresses in power-plant welds
- Aerospace industry
  - Residual stresses in engine components
  - Residual stresses in structural fuselage and wing components
- Materials processing
  - Residual stresses developed by new joining technologies
    - Friction-stir welding; inertia welding

Designed for large components

- 700 kg T-butt weld (Adelaide University)



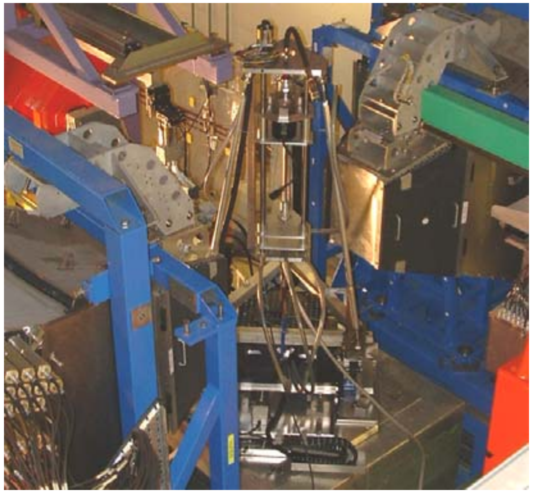


Designed for large components

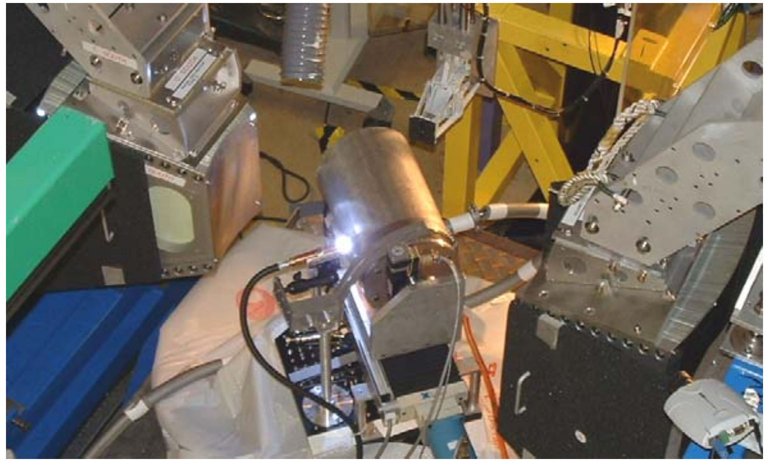
- 400 kg aluminium extrusion (Bristol University and Airbus)

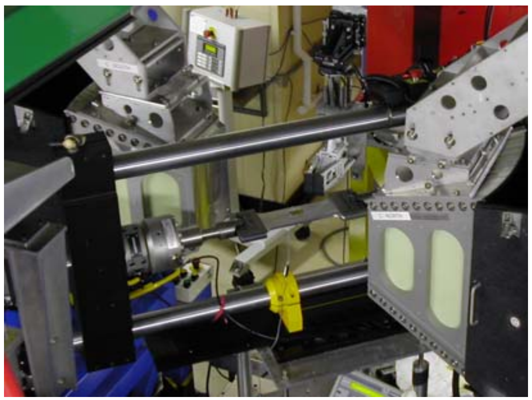
In-situ processing

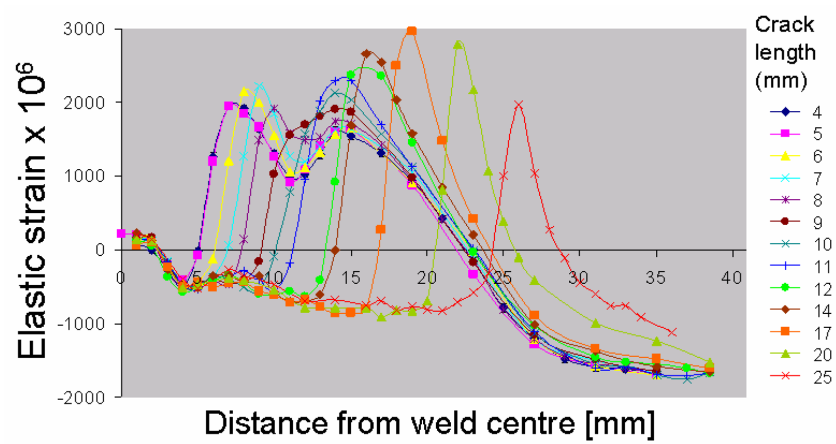
EDM (Bristol Uni)



TIG welding (Imperial College)







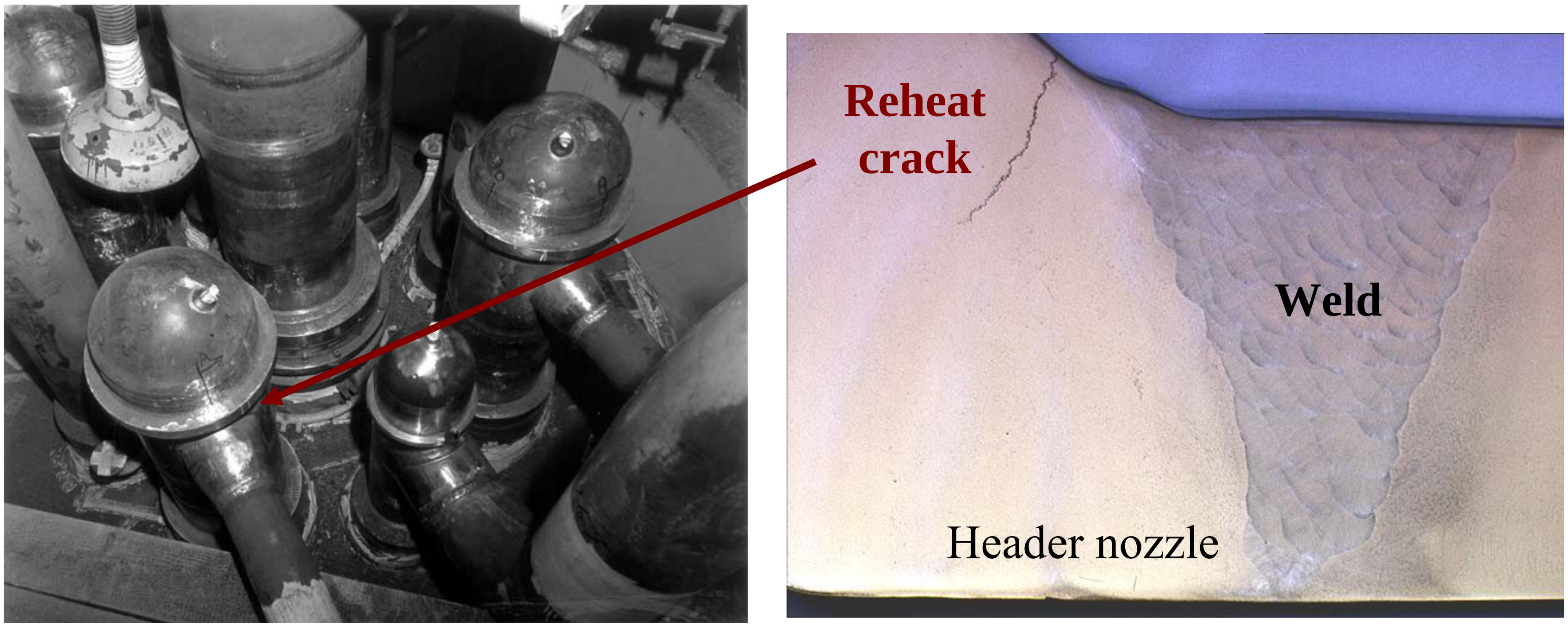
Fatigue crack growth (OU)

Example: nuclear industry

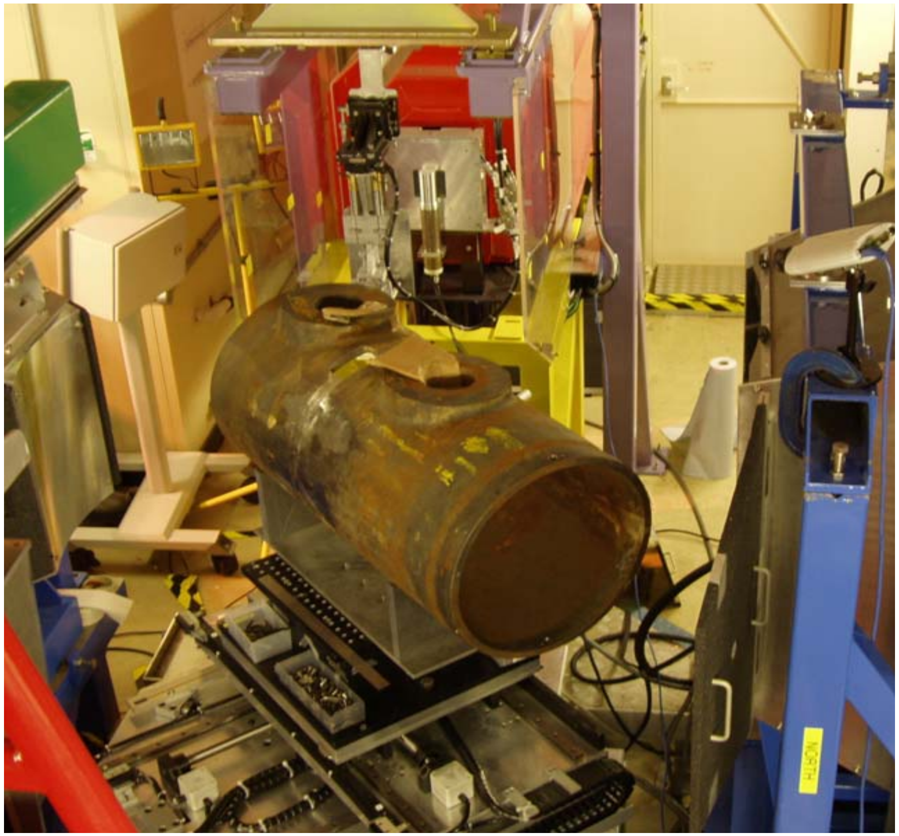
- British Energy (BE) owns and operates eight nuclear power stations in the UK, generating around 20% of the nation's electricity
- Has used a range of techniques for the determination of residual stress in the past decade, including neutron diffraction

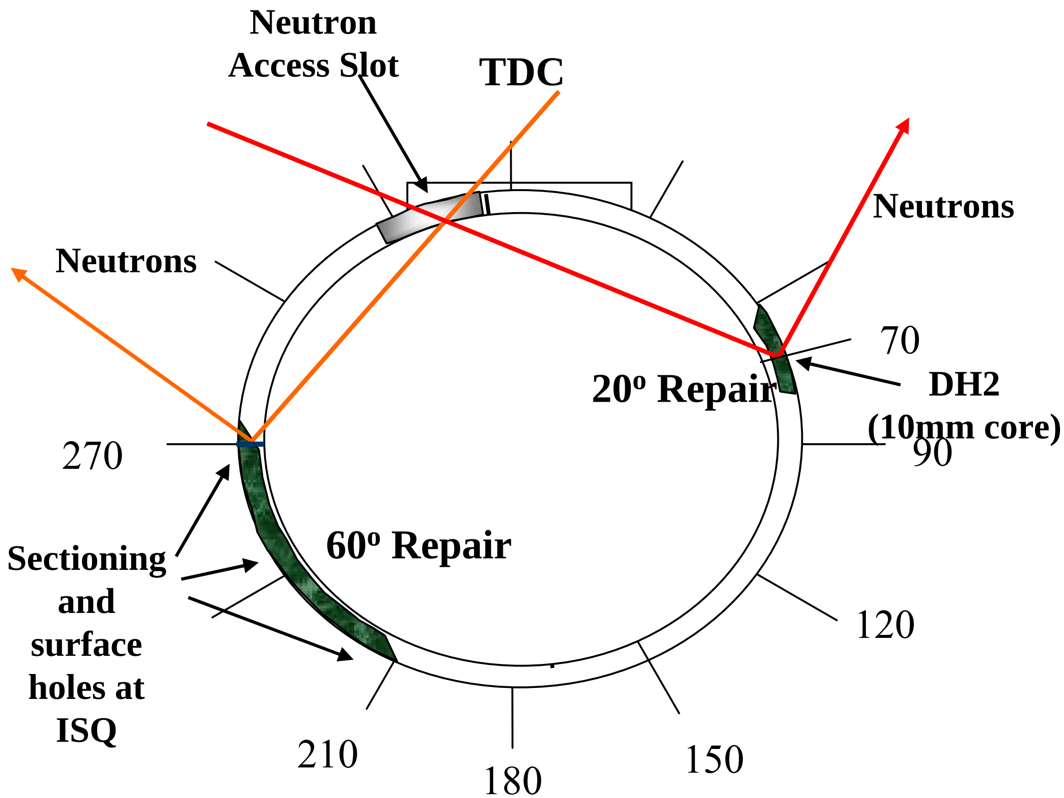
Power plant welds

- A nuclear power station has many 1000’s of welds e.g. □2000 welds in large bore steam pipework
- Welded joints are particularly vulnerable to plant degradation and material ageing

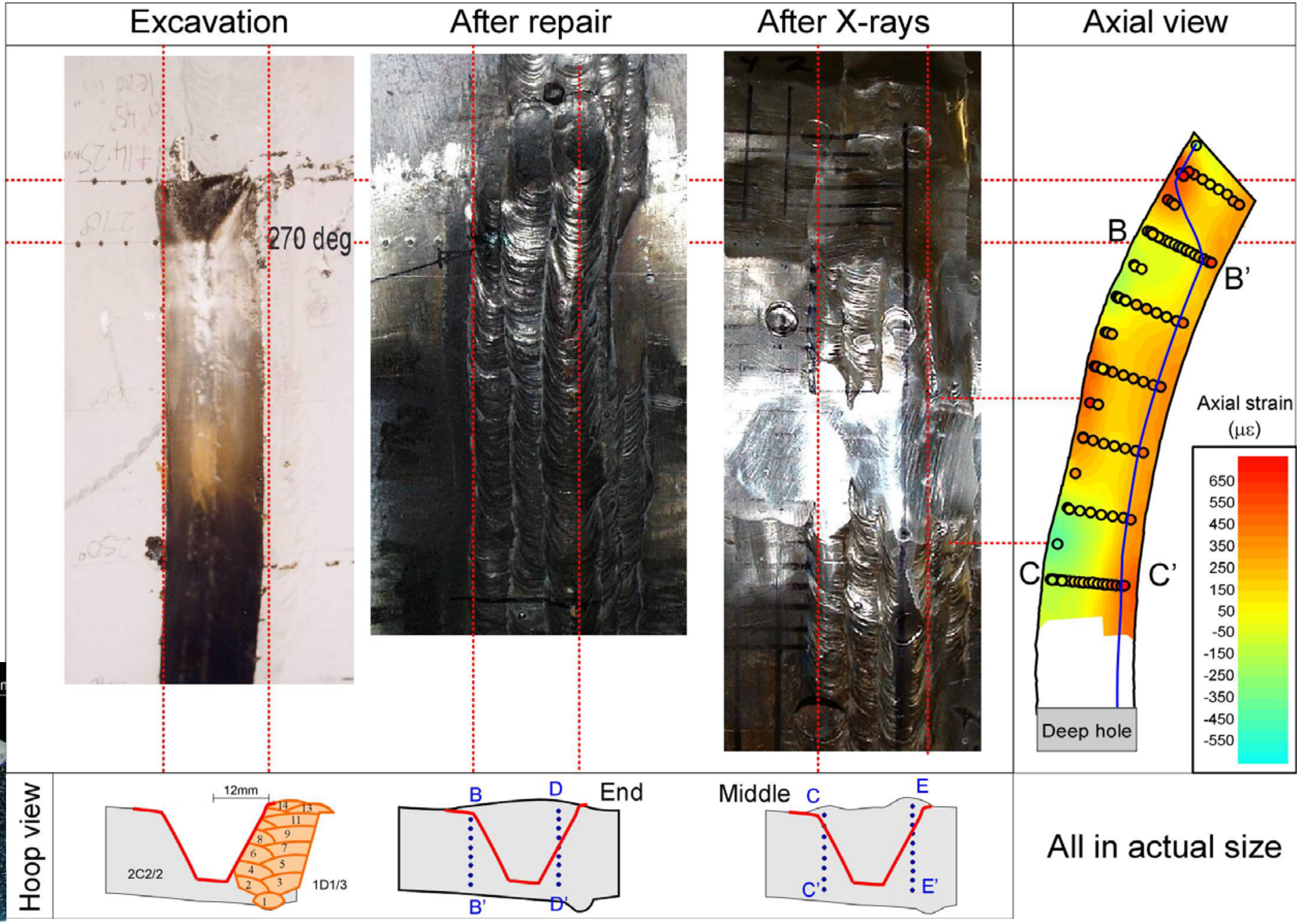


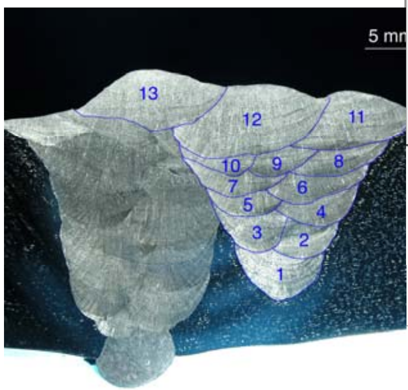
Mock header butt-weld





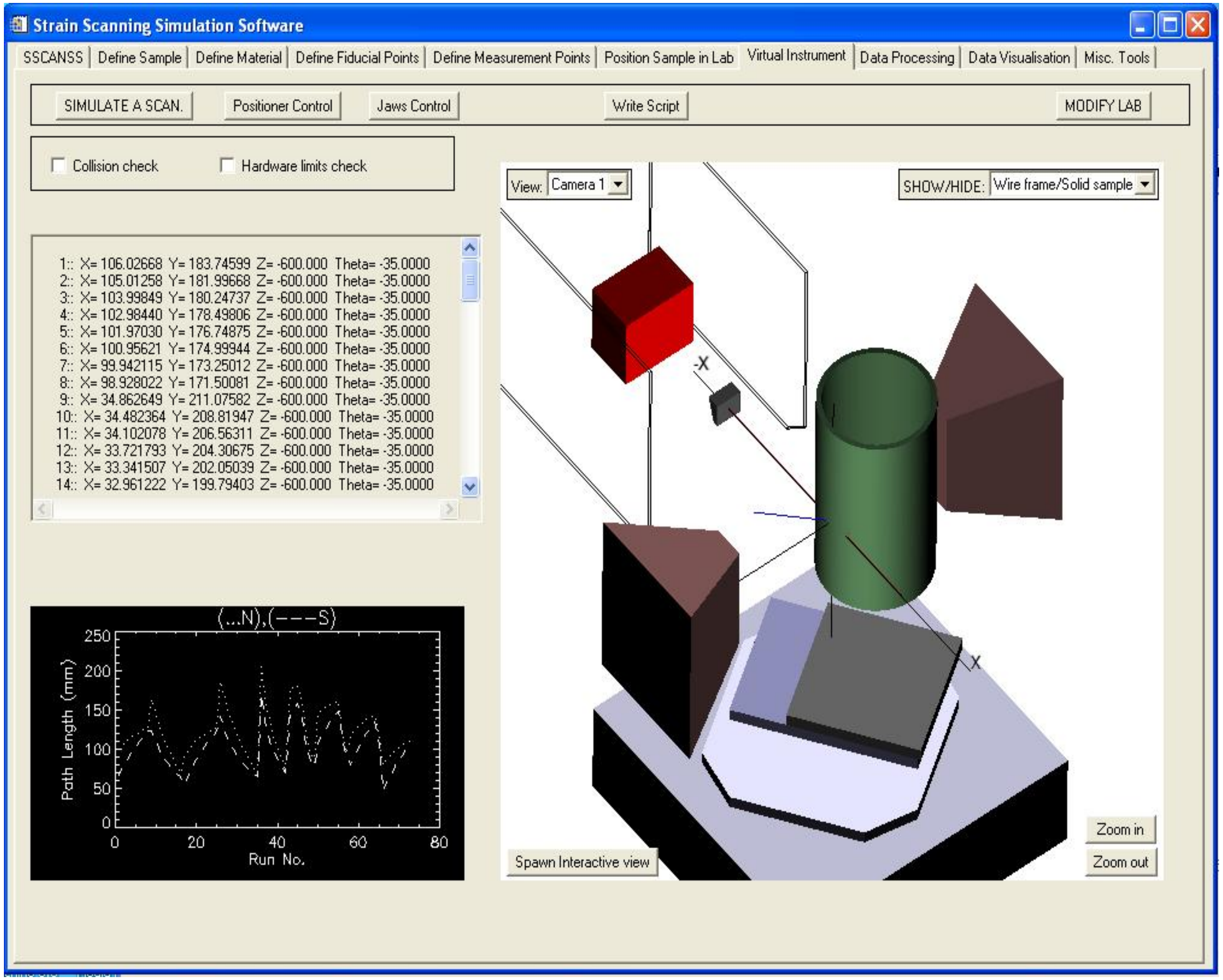
Measurement location is critical

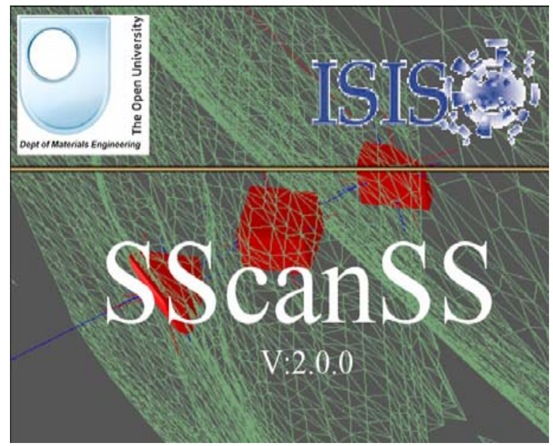




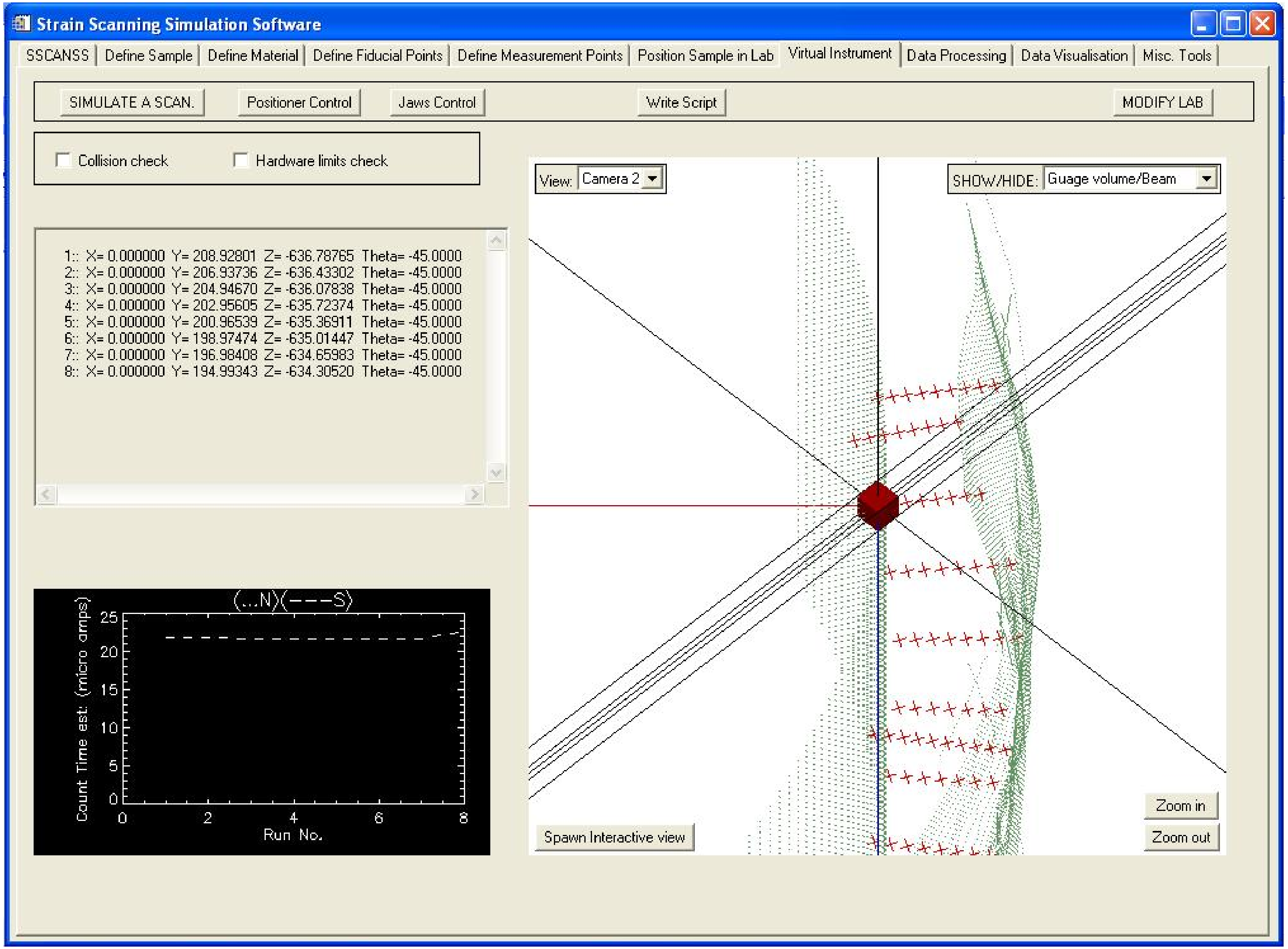
Experiment design and execution

- SScanSS software aids and optimizes set-up and measurement

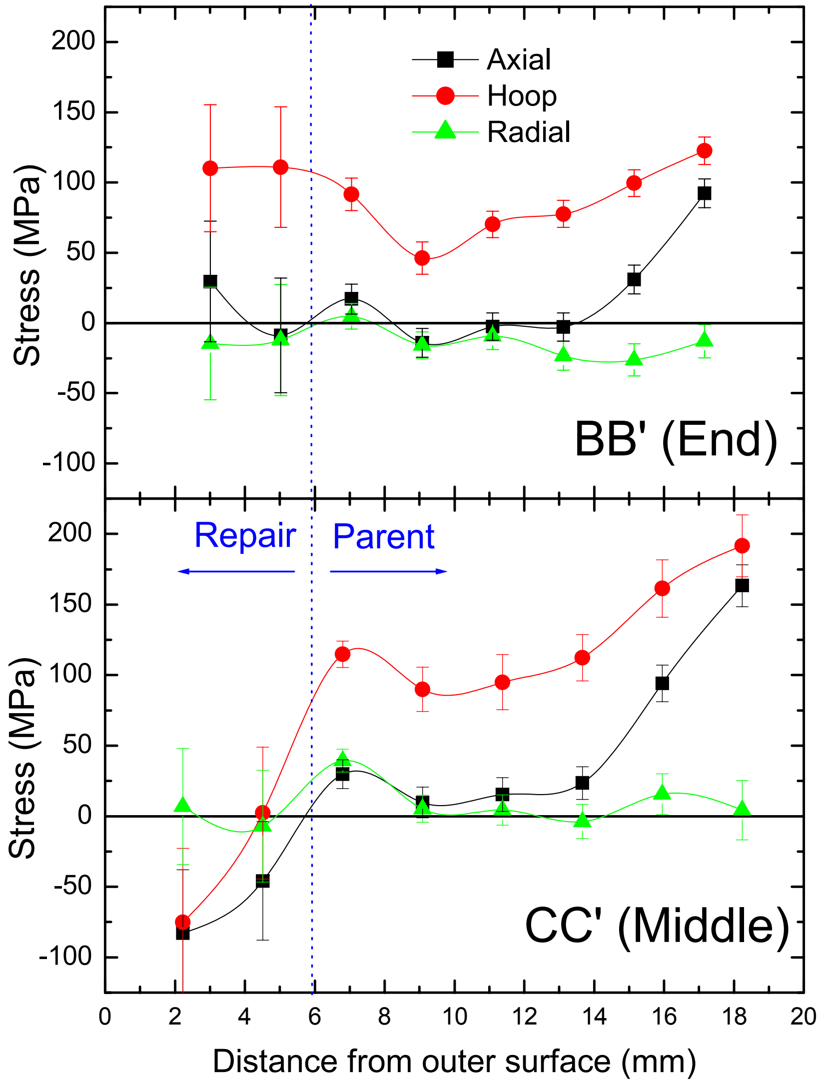


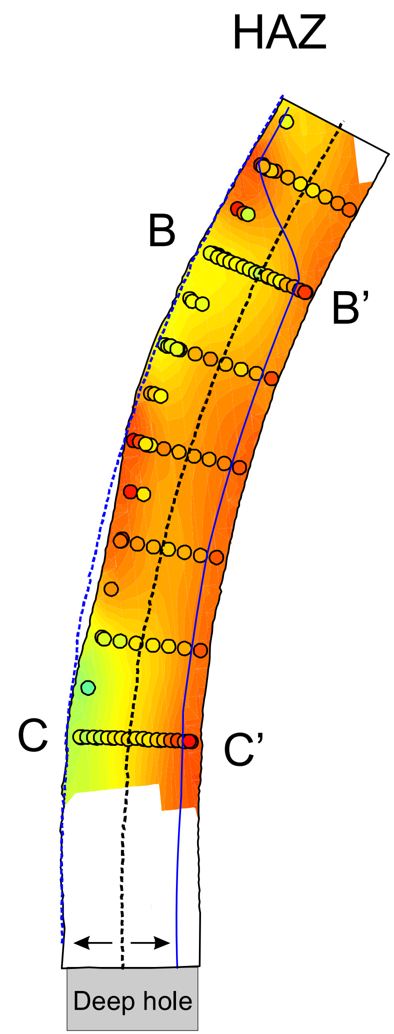


Measurement detail



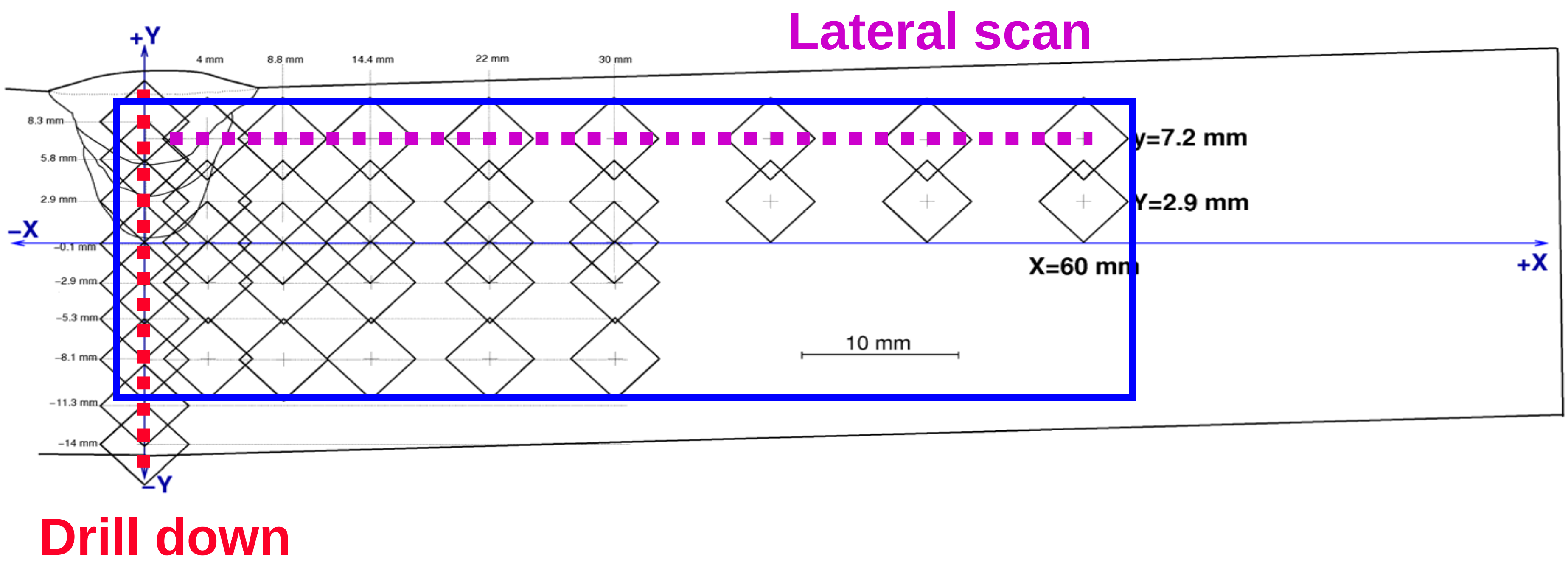
Example results



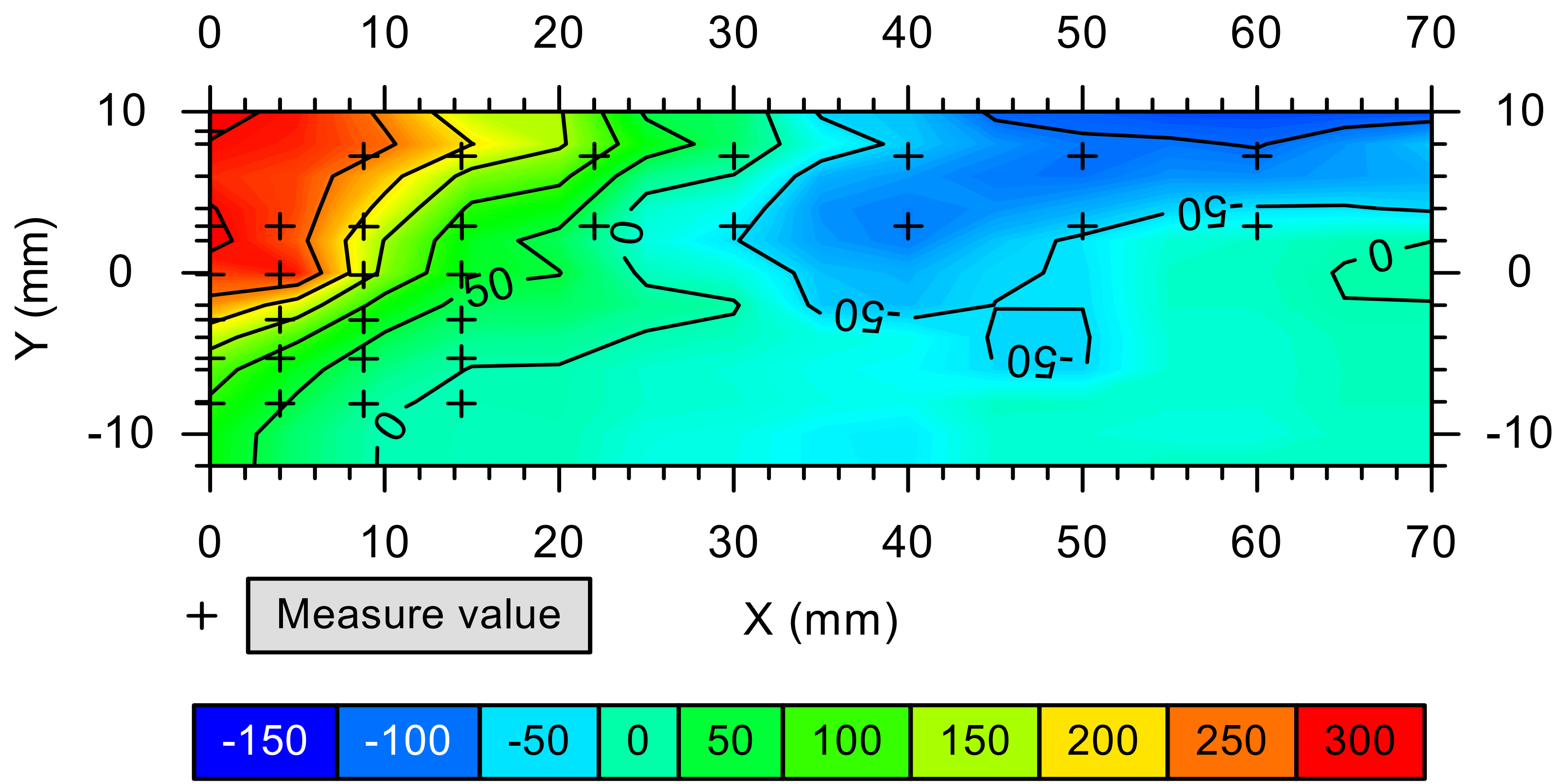


Comparison and validation

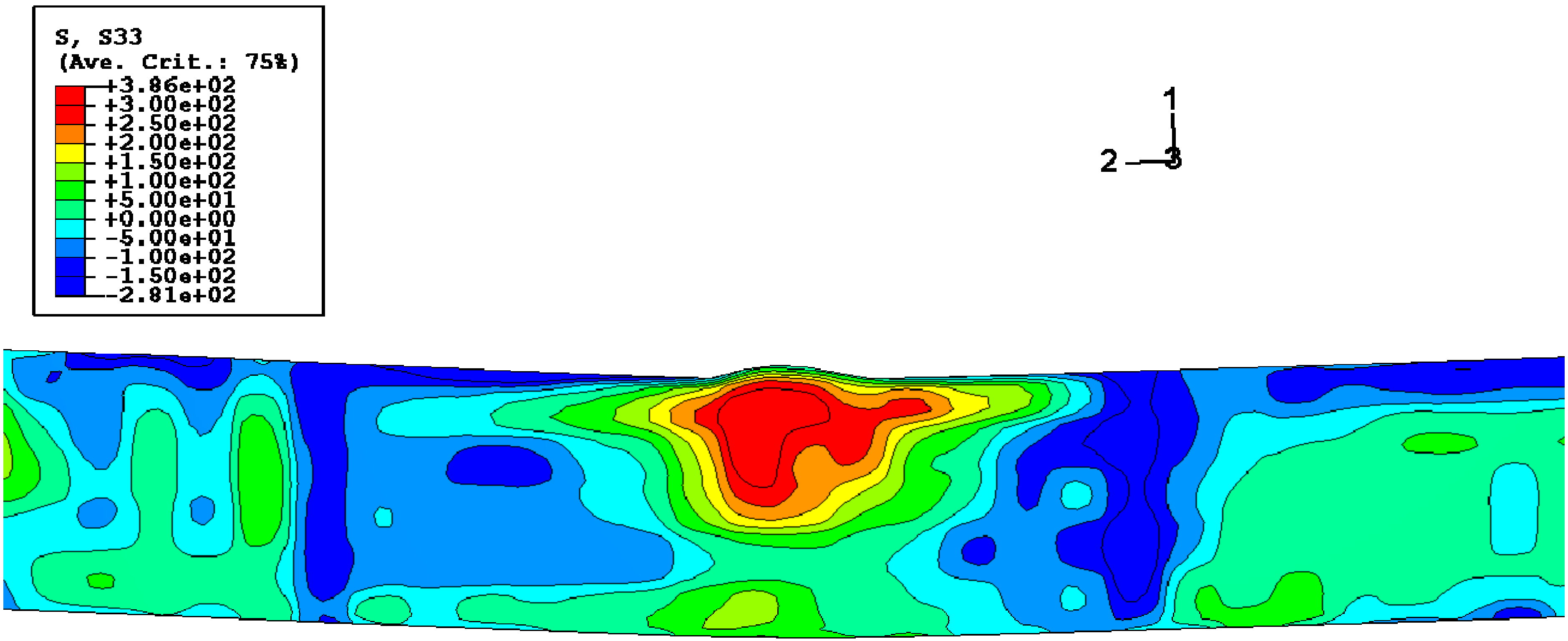
- Model sample: three-pass groove weld



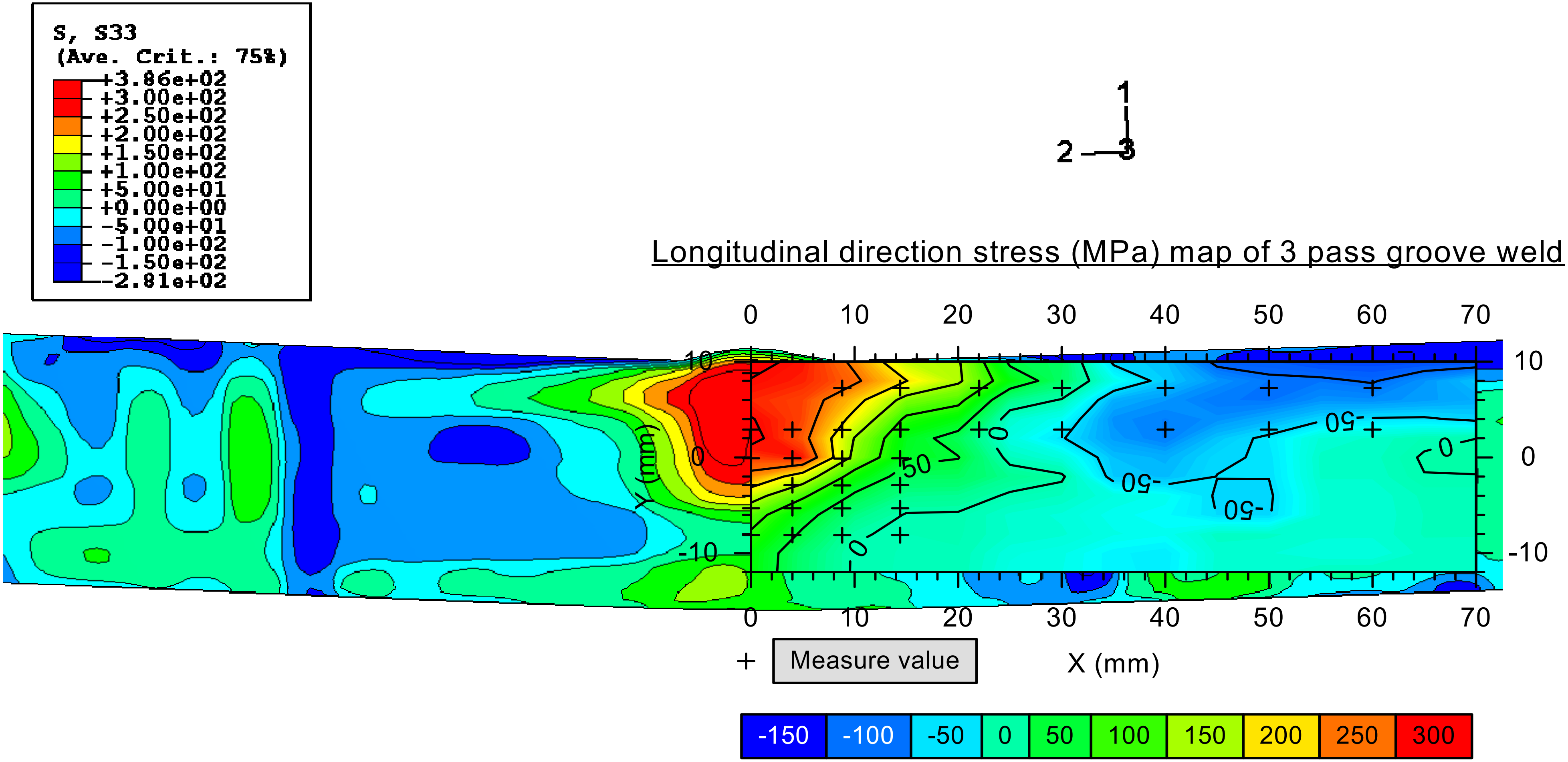
Measured longitudinal stresses



Contour method stress map



Comparison stress map

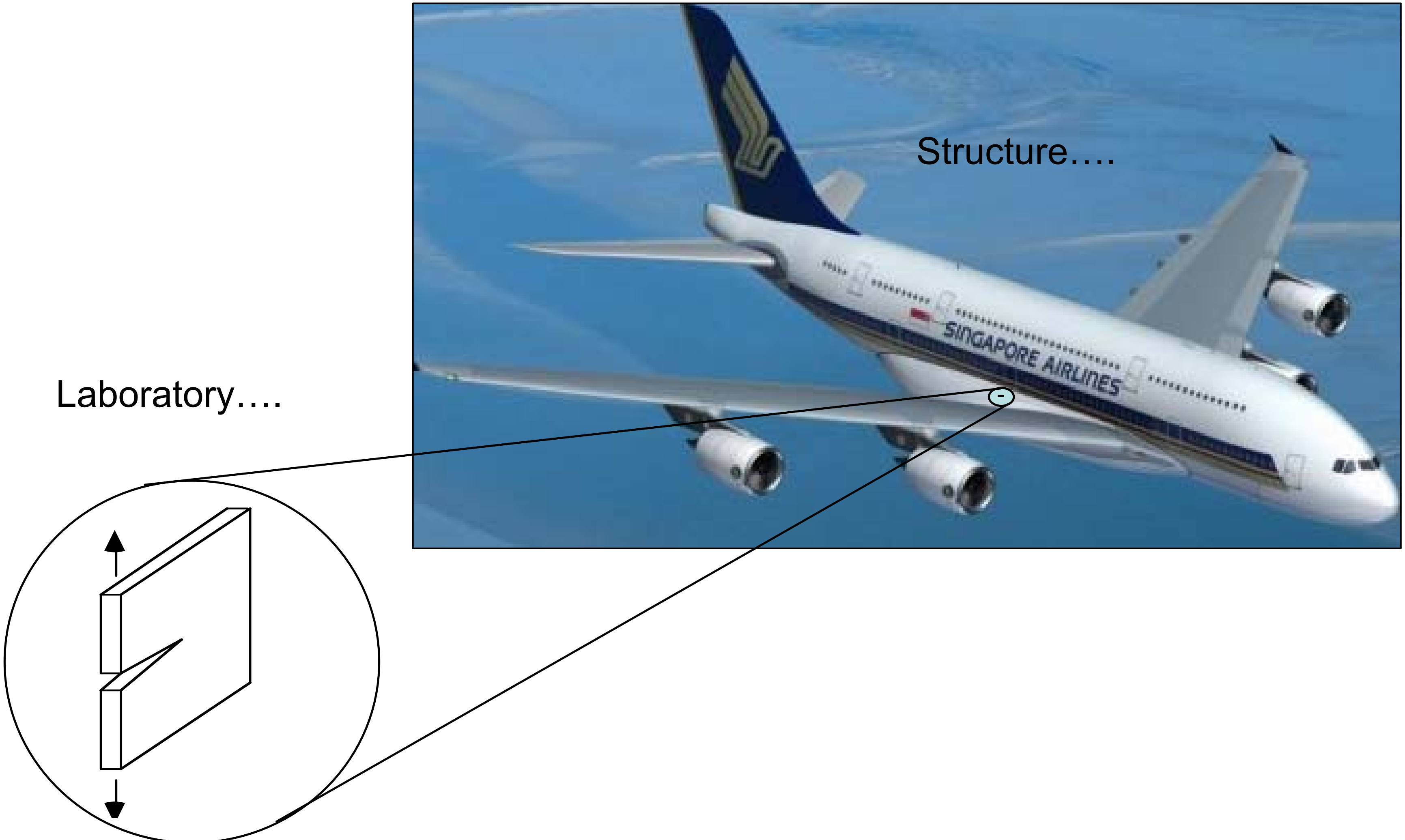


Example: welded aircraft

- Welding offers a cost-effective, weight-saving alternative to conventional joining methods (riveting)
- Fastener joints in aircraft can initiate fatigue damage, but the design provides good damage tolerance
- For effective damage tolerance design calculations, weld residual stresses need to be well-quantified, along with the fatigue properties of the weld and heat-affected zones

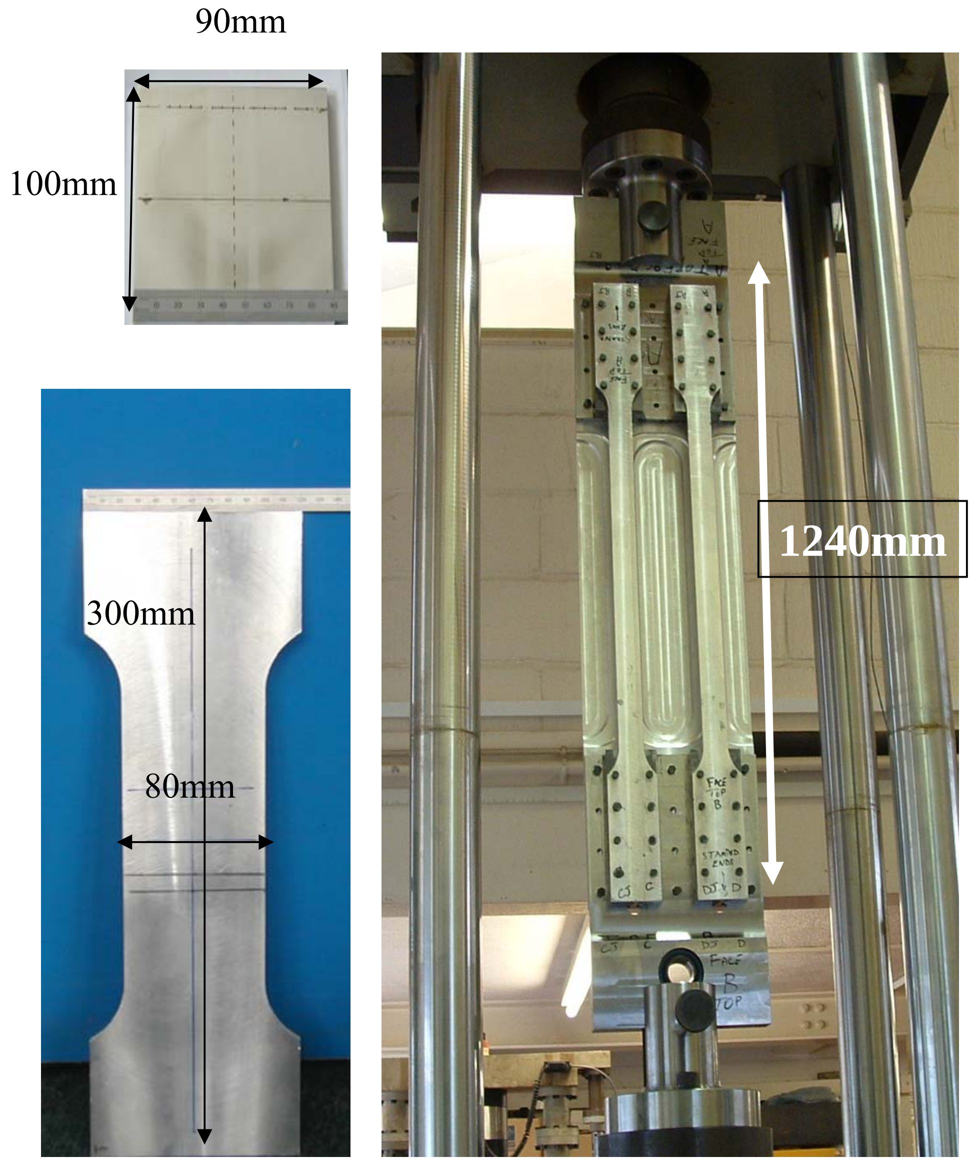
Using ‘laboratory’ test data in design

- Similitude is necessary for design calculations
- Does similitude apply for residual stress?

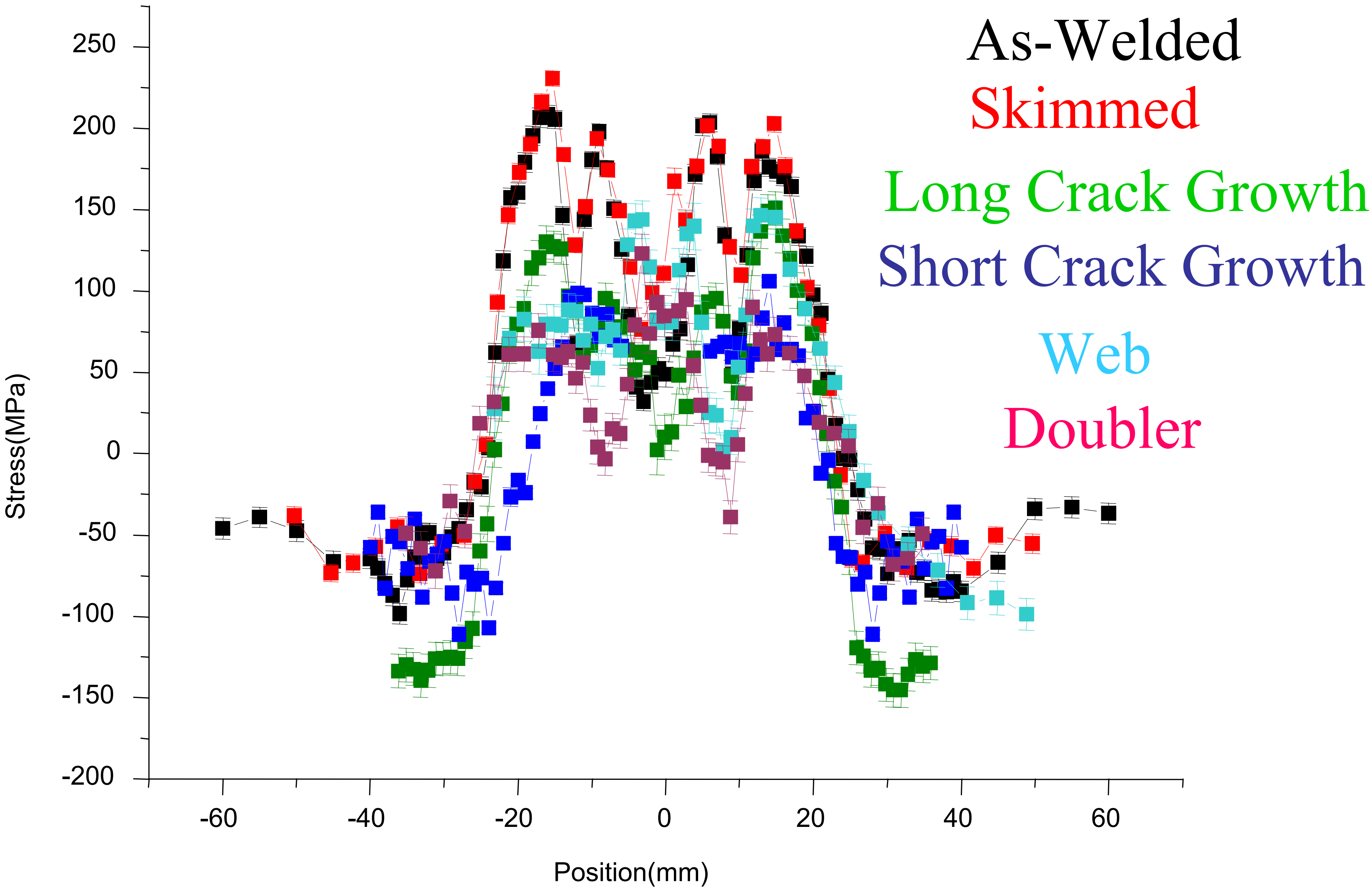


‘WELDES’ programme

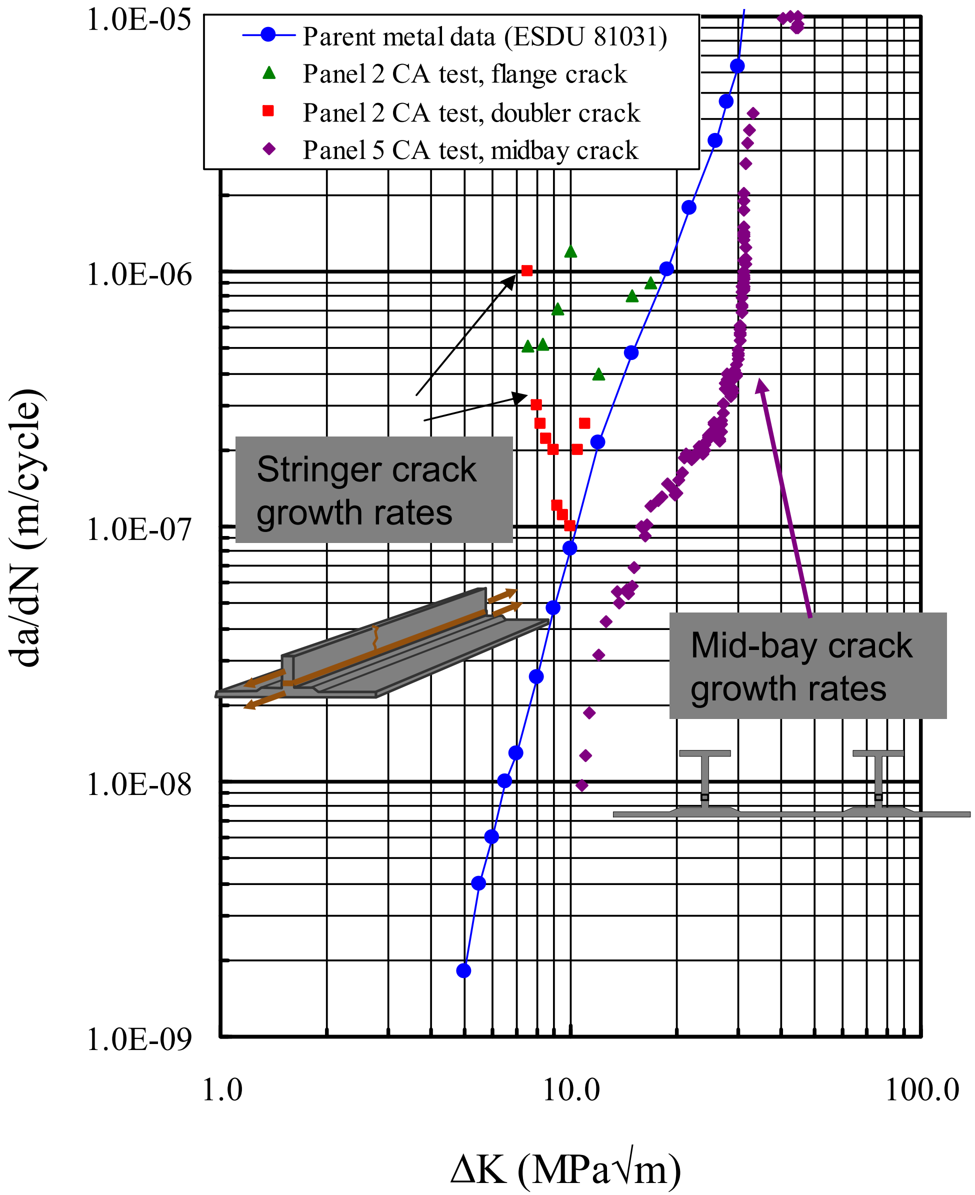
- OU, Cranfield, Southampton, Airbus UK, ALCOA
  - Wing structures machined after welding
  - Typically welded at 12.5mm and skimmed to ≈7mm
  - Short crack growth samples: 100×90×7mm
  - Long crack growth M(T) samples: 300×80×7mm
  - Prototype skin stringer panel: 1240x350×80 mm
  - Size and measurement density define the appropriate residual stress measurement method



Longitudinal residual stress evolution

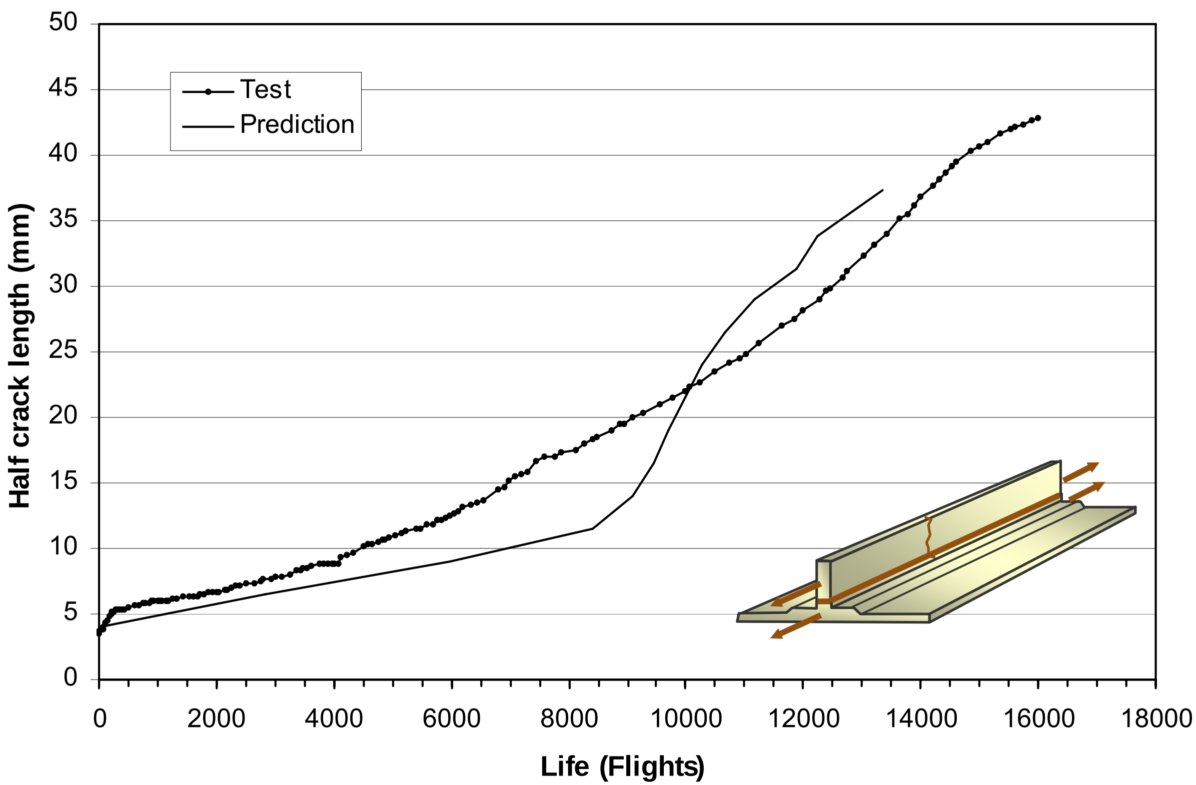


Fatigue crack growth in skin/stringer panels



- VPPA welded 2024 panel
- Constant amplitude load: σ_{max} = 88 MPa
- Accelerated crack growth rates for stringer cracks
- Retarded crack growth rate for mid-bay cracks.
- Similitude is lost as result of welding residual stress
- No crack stoppers so less damage tolerant
- Solution: bonded crack retarders

Panel mid-bay crack growth



- VPPA welded 2024 panel
- Aircraft spectrum load, σ_{max} = 138 MPa
- Final crack growth life is well predicted
- Kres from Cranfield Finite Element model
- But the form of crack length versus cycle curve is different from the test
- Probably due to residual stress re-distribution.

- Fatigue crack growth is underestimated early in life and overestimated later in life
- Is this a result of residual stress redistribution?

Access mechanisms (ISIS)

- ISIS has seven Facility Access Panels (FAPs)
  - International membership
  - Broad range of expertise
  - Facility representation
- Some panels schedule experiments across a range of instruments; the ‘Engineering’ panel is dedicated to ENGIN-X
  - (so the panel does handle some non-‘engineering’ experiment proposals – geology, archaeometry…)

Access mechanisms

- The panel reviews and ranks applications on the basis of:
  - Contributions to engineering science
  - Feasibility
  - Utility
  - Publishability
- The panel looks for experiments that cover all aspects of engineering, including materials engineering and structural engineering:
  - Technique development (must be related to usefulness)
  - Validation/standardization/intercomparison of techniques
  - Developing engineering science
  - Measurements on model or real systems. This might relate to (for example) fabrication methods, design procedures, use/reliability/lifetime, forensic analysis, etc.

Access mechanisms

- ‘Direct’ access for single experiments
- ‘Programme’ access for series of experiments spread over several beam cycles
- Experiments can be linked to other projects funded by the UK research councils

- Industrial users can directly purchase beam time
  - Cost is currently ~$35k per day

Access mechanisms

- The industrial perspective

Context	**Mechanism**	**Time-scale (for industry)**
University research project Industry supported (funded by EPSRC, EU etc.)	Peer review (publish)	Long (3 -5 yrs)
University research project (Industry funded)	Peer review + top-up purchase (publish)	Medium (1 - 3 yrs)
Contract research Consultant, University or **Facility** (Industry funded)	Direct purchase (proprietary)	Short (0 – 1 yr)

Cost: the industrial perspective

- Neutron beamtime is expensive, particularly in the UK
- Can only be justified in ‘cases of urgent need’
- For medium time-scales, the option to purchase “top-up” time for peer review experiments is desirable to help deliver industrial objectives
- Directly-purchased beamtime must deliver reliable results to time with appropriate QA
  - The role and the expertise of the instrument scientist becomes crucial in delivering the results

Quality assurance

- Facility services for contract work are highly-desirable
- Appropriately trained staff must be used
- Must use national/international testing standards (where available) or defined procedures, with suitable calibration of equipment and unique identification of test samples, and use documented methods and validated software to perform numerical calculations
- Facilitate ‘Informed Customer’ witnessing
- Perform independent sample checking of reported results
- Maintain records and detailed workings for audit as necessary
- Maintain document control including internal review/approval
- Technical Review of final report by customer required prior to issue

Summary

- ENGIN-X has been highly successful in delivering engineering science measurements of residual stress and materials behaviour
- Many experiments have delivered significant value to industry, in terms of better characterization of residual stress generation and how this is influenced by process parameters
- The SSCANSS software has demonstrated that advanced software tools can significantly decrease the experimental set-up time, and optimize experimental parameters

The future?

- Around half of the experiments conducted on ENGIN-X are strain mapping, so a ‘materials characterization’ instrument on a separate beamline would increase the time available for these experiments
  - Possibilities exist with the construction of the new target station at ISIS
- Continued improvement in sample characterization and experiment design before the experimenter starts using beam time
  - More efficient use of the instrument

Thank you for your attention

Any questions?