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APPLICATIONS OF MULTIPLE RESIDUAL STRESS MEASUREMENT METHODS

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Materials Engineering

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Acknowledgements

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British Energy

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Measurement "Box of Delights"

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Physics-based

- Neutron diffraction
- Synchrotron diffraction
- X-ray diffraction
- Magnetic
- Ultrasonic & acoustics
- EBSD
- Raman

Mechanics-based

- The Contour Method
- Slitting
- Deep hole drilling
- Block removal, slitting & layering (BRSL)
- Incremental centre-hole drilling (ICHD)
- Ring-coring
- Sach's boring
- FIB milling

Over the past 25 years there has been a revolution in techniques for measuring the deformation, strain and stress in engineered structures from atomic to metre length-scales.

But what are the risks of errors in the measured results?

Dealing with uncertainties

At least 5 approaches

1. Quantifying random & systematic uncertainties of measurements
2. Correction(s) for known error(s)
3. Repeat measurements by same practitioner
   (to identify random scatter)
4. Repeat measurements by independent practitioners
   (human/procedural/ equipment variables)
5. **Application of multiple measurement methods, preferably based on diverse principles and usually done by different practitioners.**

UK nuclear industry norms

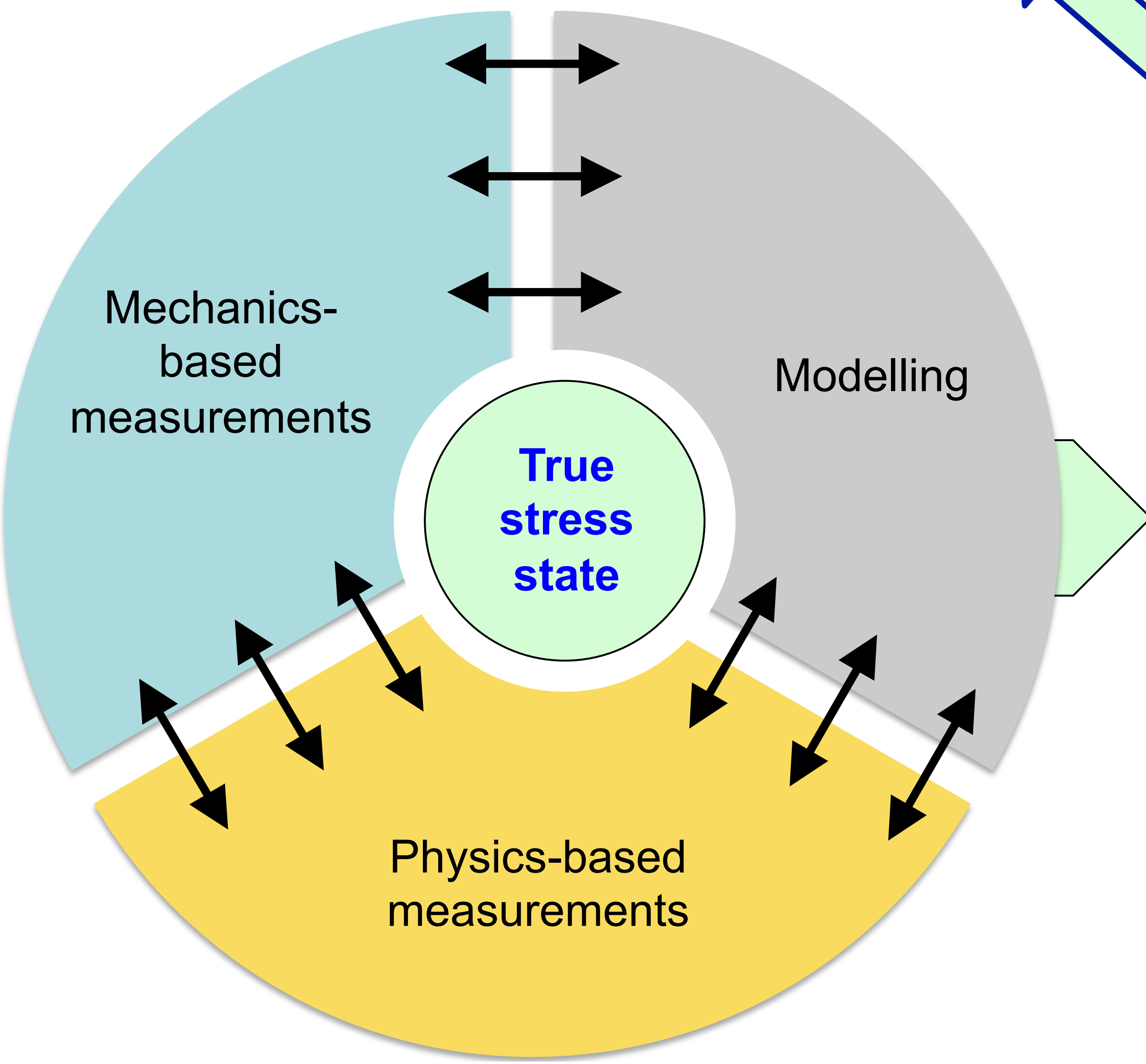
QA approach:- for structural integrity assessment calculations

- QA Grade 4: Self-checking.
- QA Grade 3: Assessment verified on a sample basis by an independent SME.
- QA Grade 2: Assessment 100% verified by an independent SME.
- QA Grade 1: Assessment to be **confirmed by an independent approach**

Safety case validation:- required for weld residual stress simulations used for high integrity applications

- Construct a full size mock-up and measure transient welding temperatures
- Measure residual stresses using at least **2 diverse techniques**

Increase prosperity & safety

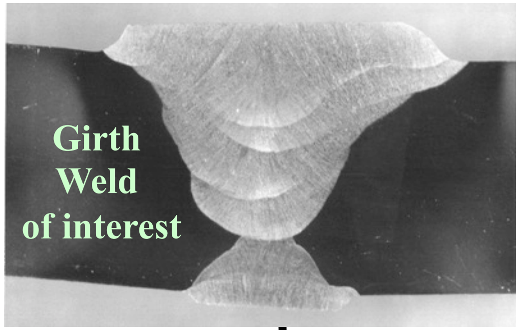


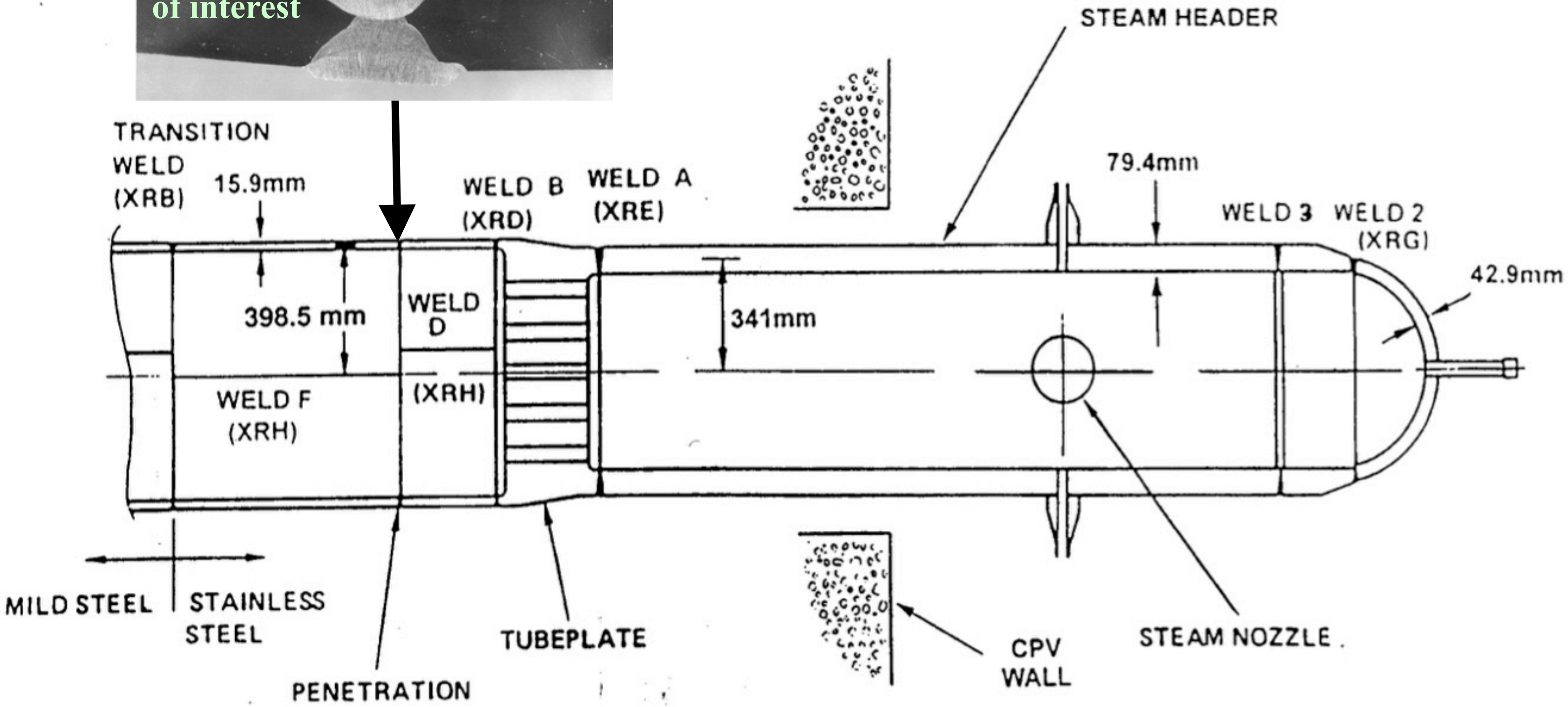
Beneficial impact
(design, productivity & costs**)**
on product life cycle

- new materials
- concept design
- process modelling & prototyping
- design by knowledge
- advanced manufacture
- assembly
- NDT, QA & non-conformance
- proof testing & commissioning
- in service inspection
- troubleshooting & forensics
- plant life extension
- recycling/disposal
- best practice codes & standards

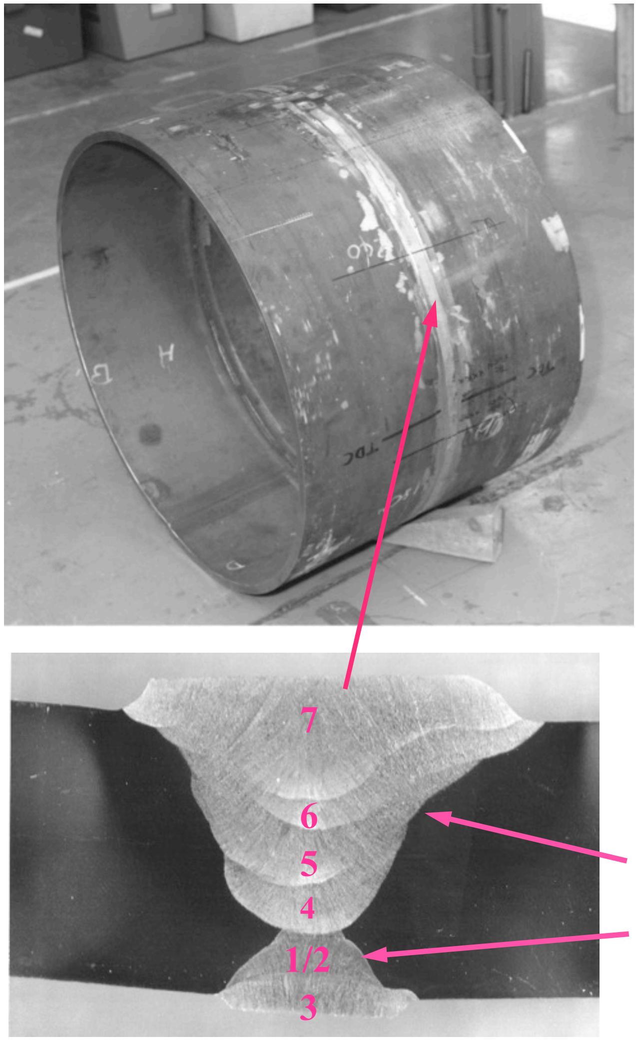
Multiple methods:- example 1

Power plant steam vessel (1995)





Weld computation mechanics



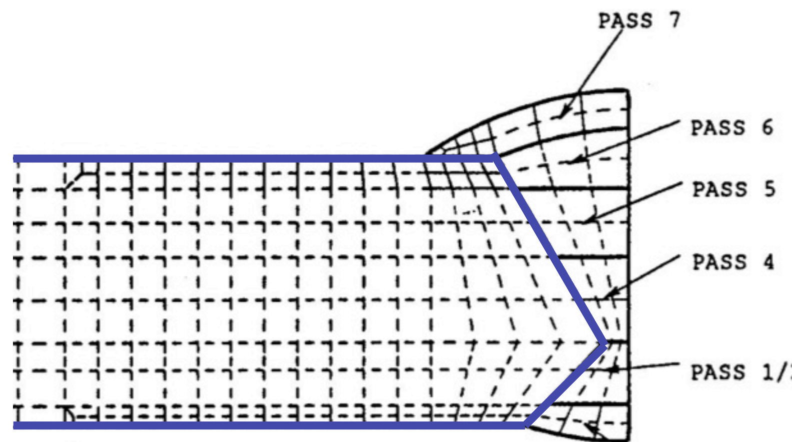
SAW - Submerged arc (4-7)

MMA - Manual metal arc (1-3)

Type 316L stainless steel

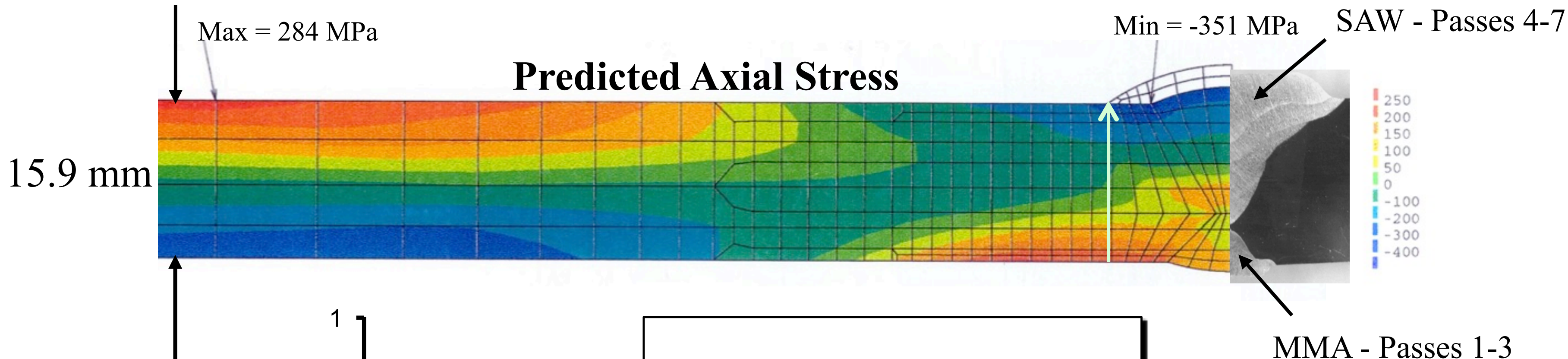
Pipe inner diameter = 390.5 mm

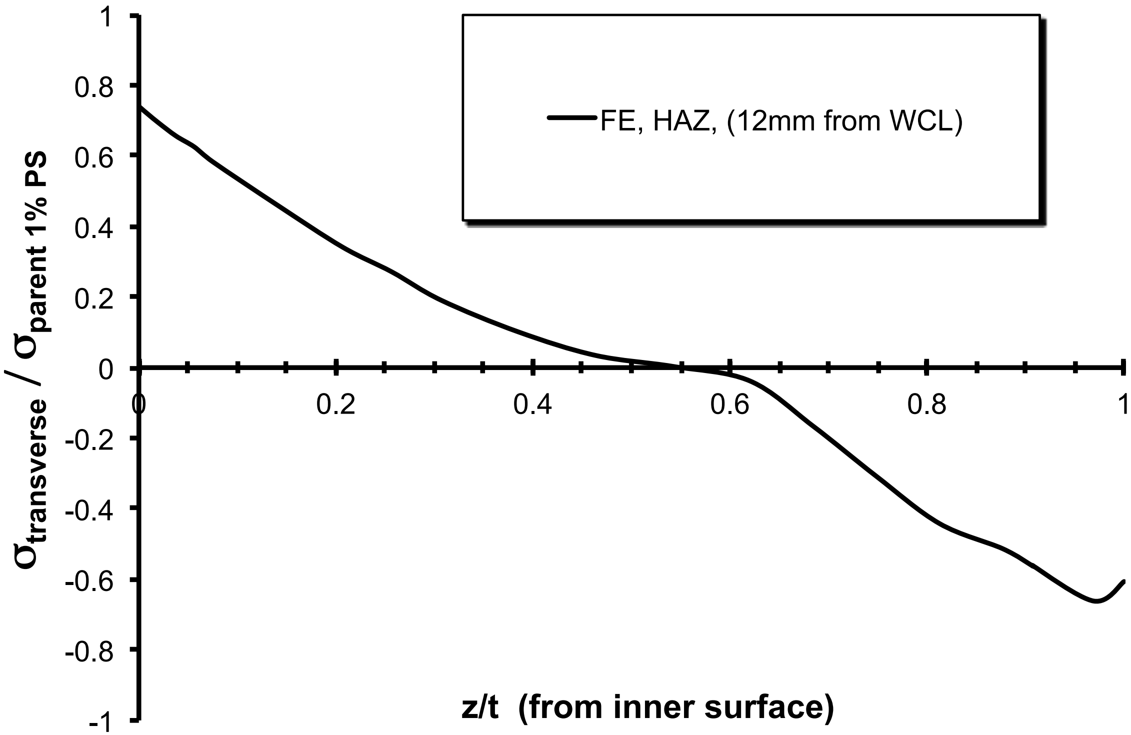
Pipe thickness = 15.9 mm



Detail of axi-symmetric model

FE predicted stress





Mock-up weldment measurements

- Welding transient temperatures & fusion boundary
- Distortion
- Hardness (plastic strain)
- Residual stress measurements:
  - ring opening
  - surface hole drilling (2 sets)
  - neutron diffraction (3 sets)
  - sectioning (BRSL)

FE vs measurements (weld HAZ line)

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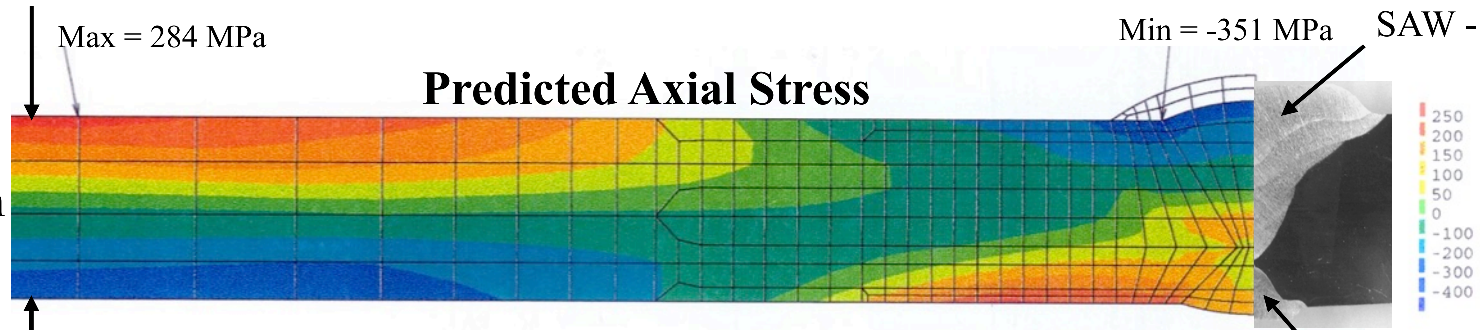
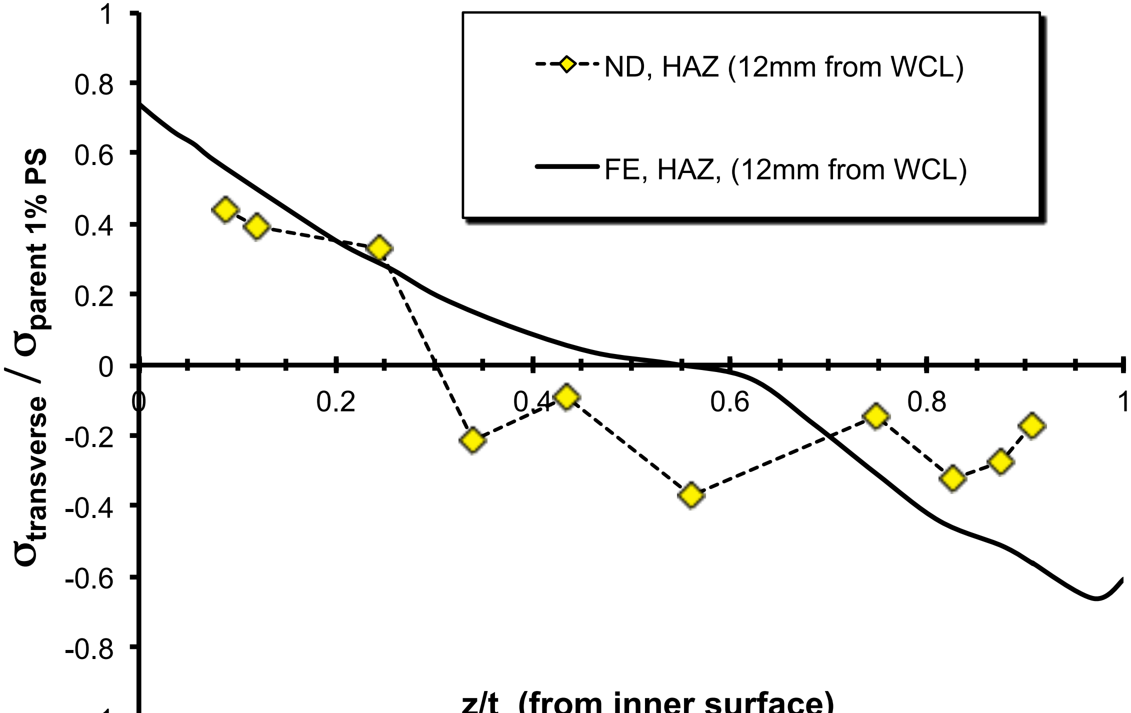
SAW - Passes 4-7

15.9 mm



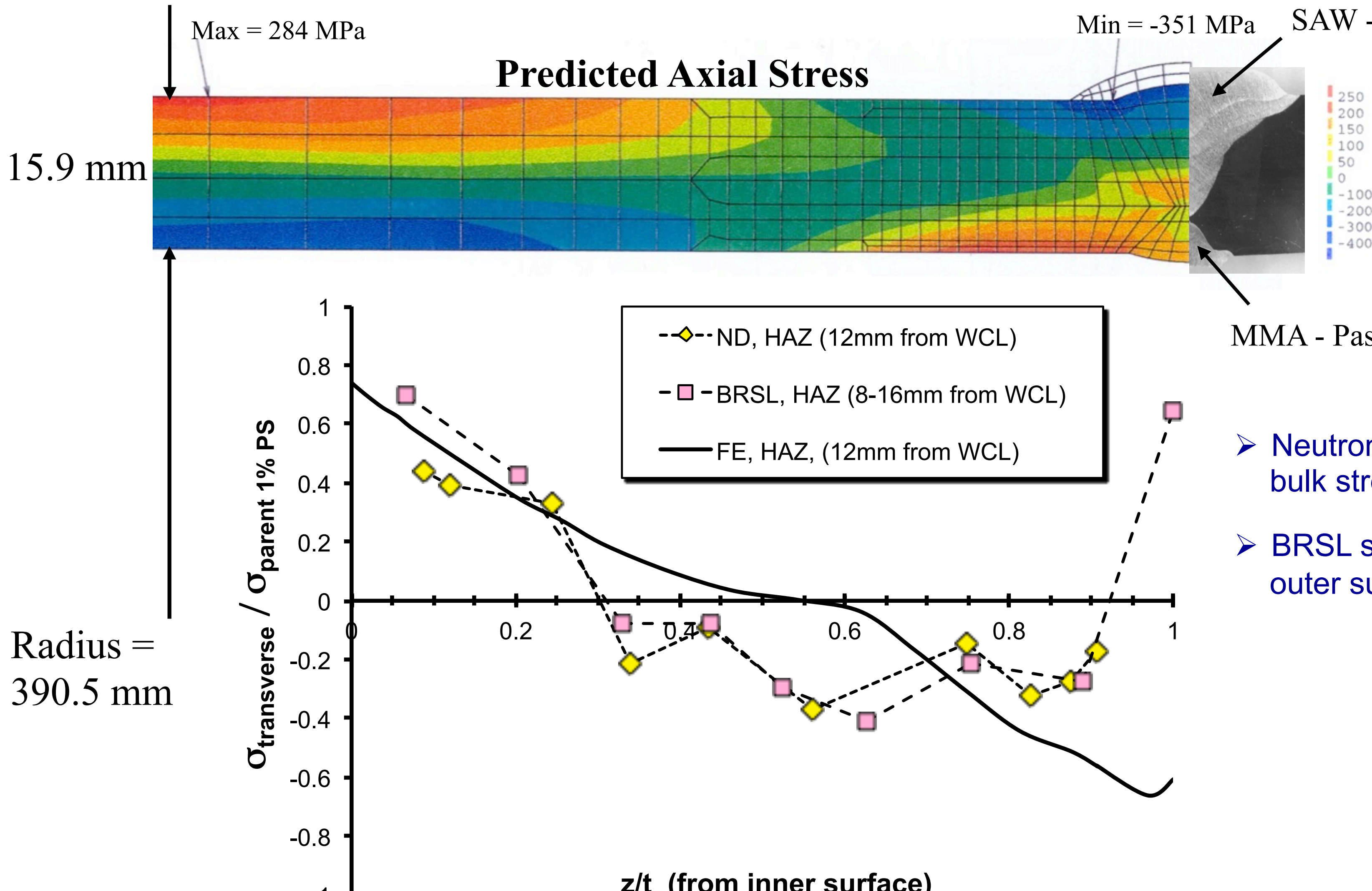
MMA - Passes 1-3

Radius =
390.5 mm



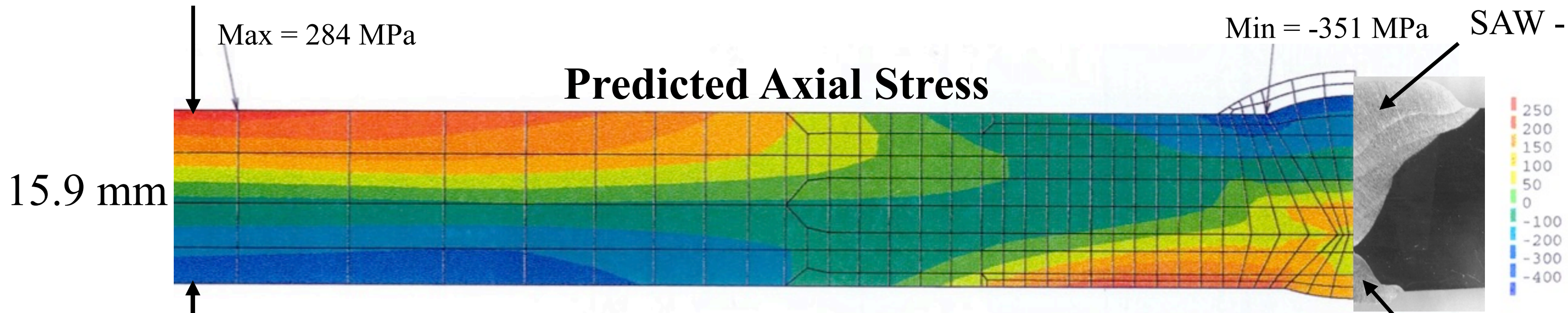
- Neutrons capture bulk stress profile

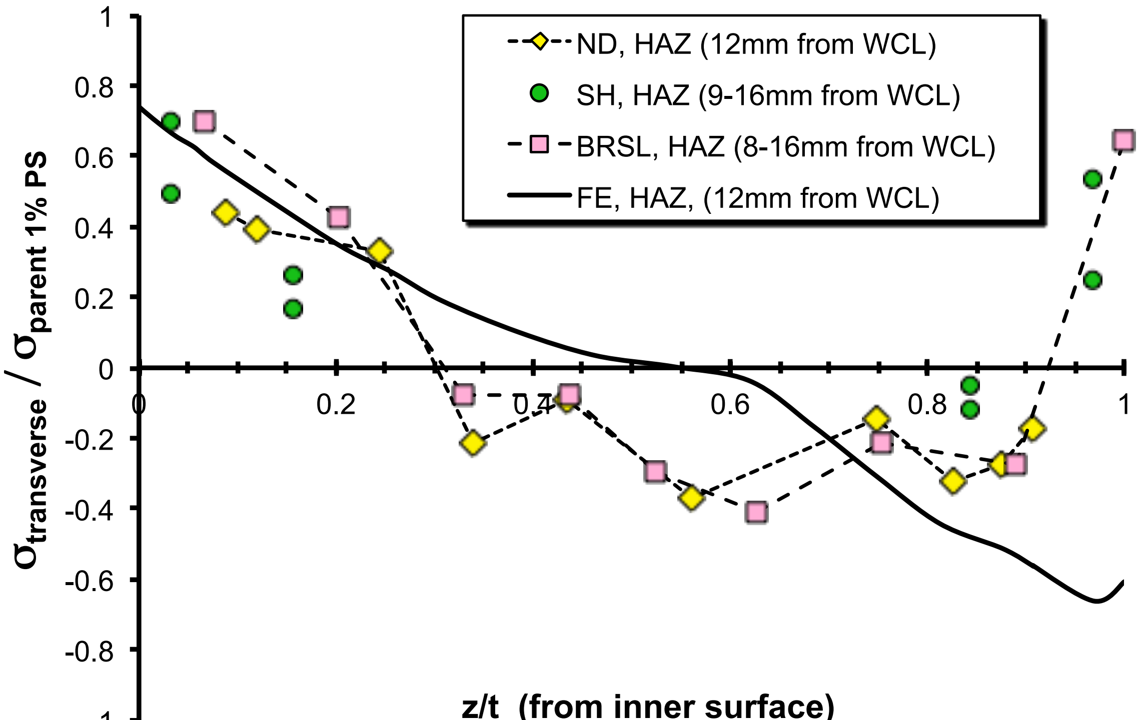
FE vs measurements (weld HAZ line)



- Neutrons capture bulk stress profile
- BRSL suggests outer surface peak

FE vs measurements (weld HAZ line)

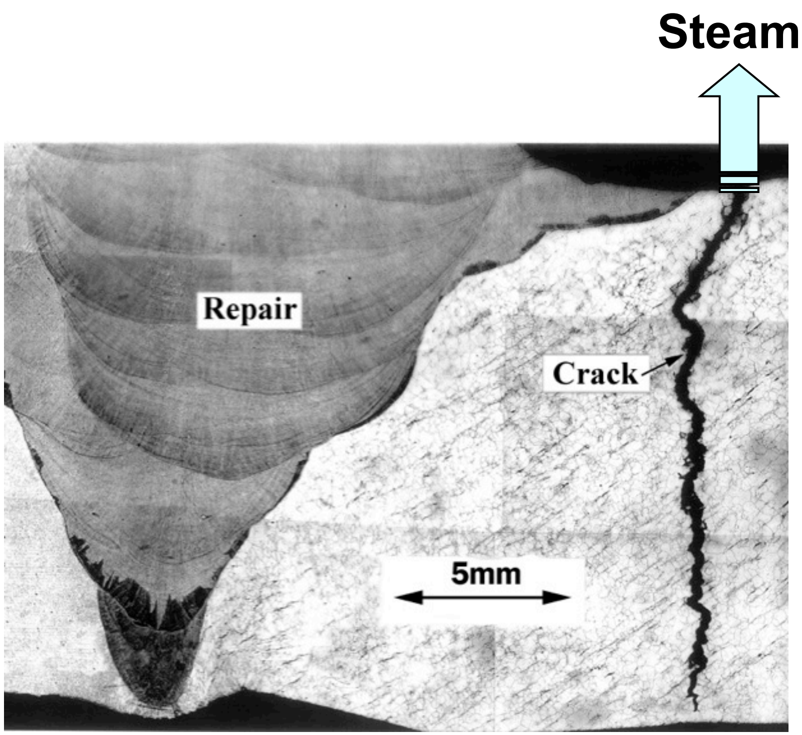


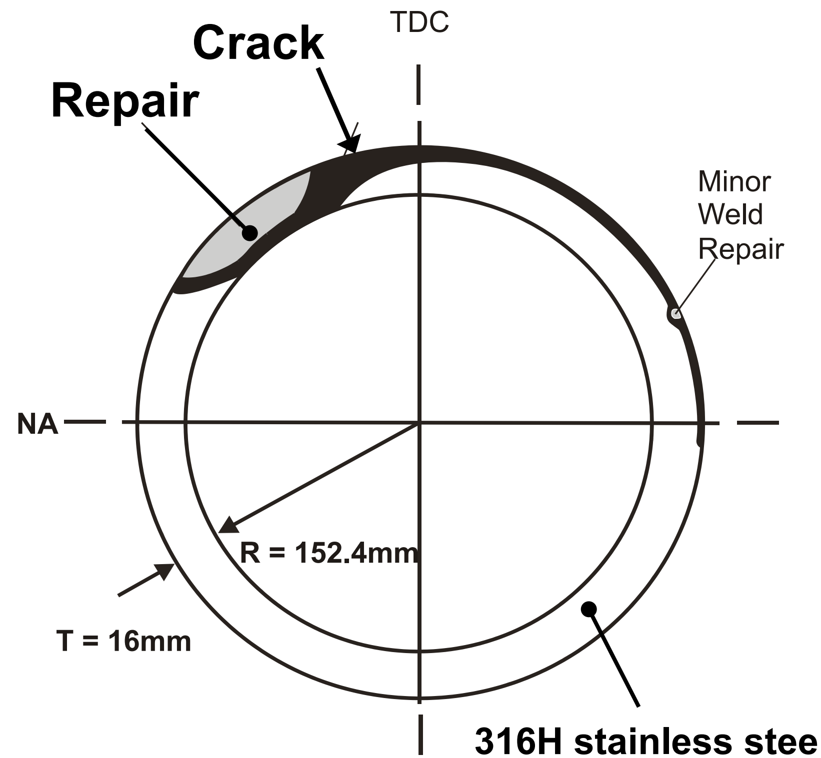


- **Neutrons capture bulk stress profile**
- BRSL suggests outer surface peak
- Confirmed by SH
- **FE does not capture up-turn at outer surface**
- **But tensile at inner surface**

Multiple methods:- example 2

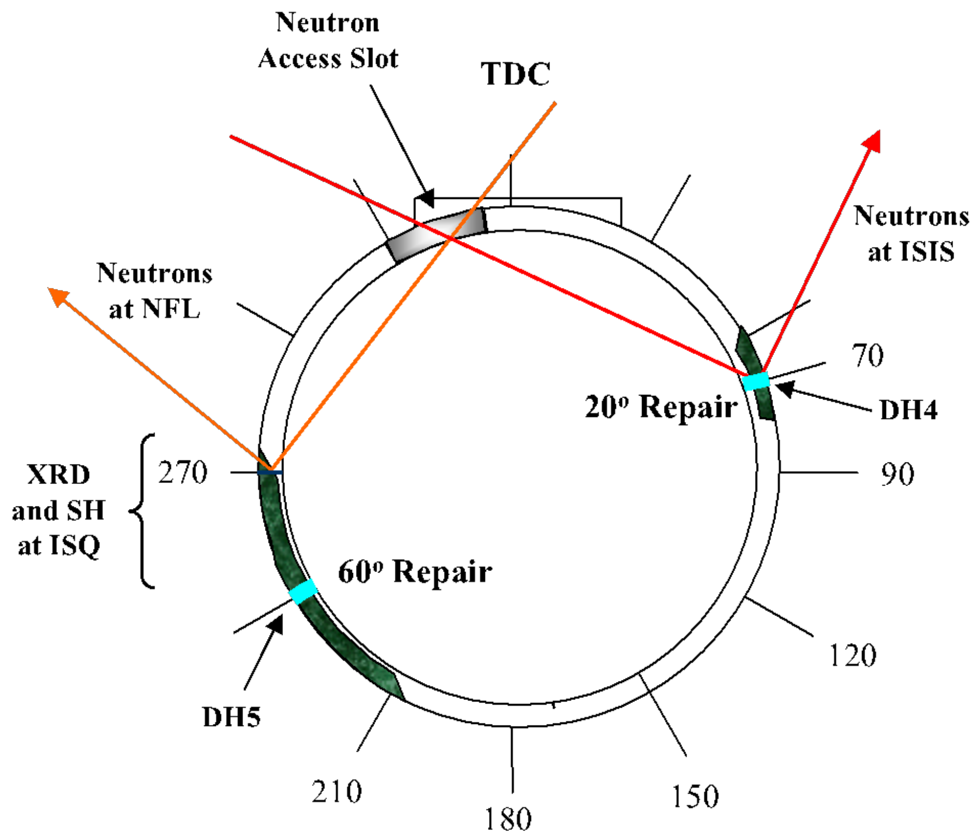
Repair welds and reheat cracking (1998)

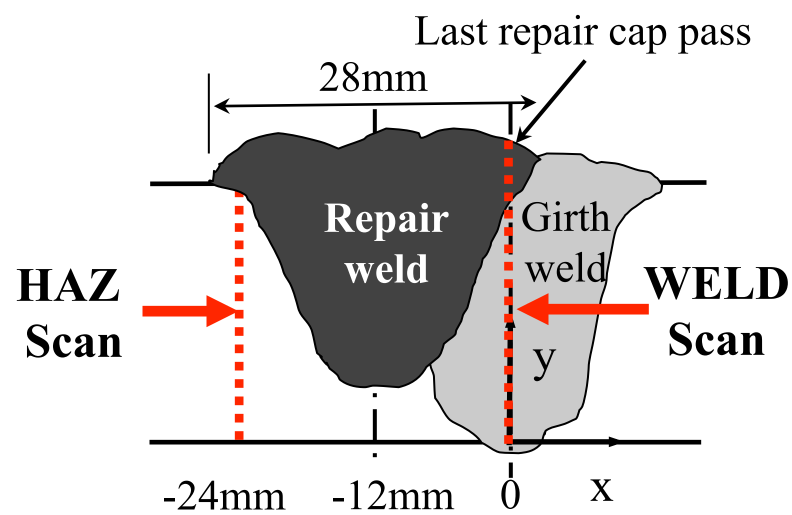


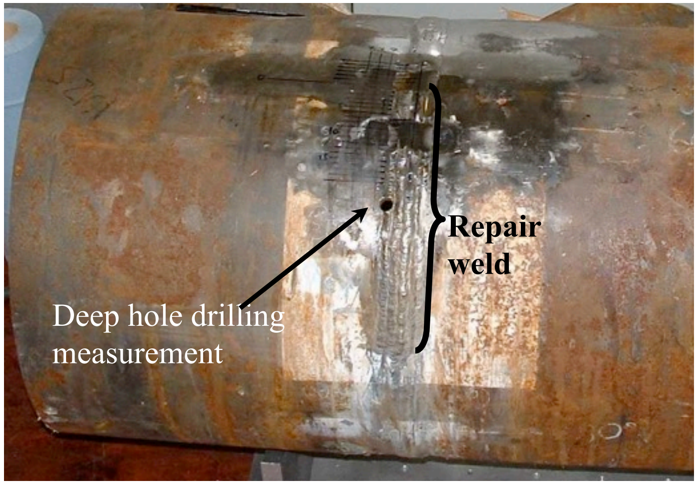


- **Reheat crack initiation » creep crack growth through-wall » steam leak**
- **Repair weld residual stress + plant loads at high temperature (>500^{o}C),**

Mock-up for weld repairs



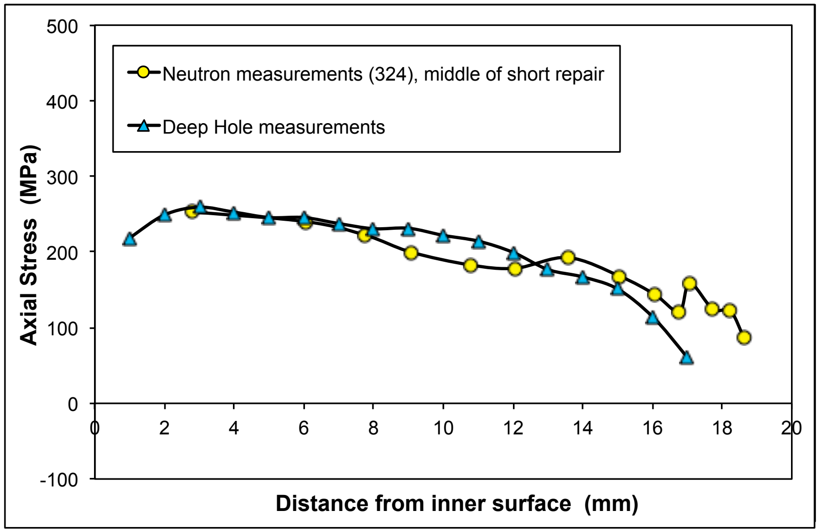


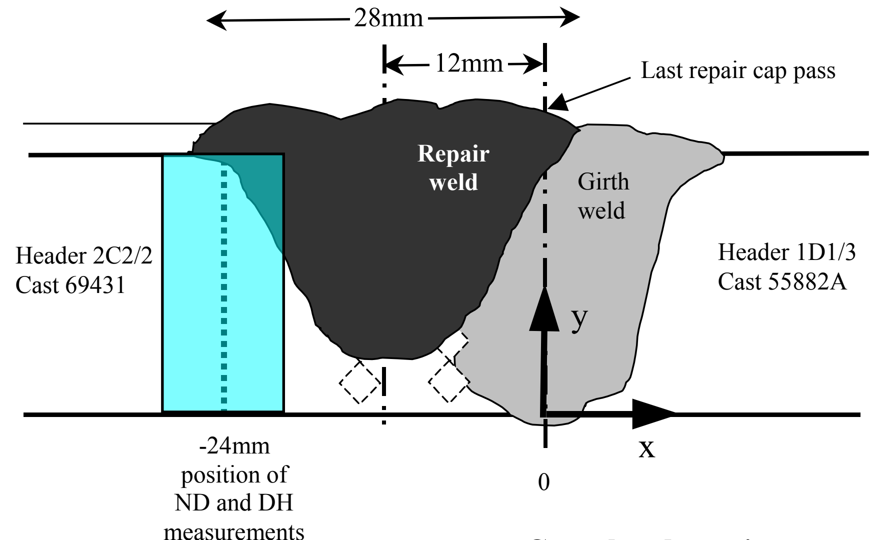


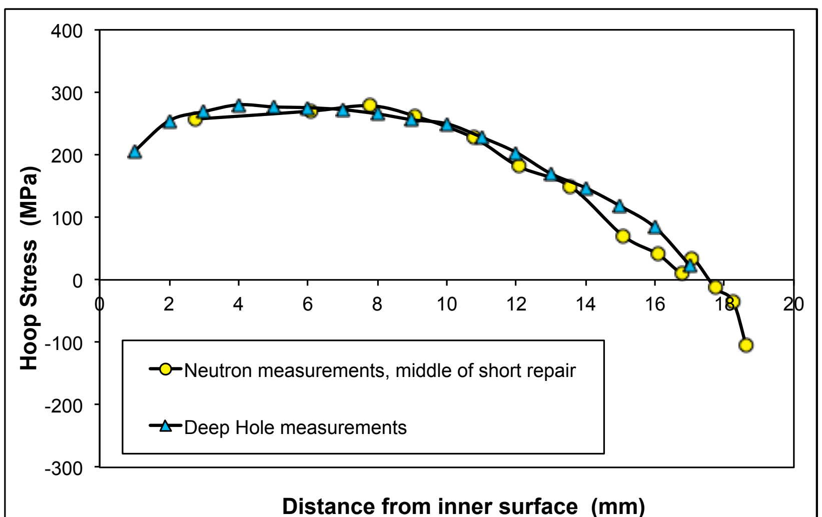
Pipe OD = 432 mm, t = 19.6 mm

Pipe length = 830 mm

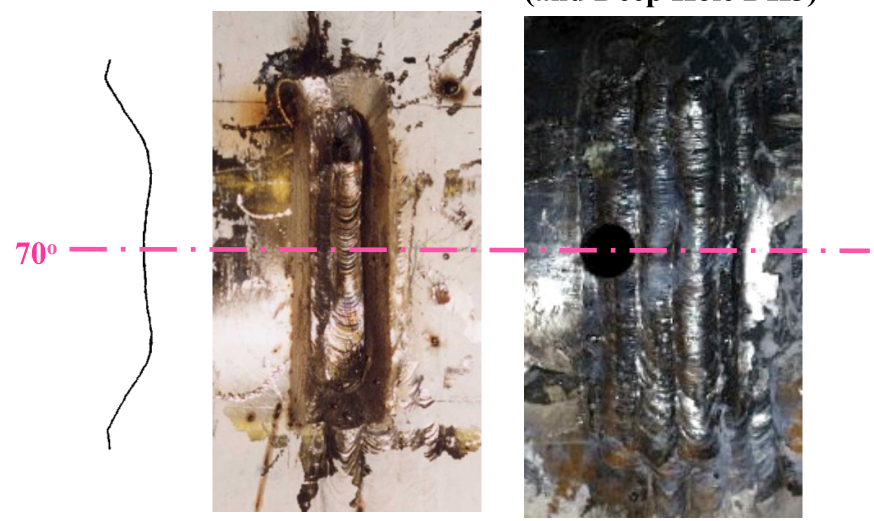
20º repair initial measurements



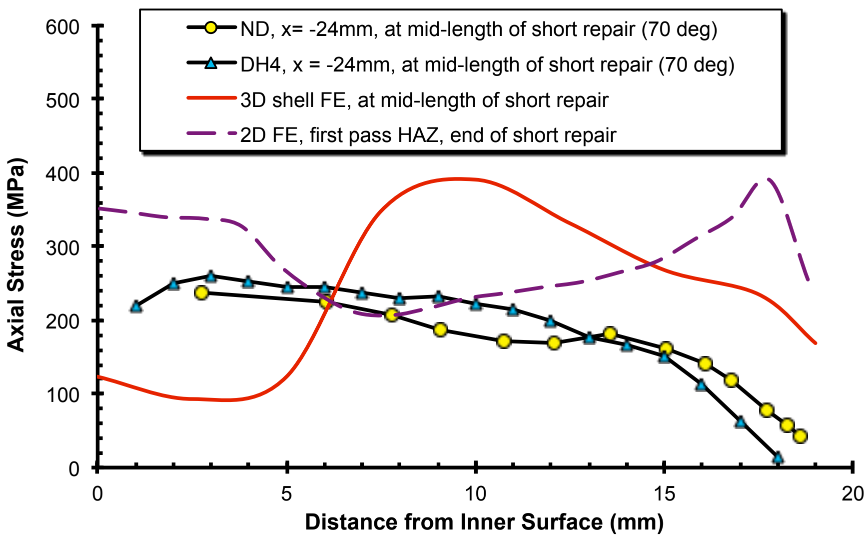


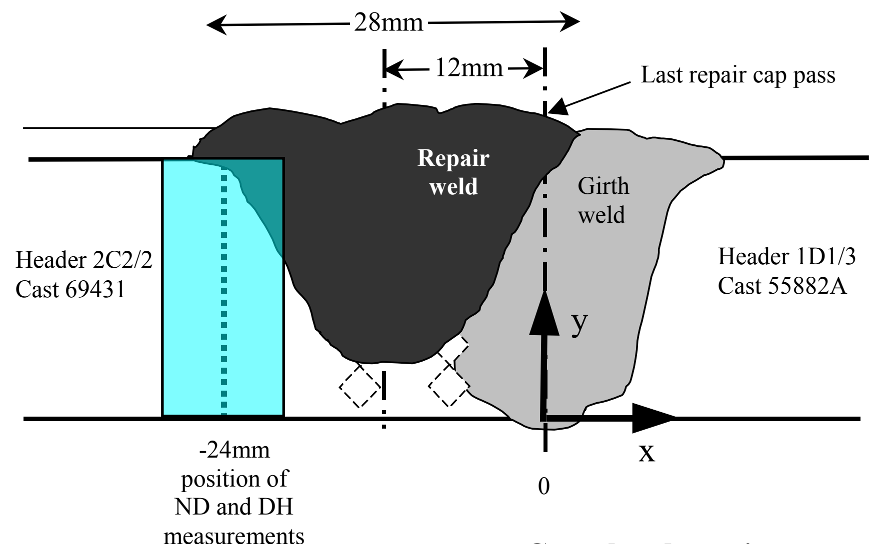


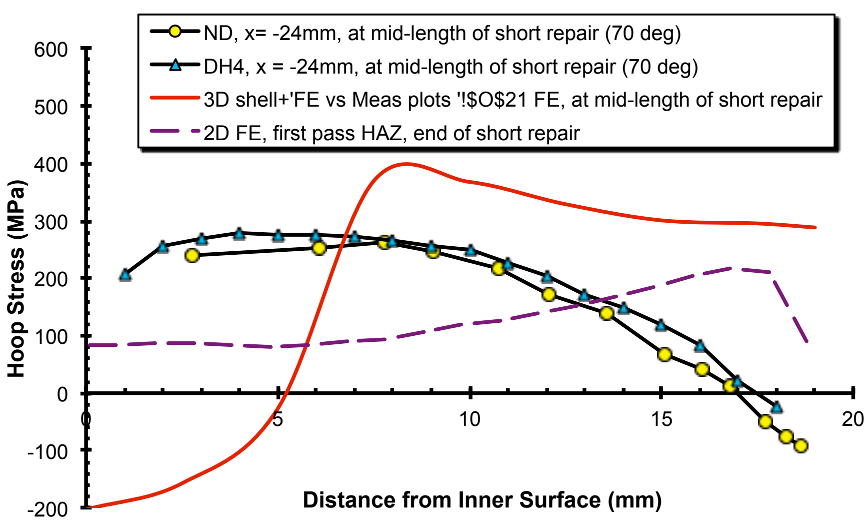
Excavation **1st bead** **Completed repair (and Deep Hole DH3)**

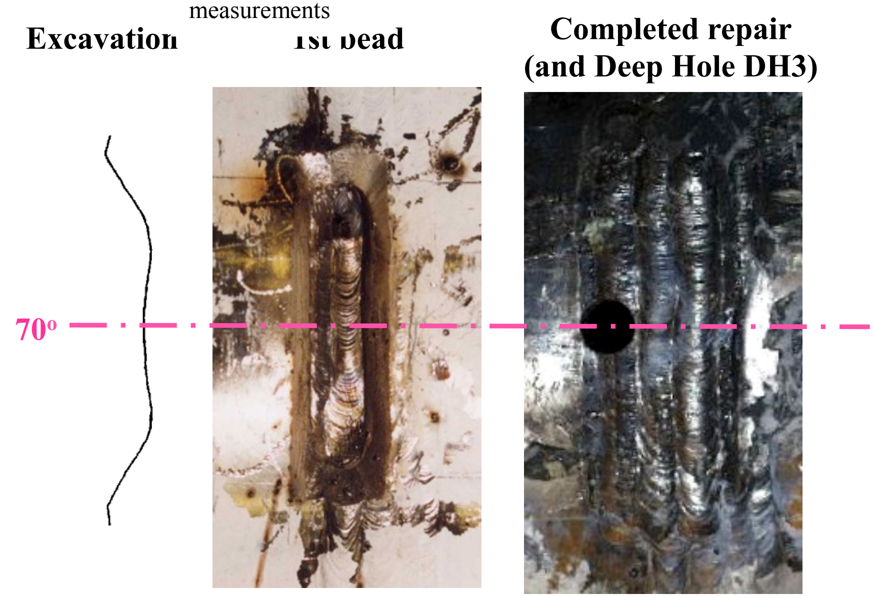


FE predictions vs measurements









Advanced 3D FE vs measurements

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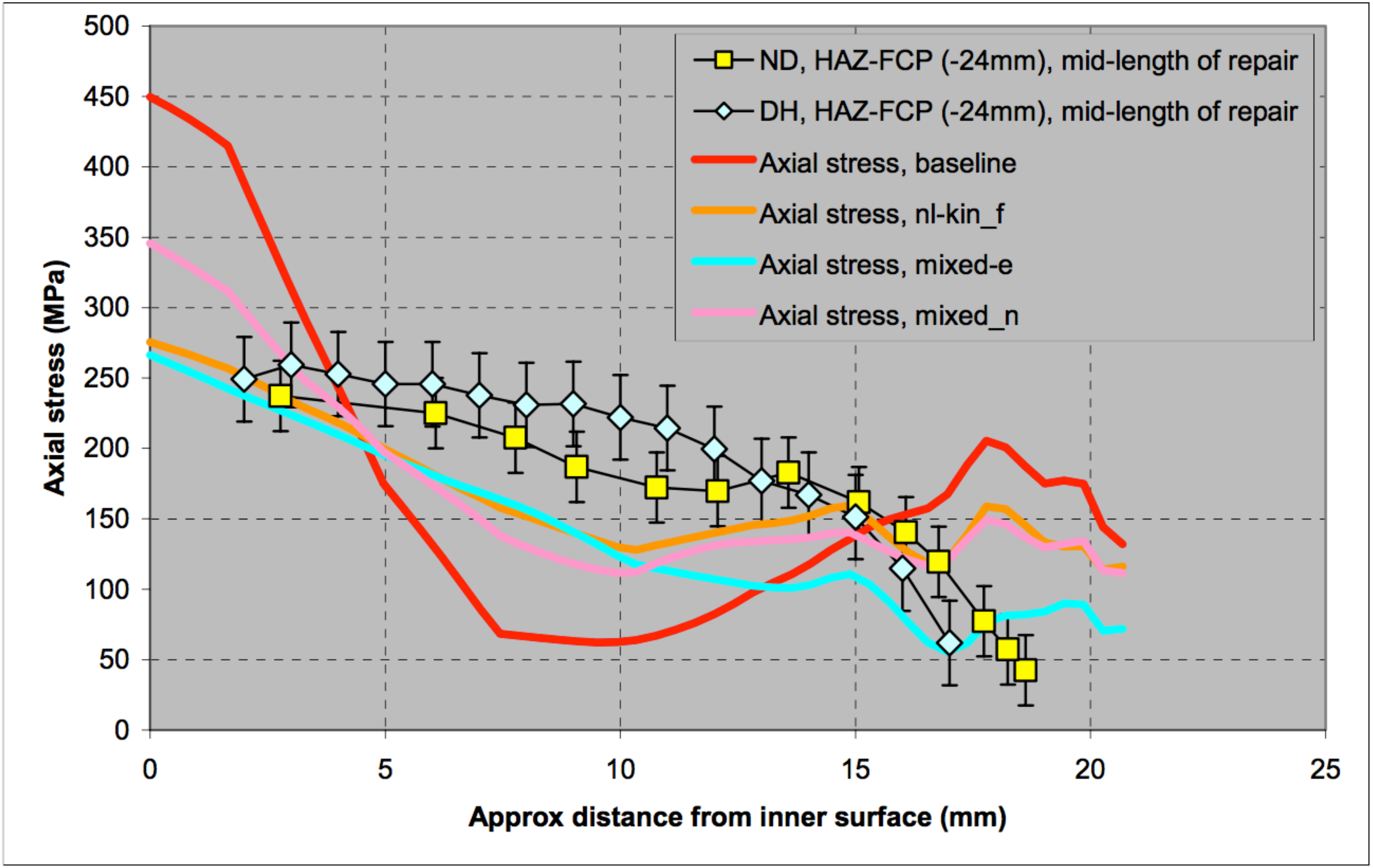
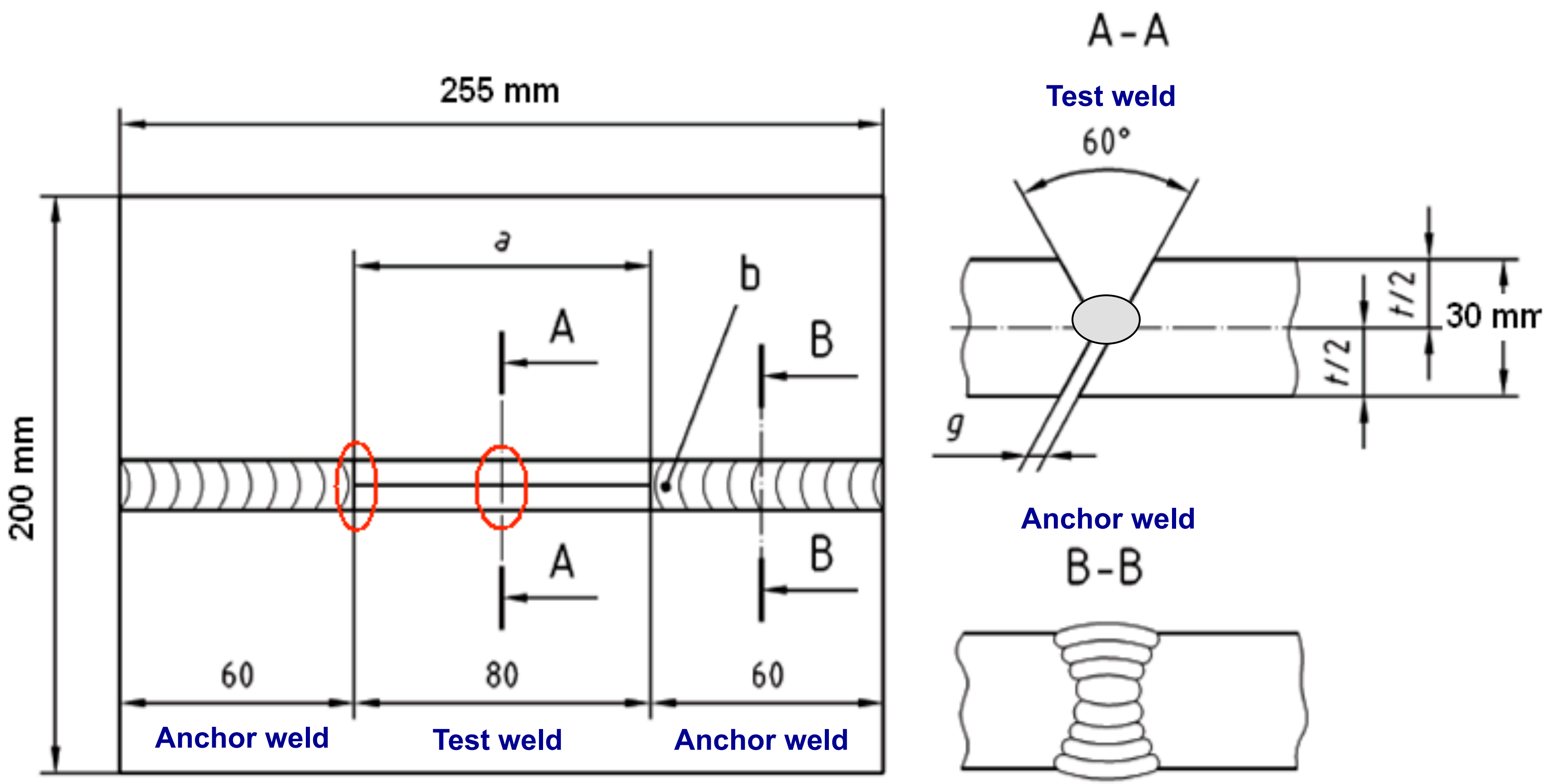
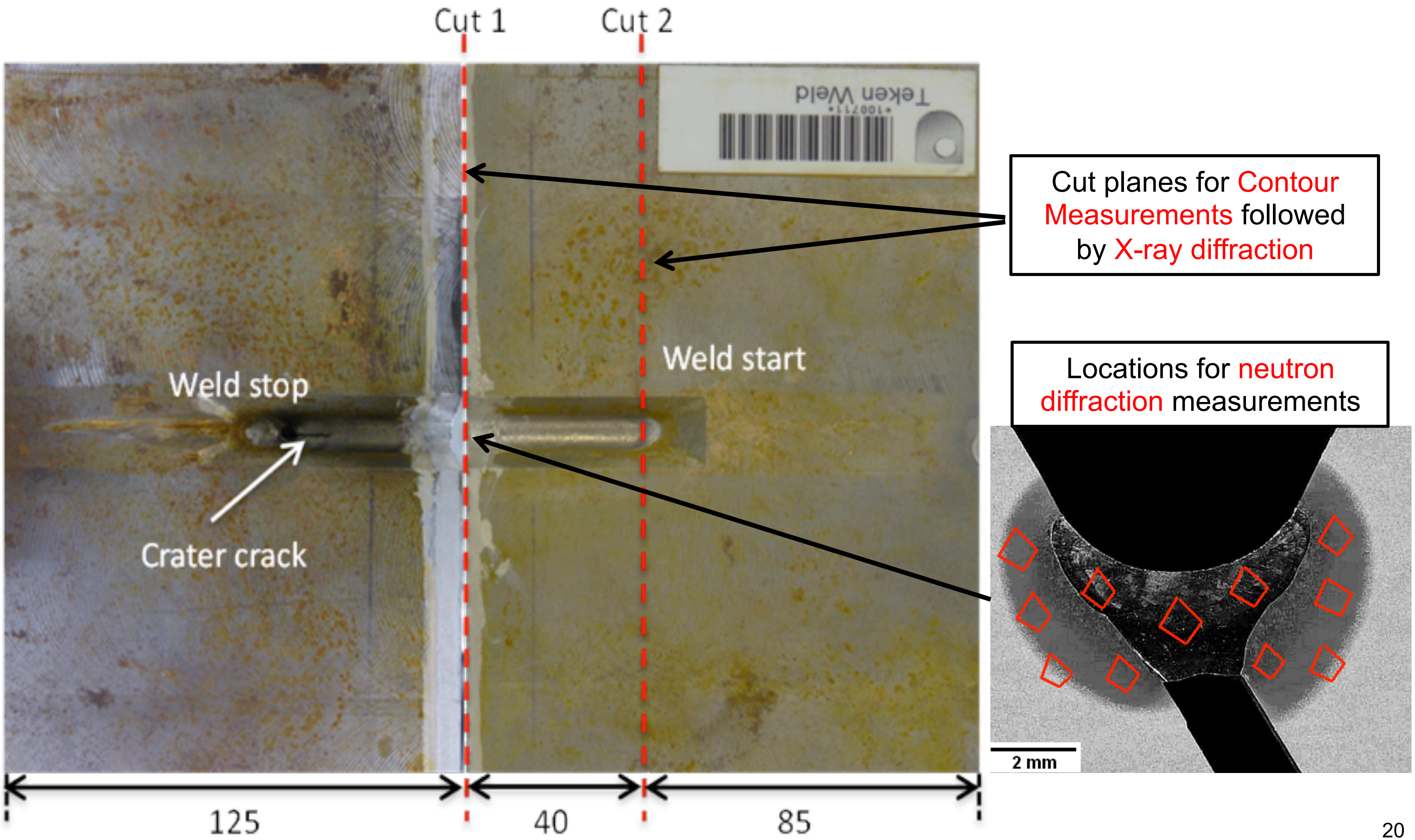


Tekken weld geometry:- Example 3

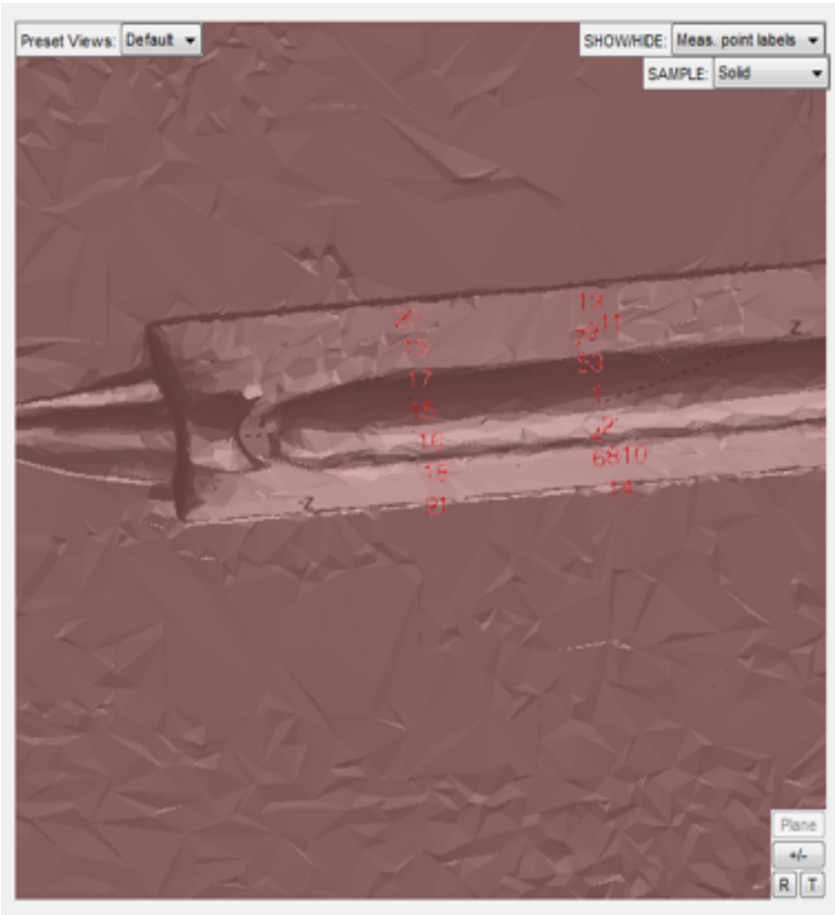


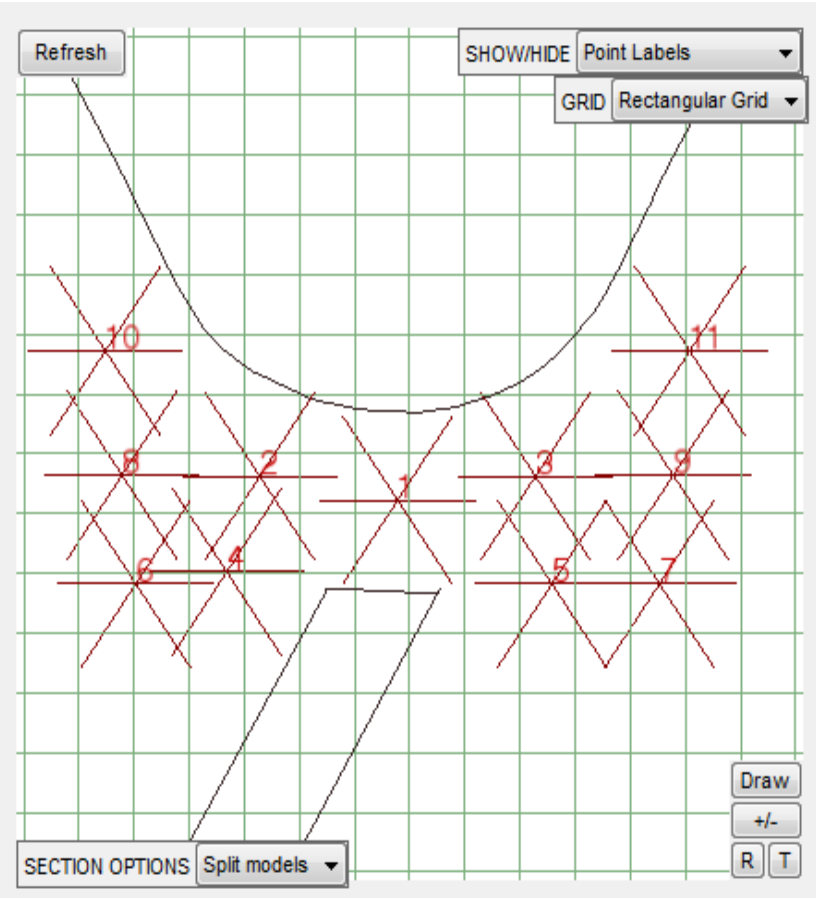
Standardised test for susceptibility of root pass welding to cold cracking

Tekken weld measurements



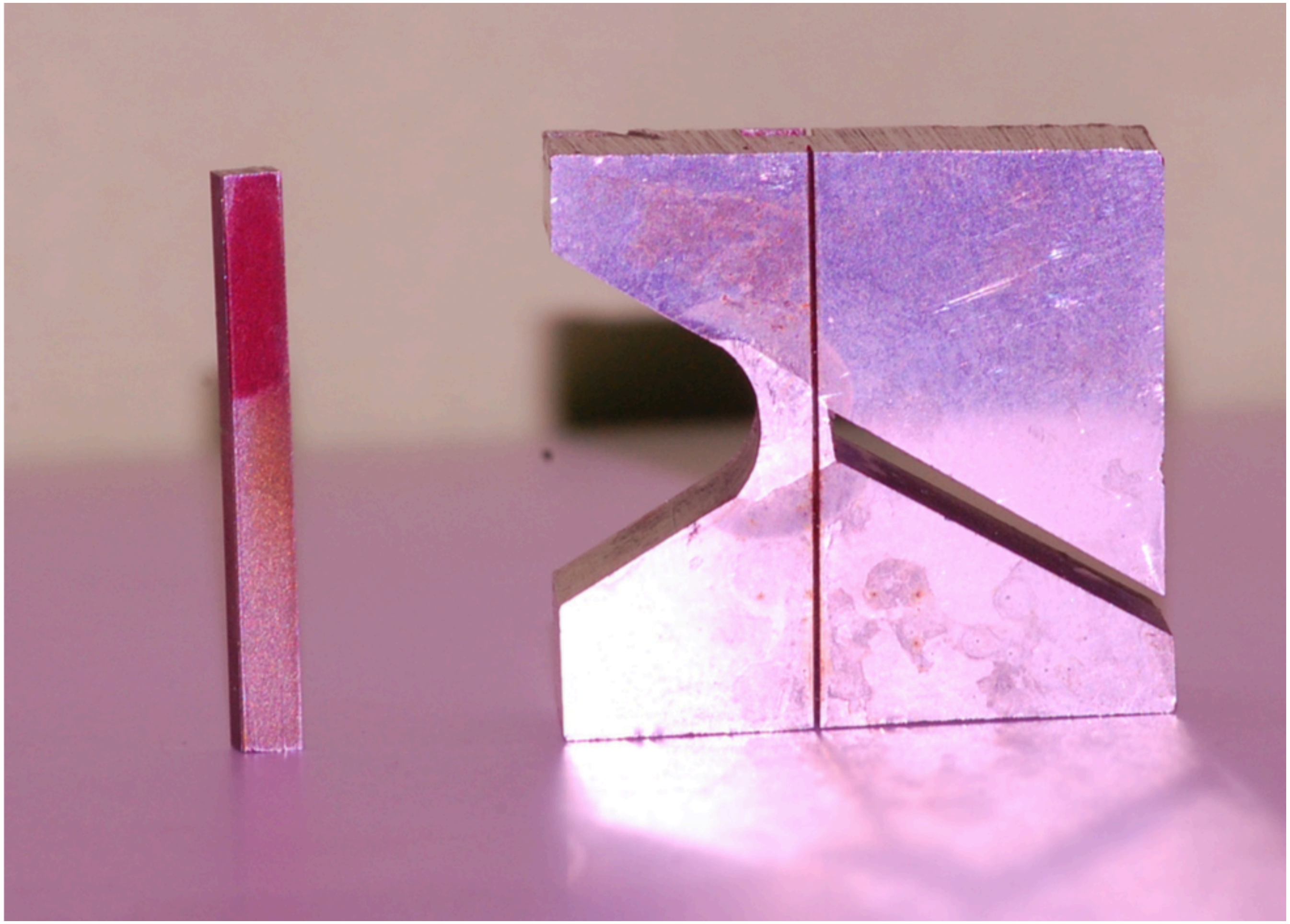
Tekken weld geometry challenge:
Neutron diffraction locations



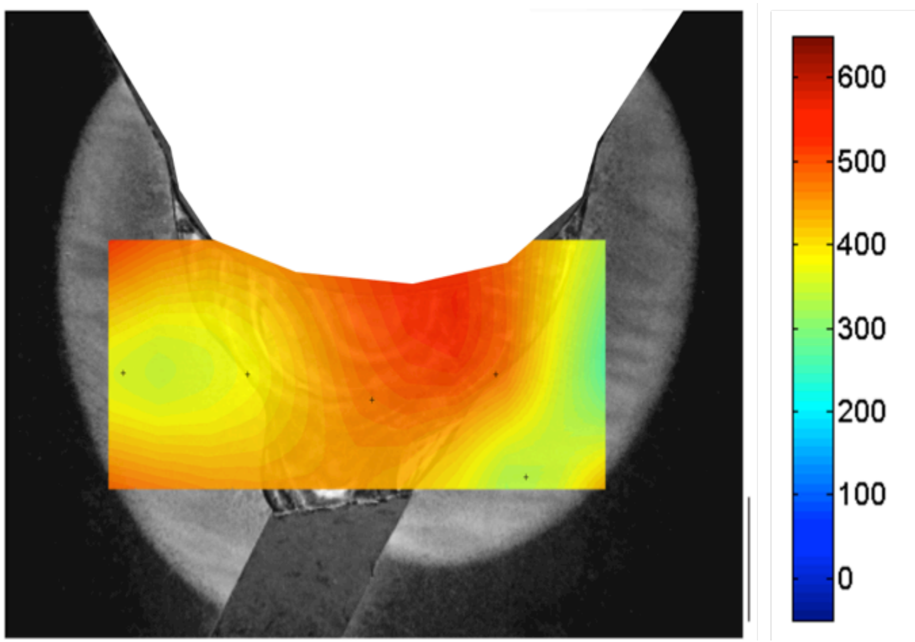


Tekken Alloy 52 weld metal challenge

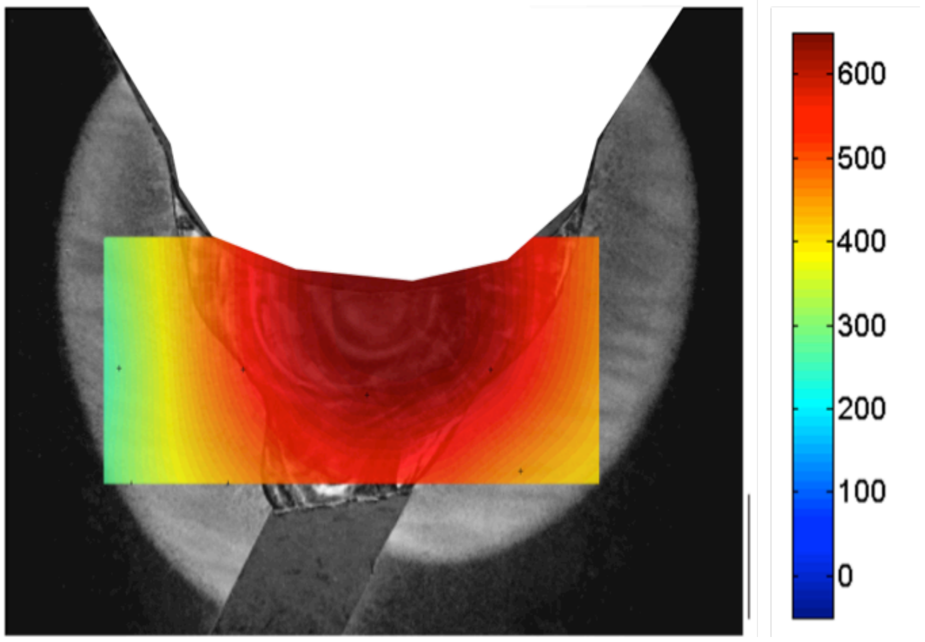
Stress-free reference matchstick



Tekken weld:
Neutron diffraction, 3 direct stress components

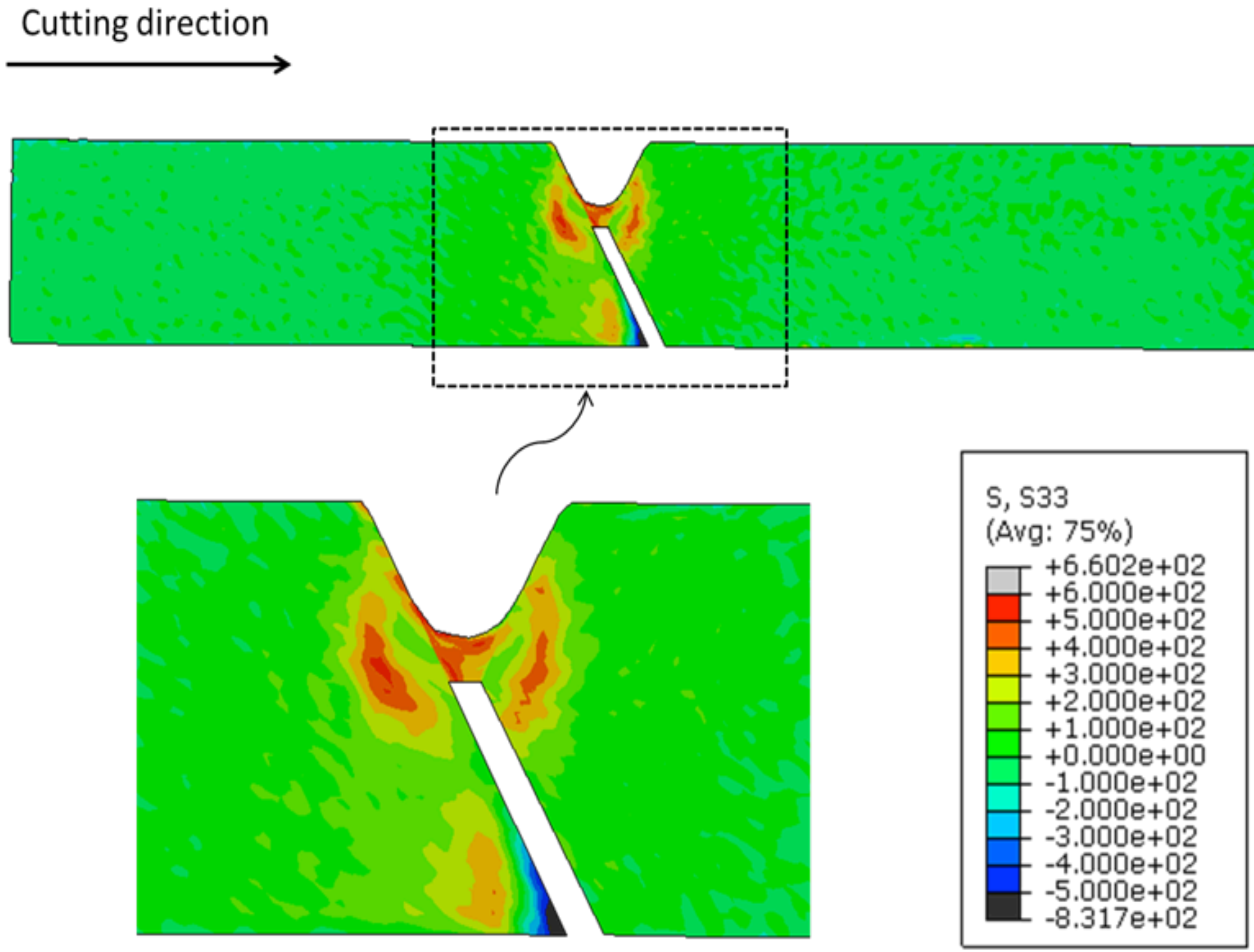


Longitudinal stresses

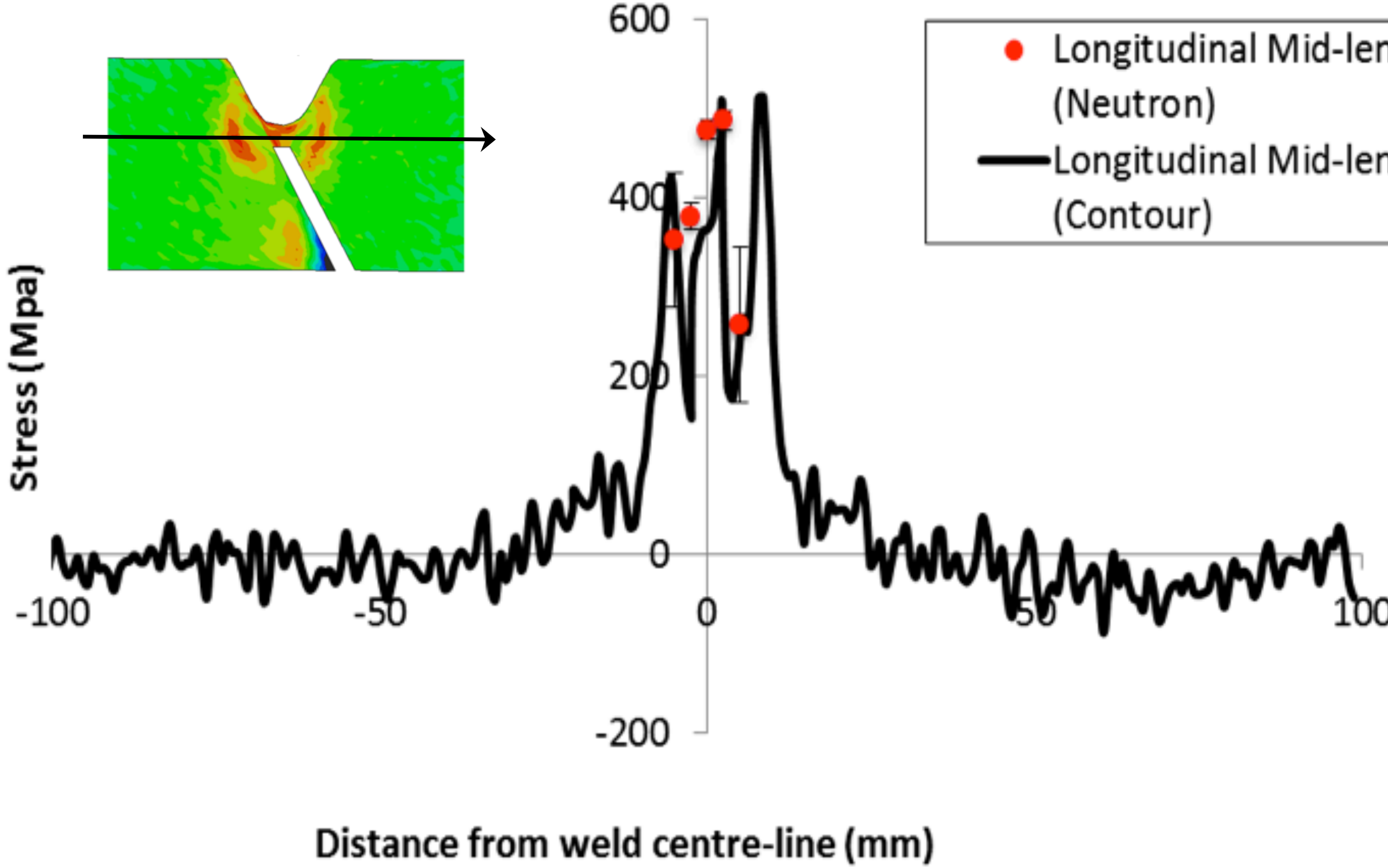


Transverse stresses

Tekken weld at mid-length
Contour method for longitudinal stresses



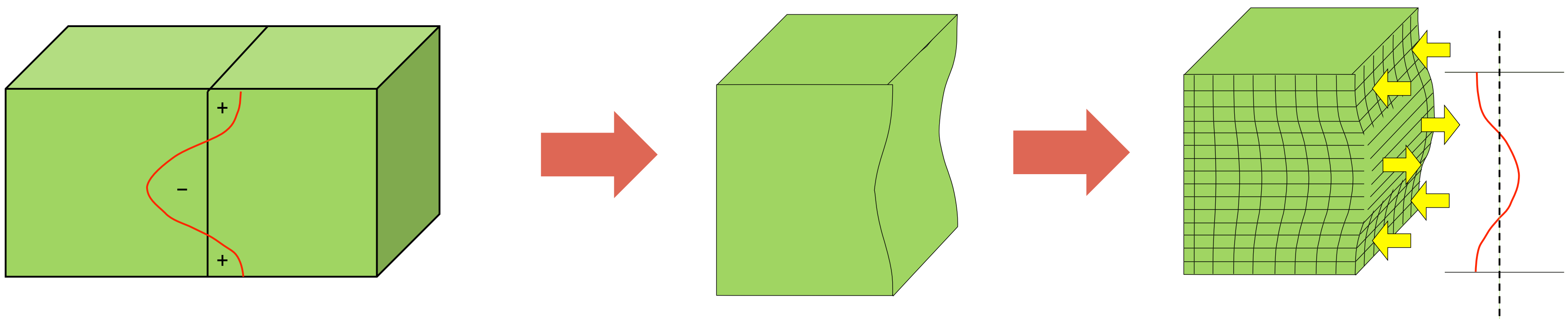
Tekken weld at mid-length:
Neutron diffraction vs contour result



Longitudinal stress line profiles, 11 mm below the top surface on a transverse plane at mid-length

Multi-cut contour & multiple methods

Principle of superposition



A: Original residual stresses

B: Partially relaxed stress state

C: Change in Stress state

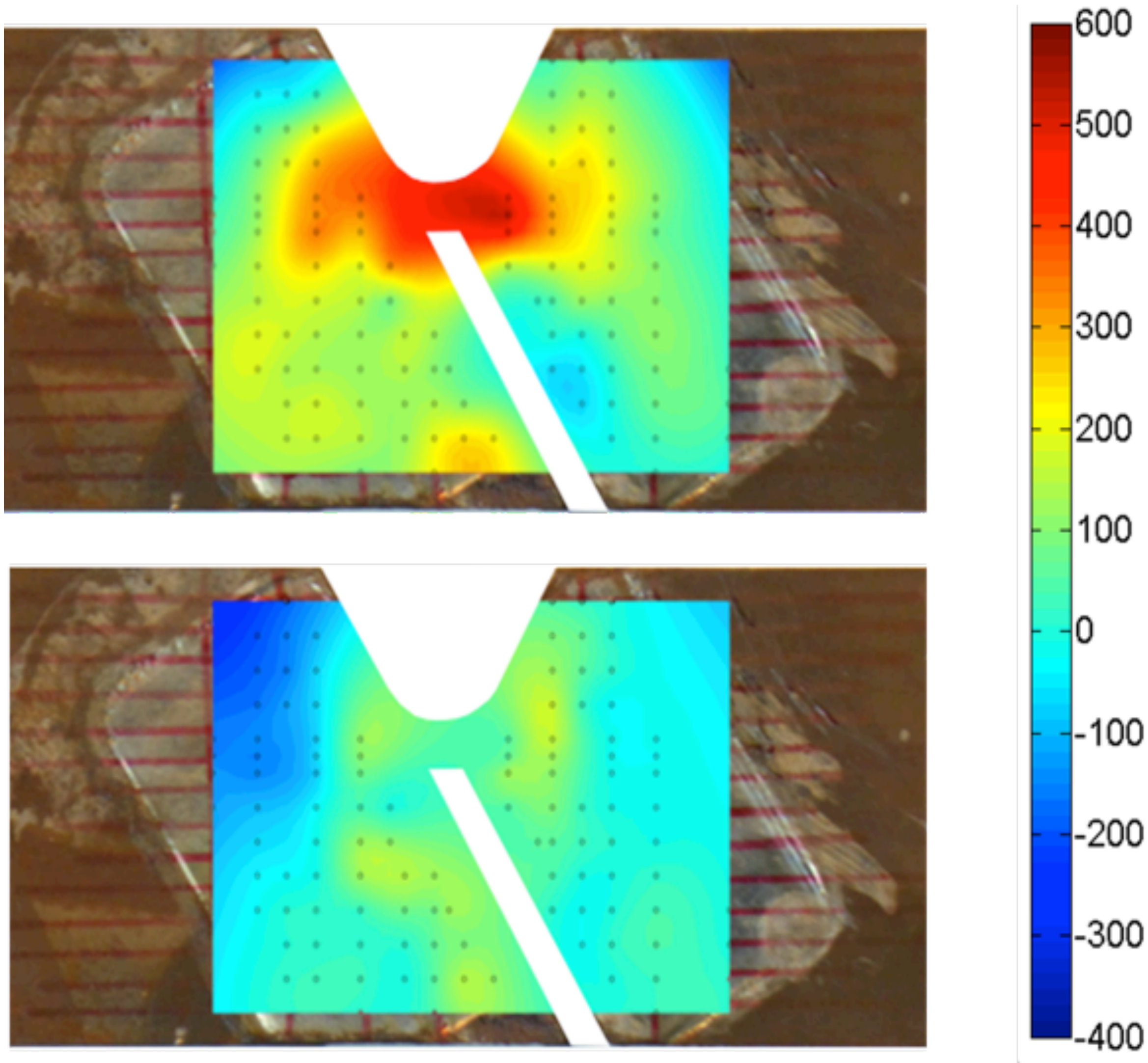
$$\sigma_A(\mathrm{x,y,z}) \quad = \quad \sigma_B(\mathrm{x,y,z}) \quad + \quad \sigma_C(\mathrm{x,y,z})$$

Measure stresses in relaxed state B and apply contour boundary conditions (change in stresses C) to determine original stress state A

Pagliaro, P. et. Al, Experimental Mechanics, 2010

Tekken weld at mid-length

X-ray + Contour transverse & normal stresses



Transverse stress (top)

Normal stress (bottom)

units are in MPa.

The black markers on the contour plots indicate the measurement positions.

The results within the Alloy 52 weld deposit are based on interpolations

Tekken weld at mid-length:
Neutron diffraction vs XRD + Contour

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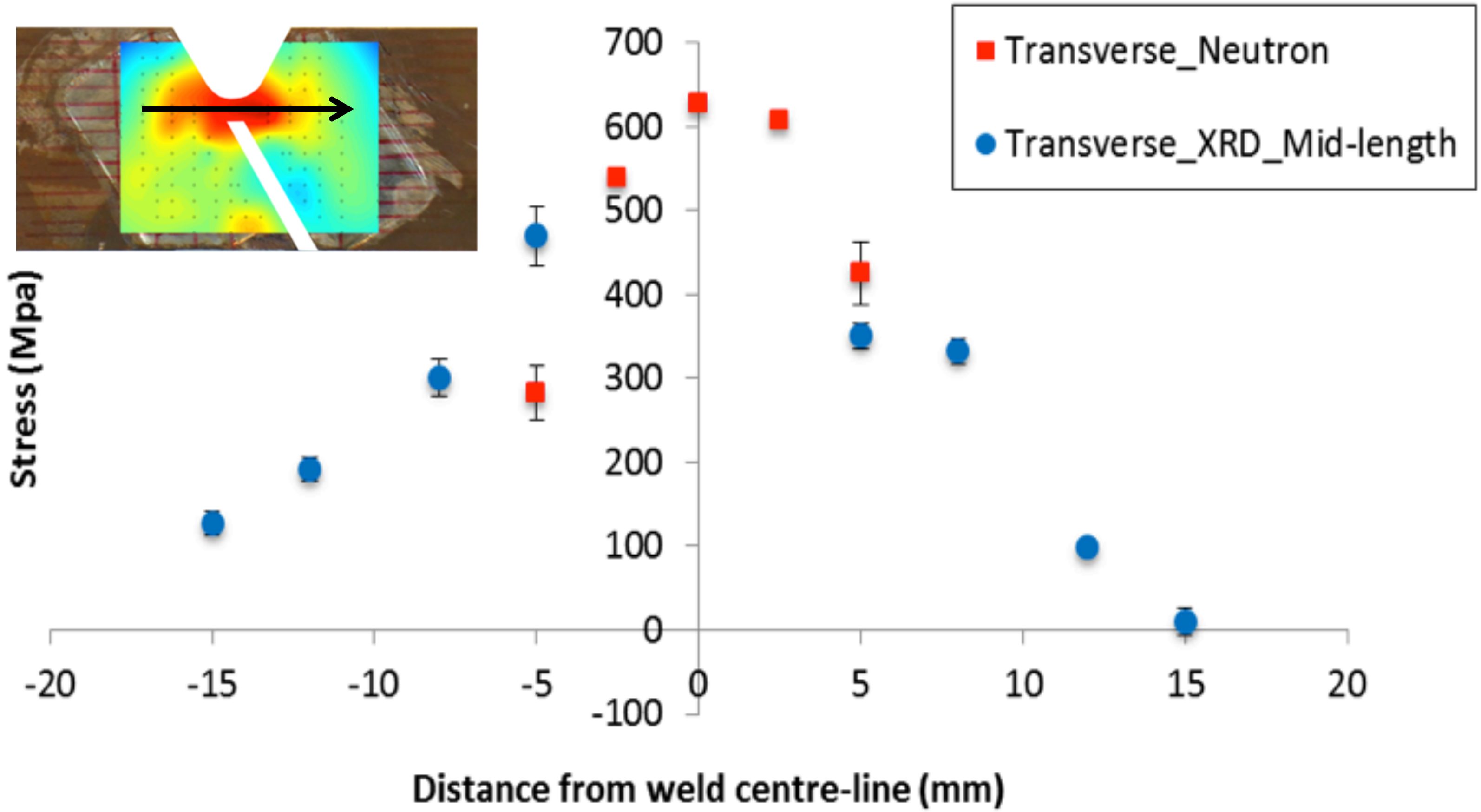
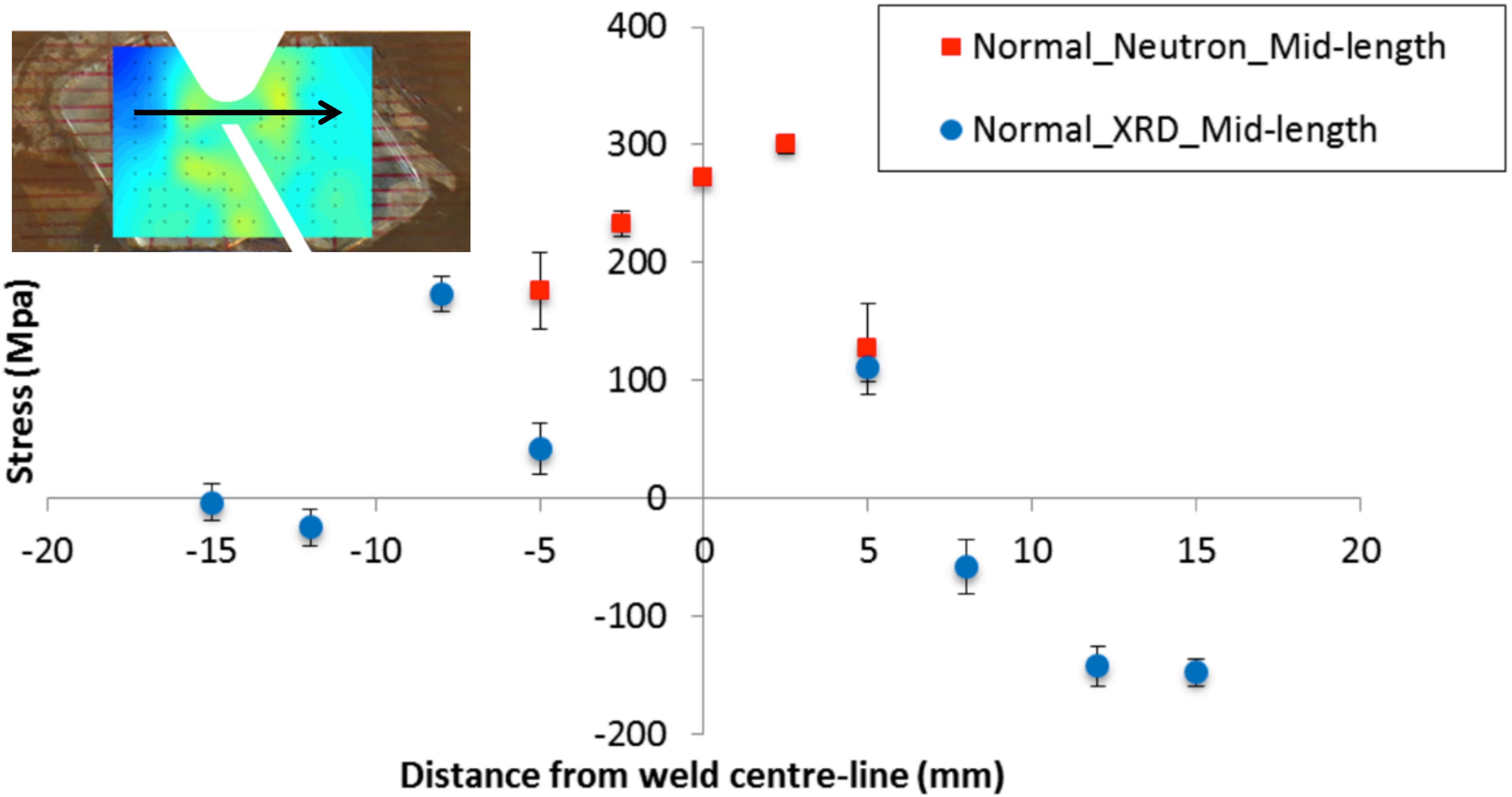


Transverse stress profiles, 11 mm below the top surface across the width on a transverse plane at mid-length, measured using the multiple-method approach (Contour + XRD) & neutron diffraction

Tekken weld at mid-length:
Neutron diffraction vs XRD + Contour



Normal stress profiles, 11 mm below the top surface across the width on a transverse plane at mid-length, measured using the multiple-method approach (Contour + XRD) & neutron diffraction

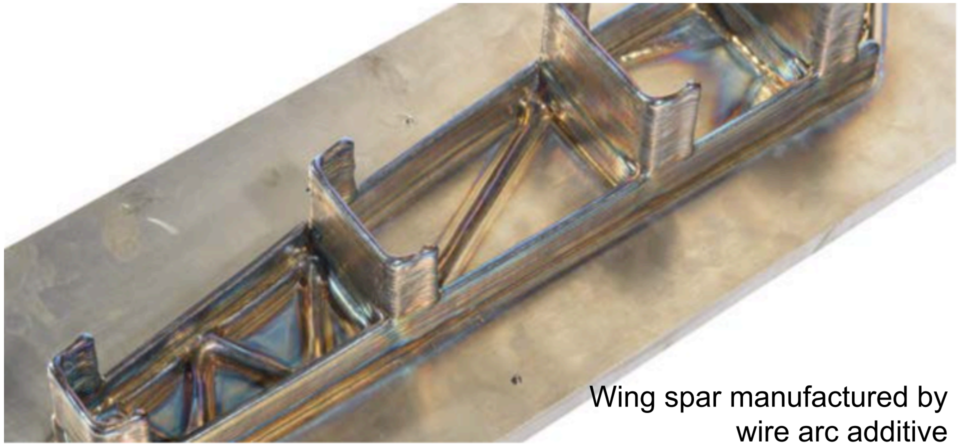
Conclusions

1. **Application of multiple methods can:-**
   - can help identify errors,
   - increase confidence in results,
   - increase spatial & tensorial coverage, and
   - help to satisfy industry QA requirements.
2. **The Contour method** offers a powerful approach for combining stress measurement methods

Widening industrial interest

Awareness of the importance of residual stress is increasing:

- Airframe design and manufacture
- Offshore wind
- Offshore oil and gas
- Shipping
- Earth moving industry
- Medical
- High value manufacturing
- Additive manufacture
- Automotive
- Railways
- Others…..



Wing spar manufactured by wire arc additive manufacture

Consequences of residual stress

- Distortion
- Over-design (heavy, higher cost)
- Degradation (e.g. fatigue, corrosion)
- Failure (safety, high cost)
- More inspection

Looking ahead

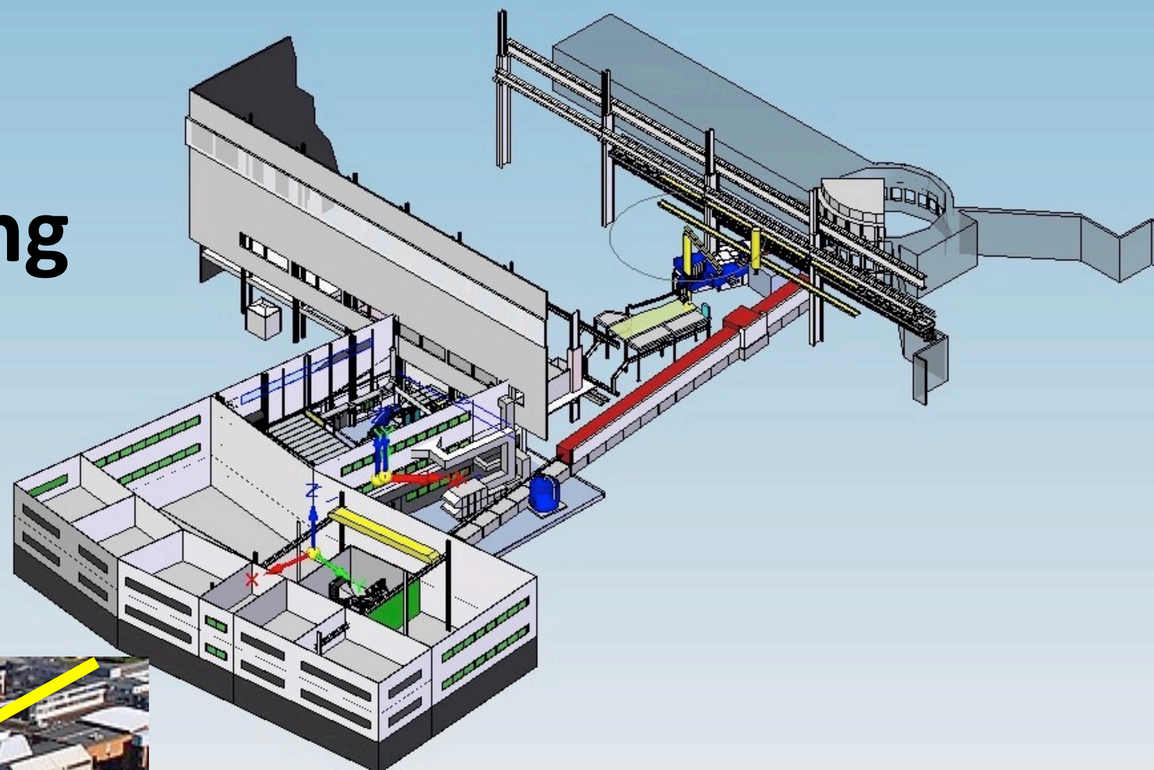
UK Capability Gaps

1. Provisions for measuring very large and heavy components using the Contour Method.
2. Long term provision of neutrons in Europe.
3. Measurement practitioners who can apply multiple methods.
4. Subject matter experts in industry who can specify, procure and assess multiple measurements that will deliver solutions.

Science & Technology Facilities Council
ISIS

The Open University

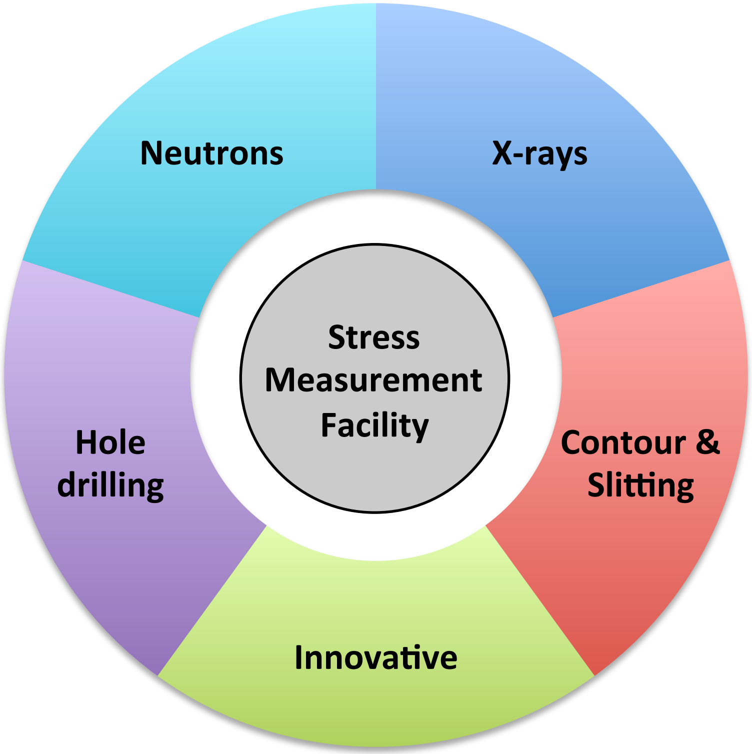
International Stress Engineering Centre (I-SEC)

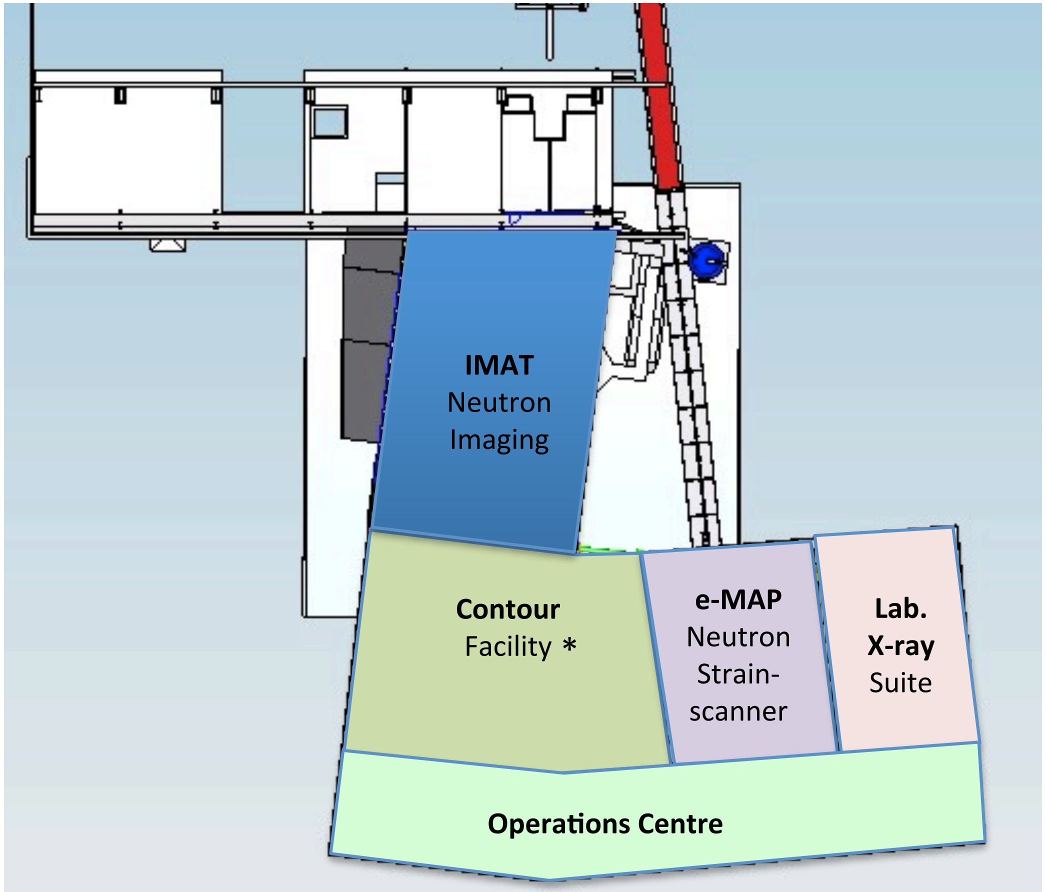


@Harwell (UK)

Coventry University

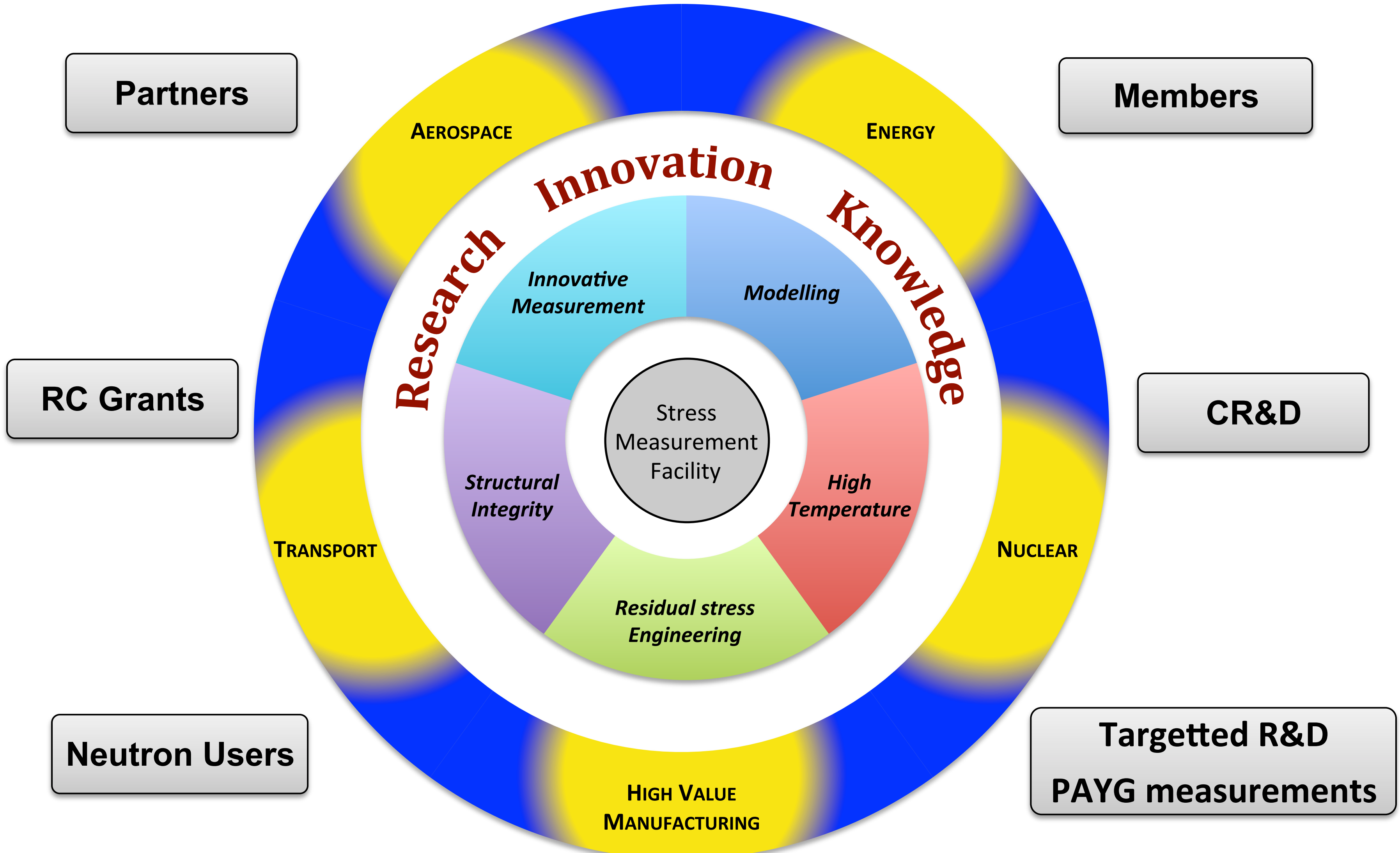
Measurement hub co-locating all methods





* Includes slitting, hole-drilling etc.

Research Hub



I-SEC Training Hub

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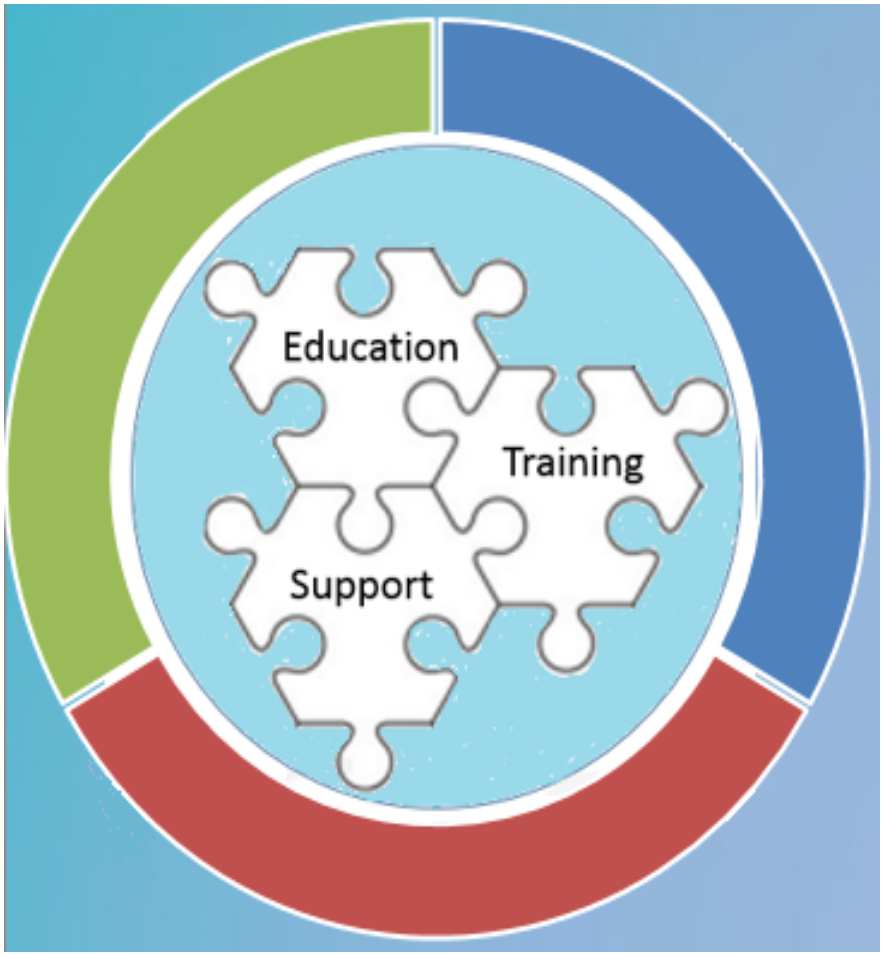

Education

(industry, universities, schools, general public)

- Stress Engineering (solid mechanics, physics of materials, forensic etc)
- Physics & mechanics of measurement methods
- Modelling, assessment & standards

Training & Support

(for industry, academic users, collaborators)

- Measurement techniques
- Specialist equipment
- Virtual laboratory
- Remote experiments
- Augmented reality
- Data analysis/visualization
- Document and data library
- User community support

I-SEC offerings - supporting the product lifecycle