



VDI-Expert Forum, 10th April 2008

Combined Use of FE-Simulations and Neutron/X-ray Experiments

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Outline

- **Introduction**
- **Failures - importance of weld residual stress**
- **Quantifying weld residual stresses**
 - » **Can we rely on FE simulation or measurements?**
- **Improving predictions of weld residual stress**
 - » **Conventional testing**
 - » **Better material hardening models**
 - » **Validation examples using diffraction techniques**
- **Conclusions**

British Energy

British Energy owns and operates 8 nuclear power stations:

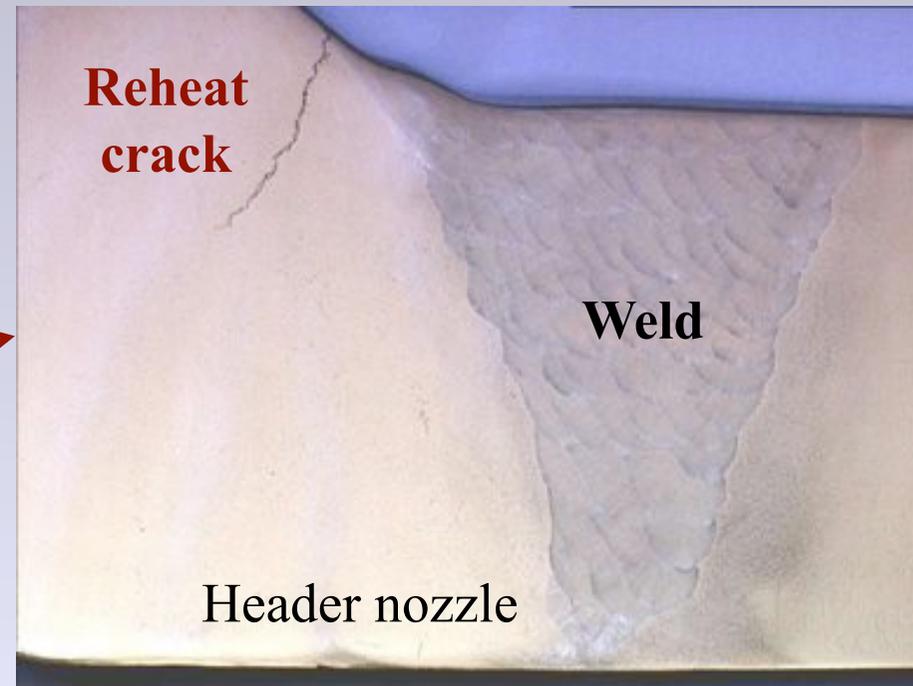
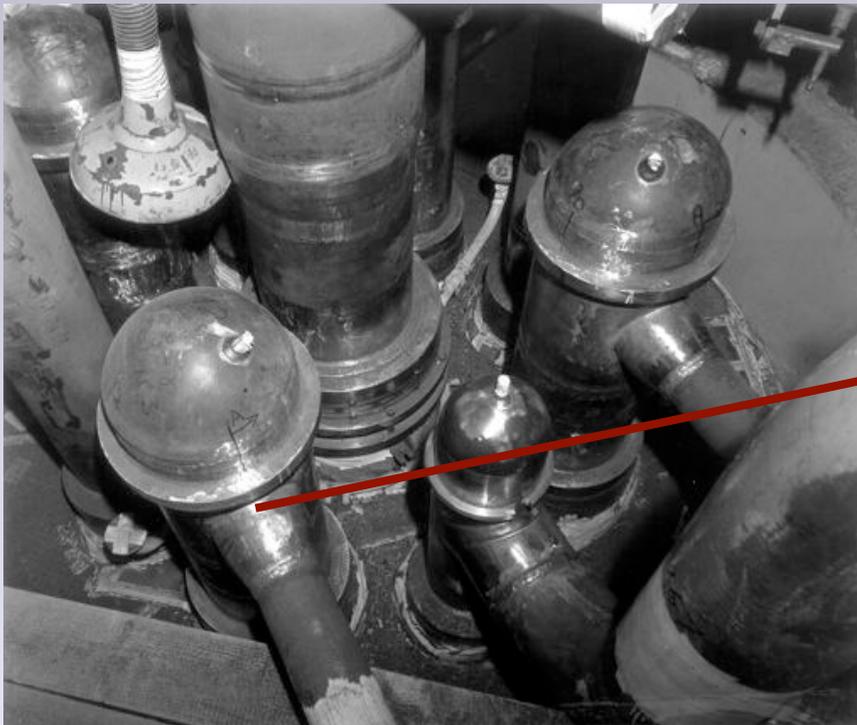
- » largest producer of electricity in the UK ($\approx 20\%$)
- » lowest carbon emitter of major UK electricity generators

British Energy's priorities include:

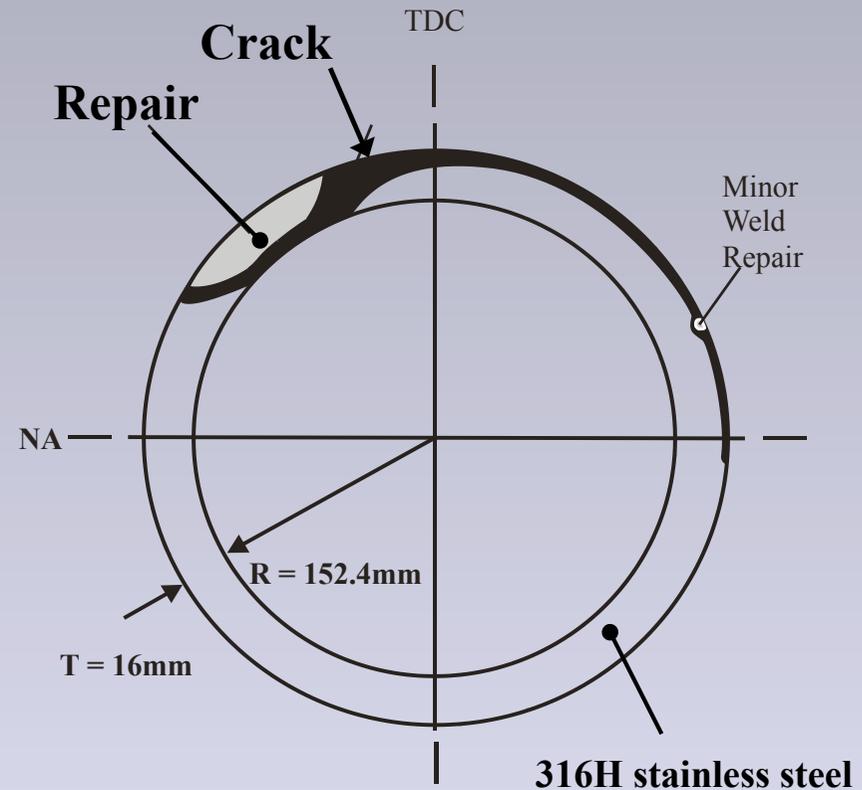
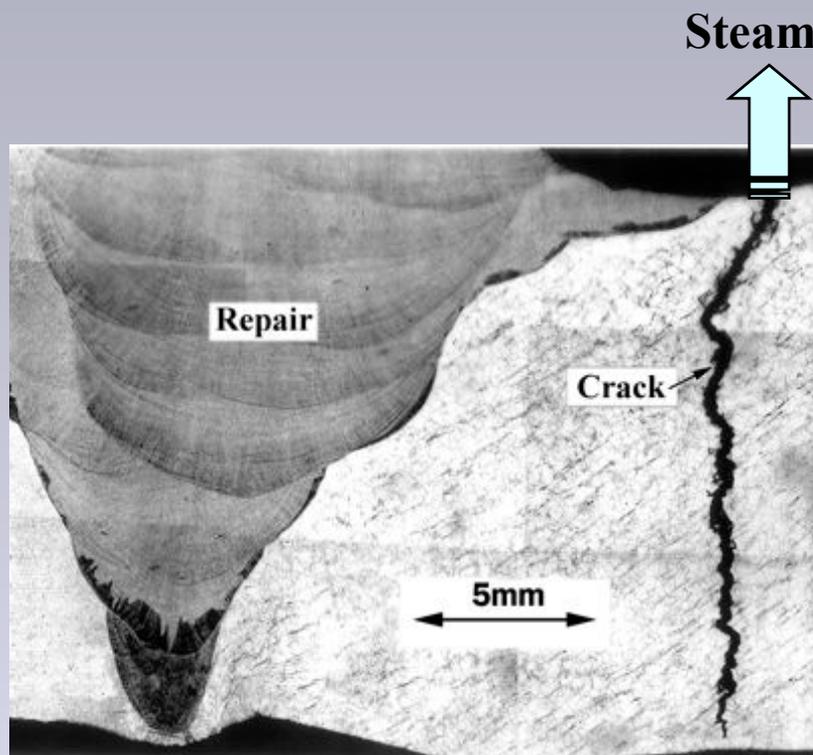
- » maintaining **safe operation** of our ageing nuclear plant,
- » improving station **reliability and performance**,
- » securing **plant life extensions** to underwrite the UK's future security and diversity of energy supply,
- » Developing a position at the heart of **new nuclear generation** in the UK

Pressurised Plant Integrity

- 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



Reheat cracking at a repair weld (1997)



Reheat crack initiation » creep crack growth through-wall » steam leak

Repair weld residual stress + plant loads at high temperature ($>500^{\circ}\text{C}$),

Is the through-wall crack stable? – What are the life and load margins?

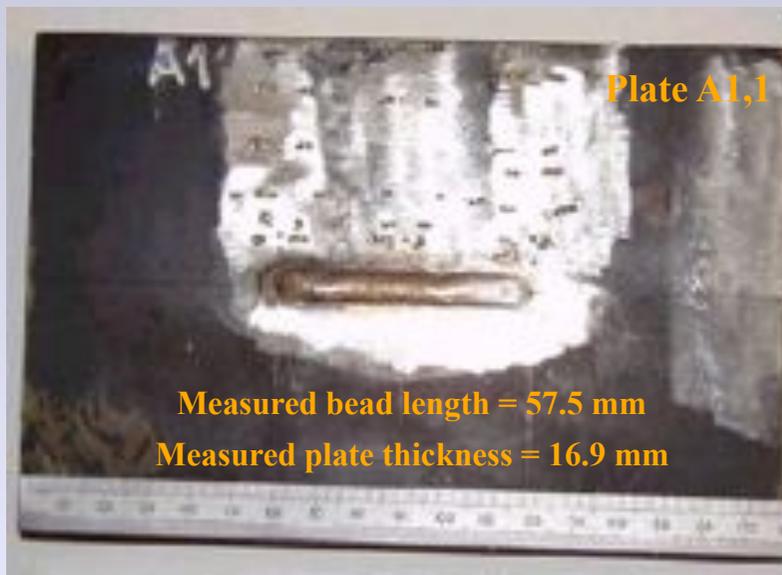
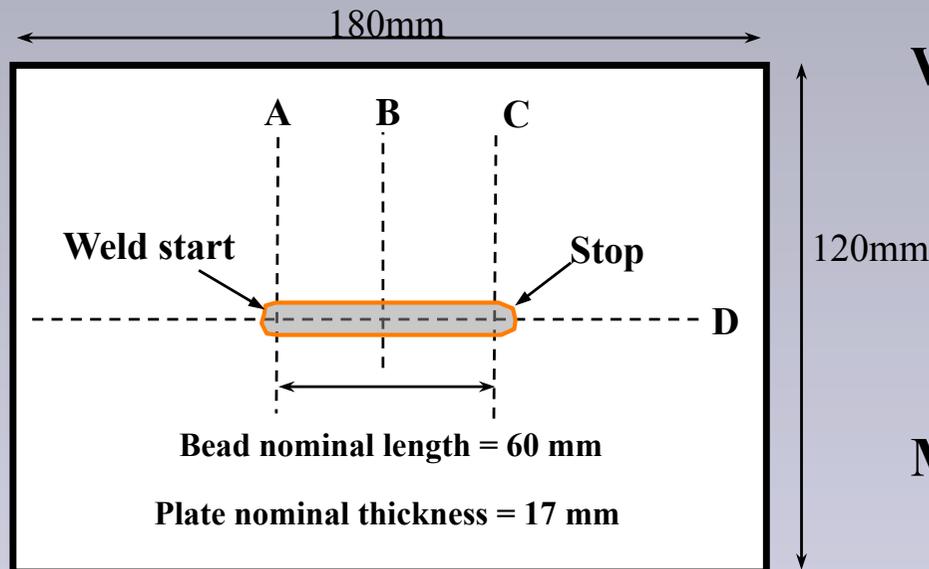
Reheat cracking - pre-cursors

- Susceptible material
 - » low creep ductility (e.g. 316H stainless steel)
 - » Strain hardening history (e.g. near a weld)
- High temperature exposure - creep deformation
 - » >450 °C for austenitic stainless steels

- **High magnitude multi-axial residual stress state**
 - » as-welded joints (not stress relieved)
 - » but difficult to quantify reliably

- Exacerbating factors
 - » applied external loads
 - » geometric features (stress concentrators)

Bead-on-plate specimen example (NET project)



Weldment Details

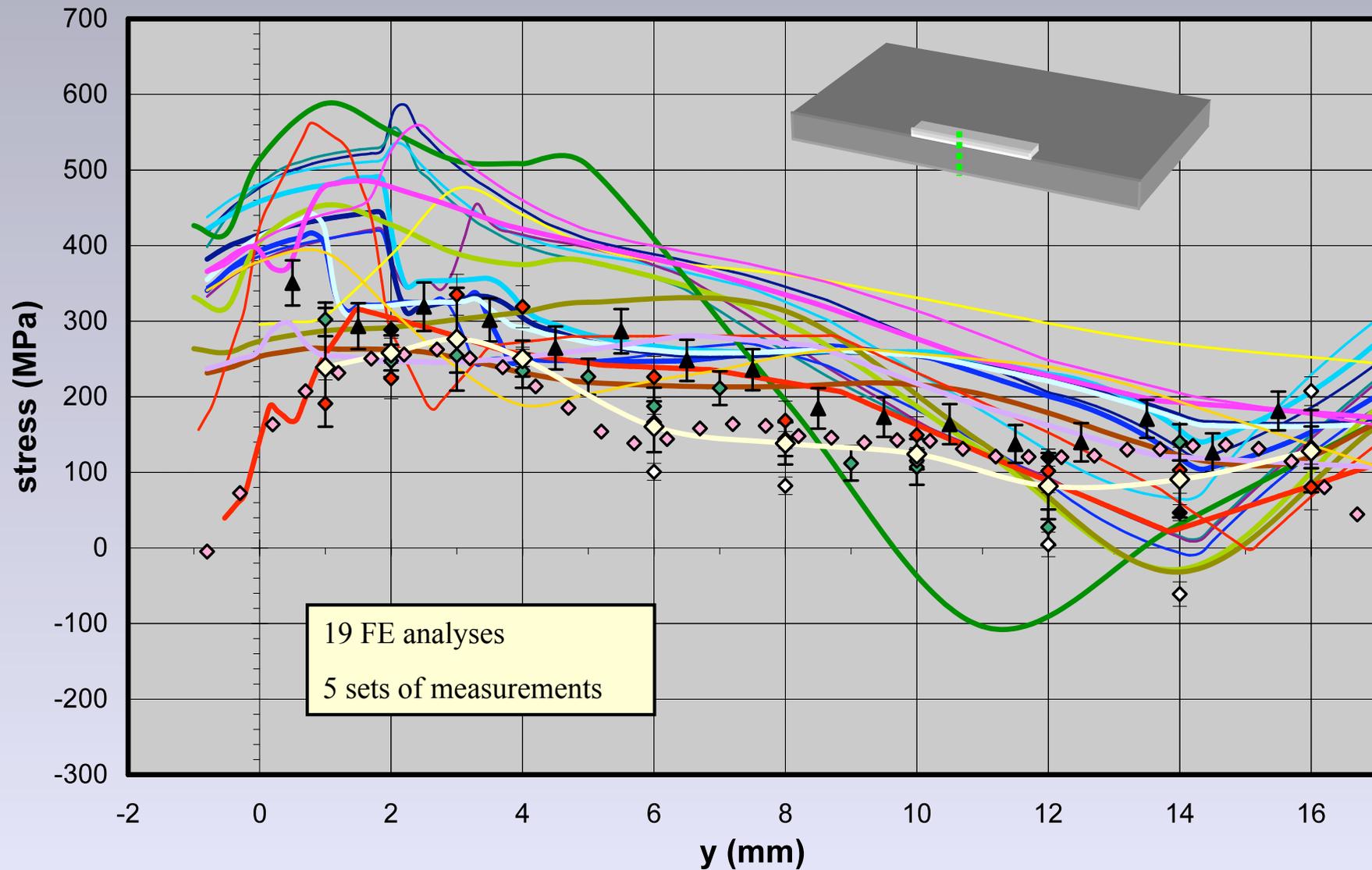
- » 316L stainless steel
- » 180 x 120 x 17mm plate
- » auto TIG weld, 60mm long
- » 4 specimens made

Measurements Round Robin

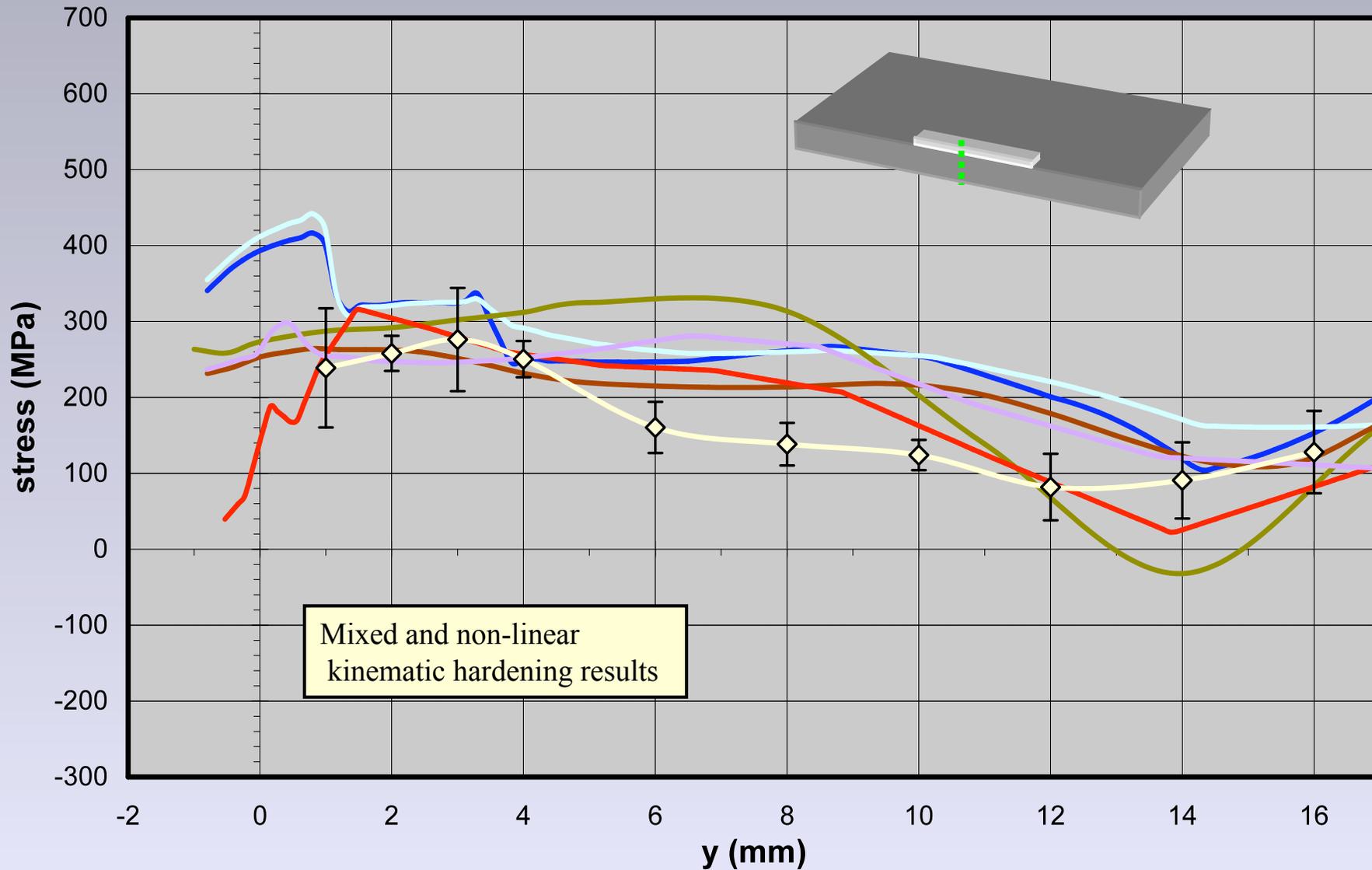
- » Thermocouples & strain gauges
- » Macrographs
- » Hardness mapping
- » Contour RS measurement
- » Neutron diffraction RS (4 sets..+)
- » Deep hole RS measurements
- » Surface hole RS measurements
- » Tensile & compressive tests

FE RS Round Robins (8 partners)

All round robin results for line BD (longitudinal stress)



Phase 2 results for line BD (longitudinal stress)



BE weld residual stress programme (2004-08)

3 Programme Objectives

- » to improve the **reliability and accuracy** of residual stress modelling for austenitic welds
- » to **validate** improved prediction methods against diverse measurements.
- » to quantify **weld repair end-effects**

Tensile test programme

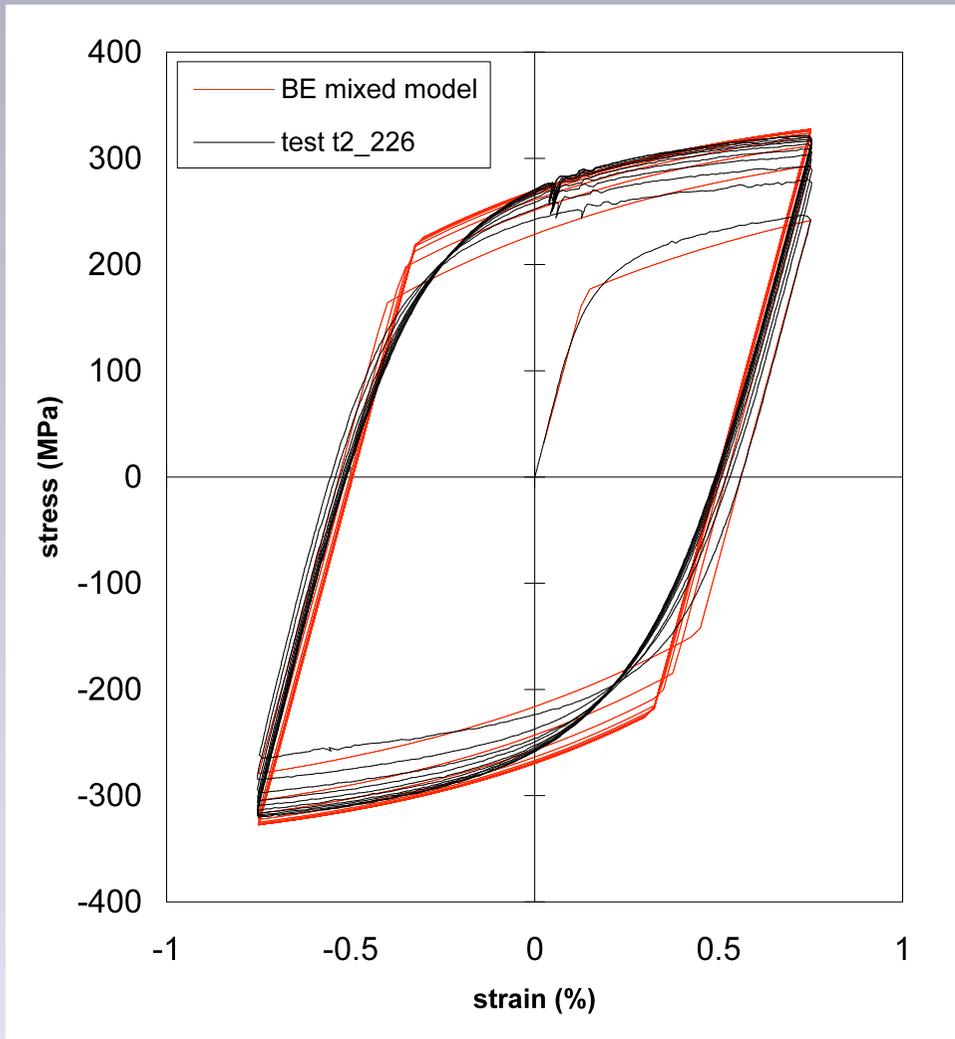
- **Materials**

- » Type 316L, 316H and Esshete 1250 stainless steels
- » Single weld bead - Type 316L and Esshete 1250
- » Multi-pass weld – Type 316L and Esshete 1250

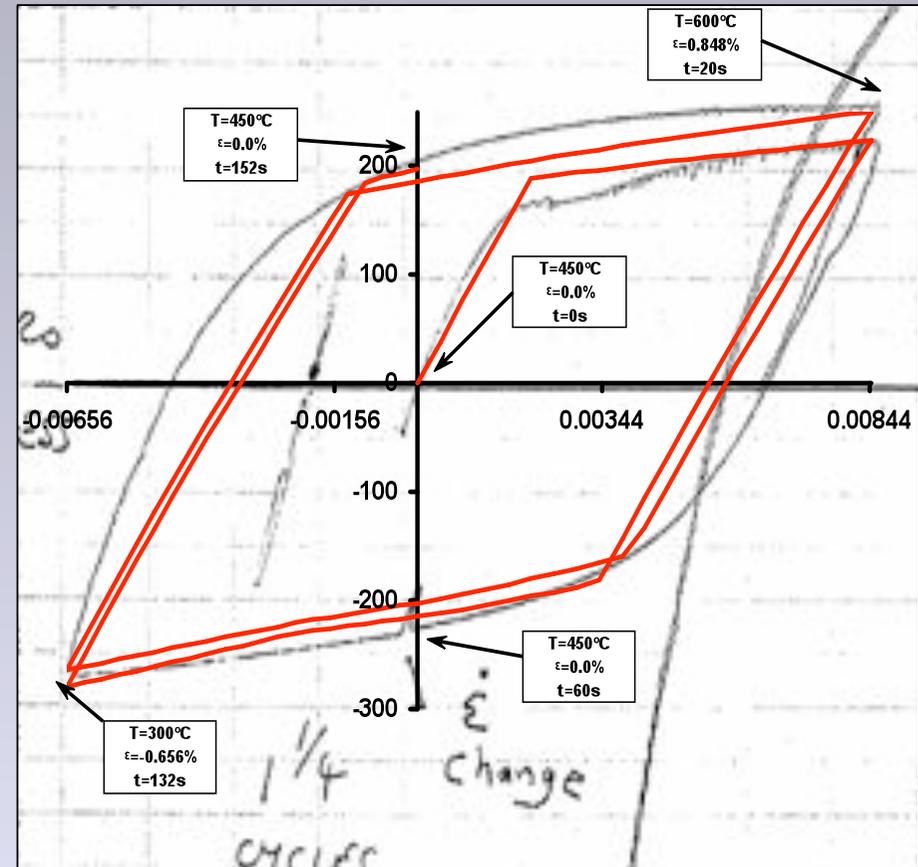
- **Types of test:**

- » Monotonic (up to 1200°C)
- » Cyclic, RT – 900°C, strain range = ± 0.75 , $\pm 1.25\%$
- » Thermo-mechanical fatigue, single pass weld metal only
- » Monotonic cross-weld ESPI tests

Cyclic response of weld metal + mixed hardening model

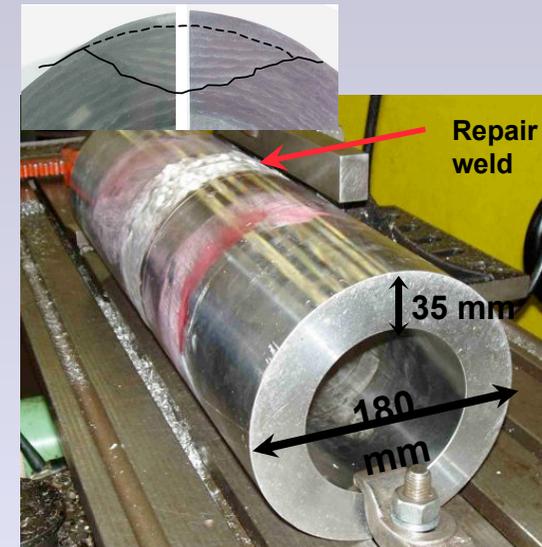
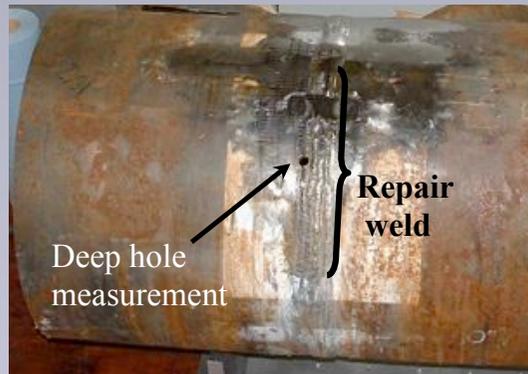


Mixed hardening model fit to single pass Type 316L weld metal isothermal cyclic test data at 600°C

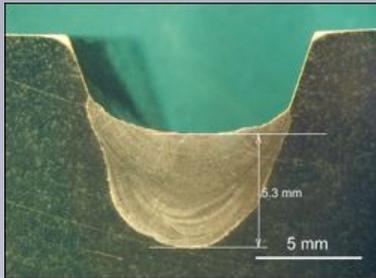


Performance of mixed hardening model for single pass Type 316L weld metal for in-phase TMF test

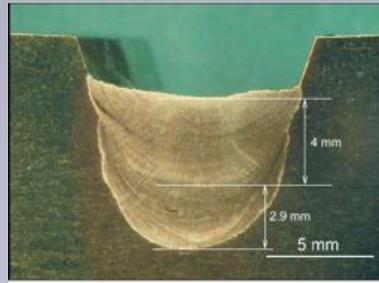
Validation mock-ups



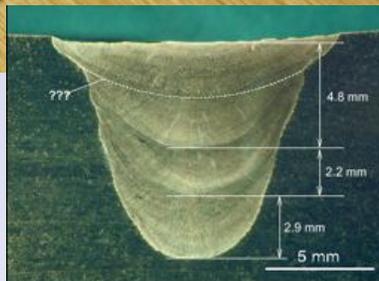
Validation - 1, 2 and 3-pass Groove Welds



(a) Single pass weld bead (plate 2.1.1)



(b) 2 pass weld bead (plate 2.1.3)



(c) 3 pass weld bead (plate 2.1.2)

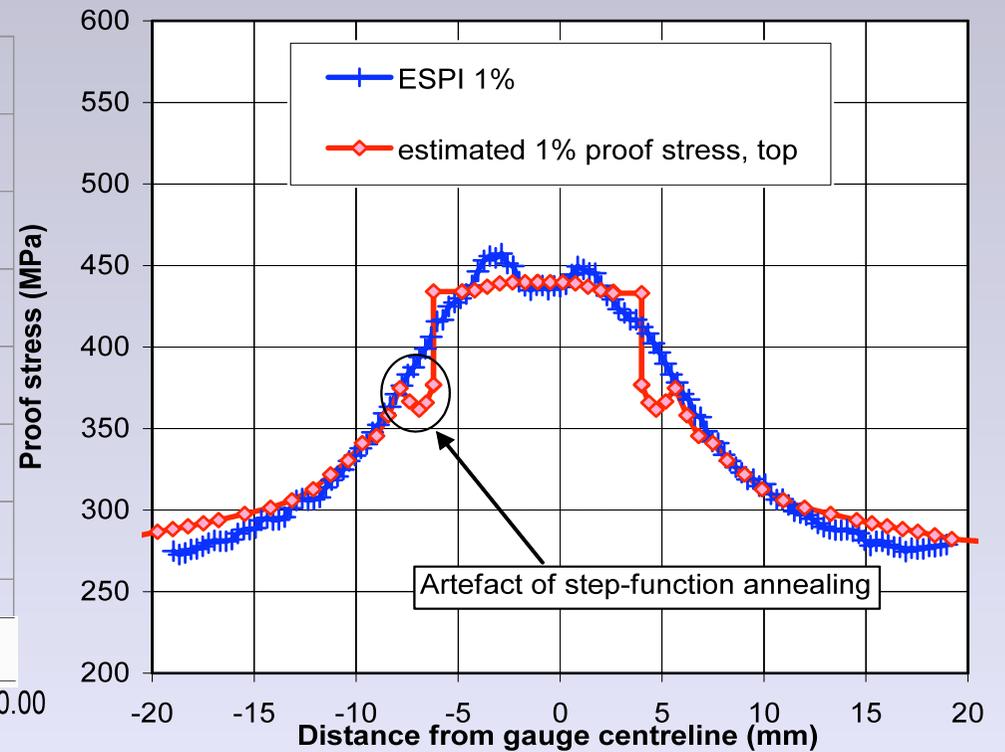
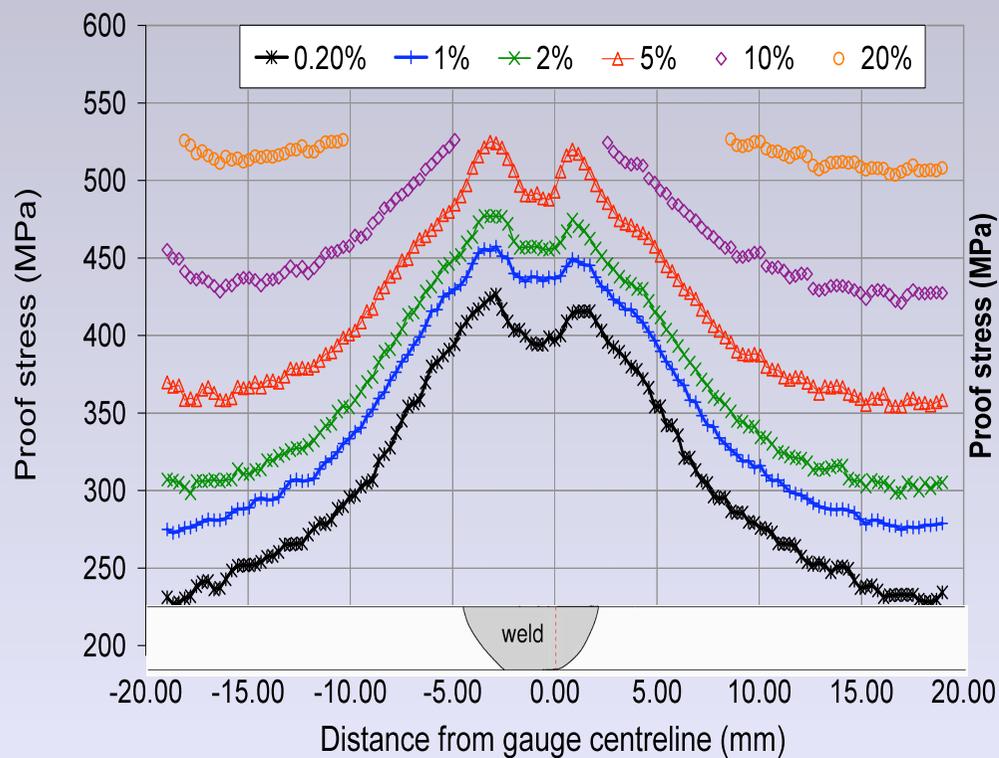
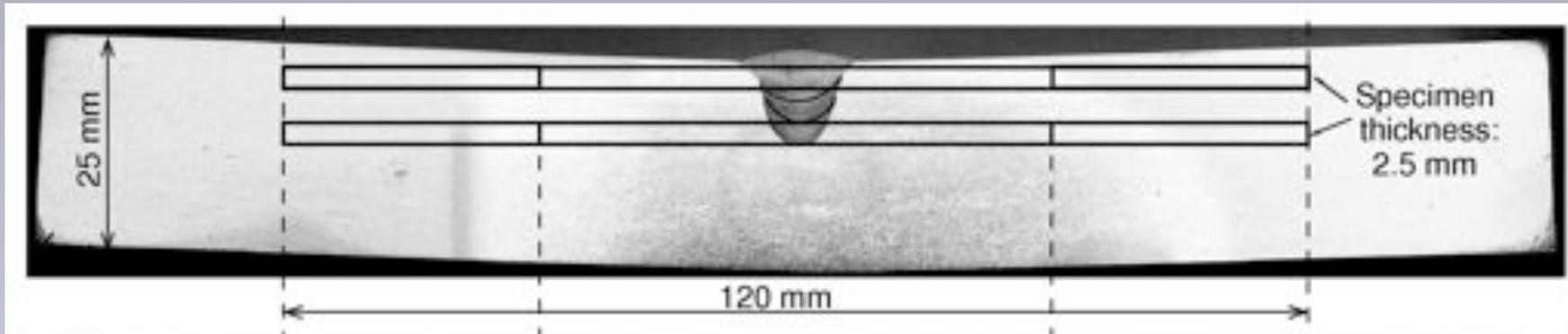
Weldment Details

- » 180 x 200 x 25mm³
- » 1, 2 & 3-pass MMA welds
- » 2 x 3-pass plates made

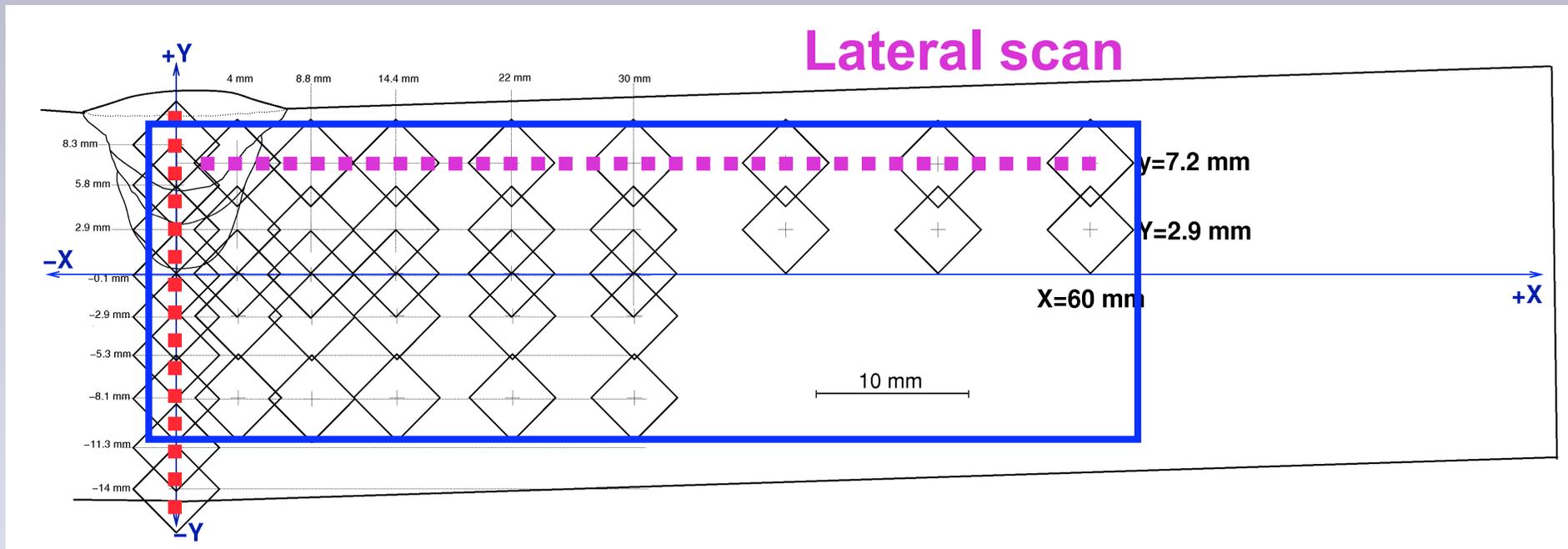
Measurements

- » Thermocouples & strain gauges
- » Witnessed/recorded welding
- » Macrographs
- » Displacements
- » Back-face image correlation
- » Hardness mapping
- » Contour measurements
- » Neutron diffraction mapping
- » ESPI cross-welds
- » Material properties (NET BoP)

Cross weld results

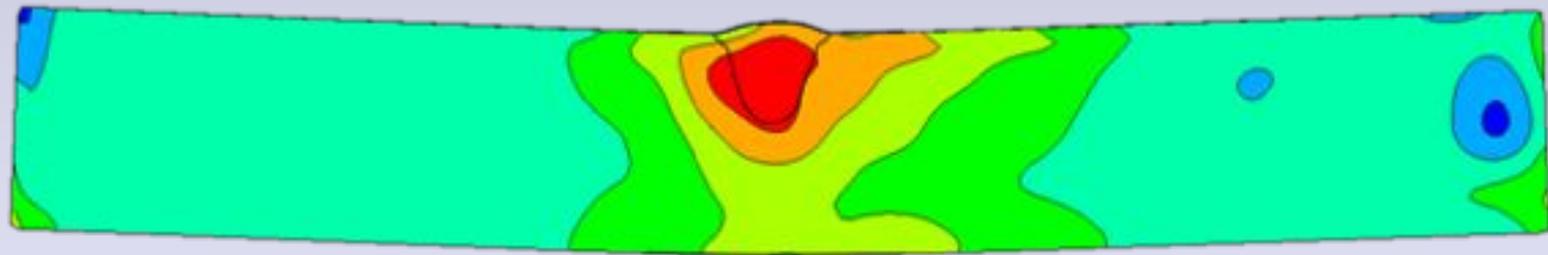
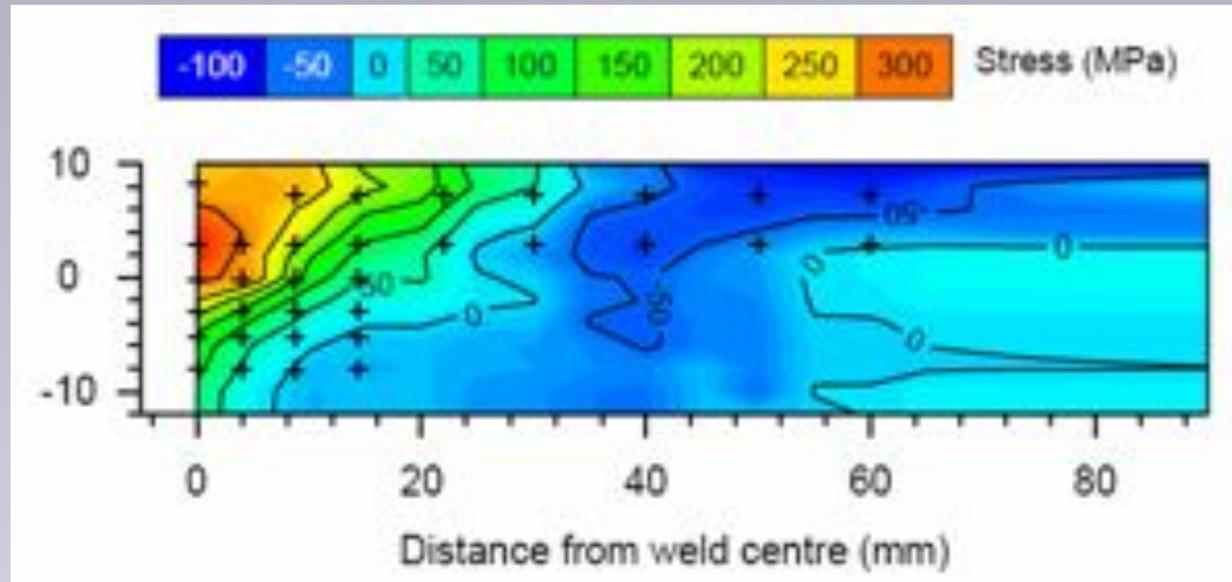


3-pass plate ND measurement positions



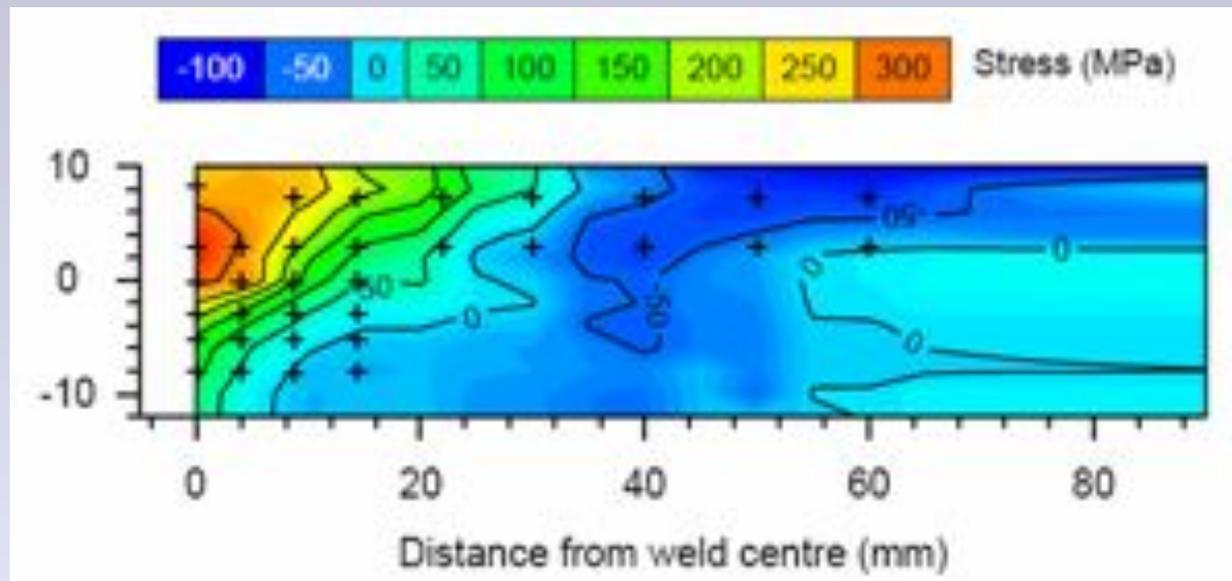
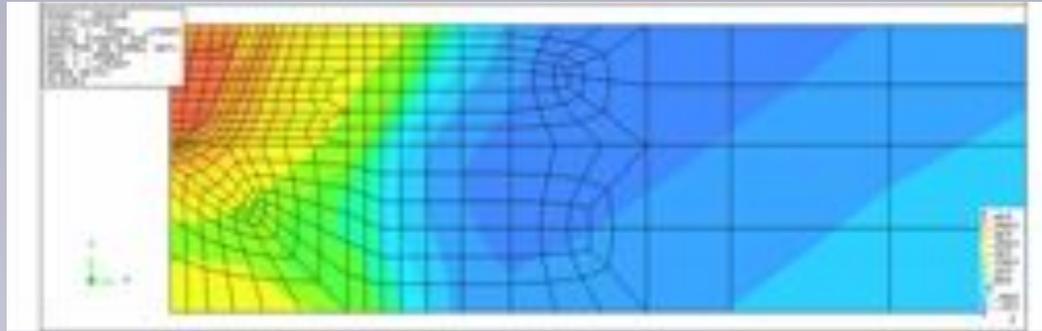
Drill down

Measured Longitudinal Stresses – ND vs Contour Method

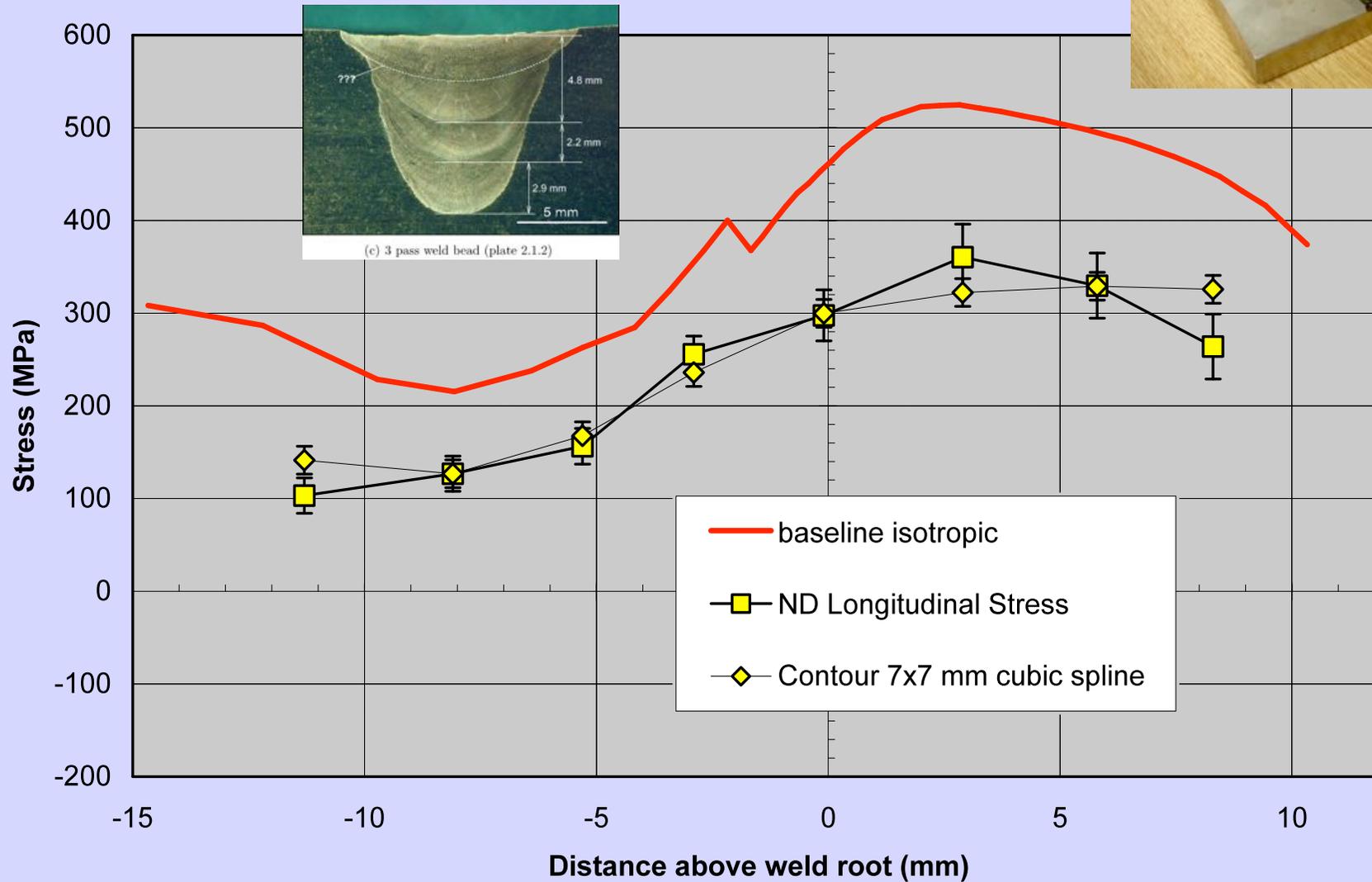


3-Pass Groove Weld

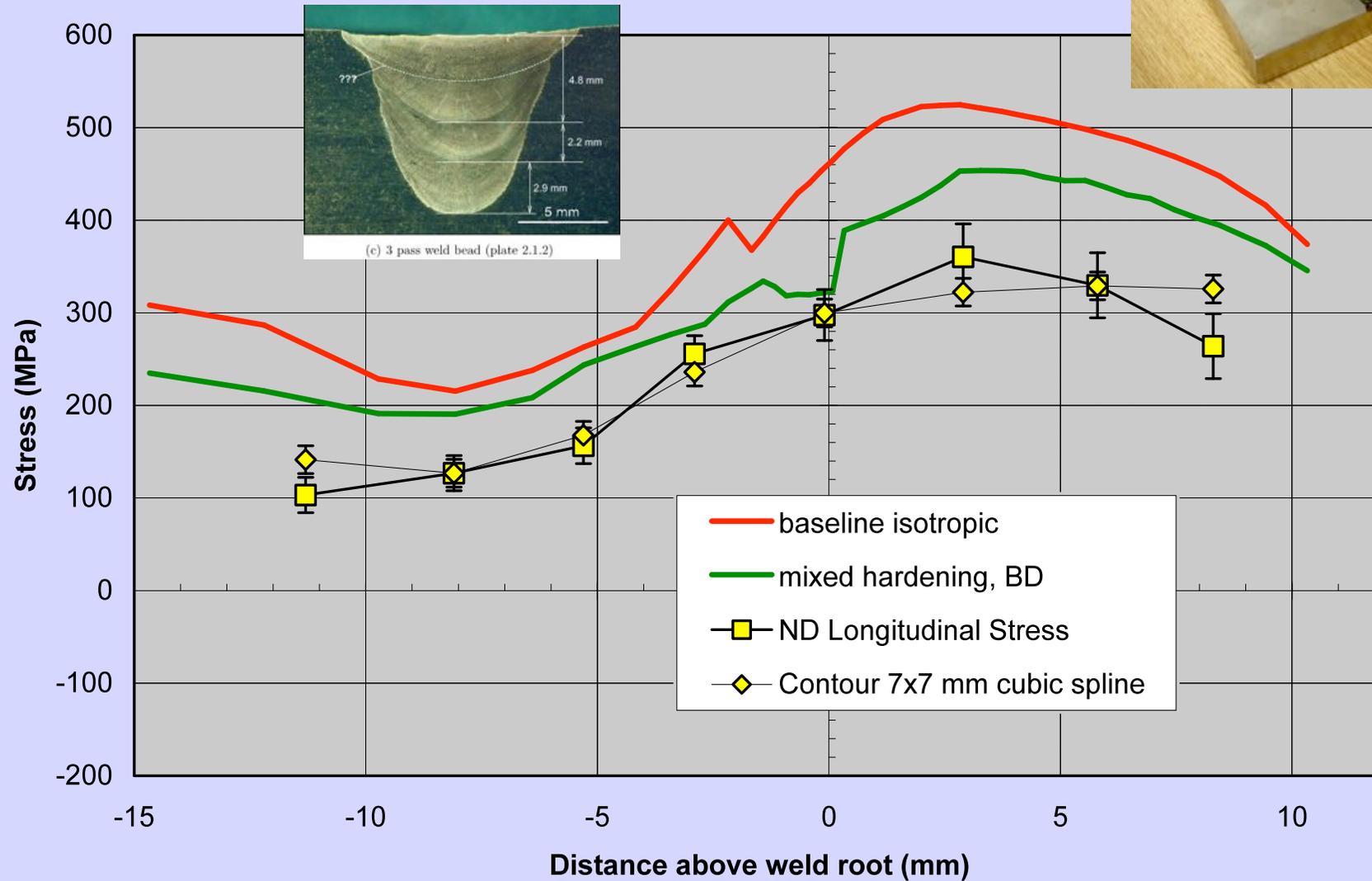
Predicted vs measured longitudinal stresses



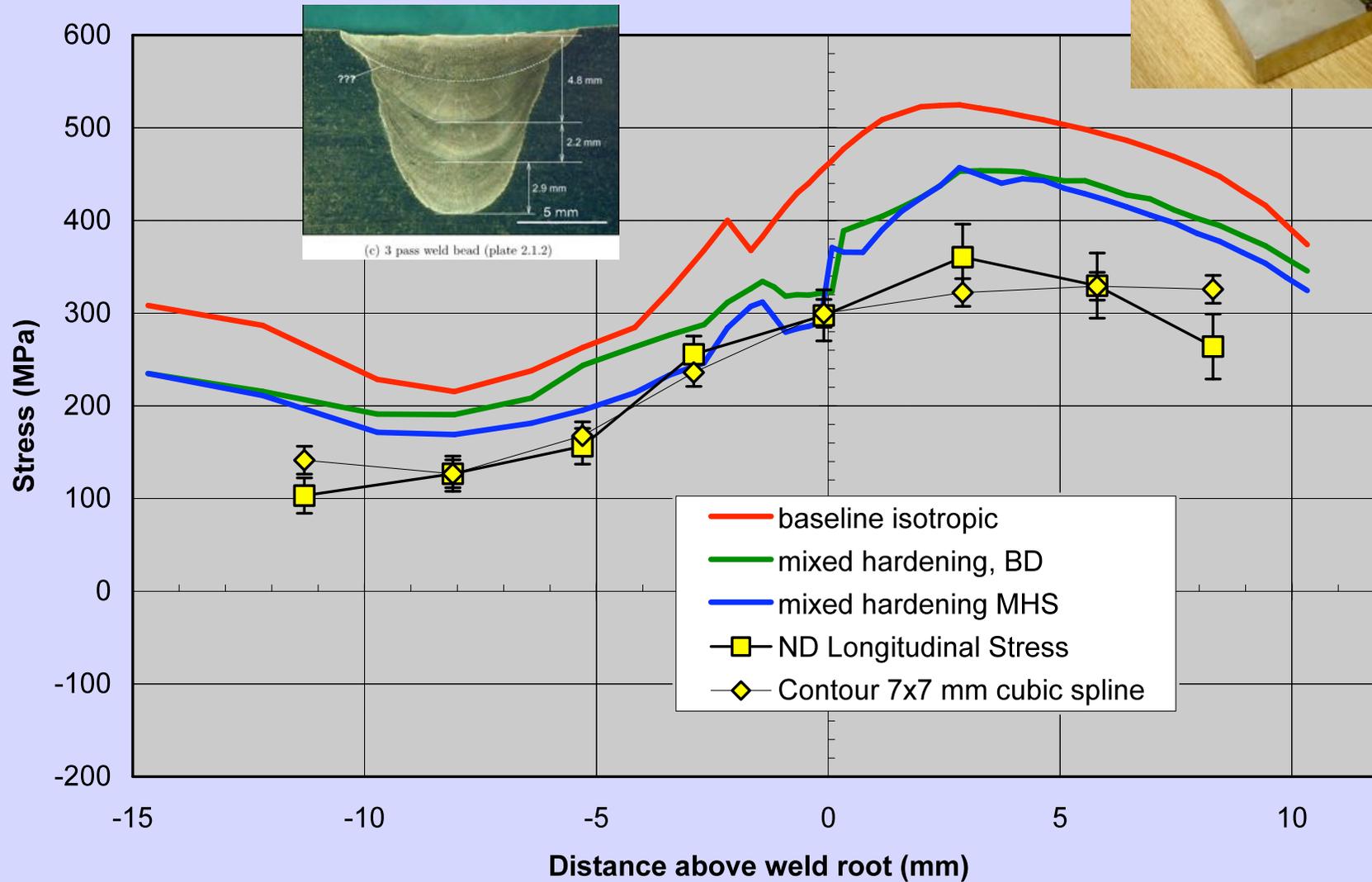
Groove weld – longitudinal stress



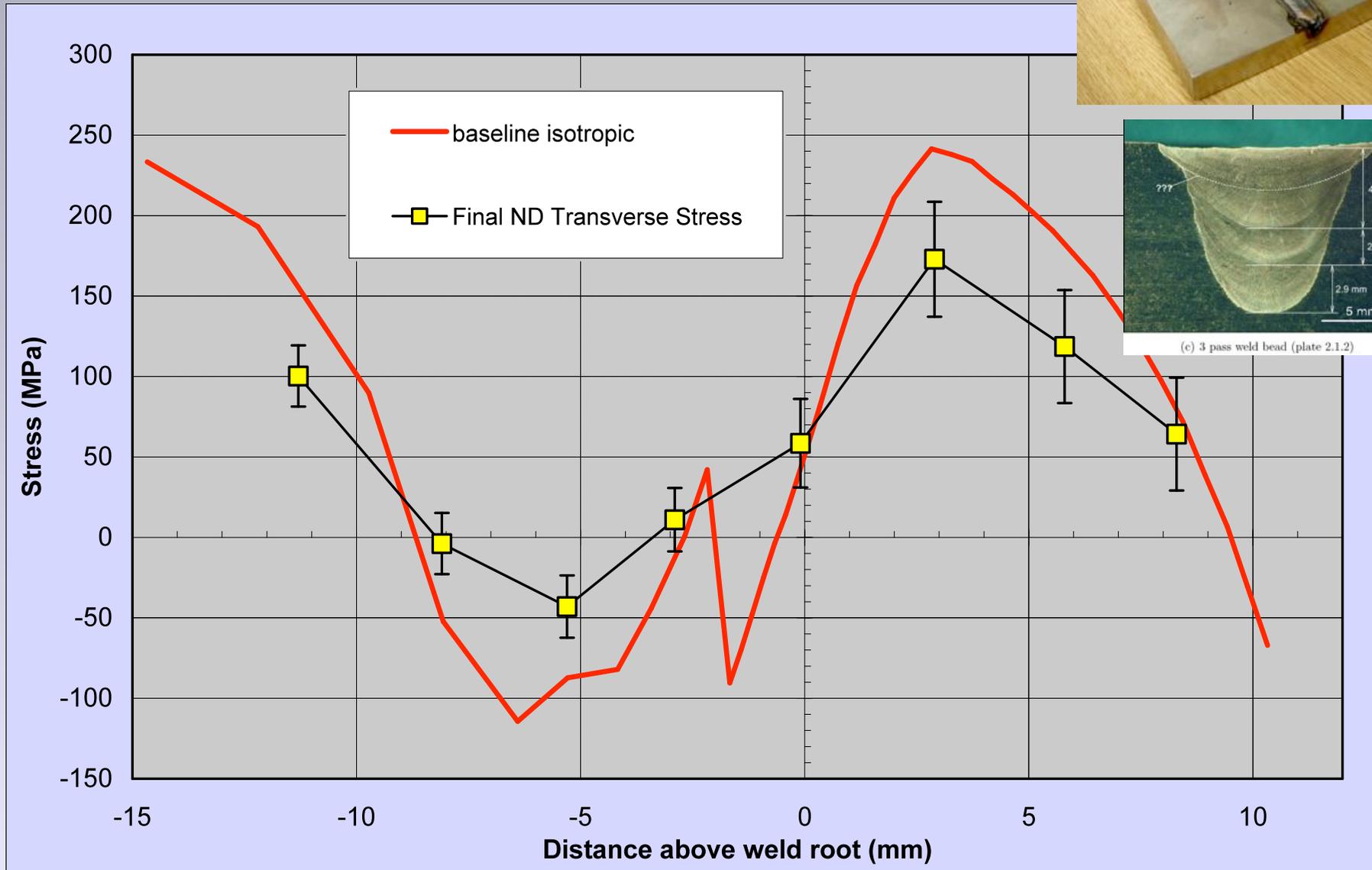
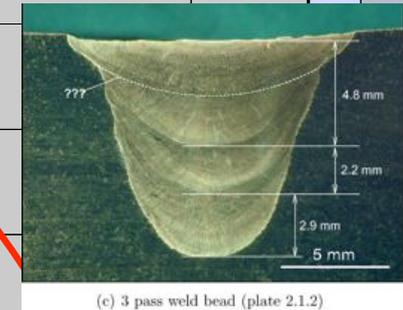
Groove weld – longitudinal stress



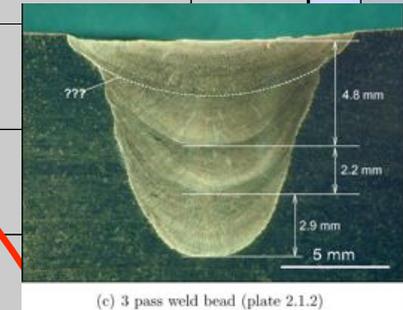
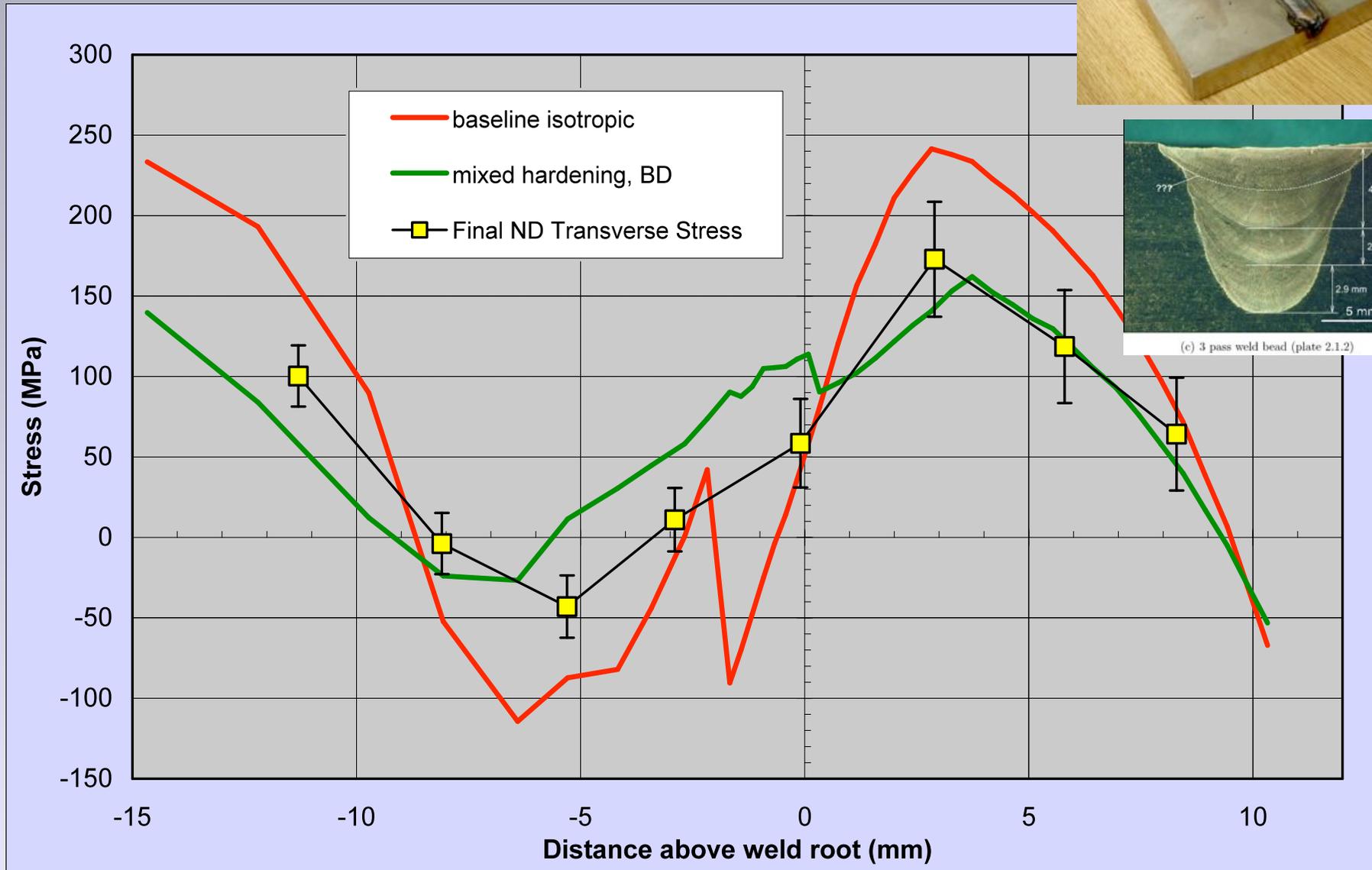
Groove weld – longitudinal stress



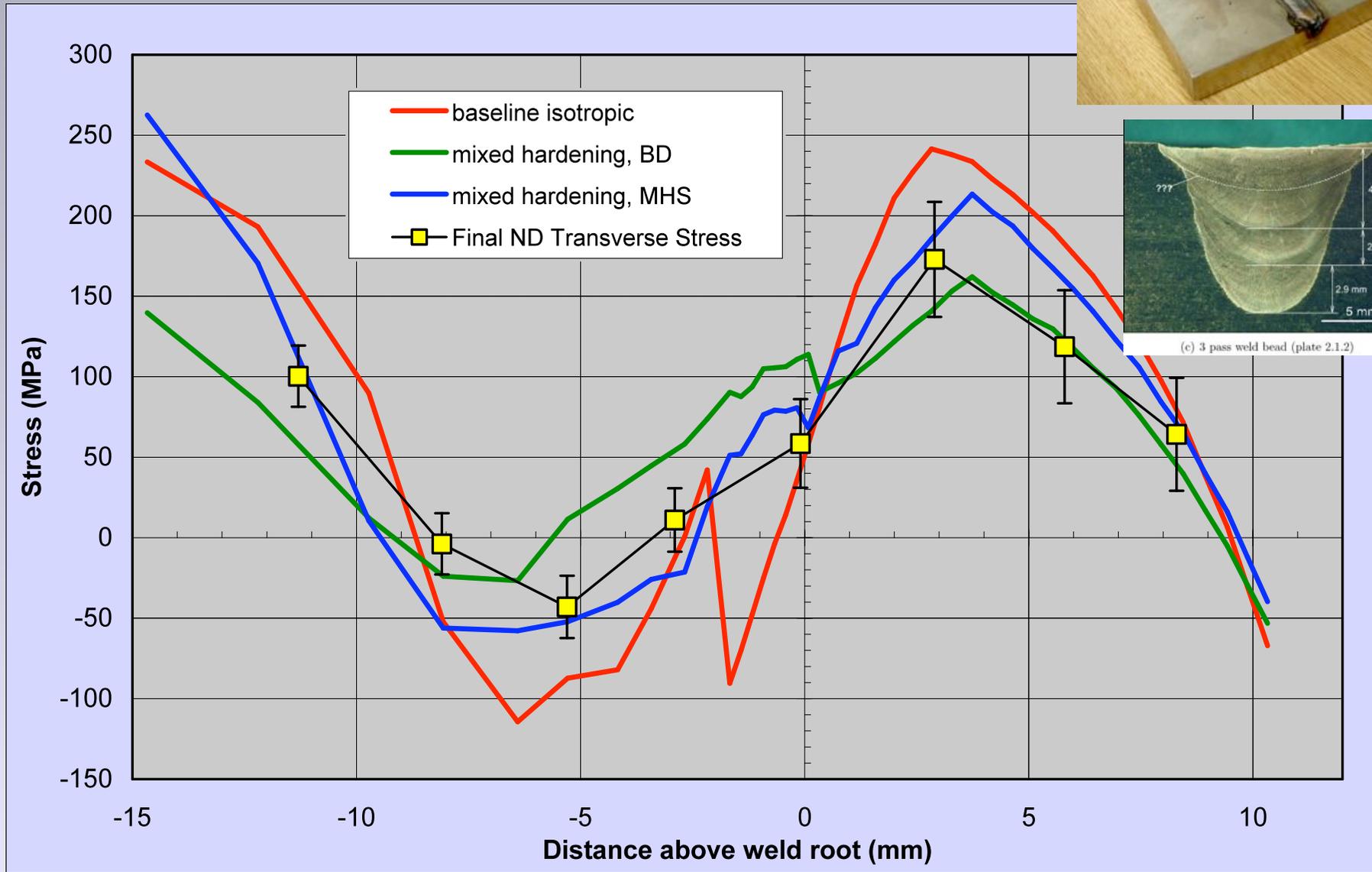
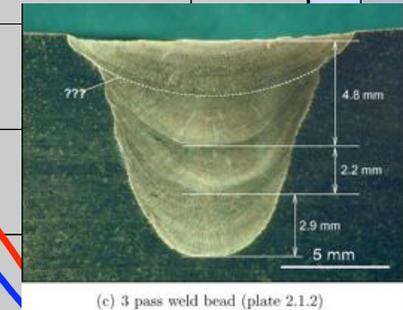
Groove weld - transverse stress



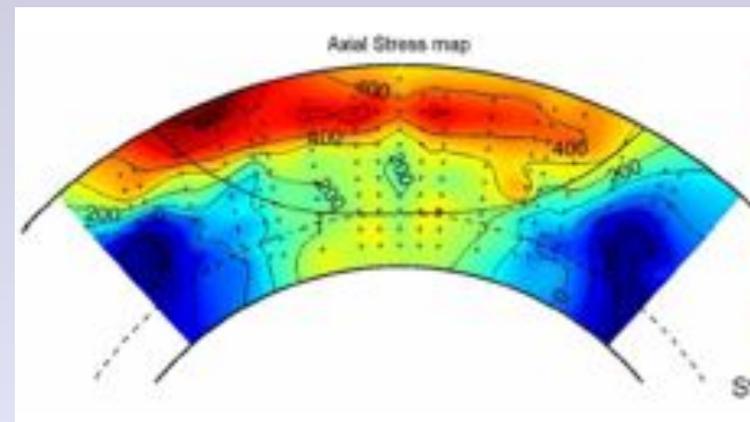
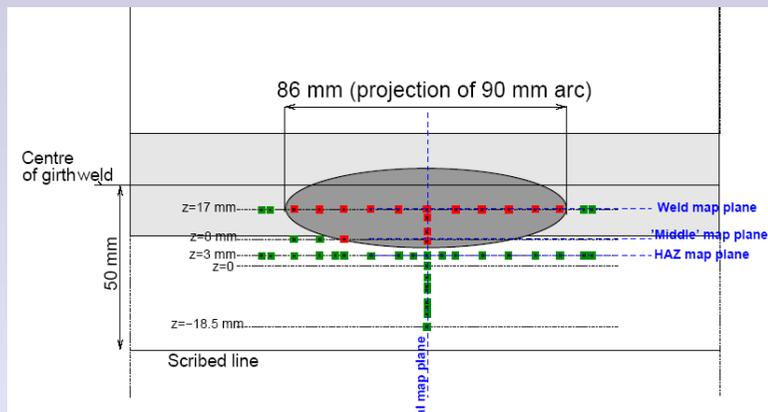
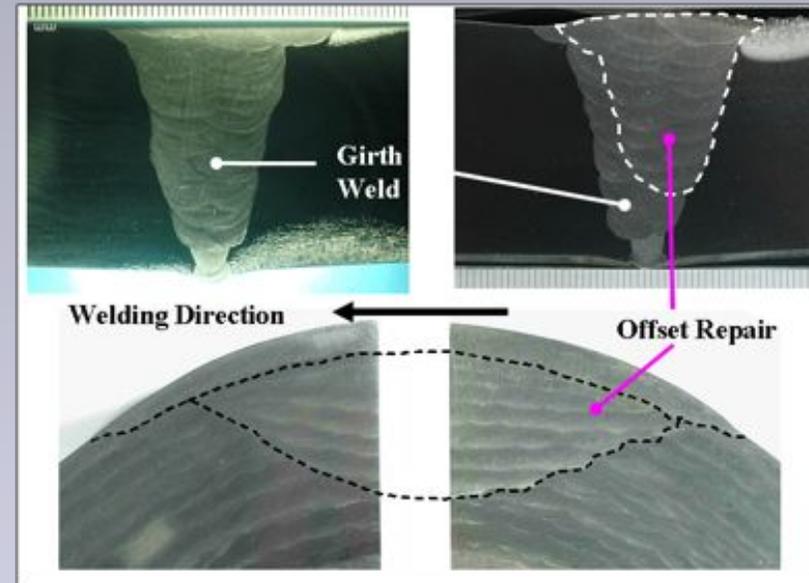
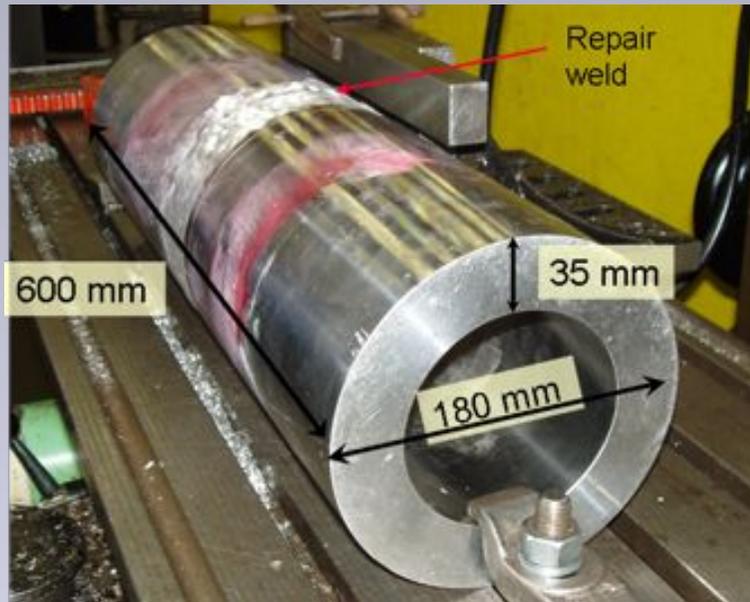
Groove weld - transverse stress



Groove weld - transverse stress



Pipe butt weld with short repair



Concluding Remarks

- BE's background experience in weld modelling and new knowledge arising from this programme will be integrated into:
 - » **Weld modelling guidelines** that are being prepared for inclusion in the R6 Defect Assessment Procedure .
 - » **A Compendium of Validation Benchmarks** will accompany the R6 modelling guidelines.
- Measurements and the FE work will be published

Acknowledgements

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