The University of Manchester
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Into the world - how NeT has influenced Structural Integrity Assessment in UK Nuclear Plant

Mike Smith – The University of Manchester

Aknowledgements

- NeT is a collaborative venture – what I have to show is the result of many individuals working over the last 20 years - too many to acknowledge individually
- But, a special acknowledgement is due to Ann Smith, who managed the later stages of TG1, all of TG4, and the early stages of TG6, herding the cats and making sure everything happened and got properly recorded.

Petten, 2013

Contents – A talk in three parts

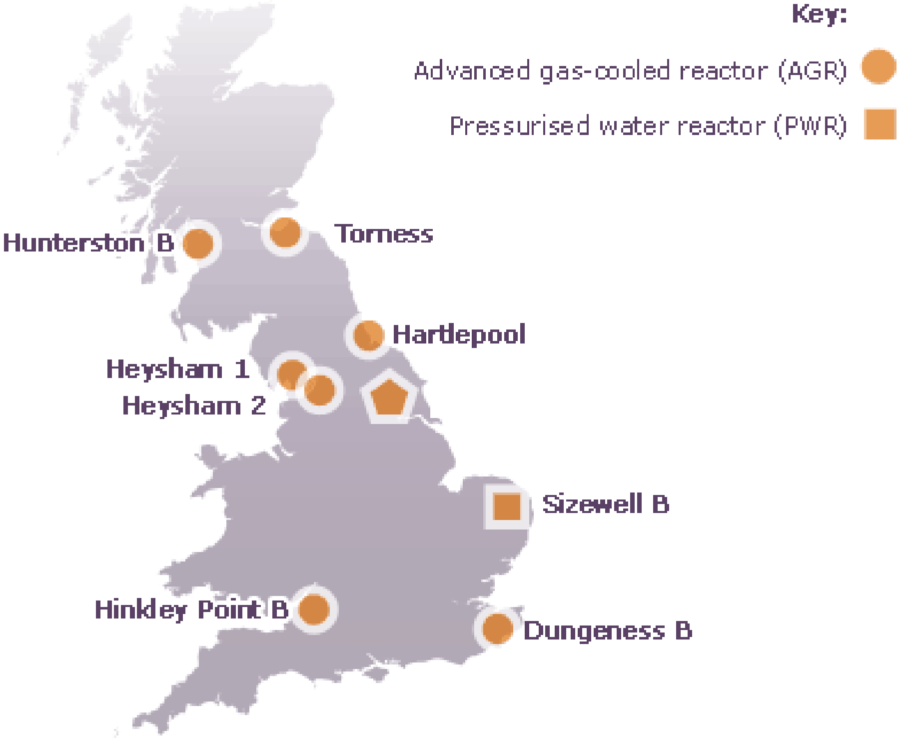
- Setting the scene – weld residual stress driven problems in UK Civil Nuclear plant
- How NeT fitted in – what has been its impact?
- A quick look forwards – what is happening now?

Residual stress driven creep cracking in AGR boilers

Setting the scene for NeT

Civil nuclear plants in the UK – EDF Energy

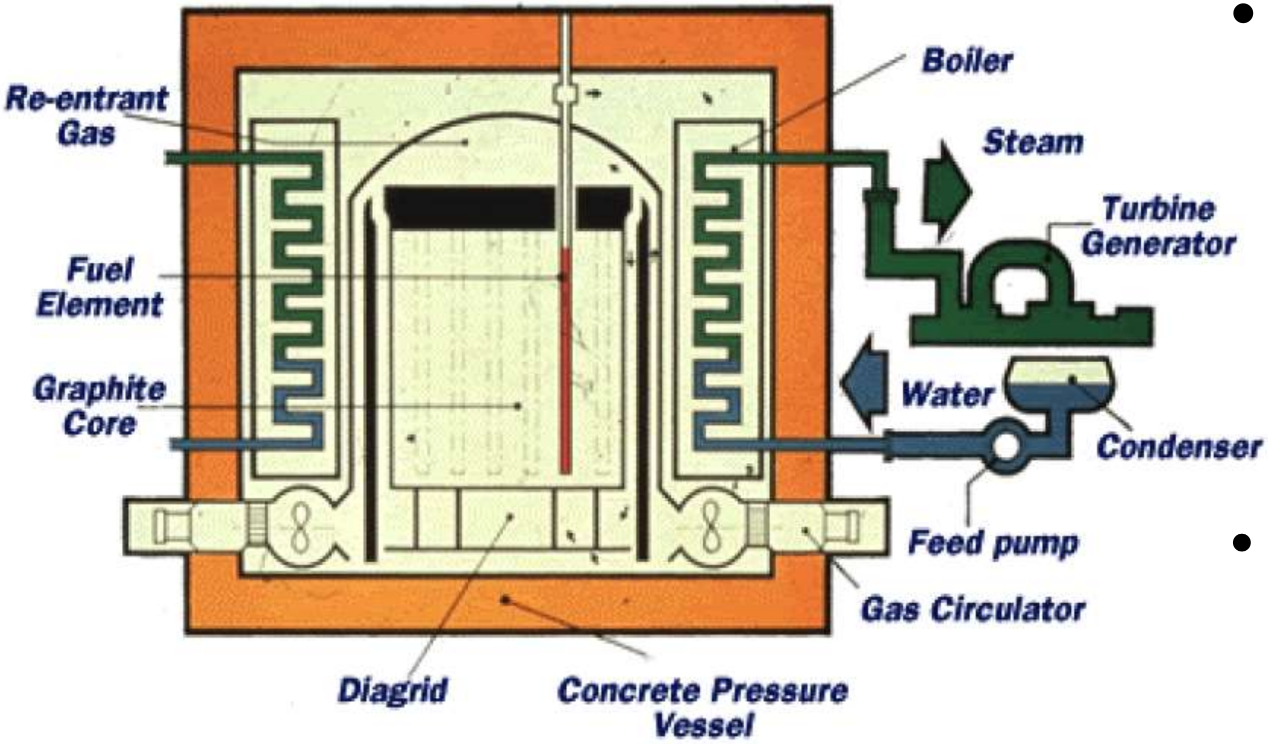
- 14 Advanced Gas Cooled reactors at 7 stations – 1.2GW thermal, CO_2 cooled, graphite moderated, 650°C T2, 550°C steam – *now starting to close*.
- One PWR - ~3.5GW thermal, 1.1GW electrical, 280°C steam – Westinghouse standard design
- One twin reactor EPR (3.2GW electrical) being built at Hinkley Point – equivalent to ~6 AGR reactors
- Further twin reactor EPR planned at Sizewell – go ahead imminent
- Prototype development of Rolls Royce SMR



Internals of an Advanced Gas Cooled Reactor

CO_2 cooled, graphite moderated

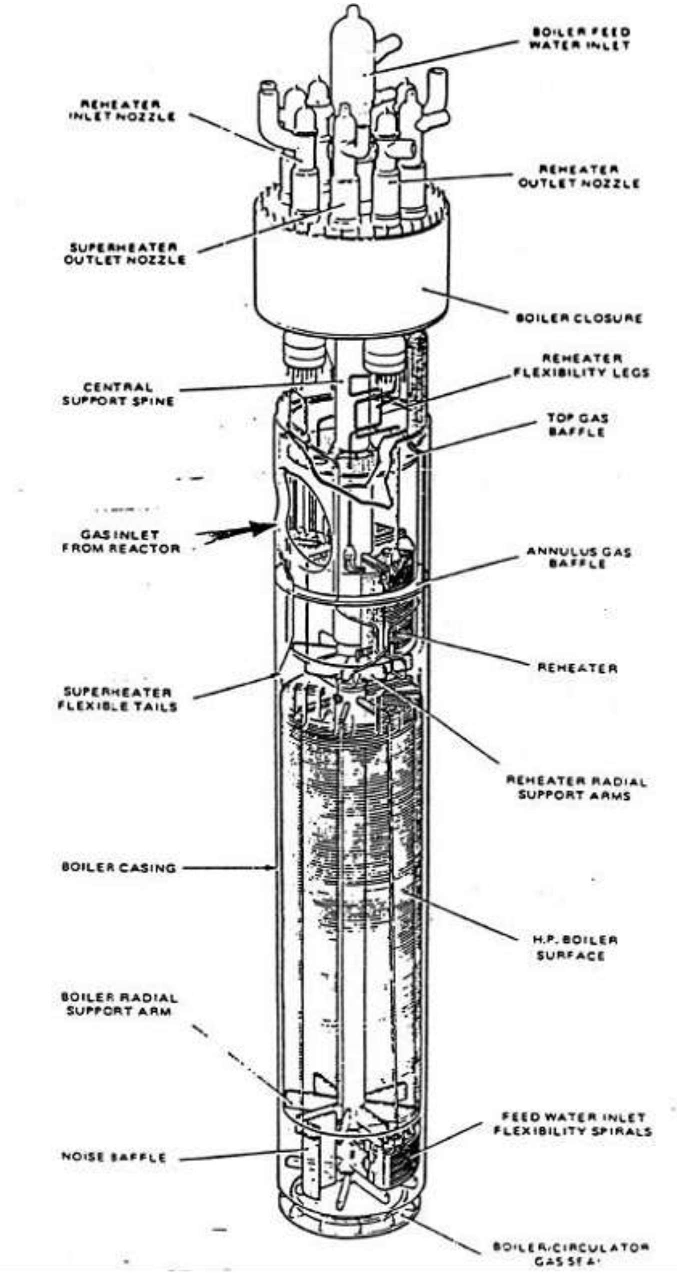
A generation 4 reactor from the 1970's



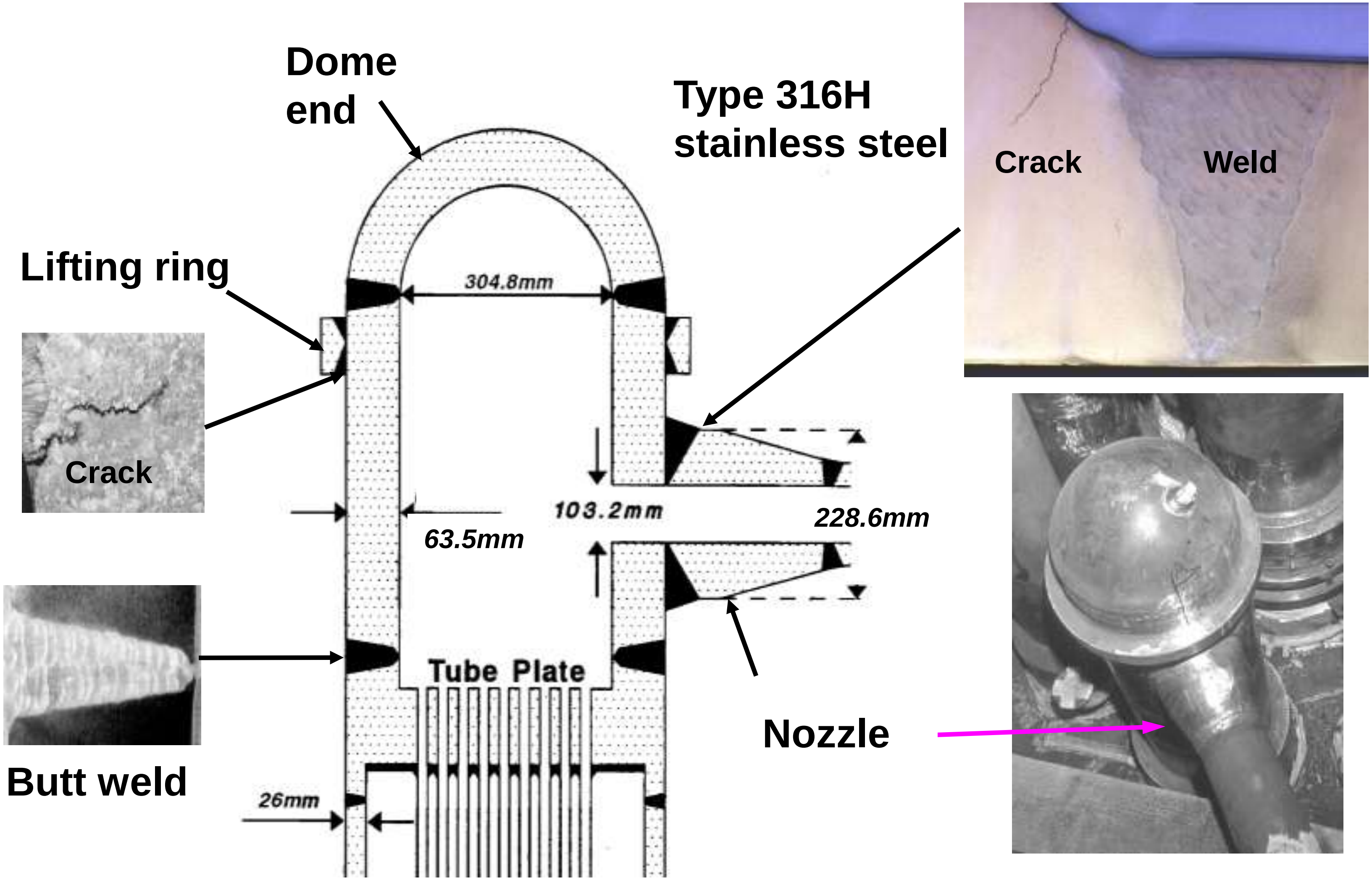
- T2 = $650^{O}C$
  - In creep regime
  - Thermal ageing – especially in welds
- Large variety of weldment types
  - Heavy section austenitics
  - Thin section austenitics
  - Carbon steels in T1 region
  - Dissimilar Metal Welds
- Significant populations of non-stress-relieved welds

Heysham 1 and Hartlepool: homes of the pod boiler

Each pod boiler is approx 20m tall and weighs 100 tonnes.
There are 8 per reactor, 32 in total.
They are non-removable, inside the concrete pressure vessel



Steam header cracking



Dome end

Type 316H stainless steel

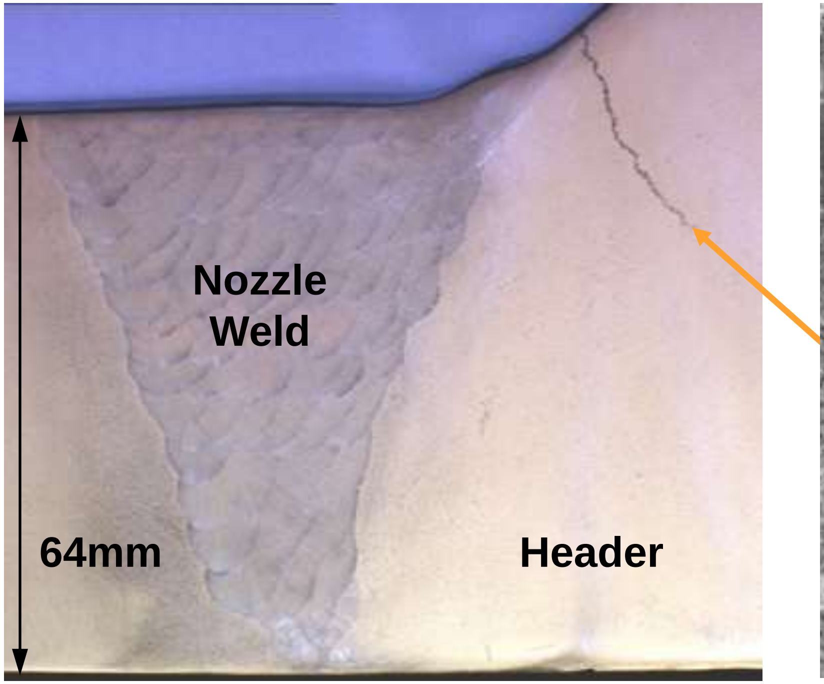
Lifting ring

Butt weld

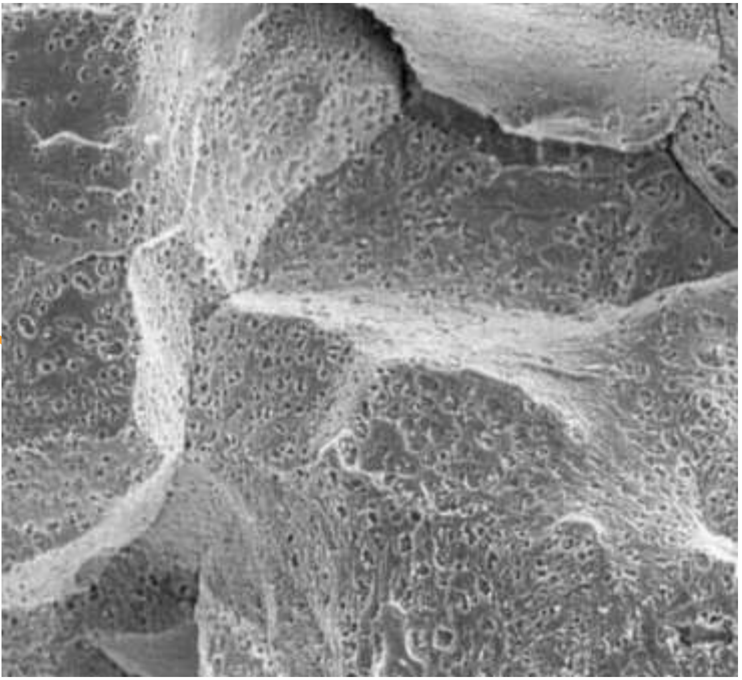
Nozzle

Diagnosis

- Late 1980’s:- Cracks at lifting rings diagnosed as IGA, weld strain induced cracking, creep fatigue…….
- Early 1990’s:- Cracks correctly diagnosed as creep damage



Service aged 55,000h at 525°C



Creep cavitation on grain boundaries 1mm ahead of crack

What is creep?

- Creep is time dependent inelastic deformation at high temperatures.
- Under a steady load creep strain accumulates continuously, and the structure eventually fails
- Design codes avoid this by ensuring that the applied stresses are low enough that the “stress rupture life” exceeds the design life of the plant
- Another, and better, way of looking at creep damage is via “ductility exhaustion” – failure occurs when a critical creep strain is reached

Reheat cracking – what is going on?

- Primary pressure stresses (design stresses) are very low
  - Stress-rupture life effectively infinite
  - Why should they crack?
- **High magnitude multi-axial weld residual stress state**
  - As-welded joints (not stress relieved– not required by design code)
  - Thick sections (high stress triaxiality)
- Susceptible material
  - Low creep ductility especially under multi-axial stresses (here AISI 316H stainless steel)
  - Strain hardening history (e.g. near a weld)
- High temperature exposure - creep deformation
  - >450 ^{o}C for austenitic stainless steels
- Exacerbating factors
  - Applied external loads
  - Geometric features (stress concentrators)

Reheat cracking predictive model (1990s)

- The plant operator developed a ductility exhaustion model to predict the time to initiation of reheat cracking based on the:
  - **predicted initial weld residual stress state**
  - predicted creep deformation & stress relaxation during plant life
  - predicted creep damage accumulation dependent on the
    - multi-axial stress state
    - uniaxial creep ductility
    - creep strain rate

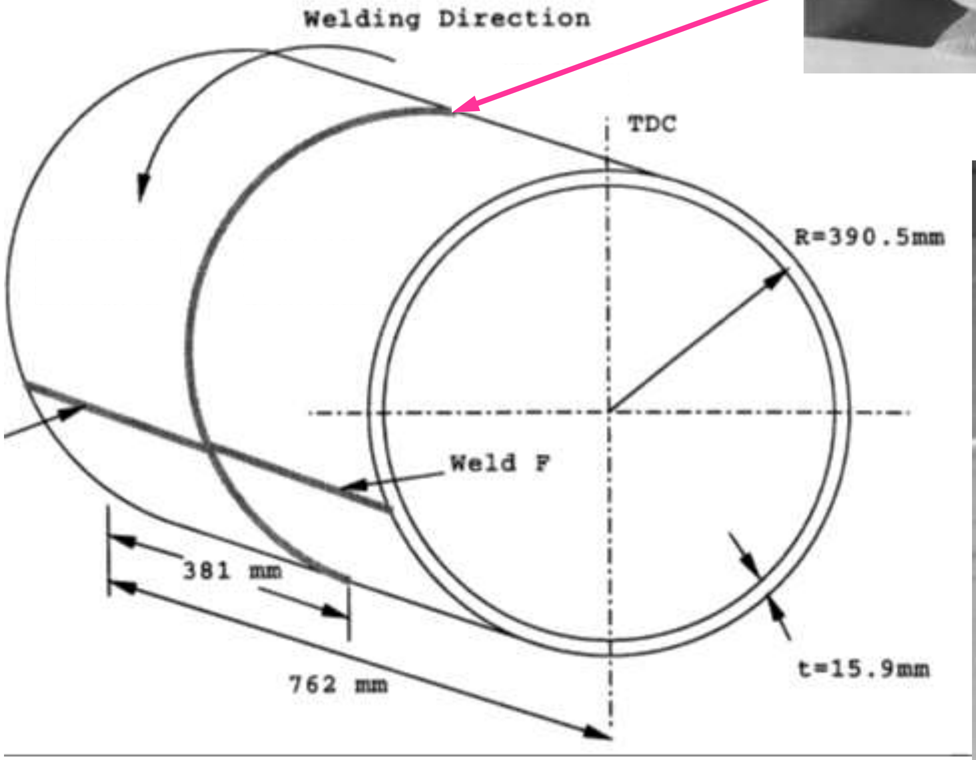
$$\text{Creep damage,}\quad d_c = \int_0^t \frac{\dot{\bar{\varepsilon}}_c}{\bar{\varepsilon}_f(\dot{\bar{\varepsilon}}_c, T)}\, dt$$

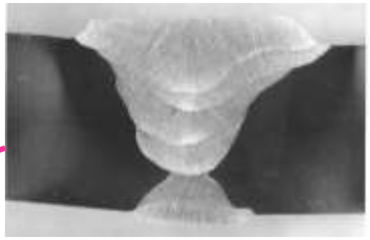
- The model was validated at various levels:
  - **measured vs predicted residual stresses**
  - notched bar creep relaxation tests
  - laboratory feature tests
  - incidence of plant cracking

Weld residual stress modelling (1990s)

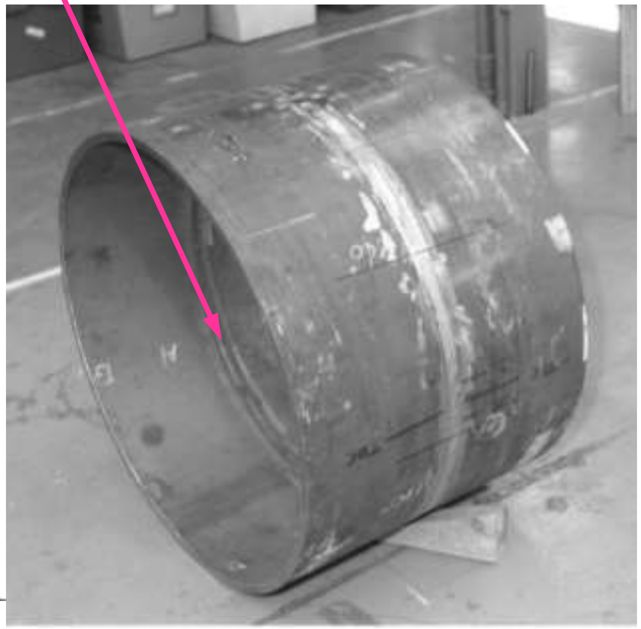
- Axi-symmetric or 2D FE models
- Austenitic stainless steel – no solid state phase transformations
- Temperature dependent material properties
- Thermal transient analysis:
  - Weld metal introduced above melting temperature and heated using body + surface heat fluxes
  - Tenuous link between modelled welding thermal transient and reality
- Mechanical analysis performed with simple material models derived from tensile tests (even though welding is a cyclic loading process)
- High temperature “annealing” effects ignored

16mm pipe girth weld mock-up (Dungeness B Weld C (AISI 316L SS))

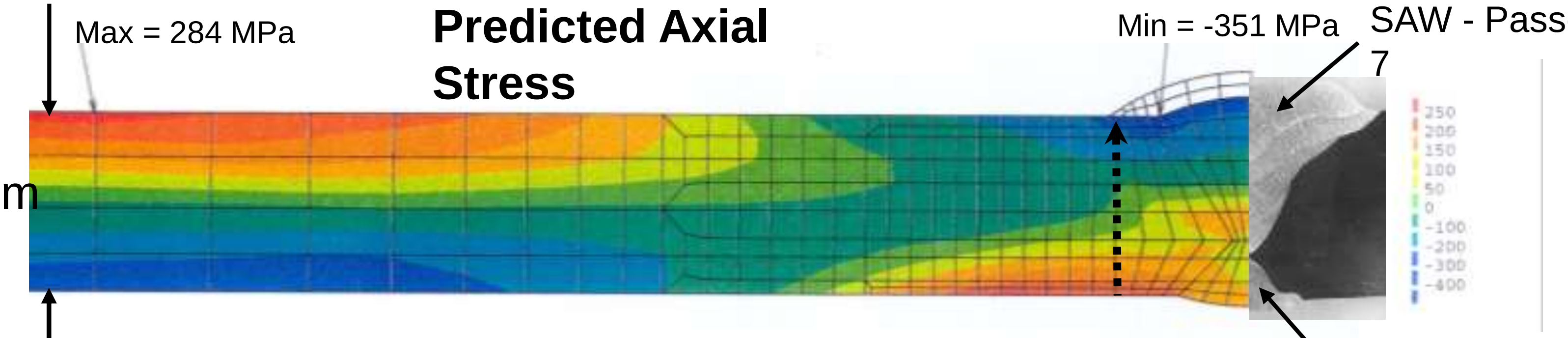




Weld Section



16mm pipe girth weld residual stresses - validation

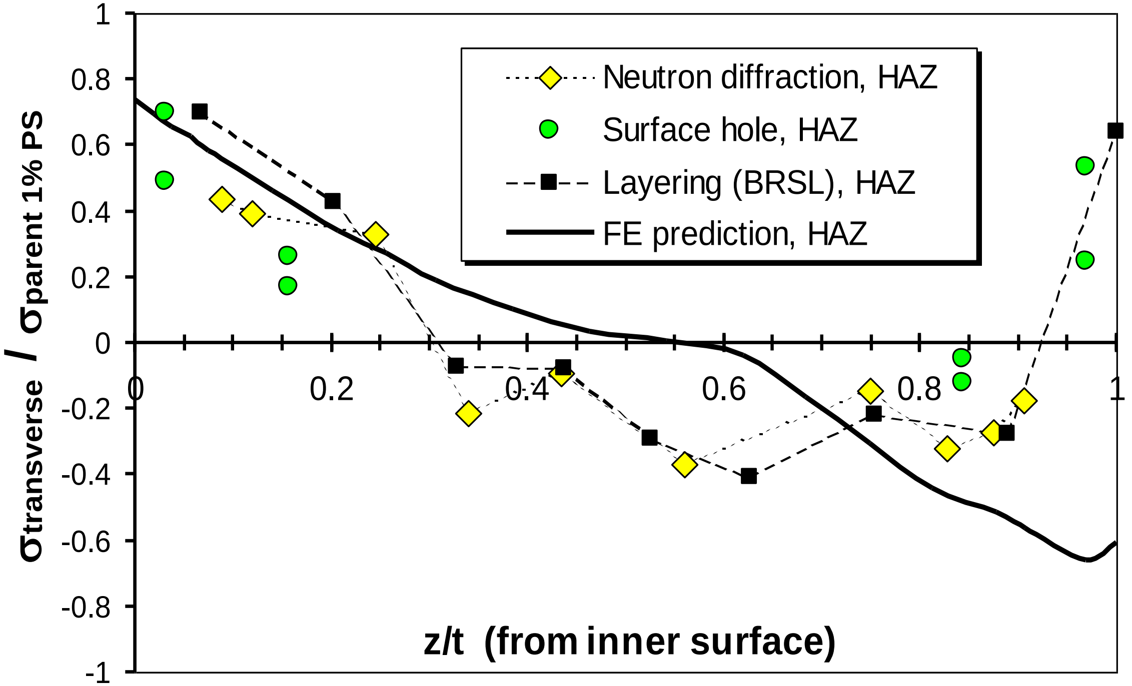


SAW - Passes 4-7

MMA - Passes 1-3

15.9 mm

Radius = 390.5 mm



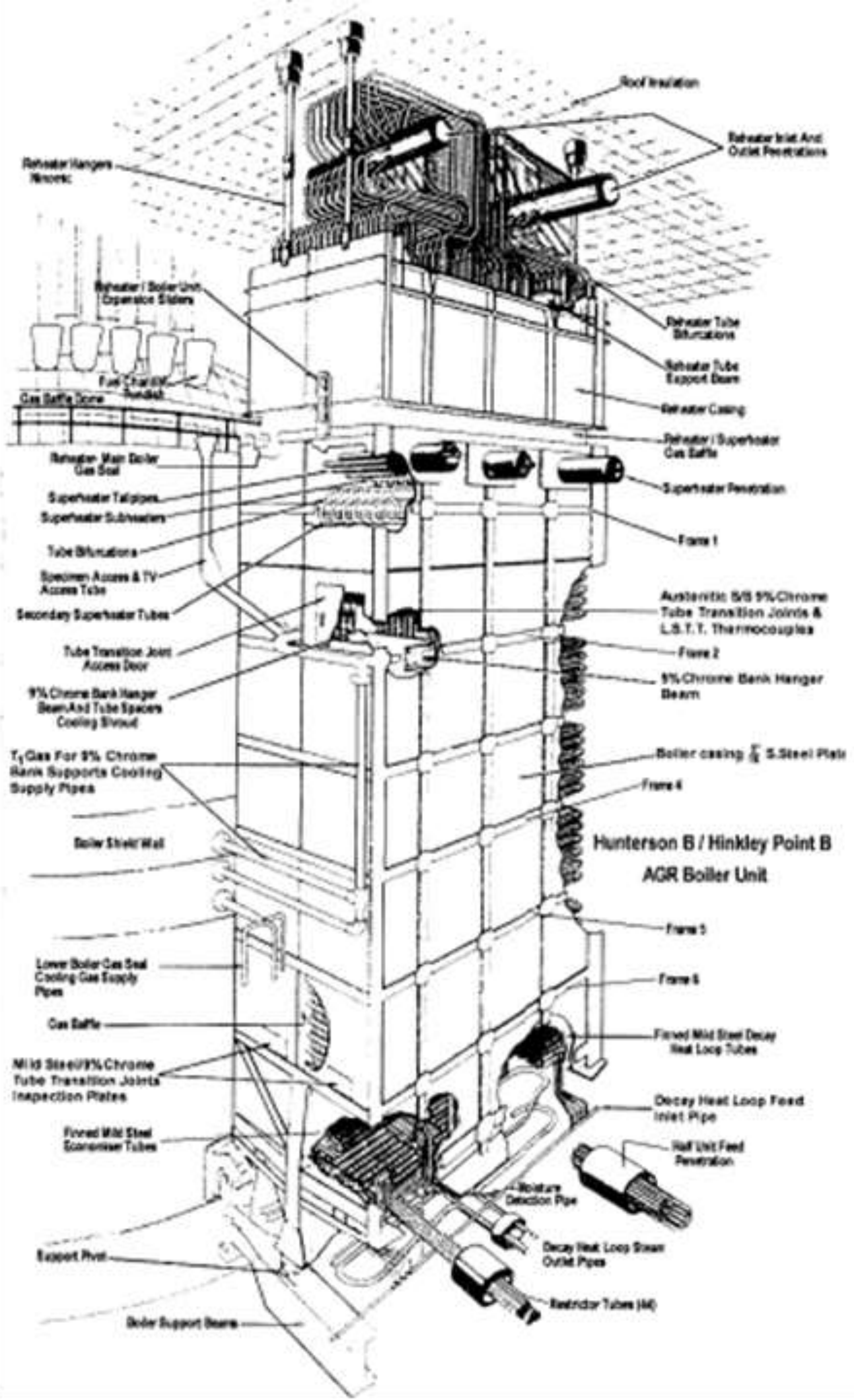
This is unusual for the time – multiple RS measurements on a relatively thin weld – most susceptible welds were too thin for ND (and too large to fit in the instruments)

Management of reheat cracking in AISI 316H

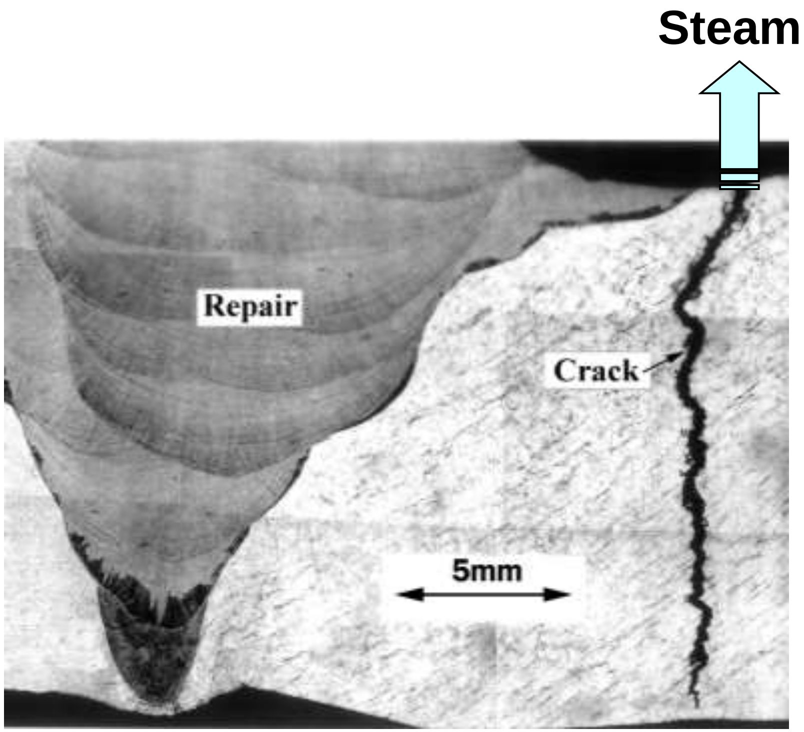
- All susceptible AISI 316H welds ranked based on understanding of failure mechanism
- Inspection programme implemented where possible.
- Axi-symmetric weld residual stress simulations and reheat cracking analyses performed for critical welds.
- Intermediate in-situ stress relief heat treatment at 750ºC developed and applied to certain welds
- Component replacement programme implemented
- “Header catchers” installed where replacement impractical and a robust safety case could not be made.
- Operating temperature limits imposed where required.
- Reheat cracking related research programmes initiated

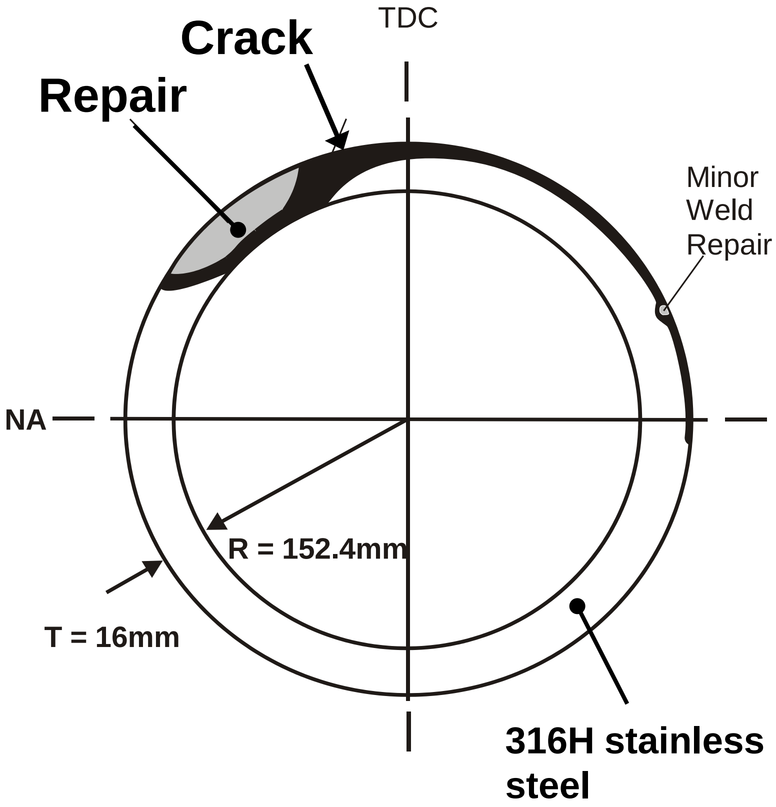
Hunterston ‘B’ – Rise of the weld repair

This boiler design does not have thick-section welds. Will it crack?



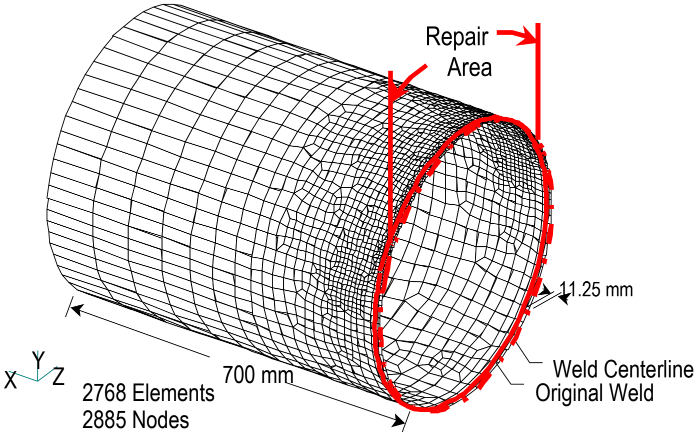
Reheat cracking at a repair weld

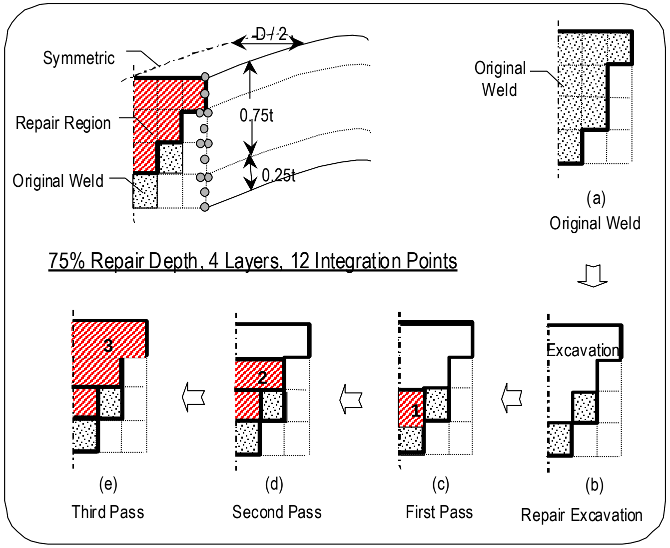


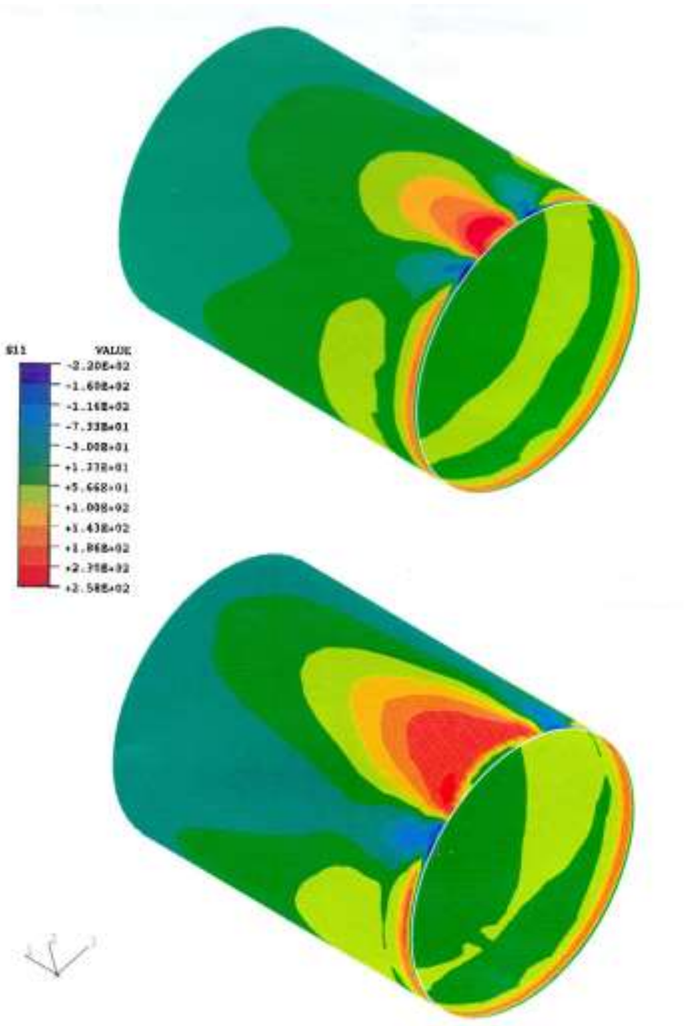


Hunterston ‘B’ developed a steam leak in 1997
Repair weld residual stress + plant loads at high temperature (>500ºC),
Creep cavitation » microcracking » crack growth » through-wall crack » steam leak

3-D Shell FE Repair Weld Simulation (19mm pipe)

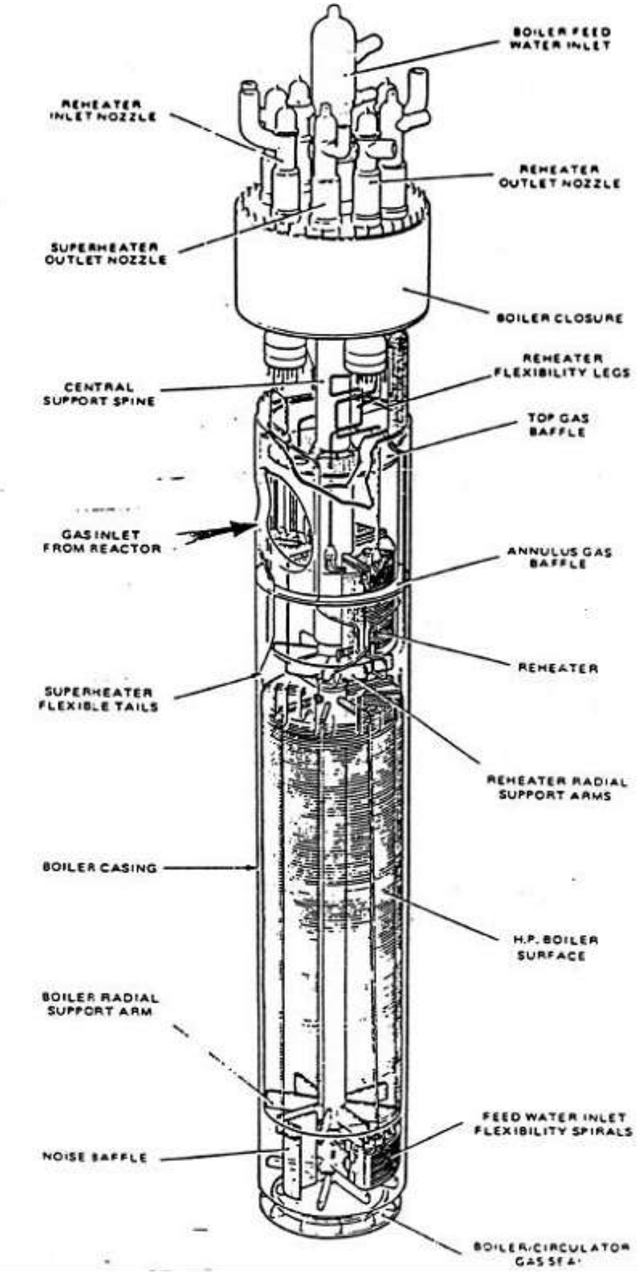




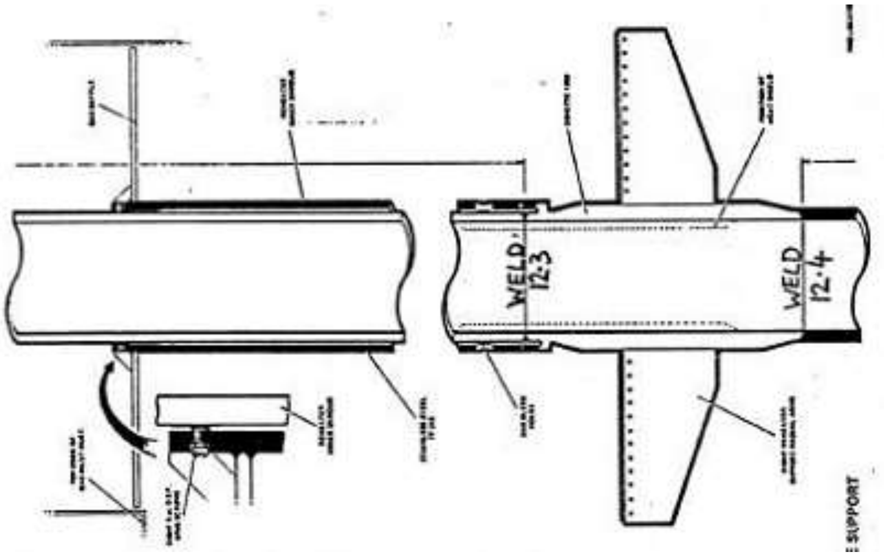


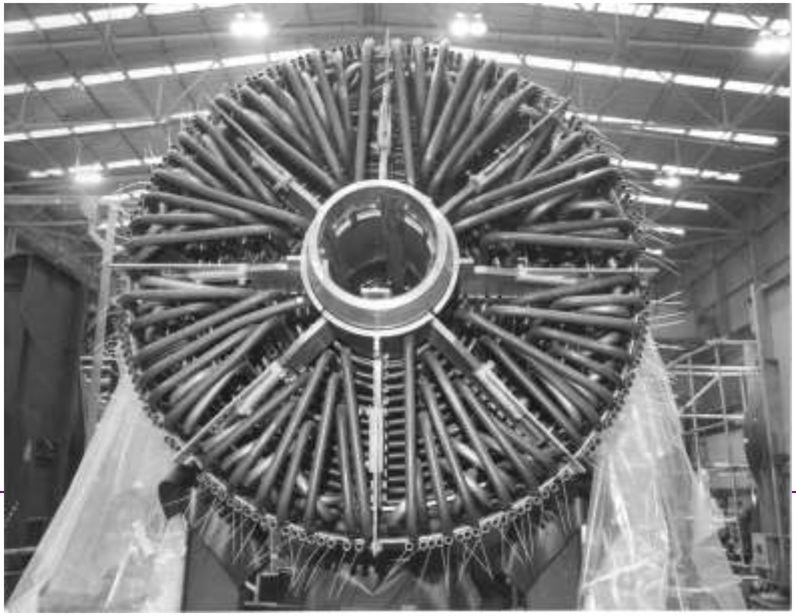
Back to the Hartlepool/Heysham pod boilers

The AISI 316H austenitic steel steam headers are not the only components that may be susceptible to reheat cracking – what about the support spine itself?



Details of the reheater section of a boiler spine

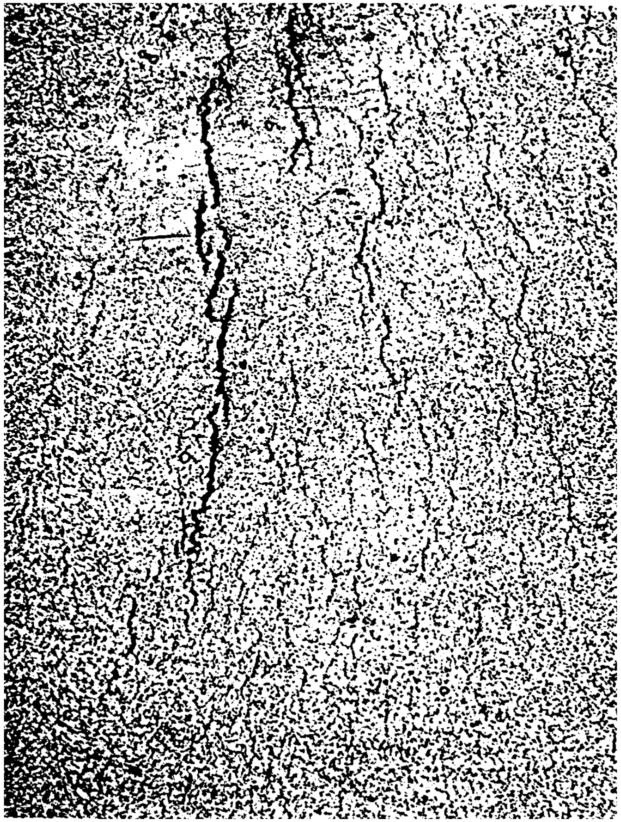




- The hottest part of the boiler support spine is the reheater section, which operates at up to 580°C, and is made from Esshete 1250.
- Esshete is an austenitic stainless steel with added Vanadium and Niobium to improve its strength at high temperature
- Welds are not stress-relieved, and some contain repairs

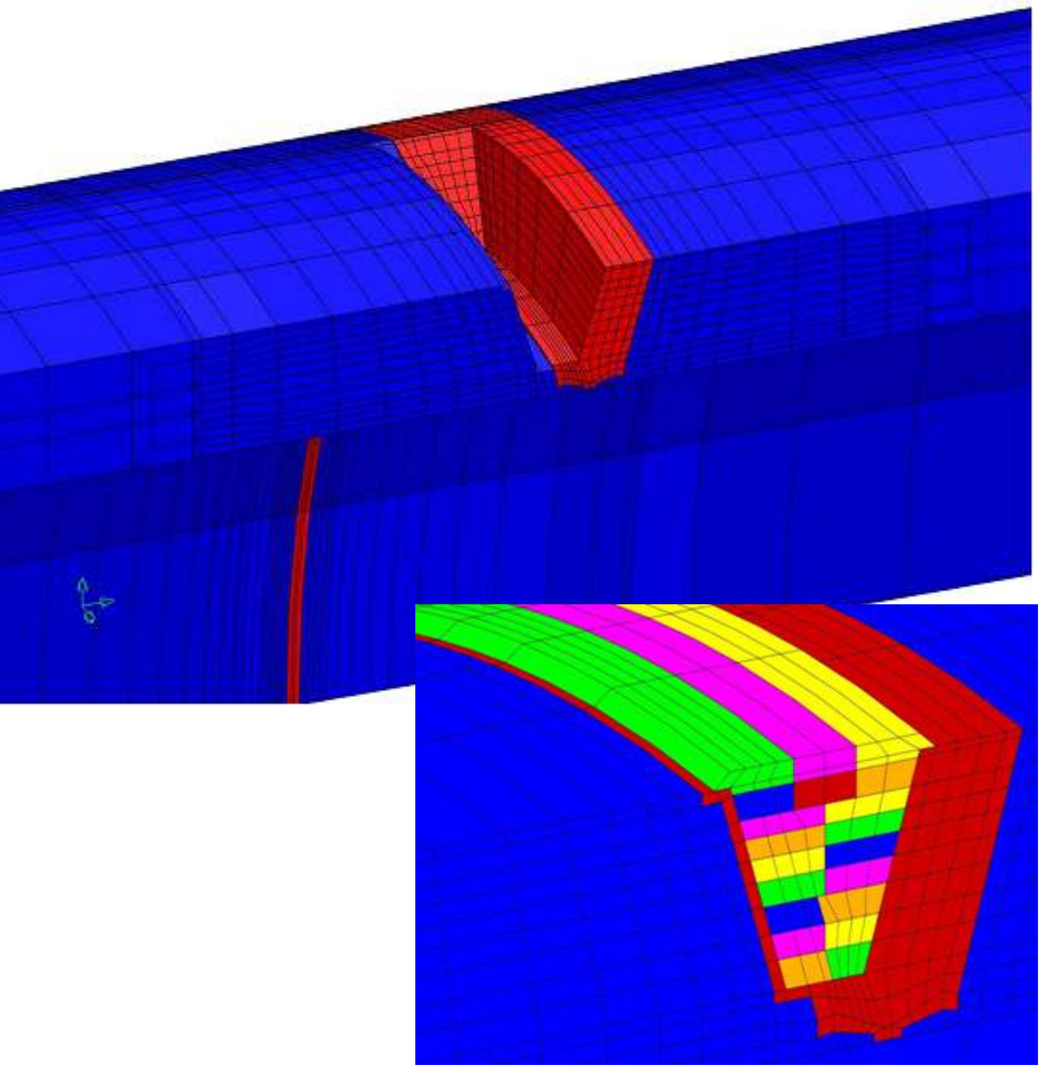
Integrity of Esshete 1250 welds

- Esshete 1250 weld metal has **low creep ductility (<1%)**
- The non-stress relieved repairs in the spine butt welds are more susceptible to reheat cracking than plain butt welds.
- Very difficult to inspect.
- High creep crack growth rates for postulated defects at repair welds
- fracture toughness of weld metal reduces with ageing at high temperature
- Defect tolerance case difficult to achieve
- It was necessary to deploy and **validate** full 3D analysis techniques to understand this problem



Esshete weld metal after solution heat treatment at 1050° C

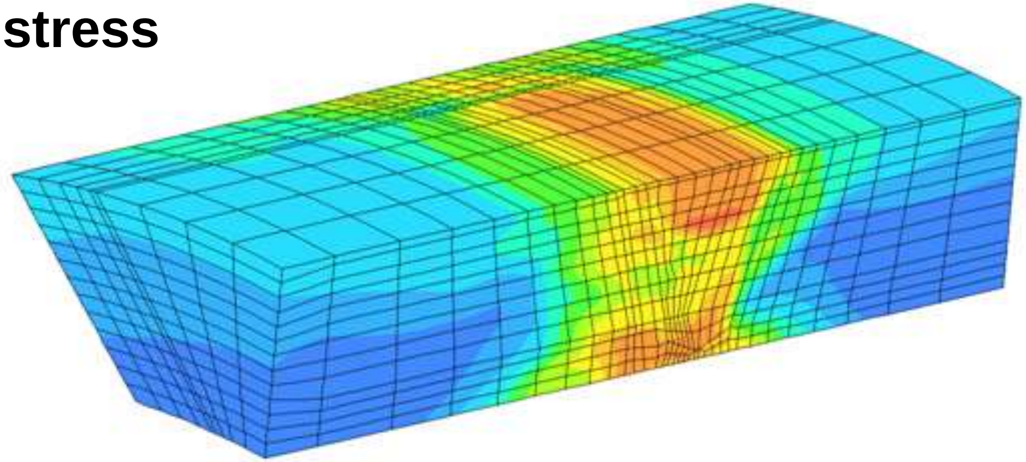
2002-2003 spine weld 12.3 model and methodology



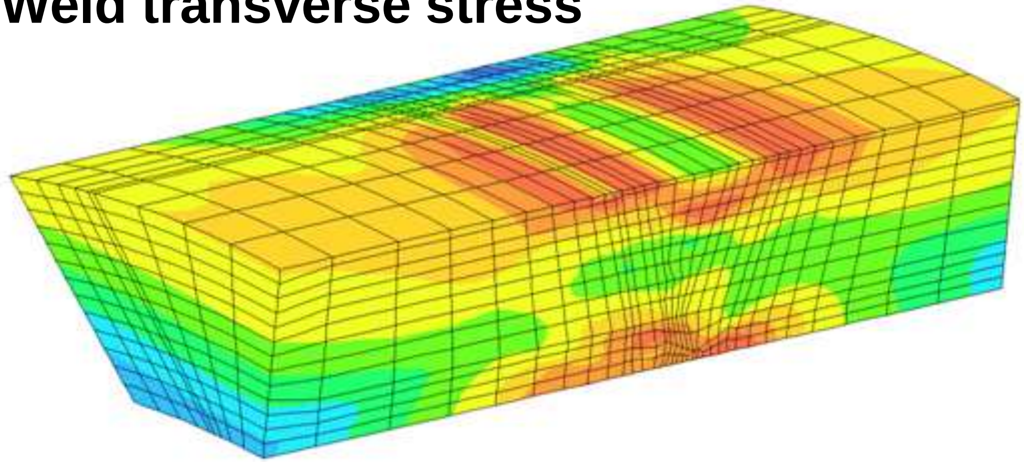
- Full 3D analysis to establish correct geometry and constraint
- Girth weld modelled axi-symmetrically, full solution mapped to 3D model
- Repair weld "block-dumped" one full bead at a time
- Simple fixed-bead temperature thermal model retained
- Simple isotropic hardening model for parent, perfectly plastic for weld
- Simple "annealing" model

2002-2003 - Predicted behaviour of weld 12.3

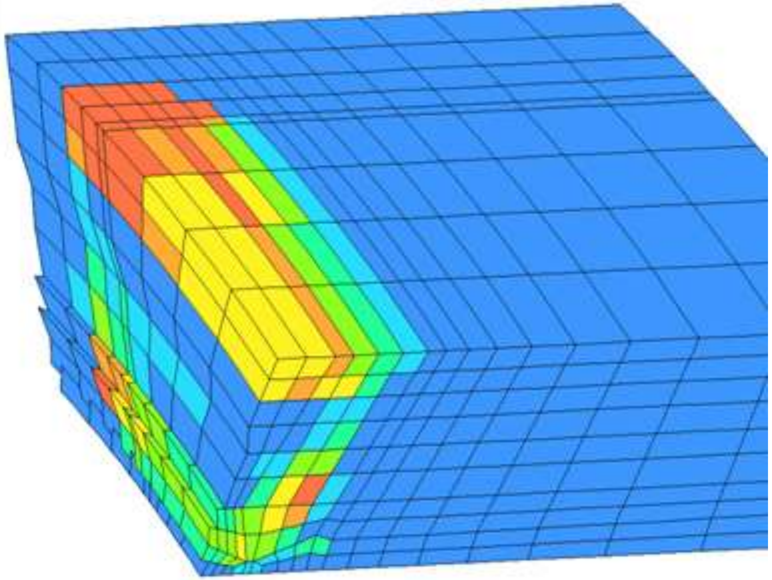
Weld longitudinal stress



Weld transverse stress

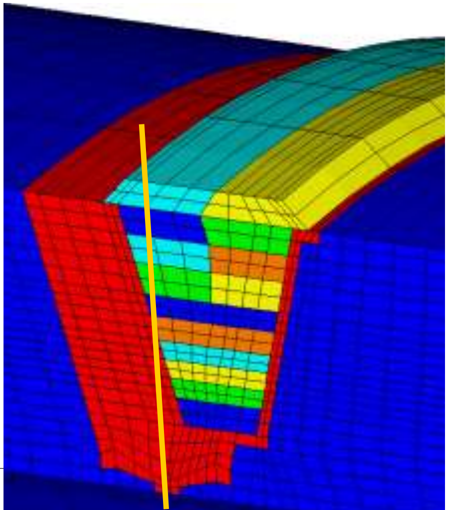


Creep damage



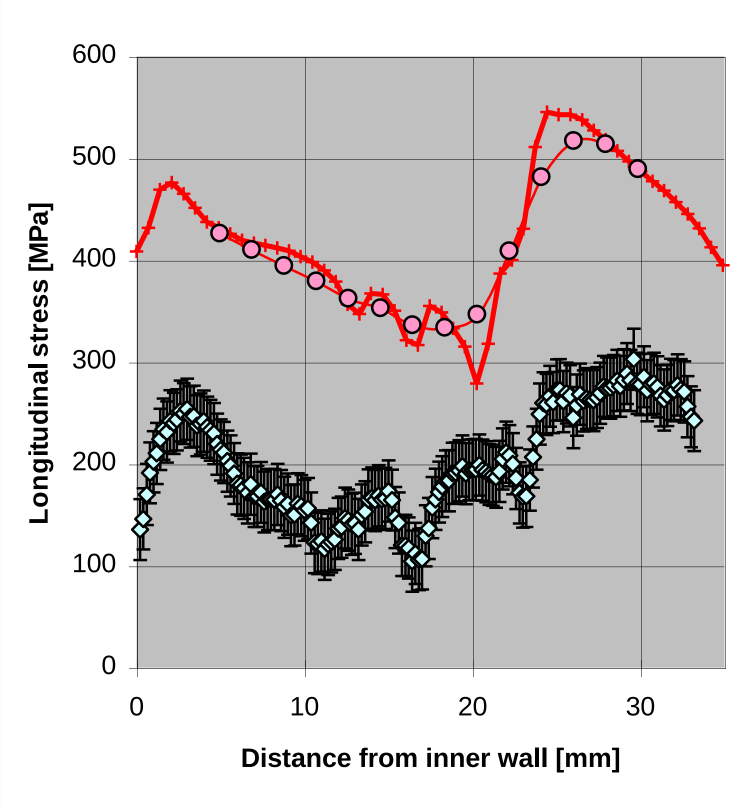
Predicted margins against reheat crack initiation were small

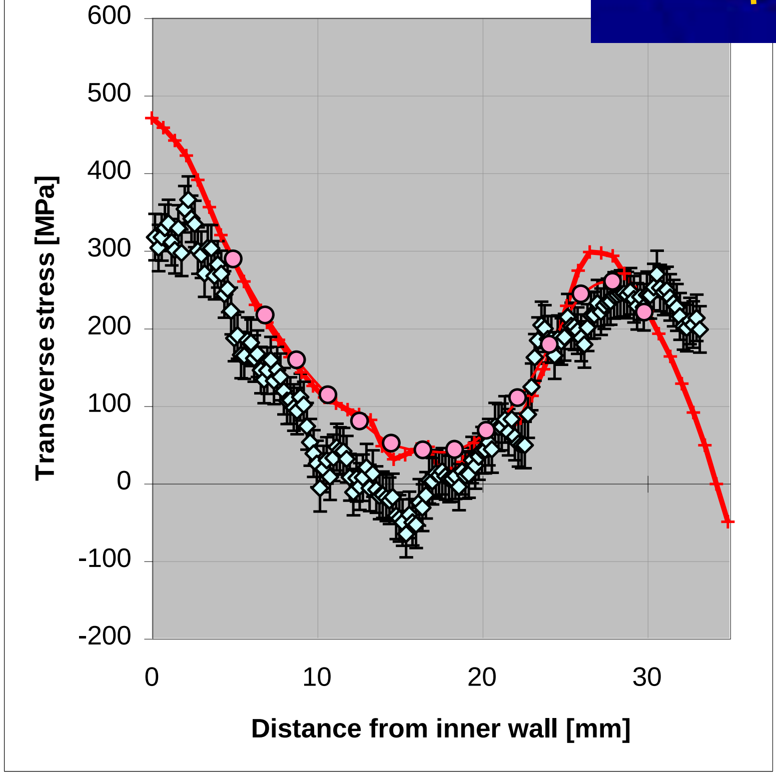
35mm pipe repair mock-up – hoop stresses over-predicted



Weld simulation methods used in 2003 tend to over-estimate longitudinal stresses in welds - so there is potential over-conservatism in the creep damage predictions

But what about relying on a single DHD measurement?

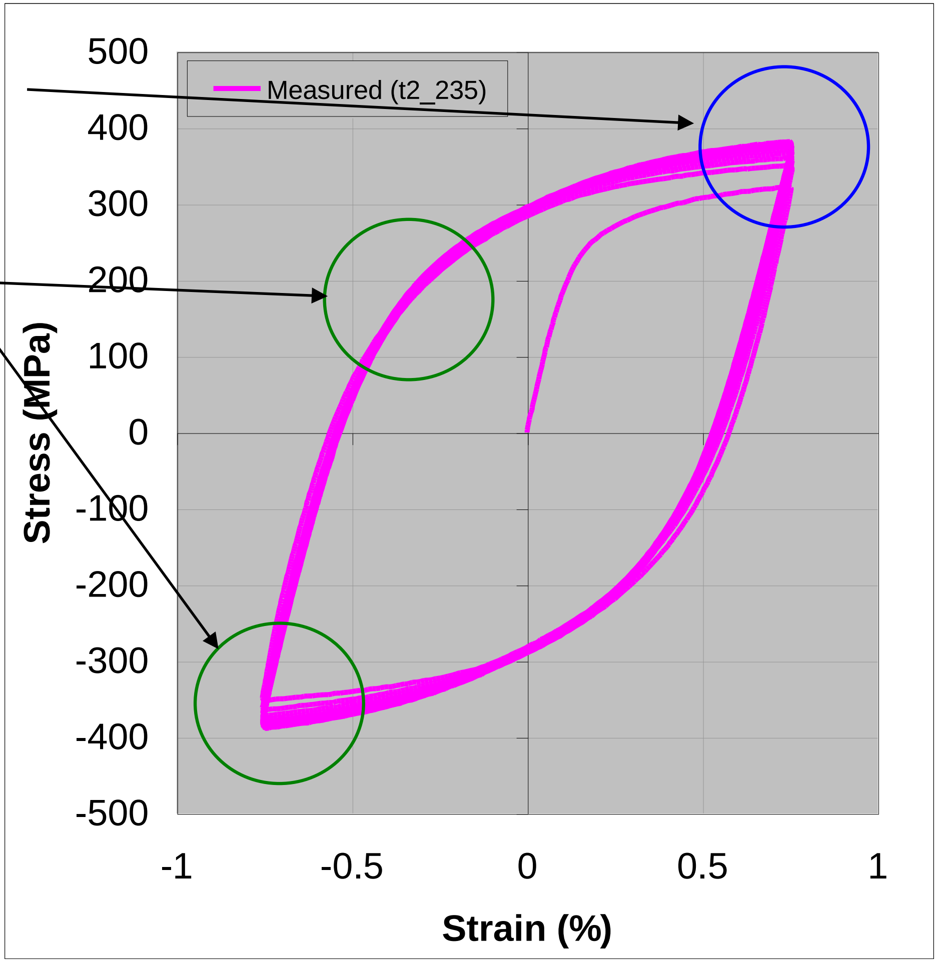


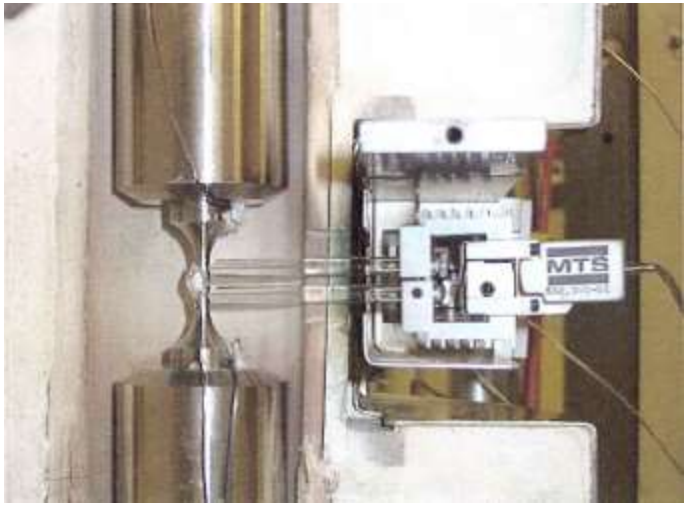


Mechanical properties

Response of metals to cyclic loading – key effects

- The material cyclically hardens or softens
- The yield stress in a given direction is reduced by prior plastic flow in the reversed direction.





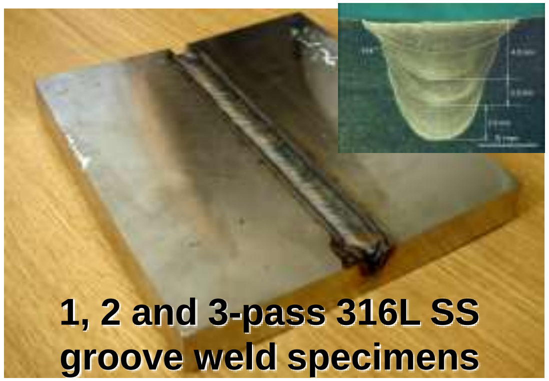
Drivers for Spines R & D programme (2004-2008)

- Predicted margins against reheat cracking in weld metal were small.
- **Only allowed to operate up to 175khr compared with design life of 250khr**.
- **If restriction not lifted reactors would have closed some years ago**
- Concern about so-called “end effects” not captured by block-dumped modelling approach
- Fixed bead temperature heat source model not physically particularly well founded.
- Simple material hardening models believed to be conservative, especially in longitudinal direction

Main objectives of spines R & D programme

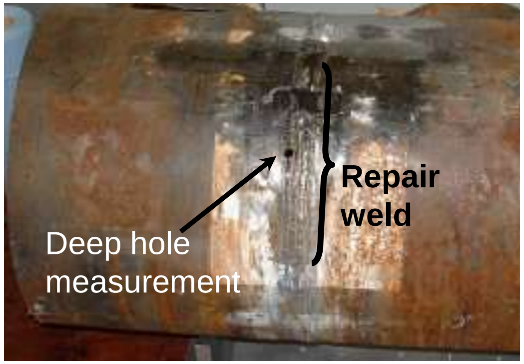
- to improve the consistency and accuracy of weld heat source modelling methods,
- to reduce the conservatism and improve the accuracy of residual stress predictions for stainless steel welds, primarily by improving the material constitutive models
- To understand and quantify so-called “end effects”
- to validate new residual stress weld modelling approaches using high quality measurements from test specimens and benchmark weldments, so less conservative assessments retained regulatory acceptance.
- To demonstrate the adequacy of the creep deformation and damage development models being used to predict the onset of reheat cracking

Validation mock-ups


1, 2 and 3-pass 316L SS groove weld specimens


NET Bead on Plate weldment

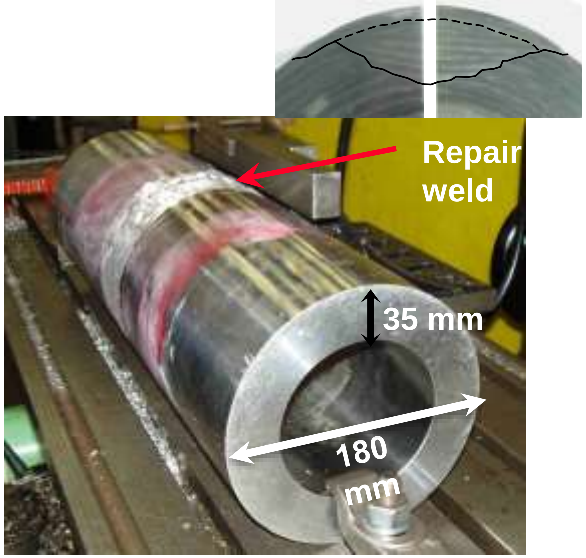

3-pass 316L SS Slot Weld



316H SS 19.6mm pipe butt weld & with short & long repairs


Esshete 1250 ring-welds(HAZ and repair designs)

316H SS, 35mm pipe butt weld and with 218mm offset repair



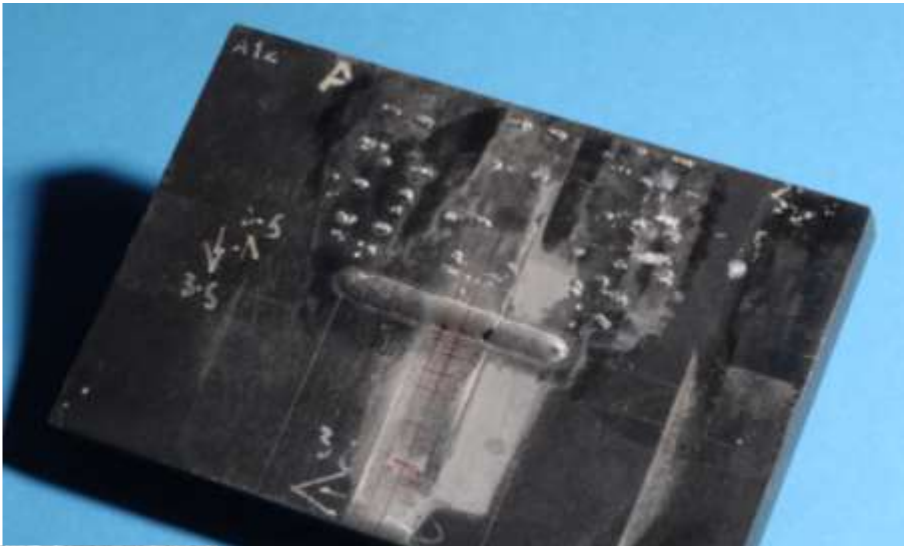
Esshete 1250 butt weld with short repair

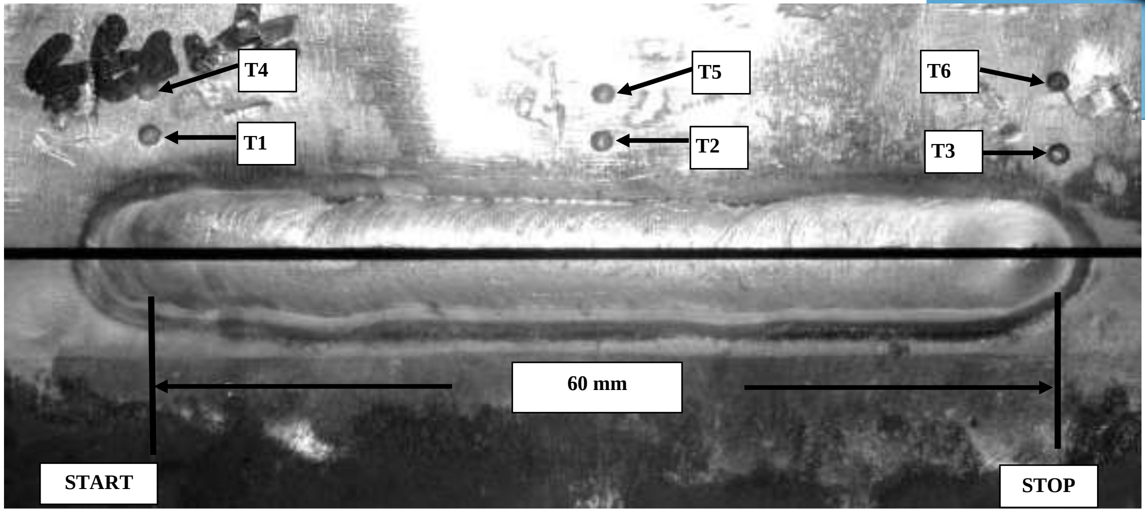
So how does NeT fit into this?

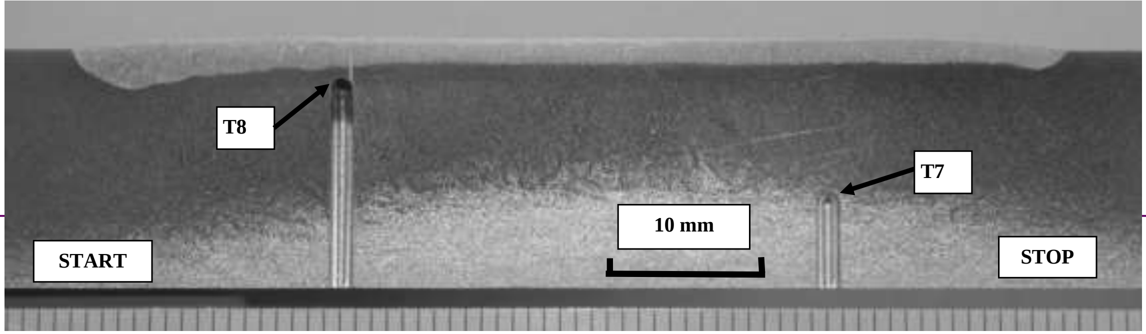
Remember – NeT kicked off in 2002, just as the Spines R&D programme was getting going

NeT TG1, 2002-2009

- Four AISI 316L plates
- Single ~60mm GTAW weld bead laid on top surface
- Array of 9 type K thermocouples on each plate
- Welded “lightly clamped”





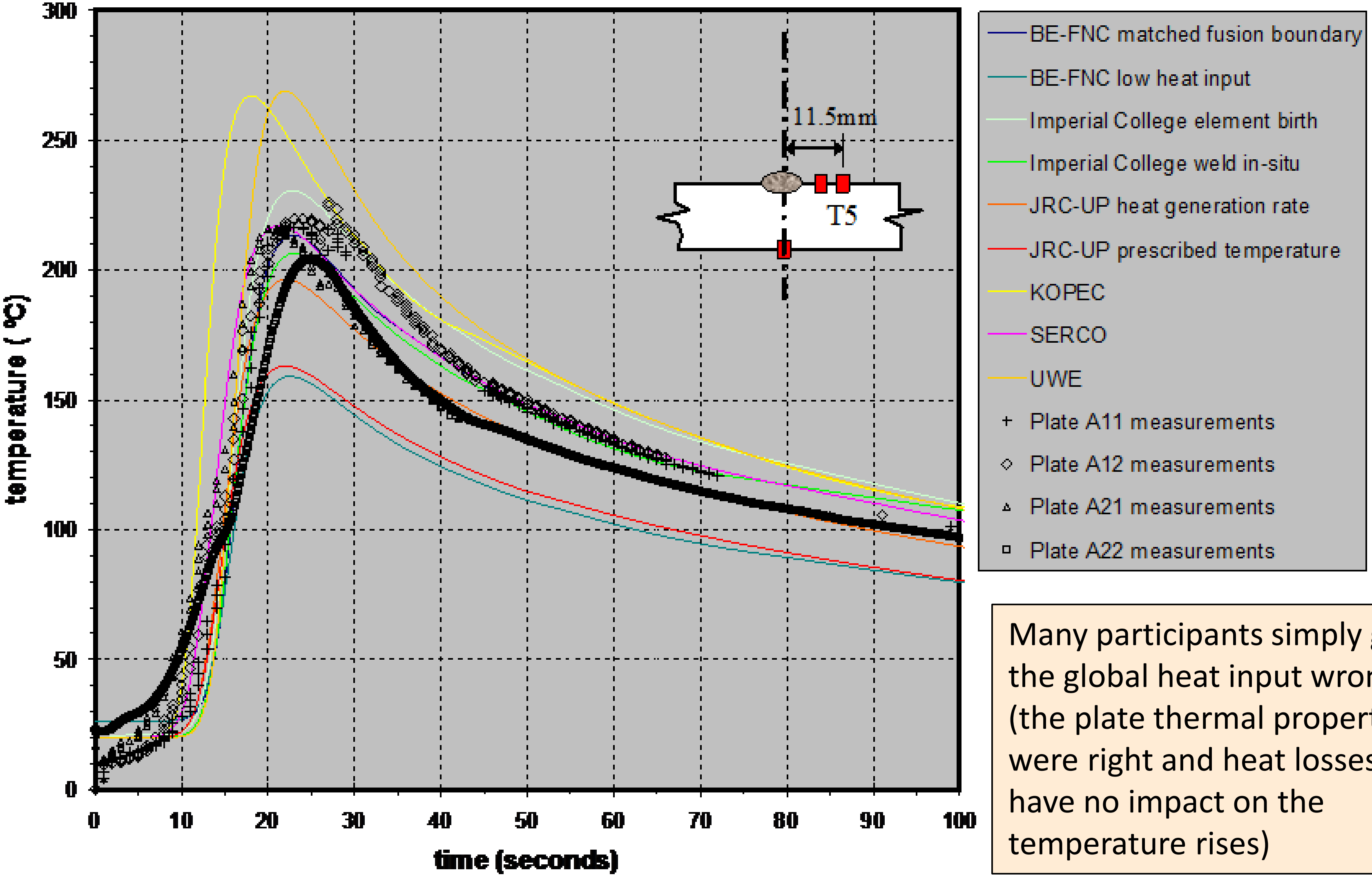


- Strongly 3D RS distribution, akin to a short weld repair
- T/C arrays to allow heat source model calibration
- Portable for multiple RS measurements at different facilities
- Relevant material
- Computationally tractable – 3D MHS
- Little weld metal
- Only one TMF cycle

History of NeT Task Group 1

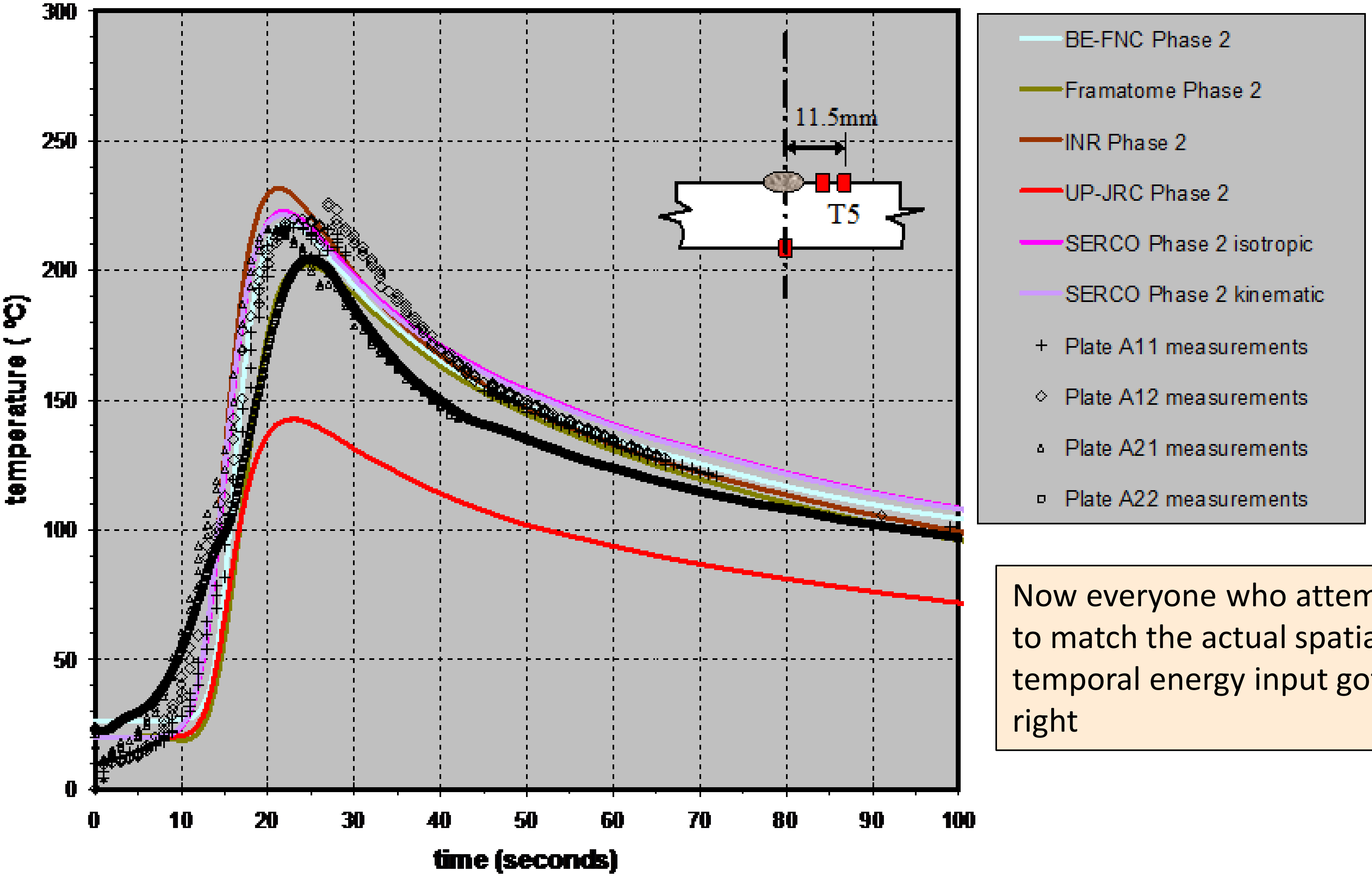
- Task Group 1 performed parallel measurement and simulation round robins
  - Both were controlled by detailed protocols
- The Phase 1 Round Robin ran from 2002 to 2005.
  - 5 sets of ND measurements on 5 instruments, 2 DHD, 2 ICHD, Contour, 2 sets of X-ray diffraction measurements
  - 8 participants in simulation round robin: 10 thermal simulations and 14 mechanical simulations
  - Some materials characterisation
- Phase 2 Round Robin ran from 2005 to 2008, using lessons learned from phase 1
  - Simulation protocol updated with fixed weld efficiency (fixed global heat input) and more accurate fusion boundary definition
  - Two further sets of ND measurements and detailed statistical analysis of measurements database
  - six participants in simulation round robin: 7 thermal simulations and approx 14 mechanical analyses

Thermal analysis performance– Phase 1 analyses



Many participants simply got the global heat input wrong (the plate thermal properties were right and heat losses have no impact on the temperature rises)

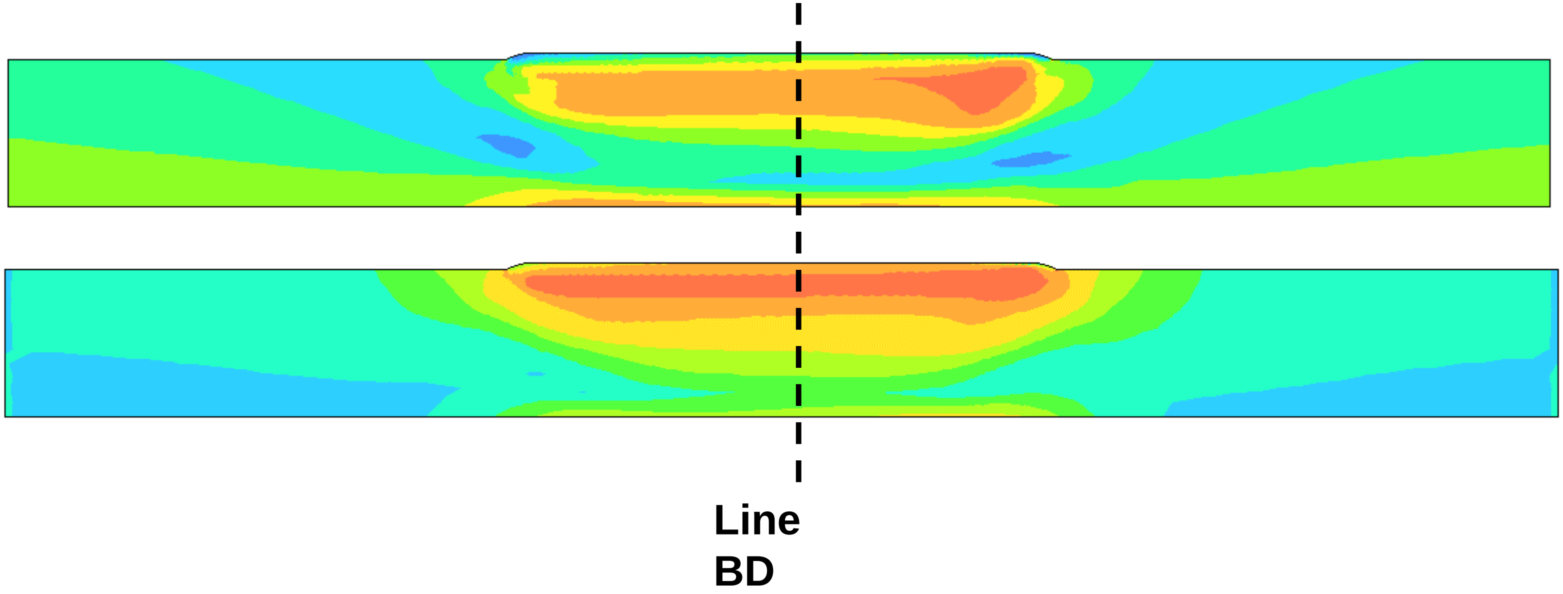
Thermocouple T5 – Phase 2 analyses



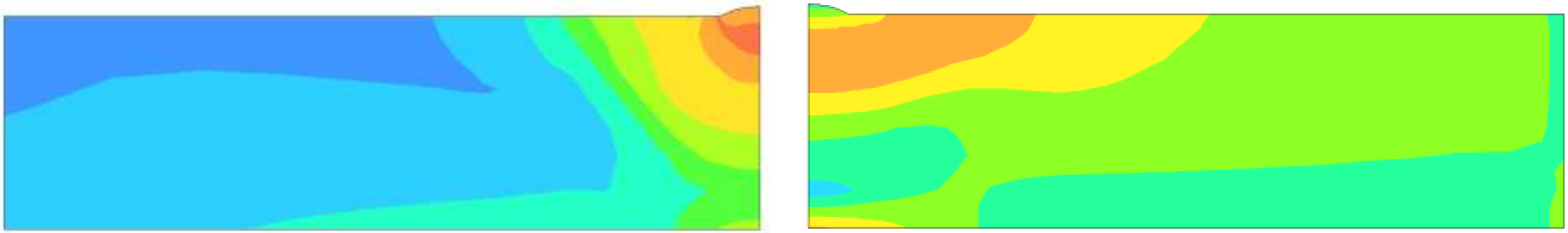
Now everyone who attempted to match the actual spatial and temporal energy input got it right

Typical predicted stress distribution

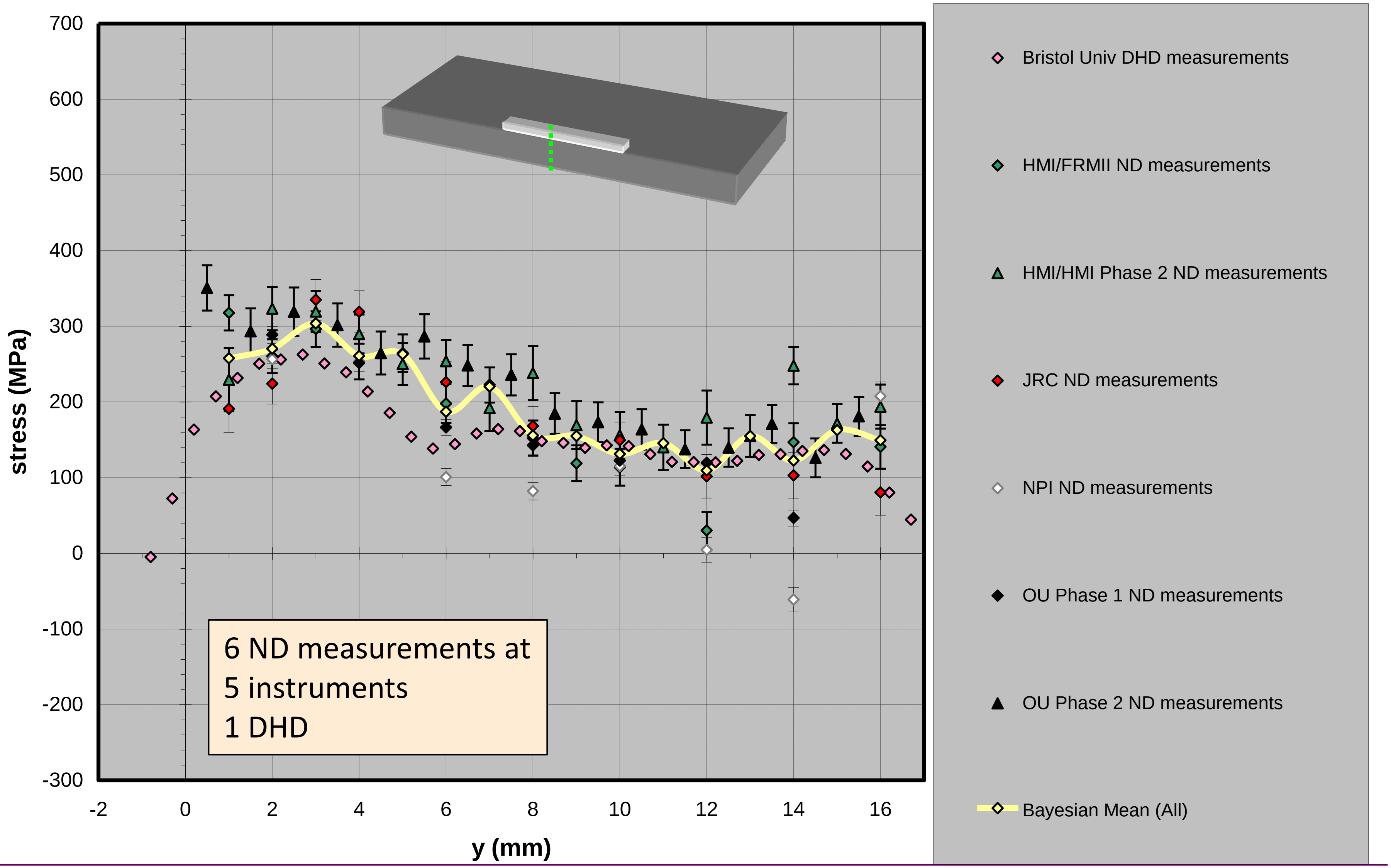
Typical predicted stresses on Plane D (Top – Transverse; Bottom – Longitudinal)



Typical predicted stresses on Plane B at mid-length (Left – Longitudinal; Right – Transverse)

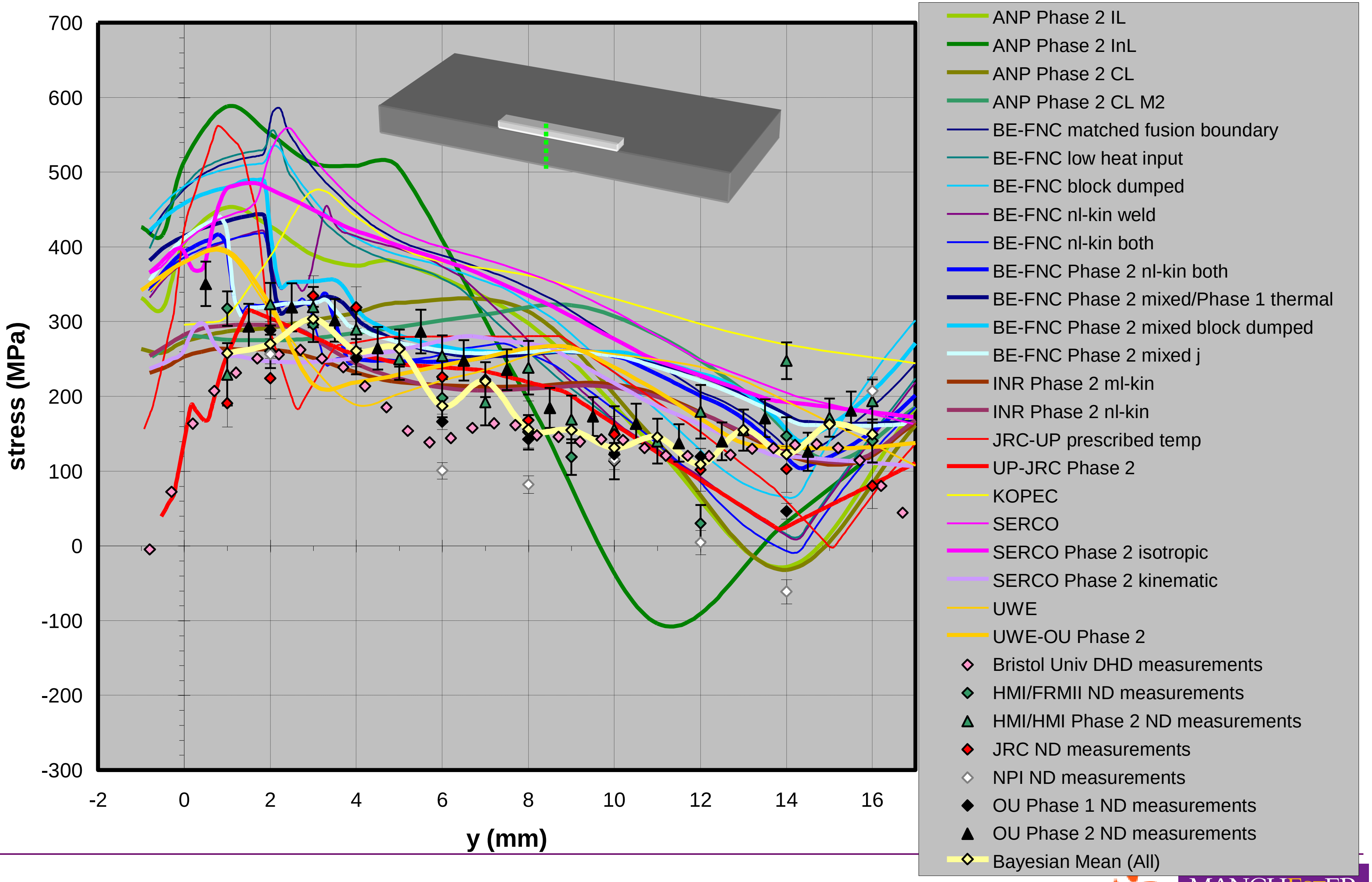


Measured longitudinal stresses on line BD

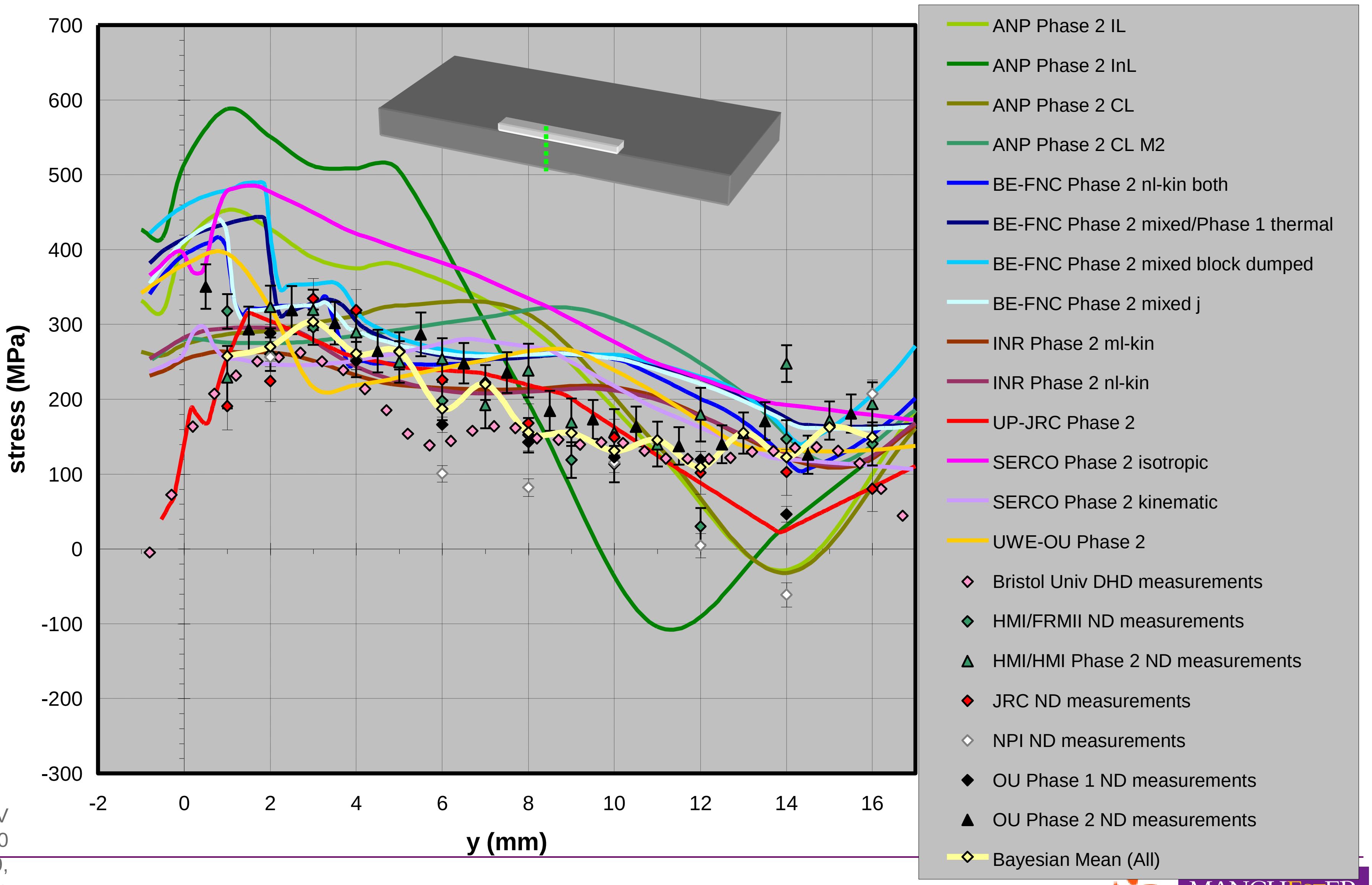


6 ND measurements at
5 instruments
1 DHD

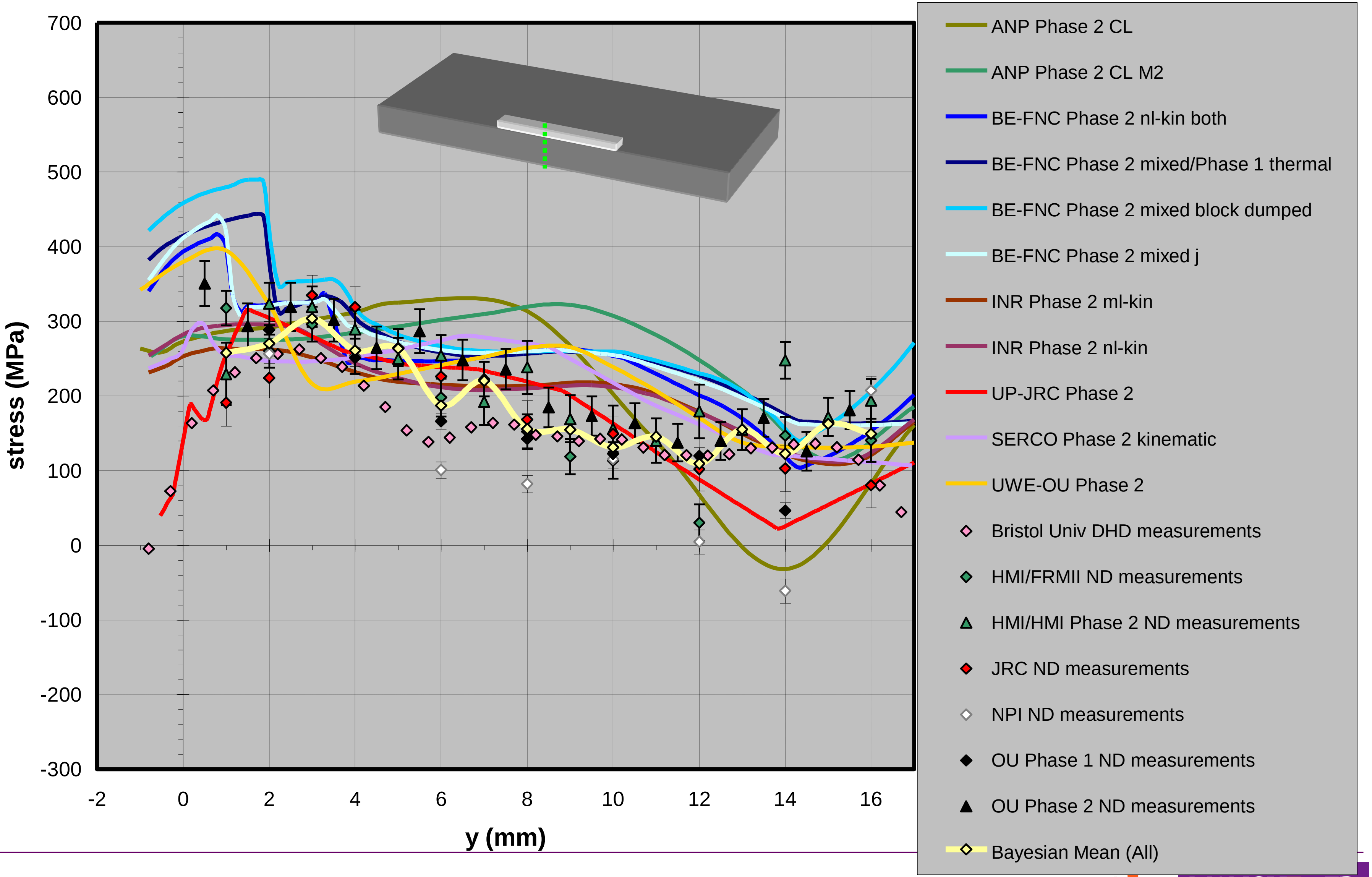
Longitudinal stresses on line BD – all analyses



Longitudinal stress on line BD – phase 2 analyses



Longitudinal stress on line BD – phase 2 analyses, kinematic and mixed hardening



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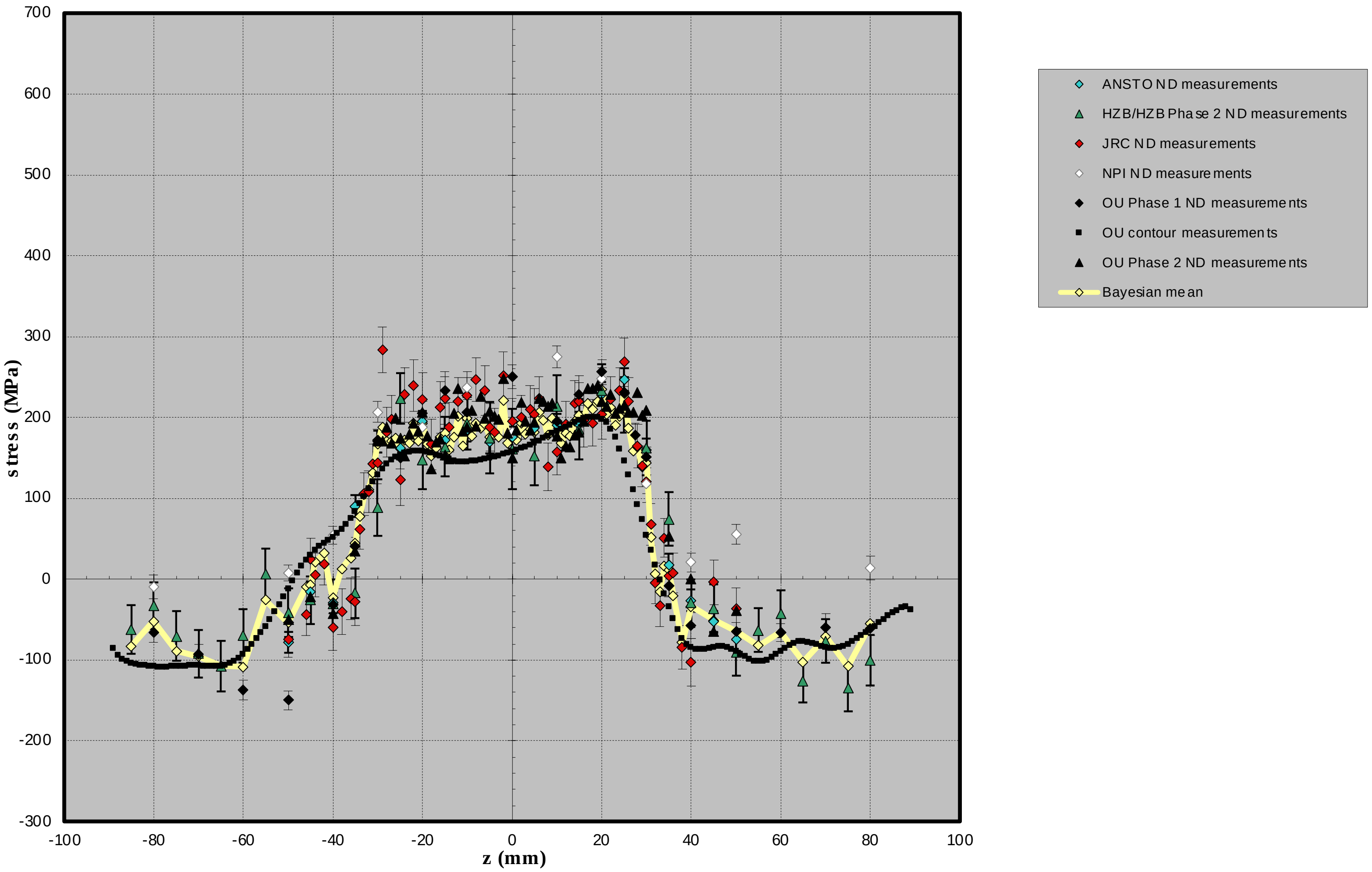
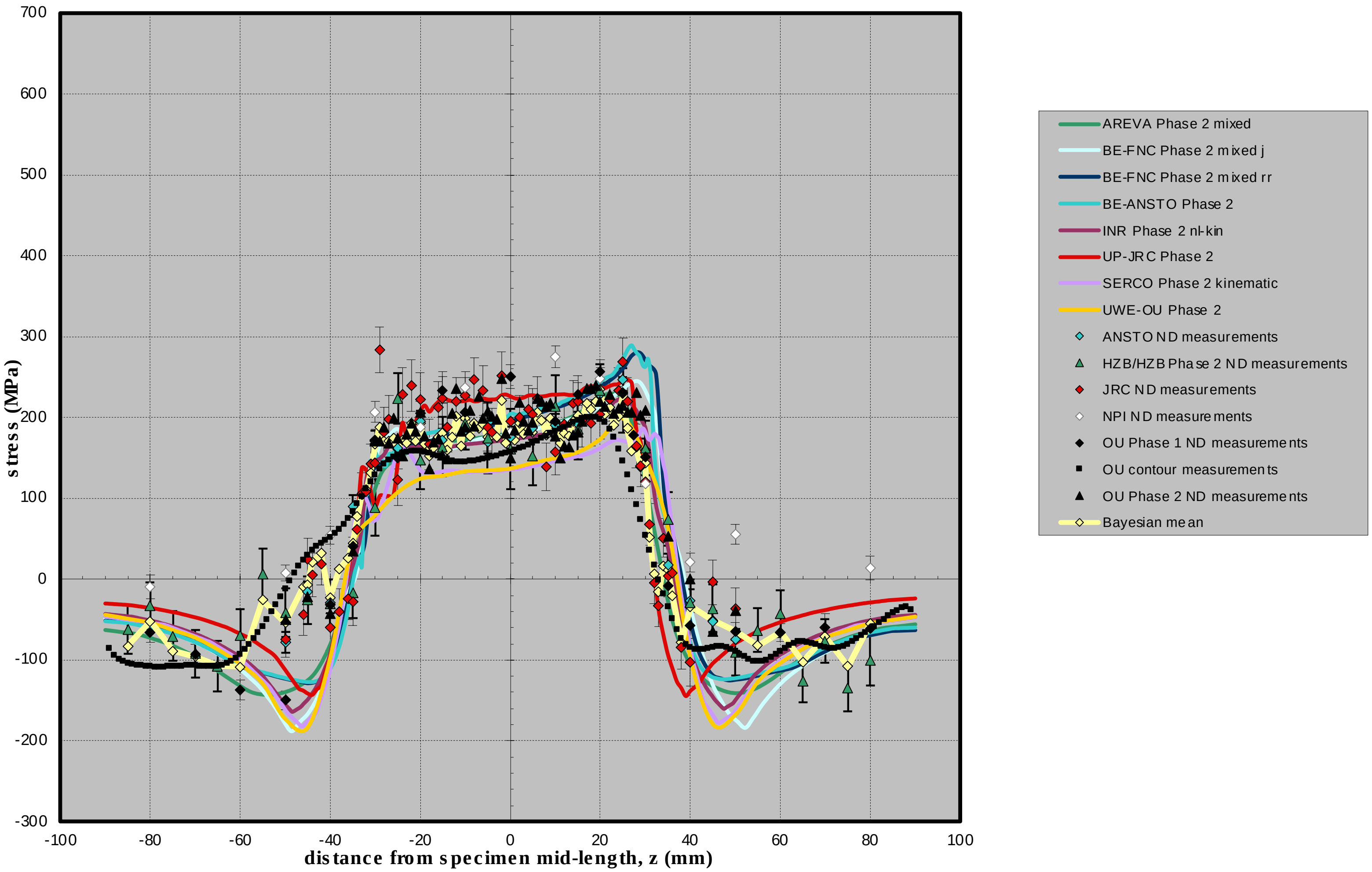
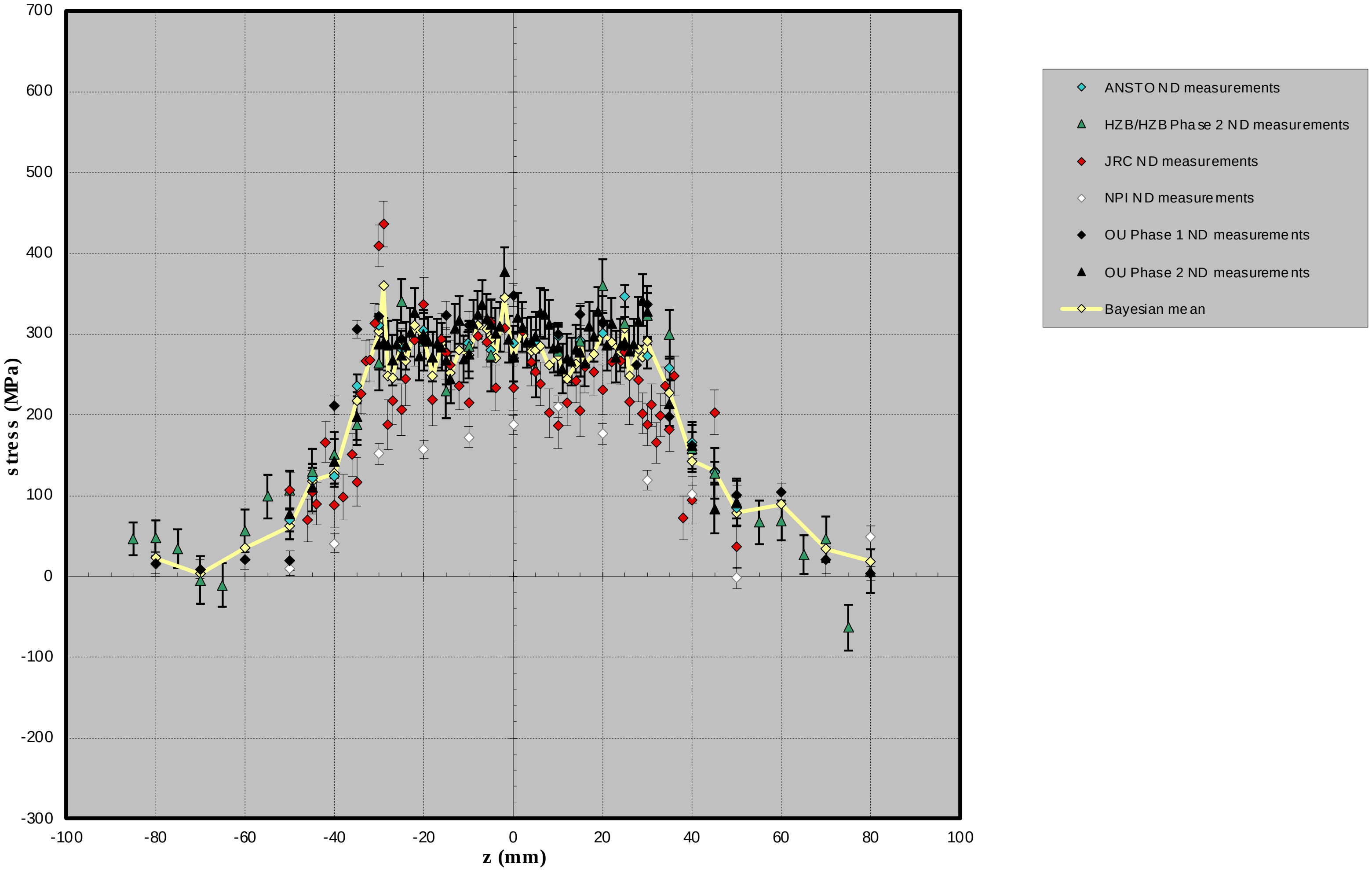
Measured transverse stresses on line D2



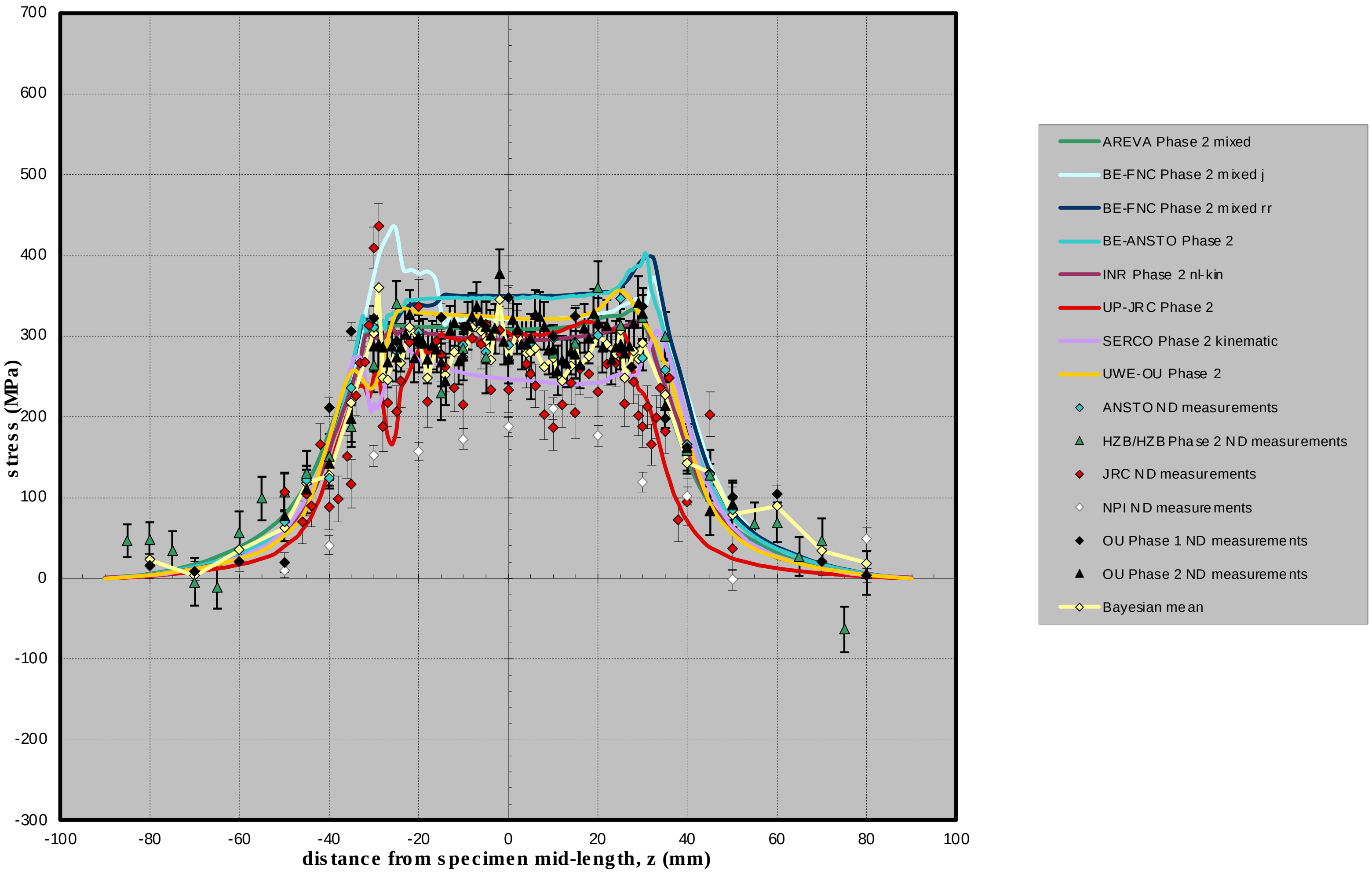
“Good” Phase 2 transverse stress predictions on D2



Measured longitudinal stresses on line D2



“Good” Phase 2 Longitudinal stress predictions on D2



What did NeT TG1 tell us?

- It is easy to get the welding heat source wrong
  - *This underwrote the development of the FEAT-WMT weld heat source modelling tool used in the UK*
- However, it is also possible to reduce uncertainty in the thermal solution to acceptably low levels –
  - *not clear whether this impacted stresses in TG1*
- Stress gradients along a ”repair weld” are visible and similar in both modelling and simulation
  - *In combination with more limited measured data from other weldments, TG1 helped to underwrite the 3D modelling approaches used for repaired spine welds*
- Even in a single pass weld, it is best to use a mixed isotropic-kinematic hardening law, at least for parent material, which undergoes cyclic loading
  - *However, there is still considerable remaining scatter between simulations*
  - *The handling of weld metal may be an issue (even though it has just cooled down from molten in TG1)*
- Measurements have scatter and often unknown/unforseen systematic errors
- ***TG1 made an important contribution to the development of the R6 weld modelling guidelines, first issued in 2009***

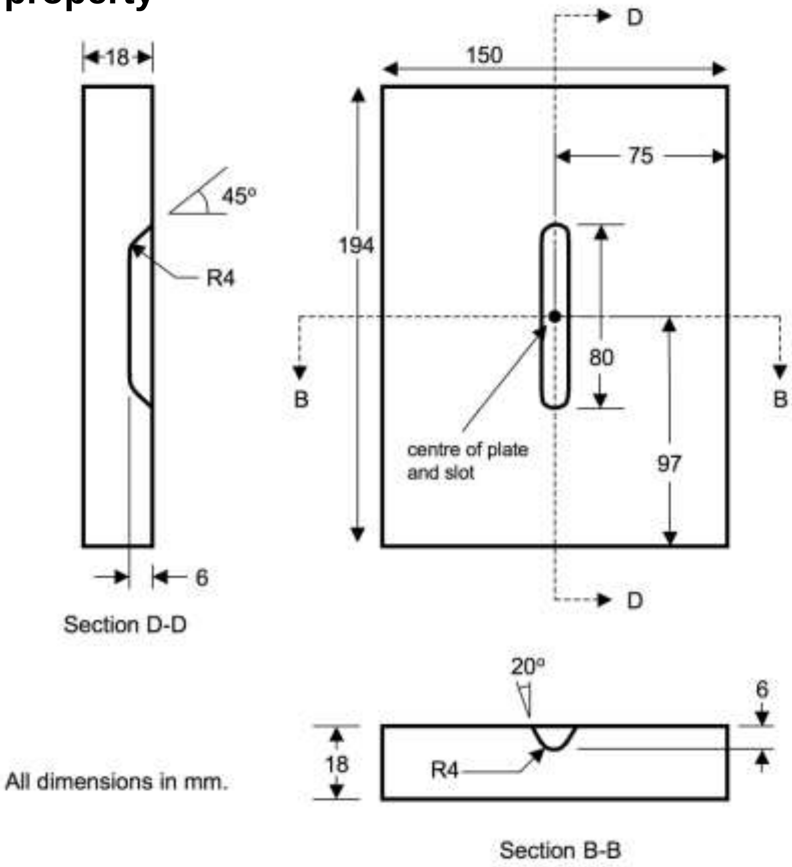
Net TG4, 2007 to ~2015 – moving to multi-pass welds

AISI 316L(N) plate containing three superimposed GTAW beads laid into a slot

- Finite length weld with strongly 3D residual stress distribution
- Simple structural boundary conditions – welded unrestrained
- **Multi-pass weld – several TMF cycles to develop material properties**
- **Significant volume of weld metal – need to handle its property development**
- No SSPT

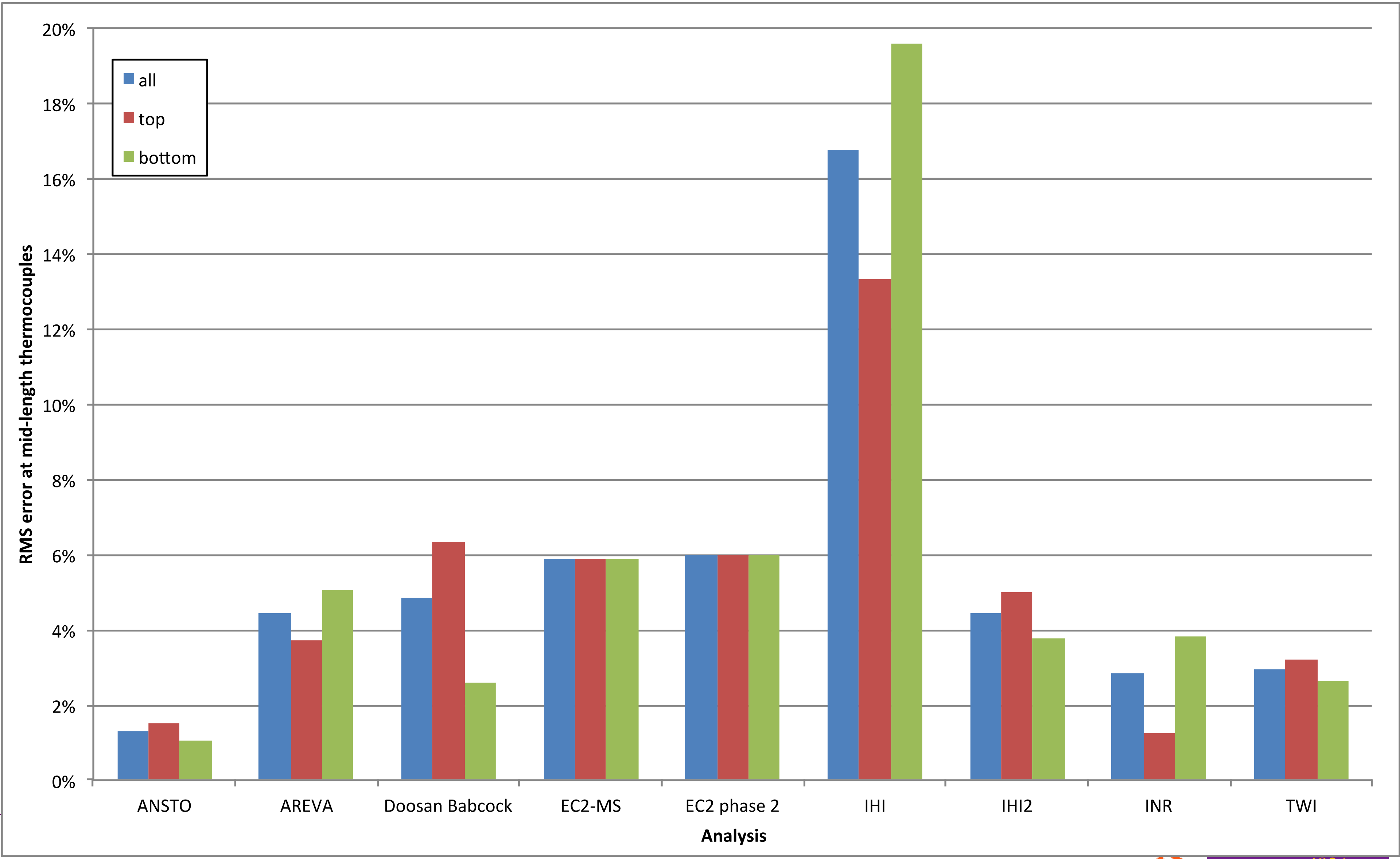
Moving heat source finite element predictions are feasible

Easy to move around the world for measurements

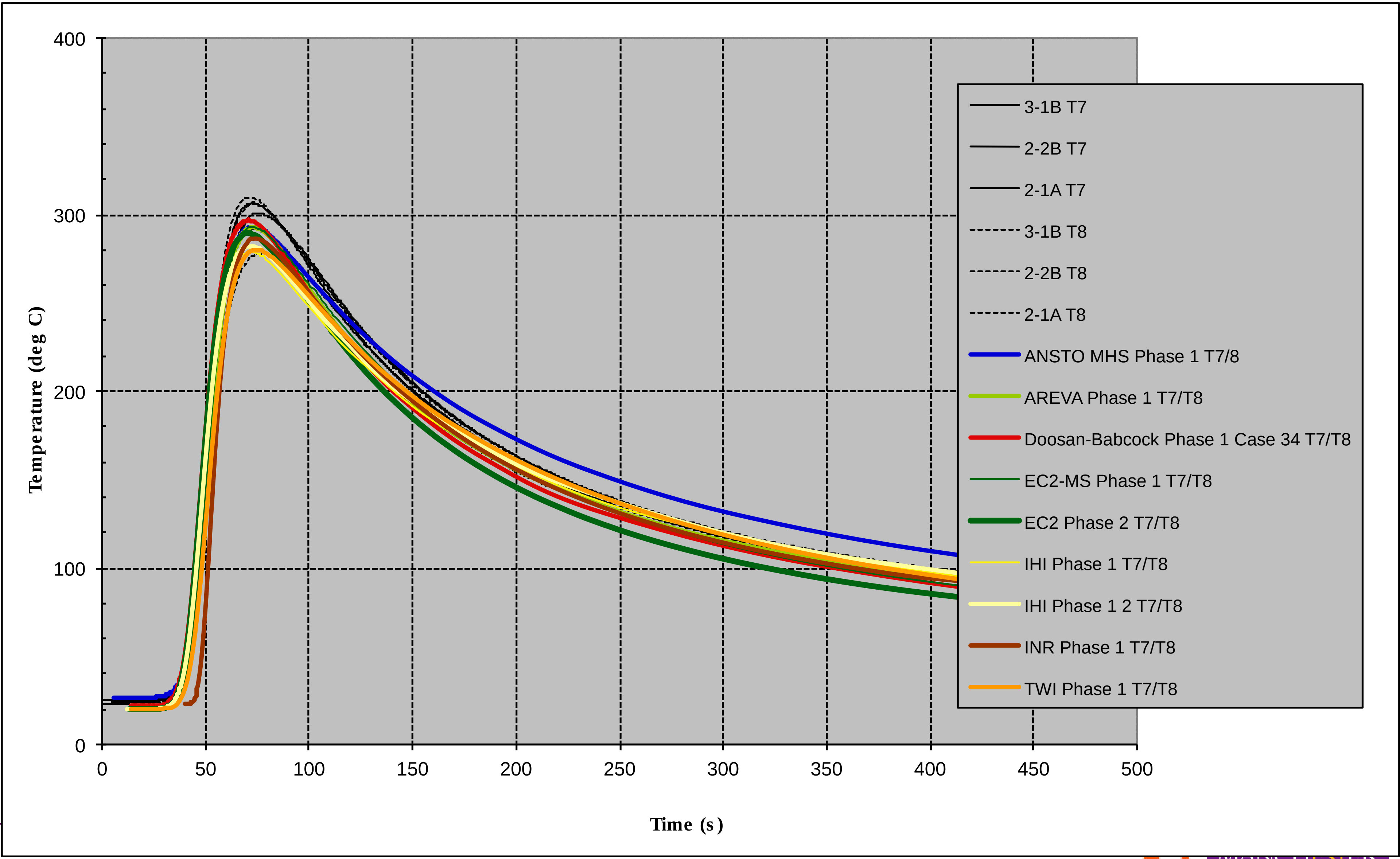


All dimensions in mm.

RMS errors in predicted temperature rises at mid-length thermocouple arrays for pass 3, NeT TG4



Typical thermocouple responses at a mid-length thermocouple – NeT TG4



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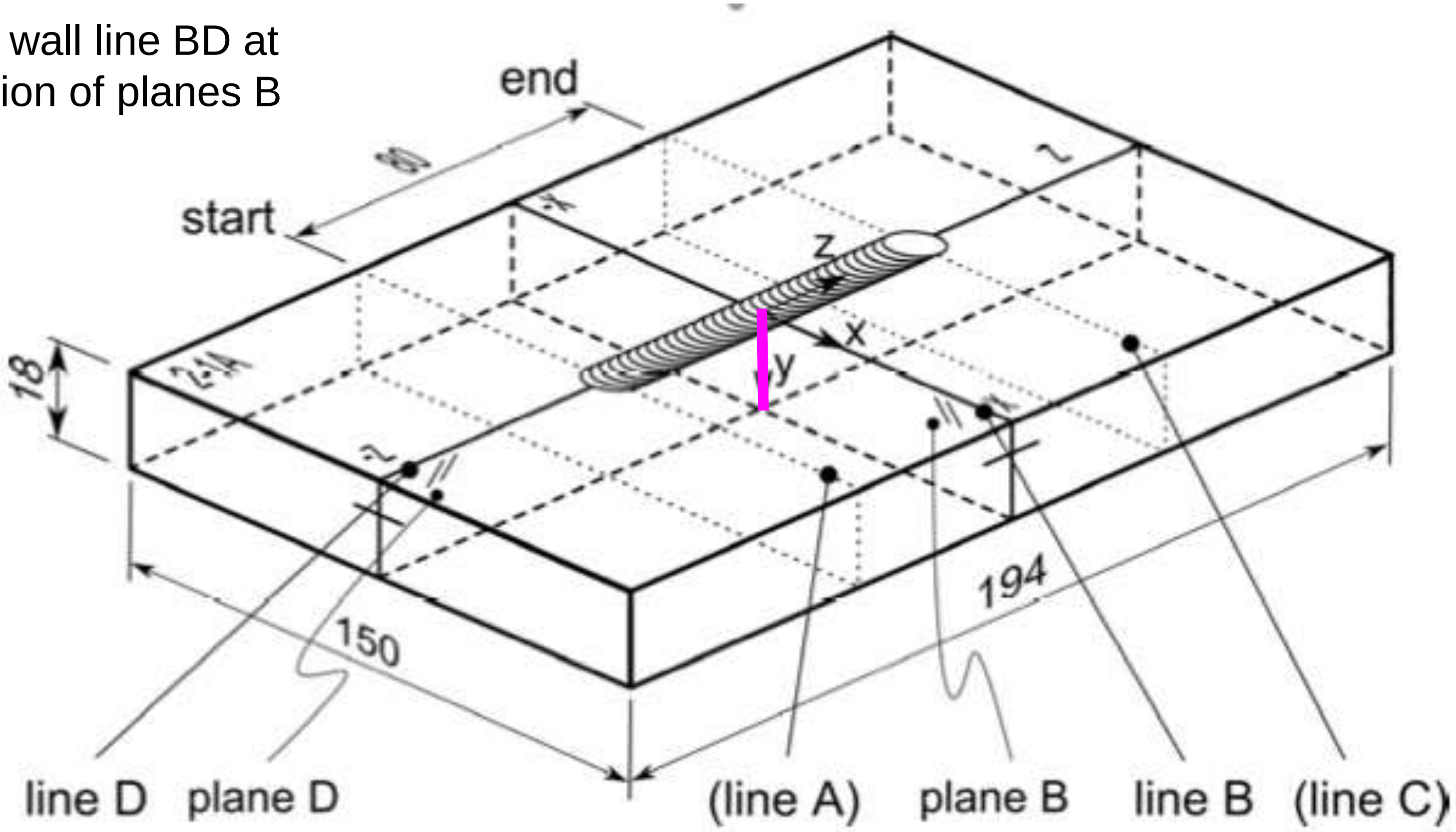
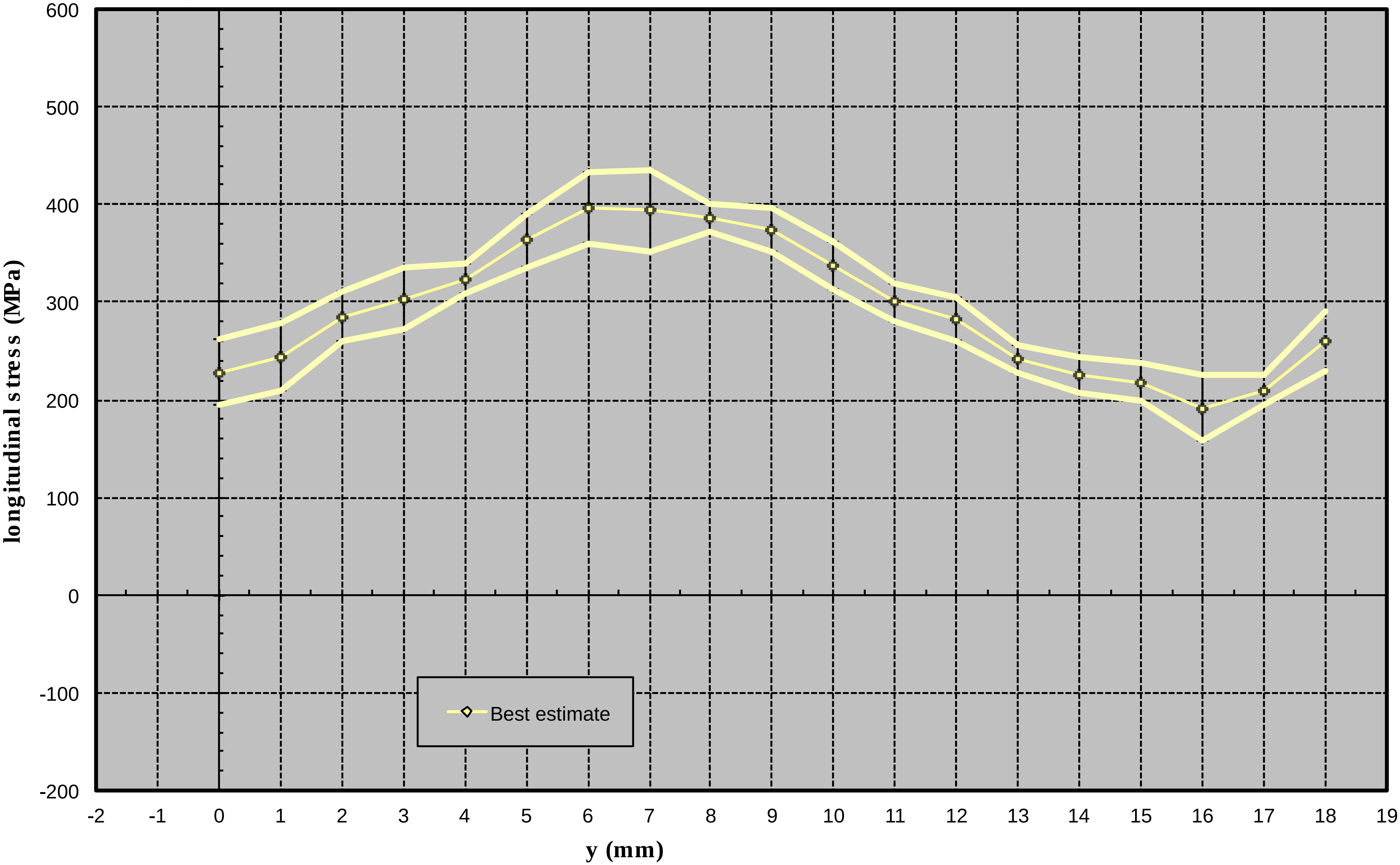
Location of example measurement line

Through wall line BD at intersection of planes B and D



Longitudinal stresses - best estimate and +/- 1 SD



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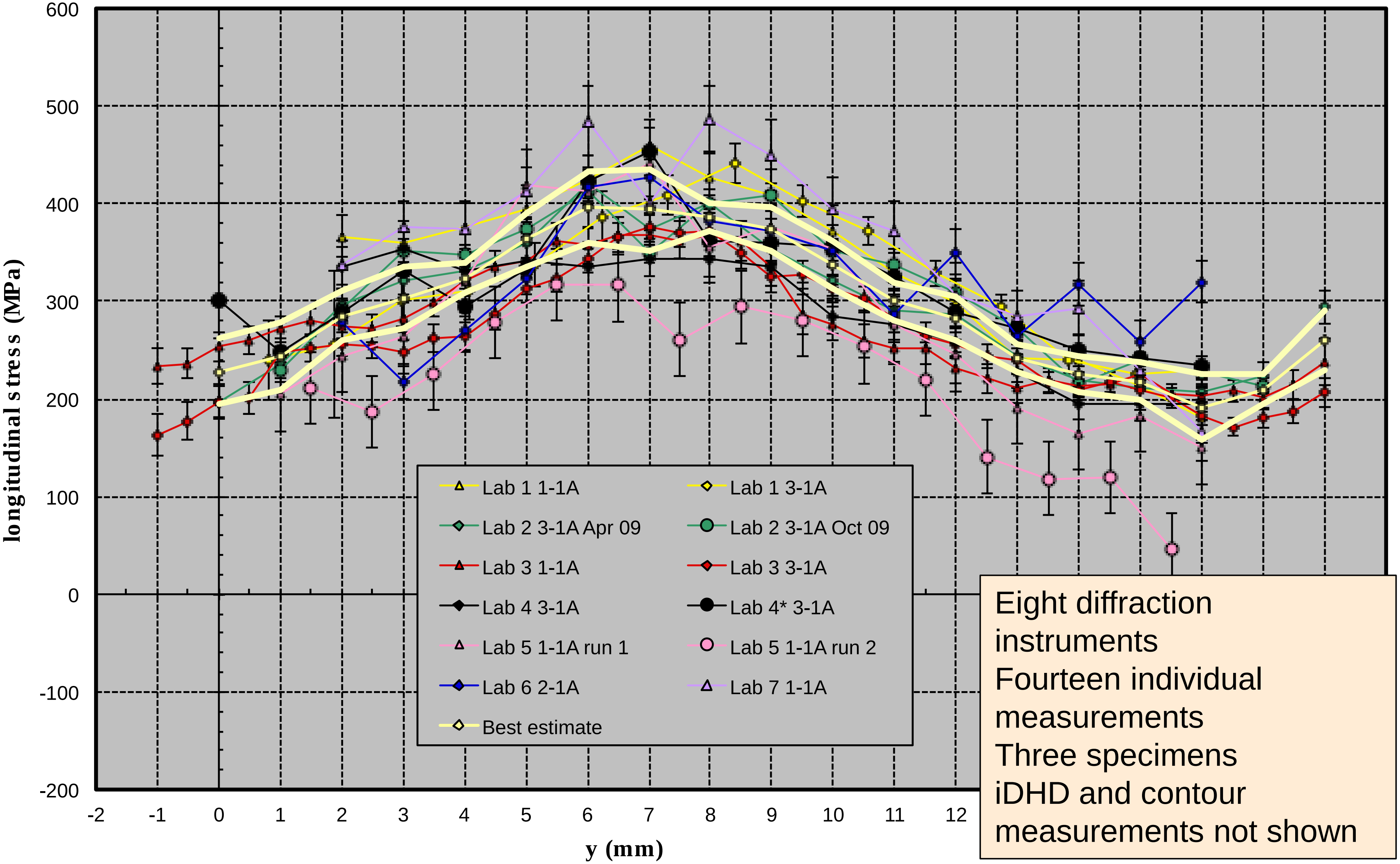
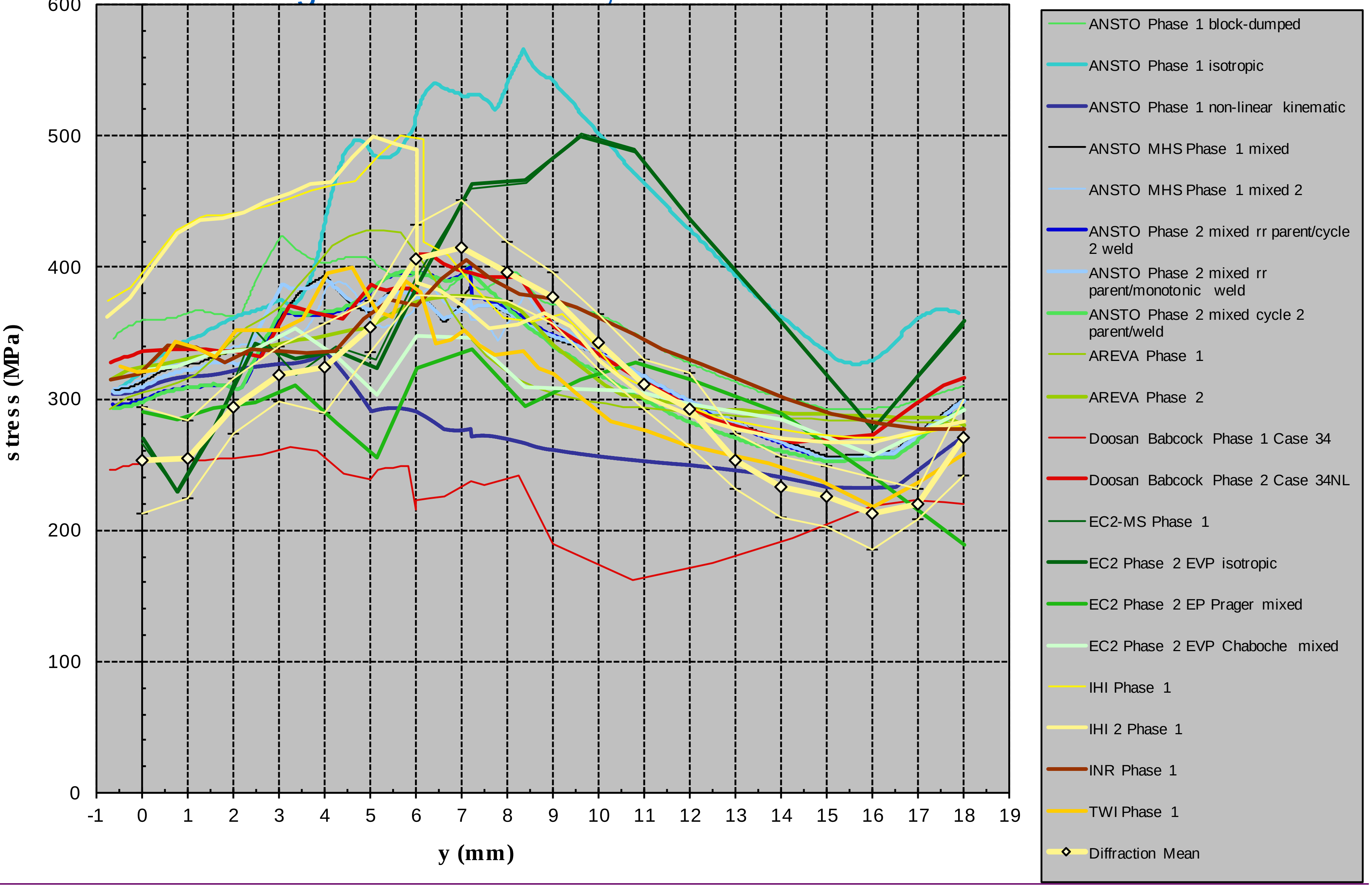
Longitudinal stresses – Diffraction-based measurements



Eight diffraction instruments
Fourteen individual measurements
Three specimens
iDHD and contour measurements not shown

Predicted longitudinal stresses, all simulations



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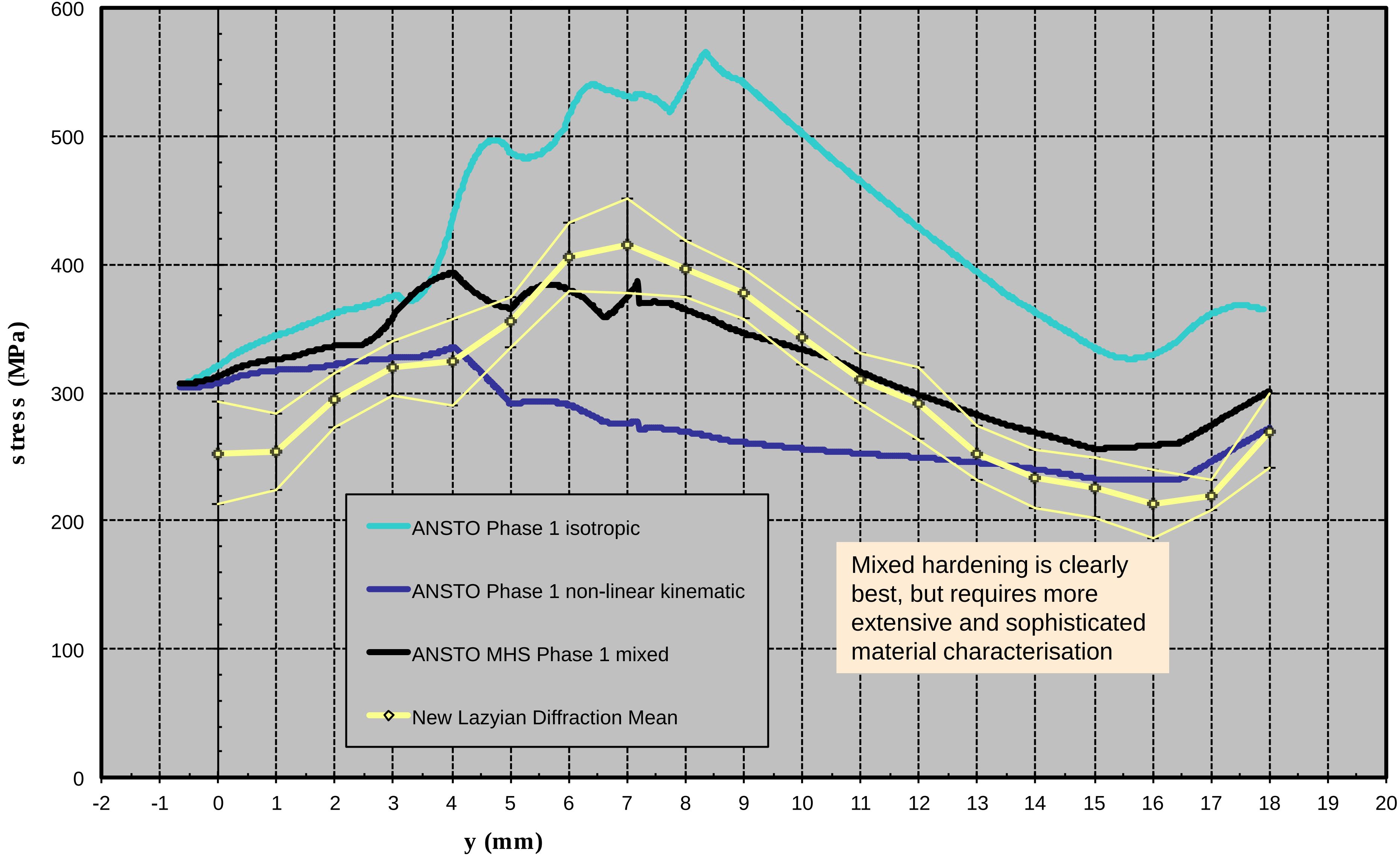
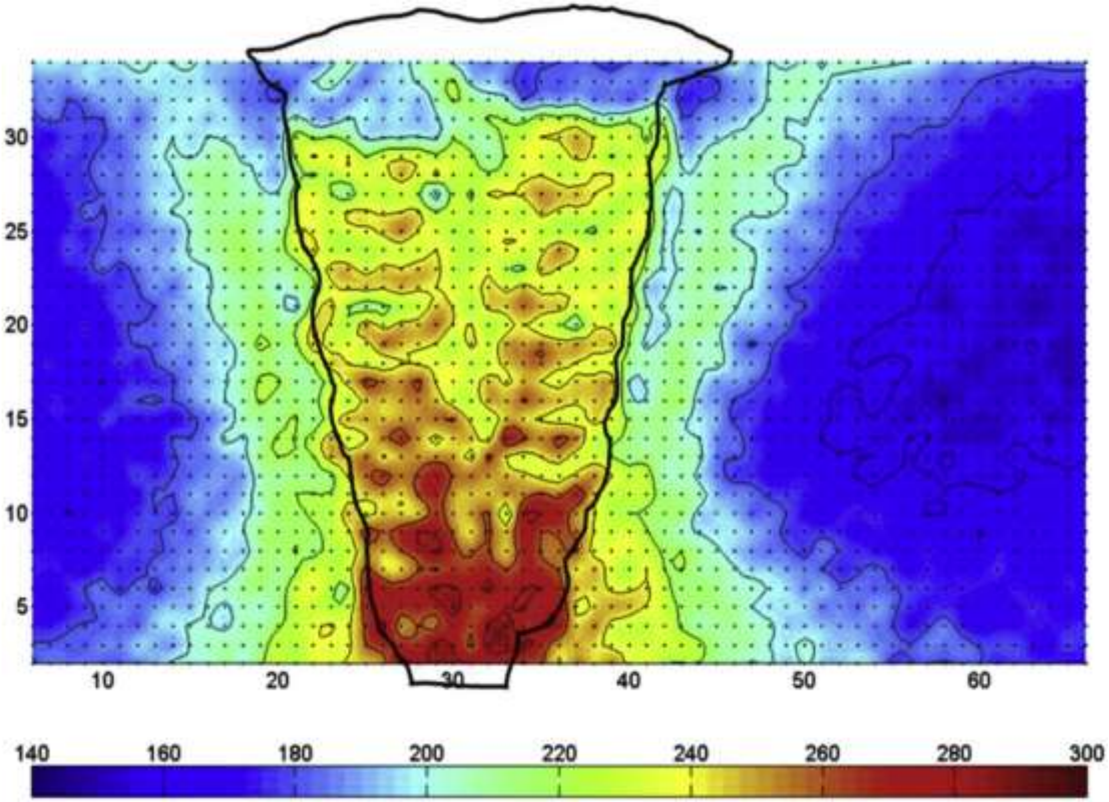
Effect of basic hardening model on longitudinal stresses



Mixed hardening is clearly best, but requires more extensive and sophisticated material characterisation

The problem of weld metal

- Austenitic weld metal shows similar cyclic hardening behaviour to parent material
- Austenitic welds show a hardness gradient from the root (hardest, longest plastic path, most cycles), to the last capping pass (softest, shortest plastic path, one cool-down cycle)
- But, when we test weld metal to develop its mechanical properties, we need to get the starting condition right to match the “as-solidified” condition of a weld bead.
- The weld metal used for small scale testing should be free of work-hardening.
- How do we achieve this?



Evaluating relevant mechanical properties for austenitic weld metal (Not all tested in NeT projects!)

Multi-pass weld pad

Single or two pass weld

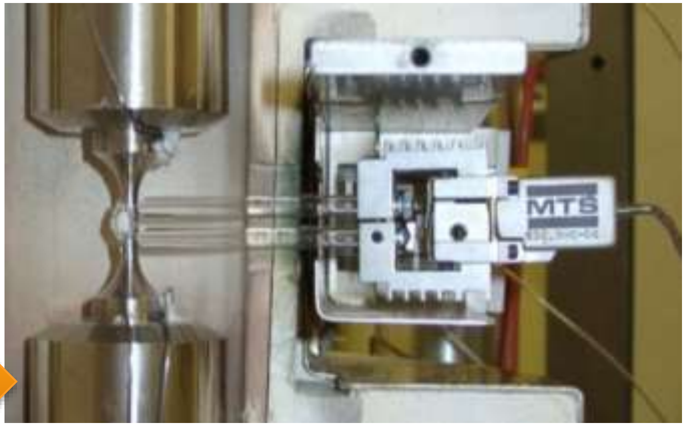
Multi-pass weld

As-welded condition

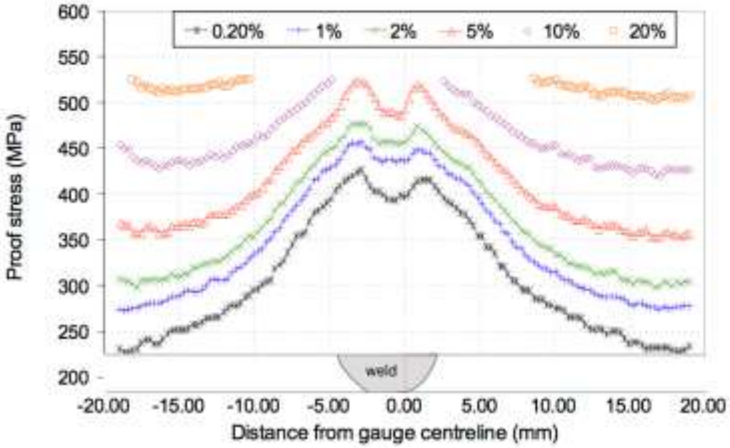
“spike-annealed”

Solution-treated

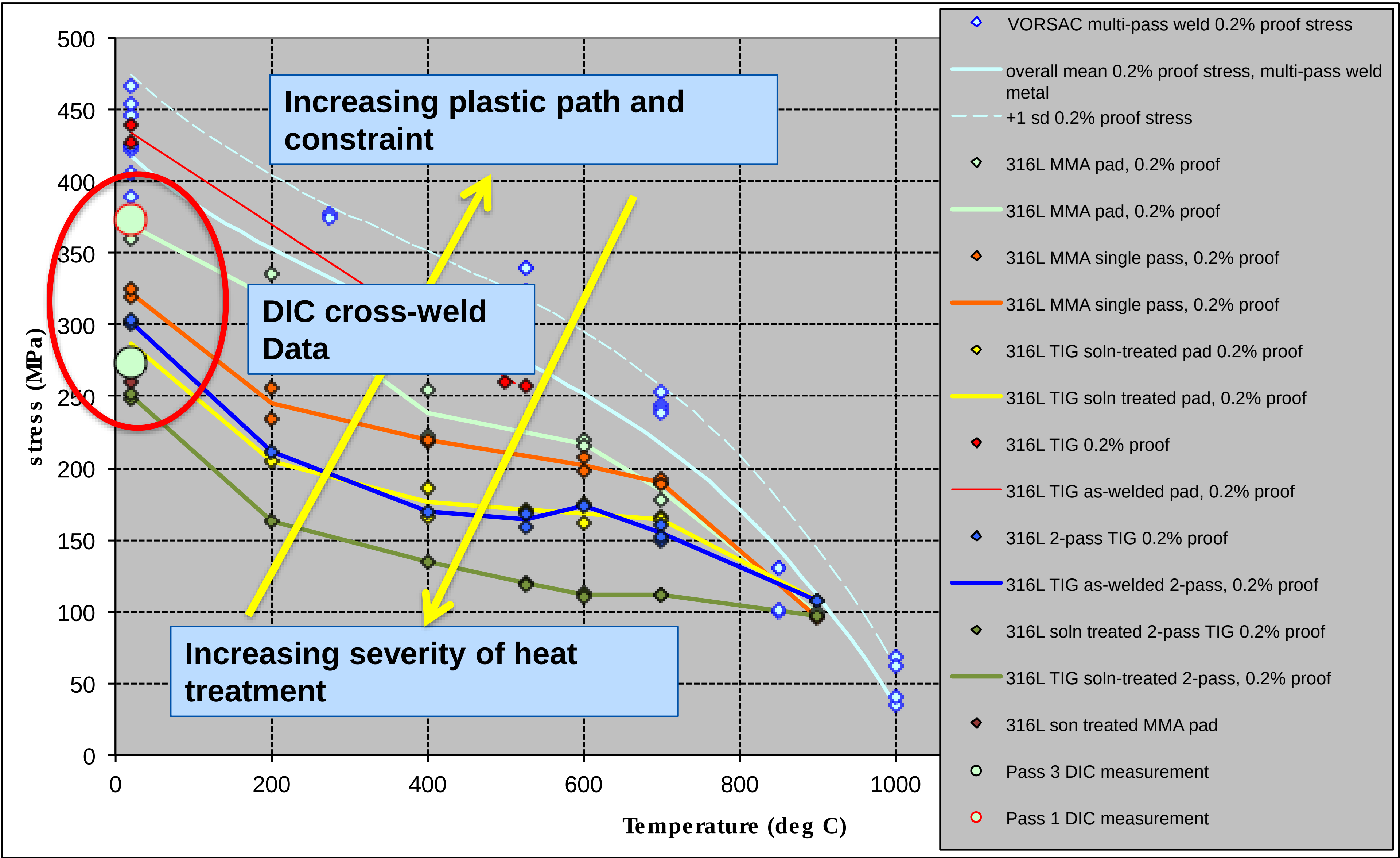
Conventional isothermal tensile and cyclic tests



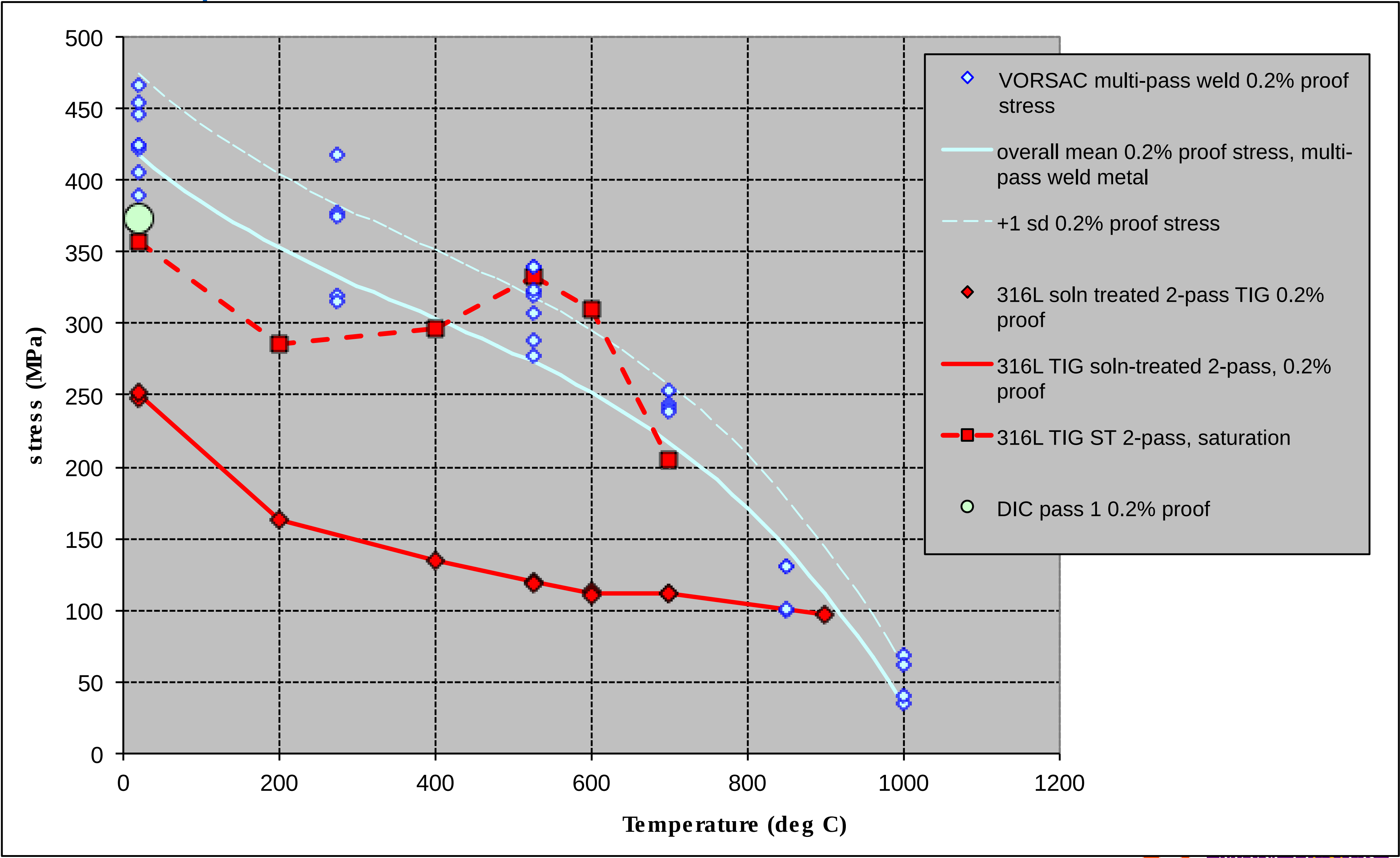
DIC or ESPI cross-weld testing



Effect of fabrication route on 0.2% proof stress of AISI 316L weld metal



Cyclic hardening behaviour of AISI 316L solution-treated two-pass TIG weld metal



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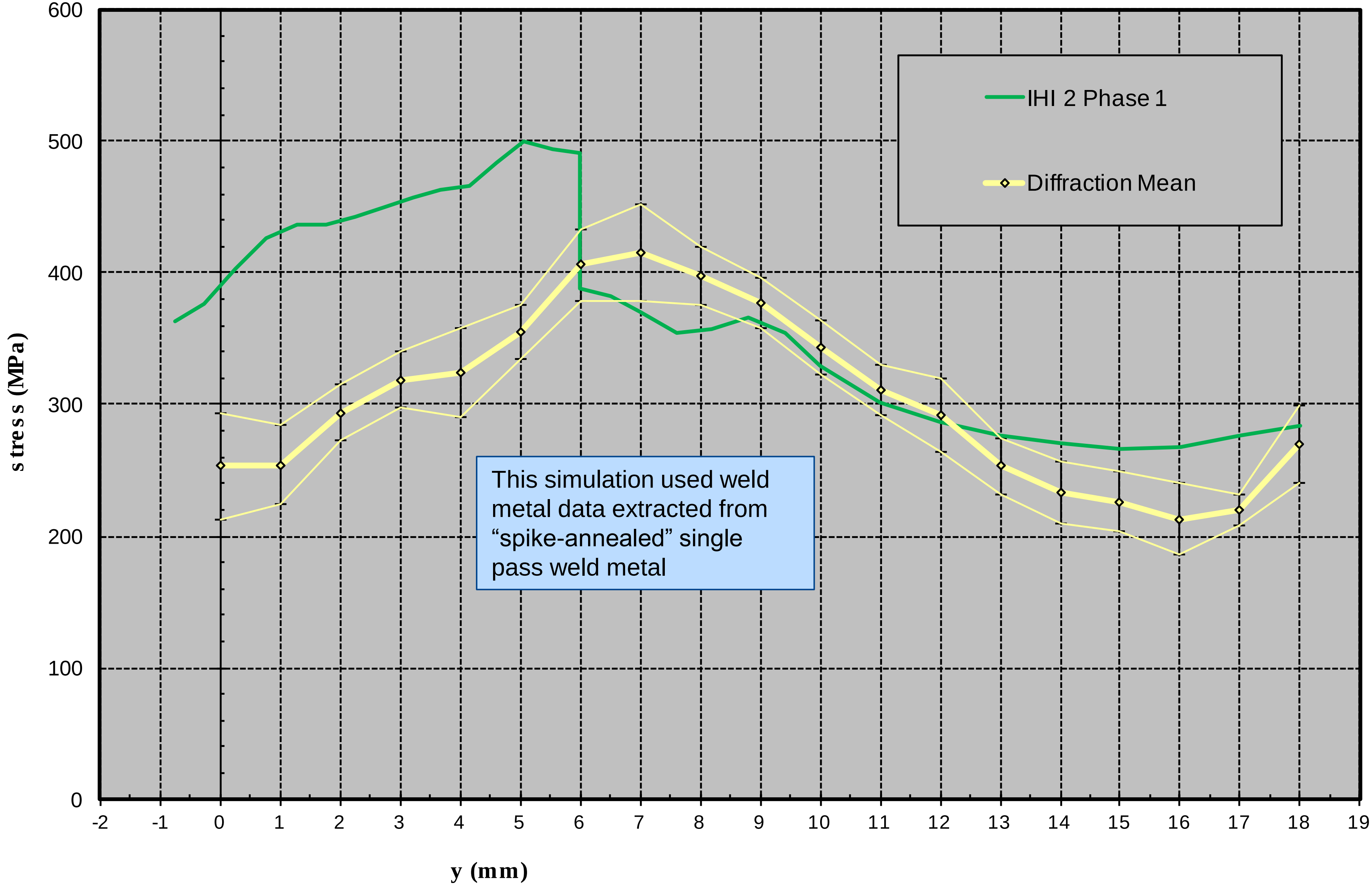
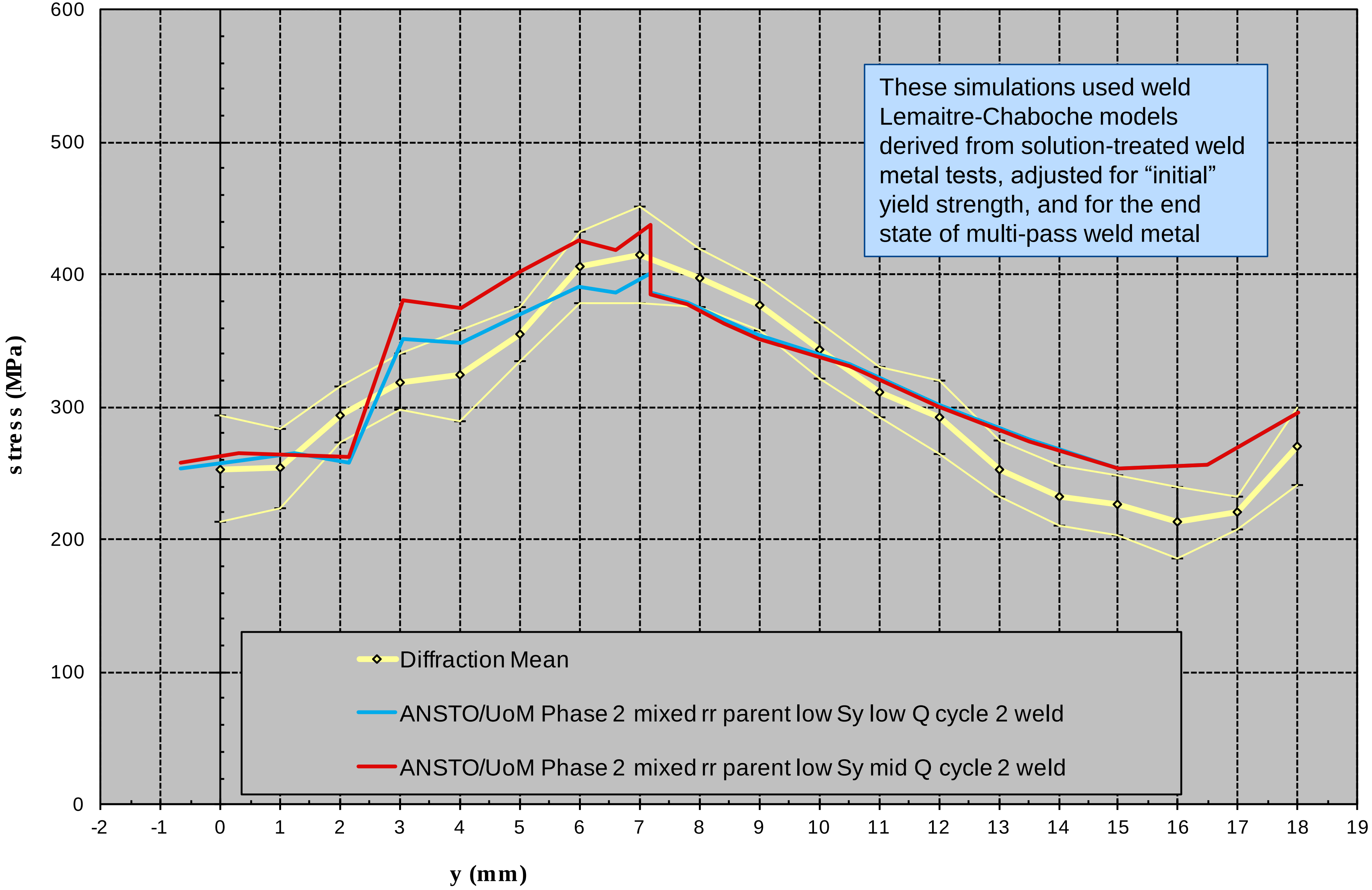
Effect of weld metal “starting point” (yield stress) on longitudinal stress



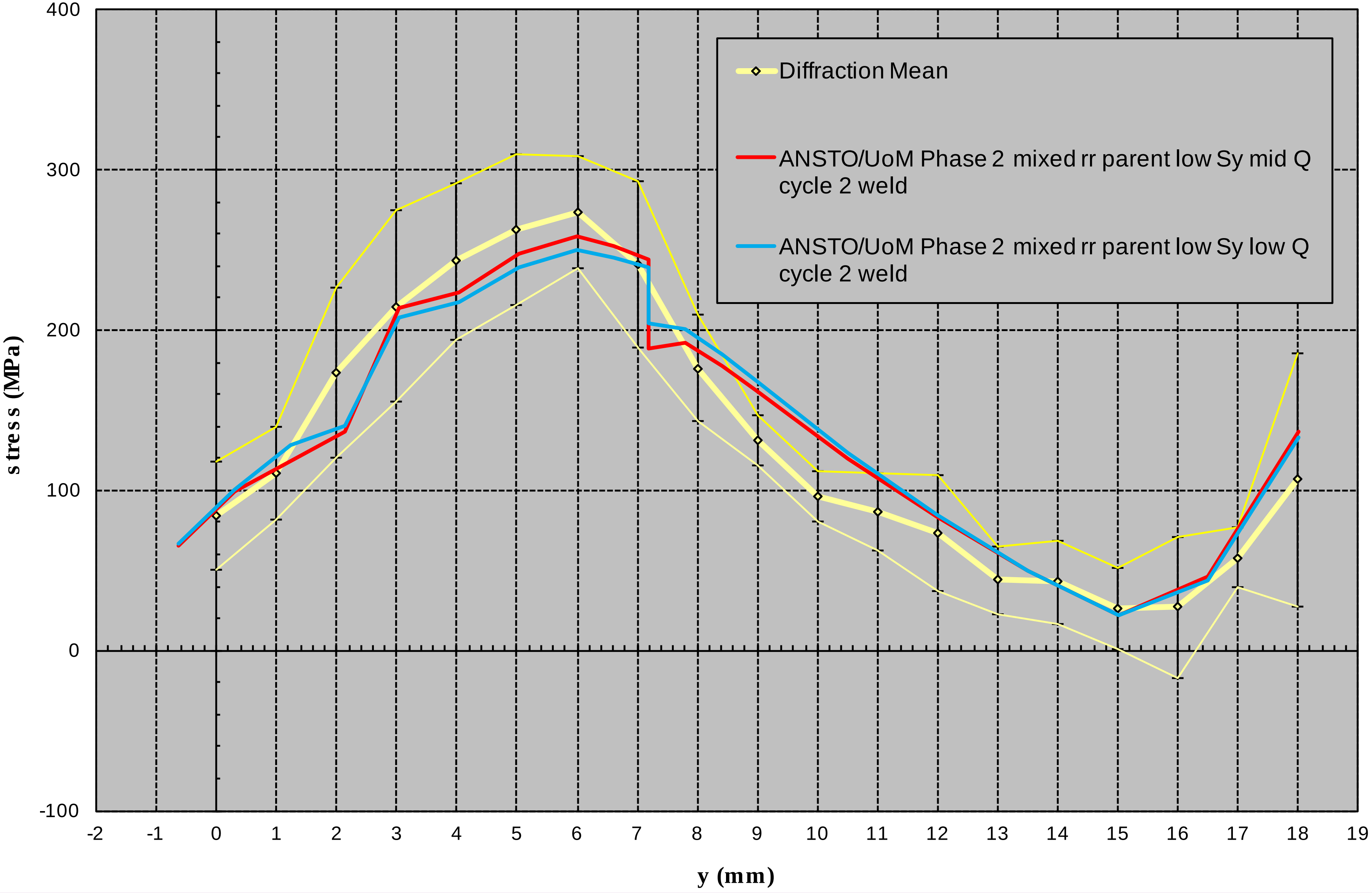
This simulation used weld metal data extracted from “spike-annealed” single pass weld metal

Effect of optimised mixed-hardening model parameters, longitudinal stress



These simulations used weld Lemaitre-Chaboche models derived from solution-treated weld metal tests, adjusted for “initial” yield strength, and for the end state of multi-pass weld metal

Effect of optimised mixed-hardening model parameters, transverse stress



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The Engineering state of the art: R6 weld modelling guidelines, 2009 onwards

- Developed in the UK to predict and manage reheat cracking in AISI 316Hand Esshete 1250 welds in AGR’s
    - Conventional arc welds (not narrow gap, no beam processes)
    - Residual stress and subsequent creep relaxation
    - No interest in weld process optimisation
    - No interest in distortion per se
    - No need to explicitly model microstructure development
- **Detailed step by step validation is a key part of the procedure**
    - **Is the thermal load sufficiently accurate?**
    - **Are the residual stresses reliable?**
- Have also been applied to DMW’s (alloy 82/182), NG welds, laser & EB welds
- Extension to steels with SSPT in progress

The R6 weld modelling procedure

1. Define analysis objectives
2. Collect input data
3. Consider resources available
4. Decide weld modeling approach
5. Create Finite Element model
6. Perform thermal analysis
7. Perform mechanical analysis
8. Validate analysis
9. Perform sensitivity studies

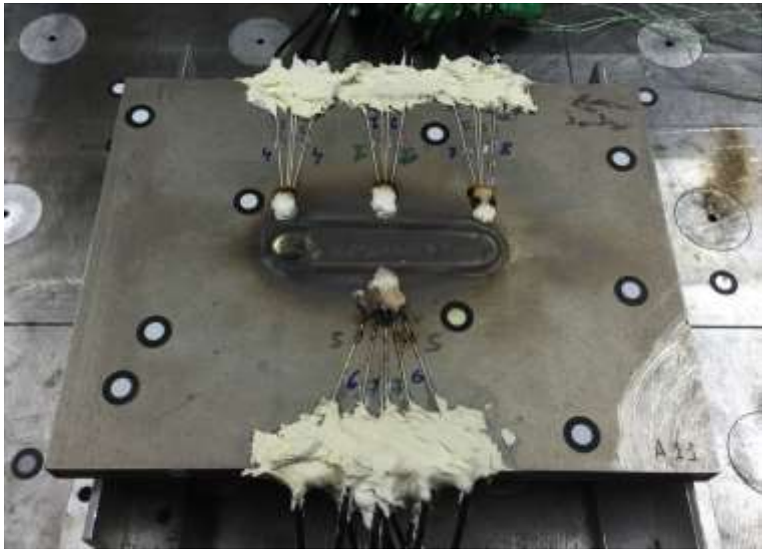
The state of the art in “simple” weld modelling of austenitic steels

- We can get the thermal solutions right
- Repeatable, reliable RS measurements still present a considerable challenge
  - The NeT approach is invaluable here
- It is possible to produce accurate weld residual stress predictions using well controlled simulation procedures, including:
  - Strict adherence to weld modeling guidelines
  - Formalised heat source modeling tools
  - Optimised mixed hardening constitutive models
  - Weld metal test data for a state that approximates a just-deposited bead
- It is still possible to get it wrong, and produce plausible rubbish
  - Trained and experienced analysts are essential
- Sensitivity studies and validation are not optional:
  - Sensitivity studies allow key variables to be identified and bounded
  - The R6 procedure does not allow the use of un-validated finite element predictions of weld residual stresses

Net TG1 and TG4 have provided key underpinning knowledge here

Looking forwards – other NeT projects

Net TG6 – 3-pass slot weld in Alloy 600/82



Extending modelling approaches for austenitic stainless steels to nickel alloys, with appropriate validation

NeT TG5 – Sa508 Gr 3 low alloy steel

Incorporating SSPT into weld residual stress prediction

(As the AGR's close, PWR materials and structures assume greater importance)