VVS2016-8820: A Summary of the Computational Methodologies and Validation Techniques Employed to Develop Updated Weld Residual Stress Guidance in API 579-1/ASME FFS-1 Fitness-For-Service

ASME Verification & Validation Symposium
May 16-20, 2016
Las Vegas, Nevada

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INTRODUCTION

• Recent progress in the simulation of weld residual stress (WRS) and in its verification and validation (V&V) has provided the opportunity to re-examine existing WRS guidance.

• This work represents a part of the Materials Properties Council (MPC) FFS Joint Industry Program (JIP) to re-evaluate the existing welding residual stress (WRS) guidance in the current API 579-1/ASME FFS-1 (API 579) Annex E.

• Key point of this presentation is to thoroughly document methods and models so that:
  – Detailed recommended WRS simulation procedures can be developed and incorporated into the upcoming release of API 579 (Annex 9.D), expected later this year
    • The goal is for consistent results to be obtained and to gain confidence in methodologies
  – Understanding and acceptance from the domestic and international technical community can be achieved

• Simulation methods have become mature, and best practices exist:
  – Open items (like plasticity modeling) are addressed and investigated
  – These methods and practices are introduced and explained in detail
  – The NeT (European Network on Neutron Techniques Standardization for Structural Integrity) is the primary source for the benchmark problems and data, though methods are well-established and extend beyond the NeT
VERIFICATION AND VALIDATION EFFORTS

• V&V techniques have received much attention in recent years as application of advanced numerical tools and methods have become more mainstream and widely available.

• This focus has extended to welding simulation; this plays a key role in ensuring the quality of weld simulation results.

• In this case, detailed V&V is applied to a few selected problems, such that the computational method itself is verified and validated, and the same level of detail need not be applied to every similar problem that utilizes it.

• However, a basic amount of V&V is still recommended for every problem (such as confirming analysis inputs and scrutinizing results).

• Detailed welding simulation methods, once substantiated, can ultimately be used to verify and validate analysis simplifications, which compliment simpler, more fundamental validations.
KEY ASPECTS OF WRS SIMULATION

- There has been much debate and work over the decades related to what really matters in numerical welding simulation.

- Key aspects of analysis:
  - Thermal modeling and heat input
  - Material hardening model (isotropic, kinematic, combined)
  - Annealing and introduction of weld material
  - Verification and Validation

- These issues and key concepts are addressed in this presentation.

- In particular, V&V techniques are discussed; appropriate validation efforts place confidence in analysis approach.
HEAT SOURCE MODEL

• The Goldak double-ellipsoid (triple Gaussian) model for the welding heat source is employed and is likely the most widely used concept for FEA of welding.
• This model is the basis for most FEA thermal weld simulation today, assuming the molten pool size is known as a boundary condition.
• Within a given ellipsoid, a heat flux or temperature assignment can be used.
  – The heat flux method is attractive because it directly incorporates the weld power (via a spatially varying power density function or power per unit volume).
  – Models like this are implemented in commercial FEA with user subroutines.

POWER INPUT – EXAMPLE OF SCATTER

• Inside radius = 390 mm
• Thickness = 15.9 mm
• The effect of power input is compared below for different WRS guidance documents.

<table>
<thead>
<tr>
<th>Axial WRS/Yield on Inside Pipe Surface</th>
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<tbody>
<tr>
<td>Power Input</td>
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<td>Low</td>
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<td>Bouchard</td>
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<table>
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<tr>
<th>Membrane Axial WRS/Yield</th>
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<tr>
<td>Power Input</td>
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MATERIAL HARDENING MODELS

• Current NeT work has isolated many experimental/physical variables so that this issue can be investigated like never before possible

• There are 3 basic types of commercially available hardening models, which define the elastic-plastic response of material past the yield stress:
  – **Isotropic** – just enter the monotonic stress-strain curve and go (the yield surface only expands)
  – **Nonlinear kinematic** – step change in complexity, but models real physical phenomena like ratcheting, mean stress relaxation and most importantly the Bauschinger effect (the yield surface only shifts – fixed elastic range)
  – **Mixed or combined** – the best of both worlds (yield surface expands and shifts)

![Diagram showing different hardening models](image)

*Fig. 1. (a) isotropic hardening model showing the expansion of the yield surface with plastic strain; (b) kinematic hardening model showing the translation of the yield surface with plastic strain; (c) mixed isotropic-kinematic hardening model showing the expansion and translation of the yield surface with plastic strain; and (d) resulting stress-strain curves showing different yield stress in compression as predicted by different plasticity models: C – kinematic hardening, D – mixed hardening, and E – isotropic hardening.*

NET TG1 (SINGLE-PASS WELD)

- R6 (Revision-4, SectionV.5) WRS validation example, a single weld bead-on-plate, has been chosen to re-establish confidence in analysis procedure and results
- R6 example is based on NeT Task Group 1 (TG1) benchmark problem

EXAMPLE OF NET TG1 RESULTS

Thermal Run

Stress Run with Temperature Cutoff

Equivalent Stress (psi)  Transverse Stress (psi)  Longitudinal Stress (psi)
NET TG1 FUSION BOUNDARY

• Complex weld fusion boundary captured in simulations:
  - 2 second initial torch dwell assumed to match observed boundary
  - Multiple heat sources with very involved heat flux parameters (size, path) varied as a function of time

• Maximum transient temperature tracked and stored (as variable “FV1”, units of °F) to visualize predicted weld fusion zone.
NET TG1 FUSION BOUNDARY

• Scale matched rigorously in comparisons to the right (FEA images not just scaled to improve fusion zone comparison).
• Very 3D and transient cross section.
• Since the weld is only 2 inches in length, this is significant.
• Intended to be representative of the challenging (and 3D) case of a repair weld.
• Note that the only cross-sections available seem to be from a plate with a narrower than nominal weld.
NET TG1 THERMAL RESULTS

- The A2 thermocouple (mid-length of weld, closest to deposit) shows variability of about 200°F between the four test plates.
- Additionally, the current FEA shows a peak 100°F lower than the lowest of the test values.
- Interestingly, this result (under-prediction of T2) is seen throughout the literature, and it was debated as to whether to even include it in R6.
- The general conclusion (from the literature) is that this TC is being heated by the arc and is not meaningful.
NET TG1 STRESS RESULTS

- Transverse stress 2 mm below plate surface along welding line (Line D2 is shown on this page and illustrated on the next slide)
NET TG1 STRESS RESULTS

- X = 0 is center of plate
- Z = 0 is top surface of plate
- Tremendous scatter in through-thickness results
- Distribution shapes captured
- Predictions of stress in welding direction are most conservative

Line D2 (results last slide)

Line BD (results this slide)

Transverse

Longitudinal

- Linear
- Transverse
- Longitudinal

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**ANNEALING STUDY**

- Annealing is investigated by using specialized pre-processing of the thermal results file to identify elements that contain integration point temperatures greater than or equal to the specified cutoff temperature.

  - These points are then saved to a set for each increment of torch advance, and dummy steps are written to take the elements out and bring them back in strain free over essentially zero time.
  - This resets the stiffness matrix and removes all strains (including elastic) and hardening.
  - Since only complete elements can be reset, 3 cases are run:
    - **Case 1:** All elements that contain ANY integration point over the cutoff are annealed
    - **Case 2:** All elements that contain ONLY integration points over the cutoff are annealed
    - **Case 3:** Neglects annealing of elastic strains
OVERALL TG1 SUMMARY

• Simulations shows good agreement with measured data thermally, and for all hardening models investigated:
  – This forms an important part of the formal verification and validation of the modeling methods.
• Through-thickness results suggest that the kinematic model that incorporates the stabilized cycle from the test data may be too conservative; however, this may not be a general conclusion since the TG1 starts in the completely annealed condition.
• Annealing of elastic strains may be neglected based on supplemental simulation results.
• Mesh refinement study shows there is certainly an effect of mesh density:
  – Consistent results are obtained across analyses (though using meshes that are both relatively refined)
  – Coarser meshes would need to be used with some amount of caution, but they could be acceptable
NET TG4 (THREE-PASS WELD)

- Three pass slot weld
- AISI 316LN stainless steel plate dimensions:
  - 194 mm x 150 mm x 18 mm
- Weld slot dimensions:
  - 80 mm long x 6 mm deep
- Stress relief after machining slot (but before welding):
  - Furnace heating from room temperature to 1050°C at 5°C/min
  - Held at 1050 (±5°) for 45 minutes
  - Furnace-cooled to 300°C and then air-cooled to room temperature

Figure 1: Schematic representation of the Net-TG4 specimen dimensions and slot configuration.
NET TG4 BACKGROUND

• Simulation and measurement protocol for TG4 has been received and reviewed by E²G (obtained through formal NeT participation).

• However, main source of existing computational results and experimental measurements:
  
  

• Experimental results in this presentation document the experiments conducted by Task Group 4 of the Neutron Techniques Standardization for Structural Integrity (NeT).
NET TG4 FUSION ZONE

• Complex weld fusion boundary captured:
  – Initial torch dwell assumed to match observed boundary
  – As with TG1, multiple heat sources with very involved heat flux parameters (size, path, etc.) varied as a function of time

• Maximum transient temperature tracked and stored to visualize predicted weld fusion zone.
THERMAL ANALYSIS RESULTS

- Thermal model tuned to reasonably match the fusion boundary observed in experiments
- Heat input parameters adjusted to achieve deeper weld penetration near the start and stop ends of the weld slot (as shown in available metallography)
- The third pass was also adjusted to extend the weld at each end of the slot as shown in longitudinal metallography
- Temperatures at thermocouple locations are also compared and are in reasonable agreement, considering the large spread in measured temperatures for some of the TCs (similar to results in TG1)

From Muransky et. al.
TG4 STRESS ANALYSIS

• Unlike the TG1, there is substantial filler metal added.
• This filler is defined at the cutoff temperature initially so that it shrinks as it cools.
• Weld elements about to become active (i.e., begin cooling below the cutoff temperature) have all strains completely reset.
• Note that weld elements are added in small groups so that conduction was not allowed into “un-birthed” weld regions.
• Total strain reset for re-melting is not used based on the TG1 supplemental analysis results.
• Also note that, for comparison sake, the ANSTO cutoff temperature of 2372°F was used with the ANSTO model – this was also the case in the TG1 analysis using the ANSTO/EDF material model.
• The E²G kinematic and isotropic hardening models again use the cutoff of 2100°F.
MEASUREMENT LOCATIONS

- From Muransky et. al.:
NET TG4 TRANSVERSE RESULTS

D plane

Isotropic Hardening

Kinematic Hardening

Mixed Hardening

(d) Experimental

(experimental results from Muransky et. al.)
NET TG4 TRANSVERSE RESULTS
NET TG4 STRESS RESULTS

• As shown, the ANSTO/EDF mixed hardening model gives extremely good WRS predictions compared to the measured data.
  – The pure kinematic hardening model fit to the stabilized cycles gives excellent and slightly conservative results.
  – The isotropic hardening model over-predicts stress in regions that cycle while under-predicting stress in regions that do not cycle.

• As in TG1, these results were not tuned in any way:
  – The only iterative part of the analysis is matching the measured fusion boundary, which is always treated as a boundary condition in FEA simulation of welding.
  – All material properties, boundary conditions, etc. are just as reported.

• Note that more measurement data is being gathered by the NeT, including measurements made with the contour method.
  – These measurements will be incorporated into the analysis as they become available.
  – To date, the available measurements (presented on the previous slides) also show very little variability.

• In general, the material models behave as would be expected, even under very complex loading (as is the case with welding).
TWO-PASS GIRTH WELD (2D VS. 3D SIMULATION)

- A type 304 stainless steel pipe girth (circumferential) weld (GTAW, 308L filler metal) presented by Deng and Murakawa is performed in two passes.
- Results are compared to experimental data and 3D analysis is compared to simplified, 2D simulations.

Heat input can be validated by plotting welding power from FEA vs. intended welding power for every step in the analysis.
GIRTH WELD SIMULATION RESULTS

- Results indicate that girth welds may be modeled as 2D without significant loss of accuracy (temperature assignment seems reasonable as well).

A summary of significant recommended scope or interpretation changes is as follows:

- Distinction is now made in some cases between stainless and ferritic weldments
- PWHT and hydrotest effects are not listed for each joint, but are treated under a single general category of “residual stress distribution modifying factors”
  - This includes the same uniform residual stresses for all joint types
  - Additionally, the previous hydrotest effect guidance has been removed
- The residual stress distribution reference point is no longer fixed in space, but depends on the joint configuration:
  - Through-wall equations are referenced from the side opposite of the widest weld groove width, or from the side opposite of the last weld pass (typically the inside surface)
  - The only exceptions to this are piping branch connection and plate tee welds, which are referenced from the weld toe (outside surface)
- All joint specific guidance is changed (based on literature survey and simulations
- A specific simulation option is added
SUMMARY AND CONCLUSIONS

• Current analyses show extremely good agreement with measured data on single and multi-pass welds:
  – Best overall match to data is the ANSTO/EDF mixed hardening model (E²G results also match ANSTO results very closely).
  – Hardening models typically affect stress results in a systematic and predictable way.
  – Even in this extreme NeT material case (dead soft starting state, dramatic hardening with initial cycles), the pure kinematic model fit to the final stabilized cycle of the test data gives excellent results, and this model is recommended for design purposes, due to it’s simplicity and availability.

• Based on TG1 and TG4 analyses as well as the girth weld example problem, substantial confidence should be placed in the methods and models described herein and the updated WRS guidance in Annex 9.D of the 2016 release of API 579.

• Analysis simplifications (2D analysis, more basic material models, neglecting annealing of elastic strains, even temperature assignment) may be appropriate in certain cases.
TECHNICAL BASIS

• All underlying analyses, background information, and V&V techniques used to update the weld residual stress guidance included in Annex 9.D of the upcoming release of API 579 are documented in a recent book.

• The book, titled Development of Revised Weld Residual Stress Guidance for Fitness-For-Service Assessment in API 579-1/ASME FFS-1 is available through the Welding Research Council.

• A summary of the updated through-wall WRS distributions that are included in the upcoming edition of API 579 for different welded joint geometries is also provided.