June 21, 2011

MEMORANDUM TO: Aladar A. Csontos, Chief
Component Integrity Branch
Division of Engineering
Office of Nuclear Regulatory Research

FROM: Howard J. Rathbun, Mechanical Engineer ***/RA/***
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SUBJECT: SUMMARY OF PUBLIC MEETING BETWEEN THE NUCLEAR REGULATORY COMMISSION STAFF AND REPRESENTATIVES OF THE NUCLEAR POWER INDUSTRY REGARDING WELD RESIDUAL STRESS FINITE ELEMENT ANALYSIS VALIDATION

On June 14-15, 2011, Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) staff hosted a public meeting with representatives from RES, the Office of Nuclear Reactor Regulation (NRR), and the nuclear power industry regarding the Weld Residual Stress (WRS) Finite Element Analysis (FEA) Validation research program. Twenty-three representatives participated from RES, NRR, RES contractors, and industry organizations including EPRI, EDF (France), AREVA, Westinghouse, Structural Integrity Associates, Exelon, and Dominion Engineering. The meeting focused on finite element modeling techniques for dissimilar metal welds, including geometry aspects, thermal / mechanical material properties, thermal models, welding parameters and structural modeling. The meeting yielded many insights into the significant contributions to WRS results calculated by FEA. NRC and industry representatives presented their comparisons of WRS models and sensitivity studies to measurements taken on various mockups and actual plant components. Remaining actions in the WRS FEA Validation program for RES staff include documentation via Technical Letter and NUREG reports that provide program results and review recommendations for NRR. The WRS FEA Validation program is being conducted cooperatively with EPRI through an NRC/EPRI Memorandum of Understanding Addendum. NRC and EPRI will independently document their analyses through separate reporting efforts; EPRI will also provide WRS FEA modeling guidance to the industry.

Summary of FEA WRS Round Robin Programs

Day one of the meeting summarized results from the Phase I (plates and cylinders), II (pressurizer surge nozzle), III (pressurizer safety/relief nozzles), and IV (cold leg nozzle) FEA WRS programs. The Phase II round robin program has the largest number of participants and studies conducted, representing a valuable dataset for WRS FEA uncertainty quantification. All FEA program results were quantitatively compared to experimental residual stress measurements. Day two of the meeting focused the specific technical aspects summarized below.

Finite Element Software Package Sensitivity Studies

The differences in ANSYS and ABAQUS WRS FEA results using identical input data has been evaluated. Results of this study include:

- Using single material property inputs leads to nearly identical WRS results.
- With multiple material property inputs, WRS results differ with the greatest variation occurring in the hoop direction after the application of the stainless steel weld. However, these differences are small relative to other modeling comparisons and are much less than the scatter observed in the FEA round robin programs.

Geometry Aspects

- For the finite element models analyzed in the current study, the weld bead geometry is defined based on the final bead configuration. This is an approximation, since in a real structure the geometry is changing throughout the weld process. Models with large shrinkage or a changing weld cavity may have variability based on the geometric assumptions; however, this is generally not a factor for thick section welds (i.e. greater than approx. 1-inch thick).
- Thermal model total heat input is sensitive to bead lumping/layering assumptions, potentially effecting WRS profiles.
- Bead sequencing sensitivity studies did not produce a significant effect on WRS profiles for the Phase II mockup geometry.

Thermal / mechanical material properties

- Isotropic hardening appears to produce the largest stress magnitudes in absolute value while nonlinear kinematic hardening produces the lowest values. Though the stresses are larger, this may not be conservative for crack growth analyses.
- Changes in plastic material properties can have a significant effect on the WRS profiles.
- Elimination of annealing can produce higher ID axial stress.
- The NRC material properties issued with the Phase II modeling package are largely consistent with the British Energy properties published at PVP2010 and similar WRS profiles are calculated with both sets of material properties.

Thermal models and welding parameters

- The Phase III WRS profiles are stable over a range of heat inputs - reducing the input heat by up to 40% does not significantly impact stress results; however, there are limits:
    - The Phase III weld macrograph is sufficient to constrain heat input and provides a stable stress solution.
    - This result differs from Phase II where bead geometry (and welding parameters) was insufficient to constrain heat input for all results.
- During fabrication, Edison Welding Institute welders used a narrow range of power inputs to fabricate high-quality welds.
- EPRI has plans to generate a table of weld bead size versus welding parameters, in order to constrain the bead size and heat input assumed in a FEA. Based on the thermal sensitivity studies conducted, this should provide sufficient constraint to FEA thermal models.

Structural modeling

- The stress versus time for an ANSYS bead element behaves similarly to an ABAQUS bead element with annealing, 'ekill' followed by 'ealive' below annealing temperature in ANSYS allows for similar response as annealing based initialization.
- Lack of annealing produces little stress change in results when kinematic hardening or elastic-perfectly plastic hardening rules are used.
- The definitions of reference temperature and initial temperature can lead to different results for ANSYS and ABAQUS calculations. In ABAQUS, if the initial temperature is different than the reference temperature, then the initial thermal strain is zero. However, in ANSYS, if the initial temperature and reference temperature are different, then a thermal strain corresponding to the temperature difference is calculated.

List of Attendees

Name	Affiliation
Lee Fredette	Battelle Memorial Institute
Doug Killian	AREVA
Eric Willis	Electric Power Research Institute
Frederic Hasnaoui	EDF (France)
Paul Crooker	Electric Power Research Institute
John Broussard	Dominion Engineering, Inc.
Guy DeBoo	Exelon
Matthew Kerr	NRC
David Eastman	NRC
John Tsao	NRC
Ali Rezai	NRC
Jay Collins	NRC
Francis Ku	Structural Integrity Associates
Michael Benson	NRC
Robert Hardies	NRC
Aladar Csontos	NRC
Stephen Marlette	Westinghouse
Bud Brust	Engineering Mechanics Corporation of Columbus
Shah Malik	NRC
Warren Bamford	Westinghouse
Rob Tregoning	NRC
David Rudland	NRC
Howard Rathbun	NRC

Enclosures:
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Presentations (25)
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