VALIDATION APPROACHES FOR COMPUTATIONAL WELD RESIDUAL STRESS MODELING
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ABSTRACT
In pressurized-water reactors, weld residual stress can drive primary water stress corrosion cracking (PWSCC). Weld process models, based on non-linear finite element techniques, can provide estimates of weld residual stress that are useful in assessing risk of PWSCC, and designing plant maintenance programs (e.g., scheduling of inspection and repair). A weld model validation approach, comprising comparison of weld model output against an established benchmark, would enable an assessment of model output precision and bias; however, the nuclear industry lacks a consensus weld model validation approach. The paper provides technical detail for a range of example data analysis approaches that provide potential validation metrics for assessment of model output relative to a benchmark, where relevant benchmarks are derived from either model or measurement data. The potential validation metrics range from simple (e.g., root mean square difference) to complex (e.g., predicted crack growth behavior). We further apply the data analysis approaches to two sets of weld model outputs, each developed in the context of an industry round robin exercise organized by the U.S. Nuclear Regulatory Commission and the Electric Power Research Institute. The analysis results provide data for consideration within the larger technical community, to support development of a consensus approach to weld residual stress model validation.

Keywords: weld residual stress, model validation, stress corrosion cracking, stress intensity factor

1.0 INTRODUCTION
In pressurized water reactors (PWRs), dissimilar metal (DM) welds join low alloy steel and stainless steel (SS) components, and DM welds made with nickel-based alloy filler metals can exhibit stress corrosion cracking in typical operating environments (i.e., in the presence of primary water at elevated temperature) [1-3]. To manage safely the structural integrity of affected PWRs, weld residual stress (WRS) data are used to predict the growth of postulated cracks, and the crack growth data are used to inform plant management decisions.

Weld process models, based on non-linear finite element analyses, provide weld residual stress (WRS) outputs that can be used in crack growth estimates. In an effort to understand the quality of WRS model outputs, with respect to their ability to support sound plant management against the risk of primary water stress corrosion cracking in DM welds, the U.S. Nuclear Regulatory Commission (NRC) and the Electric Power Research Institute (EPRI) have been engaged in a program of cooperative research on WRS. This program has consisted of four phases [4-7] as follows:

- Phase 1: scientific weld specimens (simple plates and cylinders),
- Phase 2: fabricated prototypic nozzle (international round robin mockup),
- Phase 3: cancelled plant pressurizer safety/relief nozzles,
- Phase 4: optimized weld overlay on a cold leg nozzle.

Each program phase progressively increased in complexity with the intention for later phases to address conditions that are more relevant to service.
The present work stems from Phase 2 of this cooperative research program. Phase 2 consisted of two studies: the first, known as Phase 2a, was completed in 2010 [4, 7], and the second, known as Phase 2b, was completed in 2014 [8, 9]. The objective of the two studies was to assess WRS in a prototypic PWR pressurizer nozzle mockups with a DM weld. One mockup was prepared for each study (Phase 2a and Phase 2b) under controlled conditions, with the fabrication process documented in detail, so that a large amount of input information was available to support WRS model development. Figure 1 shows the geometry of the Phase 2b nozzle mockup. Apart from some differences in overall geometry and welding details (e.g., Phase 2a had an automated weld and Phase 2b had a manual weld), the mockups were largely similar and composed of similar materials (one side low alloy steel, the other stainless steel, and a nickel DM weld).

Based upon the mockup fabrication records, NRC and EPRI jointly developed modeling problem statements for the Phase 2a [10] and Phase 2b [11] studies, and open invitations were issued to the international WRS modeling community to develop a round robin set of WRS model outputs. Model outputs were submitted by thirteen organizations for Phase 2a, and by eleven organizations for Phase 2b.

WRS measurements were performed on the Phase 2 mockups to provide data for comparison with WRS model outputs. While some neutron and x-ray diffraction residual stress measurements were performed in various parts of the NRC/EPRI WRS program, the large sizes of the Phase 2 mockups, and metallurgical details of their DM welds, made mechanical strain relief techniques more suitable for the Phase 2 studies. WRS measurement data were developed using incremental deep hole drilling (DHD) [12] the contour method [13, 14], slitting [15], and a novel biaxial residual stress mapping technique [16]. Both of the Phase 2 studies were double blind, meaning modellers and measurement practitioners were not allowed to access each other’s results prior to submitting them to the Phase 2 program manager (with one exception: the biaxial mapping data were developed after the Phase 2 modeling data were made public).

Phase 2a model outputs demonstrated the potential for modeller-dependent bias in WRS [5, 7, 17], as is clear from Figure 2, a plot of WRS model output versus radial position at the center of the DM weld. In Phase 2b, there was an attempt to reduce modeller-dependent bias by improving the problem statement and specifying model material parameters (including complete specification of the temperature dependent flow curves and hardening models to be used for the base and weld metals [11]). The summary of Phase 2b model outputs in Figure 3 shows that modeller-dependent bias remains, even if reduced, when having a more specific problem statement.

Currently, there is no established, consensus WRS model validation approach that might be used to judge the quality of WRS model output, and the Phase 2 studies provide a wealth of data that are useful in testing potential procedures for assessing WRS model outputs. A key goal of a consensus WRS model validation approach is to provide system manufacturers, operators, and regulators a basis for consistently judging model output quality, relative to the intended use of the WRS model output in supporting pressure system flaw evaluation. Therefore, a consensus WRS model validation approach would benefit a broad range of stakeholders in pressure vessel technology.

There is available guidance to support development of a consensus WRS model validation approach. Earlier documents describe weld modeling practice [5], general methods for validation of computational solid mechanics [18], a framework (without supporting detail) for weld model validation [19], as well as a framework for including WRS in flaw assessments [6].

Because WRS is a complicated quantity, comprising the variation in spatial coordinates (at all points) of a second-order tensor field, there is a need to develop from WRS information validation metrics that enable high-level observations. Useful validation metrics would facilitate the comparison of outputs from related WRS models. Central to model validation is the comparison between model output and established benchmarks, where useful benchmarks may be prior model outputs thought to have good fidelity or experimental data of good quality. For example, benchmarks being developed currently within the R6
assessment procedure [20] reflect exemplar scenarios, with a range of complexity, and include WRS model outputs, along with experimental data developed from diverse experimental techniques. The work here summarizes four potential validation metrics described earlier [17] and uses these metrics to assesses WRS data from the two Phase 2 studies. The potential validation metrics range from simple (e.g., difference between stress states) to complicated (e.g., prediction of crack growth behavior). The large amounts of WRS data from Phase 2 offer a unique opportunity to judge the suitability of the potential validation metrics.

2.0 VALIDATION METHODS

This section describes the approaches taken to explore validation concepts for weld residual stress models.

2.1 Benchmarks

Validation is defined by ASME V&V 10-2006 [18] as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model. Working from this definition, validation involves comparison of model output with a benchmark, and the benchmark should reflect the real world. A useful benchmark might be drawn from measurement data, phenomenological correlation, expert panel opinion, or exemplar model outputs.

Data from the Phase 2 studies are summarized in Figure 2 and Figure 3, where we plot the distributions of hoop and axial stress at the DM weld centerline versus position through-wall. (Modellers submitted model outputs corresponding to two steps in mockup fabrication, the first step after the DM weld and before the SS safe-end to piping weld, and the second step after both welds. Here we consider only the stresses after the SS weld, because that most closely reflects the operating condition.) For Phase 2a, the thin solid lines reflect each of the 14 model outputs submitted [17]. These outputs were developed with different material hardening models, which is known to produce significant systematic differences in WRS model output. The modellers identified the hardening models they used, most choosing either isotropic or kinematic hardening. For Phase 2a, ALL will be used to refer to all of the results, considering isotropic and kinematic results together. For Phase 2b, the thin solid lines reflect 9 of the 10 model outputs [9]; the one submission not included used the geometry from Phase 2a, and so that submission was removed from further consideration. The thin solid lines for Phase 2b, in Figure 3, reflect for each modeller the average of two different model outputs, one produced using the isotropic hardening model and the other produced using the kinematic hardening model. We use AVG to refer to those results. In both Figure 2 and Figure 3, the thick solid blue line is the average of all the model outputs. Experimental data are also shown in the figures, with results from DHD and contour for Phase 2a, and results from DHD, contour, and slitting for Phase 2b, and in each figure the mean of the measurement data is shown with a thick solid red line.

2.2 Summary of Validation Metrics

To determine the degree to which a model is an accurate representation of reality, a number of comparisons might be made between WRS from model outputs and a benchmark. Here, we use the mean of the measurement data as the benchmark, and present a set of data analyses that range from simple to complex comparisons of the model outputs with the benchmark. The degree of agreement between a model and a benchmark depends on the analysis by which agreement is assessed, so the range of analysis methods provides useful insight.

The WRS data analysis methods have been compared using four potential validation metrics derived from data analysis:

(1) RMS differences in stress,
(2) Stresses due to section forces,
(3) Stress intensity factors, and
(4) Crack growth history

A summary of these methods is given below.

**RMS differences in stress**

A simple method that can be used to assess the dispersion in WRS data is the RMS difference between a given model output and the benchmark. The room temperature yield strength of Alloy 182 weld metal (380 MPa [21]) is chosen as a relevant level of material resistance to normalize the RMS difference.

**Stresses due to section forces**

The tendency for WRS to cause mechanical deformation can be quantified by section forces computed from the WRS fields. The section forces considered here are computed from data on the DM weld centerline. The integral effect of the axial stress, which acts perpendicular to the radial-circumferential plane, and the hoop stress, which acts perpendicular to the radial-axial plane, are quantified by computing uniform (constant) and bending (linear) section forces. Stress due to the uniform section force (force divided by area) and the bending section force at the inner diameter (moment divided by section modulus) are then computed, and normalized by the yield strength of Alloy 182.

**Stress intensity factors (K values)**

Flaw assessment at welds, used to quantify the rate of potential crack growth, requires calculation of the stress intensity factor (K value) due to WRS and applied loads. The applied loads include membrane stress, bending stress, and pressure (internal pressure and/or crack face pressure).

K calculations in this paper are based on the weight function method, idealizing the nozzle as a pipe with geometry \( r_1/r_o = 0.8 \), and using closed form weight functions from earlier work by Wu and Carlsson [22] and by Glinka [23]. There are typically three types of inner-diameter flaws considered in the analysis: a complete internal circumferential flaw, an internal circumferential semi-elliptical flaw, and an internal axial semi-elliptical flaw. Because the K for a complete circumferential flaw can be similar to that at the deepest point of a circumferential semi-elliptical flaw, as found in our earlier work [17], only two flaw types are presented here, a complete circumferential flaw and a semi-elliptical axial flaw. For the semi-elliptical axial flaw, we limit our analysis to the stress intensity factor at the deepest point and consider a flaw shape with a constant aspect ratio \( c/a = 2 \), where \( c \) is half the crack surface length and \( a \) is the crack depth. It is noted that the K values reported for the semi-elliptical axial flaw case assume the residual hoop stress profile at the center of the DM weld is present at all axial positions along the crack face. This commonly used approach is consistent with the elevated hoop stress distribution generally found on the weld cross section.

Because the circumferential flaw is driven by axial stress and the axial flaw is driven by hoop stress, analysis of those two flaw types is considered sufficient for validation. It should be pointed out that assuming a constant aspect ratio is not typical of field assessments, but is useful here as a simplified basis for judging the quality of WRS model outputs.

**Crack growth history**

Given K values, SCC crack growth history can be computed, and provides a metric that can be judged relative to plant operational experience. The crack growth rate is determined from the stress intensity factor using a power-law relation, as described earlier [1], and the crack growth rate is integrated numerically to determine crack growth history (crack growth as a function of time). In the analysis, the initial flaw is assumed to be of size \( a/t = 0.1 \), where \( a \) is the crack depth and \( t \) is the thickness. Crack growth rate is determined at a set of crack size increments \( \Delta a/t = 0.001 \), to a maximum size \( a_{max}/t = 0.6 \) or
0.8, depending on the validity limit of the respective weight function. A representative operating
temperature of 343 °C (650 °F) [24, 25] was used in the crack growth calculations. It should be noted that
in practice a flaw would not be permitted to remain in service beyond 0.75t.

3.0 VALIDATION METRIC RESULTS

Results are presented here for the four potential validation metrics described above using the data from
the Phase 2 studies. Due to differences in the studies for Phase 2a, which was performed earlier, and
Phase 2b, some minor differences in approach are taken in the two evaluations:

- The Phase 2a modeling round robin did not specify which hardening model to use; therefore, each
  individual hardening result is treated as a potential solution. In contrast, Phase 2b specified that all
  modelers perform the analysis twice, once with isotropic and once with kinematic hardening, with the
  intent of averaging the two sets of results.
- In Phase 2a, each of the model submissions is indicated with an internal tracking code that identifies
  the modeler and the type of hardening model (C-ISO, D-KIN, etc.); some Phase 2a modelers
  submitted results from more than one hardening model. For Phase 2b, we also use internal tracking
  codes (A5, B1, etc.) to identify each submission. However, the tracking codes for Phase 2a and Phase
  2b do not correspond to each other, having been randomly assigned; several modelers participated in
  both Phase 2a and Phase 2b.

3.1 RMS differences in stress

Phase 2a study

The RMS difference between each model output and the benchmark, which is the mean of all
measurements, are shown in Figure 4a for axial and hoop stress (after the SS weld). For all experimental
data, the difference in axial stress is larger than that in hoop stress. And for some model outputs, the
difference in hoop stress is double the difference in axial stress.

Phase 2b study

The RMS difference between each model output (using the average of the isotropic and kinematic
hardening cases) and the benchmark is shown in Figure 4b. The RMS difference for axial stress is smaller
than that for hoop stress in almost all cases. On average, the RMS difference between model outputs and
the benchmark is larger than the RMS difference between the measurements and the benchmark. In
Figure 4b, model J1 has the highest RMS difference in both hoop and axial WRS; model E1 has a large
RMS difference in hoop WRS but is similar to other model outputs for axial WRS.

3.2 Stresses due to section forces

Phase 2a study

The normalized stress due to the net section axial and hoop forces are compared in Figure 5a, where the
blue and red dashed lines represent the normalized stress computed from the benchmark due to axial and
hoop section forces, respectively. Stresses due to axial forces are very small for all models and
measurements. This indicates that the pipe cross sectional area at the center of the DM weld is in axial
equilibrium, which agrees with the physics of the problem. However, there is a high level of stress from
hoop force in the model outputs and the measurements, which is consistent with evaluation of this section
force in a narrow strip at the center of the weld (if the analysis had evaluated the force over the entire
length of the mockup, this section force would be zero). The stress due to hoop force is generally higher
for models that used isotropic hardening (noted by “ISO” on the horizontal axis of Figure 5a) than for
models that used kinematic hardening (noted by “KIN”). This is consistent with other observed behavior
of isotropic hardening versus kinematic hardening.
The normalized stress at the weld inner diameter (ID) due to bending section forces from axial and hoop WRS for the WRS data are compared in Figure 6a. Stress from the bending section force from axial WRS is significantly higher than that from hoop WRS. One analysis shows a normalized bending moment from axial stress exceeding the nominal yield strength of the material. It is worth noting that stress from the bending section forces from axial and hoop WRS both have a significant contribution from the SS weld that is adjacent to the DM weld, where the contribution is compressive at the ID.

Phase 2b study

Normalized stress for the uniform section forces, computed from axial or hoop WRS, are shown for the model outputs in Figure 5b, where the blue and red dashed lines represent the normalized stress due to axial and hoop section forces, respectively, computed from the measurement mean benchmark. Stress due to the axial uniform section force should be zero to meet the requirement of mechanical equilibrium in the axisymmetric models and it is small for all model outputs and for the measurements. Stress due to the hoop uniform section force varies significantly among the model outputs, with two outputs having negative stress and the rest having positive stress. Model J1 has the largest stress from hoop WRS, and model E1 has a negative stress, in contrast to all other models (except A5, which has near zero stress).

The normalized stress at the weld ID due to the bending section forces from axial or hoop WRS are shown for the individual model outputs in Figure 6b, where the dashed lines again represent the benchmark values. The bending stress from axial WRS is significantly higher than that from hoop WRS. Model J1 shows small positive bending stress from both WRS components compared to negative bending stresses for other models and for measurements.

3.3 Stress intensity factors (K values)

Phase 2a study

Figure 7a shows in solid lines the total stress intensity factor results, where the total K is the sum of contributions from WRS and applied loads, for the complete internal circumferential flaw with geometry $r_i/r_o = 0.8$. The figure also shows K from applied loads alone, as a black dashed line, which consists of contributions from membrane stress, bending stress, and crack face pressure with magnitudes of 36.9 MPa, 43.2 MPa, and 15.51 MPa, respectively [1]. (For the interested reader, the contribution of residual stress alone can be determined by subtracting the K for applied stress from the total K.) The total K values above the dashed line have positive contribution from residual stress, whereas those below the dashed line have a negative contribution from residual stress. Of the 14 K versus crack size profiles shown, half of them start above the dashed line, while the other half start below, which is consistent with the sign of near-ID axial stresses observed in the modeler results (see Figure 2a). There is a clear separation of K from the three measurements and those from the model outputs. It is interesting that although K profiles from the mean model output and the contour method have opposite signs for $a/t < 0.2$, they follow each other quite closely for $a/t > 0.2$.

Figure 8a provides total K results for the internal axial semi-elliptical flaw with a cylinder geometry $r_i/r_o = 0.8$ and a crack aspect ratio $c/a = 2$, where the black dashed line is the K for applied loads acting alone, which are crack face pressure and hoop stress induced by 15.51 MPa internal pressure. For the axial flaw, the residual stress contributions to K are positive for all model outputs and measurements, which is consistent with the positive near-ID hoop residual stress (see Figure 2b). Also, K from applied loads is smaller for the axial flaw than for the circumferential flaw. The model outputs produce K values that generally fall above the K values produced by the measurement data.

Phase 2b study

The total K for the complete internal circumferential flaw is shown for the 9 model outputs, the measurements, and the model and measurement means in Figure 7b, where the total K is the sum of
contributions from WRS and applied loads. The figure also shows the \( K \) from applied loads alone, as a black dashed line, which includes contributions from membrane stress, bending stress, and crack face pressure with magnitudes of 36.9 MPa, 43.2 MPa, and 15.51 MPa [1], respectively. Total \( K \) values above the black dashed line have positive \( K \) from residual stress, whereas those below the black dashed line have negative \( K \) from residual stress. Only model J1 appears above the black dashed line for short cracks, with other models falling below it. The sign of the WRS contributions to \( K \) are consistent with the sign of axial stress near the ID in Figure 3a. For \( a/t < 0.2 \), the \( K \) computed from most models is within ±10 MPa \( m^{0.5} \) of the benchmark, and for \( a/t > 0.2 \), the output mean follows the benchmark quite closely.

Figure 8b provides total \( K \) for the internal axial semi-elliptical flaw, where the black dashed line is the \( K \) for applied loads acting alone, which consist of crack face pressure and hoop stress caused by internal pressure of 15.51 MPa. Nearly all total \( K \) values are above the \( K \) values for the applied loads, which is consistent with positive hoop stress near the ID in Figure 3b. Similar to the circumferential flaw, for the axial flaw when \( a/t < 0.2 \), the \( K \) computed from most models is within ±10 MPa \( m^{0.5} \) of the benchmark, and for \( a/t > 0.2 \), the output mean follows the benchmark quite closely. Model J1 (pink line) falls significantly above the other models, and model E1 (blue-green line) falls significantly below.

3.4 Crack growth history

Phase 2a study

The crack growth history computed from the total \( K \) for the complete internal circumferential flaw is presented in Figure 9a. As shown in Figure 7a, negative \( K \) values occur in some cases for the circumferential flaw evaluations. Cracks are assumed not grow under negative \( K \), so crack depth does not change during the 720 months (60 years) of operating time shown in Figure 9a. For the complete circumferential flaw, no crack growth is predicted for WRS data from DHD #1, contour, and 4 out of 14 model outputs.

The crack growth history for the deepest point of the internal axial semi-elliptical flaw with constant aspect ratio \( c/a = 2 \) is shown in Figure 10a. As demonstrated in Figure 8a, there are no negative values of \( K \) for any of the cases. Additionally, the \( K \) values are significantly higher for the axial flaw than for the circumferential flaw, which is consistent with the hoop stress being large and mostly tensile through wall. As a result, the flaw grows deeper and faster, in some cases predicted to reach \( a/t = 0.8 \) in less than 80 months. Throughout the entire 720 months, \( K \) and crack size computed from the model output mean are significantly greater than those derived from the measurement data.

Phase 2b study

Crack growth history for the circumferential flaw is presented in Figure 9b. Because the total \( K \) is negative for small cracks with WRS from all measurements and most of models, as shown in Figure 7b, crack growth is predicted to occur only for two models, with results from model J1 (pink line) showing faster crack growth than would occur for applied loads alone, which is shown by the black dashed line. Figure 10b shows crack growth history for the internal axial semi-elliptical flaw. Most models and all measurements predict some crack growth over 720 months of operation. Throughout the entire 720 months, crack size derived from the model output mean is larger than the benchmark, which suggests that the models are conservative with respect to the benchmark, on average. This difference is consistent with the difference between the \( K \) determined from model output and measurement means at small crack sizes (see Figure 8b). Of models that are conservative, most predict time to 80% through wall crack size that is within a factor of 2 of the 650 months predicted by the benchmark. Model J1 (pink line) predicts very fast growth, reaching 80% through-wall about 6 times faster than the benchmark, and 3 times faster than the next most conservative model.
4.0 DISCUSSION

4.1 Comparison of Phase 2a and Phase 2b model dispersion

While the RMS difference in stress does not indicate whether a model output has WRS higher or lower than the benchmark, it provides a simple way to quantify dispersion and therefore offers a means to compare results of the two Phase 2 studies. The average RMS difference from the measurement mean benchmark for Phase 2a and Phase 2b are shown in Table 1, where each row reports results by hardening model, and the values listed are specific to that output from that hardening model. For example, the row marked ISO reports the average RMS difference of all Phase 2a or Phase 2b isotropic model outputs relative to the Phase 2a or Phase 2b measurement mean, the row marked KIN reports the average RMS difference of all kinematic model outputs relative to the measurement mean, and so on. In the table, AVG refers to the average of kinematic and isotropic models, and ALL refers to all of the isotropic and kinematic results considered together. Average hardening could not be assessed for Phase 2a because only three participants submitted results for both isotropic and kinematic hardening.

For axial WRS, the average of isotropic and kinematic hardening used in Phase 2b (AVG) has the lowest average RMS difference between model and measurement. For hoop WRS, the 5 models using kinematic hardening (KIN) in Phase 2a and the average hardening in Phase 2b (AVG) show the lowest difference between model and measurement. When not controlling for hardening rule (ALL), there was a similar level of difference between models and measurement in Phase 2a and Phase 2b, which suggests that controlling the hardening model is useful in controlling dispersion in model output.

4.2 Comparison of validation metrics

The following are comparison points for Phase 2a and Phase 2b relative to the potential validation metrics:

1. Stresses due to Section Forces
   - Uniform section force from axial WRS were near zero in both studies (see Figure 5a for Phase 2a and Figure 5b for Phase 2b), which is consistent with mechanical equilibrium.
   - Stress due to uniform section force from hoop WRS is mostly positive in Phase 2b (Figure 5b) and was lower than for Phase 2a (Figure 5a). There was more dispersion on these uniform section forces in Phase 2a than in Phase 2b.
   - Stress due to bending section forces from axial and hoop WRS exhibit similar dispersion in both studies, where the models are biased above the measurement mean for hoop (the red dashed line in Figure 6) and not strongly biased relative to the measurement mean for axial (the blue dashed line in Figure 6).

2. Stress Intensity Factors (K values)
   - For the internal circumferential flaw, there is better agreement between the output mean and measurement mean for Phase 2b (see Figure 7b) than there was for Phase 2a (see Figure 7a). But the degree of dispersion among the models is similar for both Phase 2a and Phase 2b.
   - For the axial semi-elliptical flaw, the level of agreement between the output mean and measurement mean is quite good in Phase 2b (see Figure 8b), with even dispersion of individual model results on each side of the measurement mean (the solid red line). In Phase 2a (see Figure 8a), there is a clear separation between the output mean and measurement mean, with all of the model results falling above the measurement mean.

3. Crack Growth History
   - For the internal circumferential flaw, there is no crack growth predicted from most models in Phase 2b, except for two (see Figure 9b), and hence it is difficult to judge dispersion. In Phase 2a (see Figure 9a), most models predict crack growth, while the measurement mean predicts no
growth. Therefore, it is difficult to use circumferential crack growth as a validation metric to compare Phase 2a and Phase 2b.

- For the axial semi-elliptical flaw, a separation between output mean and measurement mean can be seen in both studies (see Figure 10a for Phase 2a and Figure 10b for Phase 2b). In Phase 2b, the dispersion among models is distributed evenly relative to the measurement mean. In Phase 2a, most dispersion is toward faster crack growth relative to the measurement mean.
- A significant factor in the dispersion of crack growth history for both Phase 2a and Phase 2b are the low $K$ values for small cracks in both orientations. Small differences in $K$ for shallow ID flaws can lead to large differences in calculated crack growth time under these conditions.

4.3 Simplified validation metric: depth-average stress

Because the intended use of WRS model output is to assess the integrity of plant components in terms of life and timing of inspections, the SCC crack growth history is probably the most relevant quantity in WRS model validation. It provides a metric that can be judged relative to plant operational experience. However, in order to calculate the crack growth history, one must know the $K$ value of the corresponding flaw geometry. Obtaining $K$ is not always straightforward due to the calculation complexity and limitations in methodology. A simplified method that can be used to judge the quality of WRS model output without the need to perform complicated calculations would be useful.

On that note, we consider a depth-average stress as a simplified metric that has good correlation with stress intensity factor. The depth-average stress is the average of the stress component computed over a stated range of depth, such as from ID to 10%, 25%, 50%, or 75% through-wall. Analysis of the Phase 2 study data shows that depth-average stress from ID to 10% or 25% through-wall correlates well with $K$ values for short cracks, and depth-average stress from ID to 50% or 75% through-wall correlates well with $K$ values for long cracks. A review of data in Figure 7 through Figure 10 shows that crack growth history is strongly influenced by $K$ values for short cracks. Hence, depth-average stresses from ID to 10% or 25% through-wall are relevant to crack growth history. Because typical flaw assessments have a starting flaw size of 10% thickness, we suggest using depth-average stress from ID to 25% through-wall as a basis for comparison of WRS data for the purpose of model validation.

Table 2 presents depth-average stress from ID to 25% through-wall for Phase 2a axial and hoop WRS normalized by the yield strength of Alloy 182 weld metal (380 MPa), and Table 3 shows depth-average stress for Phase 2b. In Table 2, model outputs with normalized depth-average stress below (or, above) the benchmarks correspond to model outputs that produce $K$ profiles that are also below (or, above) the benchmark (see Figure 7a and Figure 8a). Given that the $K$ profiles are integrated to compute the crack growth history in Figure 9a and Figure 10a, the trend of depth-average stress foretells the trend in crack growth history. The correlation between depth-average stress and $K$ is clearer for Phase 2b. In Table 3, the four average axial stress values above the benchmark correspond to the four $K$ profiles above the benchmark in Figure 7b. Model J1 (pink line), which lies significantly above other models in Figure 7b and Figure 9b, shows a positive depth-average axial stress value in Table 3, and the same model appears above the other models in Figure 8b and Figure 10b, having the most positive depth-average hoop stress in Table 3. Whereas model E1 (blue-green line), which falls significantly below other models in Figure 8b and Figure 10b, has the most negative average hoop stress value in the table.

4.4 Preliminary analysis of two-dimensional stress fields from Phase 2b

To date, all analysis of Phase 2 study data has focused on WRS at the center of the DM weld (as in Figure 2 and Figure 3), but residual stress is a field quantity, and the full field stress variation would be useful to consider. For nozzle configurations, the stress fields are commonly assumed axially symmetric, and typical WRS models provide a two-dimensional stress state variation, with WRS determined as a field quantity on the radial-axial cross-section, such as in Figure 1 for Phase 2b. The problem statement for Phase 2a only specified that modellers submit WRS on the line at the center of the DM weld, but the
problem statement for Phase 2b also specified submission of two-dimensional stress variation. Figure 11 and Figure 12 show Phase 2b WRS output submissions for the average of the two hardening models (AVG). The results are cropped to highlight the area near the DM weld. The weld cross-section is shown for reference at the top left of each figure, where the cross hatching differentiates the low alloy steel (left), stainless steel cladding, weld butter, main DM weld, DM back weld, and the safe-end (right). At the top right, each figure also shows measurement data developed from a new bi-axial residual stress mapping technique [26]. Both figures show a significant degree of agreement among the model outputs, and between and model outputs and the measurement data. In both figures, the blue dashed line on each subfigure indicates the DM weld centerline, which is not at the same axial position in each model.

In practice, a flaw assessment in a two-dimensional stress field would include a step to identify the location of the initial flaw and the plane on which to assess crack growth. While there is no specific, published guidance on how to identify the location and plane for flaw growth analysis in a DM weld, in principle the location and plane selected should provide the most conservative crack growth assessment (fastest crack growth). As a first step, we have assessed the two-dimensional WRS data and identified the axial position having the largest depth-average WRS from ID to 25% thickness (average computed along a radial line). This position is shown with a red solid line on each subfigure in Figure 11 and Figure 12. In general, the position of maximum depth-average stress is not at the DM weld center, and the position for maximum depth-average axial stress is different from the position for maximum depth-average hoop stress. Positions of maximum depth-average stress tend to fall toward the nozzle side of the DM weld for both stress components (with only one model showing the position toward the safe end (model D1 for hoop stress and model I1 for axial stress). Future work will develop crack growth assessments from each set of two-dimensional WRS data using an initial flaw location that provides the fastest flaw growth.

CONCLUSIONS

Four potential validation metrics were described and exercised on two sets of weld residual stress data from the Phase 2 studies performed as part of the cooperative EPRI/NRC program on weld residual stress. Assessment of RMS difference in stress showed that Phase 2a had somewhat more dispersion than Phase 2b, with the lower dispersion in Phase 2b consistent with a clearer specification of material data, and the material hardening model, provided in the Phase 2b problem statement.

The results of the validation approaches discussed in this work demonstrate the importance of the accuracy of the WRS input to crack growth calculations. An in-depth analysis of Phase 2b two-dimensional stress field would shed more light on the WRS model validation effort.

ACKNOWLEDGMENTS

The authors would like to thank the participants in the Phase 2a and Phase 2b studies, who contributed model outputs and measurement data; without them, this work would not have been possible. The Electric Power Research Institute Materials Reliability Program provided funding for this work, and we acknowledge the guidance and support of Paul Crooker, Principal Technical Leader. The authors acknowledge John Broussard of Dominion Engineering, Inc. for helpful comments and discussion. Finally, the authors would also like to thank the staff at U.S. Nuclear Regulatory Commission for technical cooperation, particularly Michael Benson and David Rudland.

REFERENCES


Table 1. Comparison of average RMS differences relative to measurement

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Table 2. Phase 2a, normalized average stress to 25% through-wall

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<td>Meas. mean</td>
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Table 3. Phase 2b, normalized average stress to 25% through-wall

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Figure 1. Phase 2b pressurizer surge nozzle mockup geometry

Figure 2. Phase 2a, individual WRS model outputs at the center of the DM weld, post-SS weld, along with the mean of all model outputs (output mean), the mean of all measurements (meas. mean), and available experimental data (one contour method and two DHD measurements): (a) axial stress, and (b) hoop stress

Figure 3. Phase 2b, individual WRS model outputs (average stresses of isotropic and kinematic hardening results) at the DM weld centerline, post-SS weld, along with the mean of all model outputs (output mean), the mean of all measurements (meas. mean), and all available experimental data (DHD measurements, contour method, and slitting): (a) axial stress, and (b) hoop stress
Figure 4. Normalized RMS differences between model output stress and the measurement mean benchmark for (a) Phase 2a, ALL, and (b) Phase 2b, AVG

Figure 5. Comparison of normalized stress due to uniform section force computed from axial and hoop WRS, with benchmark section forces shown as dashed lines for (a) Phase 2a, ALL, and (b) Phase 2b, AVG
Figure 6. Comparison of normalized stress due to bending section force computed from axial and hoop WRS, with benchmark section forces shown as dashed lines for (a) Phase 2a, ALL, and (b) Phase 2b, AVG

Figure 7. Stress intensity factor for complete internal circumferential flaw with \( r/r_o = 0.8 \) for (a) Phase 2a, ALL, and (b) Phase 2b, AVG
Figure 8. Stress intensity factor for internal axial semi-elliptical flaw at deepest point with $r_i/r_o = 0.8$, $c/a = 2$ for (a) Phase 2a, ALL, and (b) Phase 2b, AVG

Figure 9. Operating time for complete internal circumferential flaw with $r_i/r_o = 0.8$ for (a) Phase 2a, ALL, and (b) Phase 2b, AVG
Figure 10. Operating time for internal axial semi-elliptical flaw at deepest point with $r_i/r_o = 0.8$, $c/a = 2$ for (a) Phase 2a, ALL, and (b) Phase 2b, AVG
Figure 11. Phase 2b, AVG, hoop stress field (in MPa), with DM weld centerline as blue dashed line and maximum average stress to 25% through-wall as red solid line.
Figure 12. Phase 2b, AVG, axial stress field (in MPa), with DM weld centerline as blue dashed line and maximum average stress to 25% through-wall as red solid line.