VALIDATION OF WELD RESIDUAL STRESS FINITE ELEMENT PREDICTIONS FOR USE IN NUCLEAR REGULATORY APPLICATIONS

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Abstract

Weld residual stresses (WRS) are an important driver of primary-water stress corrosion cracking (PWSCC) in nuclear reactor piping, and thus can have an large influence on crack growth predictions. Consequently, it is important to be able to accurately predict WRS using finite element (FE) modeling. This study describes a proposed procedure for the validation of WRS predictions in nuclear primary piping systems using 2D axi-symmetric FE models.

1. Introduction

Weld residual stress (WRS) is known to be an important driver of primary water stress corrosion cracking in safety-related nuclear piping. For this reason, it is desirable to formalize finite element modeling procedures for residual stress prediction. The U.S. Nuclear Regulatory Commission (NRC) and the Electric Power Research Institute have conducted joint research programs on residual stress prediction under a memorandum of understanding. These studies have involved modeling and measurement of WRS in various mockups, and have resulted in detailed residual stress uncertainty characterization, as well as recommendations on hardening laws and a WRS prediction validation method which is the subject of this paper. The validation method is a step-by-step procedure for comparing independent finite element modeling results to the acceptance measures. If an analyst meets the criteria, then the modeling procedure may be applied with greater confidence to a real case. This procedure is intended as a recommendation rather than a regulatory requirement. It provides a means to demonstrate proficiency in finite element modeling of WRS. The validation methodology is aimed at 2D axisymmetric WRS predictions for deterministic flaw growth evaluations. The nuclear industry often performs flaw evaluations when seeking alternatives to established inspection and repair/replacement rules. These evaluations require a WRS assumption. If that assumption is based on finite element results, then following the validation procedure offers the industry one method to strengthen its case when seeking NRC approval.

2. Results

A validation approach requires a benchmark, a set of metrics, and acceptance measures. An example set of metrics and acceptance measures were developed, based on a flaw growth argument whereby the FE prediction being evaluated should adequately approximate the crack growth prediction from the mean of the modeling benchmark performed in the NRC-EPRI studies (see Fig.1 for example).

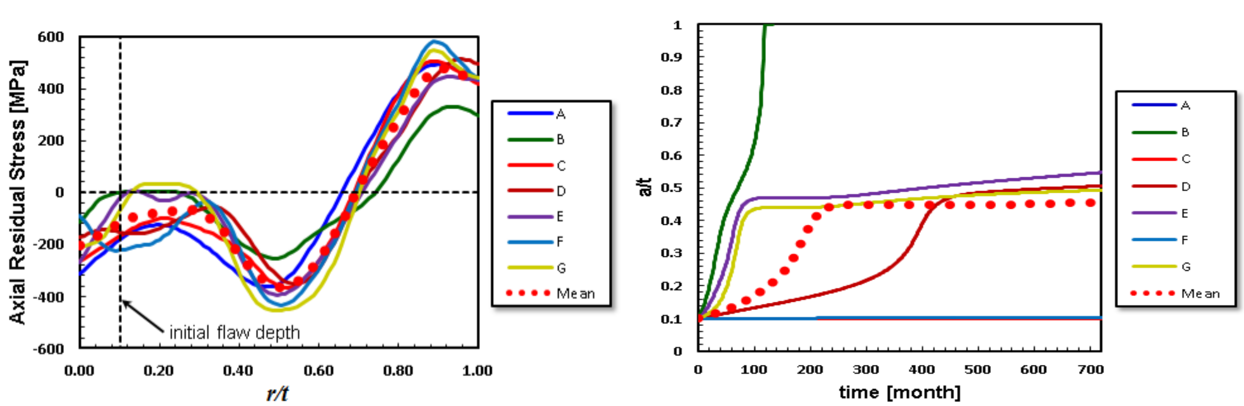

Fig.1 – Example of WRS predictions and associated crack growth predictions: Predictions D, E, and G adequately approximate the mean prediction.

The concept applied to develop the validation procedure was to find a set of metrics that were relevant to flaw growth predictions. The metrics were generated to interrogate features of a residual stress curve that are important to flaw growth. Two metrics were proposed for validating FE predictions of residual stress: the RMSE on WRS magnitude through the entire wall thickness, and the average difference up to the initial crack depth (Fig.2).

$$RMSE_{WRS} = \sqrt{\frac{1}{L}\sum_{k=1}^{L}\left(WRS_k - WRS_k^{mean}\right)^2} \qquad diff_{avg} = \frac{1}{L_{0.1}}\sum_{k=1}^{L_{0.1}}\left(WRS_k - WRS_k^{mean}\right)$$

Axial Stresses		**Hoop Stresses**	
Quality Metric	**Acceptance Criteria**	**Quality Metric**	**Acceptance Criteria**
$RMSE_{WRS}$	≤ 55 MPa	$RMSE_{WRS}$	≤ 70 MPa
$diff_{avg}$	≥ - 15 MPa ≤ 15 MPa	$diff_{avg}$	≥ 0 MPa ≤ 65 MPa

Fig.2 – Proposed WRS validation procedure metrics and acceptance criteria

Analysis of the values of the two proposed metrics for the range of predictions produced in the NRC-EPRI modeling round-robin study allowed for identification of acceptance ranges for each metric. The acceptance criteria were different for axial and hoop WRS predictions, but in both cases could accurately discriminate between adequate and inadequate predictions. The final acceptance criteria are provided in Fig.2.

3. Conclusions

NRC developed an example validation procedure along with validation metrics and acceptance criteria for WRS predictions using FE analysis. Resulting validation guidelines provide a potential method for increasing confidence in WRS predictions for nuclear power applications, which in turn may lead to more efficient NRC reviews of industry submittals and increased regulatory certainty.

The example validation scheme is most directly applicable to a dissimilar metal butt weld. Some details such as constraint condition, repair geometry and location, safe end length, and radius-to-thickness ratio need not be identical to the configuration used to develop the validation procedure to be considered covered by the proposed validation process However, there are potential scenarios encountered in the U.S. nuclear fleet where the present validation approach may not be appropriate, such as partial arc repairs or J-groove weld configurations, which may require 3D modeling.

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