Framework for PWSCC Flaw Evaluation

Inputs required

- Geometry and configuration
  - Diameter, wall thickness, overall joint geometry, boundary conditions (full agreement, residual stress may be for slightly different geometry as long as it's justified)
  - Weld geometry and manufacturing process (main DM and Safe end weld) (required)
  - Weld parameters, i.e., butter, PWHT, weld, backchip, machine ID, etc (Need to know how weld was created)
  - Repair history (Use 50% repair, if flaw evaluation is successful stop, if not look at records)
  - Safe end length (required)
- Operating loads (full agreement)
  - Normal operating loads
    - Temperature
    - Pressure (internal pressure and crack face pressure)
    - Dead Weight
    - Thermal expansion
    - Through-thickness thermal stress
  - Transient loads
    - If fatigue analysis is required
  - Emergency + Faulted loads
    - If stability analysis is required
  - Welding residual stress
    - Details later
- Crack information
  - Length (Use Code rules)
  - Depth (Use Code rules)
  - Orientation (Code rules)
  - Location, i.e., embedded, surface breaking (Code rules)
  - Multiple cracks (Code rules, additional clarification for flaw growth (future))
  - Type, i.e., fatigue, PWSCC assumed (needed)
  - Inspection coverage limitation (if applicable)
  - RMS error correction, if applicable (PDI)
- Materials
  - Yield and ultimate strength (Code minimums, CMTRs if available)
    - CS, SS, Cast SS, A82/182,A52/152
    - For allowable flaw size
  - Toughness (Z factor)
    - DM weld
    - For allowable flaw size
- Criteria (agree)
  - IWB-3600
  - Time to allowable flaw size

Models Required

- Subcritical Crack Growth Models (agree)
  - PWSCC – MRP-115 – 75th percentile growth
  - Fatigue – if required
- K-solutions (fits to stress distribution have to be reasonable over the depth of the flaw)
  - Surface crack – API579 (and Chapuliot) – semi-elliptical surface crack, stress represented as 4th order polynomial + global bending
  - Through-wall crack – API579 – idealized through-wall crack, stress represented as linear through-thickness + global bending (for additional information in low margin cases, if applicable)
- Allowable flaw size – (required) (multiple cracks reduce net section)
  - Surface crack – Net Section collapse or EPFM
  - Through-wall crack – EPFM or net section collapse with Z-factor (for additional information in low margin cases, if applicable)
    - All stresses assumed primary for conservatism

Analyses assumptions

- Loads/Stresses
  - Principal of superposition applies (of course)
  - Primary and secondary loads are applicable to subcritical cracking (conservative not to redistribute)
  - Bending moment components are summed then an equivalent moment is calculated by $M_{eff} = \sqrt{M_x^2 + M_y^2 + \left(\frac{\sqrt{3}}{2}T\right)^2}$ (or more conservative approximation)
  - Crack face pressure is a driving force but only acts as an axial load, i.e., imposed bending neglected. (of course)
  - Through-thickness stress may be represented as a 4th order polynomial or other approximation (see K-solution) (fits to stress distribution have to be reasonable over the depth of the flaw)
  - Global bending stress does not need to be treated as a pure membrane stress, i.e., global bending influence function used in subcritical cracking (use as a pure membrane stress is conservative)
- Time increment is assumed to be one day – may be modified based on crack growth rate. (needs to be small enough that the analysis converges)
- Subcritical cracking
  - Cracks are planar (of course)
  - Semi-elliptical crack growth controlled by K at deepest and surface points for surface crack and average through-thickness K for through-wall crack (or more accurate representation or point-to-point)

Welding Residual Stress

- Criteria for Choosing WRS
  - WRS chosen must be applicable for case analyzed (agree)
    - Geometry/configuration must be represented correctly (or be conservative, Binning if justified)
    - Total through-thickness stress must support crack being analyzed (in the cracked region)
  - Based on required margins for analyses, WRS profiles may be chosen based on level of conservatism, i.e., if using the very conservative assumption meets

acceptable margin, no further analyses is needed. A selection from each category may be needed in sensitivity study to account for uncertainty in WRS.

- Very Conservative
  - WRS = yield strength through thickness
- Conservative – Unknown weld procedure and repair history
  - Published or case specific solution for same geometric/material configuration and assume 50% 360 deg ID repair with no safe end weld (if safe end is ~2inches)
  - Published solution for same geometric/material configuration and assume 50% deep limited extent ID repair (WRS taken middle of weld) with no safe end weld (if safe end is larger than 2 inches)
  - Published solutions should use isotropic hardening
- Conservative – Known weld procedure and repair history
  - Published or case specific solution for same geometric/material configuration and actual ID repair (length and depth) with no safe end weld
  - If repair history is in question use unknown repair history options
  - Published solutions should use isotropic hardening
- Slightly conservative
  - Use solutions above with safe end weld represented
  - Published solutions or case specific may use combined isotropic-kinematic hardening
- Best estimate (with justifiable assumptions)
  - Case specific analysis with geometric/material configuration, repair information, safe end weld, etc
  - May use isotropic-kinematic hardening, isotropic will add conservatism
  - Lumping weld beads will add conservatism.

- Inputs for case specific WRS analysis
  - Nozzle/ safe-end/ cladding/ pipe geometry (drawings)
  - Identify materials and material properties to be used (annealed full stress-strain curves at temperatures up to melting, hardening assumption, etc) including constitutive model (use what you have-validate WRS)
  - Welding, cladding and heat treatment process sequencing of DM weld and safe end, including assumed root pass grind-out and re-weld; and geometry, material properties, locations, and process steps of repairs in the weld or the adjacent nozzle or safe end (50% is conservative; axial location, width and length to be justified, Smaller repairs are appropriate if justifiable or conservative.)
  - In-process stress relieving heat treatment parameters (fab records, wpsor specs)
  - Weld pass energy input (V, I, h, pass speed) (justify assumptions)
  - Inter-pass cooling temperature (justify from procedure)
  - Convective coefficient used for OD and ID surfaces (agree)
  - Same details for any DM weld repair or mitigation (agree)
- Using WRS in PWSCC growth analyses
  - Use WRS at operating temperature (agree)
  - Use appropriate stress component, i.e., Hoop stress for axial crack (agree)
  - Choose through-thickness path that represents most likely growth, i.e., highest stress (agree)
  - Represent the distribution as dictated by K-solutions, e.g., 3rd order not appropriate for many cases (agree)

Sensitivity studies for case specific analyses

- When are they not needed?
  - Extremely conservative assumptions, eg., 50% repair, yield through thickness, etc.
  - Large margin in results
- What is considered by NRC in the SS?
  - WRS
    - Repair or not
    - Repair size
    - Safe end or not, or length of safe end
  - Crack growth rate
    - Higher – 95%
  - Temperature
    - Design
  - Critical flaw size calculation
    - Material properties use
    - EPFM versus Net section collapse
- What has to be provided from the SS?
  - Not required from industry analyses
  - Variations in results that may not be expected?
  - Confidence in the case specific analyses.
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