Evaluation of Overlaid Welds for Critical Flaw Size and Leak Rate in LBB Assessment

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International Workshop on LBB in RCS Components with Active Degradation Modes

January 9-11, 2008

Outline of Presentation

- Overview of SRP 3.6.3 Approach
- Evaluation of Critical Through-wall Flaw Sizes for Overlaid Pipe
- Enhancements for Leak Rate Prediction
- Example
- Some Observations
- Conclusions and Recommendations

SRP 3.6.3 LBB Evaluation Approach

- Postulate Through-Wall Leakage Flaw
  - Large enough to leak 10 time greater than leakage detection system capability with normal loads
- Determine Critical Flaw Size
  - Use fracture mechanics stability analysis or limit load analysis
  - Critical flaw must be at least 2 times leakage flaw size for Normal + SSE loads
  - Also check that critical flaw size > leakage flaw with 1.4 x (Normal + SSE) or 1.0 x (Normal + SSE) if loads combined by absolute sum
  - Approach provided for using limit load analysis

WOL Limit Load Limitations

- **Current SRP 3.6.3 and ASME XI**
  - **Limit load methods based on thin cylinder with single material**
  - **Combination of thermal expansion stresses**
    - not required for high toughness material
    - required for low toughness materials
    - no defined methods for weld overlays
  - **SRP 3.6.3 based only on stainless steel properties**
- **SRP 3.6.3 Has Master Curve Approach**
  - **Technically equivalent to ASME limit load approach**

WOL Limit Load Limitations

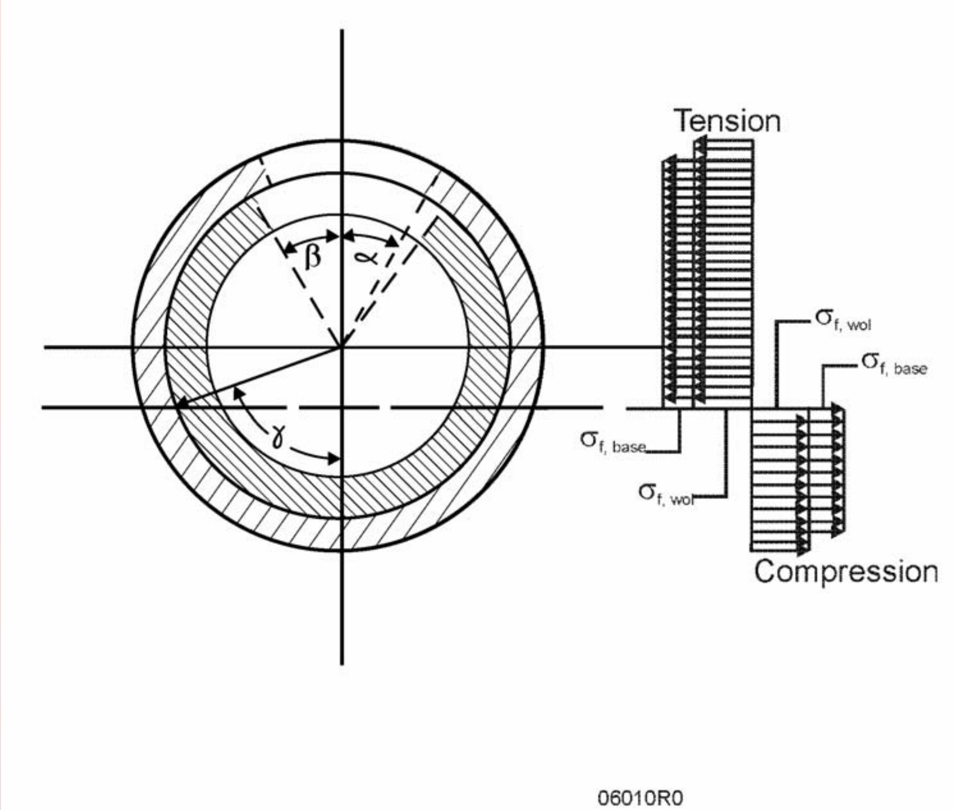
- **For Weld Overlays**
  - **There are two materials**
  - **Each layer has different**
    - properties
    - toughness
    - mean radius
  - **Each layer participates in sharing the load**
- **No guidance in SRP 3.6.3 or ASME Section XI**

Limit Load Approach for Overlaid Weld

- **General Method Published in 2006 PVP Paper**
  - **"Net Section Collapse Analysis of Two-Layered Materials and Application to Weld Overlay Design" PVP2006-ICPVT11-93454**
- **Method Would Be Equally Applicable for Through-Wall Flaws**
- **Several Additional Considerations for Weld Overlaid Regions**
  - **Weld overlay has greater radius than base pipe so inherently has more load resistance than material beneath**
  - **Toughness of weld overlay and material beneath may be different, e.g.**
    - weld overlay has high toughness and would not require consideration of Z-factor or thermal expansion stresses
    - weld in underlying region may require these factors if evaluated alone
  - **Pressure on crack face may be important**

Limit Load Approach for Overlaid Weld

Integration of Force and Moment is Equivalent to That for Single Layer



Equation For Tension/Compression Angle (like β in ASME XI)

- For angle γ from bottom of pipe

$$\gamma = \frac{A(\pi - \alpha) + B\Phi_t(\pi - \beta) - R - F_{CFP}}{2A + B(\Phi_t + \Phi_c)}$$

where:

α = half through-wall (TW) crack angle in weld overlay

β = half TW crack angle in original pipe

Φ_t = factor to be applied to flow stress of original piping material for tensile region

Φ_c = factor to be applied to flow stress of original piping material for compressive

$A = r_a\, t_a\, \sigma_{fa}$ (defined to abbreviate the equations) – for weld ovelay

$B = r_b\, t_b\, \sigma_{fb}$ (defined to abbreviate the equations) – for original weld/base material

R = remote force on pipe (pressure + applied loads)

F_{CFP} = force due to crack face pressure

Equation For Limit Moment

- **Pipe Limit Moment (M_r) and Bending Stress (P'_b) Remote from Crack/WOL**

$$\frac{M_r}{2} = A'(2\sin\gamma - \sin\alpha) + B'[(\Phi_t + \Phi_c)\sin\gamma - \Phi_t \sin\beta] - M_{CFP}$$

$$P'_b = \frac{M_r \sigma_{fb}}{\pi B'} \qquad = \frac{2\sigma_{fb}}{\pi B'} \text{x} \frac{M_r}{2}$$

where:

$A' = r_a^2\, t_a\, \sigma_{fa}$

$B' = r_b^2\, t_b\, \sigma_{fb}$

M_{CFP} = moment due to crack face pressure for ½ pipe section

Equation For Combined Loads

- **Equation for Allowable Remote Primary Bending Moment for Two-Layer Solution, P^*_b**

$$P^*_b = [P'_b + P_m - ZM^*P_e]/[1 + M^*(Z-1)] - P_m$$

where:

P_m = remote primary membrane stress

P_e = remote thermal expansion bending stress

Z = Z factor for correcting for low toughness material

M* = ratio of tension region material moment due to base material divided by total moment for tensile material

Equation For Combined Loads

- Limits of Equation
- Case with Complete Crack in Original Material – $M^* = 0$

$$P'_b = P^*_b$$

- Case with Extremely Small WOL – $M^* = 1$

$$P'_b = Z(P^*_b + P_m + P_e) - P_m$$

Considerations for Leakage Calculation

- **Current Methodologies of PICEP and SQUIRT Address Single Materials in Evaluations**
- **SQUIRT Modified to Address Modified Morphology**
  - **Roughness, number of turns and effective flow path length vary with crack opening displacement (COD)**
  - **PICEP requires constant properties for each evaluation – no change for increasing crack size/ COD**
- **Neither Address Crack Face Pressure**
  - **But maybe not important**

Modified Method for Using PICEP

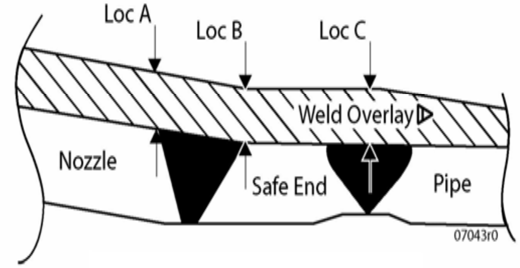
- Run An Initial Case (for Comparison)
  - Yields COD versus Crack Size
- Make Series of Runs to Assess Crack Face Pressure
  - Modify axial loads and moments for each crack size – need an estimate for crack pressure distribution – available from PICEP output
  - Produces alternate COD versus crack size accounting for crack face pressure
- Make Second Series of Runs
  - Modify roughness and number of turns for each crack size
- Interpolate Results to Get Crack Size for Desired Leakage Amount

Modified Turns and Roughness for PICEP

- Implements NUREG/CR-6300 Method for PWSCC Crack Morphology
- Specific PICEP Run Needed for Each Crack Size
- Revised Friction Factor (f_{eq}) and Roughness (ε)
  - $f_{eq}(t/D_h) = \Sigma f_i (L_{a,i}/D_h)$
  - $f_{eq} = (2 \log(D_h/2 \varepsilon_{eq}) + 1.74)^{-2}$ from which equivalent roughness may be determined
- Revised Number of Turns
  - $N_{PICEP-90} = (\Sigma n_{t,i} K_{90})/(50 f_{eq})$

Example for 12-inch Pipe – Original Evaluation

- Surge Nozzle Configuration
  - LAS nozzle with cast austenitic (CASS) safe end and pipe and SS SMAW weld material
  - Pre-overlay evaluation was for crack in LAS, SMAW at nozzle, SMAW at SE, CASS at SE + similar at SE/pipe weld – Alloy 82/182 weld material was not specifically considered



- Pre-overlay Critical Location Was CASS at SE/nozzle Weld
  - Material Toughness adversely affected by thermal aging
  - Evaluation based on fatigue cracking
  - Margin on crack size with factor of 10 on leakage (1 gpm detection limit) was slightly less than two – but accepted in NRC staff review
- Critical Crack Size Was for Low Temperature Stratification

Example for 12-inch Pipe –w/WOL

- Considered Effect of Weld Overlay (2 locations)
  - Original critical location (CASS at nozzle/SE)
  - Alloy 82/182 location adjacent to LAS nozzle
- Analysis Considerations
  - High toughness of Alloy 52 weld overlay material
  - WOL design and maximum allowable thickness
  - Fatigue cracking only in WOL and CASS material
  - PWSCC morphology (crack growth parallel to dendritic grains) in original Alloy 82/182 weld
  - Looked at critical crack size and leakage with and without pressure on crack face

Example for 12-inch Pipe w/WOL

- For CASS Location
  - ½ critical crack size increased from ~7" (w/o WOL) to ~12" (min WOL) or ~14"(max WOL)
  - Leakage increased from 10 gpm to ~ 22 gpm for ½ critical flaw sizes
  - 10 gpm crack size ~ 10" for overlaid section
  - Controlling case for critical flaw was NOP + SSE (previous had been low-temperature stratification)
  - Pressure on crack face had little affect on margins

Example for 12-inch Pipe w/WOL

- **For Alloy 82/182 Location**
  - **½ critical crack size**
    - ~15-16" without crack face pressure
    - ~14-15" with crack face pressure

      (Ave. ½ RCS pressure assumed only on Alloy 600)
  - **Leakage ~6 gpm (max WOL) to ~7 gpm (min WOL)**
    - crack face pressure had little effect – with pressure smaller critical crack size but more leakage per unit length
  - **Margin on critical crack size for 10 gpm leakage ~1.8 for min WOL and ~1.85 for max WOL**

Observations re SRP 3.6.3

- LBB Developed Long Before Probabilistic Methods for Rupture Evaluation and Before NRC Acceptance of Risk-Informed Decision Making
- LBB Judged by NUREG-1061 Committee to Provide “Extremely Low” Probability of Pipe Rupture
    - But actual probability not quantified
    - What is the probability given requirements in SRP 3.6.3?

Observations re SRP 3.6.3 Margins

- There has been Significant Experience with Plant Operation, Inspection and Leakage Monitoring in Last 20+ years Since LBB Developed
- Requiring Leak Detection per RG 1.45 Over-Conservative
  - It takes a long time for 1 gpm leakage to develop
  - Leakage of < 1 gpm can be detected
    - outage observations
    - long term trending
- Factor of 2 on Flaw Size <u>And</u> 10 on Leakage
  - Requiring both is extremely conservative
  - Factor of 10 developed since there were uncertainties in leakage determination and detection at that time – unreasonable to have to apply it on top of hypothetical morphology factor
- Inspection Methods have Improved and Should be Considered
- Ability to Detect and Trend Leakage has Improved

Observation on Overall Approach

- **LBB is a <u>Method</u> to Show Resistance to Pipe Rupture**
  - **It includes a number of considerations when combined together reduce the probability of pipe break**
    - Piping must be fracture resistant
    - Snubbers must be reliable
    - Must be no corrosion mechanism that might cause failure
    - Etc.
  - **Critical flaw size and leakage margins judged to be over-conservative – especially when combined**
  - **There should be alternate approaches allowed that will result in equivalent margins**
    - Improved leakage detection
    - Inspection/mitigation of corrosion
    - Etc.

Recommendations

- **Need Validation of Methods for Assessing Critical TW Crack Sizes for Overlaid Welds**
  - **Perhaps experimental and composite J/T eval.**
- **Margins for Flaw Size <u>And</u> Leakage Need to be Re-assessed**
- **Probabilistic Evaluations Need to be Conducted**
  - **Establish realistic goal for "Extremely Low Probability of Rupture"**
  - **Give credit for realistic operator action for lower levels of leakage**
  - **Give credit to inspections**