Fatigue Testing and Life Estimates of Welded Flat Head Pressure Vessel Joints

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Introduction

1. Test Specimens and Experimental Results
2. FEA Analysis and Fatigue Design Methods
3. Discussion of Results
What was done...

• Test based on Kalnins, Rana, Bergman 2005 PVP paper.
• Kalnins et al reported large variation in allowed cycles.

• Applied fatigue rules in a “real world” case.
  • Design - build - verify
• Our interest is applying the design rules to specific test results.
Goals

- Provide failure data to complement PVP 2005 paper by Kalnins, Rana, Bergman.
- Support development of new fatigue evaluation procedures.
- Provide more data for PVP geometries.
- Thickness effects and material dependency
- “If we build it and test it, do the rules predict it?”
What is unique about these tests?

Incorporates what we know to influence fatigue lives of welded geometries:

• Thin plate
• High bending-to-membrane stress ratio
• Lower cycle range

Less technical, but equally important:

• Easy to analyze
• Easy to replicate
• Low cost, no expensive equipment necessary
Test Specimens

- Cylindrical shells with flat heads attached
- Four carbon steel, one austenitic stainless steel
- TIG, GMAW, FCAW welding processes
- ASME certified welders and shops
- Full penetration welds
  - Double sided
  - Single sided (well, almost)
Test Specimens
Weld Details

WELD TYPE 'A'

WELD TYPE 'B'

1/8” 3.2 mm

3/16” 4.8 mm
Nondestructive Examination

- All tests were inspected using PT and VT.
- Test #1 also included radiography.
- Minor undercut in some tests (<5% wall thickness).
- Lack of penetration, porosity.
- Initial flaws were not repaired.
- Flaws were not initiation sites and did not affect failure results.
Experimental Procedure

- Cycle between zero and 60 psig (0.414 MPa)
- Tests conducted full of water
- Pressure range produces structural stress < 2*Sy
- Repaired flaws and continued testing if possible
Failure Criteria

- Thru thickness crack with visible leakage.
- Same failure criteria as Markl, but different than typical structural fatigue tests.
- Additional failures which occurred adjacent to fatigue repairs are not included in results.
Experimental Results

- Pressure range is constant for all tests, but stress varies between tests due to as-built weld dimensions and plate thickness.
- Expected larger scatter, but didn’t see it.
- Didn’t see difference between TIG and MIG welded test specimens.
- Largest scatter is seen within Joint #4 – this illustrates the variability of single sided joints.
Fatigue Failures in Double Sided Joints

- Failures in Joints #1, #2, #3, and #5 began at inside weld toe and extended to outer weld toe.
Joint #4 Fatigue Failures – Single Sided Weld

- Failures in single sided joint initiated at “fillet like” root reinforcement and extended thru face of outer weld.
- No weld throat or root failures.
- No failure from external toe (compressive stress range?)

Crack Plane
Root Reinforcement in Joint #4
Summary of Testing

- Five test specimens
- 19 unique failure sites
- Repeatable test results
- Stainless and Carbon Steel
- Double and Single Sided Welds
FEA Analysis and Fatigue Design Rules
Finite Element Analysis

- Axisymmetric models used to determine stress
- As-built dimensions used in all calculations.
- Several models constructed for each test:
  - Structural stress, extrapolations, etc
  - Notch stress (0.50mm and 1.0mm radius)
  - Stress on weld throat
<table>
<thead>
<tr>
<th></th>
<th>Joint #1</th>
<th>Joint #2</th>
<th>Joint #3</th>
<th>Joint #4</th>
<th>Joint #5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Toe of Fillet</td>
<td>Toe of Fillet</td>
<td>Toe of Fillet</td>
<td>Toe of Fillet</td>
<td>Root or Throat Reinf.</td>
</tr>
<tr>
<td><strong>Peak Stress w/ 0.5mm Radius</strong></td>
<td>135,950 (937.34)</td>
<td>129,380 (892.04)</td>
<td>128,574 (886.49)</td>
<td>107,710 (742.63)</td>
<td>85,142 (587.03)</td>
</tr>
<tr>
<td><strong>Peak Stress w/ 1.0 mm Radius</strong></td>
<td>111,114 (766.10)</td>
<td>106,554 (734.66)</td>
<td>105,448 (727.04)</td>
<td>86,776 (598.30)</td>
<td>61,780 (426.96)</td>
</tr>
<tr>
<td><strong>Direct Membrane Stress</strong></td>
<td>1,641 (11.31)</td>
<td>1,596 (11.00)</td>
<td>1,612 (11.11)</td>
<td>1,559 (10.75)</td>
<td>382.43 (2.64)</td>
</tr>
<tr>
<td>(Linearized membrane normal to weld)</td>
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<tr>
<td><strong>Direct Bending Stress</strong></td>
<td>70,952 (489.20)</td>
<td>65,598 (452.28)</td>
<td>65,221 (449.68)</td>
<td>56,480 (389.42)</td>
<td>20,055 (138.27)</td>
</tr>
<tr>
<td>(Linearized bending normal to weld)</td>
<td></td>
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<tr>
<td><strong>Direct Structural Stress</strong></td>
<td>72,593 (500.51)</td>
<td>67,194 (463.29)</td>
<td>66,834 (460.80)</td>
<td>58,039 (400.16)</td>
<td>20,272 (139.77)</td>
</tr>
<tr>
<td>(Linearized stress normal to weld)</td>
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<tr>
<td><strong>EN 13445 Extrapolated Stress</strong></td>
<td>72,691 (501.19)</td>
<td>67,292 (463.96)</td>
<td>66,932 (461.48)</td>
<td>58,124 (400.75)</td>
<td>---</td>
</tr>
<tr>
<td><strong>Master Curve Equivalent Stress</strong></td>
<td>76,553 (527.81)</td>
<td>71,353 (491.96)</td>
<td>70,803 (488.17)</td>
<td>61,676 (425.24)</td>
<td>---</td>
</tr>
<tr>
<td><strong>Master Curve Eq. Pseudo Stress</strong></td>
<td>86,560 (596.81)</td>
<td>79,582 (548.70)</td>
<td>78,861 (543.70)</td>
<td>67,282 (463.89)</td>
<td>---</td>
</tr>
<tr>
<td>(with Neuber’s rule applied)</td>
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</tbody>
</table>
Fatigue Design Rules

Fatigue design methods used in comparisons:

- ASME Section VIII, Division 2, Appendix 5 using 0.50 mm effective weld radius.
- IIW Notch Stress Method using 1.0 mm effective weld radius and FAT 225.
- PD 5500 – Curves F and W
- EN 13445 – Curves 71 and 40
- API 579 – Curves 63 and 40
- Master S-N Method
- Master S-N Method with Neuber’s correction
Some notes on fatigue rules

- ASME is dependent upon notch radius, but still conservative for 0.5mm and 1.0mm.
- Plasticity correction factors not used since structural stress < 2*Sy
- For Master S-N method, plasticity correction factors are applied for structural stress > 1.0*Sy
- IIW Notch stress method only validated for plate thicknesses 5mm and greater.
- Environmental effects (if any) are not included.
Design Comparison with Test Results

Test #1
Double Sided Weld - Carbon Steel

<table>
<thead>
<tr>
<th>Actual Failure</th>
<th>ASME VIII-2</th>
<th>ASME VIII-2</th>
<th>IIW Notch Stress</th>
<th>PD 5500</th>
<th>EN 13445</th>
<th>API 579</th>
<th>Master Curve</th>
<th>Master Curve</th>
<th>Master Curve</th>
<th>Master Curve</th>
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<tbody>
<tr>
<td>Cycles</td>
<td></td>
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<td></td>
<td></td>
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<td></td>
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<td></td>
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</table>
Design Comparison with Test Results

Test #2
Double Sided Weld - Carbon Steel

<table>
<thead>
<tr>
<th></th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Failure</td>
<td>37,538</td>
</tr>
<tr>
<td>ASME VIII-2 0.5mm Radius</td>
<td>1819</td>
</tr>
<tr>
<td>ASME VIII-2 1.0mm Radius</td>
<td>3313</td>
</tr>
<tr>
<td>1.0mm Radius</td>
<td>57,453</td>
</tr>
<tr>
<td>Class F</td>
<td>7058</td>
</tr>
<tr>
<td>Class 71</td>
<td>7169</td>
</tr>
<tr>
<td>Class 63</td>
<td>4666</td>
</tr>
<tr>
<td>-2σ</td>
<td>33,565</td>
</tr>
<tr>
<td>-3σ</td>
<td>24,176</td>
</tr>
<tr>
<td>-2σ (pseudo σ)</td>
<td>23,841</td>
</tr>
<tr>
<td>-3σ (pseudo σ)</td>
<td>17,172</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Failure</td>
<td></td>
</tr>
<tr>
<td>ASME VIII-2 0.5mm Radius</td>
<td></td>
</tr>
<tr>
<td>ASME VIII-2 1.0mm Radius</td>
<td></td>
</tr>
<tr>
<td>1.0mm Radius</td>
<td></td>
</tr>
<tr>
<td>Class F</td>
<td></td>
</tr>
<tr>
<td>Class 71</td>
<td></td>
</tr>
<tr>
<td>Class 63</td>
<td></td>
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<tr>
<td>-2σ</td>
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<tr>
<td>-3σ</td>
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<tr>
<td>-2σ (pseudo σ)</td>
<td></td>
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<tr>
<td>-3σ (pseudo σ)</td>
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</tbody>
</table>
Design Comparison with Test Results

Test #3
Double Sided Weld - Carbon Steel

<table>
<thead>
<tr>
<th>Actual Failure</th>
<th>0.5mm Radius</th>
<th>1.0mm Radius</th>
<th>1.0mm Radius</th>
<th>Class F</th>
<th>Class 71</th>
<th>Class 63</th>
<th>-2σ</th>
<th>-3σ</th>
<th>-2σ (pseudo σ)</th>
<th>-3σ (pseudo σ)</th>
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</thead>
<tbody>
<tr>
<td>31,515</td>
<td>1,849</td>
<td>3,425</td>
<td>59,280</td>
<td>7,182</td>
<td>7,285</td>
<td>4,742</td>
<td>34,385</td>
<td>24,767</td>
<td>24,529</td>
<td>17,667</td>
</tr>
<tr>
<td>ASME VIII-2</td>
<td>ASME VIII-2</td>
<td>I IW Notch Stress</td>
<td>PD 5500</td>
<td>EN 13445</td>
<td>API 579</td>
<td>Master Curve</td>
<td>Master Curve</td>
<td>Master Curve</td>
<td>Master Curve</td>
<td></td>
</tr>
</tbody>
</table>

Cycles
Design Comparison with Test Results

Test #4
Single Sided Weld - Carbon Steel

<table>
<thead>
<tr>
<th>Cycles</th>
<th>Actual Failure</th>
<th>0.5mm Radius</th>
<th>1.0mm Radius</th>
<th>1.0mm Radius</th>
<th>Class F</th>
<th>Class 71</th>
<th>Class 63</th>
<th>-2σ</th>
<th>-3σ</th>
<th>-2σ (pseudo σ)</th>
<th>-3σ (pseudo σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>153,663</td>
<td>ASME VIII-2</td>
<td>7,160</td>
<td>12,147</td>
<td>193,242</td>
<td>46,088</td>
<td>8,295</td>
<td>30,427</td>
<td>185,430</td>
<td>133,359</td>
<td>154,880</td>
<td>111,555</td>
</tr>
</tbody>
</table>

(Additional data and analysis might be required for a comprehensive understanding.)
Design Comparison with Test Results

Test #5
Double Sided Weld - Stainless Steel

<table>
<thead>
<tr>
<th>Cycles</th>
<th>0.5mm Radius</th>
<th>1.0 mm Radius</th>
<th>1.0 mm Radius</th>
<th>Class F</th>
<th>Class 71</th>
<th>Class 63</th>
<th>-2σ</th>
<th>-3σ</th>
<th>-2σ (pseudo σ)</th>
<th>-3σ (pseudo σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Failure</td>
<td>14,037</td>
<td>37,272</td>
<td>78,940</td>
<td>12,672</td>
<td>10,828</td>
<td>5,940</td>
<td>39,741</td>
<td>28,624</td>
<td>35,650</td>
<td>25,680</td>
</tr>
<tr>
<td>ASME VIII-2</td>
<td>ASME VIII-2</td>
<td>IIW Notch Stress</td>
<td>PD 5500</td>
<td>EN 13445</td>
<td>API 579</td>
<td>Master Curve</td>
<td>Master Curve</td>
<td>Master Curve</td>
<td>Master Curve</td>
<td></td>
</tr>
</tbody>
</table>

Graph showing comparison between actual failure cycles and various test results for different stress conditions and standards.
Summary of Fatigue Calculations

- ASME, PD 5500, EN 13445, API 579 are conservative in all cases.
- IIW Notch Stress method is non-conservative in four test cases.
- Master S-N method is borderline conservative/non-conservative in these tests.
- ASME allows significantly greater fatigue lives for stainless steel.
Discussion of Results
Mean Curve Comparisons

• Do we have enough data to compare against mean curves?
• Carbon steel data matches ASME mean curve
• Stainless steel data is lower than current ASME curves for stainless steels
• Estimating mean curve by +2 curve classes for structural methods didn’t produce good comparison
• Master S-N mean curves are higher than failure data (with and without Neuber’s correction)
ASME Mean Curve for Carbon Steel
ASME Mean Curve for Stainless Steel

[Graph showing cyclic stress-life data with different markers and lines representing existing ASME, SF 20 on cycles, SF 2 on stress, and weld joint #5 (stainless)].
# Master S-N Mean Curve Predictions

<table>
<thead>
<tr>
<th>Weld Joint</th>
<th>Mean Curve</th>
<th>Mean Curve w/ Neuber’s</th>
<th>Average Cycles to Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>83,527</td>
<td>56,848</td>
<td>30,725</td>
</tr>
<tr>
<td>#2</td>
<td>104,067</td>
<td>73,920</td>
<td>37,853</td>
</tr>
<tr>
<td>#3</td>
<td>106,611</td>
<td>76,051</td>
<td>31,384</td>
</tr>
<tr>
<td>#4</td>
<td>574,129</td>
<td>480,196</td>
<td>153,663</td>
</tr>
<tr>
<td>#5</td>
<td>123,214</td>
<td>110,530</td>
<td>165,486</td>
</tr>
</tbody>
</table>
Stainless Steel

• Significant variation in the treatment of stainless steel vs. carbon steel fatigue life.
• Current ASME mean curve may over predict fatigue life.
• Jaske & O’Donnell mean curve matches test data.
• Structural stress methods are very conservative for the current test.
• Literature is mixed, although latest research shows equivalent fatigue lives.
Single Sided Welds

- So simple, yet so complex.
- Idealized during design, but rarely ideal in the end.
- Difficult to control quality at weld root.
- Many potential failure sites to consider.
Single Sided Welds

- Application of throat stress calculations for high bending stress conditions is not clear.
- “..the load carried by the weld divided by the throat area.” – per PD 5500.

\[ S = \sqrt{\sigma_N^2 + \tau^2} \]
Are both the following statements true?

• Fatigue life reduces with increasing thickness.
• Decreasing thickness results in increased fatigue life.

If the second statement is true then…

Is there a reasonable limit to the increased fatigue life for thin plate geometries?
Thickness Effects

- All structural stress methods utilize a thickness correction in consideration of size effects.
- PD-5500, EN 13445, API 579 only apply correction factor above a reference value (near 25mm).
- Master S-N method applies thickness correction thru entire range of thicknesses.
- At plate thickness less than 0.25”, Master S-N correction provides significant increase in allowable cycles.
Influence of Thickness Corrections

- Master S-N (3rd Std Dev)
- Master S-N (2nd Std Dev)
- Adjusted Master S-N (3rd Std Dev)
- Adjusted Master S-N (2nd Std Dev)
- PD 5500
- API 579
- EN 13445

Allowed Cycles vs. Thickness (in)
Thickness Effects

- DeJesus tests suggest thickness effects are less significant in thin plate failing at low cycles.
- Research by Gurney suggest thickness correction extends into lower thicknesses, but a limit does exist.
- Gurney showed that thickness effects are not as apparent at lower cycle life when subjected to bending stress.
Conclusions

• “Code” methods are conservative for these test results. IIW notch stress method and Master S-N curve were the exception.

• ASME Mean curve matches test data. Master S-N is significantly greater.

• Single sided welds are difficult to predict and control

• Weld throat failure criteria needs to be clarified for bending dominant stress field.

• The relationship between thickness effects and cycles to failure needs further review.

• Fatigue of stainless weldments needs to be harmonized.
Further testing:

- Study thickness effects.
- More stainless steel tests – both TIG and MIG welded.
- Environmental effects?
- Test similar welds and thicknesses in structural type tests to full section failure.
Questions?

Available for download at:

www.paulin.com