Fatigue Assessment of Weld Joints Using ANSYS, BSS & FE-Safe **

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** BSS, Battelle Structural Stress Method Proposed by Dr. Dong and His Colleagues at Battelle
Fatigue Assessment of Weld Joints Using ANSYS, BSS (Verity) & FE-Safe **

- Background
- Battelle Structural Stress (BSS) Method & Mesh Sensitivity
- Master S~N Curve?
- Example Application
- References
Background
Fatigue Assessment – Unwelded Structures

Parameters
Initiation: S, ε
Propagation: G, J

Factors:
- σm
- Environment
- Size
- Surface
- SCF
- Residual Stress

Damage Rule: \( \sum \frac{n_i}{N_i} = 1 \)
It’s been commonly recognized that the fatigue life of the polished specimen is dominated by fatigue crack initiation, whereas that of welded structures is dominated by small crack propagation from some pre-existing discontinuity.
Background
Fatigue Assessment – Welded Structures

• Nominal Stress Method (BS, IIW)
  – The nominal stress range is used to develop the S~N curves using samples with actual weld joint geometry
  – The life curves refer to particular weld details, there is no need for the user to attempt to quantify the local stress concentration effect of the weld detail itself
• Hotspot Stress Approach (structural stress, geometric stress, BS, IIW, CEN, DNV)
  – This procedure uses hot-spot stress range as a parameter
  – The S–N curves are obtained from tests of actual welded joints based on the hot-spot stress range rather than the nominal stress range
Local Notch Stress Method (ASME, BS, IIW).

- The notch stress approach attempts to include all sources of stress concentration in the stress used with the design S~N curve.
- Thus a single S~N curve may be sufficient for a given type of material.
- The problem is that the local geometry of the toe or root of a weld is highly variable.
- It may be hard to achieve consistent results.
Background
Fatigue Assessment – Welded Structures

• The Fracture Mechanics Approach (For crack propagation life)
  – The parameter widely used is SIF, K
  – The fatigue resistance is represented by fatigue crack growth rate 
    \( \frac{da}{dN} \)
  – Many crack propagation laws are available
  – The simplest one is Paris Law in which the crack growth law approximates to a linear relationship:
    \[
    \frac{da}{dN} = C (\Delta K)^n
    \]  
    (1)
  – For a flaw size starts from \( a_0 \) to a critical fatigue crack size \( a_f \), the
    remaining fatigue life \( N \) under stress range \( S \) is obtained by integrating Eq (1):
    \[
    \int_{a_0}^{a_f} \frac{da}{(\Delta K)^n} = C \cdot N
    \]  
    (2)

• Verity Equivalent Structural Stress Method (Battelle)
  – Equivalent Structural Stress + Single Master S~N Curve
Battelle Structural Stress (BSS) Method & Mesh Sensitivity

(a) Normal Stress at the sharp corner

\[ \sigma_x = \sigma^t + p_s \]

\( \sigma^t \) (Structural Stress)

0.4 t

(b) Comparison of SCF predicted by various modeling procedures and extrapolation based HSS at the weld toe [12].

(c) Structural Stress Using Verity Method

\[ \frac{\sigma_{FE}}{\sigma_{Nominal}} \sim (\text{Human Factor}) \]

\( \sigma_{FE} \)

\( \sigma_{Nominal} \)
Why BSS Is Not Sensitive To FE Mesh?

Calculation of Structure Stress

3-D Solid Element:

i. Calculate nodal force

ii. Transformation of nodal force to neutral axis to obtain resultant forces (N, m).

iii. Calculation of structural stress

\[
\sigma^t_m = \frac{N}{A} \quad \sigma^t_b = \frac{m}{W} 
\]

Shell Element:

i. Calculate nodal force \((N', m', Q')\)

ii. Calculation of structural stress

Because equilibrium has to be satisfied

Thus: \(m' = m\)

\(Q' = Q\)  And \((\sigma^t_m)' = \sigma^t_m, (\sigma^t_b)' = \sigma^t_b\)

The equations in the calculation of structural stress are the same. Hence, the structural stress is mesh independent.
## Master S~N Curve

**Weld Joint Categorization**

### Categorization of Weld Joints (BS 7608)

Most codes divide weld joints into different types

### Weld Joints (IIW)

<table>
<thead>
<tr>
<th>No.</th>
<th>Structural detail</th>
<th>Description</th>
<th>Requirements</th>
<th>FAT Test</th>
<th>FAT Alt.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vee joint</td>
<td>As-welded, HT CT</td>
<td>As-welded, HT CT</td>
<td>100</td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td>Combination of 2-vee joint with full penetration side welds</td>
<td>Transverse or horizontal reinforcement, net section more than mean plate, as welded</td>
<td>100</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>U type load carrying fillet welds</td>
<td>Transverse or horizontal reinforcement, net section more than mean plate, as welded</td>
<td>100</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Breakerheads, ends of longitudinal stiffeners</td>
<td>Fillet welds welded around or not, as welded</td>
<td>100</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Cover plate ends and corner joints</td>
<td>Fillet welds welded around or not, as welded</td>
<td>100</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Cruciform joints with load-carrying fillet welds</td>
<td>Fillet welds, as welded</td>
<td>90</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Lap joint with load-carrying fillet welds</td>
<td>Fillet welds, as welded</td>
<td>90</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Type &quot;B&quot; joint with short reinforcement</td>
<td>Fillet or full penetration weld, as welded</td>
<td>100</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Type &quot;B&quot; joint with long reinforcement</td>
<td>Fillet or full penetration weld, as welded</td>
<td>90</td>
<td>36</td>
<td></td>
</tr>
</tbody>
</table>
Example Design S~N curves for welded joints: (a) Steel weld joint S~N curves (BS 7608); (b) Weld joint type and S~N curves (IIW recommendations); (c) Aluminum weld joint S~N curves (IIW recommendations)

Multiple S~N curves provide flexibility for the selection of life curves and increase difficulty to select the proper one due to the variation of actual joints.
## Master S~N Curve

### Weld Joints (IIW)

<table>
<thead>
<tr>
<th>No.</th>
<th>Structural Detail</th>
<th>Description</th>
<th>FAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>211</td>
<td>Transverse located butt weld, groove or V groove ground flush to plate.</td>
<td>100% ND7</td>
<td>100</td>
</tr>
<tr>
<td>212</td>
<td>Transverse butt weld made in shop in the position toe angle = 45°.</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>213</td>
<td>Transverse butt weld not satisfying conditions of 211.</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>217</td>
<td>Transverse partial penetration butt weld, analysis based on stress in weld throat sectional area weld root not to be taken into account.</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>221</td>
<td>Transverse butt weld ground flush, ND7, with transition in thickness and width.</td>
<td>90</td>
<td>100</td>
</tr>
<tr>
<td>222</td>
<td>Transverse butt weld made in shop, located in the position, weld profile controlled, ND7, with transition in thickness and width.</td>
<td>90</td>
<td>100</td>
</tr>
</tbody>
</table>

### Nominal Stress Method (BS)

### Hot Spot Stress Method (IIW)

- **Master Curve Mean Line**

### BSS Method

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Master S~N Curve?
A Unified Stress Intensity Factor

(a) Weld geometry with a hypothetical crack $\ell$
(b) Actual normal stress distribution
(c) Simplification
(d) Decomposition
(e) Equilibrium-equivalent structural stress or far-field stress
(f) Self-equilibrating stress (notch stress) with respect to a reference depth $t_1$

\[ \sigma'_x = \sigma^t + \Delta\sigma \]
\[ \Delta\sigma = \sigma'_x - \sigma^t \]
The drive force for crack to start and grow is the crack tip stress, introduce crack surface traction $p_s$ called self equilibrating surface traction due to $\Delta\sigma$ (notch effect).

$$K = K_n(\sigma^t) + K_s(\Delta\sigma) \quad (0 < 1 < t)$$

$$K_s(\Delta\sigma) \approx K_s(p_s) = K_s(\sigma^t, \sigma'_x) \quad (0 < 1 < t)$$
Master S~N Curve?
A Unified Stress Intensity Factor

\[ K = K_n(\sigma^t) + K_s(p_s) \]

(0 < t < T)

Notch Effect
Structural Stress, Far field stress

Stress intensity solutions using published weight function results: (a) remote tension; (b) remote bending.
SIF Magnification Factor $M_{kn}$

$$K = K_n(\sigma^t) + K_s(p_s) \quad (0 < 1 < t)$$

Introduction of notch induced SIF magnification factor $M_{kn}$:

$$M_{kn} = \frac{K_n(\sigma^t) + K_s(p_s)}{K_n(\sigma^t)} \geq 1.0 \quad (0 < 1 < t)$$

$$K = M_{kn} K_n(\sigma^t) \quad (0 < 1 < t)$$

Comparisons of stress intensity magnification factor $M_{kn}$ at 135° sharp V notch for various specimen geometries and loading conditions:

(a) Edge crack solutions;  
(b) Elliptical crack solutions for $a/c = 0.4$
Modified Paris Law

Paris Law:
\[
\frac{da}{dN} = C \Delta K_n^m \quad (a)
\]

Introduce the Unified SIF:
\[
\frac{da}{dN} = C M_{kn}^n \Delta K_n^m \quad (b)
\]

Figures showed the significant improvement for the application of Paris Law and its application

More important the crack starts from zero that covers crack initiation life
Using the Unified Paris Law,
\[
\frac{da}{dN} = CM_{kn}\Delta K_n^m
\]

S ~ N curve can be obtained  \( \rightarrow (a) \)

\[
N = \int_{a=0}^{a=a_f} \frac{da}{CM_{kn}\Delta K_n^m}
\]

(b)

Introduction of generalized SIF range, leads to,

\[
N = \frac{1}{C} \left( \frac{1}{t} \right)^{1-m} \Delta \sigma_s^m l(r)
\]

(c)

Where, \( l(r) = \int_{a/t=0}^{a/t=1} \frac{d(a/t)}{M_{kn}\{f_m(a/t) - r[f_m(a/t) - f_b(a/t)]\}^m} \)

(d)

Then

\[
\Delta \sigma_s = C^{\frac{1}{m}} \left( \frac{2-m}{2m} \right) \left( \frac{1}{l(r)} \right)^{1/m} \left( \frac{1}{N} \right)^{1/m}
\]

(e)

Introduce Equivalent Structural Stress Range,

\[
\Delta S_s = \frac{\Delta \sigma_s}{\left( \frac{2-m}{2m} \right) \left( \frac{1}{l(r)} \right)^{1/m}} \rightarrow \Delta S_s = C^{\frac{1}{m}} \left( \frac{1}{N} \right)^{1/m}
\]

(f)
Example Application
ANSYS, Verity, Fe-Safe: Weld Analysis Procedure

**Ansys Preprocessing**
- Meshing per Verity requirements
- Linear material properties
- Apply load
- Solution

**Verity, Fe-Safe Weld analysis**
- Verity Analysis (Eq. Structural Stress calculations along the weld line)
- Fe-Safe analysis (Weld life calculations using Master S-N curve)

**Ansys Post processing**
- Import .rst file
- Post processing

**Calibration**
- Quantify loading relative to the test for FEA

**Reliability Testing**
- Verity result validation and comparison
Ansys Preprocessing- FE Model

- Mesh Requirements
- Shell Elements:
  - 3D mid-surface element with no through-thickness dimension
- Solid Element:
  - Rectangular faces required along the through-thickness cut from the weld line
  - Regular mesh along the through thickness cut from weld line
  - Recommended elements: Hexahedral (brick) and Pentahedral (wedge)
  - Tetrahedral elements can be used. Requires special handling.

Linear material properties
(E = 29,000 KSi, ν = 0.29)

Symmetry BC
On sides

Hex elements along weld line

Top & Bottom fixed

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Verity Procedures

- Structural Stresses calculated along the weld line at each node
- Fe-Safe builds a connectivity table and maps the stresses to elemental stresses.
- These stresses are inserted into the stress matrix to be used for fatigue evaluation
Fe-Safe Analysis – Weld life predictions using Master S~N Curve

• Fully reverse loading defined
• Fe-Safe calculates weld fatigue life based on the Battelle’s Master SN curve
• The weld life (log N) data at each node is written in the ANSYS .rst format
Minimum life at element # 4436, node # 4212
Comparison of Verity Predictions with Reliability Test Results

Conservative life estimate!
Predicted Failure Location correlated well with the test failures!!
Conclusions

• The Structural Stress Method developed at Battelle is mesh insensitive that removes the uncertainty in the calculation of structural stress for weld joint fatigue assessment.

• The nature of weld joint fatigue is considered through the introduction of Equivalent Structural Stress based on fracture mechanics, which enable most fatigue curves of weld joints merged into a narrow band, the Master S~N curve. Thus one S~N curve can be used for majority of weld joints.

• ANSYS could be used for the fatigue assessment of welded joints in conjunction with Verity & Fe-Safe.

• Verity Generally provides conservative estimate of the weld life.

• Good correlation with the predicted and test failure locations.

• Note:
  – We believe that the weld joints have to be stress concentration dominant to achieve consistent results with test data.
References

[7]. Harrison J D and Maddox S J: 'A critical examination of rules for the design of pressure vessels subject to fatigue loading' in Proc. 4th Int. Conf. on 'Pressure Vessel Technology', Mech E, London, 1980.