A 3D CRACK EVOLUTION IN WELD METAL, BASE METAL AND THE TRANSITIONAL FUSION LINE UNDER A MIXED FATIGUE LOADING

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Introduction

• General problem description
• Geometry, material data and loading condition
• Modelling principle
• Crack growth life calculation methodology
• Results and discussion
• Conclusions
General problem description

• Linear type defects are frequently detected in welds through radiography.

• They are mostly rejected by welding codes unless the Remaining Useful Life (RUL) is precisely calculated on a case-by-case basis.
  • Finite Element (FE) algorithms of life prediction are authorized by codes for the case-specific life calculation of structures containing defects.
  • However, the existing capability of predicting crack behaviour in weld and welded structures, which are the most susceptible regions to contain a defect, are limited.
    • Complex load histories, crack growth laws (with dependency on stress ratio, temperature, environment), crack shape development, multiple materials, residual stress, HAZ
General problem description

• Although a large variety of fracture resistant materials are available, failure is often observed to occur in structures after a relatively low in-service life and is frequently reported in welds.

• Linear elastic fracture mechanics (LEFM) has been the primary approach to fatigue studies through using incremental crack extension per cycle and experimental data from ASTM E647.

• A general approach is presented, by application to a butt weld in a pipeline, that allows crack growth prediction for defects in a multi-material environment (i.e. crossing a weld fusion line) under mixed load conditions.
**Geometry data**

**Pipe:**
- Outer diameter: 57mm
- Wall thickness: 9.5mm
- Max. internal pressure: 11ksi (758bar)

**Butt weld:**
- Length on OD: 19mm
- Length on ID: 8mm
- Max. thickness: 10.5mm

**Initial crack:**
- Lack of fusion defect
- Inclined at 10 degrees to the pipe axis
- Ellipse major, minor axes: 3.6mm, 1.8mm
- Ellipse centre w.r.t. point A:
  - Axial offset 1mm, radial offset 1.5mm

**Diagram:**
- Initial elliptic crack
- Weld
- Base metal
Loading condition

- Cyclic load sequence is a variation of internal pressure
  - Low frequency high amplitude cycle
    - One cycle per hour
    - R=0 (0-758 bar)
  - High frequency low amplitude cycle
    - One cycle per minute
    - R=0.85 (644-758 bar)

- Load spectrum idealised as:
  - A single cycle of LFHA
  - Followed by a constant amplitude block of 60 cycles of HFLA
Material data

Mechanical properties:

<table>
<thead>
<tr>
<th>Tensile Modulus of Elasticity (GPa)</th>
<th>Poisson Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld Metal</td>
<td>210</td>
</tr>
<tr>
<td>Base Metal</td>
<td>205</td>
</tr>
</tbody>
</table>

Fracture mechanics properties:

<table>
<thead>
<tr>
<th></th>
<th>LFHA, R = 0</th>
<th>HFLA, R = 0.85</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>m</td>
</tr>
<tr>
<td>Weld Metal</td>
<td>1.35x10&lt;sup&gt;-12&lt;/sup&gt;</td>
<td>3.6</td>
</tr>
<tr>
<td>Base Metal</td>
<td>1.60x10&lt;sup&gt;-14&lt;/sup&gt;</td>
<td>4.8</td>
</tr>
</tbody>
</table>

Paris law coefficients C and m are for da/dn in m/cycle, stress intensity factor in MPa-m<sup>1/2</sup>. The Paris law is expressed in terms of K<sub>max</sub> rather than ΔK:

\[
\frac{da}{dn} = C (K_{max})^m
\]

High frequency low amplitude cycles have a significantly higher threshold than the R=0 cycle and are activated only when the local stress intensity factor exceeds 21MPa-m<sup>1/2</sup>.
Material data

Paris data for the four equations
Material data

Dotted lines show the combined effect of the R=0 and R=0.85 cycles on da/dn for a single spectrum pass.
Modelling principle

• Linear elastic fracture mechanics approach using the finite element method applied to a 3D mesh
  • Zencrack for the crack insertion and crack growth calculations, coupled with,
  • Abaqus/Standard for the finite element solution

• Standard 3D techniques used in modelling the crack including:
  • Collapsed crack front elements with quarter point nodes for $r^{-\frac{1}{2}}$ stress singularity
  • Rings of elements around the crack front for contour integral evaluation
  • Appropriate update of the mesh, boundary conditions and loading as the crack advances
  • Two phase analysis – elliptic phase then breakthrough phase
Modelling principle

- The initial crack is inserted into an uncracked mesh
- Red line shows the required crack position
Modelling principle

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• Red line shows the required crack position
Modelling principle

• Meshing requirements for the material interface and the crack clash with one another
Modelling principle

• Meshing requirements for the material interface and the crack clash with one another
• In general a mesh suitable for the crack cannot also conform to the material interface
Modelling principle

• Solution:
  • Define material properties in user subroutines as a function of position
  • Mesh does not have to follow the material interface
  • The crack can grow across the interface

Abaqus field variables allow the material to be defined by position throughout the mesh (subroutine usdfld).

Zencrack applies a material id to each crack front node position and updates the id as necessary as the crack advances (subroutine material_id).
Modelling principle

- **Solution:**
  - Define material properties in user subroutines as a function of position
  - Mesh does not have to follow the material interface
  - The crack can grow across the interface

Typical mesh during breakthrough phase
Modelling principle

• The calculation of fracture mechanics parameters for nodes near the material interface avoids theoretical complexities of the discontinuity in the stress field at the interface by taking a pragmatic view:
  • The calculation fracture mechanics parameters follow the procedures that would be used in a single material model:
    • appropriate data for one or both materials is used as required
    • there will be some approximation when a crack front node is very close to the interface
  • Studies for inclined cracks in multi-material plates have shown that the effect of the interface is highly localised in terms of global behaviour of the crack shape. The approximation in the modelling of this local effect does not have a globally significant effect on the overall crack behaviour.
  • Small approximations in the numerical approach must be weighed against the reality that fusion lines are not perfectly straight boundaries with instantaneous change of material properties.
Crack growth life calculation methodology

• The crack is analysed at discrete positions during a growth analysis
  • Each discrete position is a new finite element analysis
  • Each position provides a new set of values for the fracture mechanics parameters

• The integration scheme calculates how many cycles of the applied load sequence are used in moving from one discrete crack position to the next

• The integration scheme also controls the crack shape development by using multiple points along the crack front
Crack growth life calculation methodology

• The crack growth prediction scheme in Zencrack is based on the distribution of maximum energy release rate vector, $G_{\text{max}}$, along a crack front.

• Each corner node on the crack front is treated separately.

The values $G_{\text{max}}$ and $\theta_{\text{max}}$ are the nodal growth parameters.
Crack growth life calculation methodology

• Fracture mechanics parameters along the crack front are combined with the spectrum sequence and crack growth law during the integration process
  • Appropriate material id for each crack front node
  • Full account of threshold values in the growth law
    • This has implications for shape development as some crack front points may be below threshold for some or all parts of the spectrum
Crack growth life calculation methodology

• The increment of growth between f.e. analyses controlled by the maximum allowable change in da ($da_{\text{max}}$)

• Integration is then a two-pass process:

Pass 1 integrates all nodes to $da=da_{\text{max}}$. Each node has a different cycle count. A “critical” node having the lowest dN value ($dN_{\text{low}}$) is identified. In this example $dN_1$ is taken as the critical position and so $dN_{\text{low}}=dN_1$.

Pass 2 re-integrates all nodes to the same number of cycles, $dN_{\text{low}}$. In general, the critical node will advance by $da_{\text{max}}$, and all the other nodes will advance by less than $da_{\text{max}}$. 

All nodes integrated to $da_{\text{max}}$. 

All nodes integrated to $dN_{\text{low}}$. 

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Results and discussion

• For comparison purposes results are presented for two cases:
  • LFHA R=0 load only
  • LFHA R=0 load plus HFLA R=0.85 load

• Animations of crack growth for the combined LFHA and HFLA load are shown on the following slides to give an overview of the general behaviour
LFHA R=0 & HFLA R=0.85 load case

Elliptic and breakthrough phases
LFHA R=0 & HFLA R=0.85 load case

Breakthrough phase
LFHA R=0 load case
LFHA R=0 & HFLA R=0.85 load case

Note that the elliptic phase is the same as the R=0 load cases because K values do not exceed the threshold of the R=0.85 equation until after breakthrough.
Comparison of both load cases
LFHA R=0 load case
LFHA R=0 & HFLA R=0.85 load case
Comparison of both load cases
Results and discussion

• While the crack growth animations and profile plots provide an overview of the general behaviour, a significant amount of information is contained within the detail of the results

• Two examples are provided:
  • Detailed distribution of $K$ along specific crack fronts
  • Behaviour of the maximum $K$ for each calculated crack profile
Raised K values after breakthrough due to application of crack face pressure.
LFHA R=0 load case

Distribution of maximum K
LFHA R=0 & HFLA R=0.85 load case

Distribution of maximum K
While the profiles contained subtle differences, the life to leak is clearly reduced by the presence of the HFLA load.

Local high K values at the ends of the crack reduce as the breakthrough crack begins to expand.

Local fluctuations in the LFHA and HFLA case at the HFLA threshold.

Raised K values after breakthrough due to application of crack face pressure.

Local fluctuation due to end of crack crossing the material interface.

- Ellipse
- Blue: Breakthrough, LFHA & HFLA
- Red: Breakthrough, LFHA only
- Dashed: HFLA threshold (Kth=21)
Conclusions

• Today’s fracture analysis requires a case-specific problem-solving capability and needs to precisely compute crack evolution using dynamic evolution of crack fronts in order to justify making structural integrity decisions, particularly for welded structures.

• The approach presented predicts the dynamic evolution of crack shape over the interface of weld and base metal (i.e. across the fusion line) under a mixed loading condition.

• We also proposed to use overall $K_{\text{max}}$ of crack front nodes to monitor and detect the critical integrity moments such as coalescence, crack opening to surfaces, and leak before break.