Session 8 – Fatigue Crack Closure
(i) Experimental evidence

Prof. D. Nowell
University of Oxford, UK

Safe Life and Damage Tolerance

• Many components are still designed on ‘safe life’ principles
  – Use of S-N curves and appropriate safety factors
    • Many components taken out of service with significant remaining life
    • Difficult to ensure required level of safety in some applications

• Safety critical applications more often designed using ‘damage tolerance’ approach
  – Component inspected and cleared of flaws above a certain detection limit
  – Crack propagation prediction from this limit to critical crack size is used to set inspection interval
  – It is therefore important to understand fatigue crack propagation
Crack propagation

- Paris ‘Law’ is often used to describe fatigue crack propagation
  \[ \frac{da}{dN} = A(\Delta K)^n \]

- However, this does not capture all the required effects:
  - Small crack behaviour
  - Load (R) ratio effects
  - Load history effects

- Normally testing is carried out at constant amplitude and fixed R.
- Component load history may be very different
  - E.g. variable amplitude

Fatigue Crack Closure

- First observed by Elber (1970)
- Offers a potential means of explaining ‘non-Paris’ influences on crack propagation rate:
  - Short crack
  - R-ratio
  - Load history
  - Threshold \( \Delta K \)
  - Short cracks

- However:
  - Usefulness of approach is still a matter of some controversy
Mechanisms of fatigue crack closure

- Oxide induced
- Roughness induced
- Plasticity induced

In this presentation, we will be primarily interested in plasticity-induced closure
Difficulties with measurement

- Difficulties in measuring crack closure may be part of the reason for lack of agreement on whether the concept is useful
  - Closure is primarily a surface (plane stress) phenomenon
    - May not show significant influence on overall specimen behaviour
  - Small relative displacements are involved
    - May be much less than overall specimen displacement
  - Crack opening is a gradual process not an event
    - Crack ‘peels open’ from the mouth to the tip
    - We are primarily interested in the point where the tip opens

Measurement approaches

- Compliance measurements
- Electrical resistance
- Full-field displacement measurement
  - Moiré Interferometry
  - Laser Speckle Interferometry
  - Digital Image Correlation
- Thermoelasticity
- Photoelasticity
Compliance measurement

- Original approach used by Elber
- Specimen compliance will be different with a fully open crack than with a partly open one
- Measure variation of displacement or strain with load and detect onset of closure

Compliance measurements

- Rather indirect measurement of closure
- Can be difficult to detect precise opening/closure point
- ‘Offset’ procedures can be helpful (ASTM E647)
Direct displacement measurements

• Most direct approach is to measure displacements of the crack faces
• Normally displacements are small, so enhanced measurement technique must be used to give sufficient resolution
  – Moiré interferometry
  – Laser speckle interferometry
  – Image correlation (with optical magnification)

Moiré interferometry

• Moiré interferometer attached to fatigue machine
• Four-point bending configuration
• Photoresist gratings used
• Fringe sensitivity 0.417 μm
• Measurement of surface displacements at several points in the loading cycle
• Enables investigation of residual displacements and strains close to the crack (also crack closure)
Moiré Interferometer

Use of two beams gives ‘virtual grating’

Typical results - Interferogram
Typical results - displacement image

Digital image correlation - Basic principle

• Original approach used simple cross-correlation
• More recent approaches carry out correlation in Fourier domain
• Sub-pixel resolution of displacement can be obtained.
• Multiple passes with different frame sizes are sometimes used

\[ c(m,n) = \sum_{i=1}^{N_f} \sum_{j=1}^{N_f} f_i(i,j)f_j(i+m,j+n) \]
Public domain software

- Example shown here uses public domain Matlab script by Christoph Eberl

Experimental programme

- Modest focussed investigation using 6082 T6 Al CT specimens to complement modelling work
- Measure crack propagation rate (optically) and crack closure (Image Correlation and remote compliance)
- Use three different thicknesses of CT specimen
  - 3, 10, and 15mm
  - Investigate whether closure is simply a surface phenomenon
- Attempt to correlate:
  - Closure measurements obtained by different techniques
  - Closure measurements with crack propagation rates, across three specimen thicknesses
- Compare results with FE modelling
Experimental setup - CT specimens

- Load cell
- Crack mouth opening displacement gauge
- Back face strain gauge
- Light box
- View from the top
- LED light
- Video camera
- Questar telescope with digital camera
- Laptop 1
- Laptop 2
- Data acquisition system

Questar image

Image shows crack tip area
Simple commercial webcam fitted to Questar microscope
Framing rates up to 30 per second, recorded as .avi file
Camera pixel corresponds to about 90μm on specimen surface
Individual images extracted from .avi file for DIC analysis

Dimensions:
- 420 μm (480 pixel)
- 540 μm (640 pixel)
Crack length, \( a = 14.095 \text{mm} \)

Five locations examined close to crack tip (approx 100 to 500 \( \mu \text{m} \) from tip)

Data averaging carried out for an array of 9 points at each location on either side of crack

**Typical recorded video**

**DIC results**

420 \( \mu \text{m} \) (480 pixel)

540 \( \mu \text{m} \) (640 pixel)
DIC results

Plot shows load/displacement curves for each of the five locations.

L1 is closest to the crack tip.

It is clear that the crack ‘peels open’ from the mouth to the tip.

‘Compliance’ curves from DIC experiment
Compliance data from strain gauges

Strain gauge data showed more noise than DIC data. Filtering (Butterworth) required – particularly for crack mouth gauge

Test programme

<table>
<thead>
<tr>
<th>Specimen Reference</th>
<th>Thickness (mm)</th>
<th>Constant amp loading (kN)</th>
<th>R-ratio</th>
<th>100% overload</th>
<th>Fatigue life</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>P_min</td>
<td>P_max</td>
<td>a (mm)</td>
<td>N cycles</td>
</tr>
<tr>
<td>CTF1</td>
<td>3</td>
<td>1.50</td>
<td>0.10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CTF2</td>
<td>3</td>
<td>2.50</td>
<td>0.10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CTF3</td>
<td>3</td>
<td>2.00</td>
<td>0.25</td>
<td>0.125</td>
<td>-</td>
</tr>
<tr>
<td>CTF4</td>
<td>3</td>
<td>1.75</td>
<td>0.26</td>
<td>0.15</td>
<td>-</td>
</tr>
<tr>
<td>CTF5</td>
<td>3</td>
<td>2.00</td>
<td>0.3</td>
<td>0.15</td>
<td>-</td>
</tr>
<tr>
<td>CTF6</td>
<td>3</td>
<td>2.00</td>
<td>0.25</td>
<td>0.125</td>
<td>29500</td>
</tr>
<tr>
<td>CTF7</td>
<td>3</td>
<td>2.00</td>
<td>0.25</td>
<td>0.125</td>
<td>-</td>
</tr>
<tr>
<td>CTF8</td>
<td>3</td>
<td>2.00</td>
<td>0.25</td>
<td>0.12</td>
<td>28500</td>
</tr>
<tr>
<td>CTMT1</td>
<td>10</td>
<td>6.00</td>
<td>0.60</td>
<td>0.10</td>
<td>-</td>
</tr>
<tr>
<td>CTMT2</td>
<td>10</td>
<td>6.00</td>
<td>0.60</td>
<td>0.10</td>
<td>-</td>
</tr>
<tr>
<td>CTMT3</td>
<td>10</td>
<td>6.00</td>
<td>0.60</td>
<td>0.10</td>
<td>-</td>
</tr>
<tr>
<td>CTMT4</td>
<td>10</td>
<td>6.00</td>
<td>0.60</td>
<td>0.10</td>
<td>45860</td>
</tr>
<tr>
<td>CTMT5</td>
<td>10</td>
<td>6.00</td>
<td>0.60</td>
<td>0.10</td>
<td>-</td>
</tr>
<tr>
<td>CTMT6</td>
<td>10</td>
<td>6.00</td>
<td>0.60</td>
<td>0.10</td>
<td>65000</td>
</tr>
<tr>
<td>CTMT7</td>
<td>10</td>
<td>6.00</td>
<td>0.60</td>
<td>0.10</td>
<td>-</td>
</tr>
<tr>
<td>CTT1</td>
<td>25</td>
<td>12.50</td>
<td>1.25</td>
<td>0.10</td>
<td>-</td>
</tr>
<tr>
<td>CTT2</td>
<td>25</td>
<td>12.50</td>
<td>1.25</td>
<td>0.10</td>
<td>-</td>
</tr>
<tr>
<td>CTT3</td>
<td>25</td>
<td>12.50</td>
<td>1.25</td>
<td>0.10</td>
<td>170000</td>
</tr>
<tr>
<td>CTT4</td>
<td>25</td>
<td>12.50</td>
<td>1.25</td>
<td>0.10</td>
<td>-</td>
</tr>
<tr>
<td>CTT5</td>
<td>25</td>
<td>12.50</td>
<td>1.25</td>
<td>0.10</td>
<td>-</td>
</tr>
</tbody>
</table>
Comparison of measured opening loads

3mm thick specimen

25mm thick specimen

Crack propagation curves

- Specimen thickness affects crack propagation rate
- For a given $\Delta K$, cracks in thick specimens propagate faster
- One possible explanation is different opening loads
Use of crack closure measurements

\[ \frac{da}{dN} = C(\Delta K_{\text{eff}})^n \]

**Effective stress intensity factor range:**

\[ \Delta K_{\text{eff}} = (\sigma_{\text{max}} - \sigma_{\text{op}})\sqrt{\pi \cdot a} \]

Hence the need to find the opening stress, \( \sigma_{\text{op}} \), experimentally.

This can then be correlated with appropriate predictive models which can be used in fatigue life prediction.

---

Use of effective delta K

- Crack growth rates plotted against effective \( \Delta K \), with opening loads taken from experimental data
- Back face gauge measurements provide better correlation than DIC closure measurements
Overload effects

• Application of a single overload during constant amplitude cycling results in significant crack retardation
  – Effect is most significant with thinner specimens

Overload effects

• Measurements show reduced closure levels immediately after an overload, then increased values, before slowly returning to original values
  – Effective delta K decrease may provide explanation for crack retardation
Summary – Session 8

• Digital image correlation appears to be a practical means of measuring fatigue crack closure
• Measured values of opening loads relate to the surface only and appear to correlate reasonably well with predictions from plane stress and 3D finite element modelling
• Differences in crack propagation rate are observed for different thickness specimens
• These differences can be explained using the experimental closure measurements
• However, back face strain gauge compliance measurements give a better correlation
• These are more representative of ‘average’ closure levels
• Fatigue crack closure is a complex phenomenon and its use in practical damage tolerant fatigue life calculations is far from straightforward.