The Effect of Stress Intensity Factor Models on Inspection Intervals

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Outline

• **K Solutions**
  ◦ Geometric & Loading Parameter Space
  ◦ Verification
  ◦ Validation

• **Fatigue Life Predictions Using New K Solutions**
  ◦ Fatigue Life
  ◦ Continuing Damage Scenario
    › Phase I Life
    › Crack Size
  ◦ Effect of r/t

• **Conclusions**
Small differences in $K$ Solutions yield large cumulative differences in fatigue life

...and large differences in $K$ solutions yield even a larger cumulative difference in fatigue life
Parameter Space

K-Solutions, $\approx 1.0$ million CPU Hours

- **Geometry**
  - Centrally Located Straight Shank Hole
    - $0.1 \leq r/t \leq 10.0$
    - $0.1, 0.111, 0.125, 0.1428, 0.1667, 0.2, 0.25, 0.333, 0.5, 0.667, 0.75, 0.8, 1.0, 1.25, 1.333, 1.5, 1.667, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0 (r/t = 0.5, 1.0)
  - Finite Width/Height Plate
    - $r/h = 0.0025$
    - $r/b = 0.0025$

- **Crack Shapes**
  - $0.1 \leq a/c \leq 10.0$
    - $0.1, 0.111, 0.125, 0.1428, 0.1667, 0.2, 0.25, 0.333, 0.5, 0.667, 0.75, 0.8, 1.0, 1.25, 1.333, 1.5, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0 (a/c = 0.2, 0.5, 0.8, 1.0, 2.0)
  - $0.1 \leq a/t \leq 0.99$
    - $0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 0.95, 0.99 (a/t = 0.2, 0.5, 0.8)

- **Load Conditions**
  - Tension
  - Bending
  - Pin Loading (Bearing)

- **5,672,700** solutions
K-Solution
Verification
Convergence: Shallow Crack

\[
\frac{K_I}{\sigma \sqrt{\pi c}} = 1.0
\]

\[
r/t = 1.0 \\
a/c = 0.1 \\
a/t = 0.1 \\
2b = 2h = 200r = 400
\]
Convergence: Deep Crack

\[
\frac{K_I}{\sigma \sqrt{\pi c}}
\]

- \( p = 2 \) \( r/t = 1.0 \)
- \( p = 3 \) \( a/c = 0.1 \)
- \( p = 4 \) \( a/t = 0.99 \)
- \( 2b = 2h = 200 \)
- \( r = 400 \)
- \( p = 5 \)
- \( p = 6 \)

Graph showing the relationship between \( \frac{2\varphi}{\pi} \) and \( \frac{K_I}{\sigma \sqrt{\pi c}} \) for different values of \( p \) and conditions.
K-Solution Validation
Test Specimen Configuration

\[ \sigma \]

\[ W \]

\[ \sigma \]

\[ c_1 \]

\[ c_2 \]

\[ a_1 \]

\[ a_2 \]

\[ t \]

Crack plane
Marker Load Spectrum

100 cycles

10 cycles

2000 Cycles

100 cycles

10 cycles

2000 Cycles

100 cycles

10 cycles

2000 Cycles

1 program = 8170 cycles
Fatigue Life Prediction

Test 3, 7075-T651
w=49.17 mm, t=6.36 mm, r=3.23 mm
c₁=2.76 mm, c₂=1.75 mm

Crack Length (mm)

Cycles

AFGROW Left Crack
Measured Left Crack
AFGROW Right Crack
Measured Right Crack
Crack Shape Development
Crack Shape Development
Crack Shape Development

![Graphs showing crack shape development](image_url)
Fatigue Life Predictions Using New $K$ Solutions
Geometry for Assessing Effect on Life

**Small Crack – Thin Sheet**

$W = 1.14$ in, $t = 0.063$ in, $D = 3/16$ in

$a_i = 0.01$ in, $c_i = 0.01$ in, $a_i/t = 0.2$

$a_i/c_i = 1.0$, $r/t = 1.5$

$TSR = 1.0$, $BSR = 0.4$

**Small Crack – Thick Sheet**

$W = 4.53$ in, $t = 0.25$ in, $D = 3/4$ in

$a_i = 0.05$ in, $c_i = 0.05$ in, $a_i/t = 0.2$

$a_i/c_i = 1.0$, $r/t = 1.5$

$TSR = 1.0$, $BSR = 0.4$

**Large Crack – Thin Sheet**

$W = 1.14$ in, $t = 0.063$ in, $D = 3/16$ in

$a_i = 0.05$ in, $c_i = 0.05$ in, $a_i/t = 0.8$

$a_i/c_i = 1.0$, $r/t = 1.5$

$TSR = 1.0$, $BSR = 0.4$
Effect on Life – Small Crack, Thin Sheet

Parameters:
- Width $W = 1.14$ in, thickness $t = 0.063$ in, depth $D = 3/16$ in
- Initial crack length $a_i = 0.01$ in, initial crack width $c_i = 0.01$ in
- $a_i/t = 0.2$, $a_i/c_i = 1.0$, $r/t = 1.5$
- TSR = 1.0, BSR = 0.4

Graph shows the percentage change in fatigue life ($N_{F,IA} - N_{F,IR}$) for different spectrum types and stress levels.
Effect on Life – Small Crack, Thick Sheet

Potential for initial inspection of damage tolerant (rogue flaw) not occurring early enough in the aircraft life

- Two Symmetric Corner Cracks
- Single Corner Crack

\[ W = 4.53 \text{ in}, \ t = 0.25 \text{ in}, \ D = 3/4 \text{ in} \]
\[ a_i = 0.05 \text{ in}, \ c_i = 0.05 \text{ in} \]
\[ a_i/t = 0.2, \ a_i/c_i = 1.0, \ r/t = 1.5 \]
\[ TSR = 1.0, \ BSR = 0.4 \]
Effect on Life – Large Crack, Thin Sheet

\[ W = 1.14 \text{ in}, \ t = 0.063 \text{ in}, \ D = \frac{3}{16} \text{ in} \]
\[ a_i = 0.05 \text{ in}, \ c_i = 0.05 \text{ in} \]
\[ a_i/t = 0.8, \ a_i/c_i = 1.0, \ r/t = 1.5 \]
\[ TSR = 1.0, \ BSR = 0.4 \]

**Potential for initial inspection of damage tolerant (rogue flaw) not occurring early enough in the aircraft life**

<table>
<thead>
<tr>
<th>Spectrum Type and Maximum Stress Level</th>
<th>CA 10</th>
<th>CA 18</th>
<th>Falstaff 10</th>
<th>Falstaff 18</th>
<th>TWIST 10</th>
<th>TWIST 18</th>
<th>Marker 10</th>
<th>Marker 18</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{N_{F/E/A} - N_{F/N/R}}{N_{F/E/A}} \times 100 ) (%)</td>
<td></td>
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</tr>
</tbody>
</table>
Geometry for Assessing Effect on Continuing Damage Scenario

\[ W = 1.14 \text{ in}, \ t = 0.063 \text{ in}, \ D = \frac{3}{16} \text{ in} \]
\[ a_1 = 0.05 \text{ in}, \ c_1 = 0.05 \text{ in} \]
\[ a_2 = 0.005 \text{ in}, \ c_2 = 0.005 \text{ in} \]
\[ \frac{a_1}{t} = 0.8, \ \frac{a_2}{t} = 0.08, \ \frac{a_i}{c_i} = 1.0, \ \frac{r}{t} = 1.5 \]
\[ TSR = 1.0, \ BSR = 0.4 \]
Effect on Continuing Damage Scenario Phase I Life

- \( W = 1.14 \text{ in} \), \( t = 0.063 \text{ in} \), \( D = 3/16 \text{ in} \)
- \( a_1 = 0.05 \text{ in} \), \( c_1 = 0.05 \text{ in} \)
- \( a_2 = 0.005 \text{ in} \), \( c_2 = 0.005 \text{ in} \)
- \( a_1/t = 0.8 \), \( a_2/t = 0.08 \), \( a_1/c_1 = 1.0 \), \( r/t = 1.5 \)
- \( TSR = 1.0 \), \( BSR = 0.4 \)

Spectrum Type and Maximum Stress Level

- CA 10
- CA 18
- Falstaff 10
- Falstaff 18
- TWIST 10
- TWIST 18
- Marker 10
- Marker 18
Effect on Continuing Damage Scenario Phase I Crack Length

- Crack Tip
  - $W = 1.14$ in, $t = 0.063$ in, $D = 3/16$ in
  - $a_1 = 0.05$ in, $c_1 = 0.05$ in
  - $a_2 = 0.005$ in, $c_2 = 0.005$ in
  - $a_1/t = 0.8$, $a_2/r = 0.08$, $a_1/c_1 = 1.0$, $r/t = 1.5$
  - $TSR = 1.0$, $BSR = 0.4$

Spectrum Type and Maximum Stress Level

- CA 10
- CA 18
- Falstaff 18
- TWIST 10
- TWIST 18
- Marker 10
- Marker 18
Effect of $r/t$ – Symmetric Corner Cracks

**Symmetric Corner Cracks**

$W/D = 100$, $a_i/c_i = 1.0$

$a_i = c_i = 0.05$ mm

"Thin Sheet" $\rightarrow a/t = 0.8$

"Thick Sheet" $\rightarrow a/t = 0.2$

- F/A Thin Sheet
- N/R Thin Sheet
- F/A Thick Sheet
- N/R Thick Sheet
Effect of $r/t$ – Single Corner Crack

Single Corner Crack

$W/D = 100, a_i/c_i = 1.0$

$a_i = c_i = 0.05$ in

"Thin Sheet" → $a/t = 0.8$

"Thick Sheet" → $a/t = 0.2$

- F/A Thin Sheet
- N/R Thin Sheet
- F/A Thick Sheet
- N/R Thick Sheet
Conclusions

• Verification
  ° \( h p \)-version FEA + Splitting Scheme = Accurate \( K \)-Solutions

• Validation
  ° Fatigue life predictions are slightly conservative

• 5,672,700 \( K \) solutions for unsymmetric corner cracks at a hole subject to tension, bending, bearing
  ° Solutions available in tabular form – currently in \textit{AFGROW}
    › 75 – 1.5MB ASCII files
  ° Source code for multi-dimensional interpolation also available
Significance

• Single vs. Double Cracks
  ◦ Difference always larger for single cracks

• Effect on Fatigue Life
  ◦ Small cracks in thin sheets: 20-50%
  ◦ Small cracks in thick sheets: 25-45%
  ◦ Large cracks in thin sheets: 90-300%
  ◦ Continuing damage scenario: 125-350%

• Effect on Inspections
  ◦ Possibility of initial inspection not early enough in aircraft life
  ◦ Possibility of recurring inspections not occurring as frequently as required

• Effect of $r/t$
  ◦ Significant for large cracks in thin sheets
  ◦ Negligible for small cracks in thick sheets