Cold Expansion Effects on Cracked Fastener Holes under Constant Amplitude and Spectrum Loading in the 2024-T351 Aluminum Alloy

By
Jacob John Warner

Mechanical Engineering Department
University of Utah
AGENDA

• Cold Expansion
• Previous Research
• Research Objectives
• Test Procedure
• AFGROW Analysis
• Results
• Discussion
• Conclusions
• Recommendations
• References
Cold Expansion

• Invented by Boeing in 1965
• Licensed technology to FTI

Fig. 1 Cold Expansion Equipment

- Mandrel
- Jaws
- Nose Cap

Mandrel retracts to cold expand hole

Fig. 2 Cold Expansion Process
Cold Expansion Effects

Fig. 3 Split Sleeve Mark from Cold Expansion

Fig. 4 Residual Stresses from Cold Expansion

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Previous Research

• Cold Expansion (CX) does not benefit cracks larger than the hole radius.$^{2,3}$
• CX only retards growth of cracks greater than 0.04”.$^{4,5,6}$
• Life benefit from CX is less for spectrum loading than constant amplitude loading.$^{3,7,8}$
• Tensile overloads increase life, compressive overloads decrease life.$^{9}$
• Residual stress models in AFGROW have good agreement with test data.$^{2,10}$
Research Objectives

- Validate test setup with ASTM E 647 standard
- Quantify life benefit of pre-cracked (PC)-CX hole
- Compare life benefit of CX hole to PC-CX hole
- Evaluate agreement of test and 0.005” Initial Flaw Size (IFS) AFGROW prediction¹¹

Fig. 5 Research Goal
Test Procedure (Specimens)

- 2024-T351 Aluminum Plate
- 4” wide x 0.25” thick
- 0.5” final diameter hole
- Pre-cracked at 20 ksi
- ~0.05” fatigue pre crack
- Constant Amplitude
  - Stress Ratio = 0.1
  - Frequency = 20 Hz
  - Max Stress 25, 20 ksi
- Spectrum
  - A-10 wing spectrum
  - Load rate = 500,000 lbs/sec
  - Max Stress 25, 30, 33, 43 ksi

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Fig. 6 Test Specimen
Test Procedure (Test Equipment)

- Interlaken™ Load Frame
- MTS™ Grips and Intensifier
- Interface™ Load Cell
- Gaertner Scientific™ Scopes
- Instron 8800 FastTrack™ Controller
  - Random Loading v. 8.0.1
  - DADN v. 8.4.12

Fig. 7 Fatigue Test Equipment
Test Procedure (Example Test, 40 ksi)

Fig. 8 Example Video Geometry
Test Procedure (Example Test)
AFGROW Analysis (Lookup File)

- ASTM E 647 lookup file baseline
  - Lookup file A (85% agreement): Always conservative
  - Lookup file B (90% agreement): More agreement with test, not always conservative

Fig. 9 Crack Growth Rate Graph

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AFGROW Analysis (Lookup File)

Fig. 10 ASTM E 647 Data and Predictions
AFGROW Analysis

- Used non CX, Constant Amplitude (CA) data from Carlson’s research.
- Optimized aspect ratio parameters.
- Generalized Willenborg model used for spectrum retardation. Shutoff Overload Ratio (SOLR) is the only input parameter.
- Optimized SOLR’s for non CX Spectrum Tests.

![Diagram of Aspect Ratio: a/c](image)

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Actual Crack Lengths</th>
<th>Average Crack Lengths</th>
<th>Percent Disagreement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vary a/c</td>
<td>Constant a/c</td>
<td>Vary a/c</td>
</tr>
<tr>
<td>Scott NCX 2024-3</td>
<td>29.23%</td>
<td>51.15%</td>
<td>29.09%</td>
</tr>
<tr>
<td>Scott NCX 2024-4</td>
<td>31.12%</td>
<td>22.98%</td>
<td>32.05%</td>
</tr>
<tr>
<td>Average</td>
<td>30.18%</td>
<td>37.07%</td>
<td>30.57%</td>
</tr>
</tbody>
</table>

Max Stress (ksi) | Average SOLR for Lookup File A | Average SOLR for Lookup File B | Average SOLR for A-10 Lookup File
--- | --- | --- | ---
25 | 1.88 | 1.82 | 1.68
30 | 1.85 | 1.79 | 1.64
33 | 1.83 | 1.78 | 1.62
43 | 1.94 | 1.90 | 1.69

Fig. 10 Aspect Ratio Optimization (Lookup File B)

Fig. 11 SOLR Optimization
AFGROW Analysis

- Lookup File A always had best fit to test data

Fig. 11 Fit of Predictions
Results (PC-CX, CA, 20 ksi)

- 2 grip failures
- Average PC-CX life 4,296,067 cycles
- Average Life Improvement Factor (LIF): 90.5
- Minimum LIF: 29.6
- Weibull $\beta=1.6$
- Prediction A: 52,606 cycles
- Prediction B: 55,099 cycles

Fig. 12 Test Data and Predictions
Results (PC-CX, CA, 25 ksi)

- CX life (Carlson)\(^{12}\): 531,776 cycles
- CX LIF: 71.4
- PC-CX life: 452,585 cycles
- PC-CX LIF: 60.8
- Weibull \(\beta\)=6
- Prediction A: 22,097 cycles
- Prediction B: 23,277 cycles

Fig. 13 Test Data and Predictions
Results (NCX Spectrum)

- **NCX 25 ksi spectrum**
  - Life: 31,521 flight hours
  - Weibull $\beta = 15.3$
- **NCX 33 ksi spectrum**
  - Life: 12,200 flight hours
  - Weibull $\beta = 10.8$
- **NCX 43 ksi spectrum**
  - Life: 4,657 flight hours

Fig. 14 Non CX Test Data
Results (PC-CX, 25 ksi, Spectrum)

- PC-CX failed in grip after 704,450 flight hours
- LIF: 22.4
- Failed in the hole after 831,641 flight hours
- LIF: 26.4
- Prediction A: 86,611 flight hours
- Prediction B: 75,729 flight hours

Fig. 15 Test Data
Results (PC-CX, 30 ksi, Spectrum)

- PC-CX life: 194,950 flight hours
- Weibull $\beta=7.3$
- LIF: 9.9
- Prediction A: 43,923 flight hours
- Prediction B: 50,197 flight hours

Fig. 16 Test Data
Results (PC-CX, 33 ksi, Spectrum)

- PC-CX life: 80,220 flight hours
- Weibull $\beta=8.7$
- LIF: 6.6
- Prediction A: 32,677 flight hours
- Prediction B: 37,277 flight hours

Fig. 17 Test Data
Results (PC-CX, 43 ksi, Spectrum)

- PC-CX life: 6,201 flight hours
- Weibull $\beta=18.7$
- LIF: 1.3
- Prediction A: 9,357 flight hours
- Prediction B: 10,031 flight hours
Discussion

- LIF decreases with increasing stress

<table>
<thead>
<tr>
<th>Loading</th>
<th>Max Stress (ksi)</th>
<th>Non-CX Life (cycles)</th>
<th>PC-CX Life (cycles)</th>
<th>LIF NCX to PC-CX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant Amplitude</td>
<td>20</td>
<td>47443</td>
<td>4296067</td>
<td>90.6</td>
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<tr>
<td>Amplitude</td>
<td>25</td>
<td>7443</td>
<td>452585</td>
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<td>Spectrum</td>
<td>25</td>
<td>31521</td>
<td>704450</td>
<td>22.3</td>
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<td></td>
<td>30</td>
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<td>194950</td>
<td>10.3</td>
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<td></td>
<td>33</td>
<td>12201</td>
<td>80220</td>
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<td></td>
<td>43</td>
<td>4658</td>
<td>6201</td>
<td>1.3</td>
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Fig. 19 LIF Plot

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Discussion

- 0.005” IFS is non-conservative at 43 ksi max stress, even with a conservative lookup file.

<table>
<thead>
<tr>
<th>Loading</th>
<th>Max Stress (ksi)</th>
<th>Average Ratio of Tested Life to Predicted Life Lookup File A</th>
<th>Average Ratio of Tested Life to Predicted Life Lookup File B</th>
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<tbody>
<tr>
<td>Constant Amplitude</td>
<td>20</td>
<td>81.60</td>
<td>77.92</td>
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<td></td>
<td>25</td>
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<td>Spectrum</td>
<td>25</td>
<td>8.13</td>
<td>9.30</td>
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<td></td>
<td>30</td>
<td>4.44</td>
<td>3.88</td>
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<td></td>
<td>33</td>
<td>2.45</td>
<td>2.15</td>
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<tr>
<td></td>
<td>43</td>
<td>0.66</td>
<td>0.62</td>
</tr>
</tbody>
</table>

Fig. 20 Non Conservative Prediction
Discussion

• Material Yield Strength: 48.1 ksi
• Yield for K_t=3: 16 ksi
• Ultimate Strength: 68.4 ksi
Discussion

- Crack growth due to CX
  - ~0.0014” growth on surface
  - ~0.003” growth down bore
- CX benefit dropped 15% for 0.05” pre-existing crack
- Average absolute error in spectrum less than 2.5%

\[
\text{Damage Parameter} = \Gamma = \left( \frac{P_{\text{actual}}}{P_{\text{command}}} \right)^m
\]

<table>
<thead>
<tr>
<th>Max Stress (ksi)</th>
<th>Load Rate (kip/sec)</th>
<th>Average Absolute Percent Error</th>
<th>Average Damage Parameter</th>
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<tbody>
<tr>
<td>43</td>
<td>500</td>
<td>1.18%</td>
<td>1.04</td>
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<tr>
<td>33</td>
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<td>1.66%</td>
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<td>1.01</td>
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<td>2.50%</td>
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<td>500</td>
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<td>1.00</td>
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<td>200</td>
<td>1.35%</td>
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<td></td>
<td>100</td>
<td>2.02%</td>
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</table>

Fig. 21 Error Loading\textsuperscript{13}
Conclusions

• Test data is valid as per ASTM E 647 standard
• Fatigue life of PC-CX holes were quantified for constant amplitude and spectrum loading
• LIF of a CX hole is decreased by ~15% due to a pre-existing 0.05” crack
• AFGROW models using 0.005” IFS were compared with test data.
• AFGROW predictions become non conservative for spectrum tests with 43 ksi max stress
• The LIF from cold expansion is greater for constant amplitude loading than spectrum loading
Recommendations

• Employ physics based model to account for residual stresses in cold expanded holes
• Conduct further testing at various stress levels to identify when the 0.005” IFS assumption becomes non conservative
• Test various edge margins to identify the stress and edge margin limits where the 0.005” IFS assumption becomes non conservative
• Investigate residual stress models available in AFGROW to determine whether one is suitable for predicting cold expanded holes
• Test the effects of common fastener systems in cold expanded holes
• Quantify the residual stress from cold expansion, especially at the crack tip
• Test the effects of other pre-existing discontinuities on cold expansion
  – Gouges, discontinuities from fretting and wear, etc.
References


References (Continued)


Questions?

- Initial Corner Crack
- P Shape Crack Front
Ream Lines

EDM notch