Analytical Verification of Crack Propagation through Cold Expansion Residual Stress Fields

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OUTLINE

• Analysis of engineered residual stress fields using ABAQUS
• Using residual stress fields in BEASY crack growth analysis
• Overview of the selected test case
• BEASY approaches used to match the test case
• Conclusions and Future Work
Analysis of engineered residual stress fields using ABAQUS

- Non-linearities evaluated:
  - Material non-linearity (plasticity)
  - Geometric non-linearity
    - Displacement
    - Contact

- Correlation/verification:
  - Physical Test (deformation, strain)
  - Laboratory Test (XRD, contour)
  - Closed-form solutions
Analysis of engineered residual stress fields using ABAQUS

1. Split Sleeve Cx Problem Definition
2. Pull mandrel through hole
3. Allow for stress relaxation
4. Final Ream
5. Remote Load Step
6. Generate Reports
7. Residual Stress (RS) Database
8. Fatigue/Fracture Analysis

Decision Points:
- Precise ream?
  - Yes → Resize ream partition
  - No / Done
- EXPLICIT
- IMPLICIT
Analysis of engineered residual stress fields using ABAQUS

- Residual Stress (RS) Database
  - **Integrating Residual Stress Analysis of Critical Fastener Holes into USAF Depot Maintenance**
    - See Section 4.6 (pp43-48).
    - Developed by APES, ESRD

- Fatigue/Fracture Analysis
  - 2D analyses
    - AFGROW (using RS database)
    - NASGRO
  - 3D discretized analyses
    - XFEM (ABAQUS)
    - FRANC3D
    - STRESSCHECK
    - BEASY

▲ RS Database visualizer

▼ SIF Solutions

▼ Cycles to Failure Estimates

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DM#740763
Analysis of engineered residual stress fields using ABAQUS

FEA Examples

- Composite Structure Analysis
- Installation Process Optimization
- Landing Gear Rib with ForceMate
- High Load Transfer Specimen with Split Sleeve Cold Expansion (section view)
Using residual stress fields in BEASY crack growth analysis

• Engineered residual stresses change the crack growth behavior
  – Compressive residual stress = slower growth
  – Tensile residual stress = faster growth
  – Crack growth rates may vary across the crack front
  – Cracks will grow through regions with varying residual stress levels

• BEASY with FEA results can be used to evaluate these effects.
Using residual stress fields in BEASY crack growth analysis

• The process for creating this residual stress simulation using BEASY
  – Create “Boundary Element” model of the cracked part
  – Add a crack or cracks to the Boundary Element model
  – Apply the residual stress field from FEA to the crack surface
  – Compute stress intensity factors via summation rule
  – Crack growth determined by desired relationship (NASGRO equation, Paris, etc)

$$\Delta K = K^A - K^B$$

$$K^A = \max(K_{\text{max}}^R + K^R, 0)$$

$$K^B = \max(K_{\text{min}}^R + K^R, 0)$$

$$\frac{da}{dN} = C\Delta K^m$$
Using residual stress fields in BEASY crack growth analysis

- FEA Model Geometry
- FEA Model Res. Stresses
- Loading Condition

BEASY BE Model

- Add crack(s)
- Compute SIFs
- Propagate Crack(s)

Create new crack geometry

Automated internal step

Automated external step

Update geo?

Continue growth?

Generate Reports

Yes

No

Yes
Overview of the selected test case

- **OH fatigue coupon geometry**
  - 5/16” fastener hole
  - 2.35” plate width
  - 0.25” plate thickness

- **2024-T3 material**
  - $\sigma_{ys} = 48.315$ ksi
  - Paris relationship
    - $C = 3.09 \times 10^{-9}$ ksi-in$^{1/2}$
    - $m = 2.895$

- **30 ksi gross stress@ R=0.05**
Overview of the selected test case

Residual Hoop Stress

Stress, psi

Radial Distance from hole, inch

Shaded area shows approximate extent of crack propagation in BEASY
Overview of the selected test case

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Cold Work</th>
<th>Max Gross Stress (ksi)</th>
<th>R-ratio</th>
<th>Run-out Definition (cycles)</th>
<th>Stop or Failed Cycles</th>
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<tbody>
<tr>
<td>FS0453-1</td>
<td>No</td>
<td>30</td>
<td>0.05</td>
<td>1,000,000</td>
<td>Failed</td>
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<tr>
<td>FS0453-2</td>
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<td>0.05</td>
<td>5,000</td>
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<tr>
<td>FS0453-3</td>
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<td>10,000</td>
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<td>0.05</td>
<td>1,000,000</td>
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<tr>
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<td>37,000</td>
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<td>Failed</td>
</tr>
</tbody>
</table>

FS0453-5 Stopped after 17,000 cycles

FS0453-6 Stopped after 37,000 cycles
BEASY approaches used to match the test case

- Initial crack geometry (first trials):
  - Entry crack initial radius = 0.005”
  - The exit crack initial radius = 0.003”
  - Cracks normal to load (Mode I only)

- Loading and propagation relationship:
  - Constant amplitude for Mode I
  - 30 ksi maximum gross stress, $R = 0.5$
  - Paris relationship, no retardation effects
  - Static residual stress field

- Simulation Aims:
  - Can we simulate the observed damage?
  - How do the fatigue results compare?
BEASY approaches used to match the test case

- Under the crack growth simulation, the computed SIF results are used to advance the crack.
- New meshes are created and new SIF values computed during the simulation.
- Due to combination of the compressive residual stresses and the dynamic opening load, the entry crack grows faster than the exit crack.

Numbers are cycle counts to grow the crack (crack nucleation is at 30000 cycles).
BEASY approaches used to match the test case

- The fatigue life for this simulation provides generally good agreement with the test results that were obtained.
- This simulation only includes cracks on one side of the hole.
- The simulation was not continued after the cracks joined.

★ FS0453-6
Stopped after 37,000 cycles
BEASY approaches used to match the test case

• The simulation with two cracks provides a good agreement with the test results but does not explain some of the crack shapes seen during test.

• The compressive residual stress slows the growth of cracks and therefore it is likely that further new cracks will initiate along the bore during the load cycling.

• This has been evaluated using a third crack along the bore.
BEASY approaches used to match the test case

- This simulation shows some agreement with crack profiles that have been viewed during the testing.
- This indicates that these profiles could be created by multiple crack nucleation along the bore.

Numbers are cycle counts to grow the cracks:
- 30000
- 35400
- 37400
- 41900
BEASY approaches used to match the test case

- During the life, it is therefore conceivable for many cracks to nucleate along the bore – here 5 cracks have been simulated

- The grown cracks here resembles those seen practice

- The crack growth was stopped at coalescence

- With crack geometry update the analysis could be continued to a point resembling the actual crack front.

FS0453-6
Stopped after 37,000 cycles

Cycle counts to grow the crack
Conclusions

• The simulation work carried out indicates that the crack growth profiles observed in testing cannot be explained purely by the Paris-driven growth of corner cracks initiating in the part
  – Observed crack growth profiles require multiple interacting cracks initiating on the hole bore.
  – Total damage is a combination of the crack initiation and growth.
  – In this scenario, we hypothesize that the initiation of new cracks is more prevalent due to the reduction in the crack growth rate.

• The simulation should ideally be continued with crack growth of the coalesced cracks until the critical crack size has been reached.
Future Work

• Further work could be carried out using this combination of residual stress evaluation and crack growth simulation:
  – Continue current analysis with joined cracks
  – Evaluate with alternate crack growth relationship

• Looking further ahead to different cases using BEASY:
  – Cracks under different load conditions (CA vs spectrum, compressive loading)
  – Cracks from filled holes
  – Cracks from ForceMated (bushed) holes
Questions?