Mitigation of Crack Damage in Metallic Materials

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Outline

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Problem Statement

- Problem
  - Portion of service life manageable by damage tolerance is too small
  - Frequent inspections are costly

- Potential Solutions
  - Improve crack inspection
    - Greater sensitivity
    - Structural health monitoring
  - Damage mitigation
    - “Healing” of cracks
Background – Crack closure

- Fatigue crack closure
  - Crack-face contact during cyclic loading
- Studied since 1960s
- Significance greatest near the FCG threshold
- Multiple crack closure mechanisms operate near $\Delta K_{th}$
• Near-threshold fatigue crack closure mechanisms
  – Plasticity
  – Roughness
  – Oxide debris

• Can crack closure be exploited?
IVHM milestones being worked

• IVHM Project Milestones Supported
  – 2.2.4.1 – Demonstrate integrated self-healing material system concepts for in-situ mitigation of fatigue crack damage in structural elements
  – 1.1.4.1 – Engineered materials for structural health management and mitigation of structural fatigue crack damage

• How this work fits into the IVHM project
  – Damage/fatigue crack mitigation
    • Mitigate further airframe damage through in-situ application of self-healing materials
    • Materials with self-healing capability of great benefit where fatigue crack inspection access is limited or damage is difficult to detect
    • New design and analysis methodologies will be developed to fully-exploit self-healing material systems concepts.
Approach

- Metallic specimen coated with healing agent
- Crack healing process
  - Cracked specimen + Energy
  - Healing agent fills crack mouth
  - Solidification
- Benefits
  - Adheres to crack faces (bridging)
  - Fills crack mouth (crack closure)
  - Reusable
Results

Crack Arrest Example (Titanium)

- Steady-state FCG
  - $\Delta K = 6.6$ ksi$\sqrt{\text{in}}$; $R = 0.1$
- Reduction in “crack length” after healing is a result of in-situ crack monitoring
- Some damage of healing material, but crack fails to propagate (never returns to original value)
Results (continued)

Crack Retardation Example (Titanium)

- Initially steady-state FCG
  - $\Delta K = 13.2 \text{ ksi}\sqrt{\text{in}}; R = 0.1$
- Reduction in “crack length” after healing is a result of in-situ crack monitoring
- Crack length returns to pre-healing value after approximately 8,000 cycles
- After healing agent is cracked, crack growth rate still slower
- Approximately 250,000 cycle delay, followed by 55% reduction in crack growth rate

\Delta K = 13.2 \text{ ksi}\sqrt{\text{in}}, R = 0.1

Cycles (x 1,000)

Effective Crack Length, $a$ (inches)

- 2.0x10^{-6} inch/cycle
- 8.9x10^{-7} inch/cycle

Damage state without healing

Before healing
- 8.9x10^{-7} inch/cycle

After healing
- 2.0x10^{-6} inch/cycle
• Results from multiple experiments plotted similar to fatigue-life curves
  – Breakdown of bridging mechanism as function of crack-driving force
  – Closure mechanism still active
• Similar result obtained for aluminum
• $\Delta K = 6.6 \text{ ksi} \sqrt{\text{in}}$ likely near “endurance limit”
• Analytical model needed to correlate healing agent properties to performance
  – Revisit selection of materials
• More results are needed to “populate” curve
Experimental Results (continued)

Titanium Healing Results (Crack Growth Rate Reduction)

- Results after breakdown of bridging
- Plotted as crack growth rate ratio
  - Ratio of steady state $da/dN$ before and after healing
- Better performance at lower crack driving forces
- In all cases tested, IVHM milestone 1.1.4.1 was more than met
  - Greater than a factor of 2 reduction in driving force
  - Significant crack growth delay
  - In one case, crack arrest occurred
- Healing process is repeatable
  - After cracking healing agent can be reactivated

Exceeded IVHM milestone 1.1.4.1
Significance of Results (Background)

• Service cracks
  – Grow from initial to critical size
• Constant-load conditions
  – $da/dN$ increases with crack size
• Healing extends fatigue life, $N_f$
  – Reduction in crack growth rate
• Critical initial flaw size*, $a_{CIFS}$
  – Largest crack that will survive four service lives

* References: (1) NASA-STD-5001, “Structural Design and Test Factors of Safety for Spaceflight Hardware”
(2) NASA-STD-5019, “Fracture Control Requirements for Spaceflight Hardware”
(3) Federal Aviation Administration FAR 25.571
Significance of Results
(Example #1 – Center-cracked plate)

- Cracking of aircraft skin
  - Majority of fatigue life initiating/propagating small crack (low $\Delta K$)
  - Minimal interaction with surrounding structure
- Modeled as a center-cracked plate
  - Crack growth analysis done using NASGRO

* Reference: NASGRO Version 5.21
Significance of Results
(Example #1 – Center-cracked plate)

• Model geometry
  – Panel width, \( W = 36 \) inches
  – Panel thickness, \( t = 0.1 \) inches
  – Tensile stress, \( S_o = 12 \) ksi
  – Service life, \( N_f = 100,000 \) cycles

• Increase in CIFS by factor of 4.9
  – No healing, \( a_{CIFS} = 0.168 \) inches
  – Healing, \( a_{CIFS} = 0.822 \) inches

![Graph depicting Crack length vs. Cycle Count](image)
Significance of Results
(Example #2 – Riveted joint cracking)

• Cracking of aircraft skin at riveted joint
  – Crack initiation at fastener hole
  – Propagate toward other fastener holes

• Modeled as a center-cracked plate
  – Crack growth analysis done using NASGRO
  – Failure: Hole-to-hole cracking or first fracture event

** Reference: NASGRO Version 5.21
Significance of Results
(Example #2 – Riveted joint cracking)

- **Model geometry**
  - Skin thickness, $t = 0.1$ inches
  - Hole diameter, $D = 0.25$ inches
  - Hole spacing, $H = 3$ inches
  - Tensile stress, $S_o = 15$ ksi
  - Service life, $N_f = 100,000$ cycles

- **Increase in CIFS by factor of 2.6**
  - No healing, $a_{CIFS} = 0.338$ inches
  - Healing $a_{CIFS} = 0.881$ inches
Summary

• Experiment
  – Proof-of-concept testing results indicate that crack mitigation is possible
  – Crack arrest at low $\Delta K$
    • Bridging and closure mechanisms active
  – Crack retardation at higher $\Delta K$
    • Bridging capability damaged, but closure still operative

• Analysis
  – Results suggest significant improvement in critical initial flaw size
  – Reduces the crack inspection burden
    • Fewer inspections (decreased costs)
    • Probability of failure reduced (improved safety)
Next Steps

• Continue crack growth experiments
  – Populate data curves
• Consider different healing materials
• Potential to improve mechanical performance of healed materials
• Development of healing system
  – Robust protection
  – Integrated healing activation
  – SBIR call (additional manufacturing skills required)
• Develop analytical models to predict crack healing performance