INTEGRATED VEHICLE HEALTH MANAGEMENT

Mitigation of Crack Damage in Metallic Materials

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Outline

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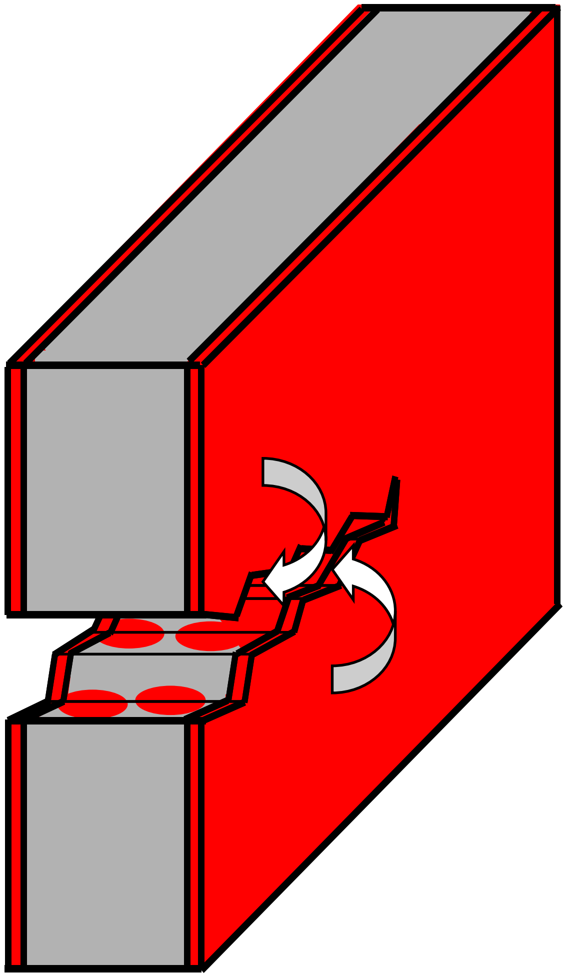
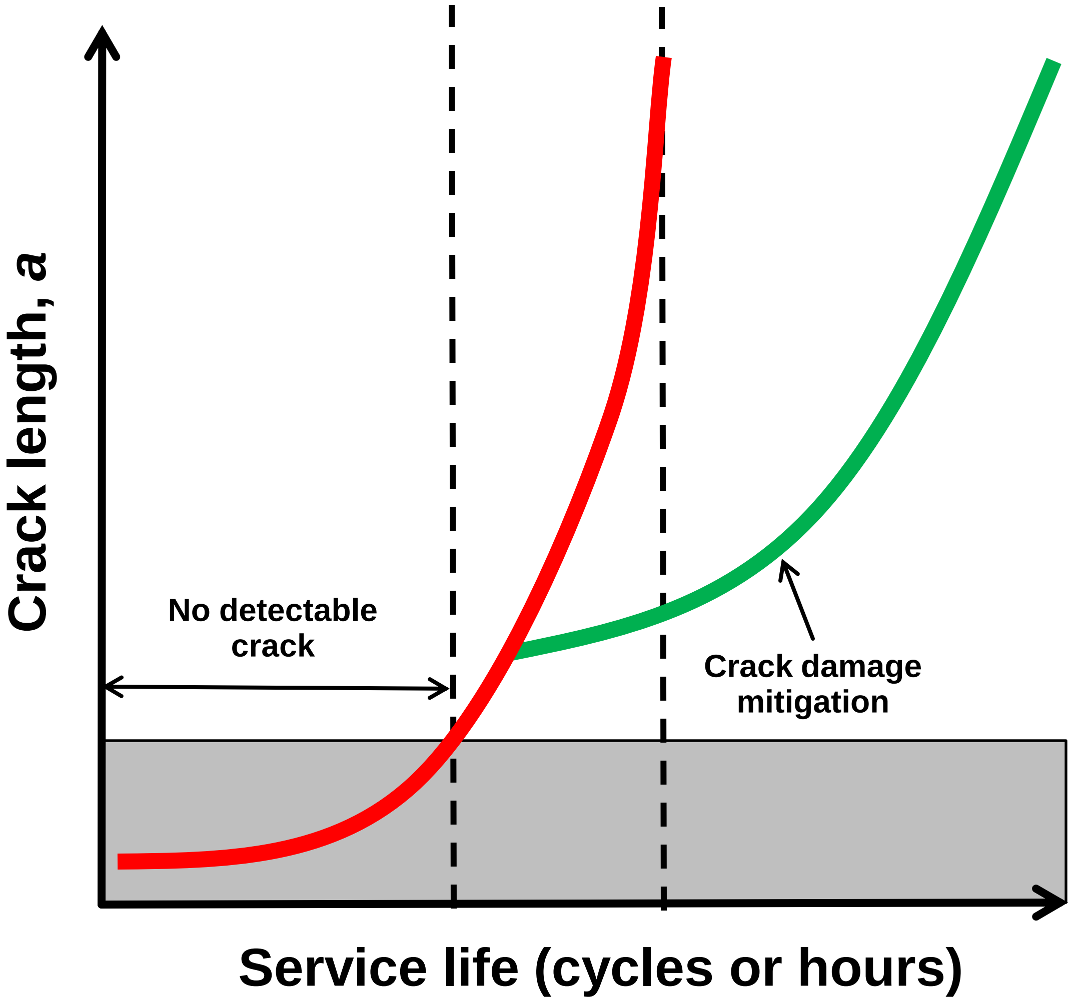


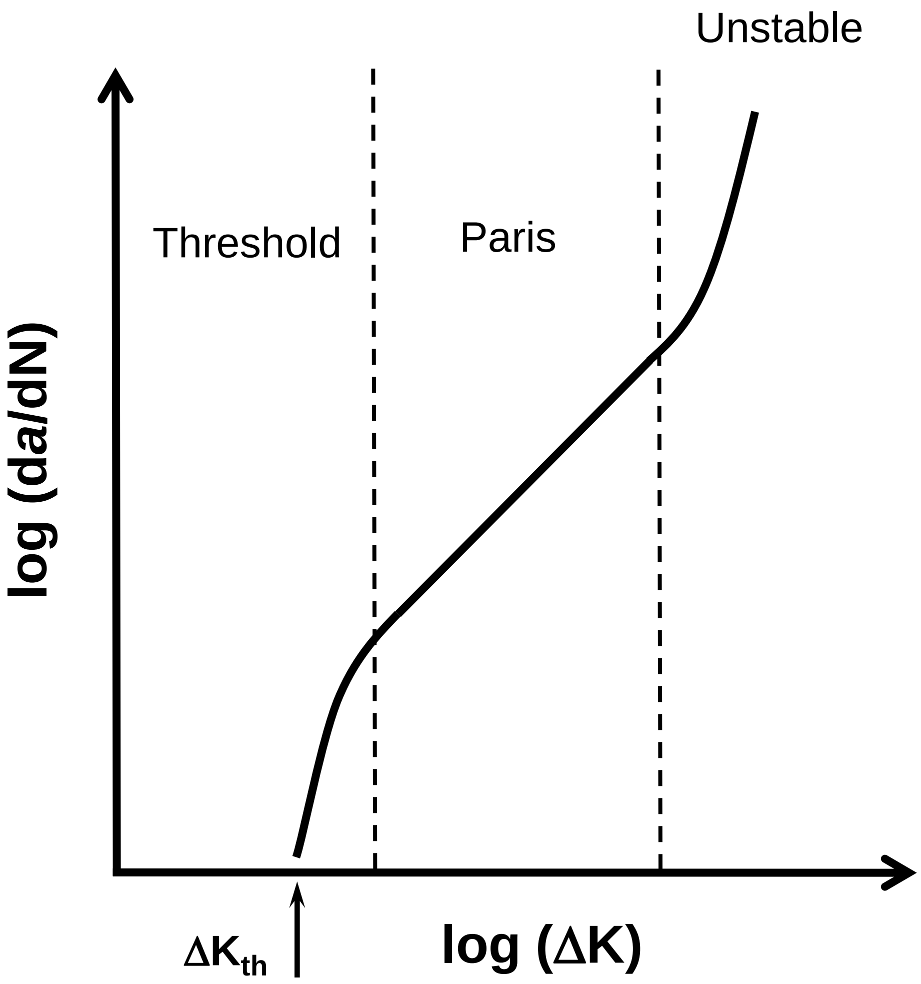
Problem Statement



- 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

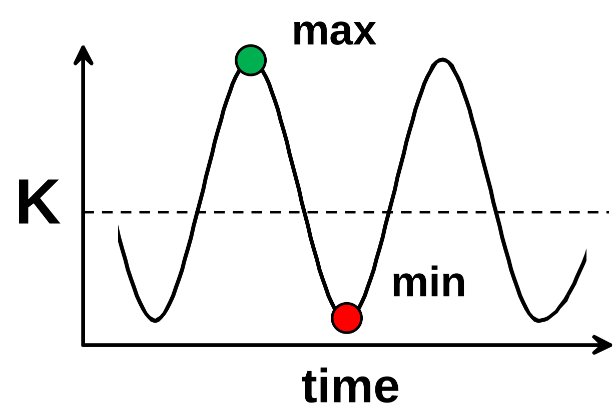
Background – Crack closure

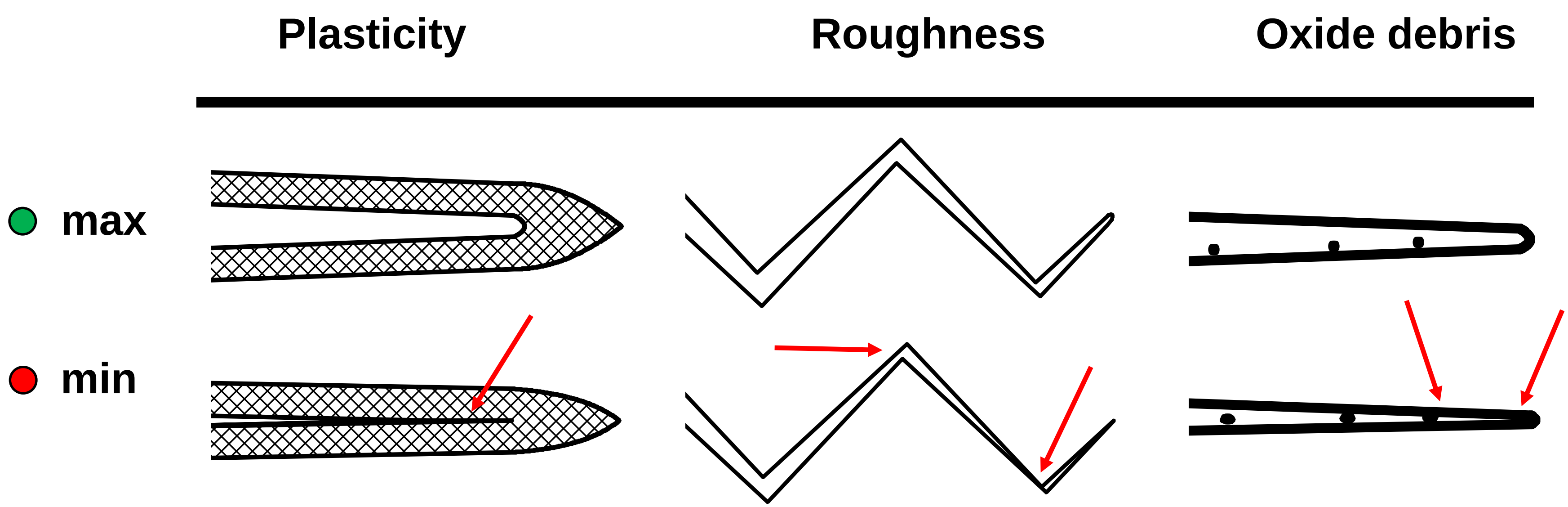
- Fatigue crack closure
  - Crack-face contact during cyclic loading
- Studied since 1960s
- Significance greatest near the FCG threshold
- Multiple crack closure mechanisms operate near ΔK_{th}



Background – Crack Closure (continued)

- Near-threshold fatigue crack closure mechanisms
  - Plasticity
  - Roughness
  - Oxide debris
- Can crack closure be exploited?



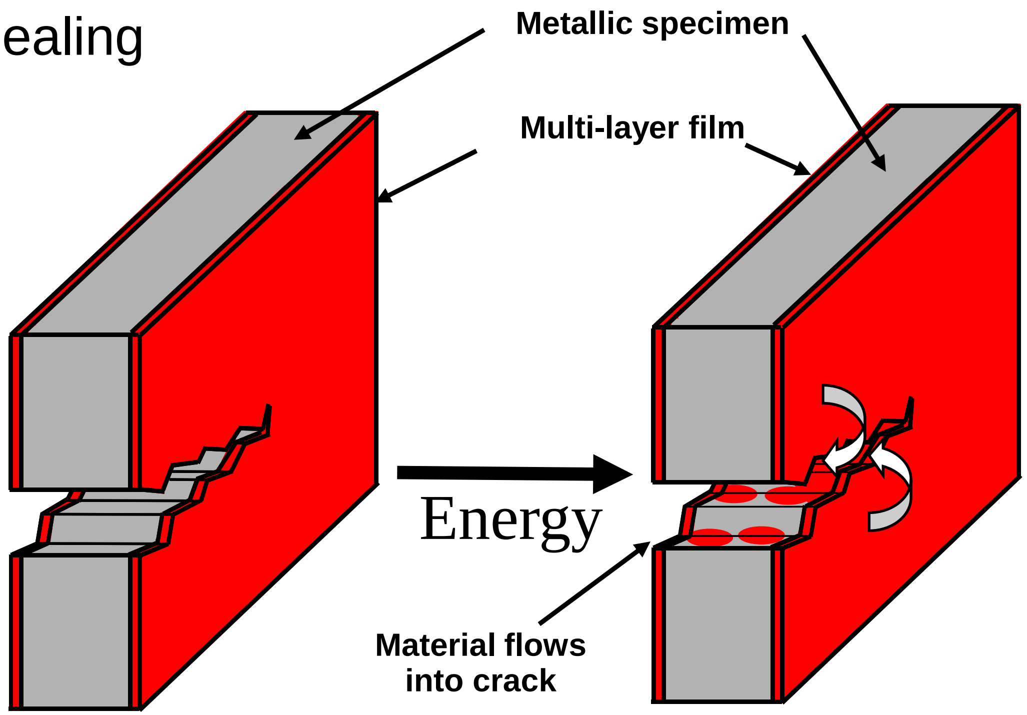


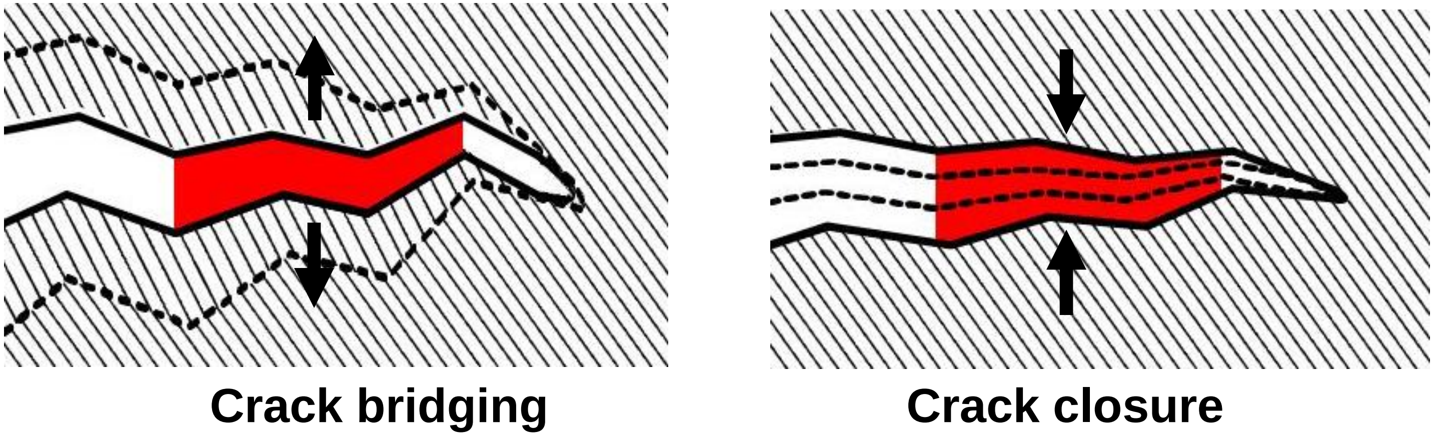
IVHM milestones being worked

- 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

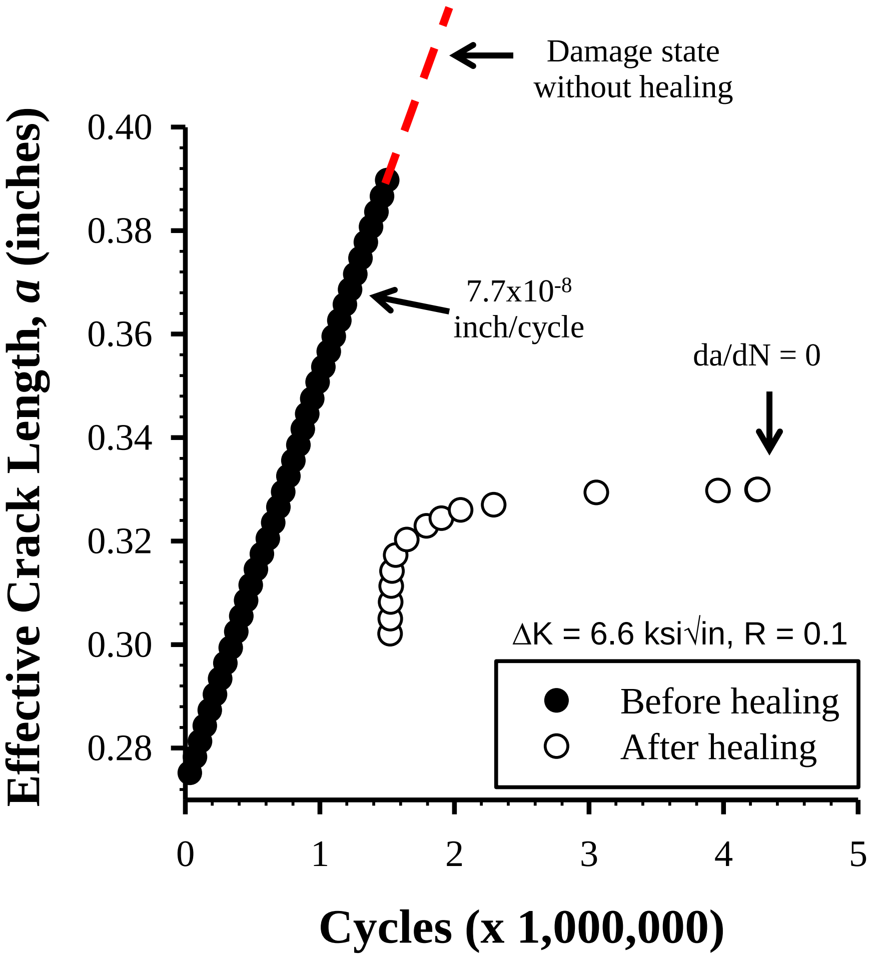




Results

Crack Arrest Example (Titanium)

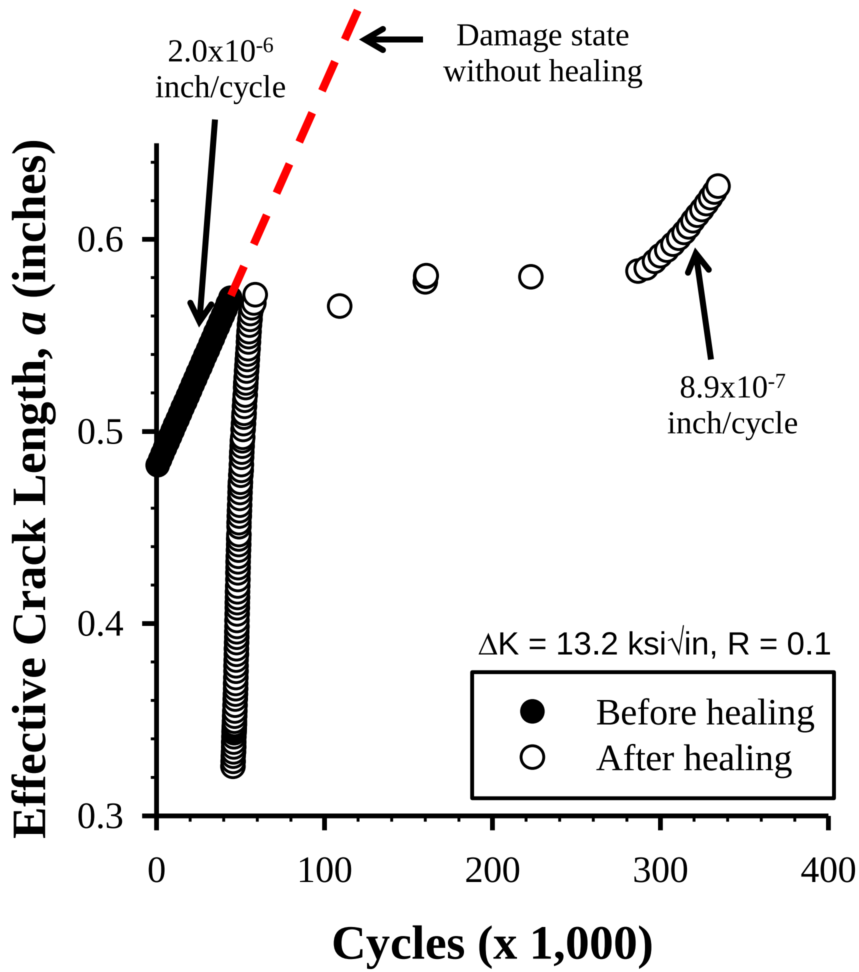
- Steady-state FCG
  - $\Delta K = 6.6$ ksi√in; $R = 0.1$
- Reduction in "crack length" after healing is a result of in-situ crack monitoring
- Some damage of healing material, but crack fails to propagate (never returns to original value)



Results (continued)

Crack Retardation Example (Titanium)

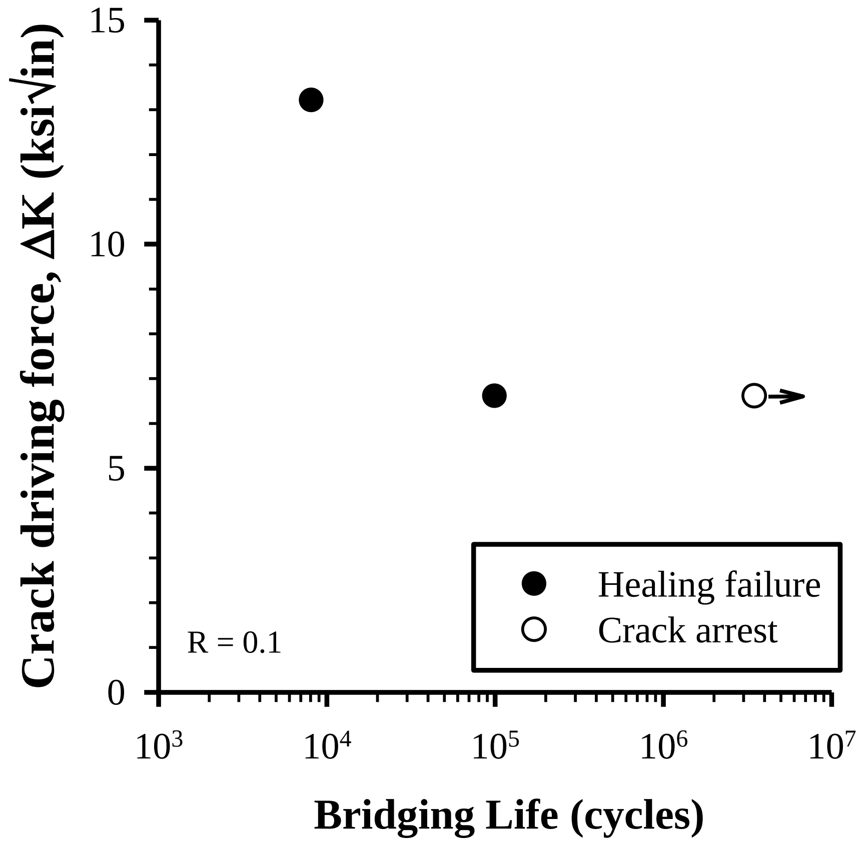
- Initially steady-state FCG
  - ΔK = 13.2 ksi√in; R = 0.1
- Reduction in "crack length" after healing is a result of in-situ crack monitoring
- Crack length returns to pre-healing value after approximately 8,000 cycles
- After healing agent is cracked, crack growth rate still slower
- Approximately 250,000 cycle delay, followed by 55% reduction in crack growth rate



Results (continued)

Titanium Healing Results (Bridging Life)

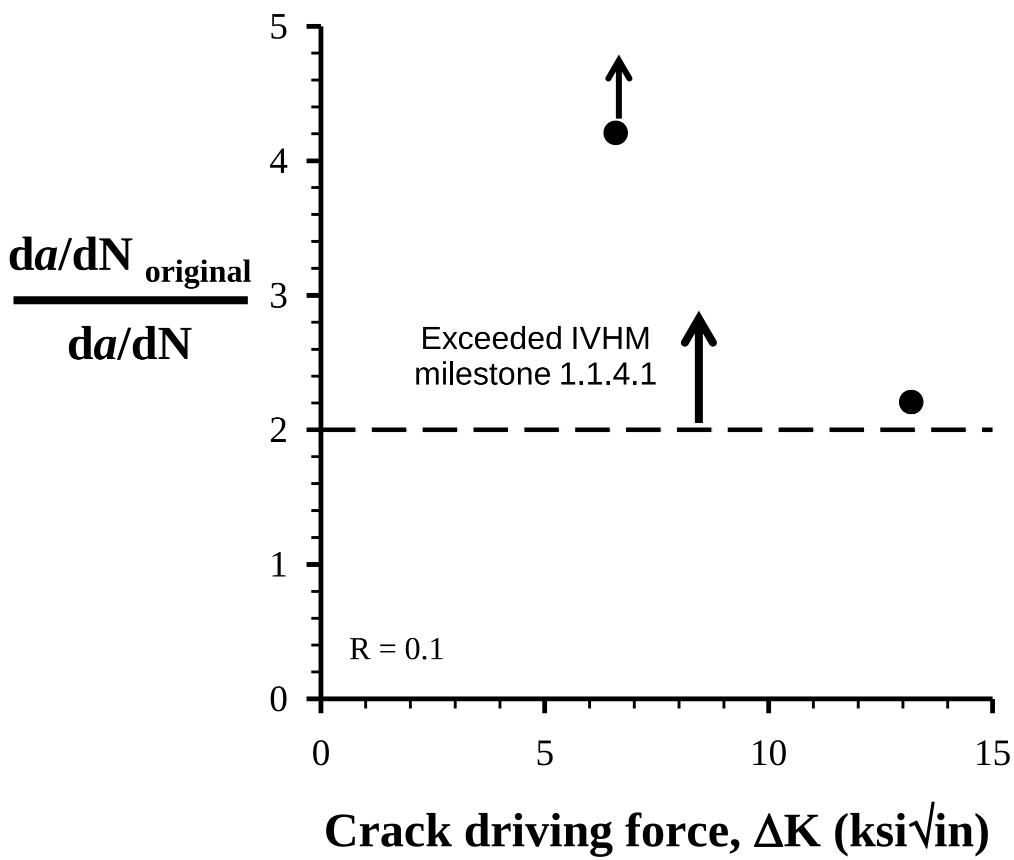
- Results from multiple experiments plotted similar to fatigue-life curves
  - Breakdown of bridging mechanism as function of crack-driving force
  - Closure mechanism still active
- Similar result obtained for aluminum
- ΔK = 6.6 ksi√in likely near "endurance limit"
- Analytical model needed to correlate healing agent properties to performance
  - Revisit selection of materials
- More results are needed to "populate" curve



Experimental Results (continued)

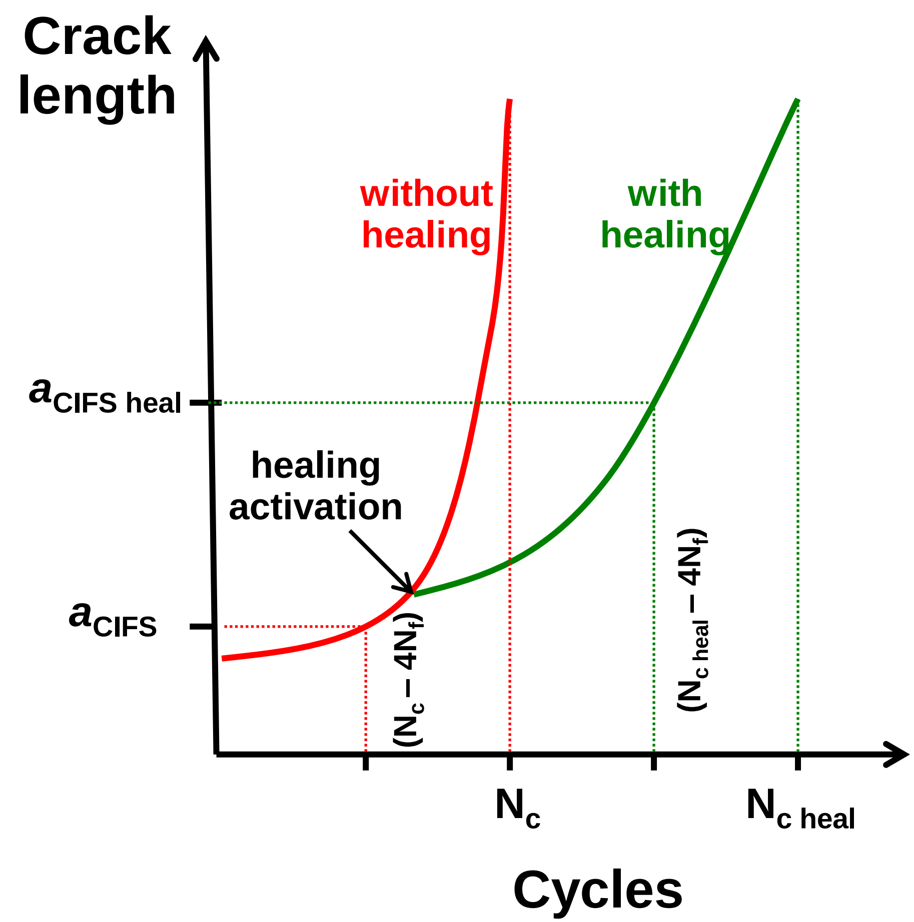
Titanium Healing Results (Crack Growth Rate Reduction)

- Results after breakdown of bridging
- Plotted as crack growth rate ratio
  - Ratio of steady state d*a*/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



Significance of Results (Background)

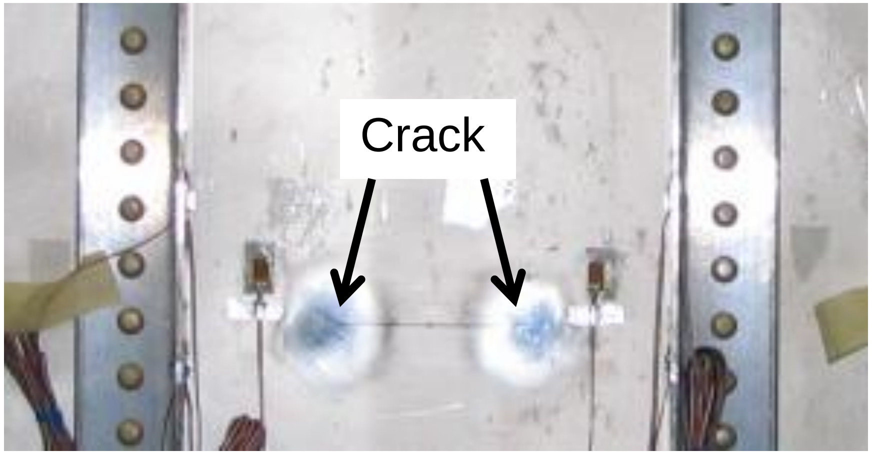
- Service cracks
  - Grow from initial to critical size
- Constant-load conditions
  - d*a*/dN increases with crack size
- Healing extends fatigue life, N_f
  - Reduction in crack growth rate
- Critical initial flaw size*, a_{CIFS}
  - Largest crack that will survive four service lives



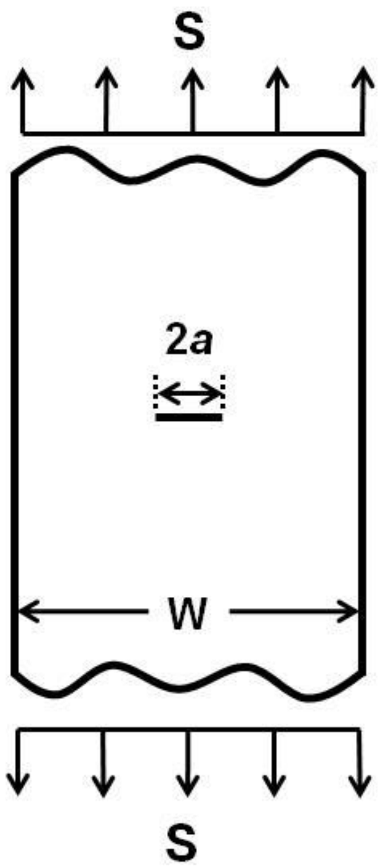
* References: (1) NASA-STD-5001, "Structural Design and Test Factors of Safety for Spaceflight Hardware"
(2) NASA-STD-5019, "Fracture Control Requirements for Spaceflight Hardware"
(3) Federal Aviation Administration FAR 25.571

Significance of Results
(Example #1 – Center-cracked plate)

Cracked aircraft panel



Model geometry*

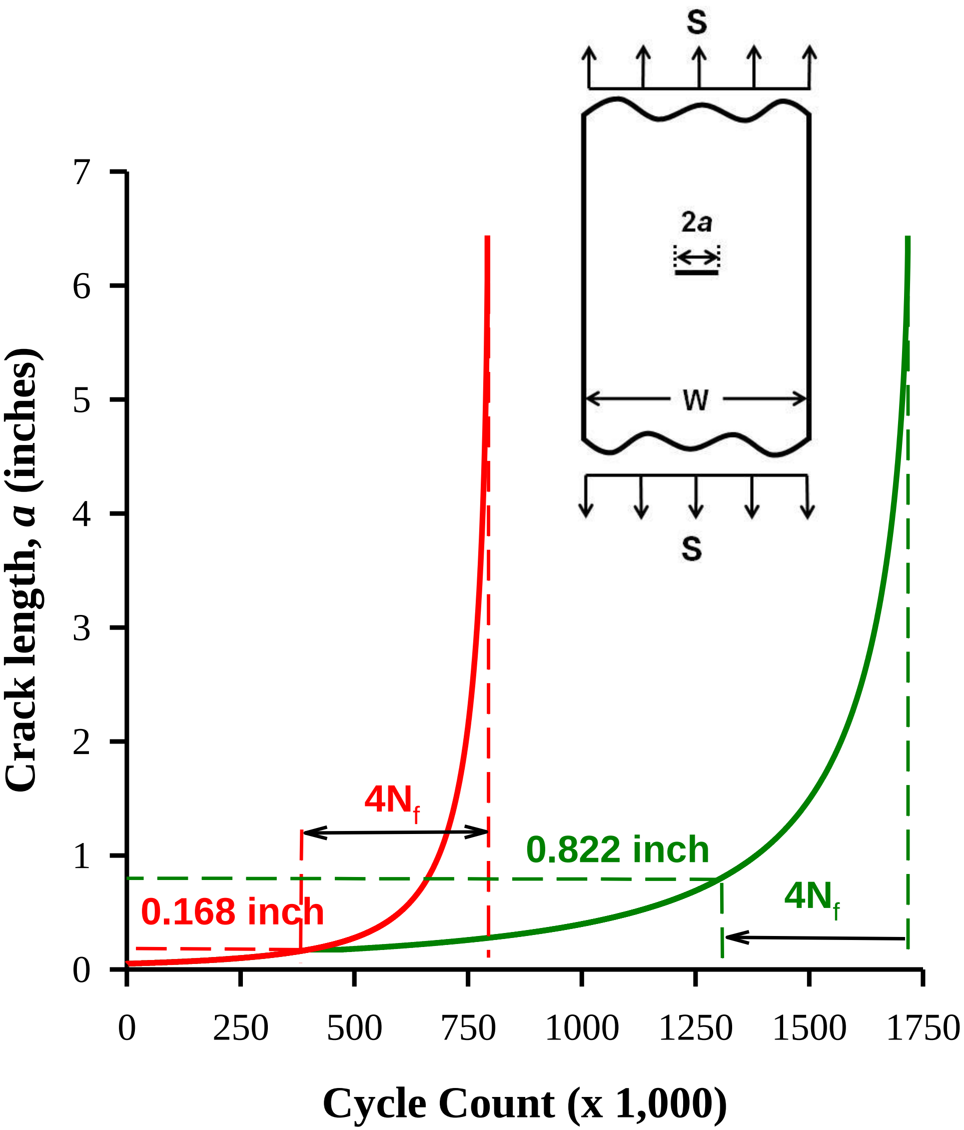


- Cracking of aircraft skin
  - Majority of fatigue life initiating/propagating small crack (low ΔK)
  - Minimal interaction with surrounding structure
- Modeled as a center-cracked plate
  - Crack growth analysis done using NASGRO

* Reference: NASGRO Version 5.21

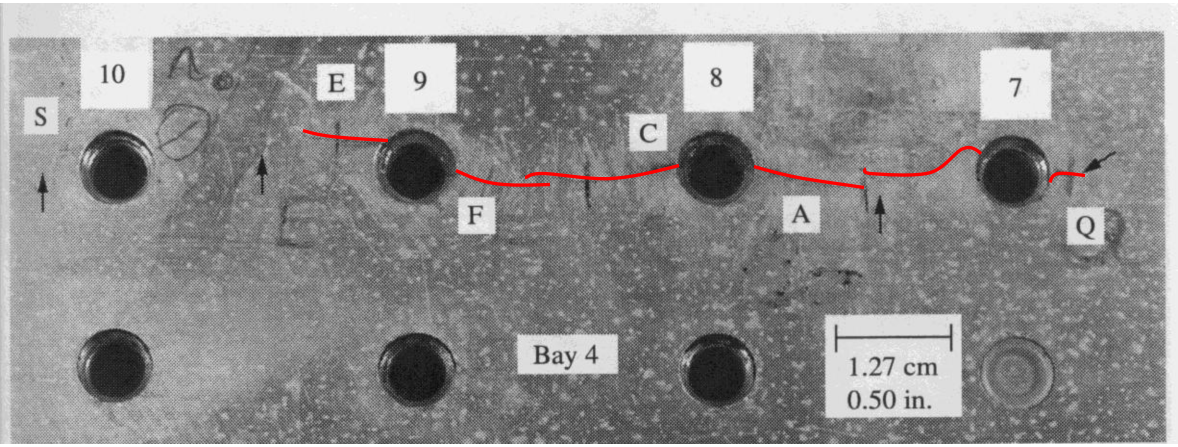
Significance of Results
(Example #1 – Center-cracked plate)

- 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

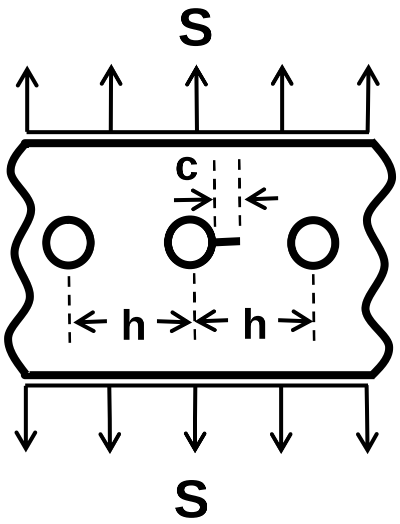


Significance of Results
(Example #2 – Riveted joint cracking)

Riveted Aircraft Structure with Multiple Cracks*



Model geometry**

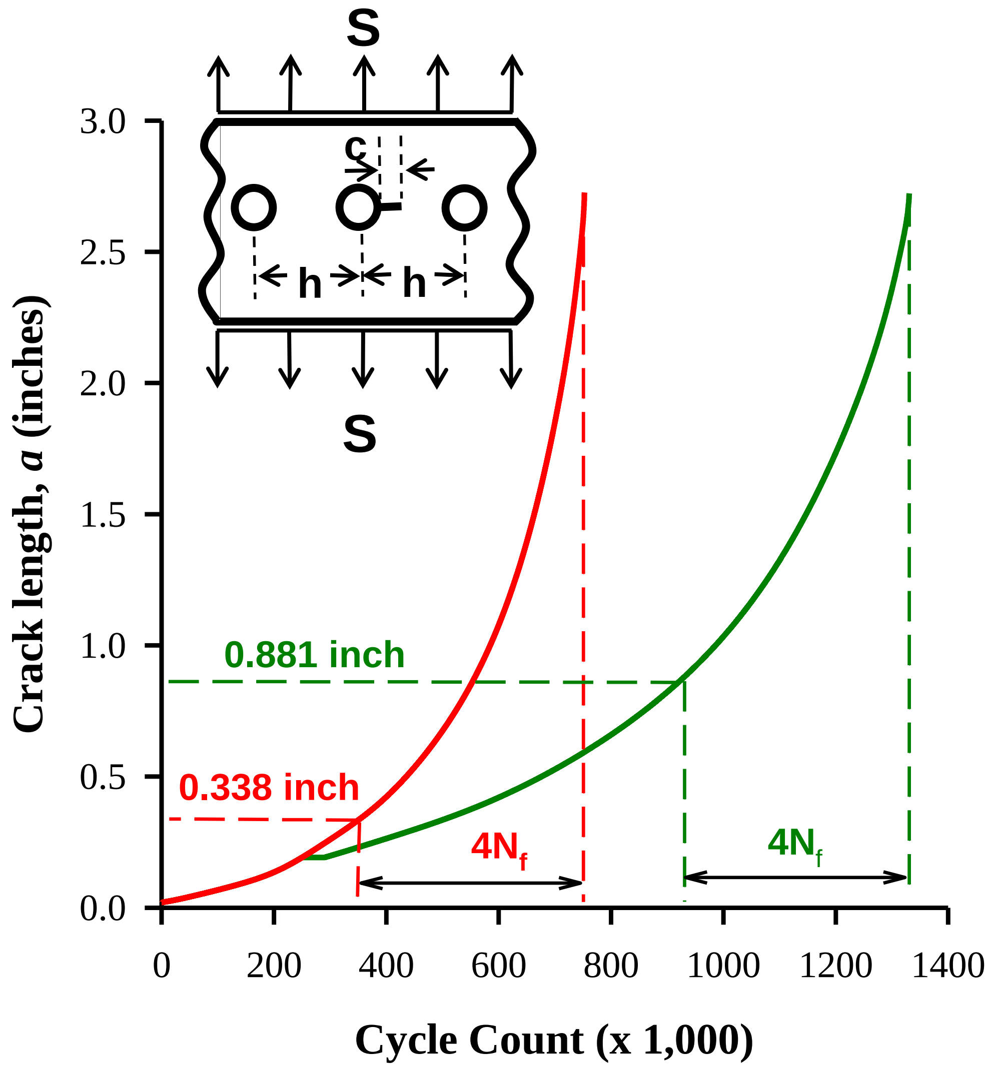


- Cracking of aircraft skin at riveted joint
  - Crack initiation at fastener hole
  - Propagate toward other fastener holes
- Modeled as a center-cracked plate
  - Crack growth analysis done using NASGRO
  - Failure: Hole-to-hole cracking or first fracture event

* Reference: R.S. Piascik and S.A. Willard, NASA/TP-97-206257
** 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 ΔK
    - Bridging and closure mechanisms active
  - Crack retardation at higher ΔK
    - 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