



Crack Damage Mitigation for Metallic Materials

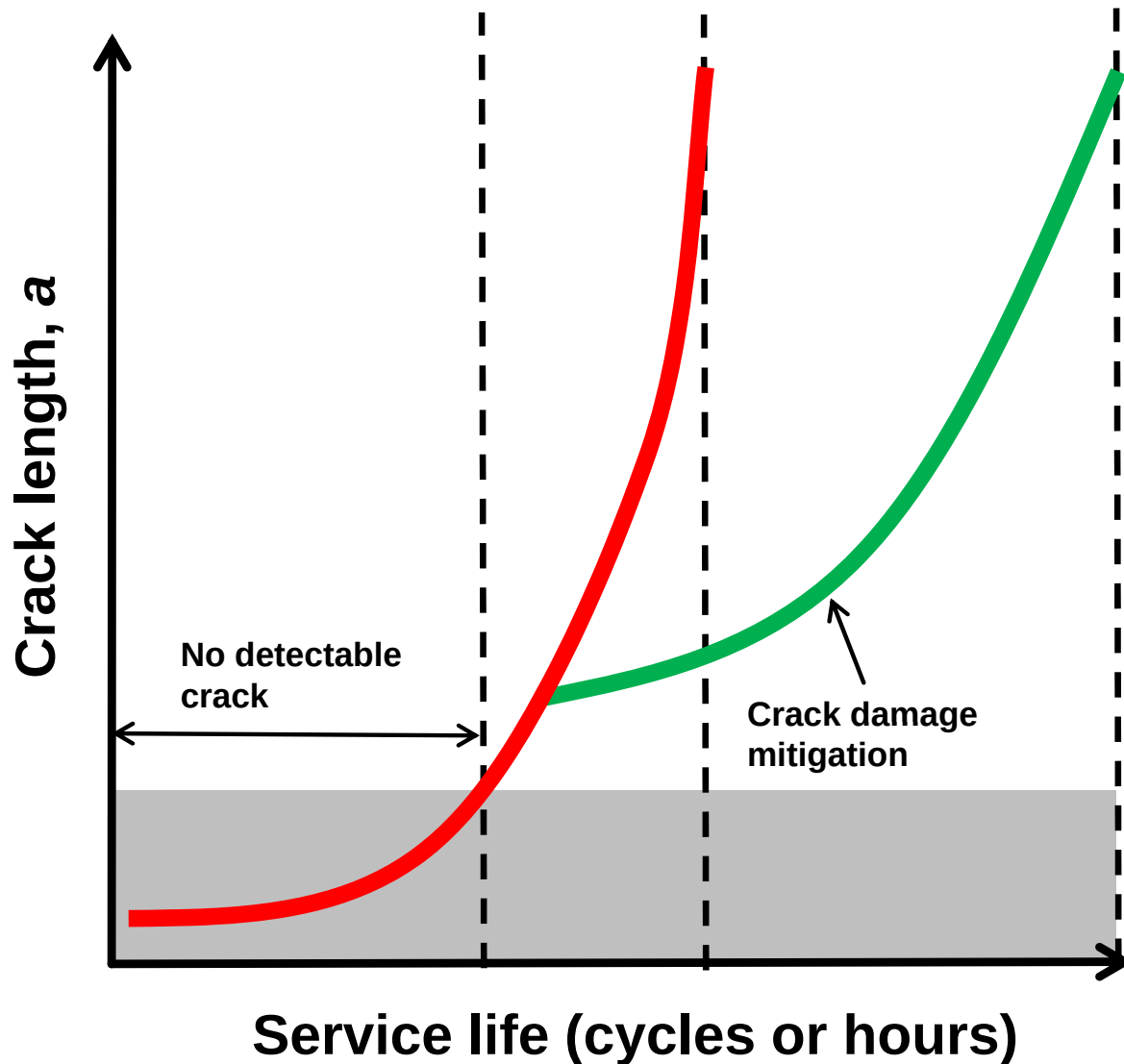
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Problem Statement

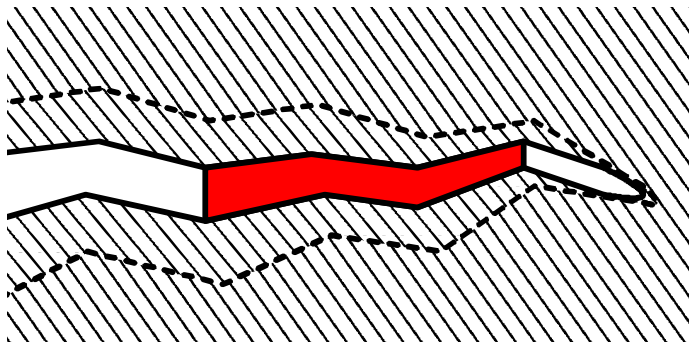
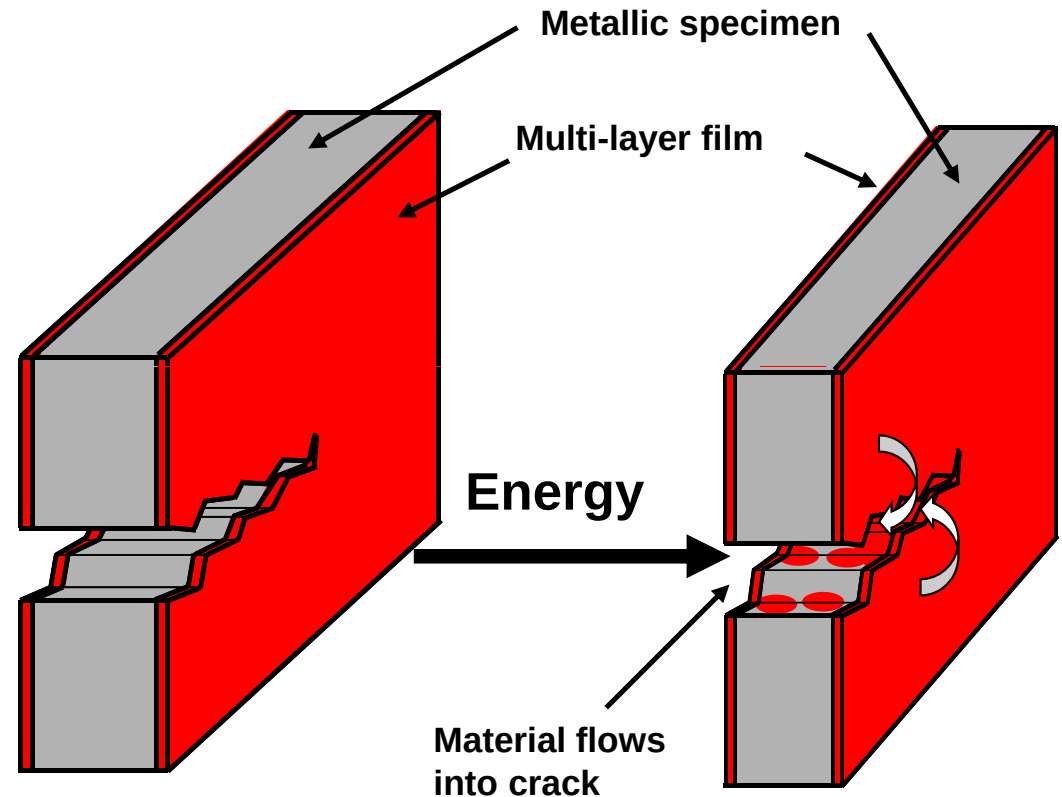


- Improvement in:
 - Safety
 - Weight
 - Cost
- Vehicle Safety Systems
 - *In-situ* healing of damage
 - Could be used in concert with on-board crack detection system

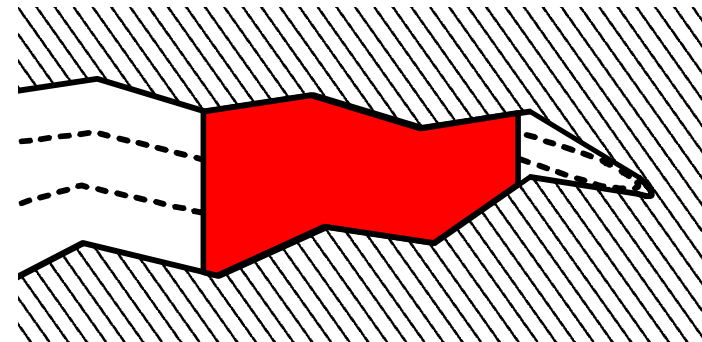
Approach



- 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)
 - Repeatable

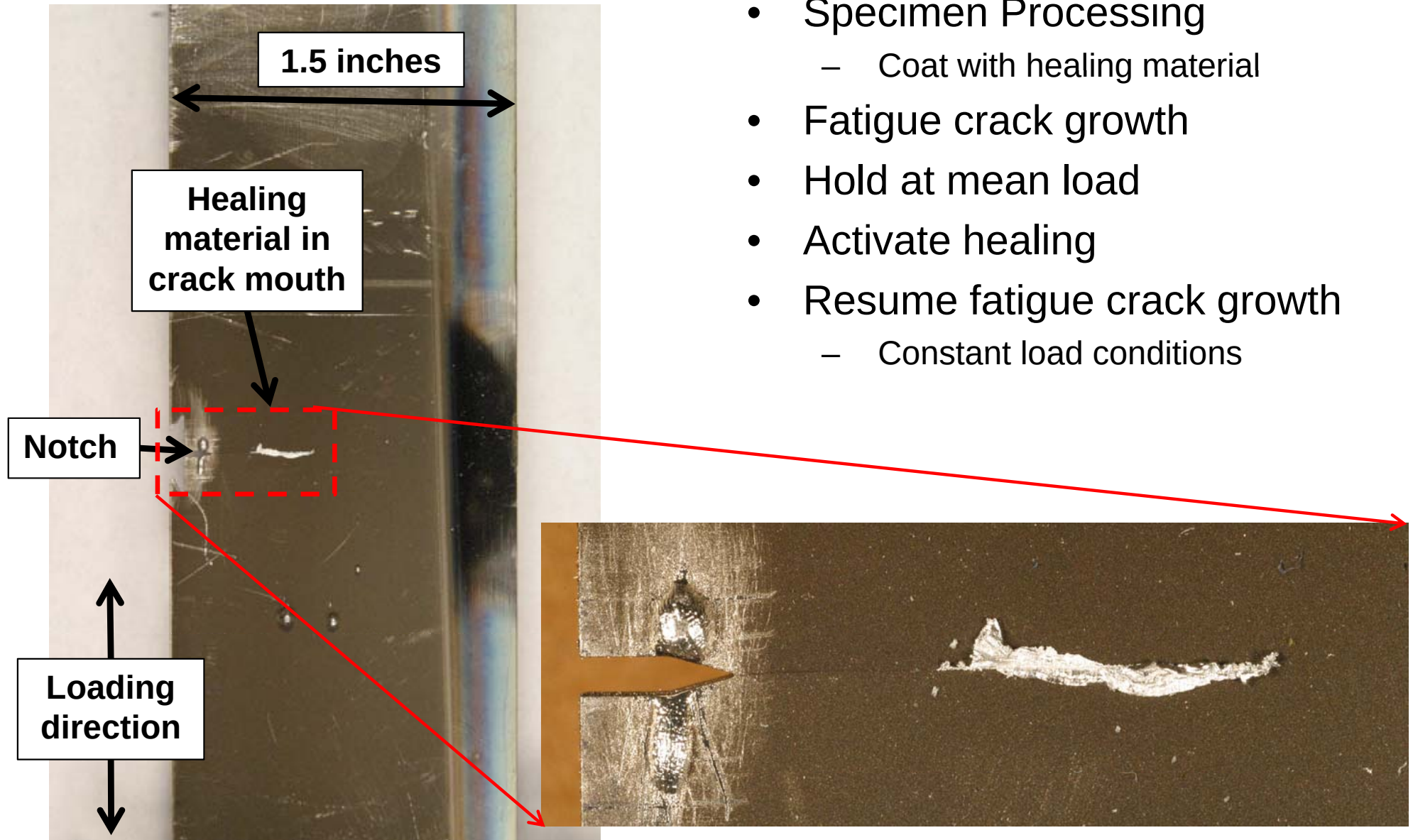


Crack bridging



Crack closure

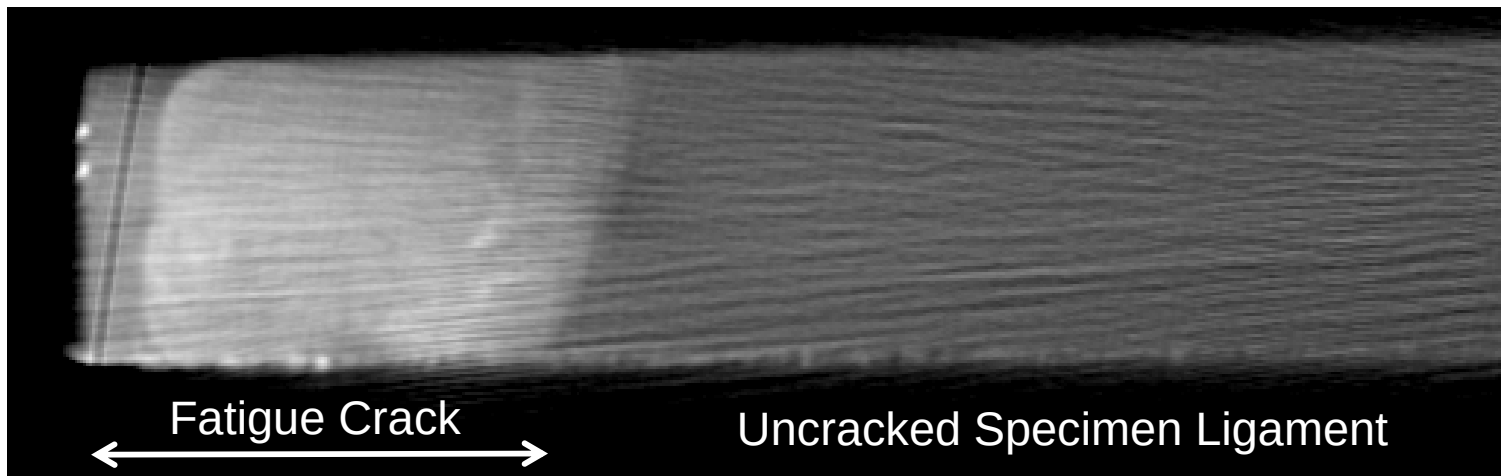
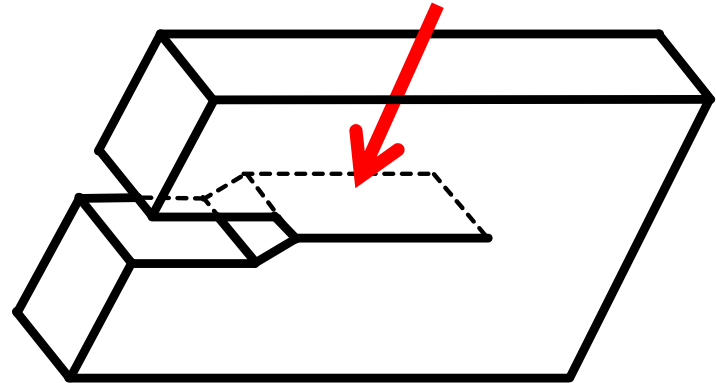
Experimental Procedure



Non-destructive Analysis



- CT Radiography results show
 - Healing material reaches crack tip
 - Coats entire crack surface (through thickness)

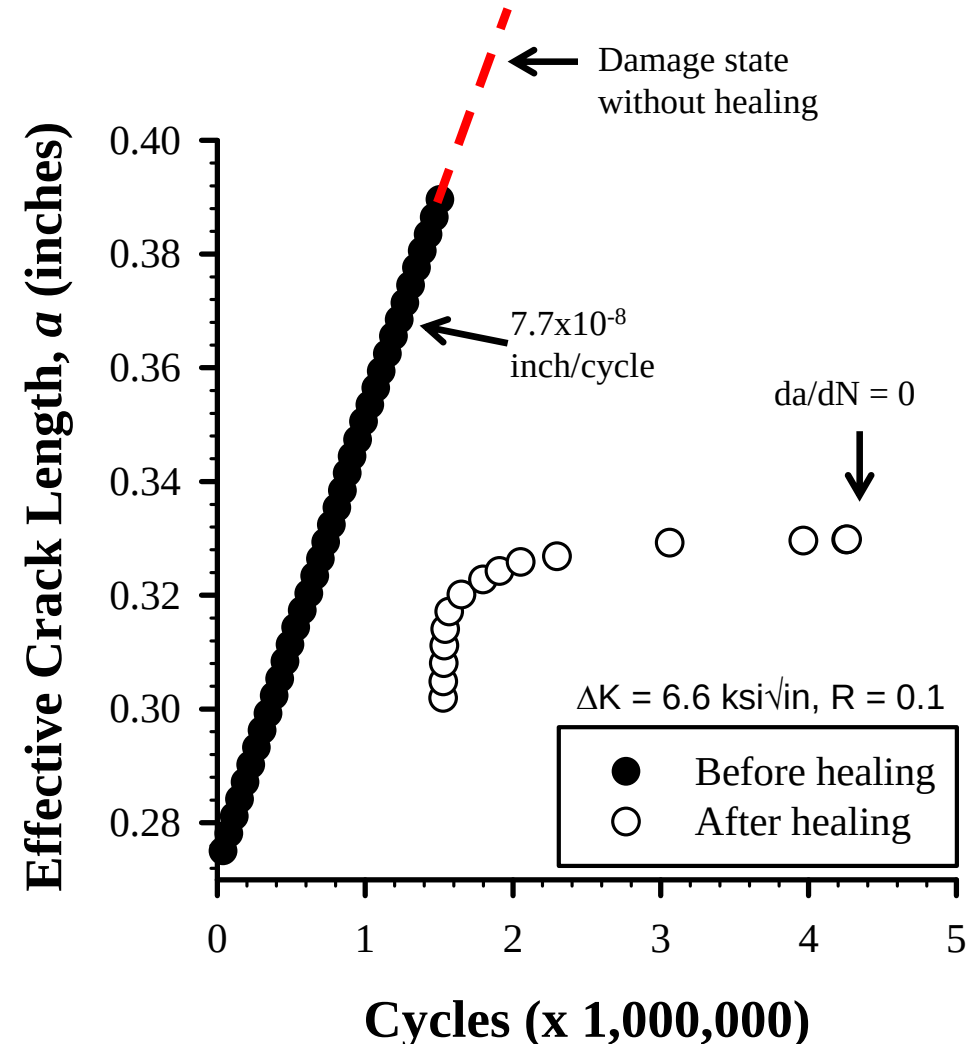


Results



Crack Arrest Example (Titanium)

- Steady-state FCG
 - $\Delta K = 6.6 \text{ ksi}\sqrt{\text{in}}$; $R = 0.1$
- 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)

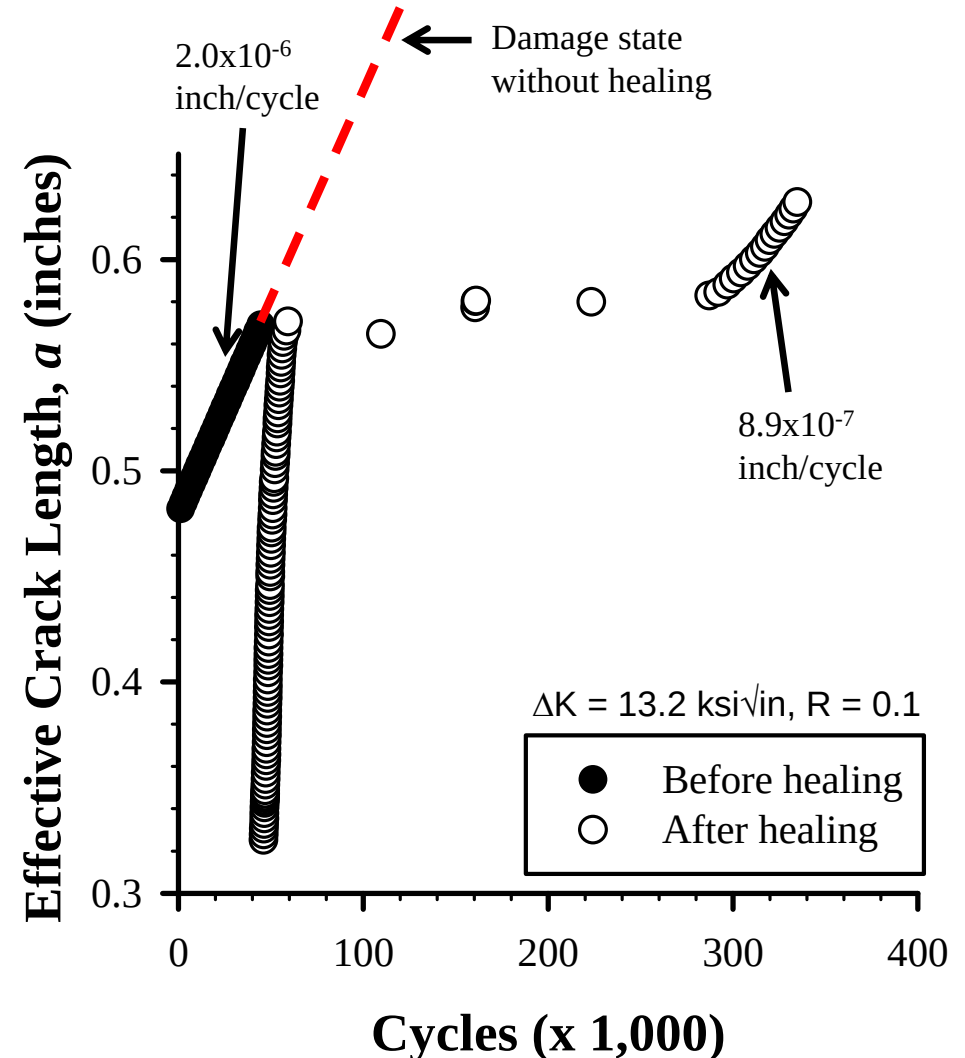


Results (continued)



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

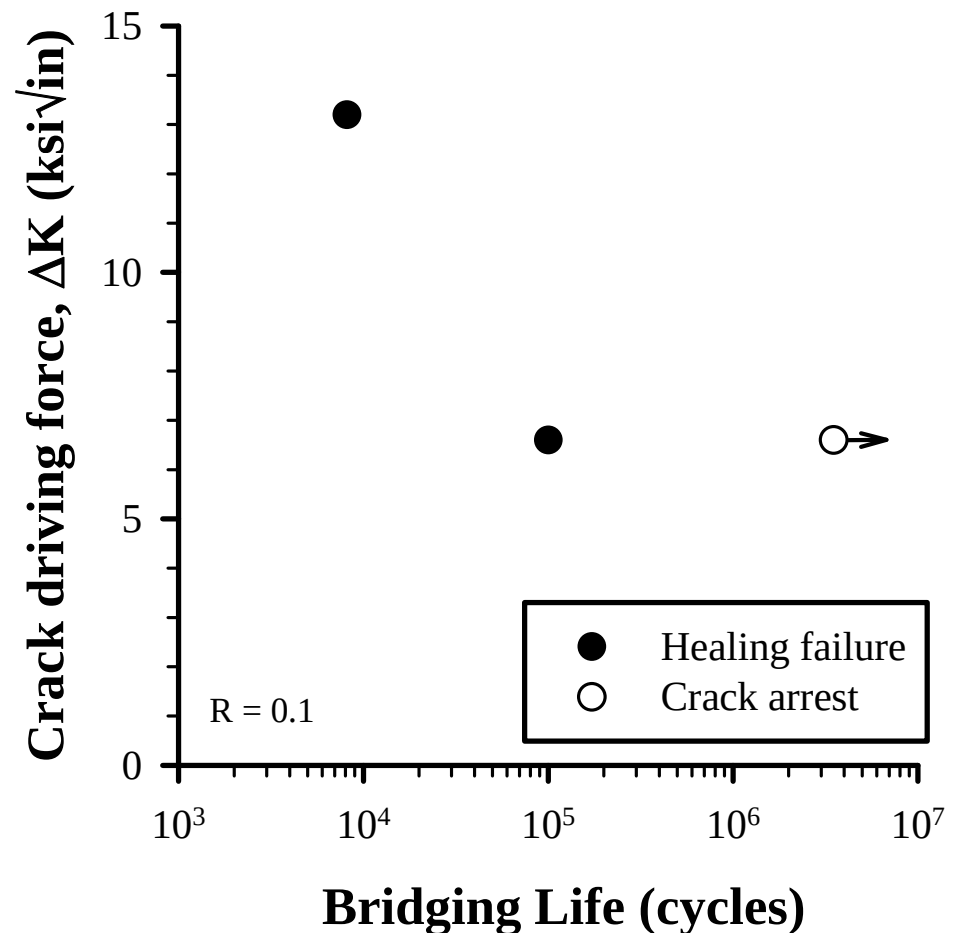


Results (continued)



Titanium Healing Results (Bridging Life)

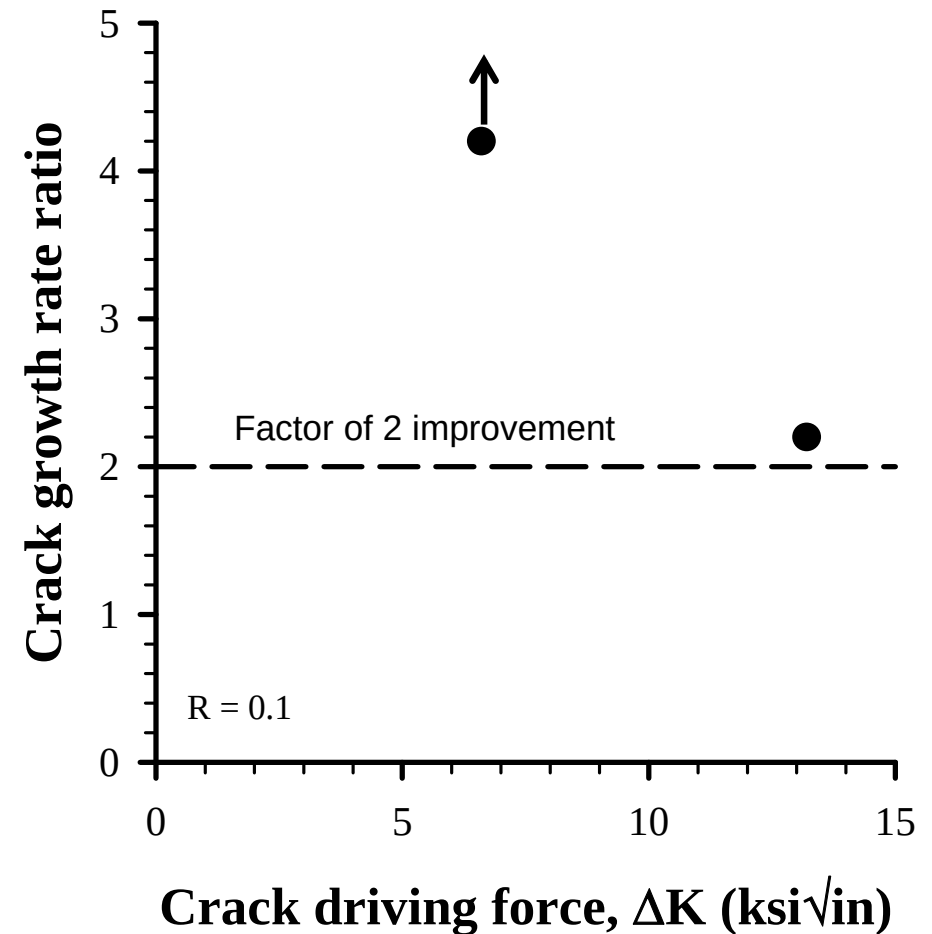
- Results from multiple experiments plotted similar to fatigue-life curves
 - Breakdown of bridging mechanism as function of crack-driving force
 - Closure mechanism still active
- Similar result obtained for aluminum
- $\Delta K = 6.6 \text{ ksi}\sqrt{\text{in}}$ likely near “endurance limit”
- Analytical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



Results (continued)



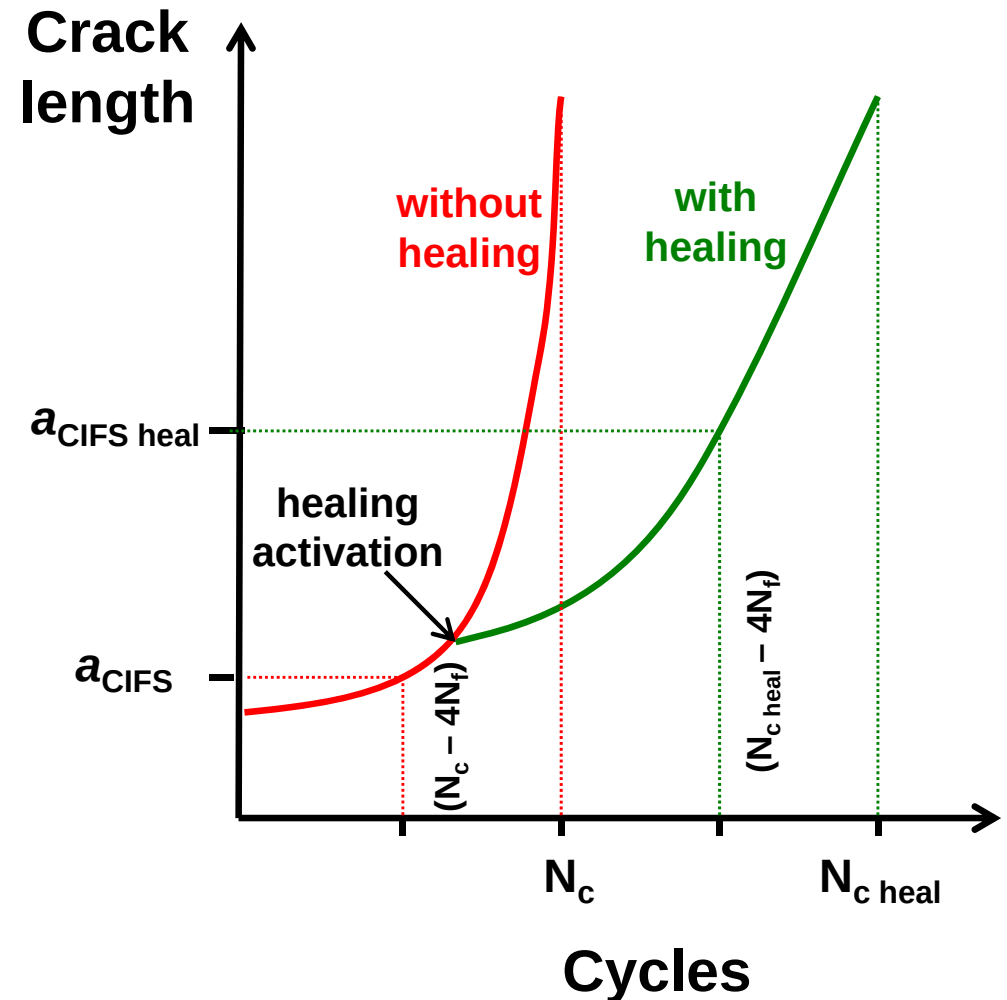
- Results after breakdown of bridging
- Plotted as crack growth rate ratio
 - Ratio of steady state da/dN before and after healing
- Better performance at lower crack driving forces
- In all cases tested:
 - Greater than a factor of 2 reduction in crack growth rate
 - Significant crack growth delay
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



Impact of Self-healing Material



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

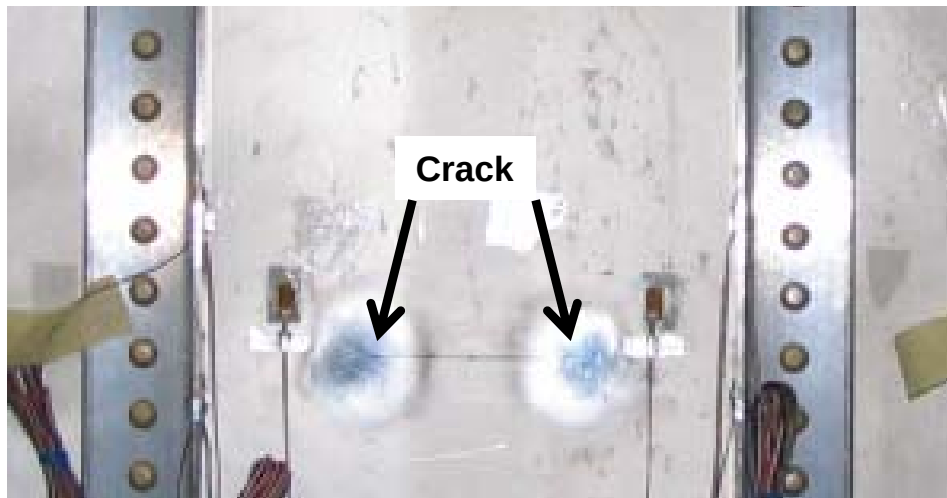


* References: (1) NASA-STD-5001, "Structural Design and Test Factors of Safety for Spaceflight Hardware"
(2) NASA-STD-5019, "Fracture Control Requirements for Spaceflight Hardware"
(3) Federal Aviation Administration FAR 25.571

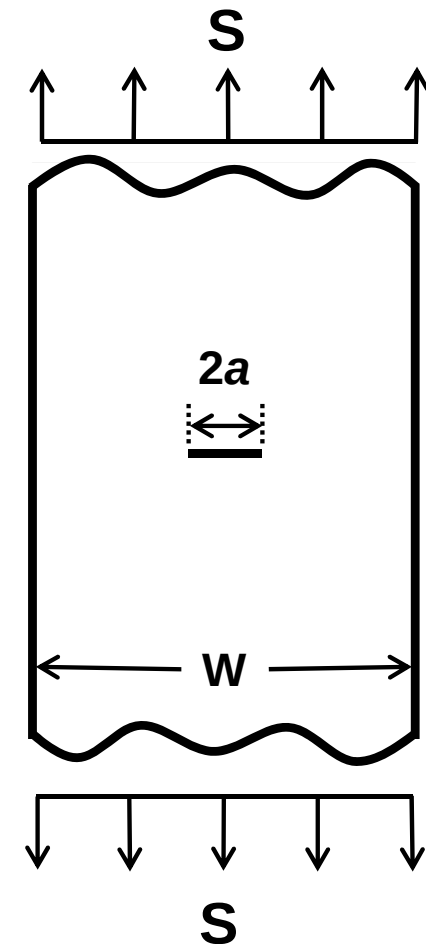
Example #1 – Center-cracked plate



Cracked aircraft panel



Model geometry*



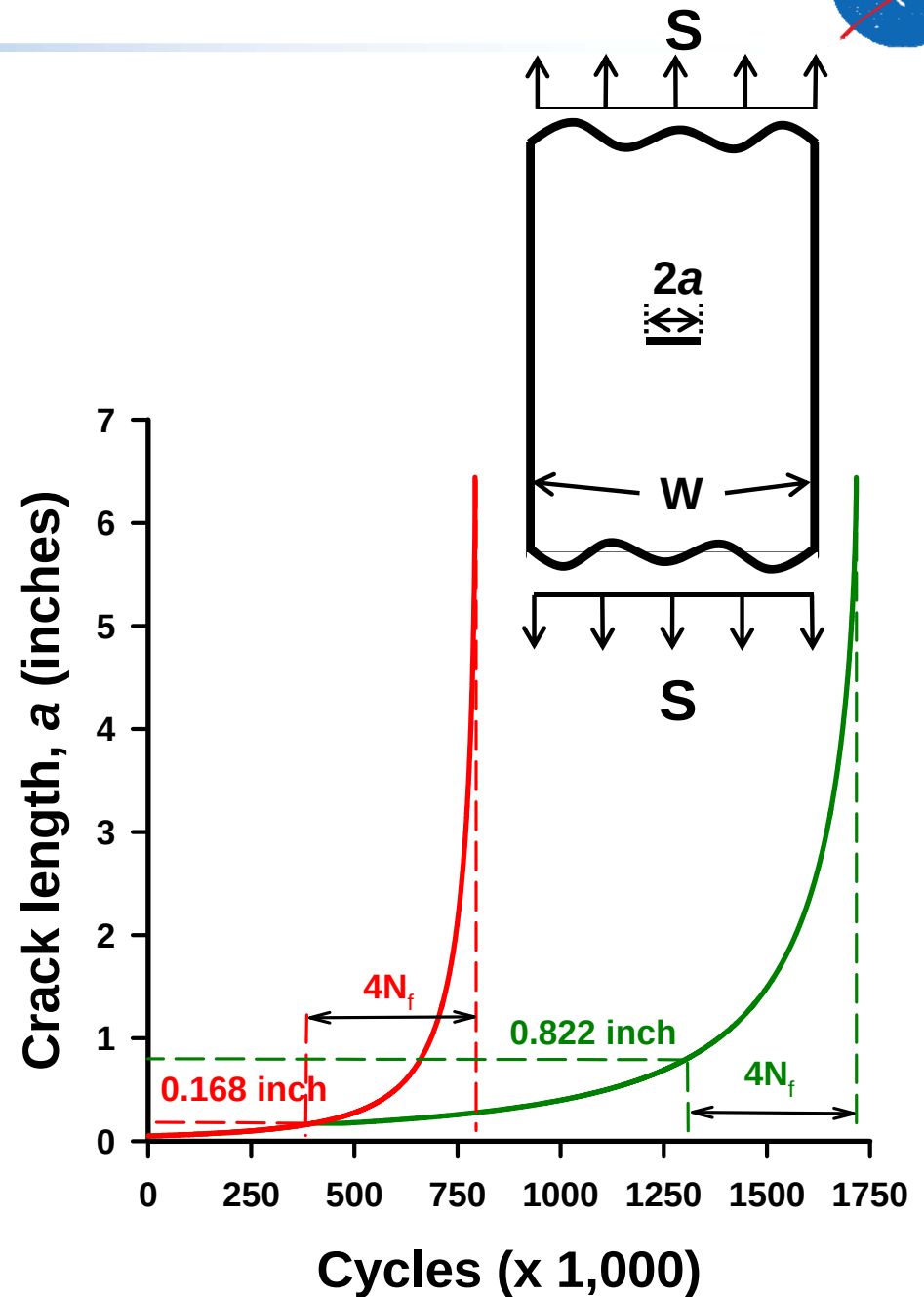
- Cracking of aircraft skin
 - Majority of fatigue life initiating/propagating small crack (low ΔK)
 - Minimal interaction with surrounding structure
- Modeled as a center-cracked plate
 - Crack growth analysis performed using NASGRO

* Reference: NASGRO Version 5.21

Example #1 – Center-cracked plate



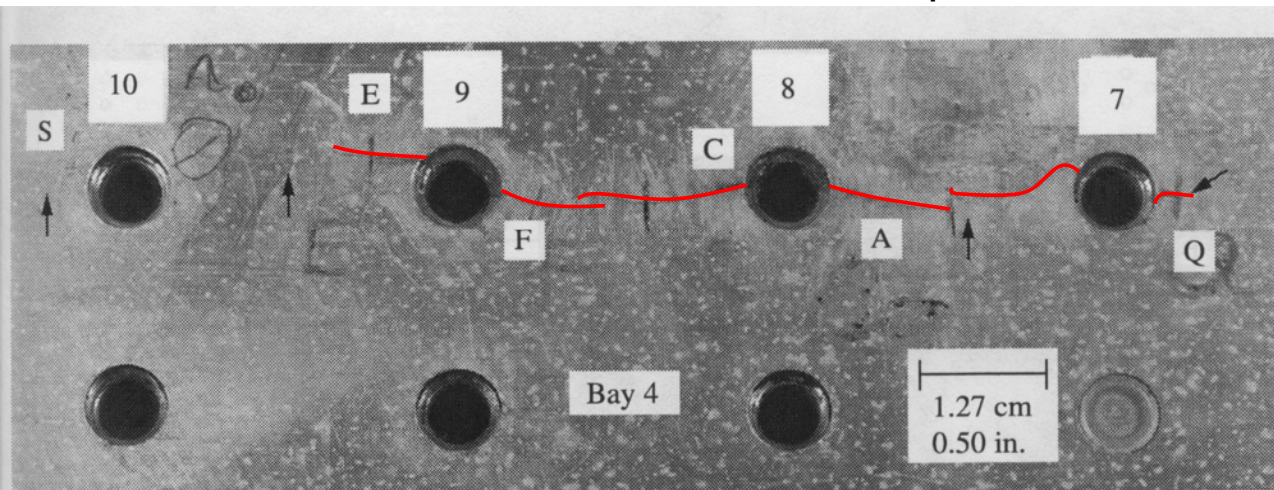
- Model geometry
 - Panel width, $W = 36$ inches
 - Panel thickness, $t = 0.1$ inches
 - Tensile stress, $S = 12$ ksi
 - Service life, $N_f = 100,000$ cycles
- Increase in CIFS by factor of 4.9
 - No healing, $a_{\text{CIFS}} = 0.168$ inches
 - Healing, $a_{\text{CIFS}} = 0.822$ inches



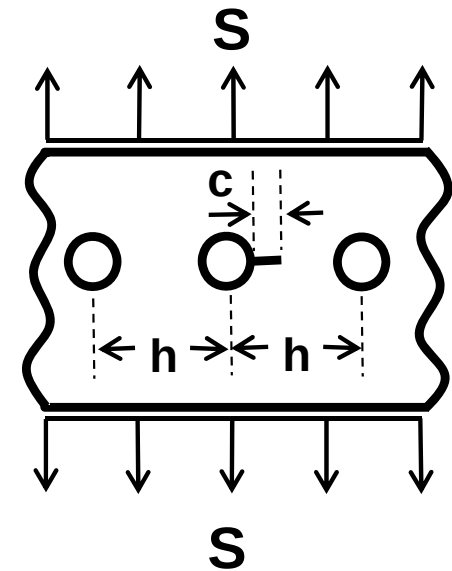
Example #2 – Cracking in Riveted Joint



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 performed using NASGRO
 - Failure: Hole-to-hole cracking or first fracture event



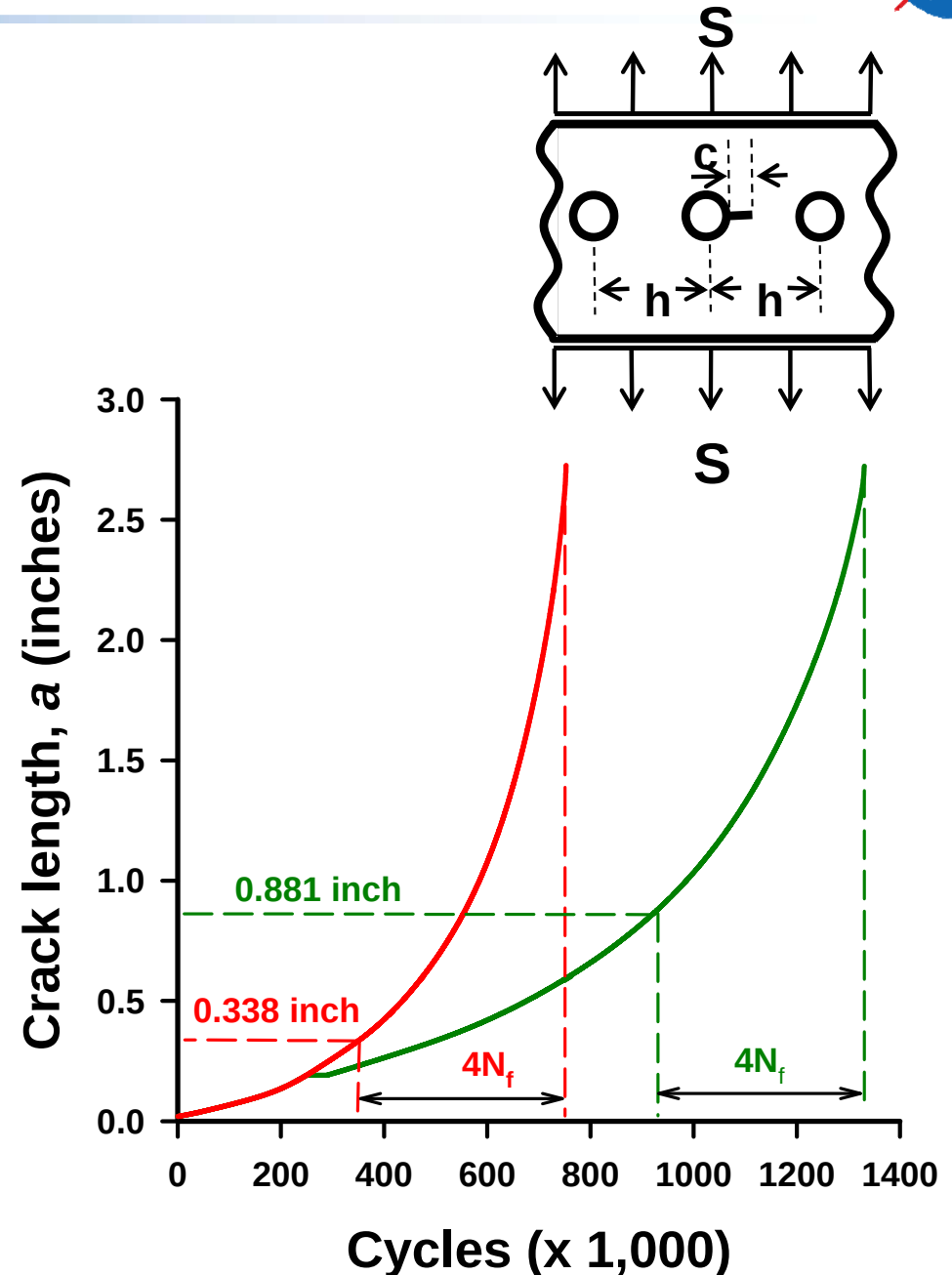
* Reference: R.S. Piascik and S.A. Willard, NASA/TP-97-206257

** Reference: NASGRO Version 5.21

Example #2 – Cracking in Riveted Joint



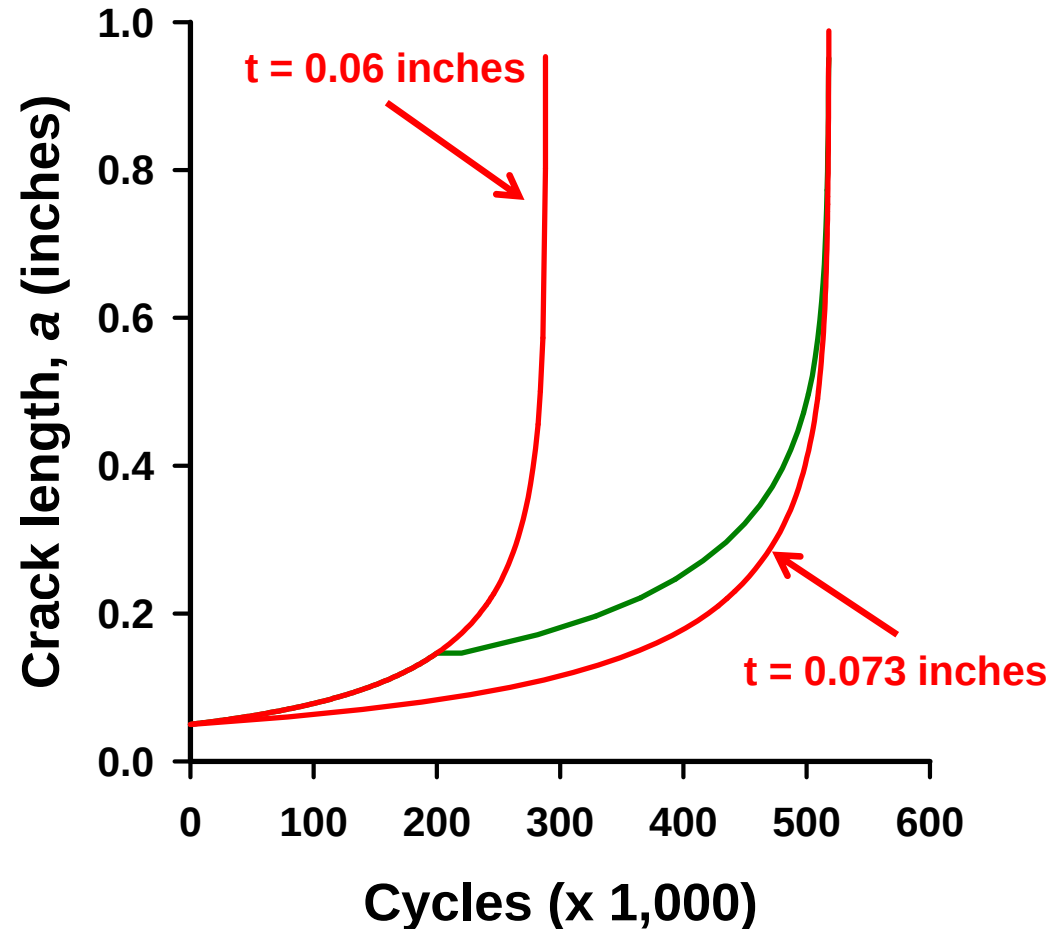
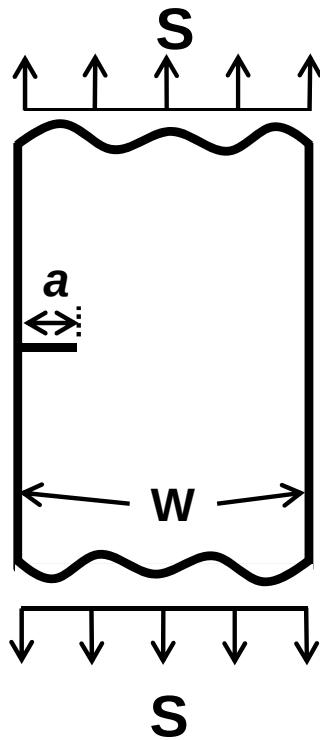
- Model geometry
 - Skin thickness, $t = 0.1$ inches
 - Hole diameter, $d = 0.25$ inches
 - Hole spacing, $h = 3$ inches
 - Tensile stress, $S = 15$ ksi
 - Service life, $N_f = 100,000$ cycles
- Increase in CIFS by factor of 2.6
 - No healing, $a_{\text{CIFS}} = 0.338$ inches
 - Healing $a_{\text{CIFS}} = 0.881$ inches



Example #3 – Benefits of Crack Healing



- For this example, crack healing provides the same fatigue life as a component 22% thicker
 - Also, more of the fatigue life is spent with a detectable crack
 - 5-micron-thick healing film carries a negligible weight penalty





- 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)
 - Potential exists for vehicle weight reduction