Unconservatism of ANSI AIAA S081B for Damage Tolerance Life Analysis of COPVs

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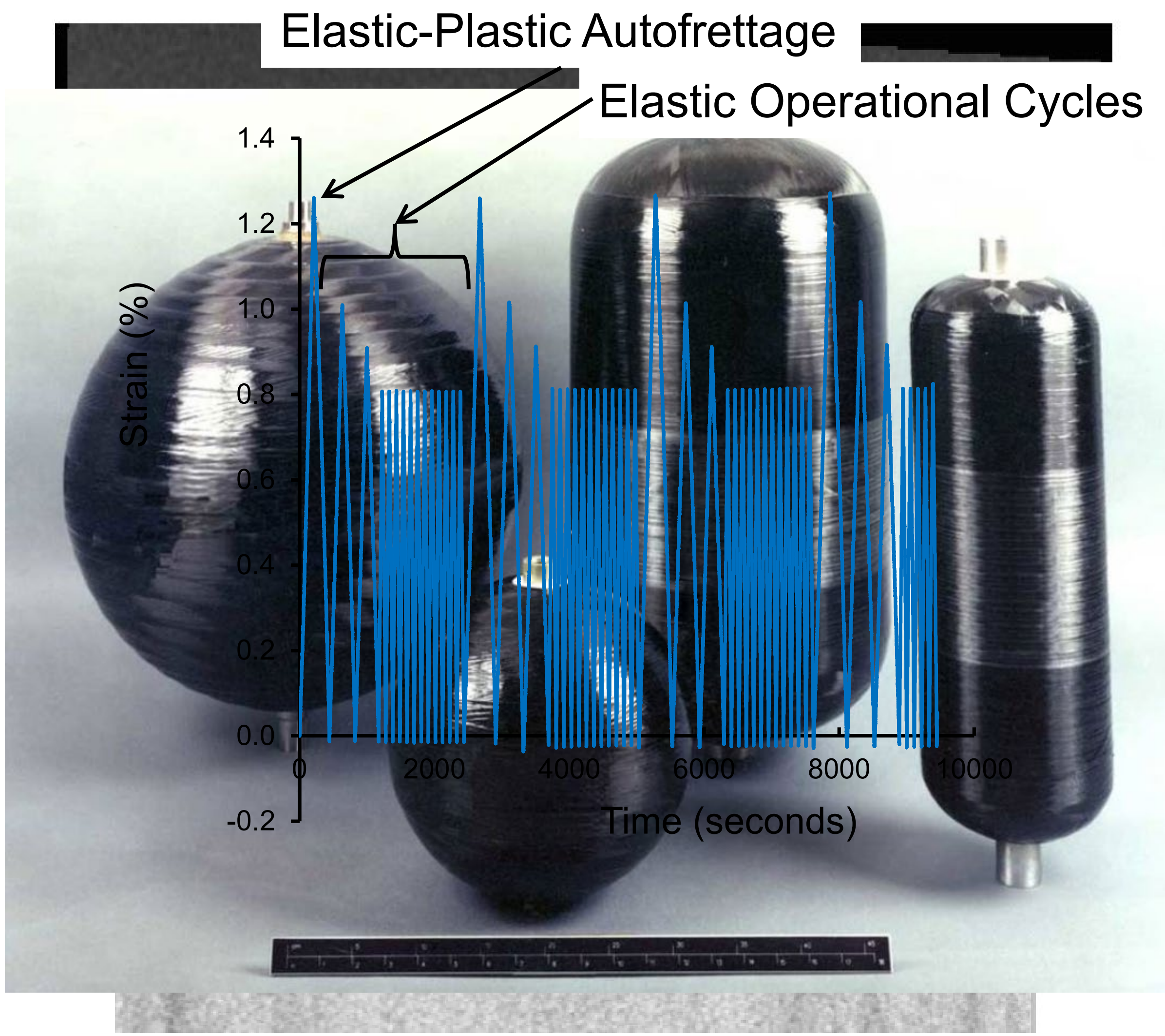
Composite Overwrapped Pressure Vessel (COPV) Overview

- A COPV consists of a metallic liner that contains the fluid or gas and a composite overwrap that provides strength
- The pressurization of the tank has an initial overpressure (the autofrettage cycle) followed by operational cycles
  - The cycles that follow the autofrettage cycle are elastic in **elastically responding COPV liners**
  - One or more of the cycles that follow the autofrettage cycle are plastic in **plastically responding COPV liners**
- Flight qualification damage tolerance requirements are specified in ANSI/AIAA S-081B
  - The liner is assumed to contain the largest crack that can be missed by a qualified non-destructive evaluation (NDE) inspection at the worst condition
  - The liner must survive 4 operational lifetimes without breaking through the back surface of the liner (i.e., leakage path)



ANSI/AIAA S-081B: Analytical Damage Tolerance Assessment

As Stated in the Standard

- Section 5.2.13.1: “The region(s) of the COPV to which damage tolerance is applied shall be designated such that the COPV liner possesses a minimum damage tolerance life of 4 times the service life”
- Section 5.2.13.1: “The initial flaw (crack) size for assessment shall be greater than or equal to the minimum NDT capability associated with the inspection technique”
- Section 7.5.1: “The analysis shall show that the COPV liner meet … alysis may be performed using a crack growth software package”
- Section 7.5.1: “For the cycles in the service life during which the … all use nominal or conservative values of fracture properties”
- Section 7.5.1: “Autofrettage may be assessed using elastic/plastic frac … M)”
- Section 7.5.1: “Beneficial retardation effects on crack growth rates fro … oading shall not be used in the analysis”
- Section 7.5.1: “The stress in the uncracked ligament shall remain below the flow stress throughout the analysis of the damage tolerance life”

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Crack Growth Due to Autofrettage (AF)

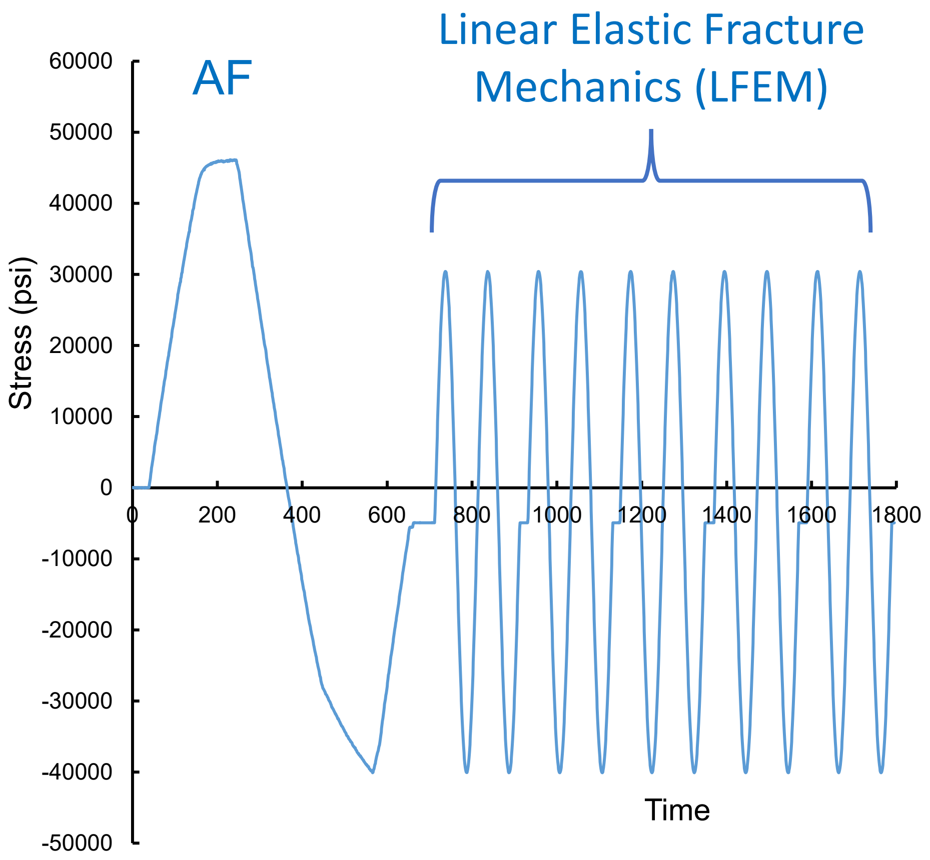
Remains Below the Flow Stress

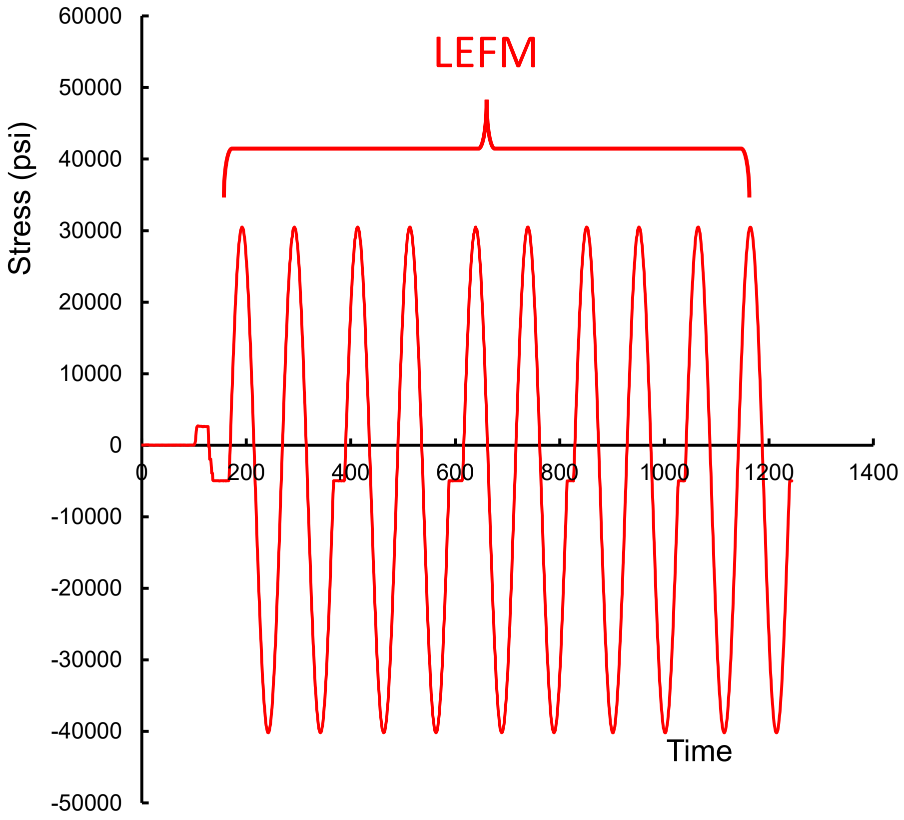
As Implemented for Elastically Responding Liners

$$a_{TOTAL} = a_{NDE} + \Delta a_{AF} + \Delta a_{LEFM}$$

$$a_{TOTAL} < t - b$$

Implications of S-081B



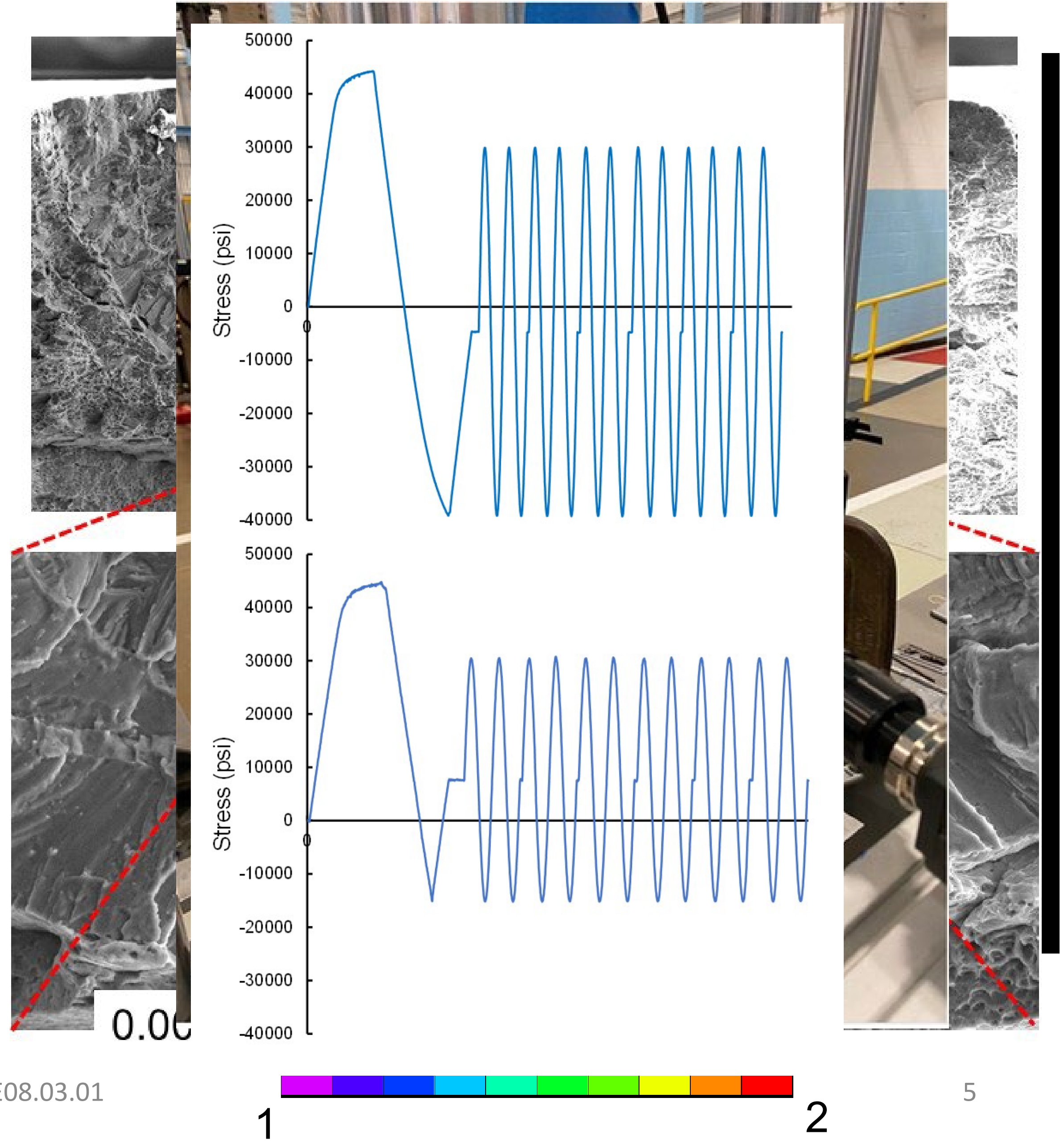


$\Delta a_{LEFM} \leq \Delta a_{LEFM}$

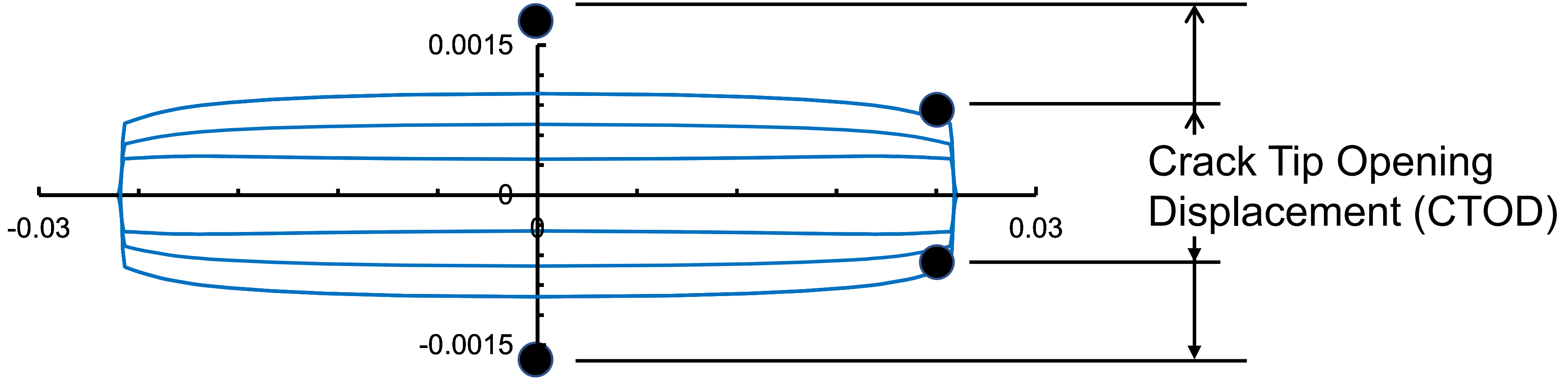
Is this true for COPV liner conditions?

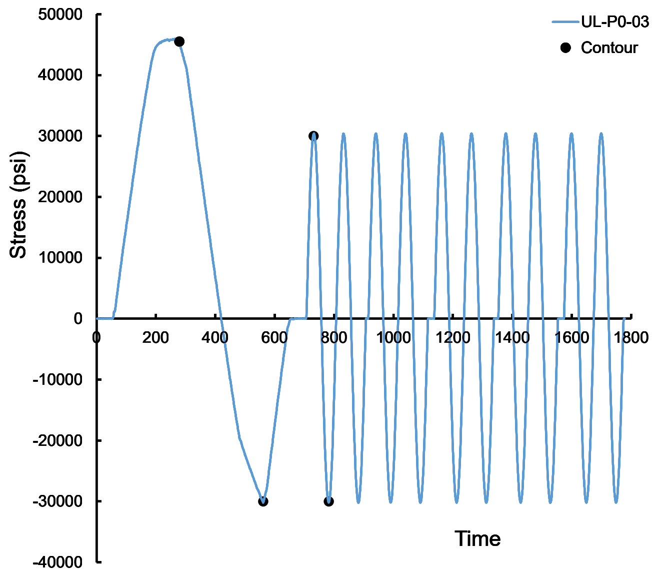
Experimental Approach

- Conduct fatigue crack growth rate tests on thin sheet aluminum materials, with and without an autofrettage
  - Use digital image correlation (DIC) to characterize material and crack mouth opening displacement (CMOD)
  - Extract crack growth from fracture surfaces
- Guide plates were used to prevent buckling at compressive loads
- Tests were conducted with different minimum stresses

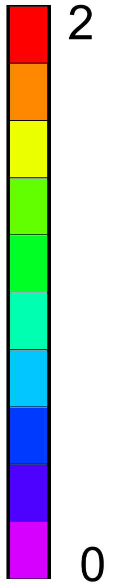


Analysis Animation of Crack Opening/Closing for Autofrettage

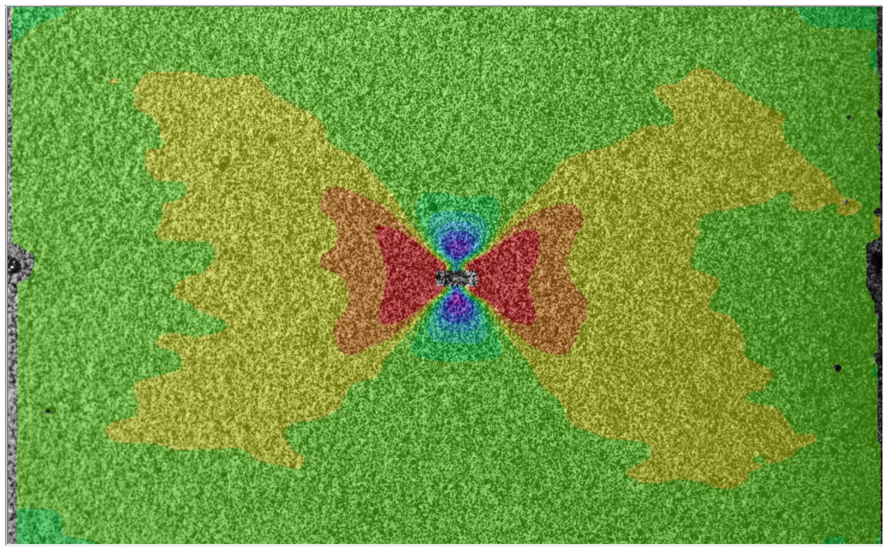




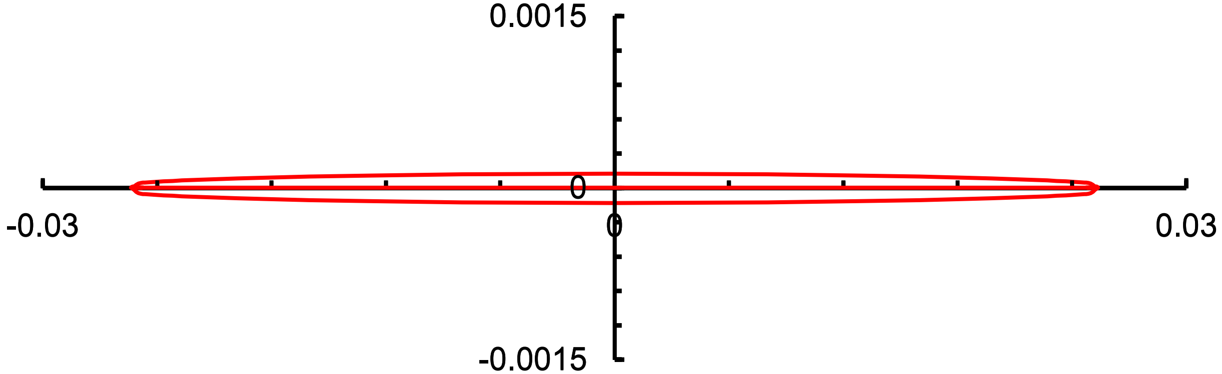
Axial Strain (%)

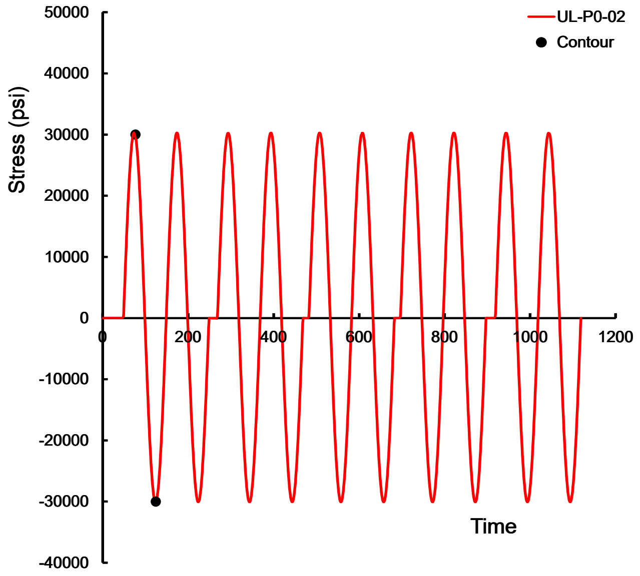


DIC Strain Field from Test

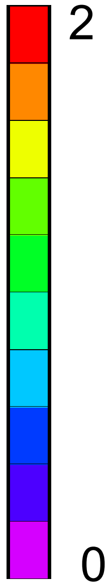


Analysis Animation of Crack Opening/Closing Without Autofrettage

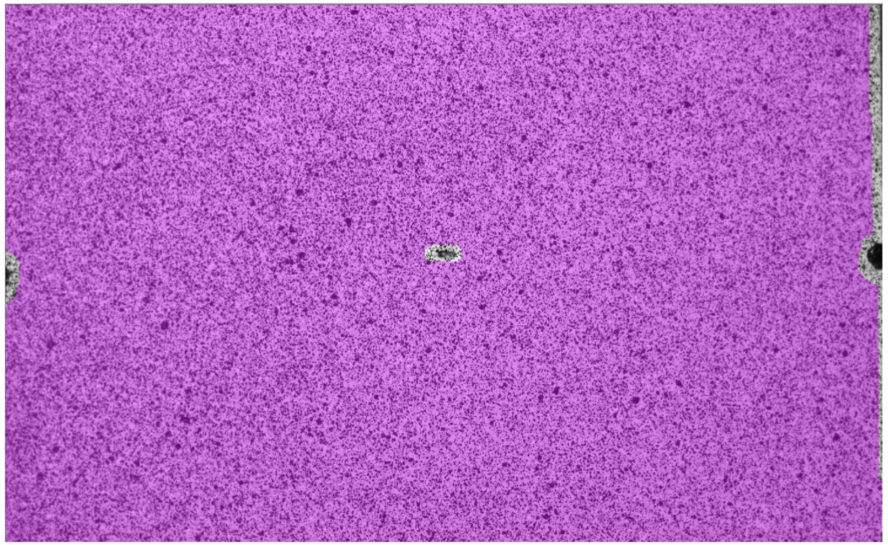




Axial Strain (%)



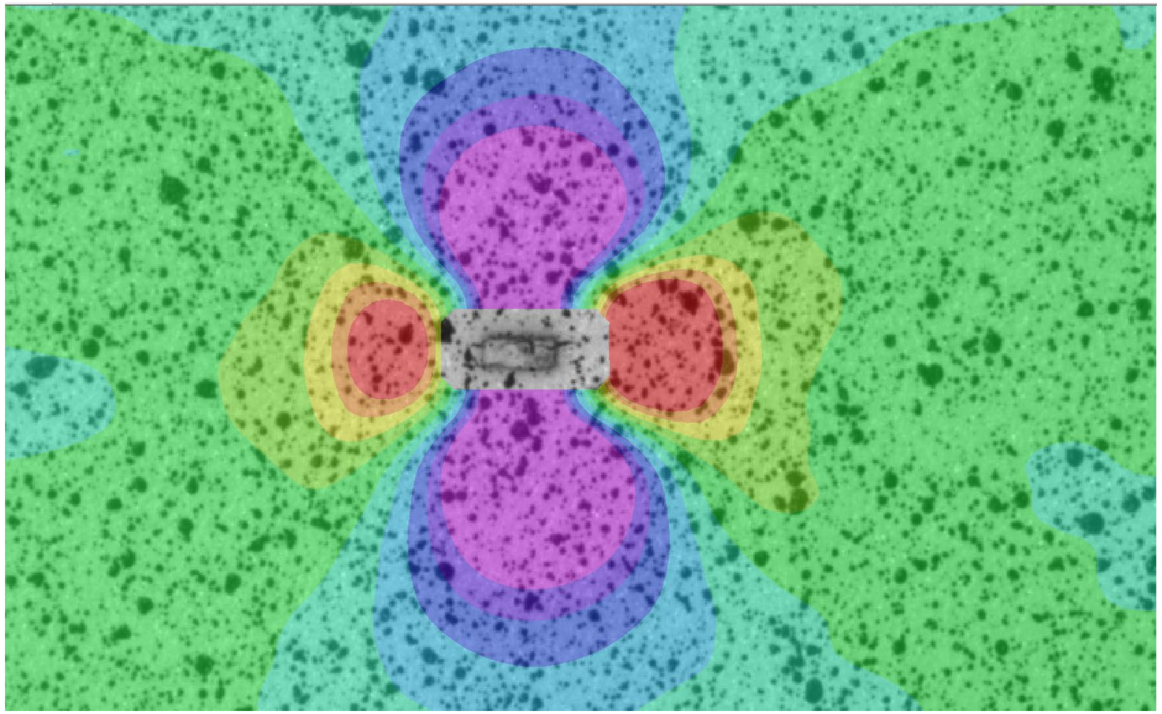
DIC Strain Field from Test



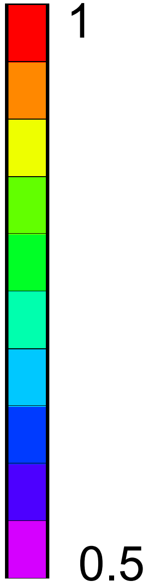
Cyclic Strain Contours (MDP: −40 ksi to +30 ksi)

The minimum stress of the first maximum design pressure (MDP) cycle (−40 ksi) was used as the reference image and the strain contour was measured for the peak stress of the second MDP cycle (+30 ksi) to characterize the cyclic strain that occurs during the damaging portion of the cycle (i.e., the increase in strain from the minimum stress to the peak stress)

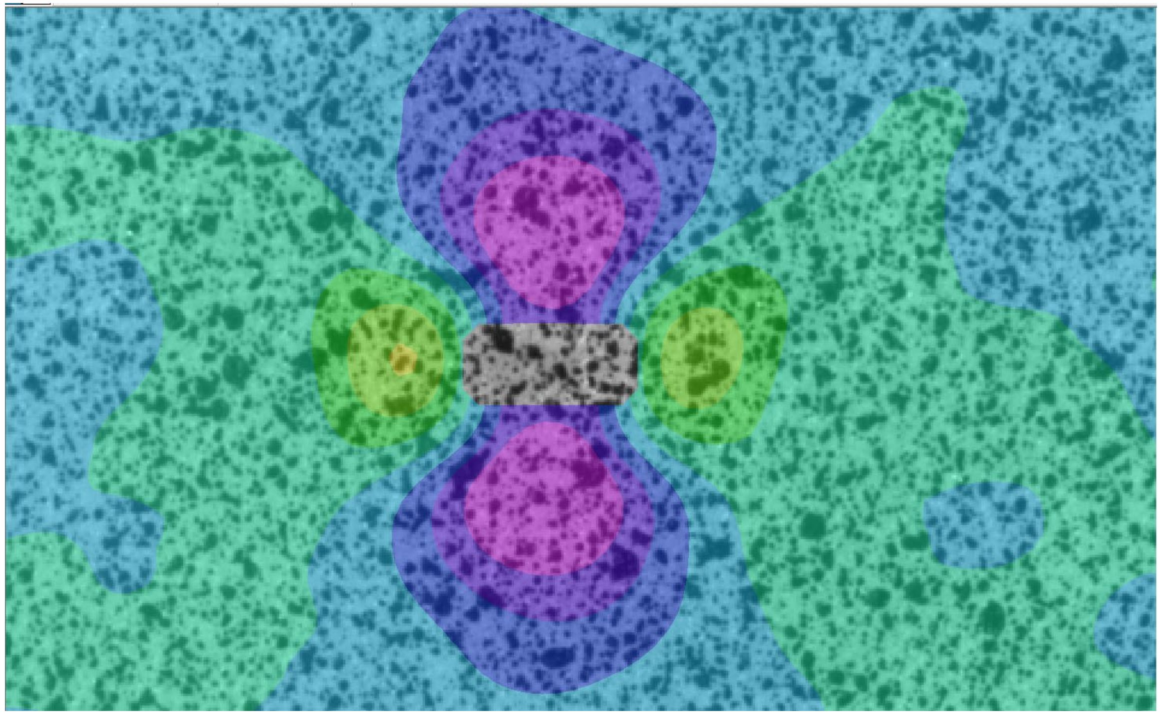
AF + MDP
(Cyclic Strain from −40 ksi to 30 ksi)



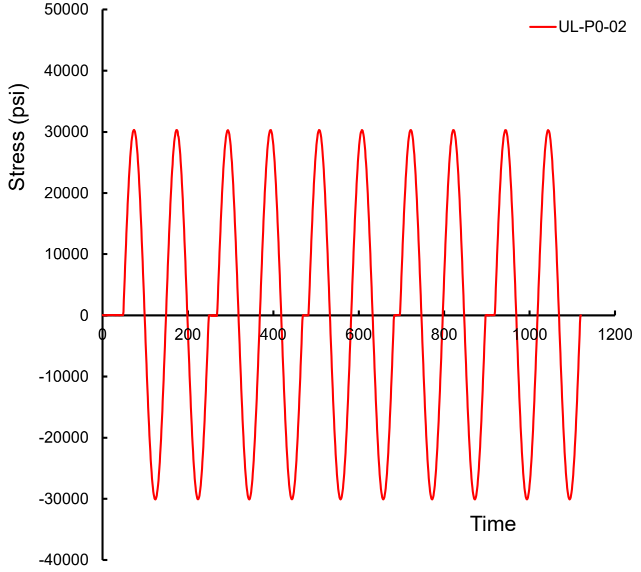
Axial Strain (%)

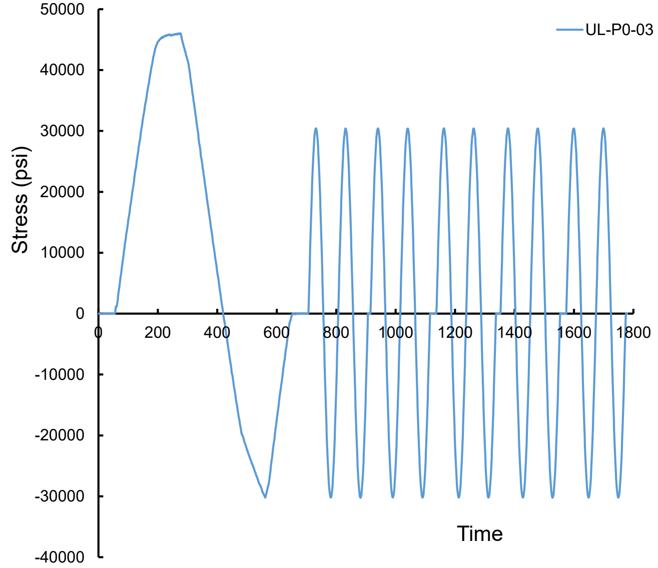


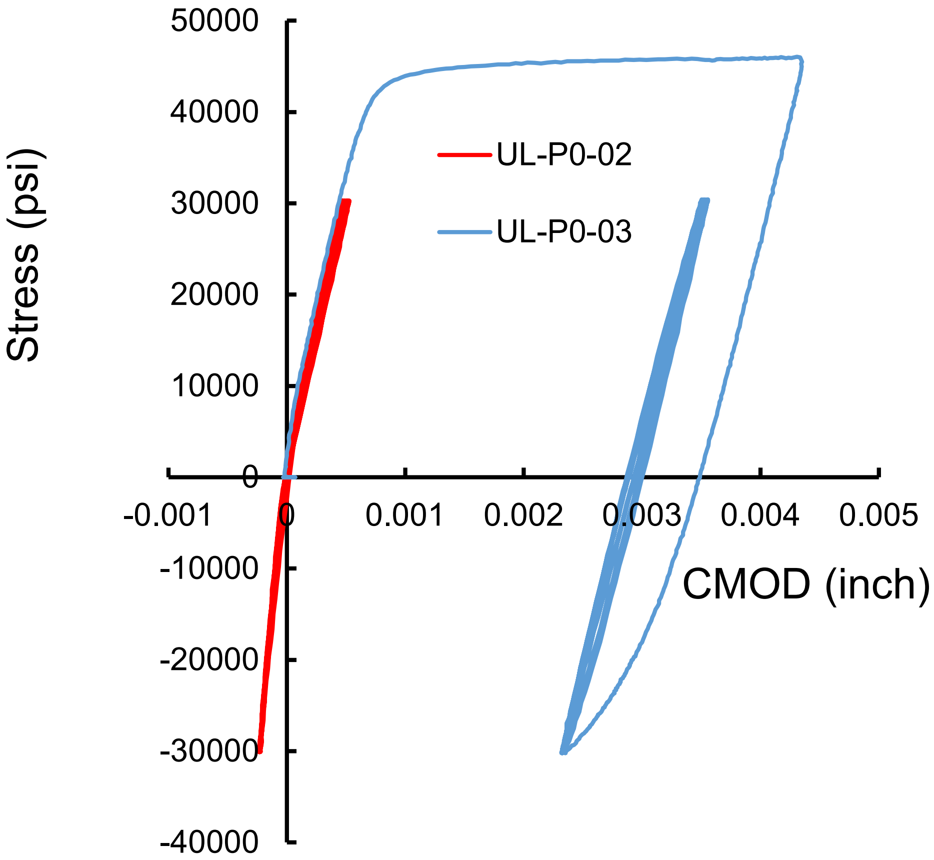
MDP Only
(Cyclic Strain from −40 ksi to 30 ksi)

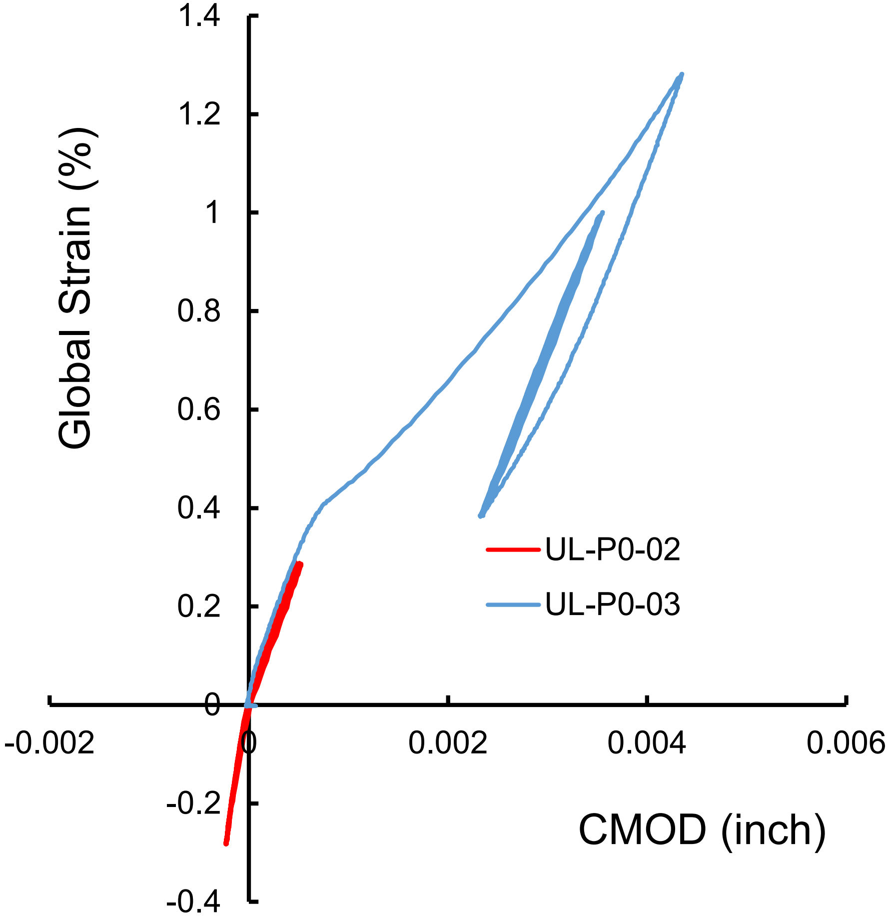


Crack Mouth Opening Displacements (CMOD)

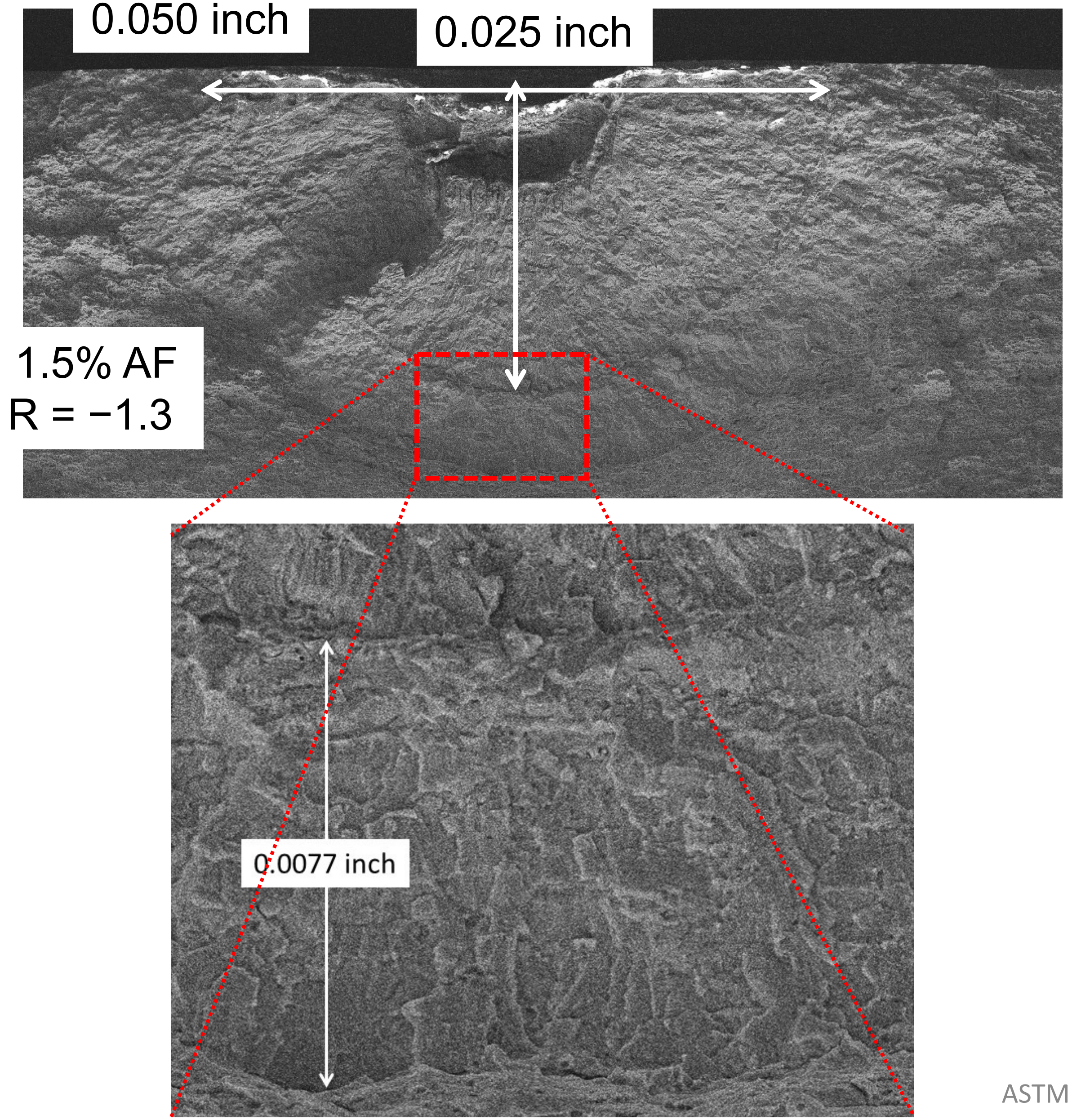


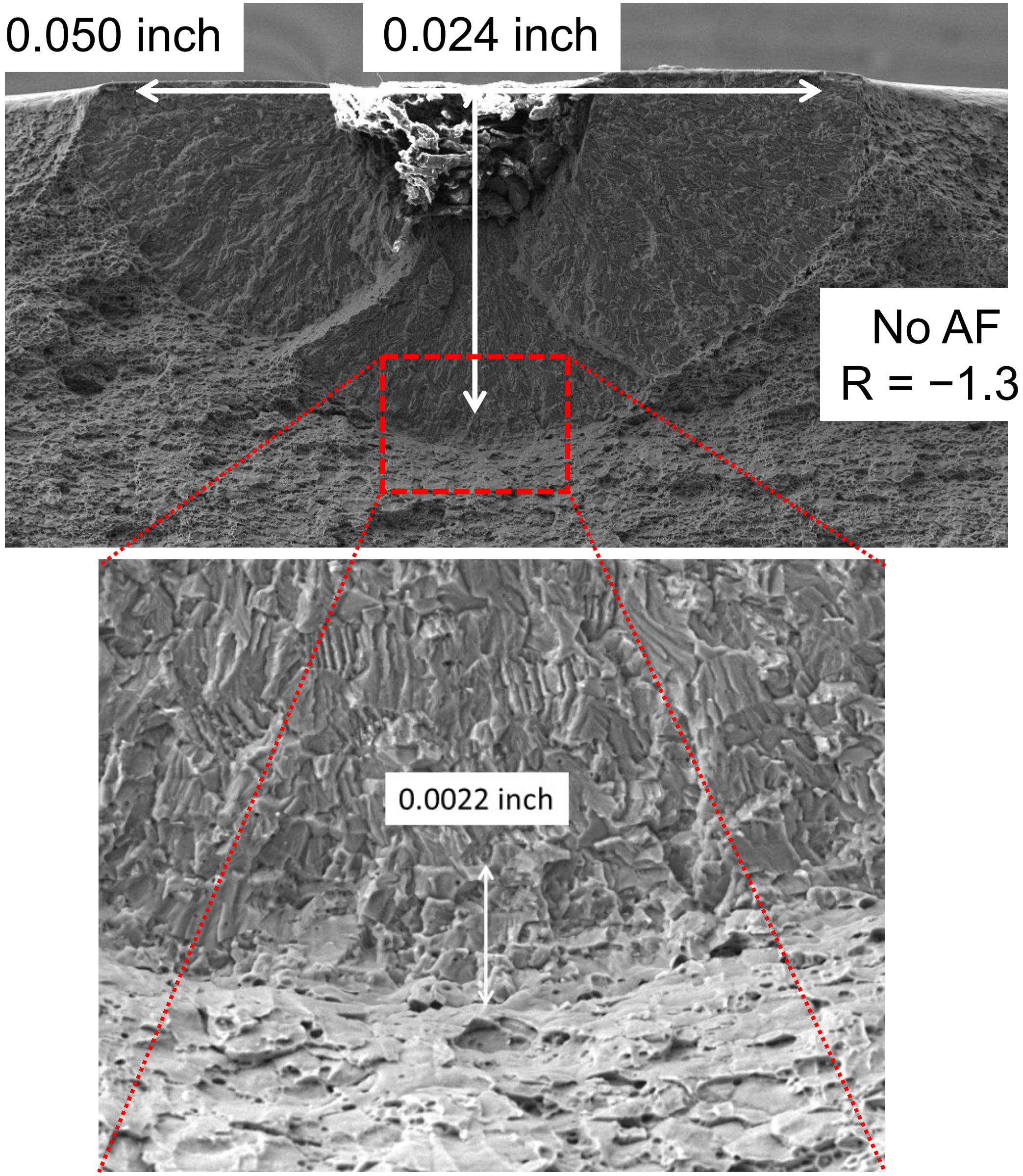




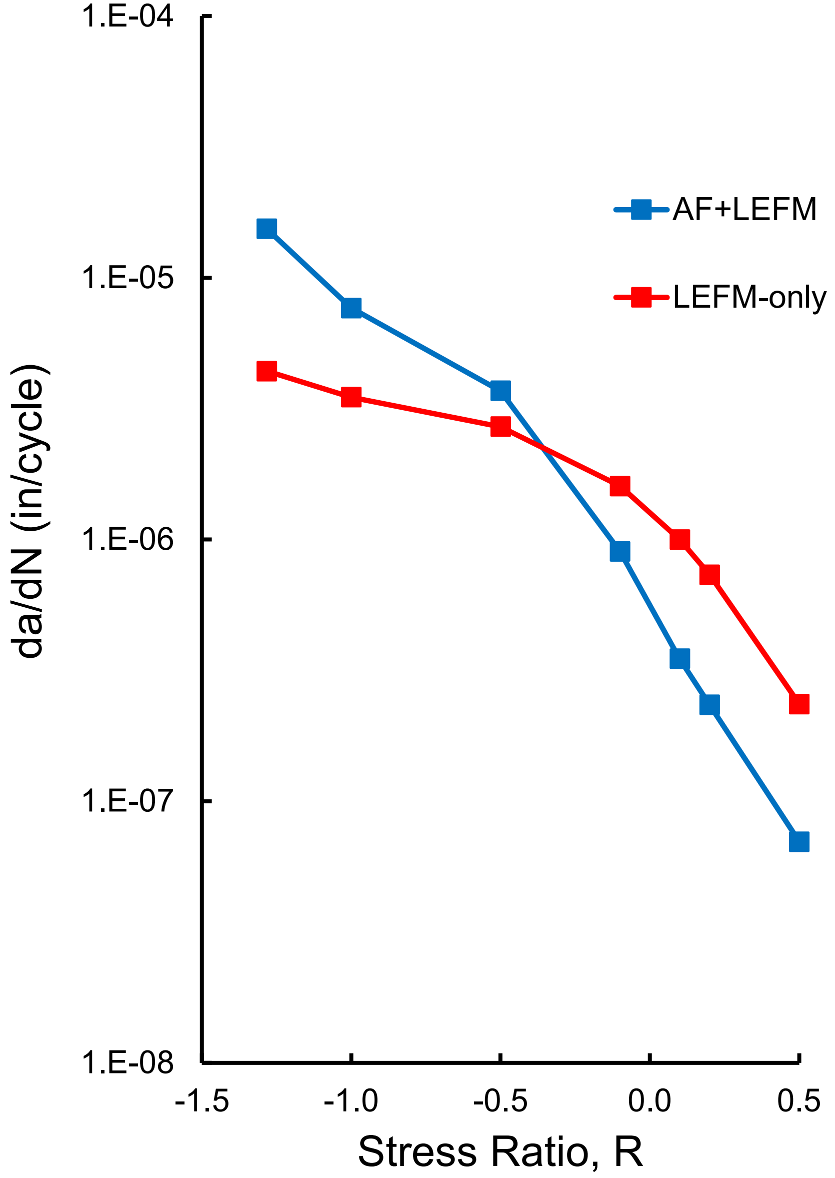


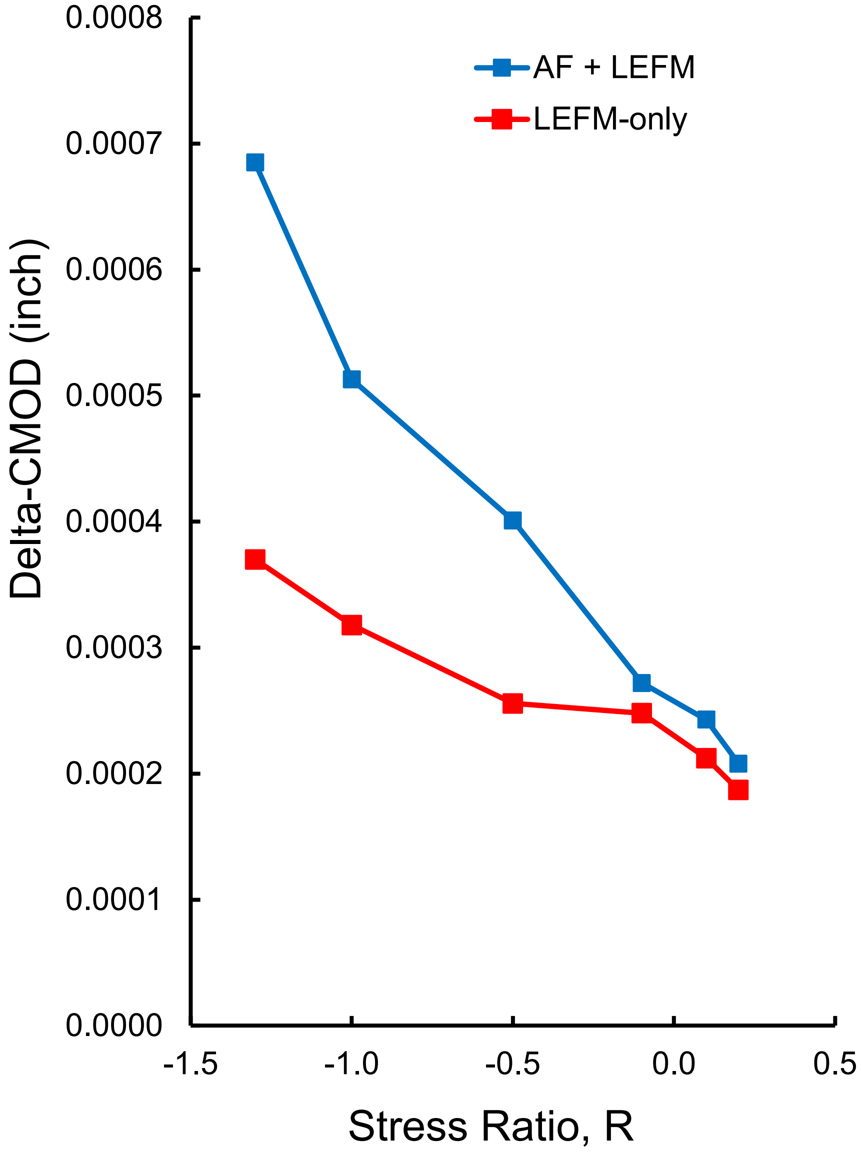
Crack Growth from Fracture Surfaces





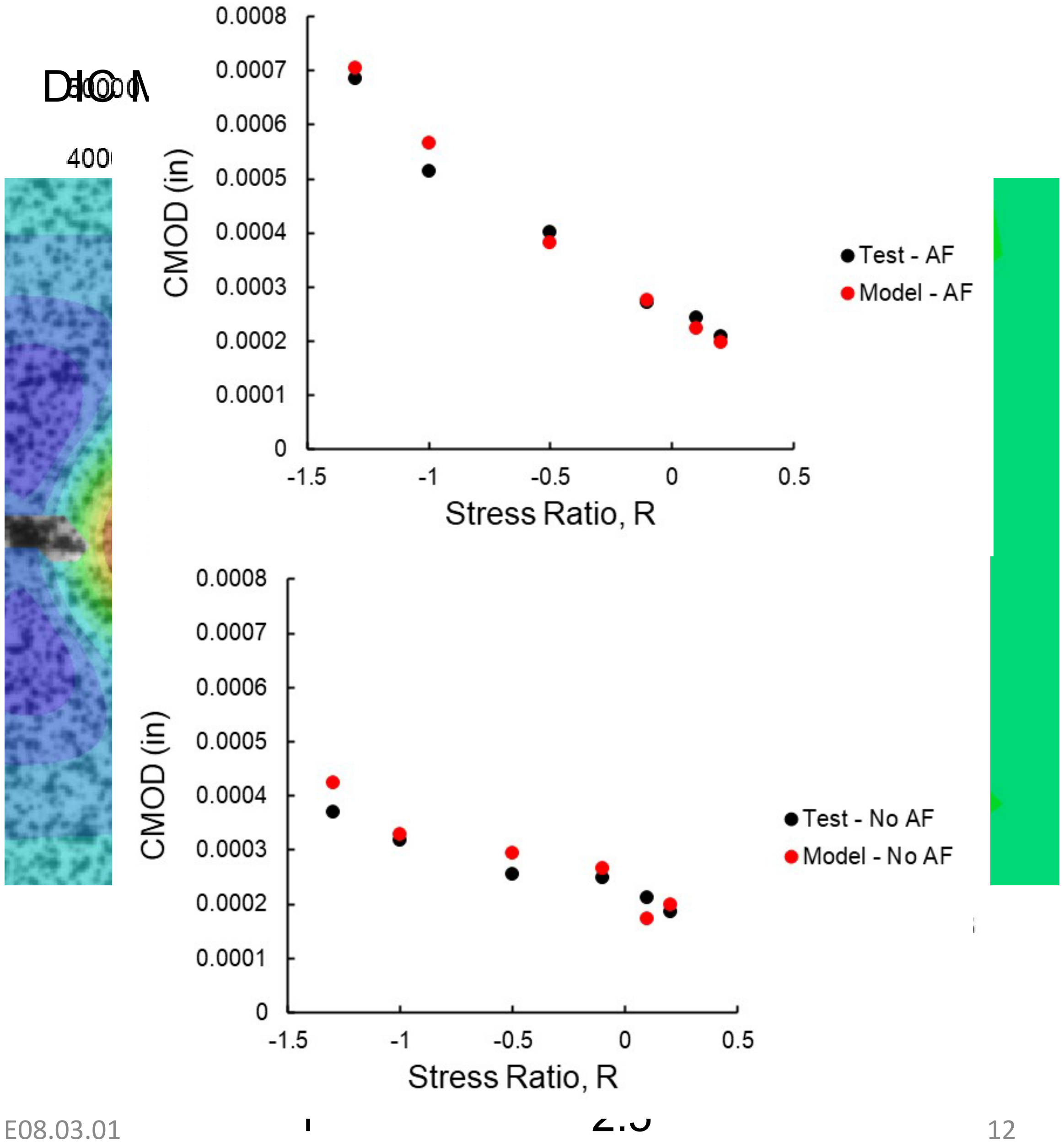
Measured Crack Growth Rates



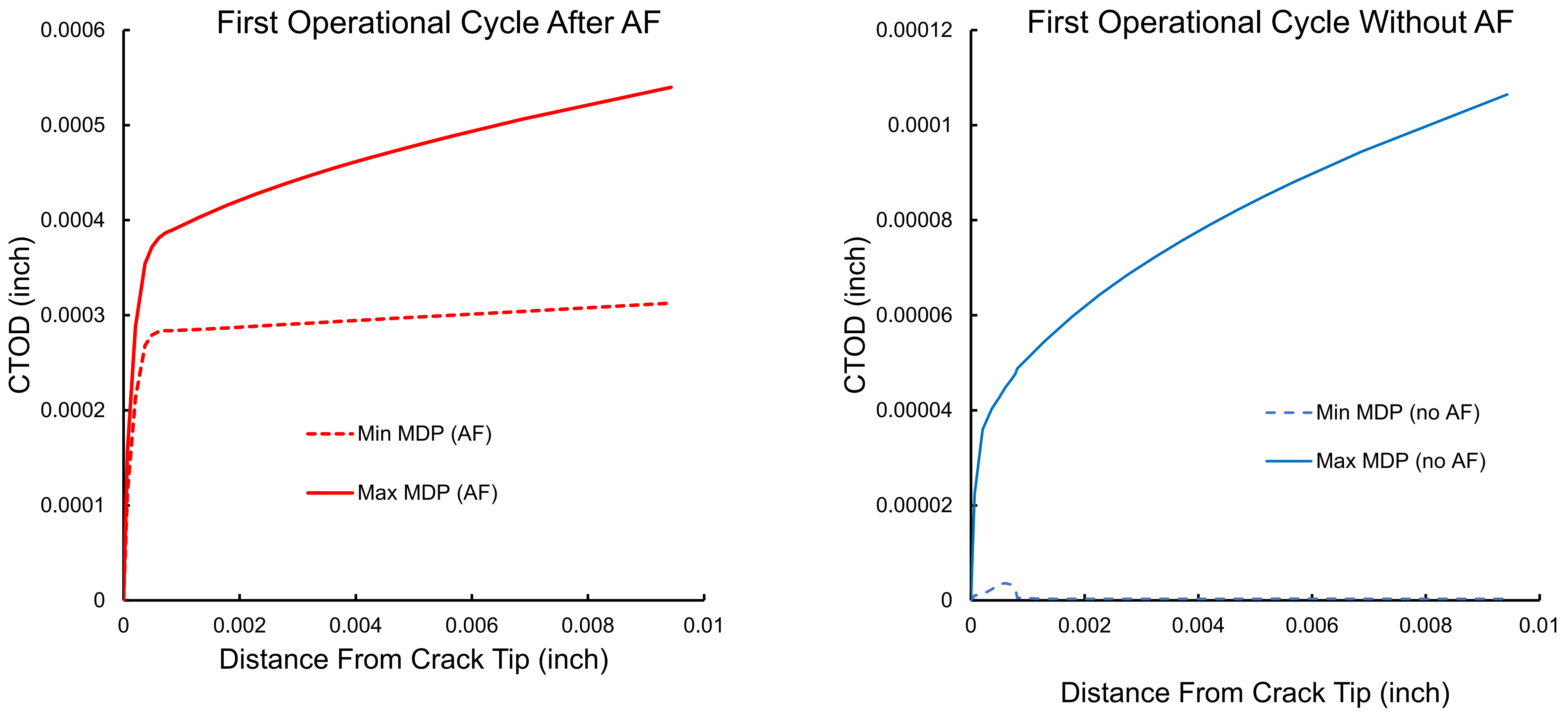


Analysis Approach

- Develop elastic-plastic material model based on cyclic tensile tests
- Validate the elastic-plastic material model
  - Compare finite element analysis (FEA) strain fields with DIC strain fields
  - Compare the FEA results with CMOD and CTOD measurements during the AF cycle
  - Compare the FEA results with CMOD measurements during the first MDP cycle for tests with different stress ratios, with and without the AF cycle
- Evaluate the CTOD, CMOD, and ΔK for the first MDP cycle at max stress and min stress
  - With and without the AF cycle
  - Uniaxial and biaxial loading

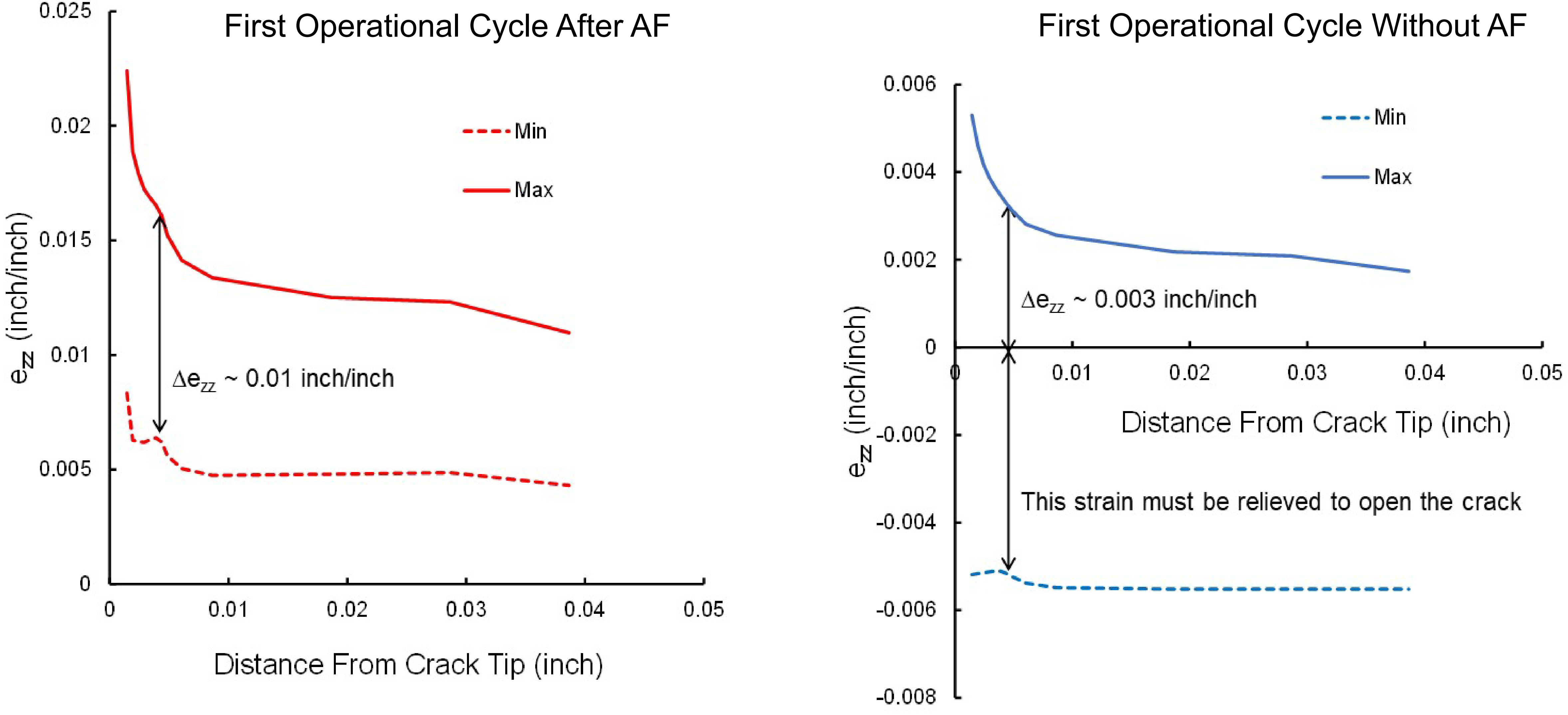


FEA Crack Opening Displacement

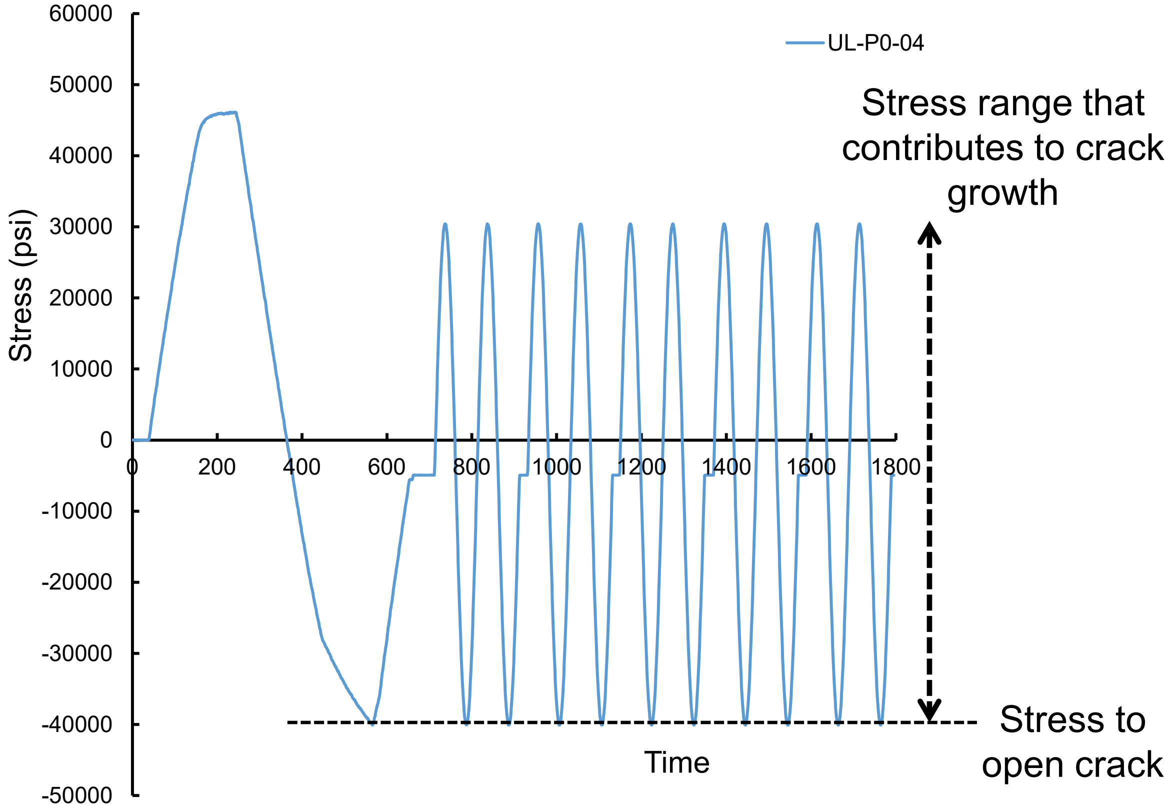


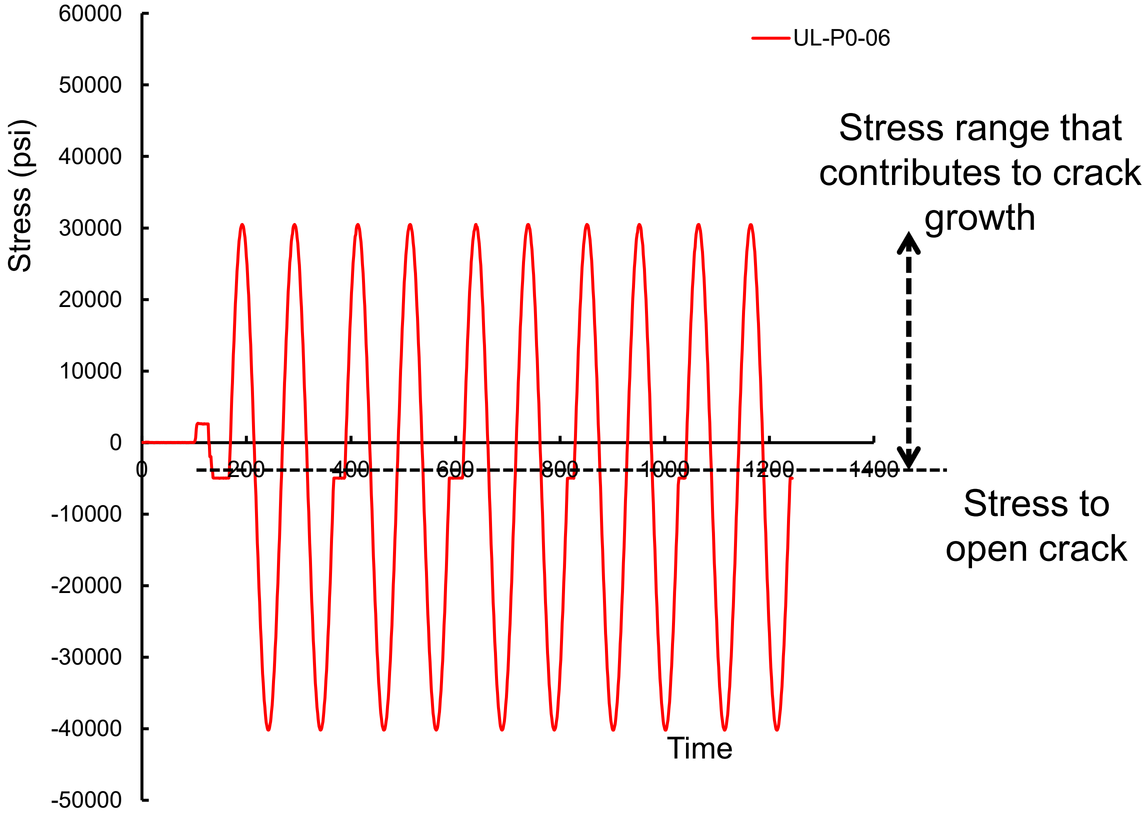
Note the vertical axis scale difference

FEA Axial Strain Ahead of Crack



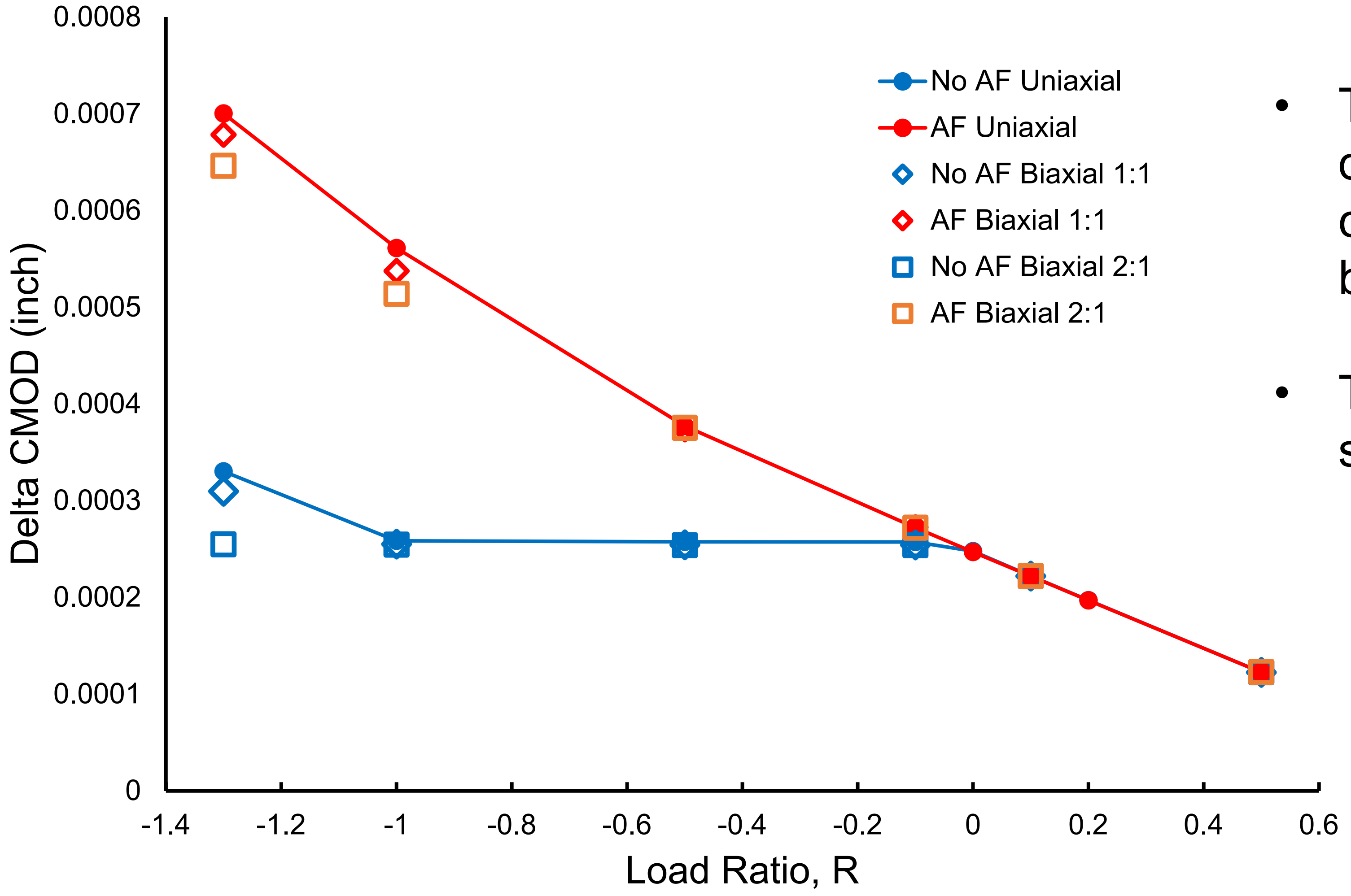
Suggested Explanation of the Increase in Crack Growth Following the Autofrettage Cycle





- The AF cycle blunts the crack tip and the crack is open, even at compressive stresses
  - The stress range that damage could occur is increased
  - The cyclic crack tip strains are increased
- The crack growth rate data for the elastic cycles is obtained from tests where the crack is closed for the compressive portion of the cycle

FEA Simulations of Bi-axial Loading



- The FEA indicates that biaxial loading does not significantly influence the cyclic crack opening (ΔCMOD) behavior
- The ΔK and ΔCTOD behavior was similar to the ΔCMOD

Conclusions

- The COPV autofrettage cycle (elastic-plastic overload) increased the crack growth rate for the subsequent elastic operational cycles

- Relative to identical tests conducted without an autofrettage cycle (what the analysis assumes), the autofrettage tests:
  - Experienced faster crack growth rates
  - The crack surfaces remained open
  - The crack tip cyclic strains were higher

- The analysis approach allowed by the ANSI/AIAA S-081B standard can result in unconservative damage tolerance life predictions for conditions relevant to COPV liners