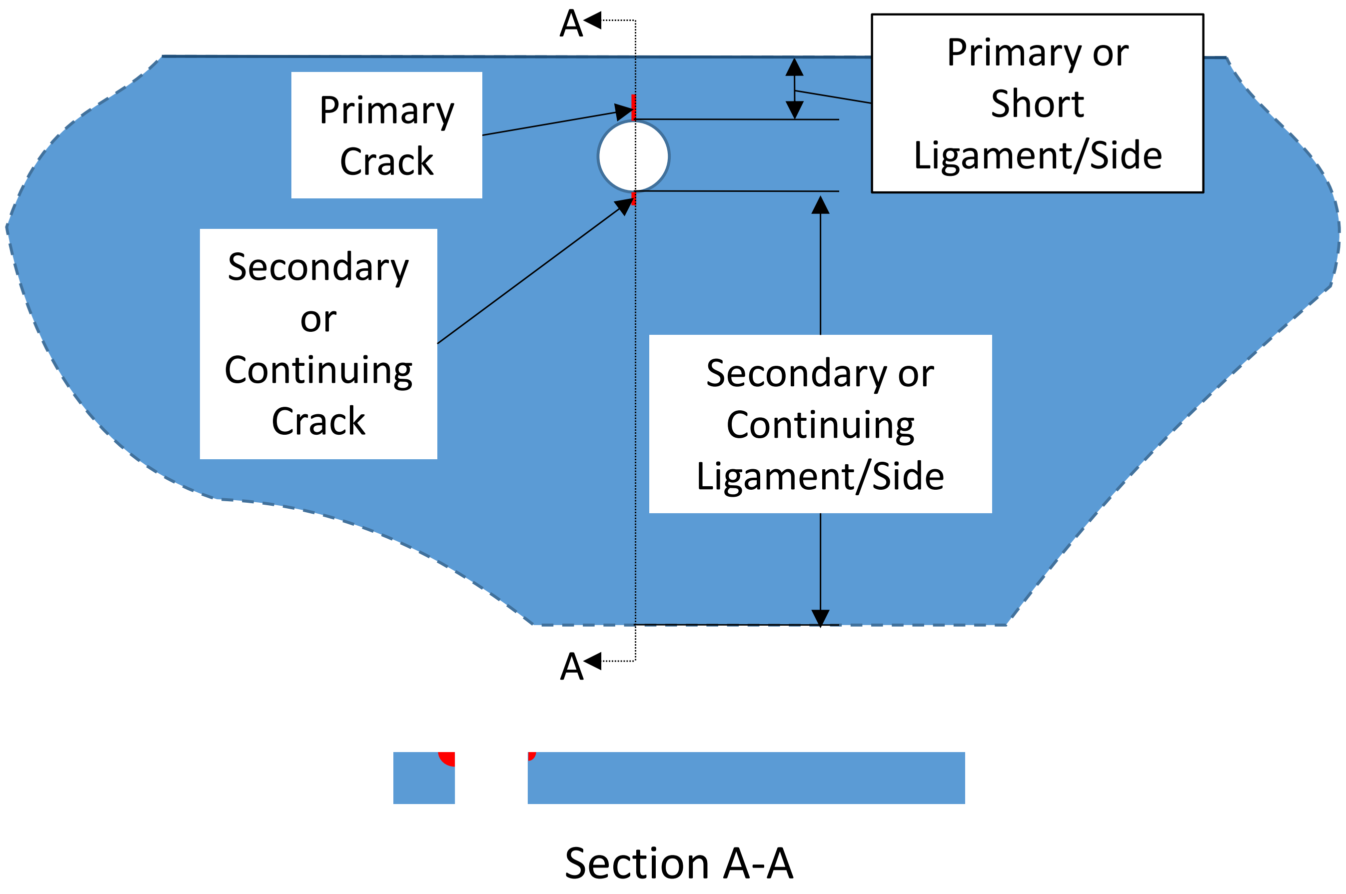
Continuing Damage Testing & Modeling

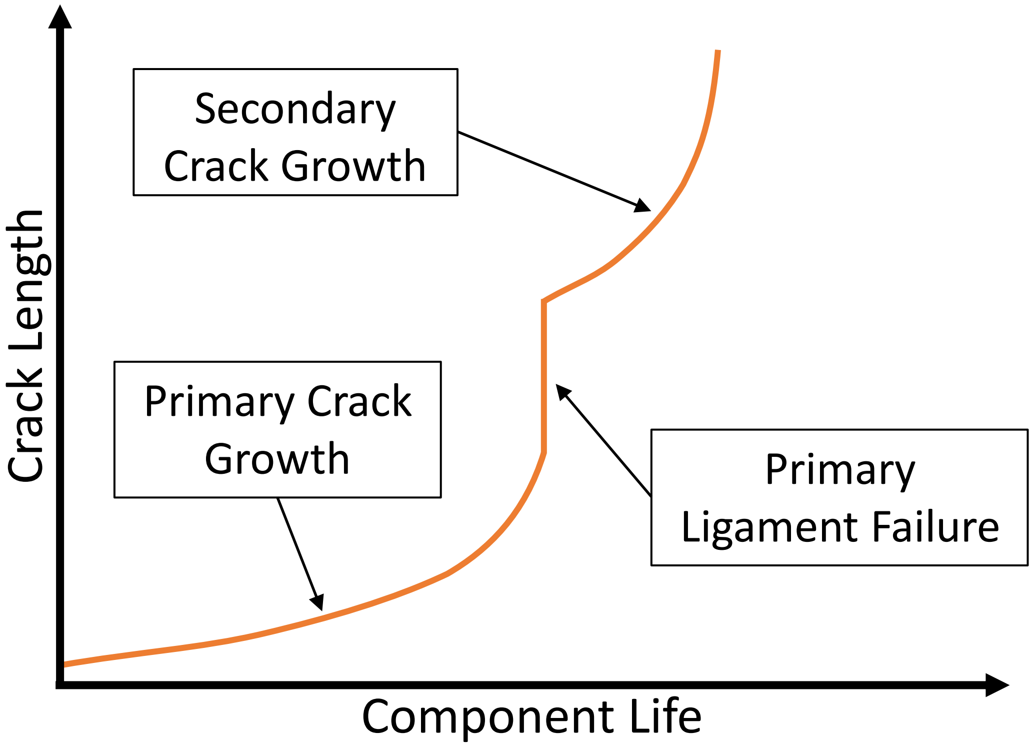
Matt Andrus

Overview

- Introduction
- Testing and Modeling
- Results and Discussion
- Conclusions

Continuing Damage Nomenclature





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Research Background

Lab

- Continuing damage can be used to justify longer inspection intervals while ensuring safe usage
- Some research has been performed:
  - Validation Testing [1]
    - 22 severed primary ligament samples tested
    - Provided confidence in continuing damage modeling methods
  - Methods Case Study [2]
    - Compared two different continuing damage analysis methods
    - Showed that simultaneous method is more conservative
- No directly comparable samples have been tested yet

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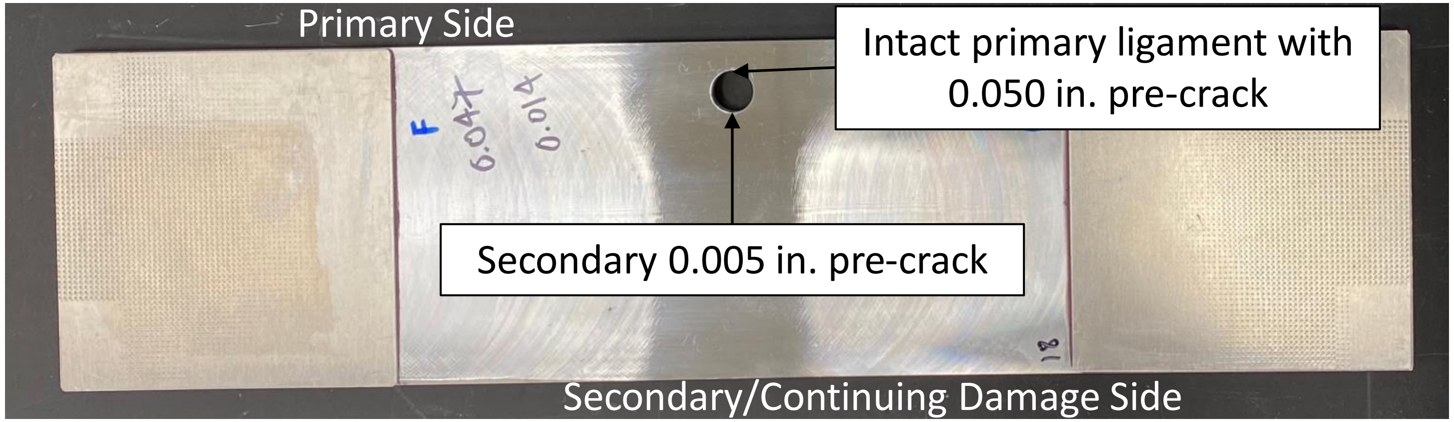
Research Goals

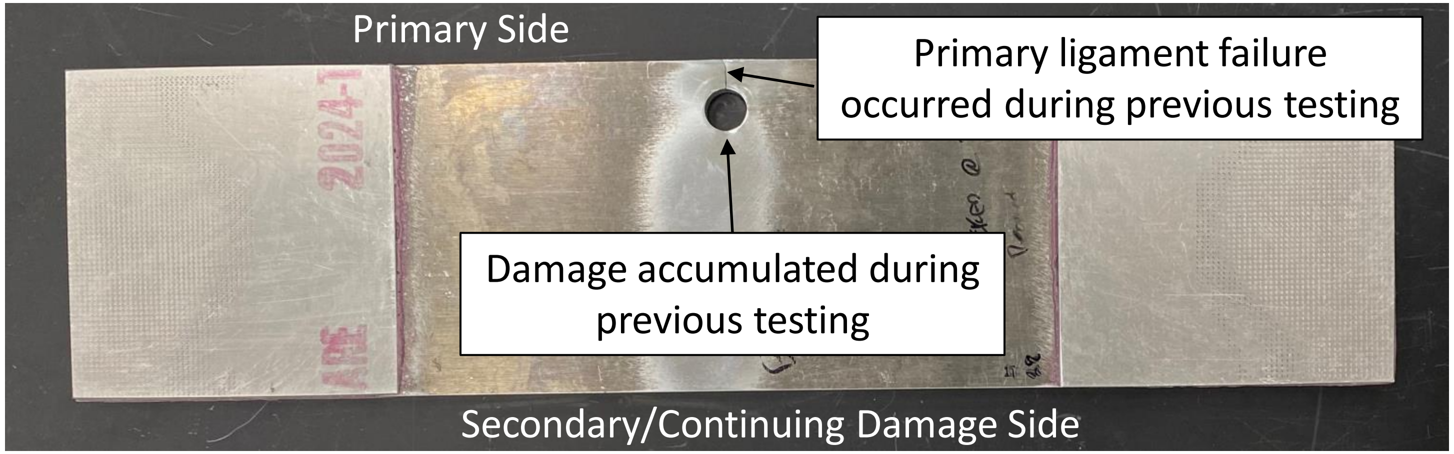
1. Test conservatism of JSSG-2006 [3] initial flaw size (0.050” primary, 0.005” continuing), modeling assumptions, and approach
2. Explore continuing damage modeling approaches and their accuracy compared to test data
3. Compare continuing damage fatigue life of specimens with induced continuing damage flaw against specimens with naturally occurring damage
4. Investigate crack size and shape of induced continuing damage and naturally accrued continuing damage

Test Plan

- Two sample forms provided by A-10 ASIP:
  - Specially manufactured coupons with cracks designed to simulate the continuing damage scenario
  - Coupons with a failed primary ligament resulting from previous testing

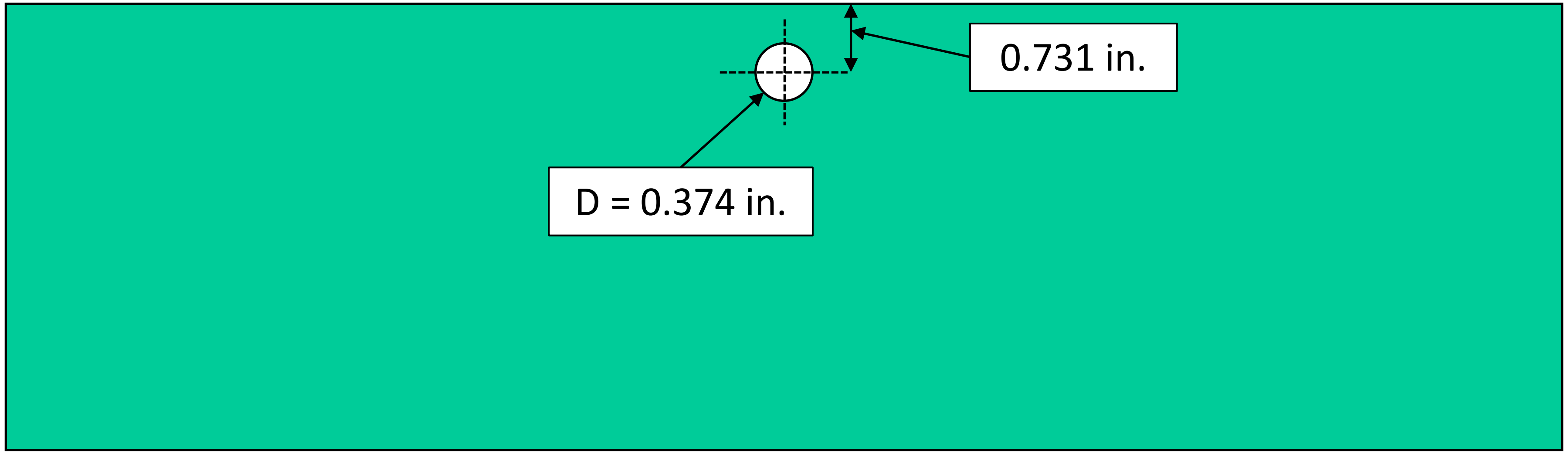


Continuing Damage (CD) Sample



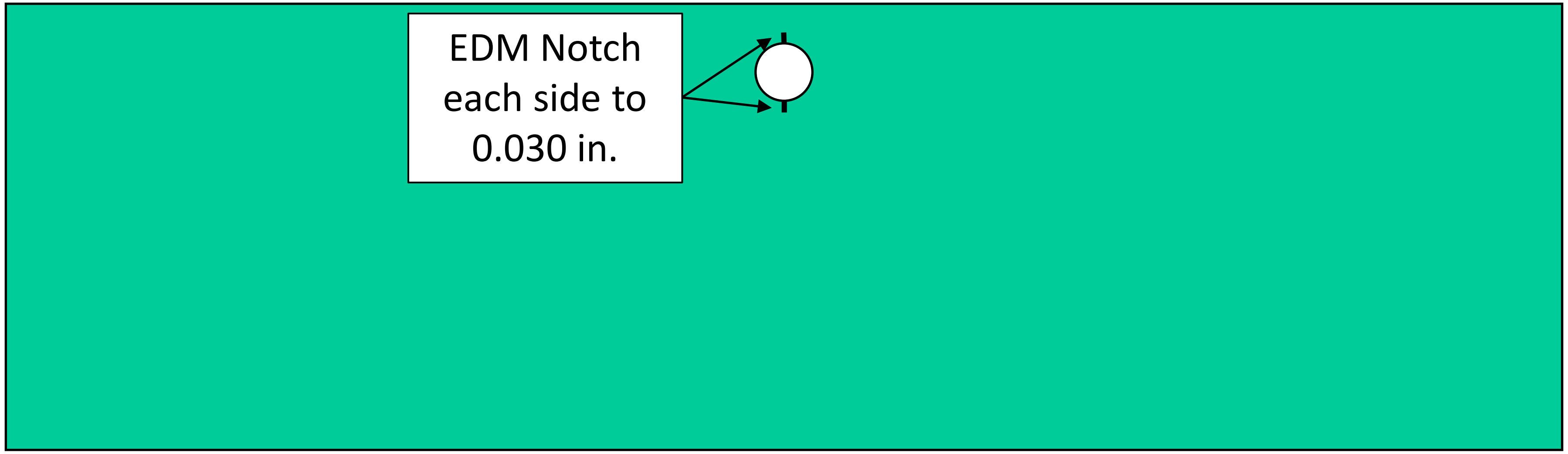
Failed Primary Ligament (FPL) Sample

CD Specimen Production



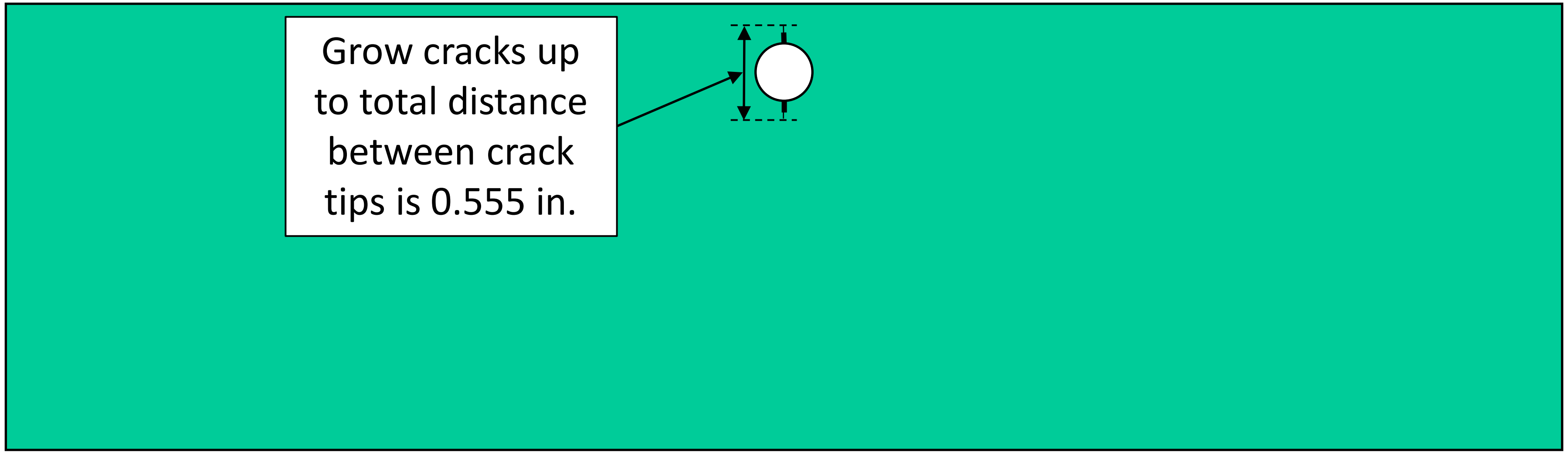
Drill Starter Hole

CD Specimen Production



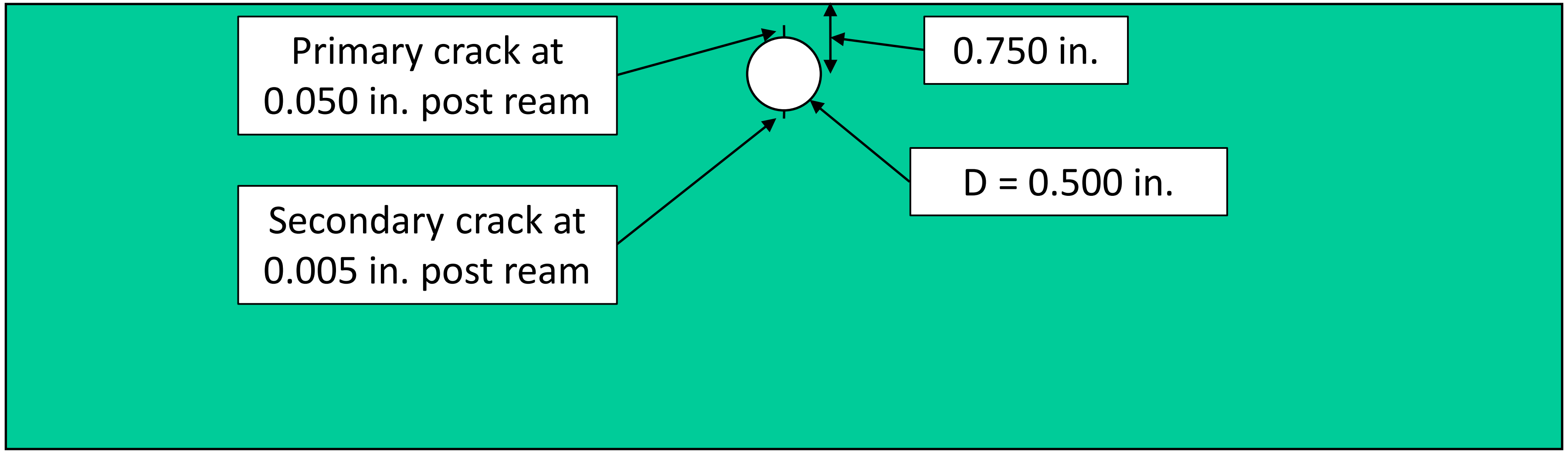
Apply Notches

CD Specimen Production



Grow Cracks

CD Specimen Production



Offset Ream to Final Diameter

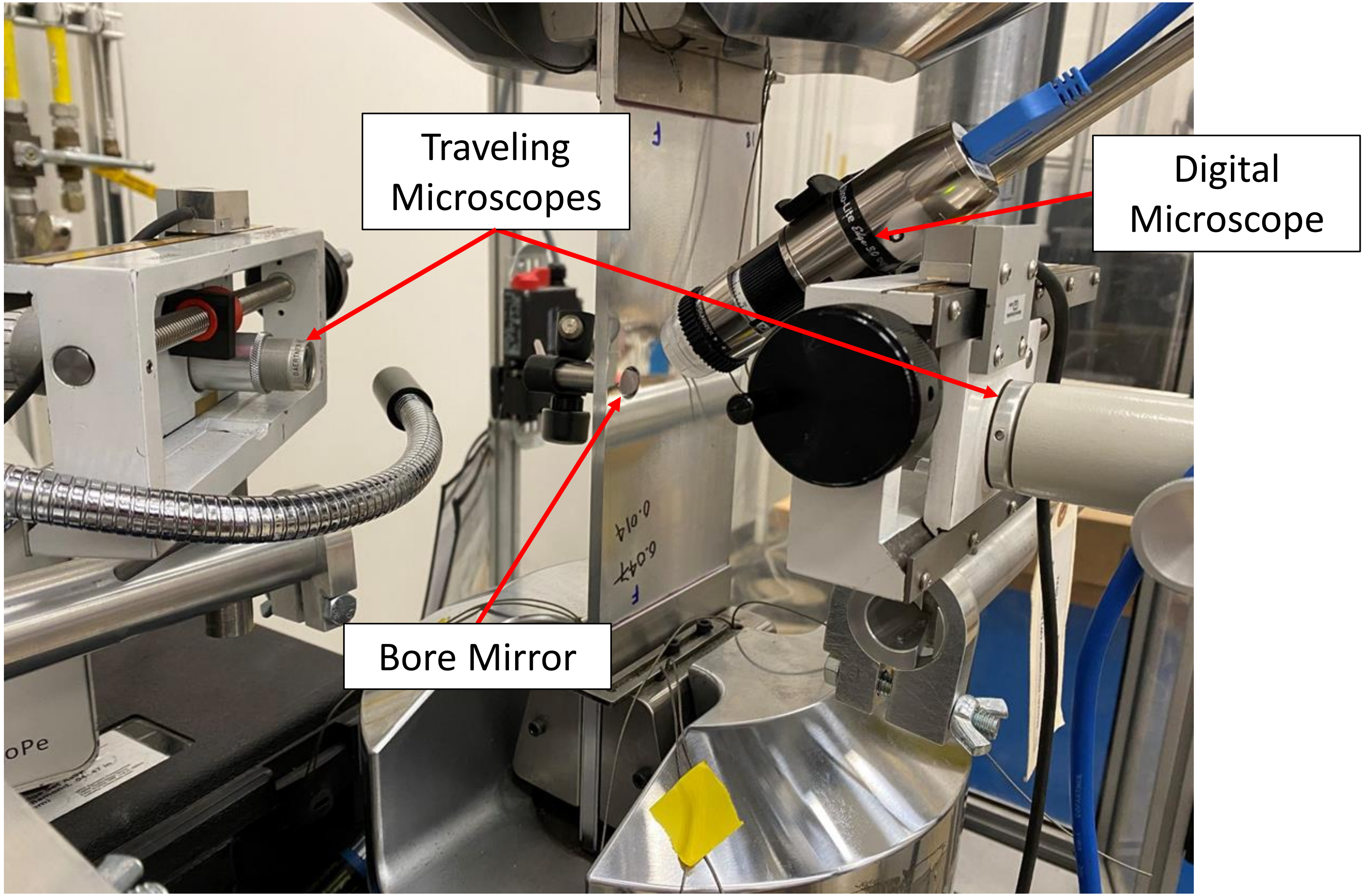
Test Plan

- Test methods similar to ASTM E647
  - Variable amplitude (VA) loading using a wing root bending spectrum based on USAF A-10 jet usage
  - Constant amplitude (CA) loading, 0.1 stress ratio

Coupon Designation	Specimens (qty)	Cold Worked	Loading Type	Max Stress §	Primary Notch	Secondary Notch	Coupon Type
24365-150-VA-NCX-16	1	No	VA	33/25 KSI	0.050 in	0.005 in	New
24365-150-VA-NCX-17	1	No	VA	30/25 KSI	0.050 in	0.005 in	New
24365-150-VA-NCX-18	1	No	CA	14/10.5 KSI	0.050 in	0.005 in	New
CX150ED-1, 2, 3	3	Yes	VA	25 KSI	FPL†	None	Existing
NCX150ED-1	1	No	VA	20 KSI	FPL	None	Existing
NCX150ED-2	1	No	VA	25 KSI	FPL	None	Existing

†Failed Primary Ligament
§ Prior to Ligament Failure/After Ligament Failure where applicable

Test Setup


Traveling Microscopes
Digital Microscope
Bore Mirror
0.014
0.047

AFGROW Modeling Approach

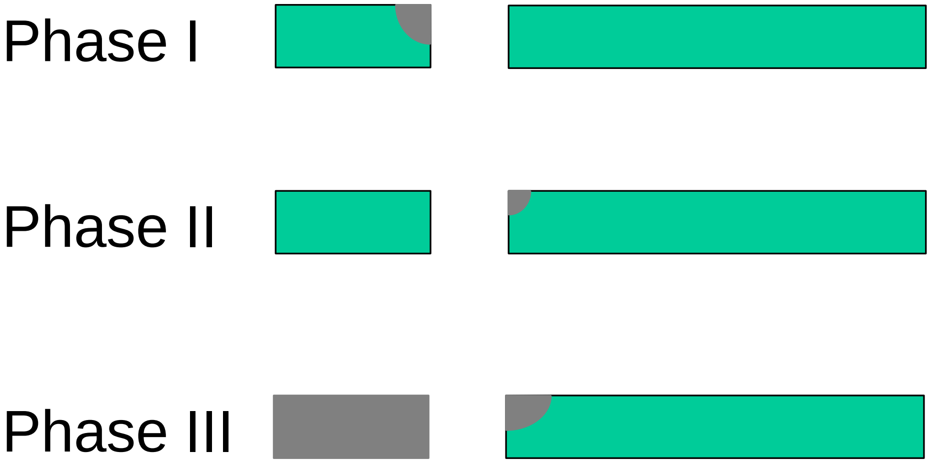
- Geometry: Crack length and shape based on either test sample measurements or JSSG-2006 [3] standard. Types included offset hole models, with and without failed ligaments, with corner crack(s) which would transition to through-thickness crack(s)
- Beta correction factors:

$$\beta_{final} = \beta_{AFGROW}\beta_{corr}$$

- Material Properties: Al 2024-T351 L-T
- Loading Schemes:
  - Variable amplitude (VA) A-10 wing root bending spectrum
  - Constant amplitude (CA) with R=0.1
- Retardation for VA loading: Generalized Willenborg model using a shutoff overload ratio (SOLR) of 1.807 from a previous research project [4]
  - Retardation is crack growth attenuation resulting from an overload in a loading spectrum

Continuing Damage Approaches

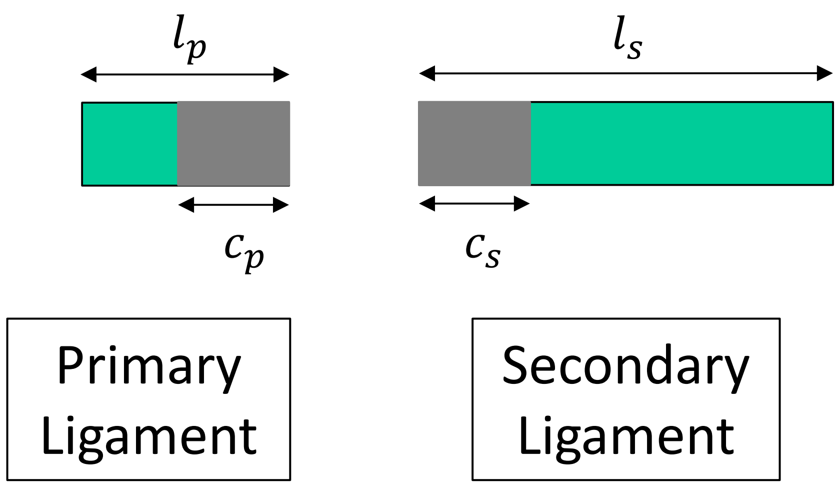
Sequential Model



Simultaneous Model

Stiffness Beta Correction Factors

- Stiffness beta factors are correction factors that account for remaining stiffness in the primary (p) and secondary (s) ligaments as cracks propagate, based on input from a USAF project advisor [6]



$$\boldsymbol{\beta_{final} = \beta_{AFGROW}\beta_{corr}}$$

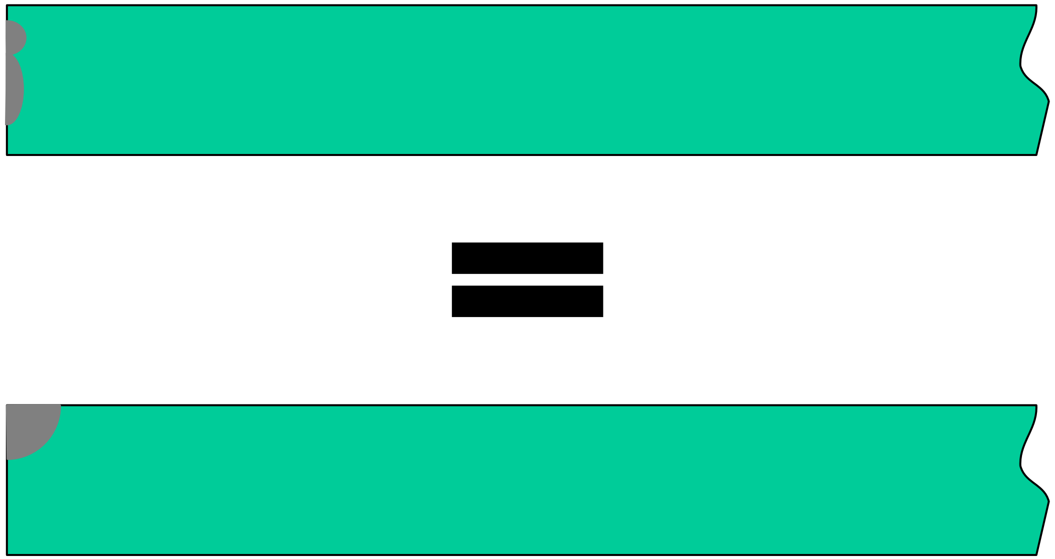
$$\boldsymbol{\beta_{corr,p} = 1 - \frac{l_p - c_p}{l_s - c_s}}$$

$$\boldsymbol{\beta_{corr,s} = 1 + \frac{l_p - c_p}{l_s - c_s}}$$

- $\beta_{corr,p}$ and $\beta_{corr,s}$ are the beta correction factors for the primary and secondary side
- l_p and l_s are the lengths of the primary and secondary ligaments, respectively
- c_p and c_s are the lengths of the primary and secondary cracks, respectively

Equivalent Initial Flaw Size

- Represents an accumulation of damage as a single flaw [5]
- Corner crack provides more directly comparable results to the secondary crack lengths at primary ligament failure computed using the JSSG-2006 model based on Air Force guidelines



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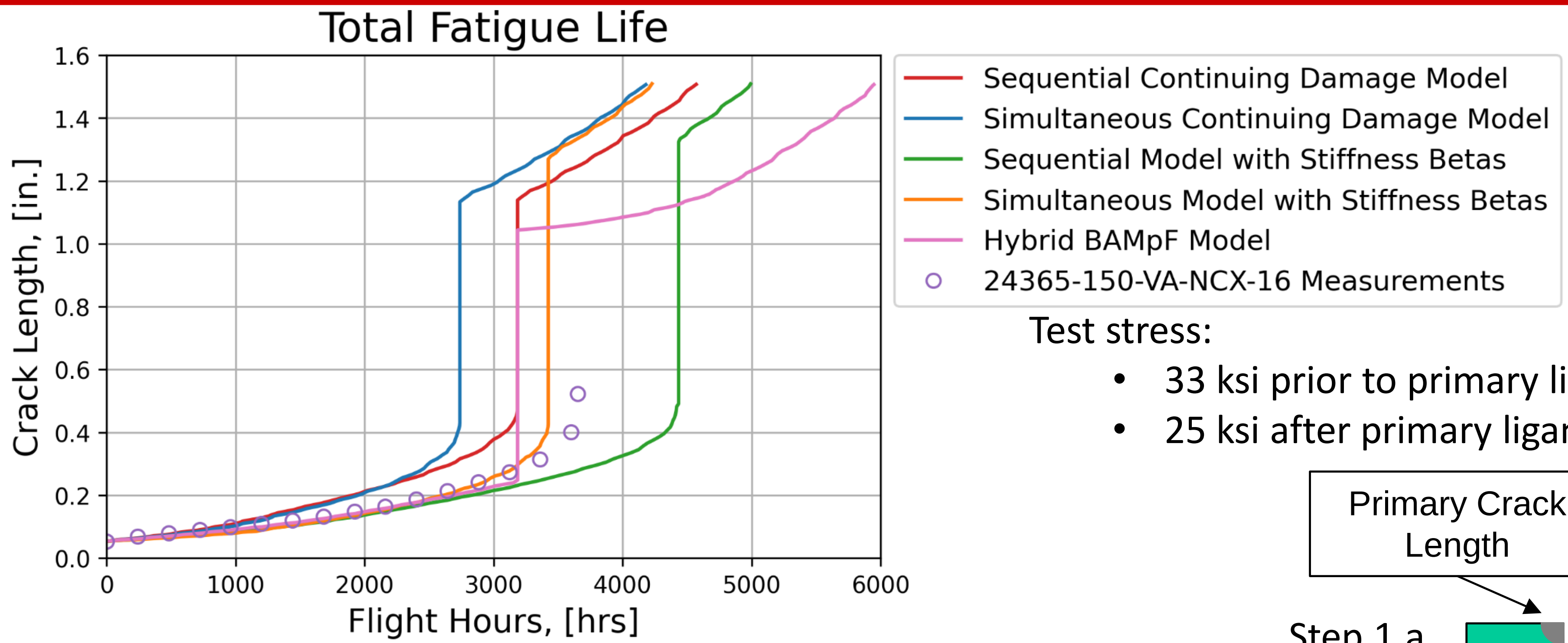
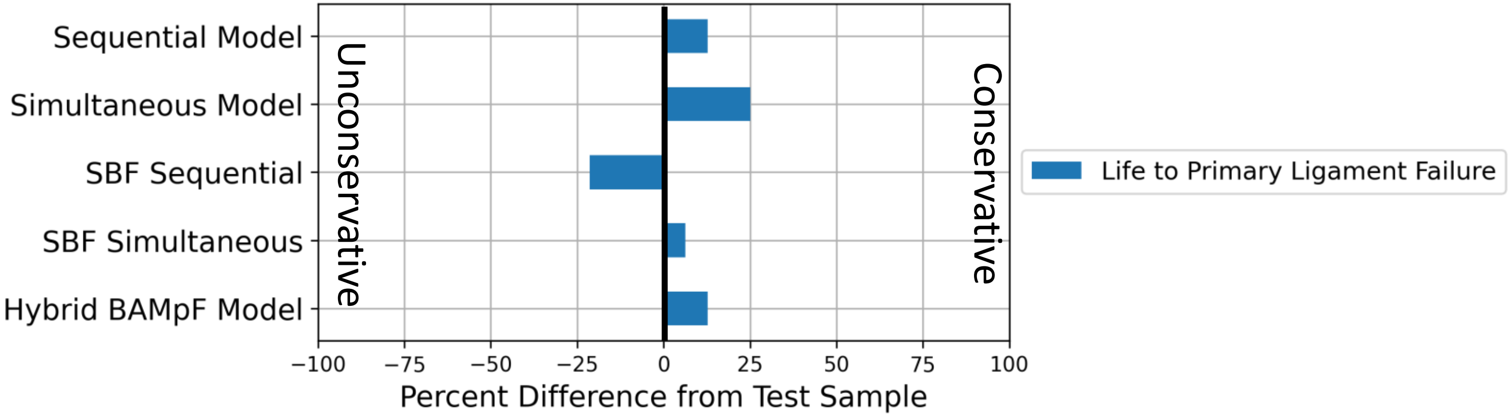
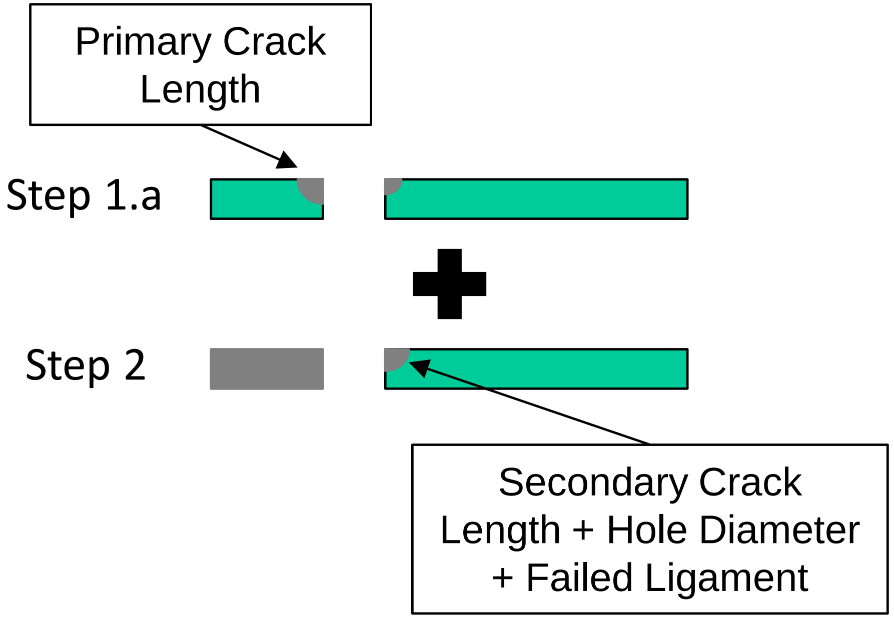
Continuing Damage Sample -16



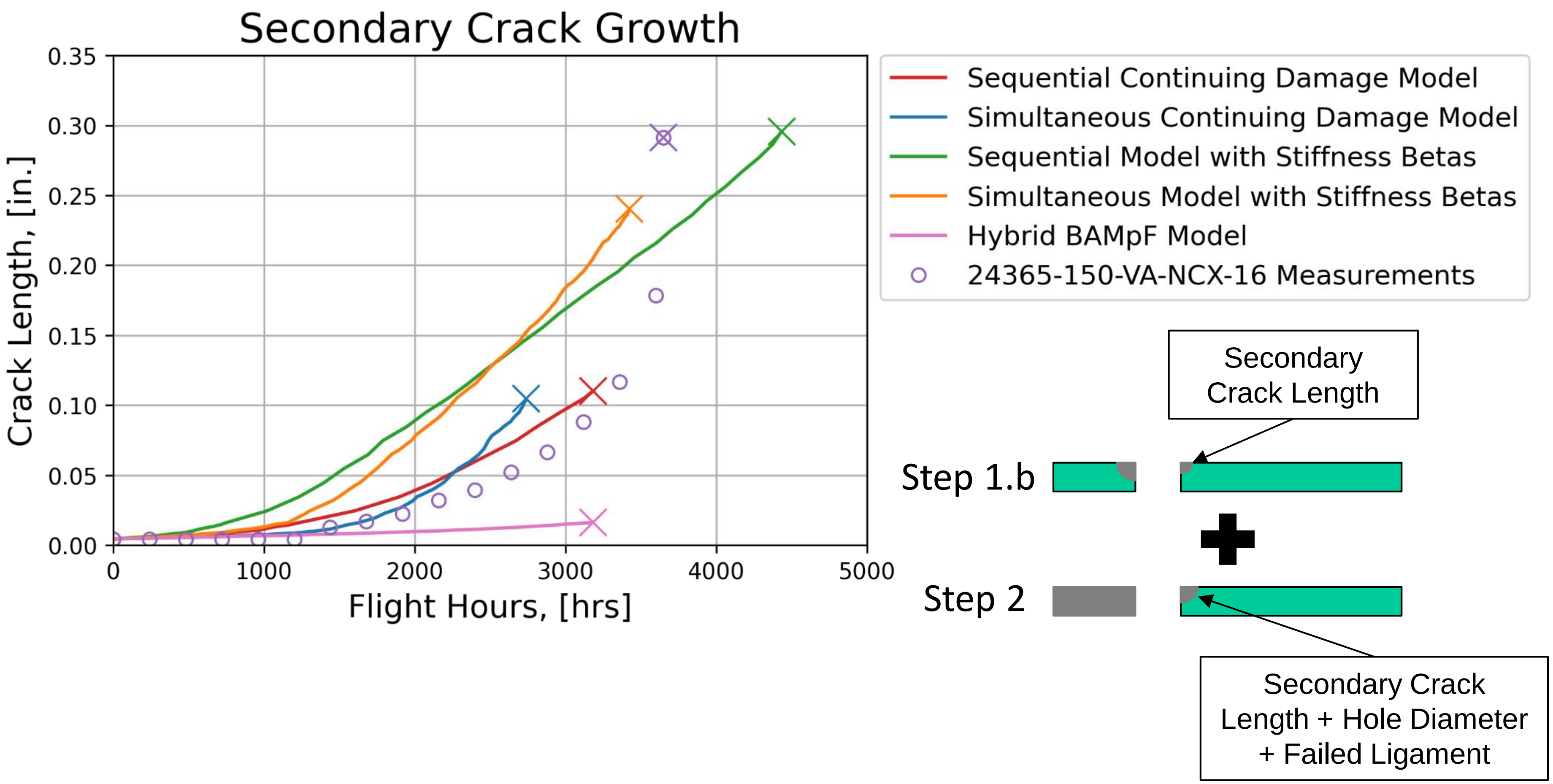


Test stress:

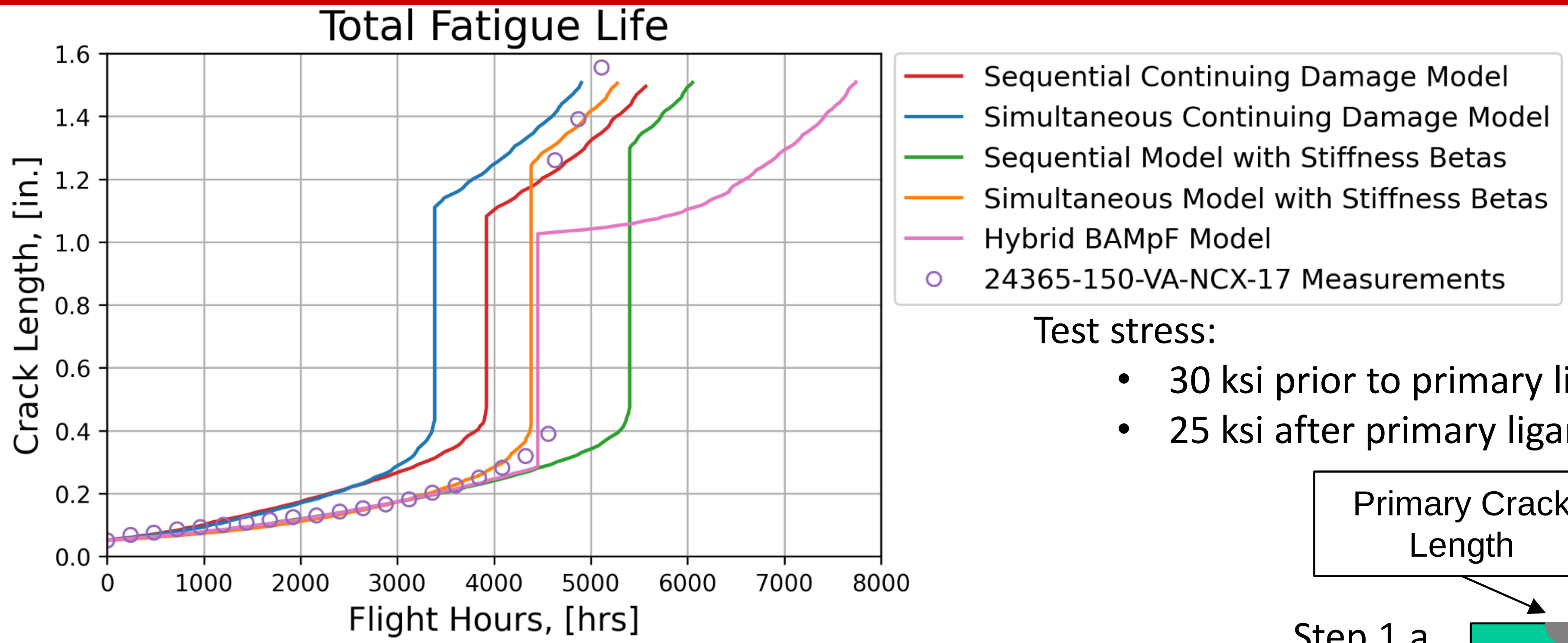
- 33 ksi prior to primary ligament failure
- 25 ksi after primary ligament failure



Continuing Damage Sample -16

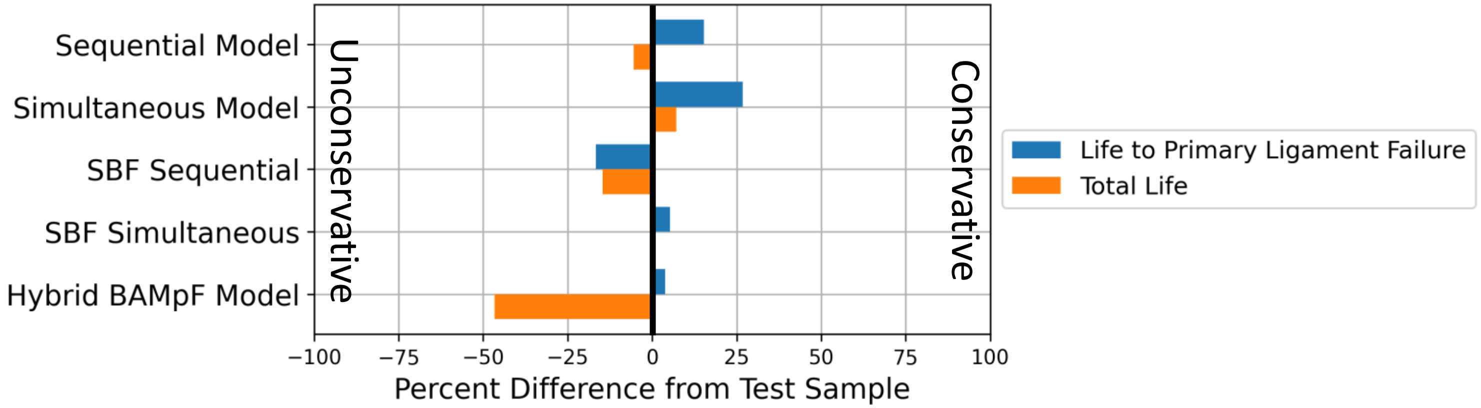


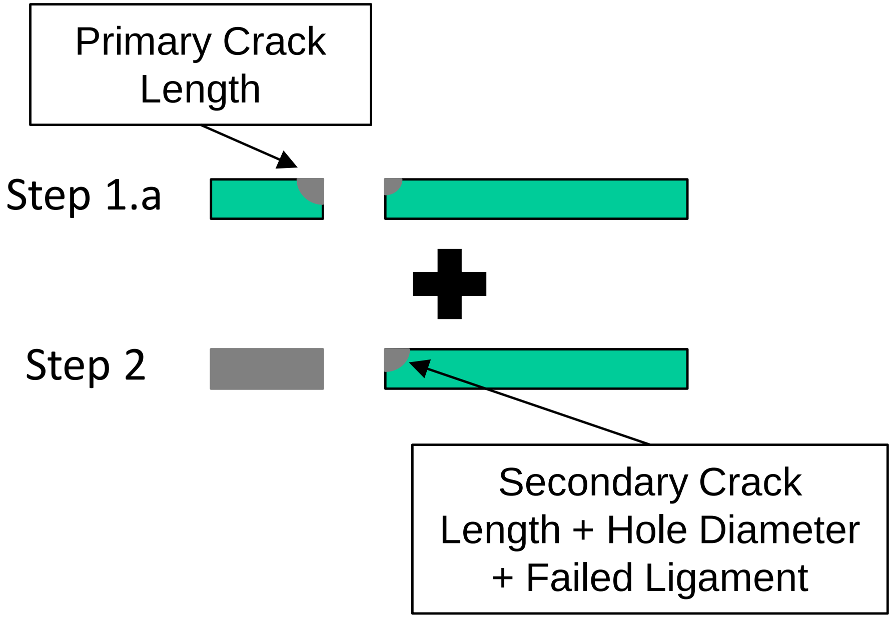
Continuing Damage Sample -17



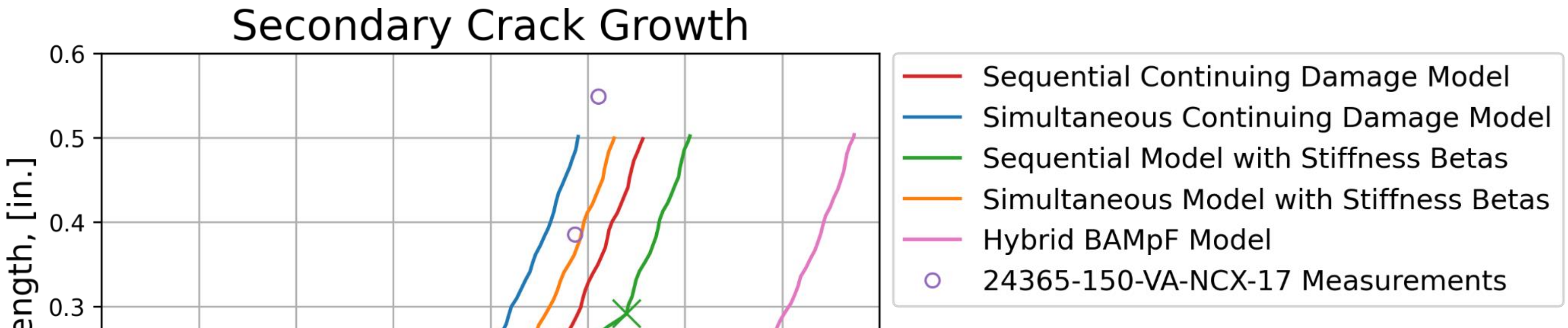
Test stress:

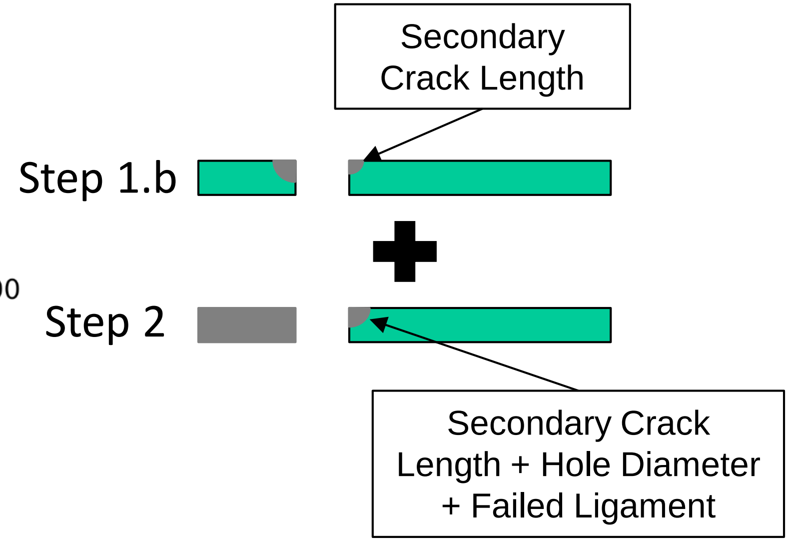
- 30 ksi prior to primary ligament failure
- 25 ksi after primary ligament failure



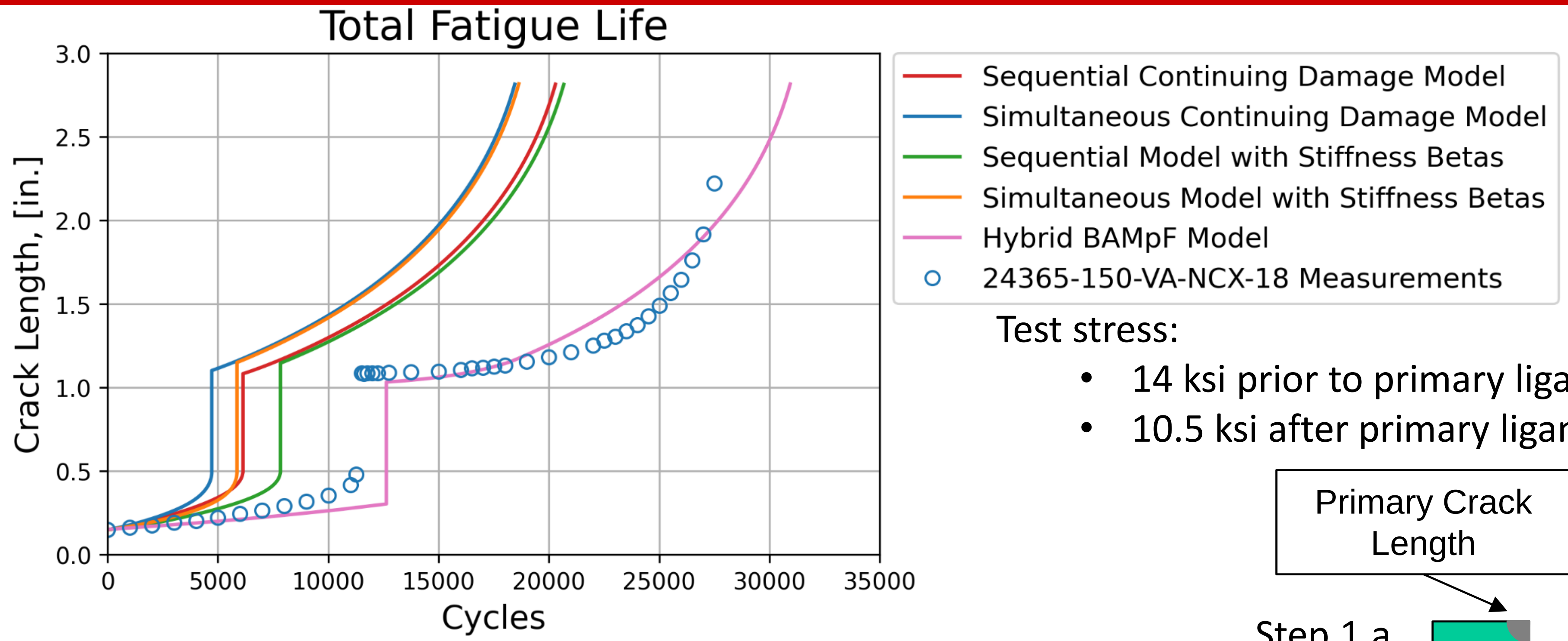


Continuing Damage Sample -17



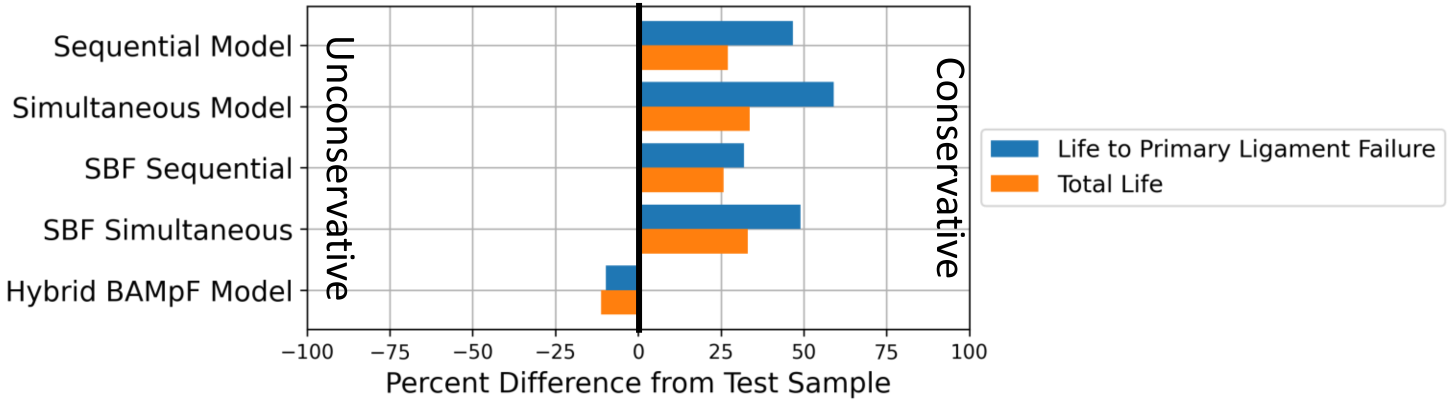


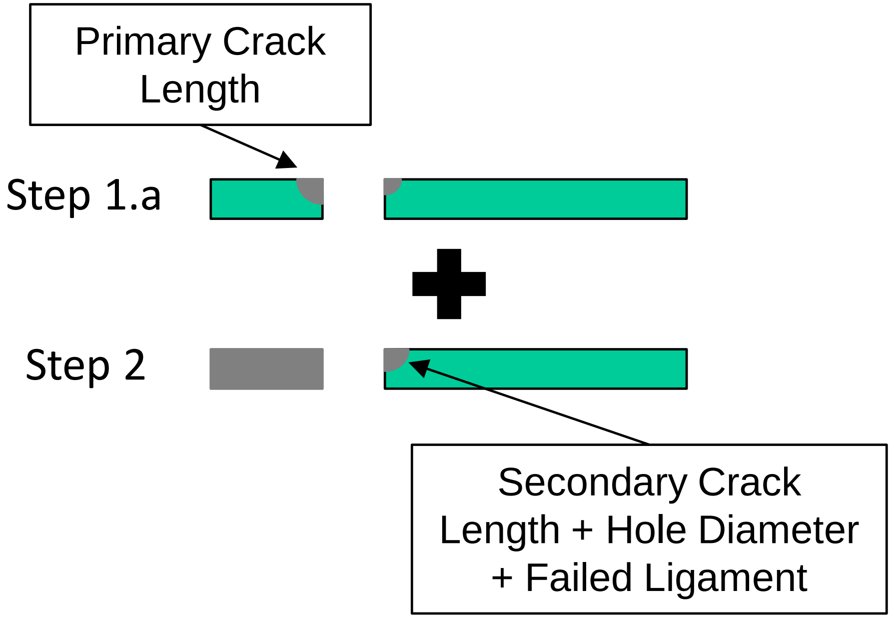
Continuing Damage Sample -18



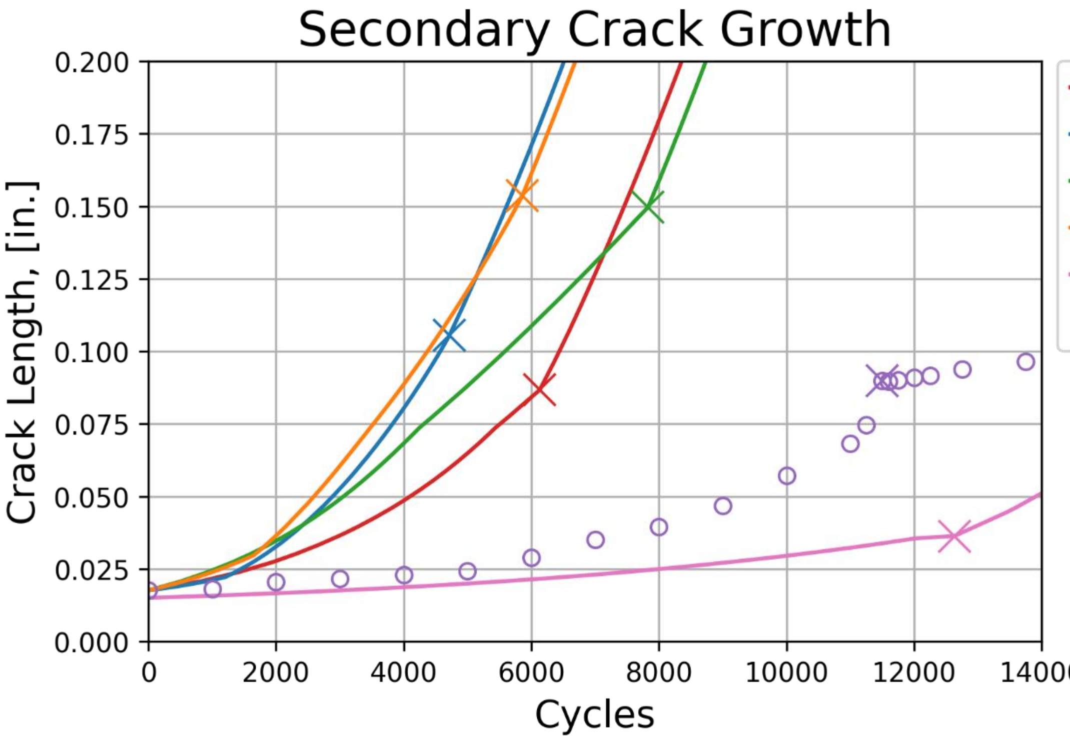
Test stress:

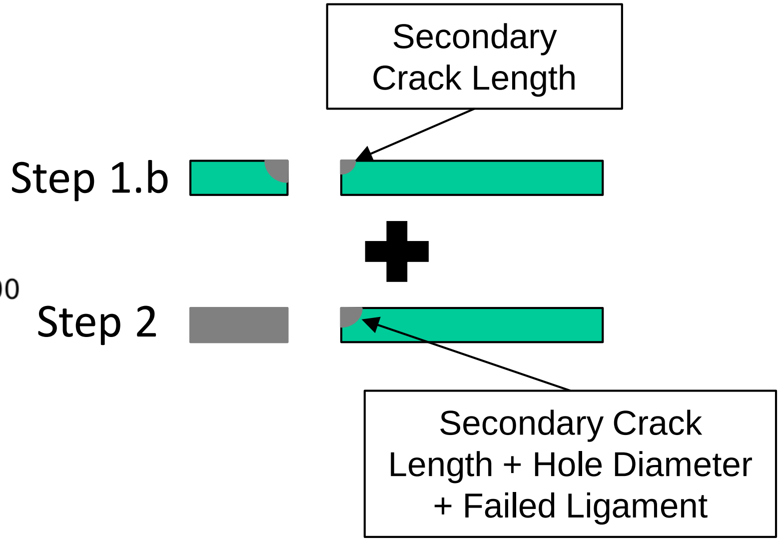
- 14 ksi prior to primary ligament failure
- 10.5 ksi after primary ligament failure



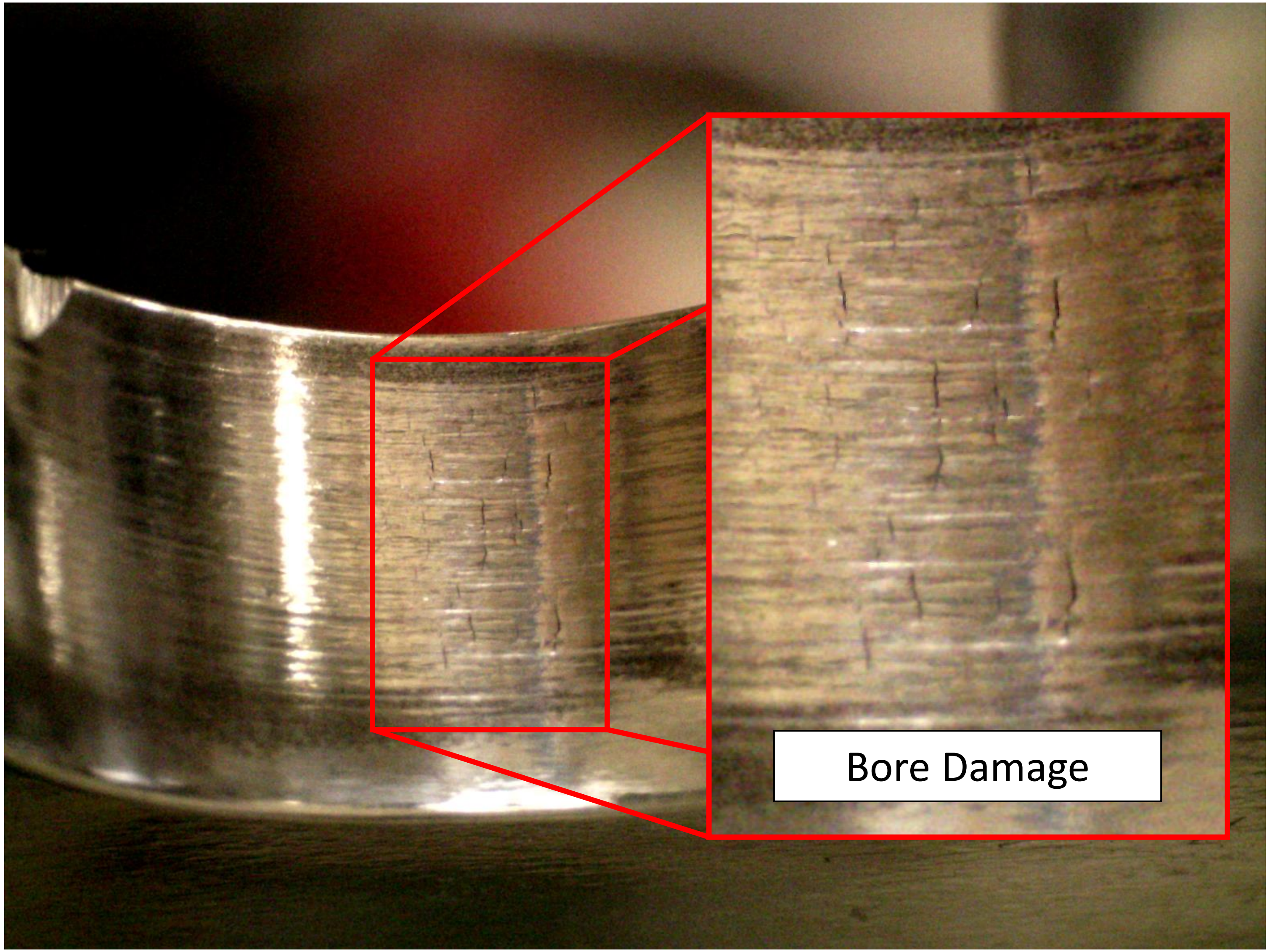


Continuing Damage Sample -18

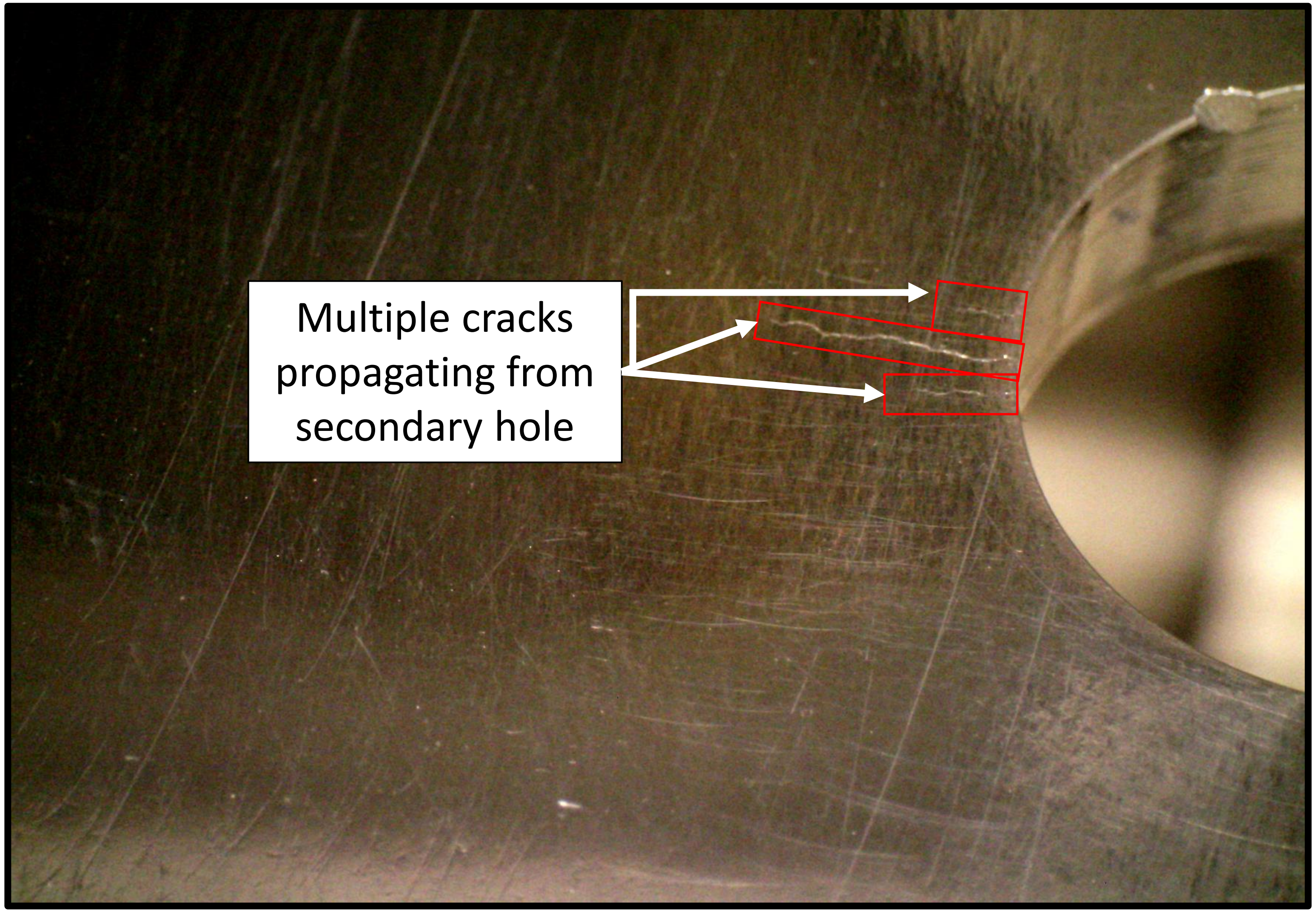




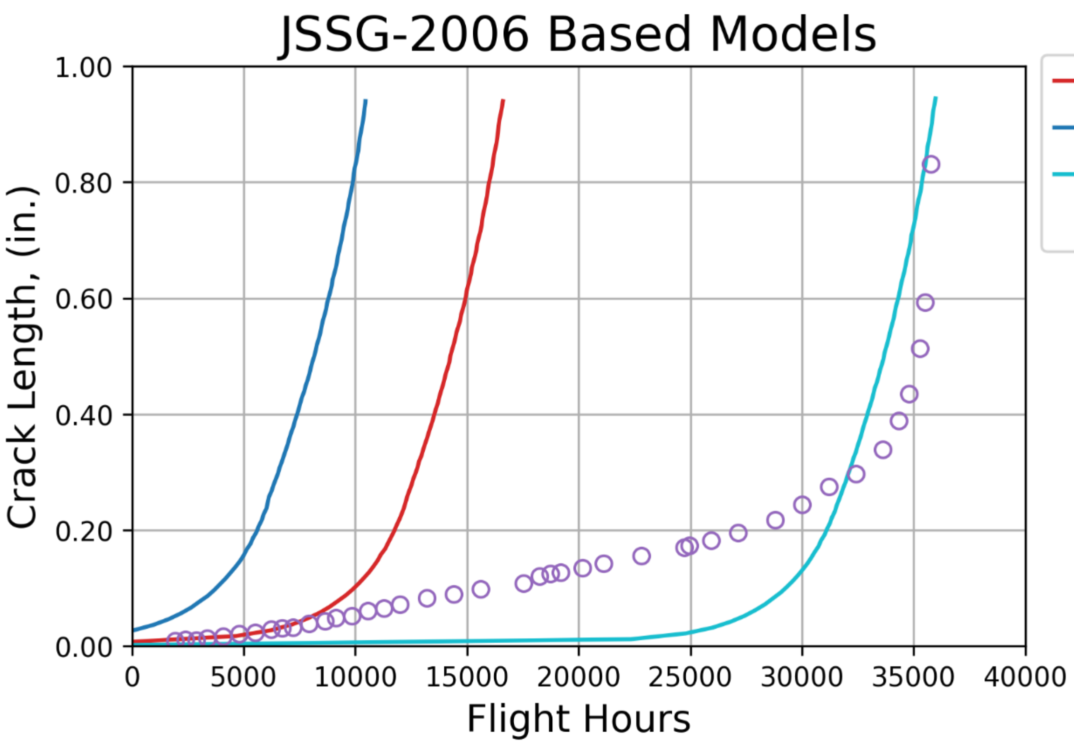
Failed Primary Ligament Testing



Failed Primary Ligament Testing

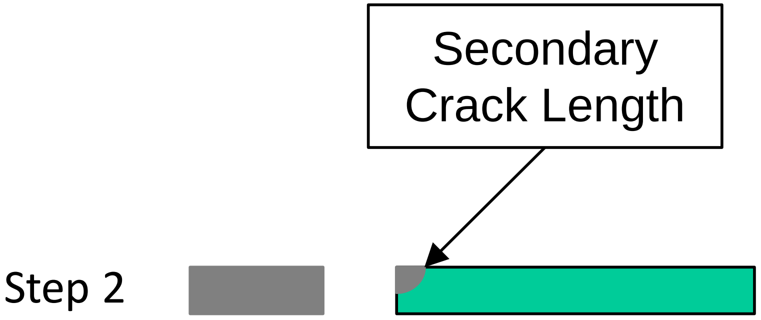


FPL Sample NCX150ED-1



Test stress:

- 33 ksi prior to primary ligament failure
- 20 ksi after primary ligament failure



JSSG-2006 Sequential SCLLF* = 0.00738 in.
JSSG-2006 Simultaneous SCLLF = 0.02647 in.
Equivalent† SCLLF = 0.00189 in.

*Secondary Crack Length upon Primary Ligament Failure
†Equivalent flaw size based on [5]

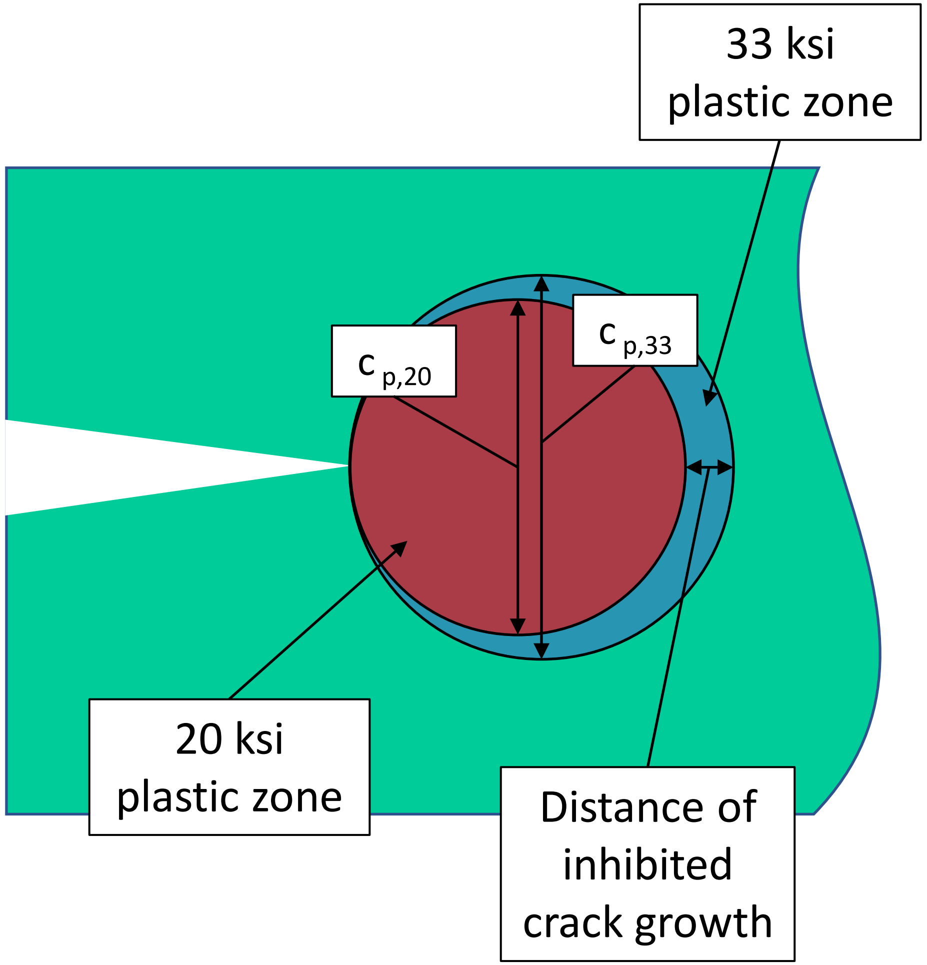
The initial flaw sizes for the analytical models are taken from results from JSSG-2006 based continuing damage models without cold expansion prior to primary ligament failure

FPL Sample NCX150ED-1

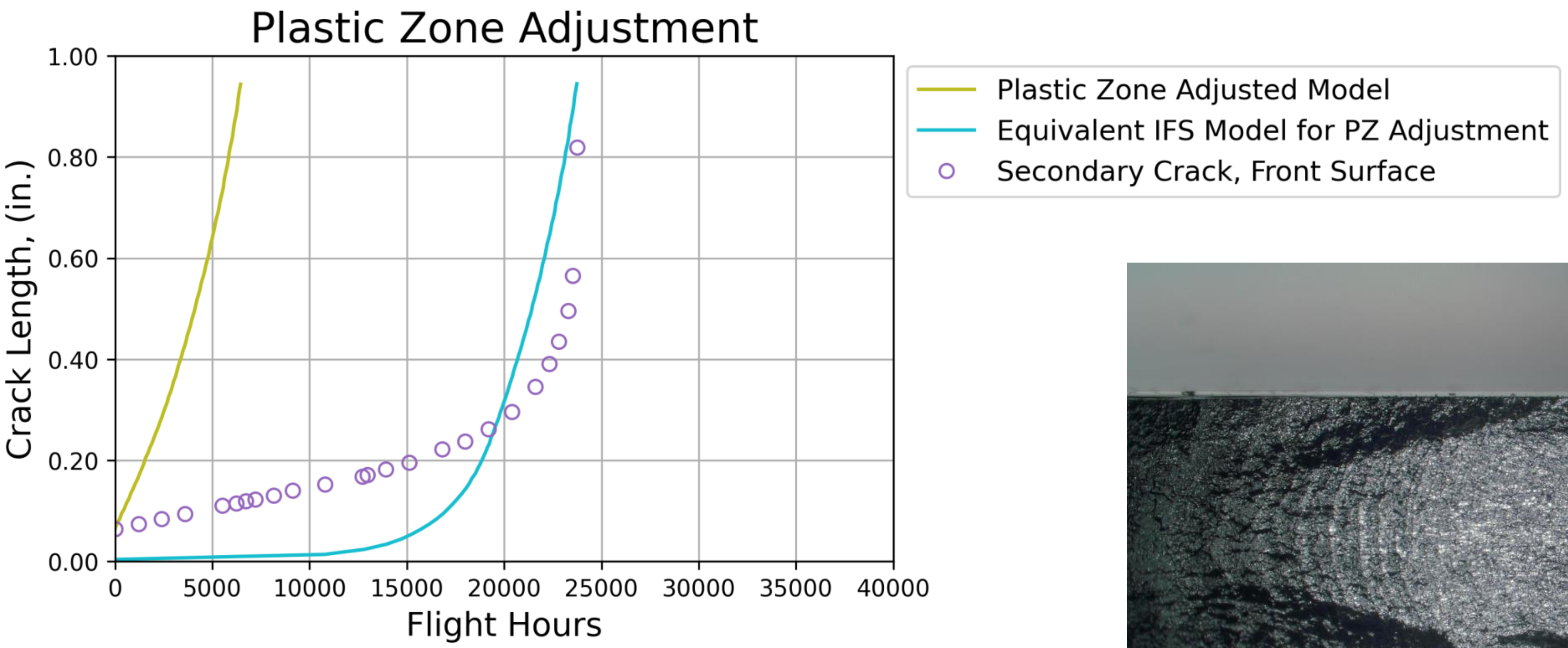
- Test stress levels went from 33 ksi to 20 ksi after primary ligament failure for sample NCX150ED-1
- The plastic zone can inhibit crack growth of subsequent loading
- Crack lengths suspected of being inhibited were eliminated to further show conservatism of modeling
- Plastic zone can be estimated as:

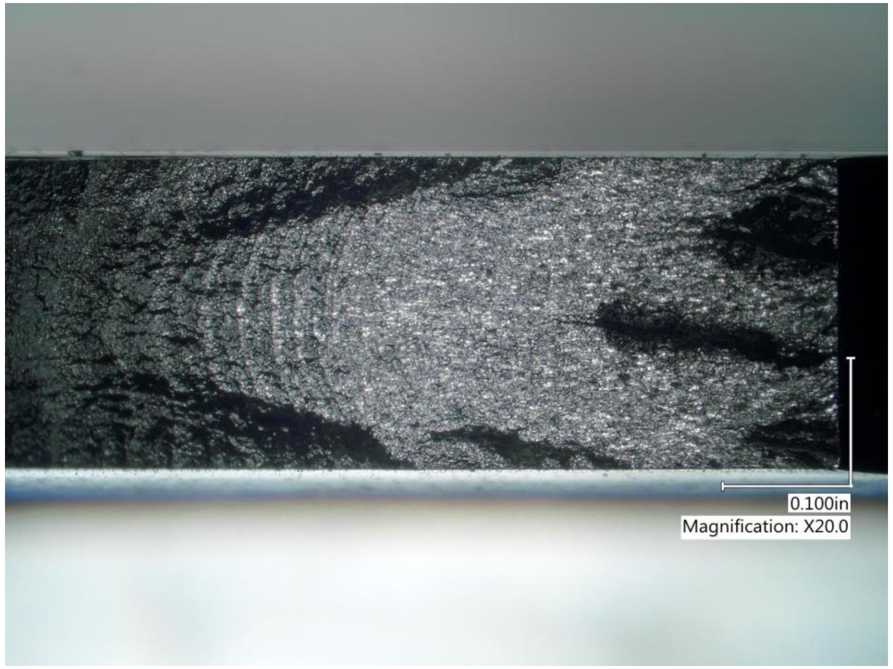
$$c_p = \frac{1}{\pi}\left(\frac{K}{\sigma_{ys}}\right)^2$$

  - K is the stress intensity factor
  - σ_{ys} is the material yield strength
- Crack breaks through plastic zone at crack lengths greater than 0.0937 in.



FPL Sample NCX150ED-1





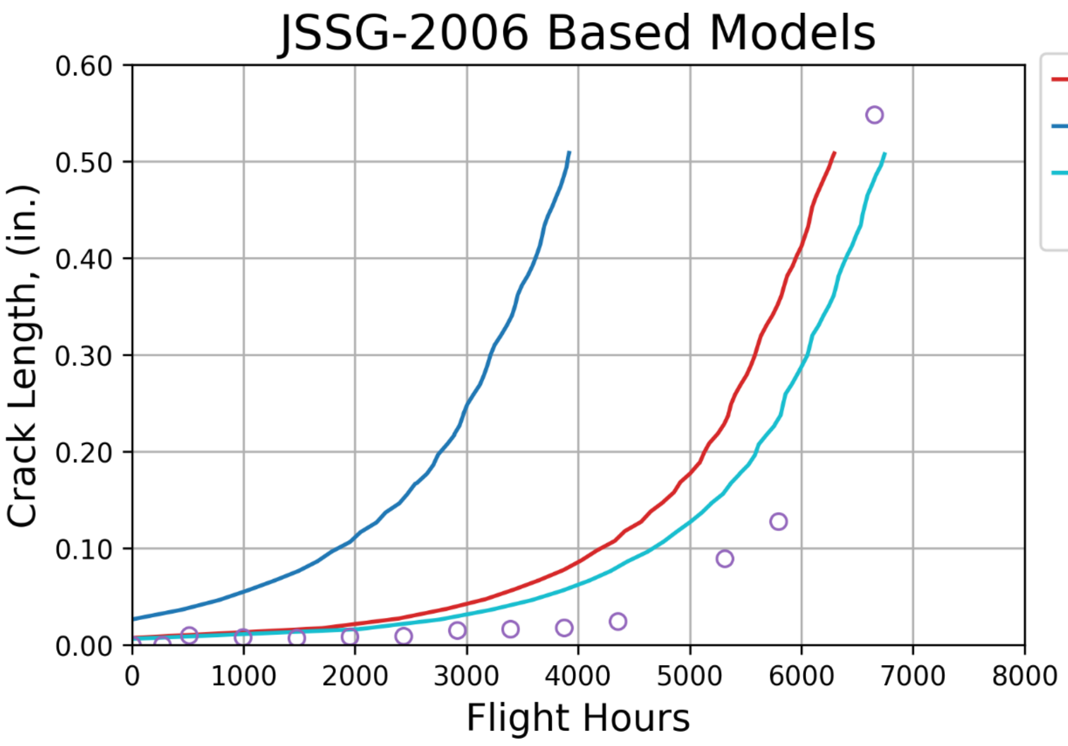
SCLLF* with Plastic Zone Adjustment = 0.09856 in.

Equivalent† SCLLF with Plastic Zone Adjustment = 0.00516 in.

*Secondary Crack Length upon Primary Ligament Failure

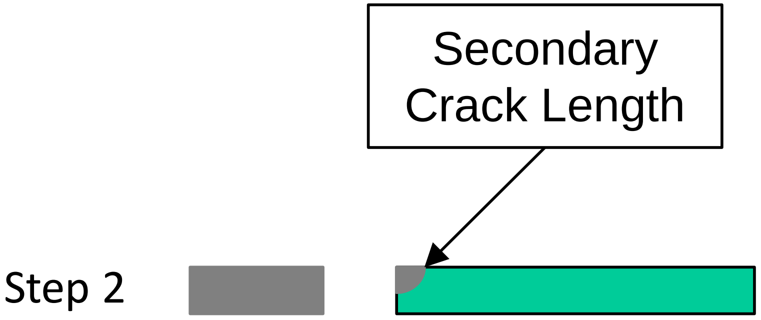
†Equivalent flaw size based on [5]

FPL Sample NCX150ED-2



Test stress:

- 33 ksi prior to primary ligament failure
- 25 ksi after primary ligament failure

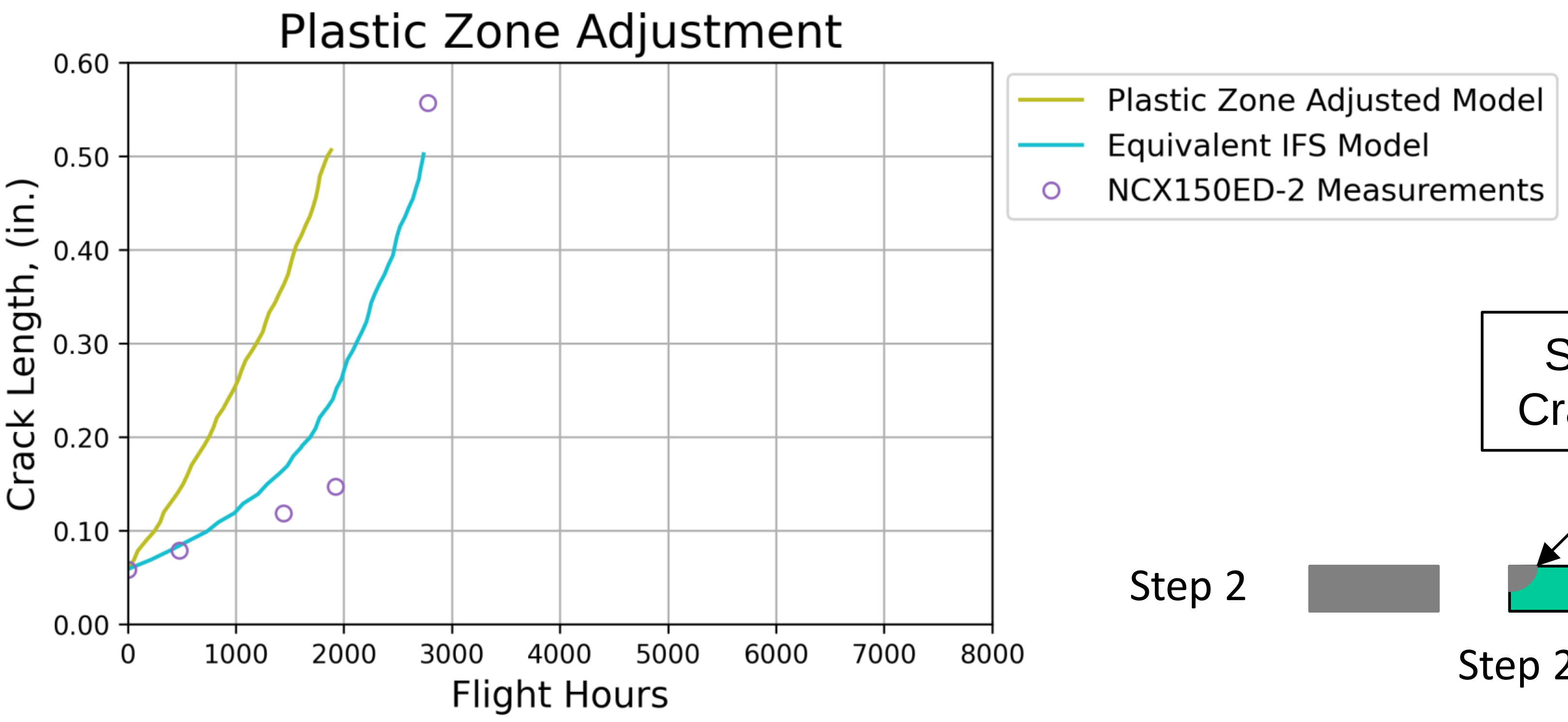


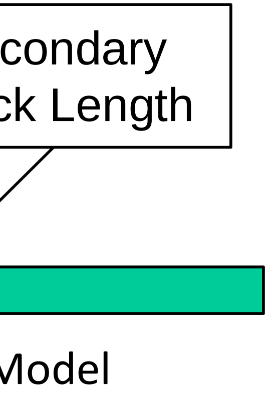
JSSG-2006 Sequential SCLLF* = 0.00738 in.
JSSG-2006 Simultaneous SCLLF = 0.02647 in.
Equivalent SCLLF† = 0.00638 in.

*Secondary Crack Length upon Primary Ligament Failure
†Equivalent flaw size based on [5]

The initial flaw sizes for the analytical models are taken from results from JSSG-2006 based continuing damage models without cold expansion prior to primary ligament failure

FPL Sample NCX150ED-2





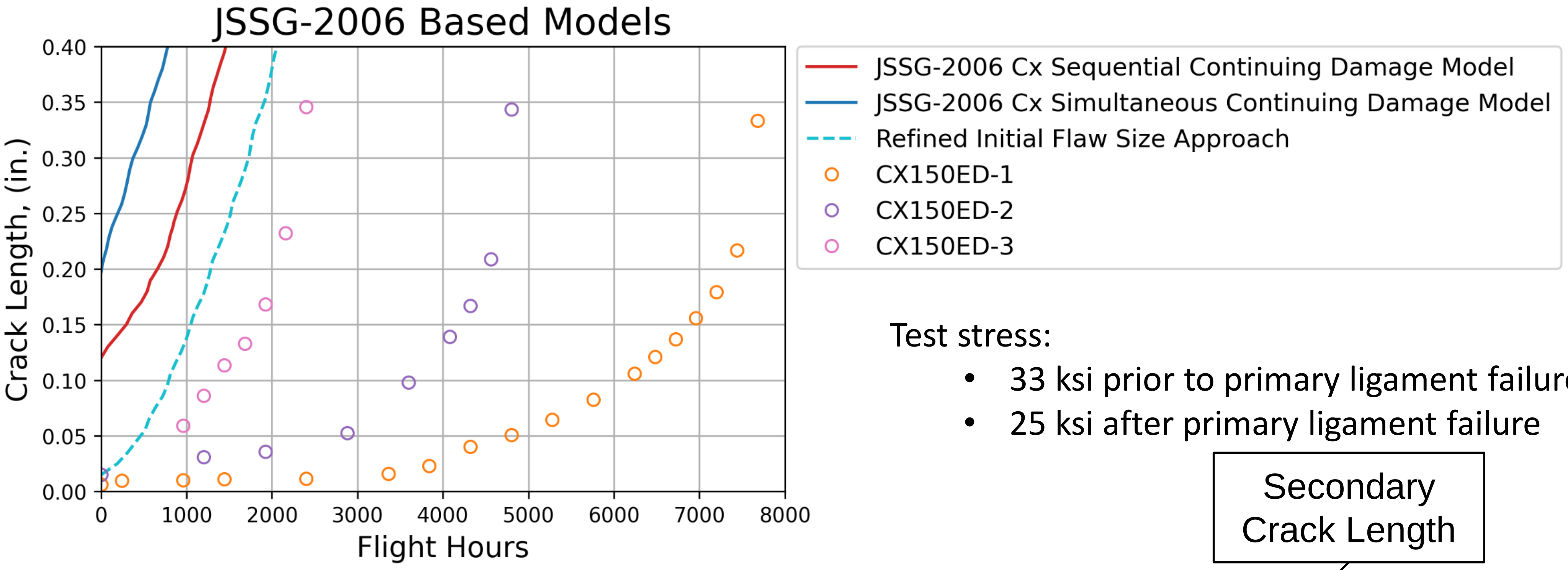
SCLLF* with Plastic Zone Adjustment= 0.05885 in.

Equivalent† SCLLF with Plastic Zone Adjustment = 0.05844 in.

*Secondary Crack Length upon Primary Ligament Failure

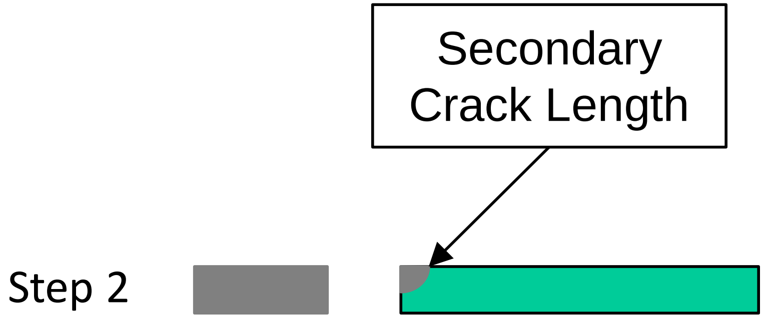
†Equivalent flaw size based on [5]

FPL CX Samples



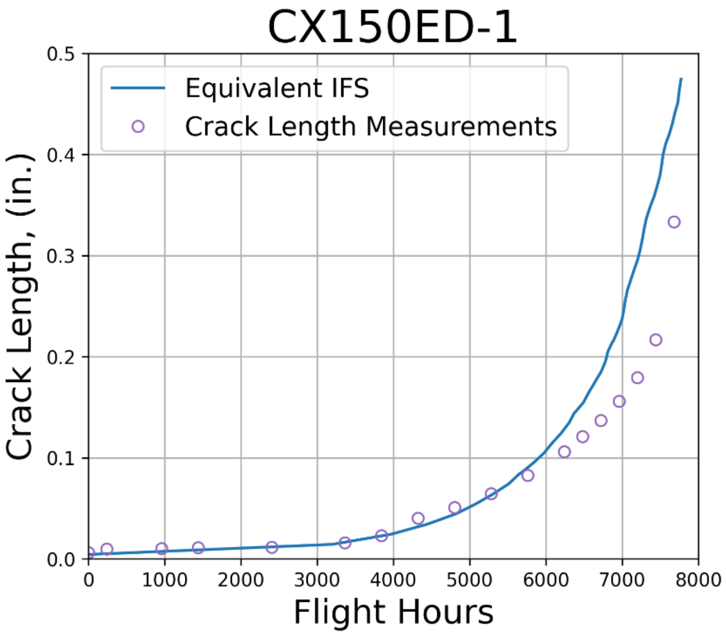
Test stress:

- 33 ksi prior to primary ligament failure
- 25 ksi after primary ligament failure

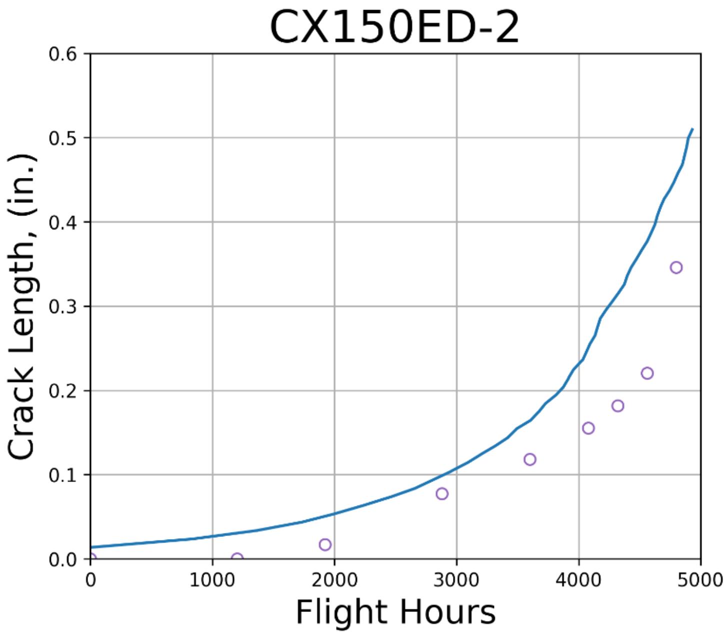


The initial flaw sizes for the analytical models are taken from results from JSSG-2006 based continuing damage models <u>with</u> cold expansion prior to primary ligament failure

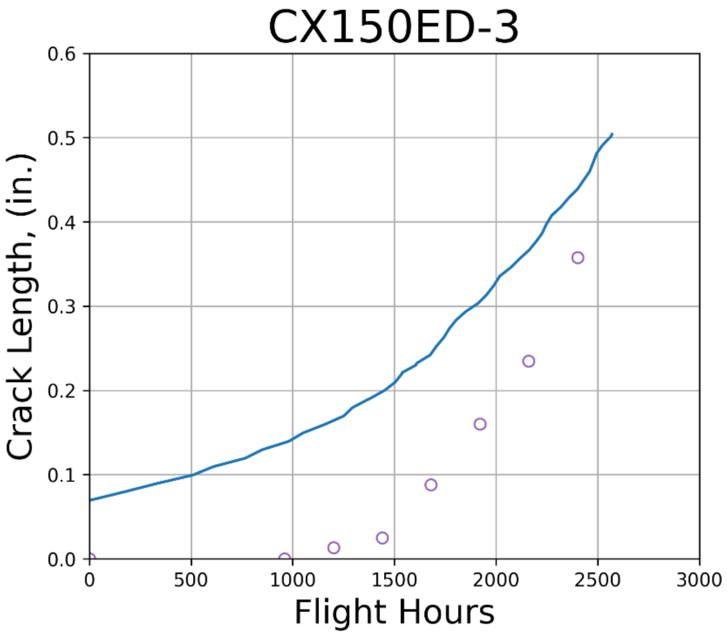
FPL CX Samples



Equivalent† SCLLF = 0.00430 in.



Equivalent SCLLF = 0.01355 in.



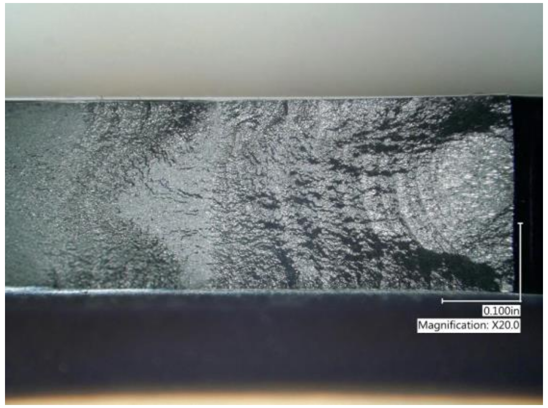
Equivalent SCLLF = 0.06930 in.

JSSG-2006 Sequential SCLLF* = 0.12006 in.

JSSG-2006 Simultaneous SCLLF = 0.19752 in.

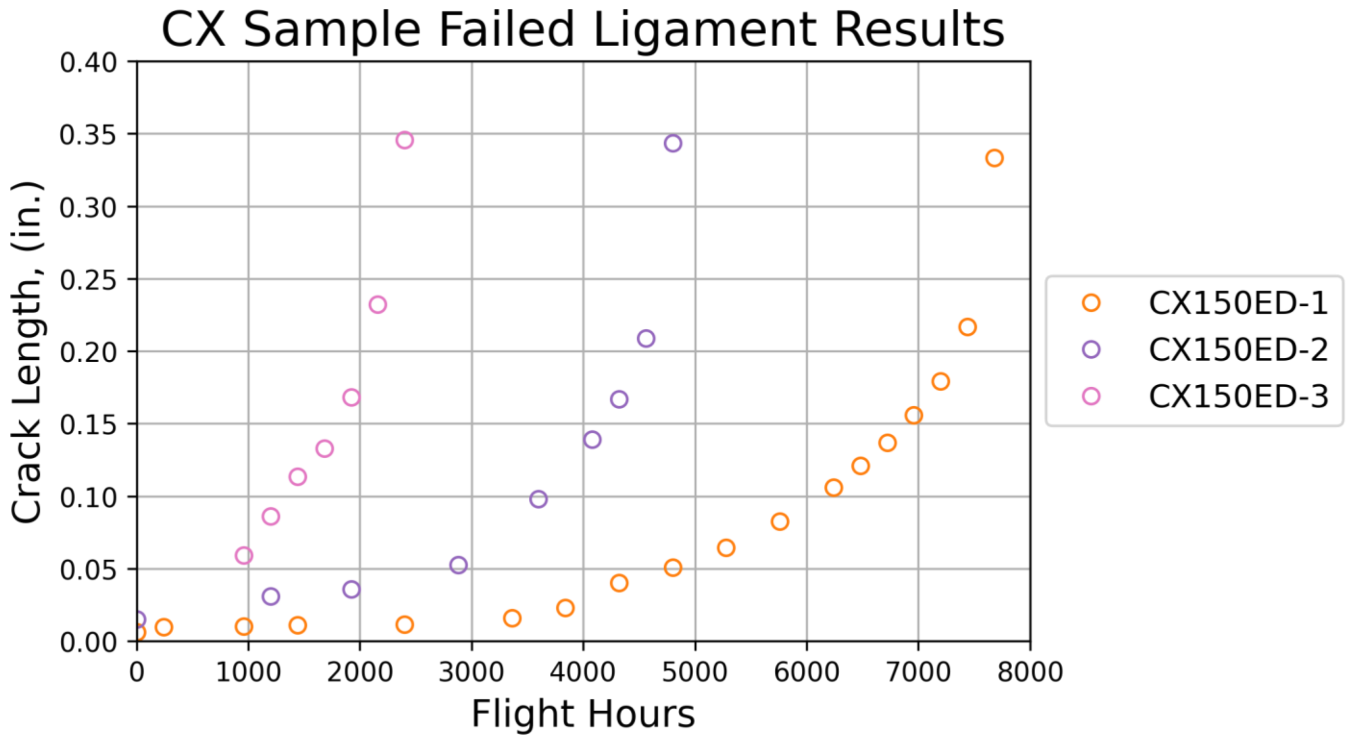
*Secondary Crack Length upon Primary Ligament Failure

†Equivalent flaw size based on [5]

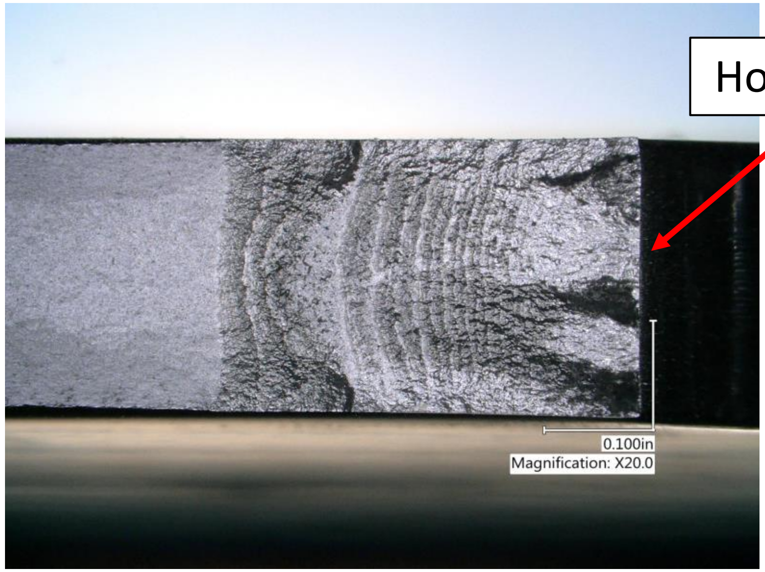


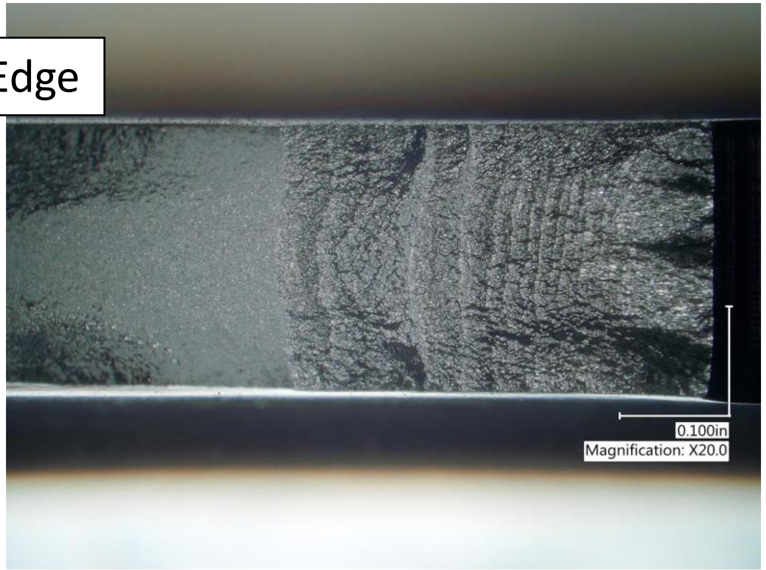
FPL CX Variability

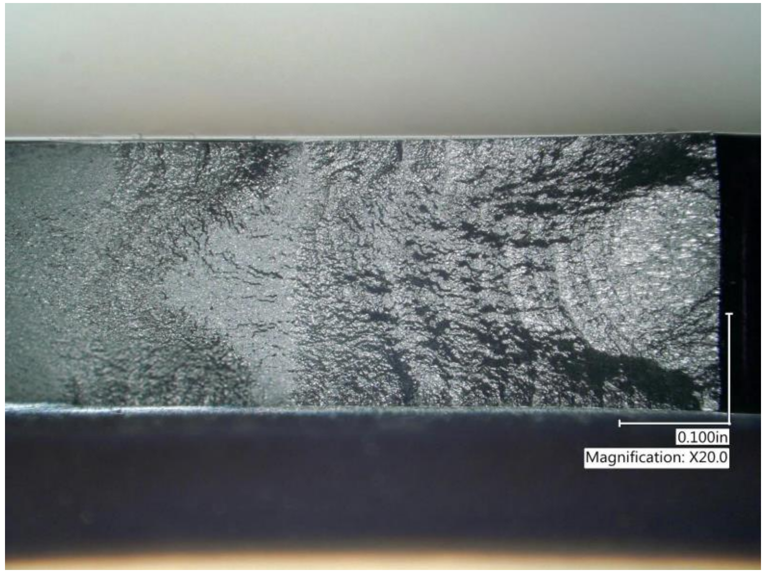
- Large difference between samples run under similar conditions
- Possible causes:
  - Loading error
  - Grip slippage
  - Undetected manufacturing defects
  - Secondary damage distribution due to intrinsic material variability



FPL CX Variability







CX150ED-1
- $R_l = 0.882$
- Continuing Damage Life = 7,782 FH

CX150ED-2
- $R_l = 0.977$
- Continuing Damage Life = 4,930 FH

CX150ED-3
- $R_l = 1.044$
- Continuing Damage Life = 2,569 FH

$R_l = L_t/L'$
- L_t is the length of the topographical profile curve after multiple cracks have merged into a dominant crack
- L' is the length of a topographical profile curve near the edge of the hole

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Conclusions

1. Test conservatism of JSSG-2006 initial flaw sizes and modeling approach
   - All models conservative compared to FPL samples
   - Sequential unconservative compared to CD samples
2. Explore different modeling approaches
   - Sequential model:
     - Conservative life predictions for FPL samples
     - Varied prediction results compared to CD samples
   - Simultaneous model:
     - Consistently conservative for both CD and FPL samples
   - Variable amplitude loading affects crack growth rate of secondary crack
   - Stiffness betas increase simultaneous model accuracy

Conclusions

3. Compare continuing damage life of CD and FPL samples
   - Variation in continuing damage life observed between FPL samples
   - Total life of VA-loaded FPL samples was significantly higher than for CD samples
4. Crack size and shape
   - FPL samples had semi-elliptical cracks
     - Cold expansion produces larger secondary flaws at primary ligament failure
   - CD samples had corner cracks
   - CD sample secondary cracks longer at primary ligament failure vs. FPL sample damage

Future Work

- Study effects of variable edge margin on primary and secondary crack growth
- Increase number of tested samples to provide confidence in test data
- Develop beta factor solutions for various combinations of primary and secondary crack lengths
- Perform continuing damage tests for different materials
- Investigate correlation between fracture surface roughness and fatigue life of samples without pre-cracks

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References

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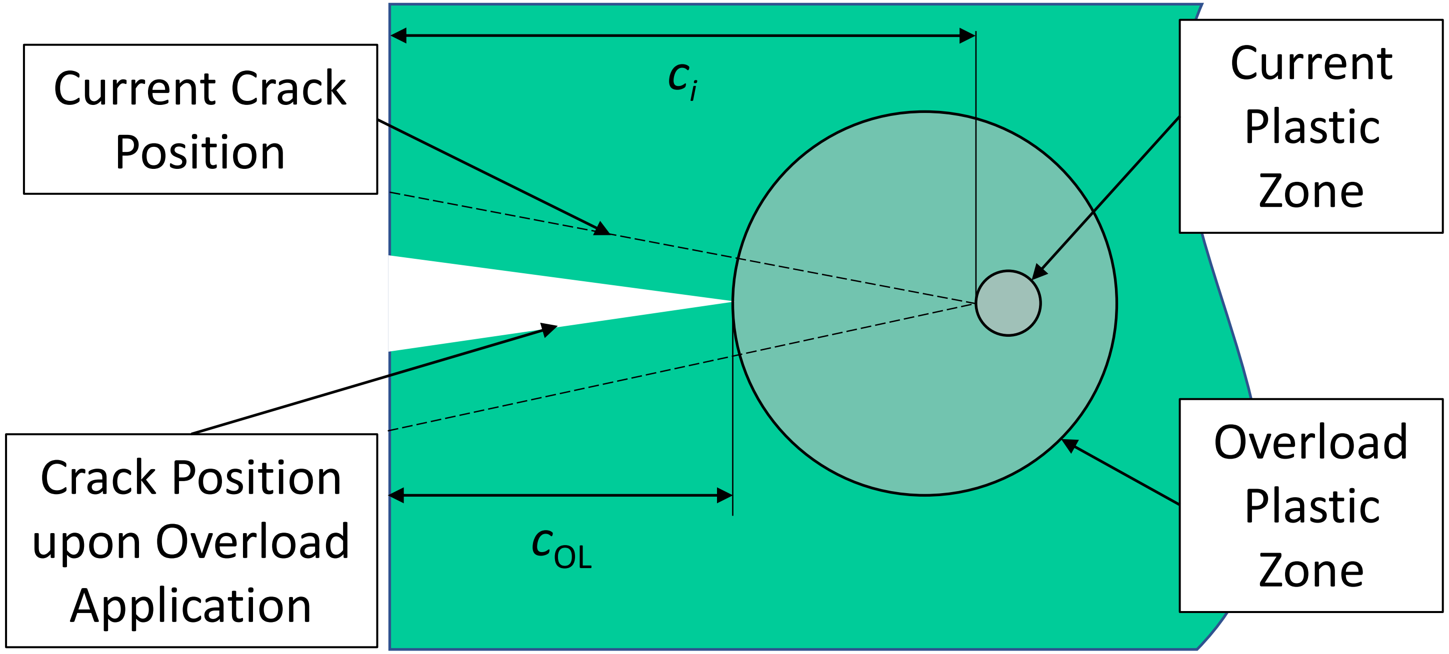
Acknowledgments

- Jake Warner, A-10 Analysis
- Evan Ross, Hill AFB Lab
- Dr. Jake Hochhalter, University of Utah
- John Pendleton, T-38 Analysis
- Chad King, T-38 Analysis

Backup

Crack Growth Retardation

- Crack growth retardation is a phenomenon commonly seen in variable amplitude loading
- Plastic zone from overload inhibits subsequent crack growth



Crack Growth Retardation

Generalized Willenborg model uses modified stress ratio for crack growth rate as follows:

Crack growth rate with R_{eff}, a modified stress ratio → $$\frac{da}{dN} = f\left(\Delta K, R_{eff}\right)$$

R_{eff} is dependent on current max and min SIFs ($K_{min,i}$ and $K_{max,i}$), as well as the overload SIF (K_R) → $$R_{eff} = \frac{K_{min,i} - K_R}{K_{max,i} - K_R}$$

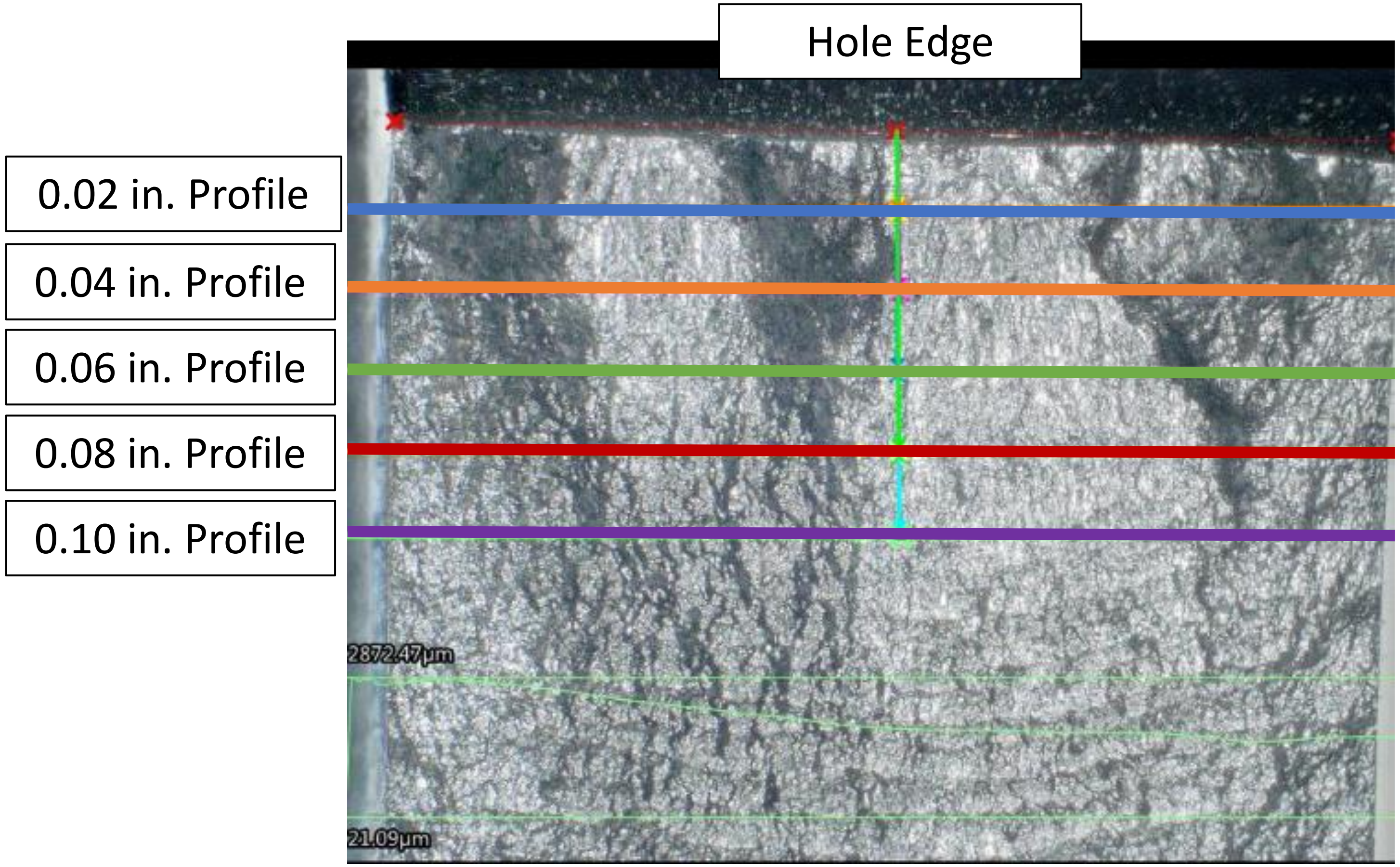
The overload SIF is a function of an empirical constant (ϕ), and the traditional Willenborg overload SIF (K_R^W) → $$K_R = \phi K_R^W$$

The empirical constant is made up of the current max SIF ($K_{max,i}$), the threshold SIF ($K_{max,th}$), and the shutoff overload ratio (S^{OL}) → $$\phi = \frac{1 - \frac{K_{max,th}}{K_{max,i}}}{S^{OL} - 1}$$

Traditional Willenborg model is based on the max SIF from overload (K_{max}^{OL}), the current cycle crack length (a_i), the crack length at overload (a_{OL}), the diameter of the plastic zone (r_{pOL}), and the current cycle's max SIF ($K_{max,i}$) → $$K_R^W = K_{max}^{OL}\sqrt{1 - \frac{a_i - a_{OL}}{r_{pOL}}} - K_{max,i}$$

FPL CX Variability

- Topographical profiles taken at 0.02 in. increments beginning at 0.02 in. away from edge of hole
- Cracks tended to merge into singular crack front around 0.1 in.

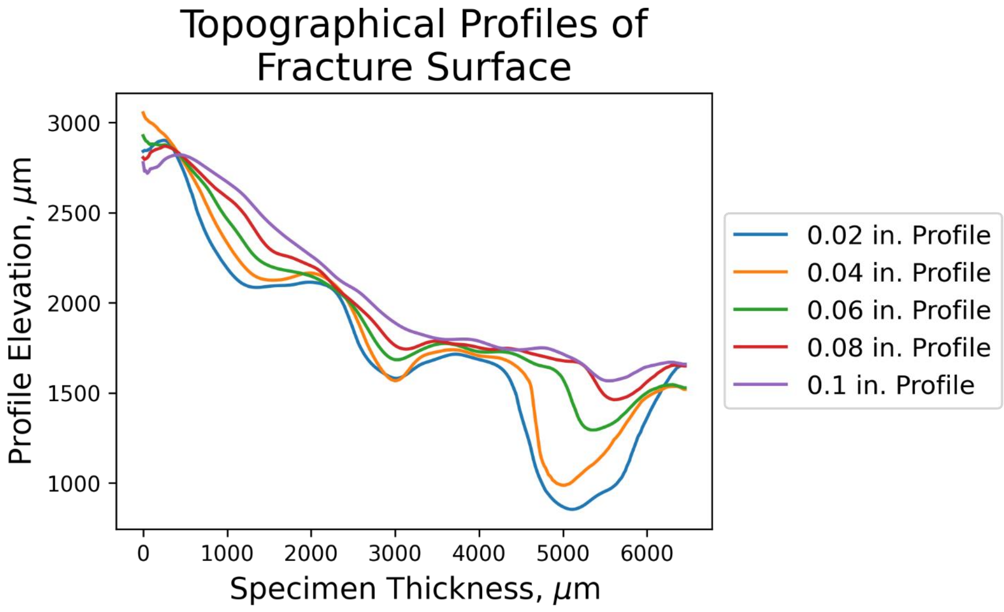


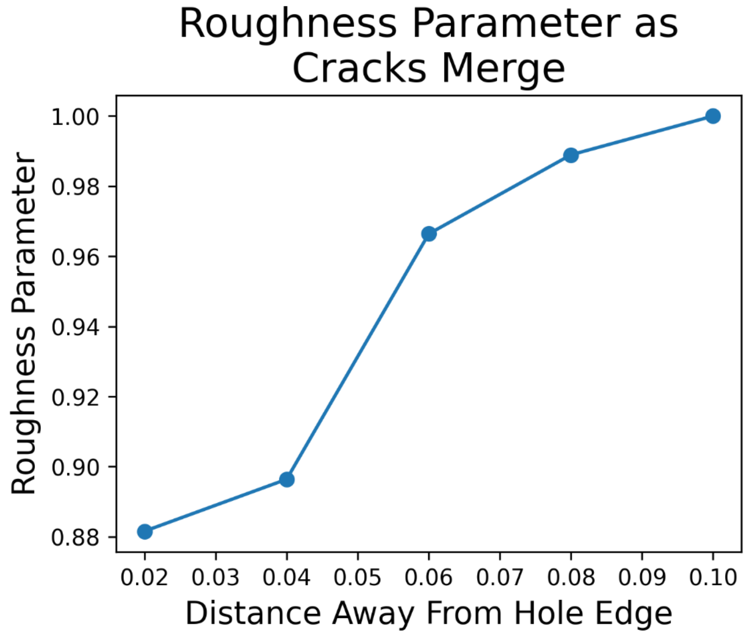
FPL CX Variability

- Roughness Parameter [7]

$$R_l = L_t / L'$$

  - L_t is the length of the topographical profile curve after multiple cracks have merged
  - L' is the length of a topographical profile curve near the edge of the hole





FPL CX Variability

- Cracks appear to converge between 0.10 and 0.15 in.
- Provides confidence in test procedures and implements