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Continuing Damage: Simultaneous or Sequential?

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September 16, 2026

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Acknowledgements to the team

USAF B-52 ASIP
- Travis Reese, Andrew Jones, Tyler Olheiser

Reliant Aero
- Brian Boeke, Jake Warner, Dallen Andrew, Casey Scott

Southwest Research Institute
- Lucky Smith, Laura Hunt

Hill Engineering
- Renan Ribeiro, Robert Pilarczyk

The Boeing Company
- Lee Ann McElroy, Brandon Leppke, Bob Lee

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Abstract

Fatigue crack growth modeling of corner cracks at a hole considering continuing damage has often been analyzed using a sequential approach, where the primary (0.05”) and secondary (0.005”) cracks grow independently, without affecting one another. Previous evaluations have shown that this approach can be unconservative relative to a simultaneous approach, where both primary and secondary cracks grow simultaneously, since the growth of the secondary crack can be influenced by the primary crack. This work evaluated both sequential and simultaneous approaches for a wide variety of B-52 fatigue details/locations. The analytical results show that for all details, the simultaneous approach leads to shorter life than the sequential approach. However, the magnitude of the difference between the approaches varies widely, with very small differences for some fatigue details, and much larger differences for others. The analytical differences are related to geometry, spectrum, retardation, and bearing stress.

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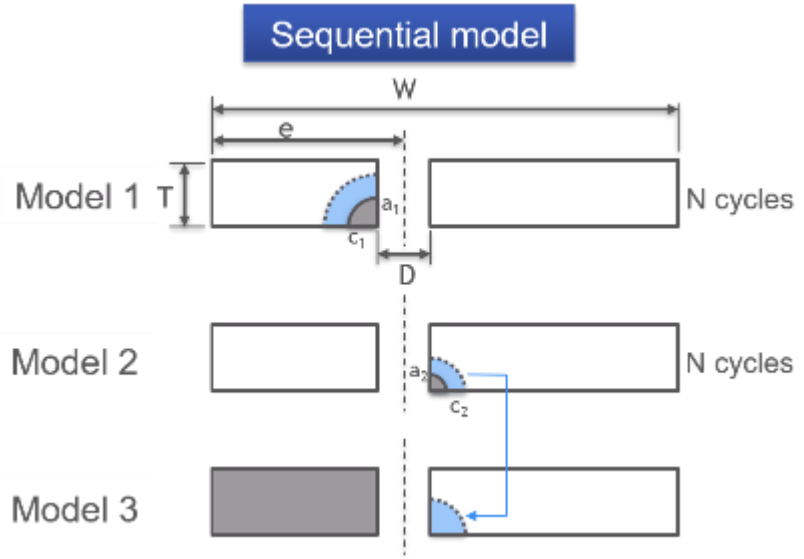
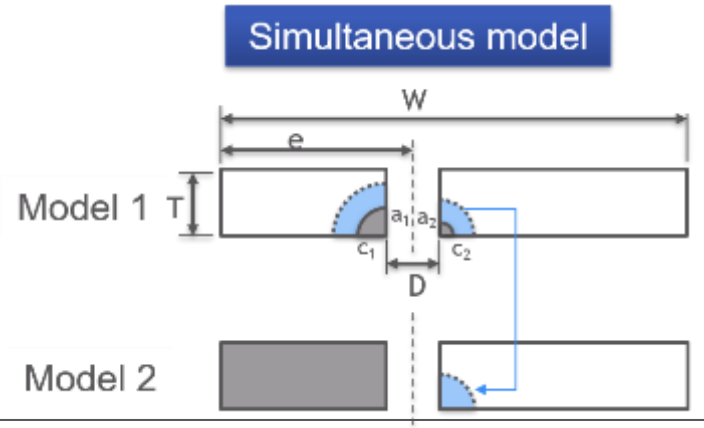
Objectives

Assess continuing damage modeling strategies for B-52 details

- Sequential model
  - Stage 1: growth of primary 0.05” crack to end of ligament (N cycles)
  - Stage 2: growth of secondary 0.005” crack at other side of hole for N cycles
  - Stage 3: failed primary ligament; growth of secondary crack to failure



- Simultaneous model
  - Stage 1: both 0.05” (primary) and 0.005” (secondary) cracks grow at the same time to end of primary ligament
  - Stage 2: failed primary ligament; growth of secondary crack to failure



Note: in AFGROW, simultaneous growth is done with a single model (model 1)

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Methods

- **First, BAMpF and AFGROW models were used to evaluate 2 fatigue details:**
  - WL-11-1-1 – wing lower location
    - Thinner section, no bearing stress, high negative-R cycles
  - WU-2 – wing upper location
    - Thicker section, no bearing stress, no high negative-R cycles

- **Then, the AFGROW COM was used to run 21 fatigue details using both sequential and simultaneous approaches**
    - Assess differences across a wide variety of locations

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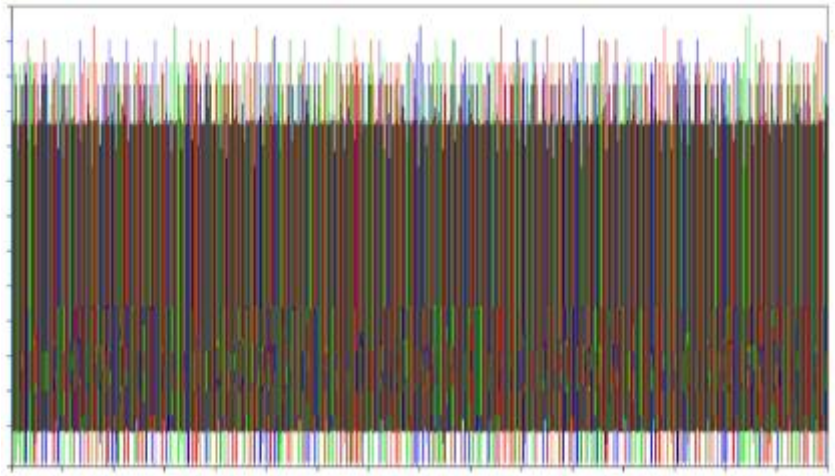
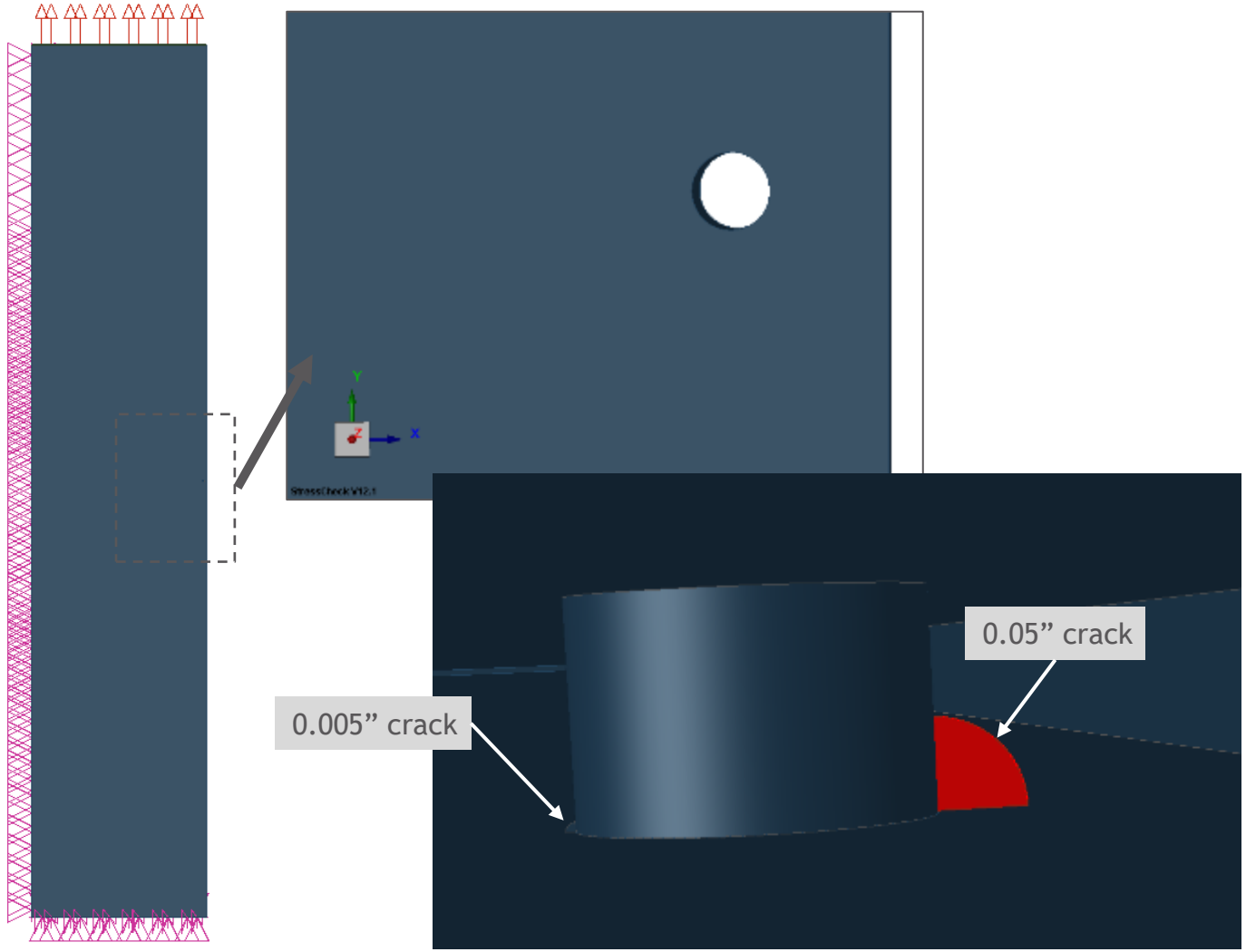
BAMpF model: WL-11-1-1

- Width, thickness, edge distance, diameter from DTA report
- No bearing stress
- No retardation
- StressCheck model with BAMpF crack growth solution

Spectrum





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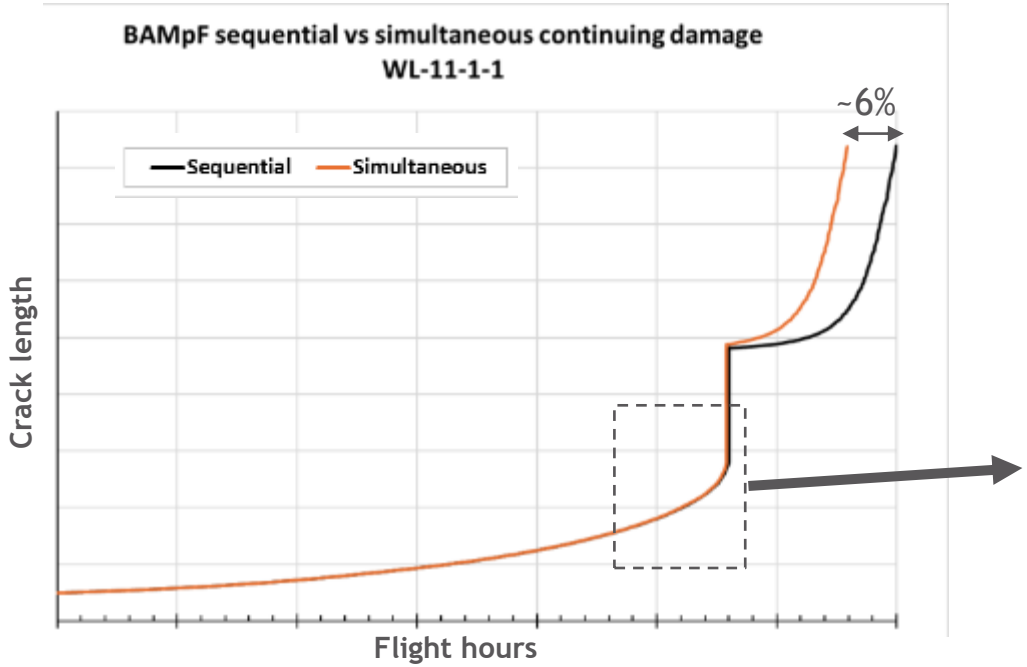
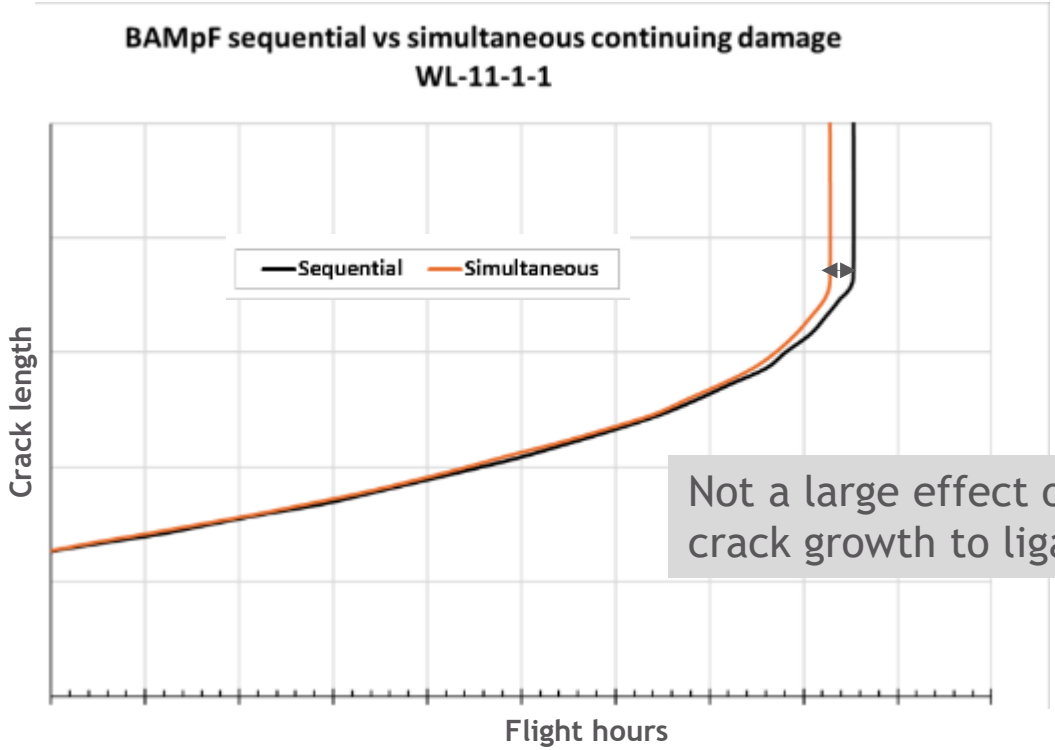
WL-11-1-1 - BAMpF

Crack growth results from both models below

- Longer life with sequential model (+6.3%)
- *Simultaneous growth results in shorter life than sequential model*





Not a large effect on primary crack growth to ligament failure

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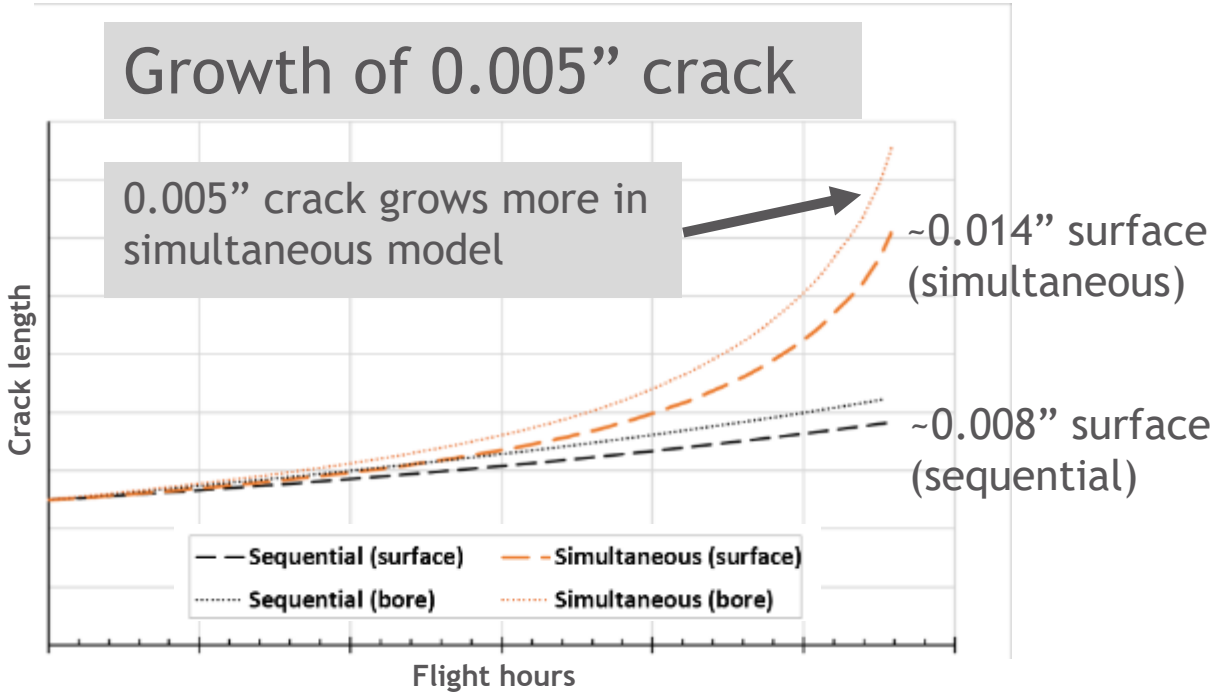
WL-11-1-1 – BAMpF

- **Secondary (0.005”) crack ends up larger when both cracks grow simultaneously**
- **Growth of primary crack accelerates growth of the secondary crack**
  - Raises SIF, accelerates growth



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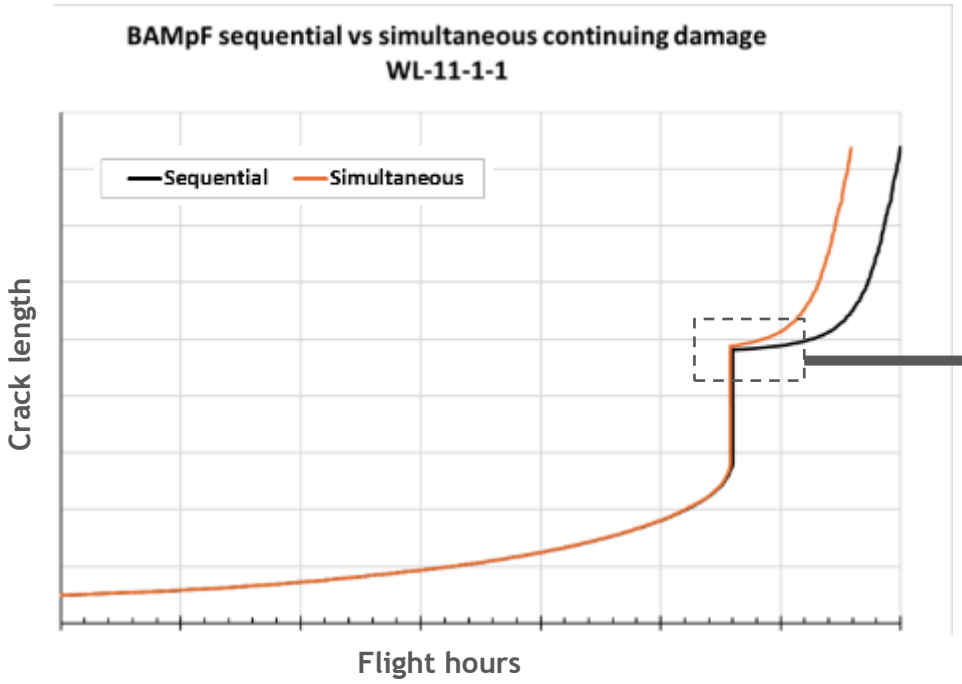
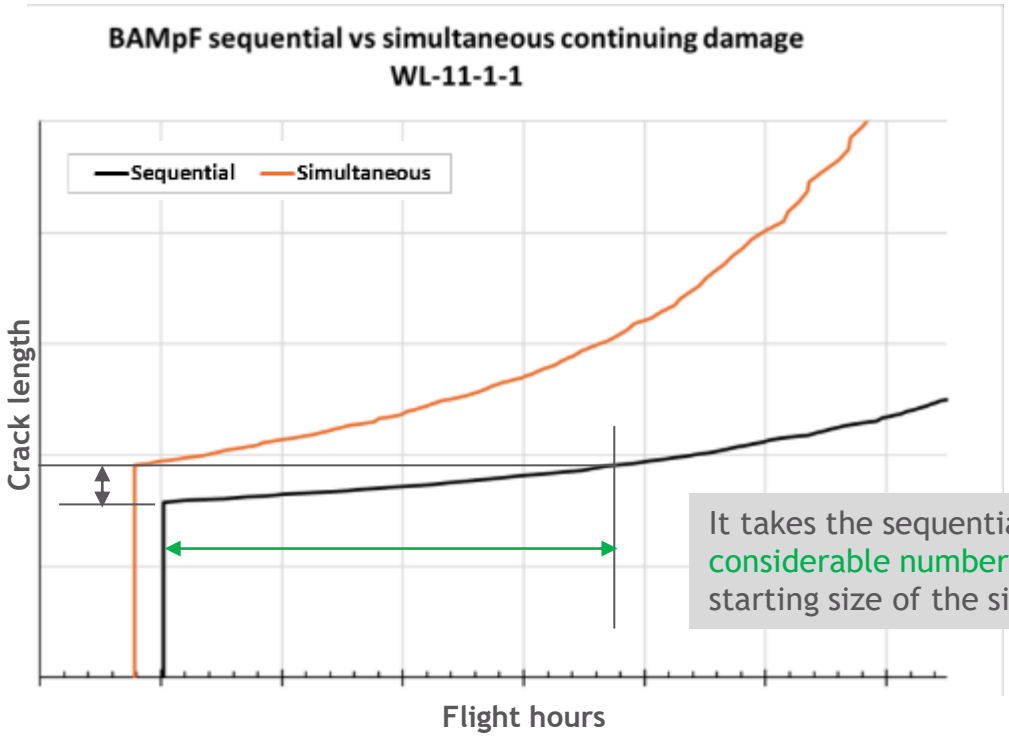
WL-11-1-1 – BAMpF

Since the secondary crack grows more during the first ligament growth, the starting crack size on the opposite side of the hole is larger for the simultaneous model





It takes the sequential model a considerable number of hours to reach the starting size of the simultaneous model

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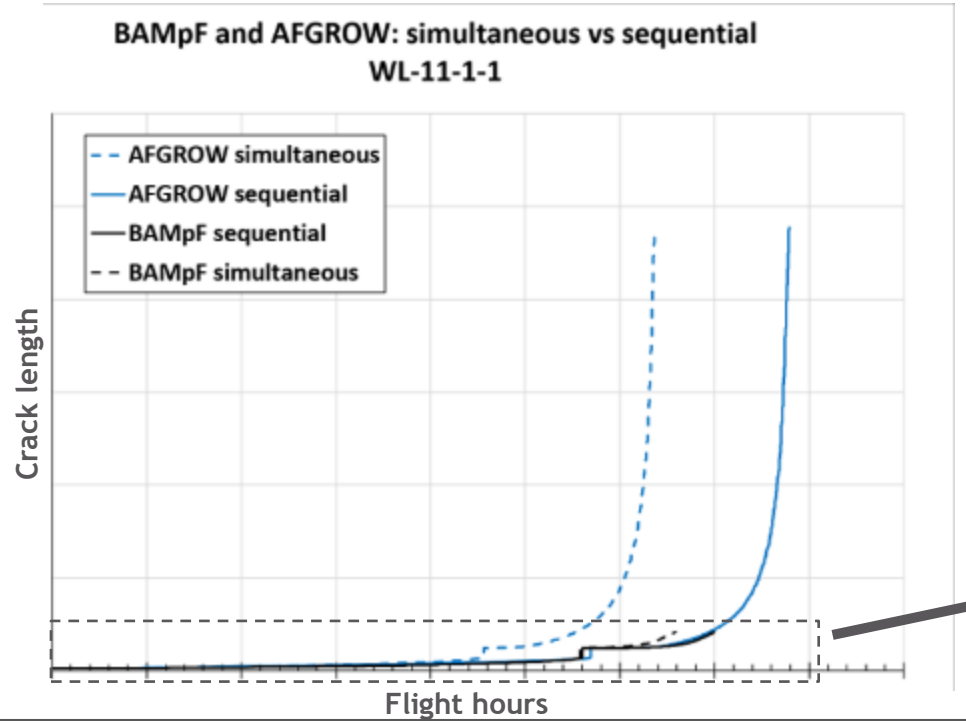
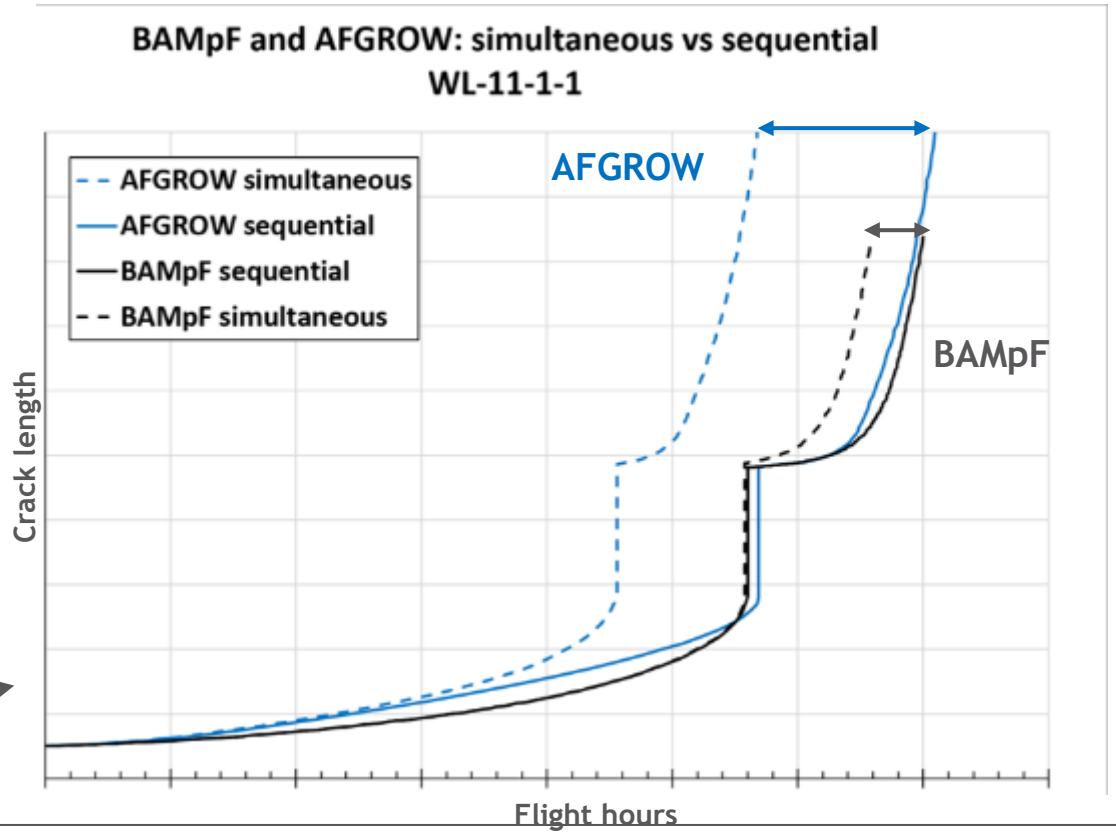
WL-11-1-1 – AFGROW

Does AFGROW show the same results?

- Sequential and simultaneous AFGROW model results below
- *Both BAMpF and AFGROW show a decrease in life with the simultaneous model*
  - *AFGROW shows a larger effect*

AFGROW vs BAMpF:
- Sequential model
  - Similar results
- Simultaneous model
  - AFGROW shows a larger effect than BAMpF





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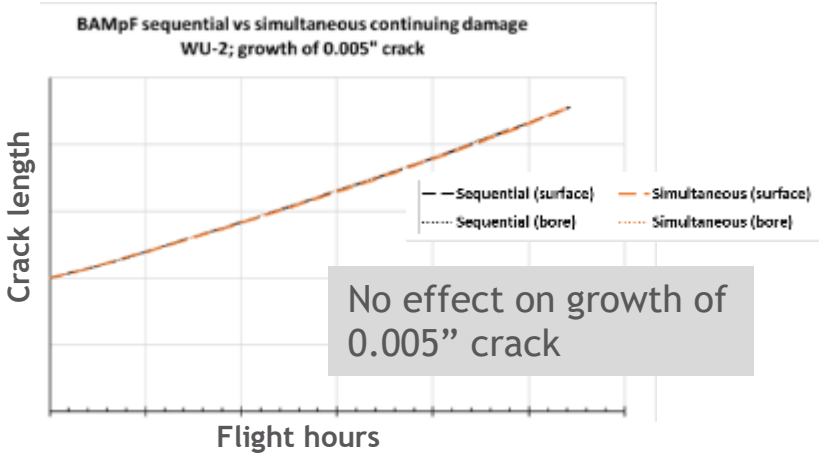
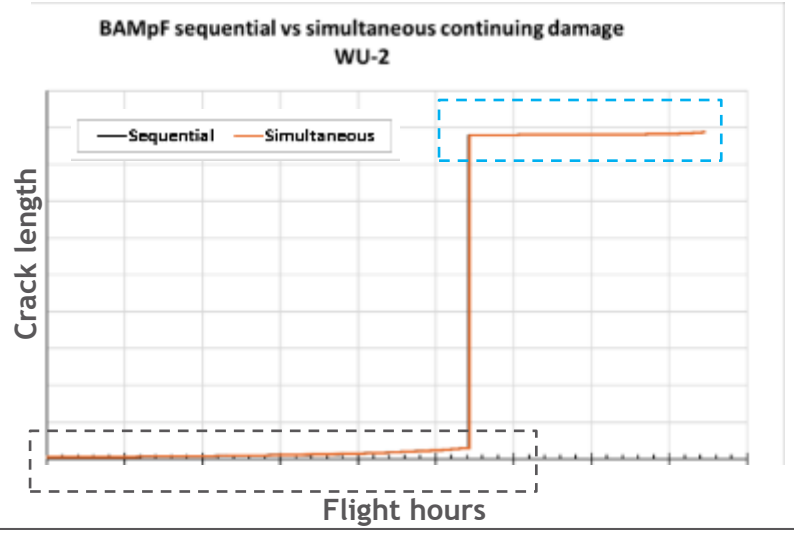
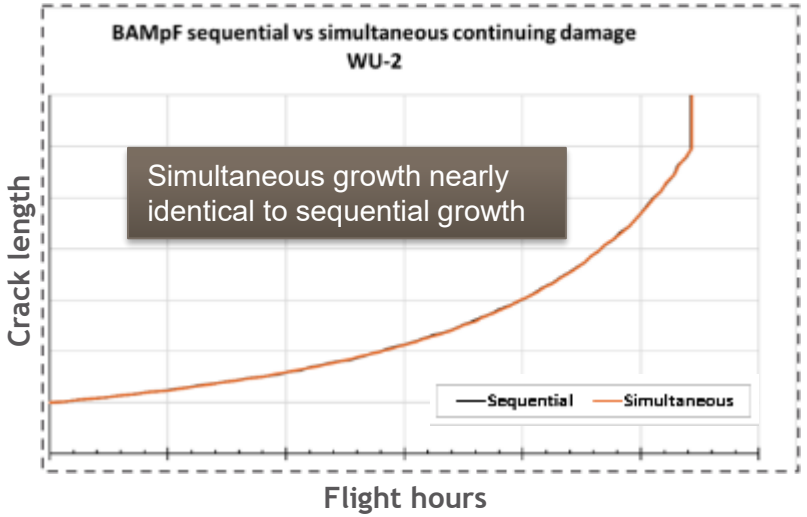
WU-2 – BAMpF

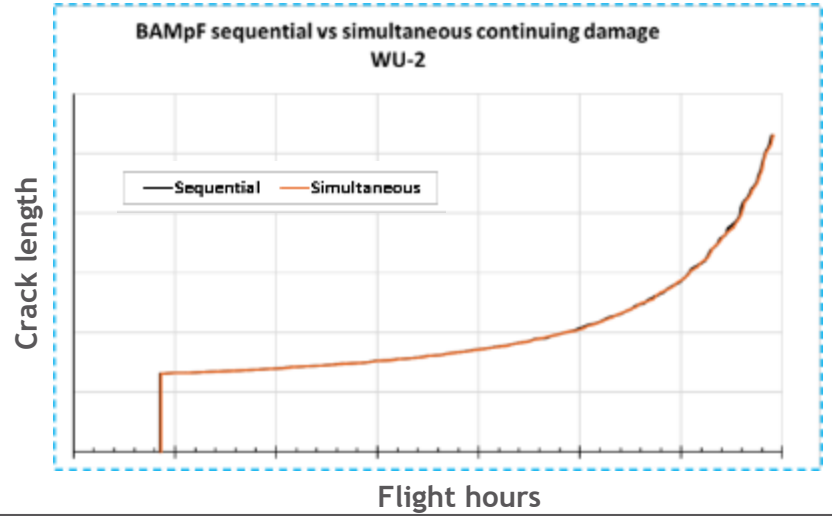
- Fuel fill hole in upper skin
- >3” diameter, >1/2” thick
- No retardation
- StressCheck model with BAMpF crack growth solution



- ***Nearly identical results between sequential and simultaneous models***
  - Note: this is a much thicker and larger cross section than the previous fatigue location
  - Growth of the primary crack does not accelerate the secondary crack







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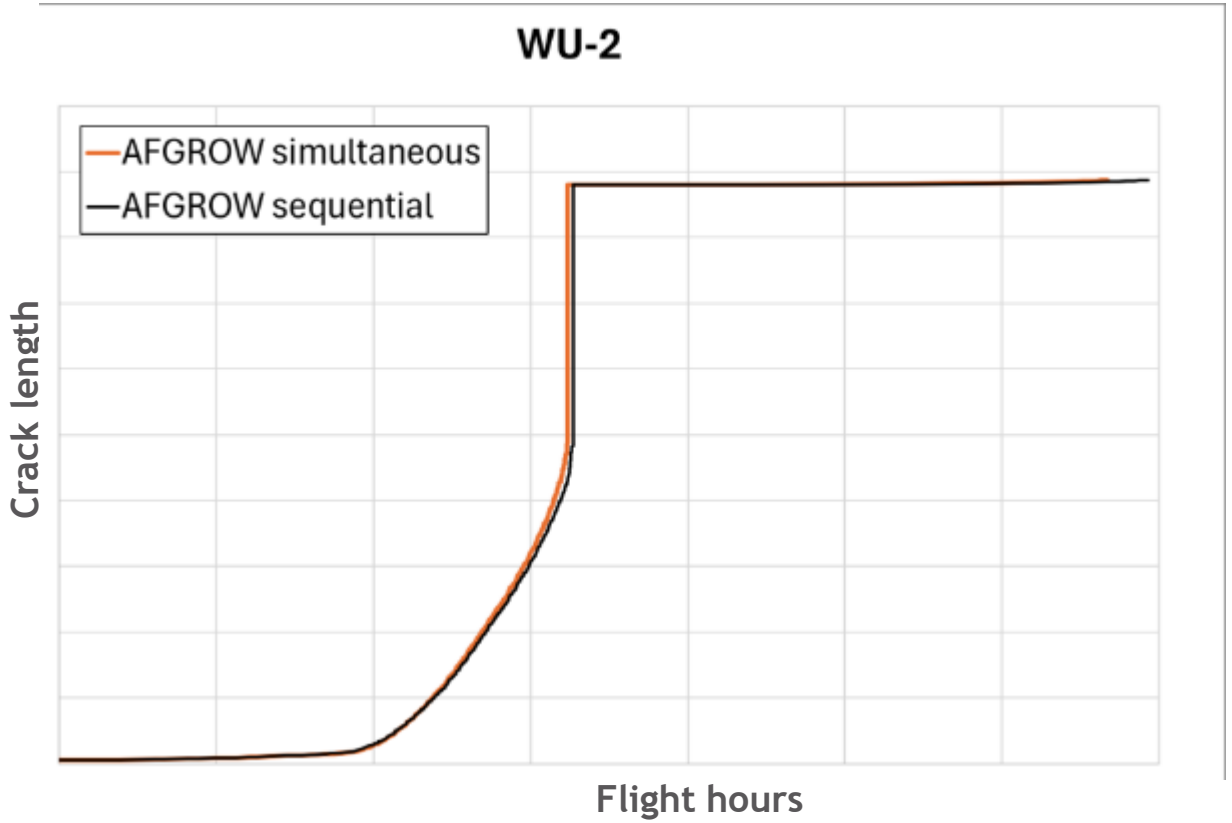
WU-2 – AFGROW

AFGROW models agree with BAMpF for WU-2

- Very little effect of simultaneous growth for this geometry



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AFGROW COM

Use AFGROW COM to run all continuing damage models with both sequential and simultaneous approaches

- Use Wheeler retardation, m = 1 for all
- Some have bearing stress (ASF calculated based on BSF, effective width, hole diameter)
- Results shown on the next slide

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Simultaneous/Sequential Differences

Table shows % difference in crack growth life relative to sequential model

- Across all details, simultaneous model always results in shorter life than sequential model (negative % values)
- However, the magnitude of the difference between sequential and simultaneous approaches varies
  - Smaller differences for some (~ -8% for B-32-1)
  - Much larger differences for others (~ -20% for WL-28-1)

CP #	% Difference
B-5-1	-11.2%
B-32-1	-7.5%
WL-8-2	-15.0%
WL-10-3	-11.5%
WL-11-1-1	-17.9%
WL-26-2	-14.1%
WL-27-2	-14.2%
WL-27-3	-14.2%
WL-28-1	-19.7%
WL-28-2	-14.8%
WL-28-3	-12.6%
WL-40-2	-14.9%
WL-45-1	-11.9%
WL-45-2	-13.4%
WL-50-2	-12.2%
WL-50-3	-9.4%
WL-51-1	-11.2%
WL-62-1	-13.8%
WL-62-3	-12.8%
WU-1	-10.9%
WU-7-2	-12.8%

Average % difference = -13.2%
Standard deviation = 2.6%

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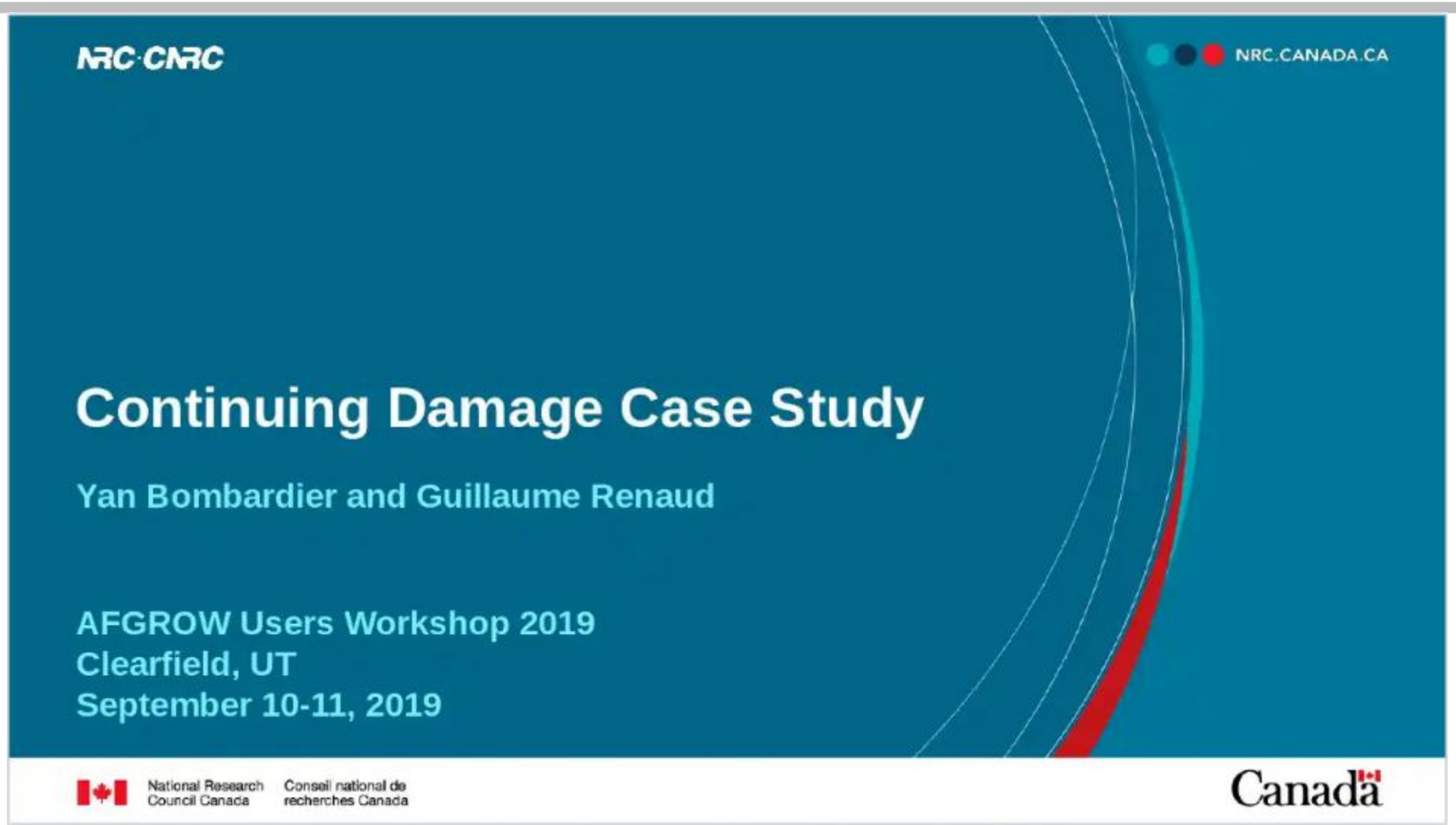
NRC Simultaneous/Sequential Study



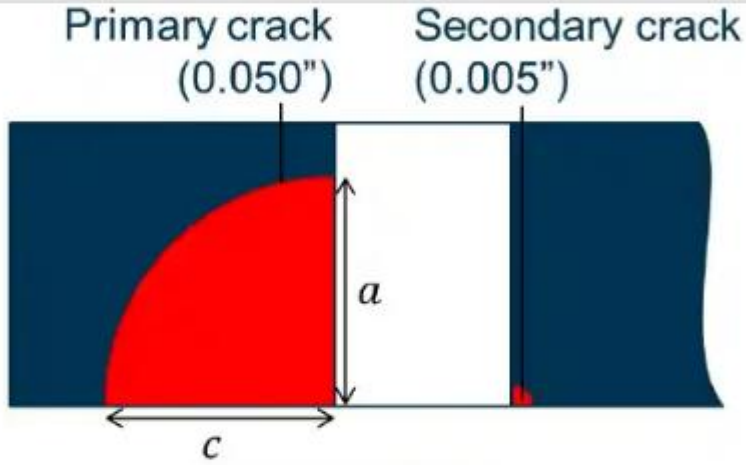
https://afgrow.net/workshop/documents/2019/Guillaume-Renaud-Continuing-Damage-Case-Study-2019.pdf

Study Details

Problem Definition

Crack Size, Shape, Sequence

- Quarter-circular cracks (fixed a/c ratio)
  - Primary crack: c_o = 0.050"
  - Secondary crack: c_o = 0.005"
  - Bearing load lost after ligament failure
  - Transition to through crack: 95% of thickness[1]
- Three AFGROW files provided by USAF:
  - File 1: Primary crack
  - File 2: Secondary crack
  - File 3: Edge crack



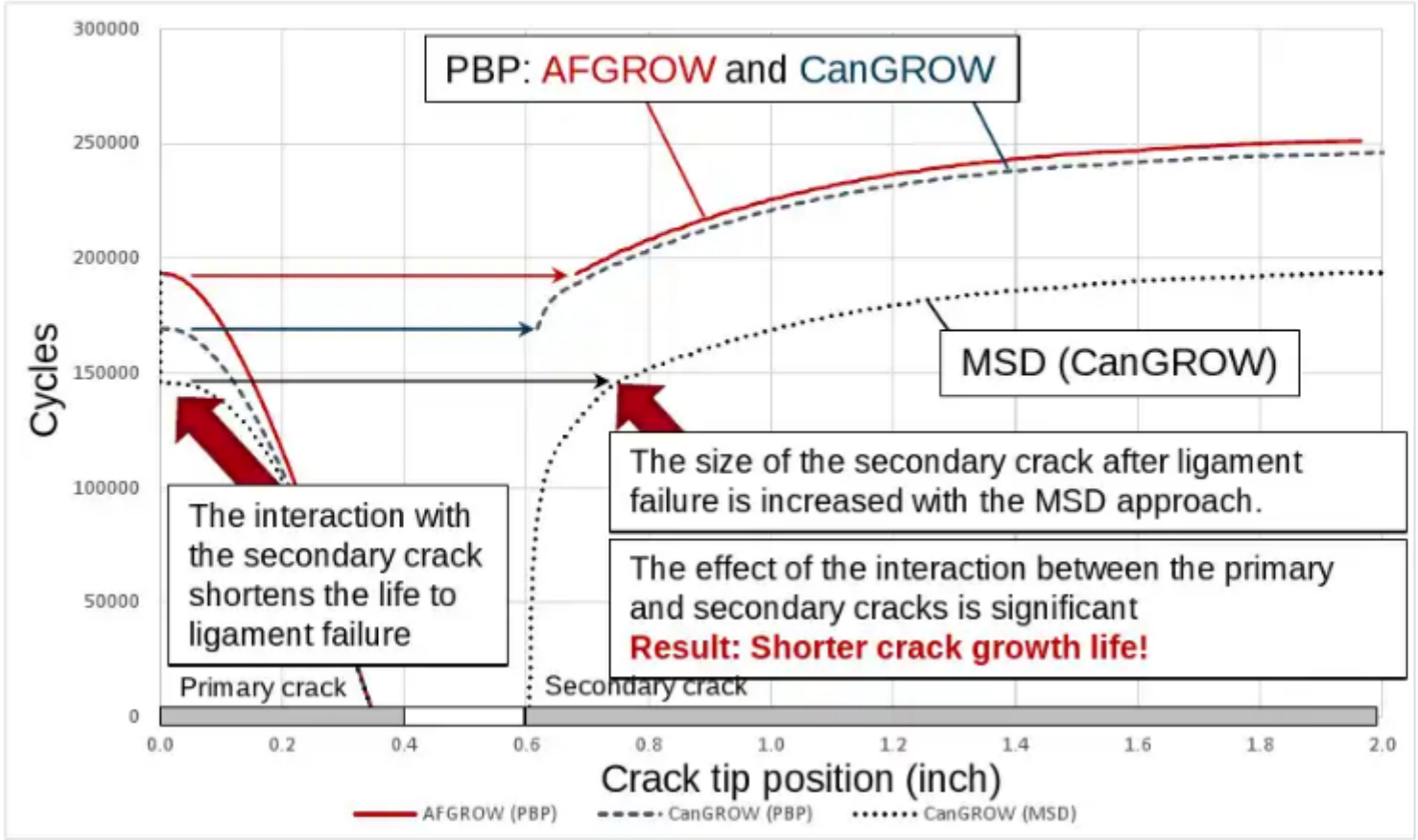
Model	Bypass stress fraction	Bearing stress fraction
Diametrical crack	0.90	1.969
Edge crack	1.00	0.000

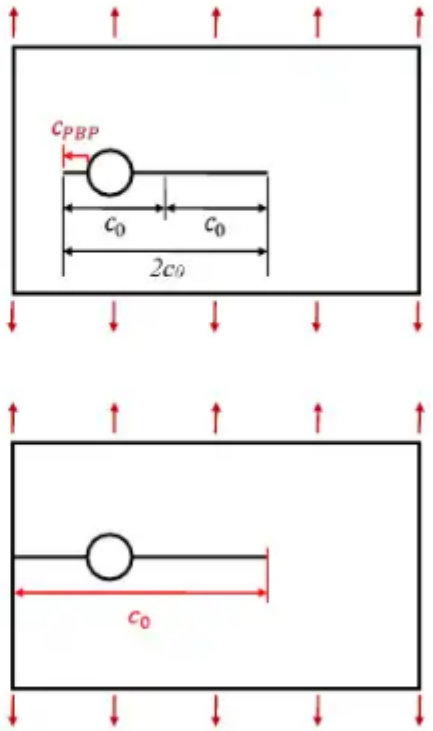
[1] Current CanGROW implementation: 100% of thickness. It is planned to be updated (e.g. transition when plasma zone reached the surface).

Influence on Secondary Crack Size

Simultaneous Crack Growth

Crack Growth Results – Crack Tip Positions vs. Cycles



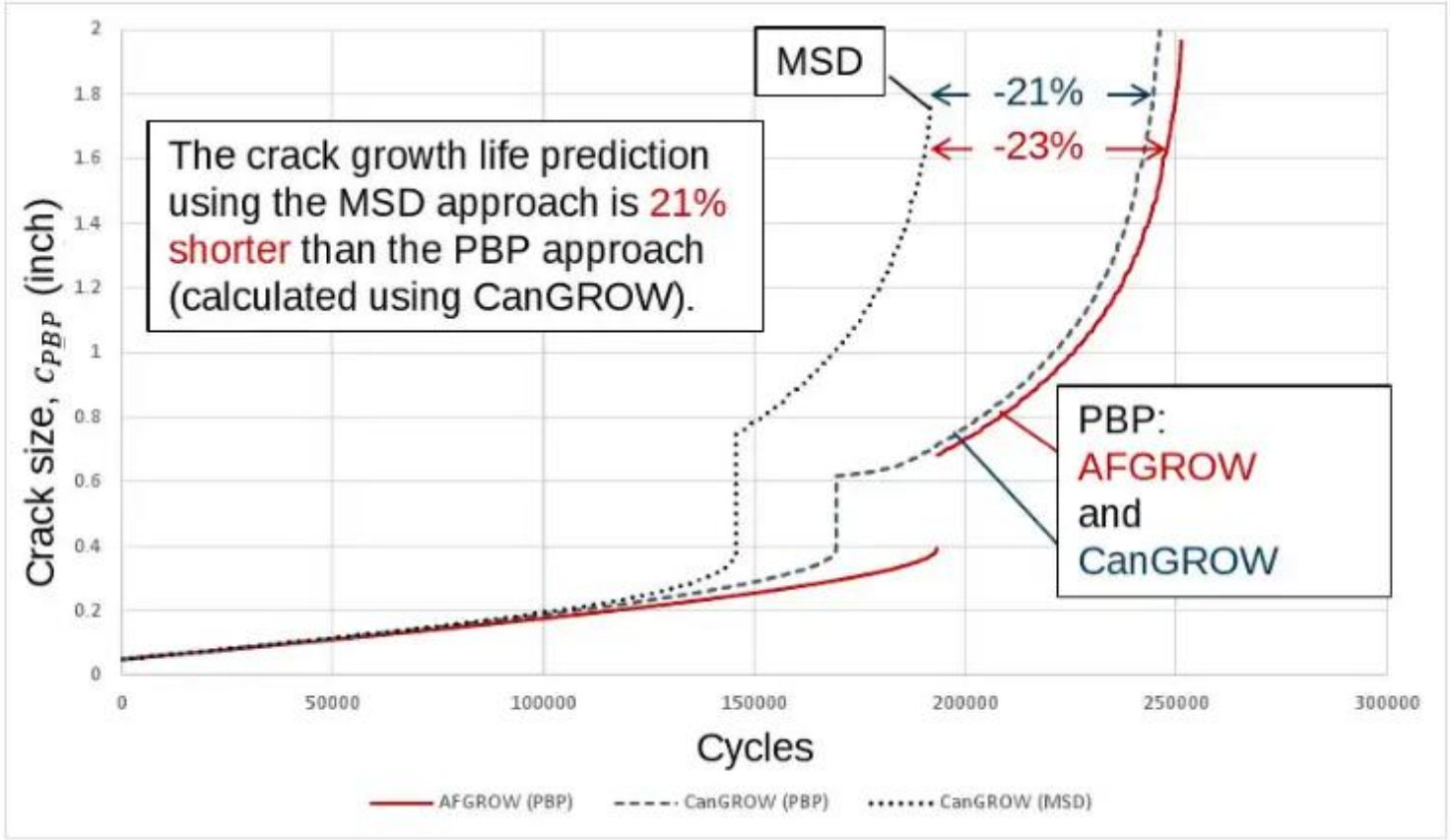


Canada

Impact on Life

Simultaneous Crack Growth

Crack Growth Results – Lead Crack



Approach	Life (cycles)
PBP/AFGROW	251,279
PBP/CanGROW	246,357
MSD/CanGROW	193,797

Approach	Cont. Crack
PBP/AFGROW	0.681"
PBP/CanGROW	0.618"
MSD/CanGROW	0.746"

Canada 24

Food For Thought

Concluding Remarks

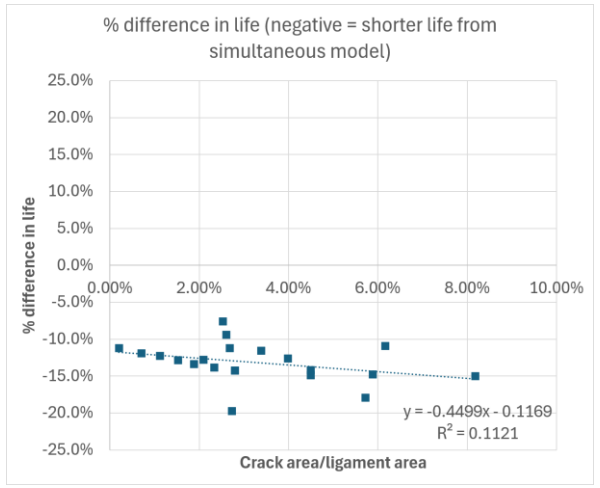
Philosophical Questions…

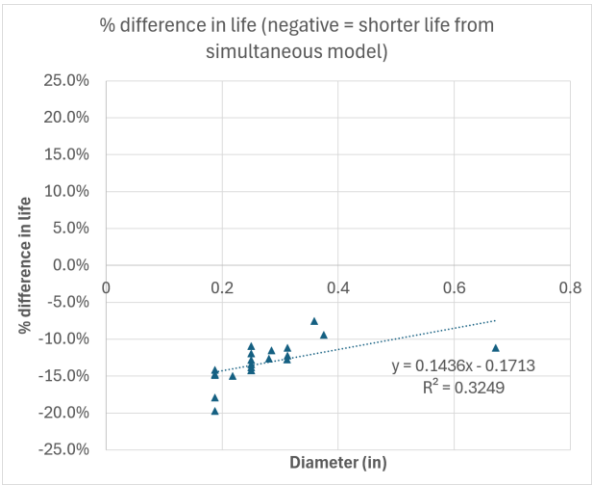
- If simultaneous crack growth (MSD approach) is more representative of the target scenario, is the legacy approach un-conservative?
- Is there un-conservativism built in the traditionally assumed initial crack sizes (0.050" for the primary crack and 0.005" for the secondary crack)?
- If simultaneous growth is used, should the secondary initial crack size assumption be modified (reduced) to be made more representative of initial material discontinuity states?
- The way forward for modelling continuing damage using simultaneous growth (e.g. MSD scenarios) needs to be addressed as the legacy PBP approach leads to longer lives if the same initial crack size assumptions are used.

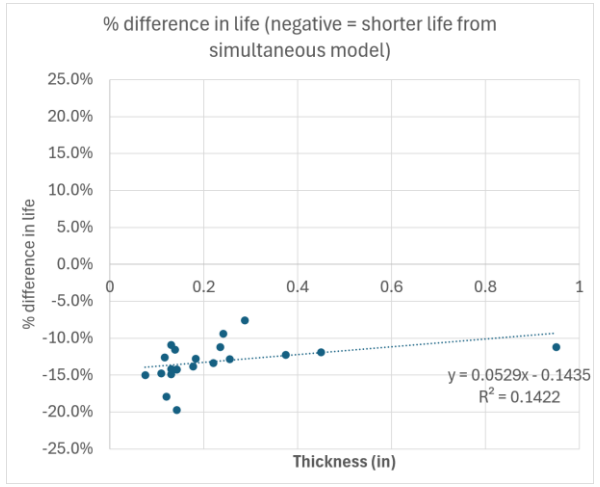
Primary Factors Influencing Simultaneous/Sequential Differences

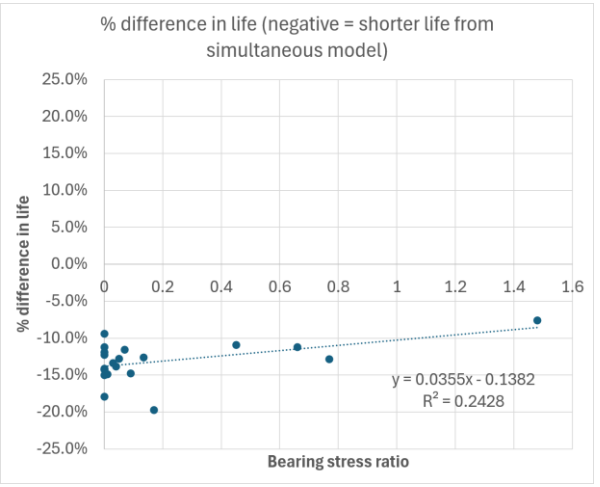
Plots show % difference in life vs discrete model parameters

- % difference does not follow a clear trend based on geometry
  - vs crack area/ligament area (R^2 = 0.11)
  - vs thickness (R^2 = 0.14)
  - vs hole diameter
    - Strongest parameter
    - Somewhat related (R^2 = 0.32)
  - Bearing stress ratio (R^2 = 0.24)
- Each prediction utilized a different spectrum
  - How significant are spectrum effects?









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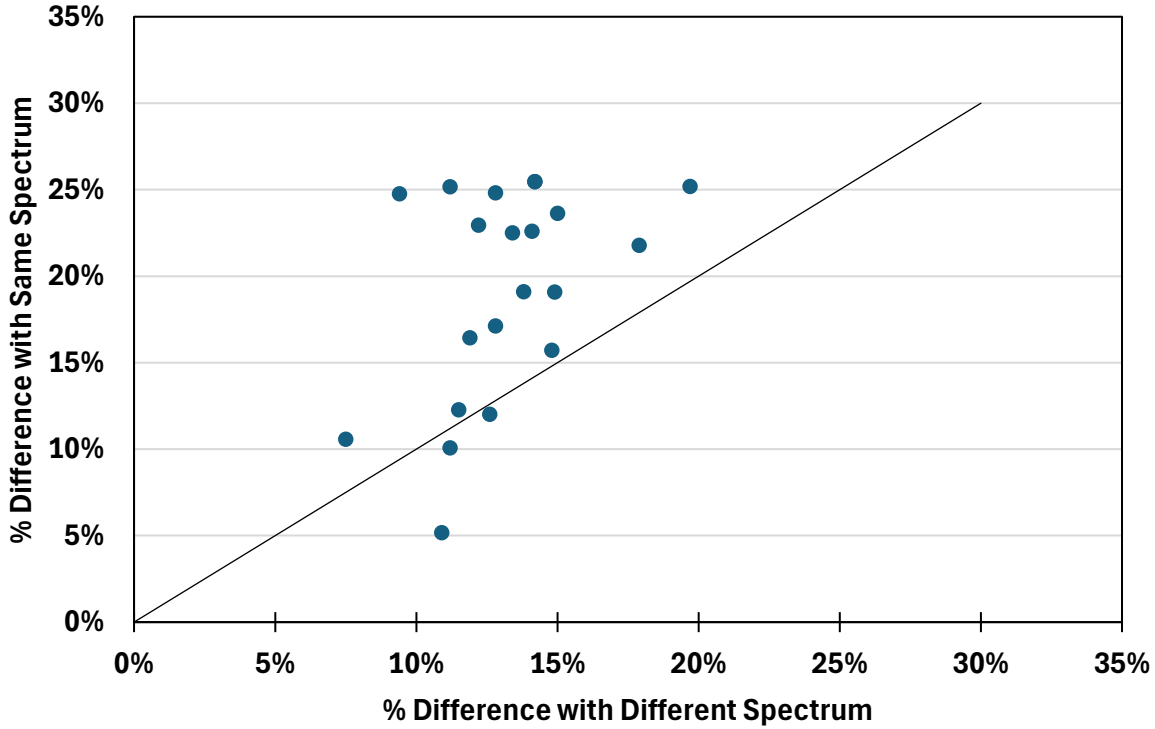
Spectrum Influence

AFGROW COM analyses repeated using a single spectrum for all locations

- **Greater difference between simultaneous/sequential approach when WL-11-1-1 spectrum used for all locations**
- **Results may be biased by the high potential for retardation benefit from the spectrum used**



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Key insights

Sequential model

- The secondary crack (0.005”) stays smaller longer (no influence from primary crack)

Simultaneous model

- The secondary crack growth is accelerated from the primary crack

Geometry influences the sensitivity of the secondary crack to the primary crack

- For a thin, small cross section
  - The secondary crack stress intensity is significantly influenced by the primary crack

- For a thick, large cross section
  - The secondary crack stress intensity is minimally influenced by the primary crack

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K Solution Validation/Verification

2007 Aircraft Structural Integrity Program Conference

The Effect of Stress Intensity Factor Models on Inspection Intervals

Lt Col Scott Fawaz
Center for Aircraft Structural Life Extension
United States Air Force Academy

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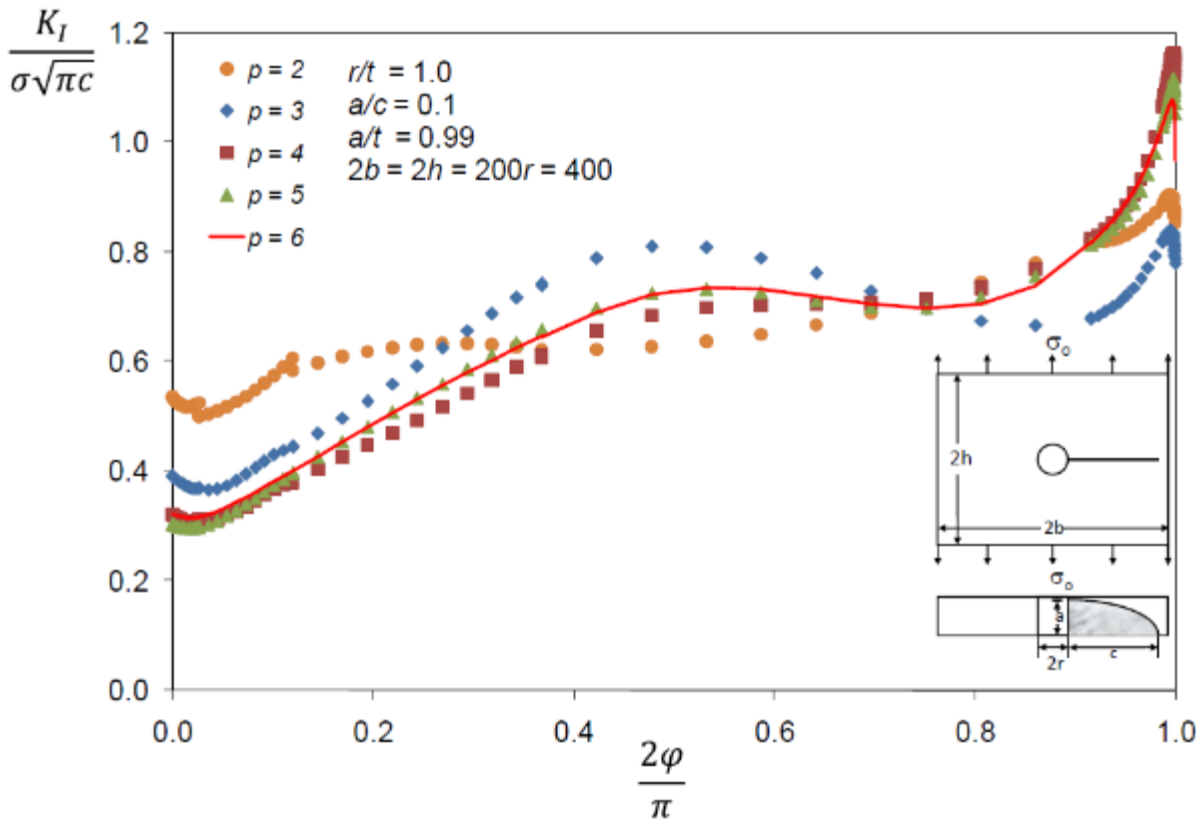
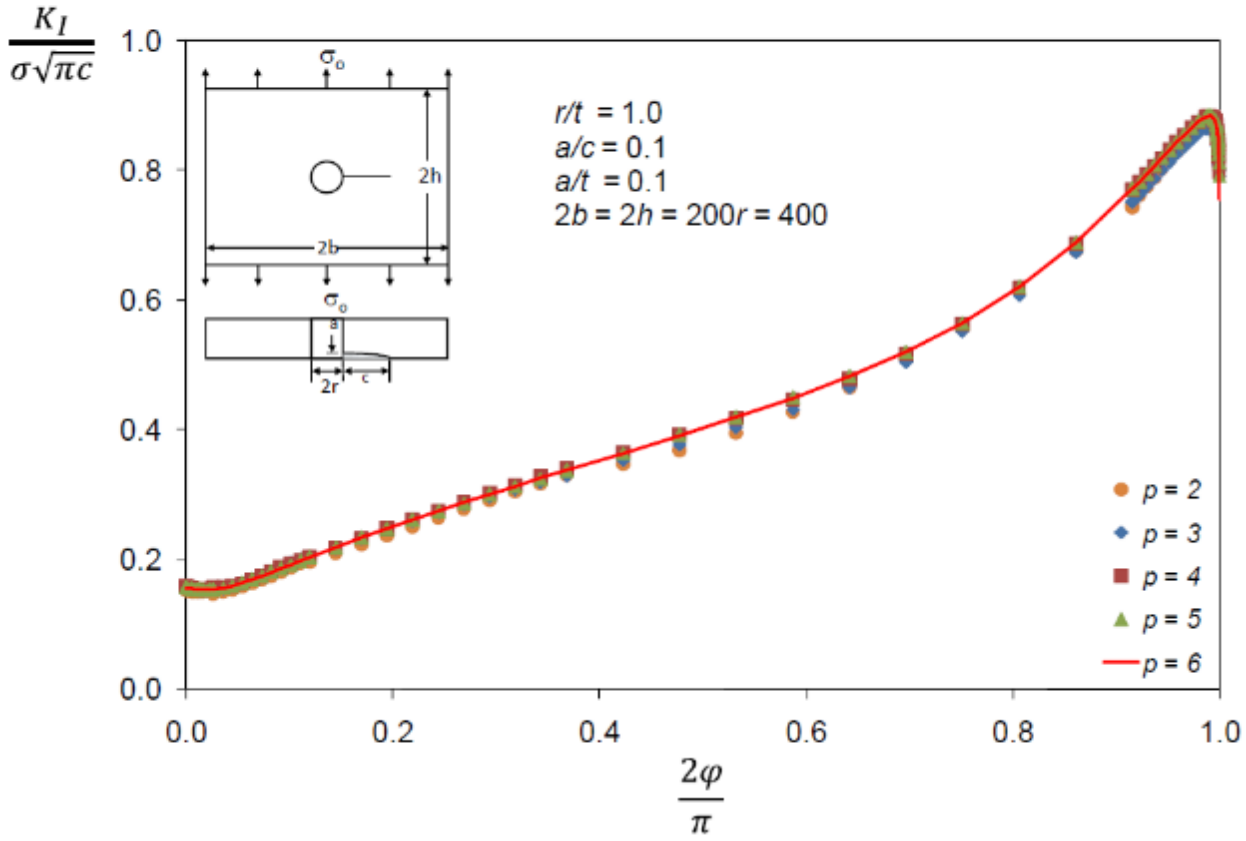
https://asipcon.com/proceedings/proceedings_2007/2007_PDFs/Tues_0230_Fawaz.pdf

K Solution Verification

Convergence: Deep Crack

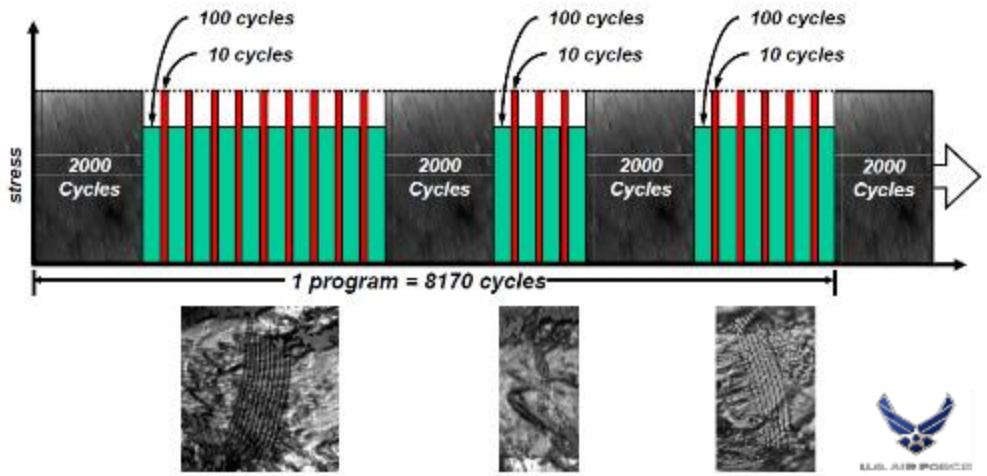


Convergence: Shallow Crack

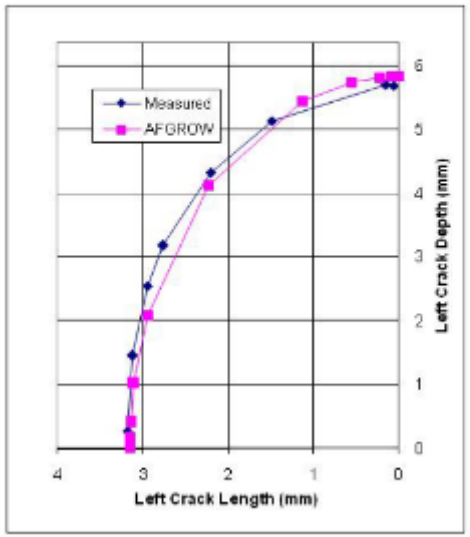


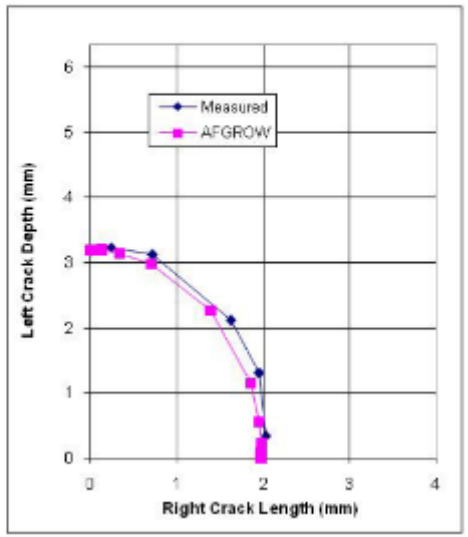
K Solution Validation

Marker Load Spectrum

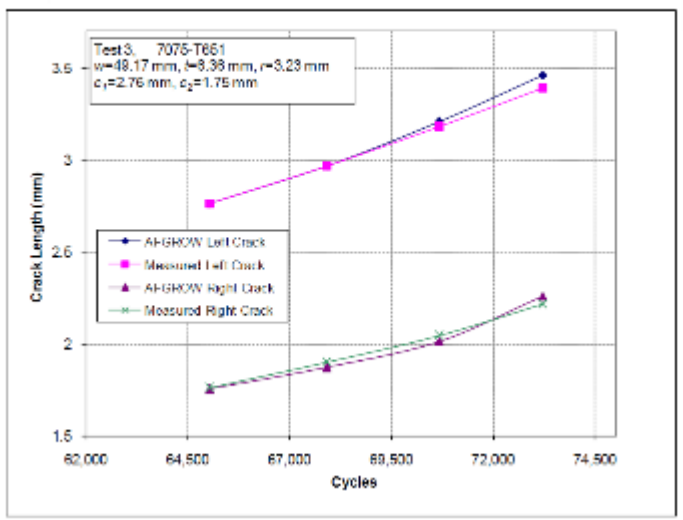


Crack Shape Development





Fatigue Life Prediction



Fawaz Percent Differences

Geometry for Assessing Effect on Continuing Damage Scenario

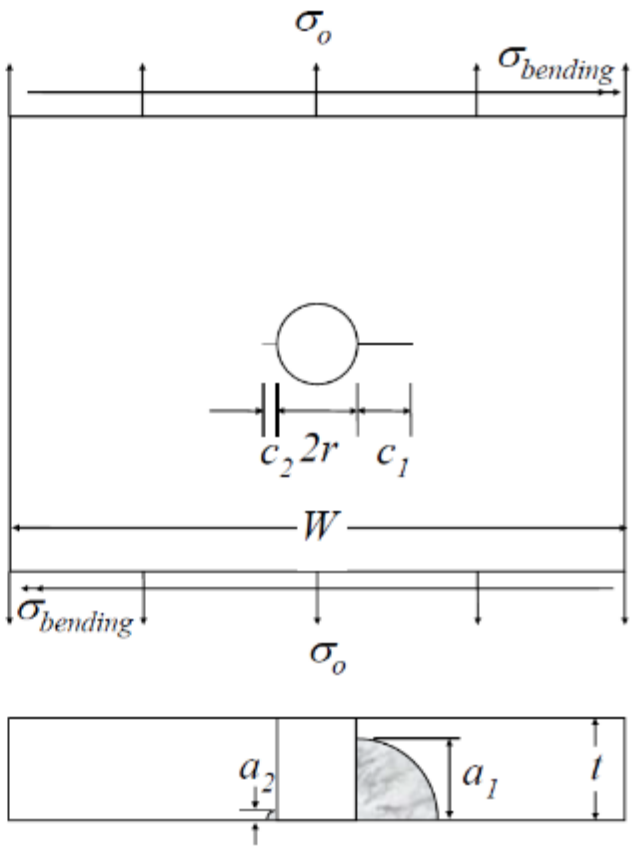
W = 1.14 in, t = 0.063 in, D = 3/16 in

a_1 = 0.05 in, c_1 = 0.05 in

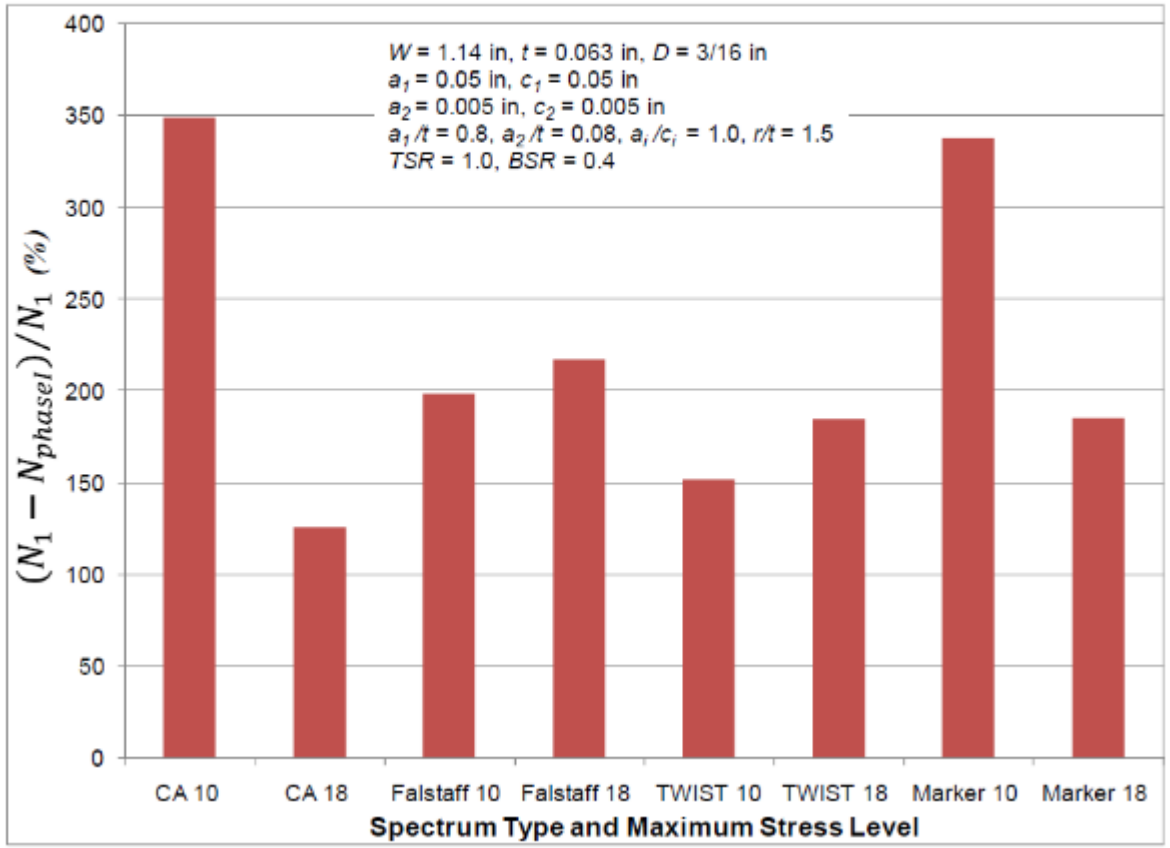
a_2 = 0.005 in, c_2 = 0.005 in

a_1/t = 0.8, a_2/t = 0.08, a_i/c_i = 1.0, r/t = 1.5

TSR = 1.0, BSR = 0.4



Effect on Continuing Damage Scenario Phase I Life

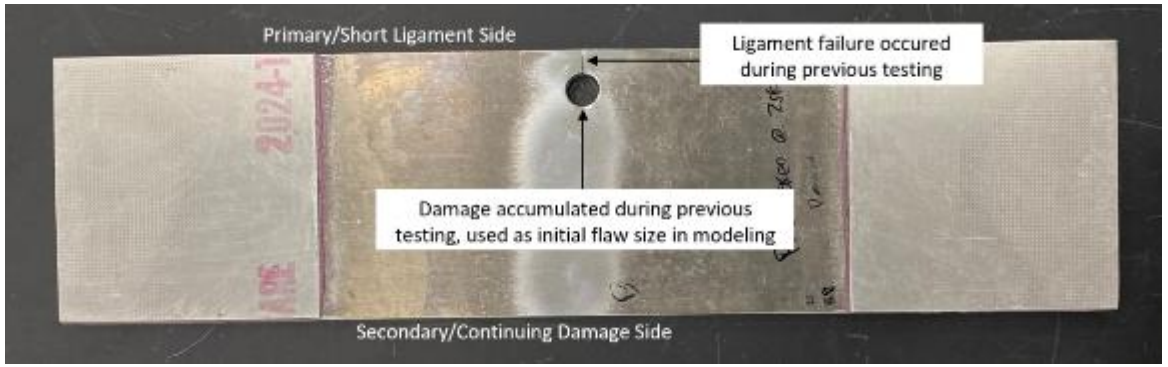


Continuing Damage Testing and Analysis 8/Mar/2022

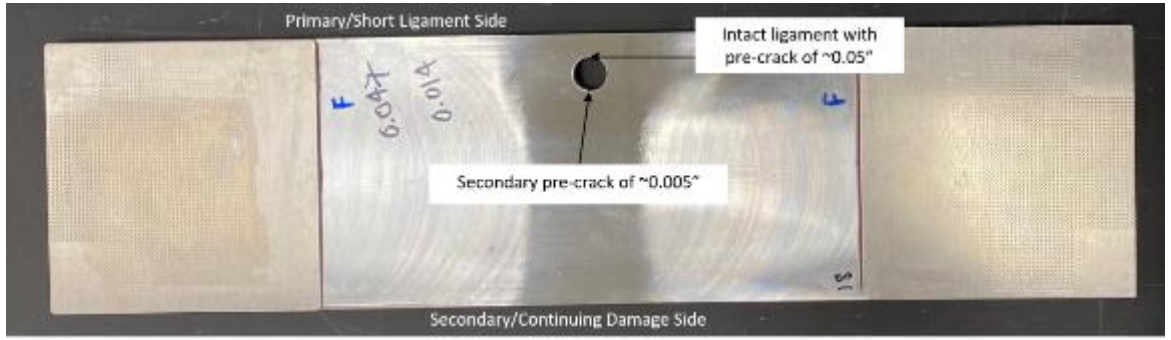
Matt Andrus, GS-11,
Mechanical Engineer,
T-38 Structural Integrity and Analysis

Test Plan

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

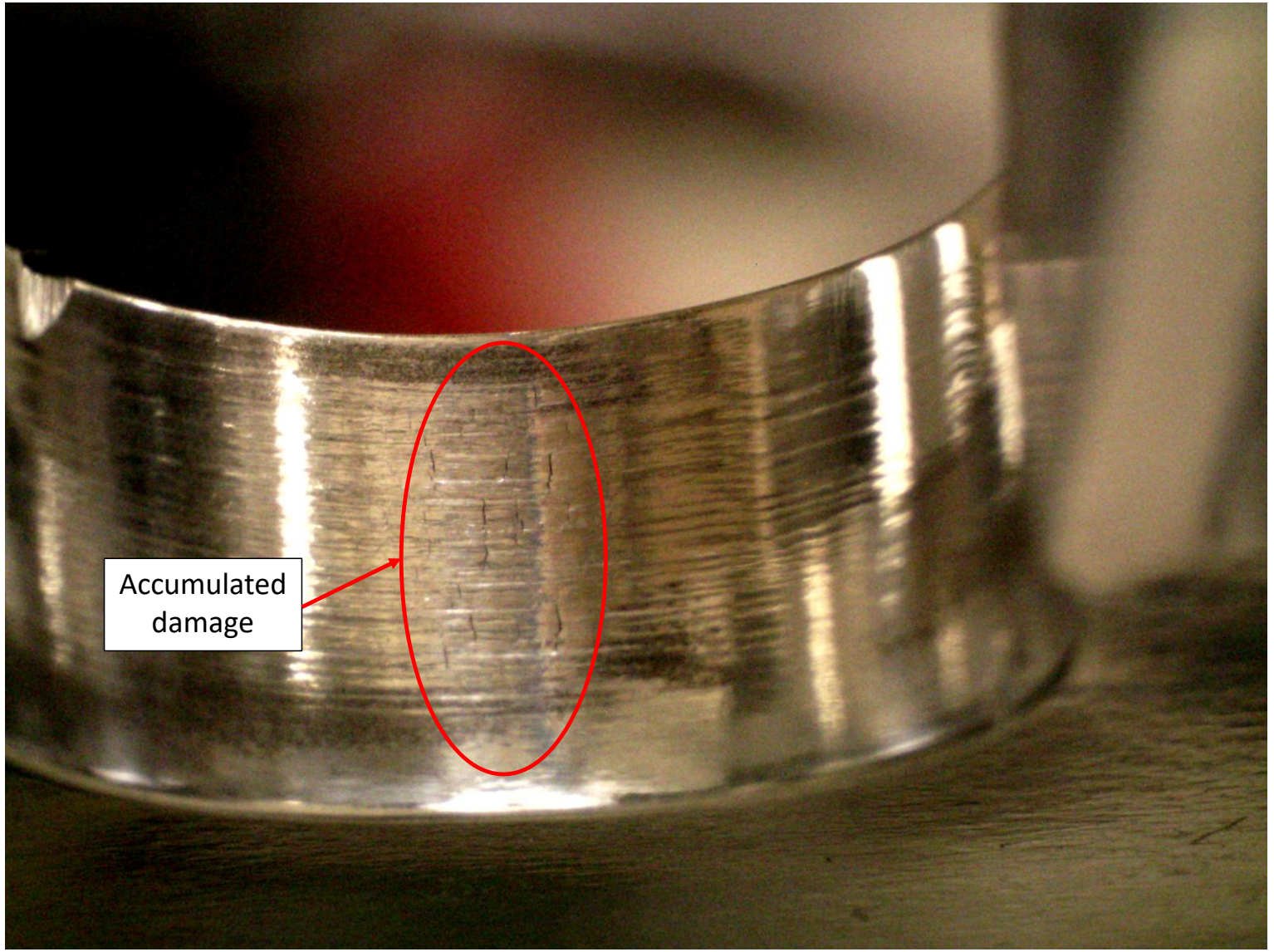


Failed Ligament Geometry

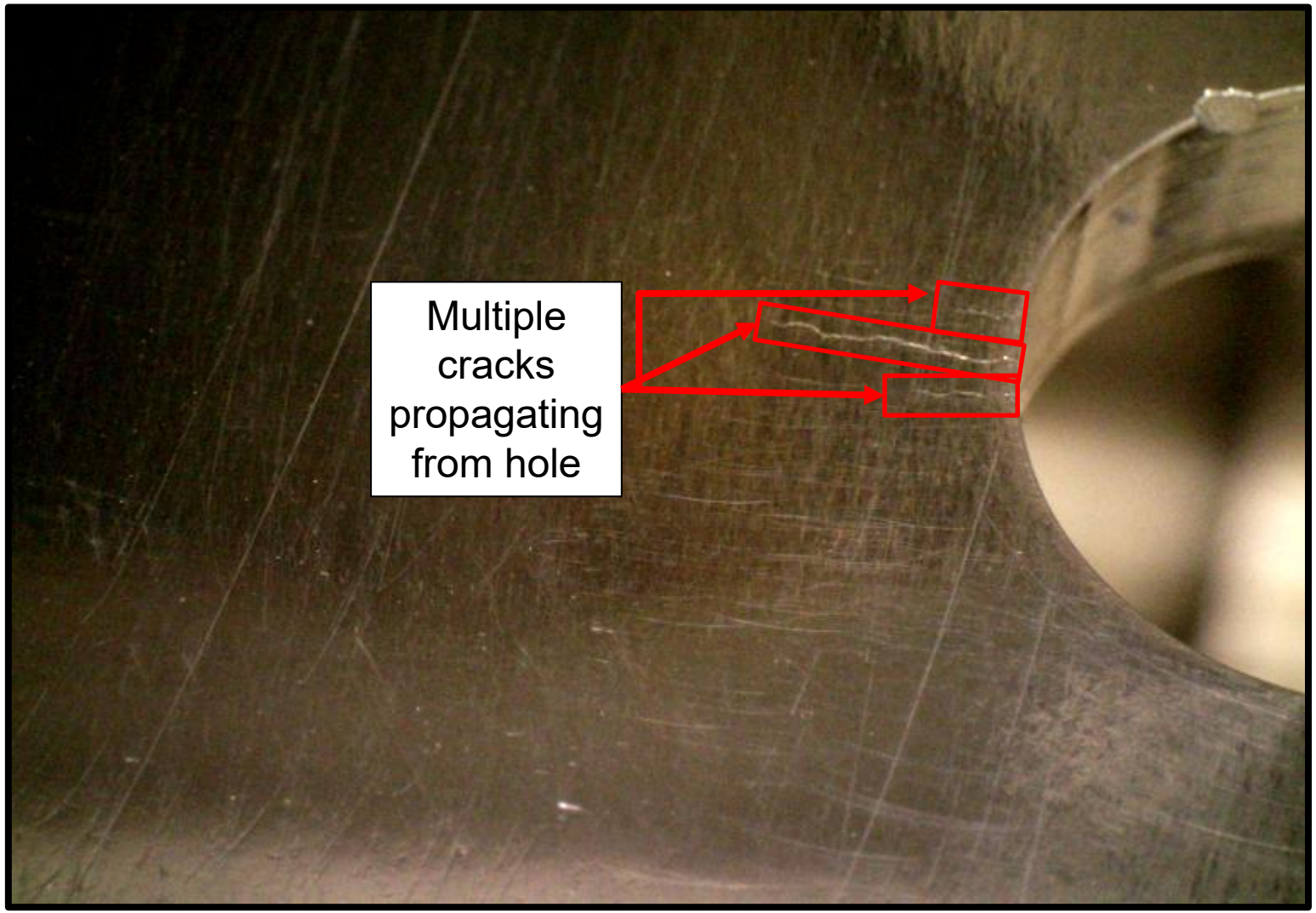


Continuing Damage (Dual Crack) Sample

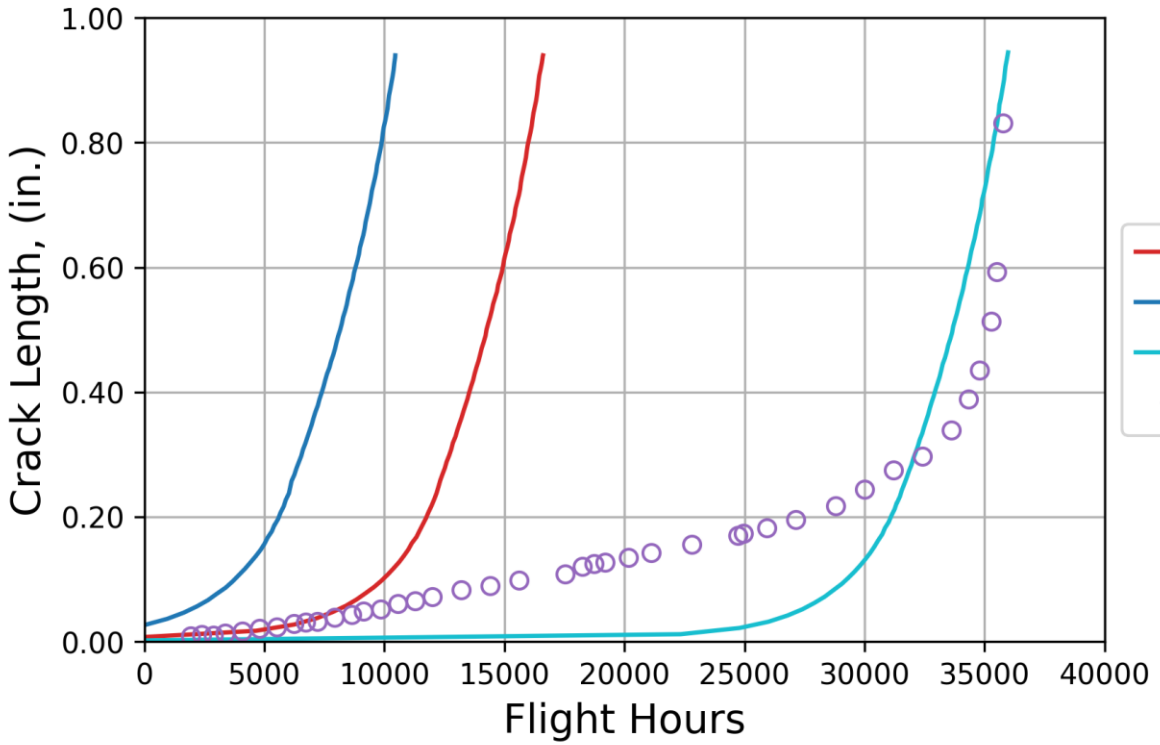
Failed Ligament Testing

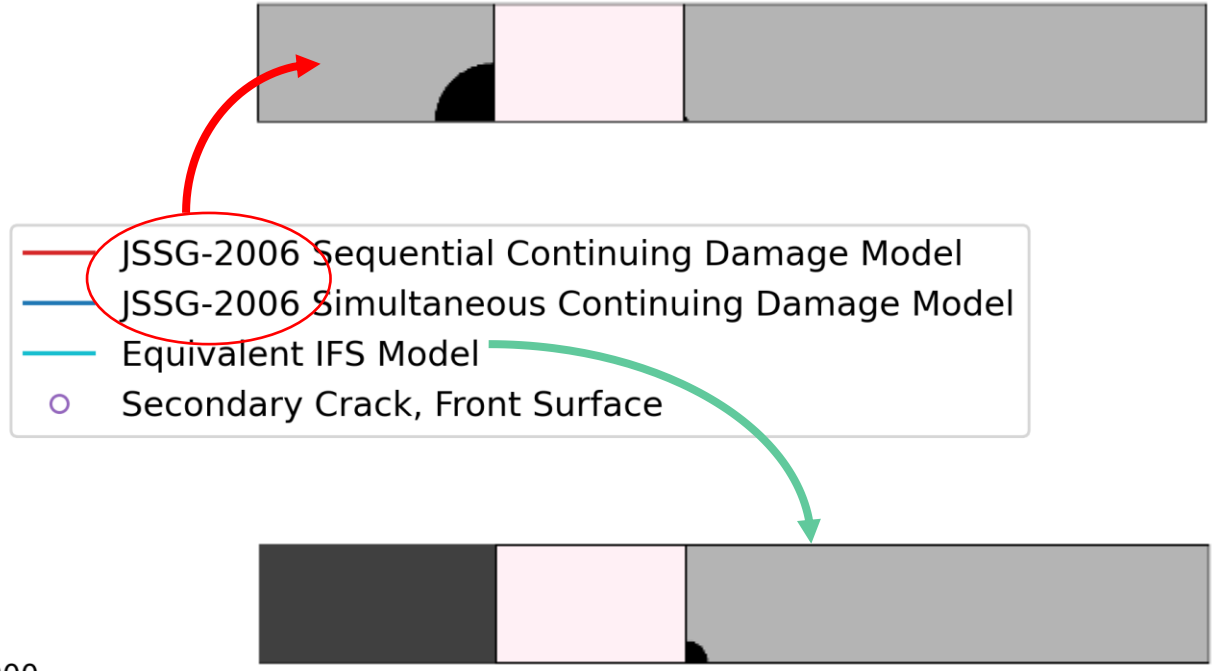


Failed Ligament Testing

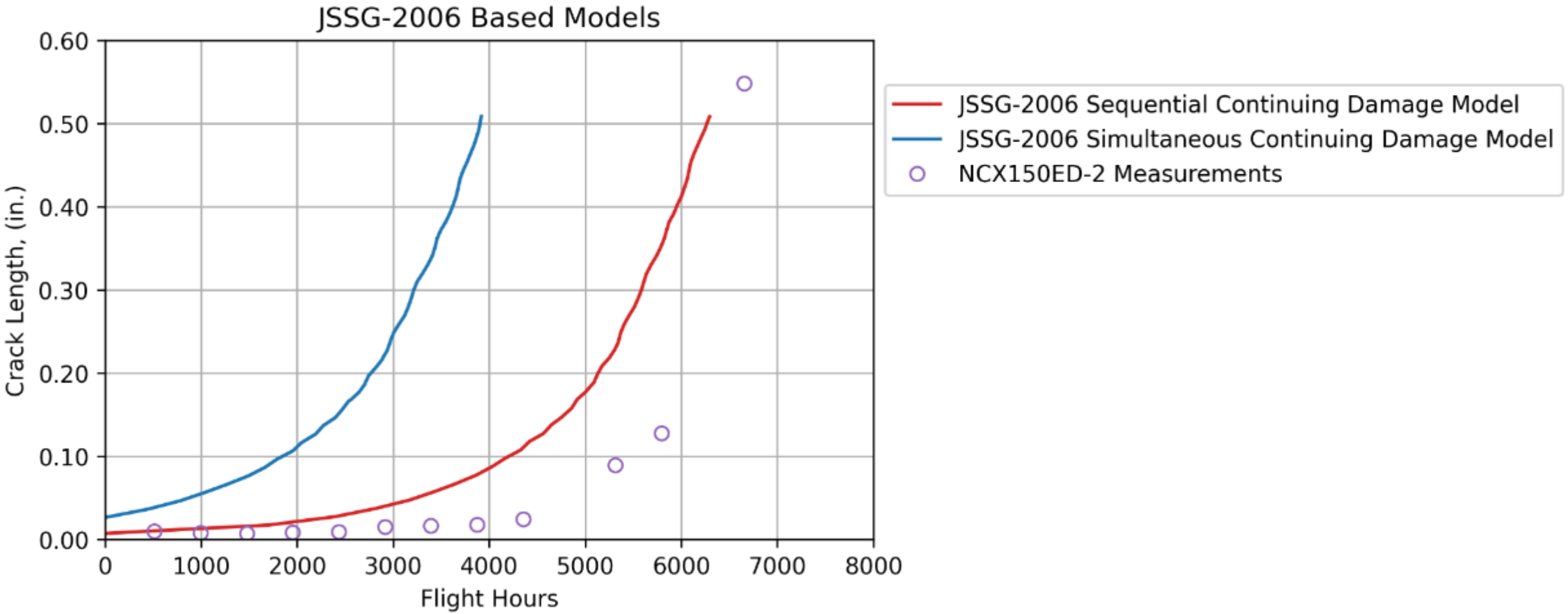


20 ksi Failed Ligament Results

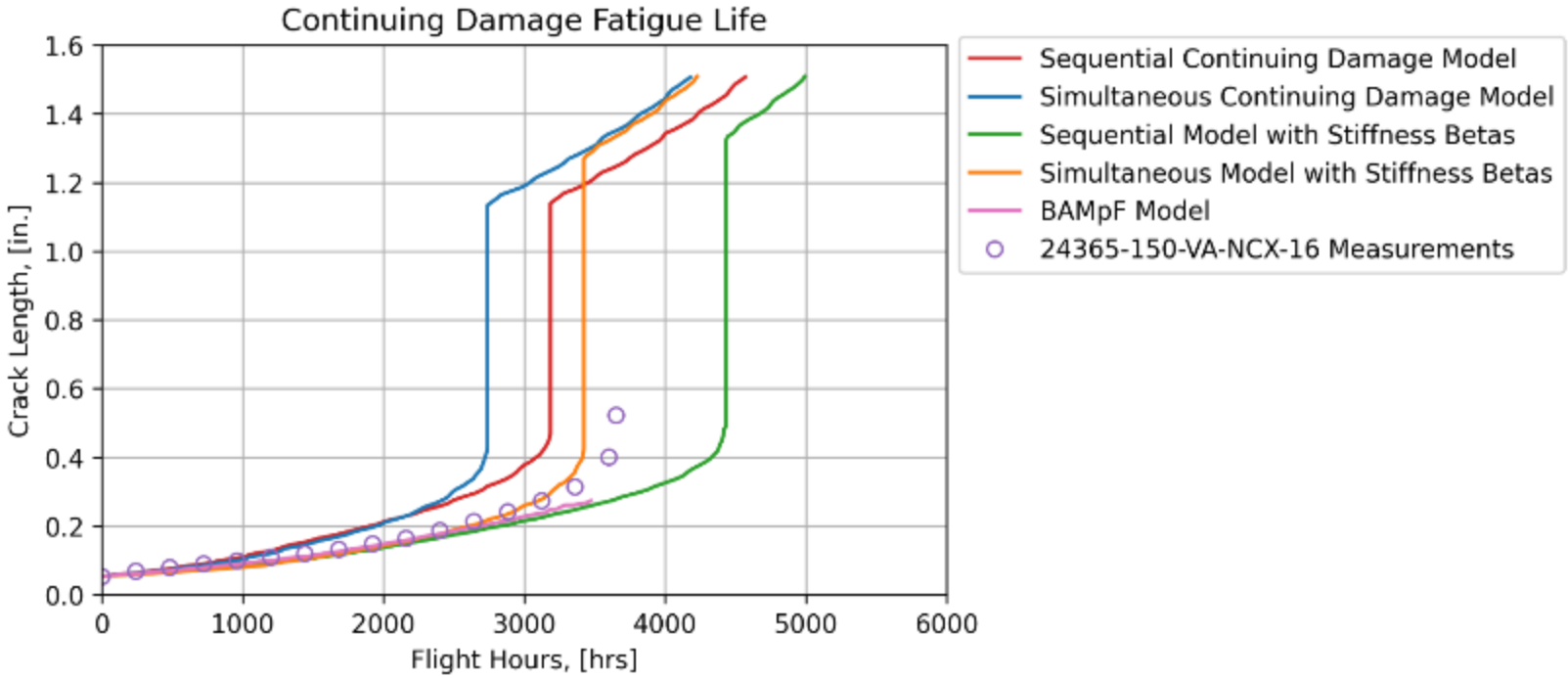


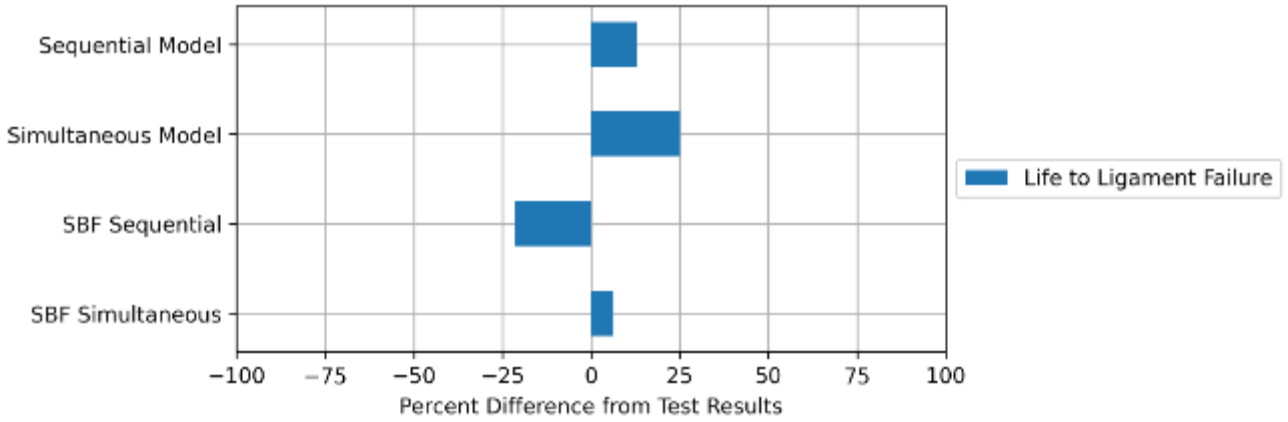


25 ksi Failed Ligament Results



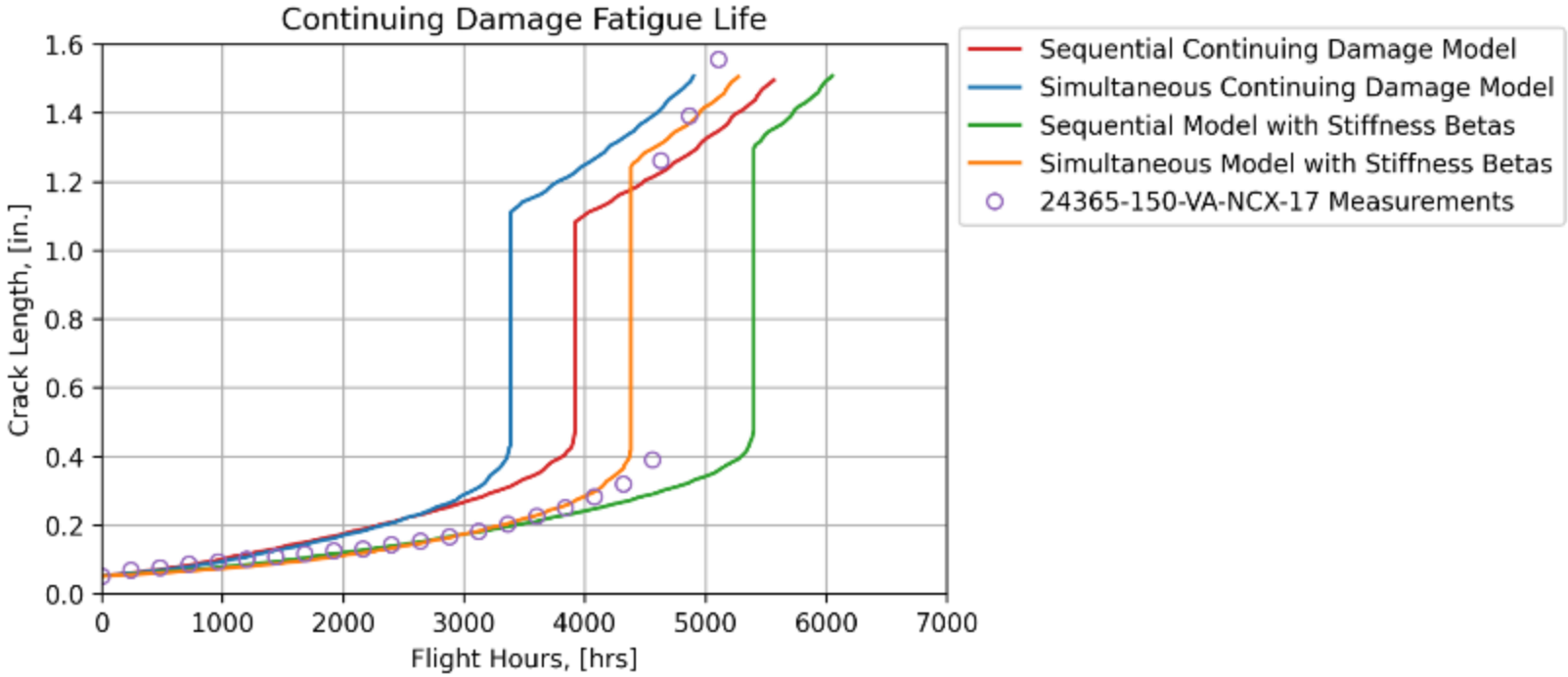
Dual Crack Test Results

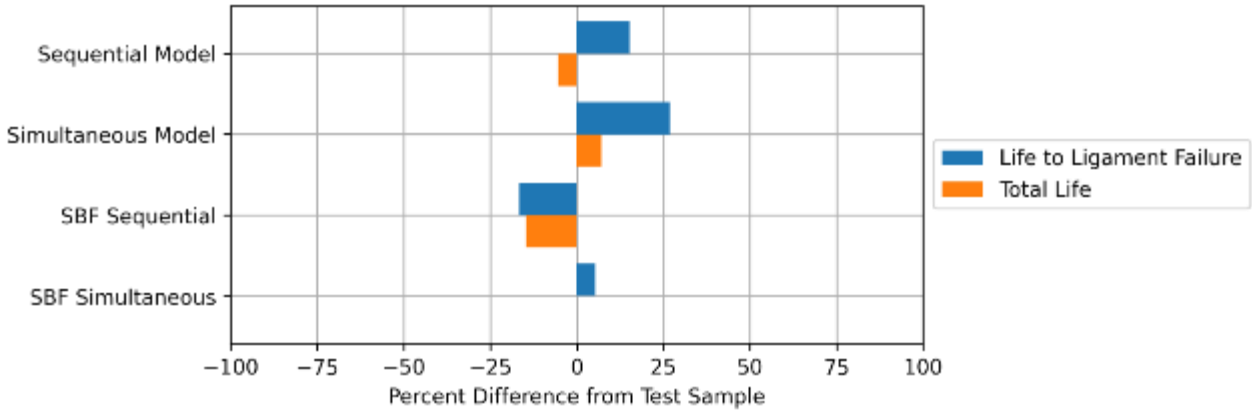




24365-150-VA-NCX-17

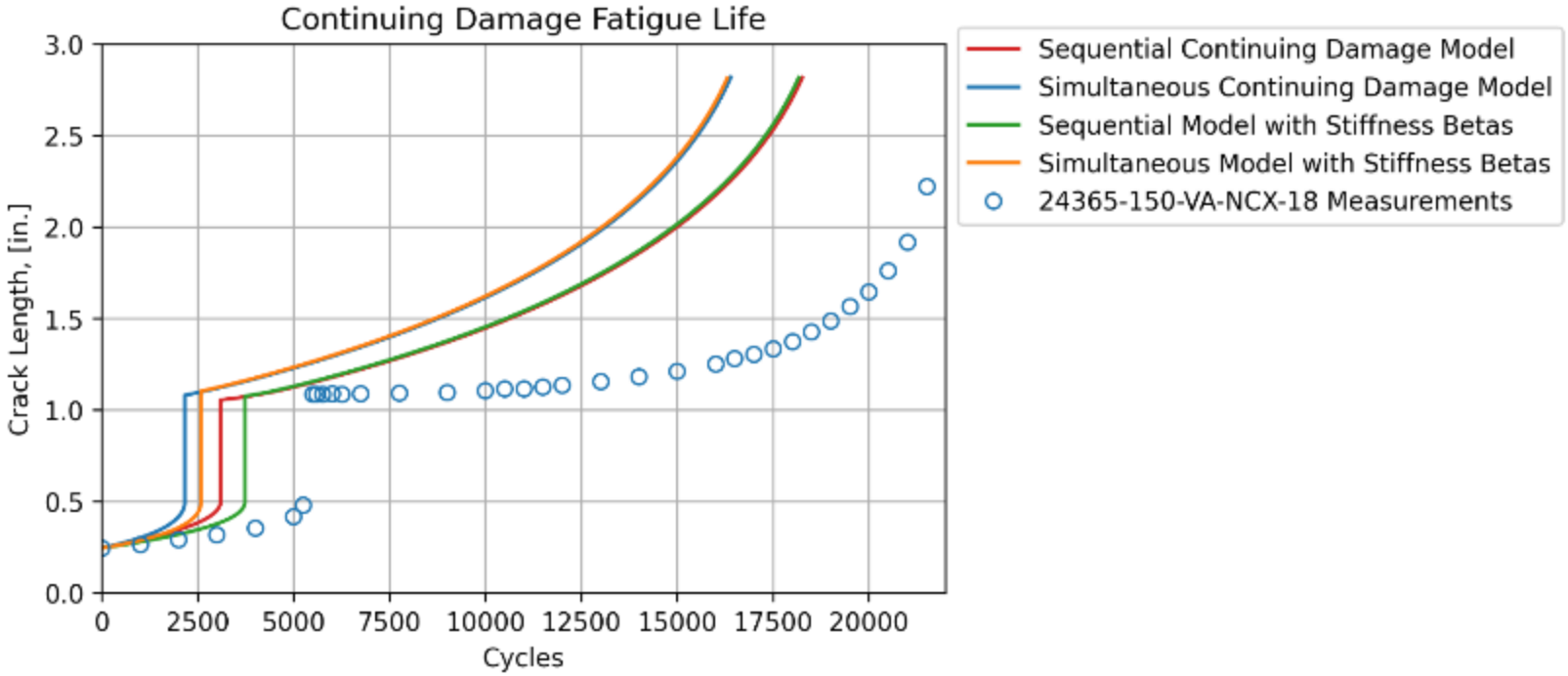
AFLCMC… Providing the Warfighter's Edge

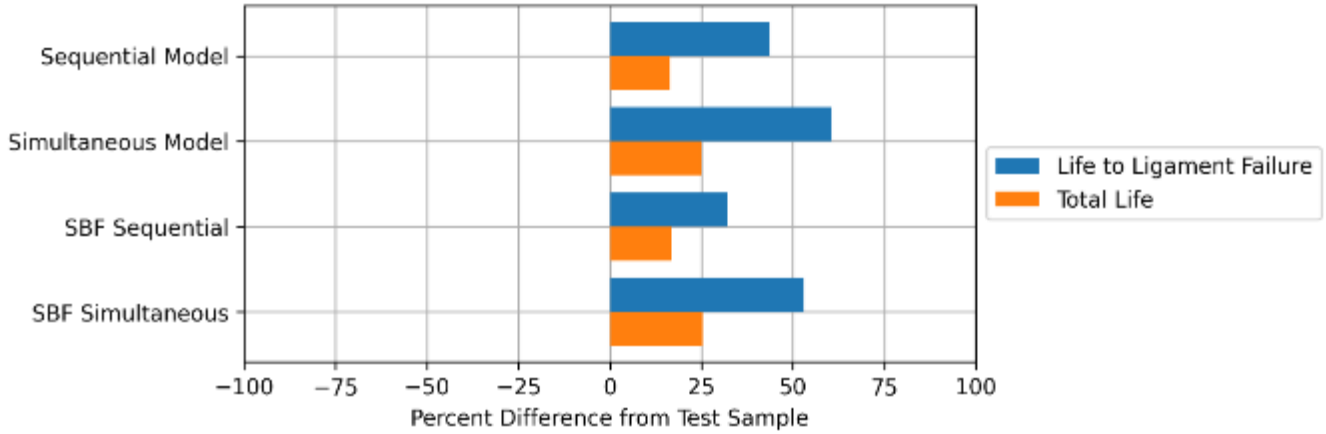




24365-150-VA-NCX-18

AFLCMC… Providing the Warfighter's Edge





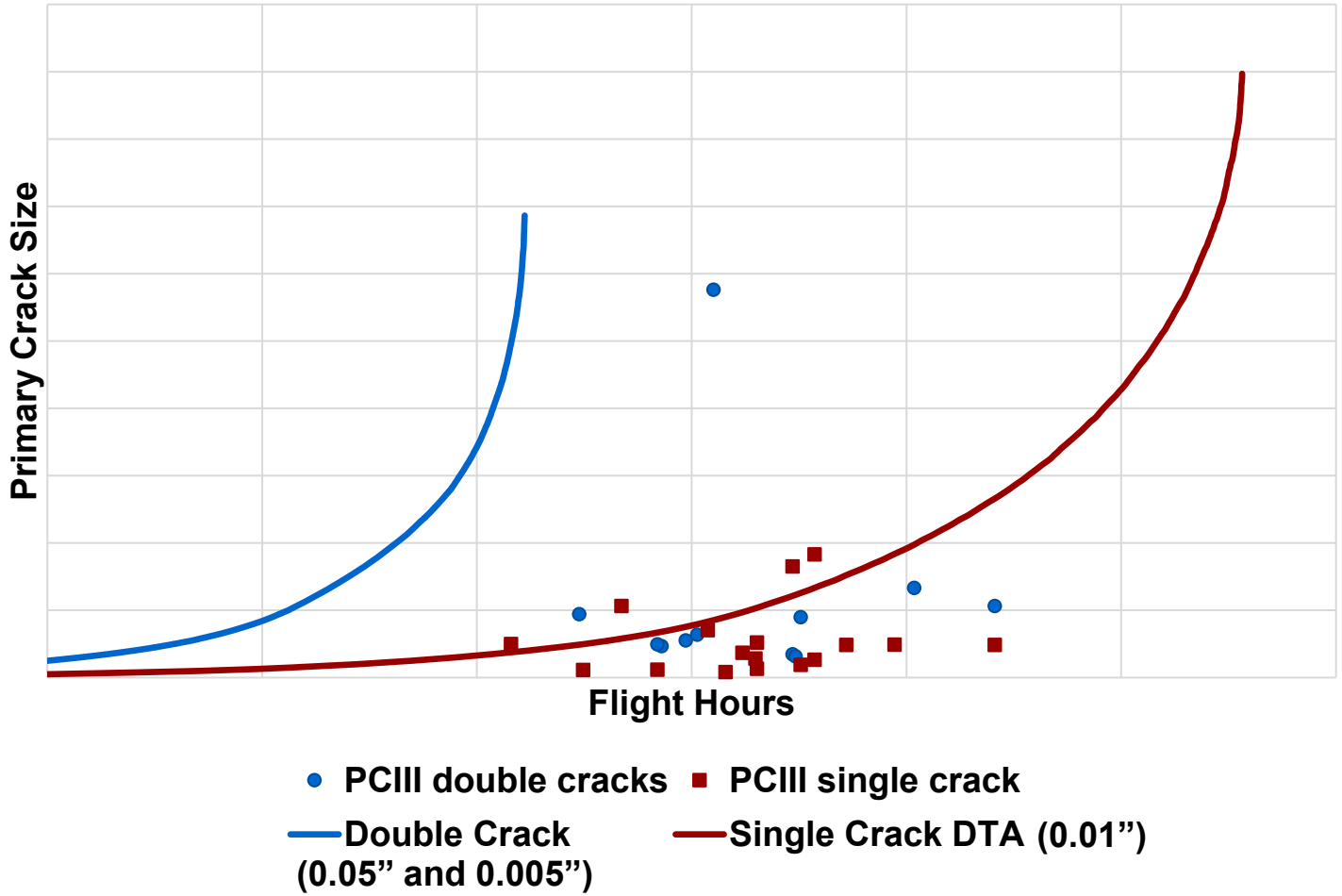
Primary Test Findings

- **Crack size and shape**
  - All failed ligament samples showed semi-elliptical cracks as opposed to the corner cracks embedded in the continuing damage samples
  - Secondary crack lengths in continuing damage (2 starting cracks) samples were consistently much longer than those found in the failed ligament samples
- **Modeling approaches**
  - Sequential model:
    - Slightly unconservative in one tested scenario
  - Simultaneous model:
    - Consistently conservative for both continuing damage and failed ligament samples
    - Needed beta correction to extend life and match test results

T-38 Teardown Data

- **Continuing damage teardown data (cracks from both sides of a single hole)**

Width: 6.61”	TSF = 1, BSF = 0
Thickness: 0.21”	Peak Stress: ~28 ksi
Diameter: 0.265”	Hole Offset: 2.38”



What is Conservative Enough?

- **Notes from Chuck Babish at ERSI:**
  - **“0.05” covers a lot of sins”**
  - **0.05” was “quite rogue, meaning the actual largest equivalent initial crack they (Chuck Tiffany and Jack Lincoln) came up with was nearly 0.03”**
  - **0.005” was originally published in a McDonnel Douglas report**
    - **Crack size distribution was based on teardown of 104 holes, 21 with fractography**
    - **EIFS distribution average ~0.0025”**

Copy number Report number A2883

F4 FATIGUE AND DAMAGE TOLERANCE

ASSESSMENT PROGRAM

VOLUME I

Revision date 30 May 1980 Revision letter A

Issue date 28 June 1974 Contract number AFSC F33657-73-A-0062

Prepared by F-4 Aircraft Structural Integrity Team

MIL-A-83444 (USAF)
2 July 1974

MILITARY SPECIFICATION

AIRPLANE DAMAGE TOLERANCE REQUIREMENTS

This specification is approved for use by all Departments and Agencies of the Department of Defense.

fillets, holes and other potentially high stressed areas. Only one initial flaw in the most critical hole and one initial flaw at a location other than a hole need be assumed to exist in any structural element. Interaction between these assumed initial flaws need not be considered. For multiple and adjacent elements, the initial flaws need not be situated at the same location, (e.g., chordwise plane in wing structure), except for structural elements where

Poor Man's Literature Review

- Renan study:
  - 8% - 20% difference in total life (simultaneous growth is always shorter life)
- NRC study:
  - 23% difference in total life
- Fawaz study:
  - 20% - 250% difference in phase 1 life
- Andrus tests:
  - Naturally occurring secondary cracks (in open holes) are semi-elliptical
  - Naturally occurring secondary cracks are much shorter than what a 0.005" crack becomes by the time ligament failure has occurred
- T-38 teardown data:
  - Simultaneous prediction could be extended ~50% and still catch "rogue flaw"

Summary

- Simultaneous growth:
  - Analytically accurate (validated/verified solutions)
  - More conservative
  - Cracks will interact
- Sequential growth
  - Approach used when assumed initial crack sizes were defined
  - Provides reasonable results (within typical scatter)

- Questions to ask:
  - Is 0.005” the right starting crack size assumption for simultaneous growth analyses?
  - How does hole fill influence these results?
    - Teardown data inherently includes hole fill, analyses done herein do not