ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Analytical Methods & Testing Committee: Overview Presentation

Engineered Residual Stress Implementation (ERSI) Workshop

February 16, 2022

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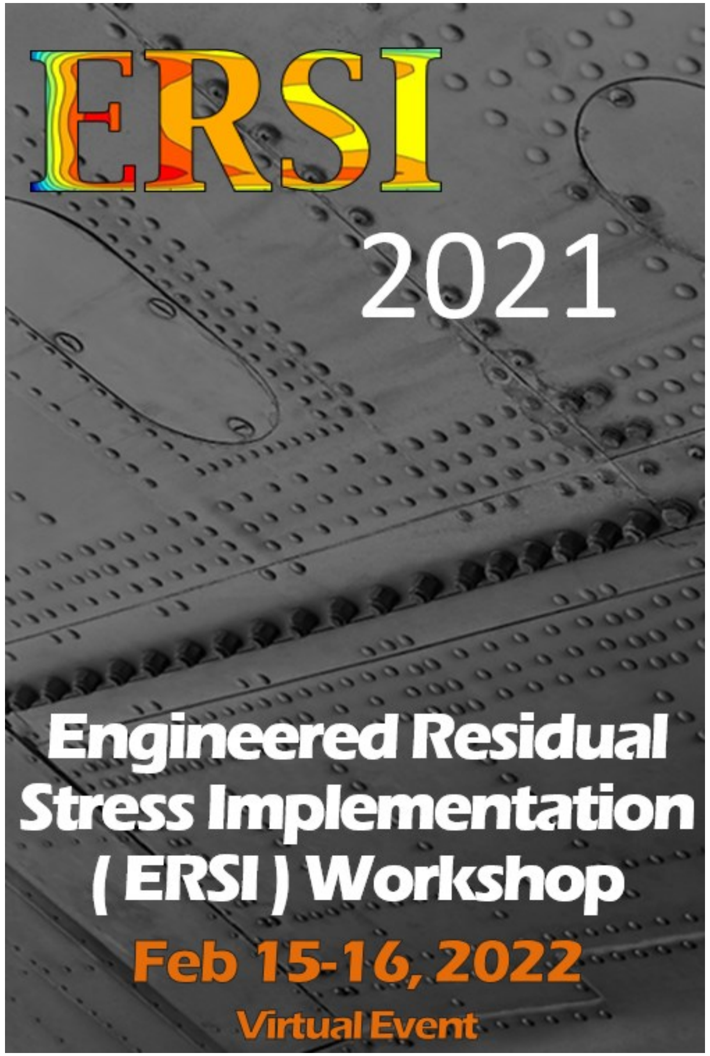
Agenda

- Mission Statement and Goals
- 2021 Achievements
  - Round Robins
    - Interference Fit Fastener Round Robin
    - Stress Intensity Factor Round Robin
    - Overload Challenge
  - Relevant Programs
    - Multi-Point MAI Program
    - Taper-Lok Analysis Methodology & Testing
  - Analysis Methods
    - Two vs. Multi-Point Analysis Comparisons
  - Testing
    - Kt-Free Coupons
- 2022 Focus Areas



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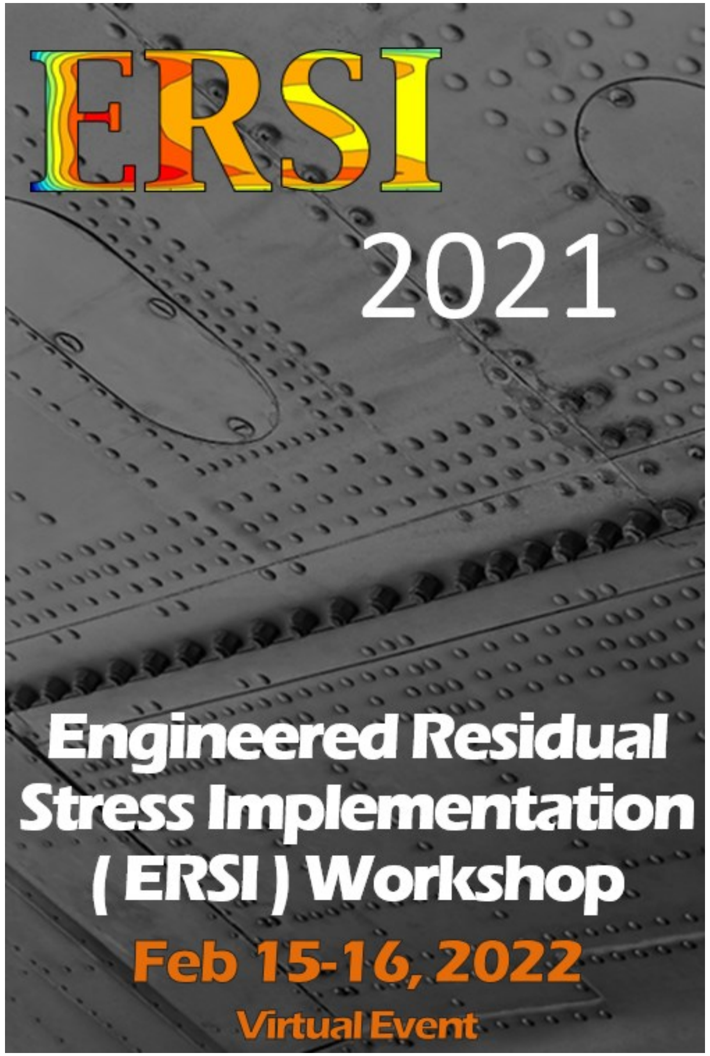

FCG Analysis & Test Committee Vision

- Mission statement:
  - Establish analytical and testing guidelines to support the implementation of engineered residual stresses
- Key objectives:
  - Develop and document best practices for the integration of engineered residual stresses into fatigue crack growth prediction methodologies
  - Establish testing requirements considering the impacts of residual stress on fatigue crack growth
  - Develop datasets and case studies to support analysis methods validation
  - Identify, define, and enable the resolution of gaps in the analytical methods state-of-the-art
  - Support the development of an implementation roadmap

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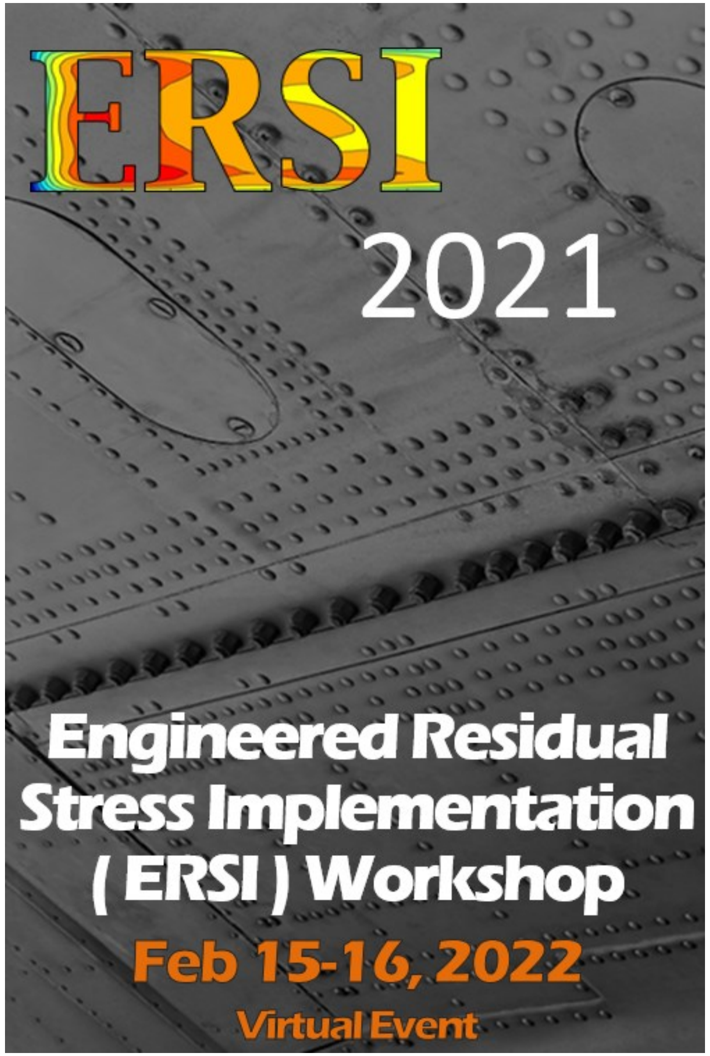
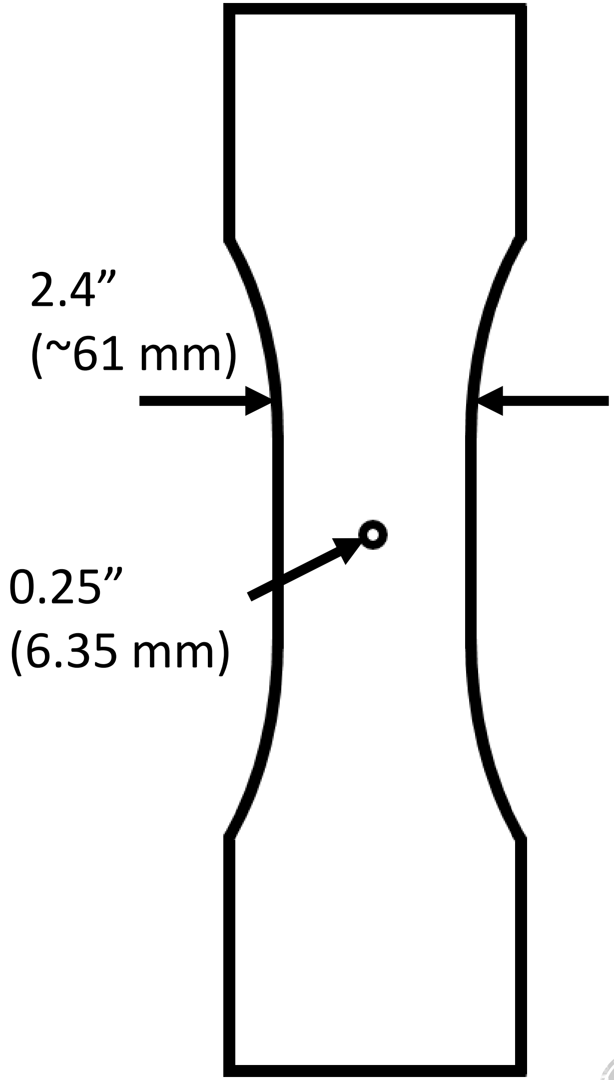


Interference Fastener Round Robin

- <u>Loading & Geometry</u>
  - Constant amplitude, R = 0.1, 27.9 ksi (192.4 Mpa)
  - 7075-T651, 0.25" (6.35 mm) thick
  - 0.027" (~0.69 mm) precrack
  - Hi-Lok (steel) fastener, target 0.4% interference

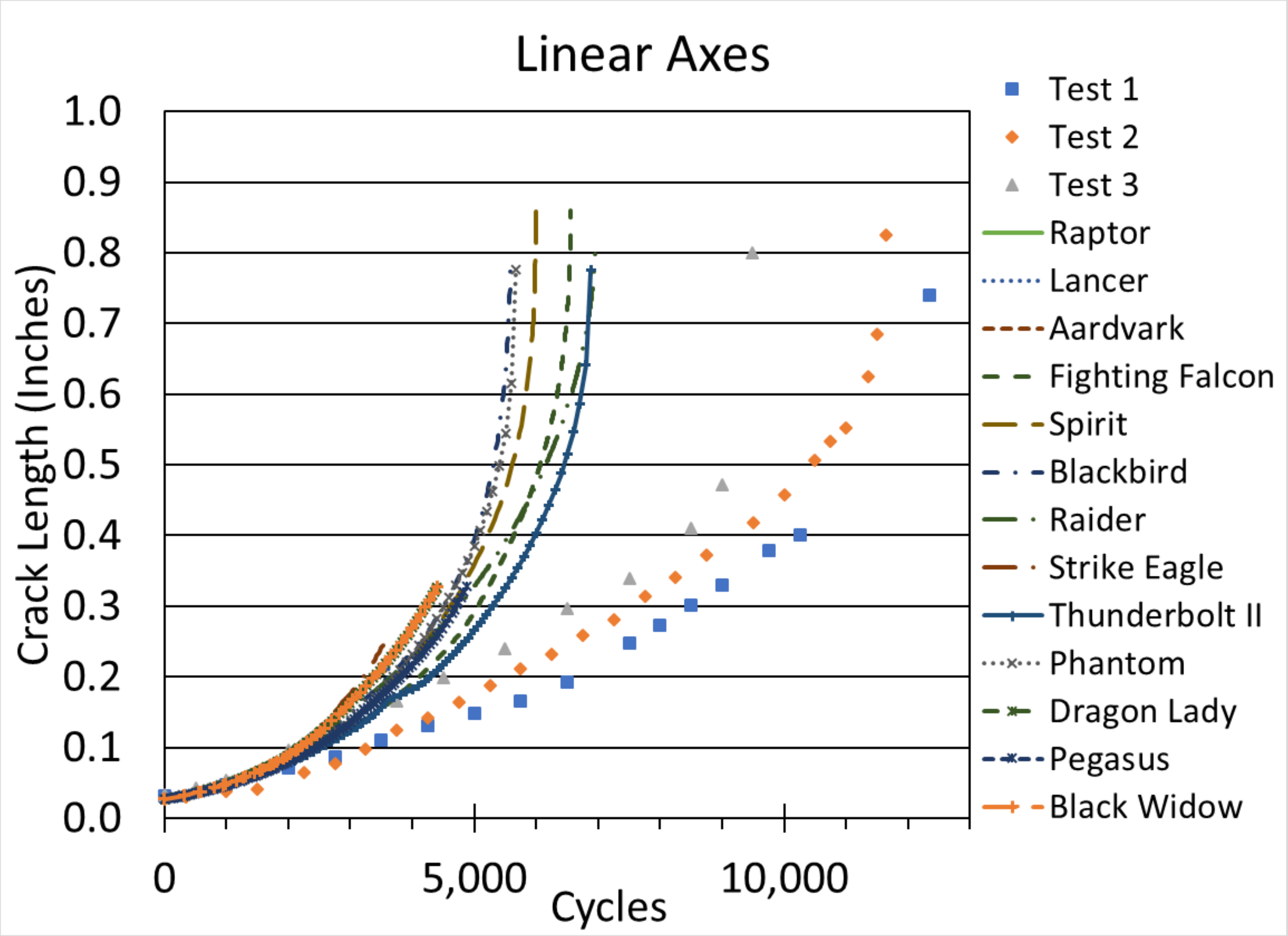
  - Two (2) conditions tested
    - Open hole
    - 0.4% interference Hi-Lok (not torqued)

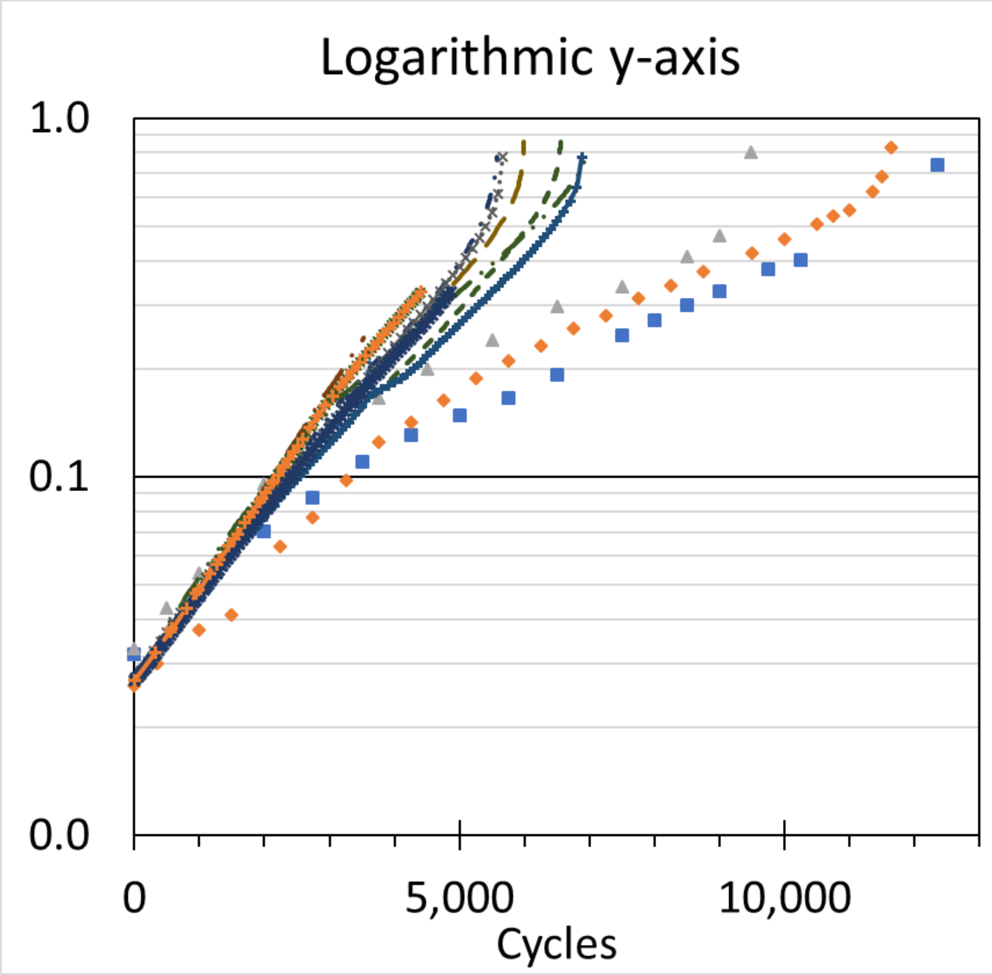
  - Three (3) conditions predicted
    - Open hole
    - 0.4% interference
    - 0.6% interference



Interference Fastener Round Robin

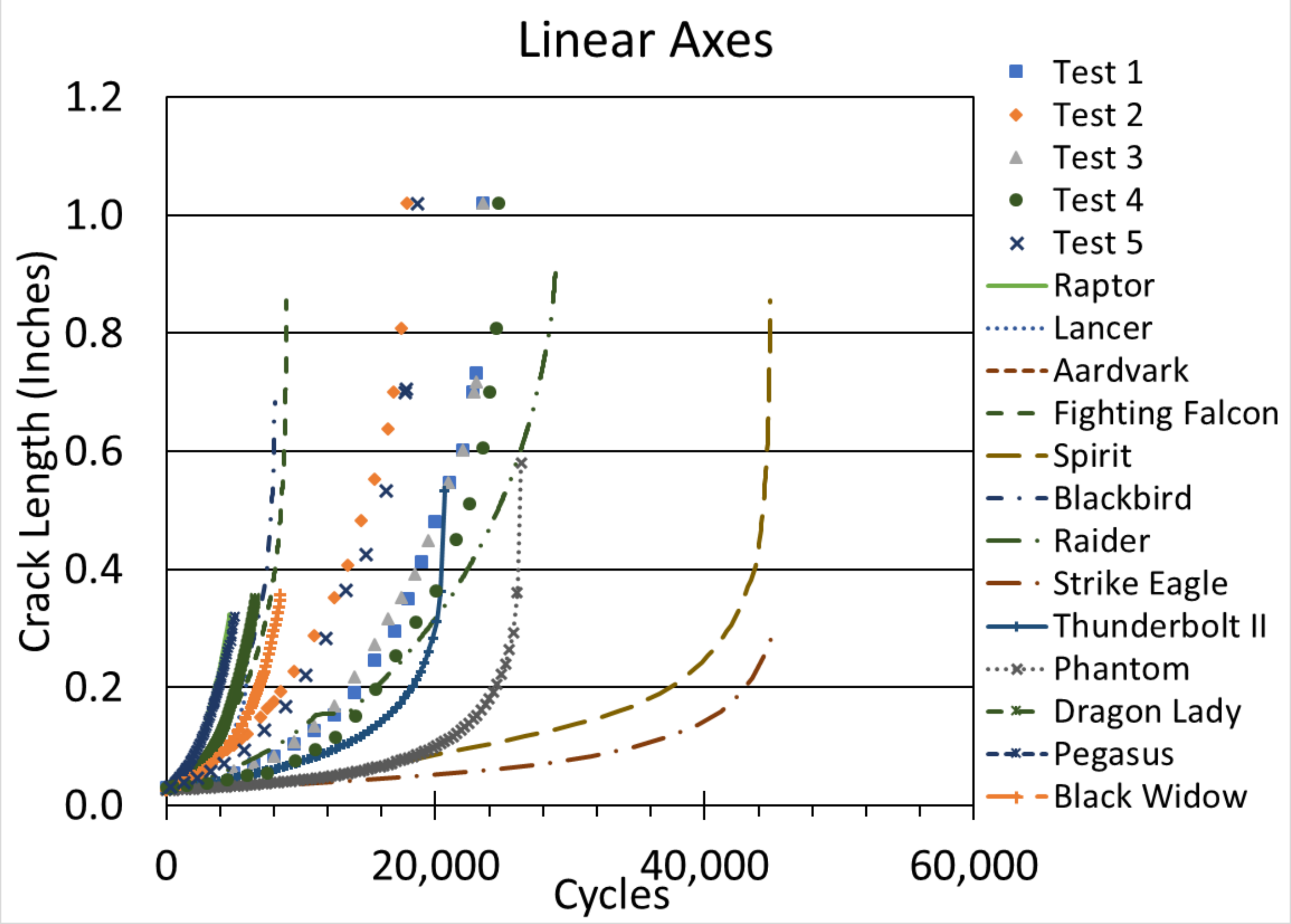
Open Hole Results Surface Crack

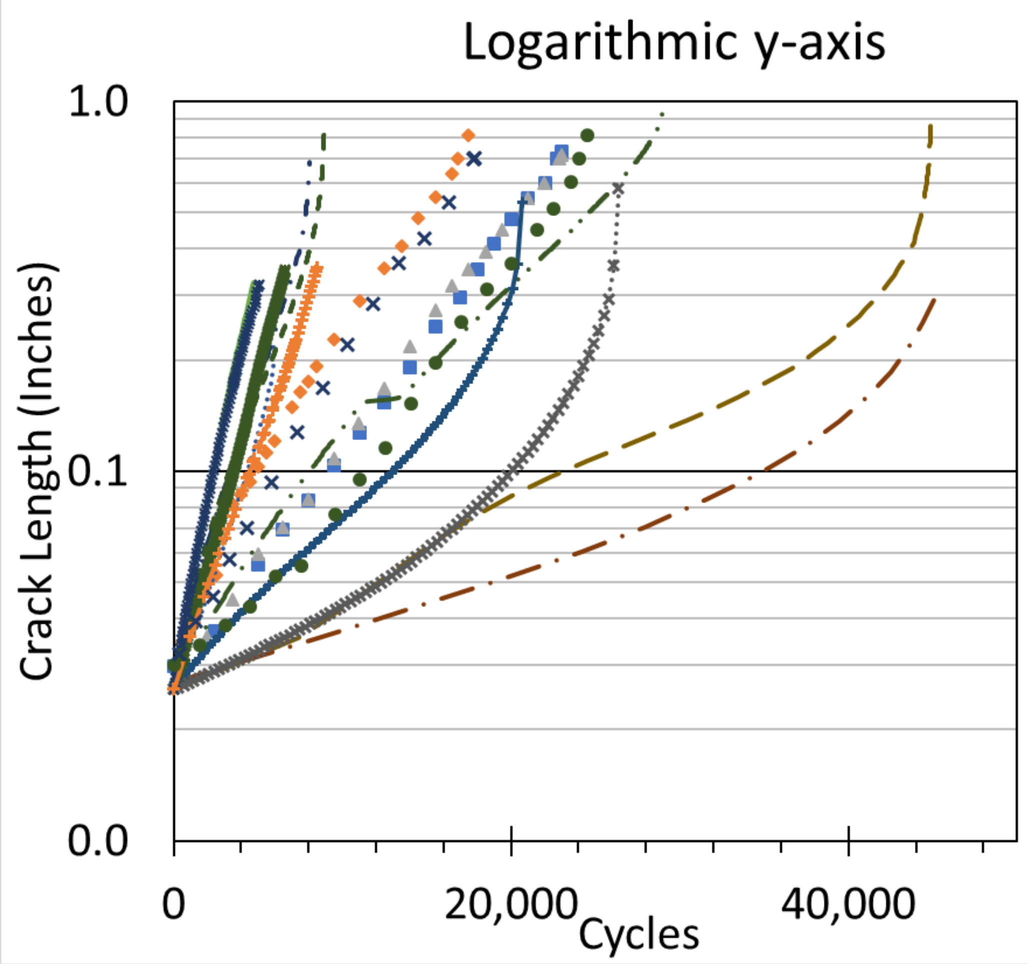




Interference Fastener Round Robin

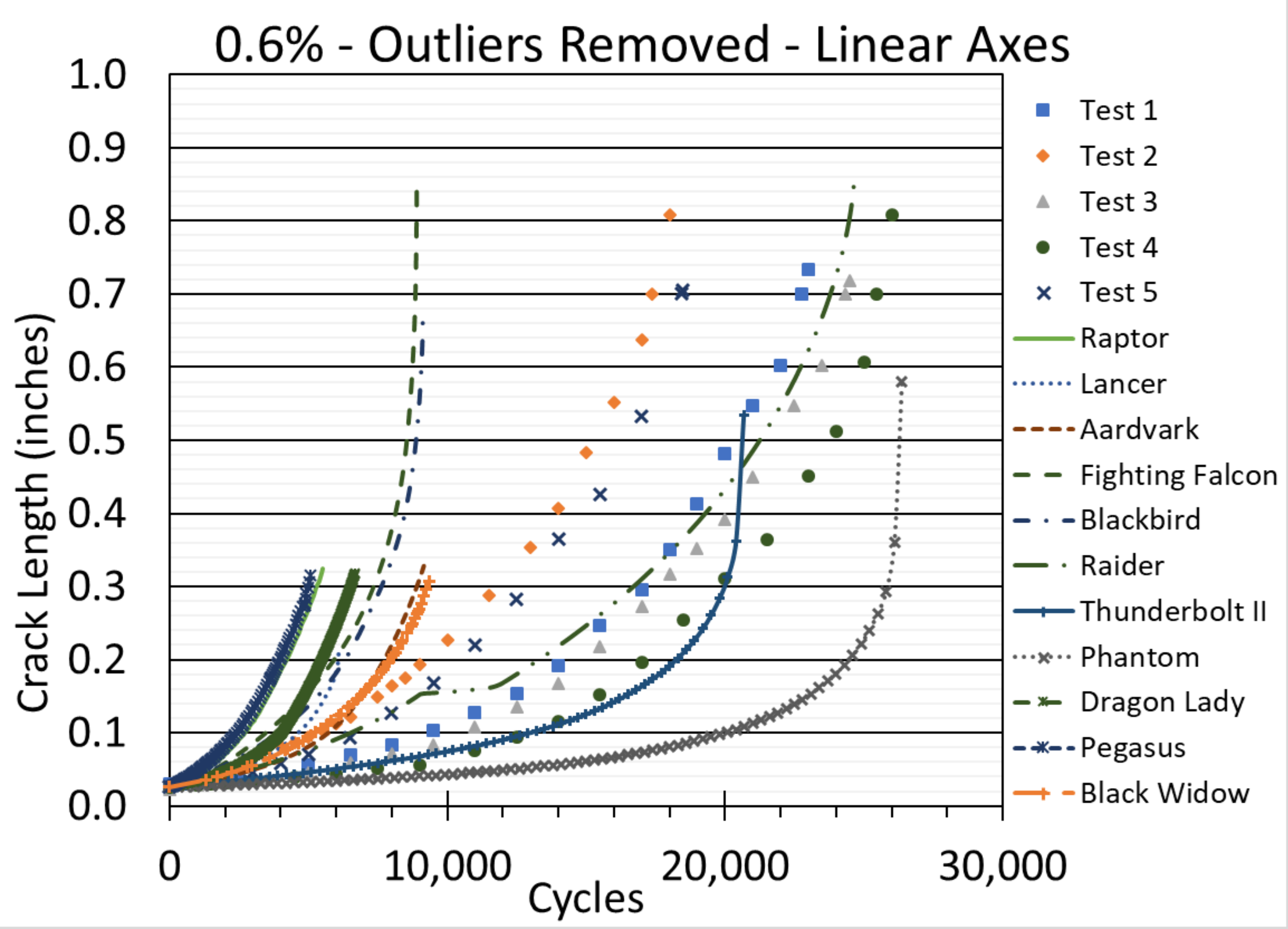
▪ 0.4% Interference - Surface Crack Growth

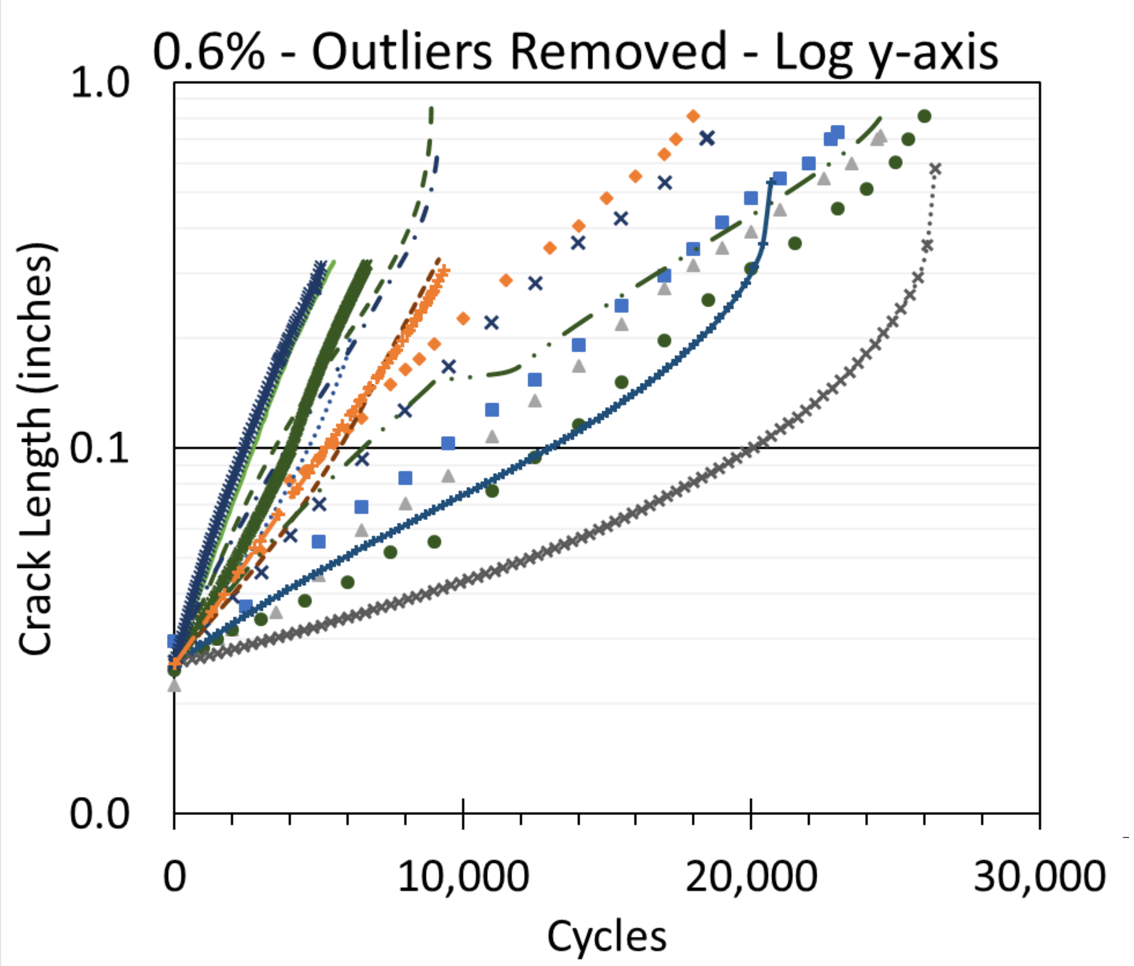




Interference Fastener Round Robin

- 0.6% Interference - Surface Crack Growth





Interference Fastener Round Robin

- Discussion
  - Is good correlation of interference fit cases a function of under predicting the open hole case? i.e. Is the analytical benefit too large and correlation appears good only because the open hole model under predicted?
  - How applicable is the surface correction offered for the open hole case?
  - Would a 27.9 ksi max stress cause plasticity effects that potentially violate the bounds of LEFM for the open hole case?
  - Would it be valuable to add a neat fit fastener condition to this set?

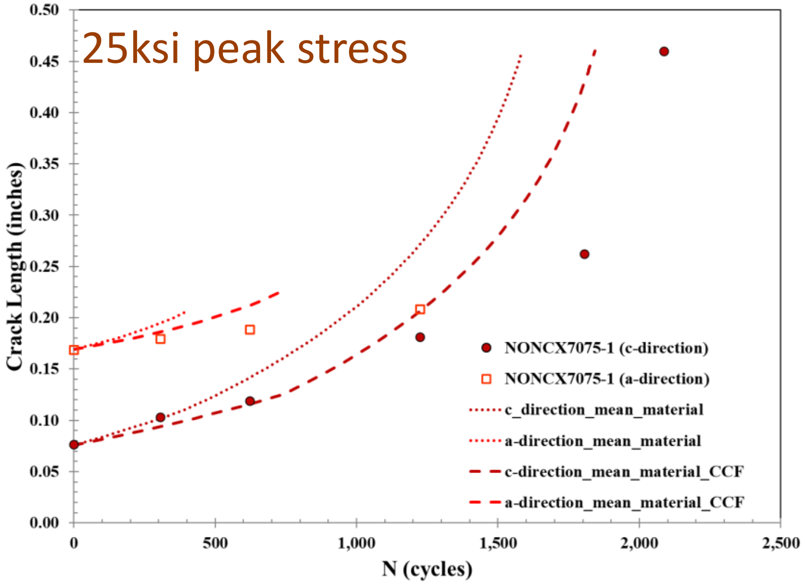
No, really.
Let's talk

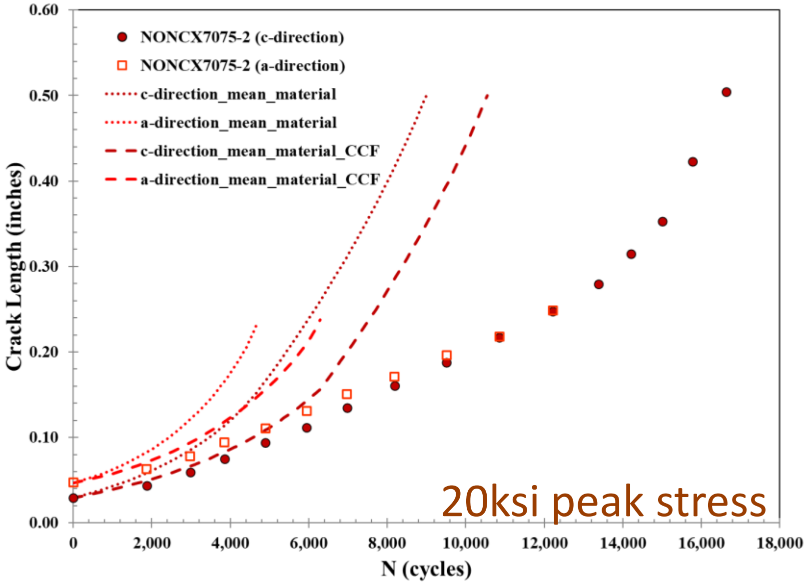
Interference Fastener Round Robin

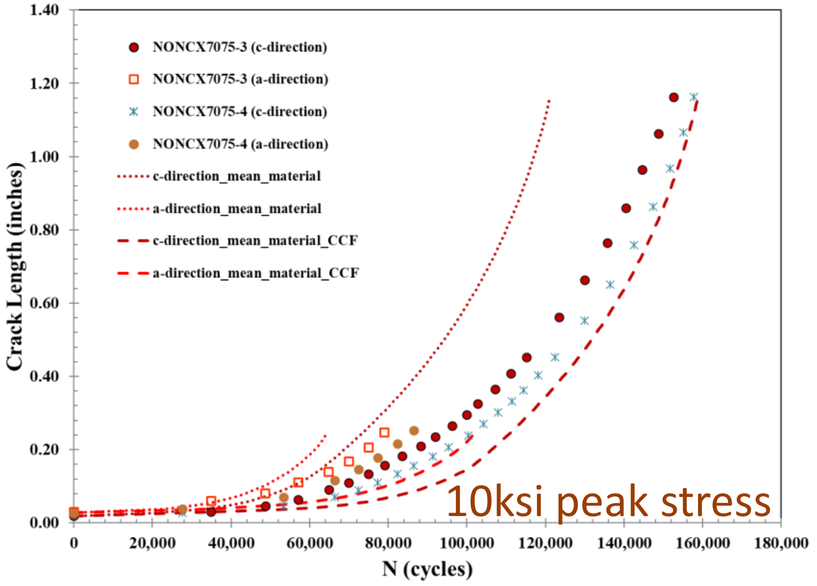
- <u>Initial Conclusions</u>
  - Tight grouping of open hole predictions, although all under predicted test data
  - Surface correction shows promise for open hole condition
  - Effective stress approach used by Raider submission closely matched life and crack growth curve shape
  - Raider approach with provided lookup file and using AFGROW matched one group of tests well with the 0.4% prediction and another set with the 0.6% prediction

Interference Fastener Round Robin

- Follow-Up Investigations
  - Utilized updated crack growth rate data, AFGROW Advanced Model [w Crack Closure Factor (CCF)] and BAMpF with surface correction predictions were completed for another test data set (Pilarczyk Master's Thesis)
  - New "mean" fit to crack growth rate data is still conservative relative to tests
  - AFGROW Advanced Model predictions with CCF improved predicted life
  - BAMpF with surface correction improved predicted life and crack growth shape







Interference Fastener Round Robin

▪ Follow-Up Investigations

Provided data

Specimen Design

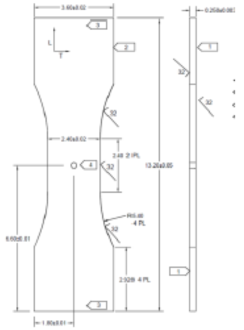
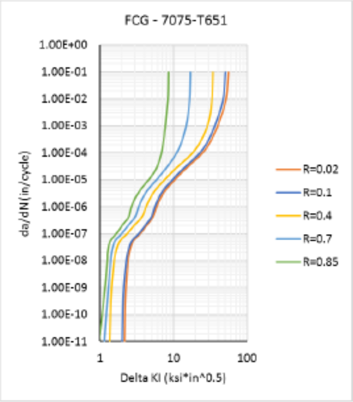


Table 1. Round-robin analysis conditions

Condition	Specimen Type	Hole Diameter (in)	Fastener Diameter (in)	Surface Precrack Length (in)	Bore Precrack Length (in)	Loading	Max Stress (ksi)
1	Open Hole	0.25	N/A	0.027	0.0278	CA (R=0.1)	27.9
2	0.4% IFF	0.2479	0.24885	0.0257	0.042		
3	0.6% IFF	0.2474	0.24885	0.0257	0.042		

Different 3D models were created based on different nominal dimensions

Fatigue Crack Growth Data



Fatigue Crack Growth Rate measurement data: Look-up Table

Experiment: Loading Conditions

R = 0.1
Max Loading = 27.9 ksi gauge section (no hole)
Interference fit values = {0%, 0.4%, 0.6%}

Material Model

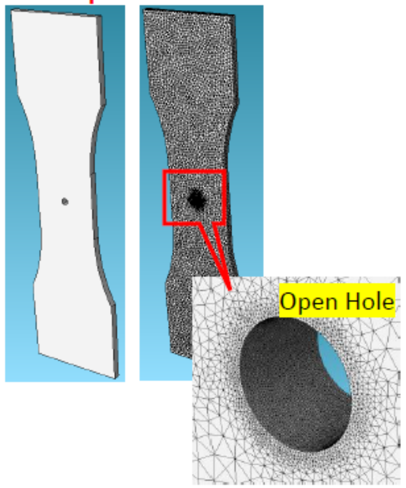
Property	Value
Material	7075-T651 plate
Modulus (ksi)	10400
Poisson	0.33

Same loading conditions and material properties used in the model

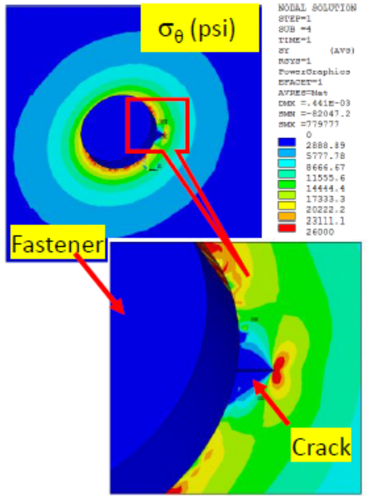
3D FEA Model

Units: psi, inch

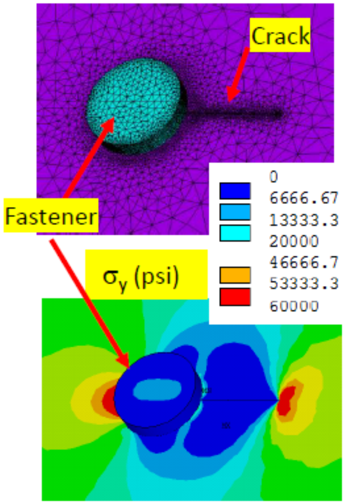
Benchmark #1
Open Hole



Benchmark #2
0.4%



Benchmark #3
0.6%



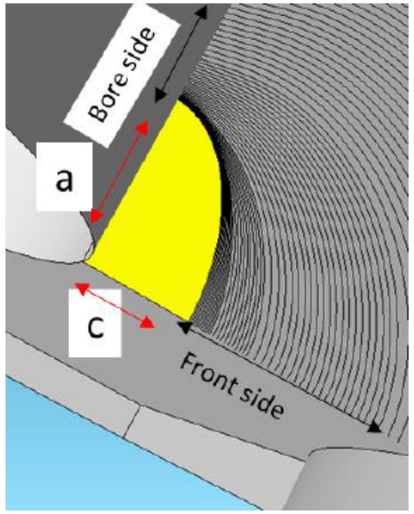
Analysis process:

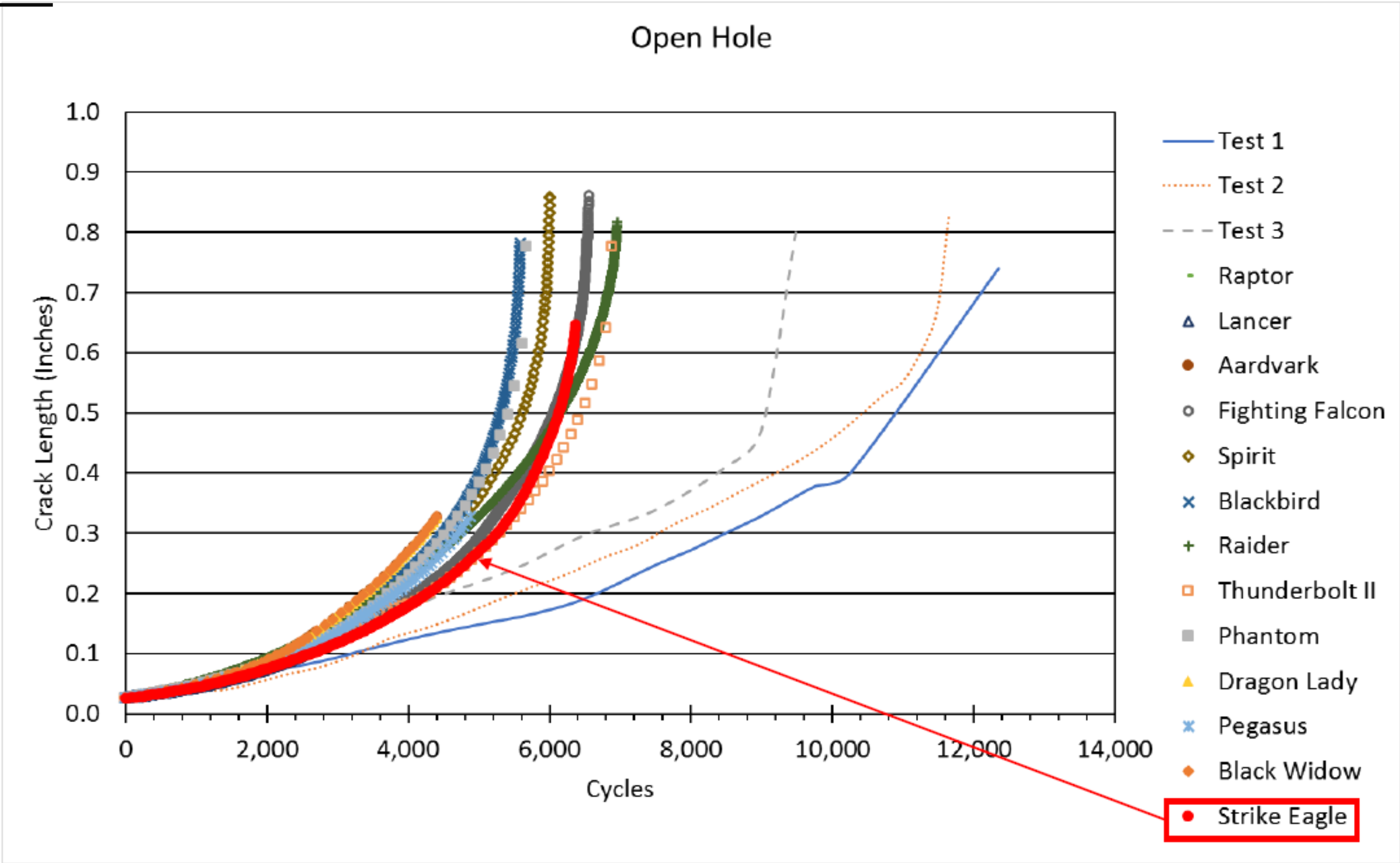
- Similar modeling process is followed for the three cases.
- Explicit crack incrementation; each crack increment has a representative 3D model; the same model setup is used for each simulated crack front.
- Two load steps for the open hole (max load, min load); three load step solution for the interference fit cases (fastener-specimen contact, max load, min load).
- Stress intensity factors computed based on displacement correlation technique. LEFM framework assumed valid.
- da/dN vs. DK table used for integration.
- The same model setup is used for each simulated crack front
- Three KI verification cases presented in the Nov. Tcon and one verification for interference fit stress field

Interference Fit Fastener Prediction Challenge
3D FEA Approach, Adrian Loghin, Simmetrix Inc.

Interference Fastener Round Robin

- Follow-Up Investigations





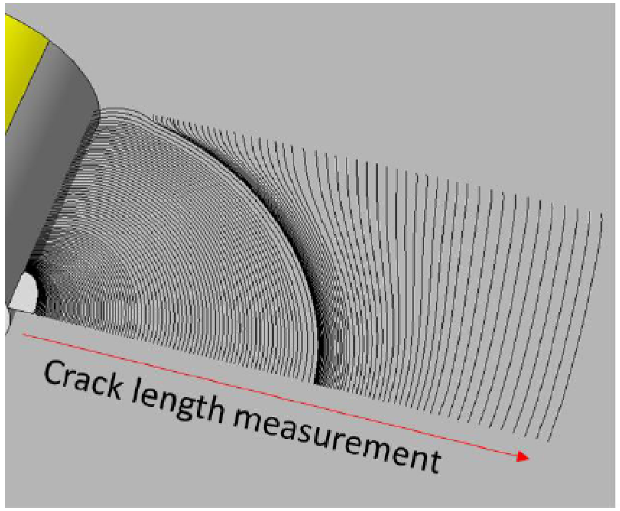
Interference Fit Fastener Prediction Challenge
3D FEA Approach, Adrian Loghin, Simmetrix Inc.

ERSI

My model prediction (red dots) is similar to the other predictions. A large gap between test data and all predictions still needs to be addressed.

Interference Fastener Round Robin

▪ Follow-Up Investigations



All experiments performed at 0.4% IFF

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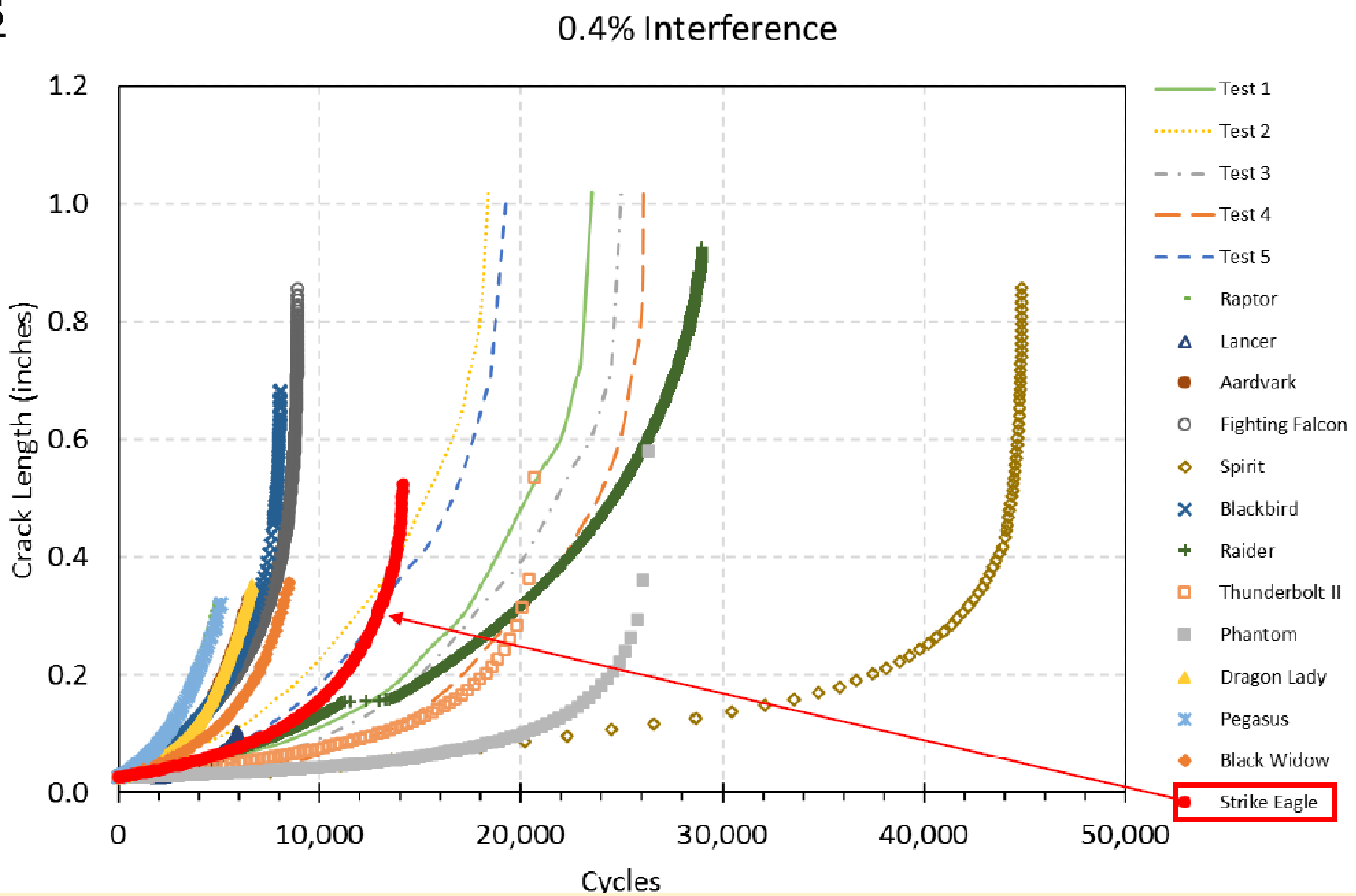
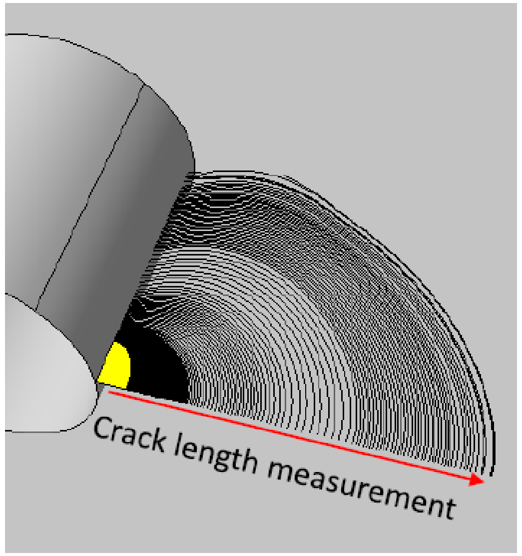


My model prediction (red dots) seems to capture better test data than the other models. One of the reasons could be that the influence of initial IFF is captured explicitly for each crack front increment.

Interference Fastener Round Robin

▪ Follow-Up Investigations



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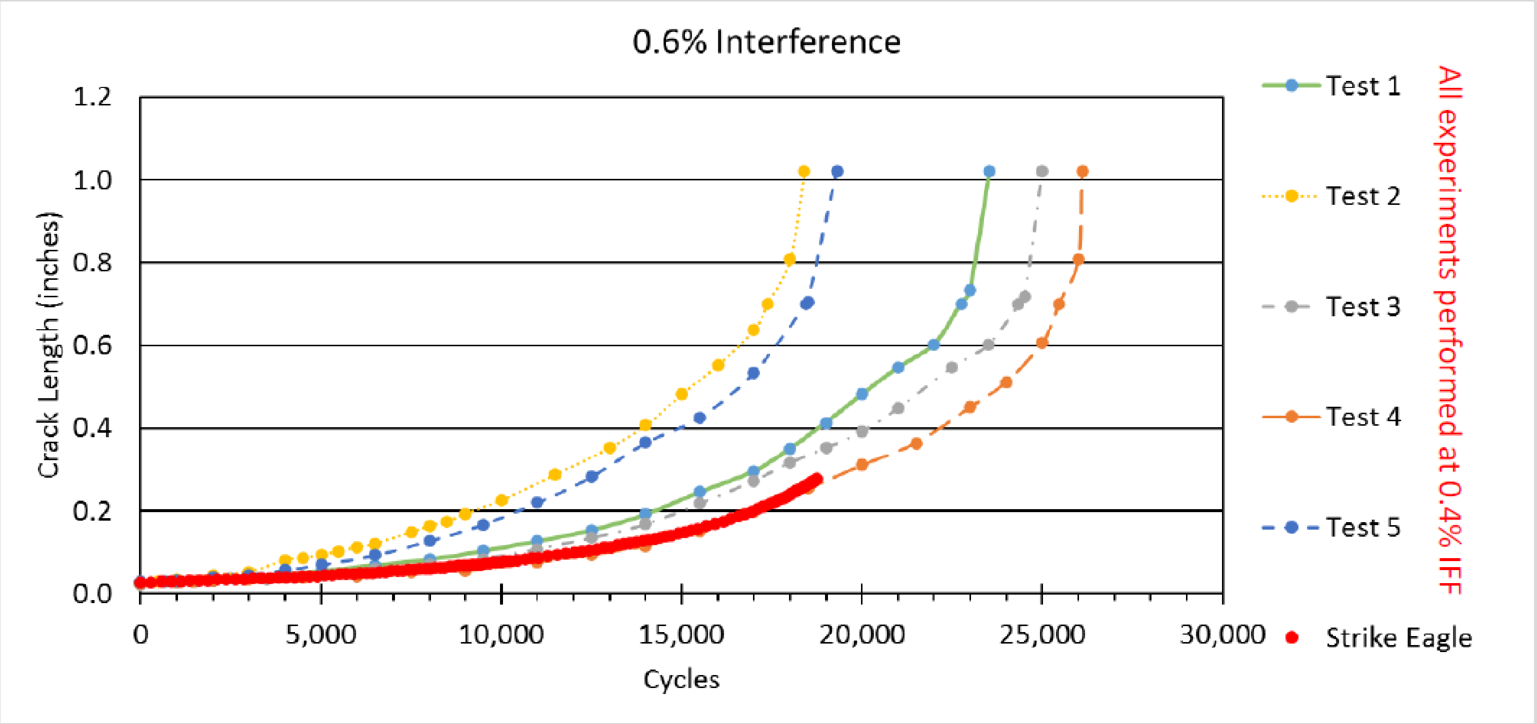


My model prediction for 0.6% IFF follows very closely Test 4 measurement (performed at 0.4% IFF).

Currently I am evaluating sensitivity of prediction relative to interference fit variability along the bore, specimen misalignment in the grip.

Interference Fastener Round Robin

- Future Work
  - Test a 0.6% or other slightly higher interference to understand life impacts
    - Is there an interference level at which greater interference is no longer beneficial?
    - Raider approach predicts shorter life for 0.6% interference than 0.4%
  - Understand applicability of surface correction proposed for open hole
  - Repeat similar effort with a neat fit fastener
  - Develop inspection tools capable of determining interference level of installed fasteners

Stress Intensity Factor Round Robin

- Overview
  - An initial FCG Analysis Methods round robin was completed to quantify the epistemic uncertainties in the prediction of crack growth life, given a fixed set of input data, for baseline and cold expanded (Cx) fastener holes [1,2]
  - During this initial round robin, the prediction sensitivity to the analysis inputs was highlighted with one specific case identifying the influence of error in the Mode I Stress Intensity Factor (K_I) for applied remote loading
    - For several cases, error resulted in no crack growth (ΔK_I lower than $\Delta K_{I,threshold}$)
  - As a result of these findings and subsequent discussions amongst the fatigue crack growth community, a follow-on collaborative round robin was established to investigate differences in stress intensity factors readily available in commercially available software like AFGROW and NASGRO

Stress Intensity Factor Round Robin

- Special thanks to all the participants!!!!
  - Dr. Börje Andersson
    - BARE Research
  - Joseph W. Cardinal
    - Staff Engineer, Structural Engineering Department, Southwest Research Institute
  - Jim Harter
    - Senior Consultant, LexTech Inc.
  - Dr. Adrian Loghin
    - Senior Application Engineer, Simmetrix Inc.
  - Dr. Sebastian Nervi
    - Product Manager, Engineering Software Research and Development (ESRD) Inc
  - Dr. Jim Newman
    - Emeritus Professor, Department of Aerospace, Mississippi State University
  - Dr. Per Nordlund
    - MSC Software Corporation
  - Dr. Kevin Walker
    - QinetiQ Australia

Stress Intensity Factor Round Robin

- Objectives
  - Primary objective of the Stress Intensity Factor (SIF) round robin:

Evaluate differences between available SIF solutions for a single corner crack at a fastener hole with remote uniform tension loading

  - Evaluations included the root SIF solution and any corrections used to account for any additional corrections applied to the solution
    - Single vs multiple cracks, finite width, and hole offset
  - Solutions compared to explicit Finite Element Analysis (FEA) results of each case
  - Findings intended to drive improvements to solutions available to the fracture mechanics community

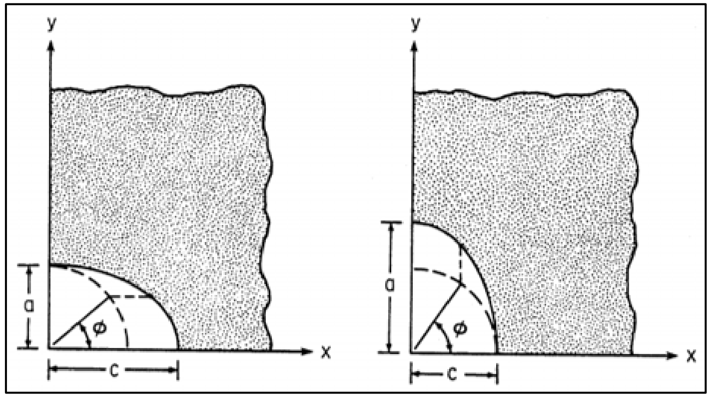
Stress Intensity Factor Round Robin

- Overview
  - Seven different cases of corner cracks at a hole were developed and SIF solutions along the crack front were requested from participants
  - A building block approach was utilized, with Case 1 representing the root SIF solution available
    - Without any corrections for single cracks, finite width, or hole offset, with a crack geometry aspect ratio (a/c) of 1.0
  - Each case added an additional level of complexity with corrections to the root solution as well as variations in the crack aspect ratio

Case #	Configuration
1	Infinite Plate, Double Crack
2	Infinite Plate, Single Crack
3	Finite Plate, Single Crack
4	Finite Plate, Single Crack, Offset Hole
5	Narrow Plate, Single Crack
6	Infinite Plate, Single Crack, a/c=1.5
7	Infinite Plate, Single Crack, a/c=0.5

Stress Intensity Factor Round Robin

- Analysis Inputs
  - Participants reported Mode I SIF versus the parametric angle
    - Minimum of 30 SIF extraction points along the crack front
  - For finite plate configurations (Cases 3-5), L = 3W
  - All cases considered a/c = 1 except:
    - Case 6, which considered a/c = 1.5
    - Case 7, which considered a/c = 0.5



Case #	Surface Crack Length (c) (inches)	Bore Crack Length (a) (inch)	a/c	Crack Configuration	Width (inch)	Thickness (inch)	a/t	Hole Diameter (inch)	W/D	r/t	r/W	Offset (inch)	Loading	Reference Stress (ksi)	Notes
1	0.050	0.050	1.00	Double Symmetric Corner Cracks	100.00	0.25	0.20	0.50	200.00	1.00	0.00	50.00	Tension	10.00	Infinite Plate, Double Crack
2	0.050	0.050	1.00	Single Corner Crack	100.00	0.25	0.20	0.50	200.00	1.00	0.00	50.00	Tension	10.00	Infinite Plate, Single Crack
3	0.050	0.050	1.00	Single Corner Crack	4.00	0.25	0.20	0.50	8.00	1.00	0.06	2.00	Tension	10.00	Finite Plate, Single Crack
4	0.050	0.050	1.00	Single Corner Crack	4.00	0.25	0.20	0.50	8.00	1.00	0.06	0.60	Tension	10.00	Finite Plate, Single Crack, Offset Hole
5	0.050	0.050	1.00	Single Corner Crack	1.20	0.25	0.20	0.50	2.40	1.00	0.21	0.60	Tension	10.00	Narrow Plate, Single Crack
6	0.050	0.075	1.50	Single Corner Crack	100.00	0.25	0.30	0.50	200.00	1.00	0.00	50.00	Tension	10.00	Infinite Plate, Single Crack, a/c=1.5
7	0.100	0.050	0.50	Single Corner Crack	100.00	0.25	0.20	0.50	200.00	1.00	0.00	50.00	Tension	10.00	Infinite Plate, Single Crack, a/c=0.5

Stress Intensity Factor Round Robin

- Submissions Summary
  - Nine submissions were received from eight participants, with solutions utilized by
    - AFGROW
    - NASGRO
    - Newman/Raju
    - Fawaz/Andersson
    - Explicit FEA
  - FEA approaches utilized various tools and methods which provides an additional opportunity to evaluate the different FEA approaches and their impact on the accuracy of the SIF
  - Seven reference solutions which have relative errors in K_I on the order of 0.03% or less were provided by Andersson (Submission 6), and were utilized as the reference solutions for each case evaluated

▪ Submissions Summary

Submission #	Title	SIF solution source	Single Corner Crack Correction (Cases 2, 3, 4, 5, 6, 7)	Finite Width Correction (Cases 3, 4, 5)	Offset Hole Correction (Cases 4, 5)
1	Fawaz-Andersson Solutions, AFGROW	Fawaz-Andersson [3] (as implemented in AFGROW Advanced Model)	n/a	Newman correction [5]	Harter correction [6]
2	Newman-Raju Fit to Fawaz-Andersson	Updated equations by Newman [7] based on fit to Fawaz-Andersson solutions [4]	Shah-Newman Correction (2020) [8]	Tada, Paris and Irwin correction [9]	• center hole (conservative option) • Kt match approach
3	Newman-Raju (1986)	1986 Newman-Raju solution [9]	Shah correction	Newman correction [5]	Kt match approach
4	NASGRO (CC04 & CC02): Newman-Raju	1986 Newman-Raju solution [9] (as implemented in NASGRO CC04)	Shah correction (as implemented in NASGRO CC02)	NASGRO CC02 [12]	NASGRO CC02 [12]
5	NASGRO (CC16): Fawaz-Andersson	Fawaz-Andersson solutions [3] (as implemented in NASGRO CC16)	n/a	Modified version [13] of the Newman correction [5]	Harter correction [6] (as implemented in NASGRO CC16)
6	Andersson: FEA (2021)	Explicitly modeled each condition utilizing the STRIPE FE-software for the hp-version of the finite element method			
7	SimModeler Crack: FEA (2021)	Utilized SimModeler Crack to create 3D FEMs and compute Mode I SIFs via displacement correlation technique			
8	StressCheck: FEA (2021)	Utilized StressCheck to create 3D FEMs and compute Mode I SIFs			
9	MSC Marc: FEA (2021)	Utilized MSC Marc to create 3D FEMs and compute Mode I SIFs			

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6	Infinite Plate, Single Crack, a/c=1.5
7	Infinite Plate, Single Crack, a/c=0.5

- Summary of Results
  - The following slides summarize comparisons for the seven cases evaluated
    - For these comparisons, the Mode I SIF is plotted along the crack front as a function of normalized parametric angle
    - Percent difference relative to Submission 6 from Andersson is also presented

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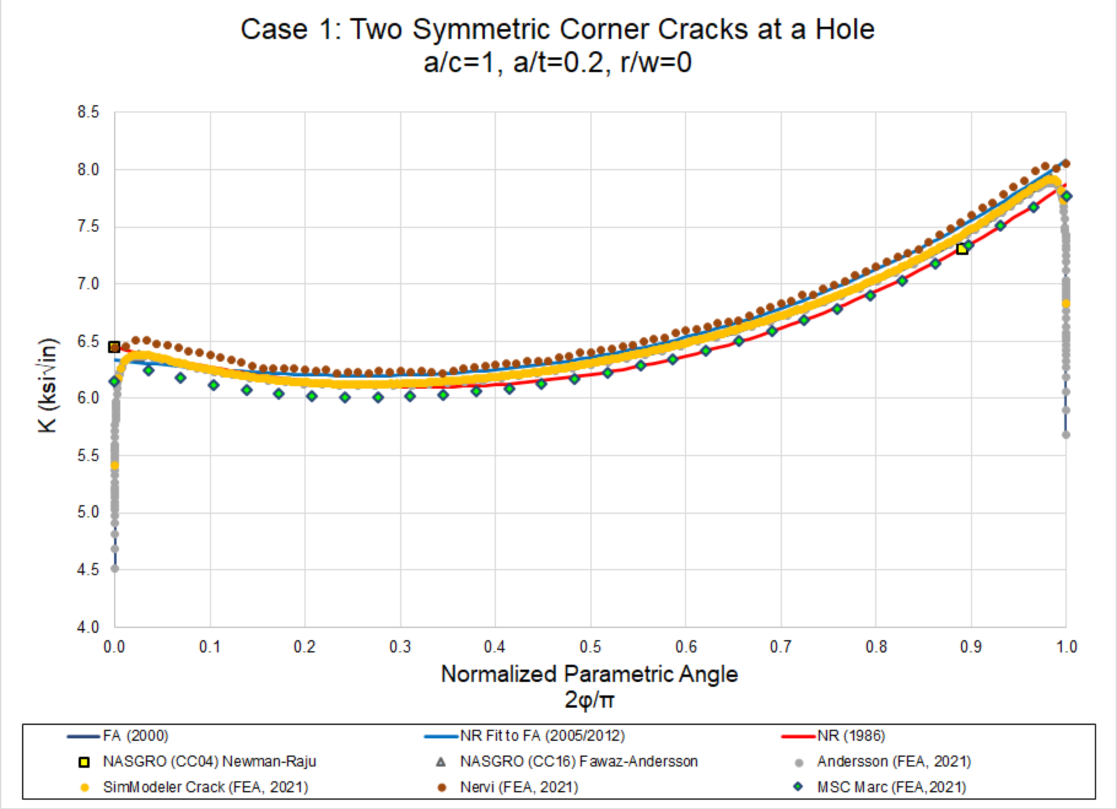
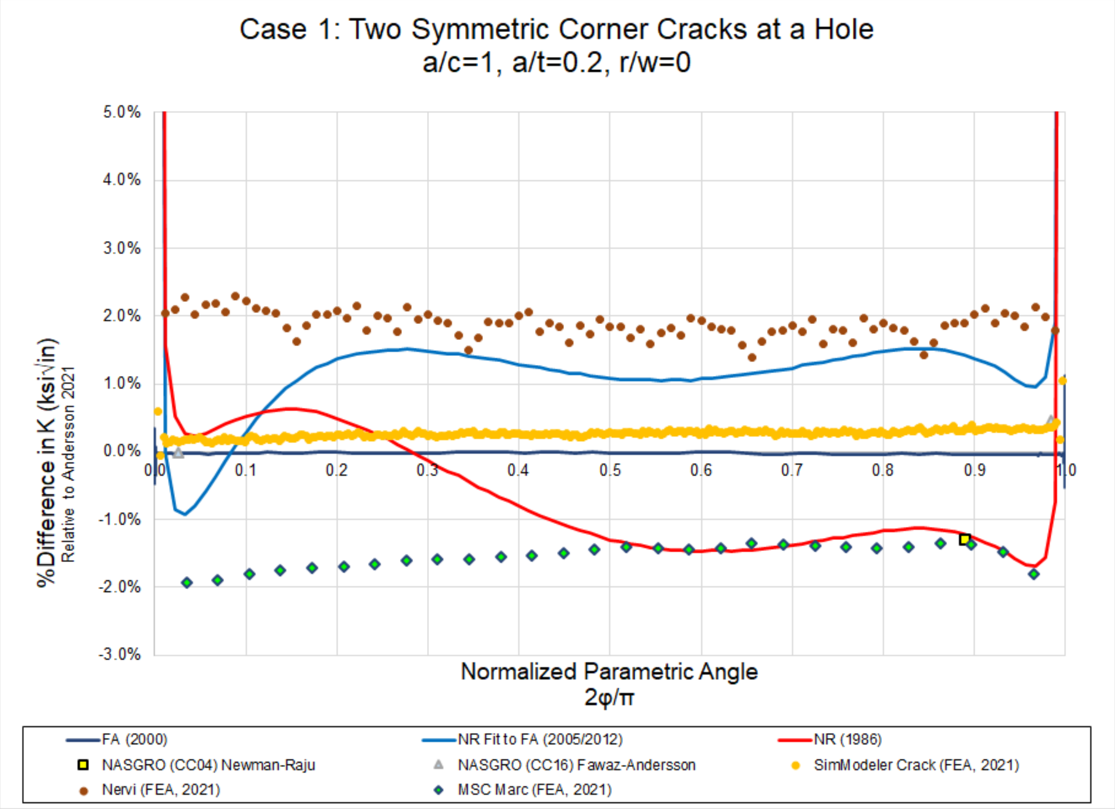
Stress Intensity Factor Round Robin

- Case #1: Two Symmetric Corner Cracks at a Hole, Infinite Plate
  - Initial starting point to evaluate the root SIF solutions
    - For this case, single crack, finite width, and hole offset corrections are not utilized
  - Results within ±2% of Andersson submission, except near surface points

Case #	1
Configuration	Infinite Plate, Double Crack
Crack Configuration	Double Symmetric Corner Cracks
Surface Crack Length (c)	0.050
Bore Crack Length (a)	0.050
Width	100.00
Thickness	0.25
Hole Diameter	0.50
Hole Offset	50.00
a/c	1.00
a/t	0.20
W/D	200.00
r/t	1.00
r/W	0.00



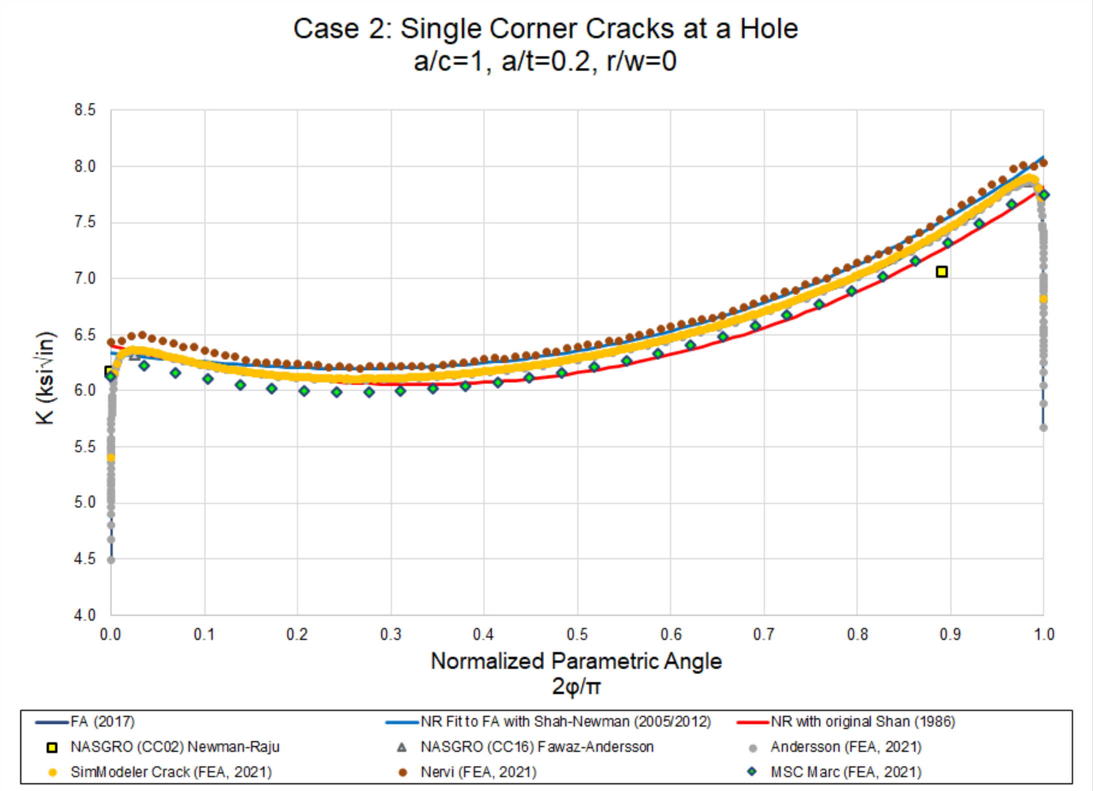


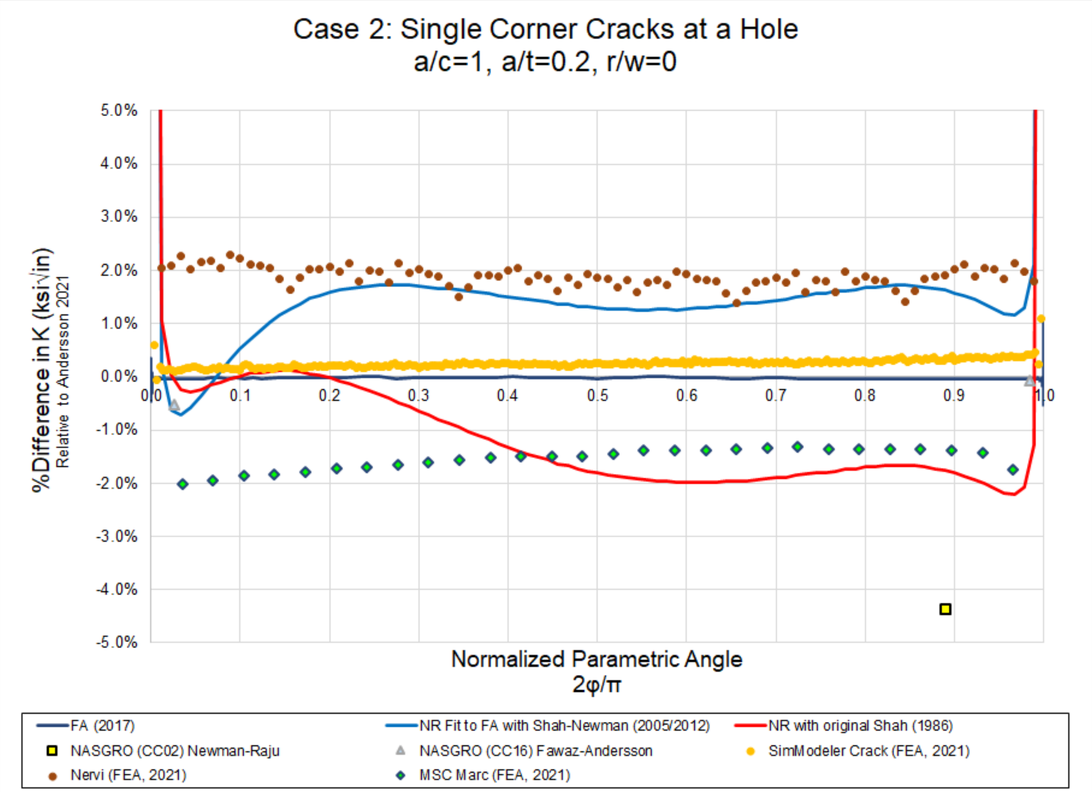
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Stress Intensity Factor Round Robin

- Case #2: Single Corner Crack at a Hole, Infinite Plate
  - Continuation from Case #1, incorporating effects of a single corner crack
    - Submissions 2-4 utilize Shah or Shah/Newman corrections to adjust from double corner crack to single crack
    - Submissions 1 & 5 utilized single crack modeling in development of root SIF solution
  - Results generally within ±2% of Andersson submission, except near surface points
    - Submission 4 (NASGRO CC02) differences exceeded 4% for point representative of hole bore

Case #	2
Configuration	Infinite Plate, Single Crack
Crack Configuration	Single Corner Crack
Surface Crack Length (c)	0.050
Bore Crack Length (a)	0.050
Width	100.00
Thickness	0.25
Hole Diameter	0.50
Hole Offset	50.00
a/c	1.00
a/t	0.20
W/D	200.00
r/t	1.00
r/W	0.00



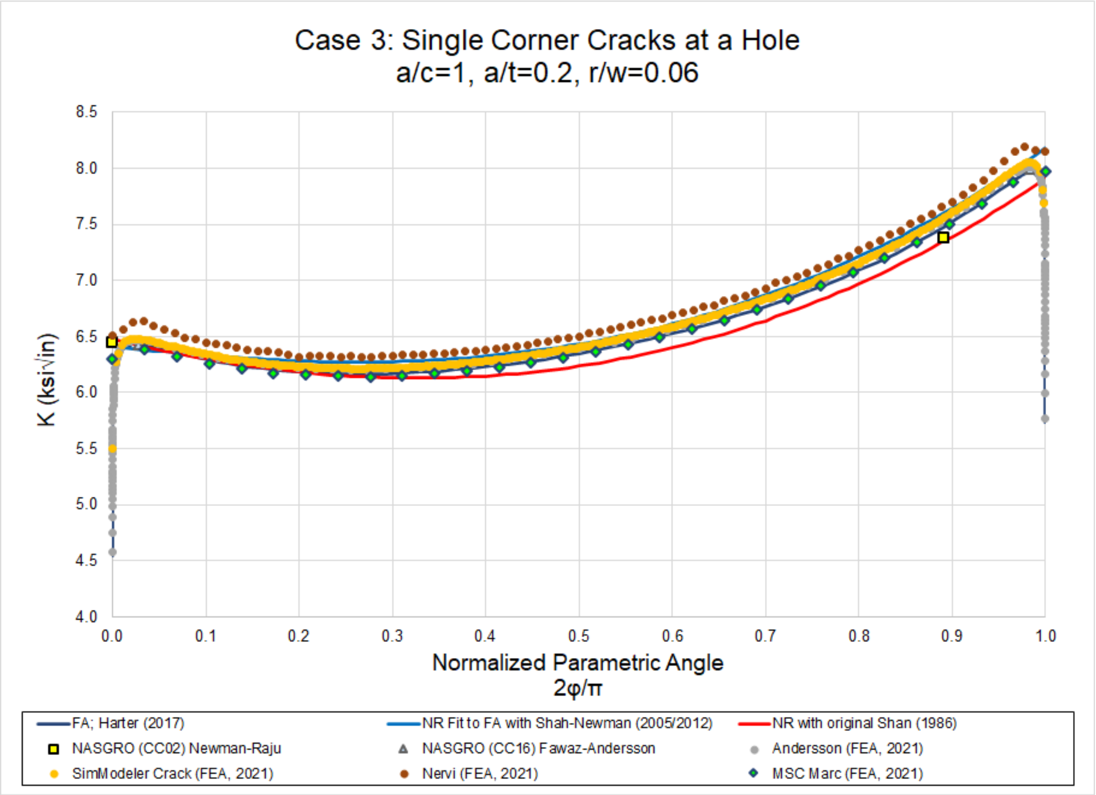


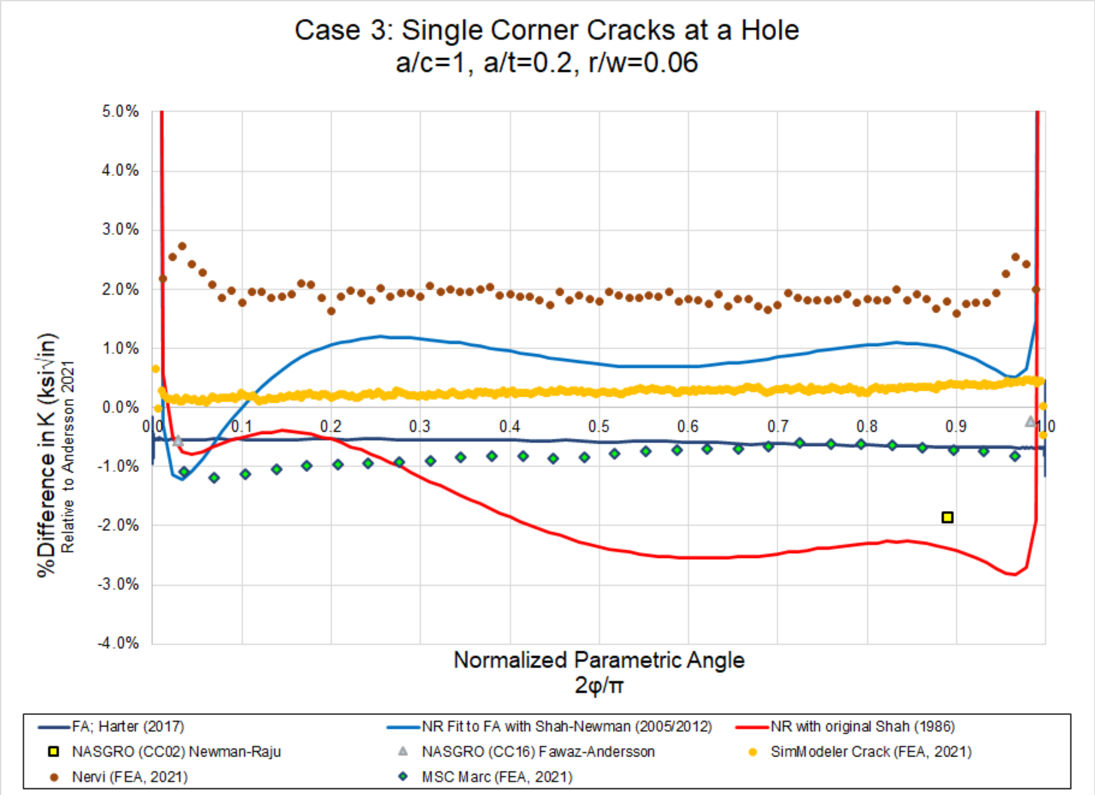
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Stress Intensity Factor Round Robin

- Case #3: Single Corner Crack at a Hole, Finite Plate
  - Continuation from Cases 1-2, incorporating finite width effects
    - Submissions 1-3 utilized the Newman finite width correction. Submission 4 used the correction from [12] and Submission 5 used the correction from [13]
  - Results generally within ±2% of Andersson submission, except near surface points
    - Submission 3 (Newman-Raju 1986) differences exceeded 2% over a range of 0.4-1.0 normalized parametric angle, representative of crack front near the hole bore

Case #	3
Configuration	Finite Plate, Single Crack
Crack Configuration	Single Corner Crack
Surface Crack Length (c)	0.050
Bore Crack Length (a)	0.050
Width	4.00
Thickness	0.25
Hole Diameter	0.50
Hole Offset	2.00
a/c	1.00
a/t	0.20
W/D	8.00
r/t	1.00
r/W	0.06



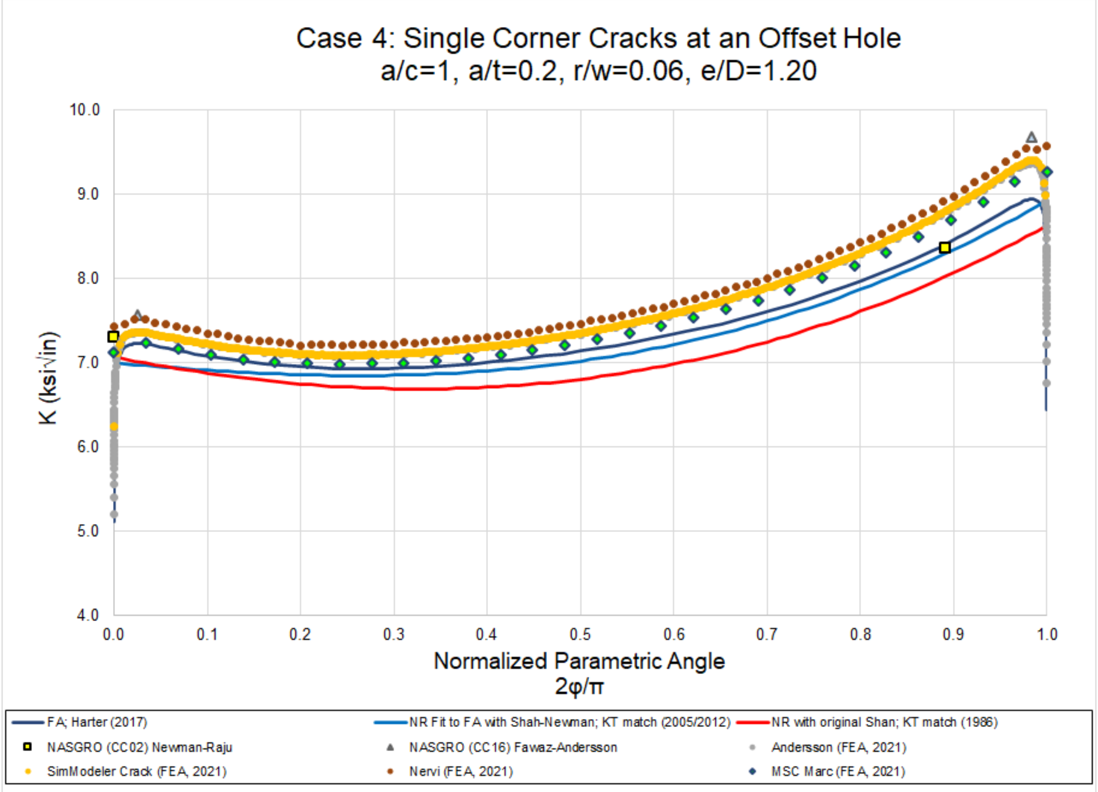


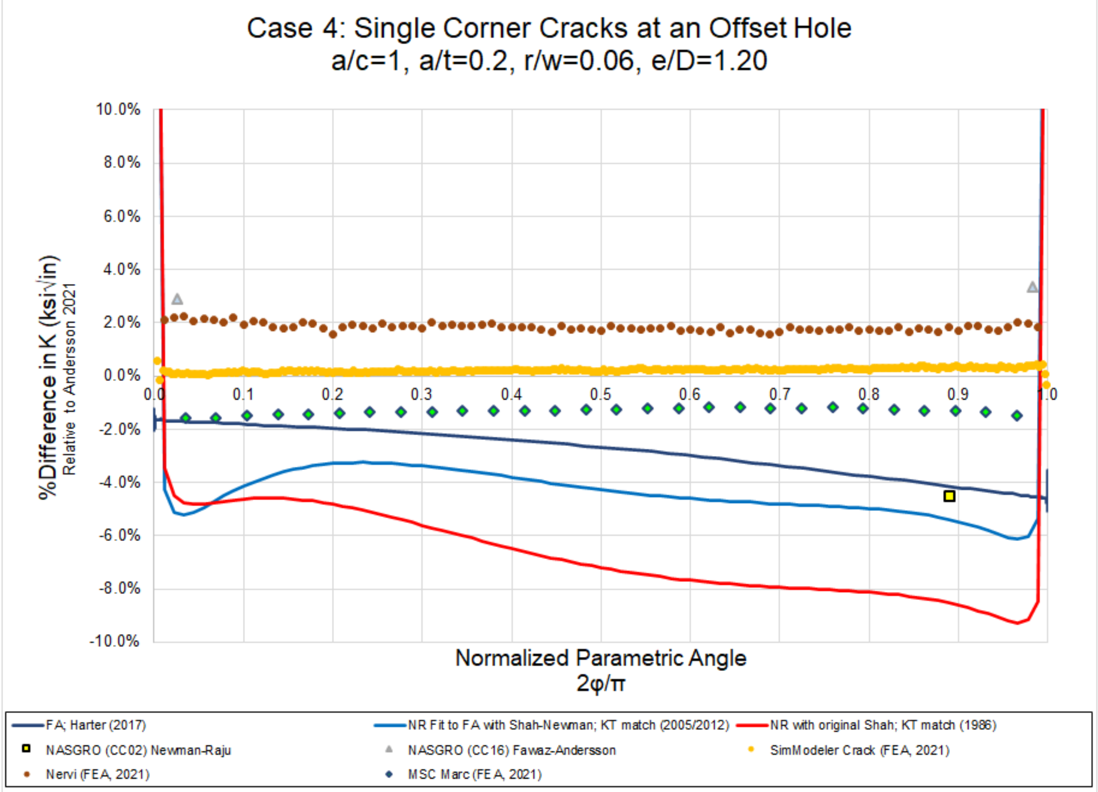
ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Stress Intensity Factor Round Robin

- Case #4: Single Corner Cracks at a Hole, Finite Plate, Offset Hole
  - Continuation from Cases 1-3, incorporating hole offset effects
    - Submission 1 utilized the Harter offset correction
    - Submission 2-3 investigated two approaches to characterize the short offset, however, the Kt match approach was utilized for comparison
    - Submission 4 used the correction from [12] and Submission 5 used the correction from [13]
  - Significant differences (nearly 10% relative to Andersson submission) observed for Submissions 1-4

Case #	4
Configuration	Finite Plate, Single Crack, Offset Hole
Crack Configuration	Single Corner Crack
Surface Crack Length (c)	0.050
Bore Crack Length (a)	0.050
Width	4.00
Thickness	0.25
Hole Diameter	0.50
Hole Offset	0.60
a/c	1.00
a/t	0.20
W/D	8.00
r/t	1.00
r/W	0.06

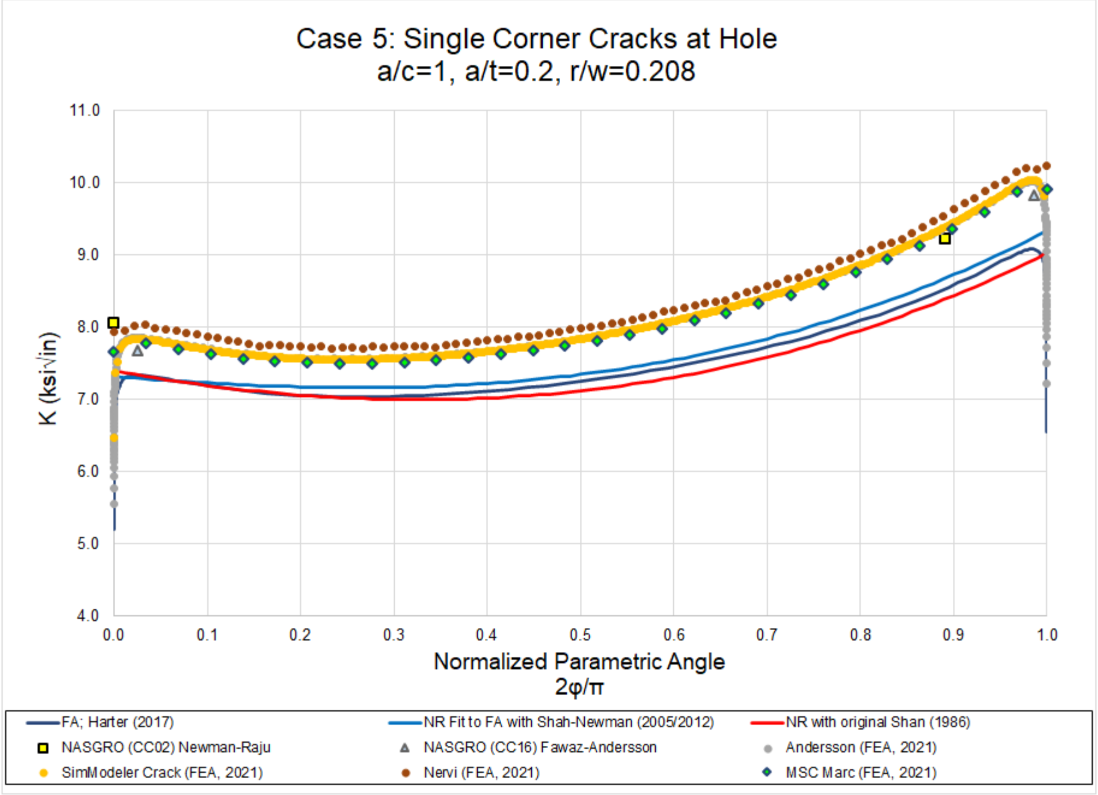


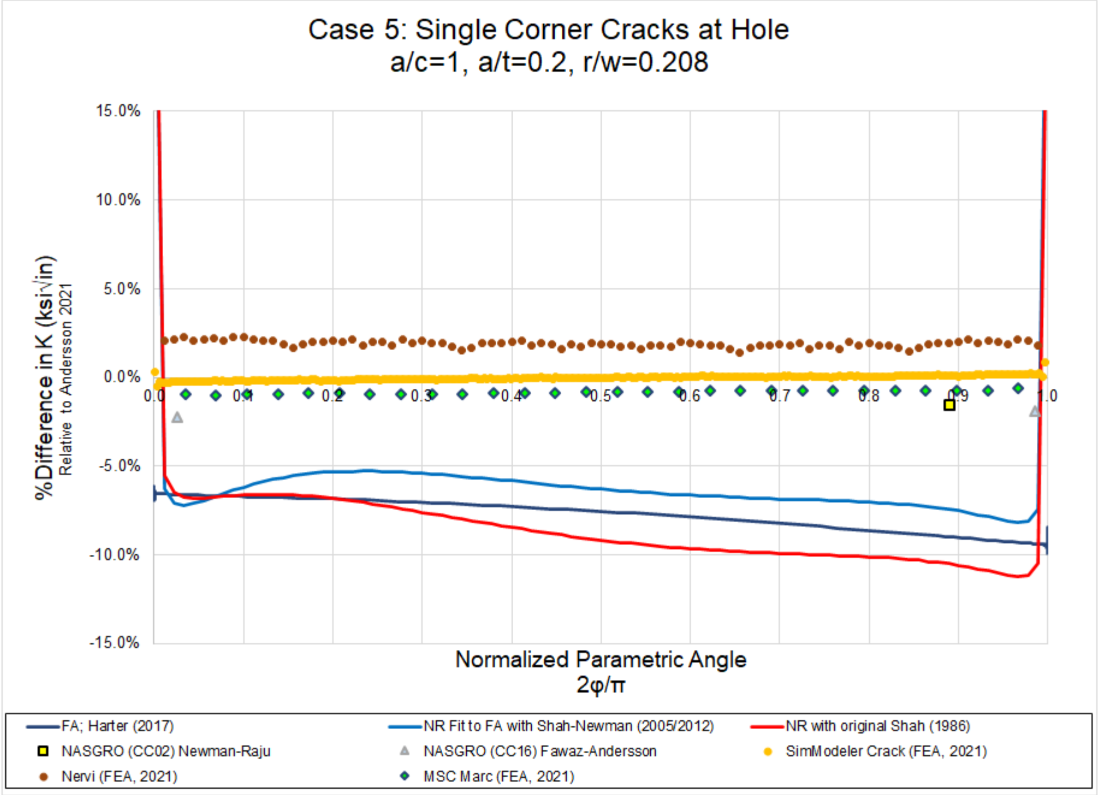


Stress Intensity Factor Round Robin

- Case #5: Single Corner Crack at a Hole, Narrow Plate
  - Continuation from previous cases, but for relatively "narrow" width
    - Submissions 1-3 utilized the Newman finite width correction
    - Submission 4 used the correction from [12] and Submission 5 used the correction from [13]
  - Significant differences (5-12% relative to Andersson submission) observed for Submissions 1-3, which utilized Newman finite width correction

Case #	5
Configuration	Narrow Plate, Single Crack
Crack Configuration	Single Corner Crack
Surface Crack Length (c)	0.050
Bore Crack Length (a)	0.050
Width	1.20
Thickness	0.25
Hole Diameter	0.50
Hole Offset	0.60
a/c	1.00
a/t	0.20
W/D	2.40
r/t	1.00
r/W	0.21

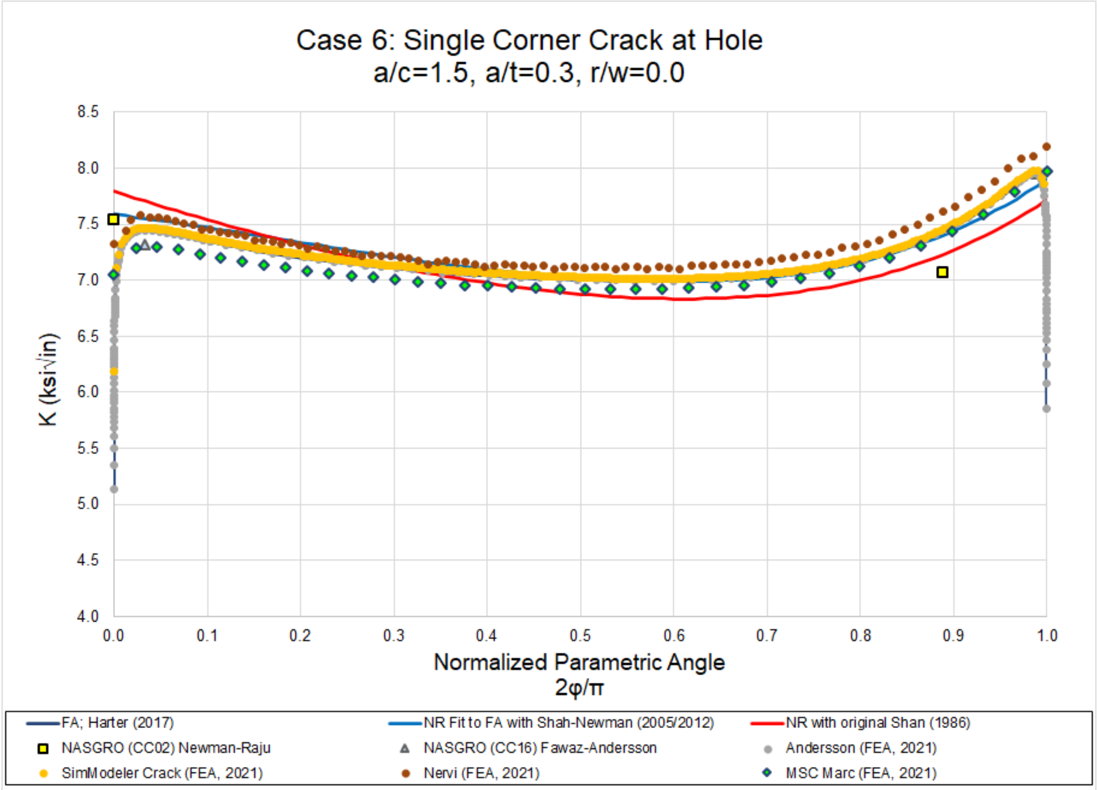


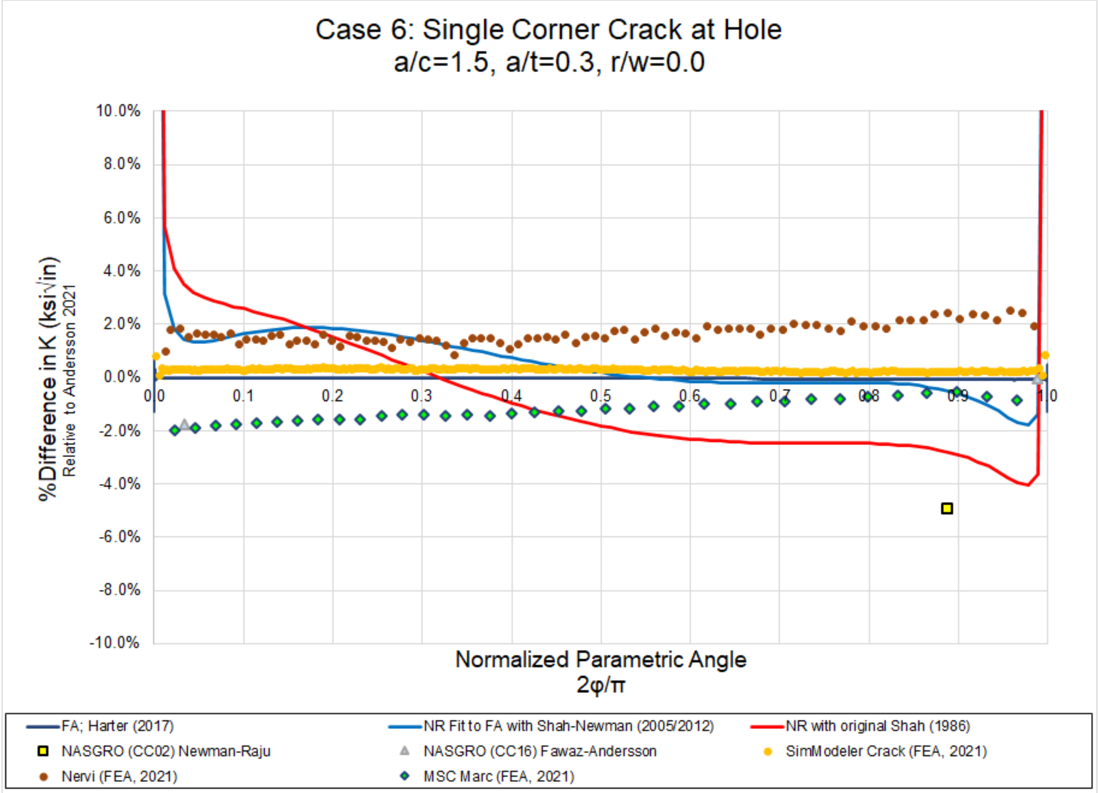


Stress Intensity Factor Round Robin

- Case #6: Single Corner Crack at a Hole, Infinite Plate, a/c=1.5
  - Replicate of Case #2 but with a crack aspect ratio of a/c=1.5
  - Results generally within ±2% of Andersson submission, except near surface points
    - Submission 3 (Newman-Raju 1986) showed differences of ±4% across crack front
    - Submission 4 (NASGRO CC02) showed differences over 4% for point representative of hole bore

Case #	6
Configuration	Infinite Plate, Single Crack, a/c=1.5
Crack Configuration	Single Corner Crack
Surface Crack Length (c)	0.050
Bore Crack Length (a)	0.075
Width	100.00
Thickness	0.25
Hole Diameter	0.50
Hole Offset	50.00
a/c	1.50
a/t	0.30
W/D	200.00
r/t	1.00
r/W	0.00

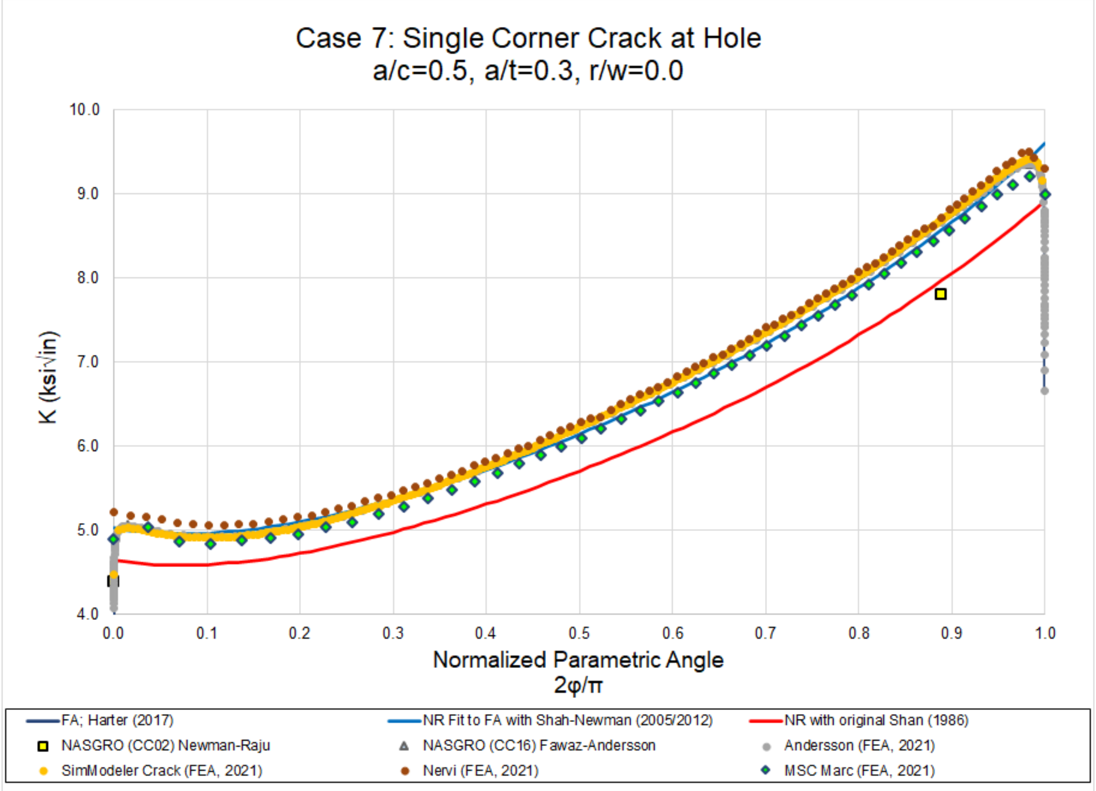


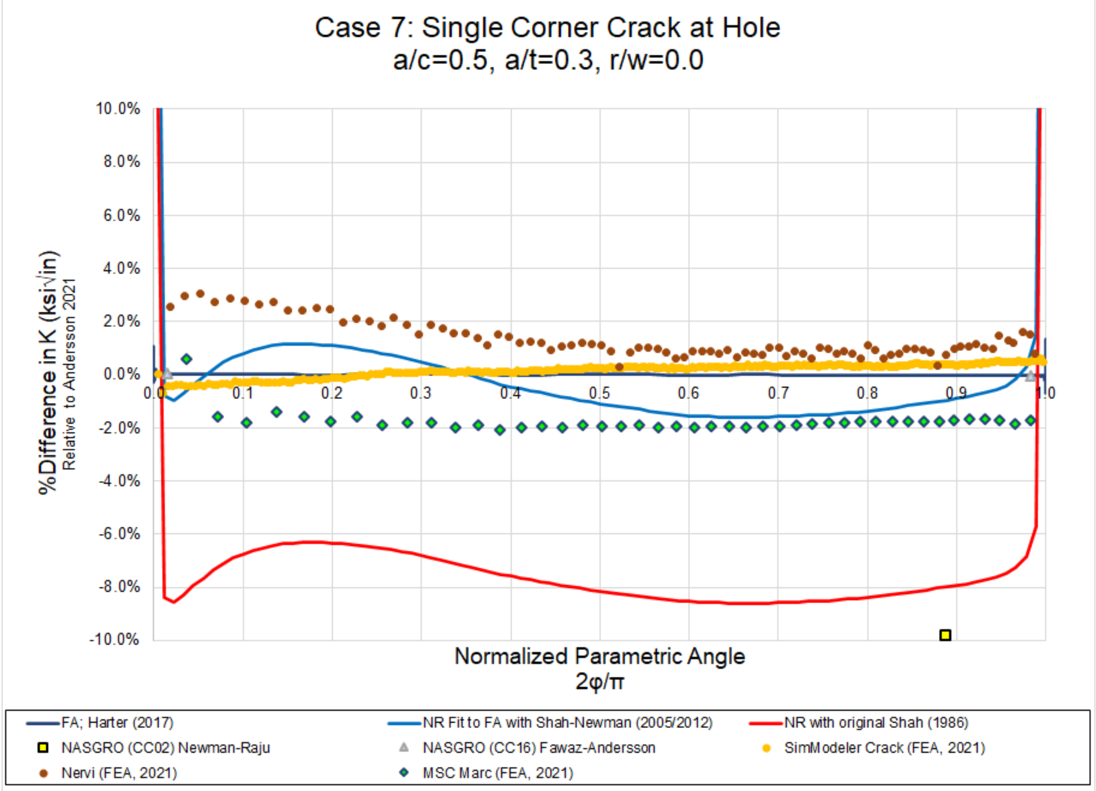


Stress Intensity Factor Round Robin

- Case #7: Single Corner Crack at a Hole, Infinite Plate, a/c=0.5
  - Replicate of Case #2 but with a crack aspect ratio of a/c=0.5
  - Results generally within ±2% of Andersson submission, except near surface points
    - Submission 3 (Newman-Raju 1986) showed differences averaging ~8% across the crack front
    - Submission 4 (NASGRO CC02) showed differences of 10% for point representative of hole bore

Case #	7
Configuration	Infinite Plate, Single Crack, a/c=0.5
Crack Configuration	Single Corner Crack
Surface Crack Length (c)	0.100
Bore Crack Length (a)	0.050
Width	100.00
Thickness	0.25
Hole Diameter	0.50
Hole Offset	50.00
a/c	0.50
a/t	0.20
W/D	200.00
r/t	1.00
r/W	0.00

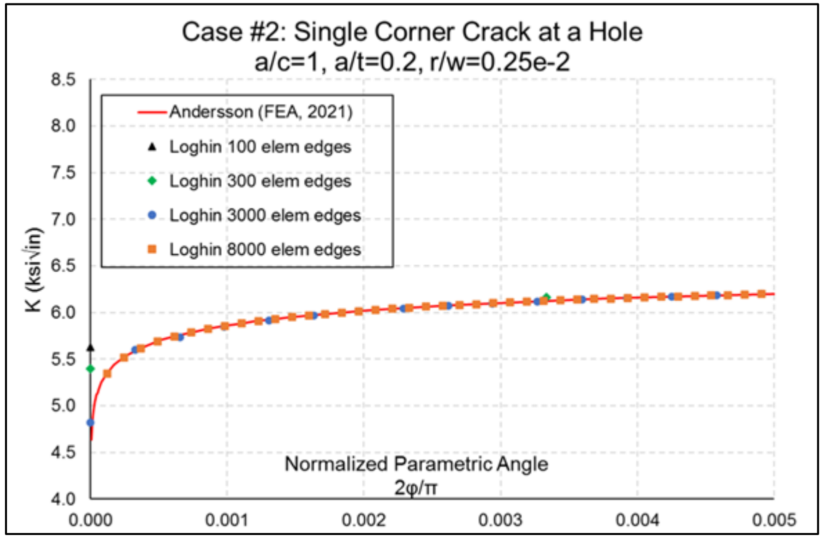


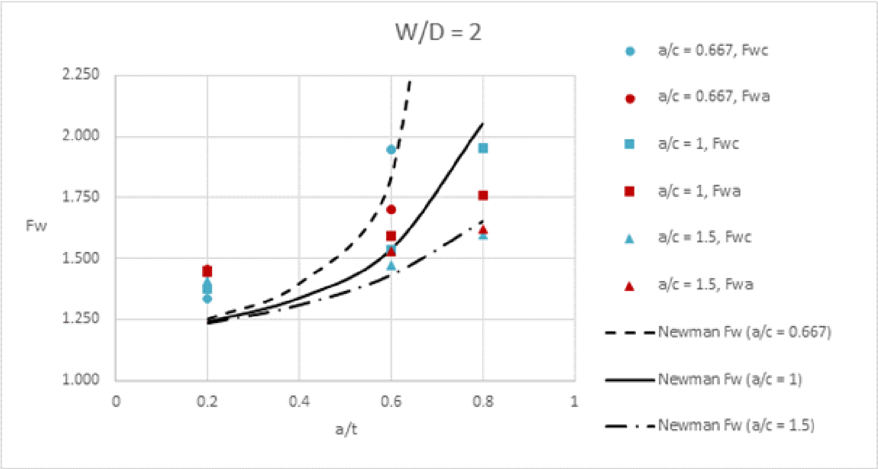


Stress Intensity Factor Round Robin

- Overall Summary and Conclusions
  - Successful SIF comparisons completed utilizing a wide array of available solutions and toolsets, with submissions provided by (8) different participants
  - Overall, results were within 2% of the reference case, however, deviations were observed for narrow width and varying aspect ratio cases exceeding 10% in some cases
  - Issues with commonly utilized finite width corrections were discovered
  - A robust dataset was developed that can be utilized as a reference set for follow-on studies
  - Comparisons between varying FEM approaches have highlighted the opportunity to identify modeling best practices and provide guidance to the community

- Follow-on Investigations
  - Case #2 Convergence Study: Two studies were carried out in parallel
  - Finite Width Correction
  - Submission 8 (StressCheck FEA) updated meshing strategy & associated results





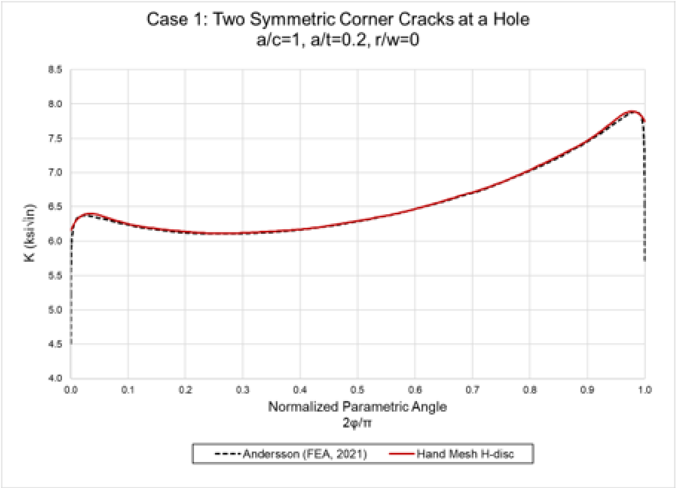


Figure 20 – Comparison of SIF extraction along the crack front with Andersson's reference solution for case 1.

Stress Intensity Factor Round Robin

- Next Steps
  - Finalizing summary report documenting round robin approach, results, conclusions, and follow-on investigations
  - New finite width corrections in work to support the community
  - Collaboration to identify FEA best practices and lessons learned
  - Consider publication of papers/presentations to share results with community

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Stress Intensity Factor Round Robin

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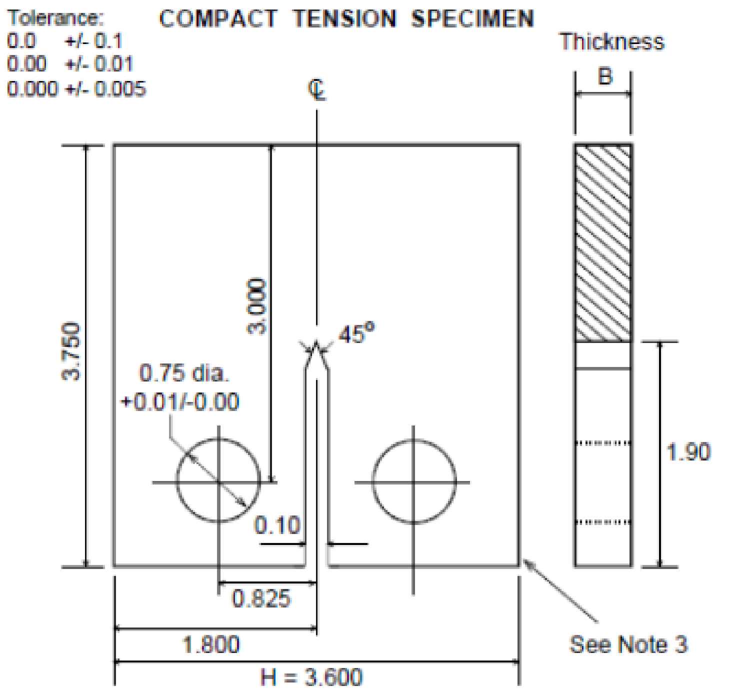
Overload Challenge

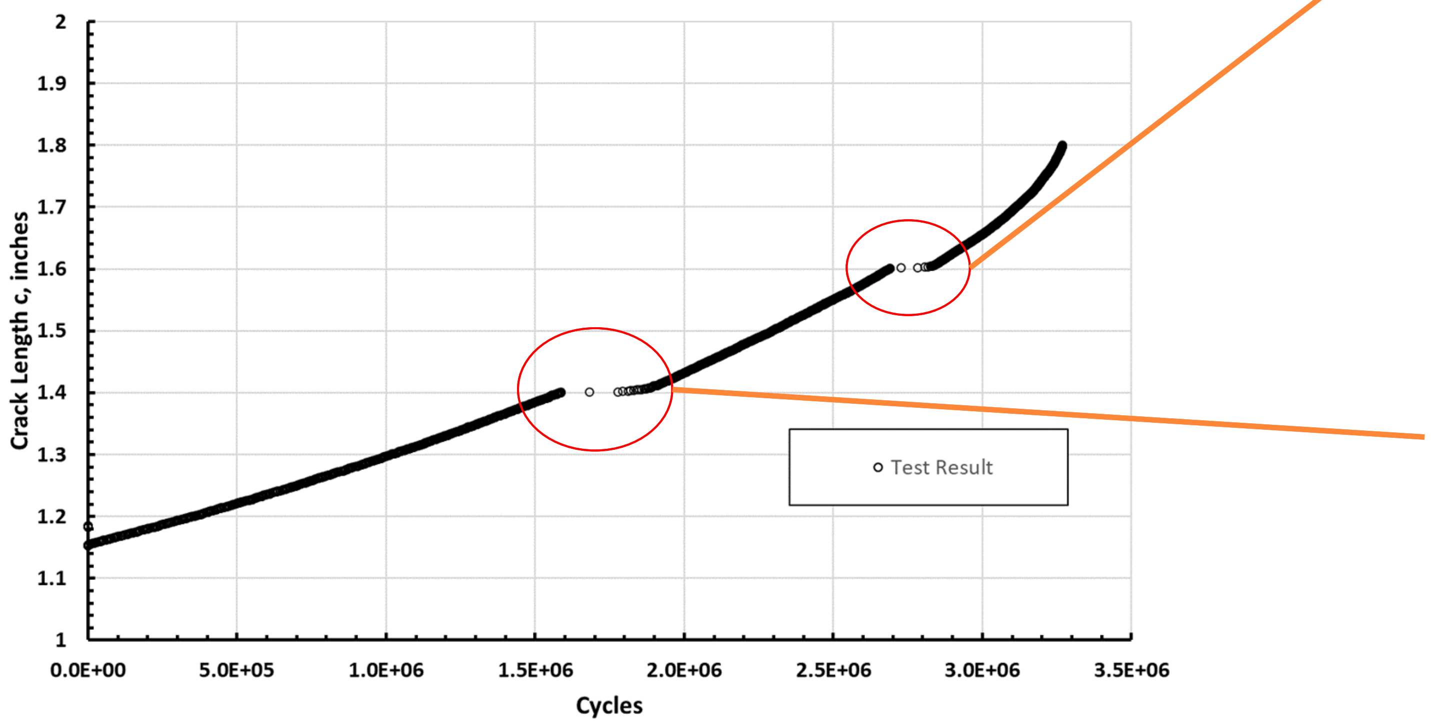
- Description
  - Compact tension specimen manufactured from 7075-T6
  - 3 inches wide, 0.125 inches thick
  - Initial notch length 1.15 inches
  - Constant amplitude loading
    - Pmax = 100 lb, Pmin = 10 lb
  - Single factor 2 (200 lb) spike overload applied when the crack length reached 1.4 inches, and then again at 1.6 inches
  - Participants in the challenge were invited to perform a blind prediction analysis, using whatever tool and method they preferred
  - Two submissions were received:
    - Submission 1: Jake Warner, USAF. Using AFGROW and the Generalised Willenborg retardation model
    - Submission 2: Luciano (Lucky) Smith, SWRI. Using NASGRO and the Generalised Willenborg retardation model

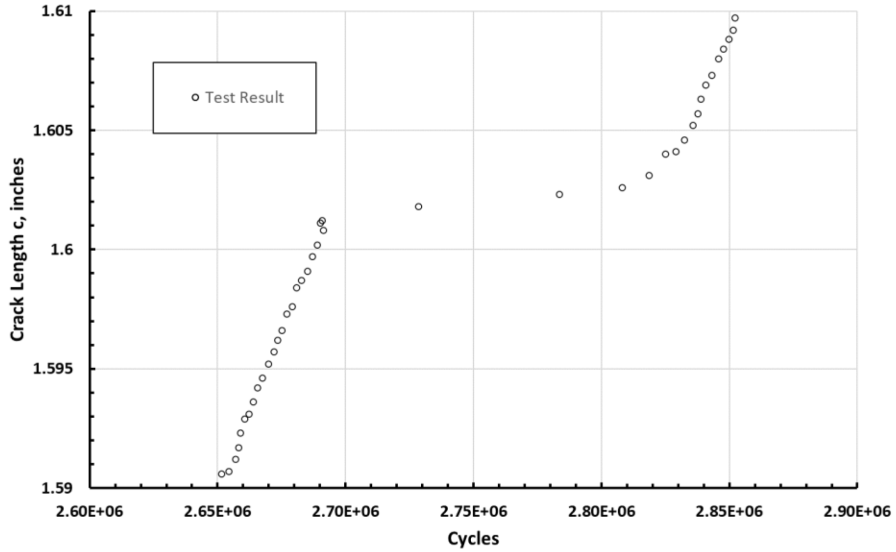


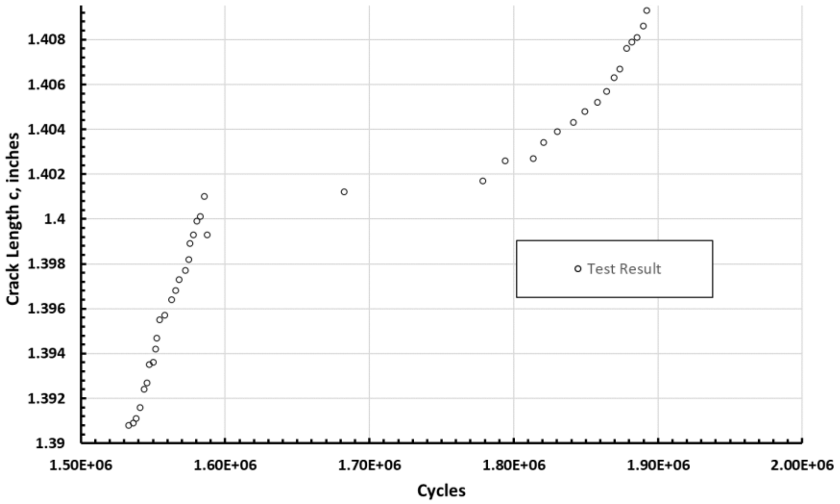
Notes:
(1) All dimensions are in inches.
(2) All surfaces perpendicular and parallel (as applicable) to within +/- 0.002 W, TIR
(3) Machine outer dimensions and holes before cutting notch.
(4) Measure and record height (H) of specimen before and after machining of notch (residual stress check).
(5) Notch may be machined or electrical-discharge machined but 45-degree V-notch root radius shall not exceed 0.003 in.

Overload Challenge

- Test Results
  - Total life to reach 1.8 inches – 3,269,818 cycles
    - Delay at OL1 about 220,000 cycles
    - Delay at OL2 about 120,000 cycles







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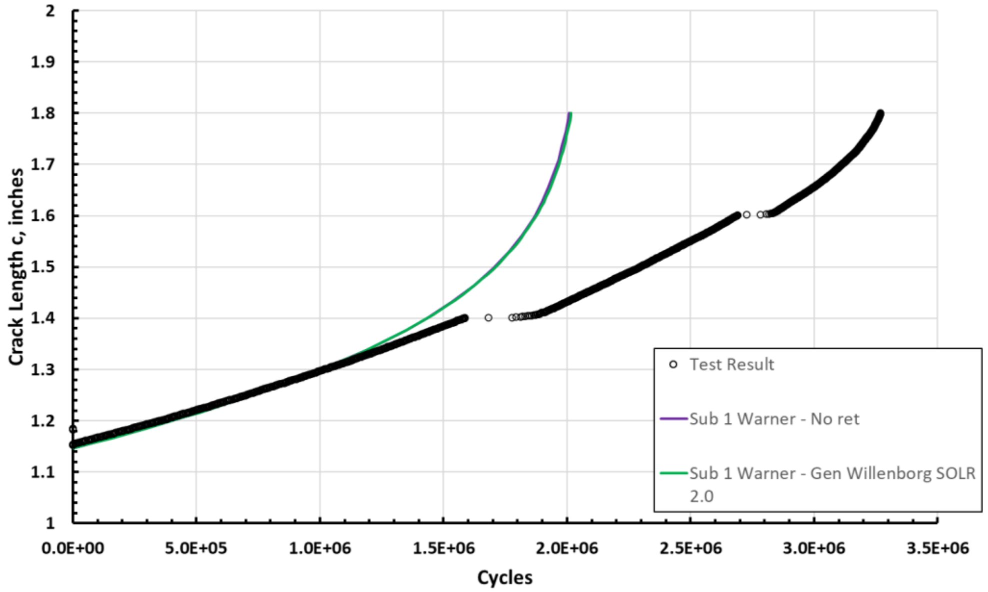
Overload Challenge

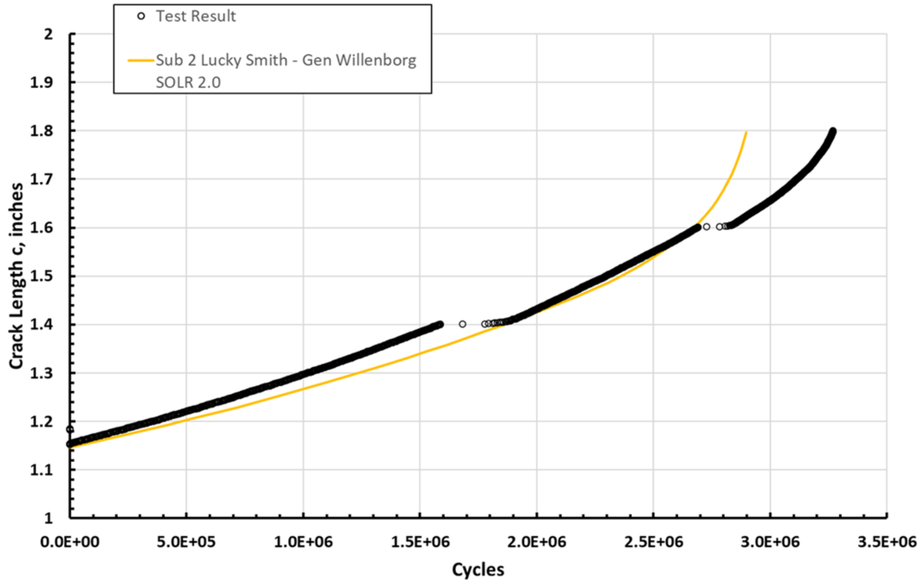
Submission 1: AFGROW

- Baseline prediction (no retardation/load interaction)
- Prediction with retardation:
  - Generalised Willenborg model SOLR=2.0
  - 2.0 was the lowest possible value without causing crack arrest



Submission 2: NASGRO

- Generalised Willenborg retardation SOLR=2.005
- 2.005 was the lowest possible value without crack arrest
- First overload added about 2,000 cycles. Second overload added about 5,000 cycles, i.e. very similar to Jake Warner's results



Overload Challenge

- Post-Test Analyses
  - FASTRAN Version 5.76 –Pseudo blind and Calibrated
  - AFGROW with different retardation models, including Hsu, Closure, Wheeler
  - Comparisons in the plastic zone region

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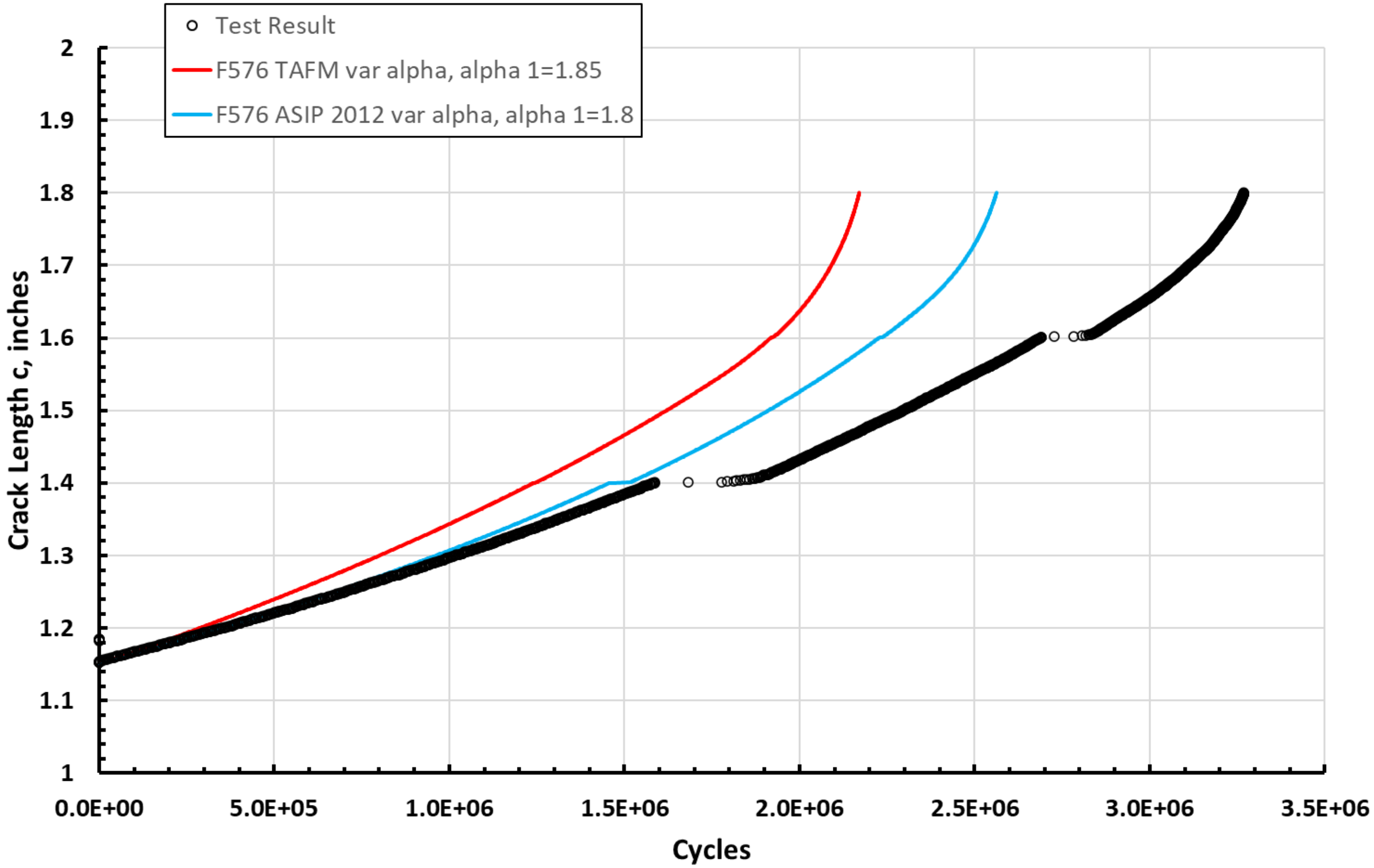
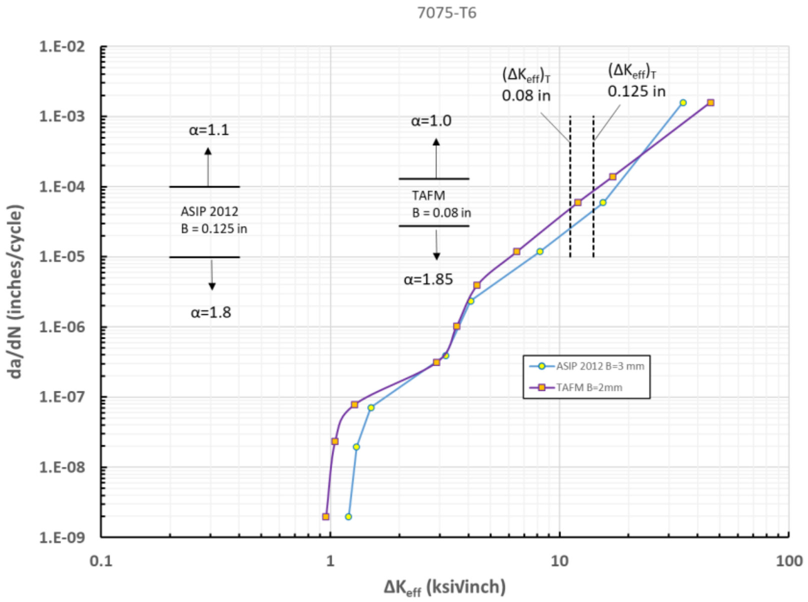
Overload Challenge

- FASTRAN analyses, Pseudo-blind
  - ASIP 2012 rate data from: Walker, K.F., and Newman, J.C., Jr., *Development and validation of improved experimental techniques and modelling for fatigue crack growth under constant amplitude and spectrum loading*, in *USAF ASIP Conference*. 2012: San Antonio Texas USA.
  - TAFM rate data from: Newman, J.C. and K.F. Walker, *Fatigue-crack growth in two aluminum alloys and crack-closure analyses under constant-amplitude and spectrum loading.* Theoretical and Applied Fracture Mechanics, 2019. **100**: p. 307-318.

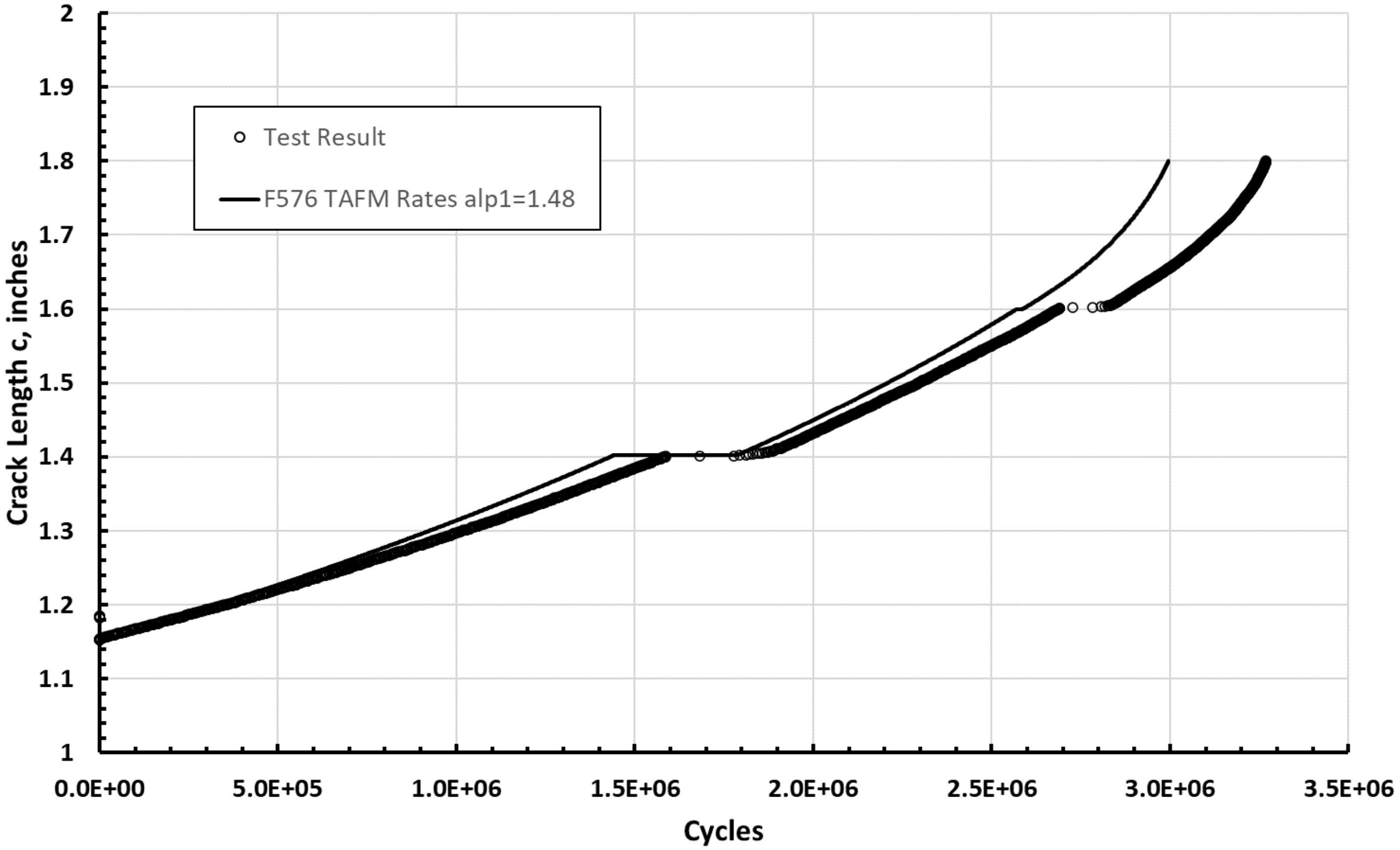




ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Overload Challenge

- FASTRAN Calibrated
  - $\alpha 1 = 1.48$ Lower than expected/used for regular spectrum loading cases. Should be around 1.8

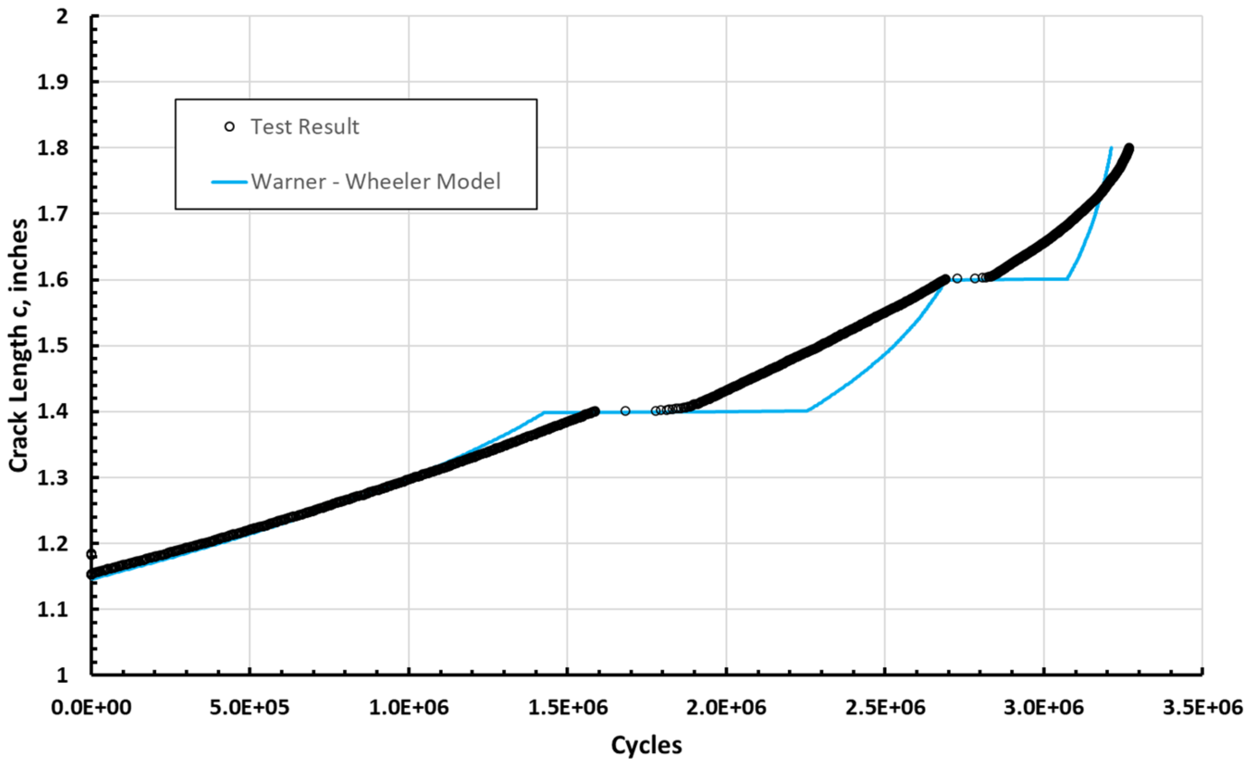


Overload Challenge

- AFGROW - Other retardation models
  - Hsu and Closure models showed similar behaviour to the Willenborg model, i.e. either little or no effect with variations in the parameters, or full crack arrest

Overload Challenge

- AFGROW with "calibrated" Wheeler model
  - Used trial and error to identify the "optimum" value of the Wheeler exponent "m".
  - Found that m=5.47 produced the best result



Overload Challenge

- Conclusions – Spike Overload
  - Despite what you might think, a simple spike overload scenario is difficult to predict/analyse
  - The overload effects seem to act over a length scale comparable with the plastic zone size, although they do persist well beyond that to a lesser extent
  - Retardation models focus attention on the plastic zone which appears justified and appropriate
  - The Willenborg, Hsu and Closure models as implemented in AFGROW (and NASGRO in the case of Willenborg) seemed unable to predict or correlate well to this case, blind or non-blind
  - The Wheeler model was able to qualitatively approximate the behaviour seen on the test with an empirically adjusted value of the exponent m. But some aspects including the rate after overloads did not match well.
  - The FASTRAN approach approximated the behaviour reasonably well, but only when the value of the constraint factor α was empirically adjusted to a low value (1.48 in this case, where 1.8-1.85 would be expected). The second overload effect was considerably under-estimated
  - Understanding and improving our ability to model spike overload cases is considered fundamental to the prediction for spectrum loading

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Overload Challenge

- Suggestions for further work
  - Continue research into spike overload cases and see if any existing models/software/approaches can better correlate to the case presented here, and others like it from the literature
  - Conduct further spike overload tests for the C(T) geometry, but also importantly for the M(T) geometry
  - Continue research into the constraint effects as modelled in FASTRAN to see if there is an effect which is not properly understood and modelled
  - Compressive constraint factor (β) in FASTRAN is typically set at 1.0. But that may not be always appropriate. Further investigation required.

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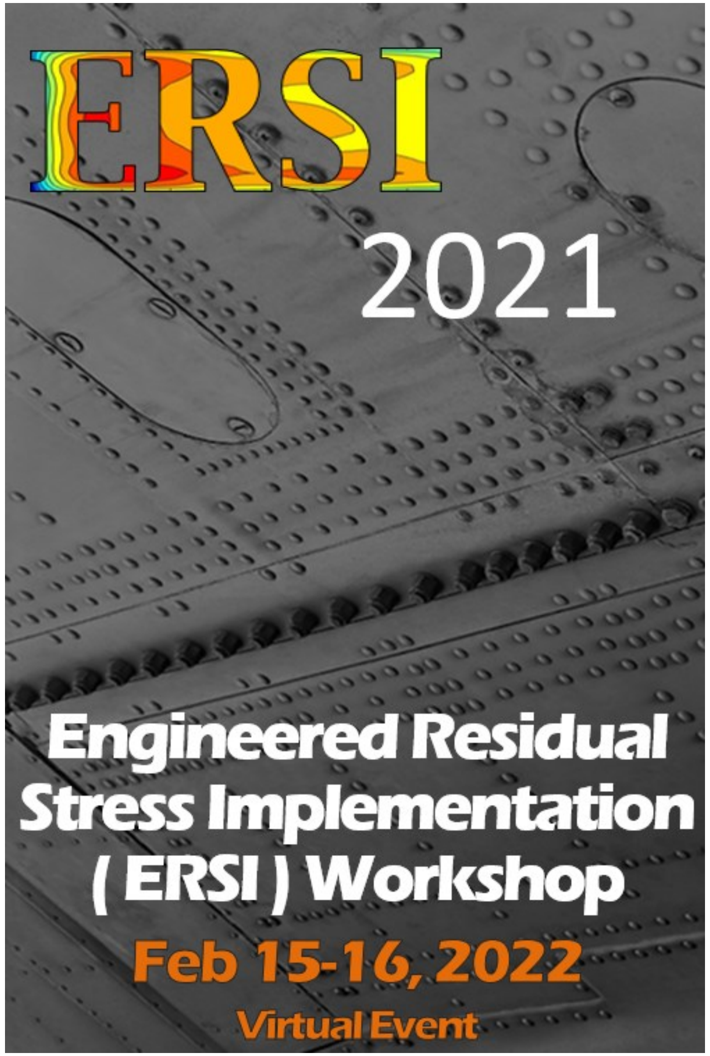
Agenda

- Mission Statement and Goals
- 2021 Achievements
  - Round Robins
    - Interference Fit Fastener Round Robin
    - Stress Intensity Factor Round Robin
    - Overload Challenge
  - Relevant Programs
    - Multi-Point MAI Program
    - Taper-Lok Analysis Methodology & Testing
  - Analysis Methods
    - Two vs. Multi-Point Analysis Comparisons
  - Testing
    - Kt-Free Coupons
- 2022 Focus Areas



Multi-Point MAI Program

- <u>Verification, Validation, & Demonstration of Multi-Point Fracture Mechanics Codes</u>
  - NG-11 is a new program associated with the Metals Affordability Initiative and is being performed cooperatively with a team of government and industry participants

Air Force Research Laboratory
ATI ADVANCED TECHNOLOGY INTERNATIONAL
NORTHROP GRUMMAN
HILL ENGINEERING
Fracture Analysis Consultants, Inc

  - Objective
    - Validate and assess capability of three (3) multi-point fracture mechanics MPFM codes as applied to the linear elastic fracture mechanics (LEFM) analysis of Cx holes

BEASY
FRANC3D
BAMpF

Multi-Point MAI Program

- Test/Analysis Conditions

Description	Analysis Configurations
Task 3.1 - Baseline Verification Specimens	
Analytical – Embedded Ellipse	2
Empirical – Compact Tension C(t)	1
Task 3.2 - Validation to level commensurate with traditional DTA methods	
Corner Crack at an Open Hole - Axial	4
Task 3.3 - Validation to level beyond traditional DTA methods	
Corner Crack at a Cold Worked Open Hole – Axial Load	8
Corner Crack at an Open Hole – Complex Load	2
Corner Crack at a Cold Worked Open Hole – Complex Load	2
Task 4 - Demonstration	
Fatigue Critical Location	1

Technical POCs:
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Dr. TJ Spradlin (USAF AFRL), thomas.spradlin.1@us.af.mil

Taper-Lok Analysis & Testing

- **Primary Objective:**
  - Develop a robust analytical approach to predict Damage Tolerance (DT) life at Taper-Lok fastener holes

Physics Based Analytical Methodology → Blind Predictions

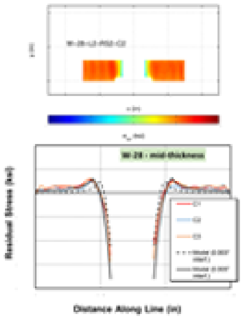
Validation Testing & Evaluations → Blind Predictions

Blind Predictions → Refined Analytical Approach Defined Best Practices → Updated B-1 DTAs

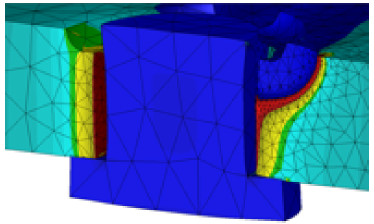
Multi-Point Analysis

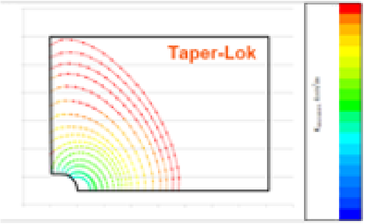
BAMpF (Broad Application for Multipoint Fatigue)

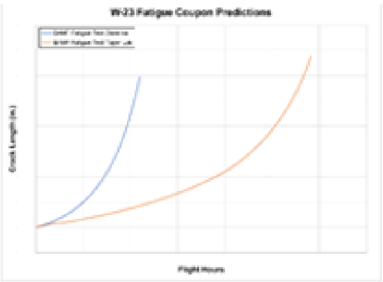
Residual Interference and Stress



Explicit Modeling of Geometry

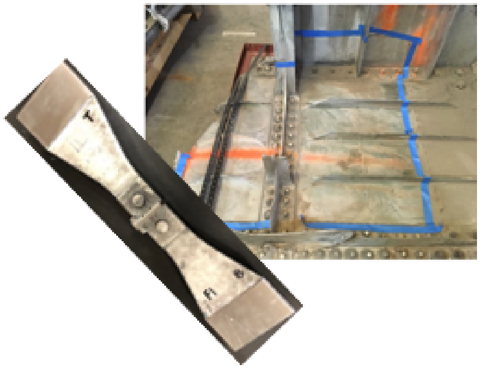






Representative Coupons

Excised Components



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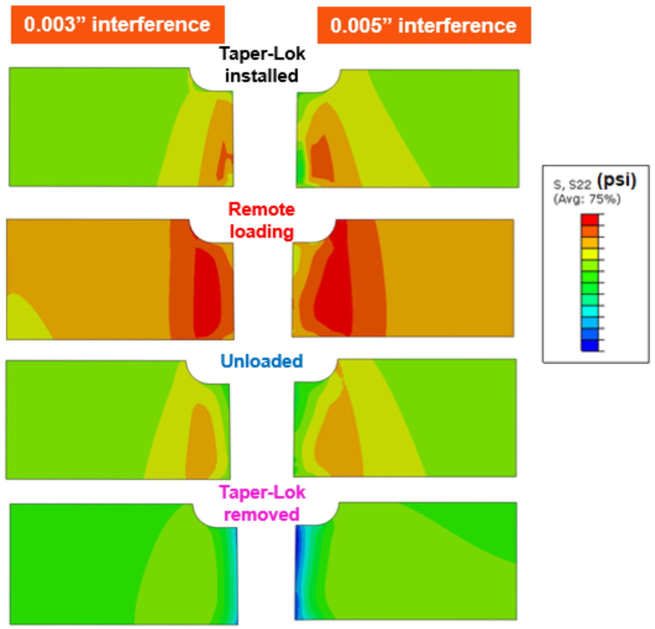
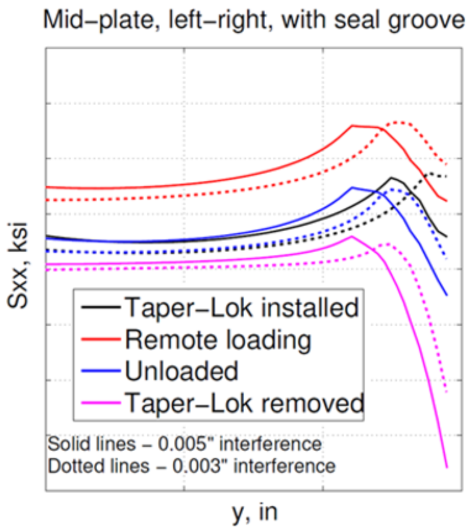
Taper-Lok Analysis & Testing

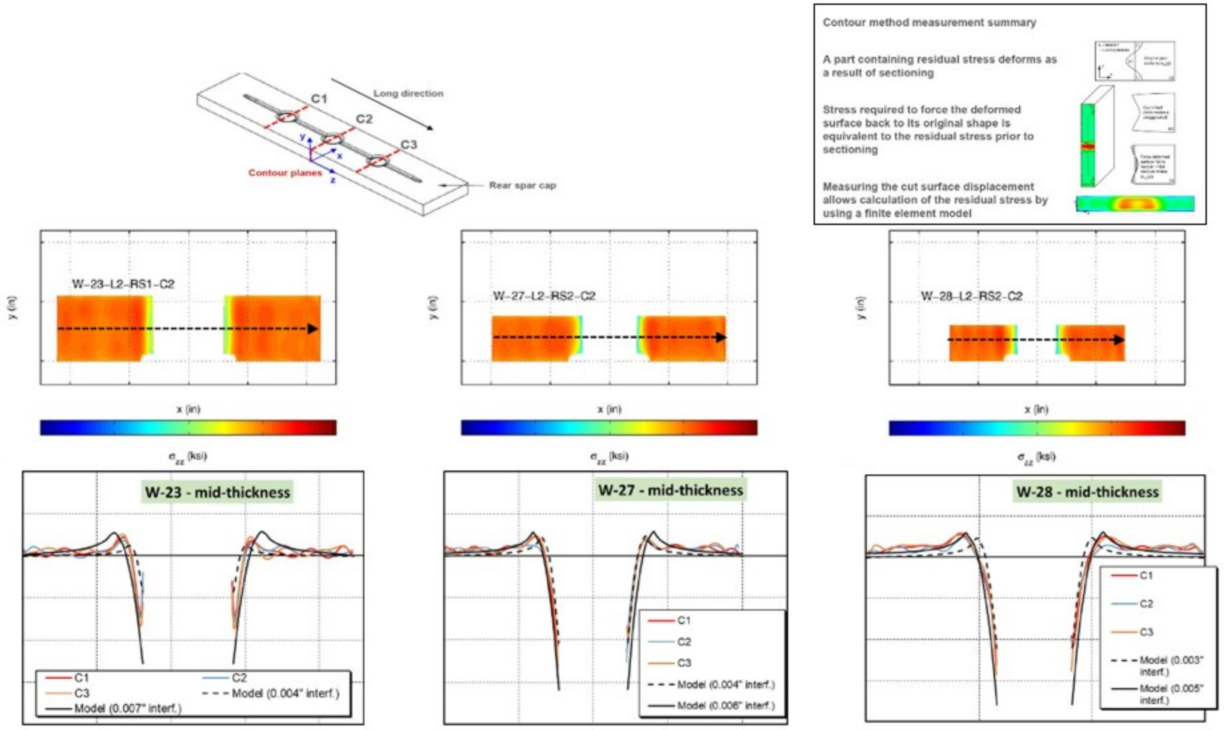
▪ Modeling and Measurements:

Process Model Results





Residual Stress Measurements



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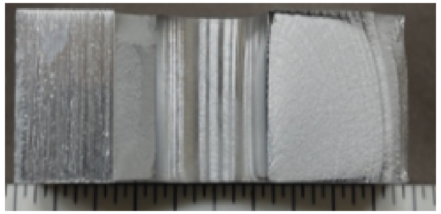
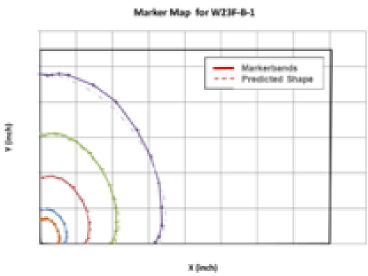
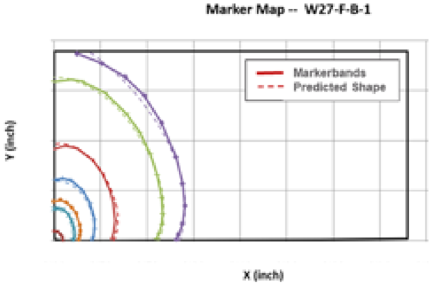
Taper-Lok Analysis & Testing

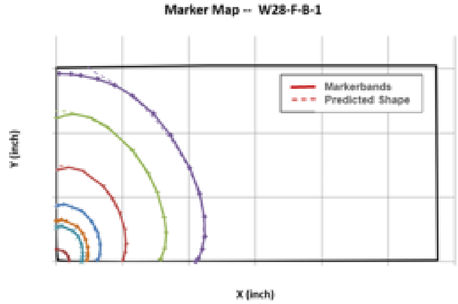
Baseline Comparisons:

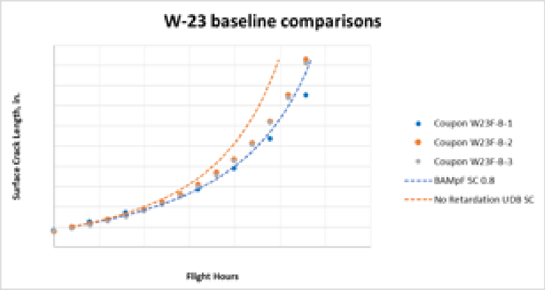
- Blind predictions* compared to test results
- Flaw size based on initial MB shape
  - Coupon W23-F-B-1 (0.0415in x 0.0582in)
  - Coupon W27-F-B-1 (0.0535in x 0.0783in)
  - Coupon W28-F-B-1 (0.046in x 0.063in)

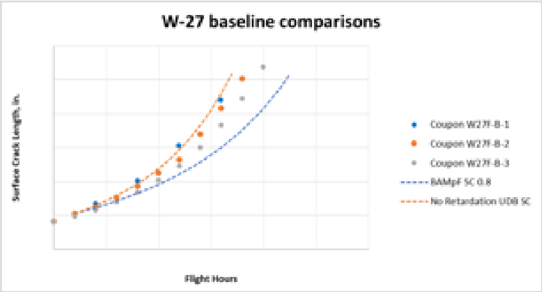


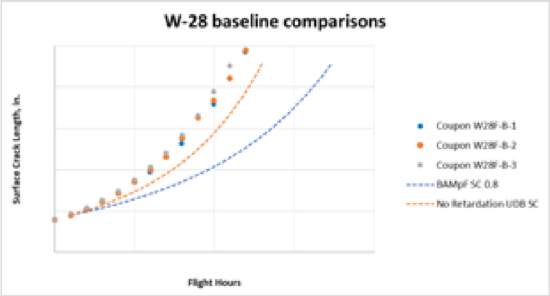












*BAMpF predictions utilized surface correction based on REF[1] AFGROW Presentation "The crack wants what it wants"

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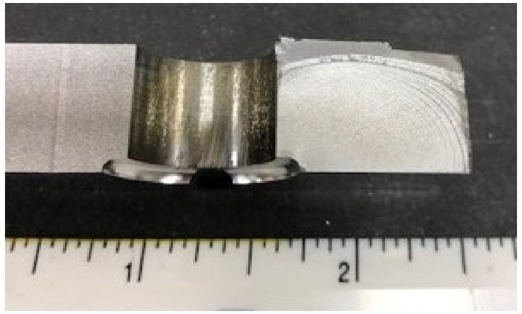
Taper-Lok Analysis & Testing

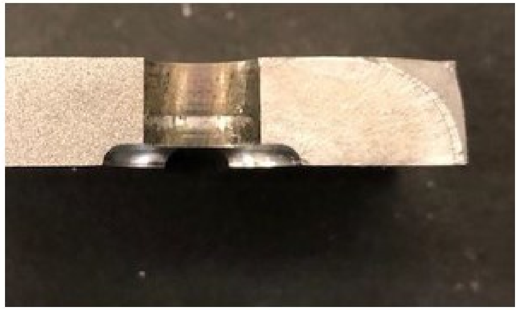
- Taper-Lok Comparisons:

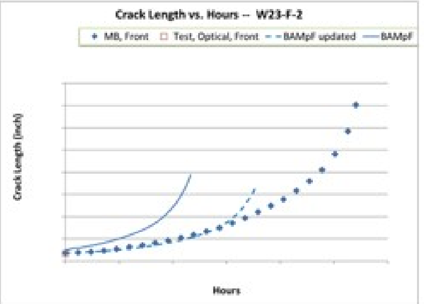
W23F-2

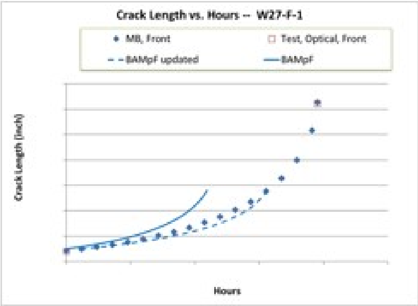


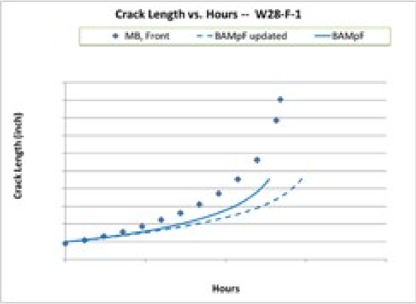
W27F-1

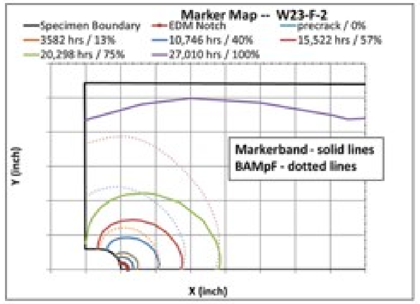
W28F-1

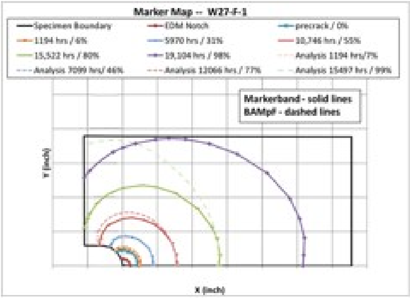


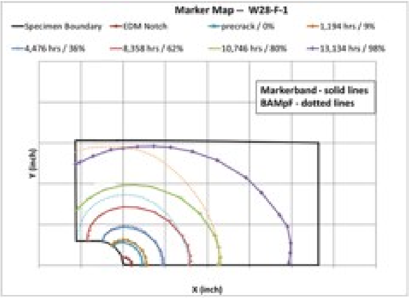












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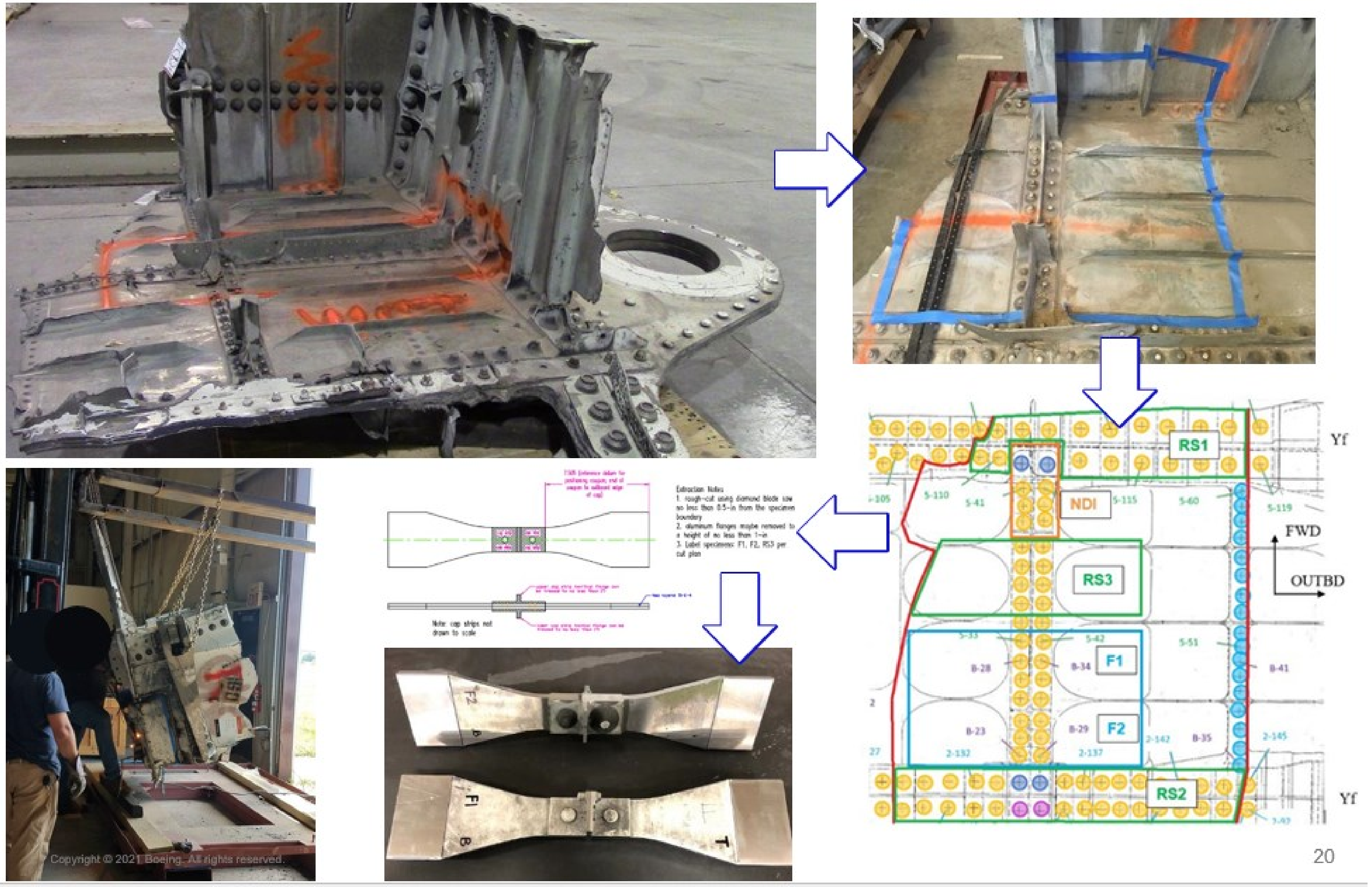
- <u>Component Coupons – Extracted B-1 Structure:</u>



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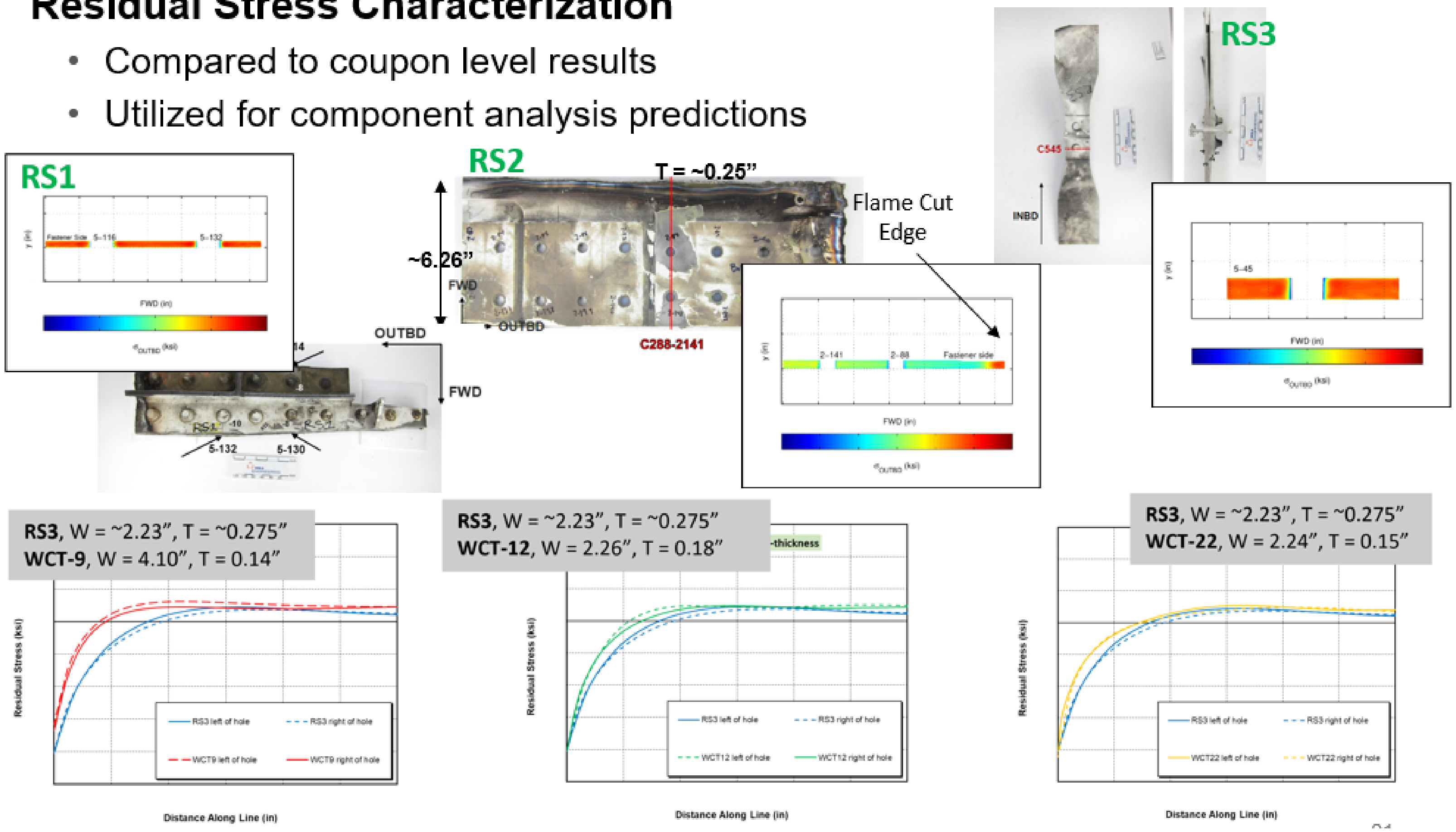
Component Coupons – Extracted B-1 Structure:

Multiple Extracted Sections of Wing Carry-Through Utilized for Residual Stress Characterization

- Compared to coupon level results
- Utilized for component analysis predictions



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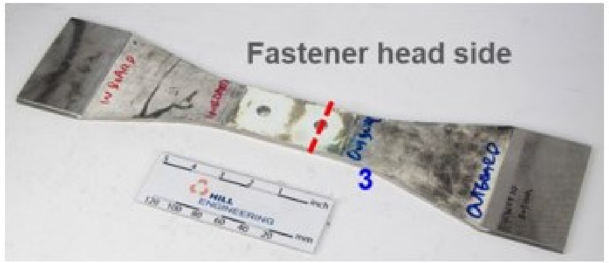
Component Coupons:

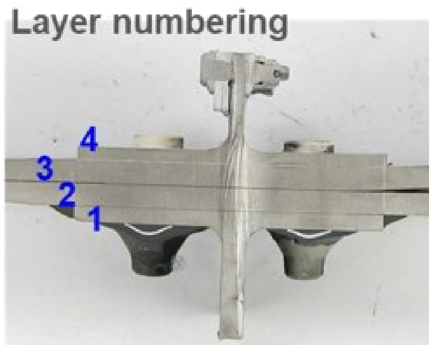
Component Coupon F2 Failed Near Grip at ~144k Flight Hours

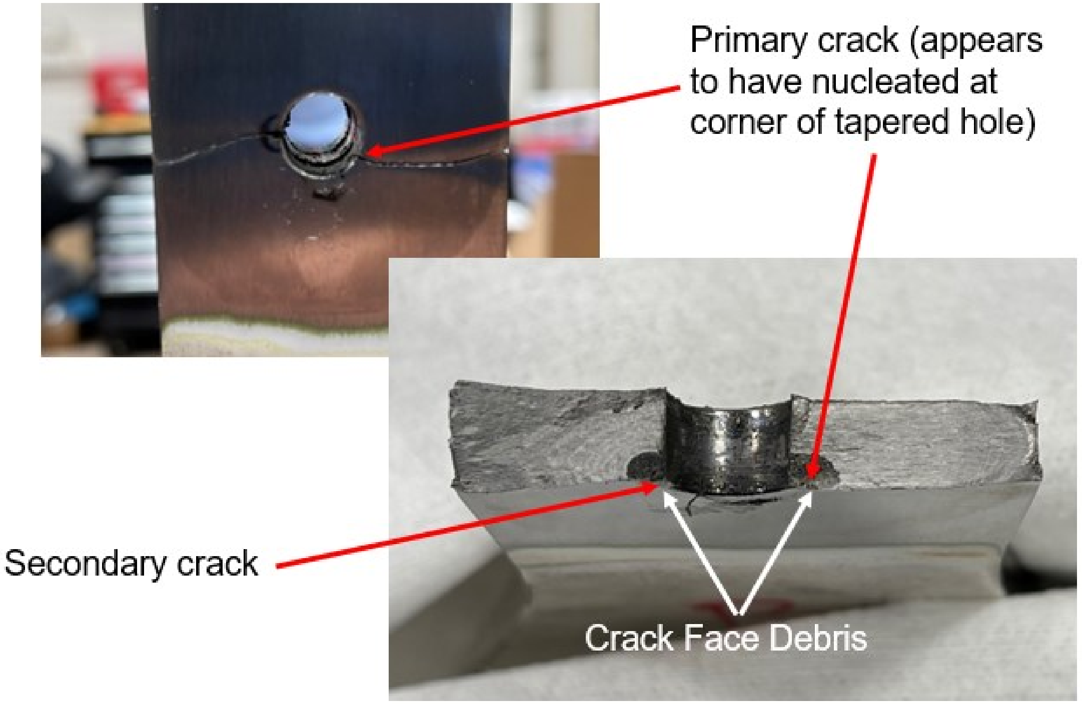
- Far exceeded life prediction with no RS benefit
- No induced notch

Component Coupon F1 Successfully Failed at Taper-Lok at ~ 352k Flight Hours

- Embedded EDM DT flaw at Taper-Lok hole to maximize potential of failure at gage section







Taper-Lok Analysis & Testing

- Conclusions:
  - Analytical Process
    - Robust analytical process established to characterize behavior at Taper-Lok fastener holes
    - Key data (residual stress and interference) characterized to support analyses
    - Consistent residual stress and interference results between coupons and extracted components
  - Testing
    - Efficient truncation and markerband approach established to support testing
      - Significant reduction in cycles
      - Marker bands easy to find for measured crack curve correlation
    - Baseline coupons correlated well with predictions
    - Taper-Lok coupons achieved failure at desired location
      - Challenging with RS benefit coupons
    - Coupon results were very repeatable
    - Component coupon showed long life and verified RS
      - Successful failure at Taper-Lok after 352k hours
  - Taper-Lok fasteners create significant life benefits from ERS

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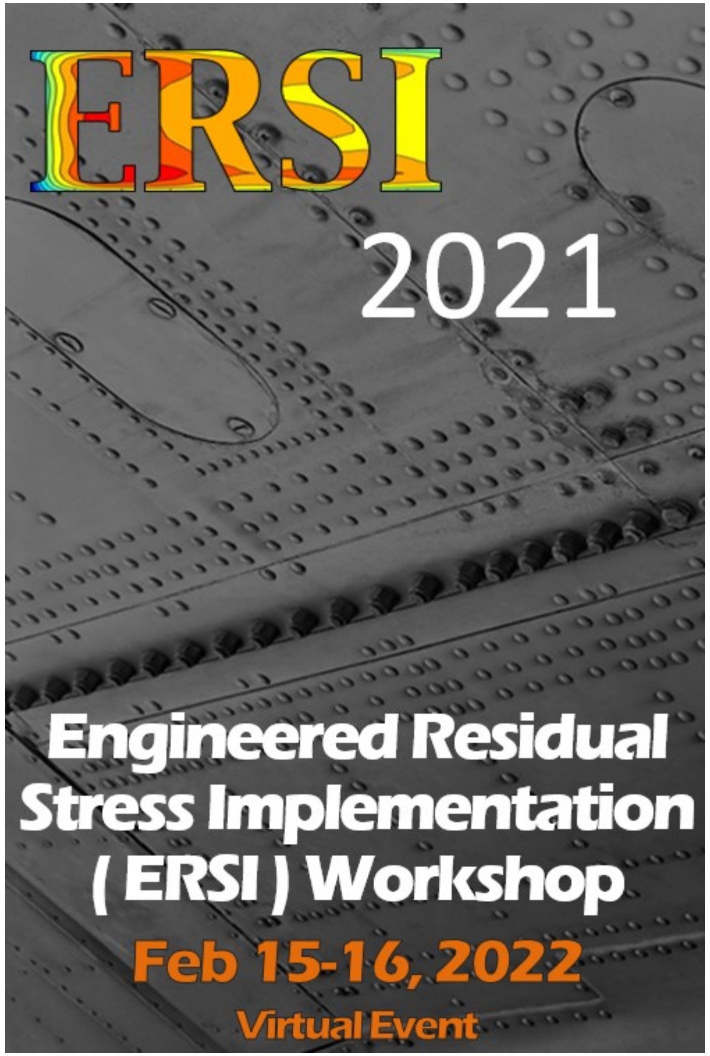
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

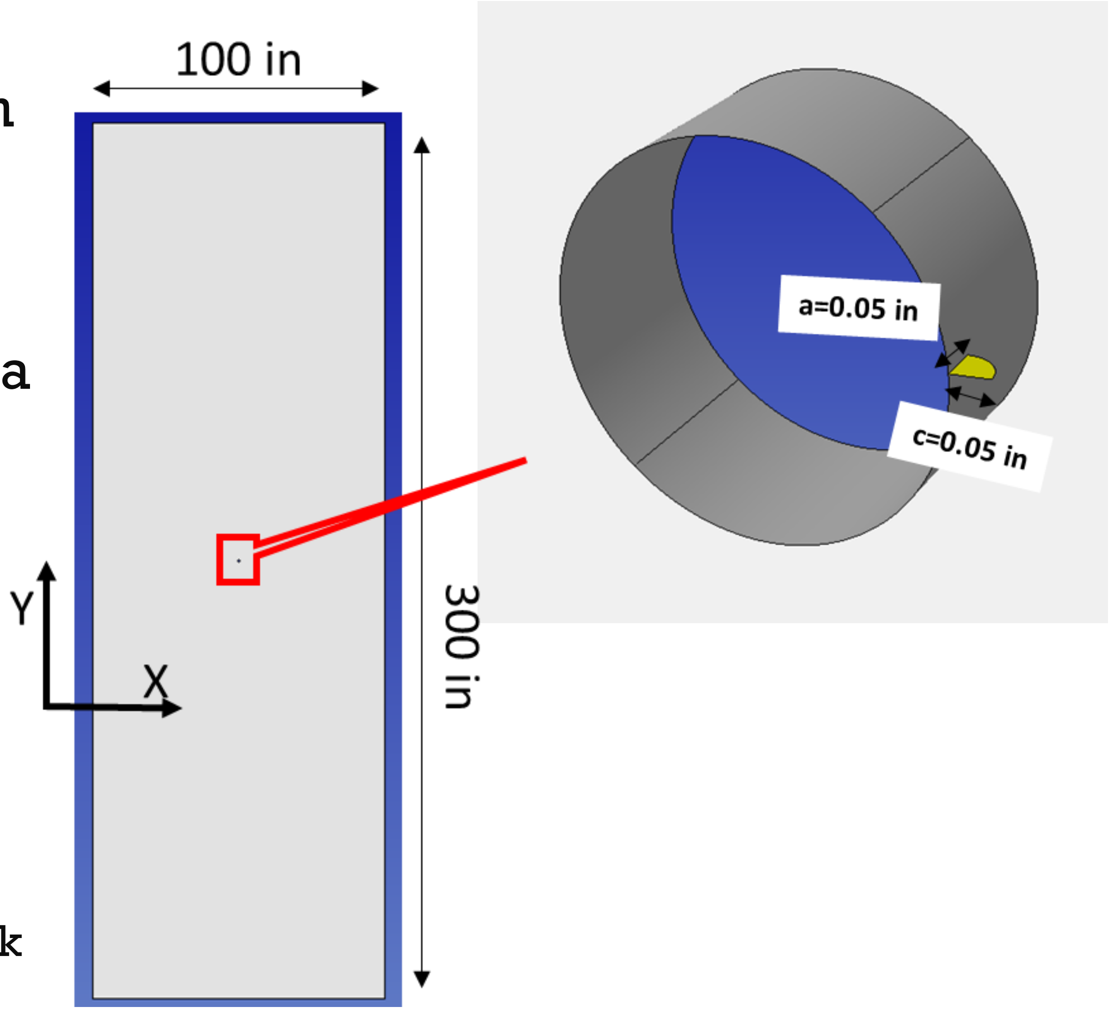
Agenda

- Mission Statement and Goals
- 2021 Achievements
  - Round Robins
    - Interference Fit Fastener Round Robin
    - Stress Intensity Factor Round Robin
    - Overload Challenge
  - Relevant Programs
    - Multi-Point MAI Program
    - Taper-Lok Analysis Methodology & Testing
  - Analysis Methods
    - Two vs. Multi-Point Analysis Comparisons
  - Testing
    - Kt-Free Coupons
- 2022 Focus Areas



Two vs. Multi-Point Comparisons

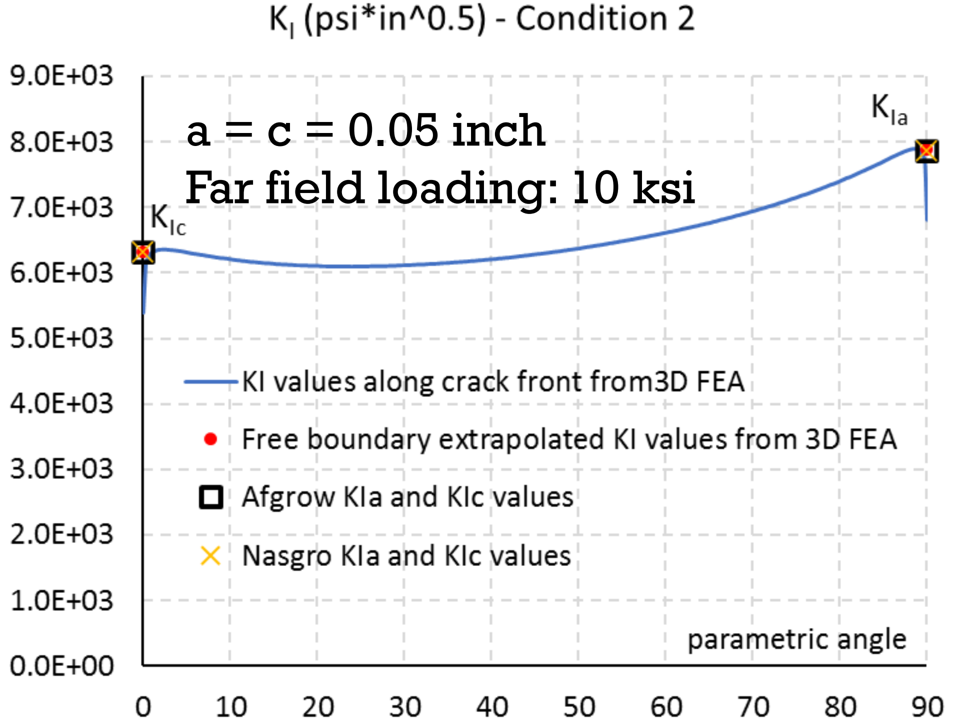
- Benchmark Problem
  - Assess the fatigue crack growth solution difference due to an elliptical crack assumption between 2-point (DKIa, DKIc) reduced order models, multi-point (DKI values along given cross-sectional paths) reduced order modeling and, explicit 3D finite element modeling
  - Model definition: corner crack at a bolt hole in a panel under far field uniform tensile, axial loading ("condition 2" from Mode I stress intensity factor benchmarking).
    - Thickness = 0.25 inch, hole diameter = 0.5 inch
    - Material Properties: E = 10.4e6 psi, n = 0.3
    - Uniform tensile far field loading
    - Loading cycle: min(sy)=0 to max (sy)= 10 ksi, R =0
    - Initial crack size: c = a =0.05 inch
    - C = 1e-8, n = 3.2, US customary units (ksi, ksi*sqrt(in), inch/cycle), AA 2024-T62
    - B. Farahmand: "Fatigue and Fracture Mechanics of High Risk Parts"



Two vs. Multi-Point Comparisons

- Procedure for Solution Comparison
  - A 2-point (DKIa, DKIc) crack growth modeling procedure is emulated in the explicit 3D FEA simulation
    - The free boundary KI gradient is removed from the KI solution along each crack front
    - The KI values are extrapolated to the free boundary
    - Advancement along the free boundary (Da, Dc) is estimated (Paris relationship)
    - An elliptical crack front increment is defined based on free boundary increments. Each crack front increment in the automatic 3D FEA simulation is elliptical.
  - The 2-point reduced order modeling solutions are then compared against multi-point and explicit 3D FEA where no shape constrained is assumed (default option)
  - Tools for solution comparison: NASGRO, AFGROW, BAMpF and, 3D FEA (SimModeler Crack capabilities).
  - No closure effects should be considered in ALL the predictions and verification of KI values is needed to make sure the solution difference is mostly attributable to the shape constraint

KIa and KIc verification agreement is reached



	Extrapolated	Afgrow	Nasgro
KIc (psi*in^0.5)	6.31E+03	6.32E+03	6.33E+03
KIa (psi*in^0.5)	7.89E+03	7.86E+03	7.86E+03

- The extrapolated values are from the 3D FEA solution after the free boundary gradient is removed
- KIc values match within 0.4%, KIa values match within 0.2%
- Nasgro's CC16 model (solution from Shak Ismonov) and Afgrow's advanced model (solution from Jim Harter) were used

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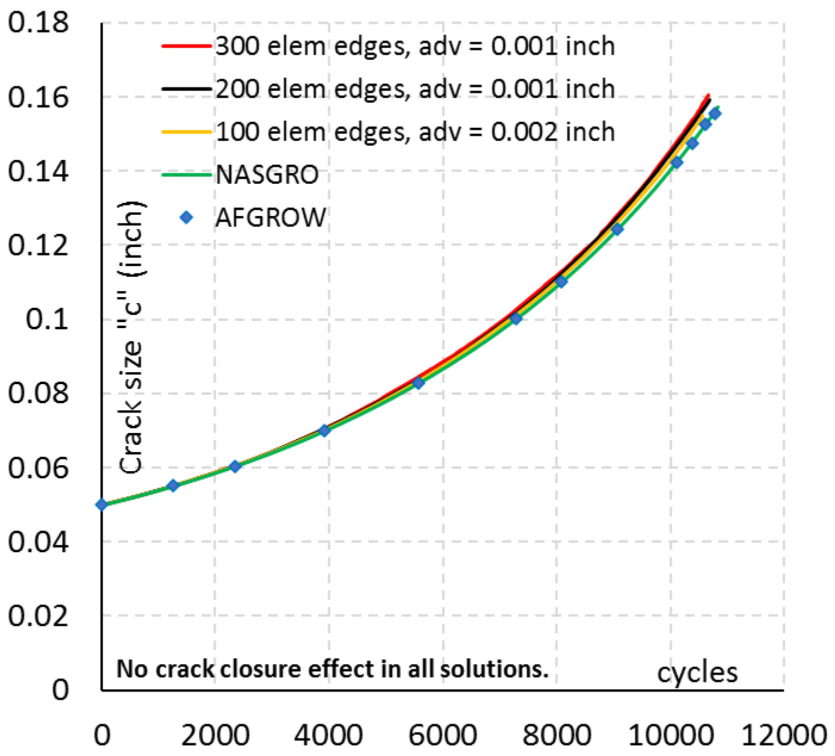
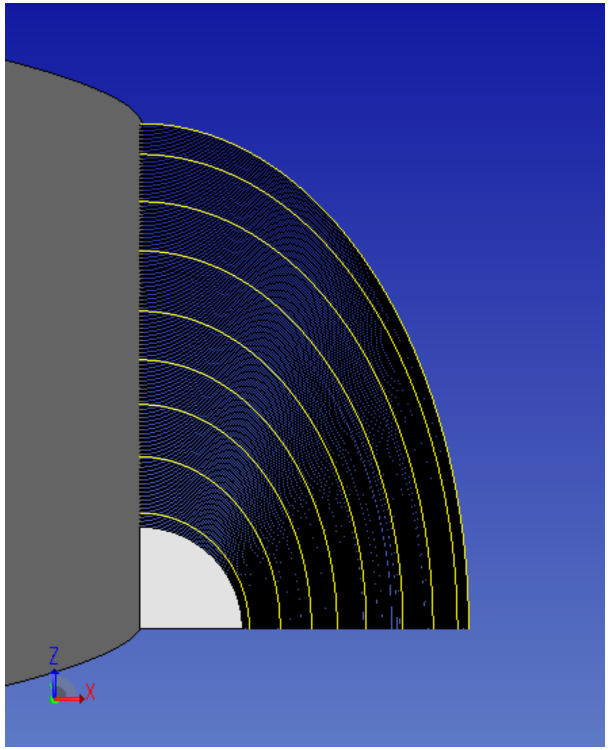
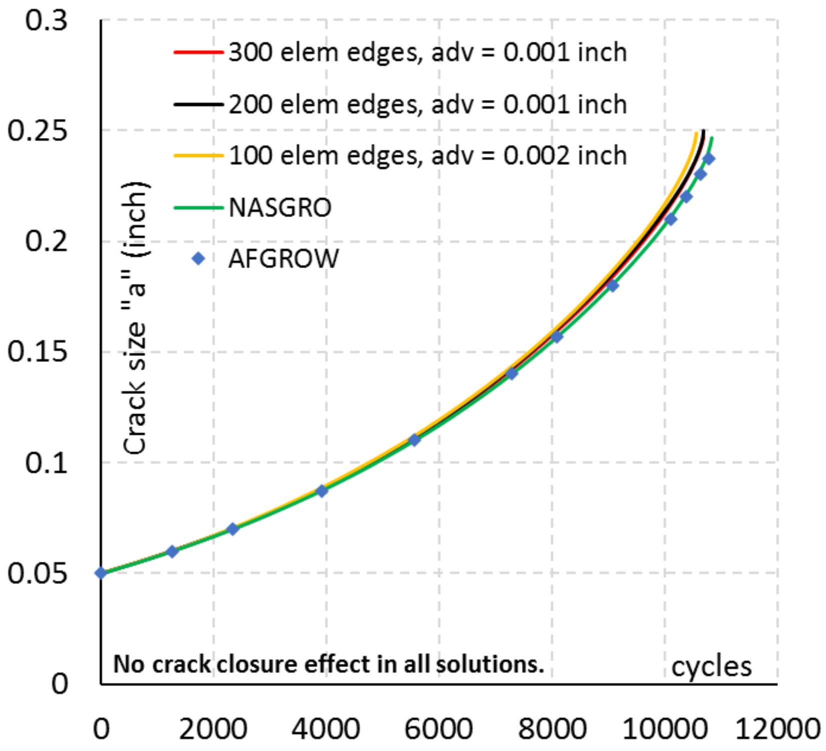
Two vs. Multi-Point Comparisons

- Solution Comparison for Elliptical Crack Front Increments
  - Quick convergence study shows that the 3D FEA explicit crack growth using elliptical crack front increments matches similar solutions using Afgrow and NASGRO models
  - The low mismatch between the reduced order model and the 3D FEA counterpart must come from slight KI numerical differences



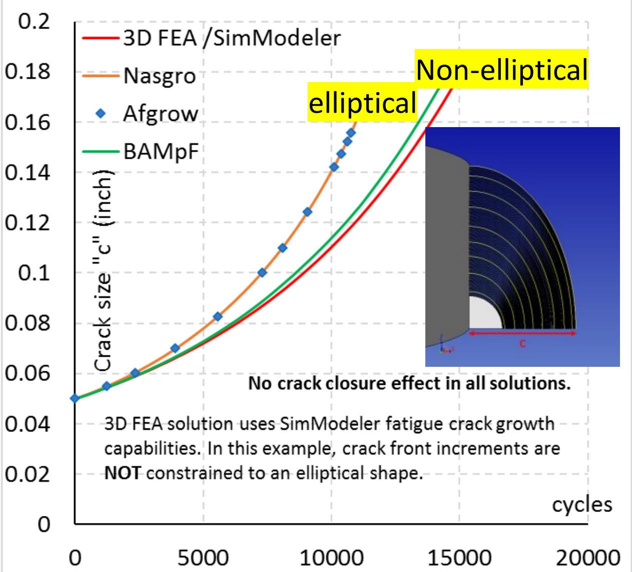


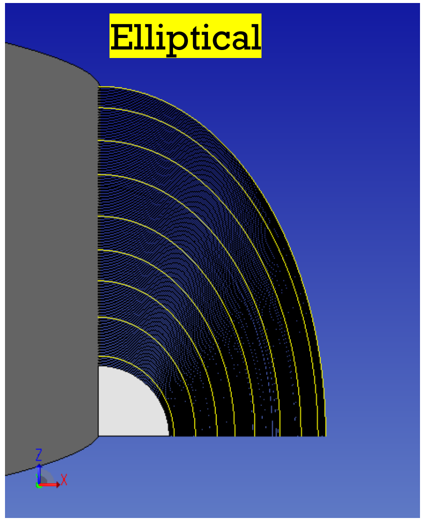
Adrian Loghin, Simmetrix

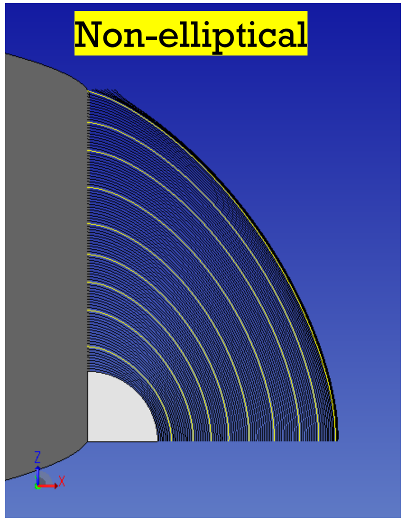


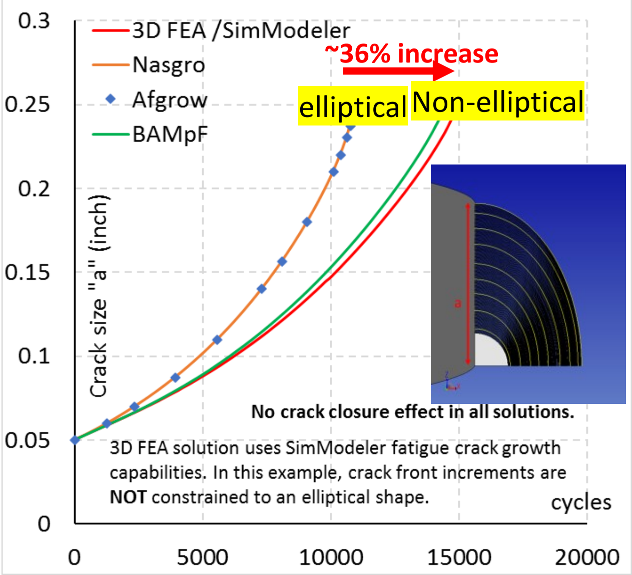
Two vs. Multi-Point Comparisons

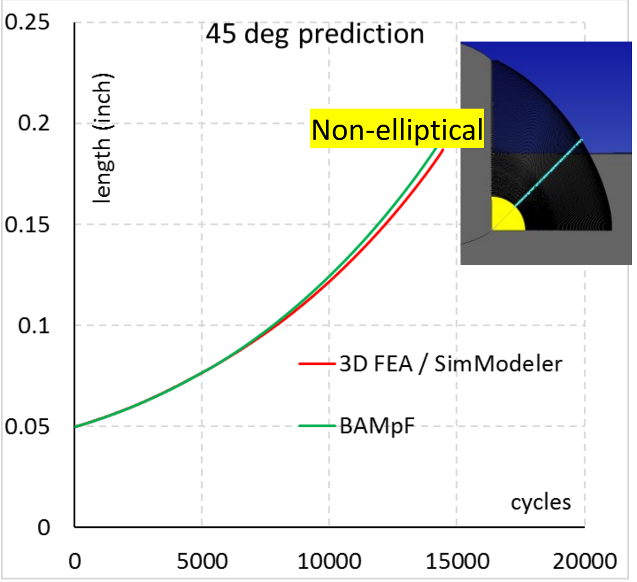
- <u>Elliptical vs. No Shape Constraint</u>
  - Using the 3D FEA verified solution for an elliptical crack front constraint, a comparison against the no-shape constraint (default option) solution can be performed
  - For this benchmark problem, if the crack front increments are not constrained to be elliptical, it is observed an increase in the predicted cycles with ~36%.
  - For the no shape constraint solutions, there is a good agreement between BAMpF and SimModeler











Adrian Loghin, Simmetrix

Two vs. Multi-Point Comparisons

- Conclusions
  - A 36% remaining useful live solution difference between the two models (enforcing elliptical crack growth and allowing the increment to take a shape controlled by the local geometry and far field loading) is assessed
  - Effective crack area was collected from both 3D fatigue crack growth simulations, with elliptical shape constraint and with no constrained imposed to the crack front shape
  - Modeling verification was reached between the 2-point reduced order modeling and 3D FEA using same the modeling assumptions
  - Modeling verification was reached between BAMpF and SimModeler solutions where crack front increments are not constrained to be elliptical
  - This 36% difference for a corner crack at a hole model might have a direct impact in solutions submitted in the round robin challenges (interference fit, Afgrow/central hole specimens)

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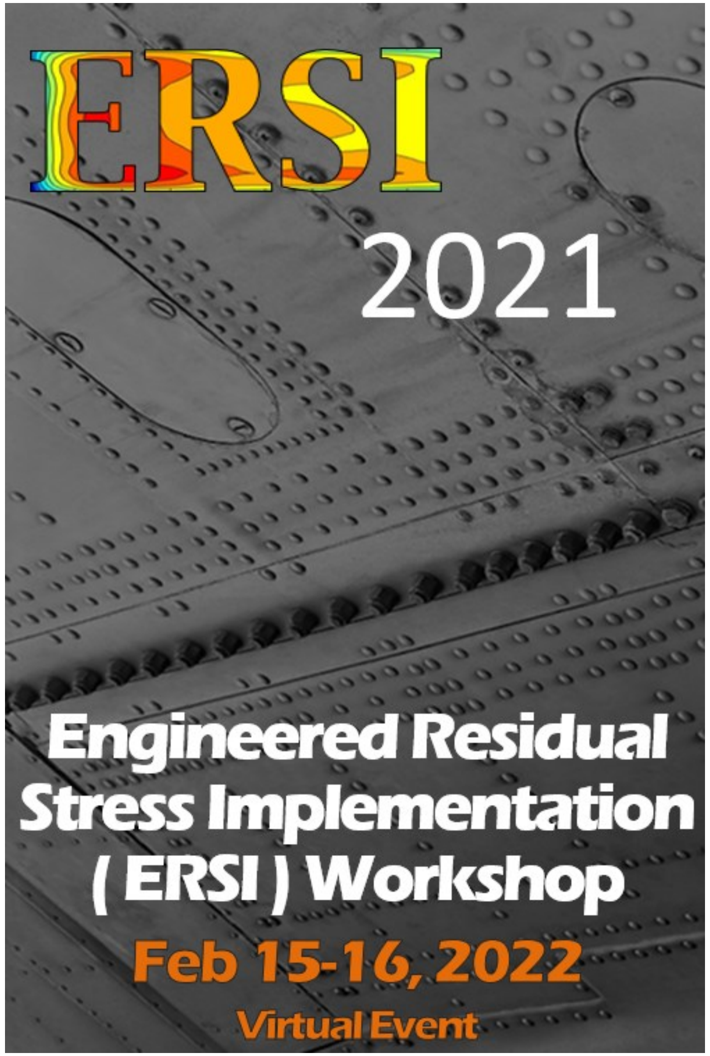
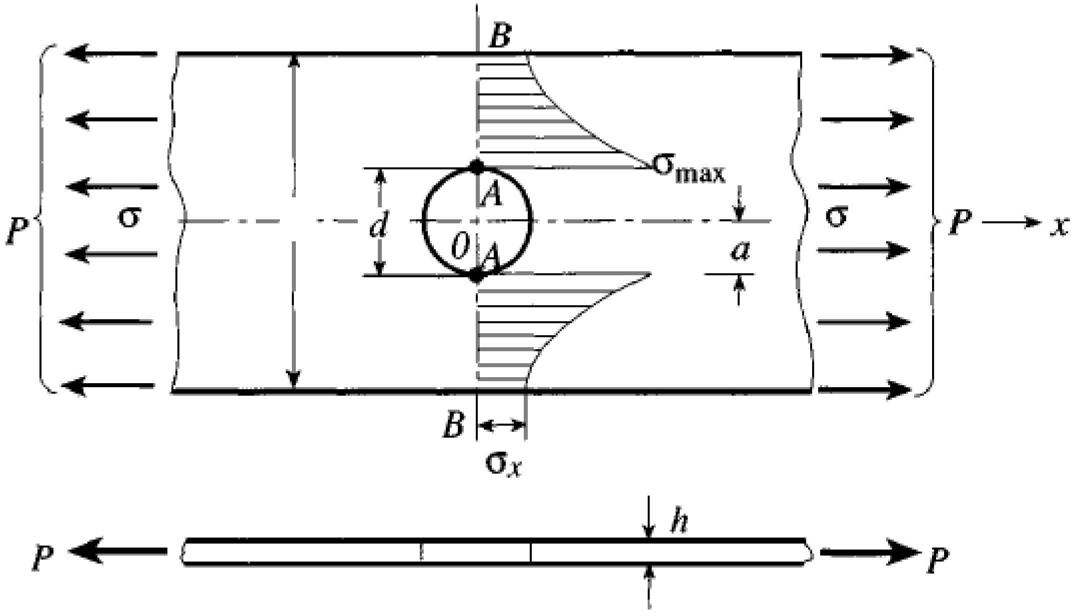
- 2022 Focus Areas



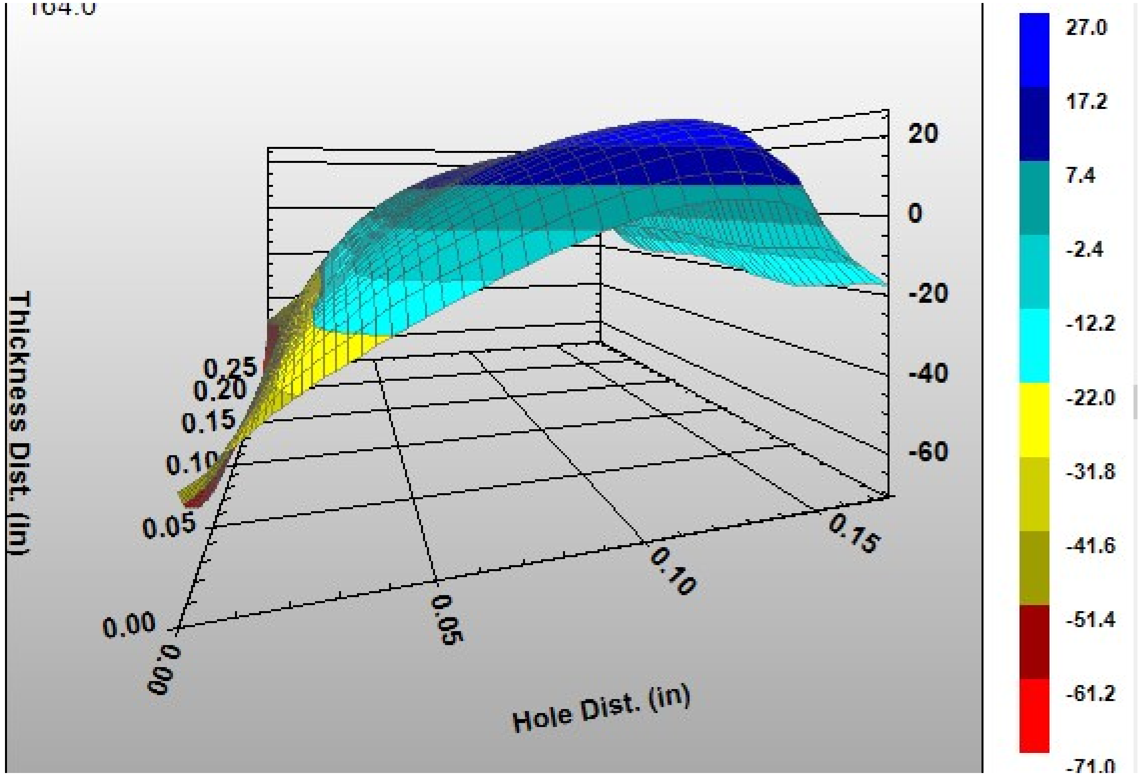
Kt Free Coupons

- The Problem
  - Residual Stress (RS) analysis has compounding steep stress gradients
    - Kt from the hole
    - Cold Expansion RS field



(a)

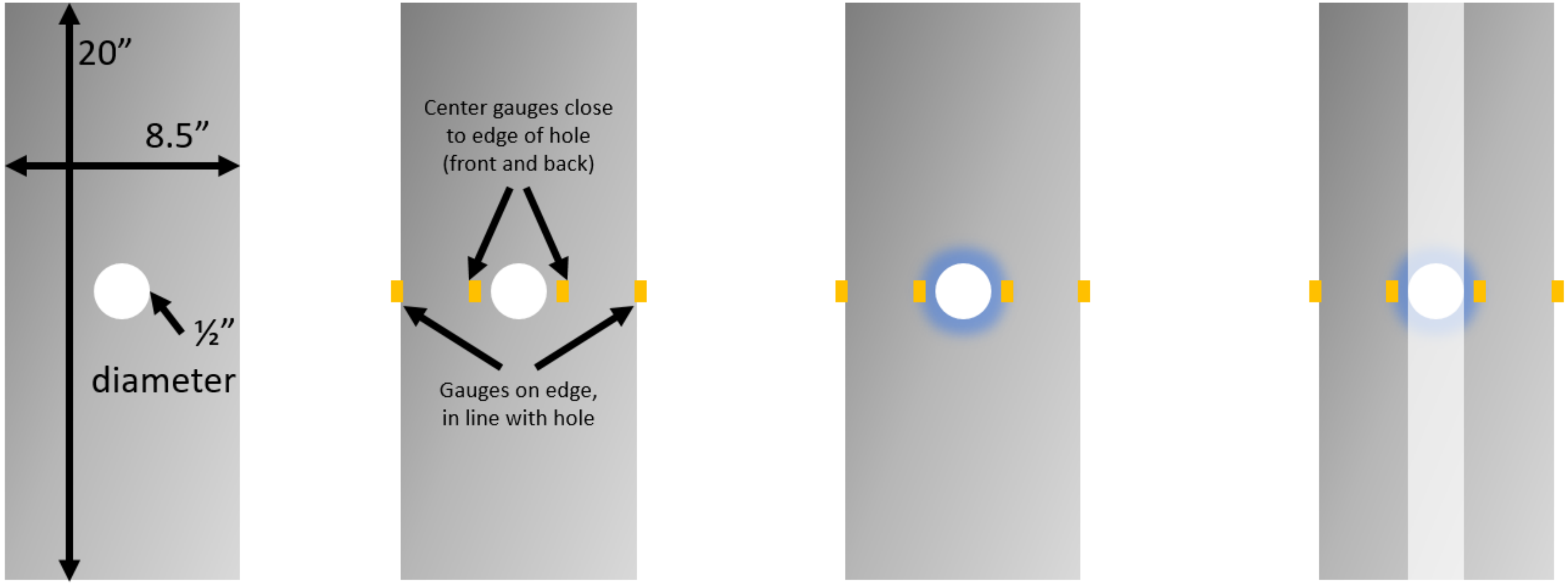
Peterson's Stress Concentration Factors, 2nd Edition



Coupon Development

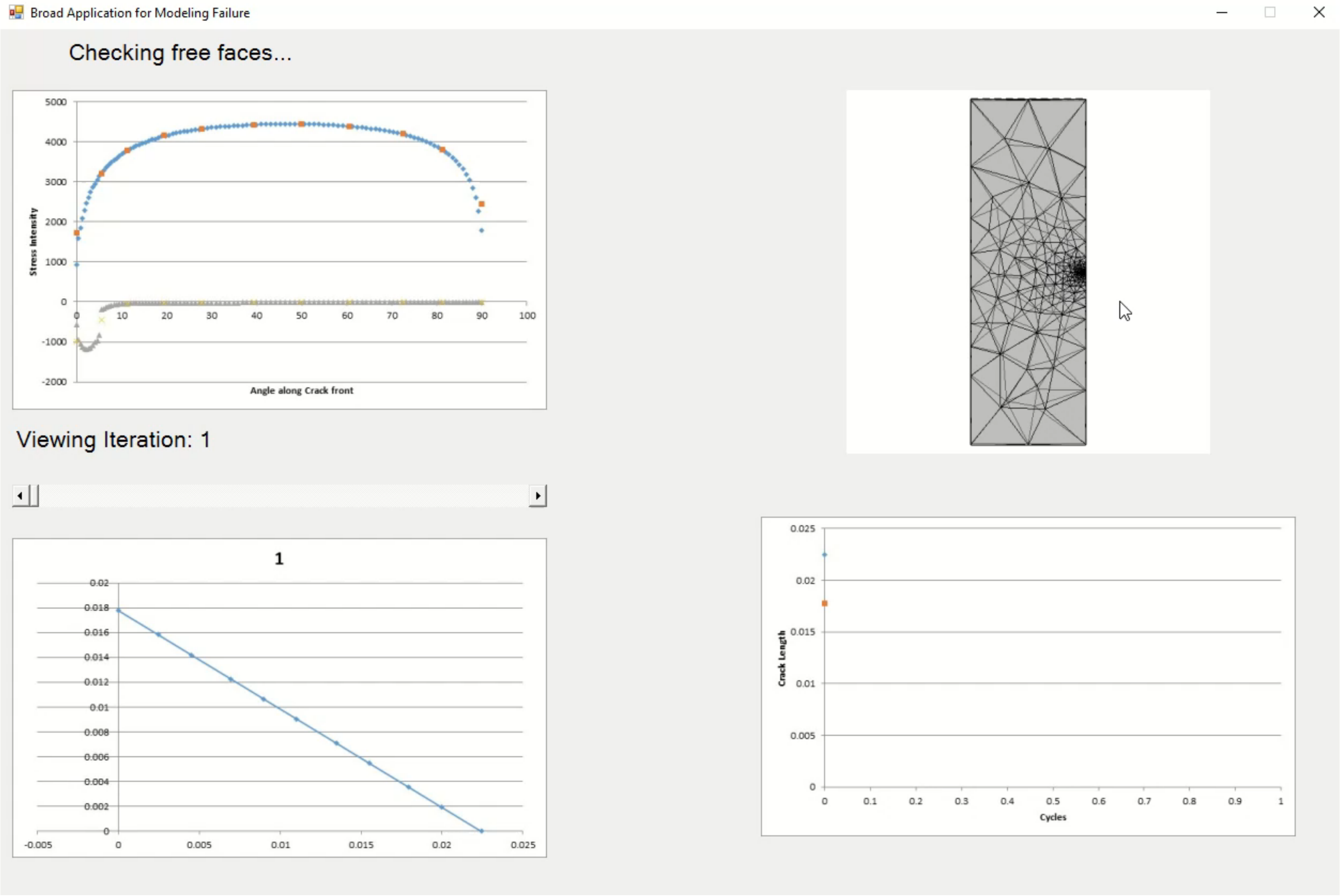
- Objective: Eliminate the effect of the hole K_t while preserving the RS field created by Cx

1. Machine ¼” thick Specimen
2. Install Strain Gauges (6)
3. CX Hole (record strain from CX) and final ream
4. Cut Specimen into two bars (measure strain to determine stress relaxation – next slide)



Kt Free Coupons

- Video of tensile at bore to avoid crack arrest



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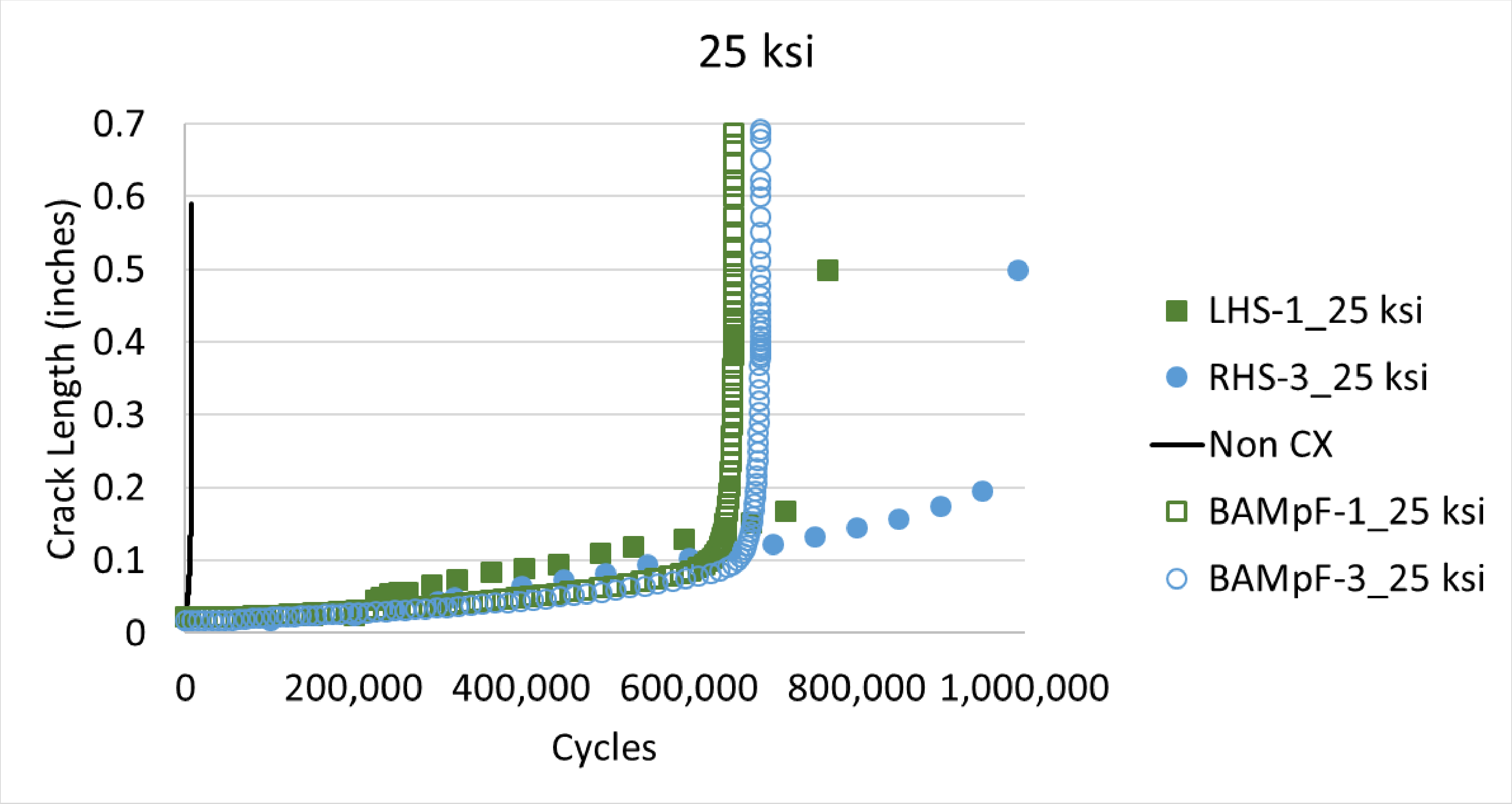
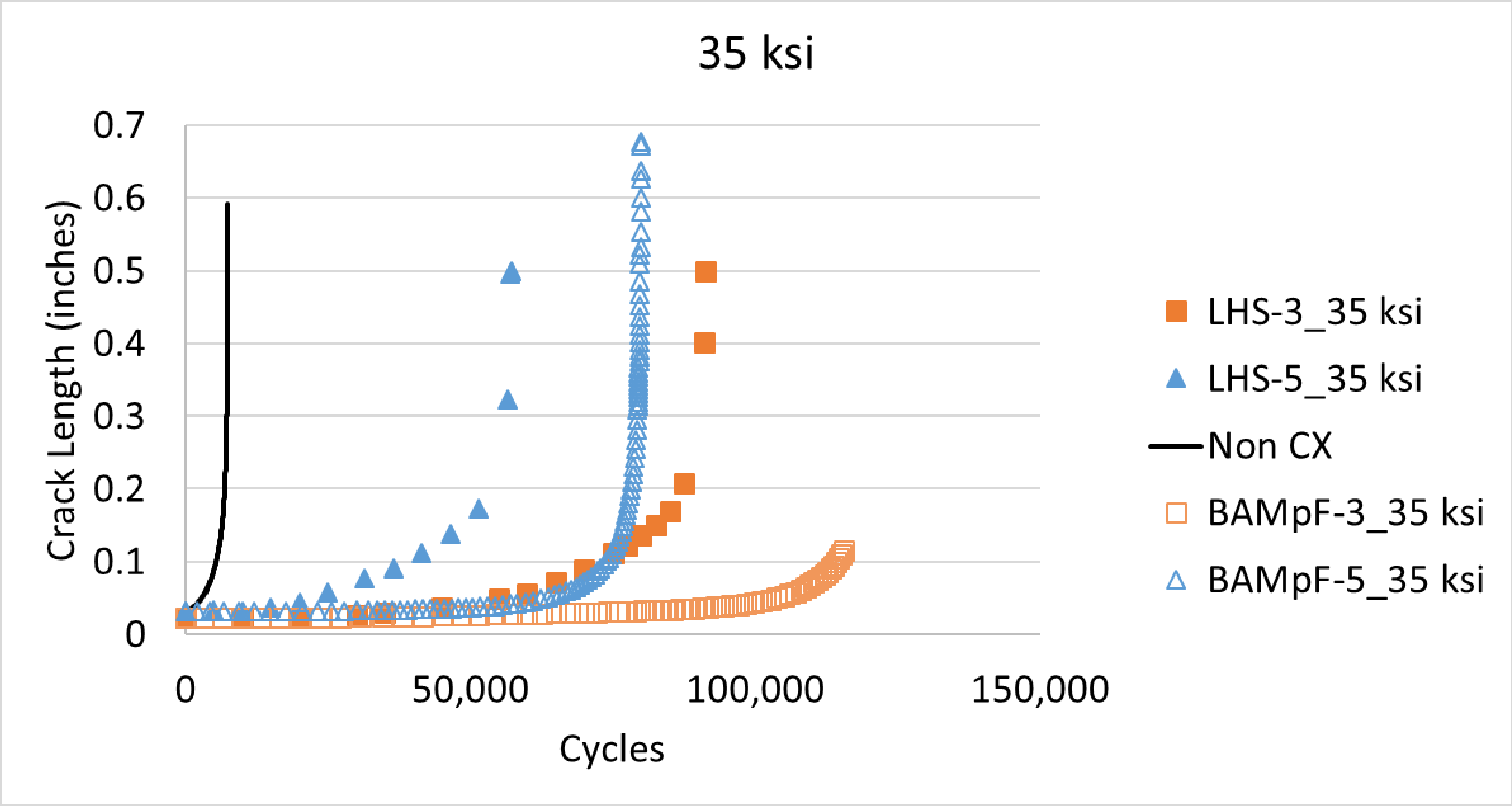
Kt Free Coupons

- 25ksi Results
  - With minimal RS until 0.02" into the part, BAMpF results correlate very well



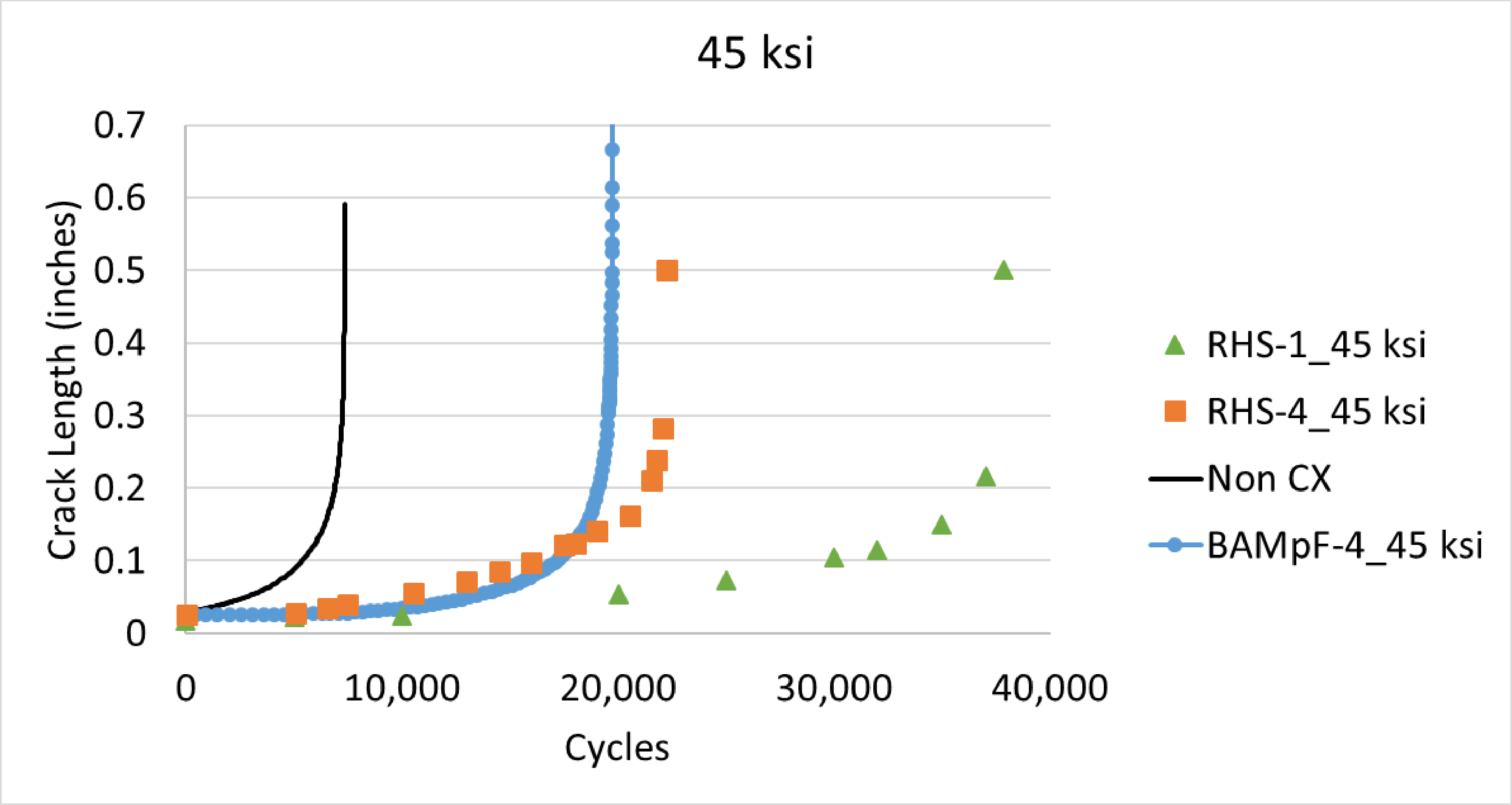
Kt Free Coupons

- 35ksi Results
  - Minimal RS for first 0.02" over predicts



Kt Free Coupons

- 45ksi Results
  - Model correlates well for .02" minimal RS approach



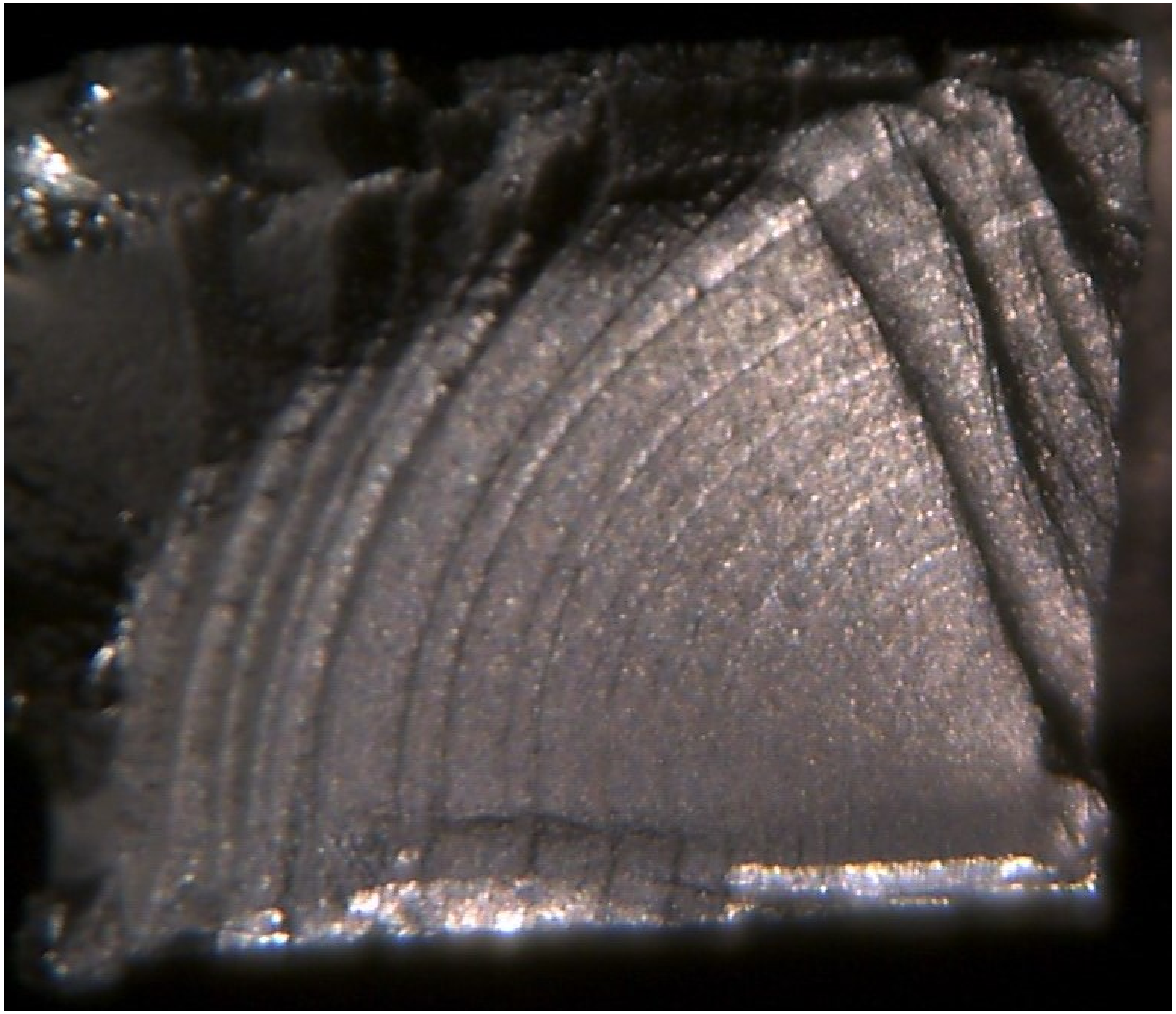
Kt Free Coupons

- Conclusions/Questions
  - Tests ran shorter than initially predicted
  - For analysis to correlate with prediction RS field needed to be changed
  - Why did blind predictions not correlate well?
  - How does thru thickness growth rate of Kt free tests compare to standard CX hole tests?
  - How does surface growth compare to standard CX hole tests?
  - How does aspect ratio compare to cracks from a standard CX hole?
  - Can strain data from machining operations inform better predictions?

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Kt Free Coupons

- Questions?



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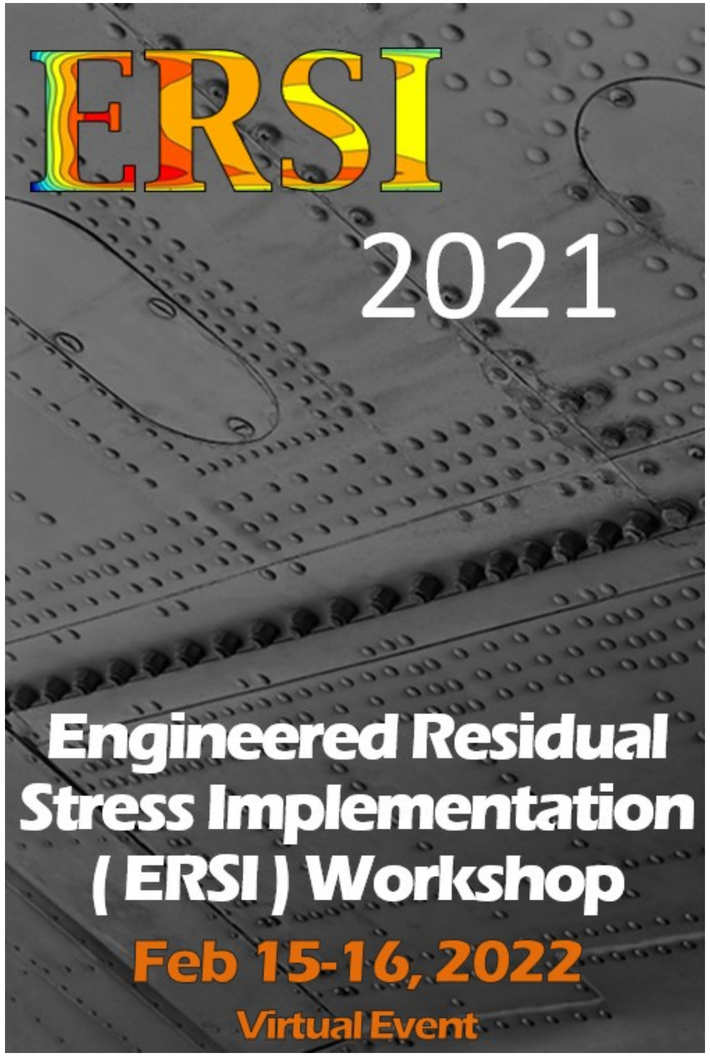
    - Surface Corrections for Multi-Point Analysis
  - Testing
    - Kt-Free Coupons
- **2022 Focus Areas**



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2022 Focus Areas

- Spectrum Loading and Retardation
  - Investigate the appropriate methods to characterize crack retardation due to spectrum loading for conditions with residual stress
  - Gather and/or develop test data to support validation of methods
  - Document best practices and lessons learned
- Interference Fasteners and Residual Stress
  - Investigate the relationship between interference fit fasteners and residual stresses from Cx and/or Taper-Lok
  - Identify appropriate methods to incorporate interference fit fastener benefit for conditions with residual stress
  - Document best practices and lessons learned
- Durability Testing and Fatigue Life Benefits
  - Review existing test data and develop summary to document Cx life impacts on early crack nucleation and growth
  - Identify any testing needs to further refine understanding

Conclusions/Summary

- Incrementally, we are making progress within the Analysis Methods and Validation Testing Committees
  - Thanks to those individuals that have contributed
- We must continue to push forward with a focus on refining our analytical capability and addressing technical gaps

Historical

Residual Stress is considered a problem or used as a *band-aid* to address design deficiencies

→

Emerging

Residual Stress Engineering is a *conventional technology* that assures performance

Questions?