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Fatigue Life Modeling in Residual Stress Fields

Negative-R Crack Growth Testing

ERSI Workshop
Layton, UT

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ï Lucky Smith

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Background

- Much of the crack growth from CX holes can occur in regions of negative R_{tot}.
- Do we have well-characterized negative R test data, and does it have a large impact?
- Reference AFRL negative R data from 1997**
  - These data formed basis for ñR-LOò cut-off parameter
  - Below R-LO, which is a qK value, no further shift in crack growth rate curves is modeled
- **GOAL:** conduct limited negative-R crack growth testing to compare to AFRL historical data
  - center cracked M(T) panels (as AFRL tested)
  - part-through crack ñdog-bonesò

** Boyd, K., Elsner, J., Jansen, D, Harter, J.: Structural Integrity Analysis and Verification for Aircraft Structures, Volume 2, Effects of Compressive Load on the Fatigue Crack Growth Rates of 7075-T651 and 2024-T3 Aluminum Alloys, WL-TR-97-3017. August 1996.

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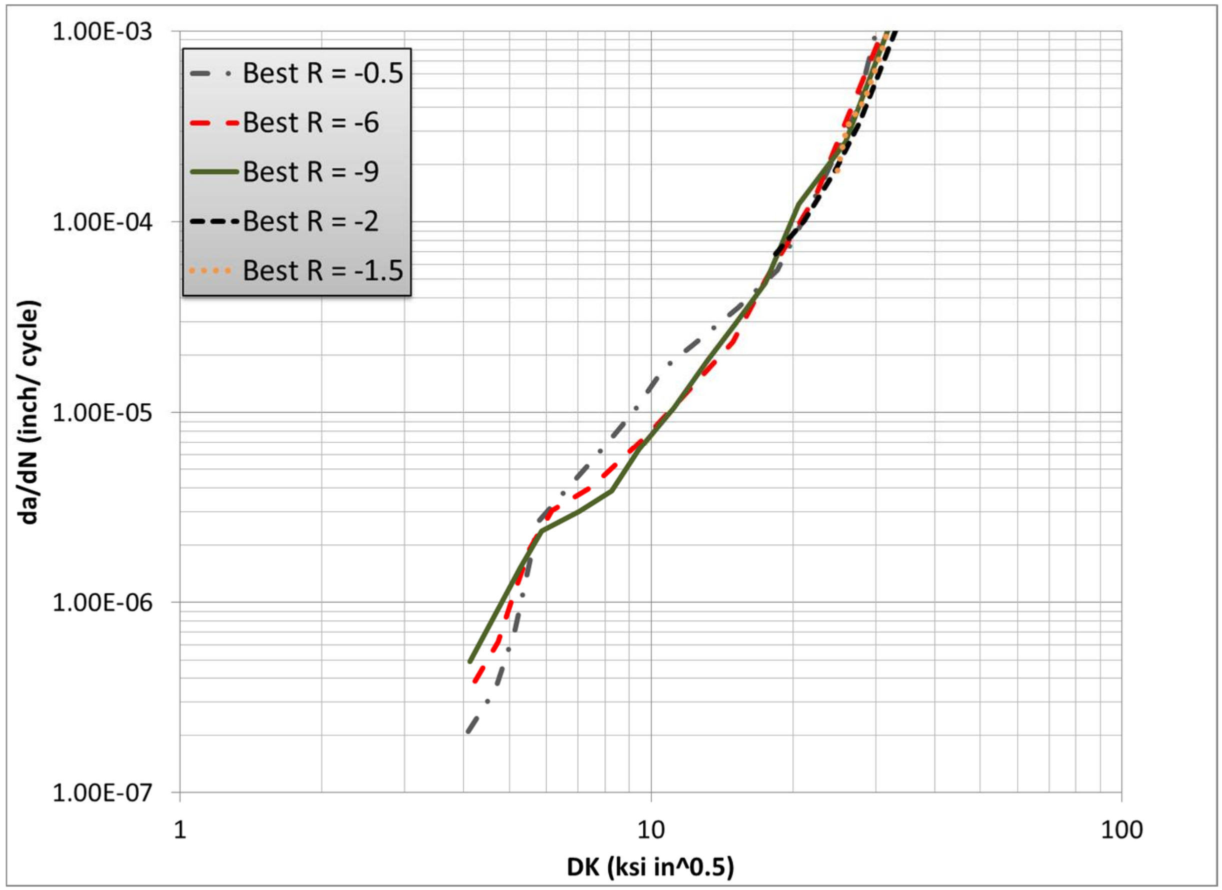
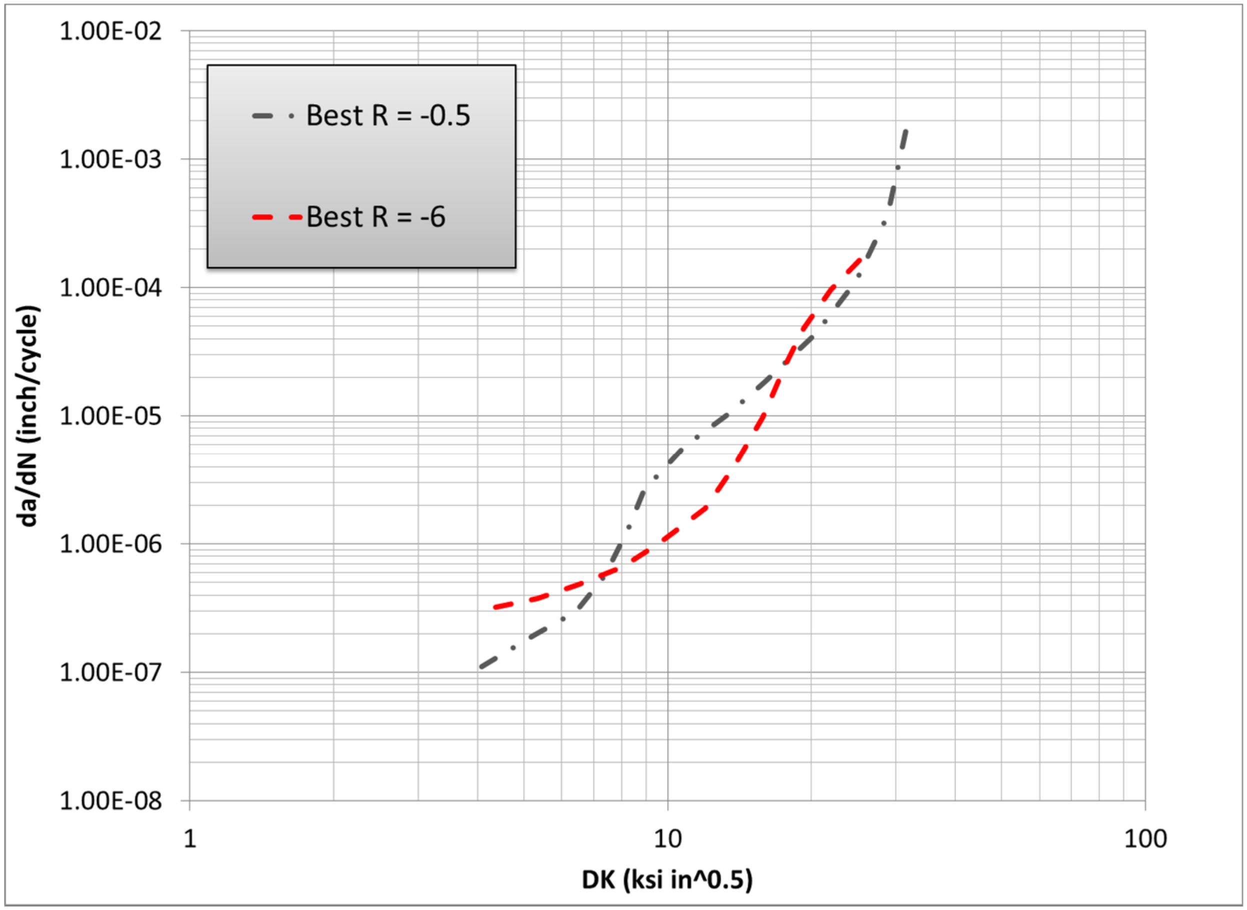
1997 AFRL Data: 7075-T651

- Original test data is not available.
- Had to use digitized data from pdf report.
- Only R = -0.5 data seems to be unique, and only up to qK of about 15
- Rest of the data seems to support no further shifts in stress ratio curves at lower R



1997 AFRL Data: 2024-T351

- Original test data is not available.
- Had to use digitized data from pdf report.
- Only 2 stress ratios tested.
- Appeared to have problems with plasticity
- R = -6 curve suspect



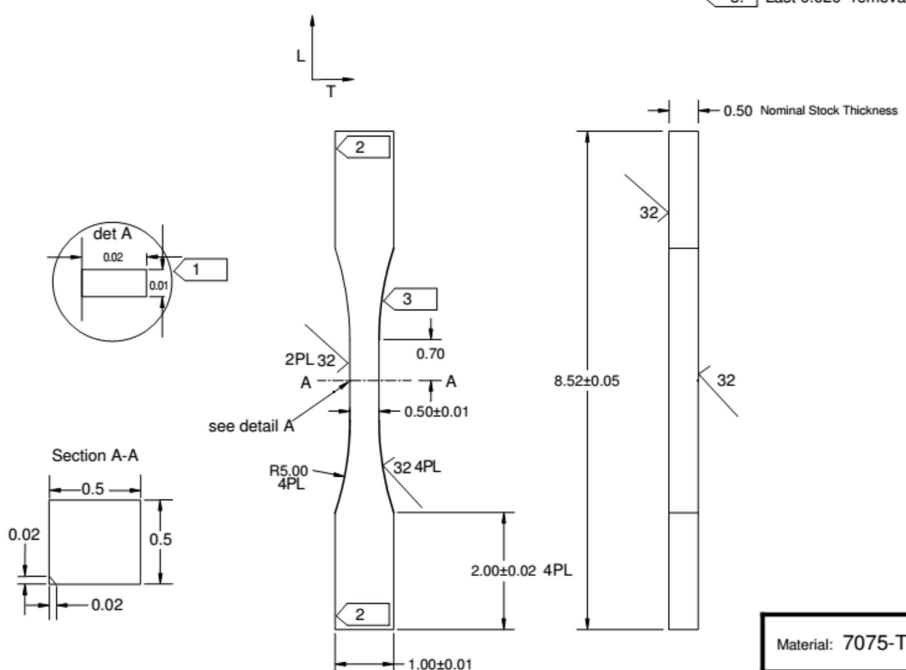
Test Matrix

- 6 specimens of 2024-T351
  - R = -1
    - 1 x M(T) same as AFRL design
      - requires buckling guides
      - through-crack design
    - 2 x dogbones
      - non-standard geometry
      - no need for buckling guides
      - part-through crack design
  - Repeat for R = -4
- Repeat 6-specimen matrix for 7075-T651

Dogbone Crack Growth Specimen

All dimensions in inches

1. Use fine saw or EDM to place notch on one corner of specimen (also see Section A-A)
2. Specimen ID: 6O1-xx-D (where xx = 01 to 06)
3. Last 0.020" removal on edges must be done in 0.005" passes.



Å No buckling guides required

Å Precrack / test loads must be balanced to avoid compressive yield for R = -4 (especially in 2024-T351)

Å Specimen design avoids plastic collapse in net section throughout range of reasonably collectable data

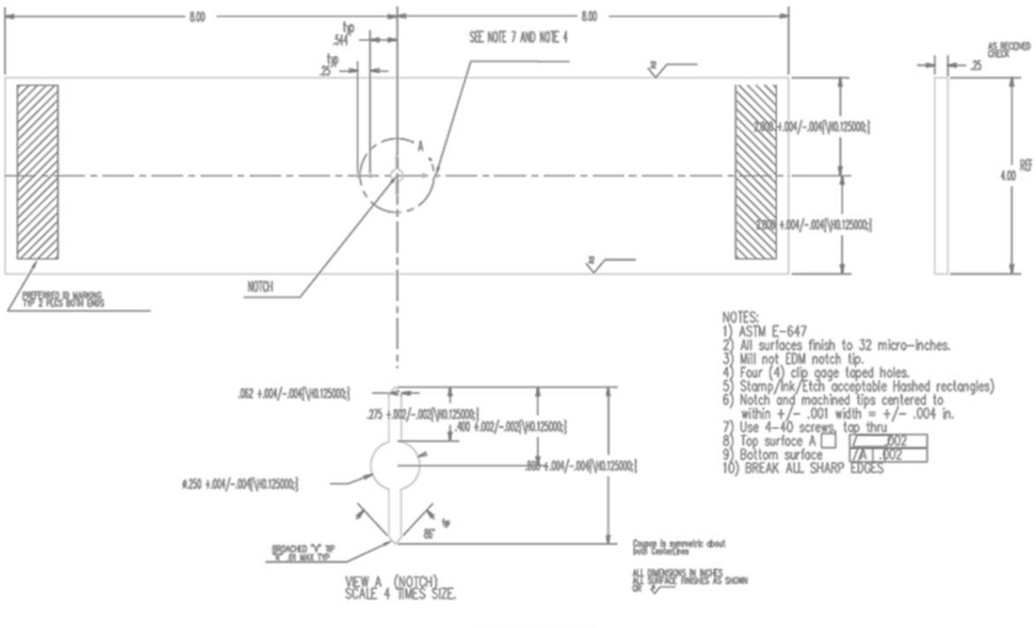
Material: 7075-T651 AL	QTY: 6	Condition:	Finish: 64 RMS unless noted
Scale:	Task: 2.10	APES, INC.	

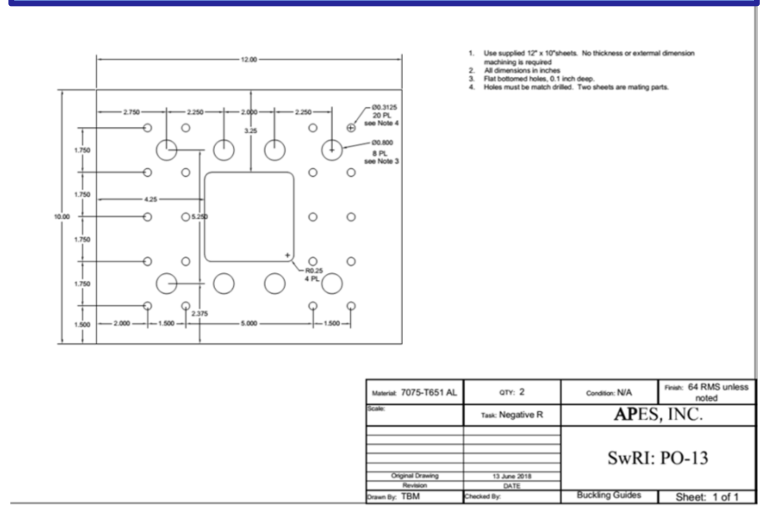
SwRI PO-13 (A-10)

M(T) Crack Growth Specimen

- Buckling guides required.
- ½ inch aluminum plate
- Nylon spacers used against specimen
- Only 8 contact points (4 front / 4 back)

Made from 0.313-inch nominal plate.





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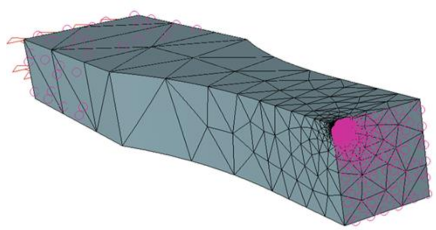
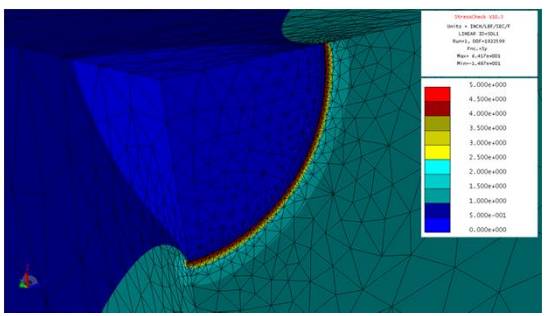
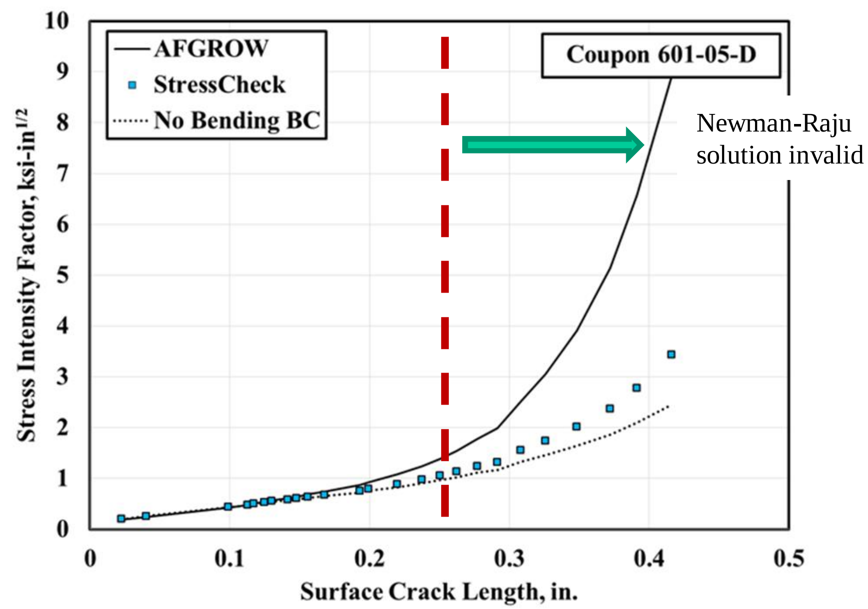
Stress Intensity Calculations

- Corner crack tests go to crack sizes beyond Newman-Raju solutions in AFGROW
  - Used StressCheck to compute K
  - Boundary conditions: modeled full wedge grip constraint:







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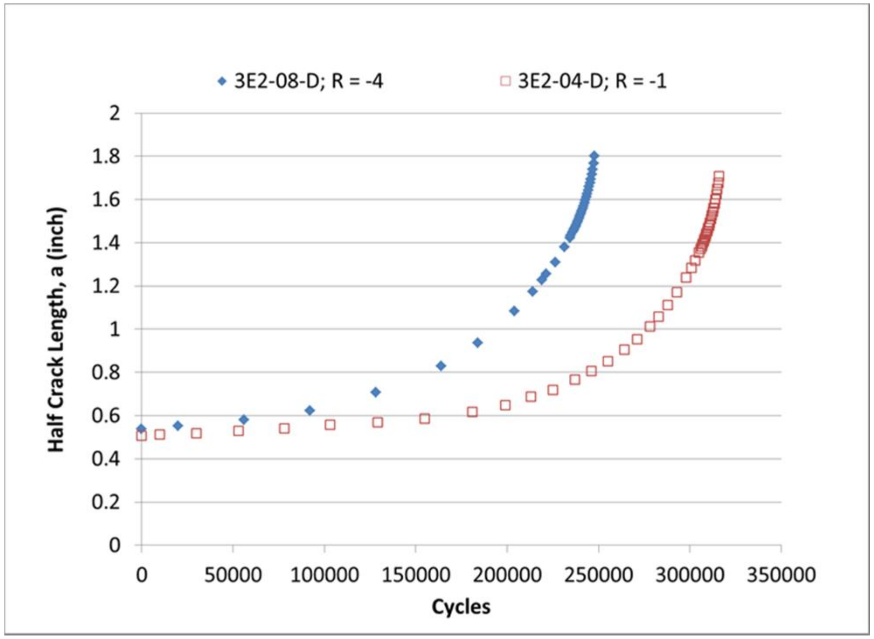
Middle-Tension Panels

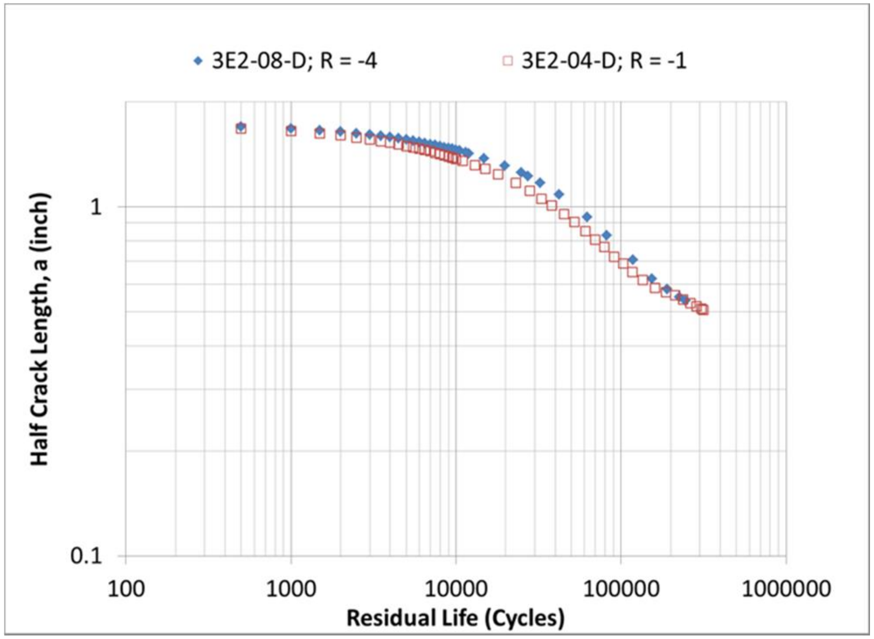
Crack Growth Data

- Crack Length vs. Cycles
- Residual Life
- Crack Growth Rate vs. ΔK

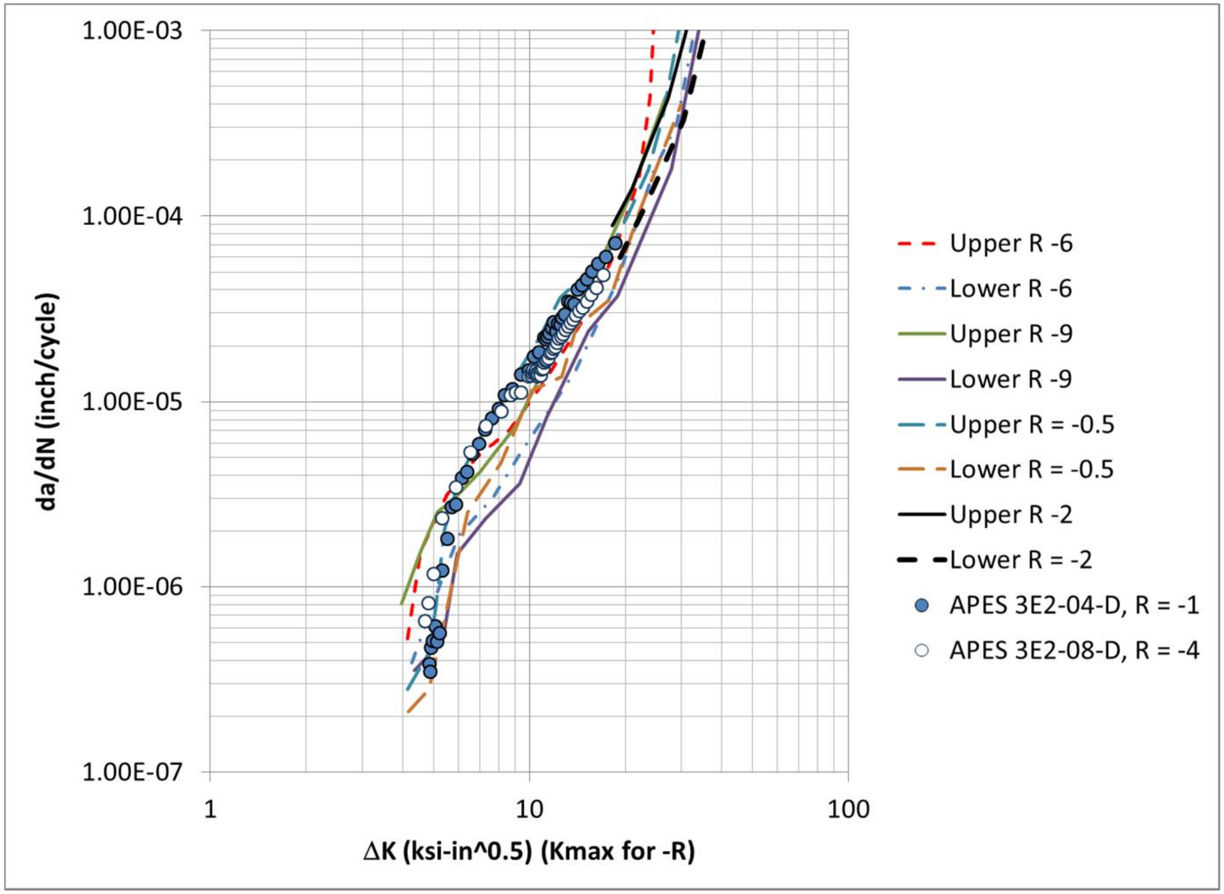
7075-T651 M(T)

Crack Growth and Residual Life





7075-T651 M(T)
Crack Growth Rate



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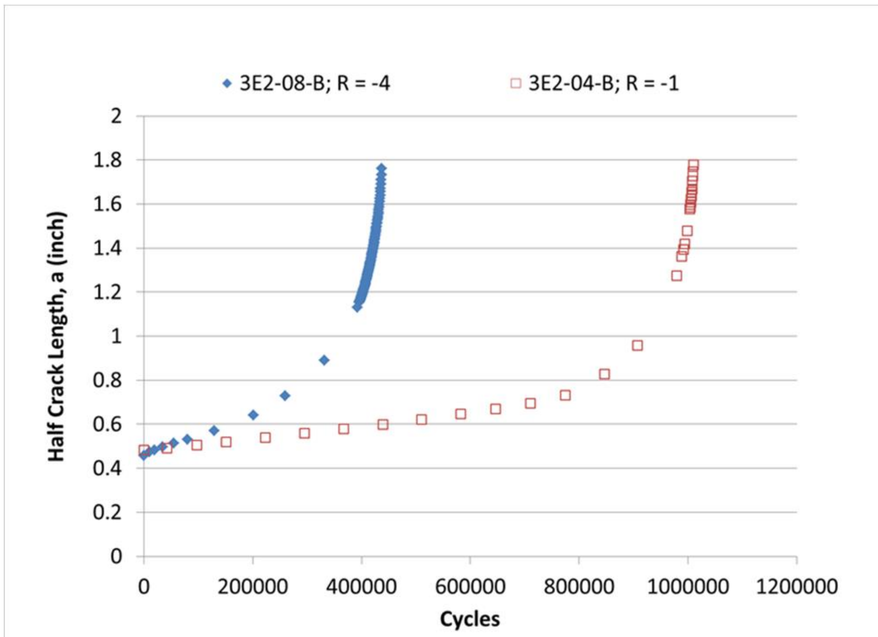
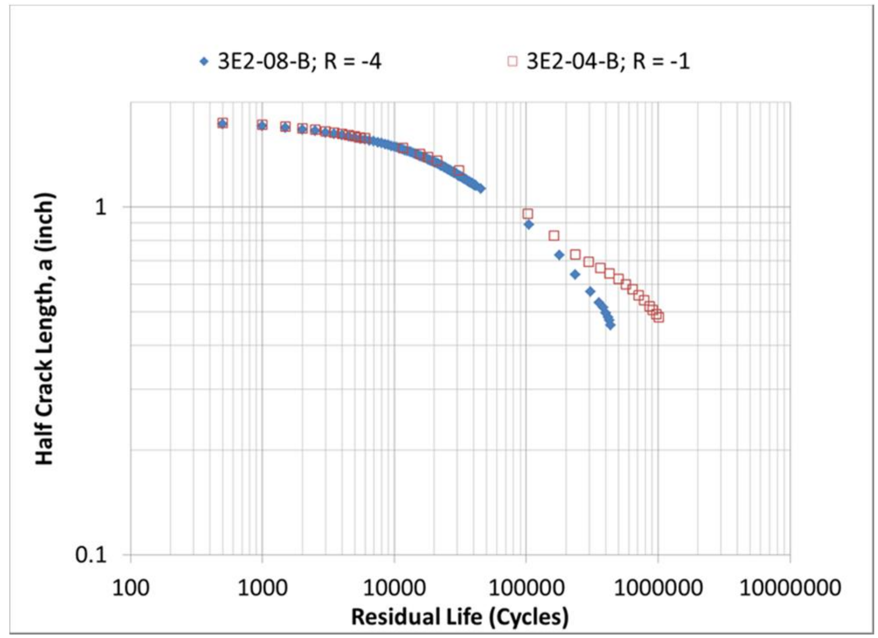
2024-T351 M(T)

Crack Growth and Residual Life





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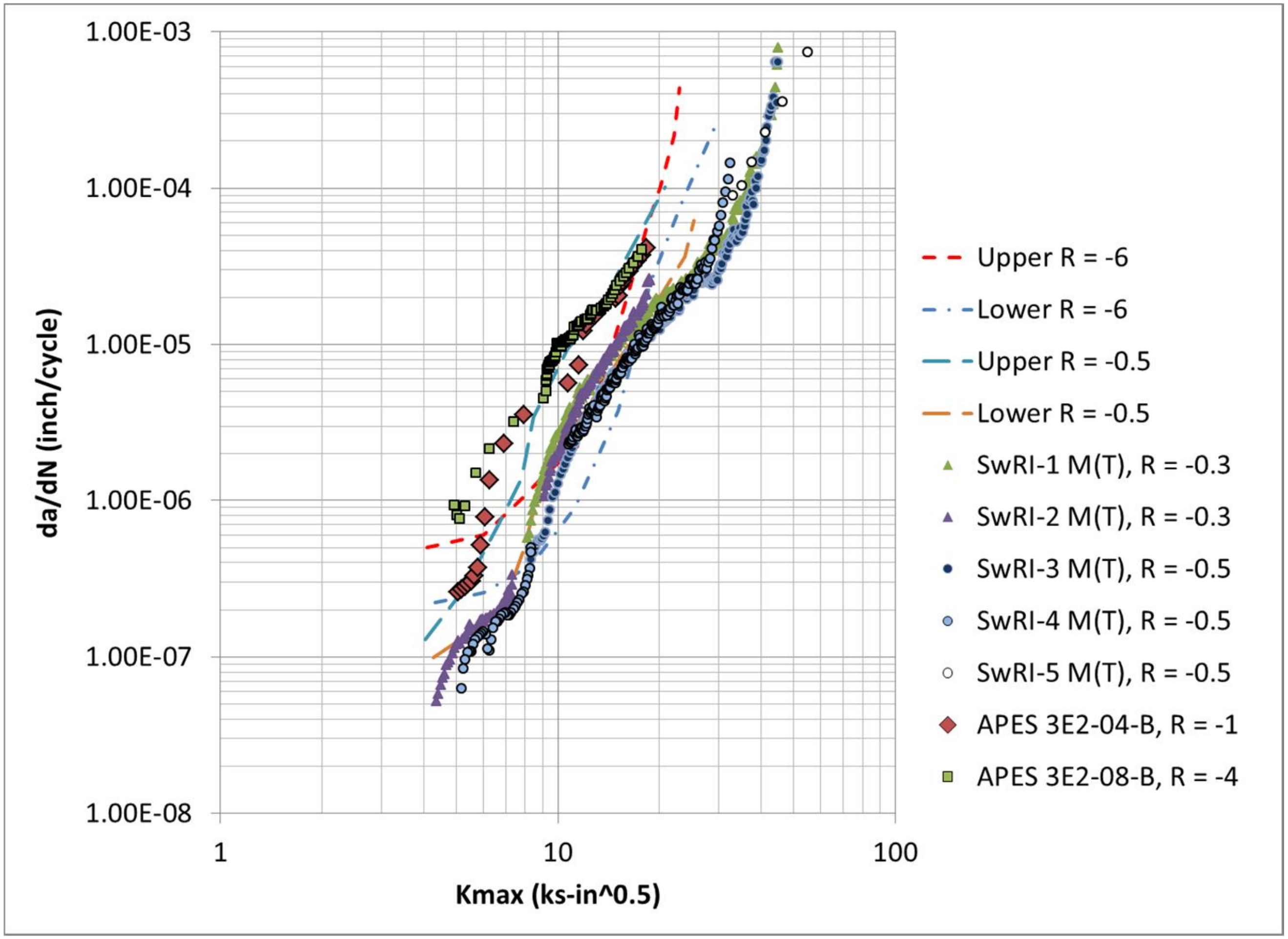
2024-T351 M(T)
Crack Growth Rate



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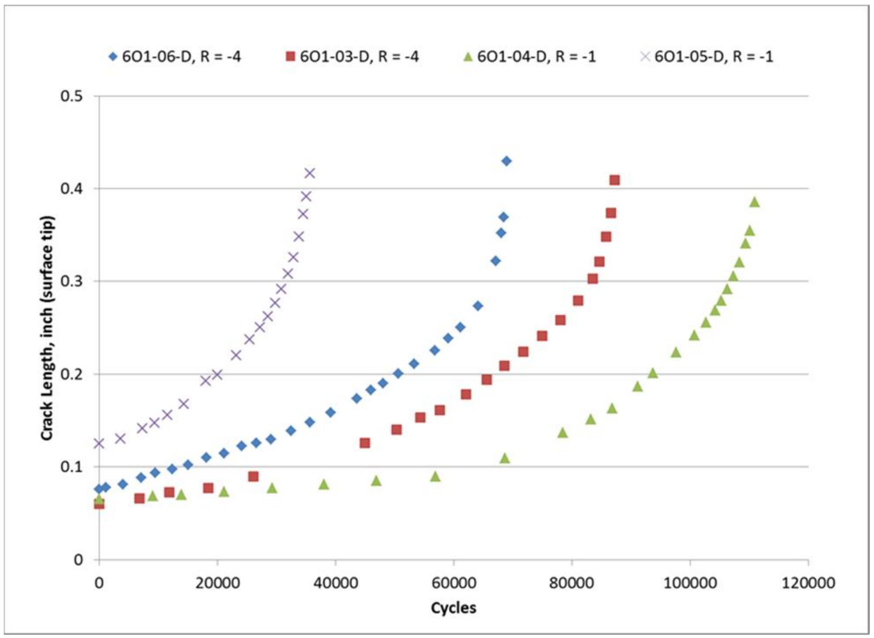
Corner Crack (CC) Dogbone

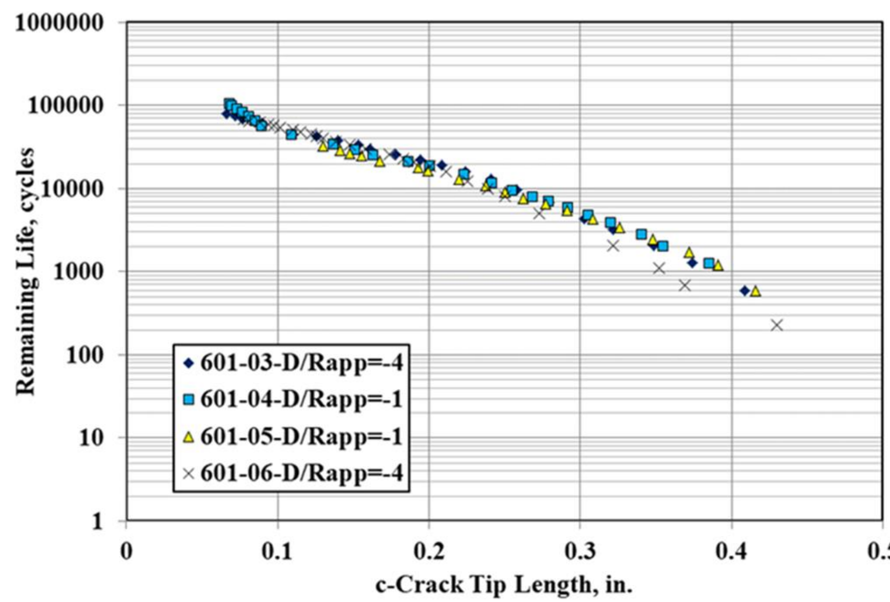
Crack Growth Data

- Crack Length vs. Cycles
- Residual Life
- Crack Growth Rate vs. φK

7075-T651 CC

Crack Growth and Residual Life





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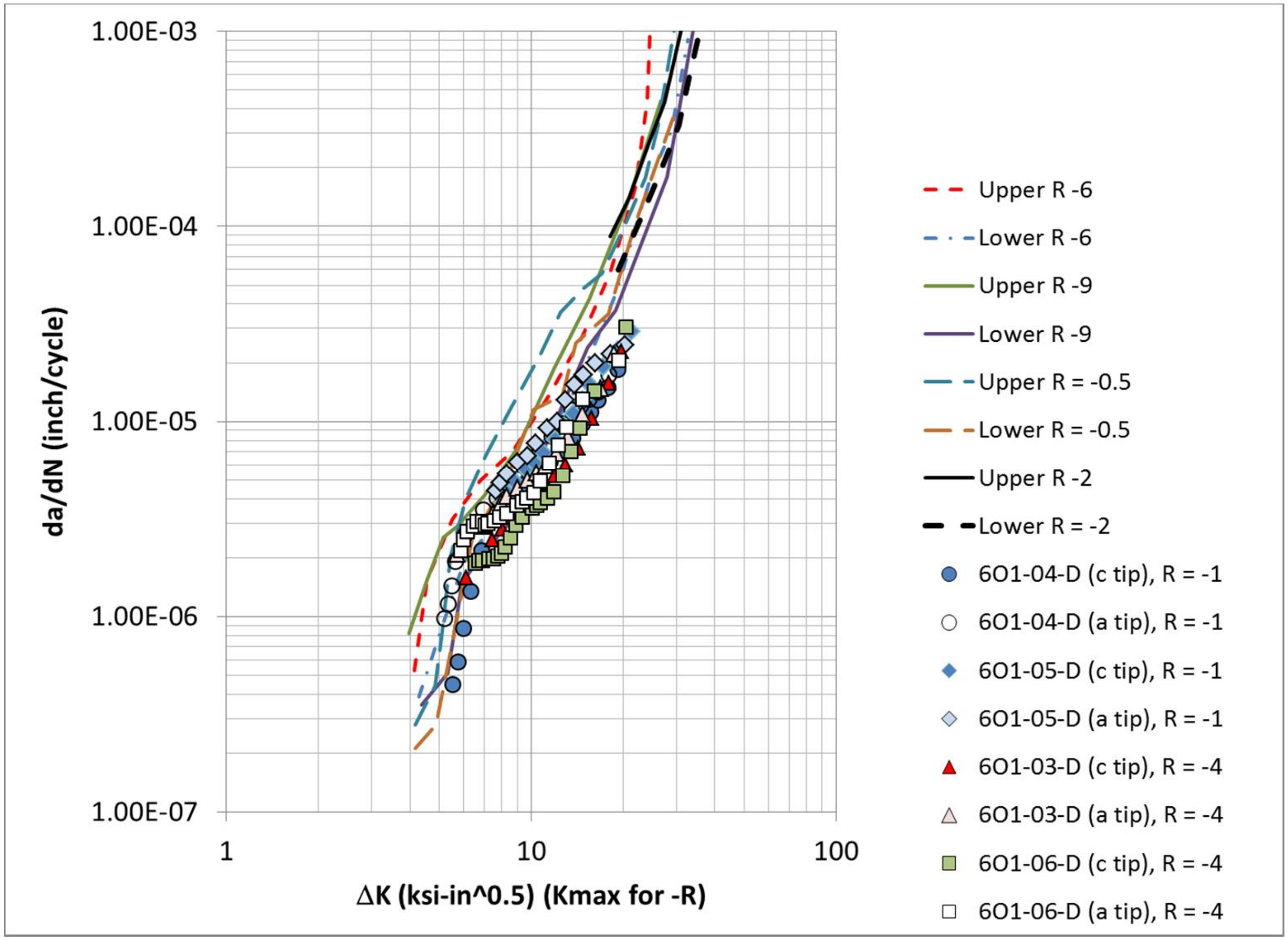
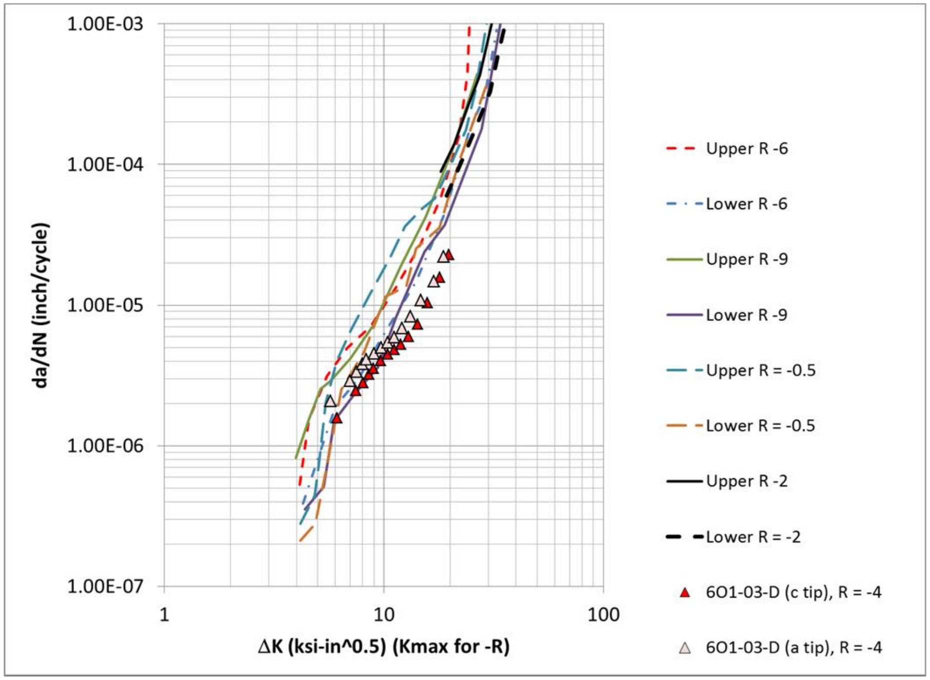
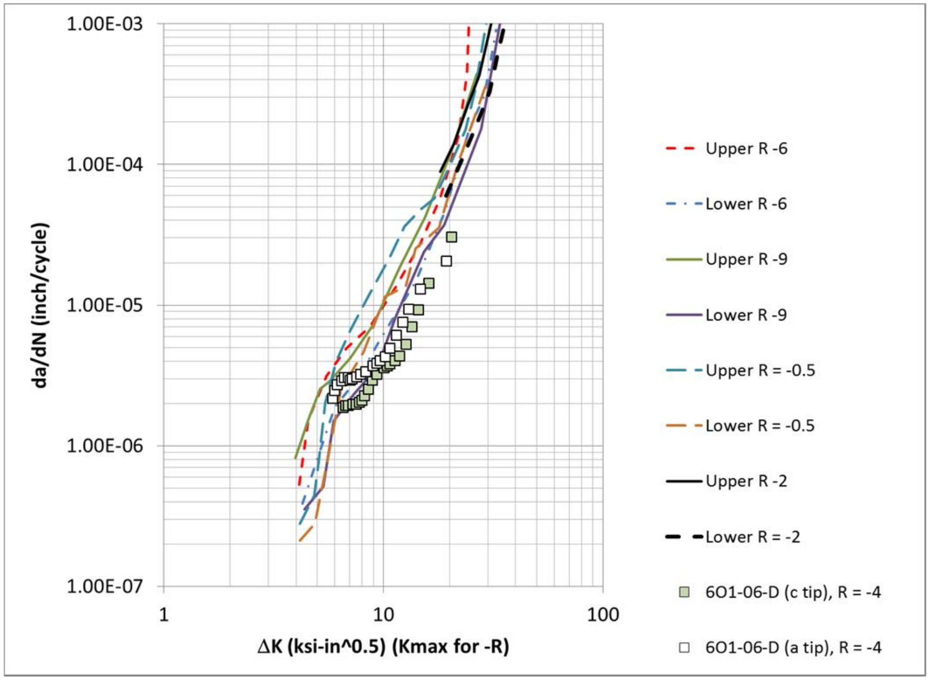
7075-T651 CC

Crack Growth Rate



7075-T651 CC (R = -4)





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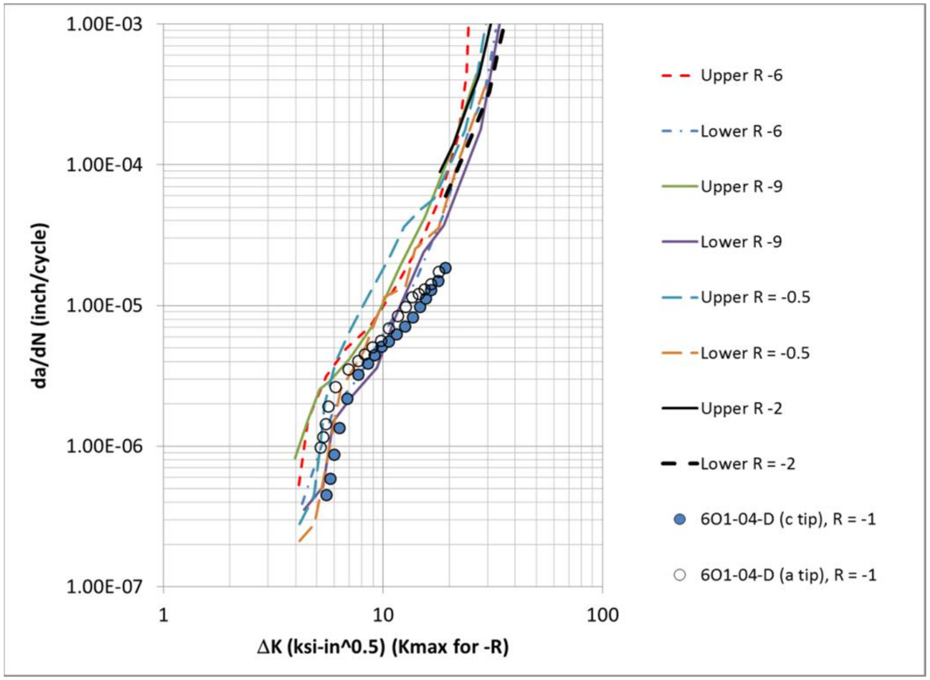
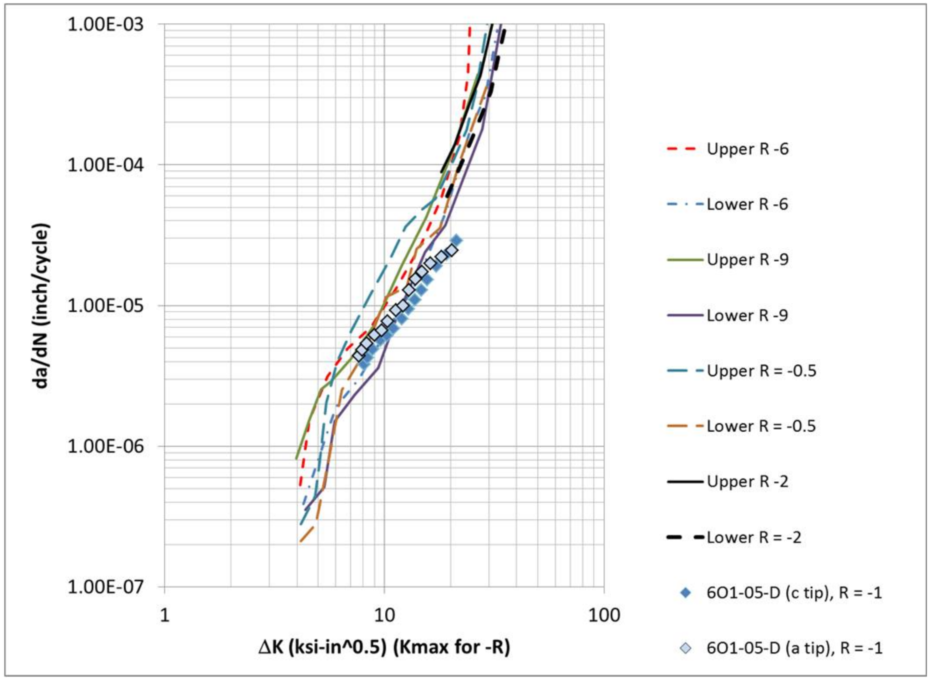
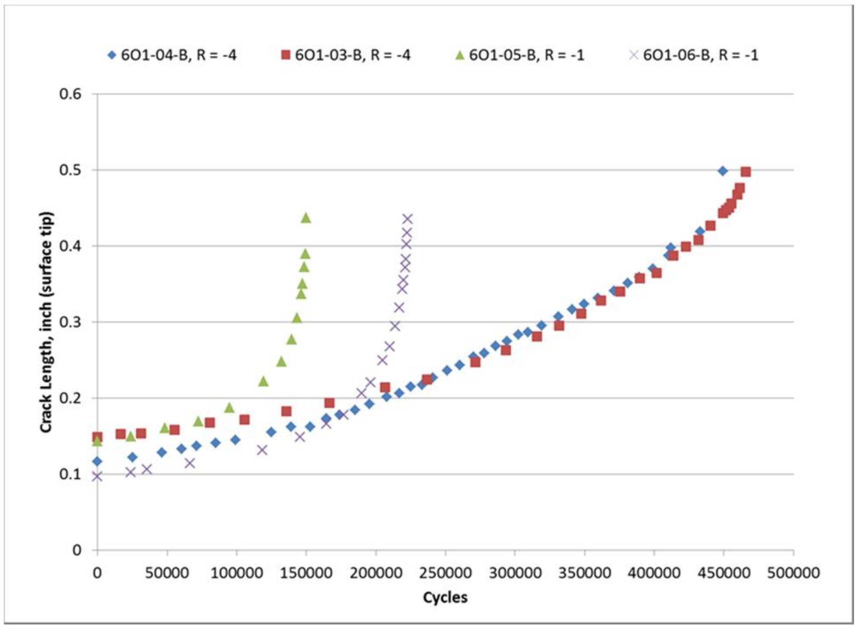
7075-T651 CC (R = -1)

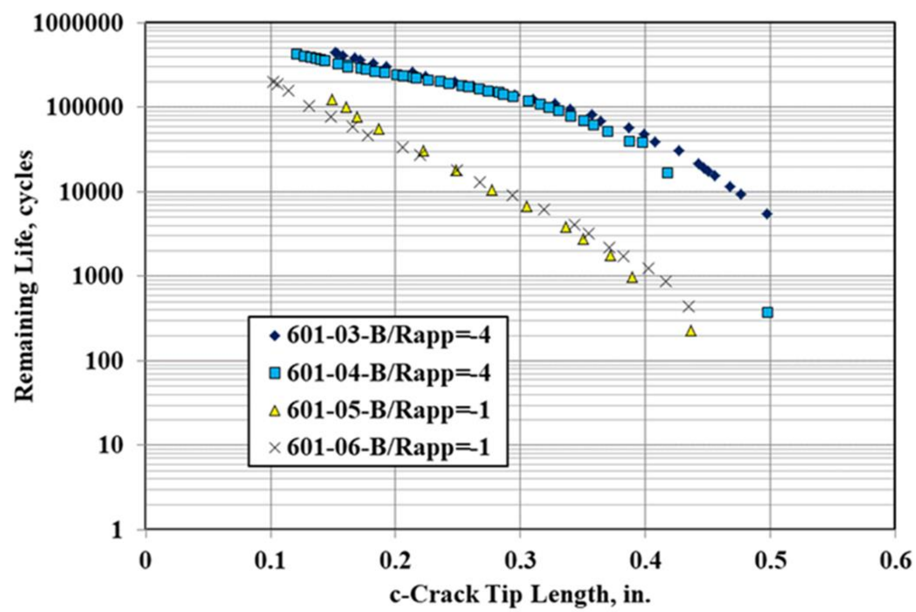




2024-T351 CC

Crack Growth and Residual Life





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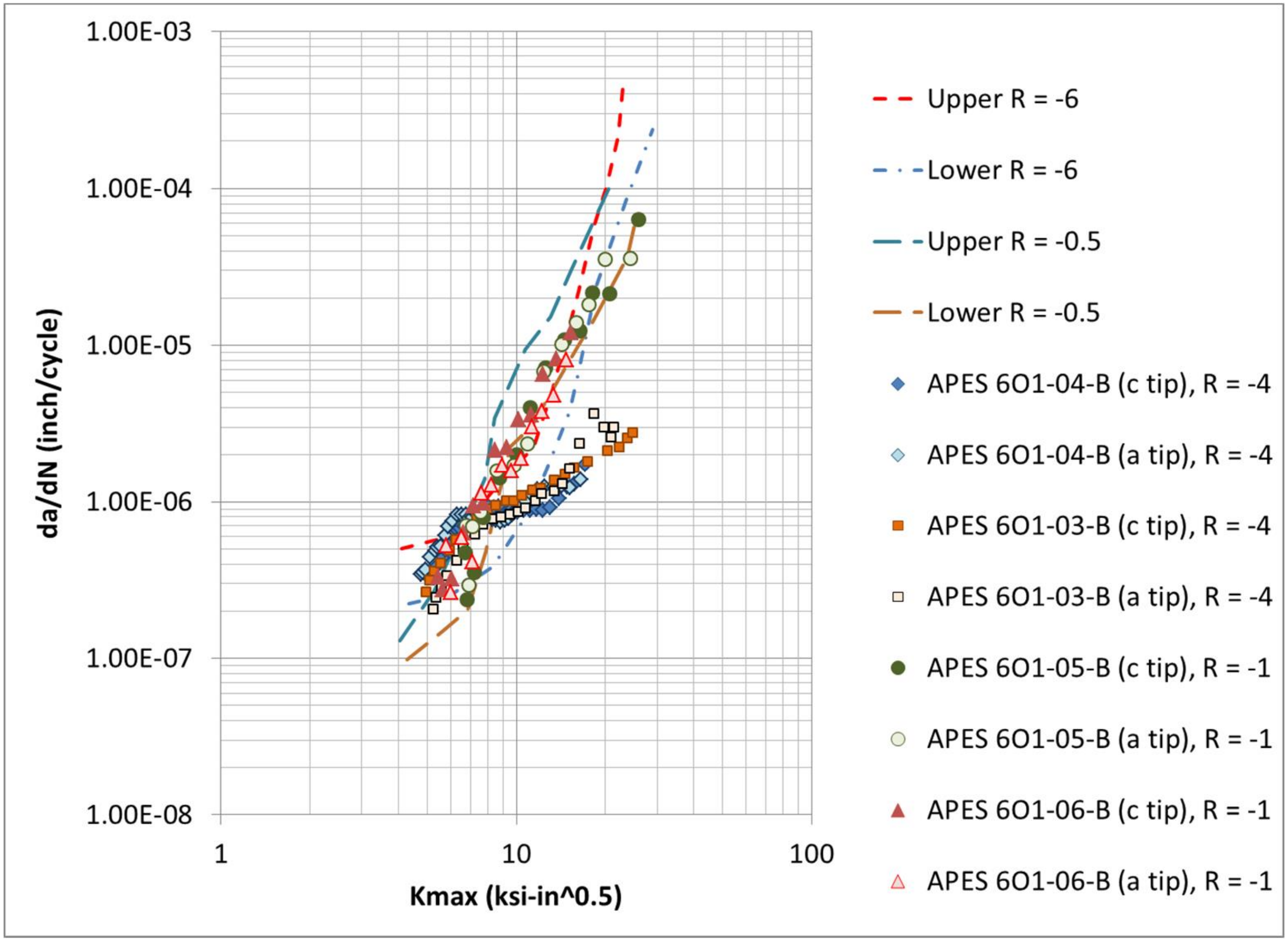
2024-T351 CC
Crack Growth Rate



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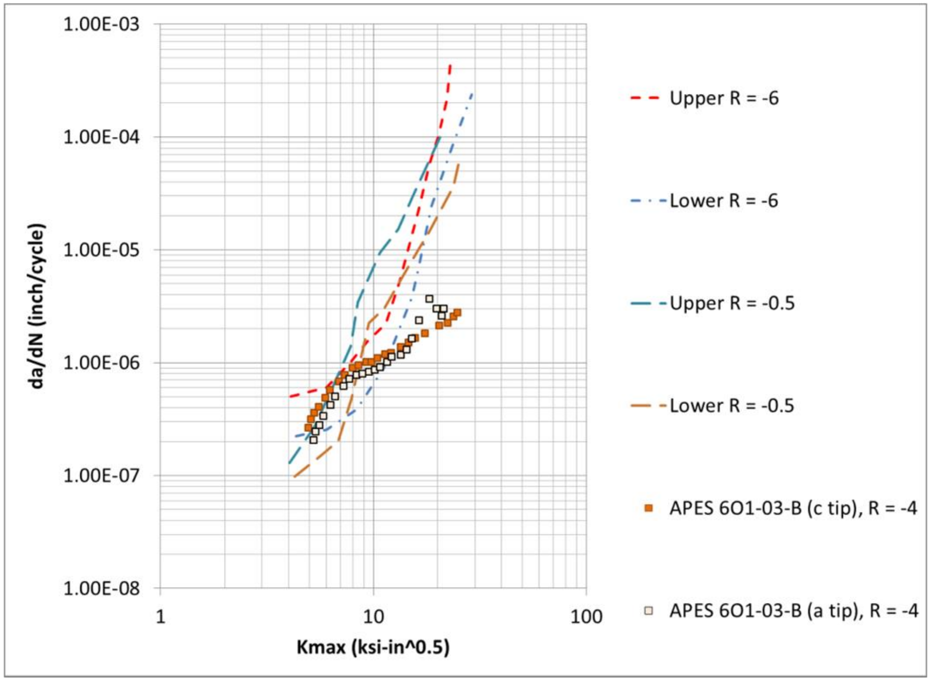
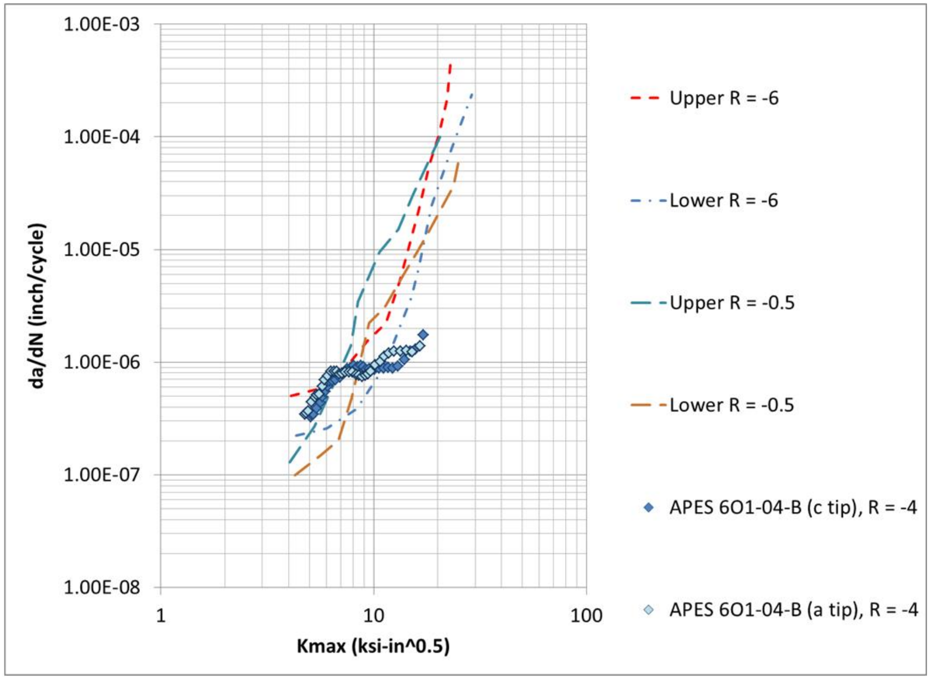
2024-T351 CC (R = -4)





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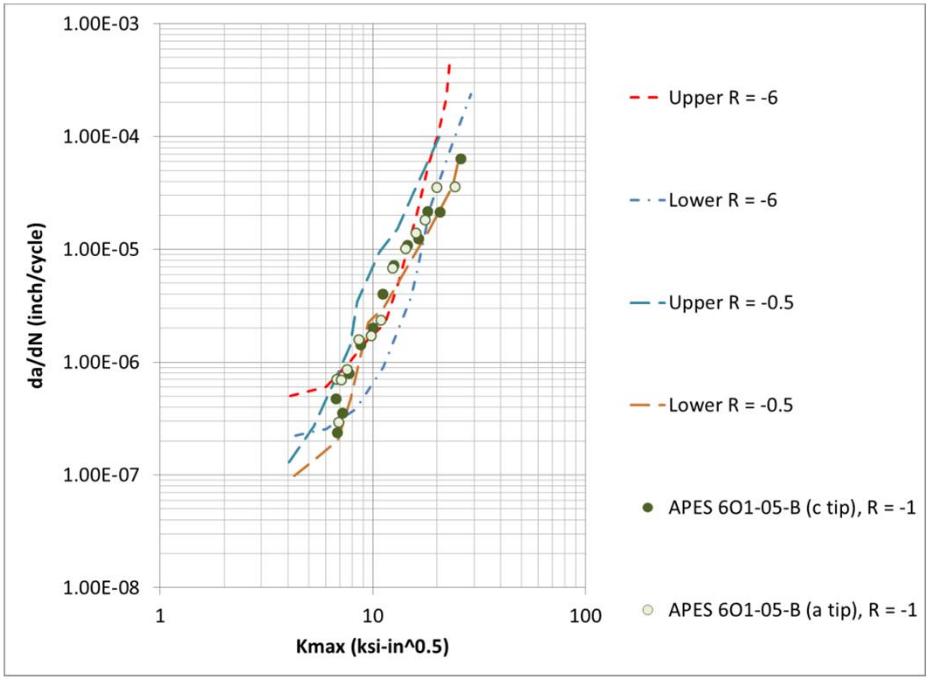
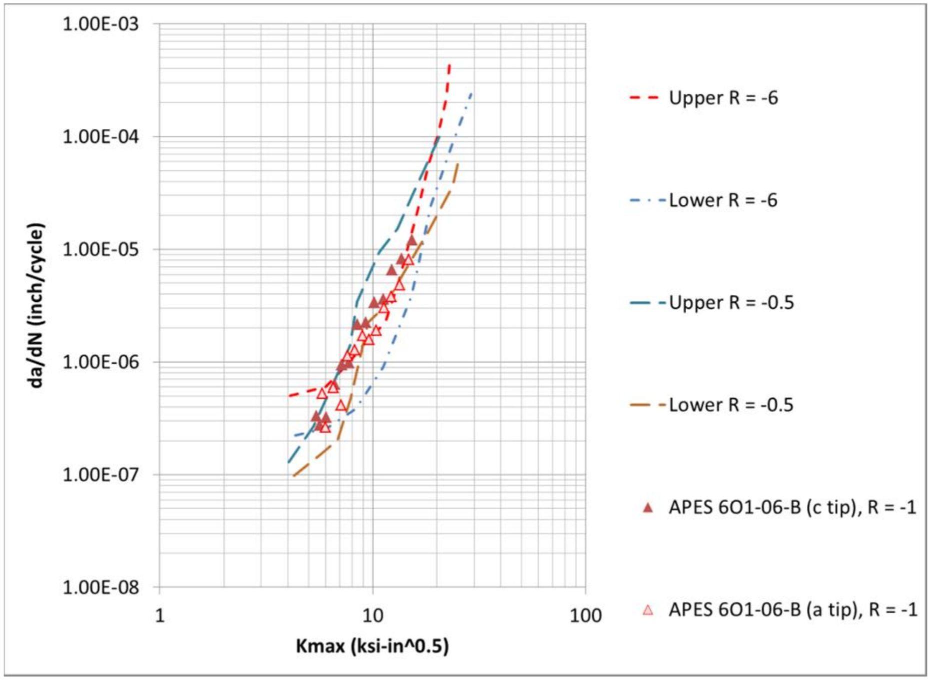
2024-T351 CC (R = -1)





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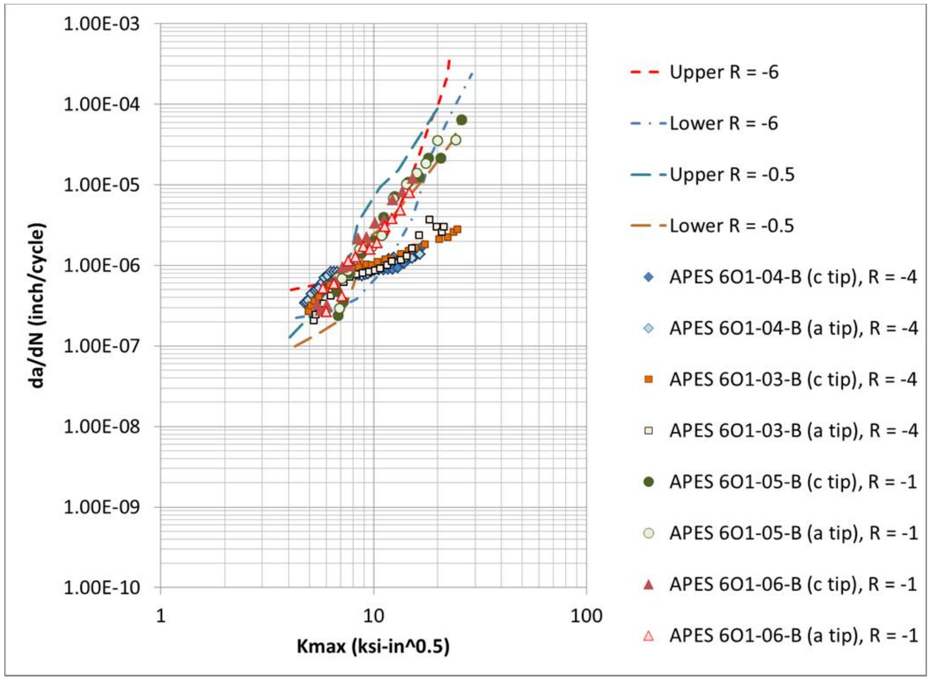
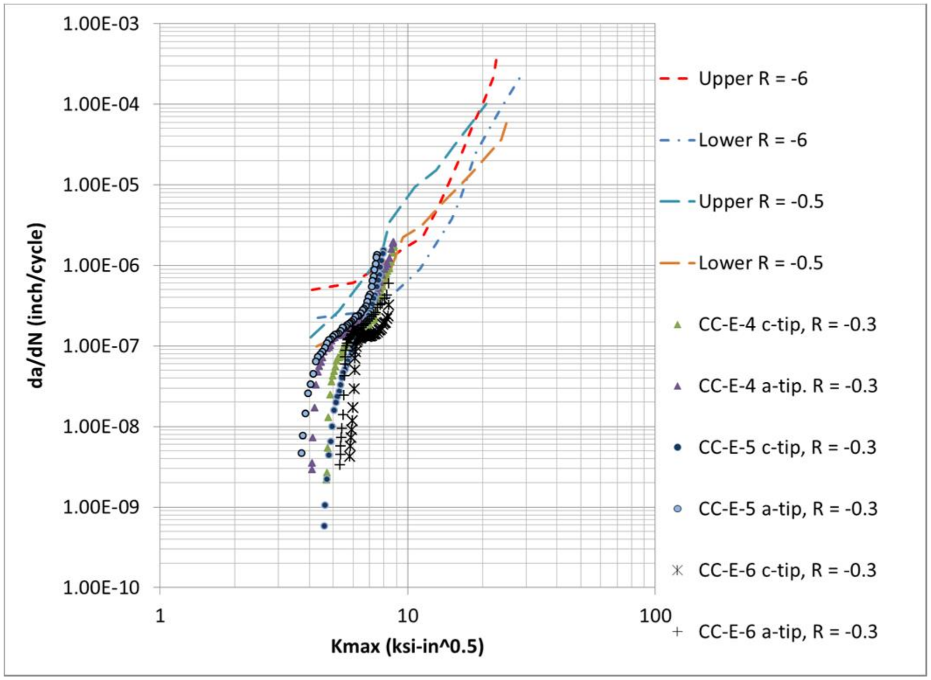
Comparison of CC Growth Rates APES vs. SwRI



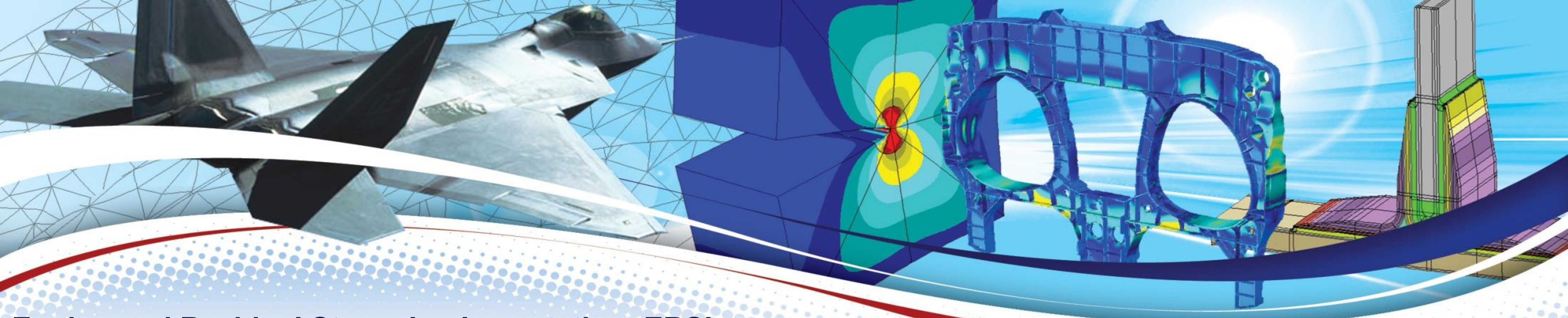


Summary

- 7075-T651 M(T) data
  - no difference between R = -4 and R = -1
  - agrees well with AFRL historical data
- 7075-T651 CC data
  - only slight difference between R = -4 and R = 1 data
- 2024-T351 M(T) data
  - residual life curves show differences below a = 0.9 inch
  - manifests as faster crack growth rates at lower qK < 7 for R = -4
  - rate curves completely collapse for qK > 11 ksiãin
  - Data at qK > 11 ksiãin agrees well with upper bounds of AFRL historical data
  - APES data categorically faster than SwRI data, which tends to lower side of AFRL data
- 2024-T351 CC data
  - residual life curves between R = -1 and R = -4 are completely different
  - R = -1 data: compare favorably with AFRL historical data
  - R = -4 data: the less said the better
    - compression side of cycle was 80% of compressive yield (L direction, A Basis, MMPDS, Table 3.2.3.0(b_1)
    - did this cause the problem ?
    - R = -4 tests in 7075-T651 CC specimens were only 50% of compressive yield.
- Differences certainly exist between R = -1 and R = -4 in 2024-T351, but this appears to be test issue rather than true material behavior.

Questions ?

Answers ?



Engineered Residual Stress Im lementation ERSI
orksho – Clear ield, tah
Analysis Methods Su committee

RS Crack Closure

Experimental Observations and Modeling

Ricardo Actis ●Thomas Mills ● Scott Prost-Domasky ● Craig Brooks

September 2018

esrd

Distribution A: Cleared for public release 88ABW-2018-4366

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- FCG data: 7075-T7351 specimens with a cold-worked hole
- Constant amplitude loading – R_{app} = 0.02, 0.10, 0.40, 0.60, 0.70, 0.80
- 24 specimen tested
- 4 for each R_{app}

EVALUATION OF EXPERIMENTAL DATA

Data Analysis

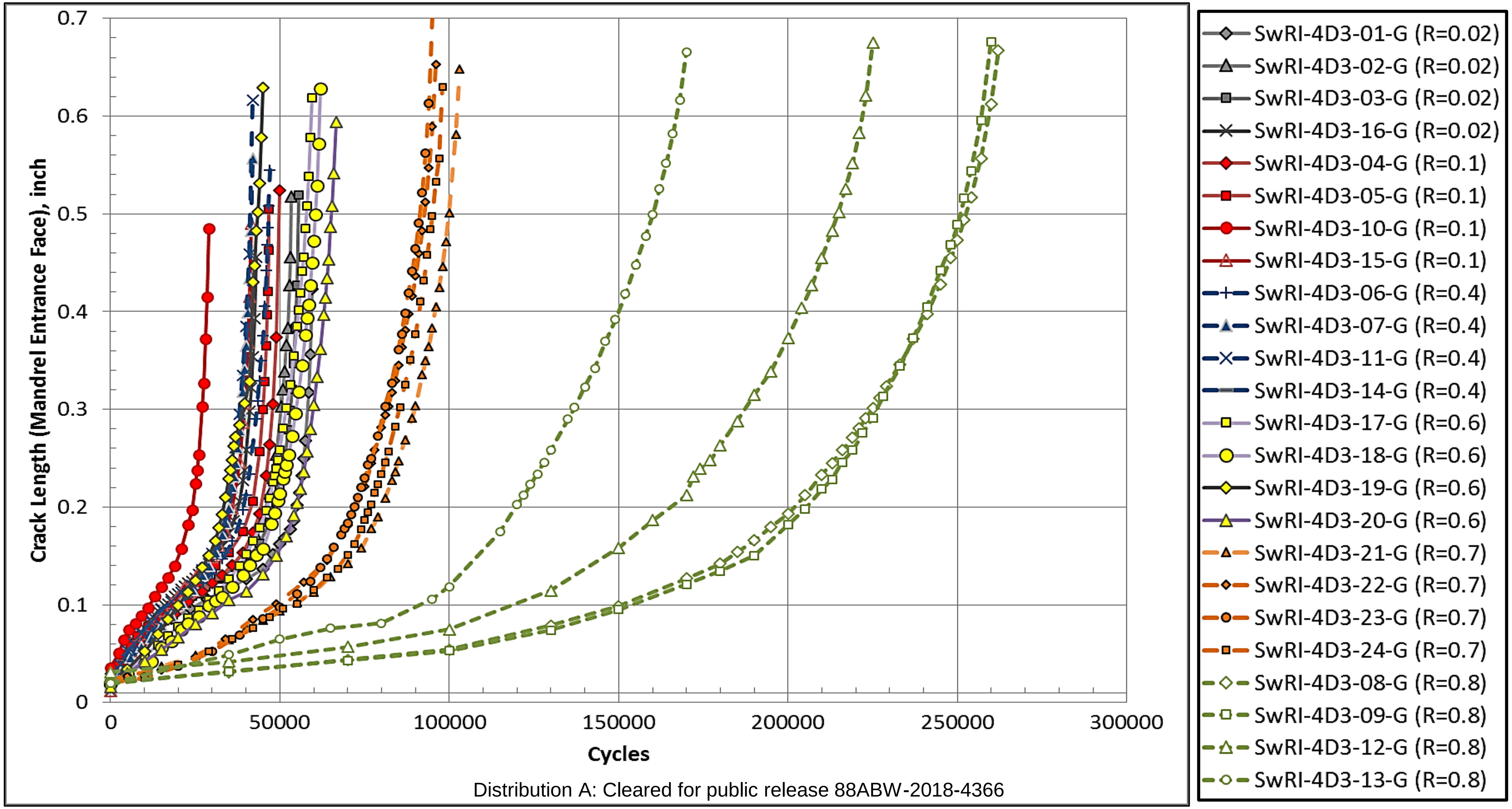
SwRI-4D3-01-G to SwRI-4D3-24-G Details

s ecimens
R_a lied

#	Coupon ID	Material	Width (in)	Thickness (in)	Diameter (in)	Edge Dist. (in)	Smax (ksi)	$R_{applied}$	Coupon Type	Initial Flaw a(in)
1	SwRI-4D3-01-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.02	Dogbone	0.0180
2	SwRI-4D3-02-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.02	Dogbone	0.0230
3	SwRI-4D3-03-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.02	Dogbone	0.0270
4	SwRI-4D3-16-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.02	Dogbone	0.0120
5	SwRI-4D3-04-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.10	Dogbone	0.0210
6	SwRI-4D3-05-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.10	Dogbone	0.0245
7	SwRI-4D3-10-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.10	Dogbone	0.0355
8	SwRI-4D3-15-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.10	Dogbone	0.0115
9	SwRI-4D3-06-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.40	Dogbone	0.0230
10	SwRI-4D3-07-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.40	Dogbone	0.0190
11	SwRI-4D3-11-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.40	Dogbone	0.0245
12	SwRI-4D3-14-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.40	Dogbone	0.0220
13	SwRI-4D3-17-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.60	Dogbone	0.0220
14	SwRI-4D3-18-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.60	Dogbone	0.0200
15	SwRI-4D3-19-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.60	Dogbone	0.0165
16	SwRI-4D3-20-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.60	Dogbone	0.0155
17	SwRI-4D3-21-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.70	Dogbone	0.0230
18	SwRI-4D3-22-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.70	Dogbone	0.0230
19	SwRI-4D3-23-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.70	Dogbone	0.0200
20	SwRI-4D3-24-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.70	Dogbone	0.0200
21	SwRI-4D3-08-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.80	Dogbone	0.0210
22	SwRI-4D3-09-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.80	Dogbone	0.0195
23	SwRI-4D3-12-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.80	Dogbone	0.0310
24	SwRI-4D3-13-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.80	Dogbone	0.0200

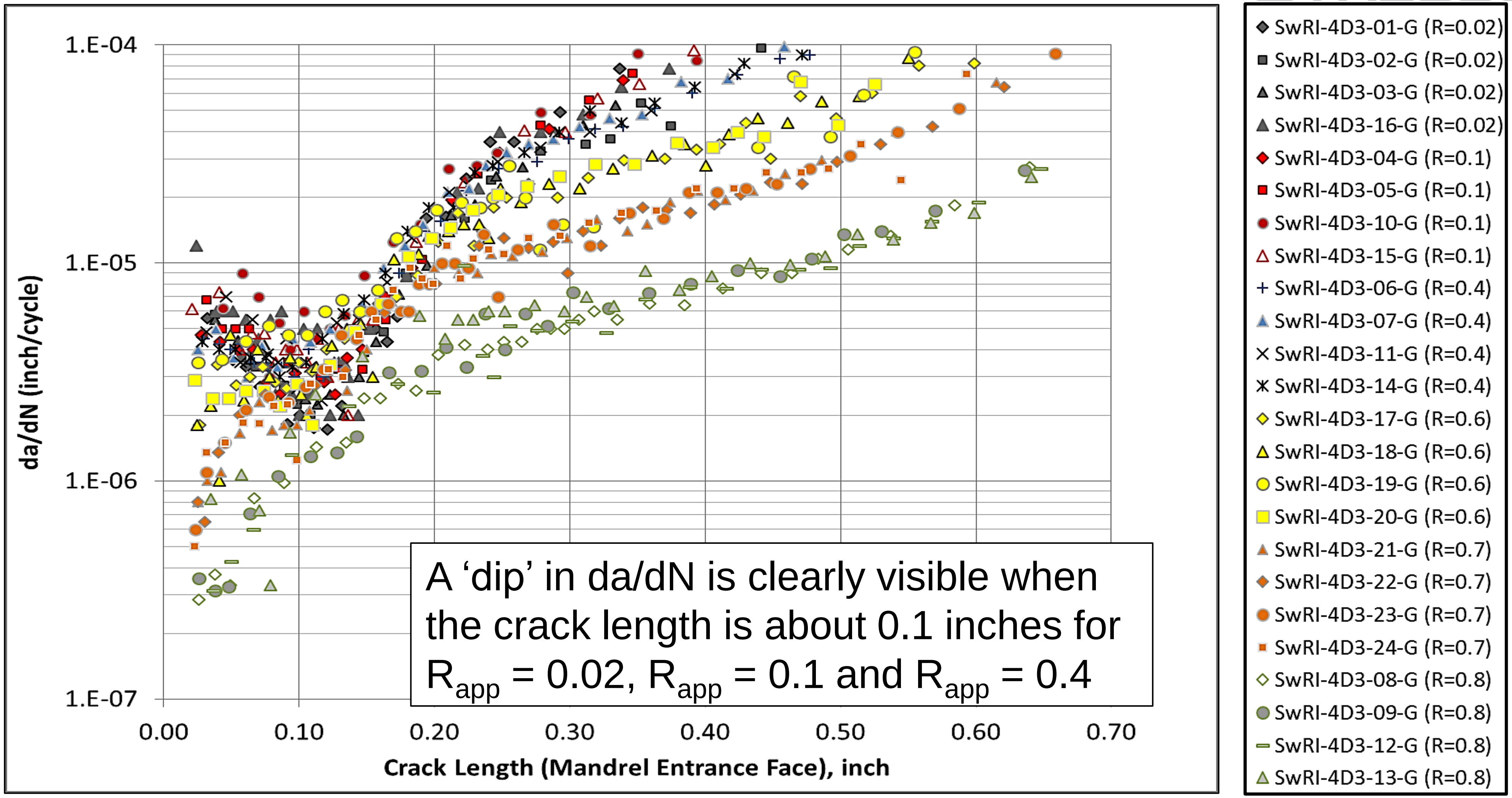
Data Analysis

All 24 Specimens: Crack Length v. Cycles



Data Analysis

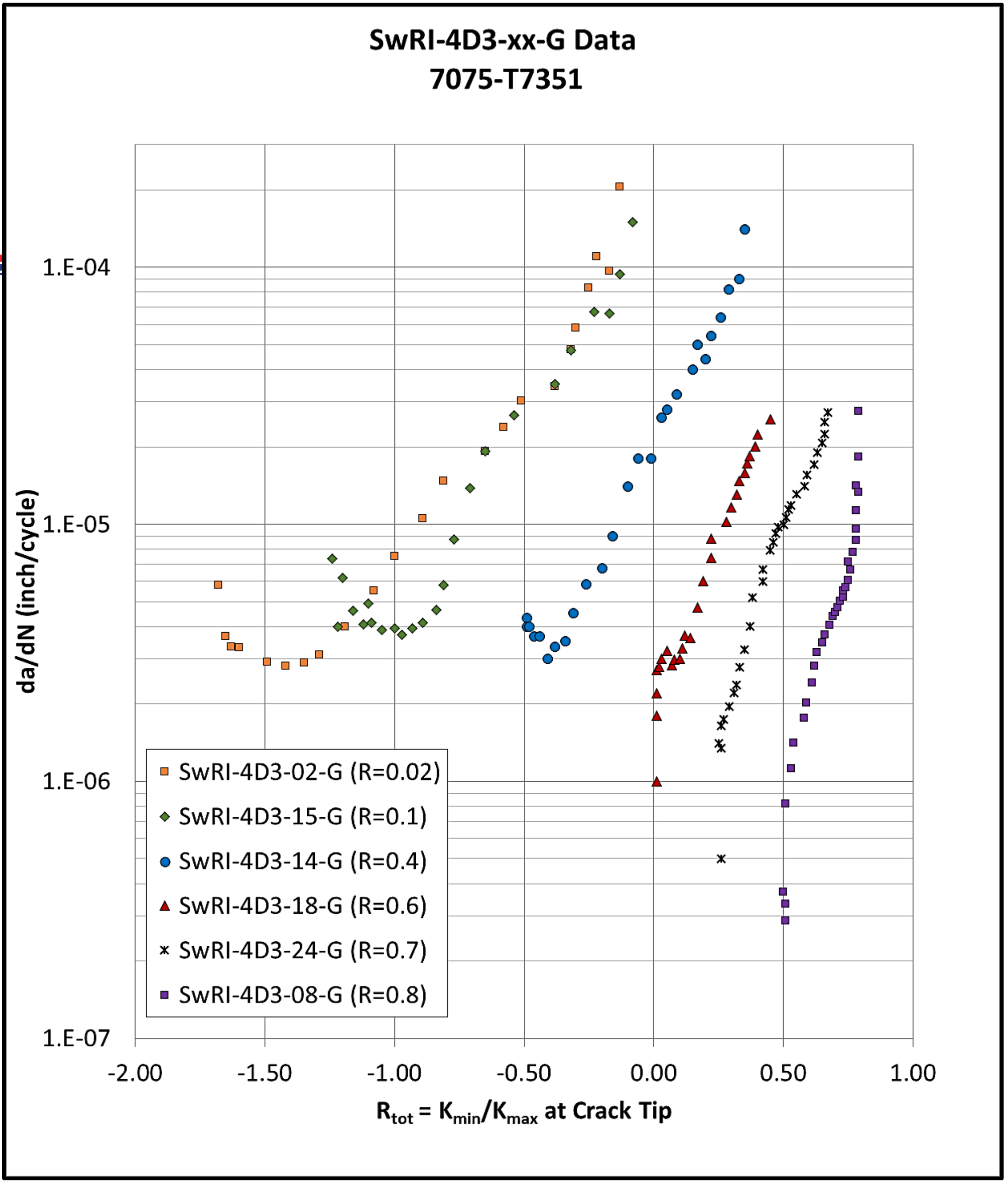
All 24 Specimens: da/dN – Crack Length



Data Analysis

da/dN – R_{tot}

- Variation of experimentally derived da/dN growth rate as a function of $R_{tot} = K_{min}/K_{max}$ at the crack tip determined from simulation
  - Observation: The 'dip' in the da/dN curve occurs for short cracks at negative R_{tot}
- For $R_{tot} > 0$, the 'dip' is not present
  - This corresponds to R_{app} = 0.6, 0.7, 0.8



Examining R_{tot}

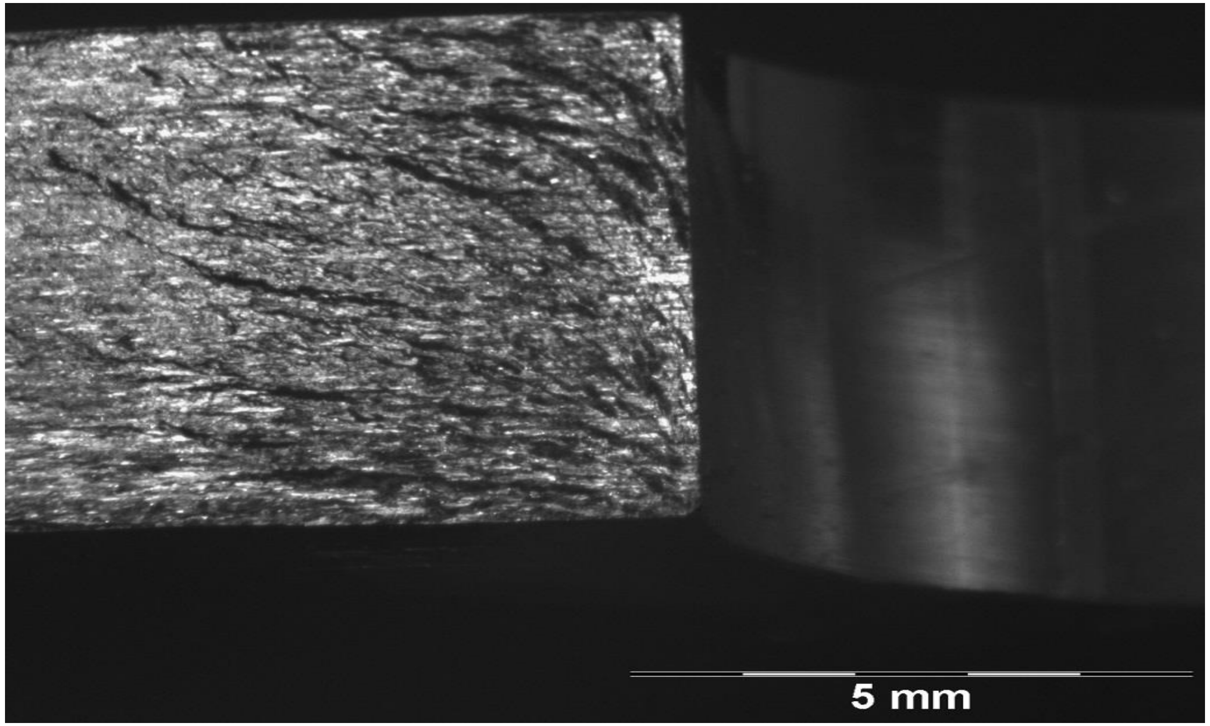
What do fracture faces tell us?

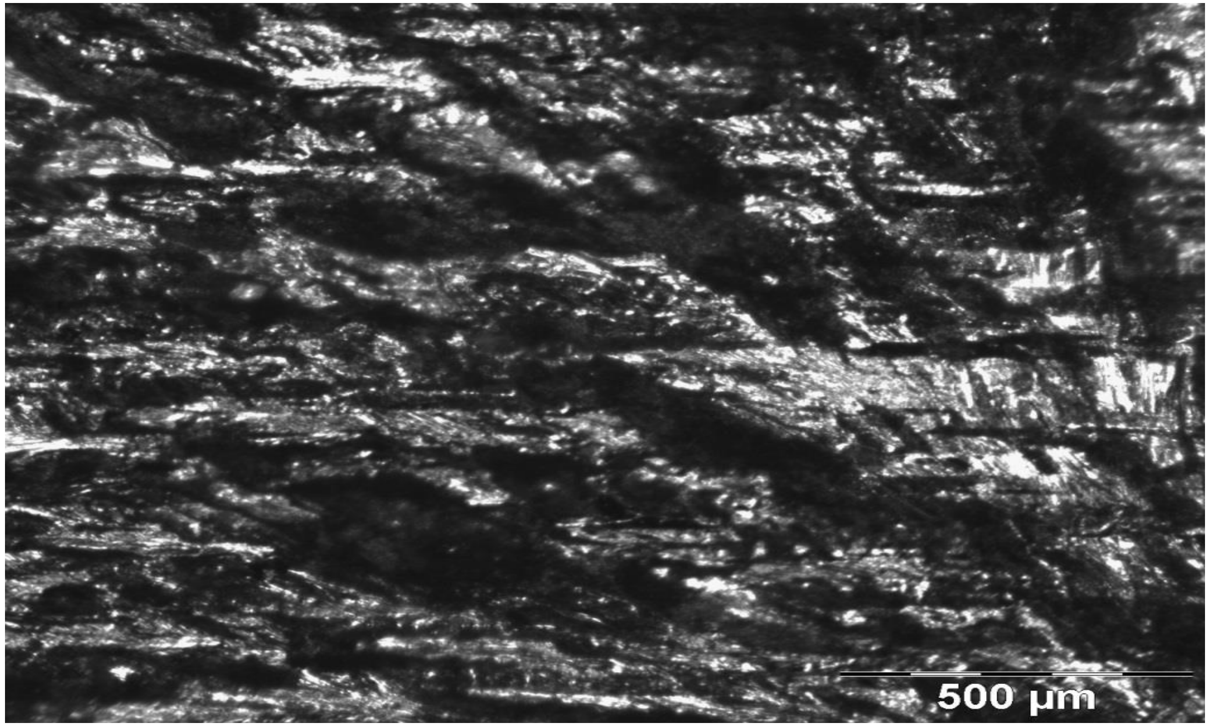
Crack origin is lower, right corner of fracture face

In higher magnification images, the origin is out of view

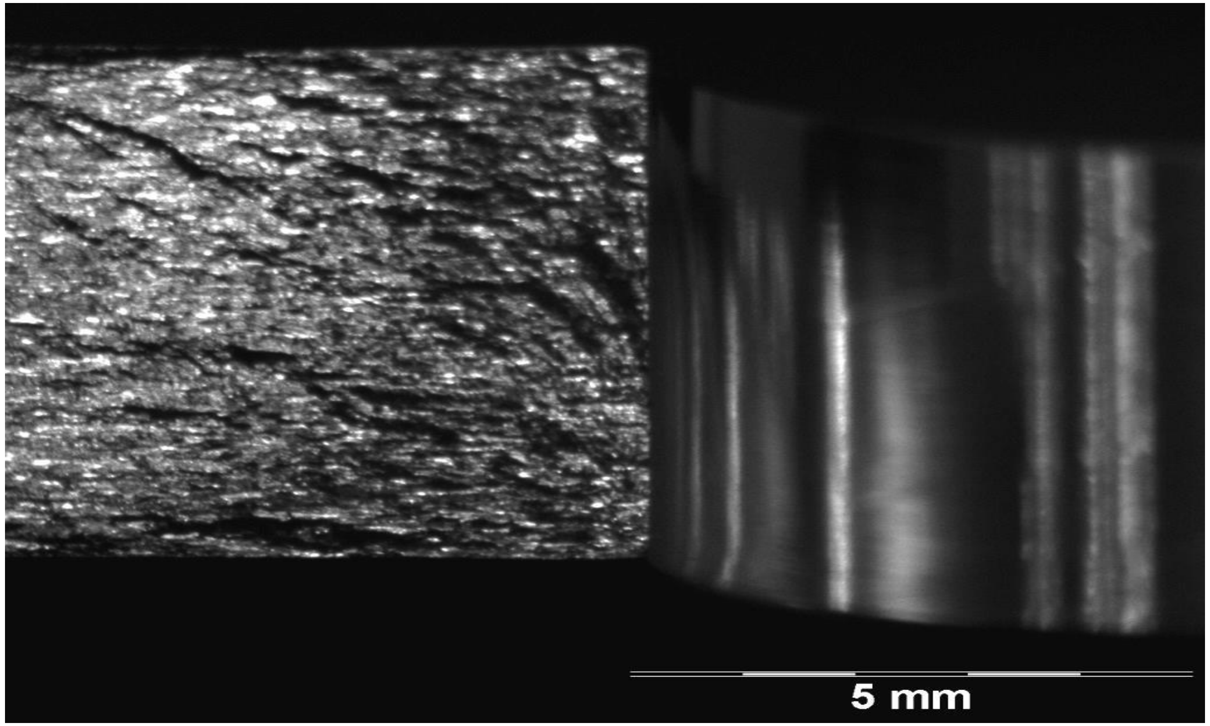
Higher magnification images centered at 0.05 x 0.05 inch from origin

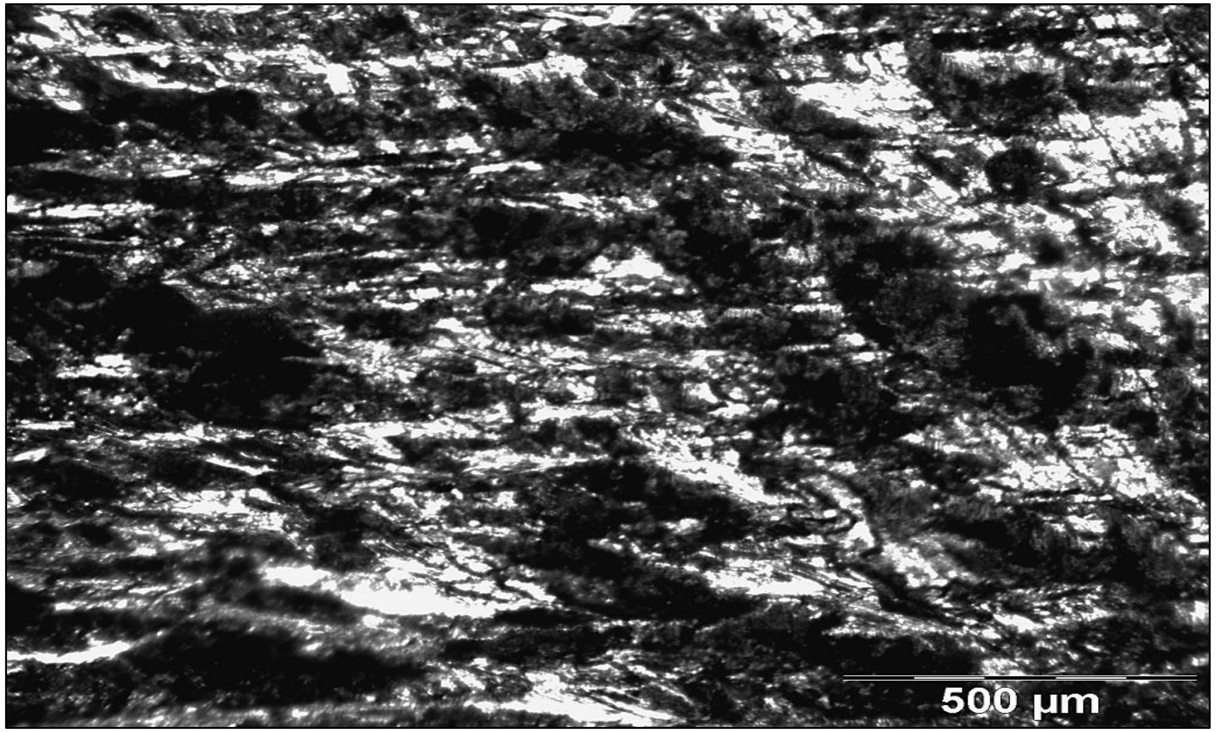
R_{app} = 0.02 Coupon (16G)



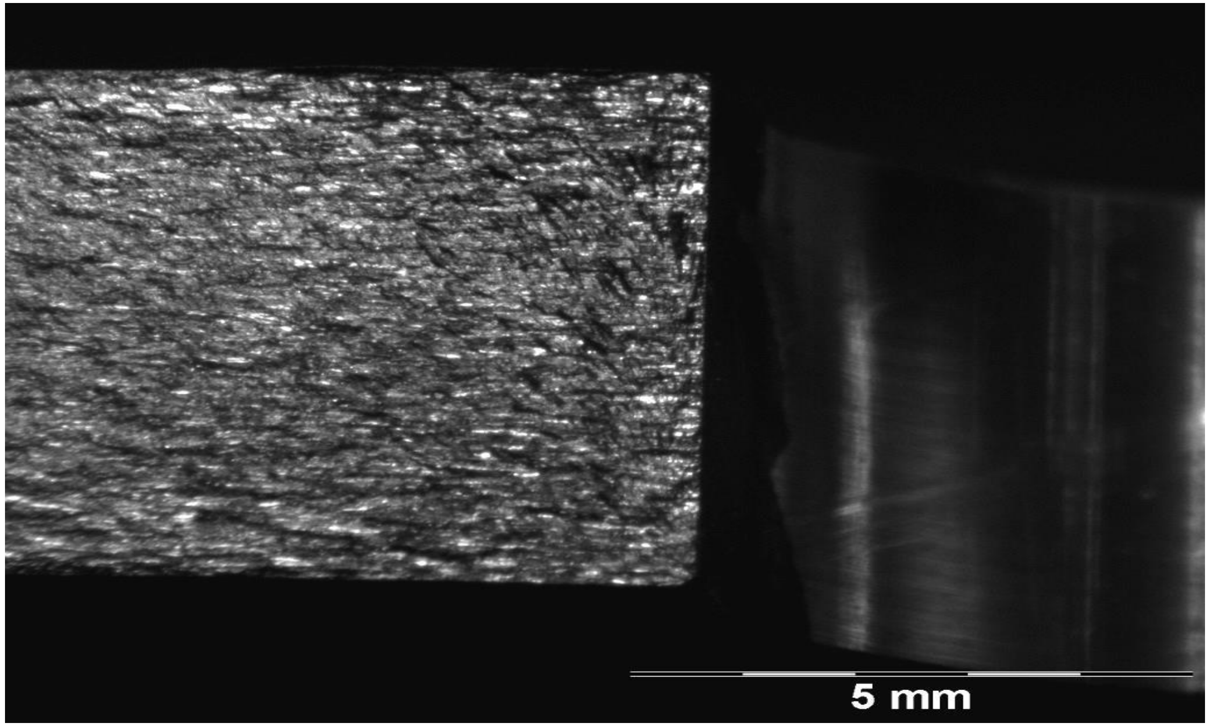


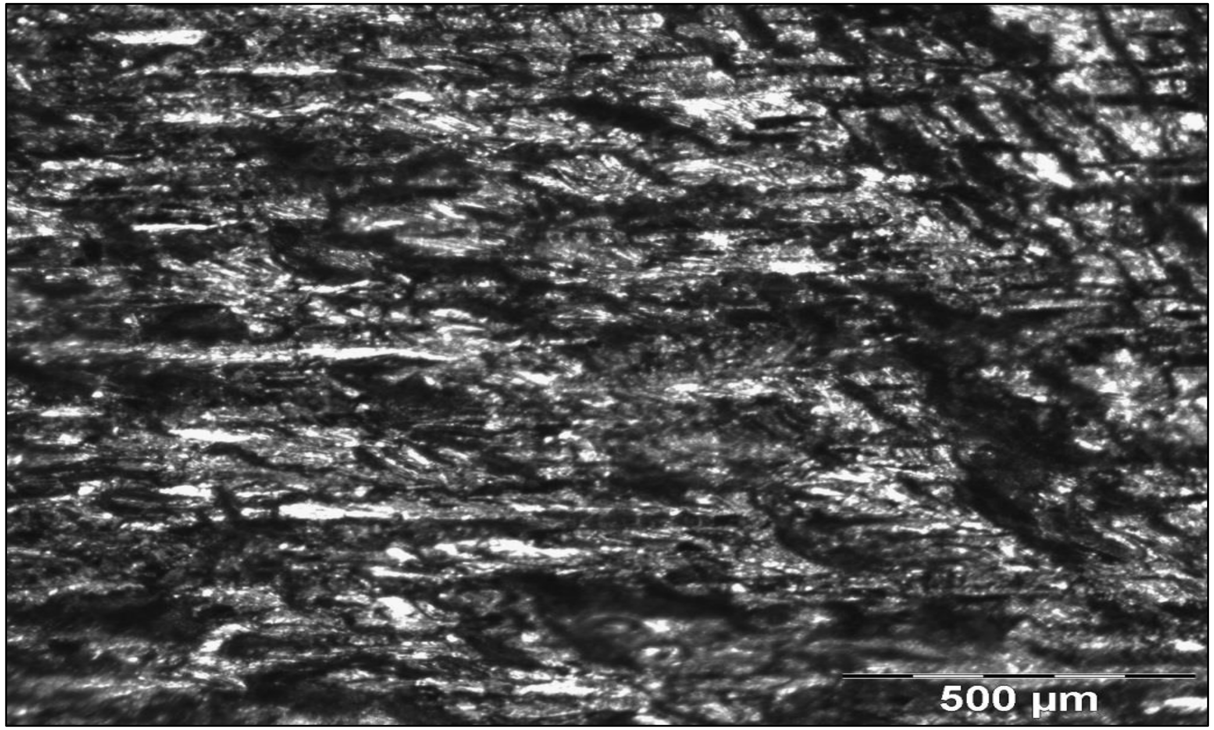
R_{app} = 0.1 Coupon (15G)



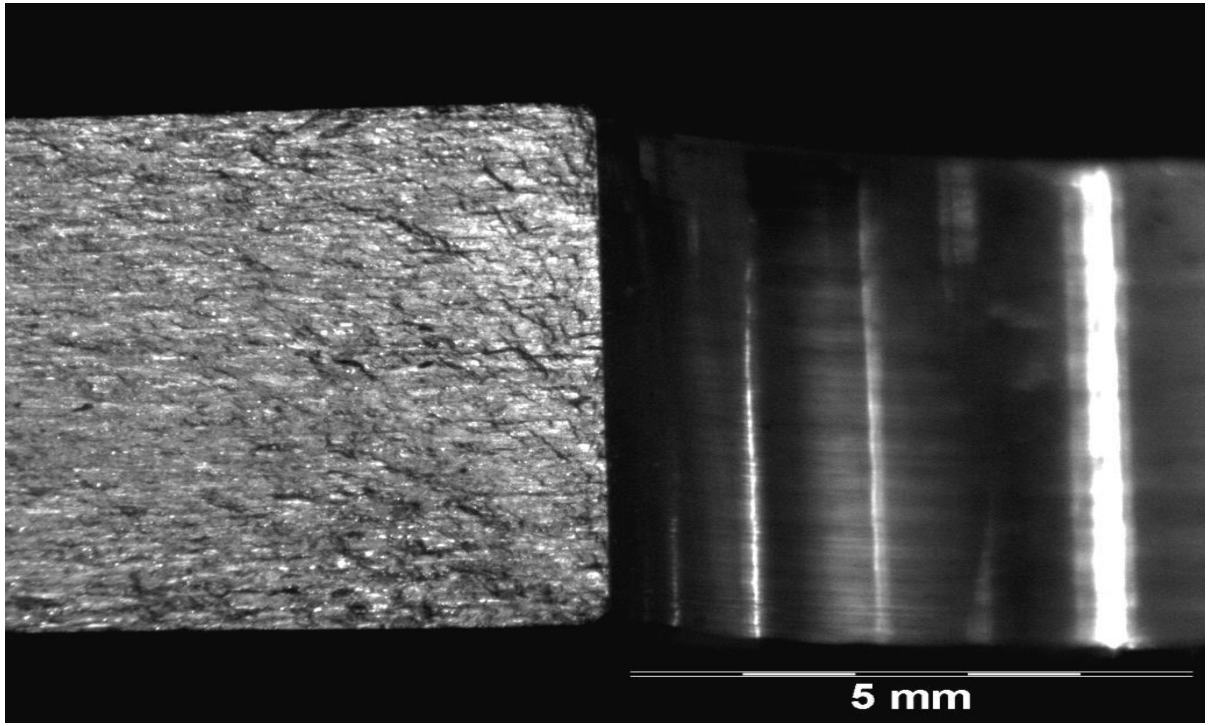


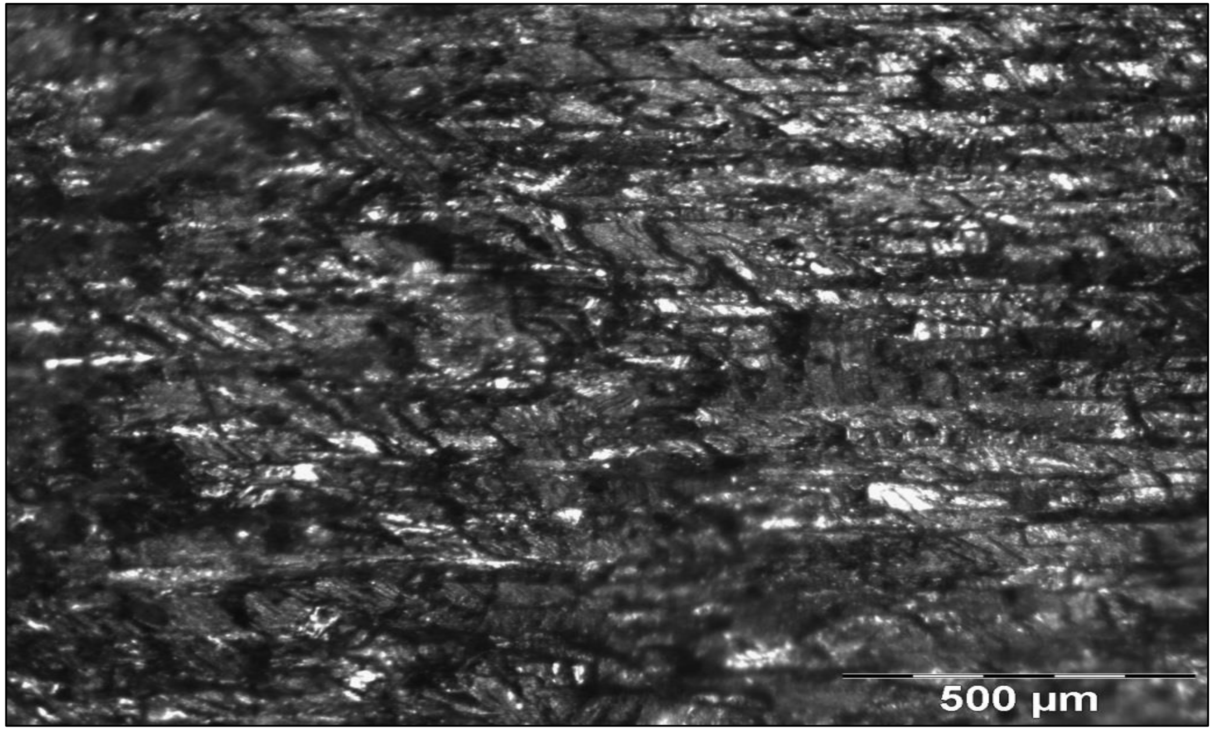
R_{app} = 0.4 Coupon (14G)





R_{a}app = 0.8 Coupon (09G)



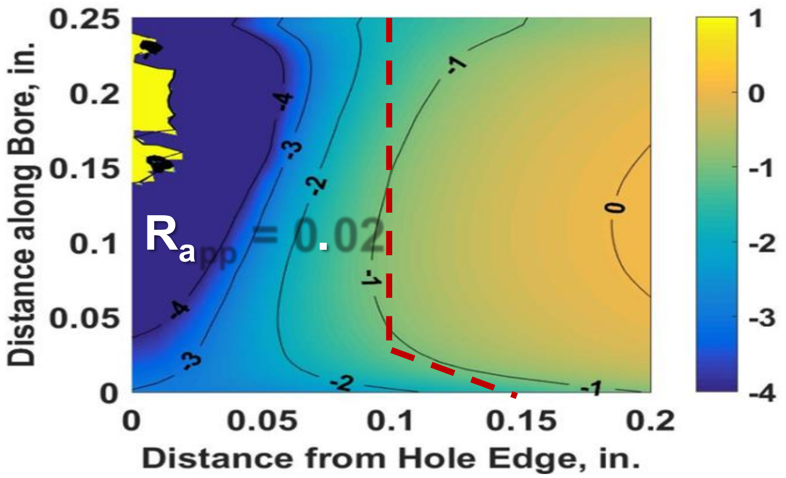


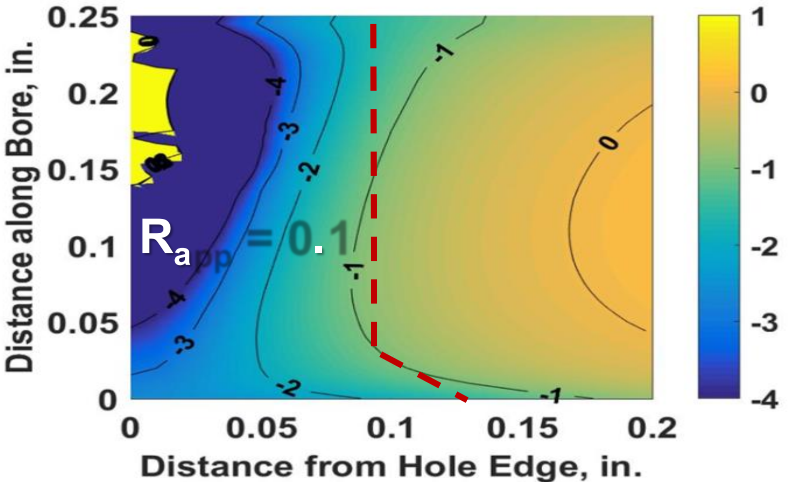
Evidence of Contact

R applied	Heavy Oxide (MEF)		Heavy Oxide (Int)		Pockets of Oxide	
	Start	End	Start	End	Start	End
0.02	0	0.15	0	0.1	0.1	0.3
0.1	0	0.125	0	0.09	0.09	0.19
0.4	0	0.11	0	0.07	0.07	0.17
0.6	--	--	--	--	0.05	0.13
0.7	--	--	--	--	--	--
0.8	--	--	--	--	--	--
	Values represent distance from bore (inch)					

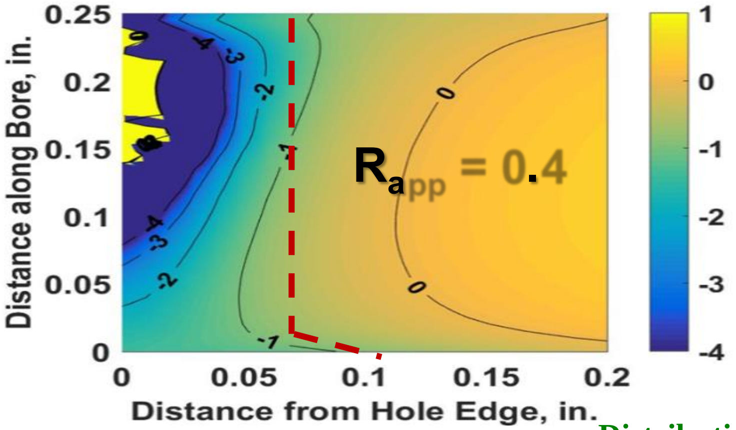
R_{tot} Contour Maps

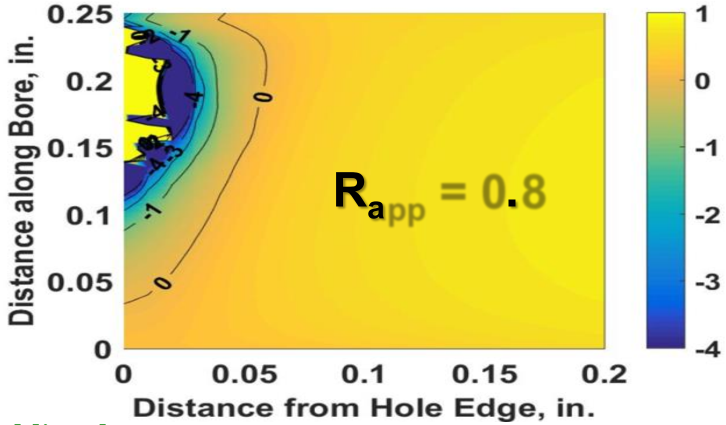
- Qualitative observations of fracture faces correlate well with these maps
- Oxide on fractures (from contact) seem to correlate with regions of $R_{tot} < -1$





Regions to the le t o red dashed lines denote heavy o ide



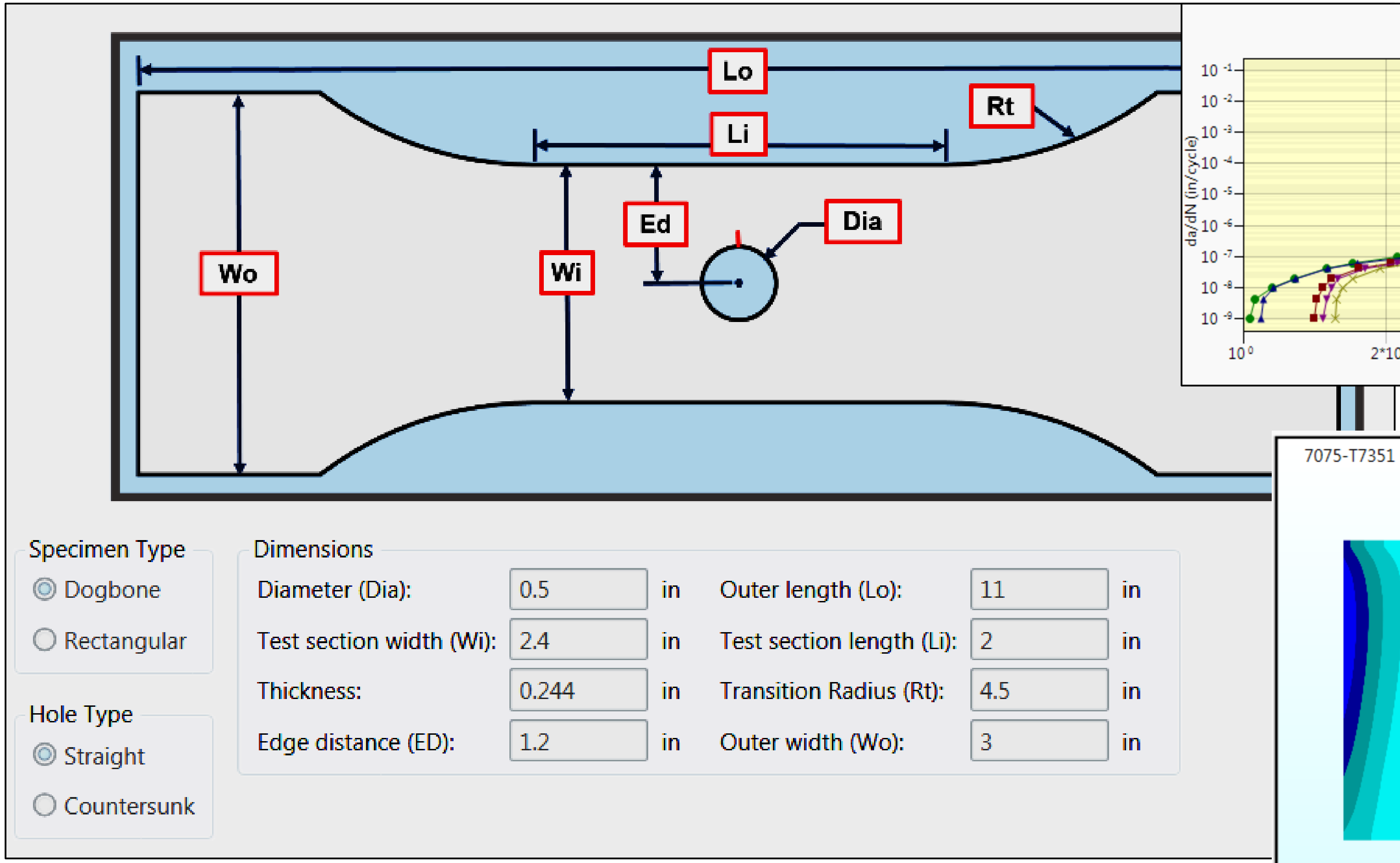


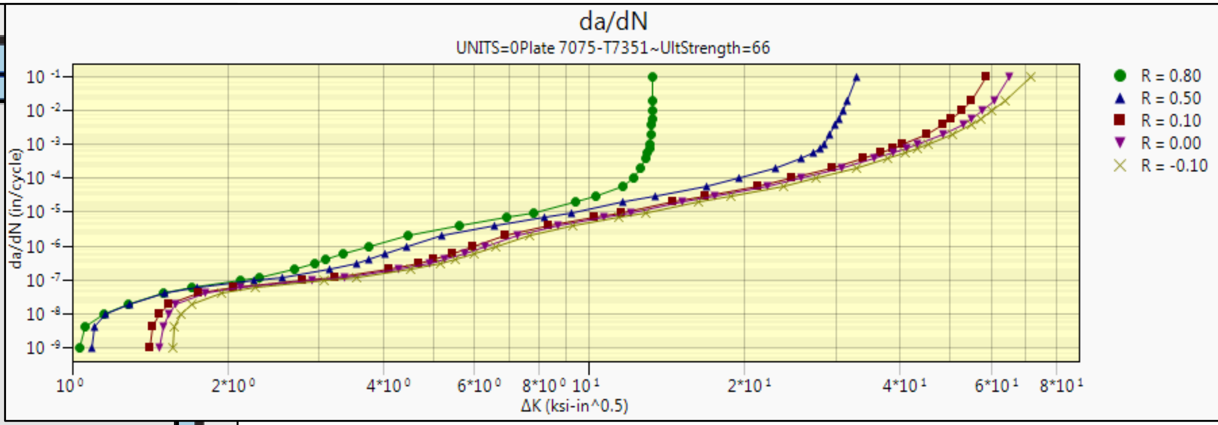
- A case for K-effective
  - Combining simulation with experimental observations

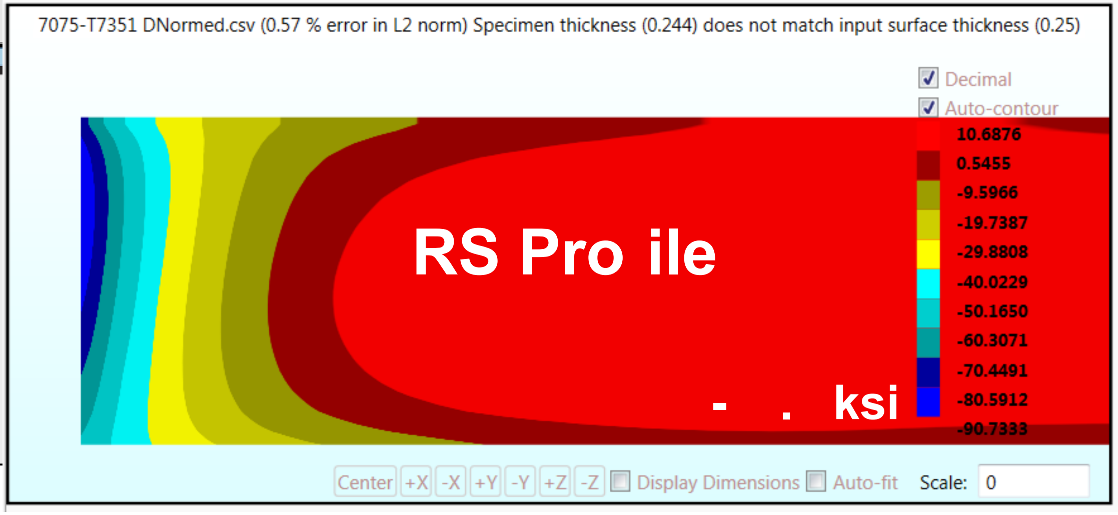
DATA ANALYSIS

Data Analysis

Specimen Dimensions & Reference RS for Simulation







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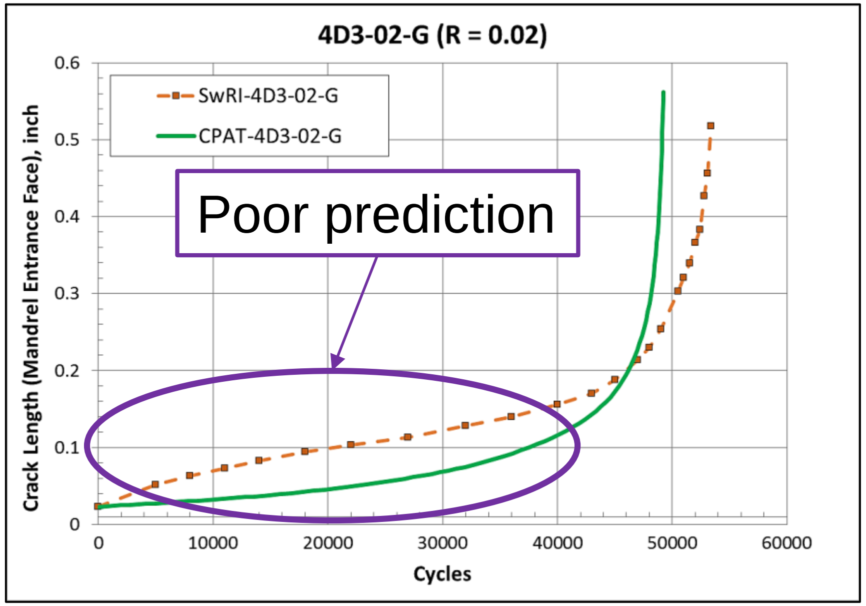
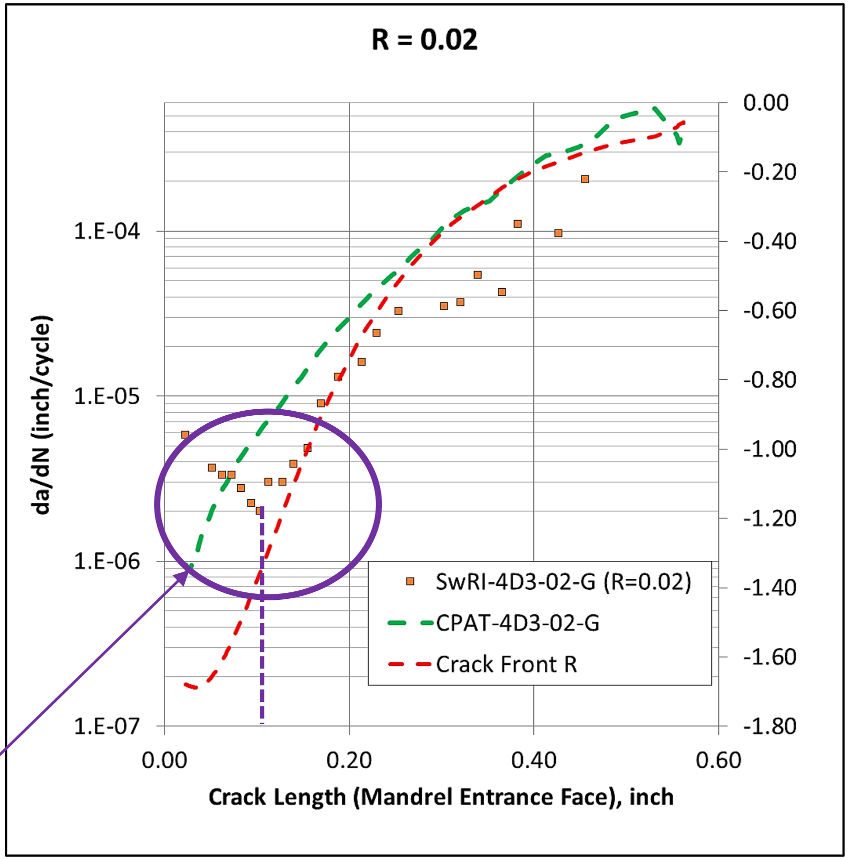
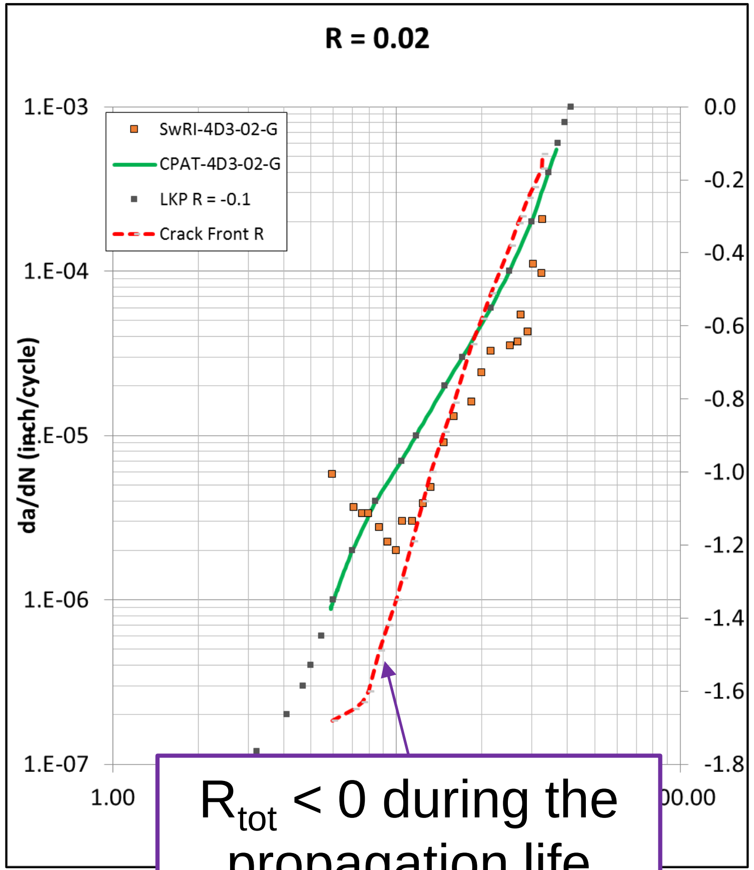
Data Analysis

Typical Prediction Using CPAT (R_{app} = 0.02)

- Simulation and test data
  - da/dN – K_{max} curve with the LKP (R = - 0.1) data. Predictions follow the R = -0.1 reference curve. Test points do not





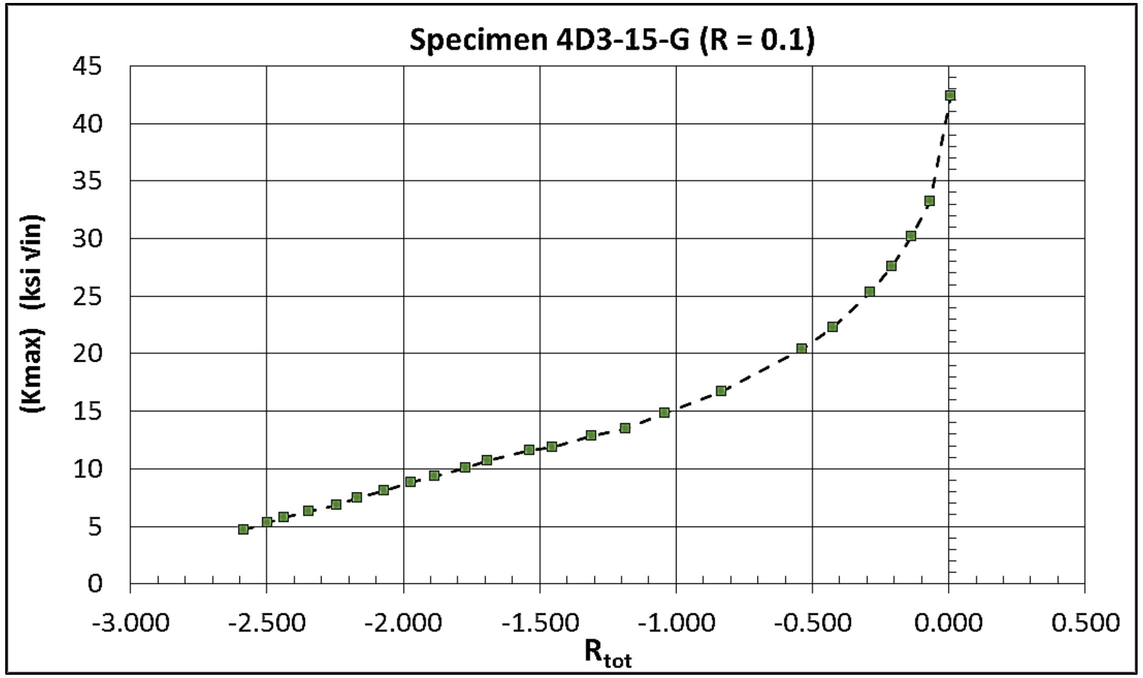


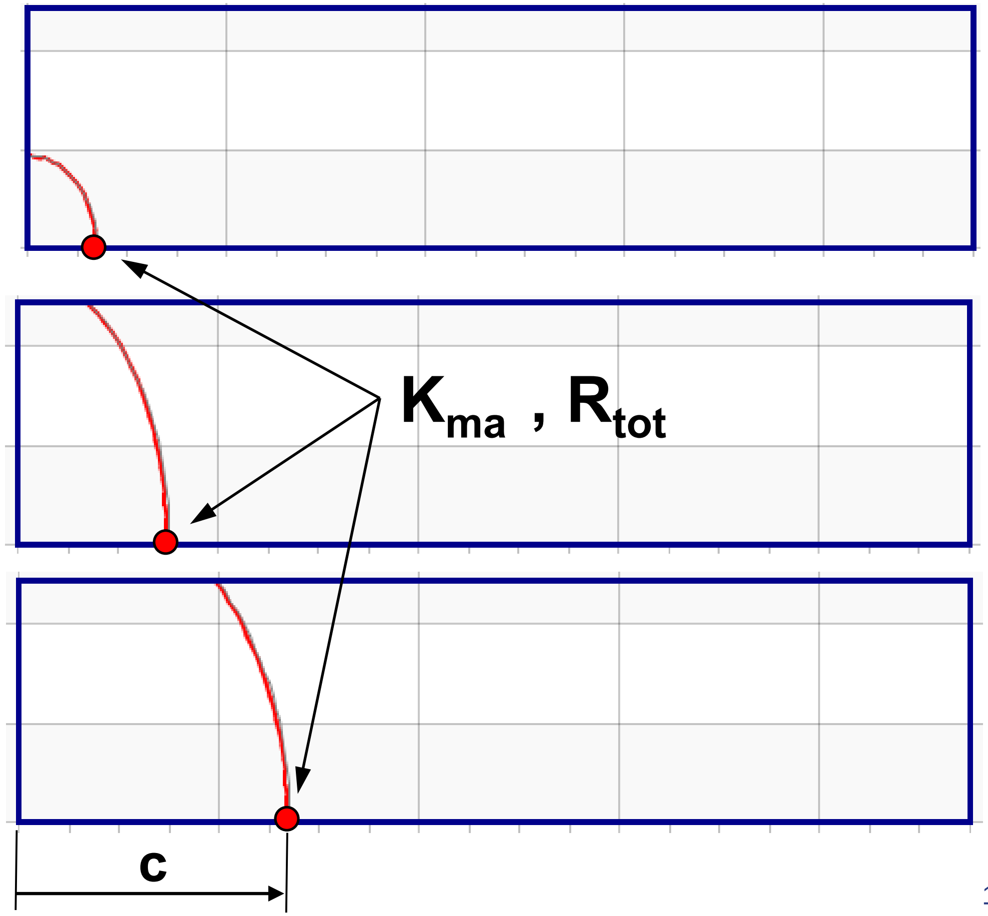
'Dip' at 0.10" crack (typical)

Data Analysis

Computing R_{tot} and K_{max}

- Assume an elliptical crack front connecting bore and surface measurements
  - Solve in CPAT for K_{mech}, K_{res} at c-tip
  - Compute K_{max}, K_{min} and R_{tot}





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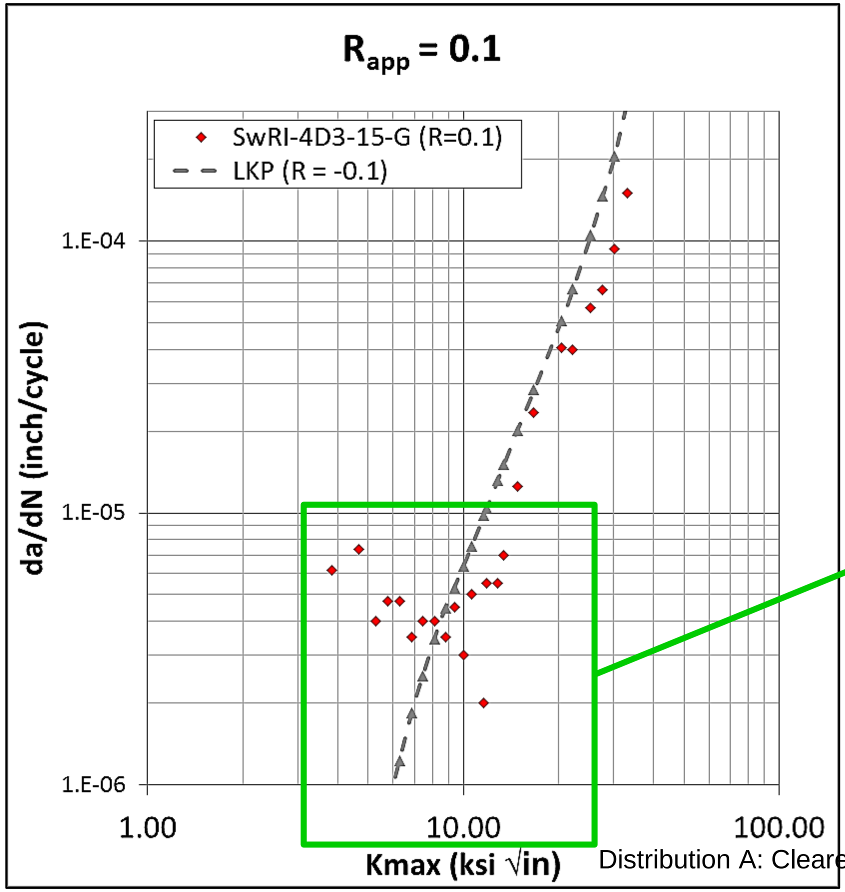
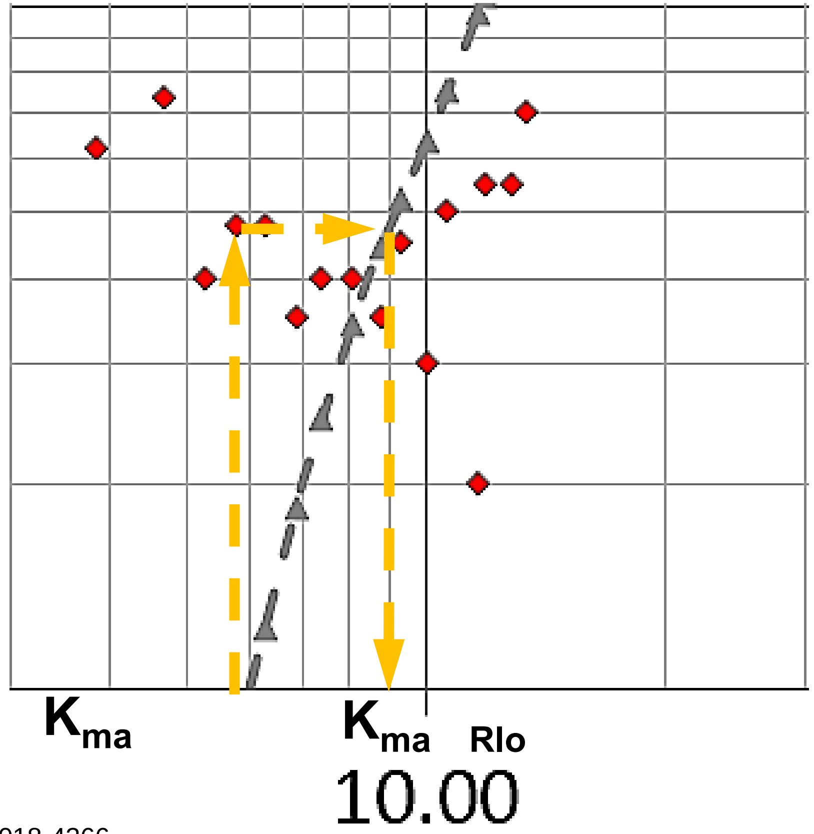
Data Analysis

Determining K-effective

- Value of $K_{max} = (K_{max})_{Rlo}$ needed to get the same $(da/dN)_{test}$ from the Rlo curve of the LKP data for each crack length



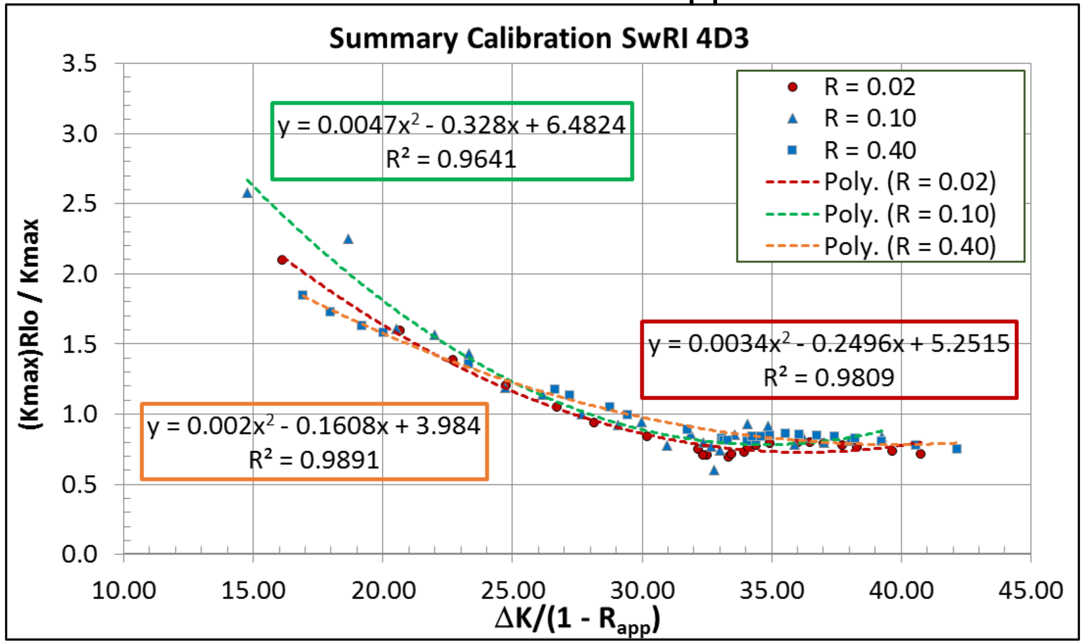


Data Analysis

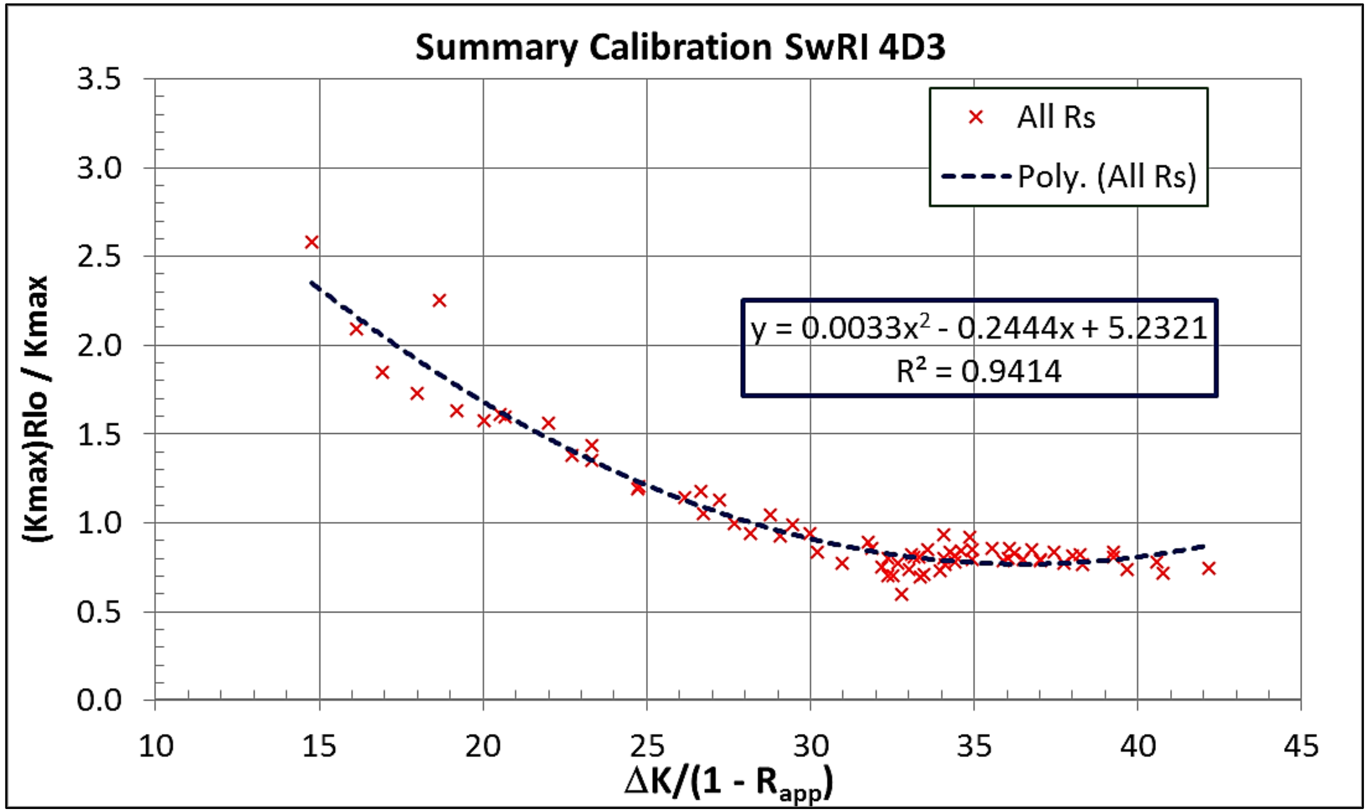
Calibration

- Applying procedure to R_{app} = 0.02, 0.10, 0.40
  - Plotting results in terms of $\Delta K / (1-R_{app})$

For each R_{app}



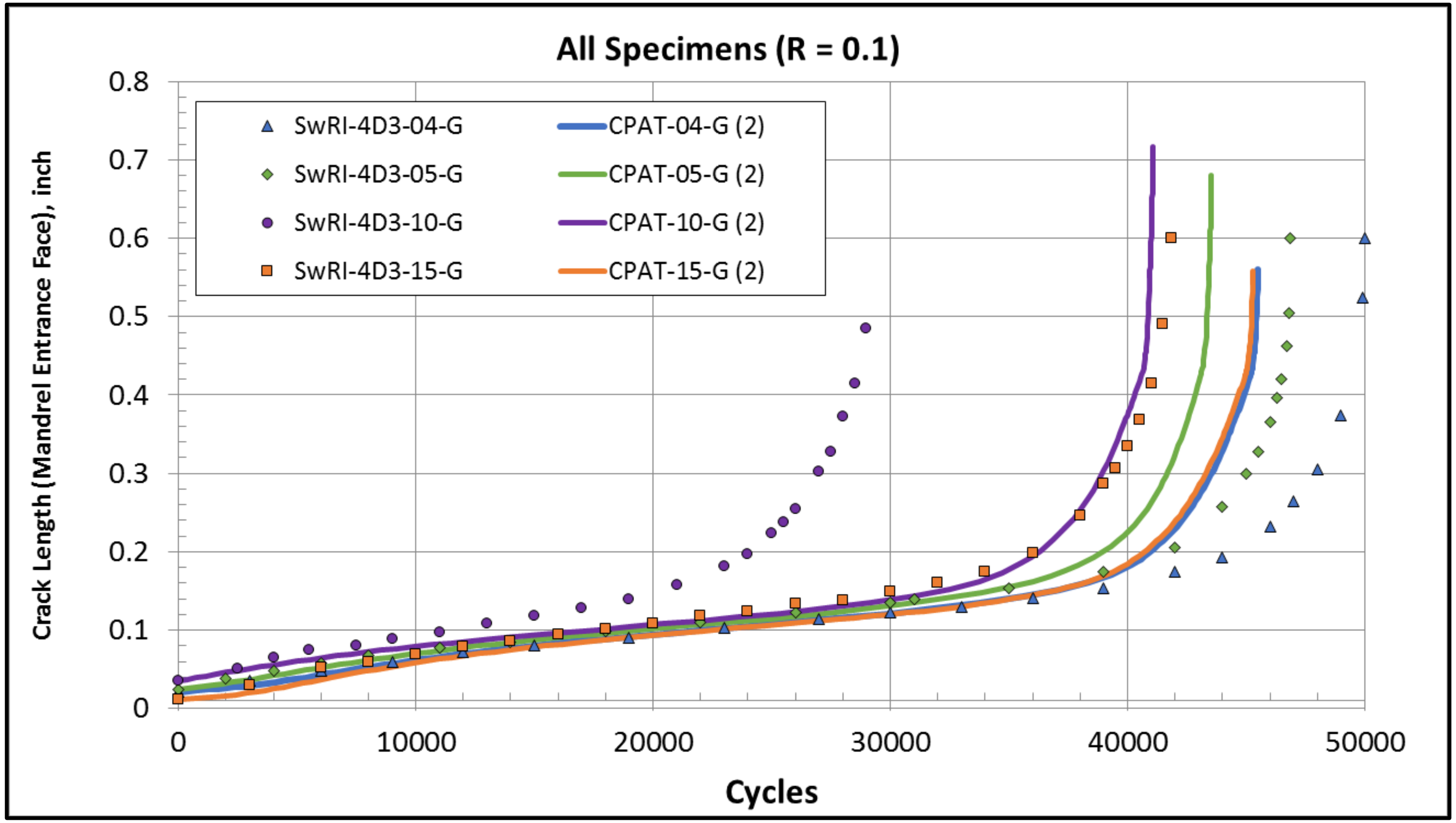
Combined

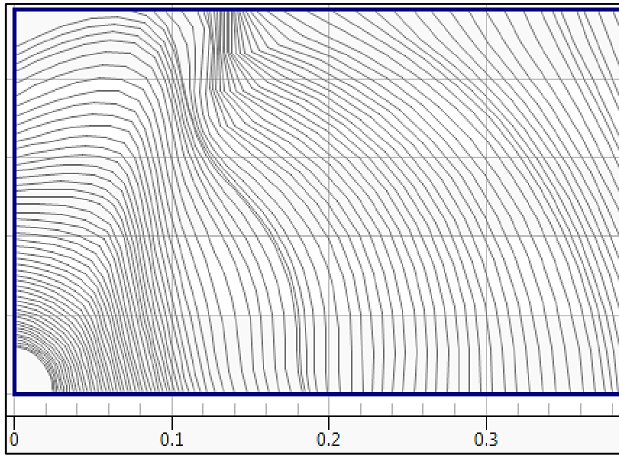


Data Analysis

Using K-effective in Predictions

- Preliminary results for $R_{app} = 0.10$

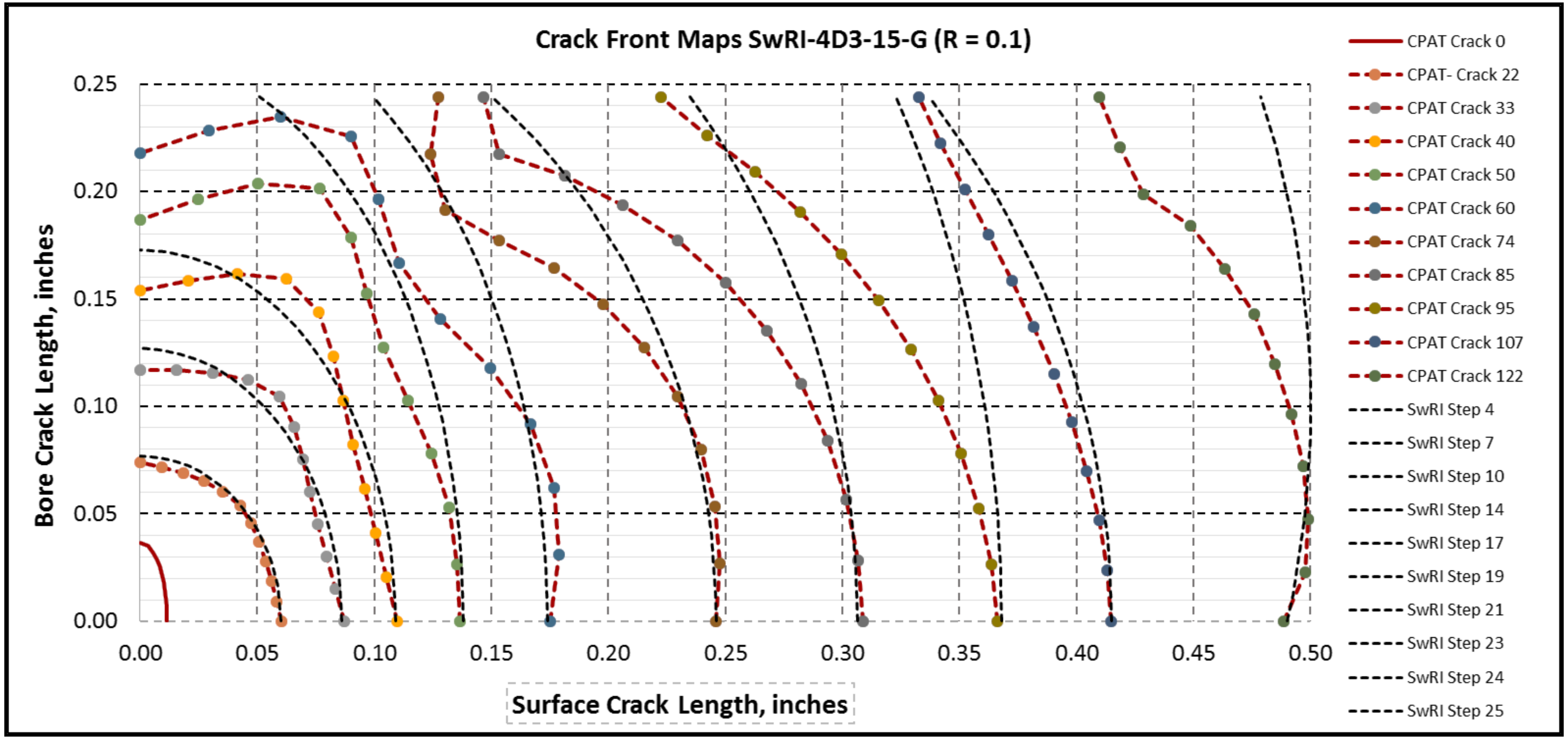




Data Analysis

Using K-effective in Predictions

- Crack Shape Specimen 4D3-15-G (Rapp = 0.10)



Summary

Data Analysis

STRESSCHECK

- Using K_{max} as the dependent variable automatically incorporates the effect of the Residual Stress in the prediction
- Using $\Delta K/(1-R_{app})$ as the independent variable consolidates the calibration data for the three R_{app} considered in the study, and is independent of the RS
- Preliminary application of the calibration curve is promising, and it fits within the traditional approach of using a K-effective to account for closure effects

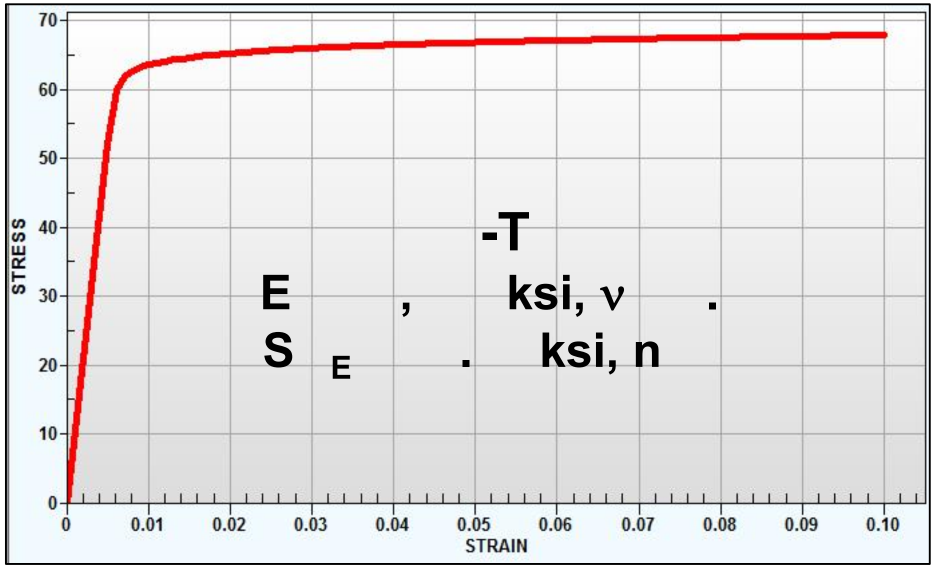
- Incremental plasticity (kinematic hardening)
- Simulation of CW + Contact + Remote Load

MODELING OF CLOSURE

Closure Model

Analysis Approach

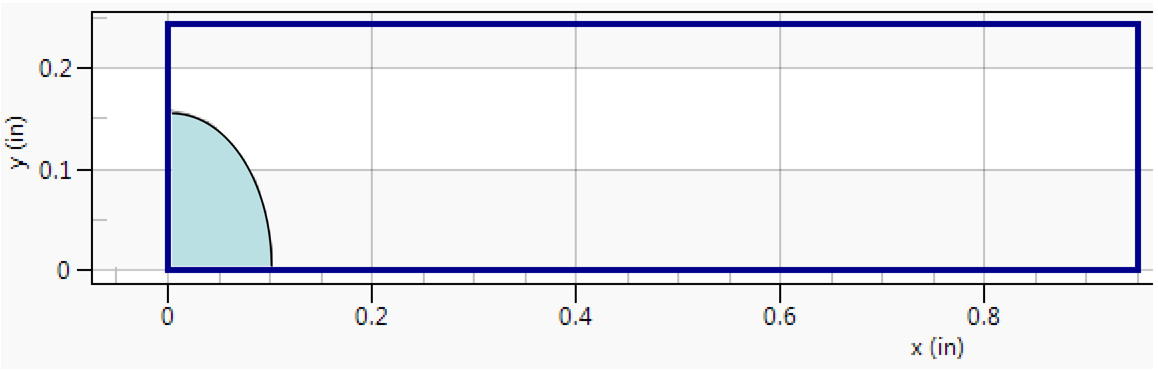
- Simulation of mandrel insertion (4%) and removal
  - Incremental plasticity – kinematic hardening
  - Ramberg-Osgood stress-strain curve
  - Distribution of residual stresses
- Introduce corner crack
  - Assume elliptical shape with dimension from test
  - Check contact effect on residual stresses
- Apply a remote load
  - Increments of 1ksi to 27 ksi
  - Check contact effect on residual stresses
  - Check crack opening as load increases



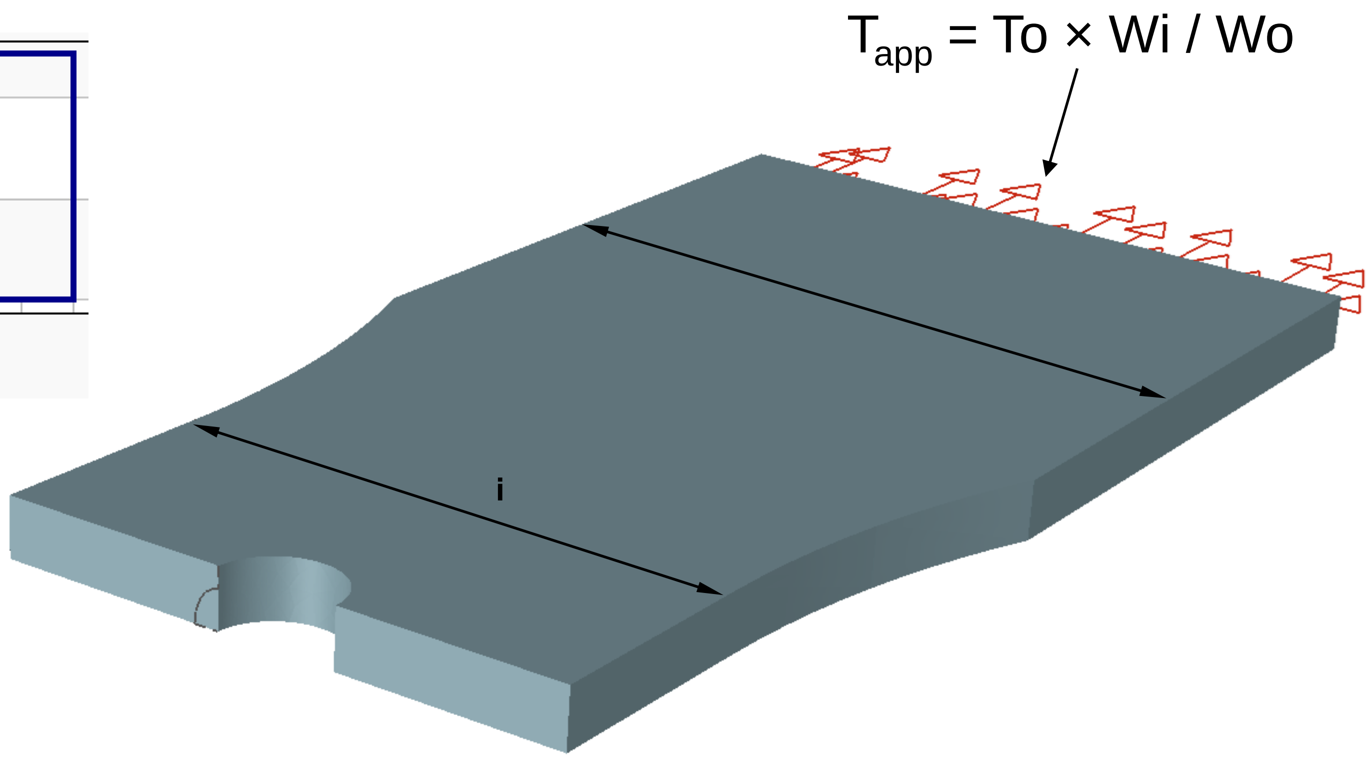
Closure Model

Crack Configuration

- 0.10 in × 0.16 in

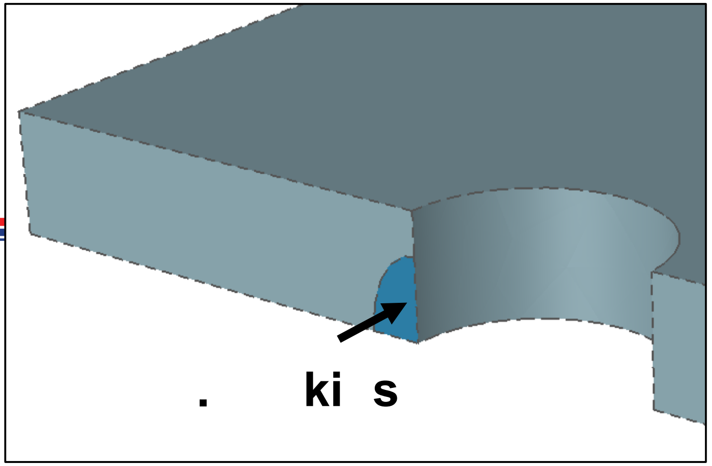


- Crack dimensions corresponding to specimen SwRI-4D3-15-G, Crack Step 9

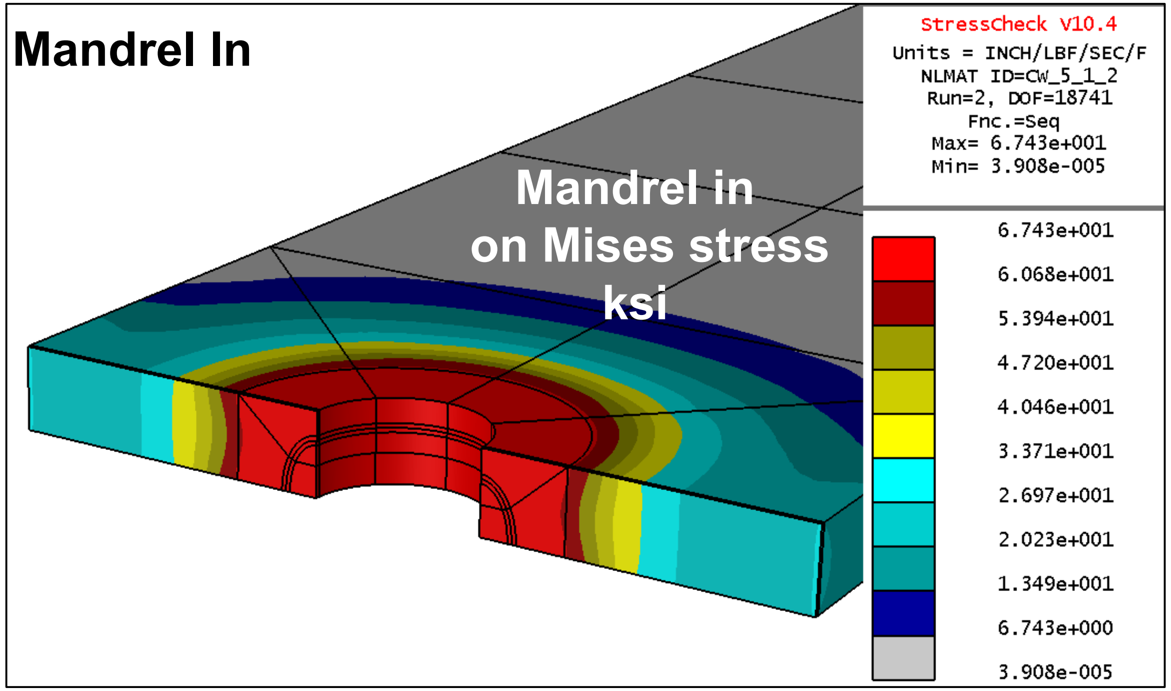


Closure Model

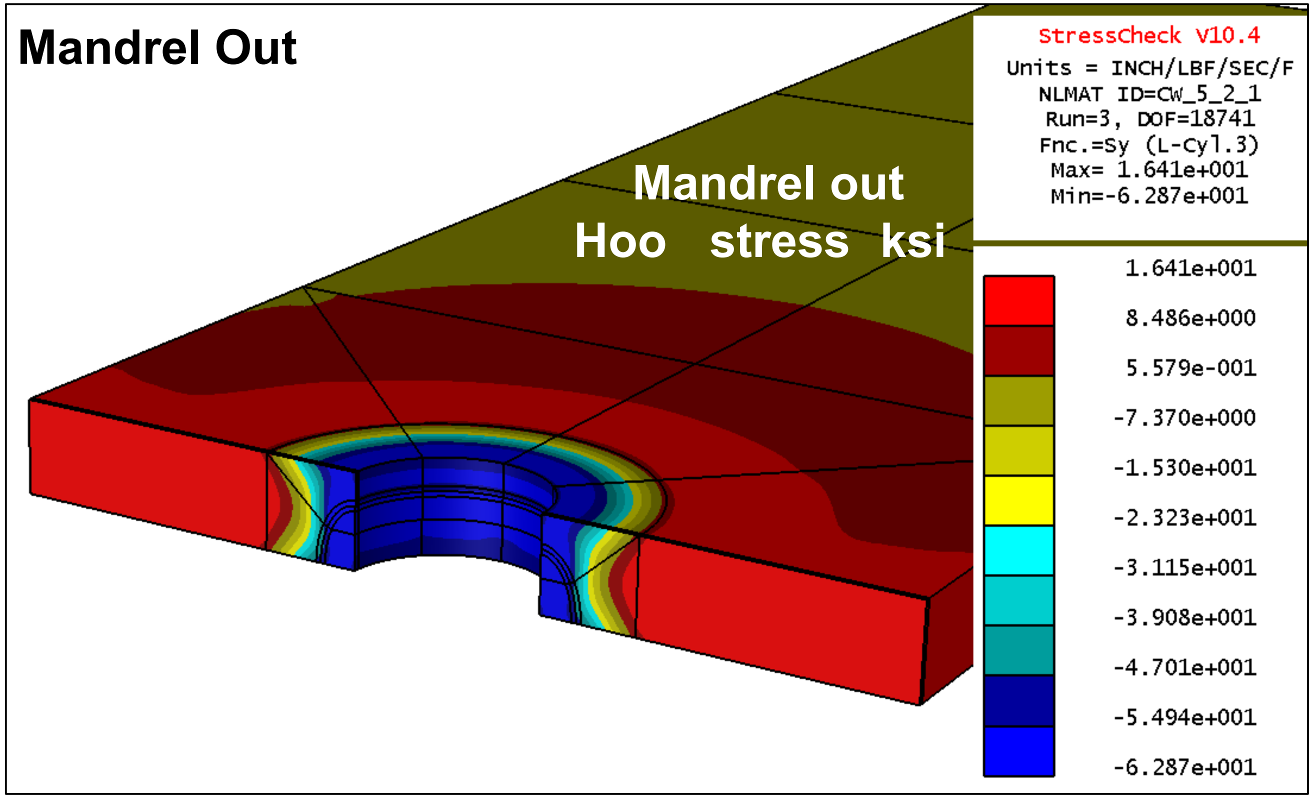
CW Simulation



orce resultant over
the area o the crack-to-
e a ter mandrel removal



E:	1.0300e+004	v:	3.3000e-001
S70E:	6.3000e+001	n:	4.8000e+001
a(th):	0.0000e+000	beta:	1.0000e+000



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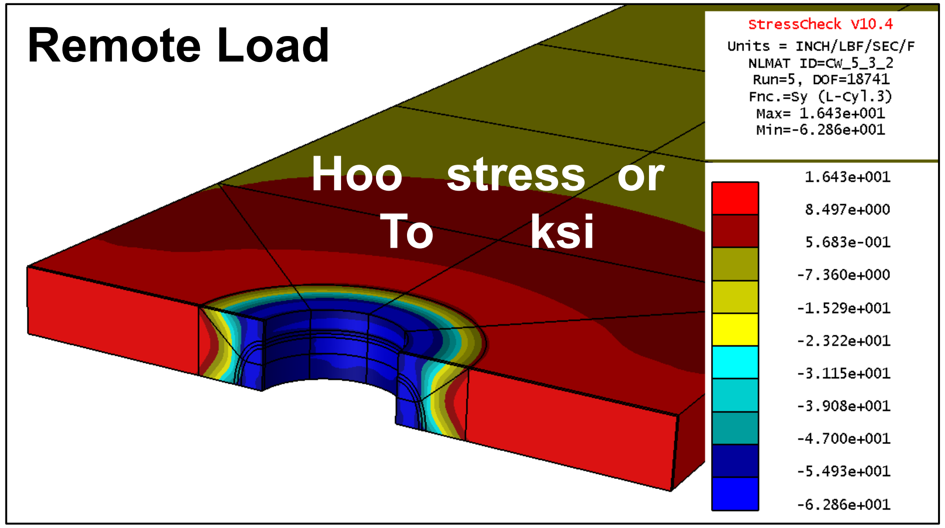
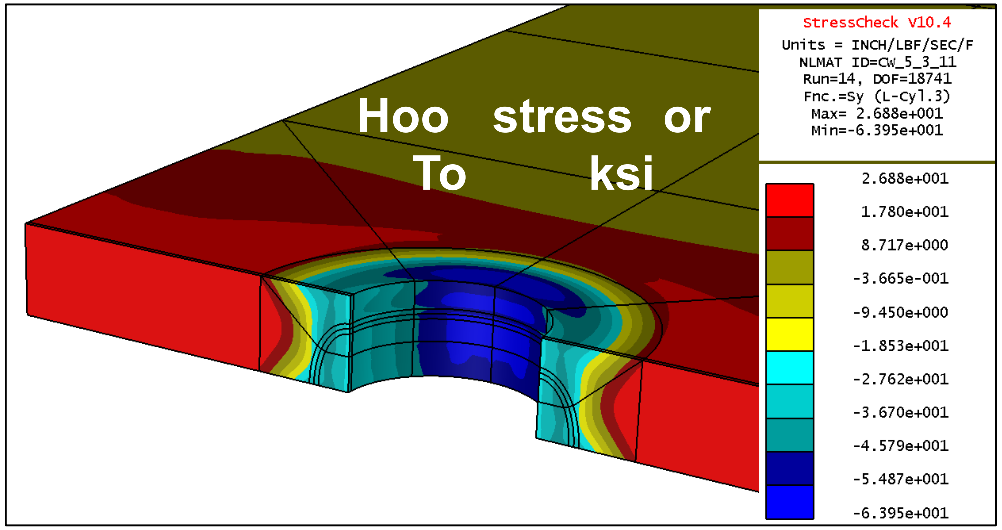
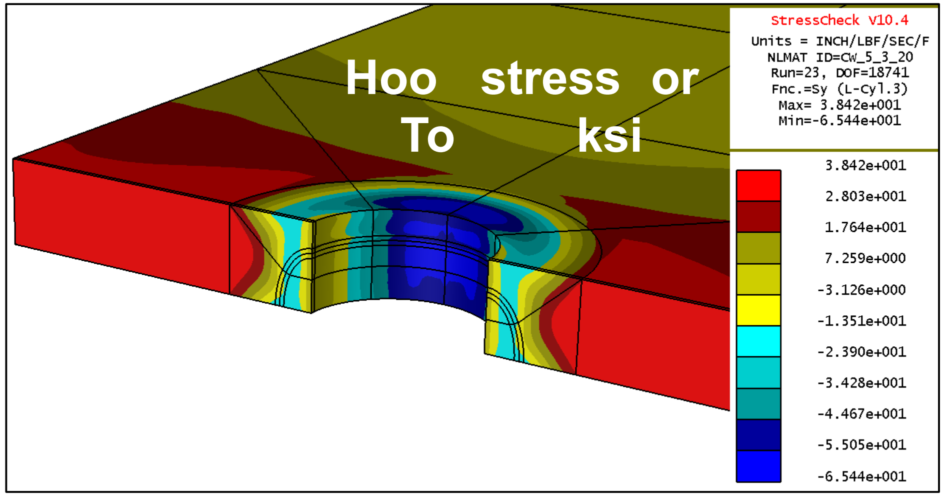
Closure Model

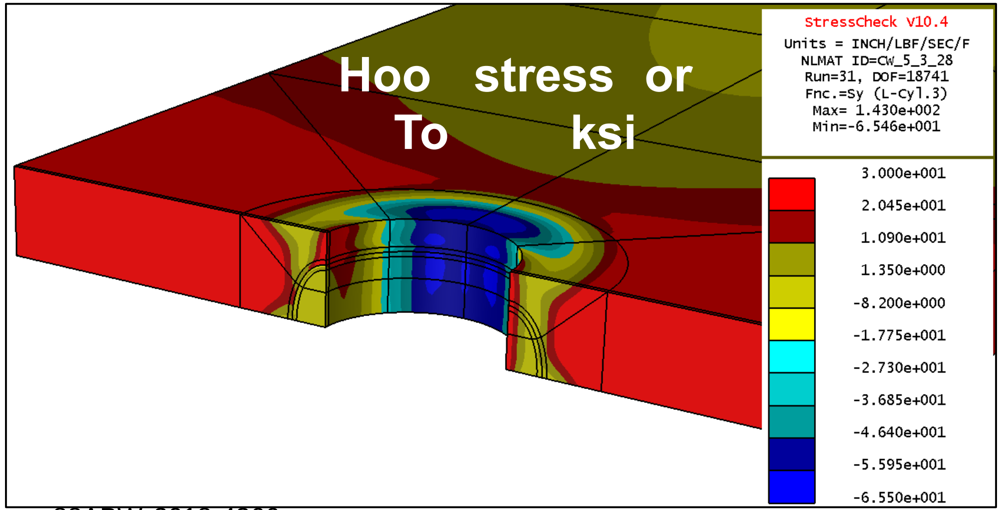
Contact + Remote Loading

STRESSCHECK







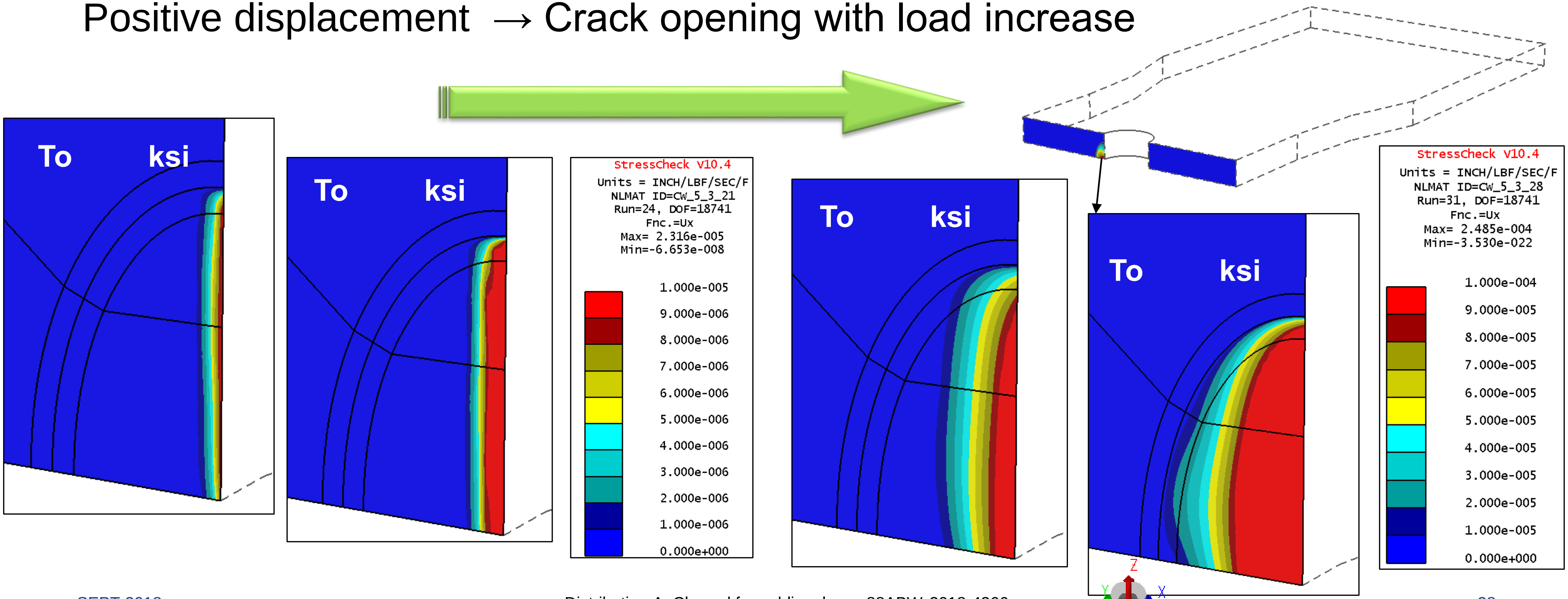


Closure Model

Contact + Remote Loading

Displacement normal to the symmetry plane

Positive displacement → Crack opening with load increase



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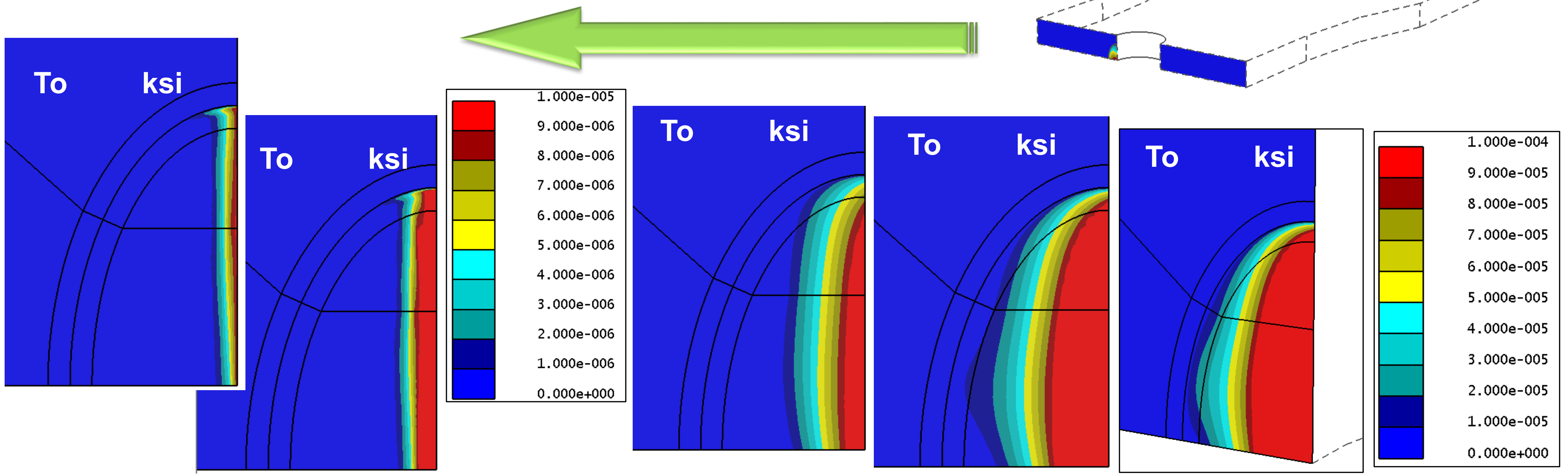
Closure Model

Contact + Remote Unloading

Displacement normal to the symmetry plane
Positive displacement → Crack closing as load decreases



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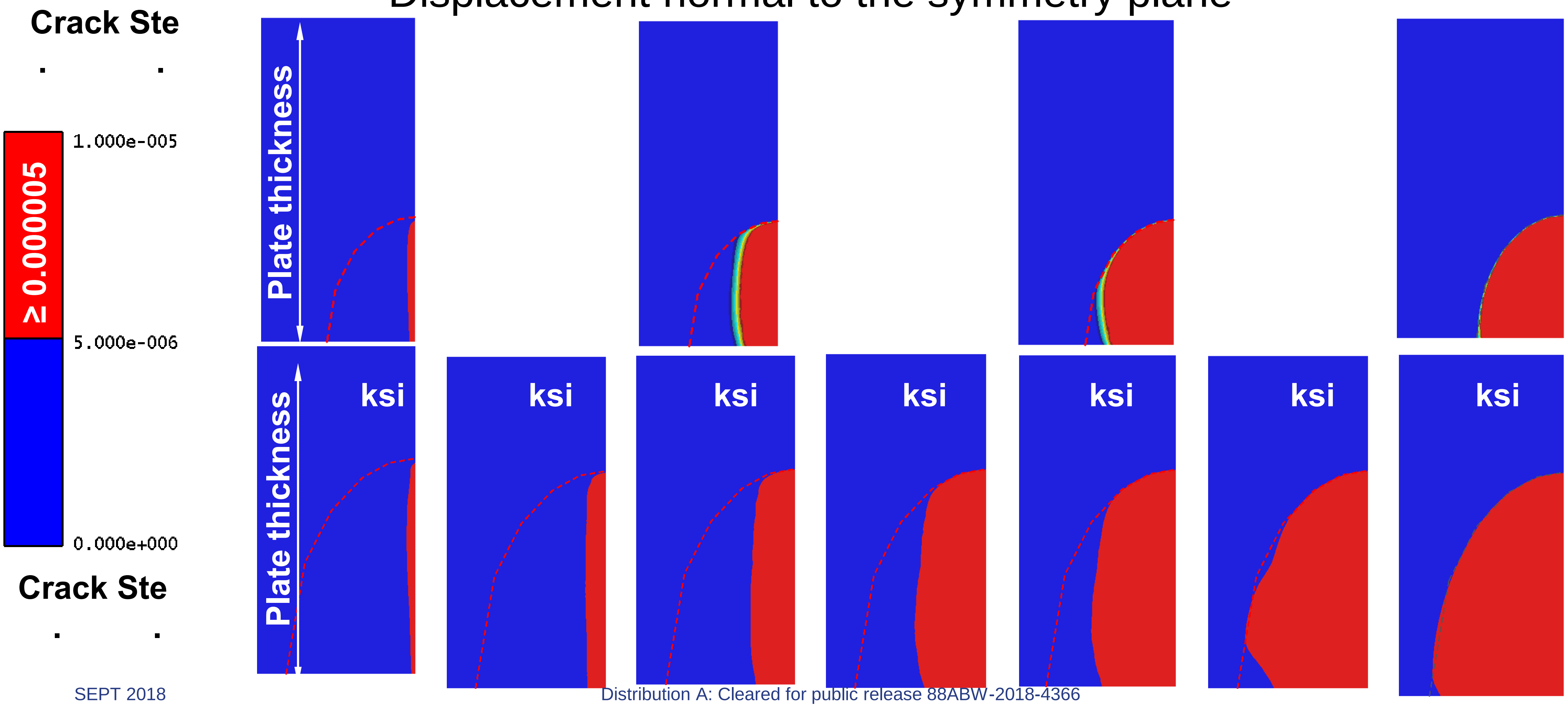
Closure Model

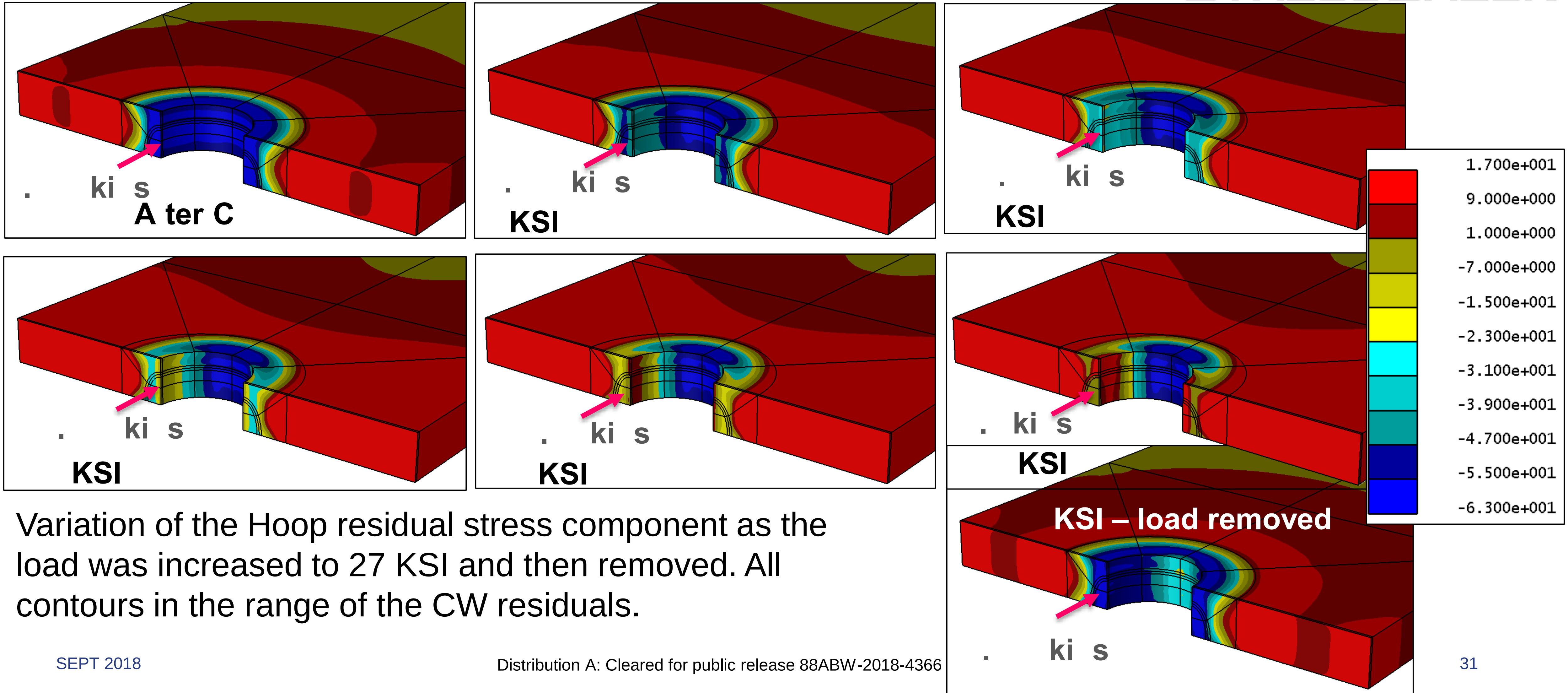
Crack Opening Summary

Displacement normal to the symmetry plane



Closure Model

Residual Stress Summary



Variation of the Hoop residual stress component as the load was increased to 27 KSI and then removed. All contours in the range of the CW residuals.

Summary

Future Work

- More work scheduled for FY19
- Check back with us at ERSI 2019!