Effect of Negative Stress Ratio Testing and Characterization on Damage Tolerance Life Predictions

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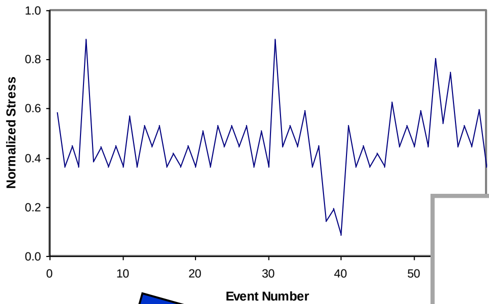
Overview

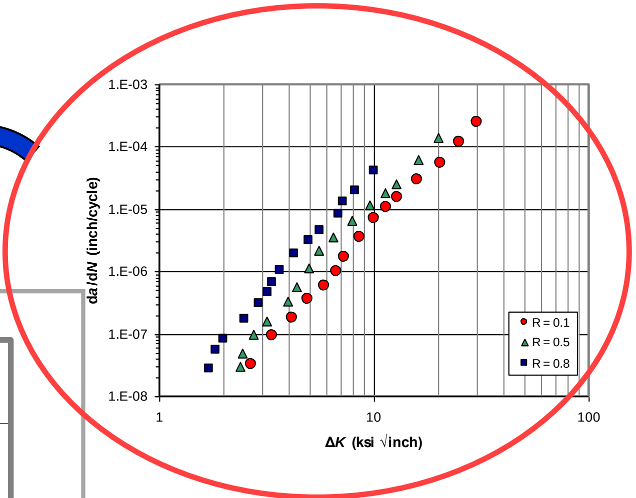
- Background
  - Generalized Willenborg, R_{eff}
- Objective
- Material Curve Fitting Process for da/dN
- Determination of R_{lo}
- Conclusions

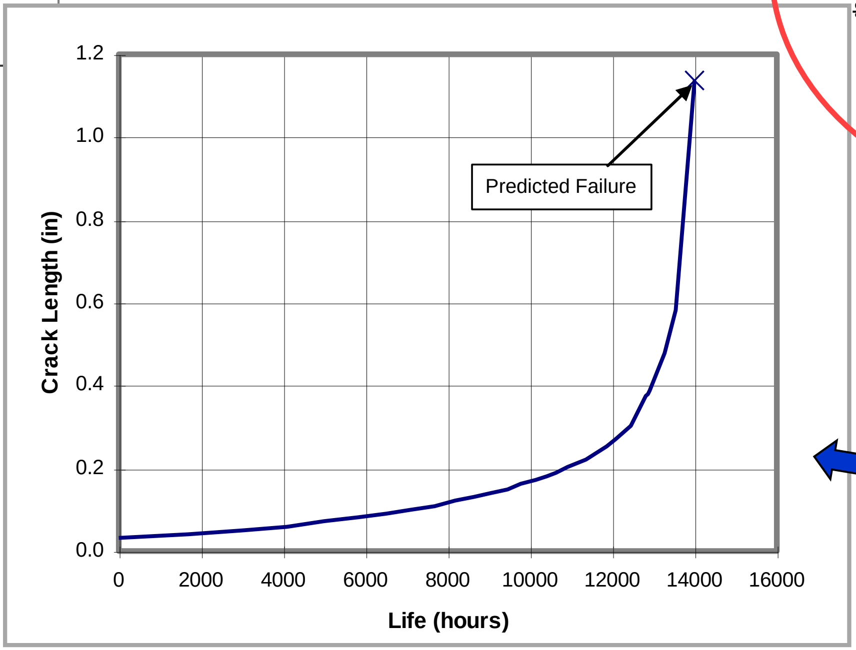
Background

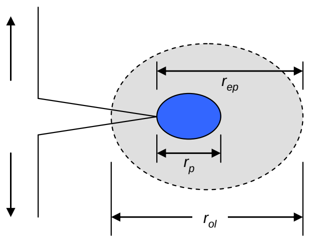
- **Damage Tolerance Analysis**

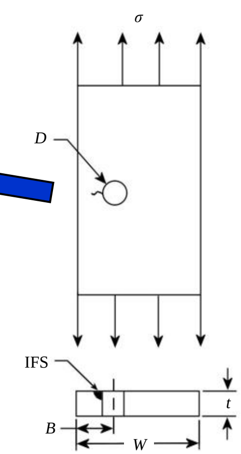
$$a_n = a_i + \sum_{j=1}^{n} da_j$$





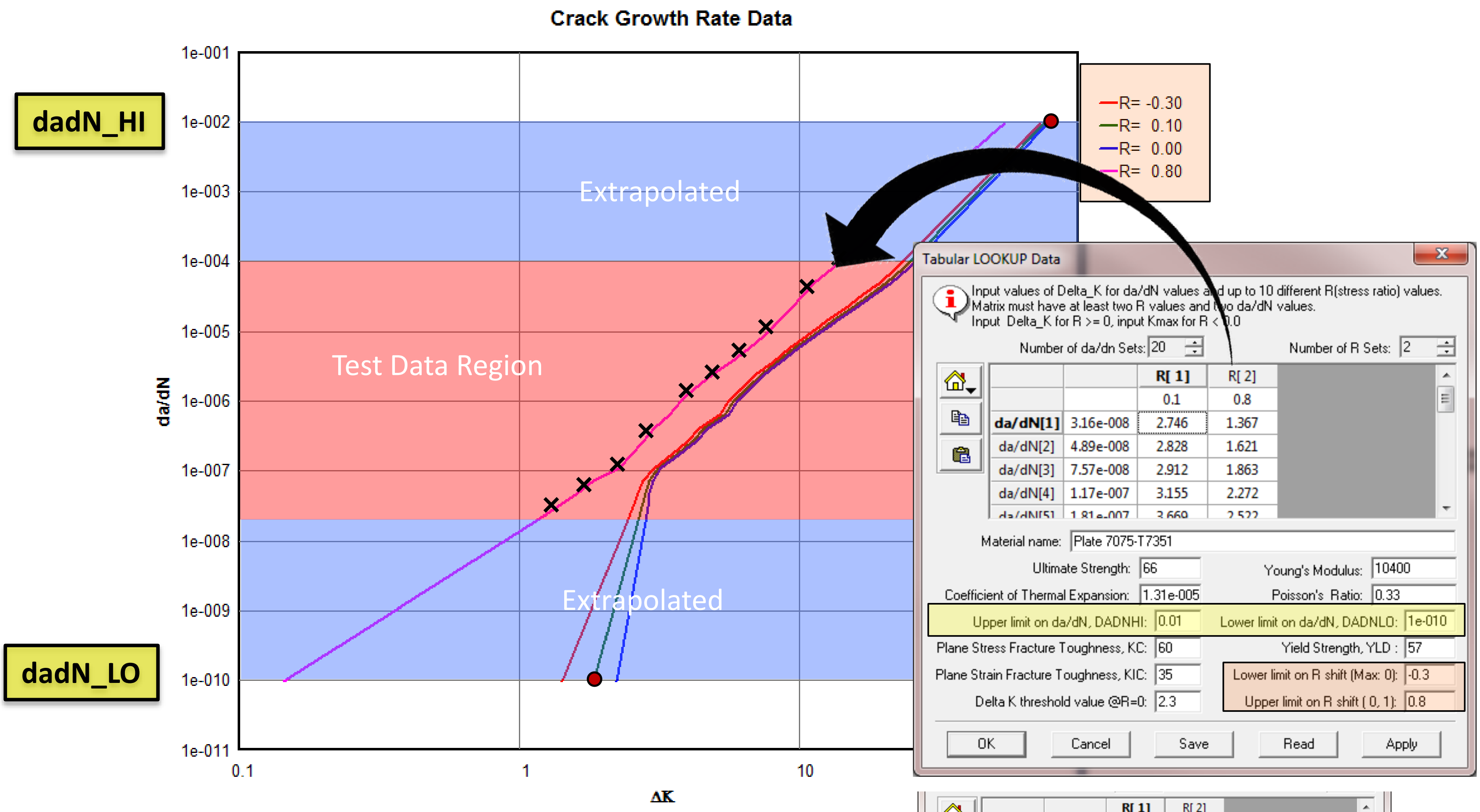




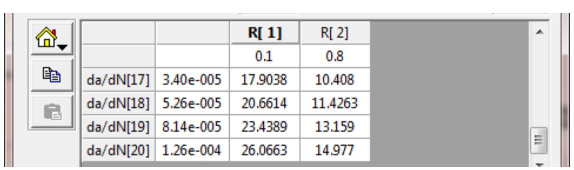


(see *Stress Ratio Influence on da/dN with the Generalized Willenborg Model* by King, 2016 AFGROW Workshop)

Background (cont.)



Note: For R < 0.0, Kmax is used instead of Delta K

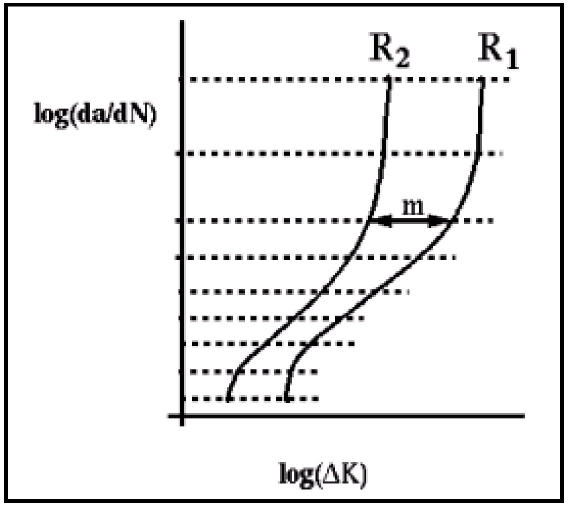


Background (cont.)

- **Harter-T Method**
  - **Shifts *da/dN* curves for any *R***
  - **Applies Walker Equation (point-by-point basis)**

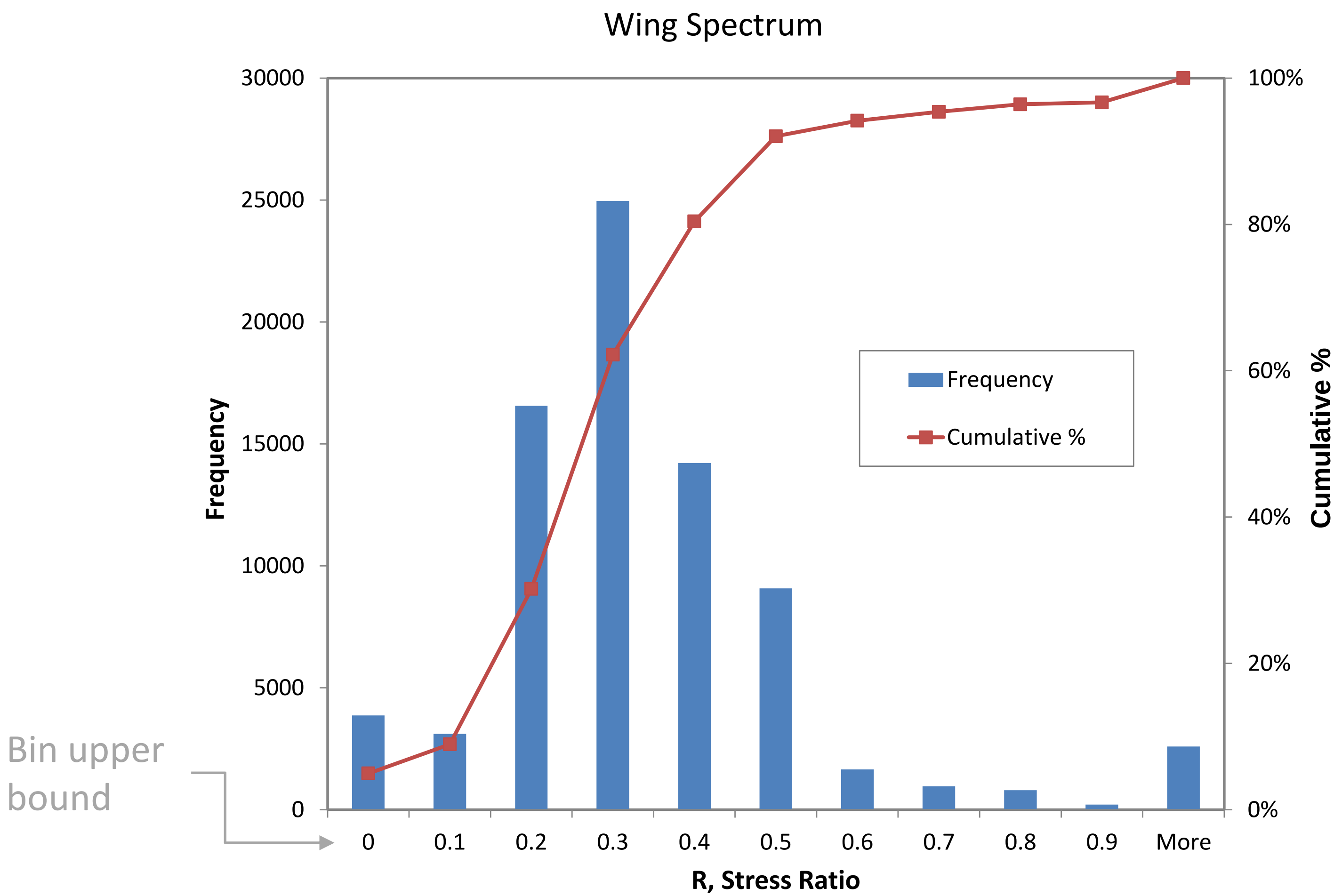
For a given crack growth rate:

$$\Delta K_1 (1 - R_1)^{(m-1)} = \Delta K_2 (1 - R_2)^{(m-1)}$$ (When, R1 & R2 > 0)



(from AFGROW Advanced Training)

Stress Ratio (*R*) Histogram



When using the Generalized Willenborg Model, this is NOT the *R* that is used to determine *da/dN*

Generalized Willenborg Model

- Adjusts *da/dN* by reducing *R* to R_{eff}

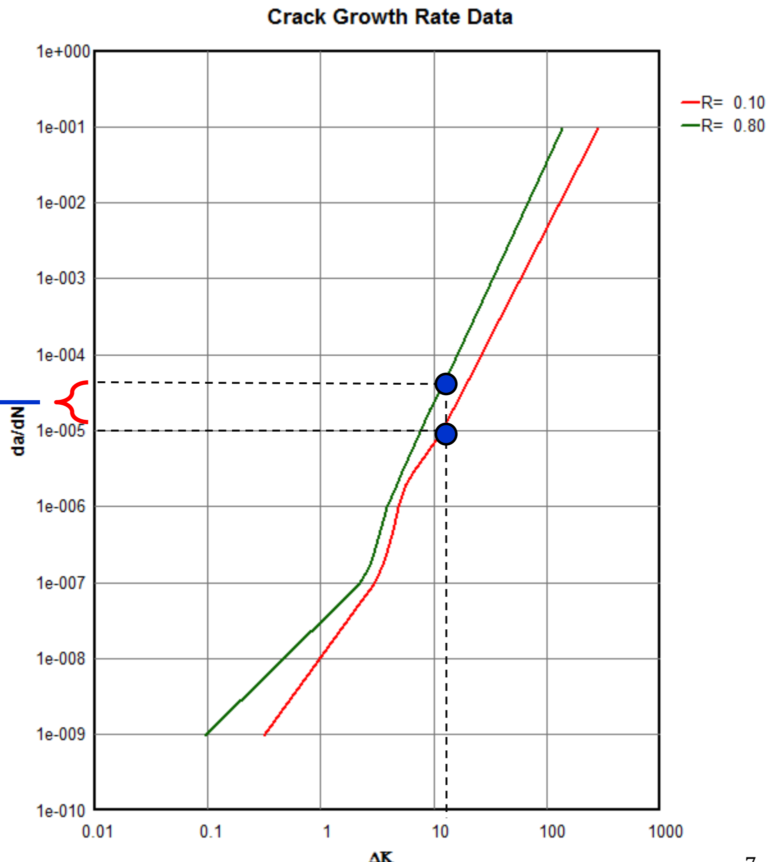
$$K_r = \frac{1-\frac{\Delta K_{th}}{K_{max}}}{(SOLR-1)}\left[K_{OL}\sqrt{1-\frac{x-x_{OL}}{r_{OL}}}-K_{max}\right]$$

$$K_{min,eff} = K_{min} - K_r$$

$$K_{max,eff} = K_{max} - K_r$$

$$R_{eff} = \frac{K_{min,eff}}{K_{max,eff}}$$

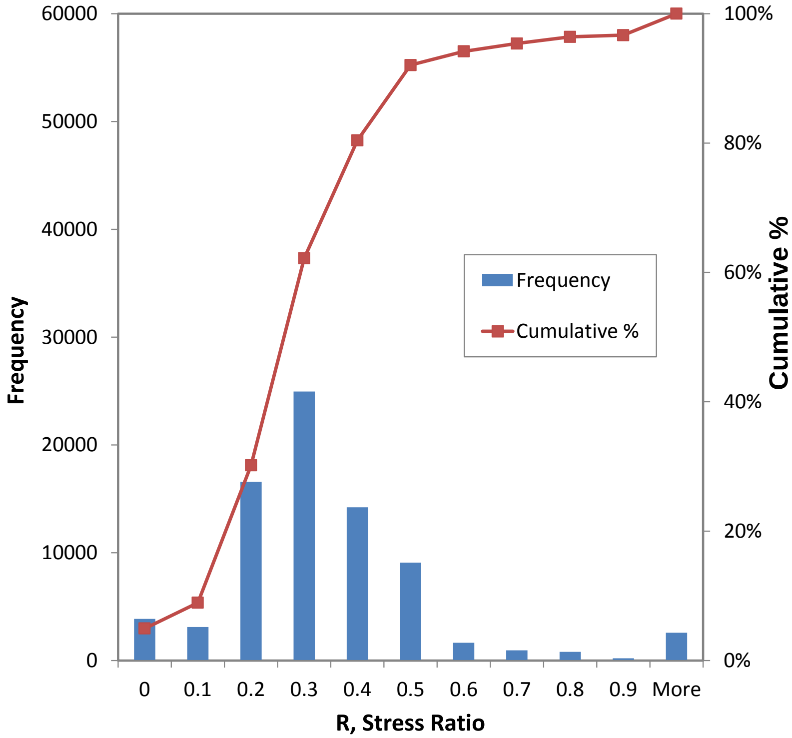
Retardation Effect:
Reduction in *da/dN*

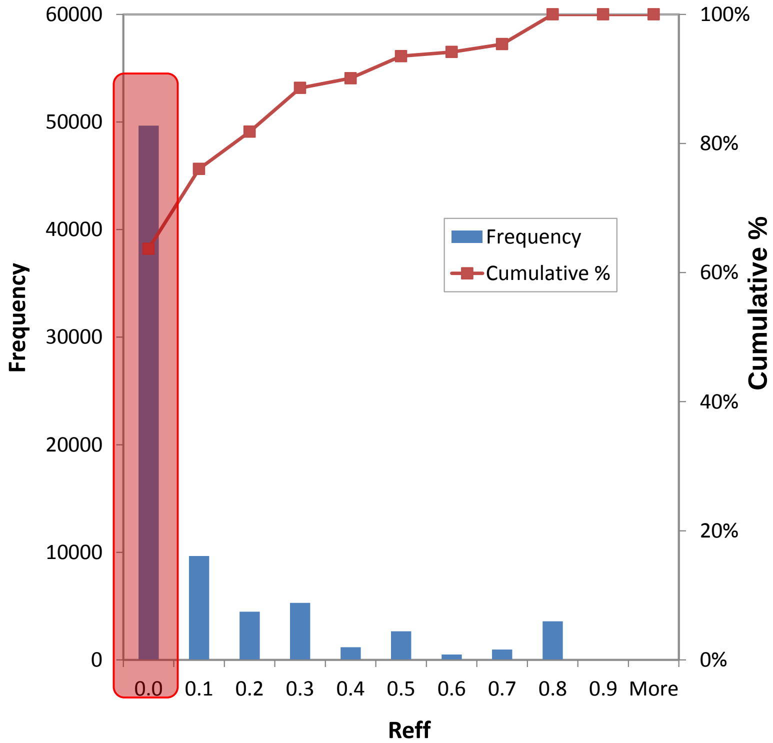


Note: For R < 0.0, Kmax is used instead of Delta K

R vs R_{eff}

Wing Spectrum





***R*, Stress Ratio**

R_{eff}, Effective Stress Ratio

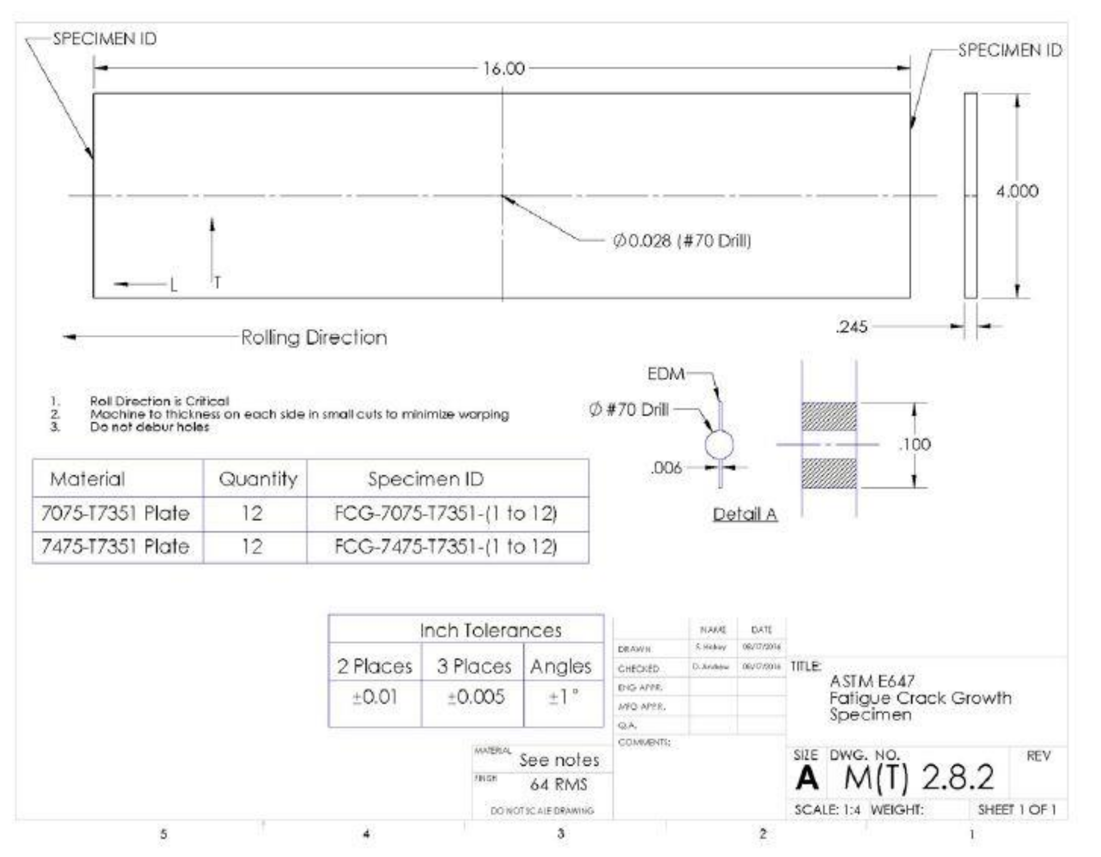
Accounts for > 50% of crack growth (based on multiple wing details)

Test Program Objectives

- Perform da/dN (E647) Tests for Negative R
  - 7075-T7351
  - 7475-T7351
  - 7075-T73511
  - 4130
- Create Curve Fits to Test Data for Negative R
  - How does that compare with the extrapolation of positive R?
- Determine R_{lo}
  - How does this compare to default value previously used?
- What is the effect of the updated material model (da/dN fits and R_{lo}) on the crack growth life predictions for FCLs?

da/dN Testing

- ASTM E647 Specimen Geometry – M(T)



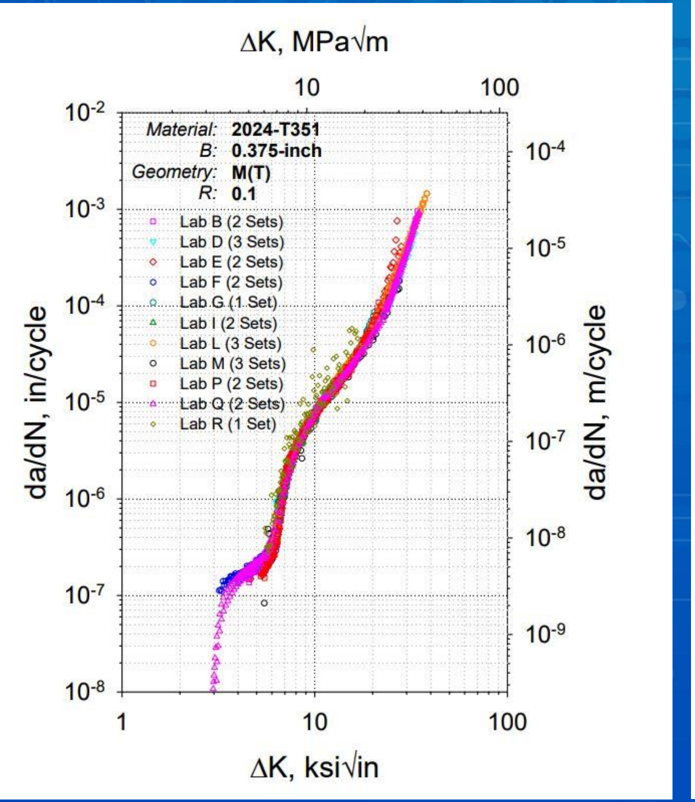
Material	R = -0.1	R = -0.2	R = -0.3	R = -0.5	R = -1
7075-T7351	3	0	3	3	3
7475-T7351	3	0	4	3	2
7075-T73511	0	6	0	5	0
4130	0	4	0	2	0

da/dN Curve Fitting Process

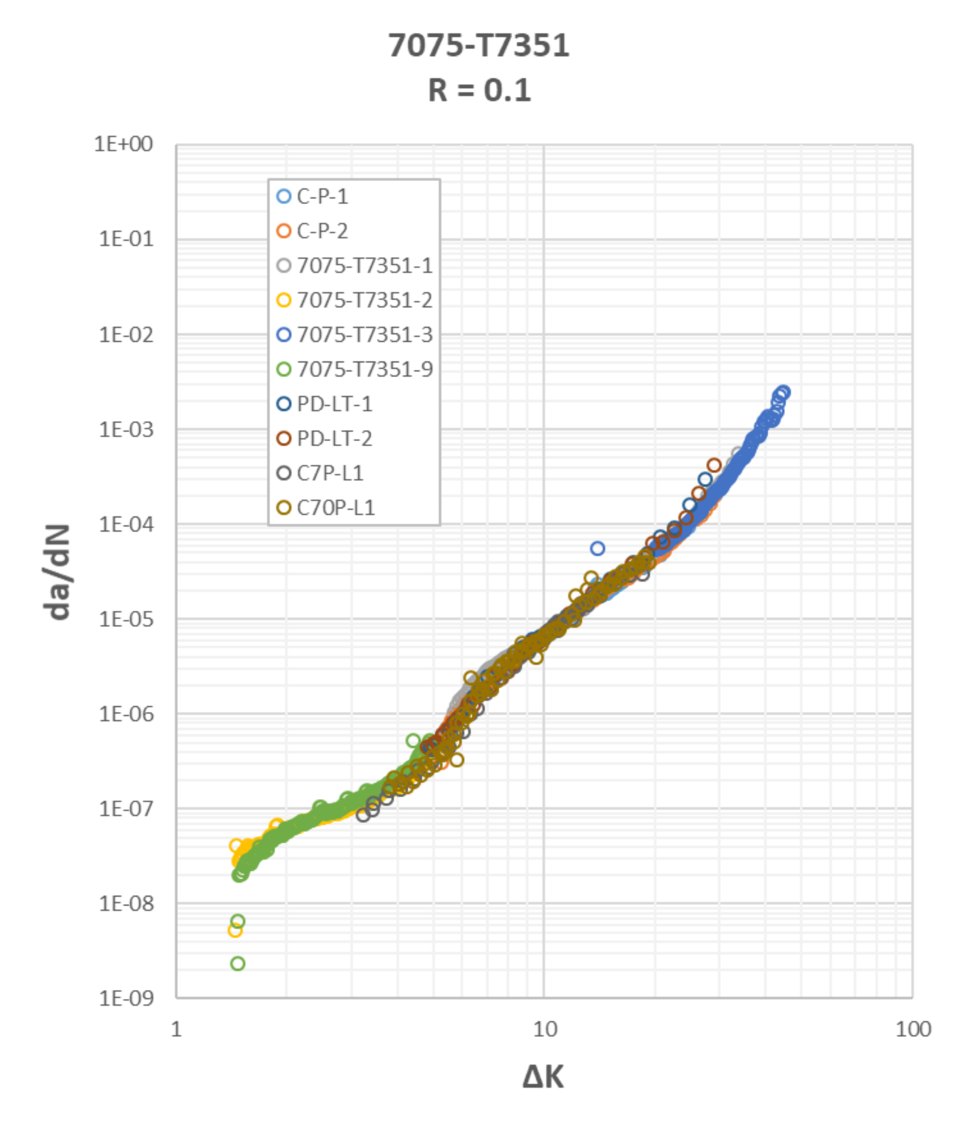
- 2017 AFGROW, *Stress Ratio Influence on da/dN…Updated Material Data & Fitting Process* – Bob Pilarczyk, Dallen Andrew
- Harter-T Method
  - Fitting data on a point-by-point basis
  - Interpolations in ΔK and R via point-by-point Walker equation
  - Captures curvature, permits different amount of shifting for different regimes of curve
- Goals
  - Match test data
  - Smooth m-curves (ensure quality of interpolation)
  - Develop fit across range of available data, preferably from ΔK_{th} to ΔK_c

Fitting +R

- Variation within lot is relatively small at a given load ratio, given geometry

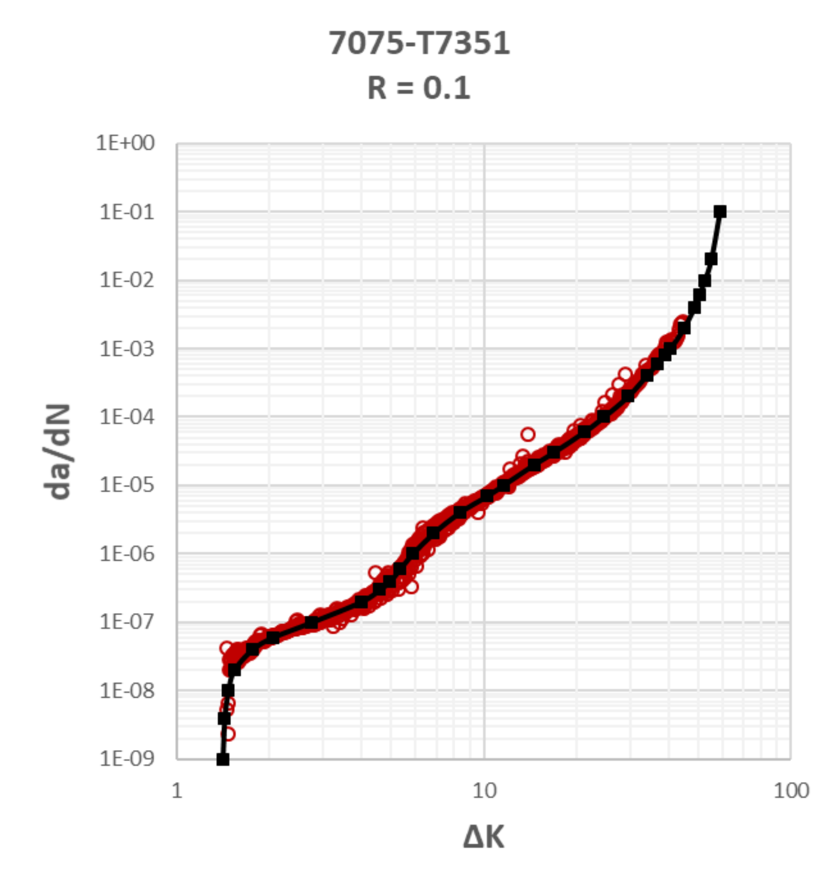


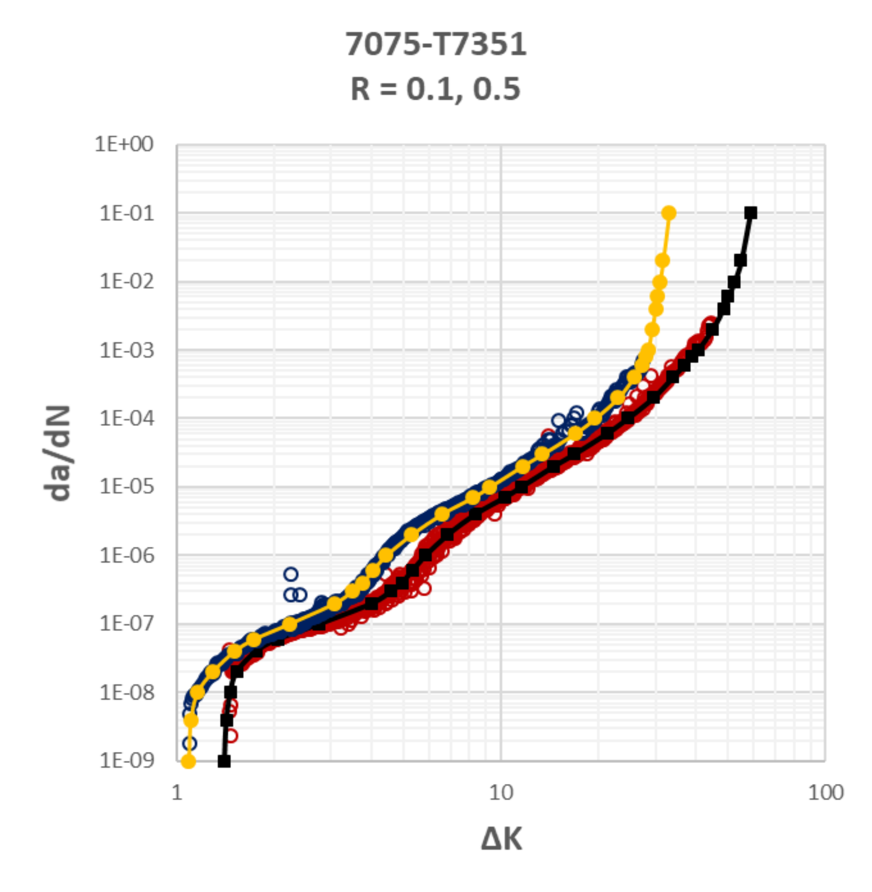
ASTM E647 Round Robin Results



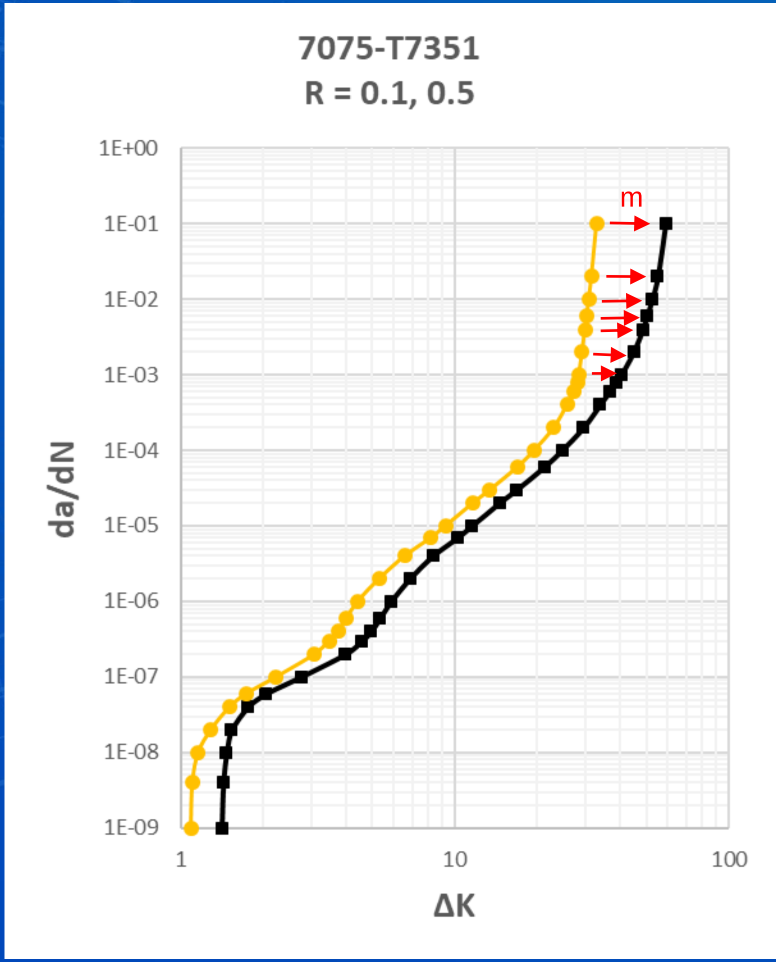
Harter-T Method

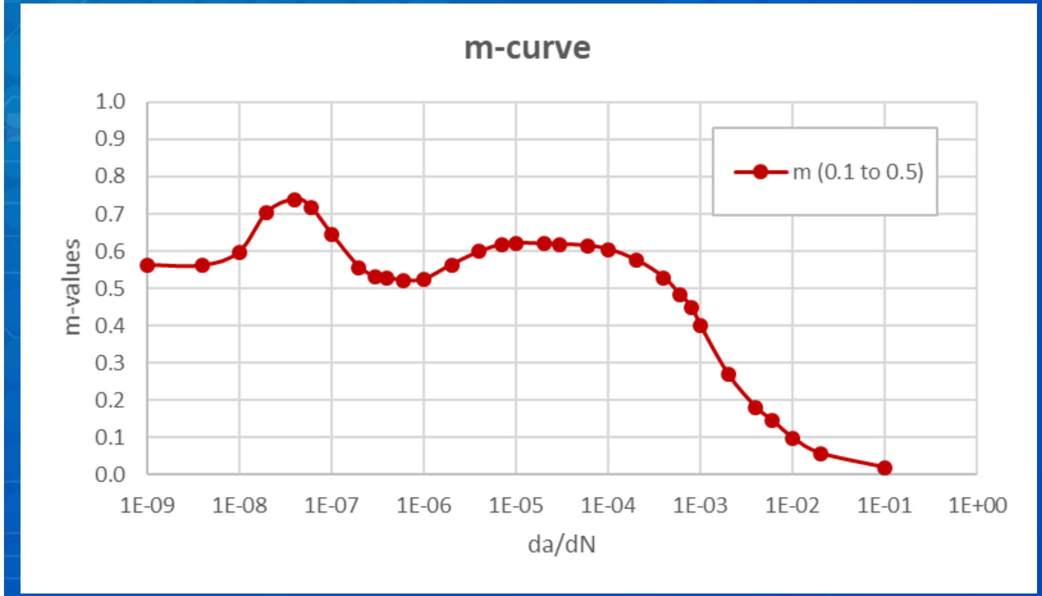
- Fitting data on a point-by-point basis





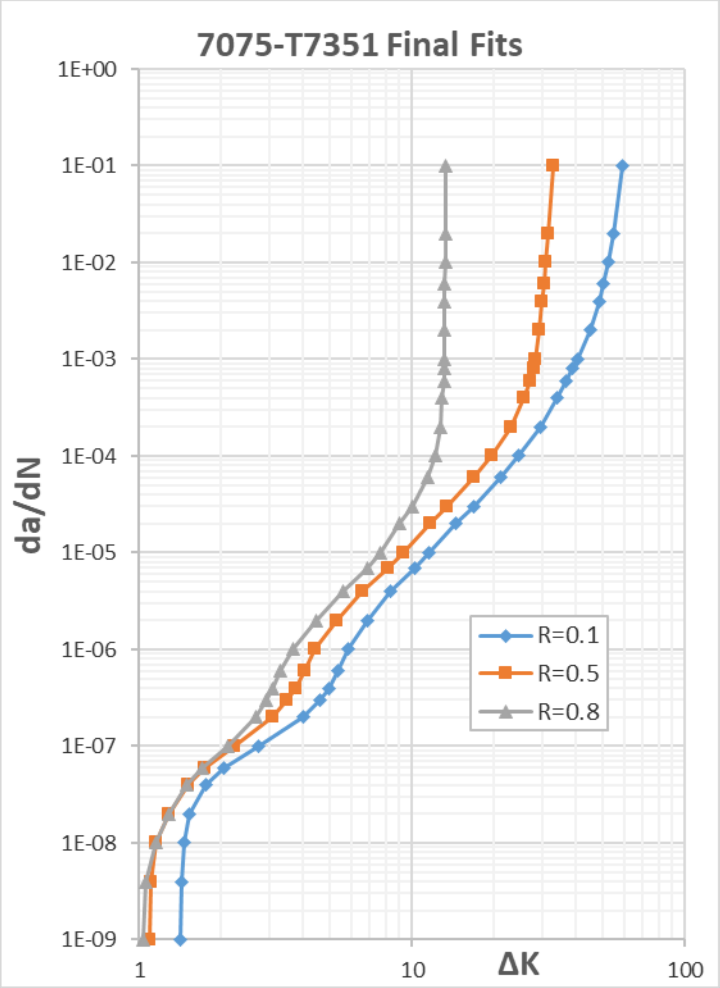
Creating m-curves

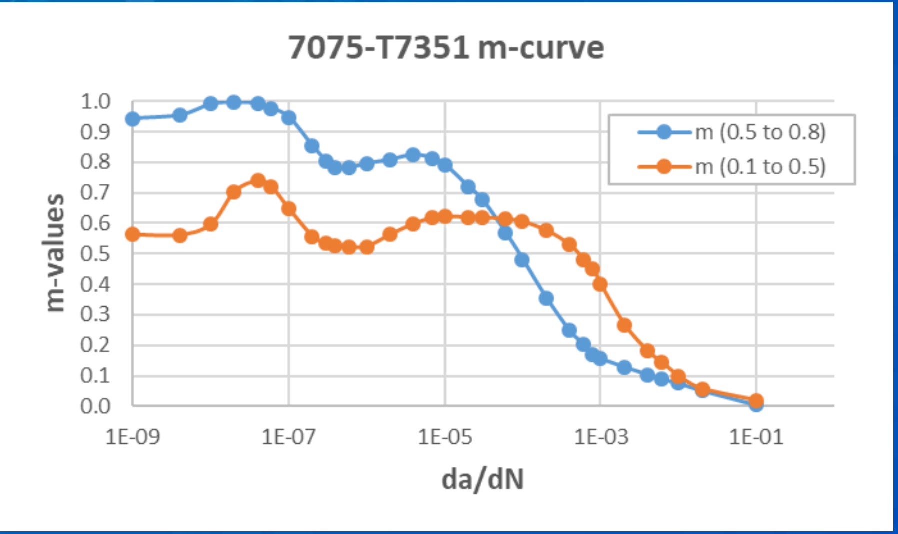




Smooth m-curve

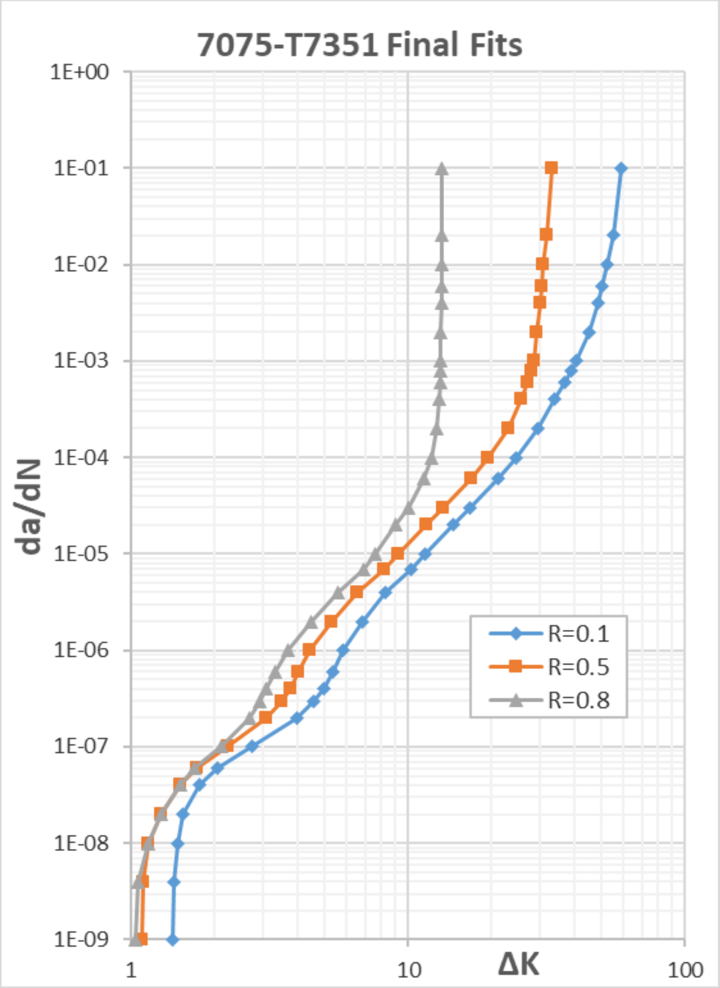
+R Final Fits and m-curves

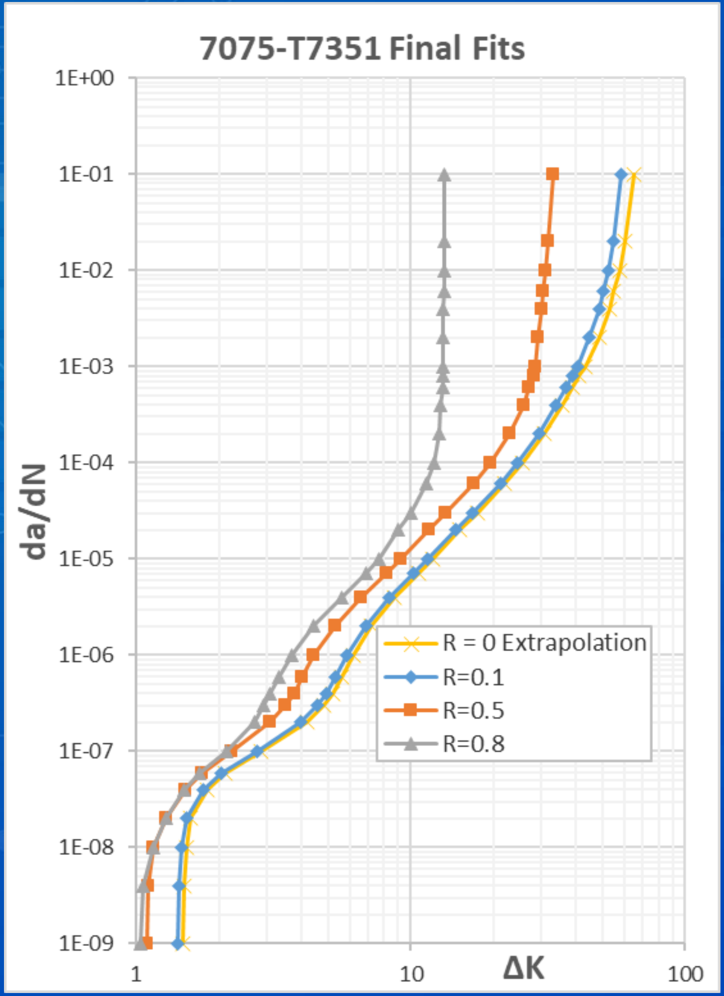




+R Final Fits and m-curves

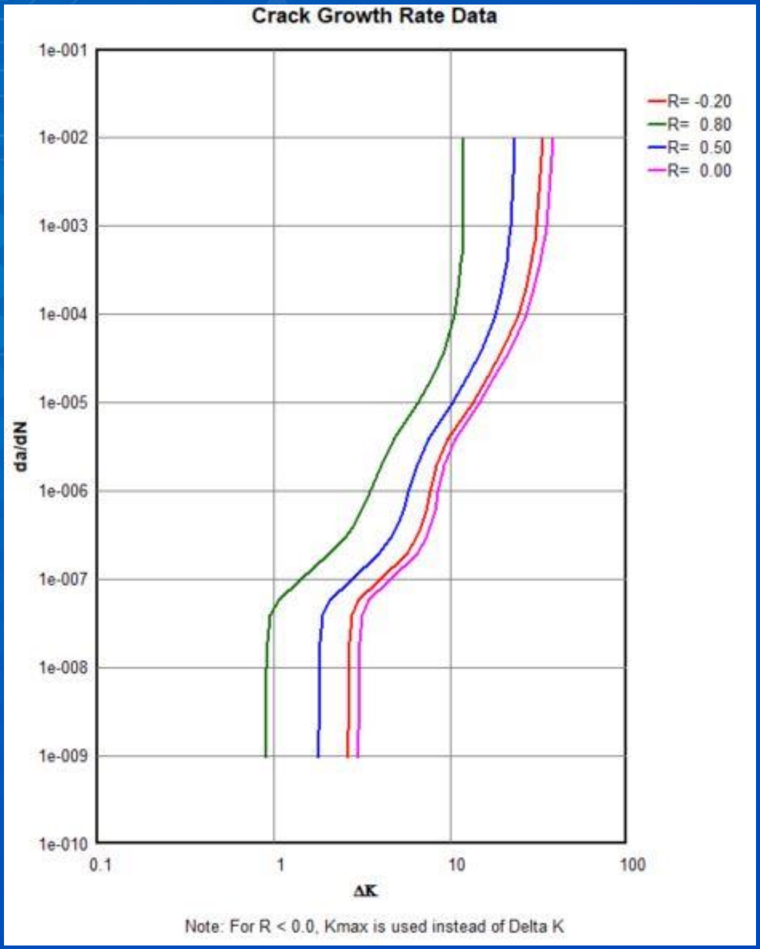
$$\Delta K(R=0) = \Delta K(R=0.1) \cdot (1 - R_{Shift})^{(m_{0.1-0.5}-1)}$$





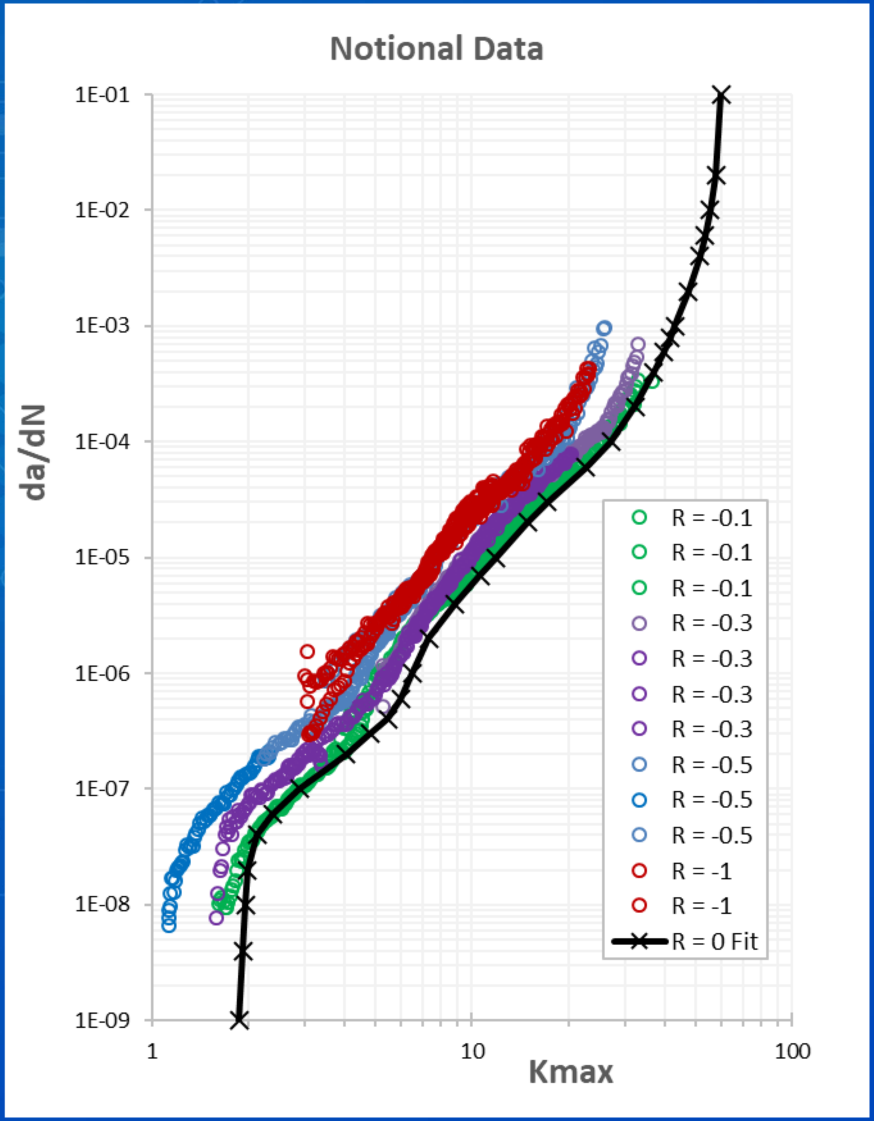
What is R_{lo}? – Visual Demonstration

- For negative stress ratios, fits are performed to the data when plotted against Kmax
- A leftward shift is observed for R < 0, when compared to R = 0
- Shifting does not continue indefinitely, stops at R_{lo}
- Traditional wisdom is $-0.5 < R_{lo} < -0.2$
- All prior T-38 material curve fits used $R_{lo} = -0.3$

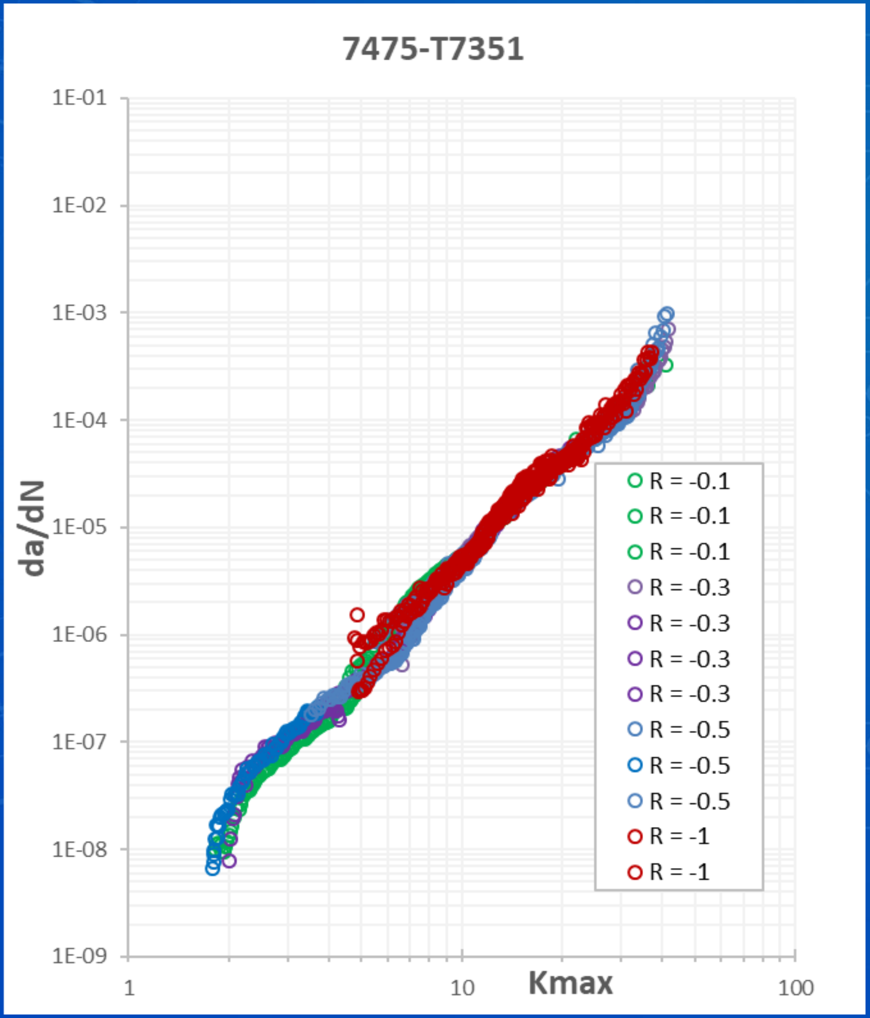


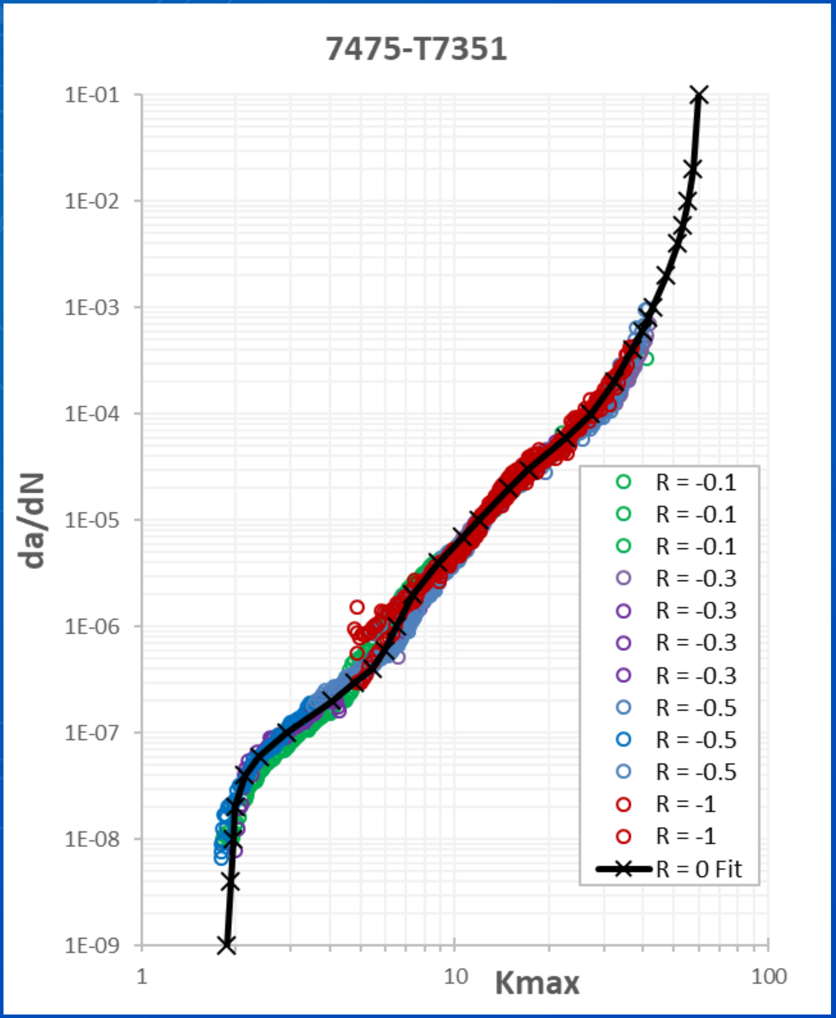
Expected R_{lo} Behavior

- As R decreases, data shifts to left (plotted against Kmax)
- As $R \rightarrow R_{lo}$, shift in data slows
- At $R < R_{lo}$, test data behaves the same as $R = R_{lo}$



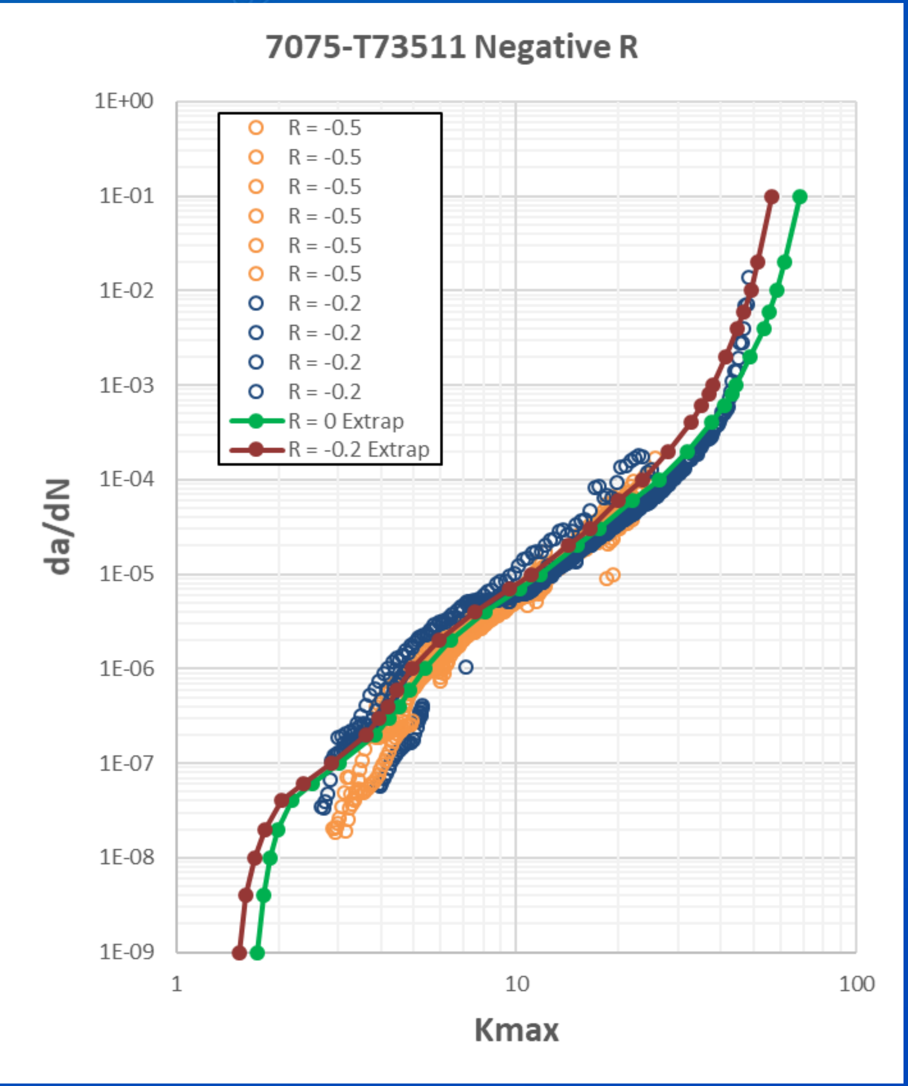
Example of -R Data (Real)





-R Fitting Challenges

- The variance of –R data is significantly greater than that of +R data
- Small shifts cannot be easily discerned
- Do small changes in R_{lo} have a significant impact on life predictions?



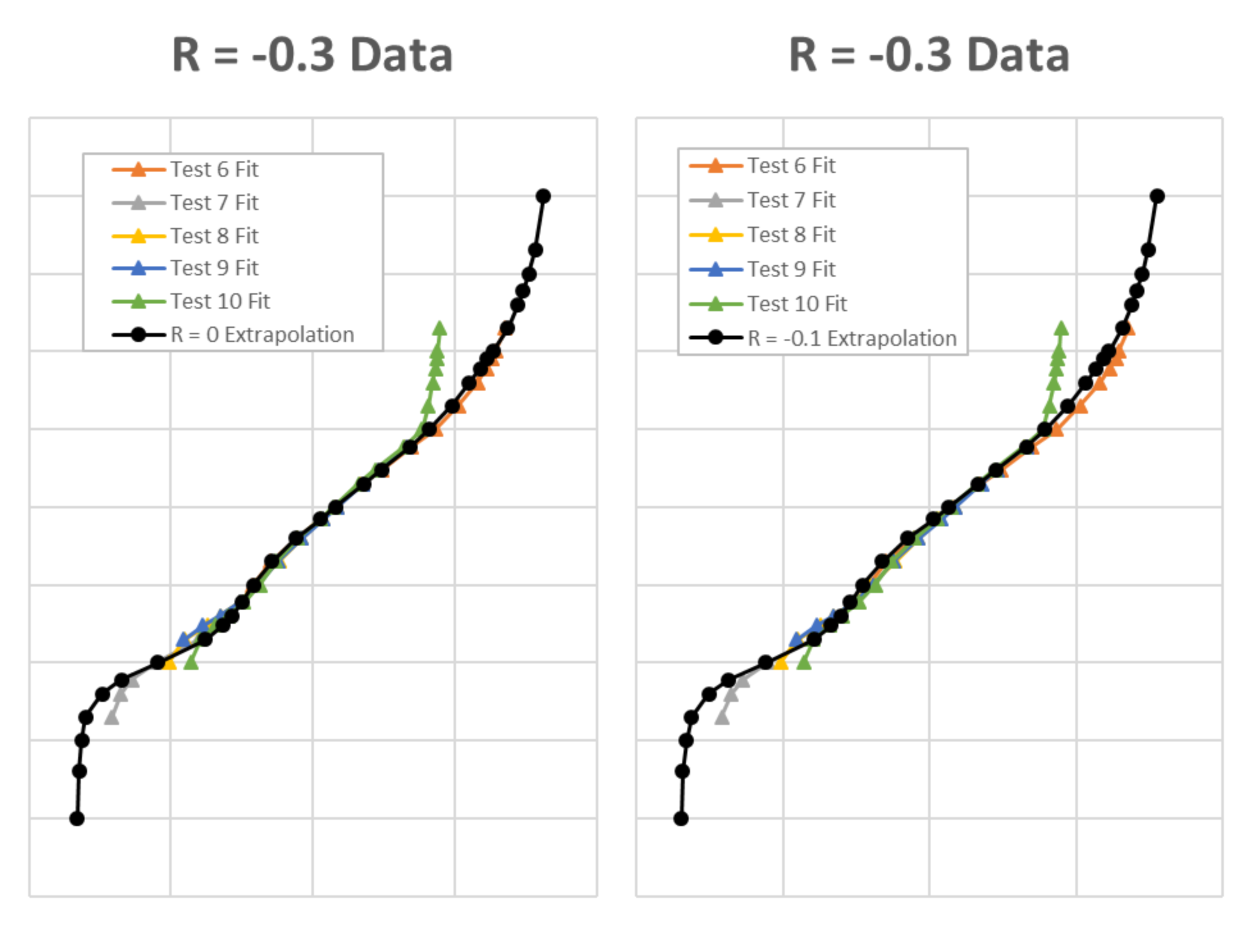
Effect of R_{lo} on Predicted Life - Significant

- Sensitivity study on effects of R_{lo}
- R_{lo} can have a significant effect on the predicted life of a component
  - USAF: Lives drive inspection intervals – Very Important
- Wing A (R_{lo} = 0 vs. R_{lo} = -0.1)
  - +9% Increase in Safety Limit
  - +9% Increase in Field Safety Limit
- Wing B (R_{lo} = 0 vs. R_{lo} = -0.1)
  - +11.5% Increase in Safety Limit
  - +10.5% Increase in Field Safety Limit
- Results show that R_{lo} is an important part of life predictions and highlight need for accurate R_{lo} characterization.

Quantitative Determination of R_{lo}

$$K_{Shift} = \Delta K(R = 0) \cdot \left(1 - R_{Shift}\right)^{(m-1)}$$

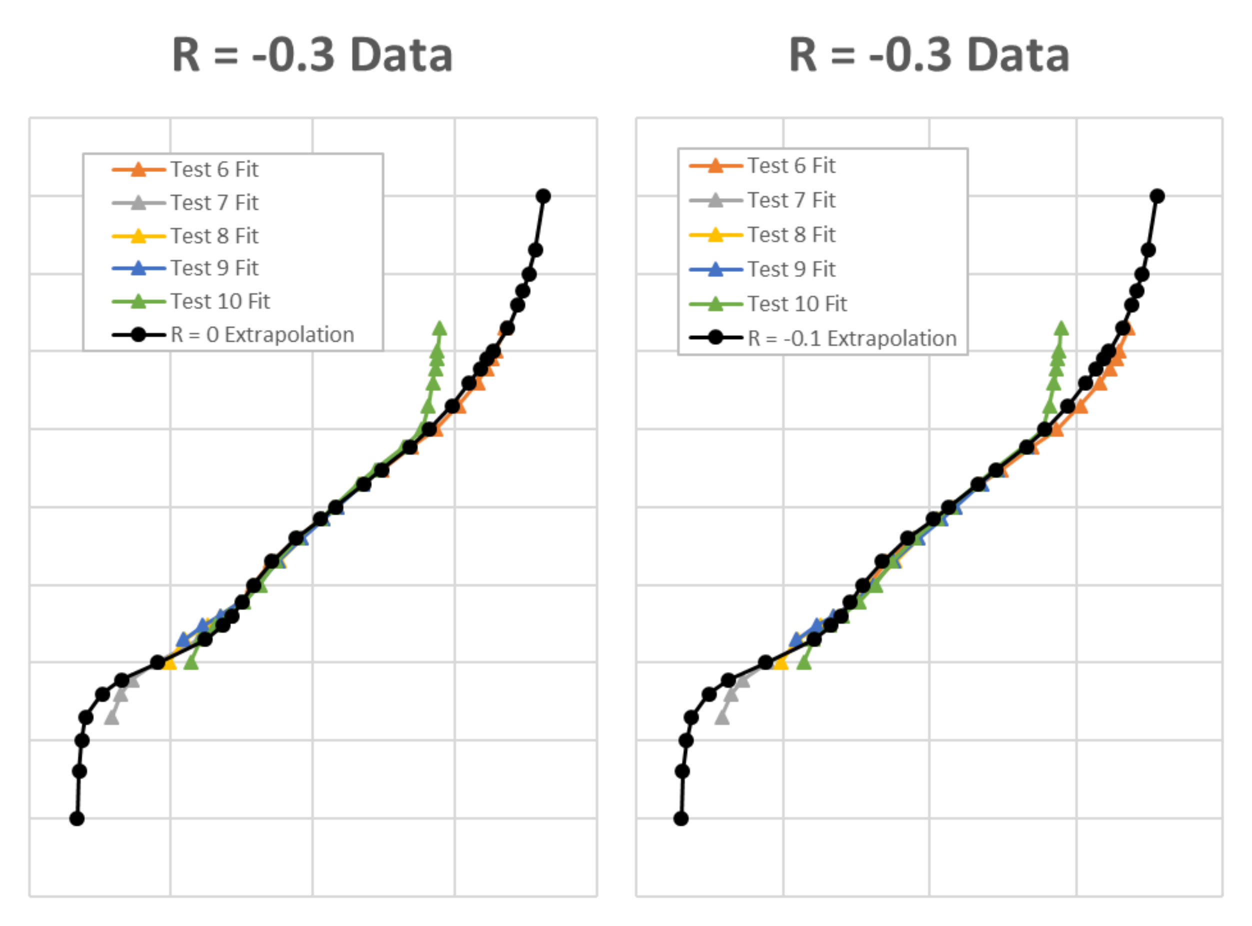
- R_{lo} calculated by extrapolating from +R fits
- m determined from +R fits



Test Data smoothed for numerical handling

Quantitative Determination of R_{lo}

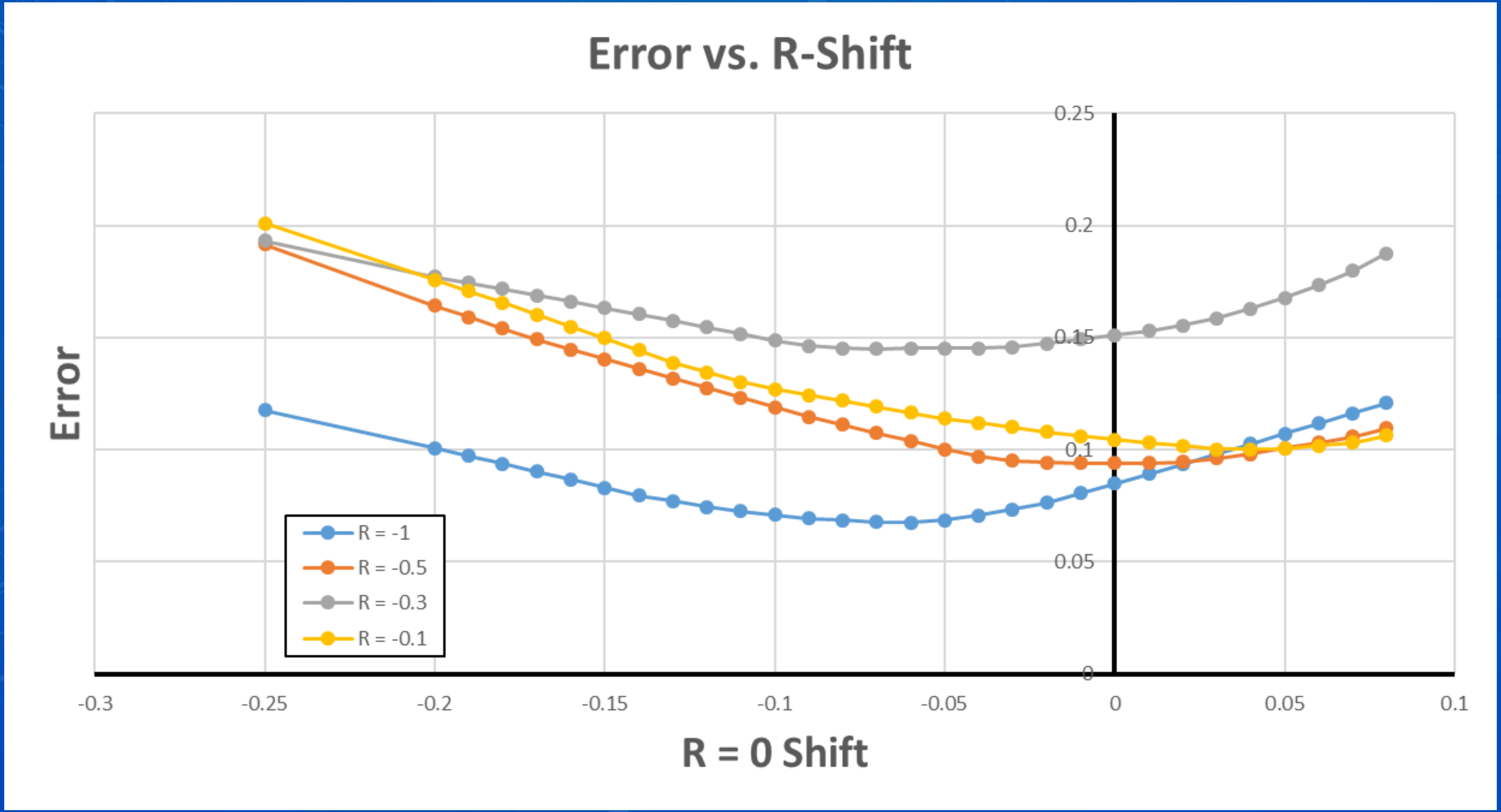
- Examine quality of extrapolations against a given stress ratio
- Define/determine "Best Extrapolation" – Extrapolation that minimizes error
- Plot Best Extrapolations (R_{lo}) vs Stress Ratio, look for behavior suggestive of R_{lo}
- At minimum, gives bounds on R_{lo}



Test Data smoothed for numerical handling

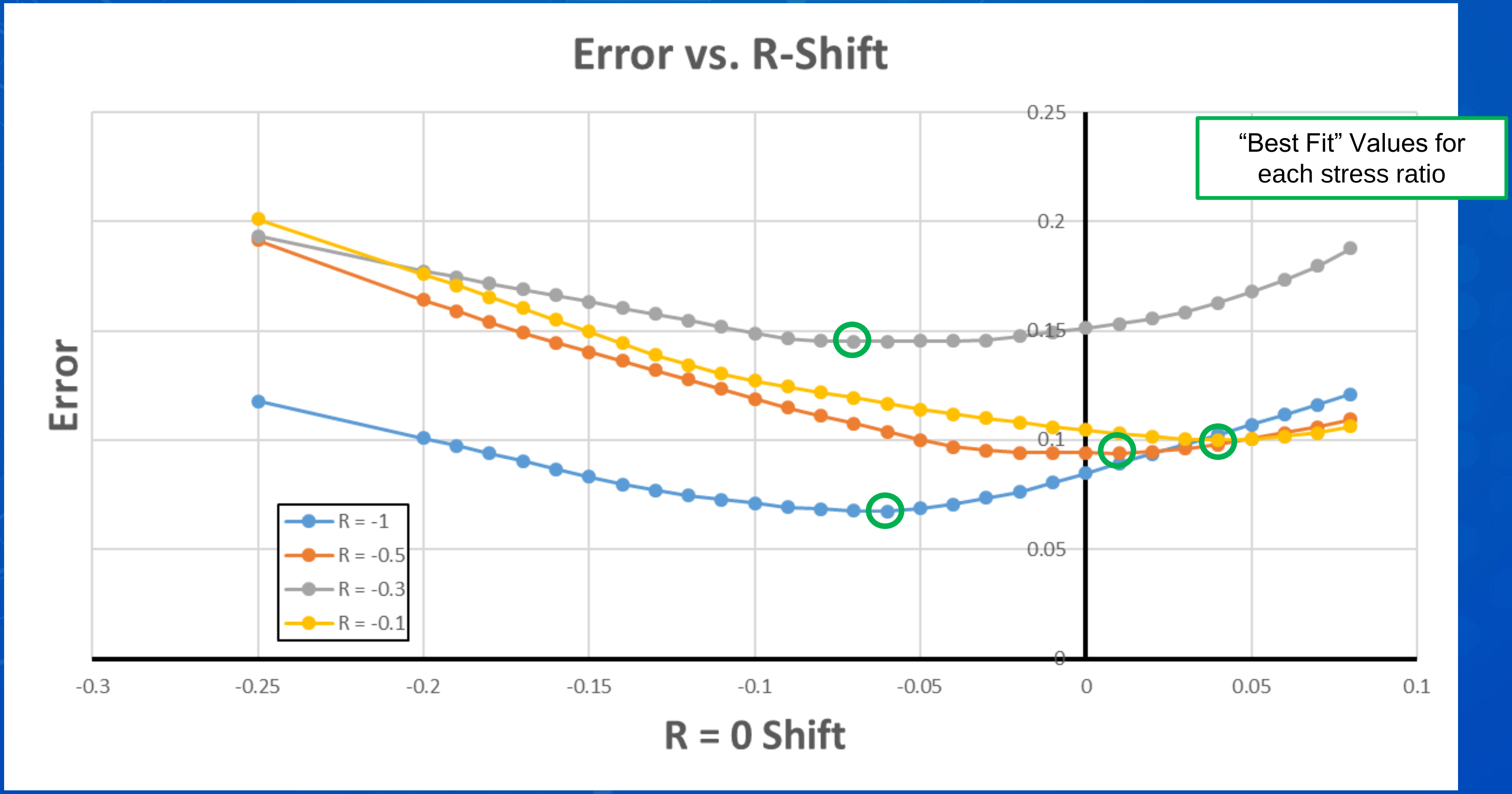
Results

7075-T7351



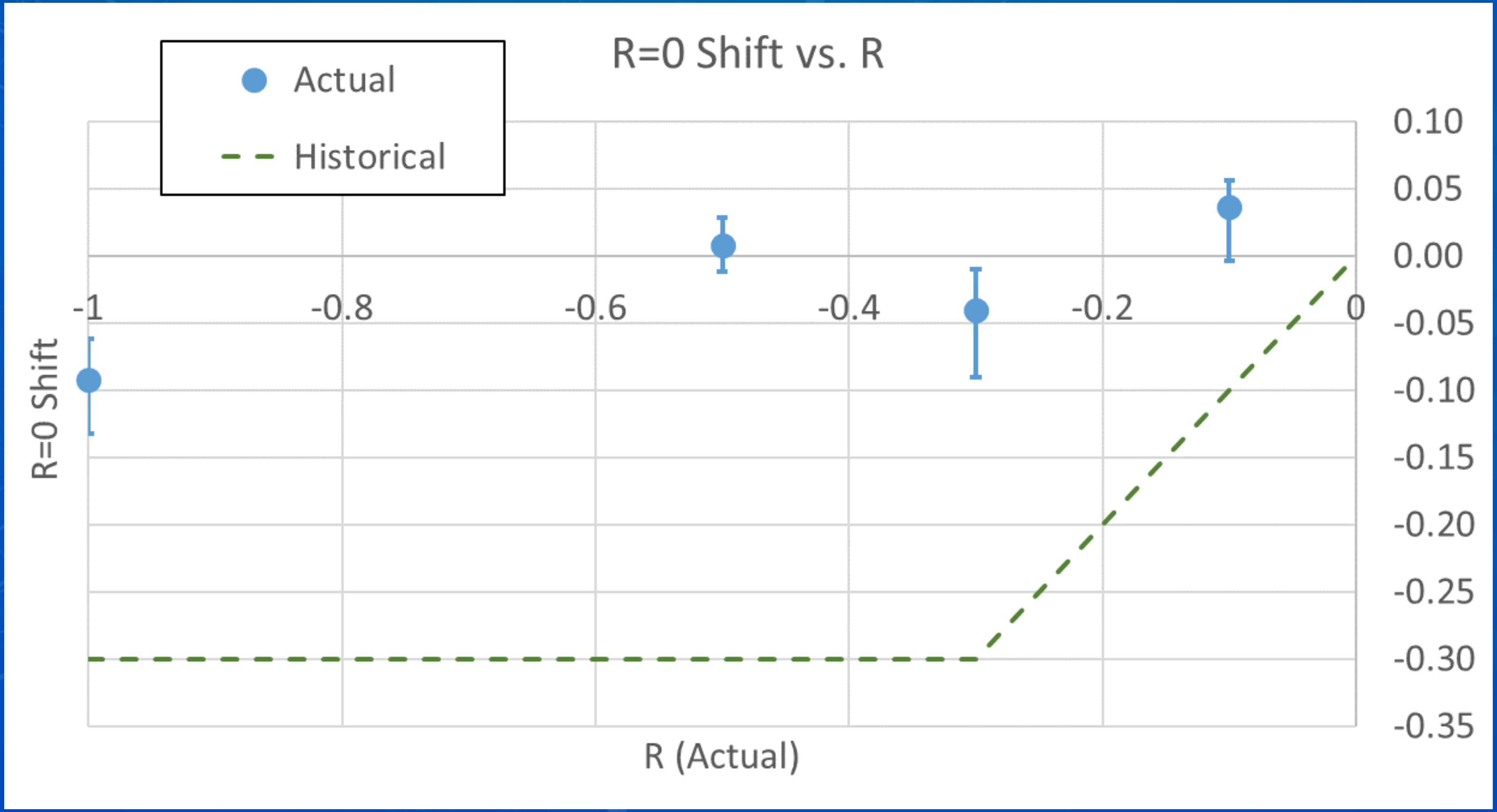
Results

7075-T7351



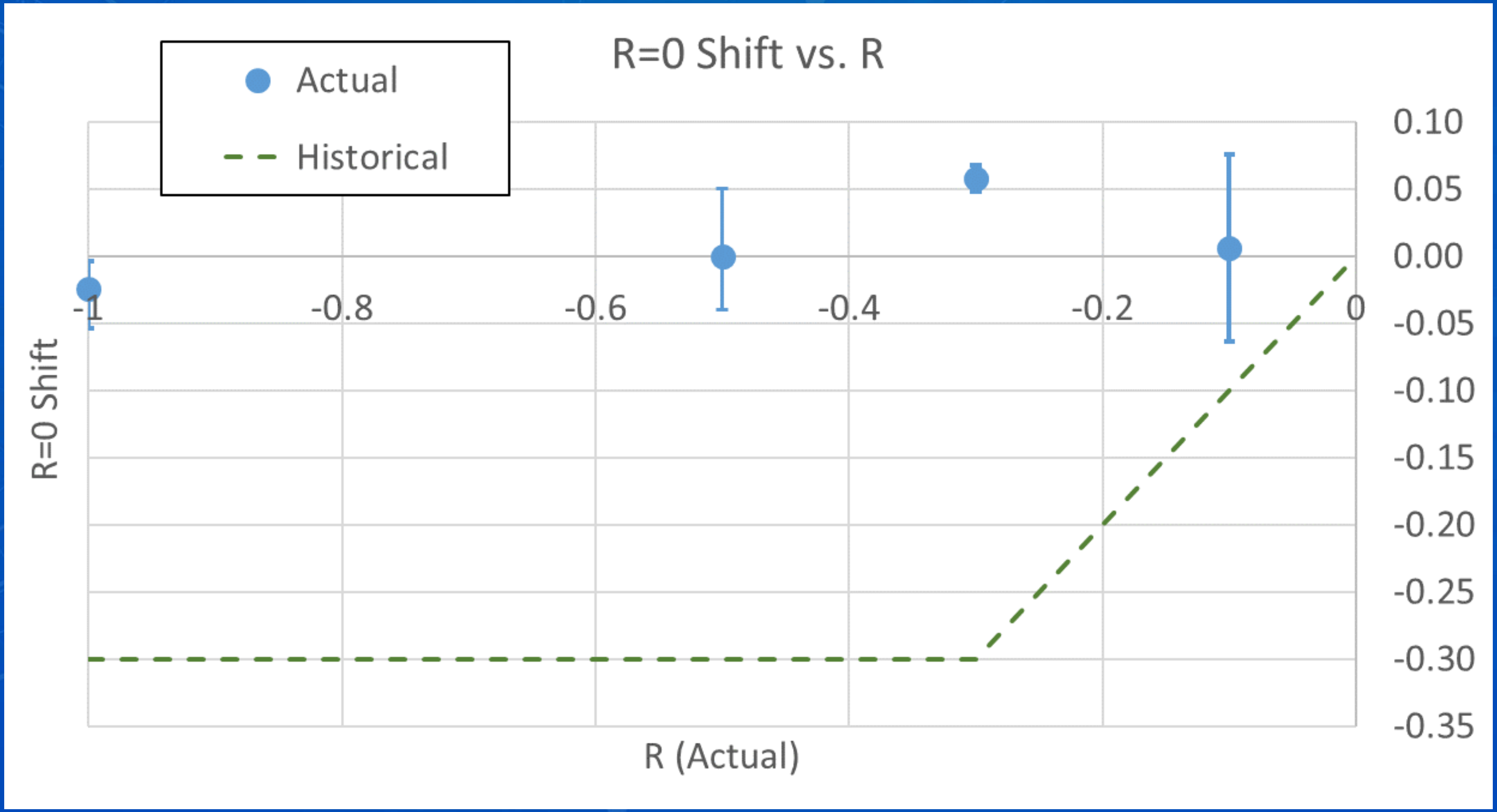
Results

7075-T7351



Results

7475-T7351



Results of Quantitative Determination

- Examined 5 different error metrics
- Results for R_{lo} – All Stress Ratios:
  - 7075-T7351: $-0.13 < R_{lo} < 0.06$
  - 7475-T7351: $-0.06 < R_{lo} < 0.08$
  - 7075-T73511: $-0.03 < R_{lo} < 0.15$
  - 4130: $0.19 < R_{lo} < 0.38$
- Used lowest calculated values from selected error metric or $R_{lo} = 0$, whichever is lower
- All results significantly higher than legacy values used in analysis

Conclusions

- Fitting negative R data presents significant challenge
- Recommended R_{lo} values based to T-38 tests are higher than historical values
- Continue efforts to fully characterize material behavior at negative stress ratios
  - Most frequently used data during a crack growth simulation when using Generalized Willenborg Retardation Models
- Attempt similar characterization on available data sets
- Examine the effect that higher growth rates, and less retardation has on crack growth model predictions