The Shutoff Overload Ratio and its Sensitivity to Analytical Parameters and Techniques

Luciano Smith
Southwest Research Institute

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Summary

- The Generalized Willenborg Equation
  - The Shutoff Overload Ratio (SOLR)
- SOLR Sensitivity to Material Properties and AFGROW Parameters
- SOLR Sensitivity to Correlation Techniques
- Recommendations for Determining SOLR

The Generalized Willenborg Equation

- Analytically accounts for spectrum effects with the incorporation of an effective stress ratio:

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

$$K_r = \frac{1 - \dfrac{\Delta K_{th}}{K_{\max}}}{(SOLR - 1)} \left[K_{\max}^{OL} \sqrt{\frac{1 - \Delta a}{r^{OL}}} - K_{\max} \right]$$

- This effective stress ratio (R_{eff}) is lower than the actual R, which causes less crack growth during each cycle

The Generalized Willenborg Equation

$$K_r = \frac{1 - \dfrac{\Delta K_{th}}{K_{\max}}}{(SOLR - 1)} \left[K_{\max}^{OL} \sqrt{\frac{1 - \Delta a}{r^{OL}}} - K_{\max} \right]$$

- **Parameter definitions:**
  - Defined by current cycle (K_{max}, Δa)
  - Defined by recent overload cycle (K^{OL}_{max} , r^{OL})
  - Material property (ΔK_{th})
  - Dependent on material and loading (SOLR)

The Generalized Willenborg Equation

$$K_r = \frac{1 - \dfrac{\Delta K_{th}}{K_{\max}}}{(SOLR - 1)} \left[K_{\max}^{OL} \sqrt{\frac{1 - \Delta a}{r^{OL}}} - K_{\max} \right]$$

- **Shutoff Overload Ratio (SOLR)**
  - **Definition: The maximum ratio of the overload maximum SIF to the subsequent maximum SIF**
  - **Effect: If SOLR is exceeded during a cycle, $K_{max,eff}$ is equal to $\Delta K_{th}/(1-R)$ and crack growth is arrested**
  - **Practical Use: Tuning parameter**

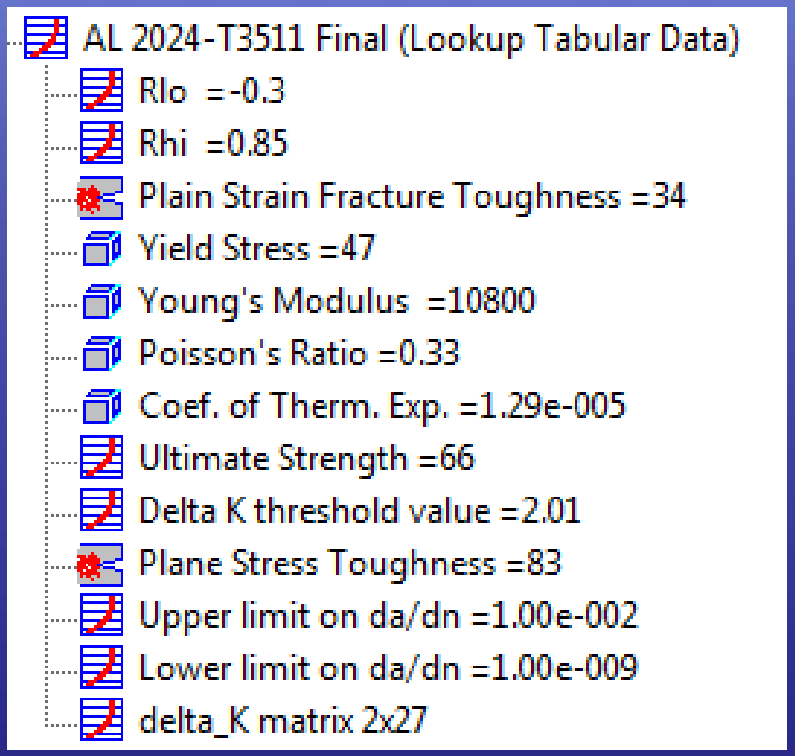
Determination of SOLR

- Coupon spectrum test
  - Test coupon design
    - Material matching actual structure
    - Geometry similar to actual structure
    - Geometry simple to analyze
    - Boundary conditions known
  - Spectrum test loads
    - Comparable to actual structure
    - Simple to determine and analyze

- Correlation analysis
  - Simulate test as closely as possible
  - Use different SOLR values until analysis matches test

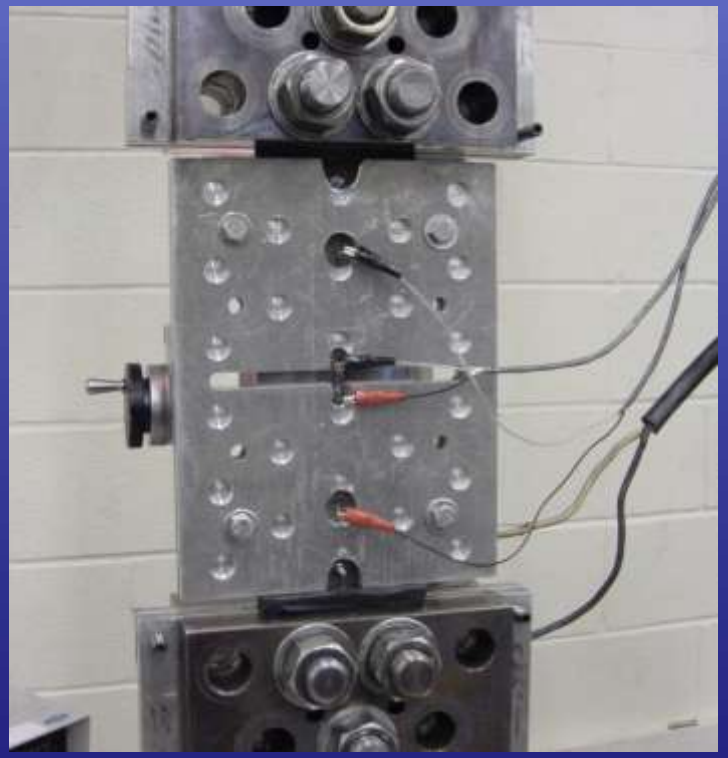
Sensitivity of SOLR to AFGROW Parameters

- Determine the effect on the correlated SOLR of changes to
  - Fracture toughness
  - Tensile yield strength
  - Crack growth rates
  - Limits on R shift
  - ΔK threshold



Sensitivity of SOLR to AFGROW Parameters

- Fracture toughness: Used by AFGROW only for determination of failure
  - Only exception is K_c when using the Forman equation
- No impact on retardation

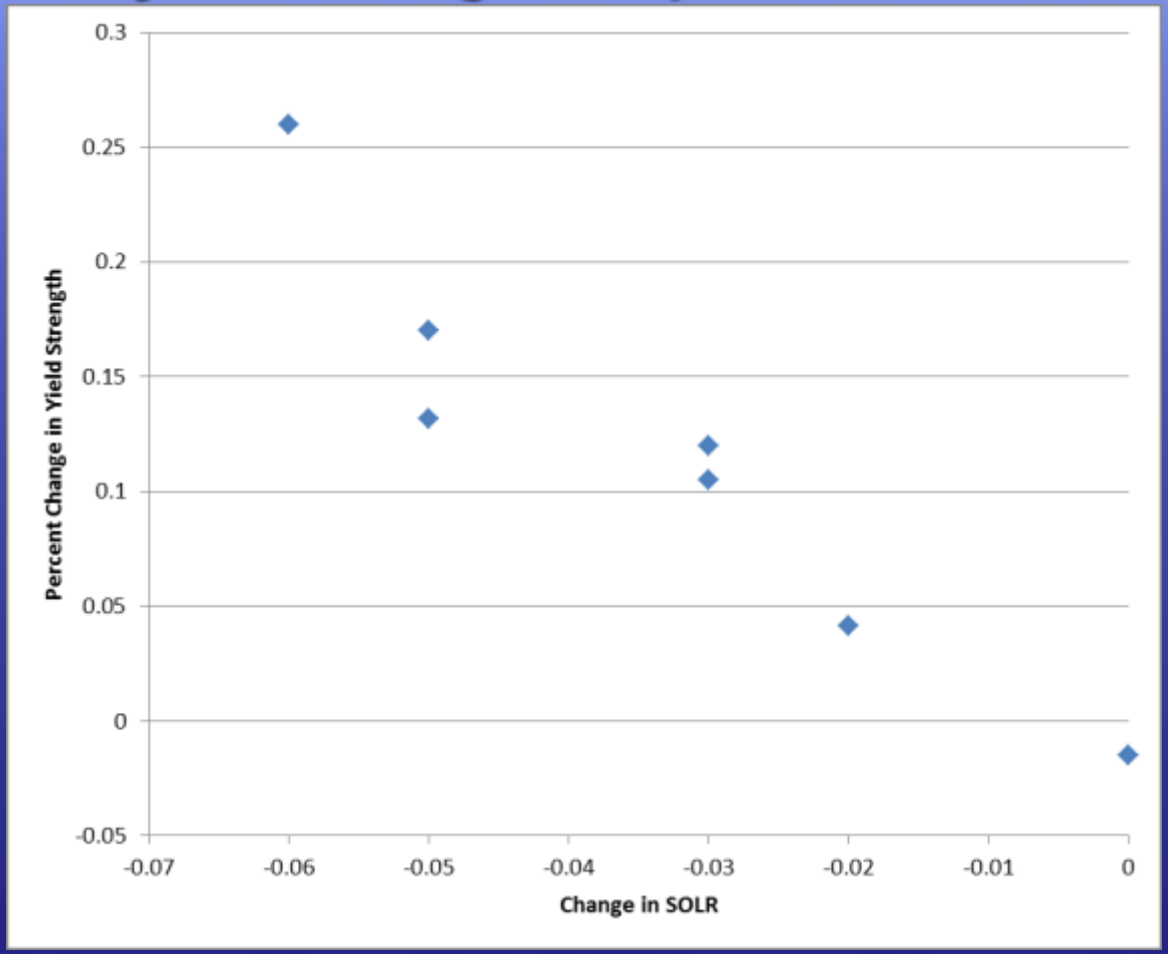


Sensitivity of SOLR to AFGROW Parameters

- **Tensile yield strength: Used in two ways by AFGROW**
  - **Determination of stress state for toughness**
    - **No impact on retardation**
  - **Calculation of yield zone size**
    - **The higher the yield strength, the smaller the yield zone**
    - **Increasing the yield strength (and leaving all other parameters constant) accelerates the analytical crack growth**

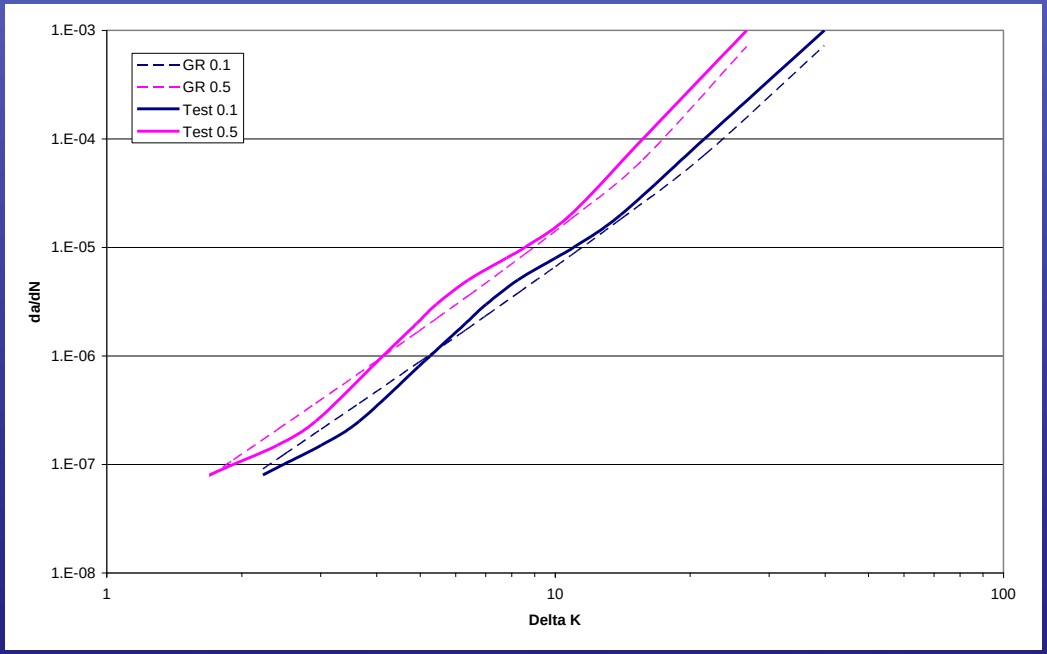
Sensitivity of SOLR to AFGROW Parameters

- Tensile yield strength: Impact on SOLR is small



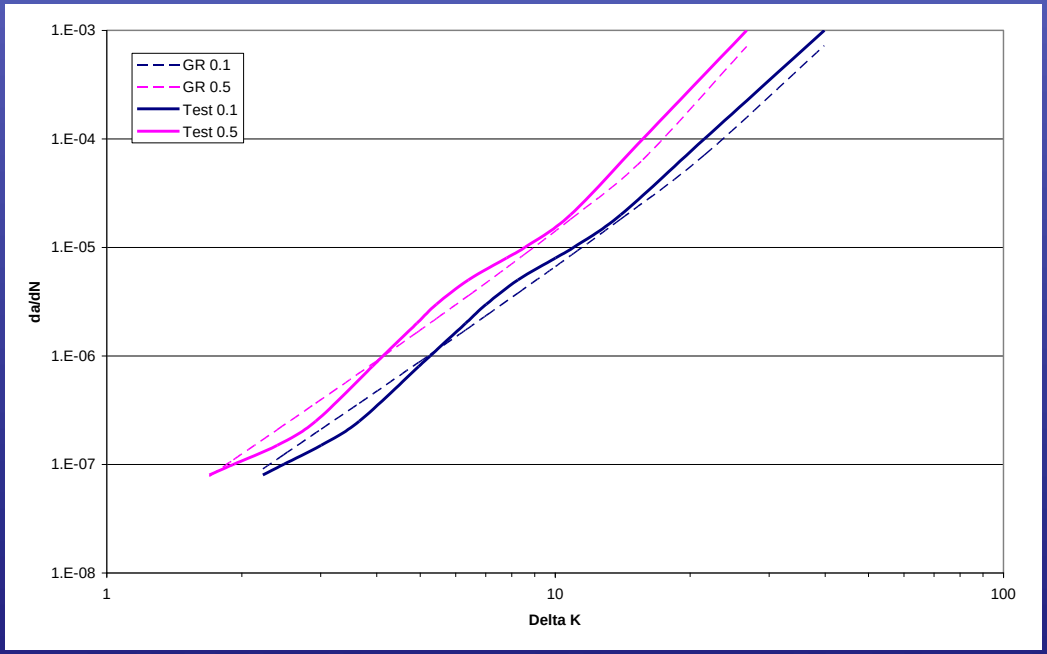
Sensitivity of SOLR to AFGROW Parameters

- Crack growth rates
  - Increasing crack growth rates accelerates the analytical crack growth
  - SwRI compared eight materials for differences between ground rules growth rates and tested rates



Sensitivity of SOLR to AFGROW Parameters

- Crack growth rates: Impact on SOLR can be large depending on the conservatism or unconservatism in data fits
- Small impact for materials reviewed

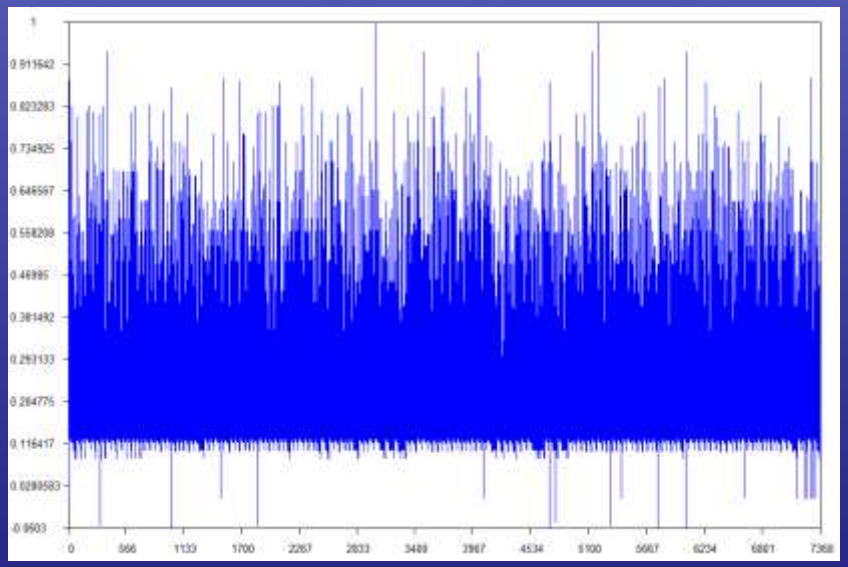


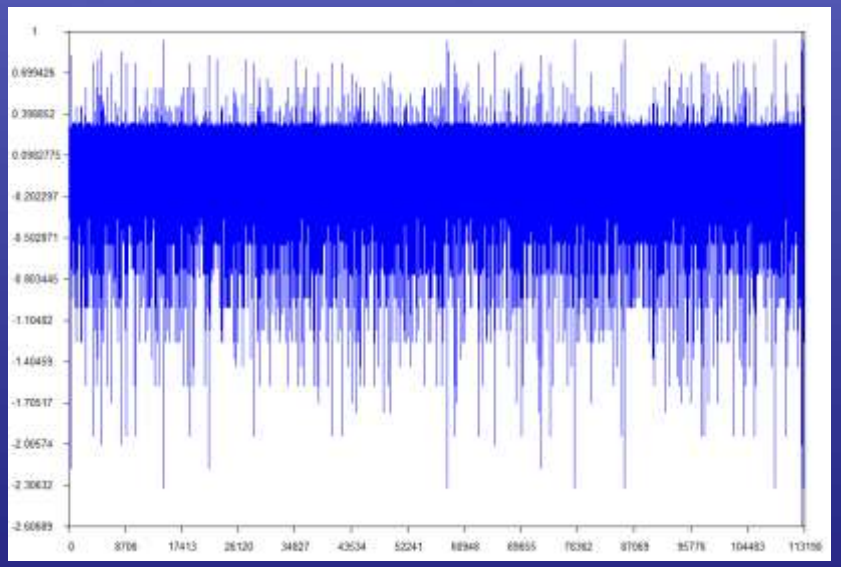
Sensitivity of SOLR to AFGROW Parameters

- **Limits on R shift: Used by AFGROW as the cutoff points for extrapolation of crack growth rates at high or low stress ratios**
  - **Higher limit on R shift (R_{HI}): At stress ratios above this value, crack growth rates (da/dN vs. ΔK) equal those at this value**
    - **Because the Willenborg equation uses an R_{eff} that is lower than the actual, R_{HI} has no impact on SOLR**
  - **Lower limit on R shift (R_{LO}): At stress ratios below this value, crack growth rates (da/dN vs. K_{max}) equal those at this value**

Sensitivity of SOLR to AFGROW Parameters

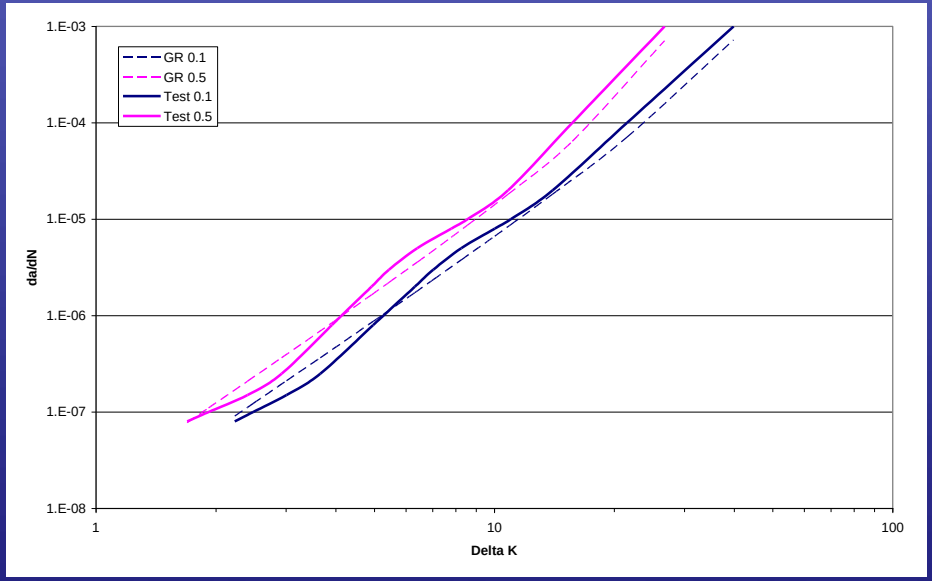
- **Lower limit on R shift: Impact is dependent on two criteria**
  - **Stress ratio of significant events in spectrum**
    - **Tension dominated spectra will show minimal impact**
    - **Compression dominated spectra will show significant impact**





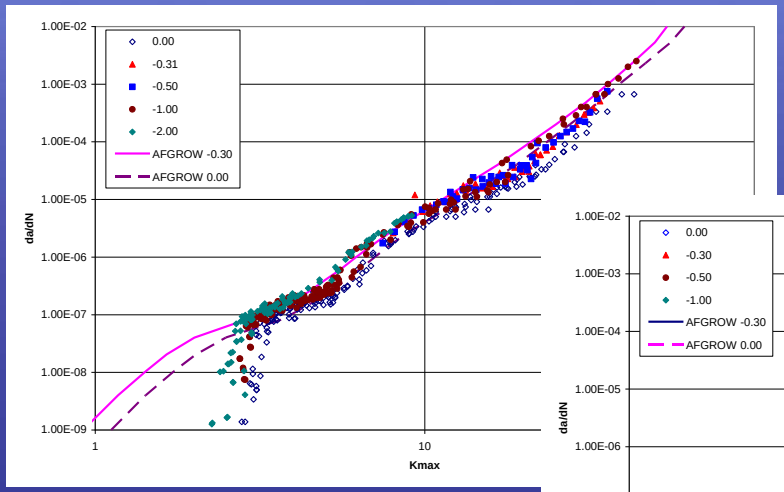
Sensitivity of SOLR to AFGROW Parameters

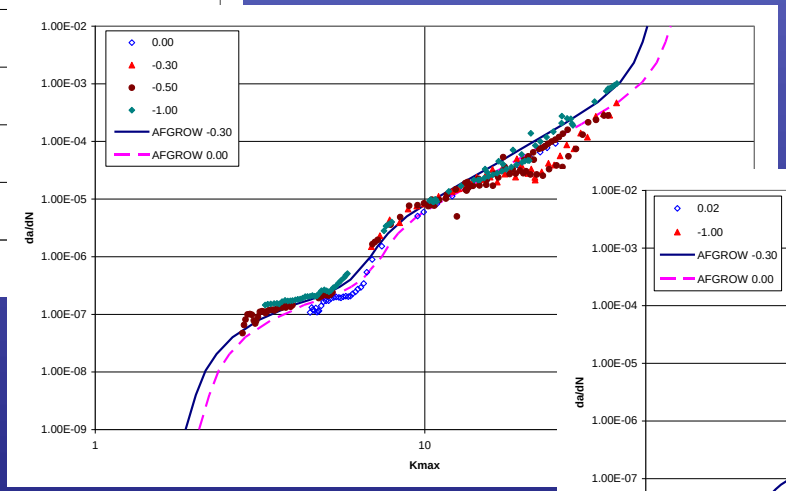
- **Lower limit on R shift: Impact is dependent on two criteria**
  - Amount of spread in crack growth rates between stress ratios
    - Wide spread will show significant impact
    - Narrow spread will show minimal impact

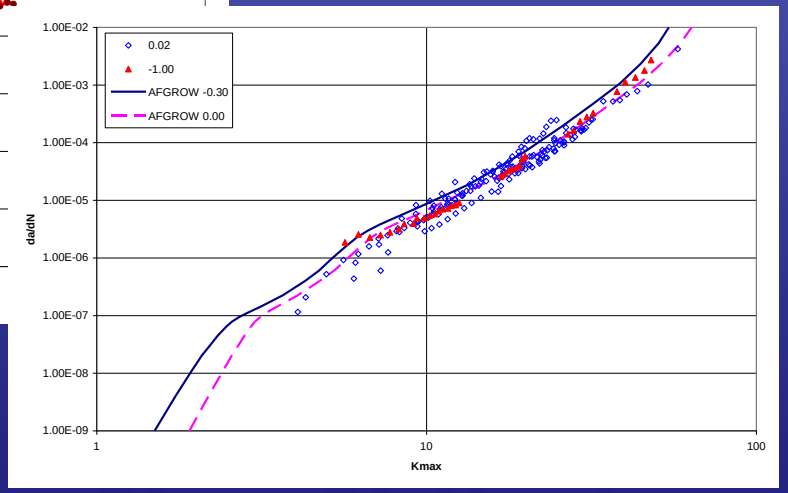


Sensitivity of SOLR to AFGROW Parameters

- Lower limit on R shift: Appropriate value?
  - Study of 9 materials shows default of -0.30 appropriate





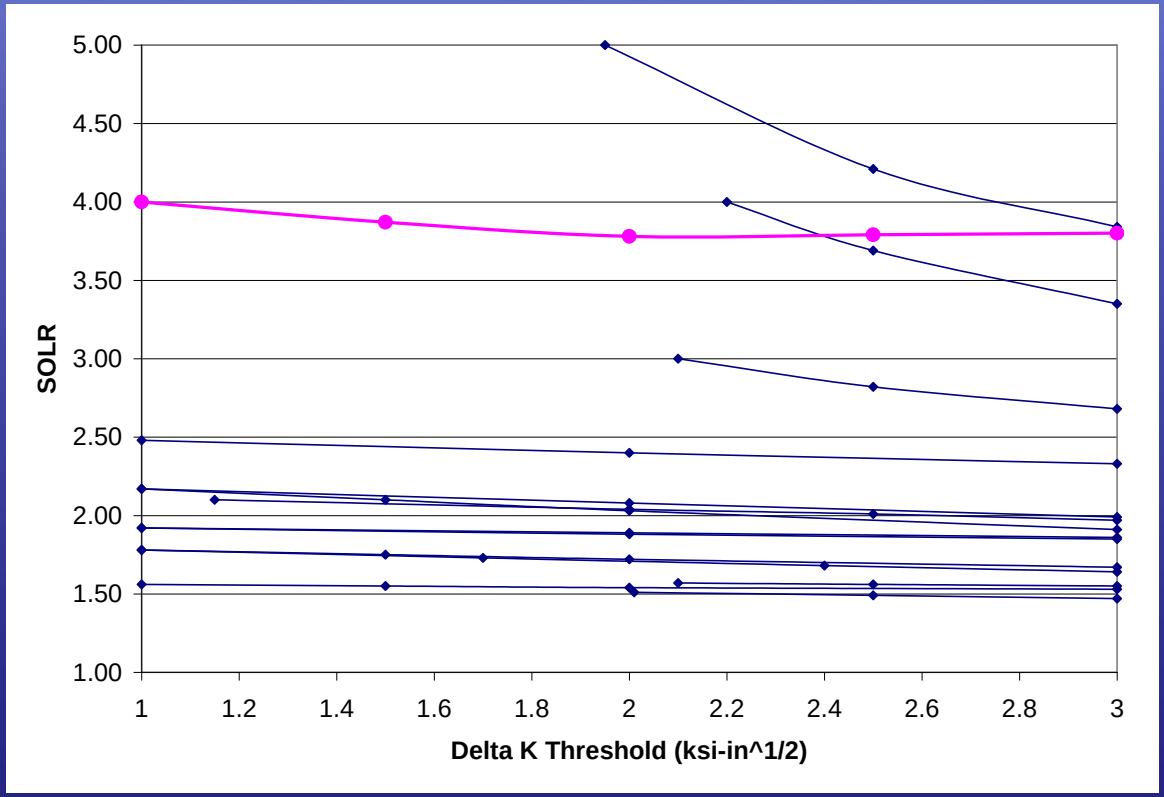


Sensitivity of SOLR to AFGROW Parameters

- ΔK threshold (ΔK_{th}): The minimum ΔK that causes crack growth at R = 0
  - Typical values between 1 and 3 ksi$\sqrt{in}$ for the materials being reviewed
  - When no retardation is assumed, an increase in ΔK_{th} slows crack growth

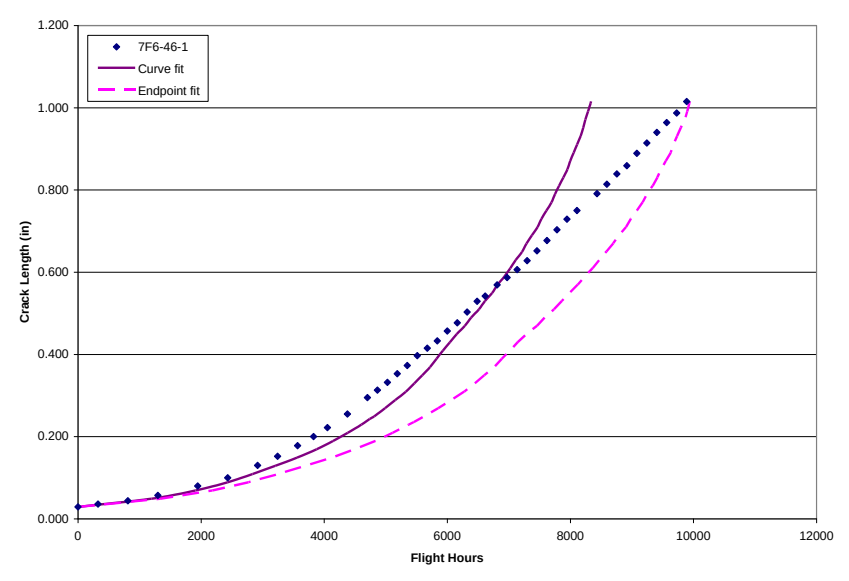
Sensitivity of SOLR to AFGROW Parameters

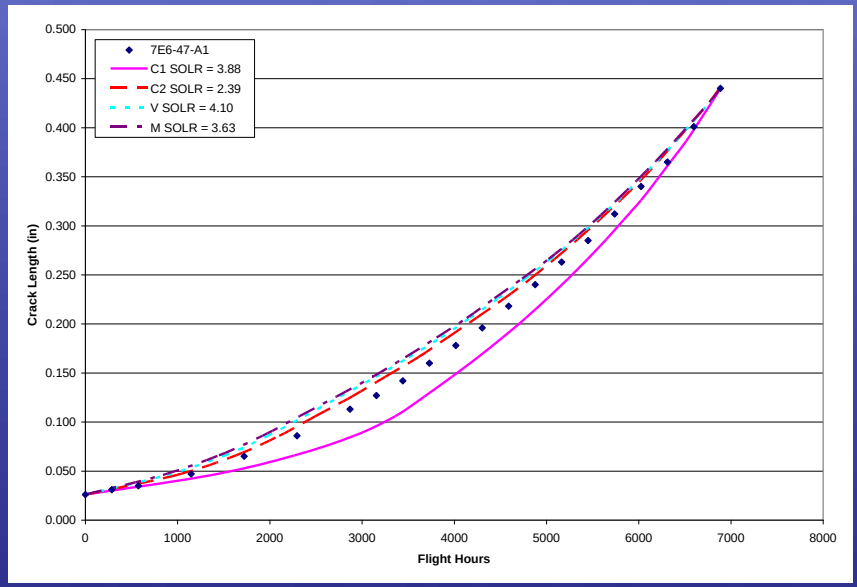
- ΔK threshold (ΔK_{th}): In general, an increase in ΔK_{th} slows analytical crack growth: Decreased SOLR



Sensitivity of SOLR to Correlation Techniques

- Determine the effect on the correlated SOLR of changes to
  - Fracture mechanics model
  - Curve vs. endpoint



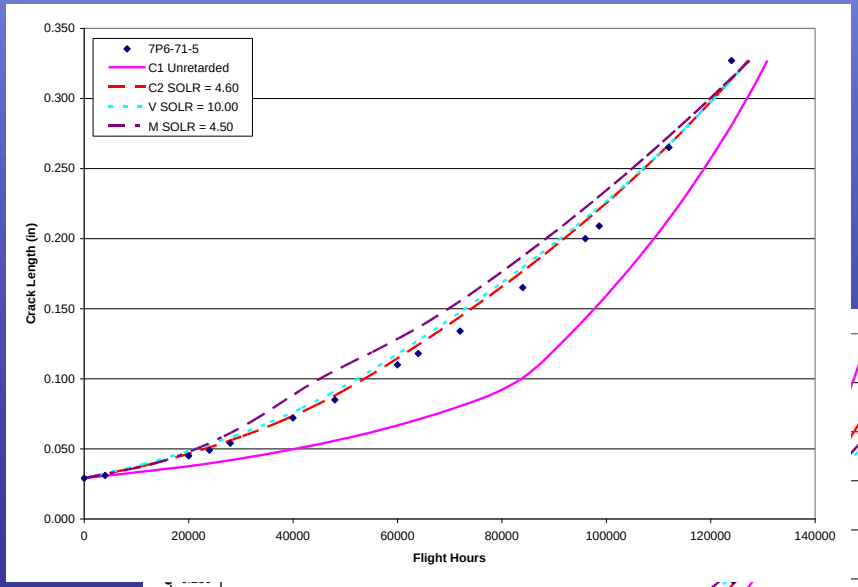


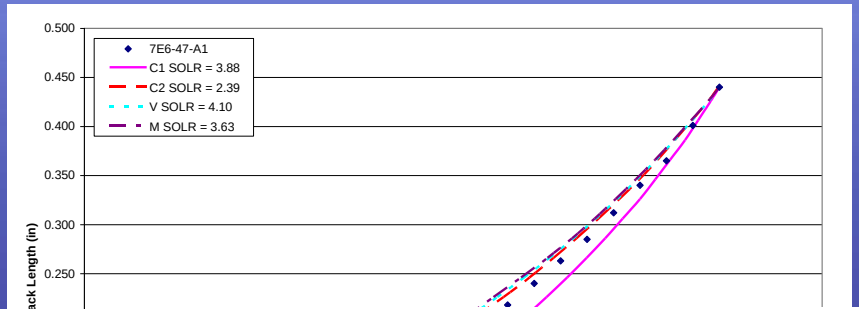
Sensitivity of SOLR to Correlation Techniques

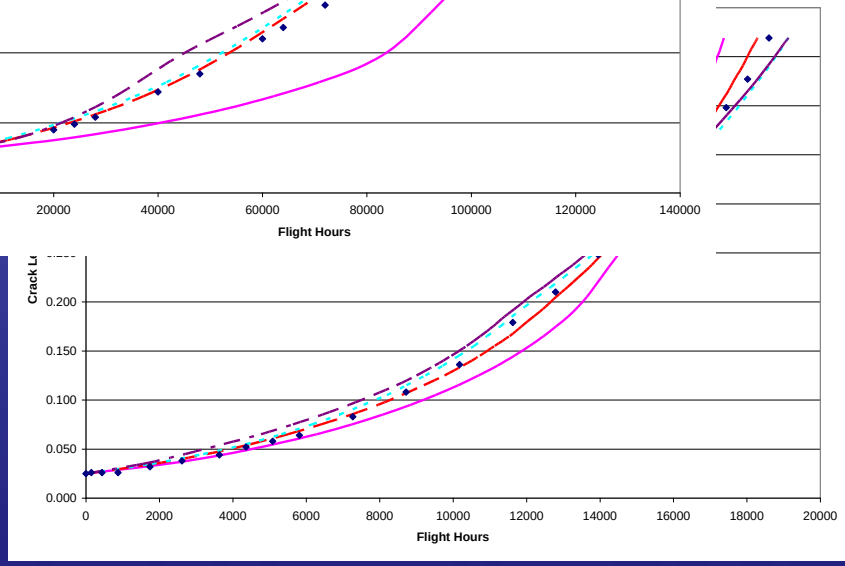
- Different methods for determining stress intensities for SOLR correlation:
  - Constant aspect ratio (a/c = 1) corner crack followed by straight through crack
  - Constant aspect ratio (a/c = initial from test) corner crack followed by straight through crack
  - Varying aspect ratio corner crack and through crack (initial a/c = initial from test)
  - Measured crack lengths and aspect ratios (input using user-defined betas)

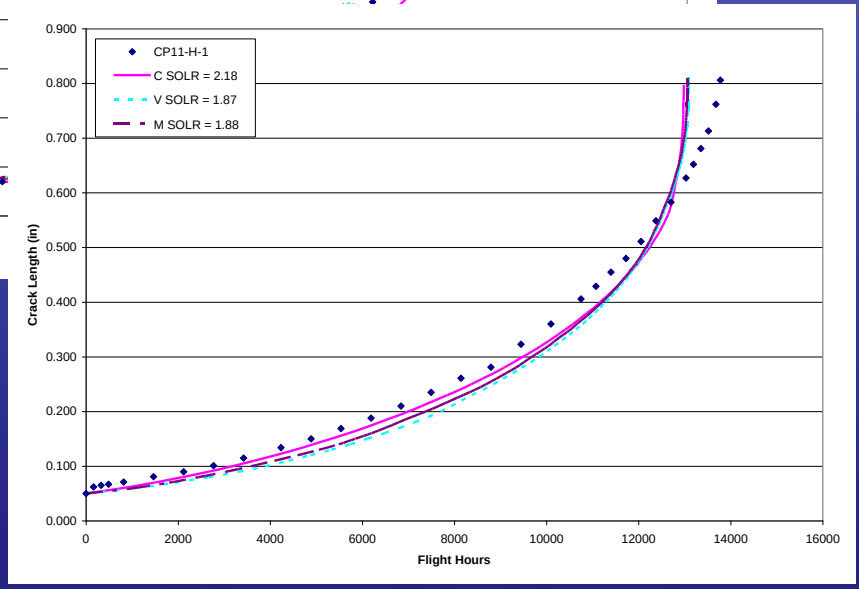
Sensitivity of SOLR to Correlation Techniques

- Different methods for determining stress intensities for SOLR correlation:







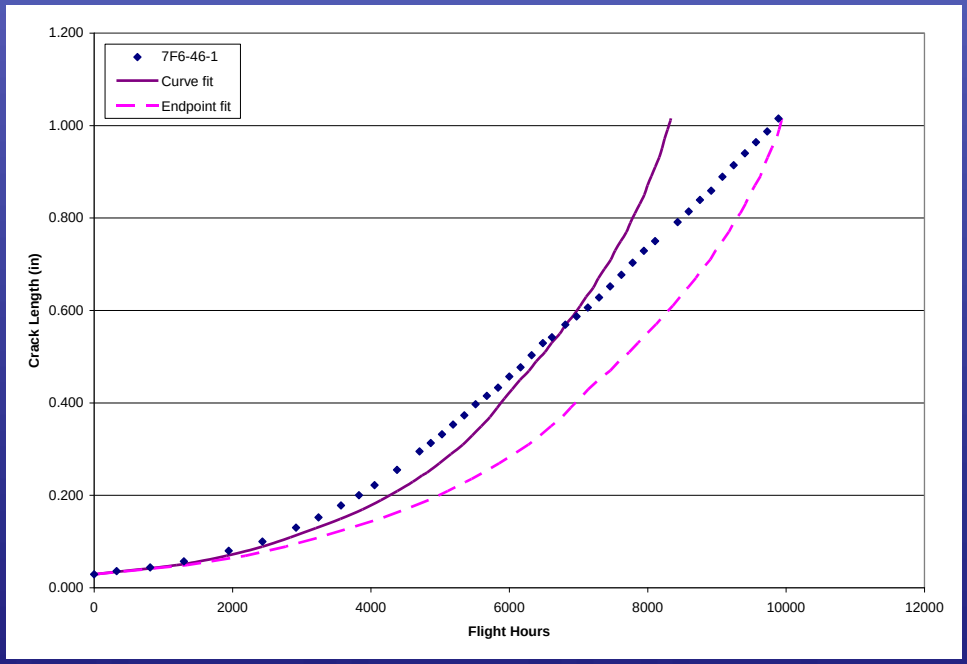


Sensitivity of SOLR to Correlation Techniques

- Different methods for determining stress intensities for SOLR correlation:
  - Significant impact in SOLR for most test specimens
  - Not much consistency to results
  - Constant aspect ratio = 1 and straight through crack method:
    - Higher on average than the other methods
    - Generally provided the worst fit
      - ➔ Corner crack growth slower than test
      - ➔ Through crack growth faster than test

Sensitivity of SOLR to Correlation Techniques

- Curve vs. endpoint SOLR correlation:
  - Depending on geometry, some SOLR values increased and some decreased
  - Curve correlation generally fits early growth better and endpoint correlation generally fits late growth better

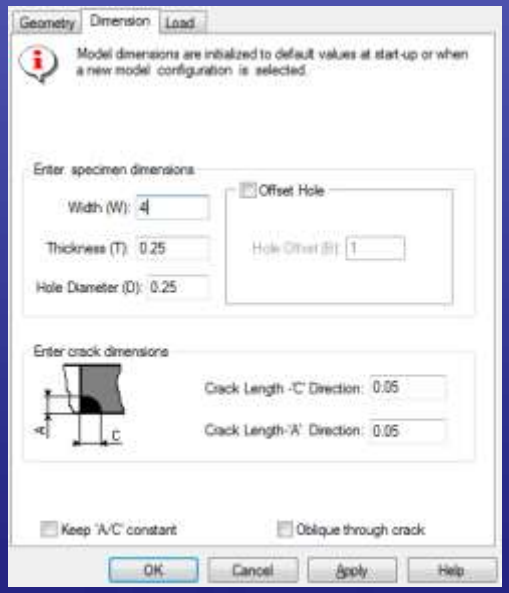


Summary and Recommendations

- Ideally, SOLR tunes crack growth to the material/spectrum loading history combination
  - Also dependent on specimen thickness, crack location, etc.
  - Also compensates for inaccuracies in the analytical model
- Because SOLR compensates for inaccuracies, making material properties conservative ends up having no effect when accounting for retardation

Summary and Recommendations

- SOLR also compensates for inaccuracies caused by correlation techniques
  - Analytical stress intensities should therefore match the test as closely as possible
- However, the analytical methods used in the final analysis should also be considered



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