Application of AFGROW to Cold-Expanded Holes in High-Strength Steel

31 August 2010

We would like to thank the Ogden-ALC for funding this work

Ms. Whitney Ponzoha, USAFA/CAStLE

Mr. Matthew Hammond, USAFA/CAStLE

Dr. James Greer, USAFA/CAStLE

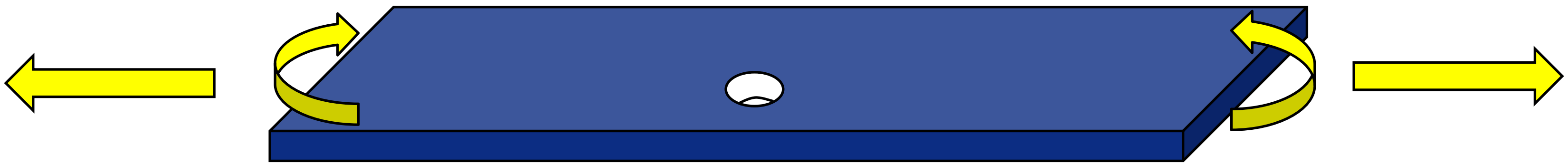
Presentation Outline

- Background / Purpose of project
- β Correction Factor Determination
- Residual Stress Data and AFGROW Prediction
- AFGROW and SOLR
- Results
- Future Analysis/Testing

BACKGROUND / PURPOSE OF PROJECT

Background / Purpose

- **How best to use AFGROW for modeling crack at Cold Expanded (CX) hole in steel plate with in-plane bending**



- **Subject Structure - Steel Stiffener**
  - **Crack Mitigation Options**
    - **Repair**
      - **Was not within the scope of this program; OEM already has design**
    - **Over-sizing holes**
      - **Not recommended based on FE results**
        - Significant life reduction if crack not cleared
    - **Cold-Expanding the holes (Current Effort)**

Background / Purpose

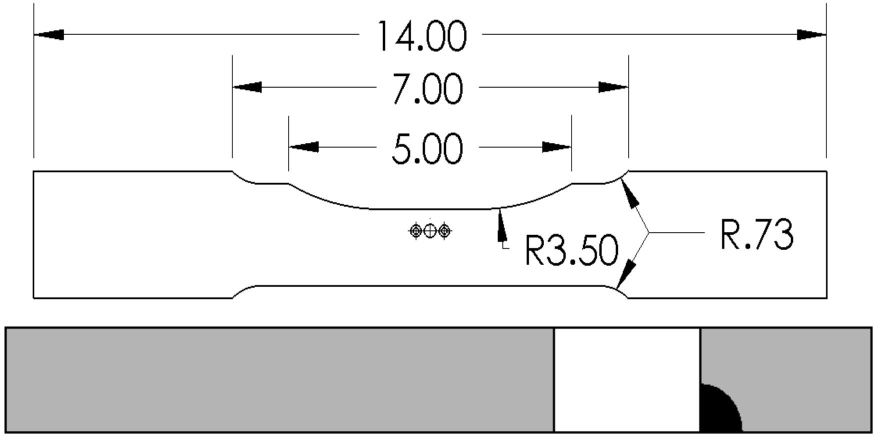
- AFGROW
  - Good Solutions Quickly
    - Large solution space of crack geometries
    - Does not directly allow in-plane bending as input (one exception)
- Project Goal:
  - Determine appropriate AFGROW inputs for more accurate modeling of this (and similar) parts
    - AFGROW inputs:
      - β correction factor: accounts for the geometry
      - Shutoff Overload Ratio (SOLR): accounts for retardation due to the spectrum loading
      - Residual stresses: accounts for the cold-expanding
      - Some combination of SOLR + beta correction + residual stress input may be best solution

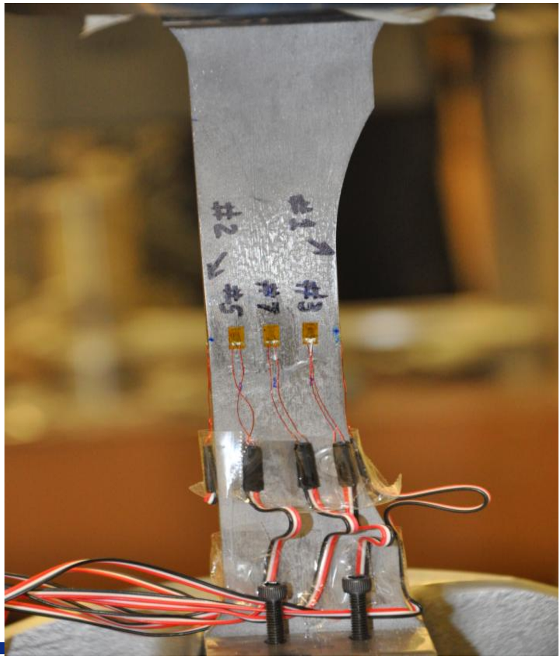
Background / Purpose

- **Specimen Design Criteria**
  - **Geometry**
    - **Complicated X-section and hard to test in the lab**
    - **Flat specimen produced the required stresses and lend itself very well to AFGROW analysis**
  - **Loading**
    - **Test specimen reproduces the same stresses (tensile, in-plane bending) in vicinity of the hole**
    - **Withstands max compressive spectrum load without buckling**
  - **Material characteristics**
    - **4340 Steel**
    - **Heat treated to approximately 170ksi**
    - **Rockwell hardness ~ 37C**

Background / Purpose

- Test Specimen
  - Strain survey specimen to validate test specimen
    - Compared to aircraft level FEA model (from OEM) design
  - Gage ratio
    - In-plane bending induced by the geometry
    - Specified stress ratio between gages 1 and 2
    - Specified gradient measured with multiple gages
  - Floating Nut Plate Installed per Drawing
    - Crack growth from nut plate holes or vice versa





Background / Purpose

	Bore-Crack						Edge-Crack	
Specimen Category	A	B	C	D	E	F	G	H
Specimen Description	Non-CX w/ 0.05" CA	Non-CX w/ 0.05" Spectrum	CX w/ 0.05" berfore CX Spectrum	CX w/ 0.05" after CX Spectrum	Non-CX w/ 0.005" Spectrum	CX w/ 0.05" CA	Non-CX w/ 0.05" Spectrum	CX w/ 0.05" Spectrum
Number of Specimens	3	3 (Baseline)	3	3	3	3 (Optional)	3 (Baseline)	3

- **Test Matrix**

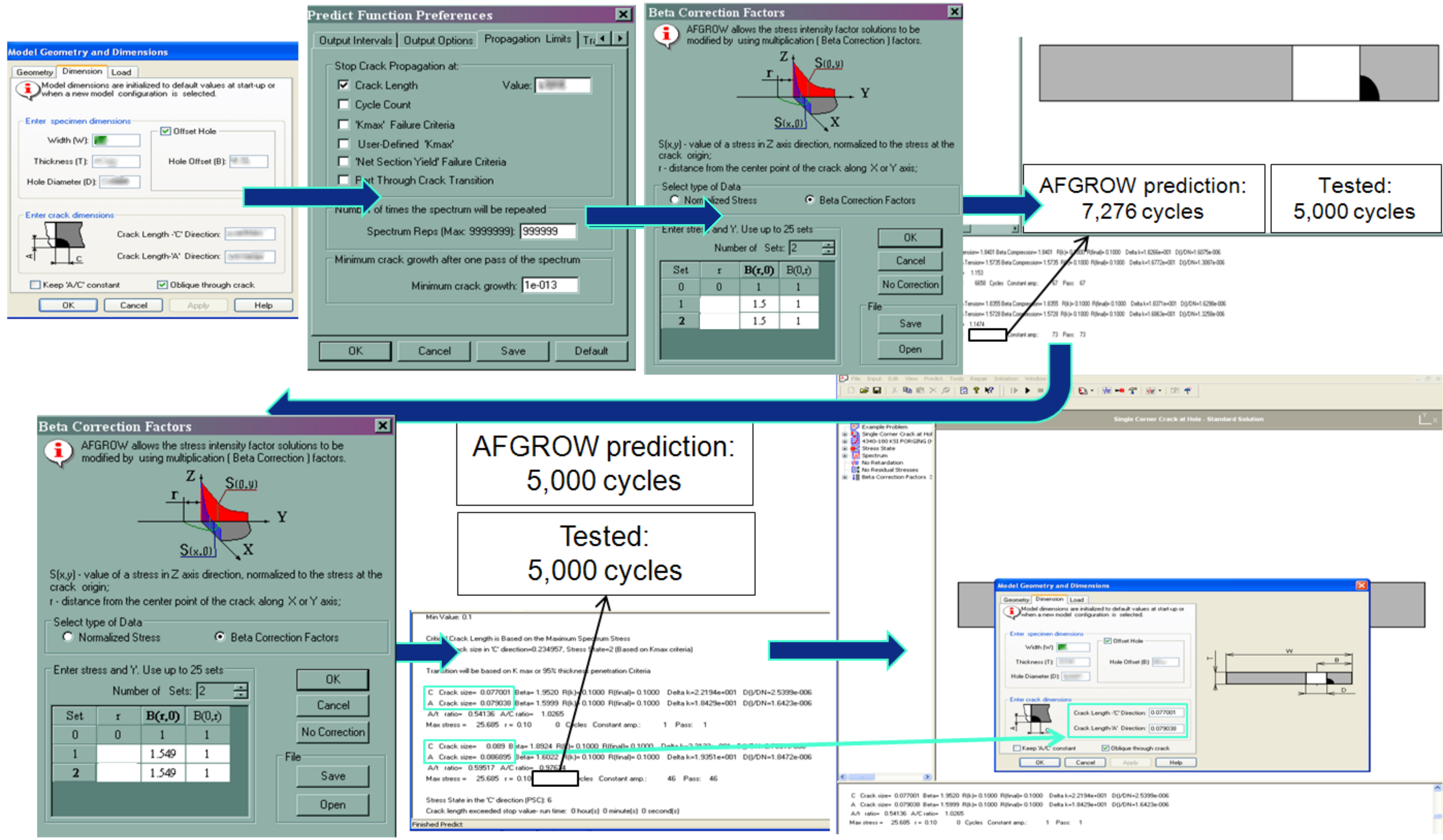
  - A – β correction factor determination for bending
  - B – Baseline test
  - C – Cold-expansion occurs after 0.05” flaw is grown
  - D – Cold-expansion occurs before 0.05” flaw is grown (status)
  - E – Will test the 0.005” IFS assumption
  - F – β correction factor determination for CX (optional)
  - G – Baseline test for edge crack
  - H – Cold-expansion occurs after 0.05” flaw is grown – edge crack

β CORRECTION FACTOR DETERMINATION

β Correction Factor Determination

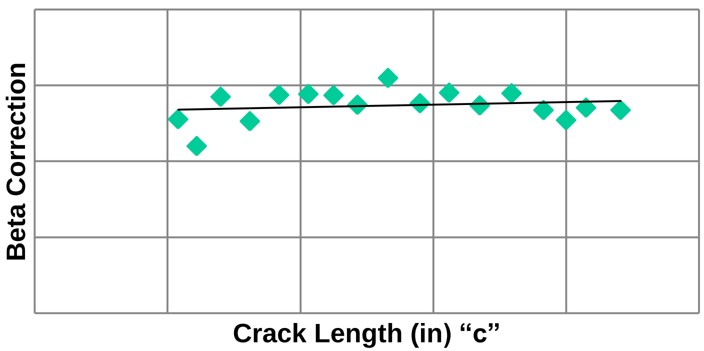
- β correction factor
  - In-plane bending not accounted for in AFGROW
  - Accounts for presence of nut plate holes
  - Specific for a particular specimen geometry and loading
    - This program's β correction factor will only be useful for this and very similar cases
- Complications of Testing 4340 Steel
  - Marker band testing (6, 10, 4)
    - 2,000 cycles σ_{max} to σ_{min}, 100 cycles at 75%, 10 cycles at 100% σ_{max}
    - 2,000 cycles σ_{max} to σ_{min}, 200 cycles at 50%, 10 cycles at 100% σ_{max}
    - $\sigma_{max} \approx$ 25ksi, R = 0.1
    - Marker bands were not visible, so…
  - CA testing
    - Measurements taken at cycles corresponding to 0.01" crack growth

"Piecewise" β Correction Factor Determination

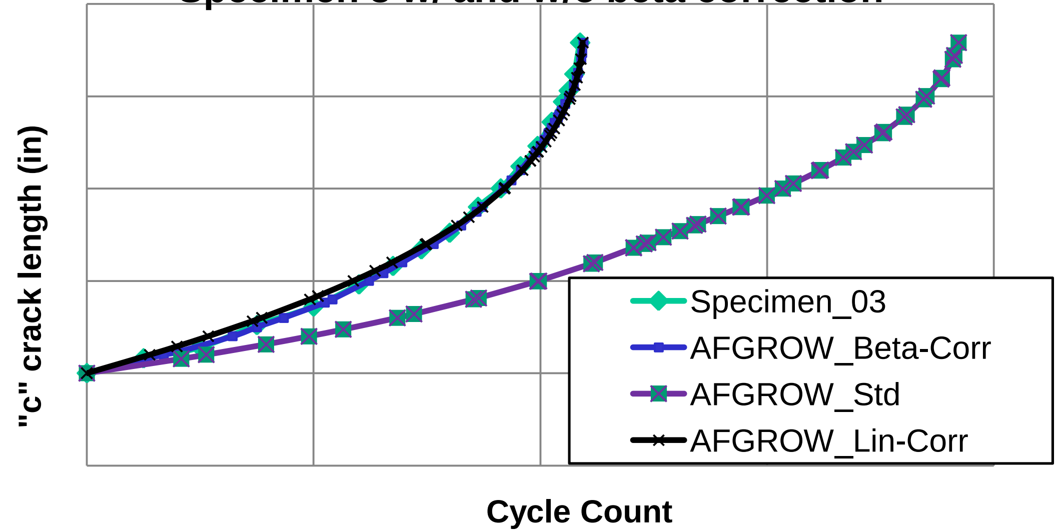


β Correction Factor Determination

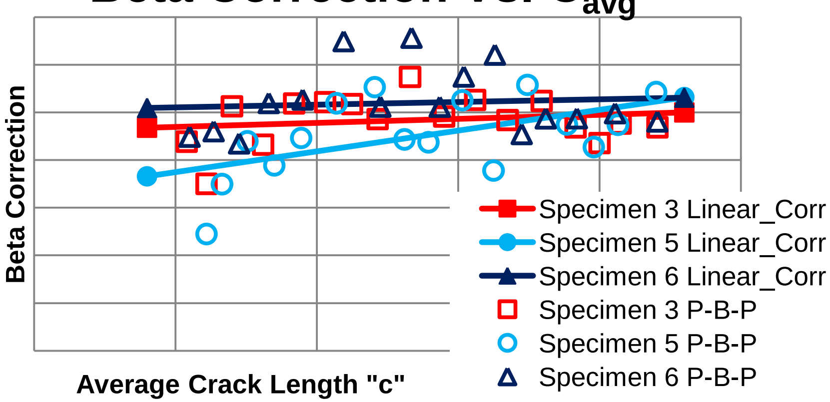
Beta Corrector Factors



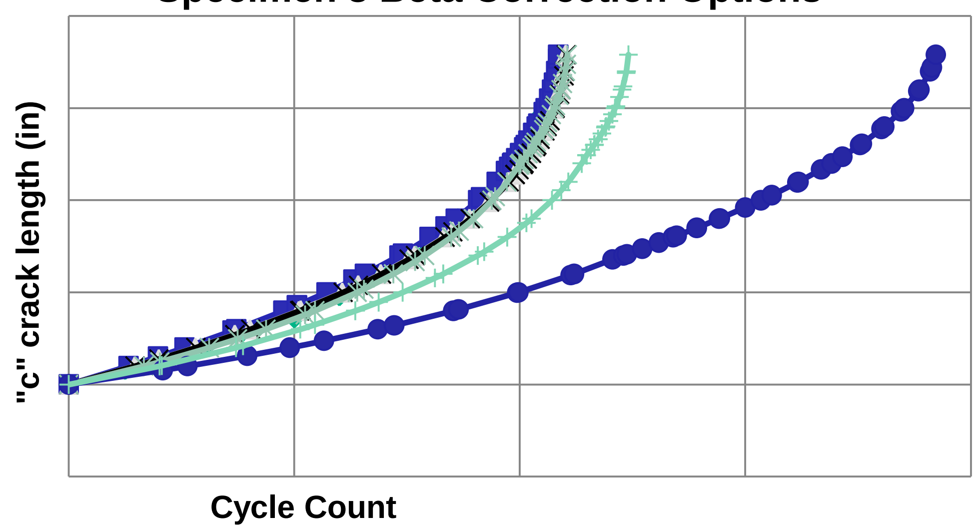
Specimen 3 w/ and w/o beta correction



Beta Correction Vs. C_{avg}



Specimen 3 Beta Correction Options



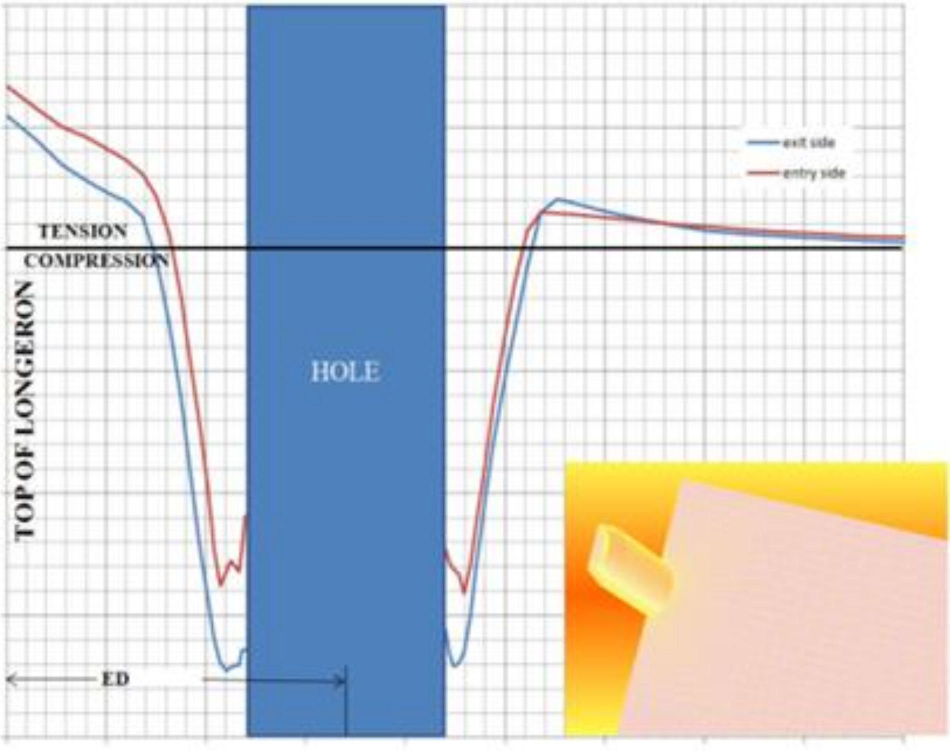
RESIDUAL STRESS DATA AND AFGROW PREDICTION

Residual Stress Data and AFGROW Prediction

- Cold-Expanding Holes
  - Insert a sleeve -> expand -> remove
  - Creates compressive residual stresses surrounding the hole

½ model with mandrel

cut-plane stresses



Residual Stress Data and AFGROW Prediction

- Residual stress profile input into AFGROW
  - AFGROW showed no growth of 0.05” flaw at hole under spectrum loading
  - High residual compressive stress – no crack growth
- Experimental Results (CX)

  - Unable to extend 0.03” x 0.03” EDM notch at CX hole using pre-crack loads
    - 200,000 at 25ksi; R= 0.1 and
    - 200,000 at 27.8ksi; R = –0.4 and
    - 3 spectrum passes (3 lives non-CX) *THEN*
    - Inserted edge notch (0.03” X 0.03” EDM) and
    - Additional 130,000 cycles at 25ksi; R= 0.1
      - Crack growth observed at edge notch (0.039” x 0.059”)
    - Began spectrum loading (again)
      - 1.5 passes to crack link-up
      - ligament failure almost immediately thereafter
      - Additional 0.86 passes to failure of entire specimen

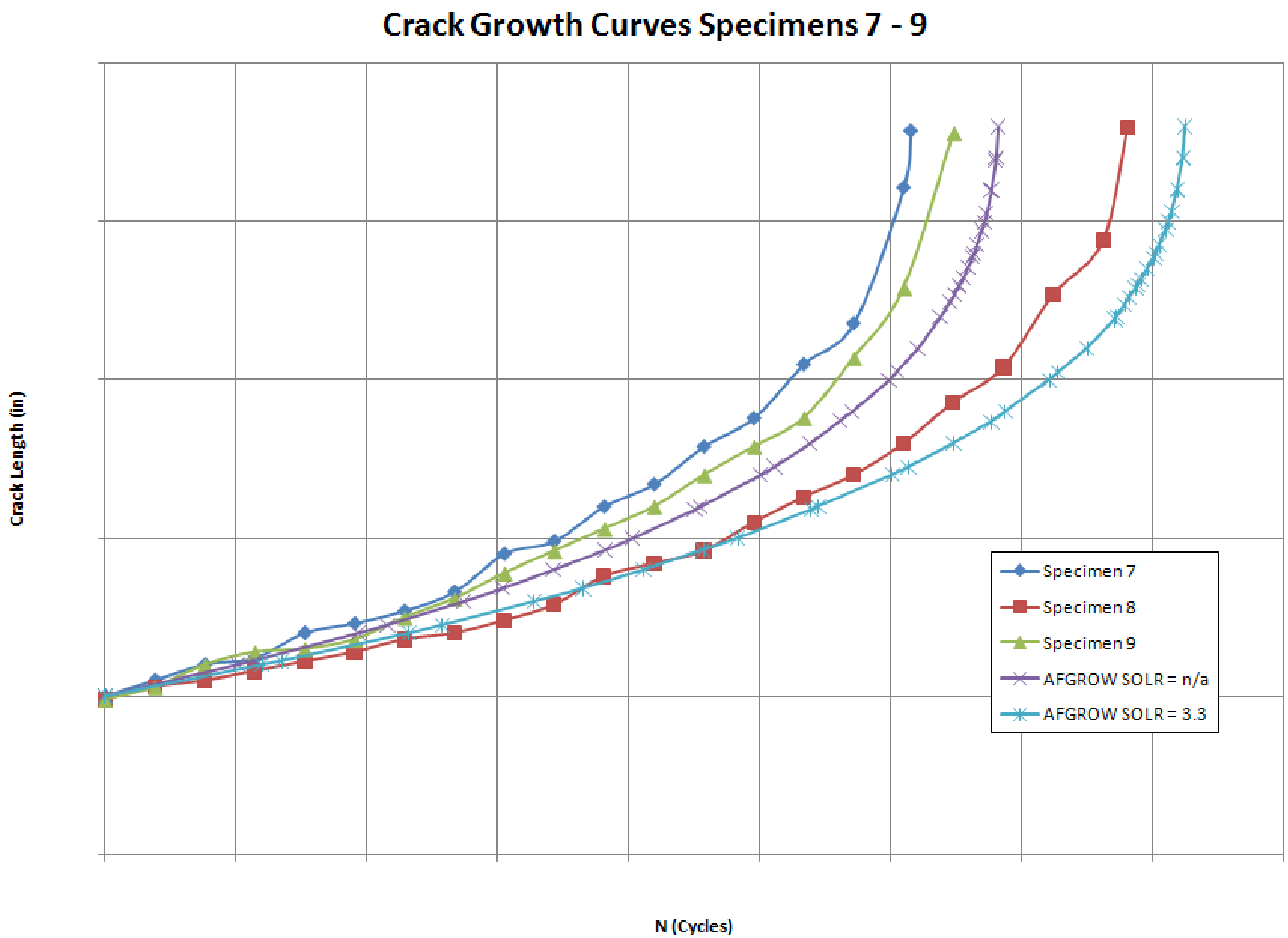
- **AFGROW can’t model this particular CX case**
  - Hole corner crack alone doesn’t grow; can’t do the two-crack geometry

AFGROW and SOLR

- Shutoff Overload Ratio (SOLR)
  - Ratio of the overload to the nominal load required to effectively stop further growth under nominal loading
  - Controls the effect of load history on the predicted life
  - Approach: vary SOLR to adjust the life prediction to match test results
  - Values for Steel
    - AFGROW Manual: 2.0 (starting point for steel)
    - Tried values from 2.0 through 6.0
    - Preliminary results show *ignoring* retardation gives results that match experiments best
- How to use SOLR in CX case is TBD
  - Will sharp flaw grow from CX hole?
    - Increase the load?
    - Increase the notch?
  - If not, could use 0.005” initial flaw as conservative estimator

AFGROW and SOLR

- **Shutoff Overload Ratio (SOLR) for Non-CX holes**



SOME PRELIMINARY CONCLUSIONS

Preliminary Conclusions

- Cold-Expanding
  - CX at hole corner flaw may kill crack; AFGROW results concur
  - Residual tensile stress may exist at free edge, but inserting flaw there did not result in drastic life reduction
  - Use of 0.005” initial flaw assumption might provide conservative bound for inspection interval
- β correction factor
  - Each approach used gave a very similar result
  - Results are dependent on geometry/loading conditions
- SOLR
  - Ignoring matched non-CX test results best
  - More CX experiments to come

Questions?


UNITED STATES AIR FORCE ACADEMY