

Center for Aircraft Structural Life Extension

Providing Structural Integrity Technology to the Aerospace Community

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



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U.S. AIR FORCE

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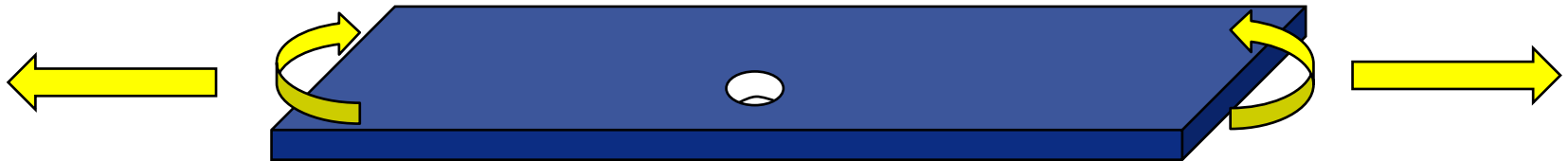


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- **Background / Purpose of project**
 - **β Correction Factor Determination**
 - **Residual Stress Data and AFGROW Prediction**
 - **AFGROW and SOLR**
 - **Results**
 - **Future Analysis/Testing**

BACKGROUND / PURPOSE OF PROJECT



- 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)



■ 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



■ 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

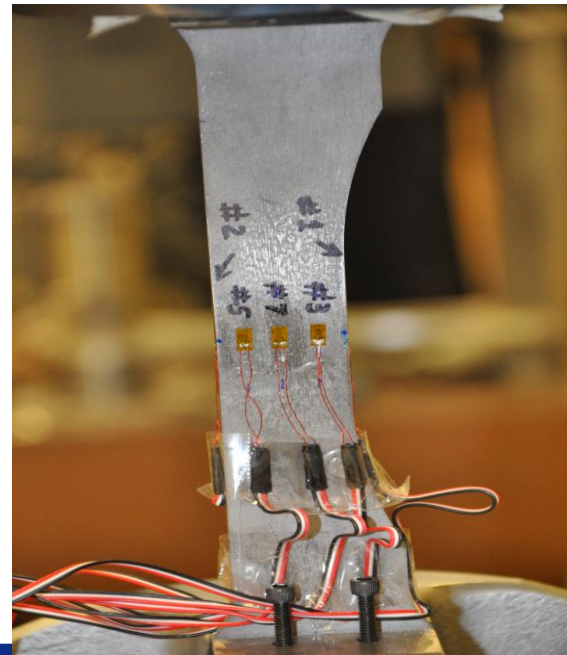
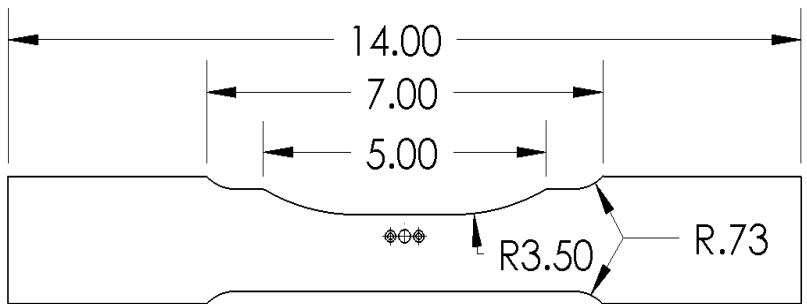
■ Material characteristics

- 4340 Steel
- Heat treated to approximately 170ksi
- Rockwell hardness ~ 37C



■ 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



	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" before 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}
 - $\sigma_{\max} \approx 25\text{ksi}$, $R = 0.1$
 - Marker bands were not visible, so...
- CA testing
 - Measurements taken at cycles corresponding to 0.01" crack growth

“Piecewise” β Correction Factor Determination

Model Geometry and Dimensions

Model dimensions are initialized to default values at start-up or when a new model configuration is selected.

Enter specimen dimensions

Width (W): Offset Hole

Thickness (T): Hole Offset (B):

Hole Diameter (D):

Enter crack dimensions

Crack Length - 'C' Direction:

Crack Length - 'A' Direction:

Keep 'A/C' constant Oblique through crack

OK Cancel Apply Help

Predict Function Preferences

Output Intervals | Output Options | Propagation Limits | Tr |

Stop Crack Propagation at:

Crack Length Value:

Cycle Count

'Kmax' Failure Criteria

User-Defined 'Kmax'

'Net Section Yield' Failure Criteria

Flat Through Crack Transition

Number of times the spectrum will be repeated

Spectrum Reps (Max: 9999999):

Minimum crack growth after one pass of the spectrum

Minimum crack growth:

OK Cancel Save Default

Beta Correction Factors

AFGROW allows the stress intensity factor solutions to be modified by using multiplication (Beta Correction) factors.

$S(x,y)$ - value of a stress in Z axis direction, normalized to the stress at the crack origin;
 r - distance from the center point of the crack along X or Y axis;

Select type of Data

Normalized Stress Beta Correction Factors

Enter stress and 'r'. Use up to 25 sets

Number of Sets:

Set	r	B(r,0)	B(0,r)
0	0	1	1
1		1.549	1
2		1.549	1

OK Cancel No Correction Save Open



AFGROW prediction:
7,276 cycles

Tested:
5,000 cycles

Example Problem

- Single Corner Crack at Hole
- 4340-100 KSI FORGING 0
- Stress State
- Spectrum
- No Retardation
- No Residual Stresses
- Beta Correction Factors

Finished Predict

Crack length exceeded stop value: run time: 0 hour(s) 0 minute(s) 0 second(s)

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Enter stress and 'r'. Use up to 25 sets

Number of Sets:

Set	r	B(r,0)	B(0,r)
0	0	1	1
1		1.549	1
2		1.549	1

OK Cancel No Correction Save Open

AFGROW prediction:
5,000 cycles

Tested:
5,000 cycles

Min Value: 0.1

Crack Length is Based on the Maximum Spectrum Stress

Crack size in 'C' direction=0.234957, Stress State=2 (B based on Kmax criteria)

Transition will be based on Kmax or 95% thickness penetration Criteria

C Crack size= 0.077001 Beta= 1.9520 Rf=0.1000 Rf(Inv)=0.1000 Delta k=-2.2194e+001 Df/DN=2.5399e-006
 A Crack size= 0.079038 Beta= 1.5999 Rf=0.1000 Rf(Inv)=0.1000 Delta k=-1.8423e+001 Df/DN=1.6423e-006
 A/r ratio= 0.54136 A/C ratio= 1.0265
 Max stress = 25.685 r = 0.10 0 Cycles Constant amp.: 1 Pass: 1

C Crack size= 0.089 0 Beta= 1.8924 Rf=0.1000 Rf(Inv)=0.1000 Delta k=-2.2194e+001 Df/DN=2.5399e-006
 A Crack size= 0.086696 Beta= 1.6022 Rf=0.1000 Rf(Inv)=0.1000 Delta k=-1.9351e+001 Df/DN=1.8472e-006
 A/r ratio= 0.59517 A/C ratio= 0.97254
 Max stress = 25.685 r = 0.10 0 Cycles Constant amp.: 46 Pass: 46

Stress State in the 'C' direction (PSC): 6
 Crack length exceeded stop value: run time: 0 hour(s) 0 minute(s) 0 second(s)

Finished Predict

Model Geometry and Dimensions

Model dimensions are initialized to default values at start-up or when a new model configuration is selected.

Enter specimen dimensions

Width (W): Offset Hole

Thickness (T): Hole Offset (B):

Hole Diameter (D):

Enter crack dimensions

Crack Length - 'C' Direction:

Crack Length - 'A' Direction:

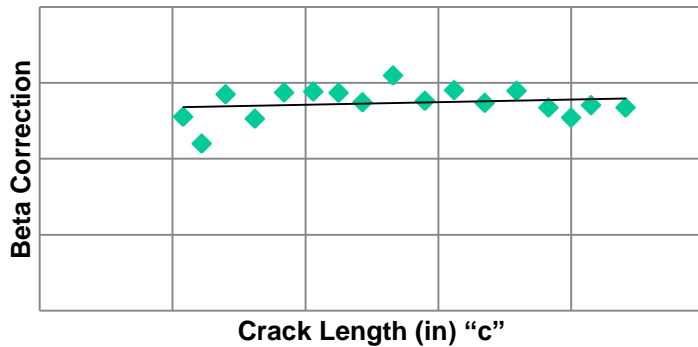
Keep 'A/C' constant Oblique through crack

OK Cancel Apply Help

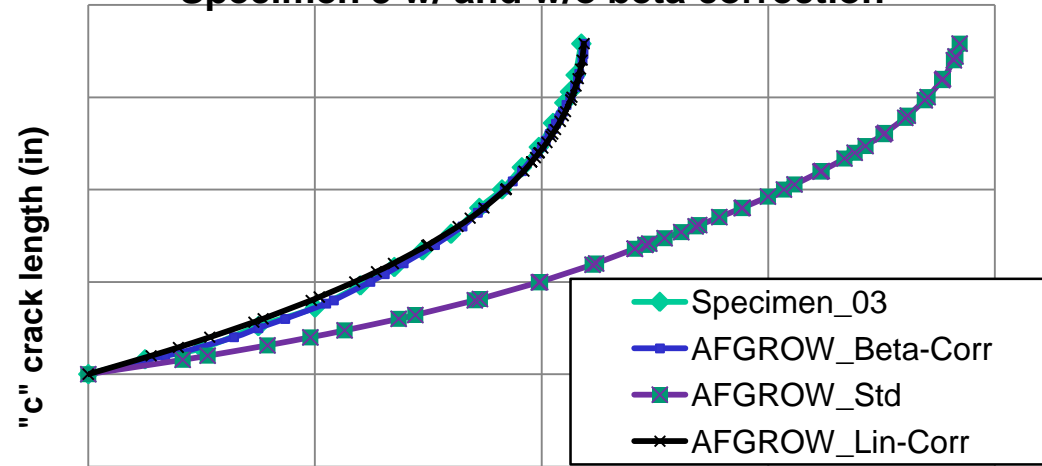
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 A/r ratio= 0.54136 A/C ratio= 1.0265
 Max stress = 25.685 r = 0.10 0 Cycles Constant amp.: 1 Pass: 1

β Correction Factor Determination

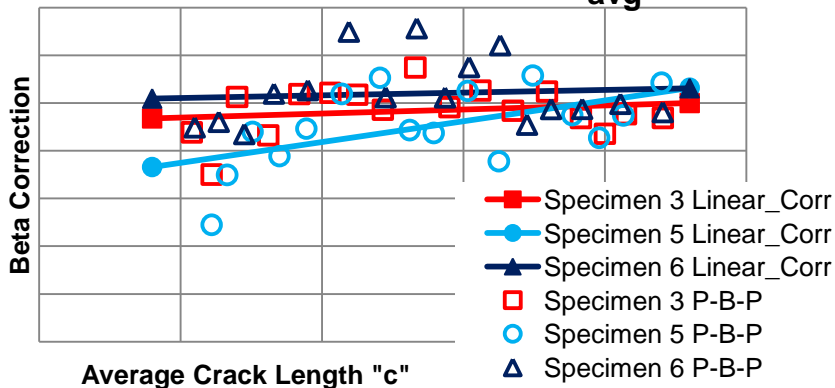
Beta Corrector Factors



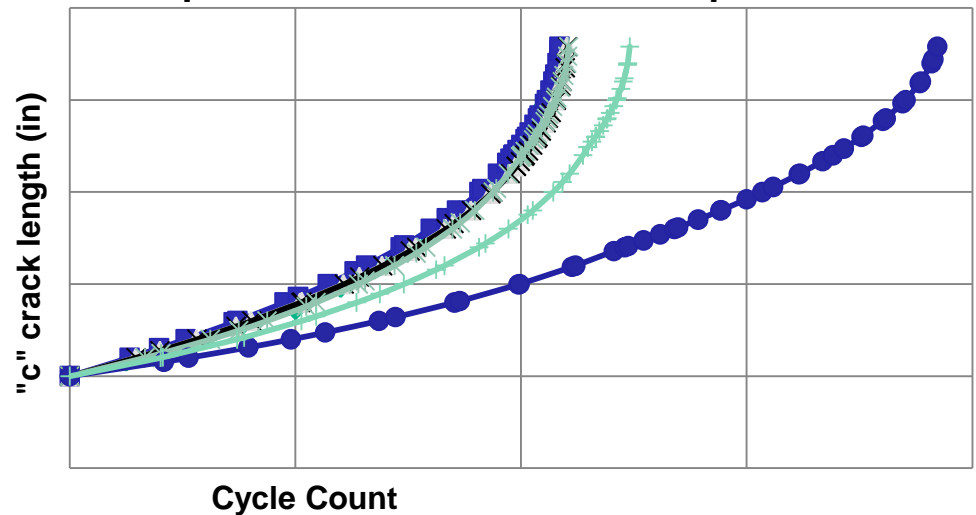
Specimen 3 w/ and w/o beta correction



Beta Correction Vs. C_{avg}



Specimen 3 Beta Correction Options



RESIDUAL STRESS DATA AND AFGROW PREDICTION

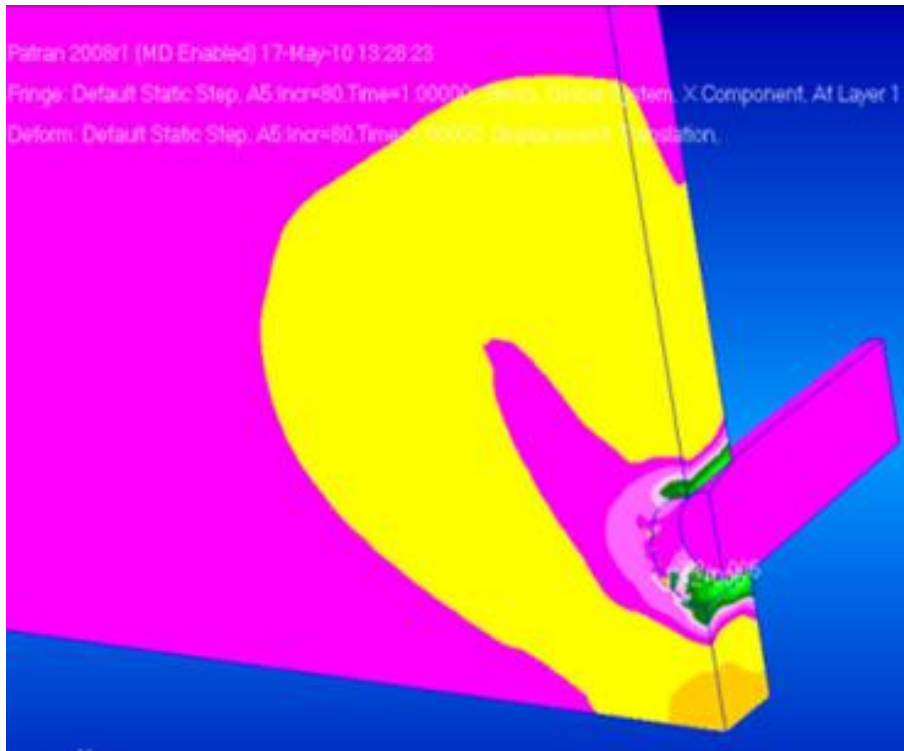
Residual Stress Data and AFGROW Prediction



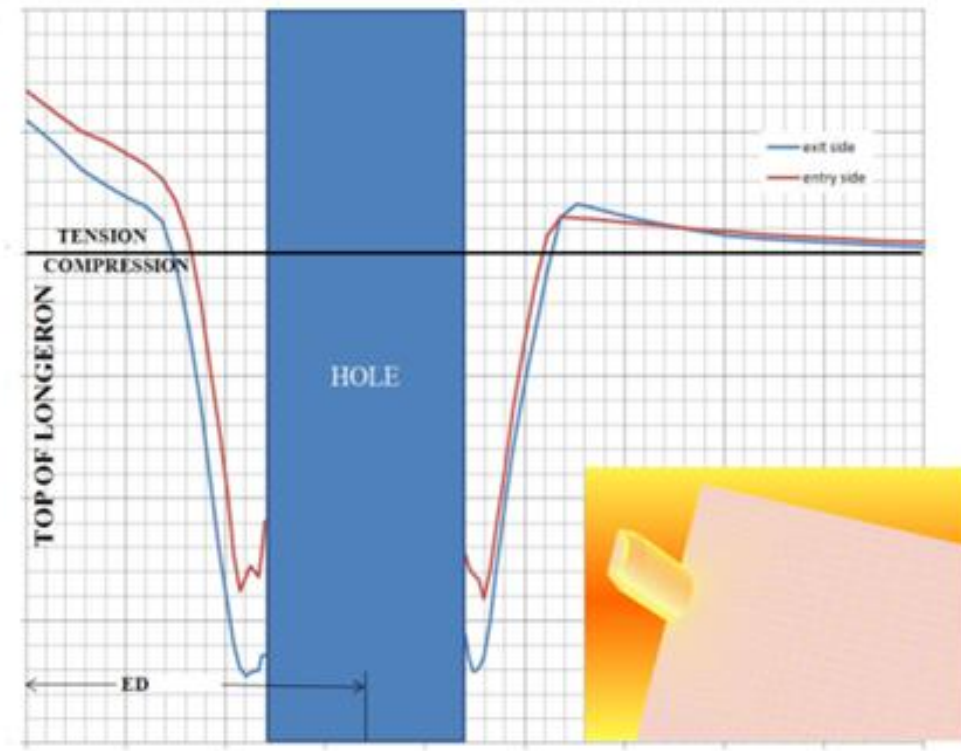
■ Cold-Expanding Holes

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

1/2 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

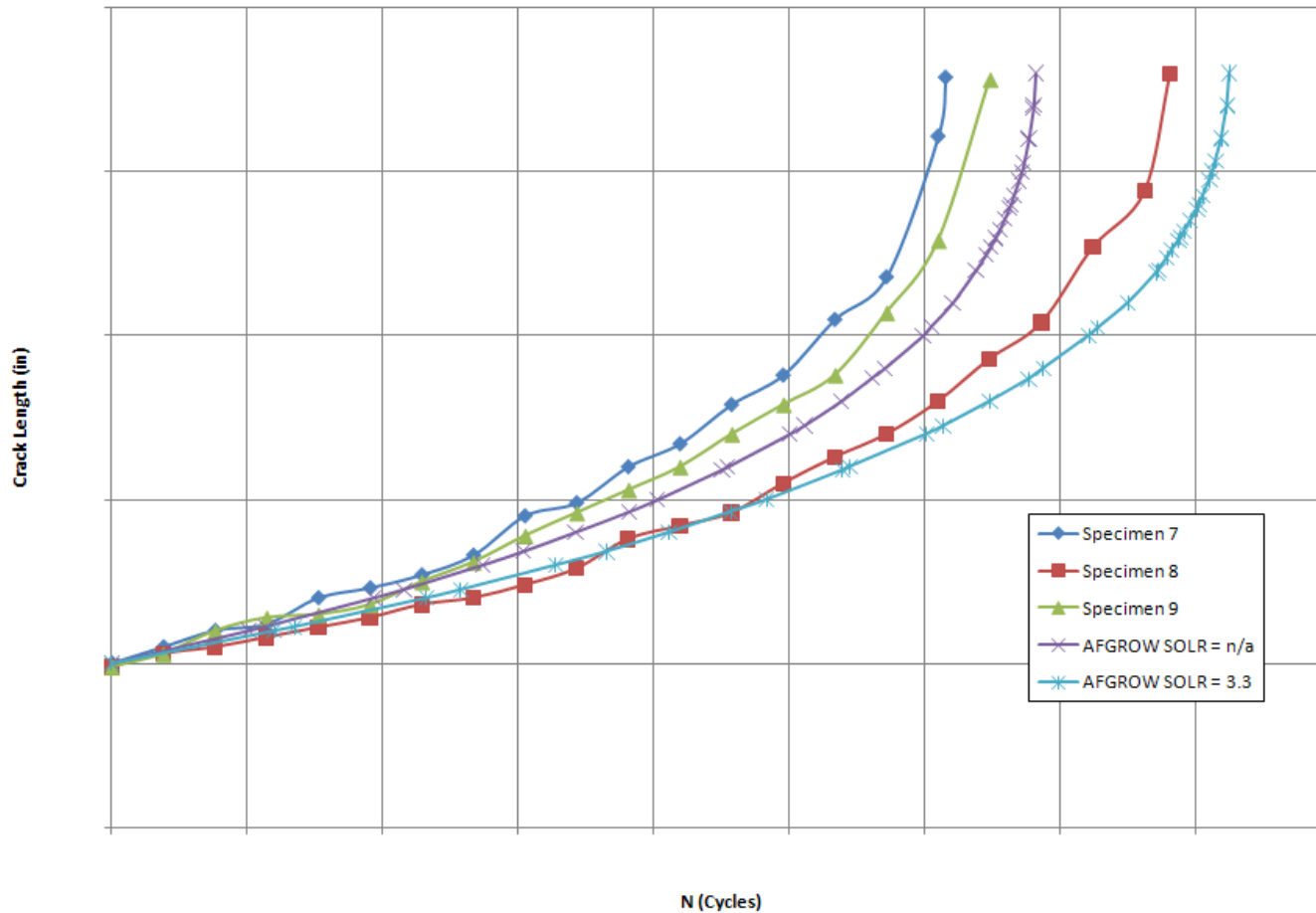


- **Shutoff Overload Ratio (SOLR)**
 - Ratio of the overload to the nominal load required to effectively stop further growth under nominal loading
 - Controls the effect of load history on the predicted life
 - Approach: vary SOLR to adjust the life prediction to match test results
 - Values for Steel
 - 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



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

Crack Growth Curves Specimens 7 - 9



SOME 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?

