

# Center for Aircraft Structural Life Extension

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*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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for funding this work*

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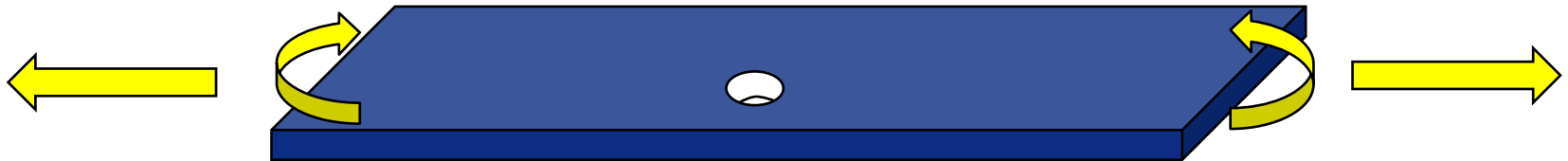
- 
- **Background / Purpose of project**
  - **$\beta$  Correction Factor Determination**
  - **Residual Stress Data and AFGROW Prediction**
  - **AFGROW and SOLR**
  - **Results**
  - **Future Analysis/Testing**

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# **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:

- $\beta$  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

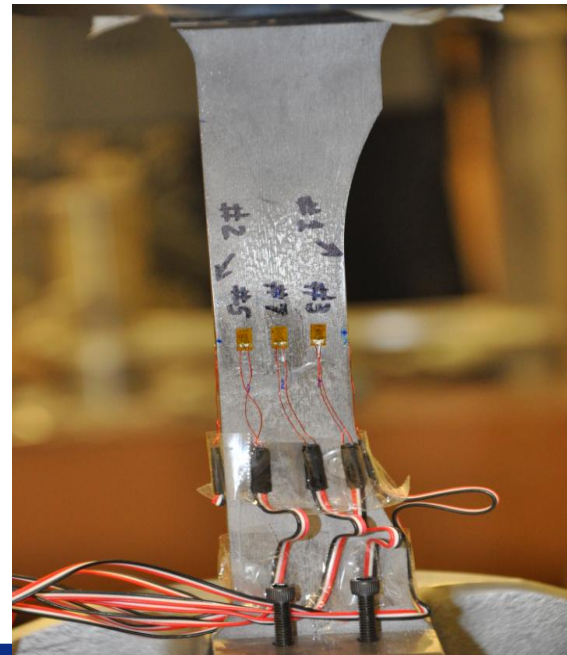
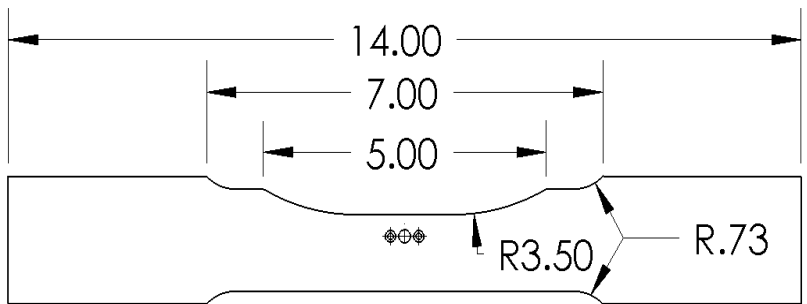
### ■ Material characteristics

- 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



Specimen Category	Bore-Crack						Edge-Crack	
	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 –  $\beta$  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 –  $\beta$  correction factor determination for CX (optional)
- G – Baseline test for edge crack
- H – Cold-expansion occurs after 0.05” flaw is grown – edge crack



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# $\beta$ CORRECTION FACTOR DETERMINATION

# $\beta$ Correction Factor Determination

## ■ $\beta$ 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  $\beta$  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  $\sigma_{\max}$  to  $\sigma_{\min}$ , 100 cycles at 75%, 10 cycles at 100%  $\sigma_{\max}$
  - 2,000 cycles  $\sigma_{\max}$  to  $\sigma_{\min}$ , 200 cycles at 50%, 10 cycles at 100%  $\sigma_{\max}$
  - $\sigma_{\max} \approx 25\text{ksi}$ ,  $R = 0.1$
  - Marker bands were not visible, so...
- CA testing
  - Measurements taken at cycles corresponding to 0.01" crack growth

# "Piecewise" $\beta$ Correction Factor Determination

### Predict Function Preferences

Output Intervals | Output Options | Propagation Limits | Tr |

Stop Crack Propagation at:

- Crack Length Value: 0.0000
- 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: 999999

Spectrum Reps (Max: 9999999): 999999

Minimum crack growth after one pass of the spectrum: 1e-013

Minimum crack growth: 1e-013

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: 2

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

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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=-1.8429e+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= 0.089000 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

Enter specimen dimensions

Width (W): [ ] Thickness (T): [ ] Hole Diameter (D): [ ]

Enter crack dimensions

Crack Length 'C' Direction: 0.077001  
 Crack Length 'A' Direction: 0.079038

OK Cancel Apply Help

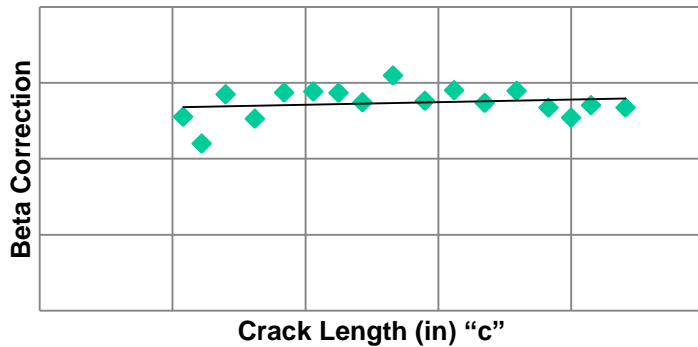
Example Problem

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

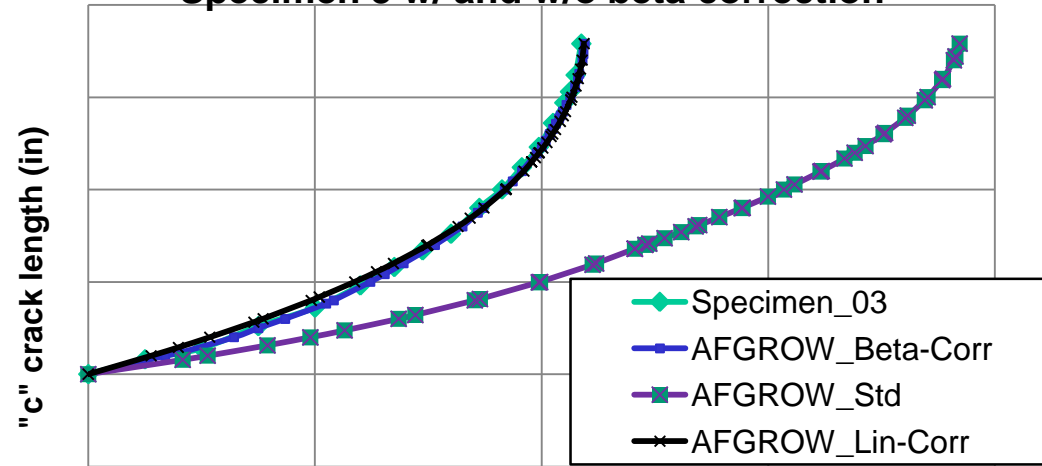
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 A/r ratio= 0.54136 A/C ratio= 1.0265  
 Max stress = 25.685 r = 0.10 0 Cycles Constant amp: 1 Pass: 1

# $\beta$ Correction Factor Determination

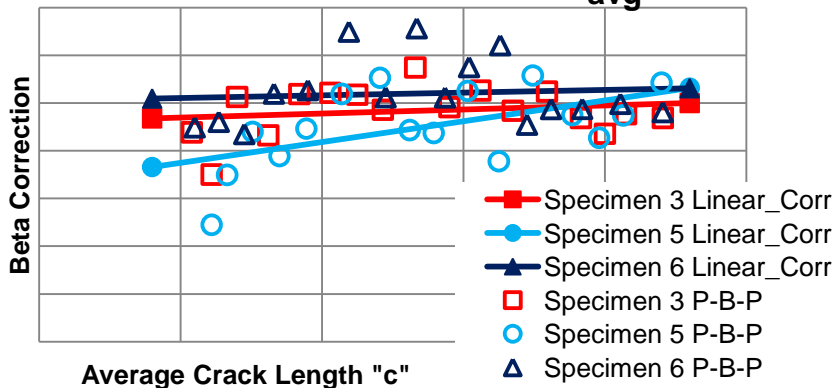
## Beta Corrector Factors



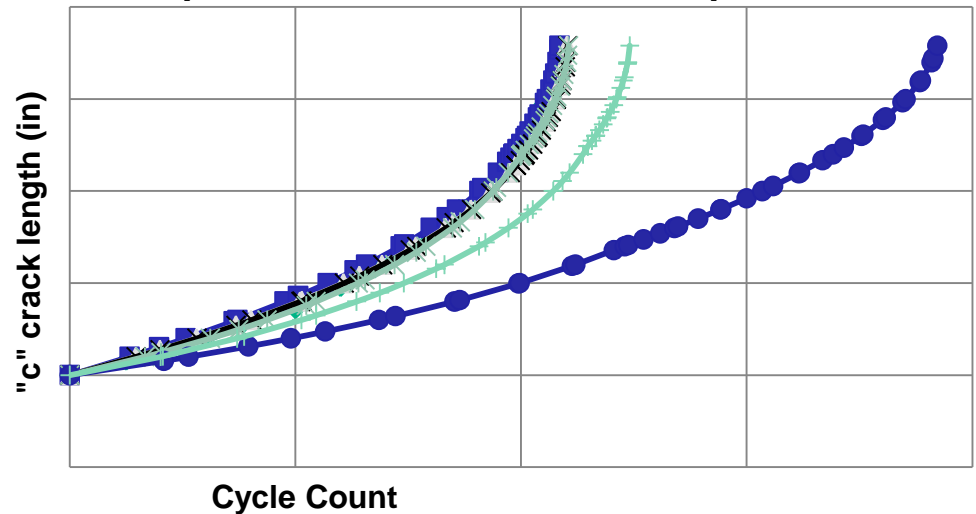
## Specimen 3 w/ and w/o beta correction



## Beta Correction Vs. $C_{avg}$



## Specimen 3 Beta Correction Options



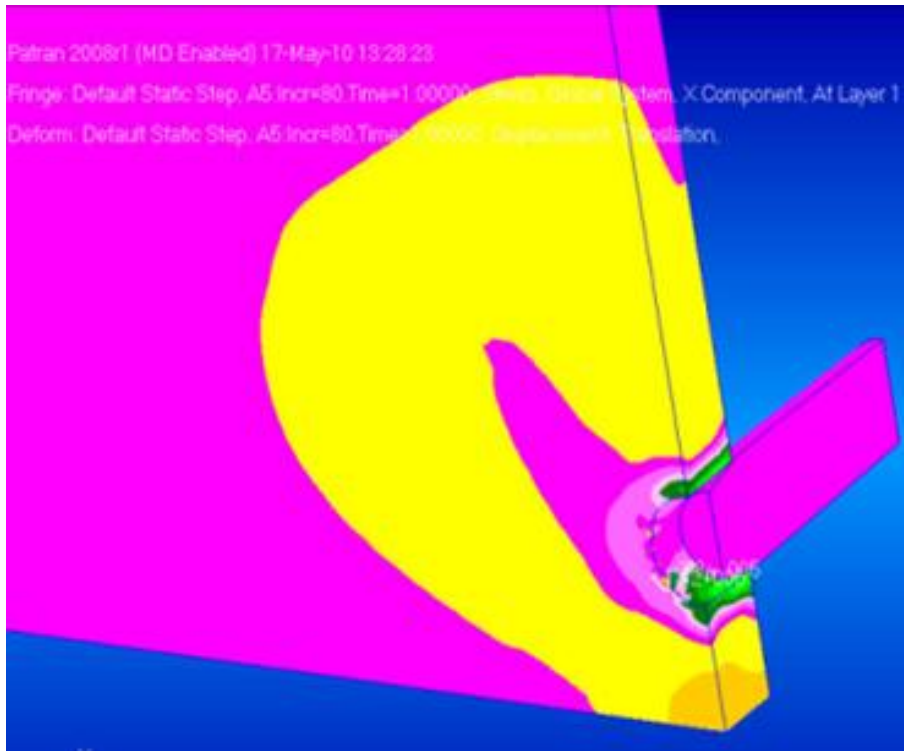
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# RESIDUAL STRESS DATA AND AFGROW PREDICTION

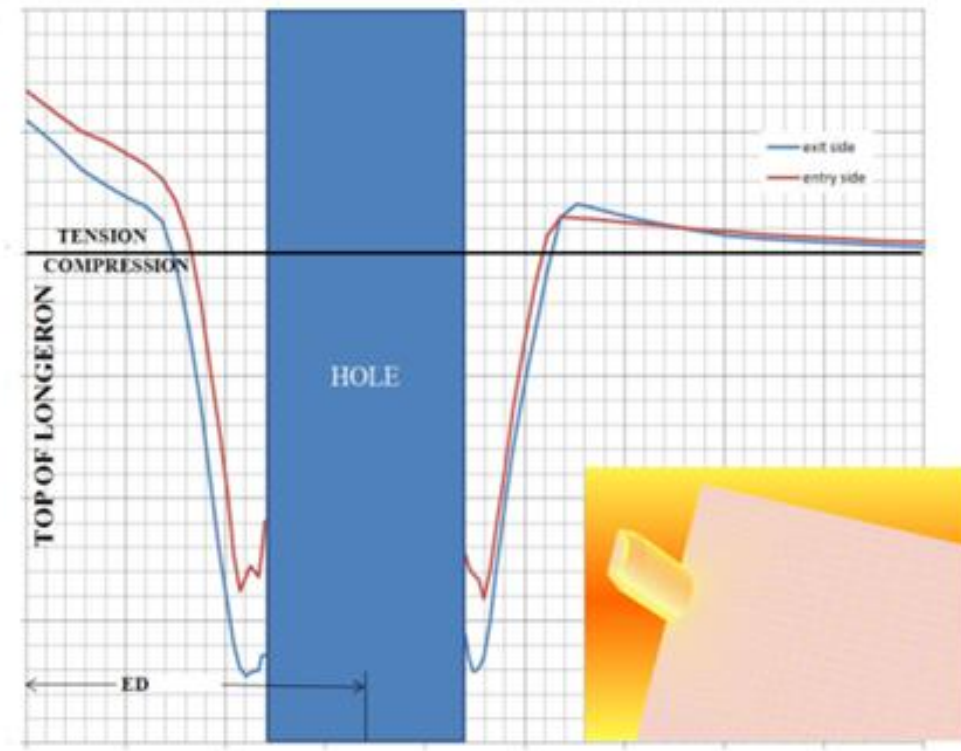
## ■ Cold-Expanding Holes

- 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 



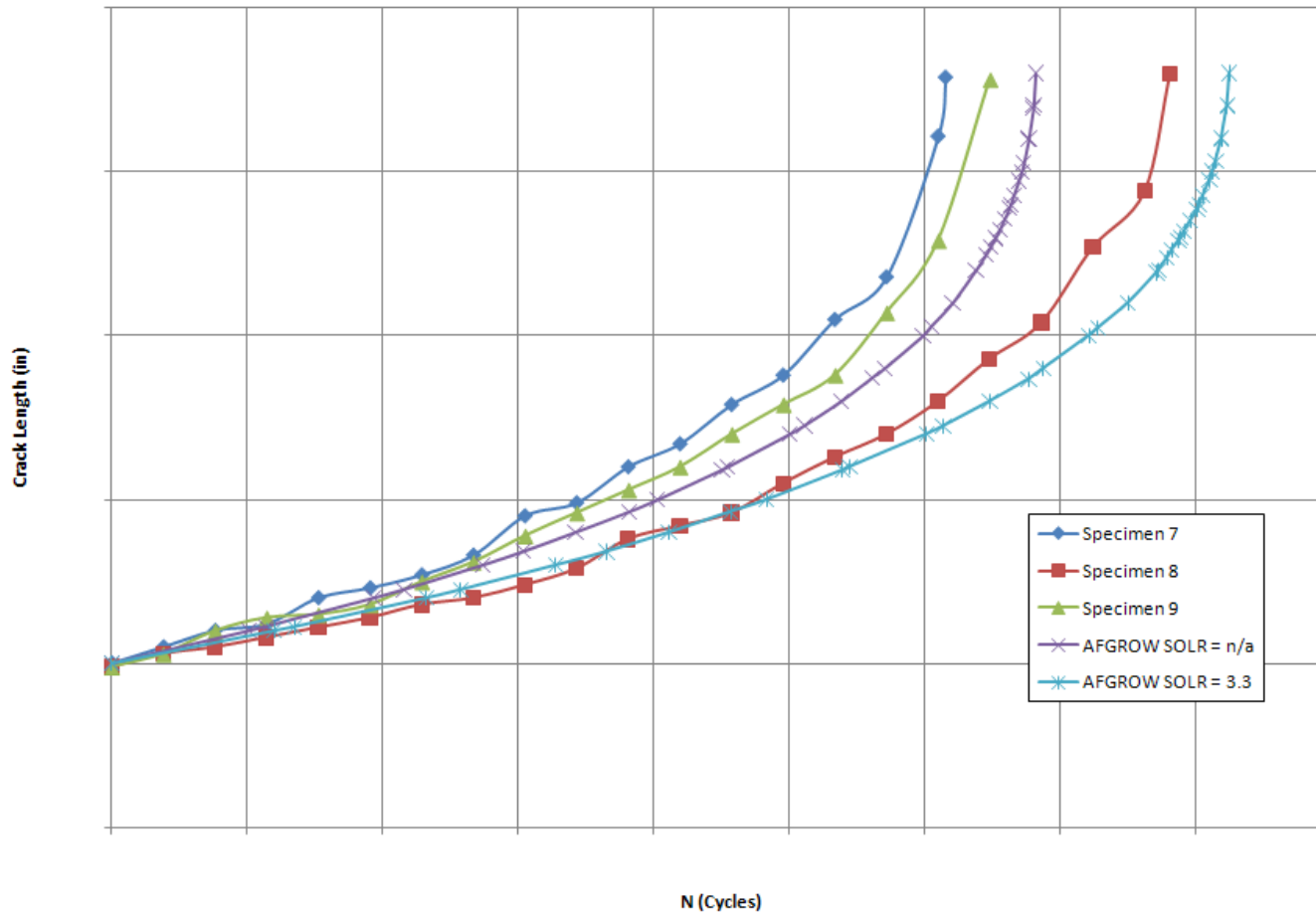
- **Shutoff Overload Ratio (SOLR)**
  - Ratio of the overload to the nominal load required to effectively stop further growth under nominal loading
  - Controls the effect of load history on the predicted life
  - Approach: vary SOLR to adjust the life prediction to match test results
  - Values for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



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# **SOME PRELIMINARY CONCLUSIONS**

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## ■ 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

## ■ $\beta$ 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

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# Questions?

