

Crack Growth under Highly Compressive Spectra

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AFGROW User Workshop 2020



Crack Growth under Highly Compressive Spectra

Outline

- Background
- Historical Al7050 Coupon Tests and Crack Growth Simulation
- New Al7075 Coupon Test and Crack Growth Simulation
- Material Data Investigation
- General Discussion / Recommendations

BACKGROUND

Crack Growth under Highly Compressive Spectra

CF-188 Problematic Life Limiting Items

NRC Project

Background

- Using the current lifing methodologies and data, the fatigue lives of multiple CF-188 life limiting items (LLIs) may not reach the revised target.

Objectives

- Identify options for increasing the demonstrated life of selected classes of problematic LLIs
 - Potential approaches:
 - Consider additional available data
 - Use **alternative analysis approaches**
 - Obtain new data by conducting additional tests.
 - The first class of problematic LLIs to be addressed are those loaded under highly compressive load spectra



CF-188 Problematic Life Limiting Items

Highly-Compressive Load Spectra

First Class of Problematic LLIs to be Investigated

- Crack “initiation” (CI) and crack growth (CG) under highly compressive load spectra
- Investigation of analysis methodologies
- Multiple CF-188 bulkhead locations
 - Hole cracks + fastener; radial cracks

Current State

- Low confidence in analysis methods and guidelines to handle these cases
 - Actual models return large (almost infinite) lives
 - Inconsistent with test and in-service data in many cases (unexpected cracks)

CRACK GROWTH SIMULATION OF HISTORICAL AL7050 COUPON TESTS

Objective: Carry out CG predictions of existing highly-compressive load test results using AFGROW

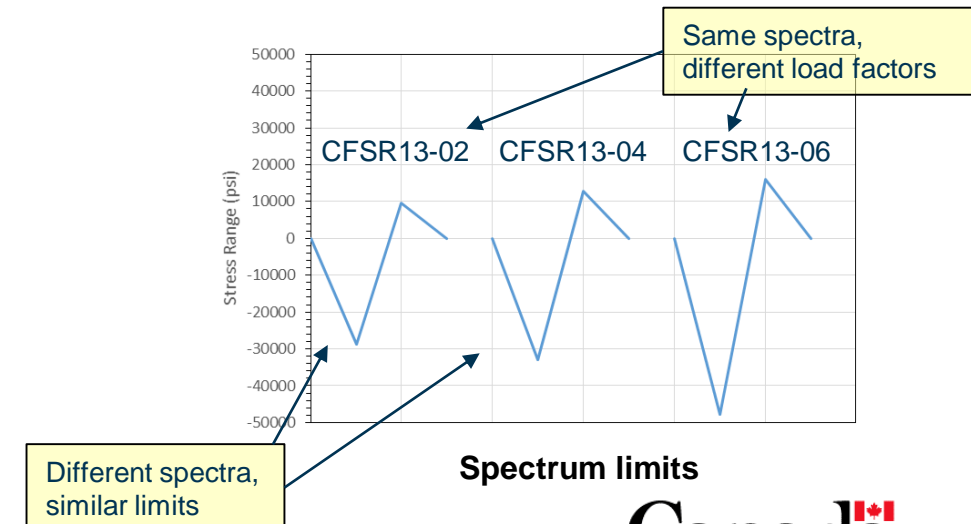
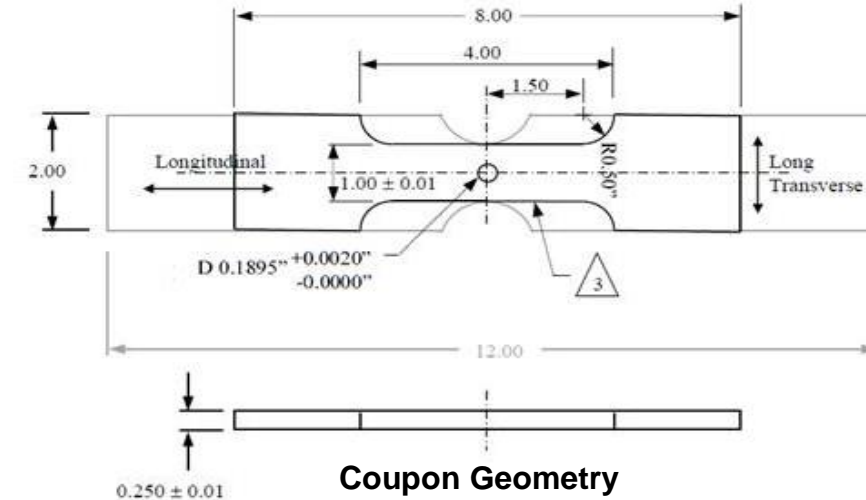
Experimental Data

Historical Test Program (Highly Compressive Load Spectra)

Coupon tests data available from 2009

- “**Initiation**” (no pre-crack) coupons with neat-fit fastener
- Inverted WRBM spectra (FT55) and Compressive Spectra 2 (CS2)
- CI and CG determined via periodic RLPI measurements
- CG data were collected for **only three coupons**:

	CFSR13-02	CFSR13-04	CFSR13-06
Spectrum (inverted)	FT55	CS2	FT55
Normalized range	[-2.99, 1]	[-3.44, 1.34]	[-2.99, 1]
LMF	2,397 lbf	2,397 lbf	4,000 lbf
Max stress	9,588 psi	12,865 psi	16,000 psi
Min stress	-28,687 psi	-32,942 psi	-47,872 psi

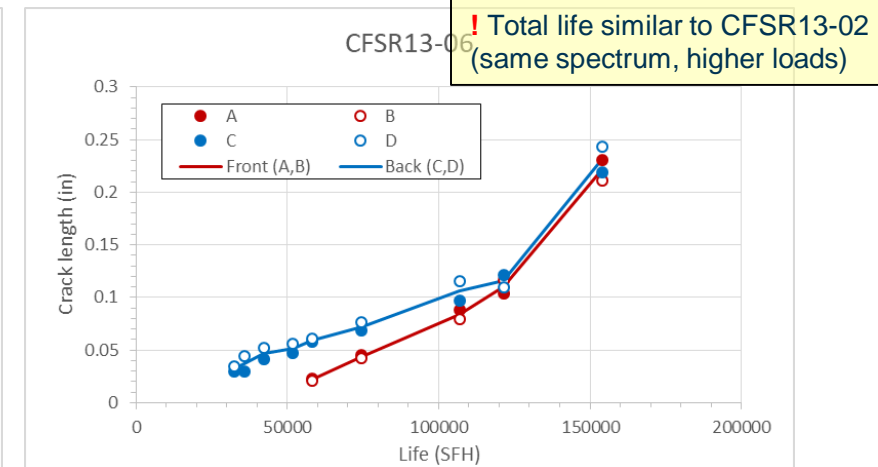
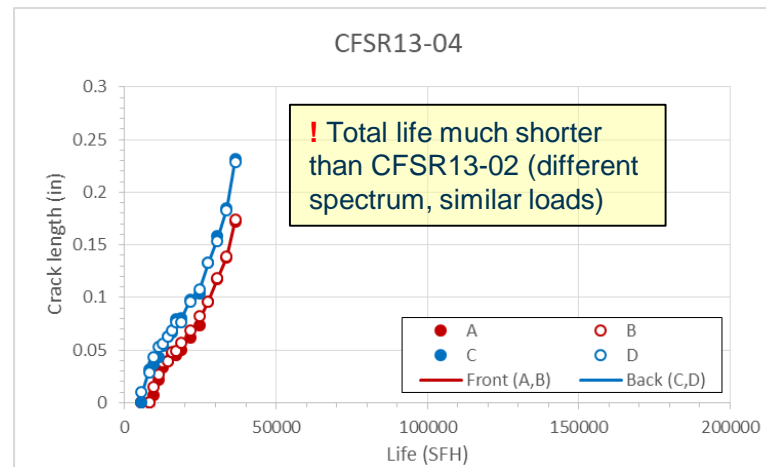
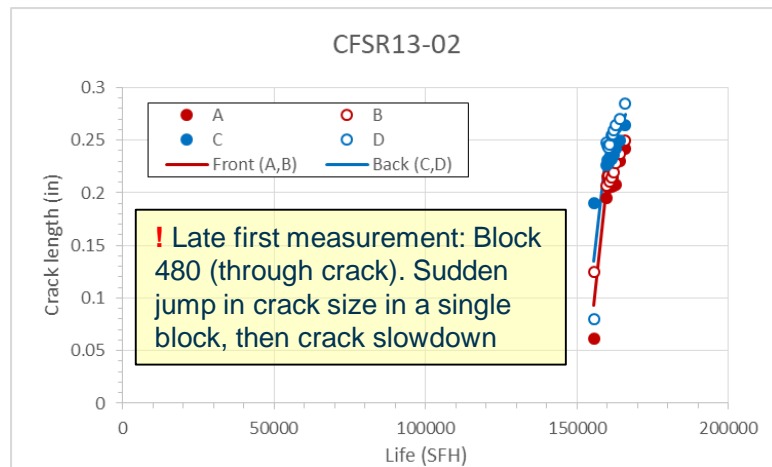
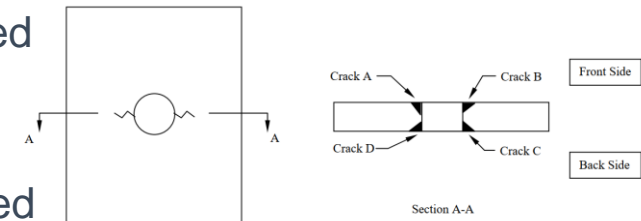


Experimental Data

Test Program (Highly Compressive Load Spectra)

Crack measurements provided to NRC

- CFSR13-02: 1st measurement: through cracks – last 4% of life was measured
- CFSR13-04: 1st measurement: uncertain – last 78% of life was measured
- CFSR13-06: 1st measurement: corner cracks – last 79% of life was measured



AFGROW Analysis

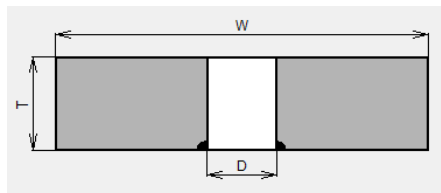
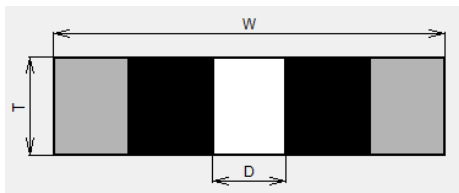
Baseline Assumptions

Material FCGR Model

- 7050-T74_T-L_Lab_Air_Forging.lkpx (AFMAT)

Initial Crack Size

- CFSR13-02 : 0.219" (average of all sizes at 2nd measurement)
 - Double Through Crack at a Hole
- CFSR13-04 : 0.0305" (average of back face sizes at 1st measurement)
 - Double Corner Crack at a Hole ($a_0=c_0$)
 - Double Through Crack at a hole
- CFSR13-06 : 0.0325" (average of back face sizes at 1st measurement)
 - Double Corner Crack at a Hole ($a_0=c_0$)



LLI 92.2: Crack growth curves from GAH-318-0583

28453 SFH of CG obtained

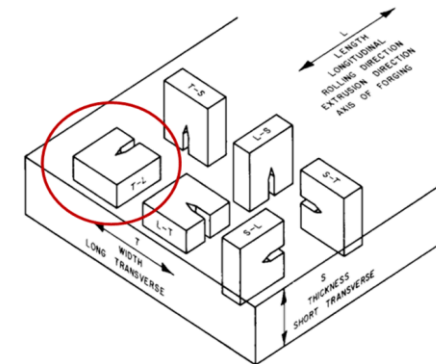
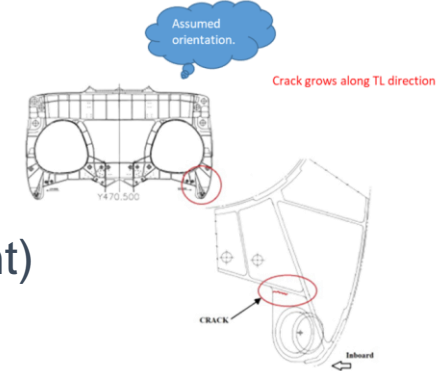
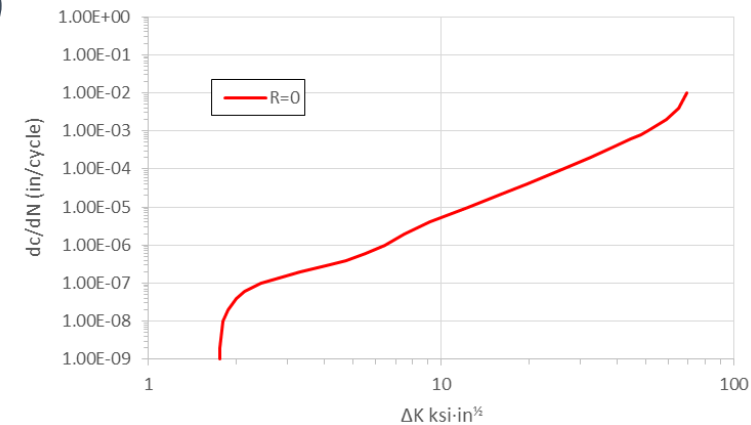


Figure 1.4.12.3(a). Typical principal fracture path directions.



AFGROW Analysis

Models

Classic Models: Newman and Raju

- **Model NR-OH: Open hole, classical solutions**
- Model NR-FH: Filled hole, unloaded (Lincoln)
- Model NR-SF: Pin effect by spectrum filter (SF)
- Model NR-RS: Residual stresses (FEA)
- Model NR-RS+SF: Pin (spectrum filter) + residual stresses (FEA)

← **Baseline Model**

Advanced Models: Fawaz and Andersson

- Model FA-OH: Open hole, advanced solutions (Fawaz and Andersson)
- Model FA-SF: Pin effect spectrum filter
- Model FA-RS: Residual stresses (FEA)
- **Model FA-RS+SF: Pin (spectrum filter) + residual stresses (FEA)**

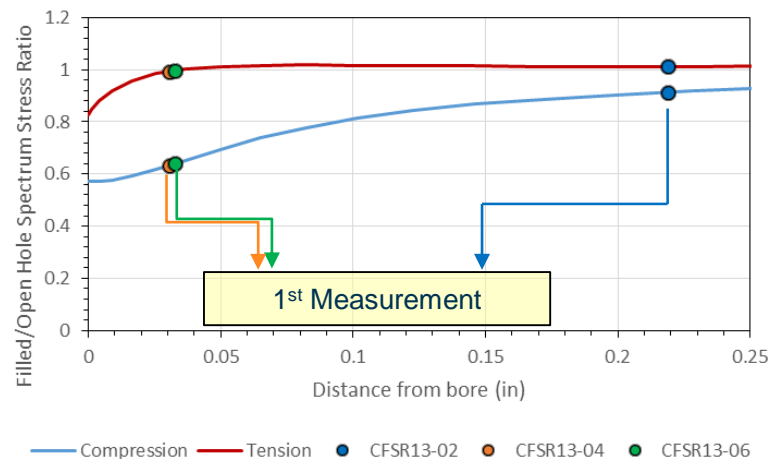
← **“Best” Model**

AFGROW Analysis

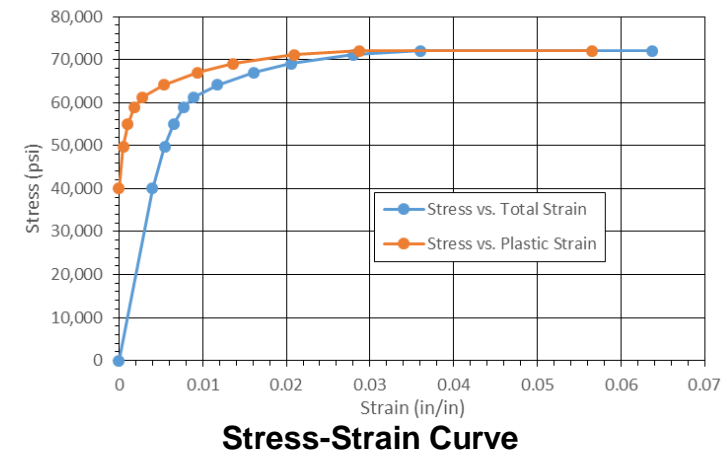
Finite Element Analysis

Residual Stress and Filled Hole Effects

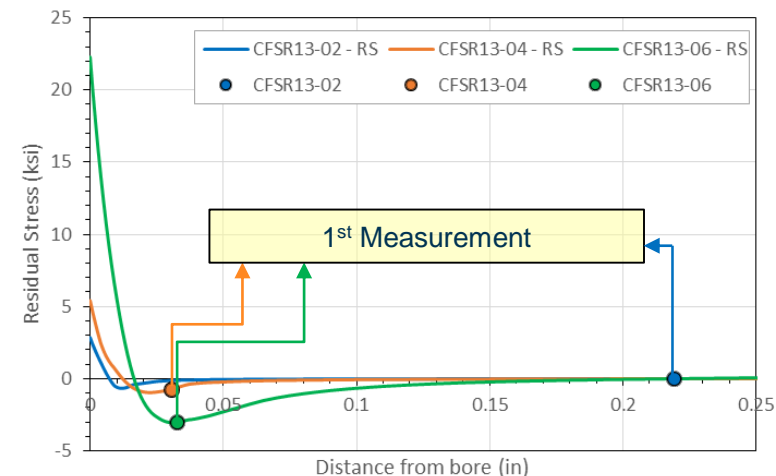
- MSC Marc simulation
 - Planar model (plane stress)
 - Steel fastener (contact, elastic, neat fit)
 - 1 cycle (min-max of spectrum) applied



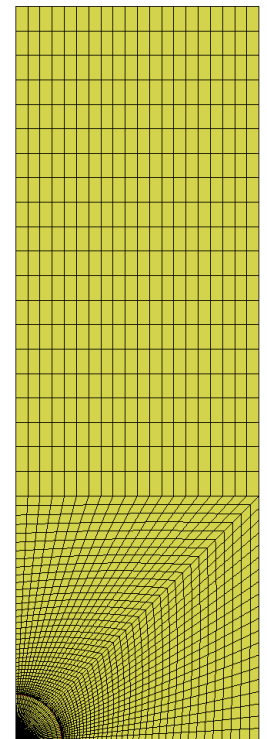
Neat Fit Fastener Effect



Stress-Strain Curve



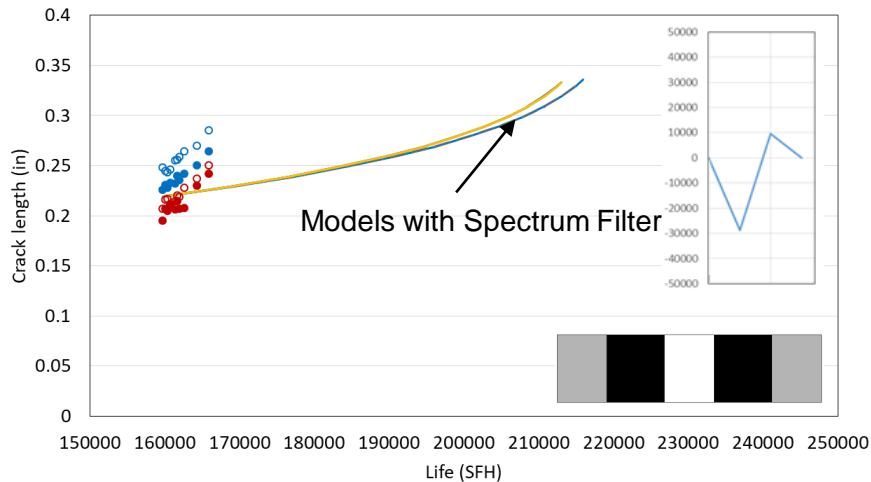
Residual Stresses from Spectrum Limits



FEM

AFGROW Analysis Results

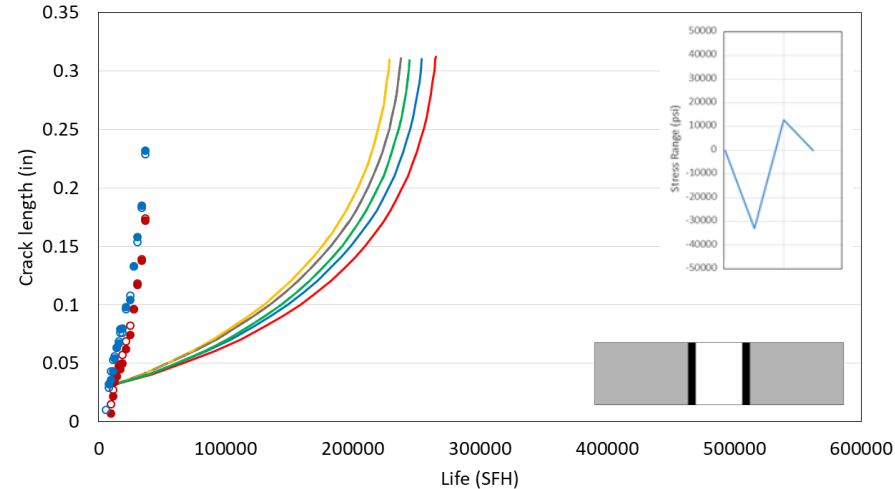
CFSR-13-02



Initial crack growth rate is highly underestimated

Modelling assumptions have limited effects (crack is far from hole)

CFSR-13-04t

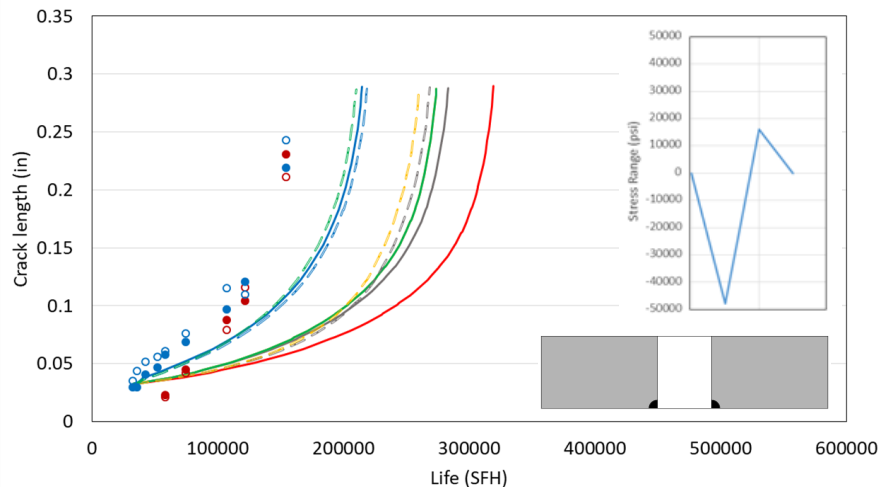


Initial crack growth rate is highly underestimated

Modeling assumptions have limited effect on the through crack model

Modelling assumptions have effect on the corner crack mode

CFSR-13-06

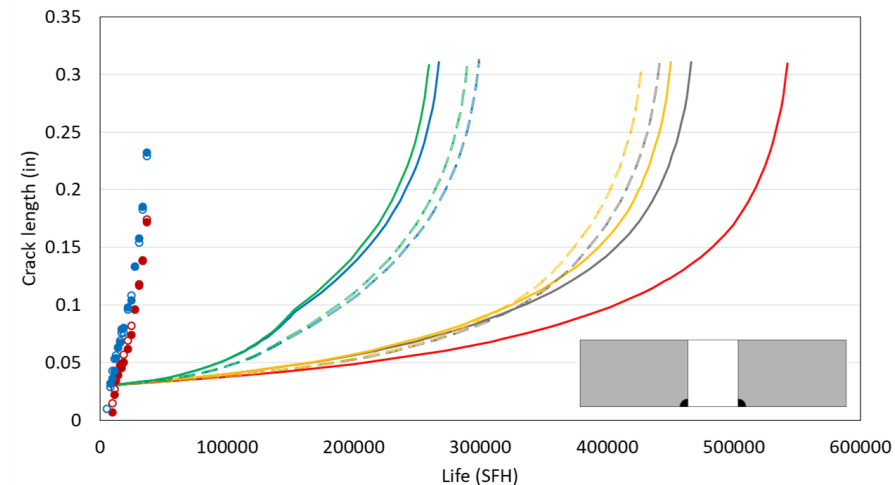


Initial crack growth rate closer to test results

Modelling assumptions have significant impact (corner cracks)

More physics improves the prediction accuracy

CFSR-13-04c



Experimental	
•	A (Exp.)
○	B (Exp.)
•	C (Exp.)
○	D (Exp.)
Newman-Raju	
—	NR-OH
—	NR-FH
—	NR-SF
—	NR-RS
—	NR-RS+SF
Fawaz-Andersson	
—	FA-OH
—	FA-SF
—	FA-RS
—	FA-RS+SF

Historical Coupon Tests CG Simulation

Note on the Provided Test Results

Provided Life Trend Inconsistent with Analysis

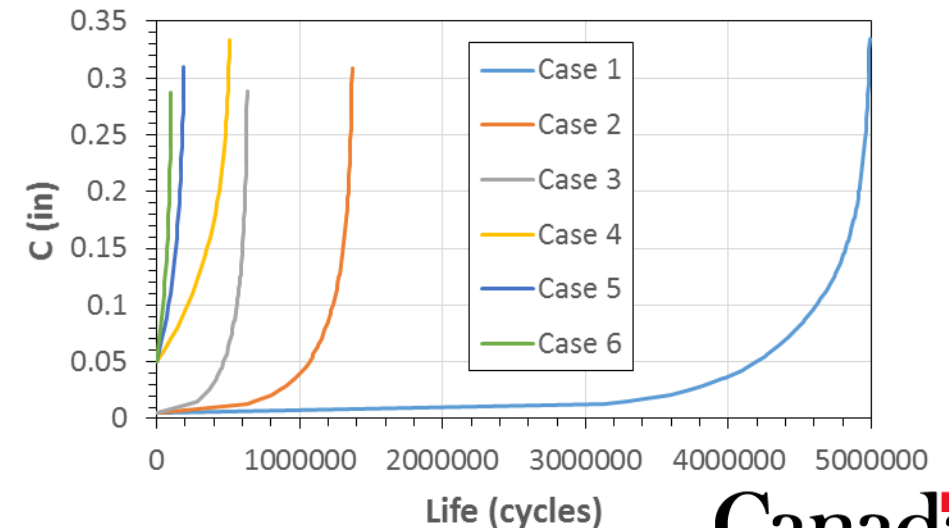
- The three spectra were assessed from common initial crack sizes (Model NR - RS+SF)
- Analytical and experimental life rankings are different (only 1 replicate per spectrum)
 - Tests are “initiation” tests / no pre-crack

Tests: CFSR13-04 CFSR13-02 CFSR13-06

Spectrum Severity

Analysis: CFSR13-02 CFSR13-04 CFSR13-06

Case	Spectrum (reversed)	SMF (ksi)	C ₀ (in)	Crack Type	Note
1	FT55	9.588	0.005	Double corner	
2	CS2	9.588	0.005	Double corner	Similar to -04c
3	FT55	16	0.005	Double corner	Similar to -06
4	FT55	9.588	0.05	Double through	Similar to -02
5	CS2	9.588	0.05	Double through	Similar to -04t
6	FT55	16	0.05	Double through	

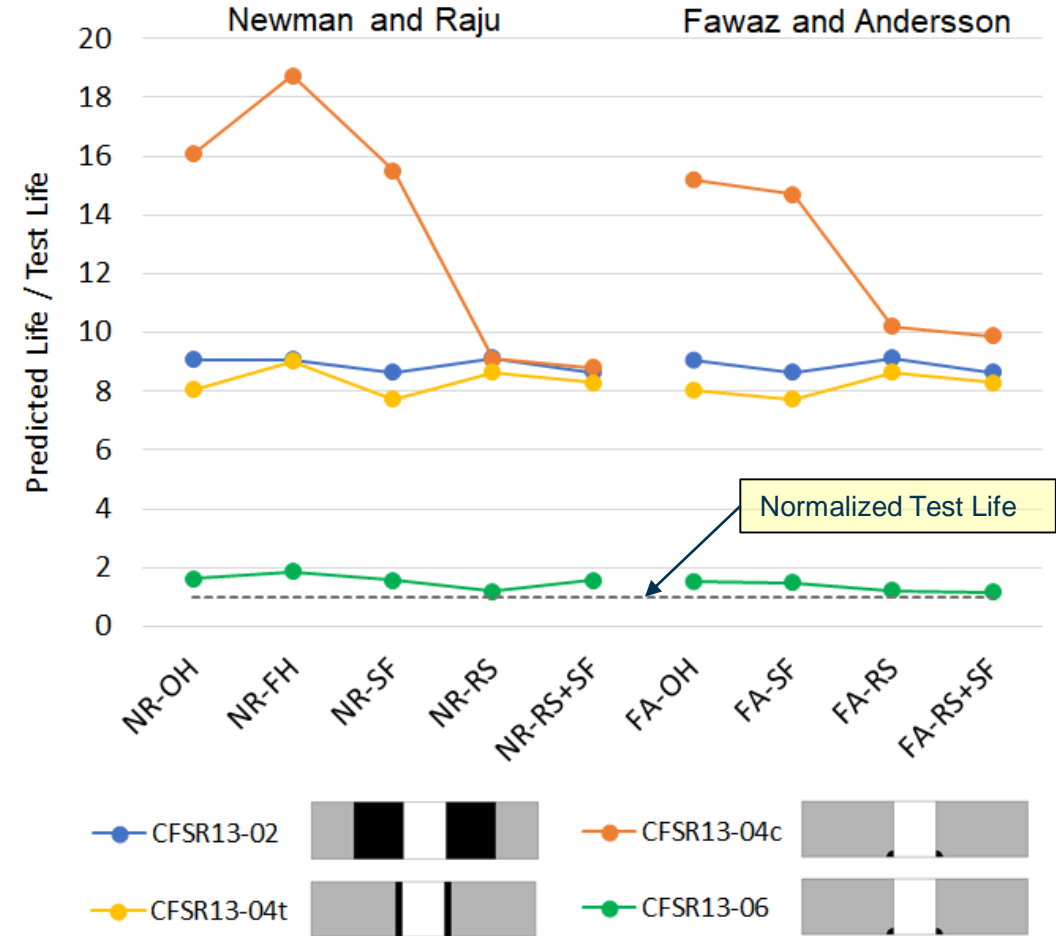


AFGROW Analysis Results

AFGROW Models

All models significantly overestimated CG life

- Analytical/Test Ratio ≥ 7 for CFSR13-02 and CFSR13-04 (different spectra, similar loads)
- Analytical/Test Ratio < 2 for CFSR13-06 (higher loads)
- Predictions are better for higher loads!**
- Fastener effect (Spectrum Filter) improves the results for all cases
- Residual stress effect improves the prediction accuracy for corner crack models only



Historical Coupon Tests CG Simulation

Comments

AFGROW Analysis

- Adding more physics (Pin, RS) improved the simulation results for corner crack models (a -tip at hole bore)
- Classic models gave similar lives to those of advanced models
- **Best predictions: FT55 with higher loads (even without residual stresses)**
- FT55 and CS2 with similar loads: similar results (intuitive but **inconsistent with test**)

Provided Test Data

- Limited number of “initiation” coupons; unclear initial crack size and shape for CG phase; captured/documentated data is scarce
- Test results have different trend from the analysis
 - Different spectra of similar loads led to very different lives
 - Same spectrum with different loads led to similar lives

Proposed Next Step

- Test new coupons with the same spectra and generate high-quality through-crack data for method validation
 - Initial low-cost solution: Al7075 M(T) coupons already available at NRC
 - Current testing phase: Al7050 M(T) coupons recycled from IFOSTP coupons
- Investigate spectrum characteristics vs. expected material behaviour

CRACK GROWTH SIMULATION OF NEW AL7075 COUPON TESTS

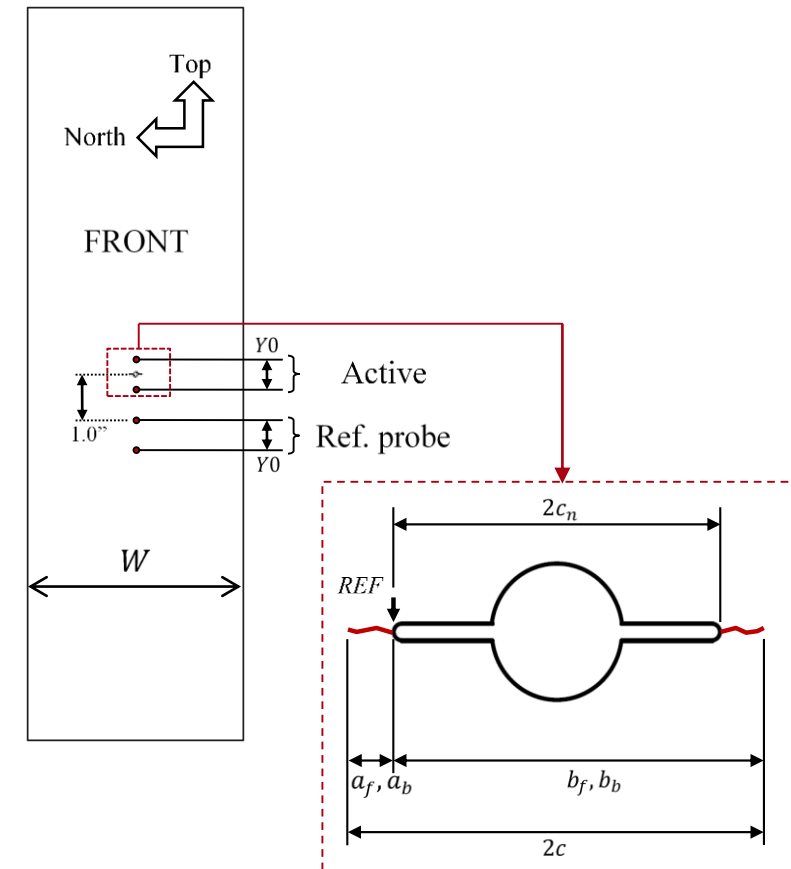
Objective: Carry out CG predictions of Al7075 middle tension coupon subjected to a highly compressive loading fatigue spectrum (no residual stress or pin effect)

Experimental Method

Preliminary Test (Highly Compressive Load Spectra)

Objective: Obtain fatigue crack growth data for highly-compressive spectra

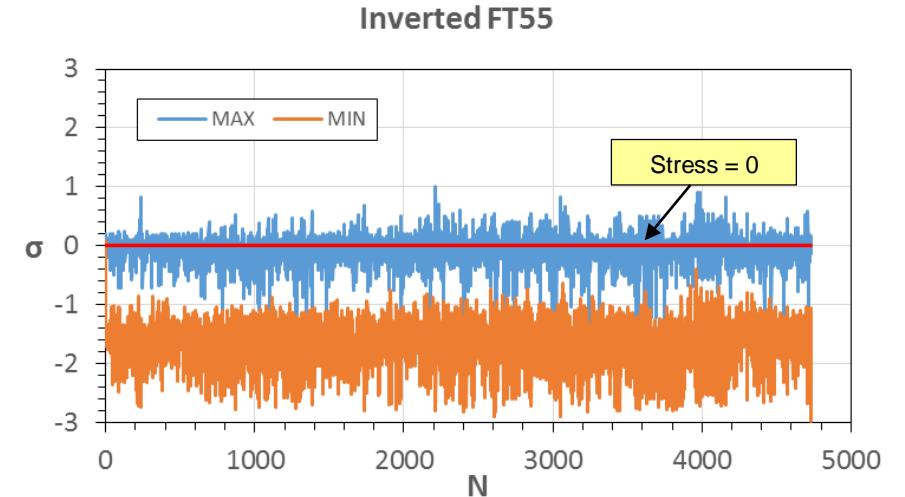
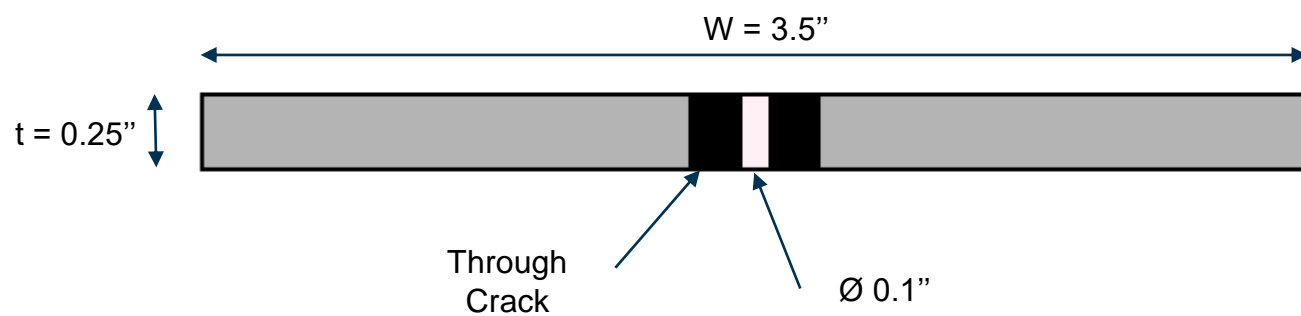
- **Material:** 7075-T651 aluminum (plate)
 - Isolate material effects (no hole, no fastener)
- **Specimens:** M(T) specimens ($W = 3.5''$, $t = 0.25''$, $2c_n = 0.2''$)
- **Pre-cracking:** $a_f \approx 0.05''$ at max stress of 7.74 ksi and 13 hz (CA)
- **Crack measurement:** DCPD method and visual measurements at 4 crack tips ($\Delta c \approx 0.010''$ to $0.020''$)
- **Test frequency:** Average is approximately $f \approx 6$ hz
- **Spectrum / Amplitude:** Inverted FT55 / -29.1 ksi to 9.68 ksi (same as CFSR13-02)
 - Increased by 20% from $n = 1\ 950\ 371$ due to slow crack growth



AFGROW Analyses

Validation Model

- **Model and Geometry:** Double through crack at hole ($W = 3.5''$, $t = 0.25''$, $2c_n = 0.2''$, $\phi = 0.1''$)
- **AFGROW Materials:**
 1. 7075-T651 Aluminium, Tabular Lookup (AFMAT)
 2. NASGRO material model
- **Spectrum:** Inverted FT55

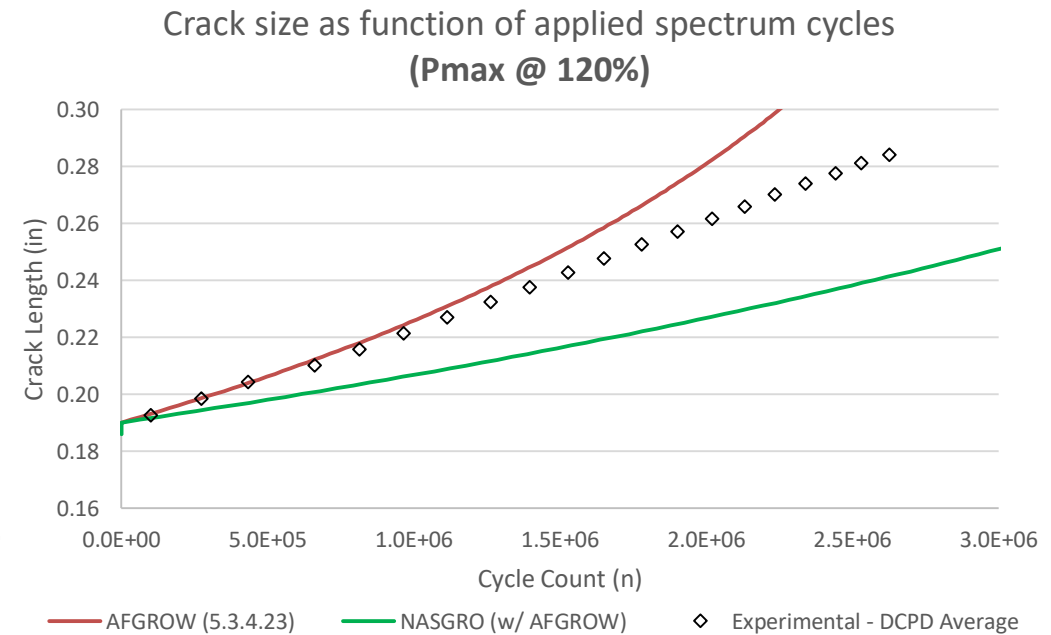
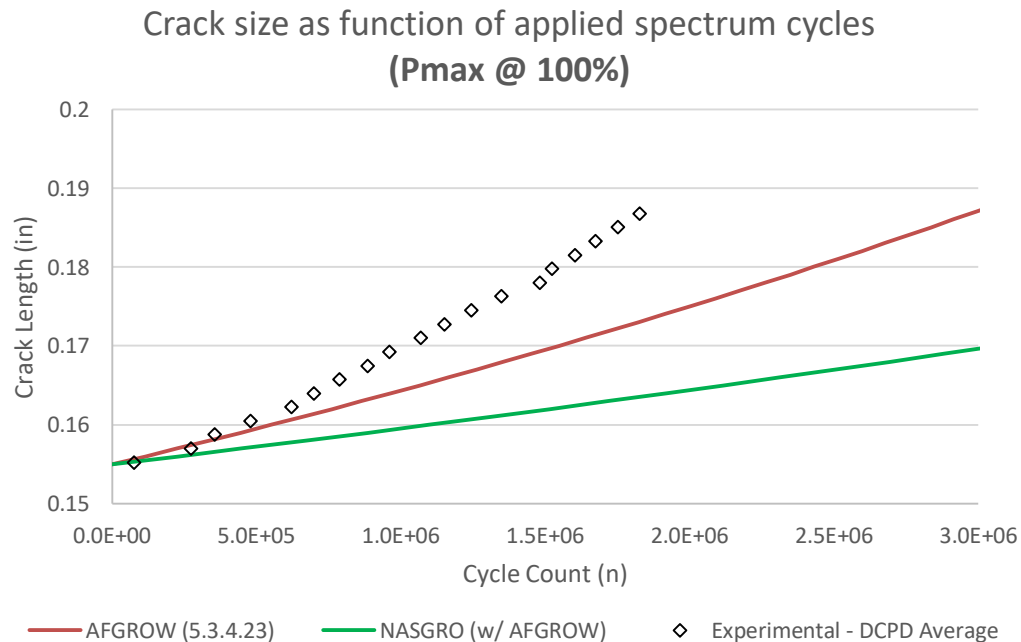
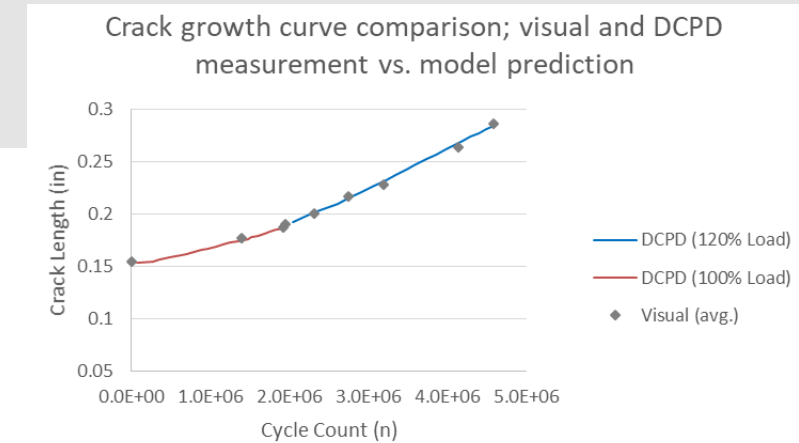


AFGROW Analyses

Experimental Results and Validation

Two Test Phases

- 100% load amplitude from pre-cracking (from $2c = 0,3099''$ and $n = 0$)
- 120% load amplitude from load increase (from $2c = 0,3801''$ and $n = 1\ 950\ 371$)



New Coupon Tests CG Simulation

Comments

AFGROW Analyses

- No residual stress or pin effect (no hole, no yielding)
- Fatigue crack growth rate at 100% load amplitude was underestimated
- **Prediction was improved for higher stress amplitudes (120% load amplitude)**
 - Results were close to the test results (AFGROW material model)
 - In accordance with experimental data from “Phase 2” coupons CFSR13-04 and CFSR13-06

MATERIAL DATA INVESTIGATION

Rationale: AFGROW results were consistently more accurate under higher loads (higher compressive and tensile loads), regardless of the residual stress or pin effects. This suggests that the threshold region and/or low- R material data may be inadequate for the considered spectra.

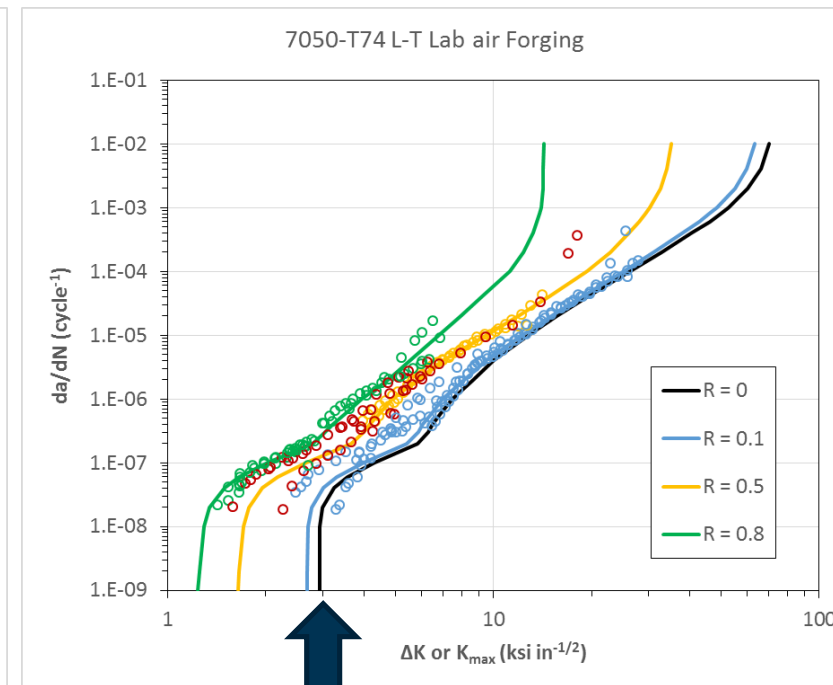
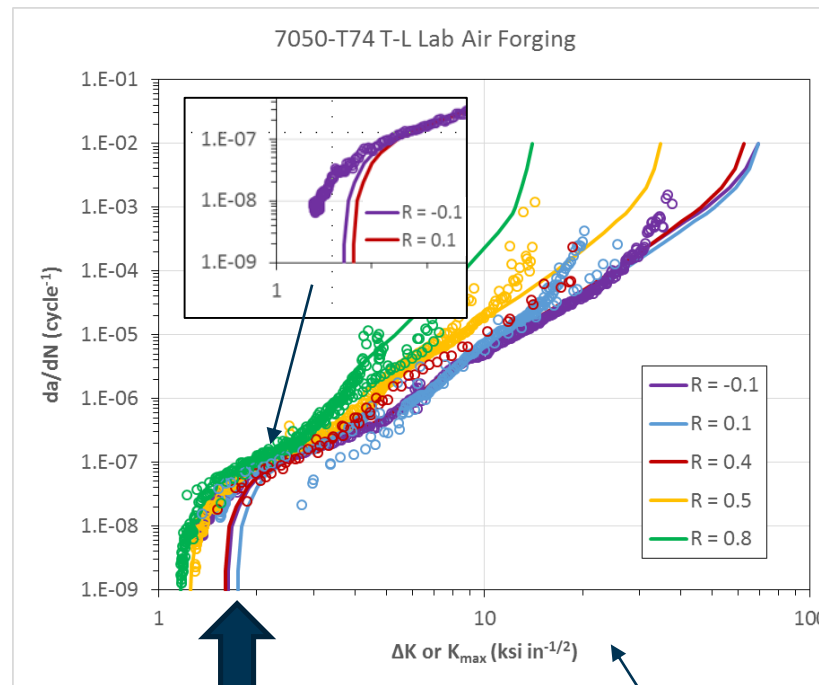
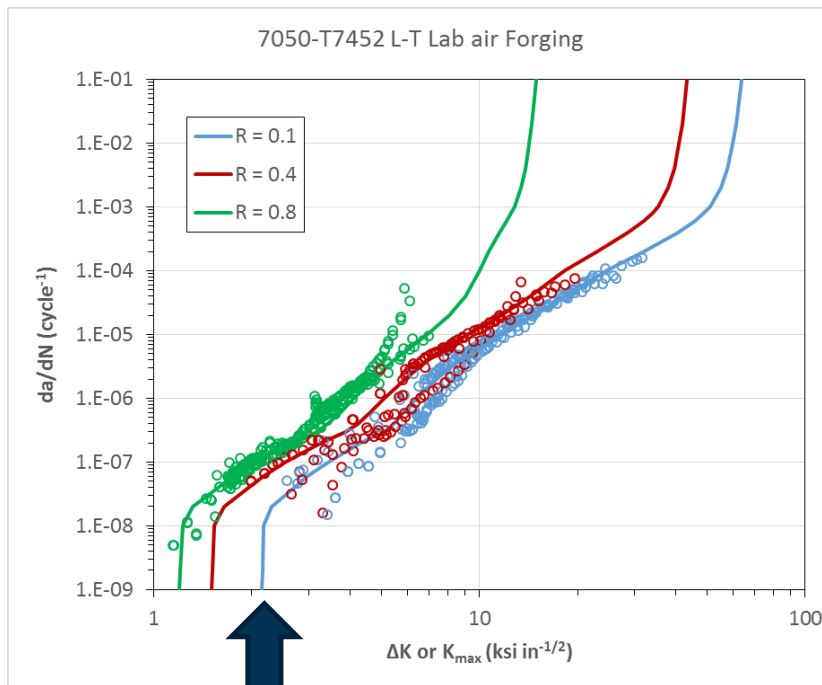
Objective: Investigate material models in terms of near-threshold and low- R behavior. Determine if calibration could be done for highly-compressive cases without affecting tensile-dominated spectrum response.

Material Data: AFGROW

AFMAT Database

7050-T74 Forging Data

Thresholds for $R \leq 0$ data are based on limited test data and engineering judgment, continuity rules (arbitrary to some extent)

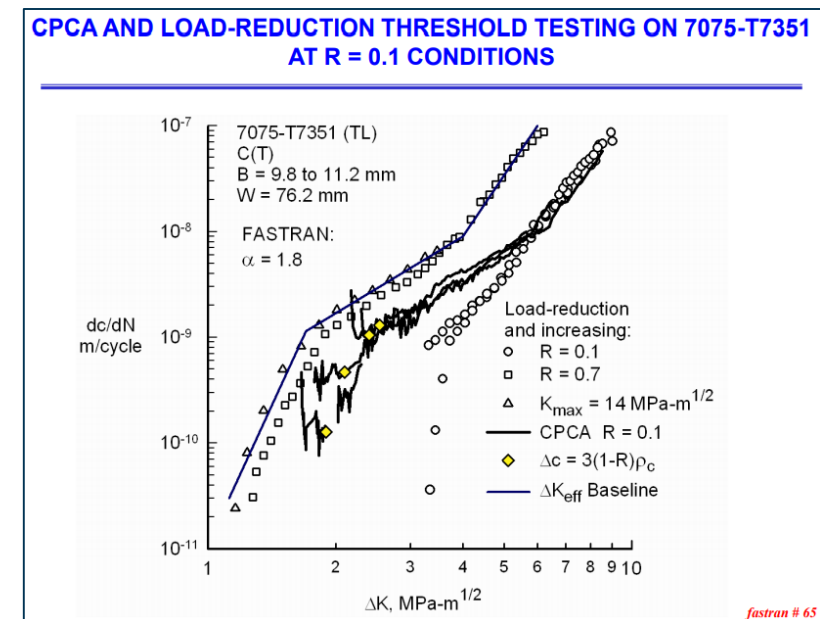


Model used in current AFGROW analyses

Material Data

Discussion

- The 7050-T7451 FCGR models available in AFGROW are based on limited test data, especially in the threshold region.
- These data were generated decades ago. Since then, concerns have been raised regarding threshold data obtained by the load-shedding method. For example, compression pre-cracking methods have been developed to generate FCGR data in the threshold region with minimal load-history effects.
- Data for highly compressive CA stress ratios are scarce and potentially unreliable (e.g. closure effects).
- AFGROW assumes that the material response does not change below a certain R value (R_{lo} , typically around $R = -0.3$).



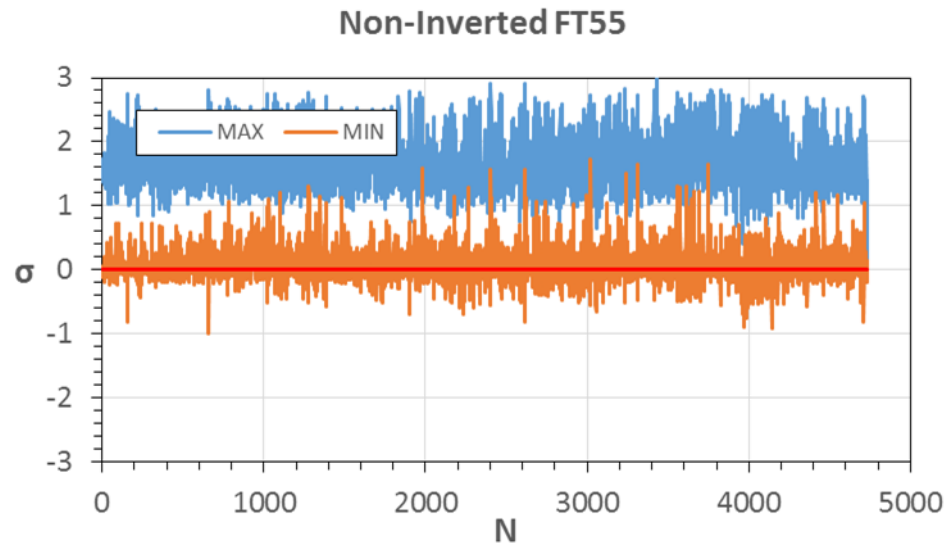
¹ Newman, J.C., "FASTRAN Fatigue-Crack-Growth Modeling Updates and Improved Test Methods", 2015 AFGROW Workshop, Layton, UT, September 2015.

Highly-Compressive Spectra

CG Threshold vs. Applied ΔK

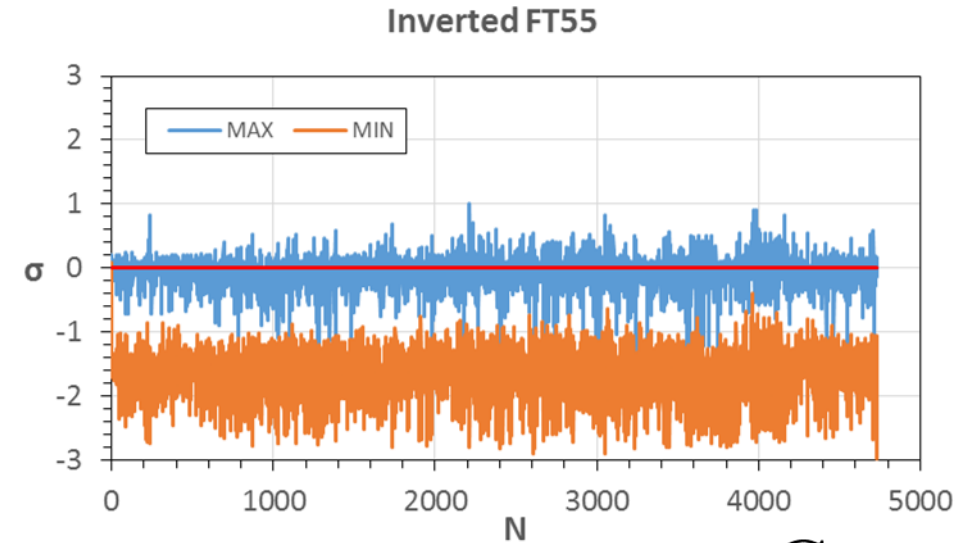
FT-55 Non-Inverted

- 4733/4733 (100%) of cycles are contributing to CG (positive peak)
 - $R_{lo} = 0.2$ for the considered FCGR model (AFMAT)



FT-55 Inverted

- Only 1670/4733 (**35%**) of cycles contribute to CG (positive peak)
 - **All but one contributing cycles are $-18,800 < R < -0.64$**

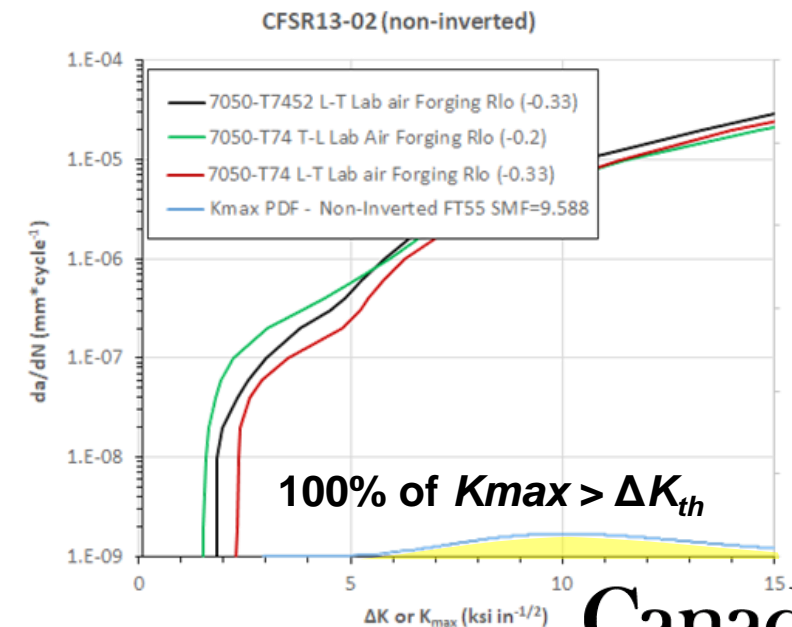
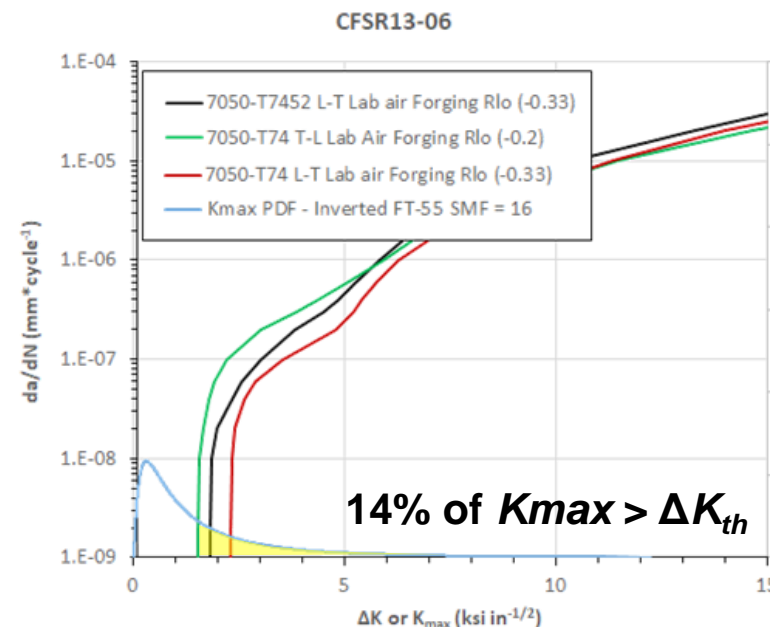
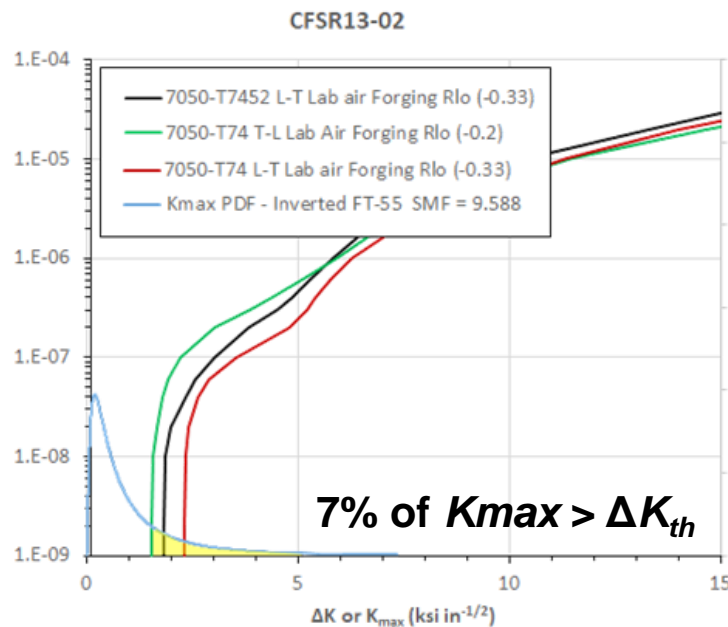


Highly-Compressive Spectra

CG Threshold vs. Applied ΔK

Assessment of Spectrum Effectiveness:

- Phase 2 coupons, Model NR-OH with $a_0 = 0.050''$
- Few cycles contributing to growth for inverted spectrum ($K_{max} > \Delta K_{th}$ @ $R_{lo} = -0.2$)
- Most cycles causing growth are near-threshold for inverted spectrum



Highly-Compressive Spectra

CG Threshold vs. Applied ΔK

Discussion

- Higher loads result in a larger number of cycles contributing to CG
- Higher loads “push” tensile peaks above the threshold (ΔK_{th})
- $R < R_{lo}$ for most cycles in inverted FT-55 spectra; same conclusion for CS2
- Better threshold characterization could increase the number of effective cycles:
 1. If better-characterized ΔK threshold is reduced for $R \leq 0$ (threshold shift to the left)
 2. If better-characterized R_{lo} is reduced (lower negative R curve to the left)

Recommendation

- Parametric studies on these two aspects

Parametric Study

R/*l*o and ΔK Threshold

- **Rationale:** Most AFGROW aluminum models have $R/l_o = -0.33$
- **Study:** Compare analytical life using original R/l_o (-0.2) and $R/l_o = -0.33$
- **Cases:** Historical coupons (AFGROW Model 6); 7050-T74 T-L Lab Air Forging
- **Outcome:** -13% for inverted spectra; marginal effect for non-inverted spectra

Inverted FT55 Spectra			
Case	Life (SFH)		
	$R/l_o = -0.2$	$R/l_o = -0.33$	Diff (%)
CFSR13-02 (FT55, 9.588 ksi)	53,935	47,131	-13%
CFSR13-04 corner (ST16, 9.588 ksi)	251,472	218,172	-13%
CFSR13-04 through (ST16, 9.588 ksi)	236,172	204,972	-13%
CFSR13-06 (FT55, 16 ksi)	172,519	149,839	-13%

Non-Inverted FT55 Spectra			
Case	Life (SFH)		
	$R/l_o = -0.2$	$R/l_o = -0.33$	Diff (%)
CFSR13-02 (FT55, 9.588 ksi)	11	11	0%
CFSR13-04 corner (ST16, 9.588 ksi)	1404	1404	0%
CFSR13-04 through (ST16, 9.588 ksi)	745	734	-1%
CFSR13-06 (FT55, 16 ksi)	164	164	0%

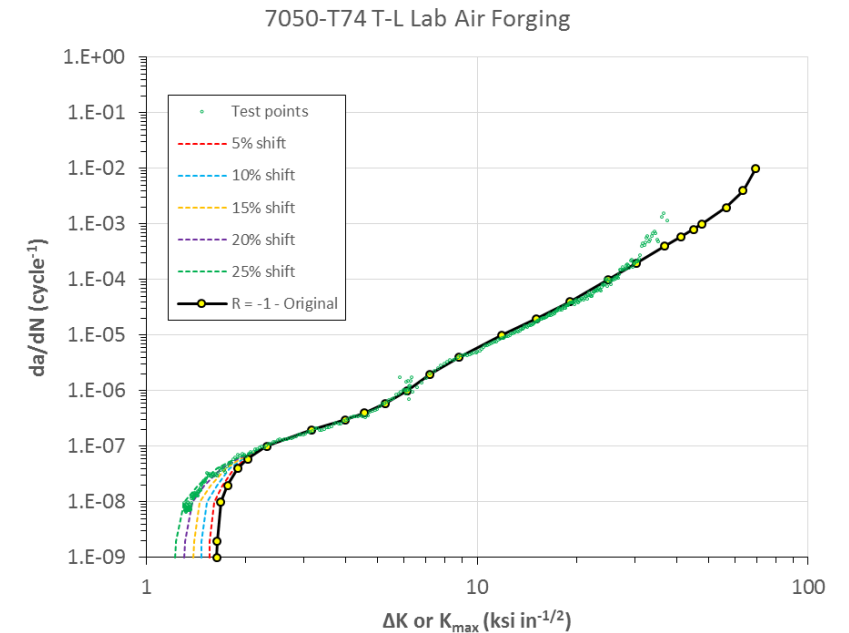
Parametric Study

ΔK Threshold

- **Rationale:** Based on AFMAT, ΔK_{th} for negative R curve(s) could reasonably decreased
- **Study:** Incremental shift of ΔK_{th} (all R s)
- **Cases:** Phase 2 coupons (Model 6); 7050-T74 T-L Lab Air Forging ($R_{lo} = -0.2$)
- **Outcome:** Up to -3.58% on inverted FT-55 spectra

Inverted Spectra

Case	Life (SFH)		
	Shift 0%	Shift 10%	Shift 25%
CFSR13-02 (FT55, 9.588 ksi)	53,935	53,611 (-0.6%)	53,611 (-0.60%)
CFSR13-04 corner (ST16, 9.588 ksi)	251,472	246,372 (-2.03%)	242,472 (-3.58%)
CFSR13-04 through (ST16, 9.588 ksi)	236,172	231,972 (-1.78%)	228,672 (-3.18%)
CFSR13-06 (FT55, 16 ksi)	172,519	171,223 (-0.75%)	170,251 (-1.31%)



0% difference for non-inverted spectra

Parametric Study

Discussion

***R*/o Modification:**

- Constant life reduction (-13%) on inverted FT55 spectra by lowering *R*/o from -0.2 to -0.33. (Shown no effect on non-inverted spectra)
- Easy implementation: **could be used as a tuning parameter**
- Coupon test would be necessary to determine the actual *R*/o value (difficult)
 - Results^{1,2} suggest that shifting may exist for *R* curves between -1 to -4

ΔK Threshold:

- Life reduction is less significant (<4%)
- Implementation is not straightforward
- New FCGR tests (e.g. CPCA) could generate more accurate data

¹ Boyd, K., Elsner, J., Jansen, D, and Harter, J., “Structural Integrity Analysis and Verification for Aircraft Structures, Volume 2, Effects of Compressive Load on the Fatigue Crack Growth Rates of 7075-T651 and 2024-T3 Aluminum Alloys, WL-TR-97-3017. August 1996.

² Mills, T., Prost-Domasky, S., Honeycutt, K. and Brooks, C., “Fatigue Life Modeling in Residual Stress Fields - Negative-R Crack Growth Testing”, 2018 ERSI Workshop, Layton, UT, September 2018.

GENERAL DISCUSSION / RECOMMENDATIONS

Highly-Compressive Load Spectra

Summary

Typical AFGROW simulations led to overestimated fatigue crack growth lives

Two major aspects were considered:

1. Effects of residual stresses (RS) and presence of a neat-fit steel fastener
 - Effect on predicted lives is more significant for corner cracks models
2. Material model (ΔK_{th}) and low stress ratio (low- R)
 - Effect may become less significant with increased stress amplitude

Observation: Higher stress amplitudes led to more accurate predictions

1. Increasing the stress amplitude “pushes” ΔK values above threshold
2. Current material models may not accurately represent near threshold (ΔK_{th}) and low- R the fatigue crack growth behaviour

THANK YOU

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