Test Demonstrated Damage Tolerance of F-22 Wing-Attach Lugs with ForceMate^{TM} Bushings

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Background

- F-22 airframe subjected to full scale fatigue test
  - Airframe subjected to 2.5 lifetimes of spectrum testing
  - Test overviews presented at previous ASIP conferences
    - » Welsh (2004)
    - » Caruso et. al. (2006)
  - This work focuses on one crack discovery at wing to fuselage joint
- Specifically discussed today:
  - Description of crack discovered on full scale fatigue test
  - Subsequent test program to understand full scale test result
  - Results and lessons learned from this test program
  - Proposed solution and validation of the solution that resulted from testing
  - Application of test results to obtain empirically derived stress intensity factors – generalizes test results to other lug geometries

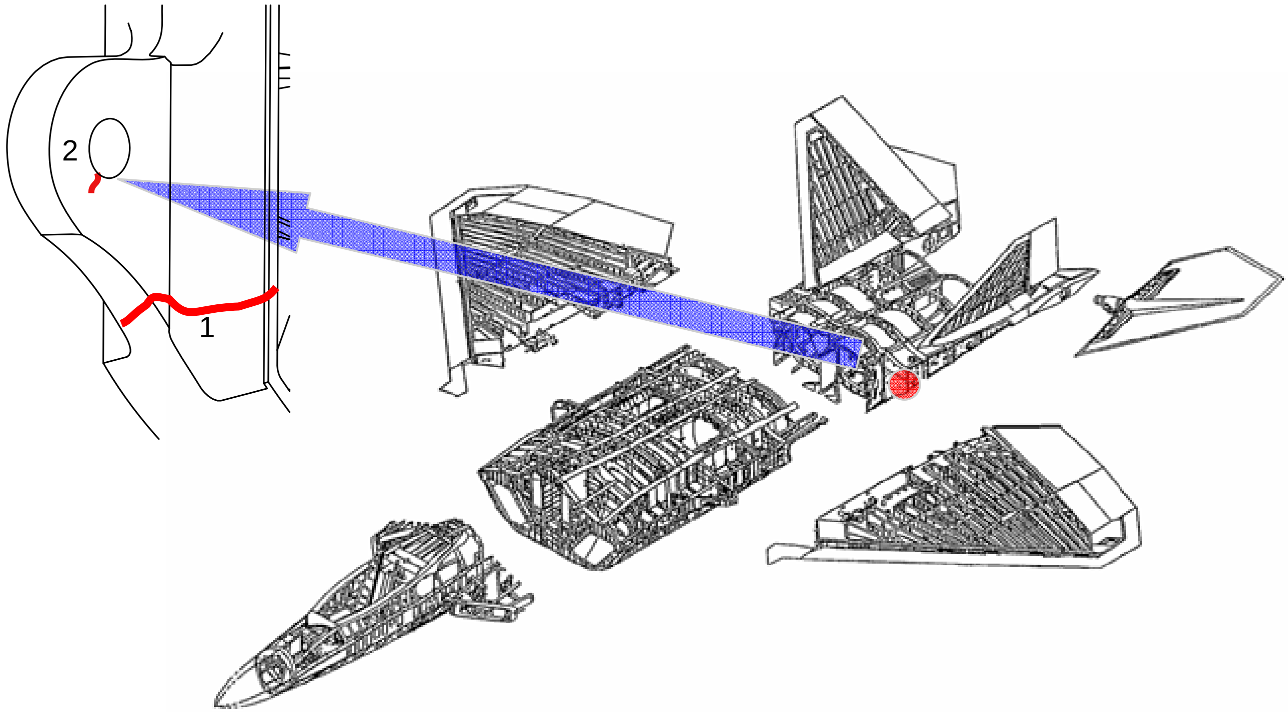
Background

- **Current work focuses on one crack location discovered after teardown**
  - **Cracking in fuselage lug bore at wing to fuselage attachment lug**
  - **Same lug experienced cracking at lower profile during test**

Crack "1" discovered and repaired at 1.2 lifetimes

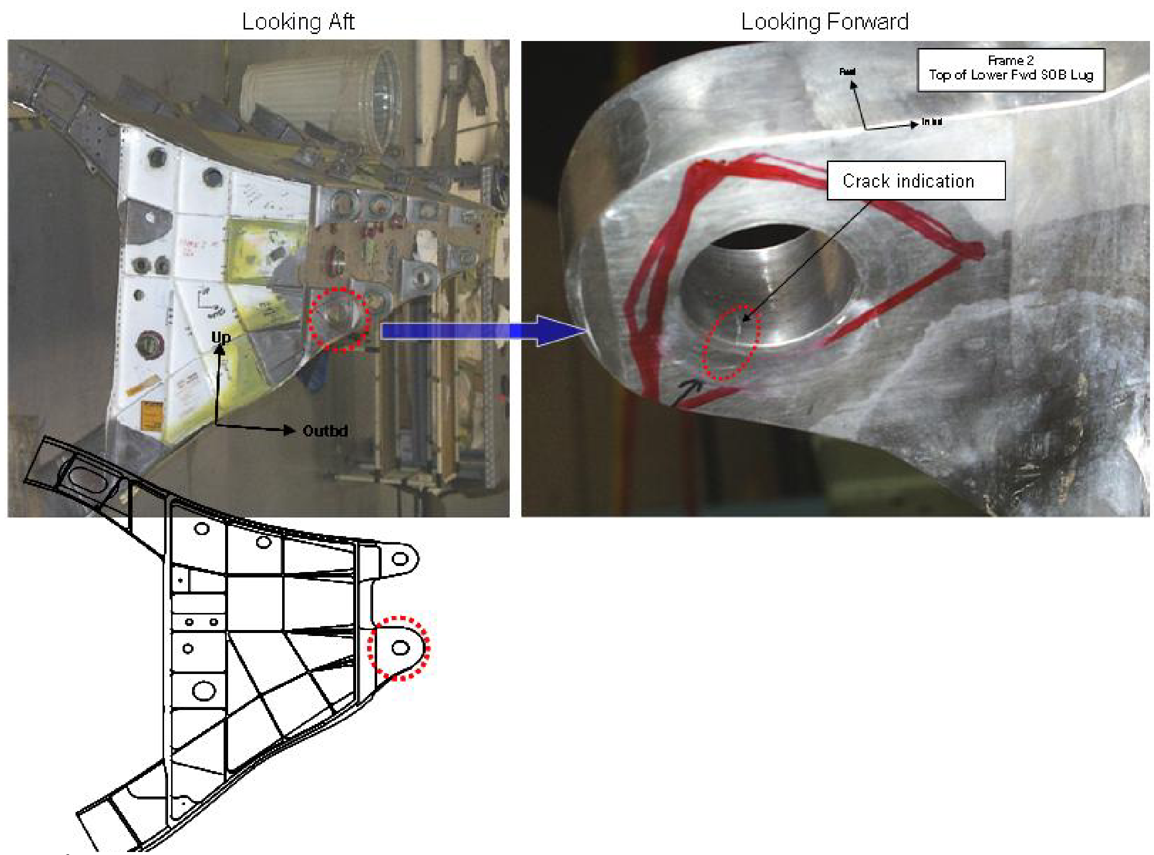
Crack "2" dicovered during teardown after 2.5 lifetimes

Similar cracking on left and right hand sides



Background

- **Cracks at STA657 lug bore**
  - **Crack on left hand side shown**
  - **Similar, shorter crack found on right hand side**



Background

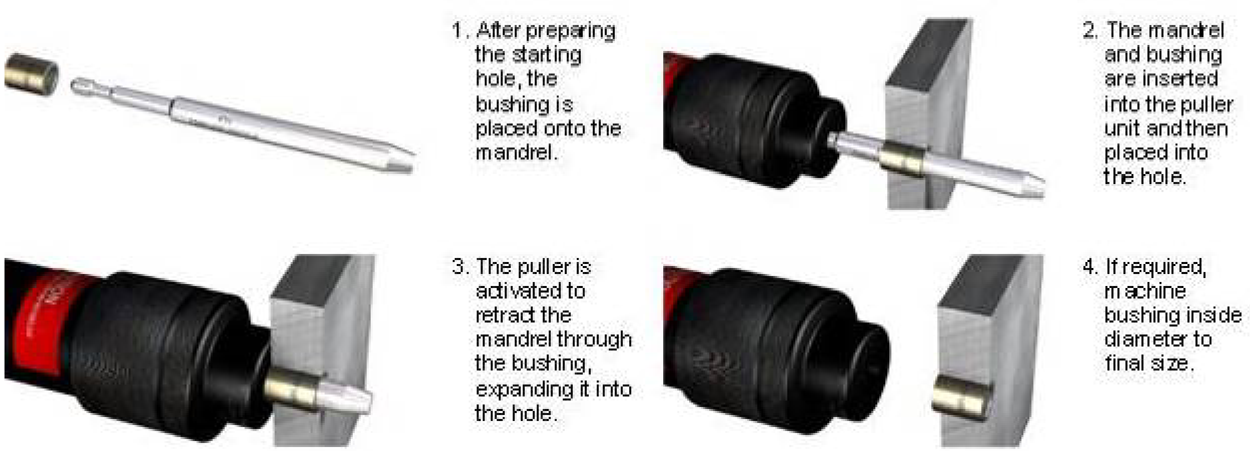
- Crack correlation efforts resulted in hypothesis that the lug bore cracking was anomalous result due to other test factors
- Evidence supporting the cracks as anomalous included
  - Close proximity to repairs made during the course of the fatigue test
  - Cracking occurred at only one station even though the nominal stresses in each lug were approximately equal
  - The lower lug pins at STA657 seized during the course of the test which allowed for significant wing bending moment to be transferred through the pin joint
- One fact disputed the notion that the cracks were anomalous
  - Symmetric cracks were observed on both the left and right hand sides of the test aircraft.

Background

- Crack growth correlation resulted in damage tolerance inspections to protect against possible cracking from a rogue flaw
  - Inspections at this location complex and undesirable
- Component test program performed to address uncertainties remaining from correlation
- The objectives of the test program were to
  - Address the possibility that the observed full scale test cracking was an anomalous result
  - Extend inspection intervals for the lugs where full scale fatigue cracking was observed
  - Develop the empirical database to establish the crack growth life improvement obtained with the interference fit bushing installation at this lug

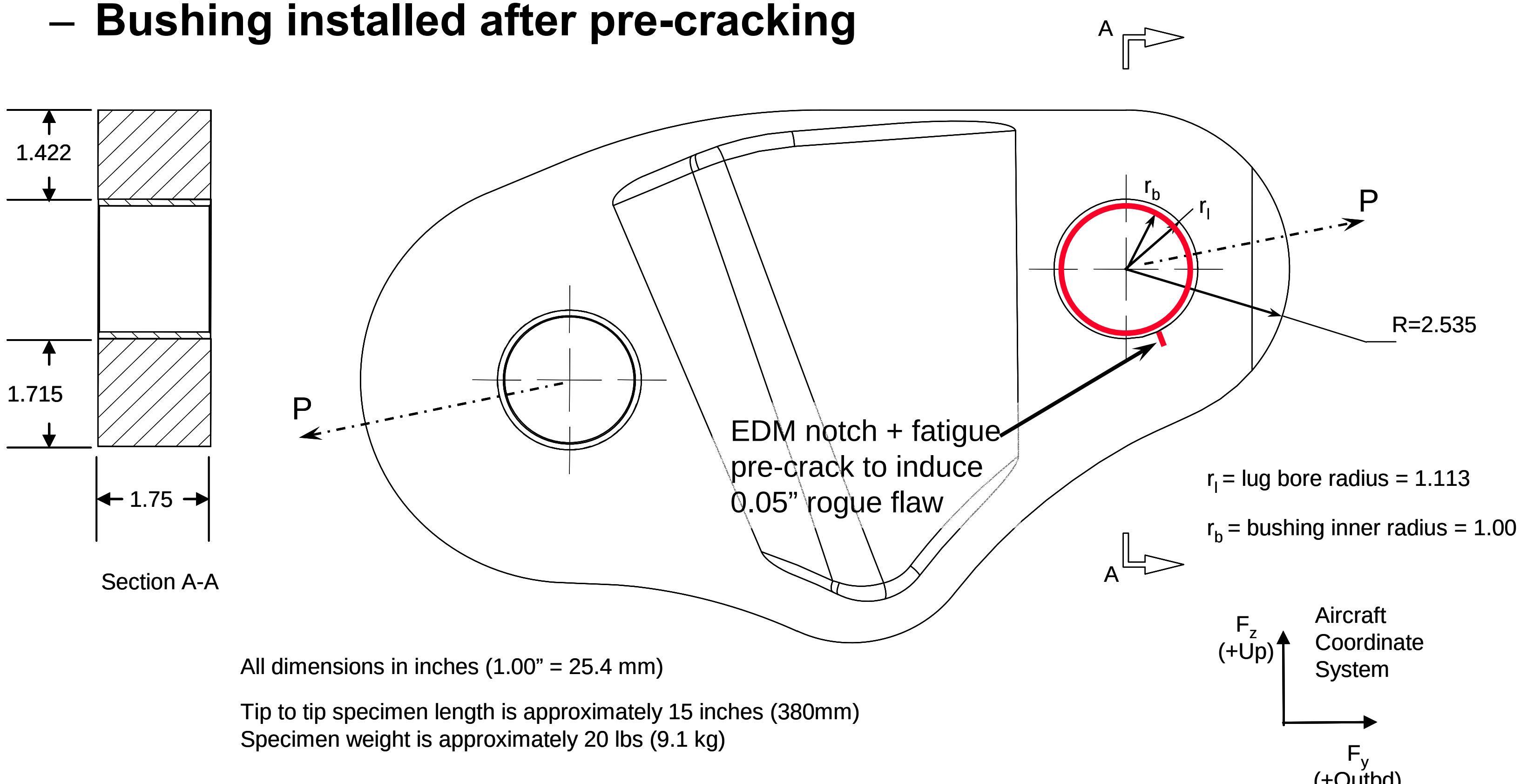
ForceMate™ Process

- **ForceMate™ is a process to expand a bushing in into a lug**
  - **Interference holds the bushing in place**
  - **Expansion imparts some cold working benefit to improve fatigue life**
    - » **Benefit results from compressive residual stresses**
    - » **Level of expansion is a design variable that can be modified to increase potential fatigue life benefit**



Specimen Design

- **Specimen designed that could be tested in single axis servohydraulic test machine**
  - **Lug geometry replicates aircraft**
  - **Load vector oriented to dominant load direction of aircraft loads**
  - **Bushing installed after pre-cracking**

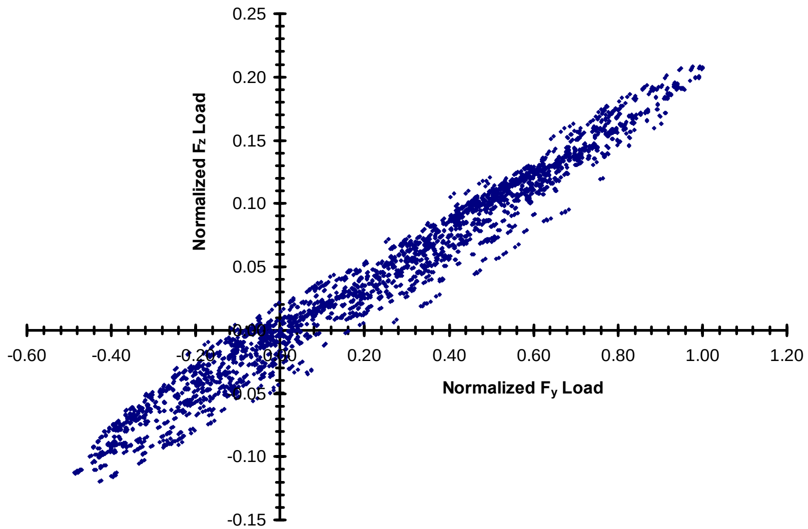


All dimensions in inches (1.00” = 25.4 mm)

Tip to tip specimen length is approximately 15 inches (380mm)
Specimen weight is approximately 20 lbs (9.1 kg)

Specimen Design
Test Load Spectrum Validation

- **Fy (+outboard) and Fz (+up) load components plotted to verify dependence between Fz and Fy**
- **Load vector angle plotted for all fatigue load conditions to verify dominant vector angle**



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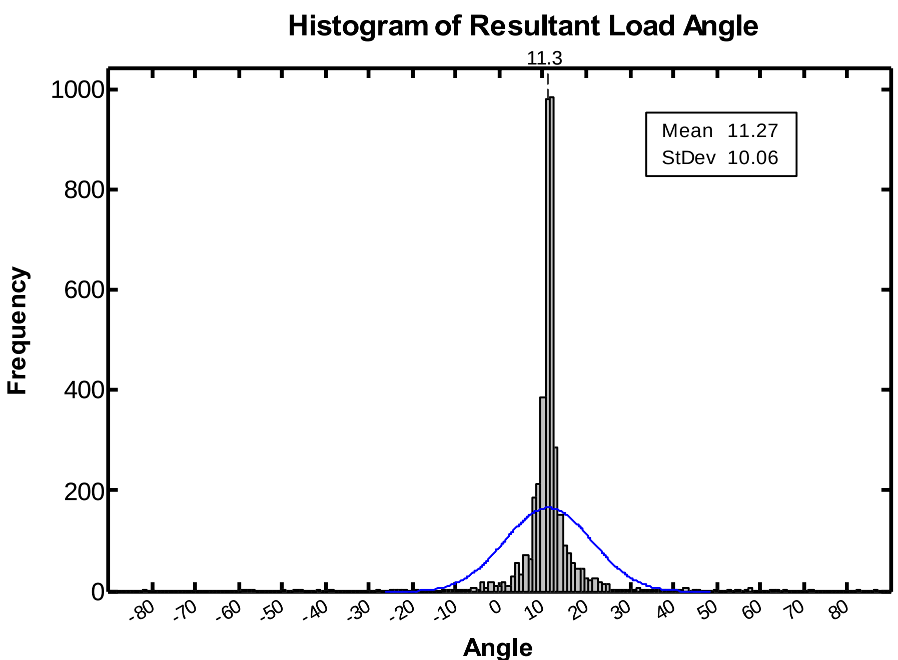

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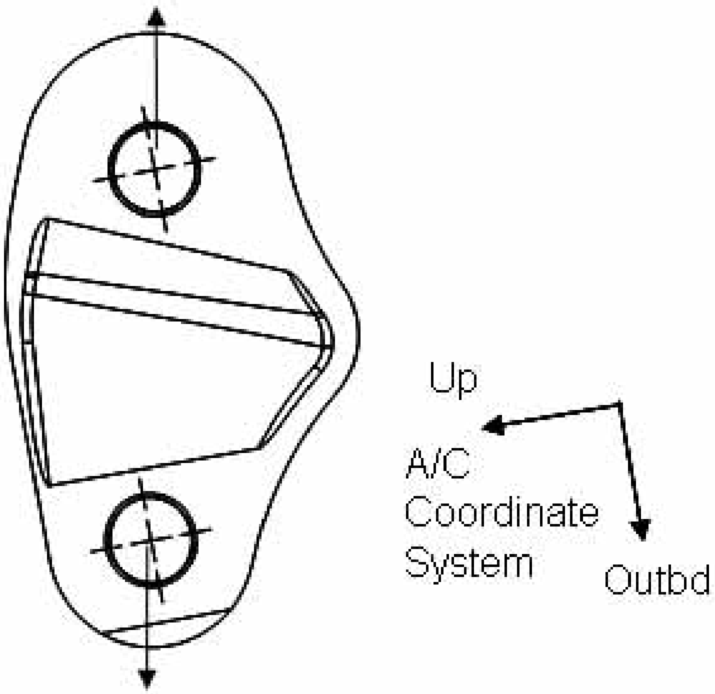
Specimen Design

- **Load applied to specimen replicates aircraft loading**

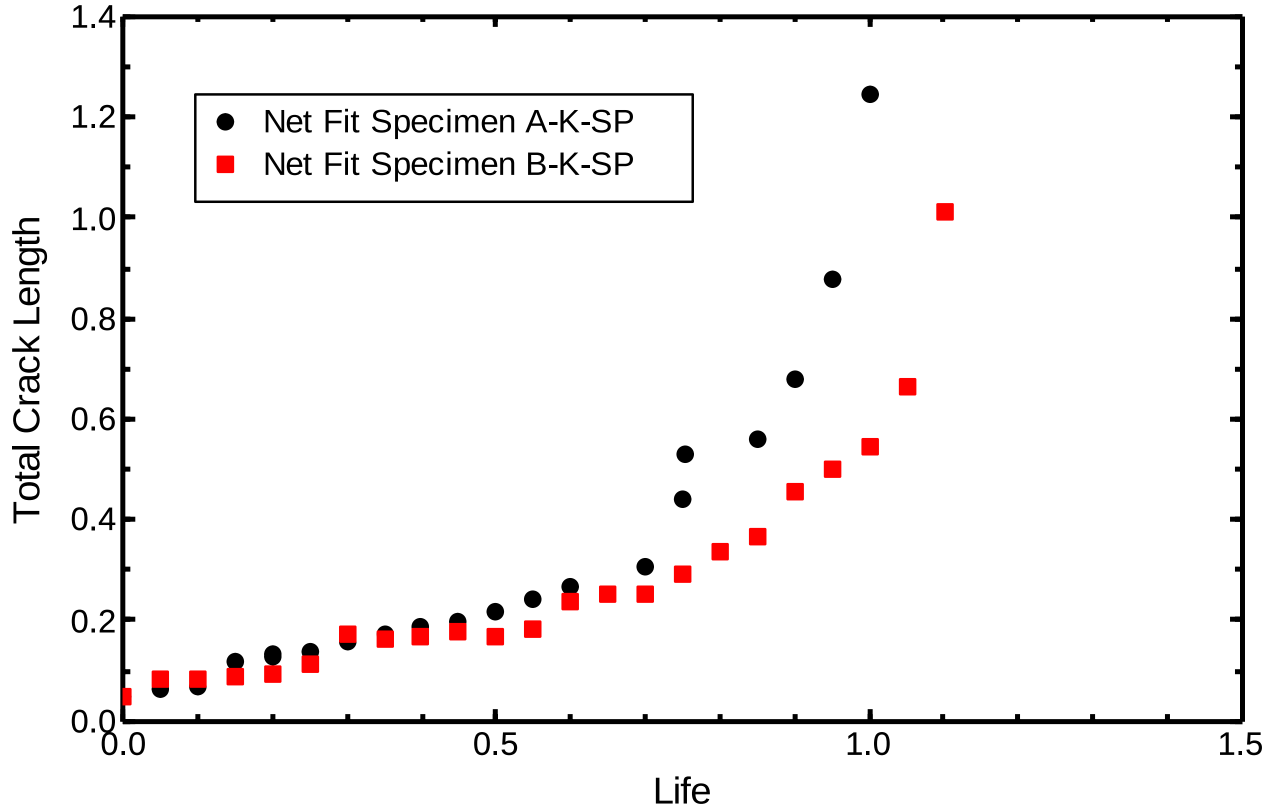


Test Matrix

Specimen ID	**Bushing**	**Notch Location**	Max Spectrum Load	**Material**	Objective
B-K-SP	Net Fit	64.3°	247 kips	Ti-6Al-4V	Provide baseline reference data
A-K-SP	Net Fit	64.3°	247 kips	Ti-6Al-4V	
B-LL-3	ForceMate	64.3°	247 kips	Ti-6Al-4V	Provide data demonstrating life improvement
A-UL-2	ForceMate	64.3°	247 kips	Ti-6Al-4V	

Experimental Results

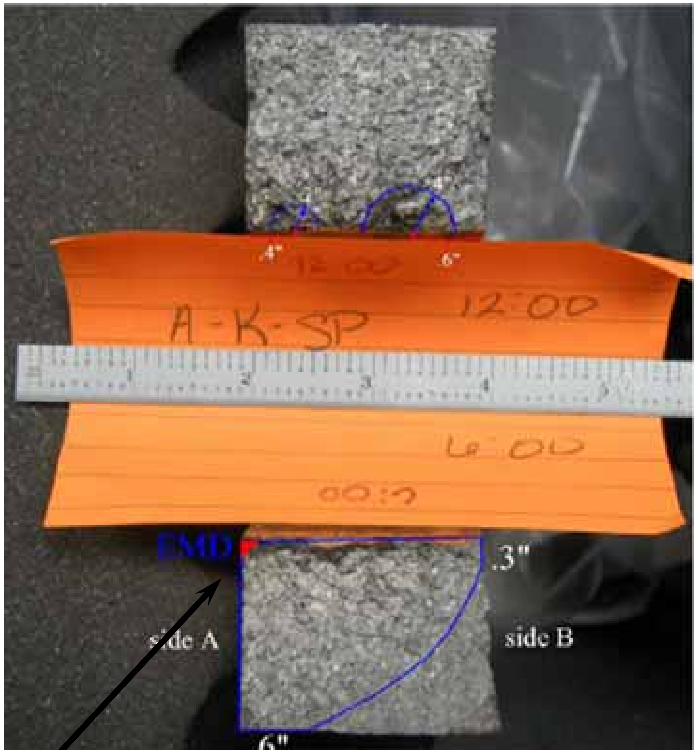
Crack Length vs Life for Baseline, Net Fit Bushing Specimens



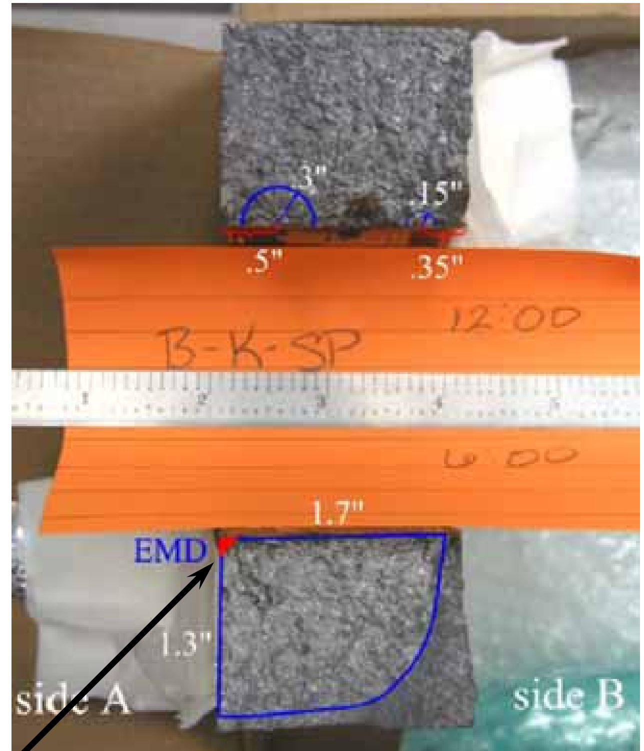
- **Net Fit Bushing Specimens tested to set baseline life without cold expansion effects of lug**
  - **provided baseline life**
  - **Validated specimen design**

Experimental Results

Specimen A-K-SP



Specimen B-K-SP

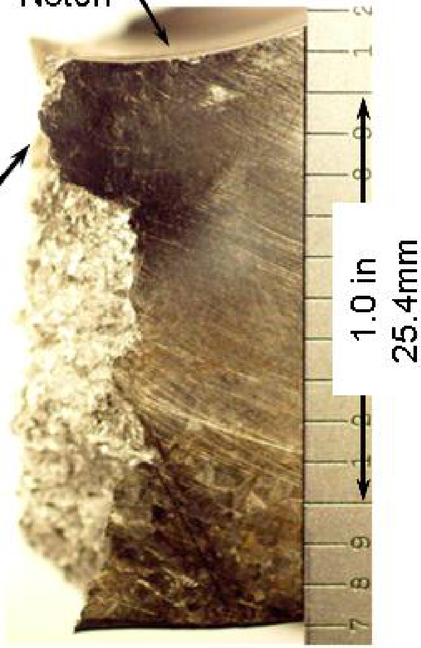


Pre-cracks from EDM flaws grew to failure

- **Failure modes for net fit specimens followed classic growth pattern for corner cracks**
  - **Test results validated specimen design**

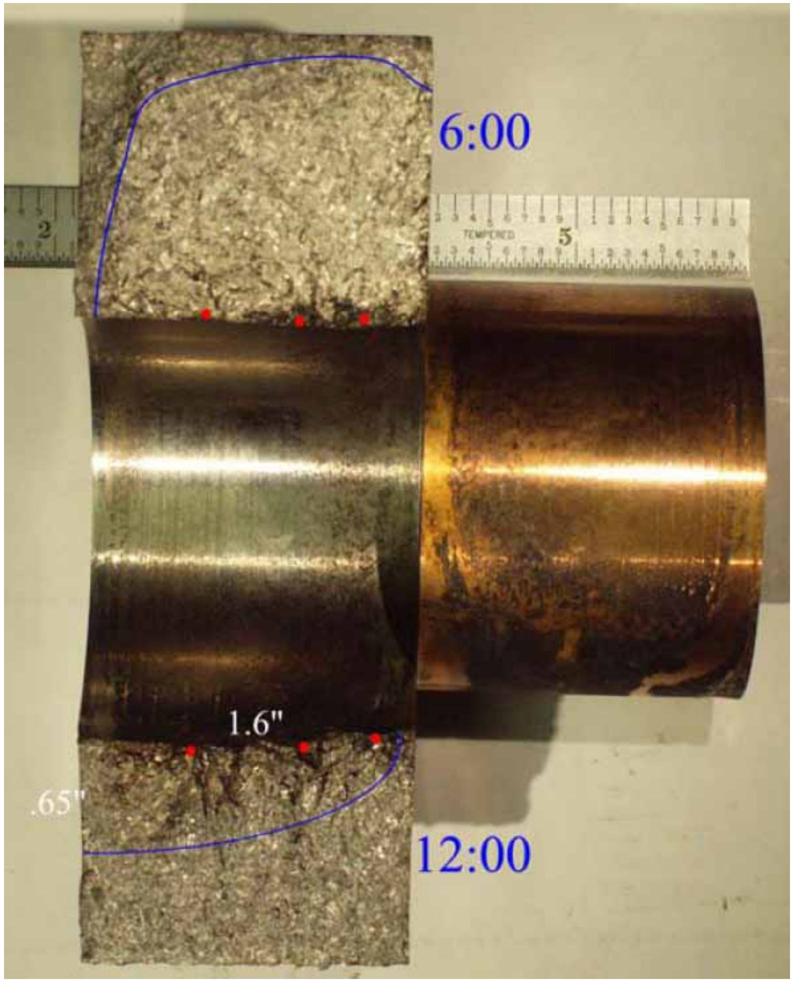
Experimental Results

- **Crack growth behavior for first 3 specimens with ForceMate specimens was unexpected**
  - **Specimens DID last longer than net fit bushing**
  - **However, failure did not occur from EDM notch**



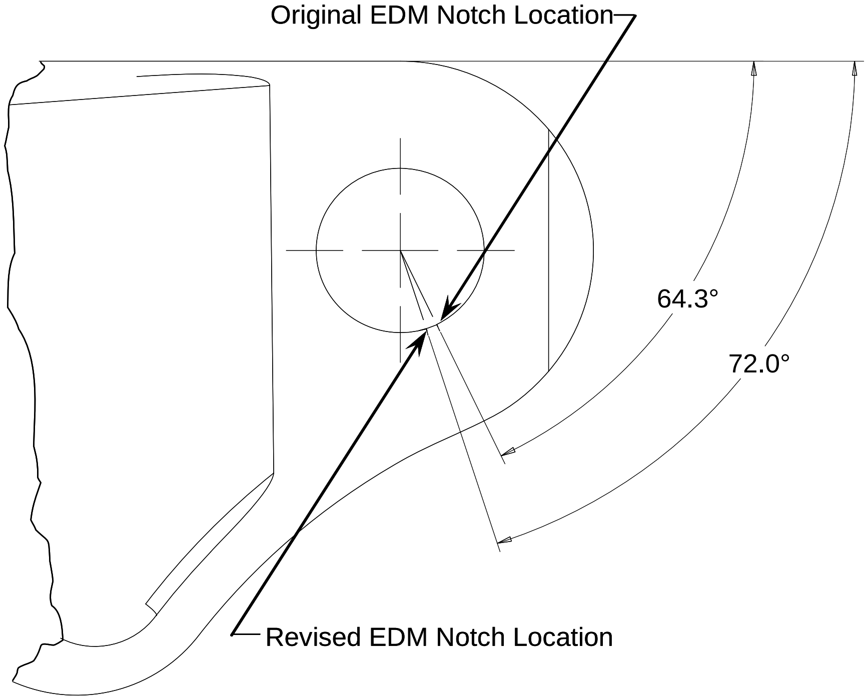
Experimental Results

- **Crack initiated along bore**
  - **Multiple initiation sites on both sides of bore**
  - **Pre-crack at EDM notch did not contribute to failure**
- **Evidence of fretting and galling observed on bushing and lug bore**

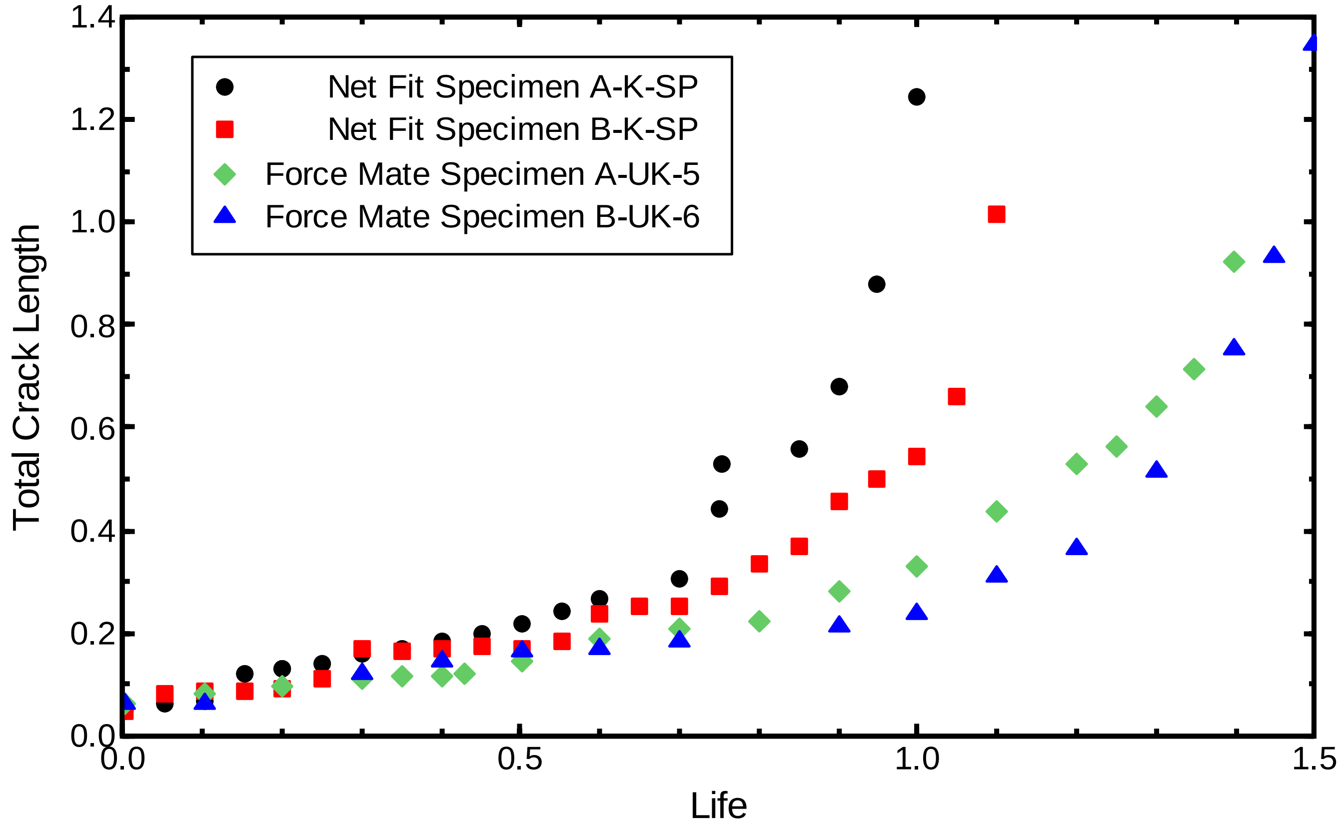


Experimental Methods

- **Cracks on first ForceMate bushing specimens observed to crack at peak stress location**
  - **EDM notch oriented to match observations on full scale fatigue test**
  - **Applied expansion retarded crack growth, but failure occurred due to fretting initiated cracks**
- **Additional specimens machined and tested with notch at peak stress location**



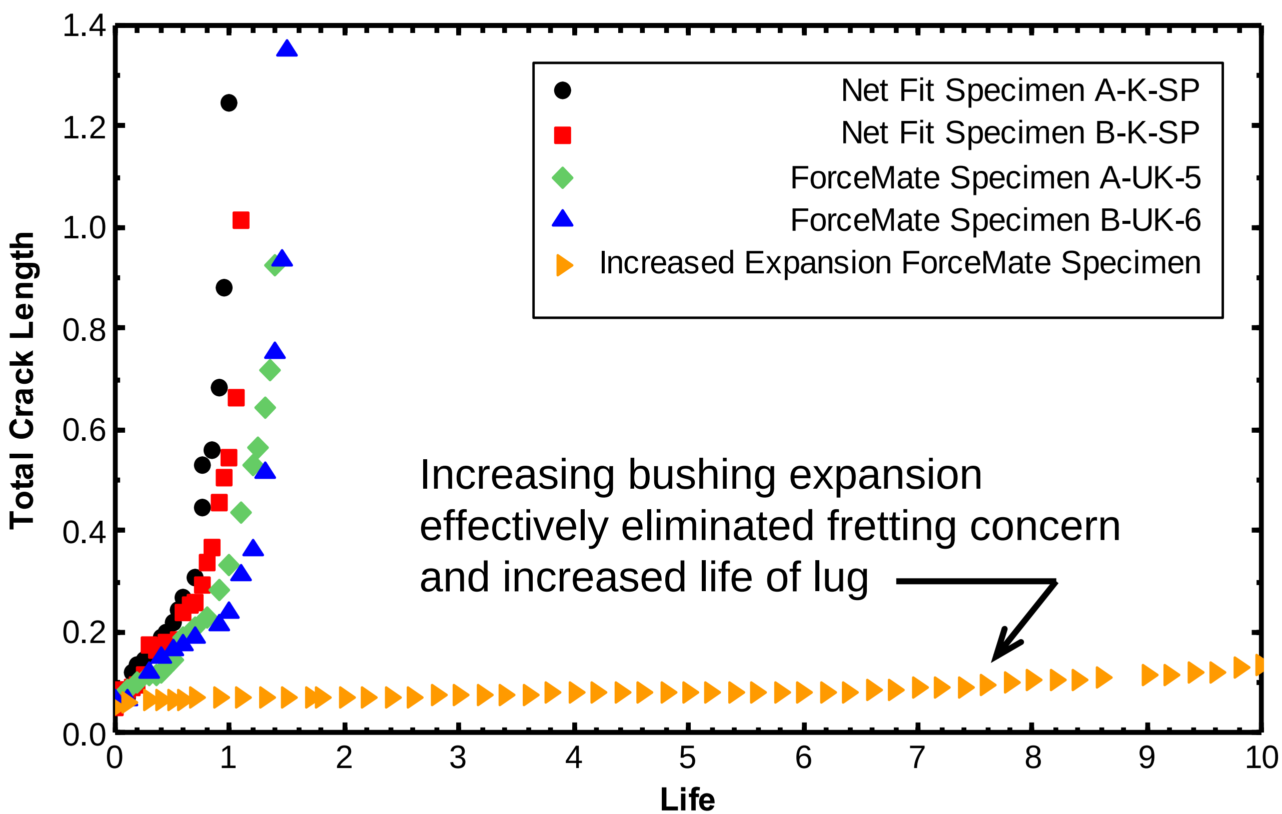
Test Results



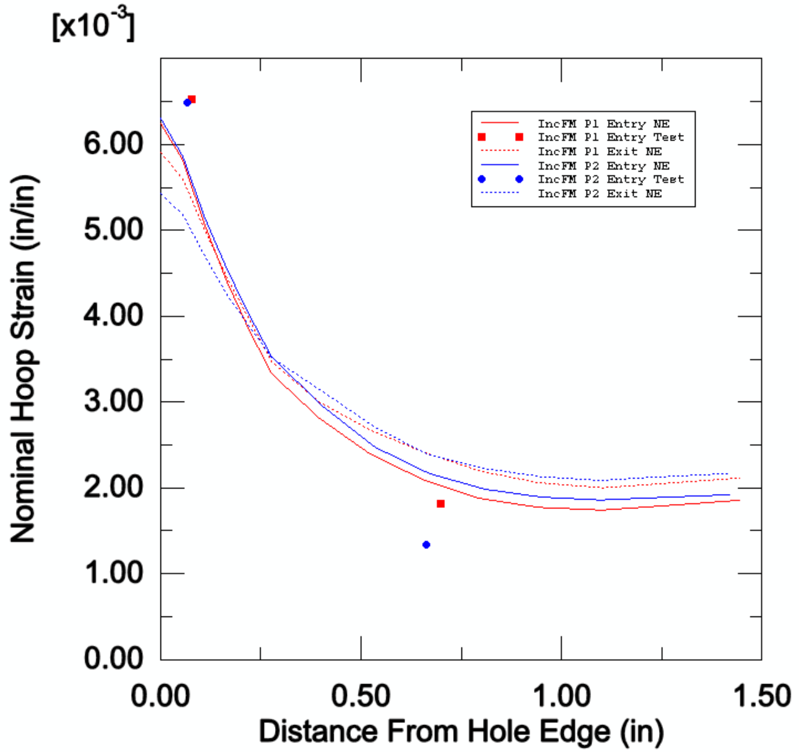
- **ForceMate bushing specimens with pre-crack notch oriented at peak stress location failed as anticipated**
  - **i.e. Corner crack from induced pre-flaw grew to failure**

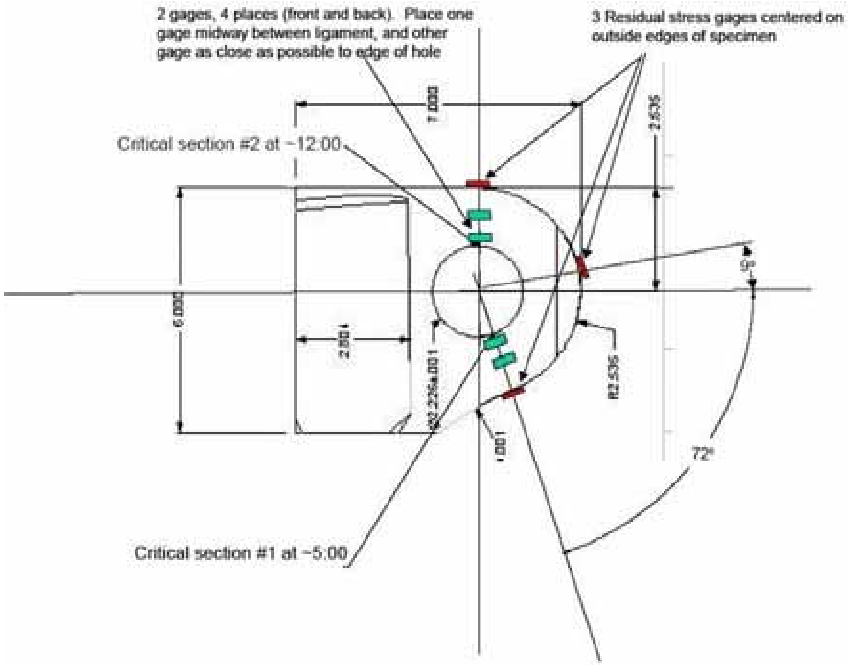
Problem resolution

- **To increase damage tolerance capability and mitigate crack initiation due to fretting**
  - **Bushing expansion level increased**



Experimental Strain Analysis





- **Experimental and analytical study to validate increased expansion installation**
  - **Experimental stress analysis**
  - **Non-linear FEM analysis to understand residual stress fields**
  - **Tested revised bushing on two lug specimens**
- **Experimental work validated models and insured no other "hot spots" resulted from increased expansion**

Test Matrix and Results Summary

Specimen ID	Bushing	Notch Location	Life to Failure	Test Result
B-K-SP	Net Fit	64.3°	1.15	*Failed due to crack growth from induced pre-flaw*
A-K-SP	Net Fit	64.3°	1.01	*Failed due to crack growth from induced pre-flaw*
B-LL-3	Current	64.3°	2.08	*Failed due to initiation of secondary cracks in the lug bore*
A-UL-2	Current	64.3°	*2.47*	*Failed due to initiation of secondary cracks in the lug bore*
A-LL-1	Current	64.3°	3.11	*Failed due to initiation of secondary cracks in the lug bore*
B-UK-6	Current	72.0°	*1.51*	*Failed due to crack growth from induced pre-flaw*
A-UK-5	Current	72.0°	*1.44*	*Failed due to crack growth from induced pre-flaw*
B-LK-7	Revised	72.0°	*>10.7*	*Increasing expansion of bushing eliminated fretting concern and increased crack growth life*
B-UL-4	Revised*	64.3°	*>8.9*	Possible to get large crack growth life benefit by retrofitting bushing after 0.5 lifetimes of loading

* B-UL-4 had a current configuration bushing installed for the first 0.5 lives of testing. This bushing was then removed and replaced with a revised configuration.

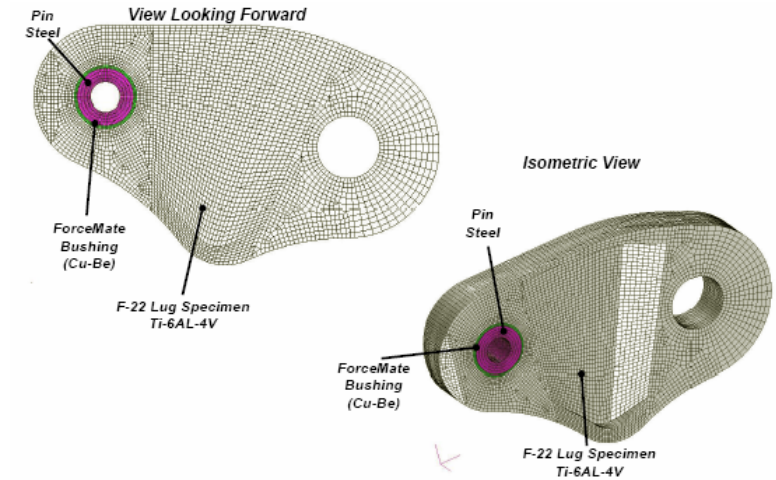
Interpretation of Test Results

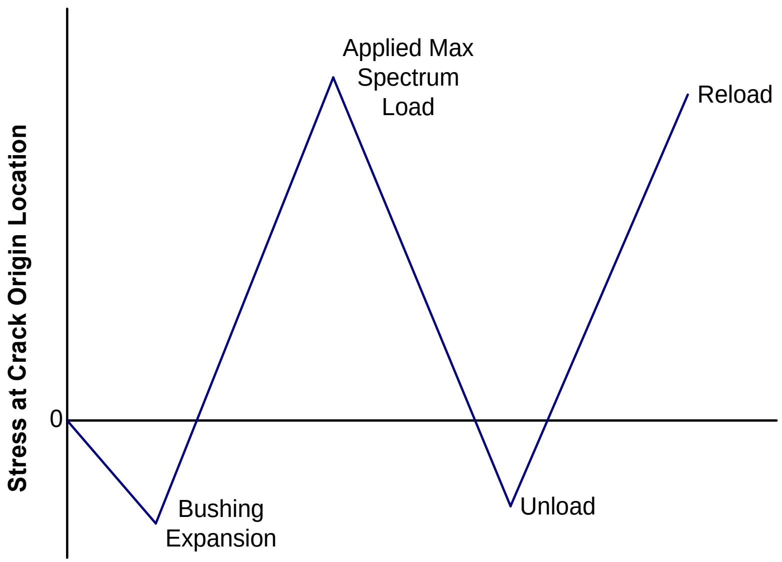
- **Test demonstrated capability of lug with ForceMate bushing with rogue flaw located and oriented in worst case location:**
  - **Tests lasted ~1.5 times longer than net fit bushing**
  - **Test demonstrated crack growth life was less than 2 lifetimes**
  - **Resulted in inspection intervals of lug during aircraft lifetime**
- **Tests with flaw at location other than worst case location:**
  - **Naturally nucleated cracks represented a durability life issue**
  - **Demonstrated that fretting was an issue for the load levels tested**
- **Increasing the bushing expansion resolves both damage tolerance and potential durability issues**

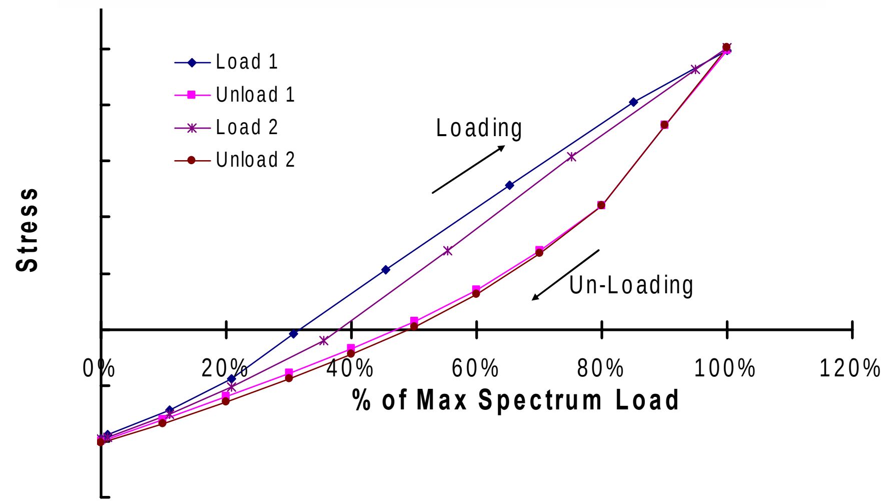
FEM Analysis for Stress Intensity Derivation

To apply test results to analysis, stress intensity factors derived using semi-empirical approach

Abaqus non-linear elastic FEM of test specimen created to relate stresses in the actual part to idealized stress intensity solution







FEM loading included bushing expansion followed by load-unload-reload cycle

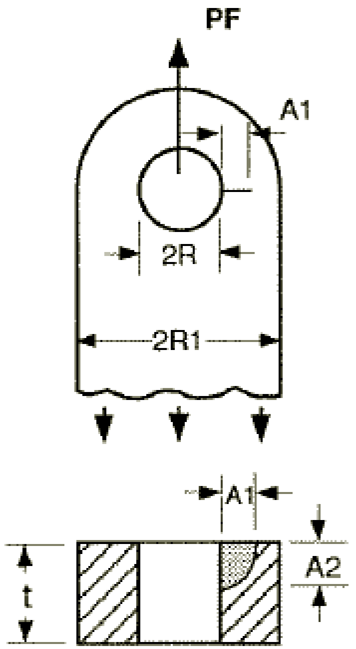
Stress distribution after final loading used to derive stress intensity correction factors

Correction Factors

Green's function method applied to correct for stress distribution differences between standard and actual geometries.

Corrections for both applied and residual stress fields

Standard solution
Axially – Loaded Straight – Lug
Single Corner – to – Through Crack

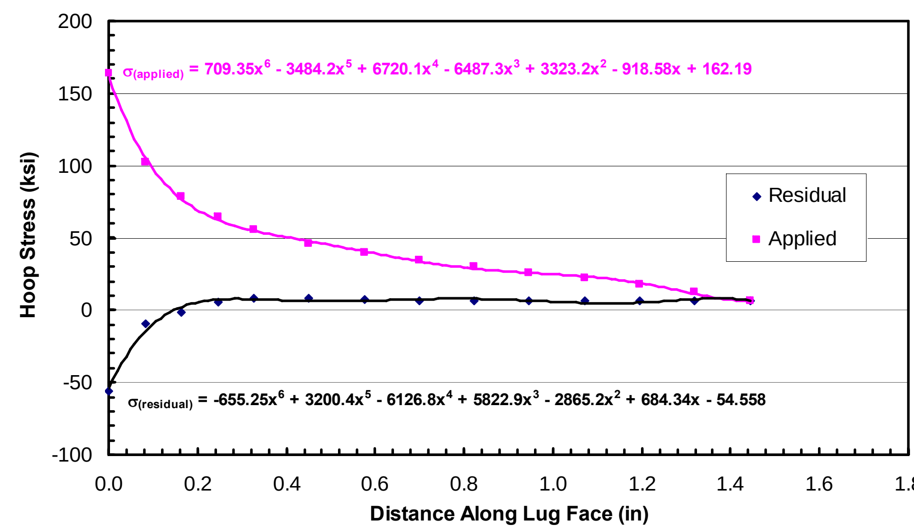


INPUT PARAMETERS:
R, R1, t

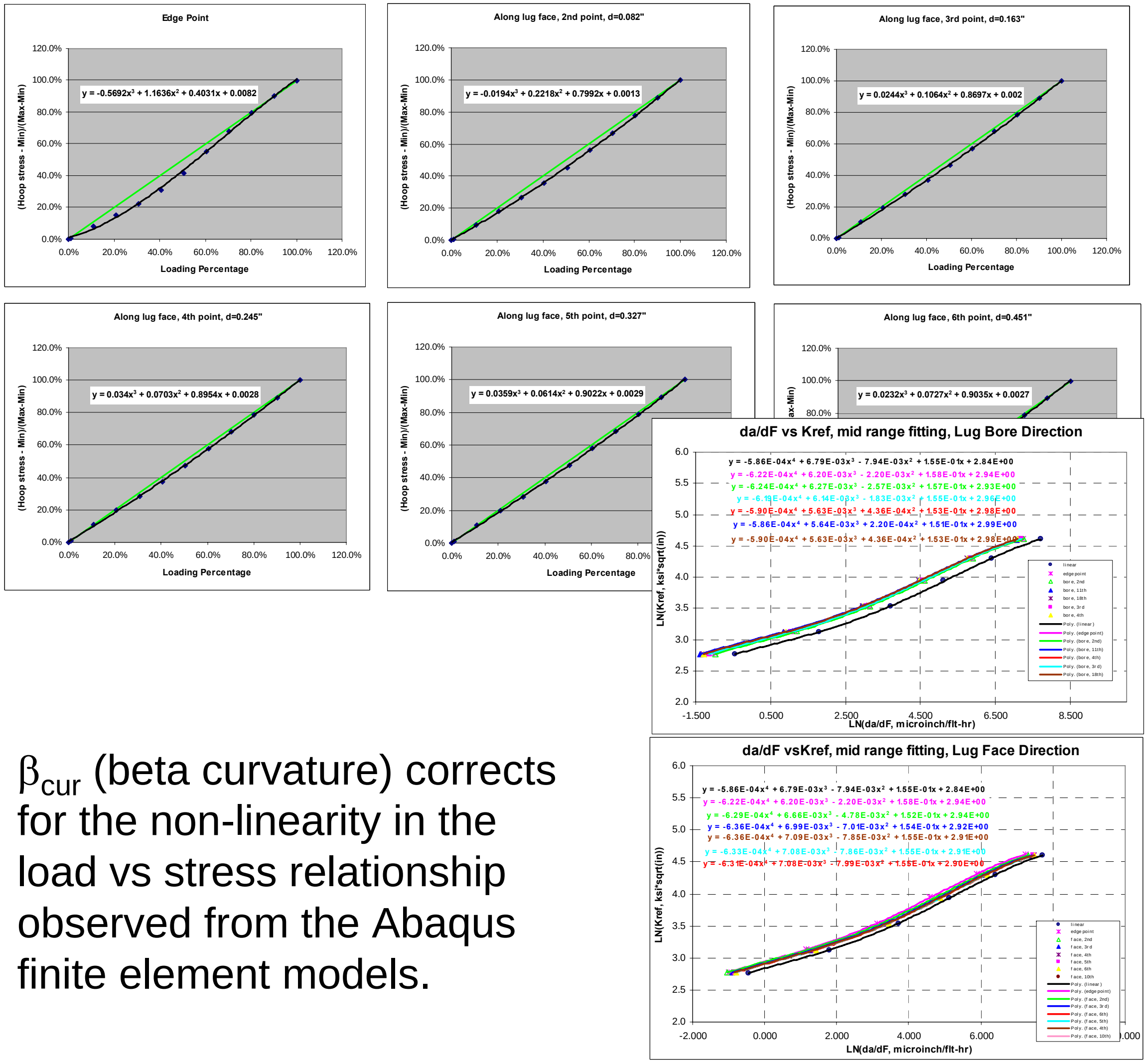
$$K = \int_0^a \sigma(x)\, G(x,a)\, dx$$

$$\beta_{stress} = K_{std} / K_{applied}$$

$$\beta_{residual} = K_{std} / K_{residual}$$

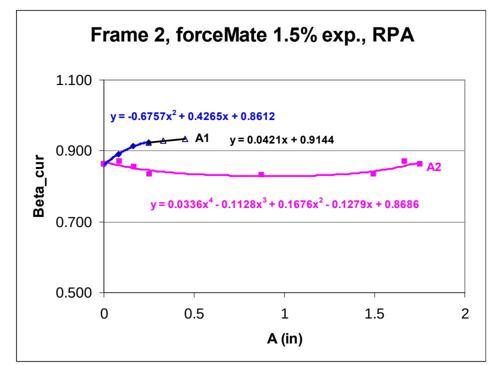


Non-Linear Load vs Stress Correction



The load vs stress relationship changes with position along the lug face

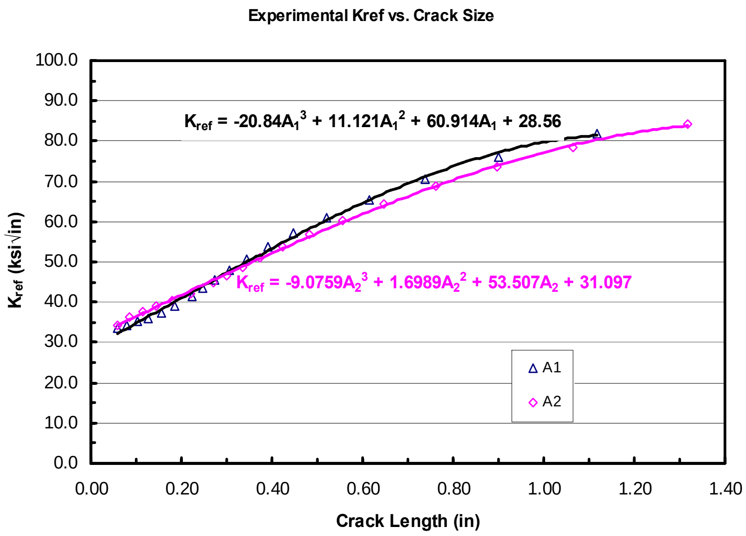
“Curvature” correction to account for this load vs stress non-linearity

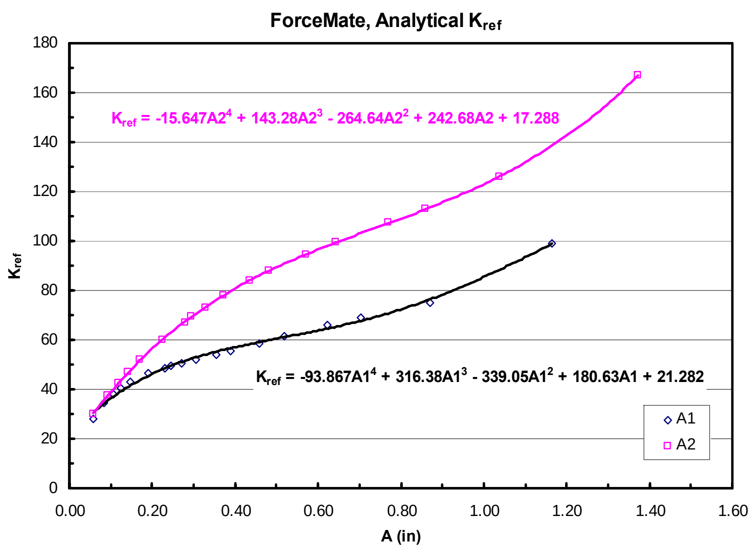


β_{cur} (beta curvature) corrects for the non-linearity in the load vs stress relationship observed from the Abaqus finite element models.

$$\beta_{cur} = K_{ref\_linear} / K_{ref\_cur}$$

Correction for Test vs Analytical Kref





Final correction based on ratio between analytical spectrum crack growth rate curve vs experimental curve

$$\beta_{test} = K_{ref\_experimental} \Big/ K_{ref\_analytical}$$

Four correction factors applied

"beta stress" – corrects for applied stress distribution

"beta residual" – corrects for residual stress distribution

"beta curvature" – corrects for non-linear load vs stress relationship

"beta test" – corrects for differences between analysis and test

$$\beta_{total} = \beta_{stress}\beta_{residual}\beta_{curvature}\beta_{test}$$

Resolution Summary

- Solution to mitigate fretting
  - Modify ForceMate bushing installation to increase expansion level
  - Increased expansion maintains preload between bushing and lug
  - Minimizes relative motion between bushing and lug
- Experimental stress analysis performed correlated Abaqus Finite Element Models
  - Experimental correlation provided confidence in model results
  - Follow-on analytical work has relied extensively on models to predict stresses on the aircraft lugs
- Test results and Abaqus models used to develop stress intensity solutions for crack growth analysis

Summary

- Full scale tests of lugs performed to understand and validate full scale aircraft fatigue test results
- Contact fatigue mechanisms identified as significant failure mechanism leading to cracking
- Increasing expansion of bushing resolved both fretting and inspection issues
- Semi-empirical analysis applied to test data to generate stress intensity factors applicable to other lug geometries
- A design change has been implemented for production aircraft to utilize the bushings at the increased expansion