Validation of Stress Intensity Solutions of Complex Structural Details

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ASTM Workshop on Verification and Validation of Solid Mechanics and Life Prediction Software

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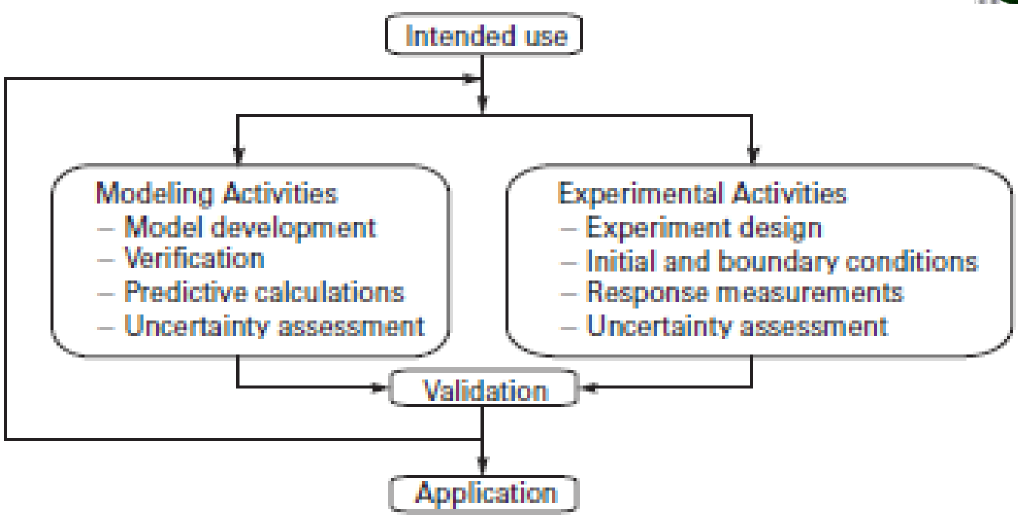
Objective

- **Verify stress intensity factors computed from crack growth analysis codes**



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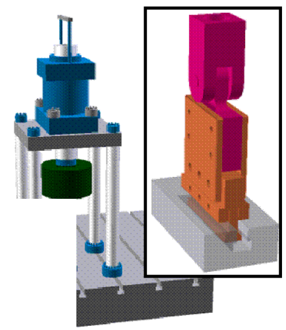
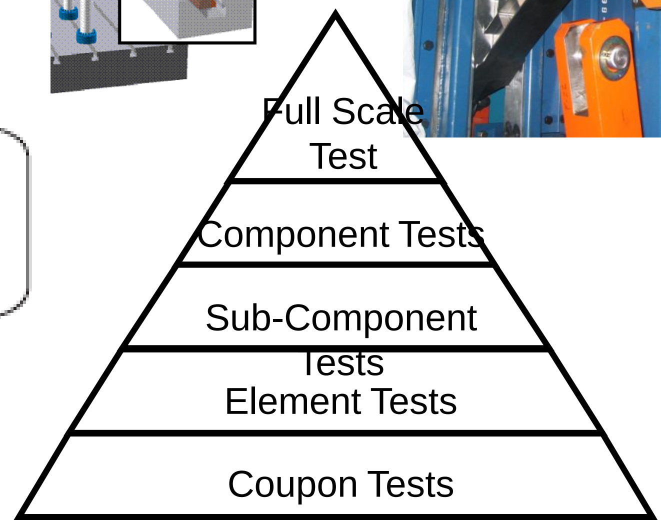
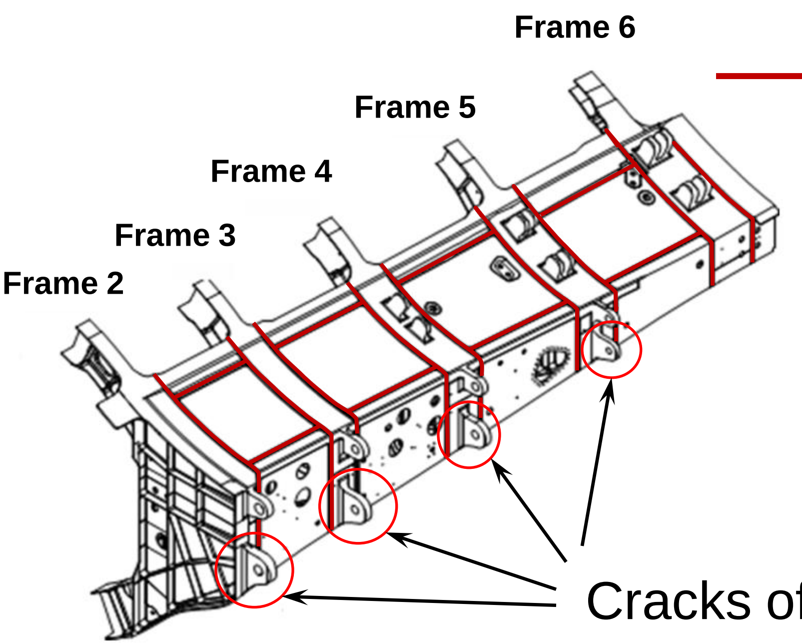




Mil-Std-1530C

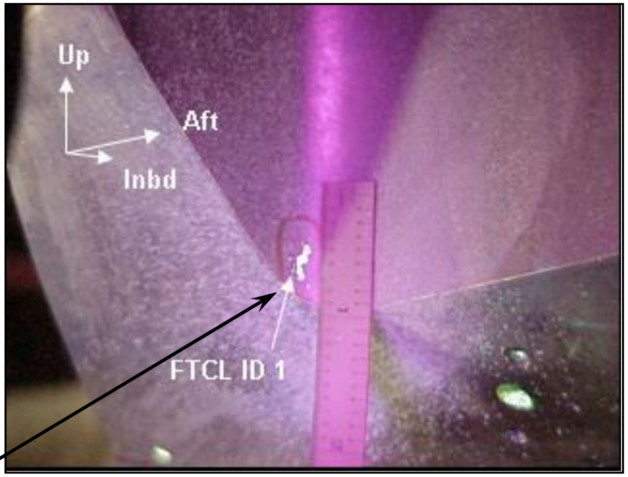
Background
F22 Full Scale Fatigue Test

- **Cracking of the lower fillet radius observed at the wing attach lugs during the Full Scale Fatigue Test (FSFT).**
- **The FSFT did not provide any data for verification and validation of crack growth models**
- **Cracks were repaired or blended away to preserve the FSFT**
  - Therefore no crack growth data were collected for model validation



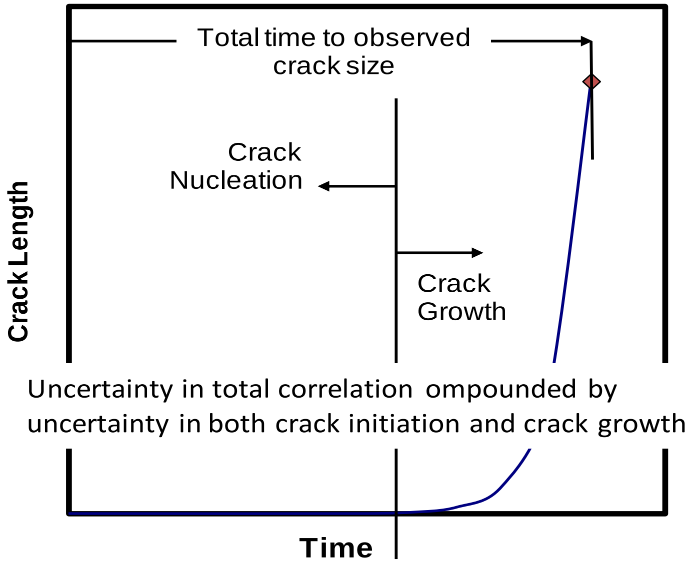
Electron Beam Weld Line

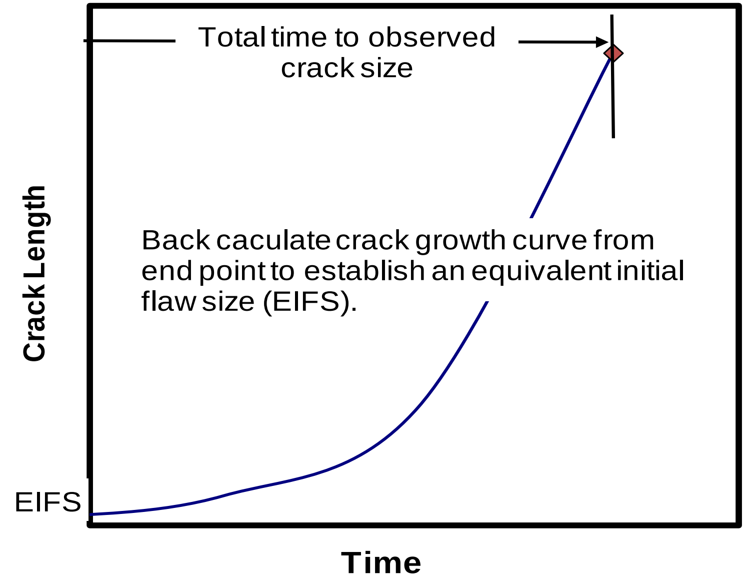
Material:
Ti-6Al-4V Beta Annealed



Cracks of interest occurred at the lower fillet radius (not at the bore)

Correlation Approaches for Single Datum





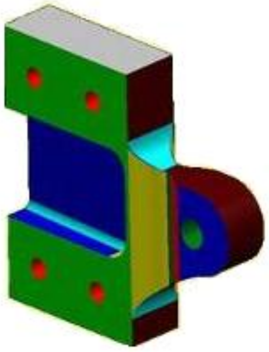
- **Stress based correlation factor (time to nucleate + grow crack)**
- **Crack growth based equivalent initial flaw sizes (EIFS)**

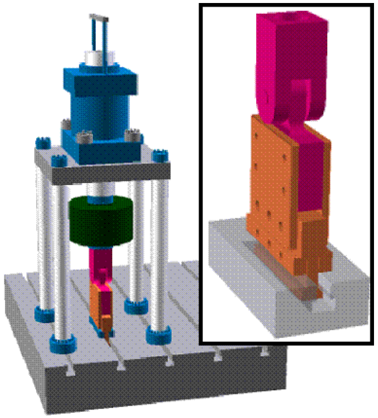
Shape of crack growth curve could not be validated from full scale test due to the lack of intermediate crack observations

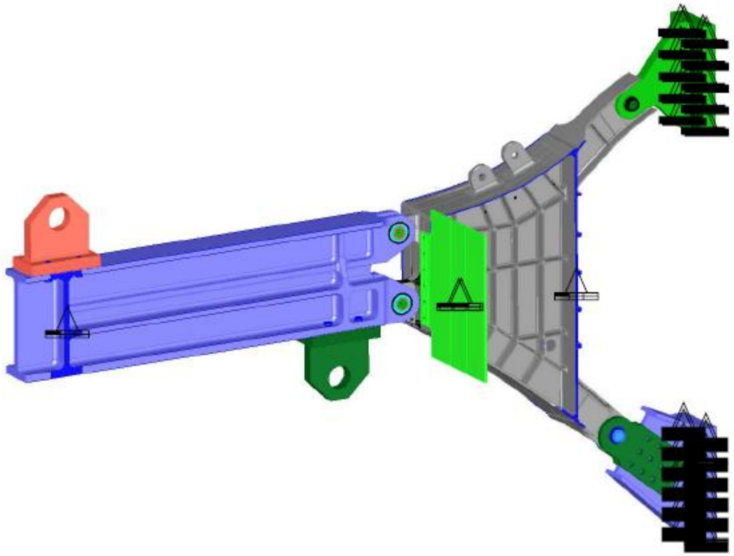
Experimental Setup

- **Design and test "simple" specimen that replicates stress gradient and is similar in configuration to actual component**
  - Constant amplitude tests
  - Spectrum fatigue tests
  - Calibrate analysis methodology

- **Test full scale components simulating wing bending spectrum loading**

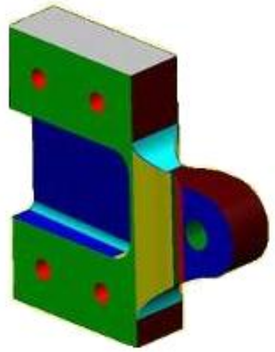


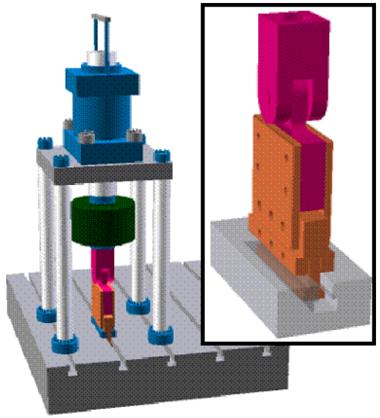




Test Specimen Configurations

- **Lug Element Specimen**
  - Representative geometry
  - ~ ½ scale of frame 2 (FS 657)
  - Relatively simple loading fixture
  - 18 spectrum fatigue specimens at 3 different load levels
  - 3 constant amplitude fatigue test specimens
  - Specimens visually monitored for crack initiation with 40x microscope
  - Crack growth monitored on both faces until longest crack measured 0.5”



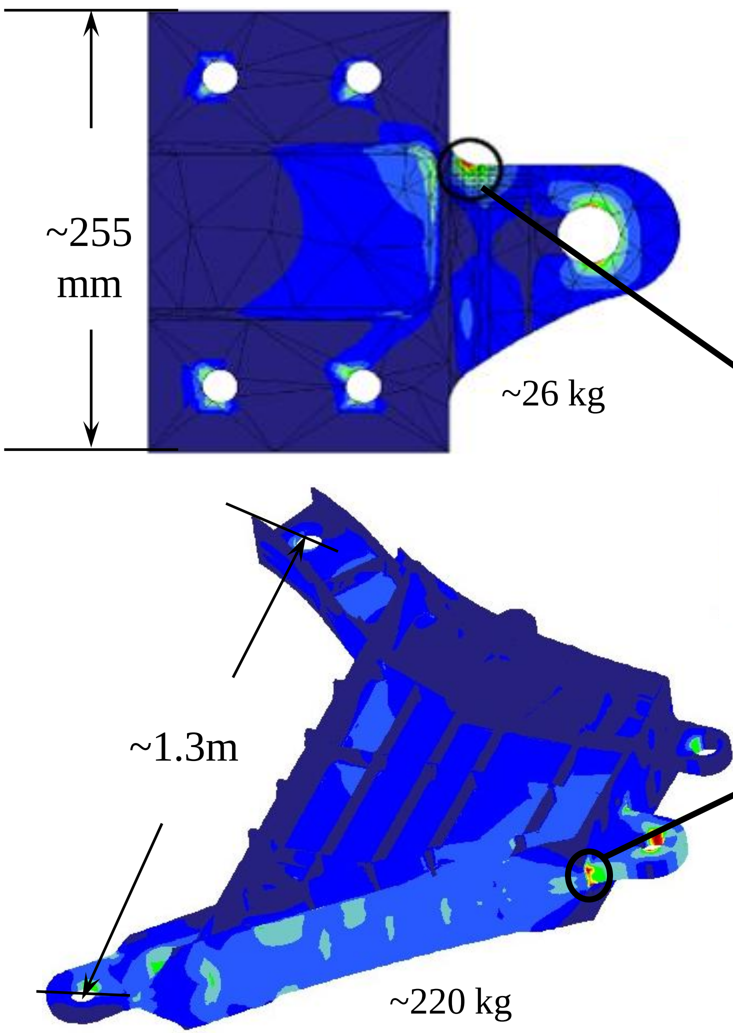


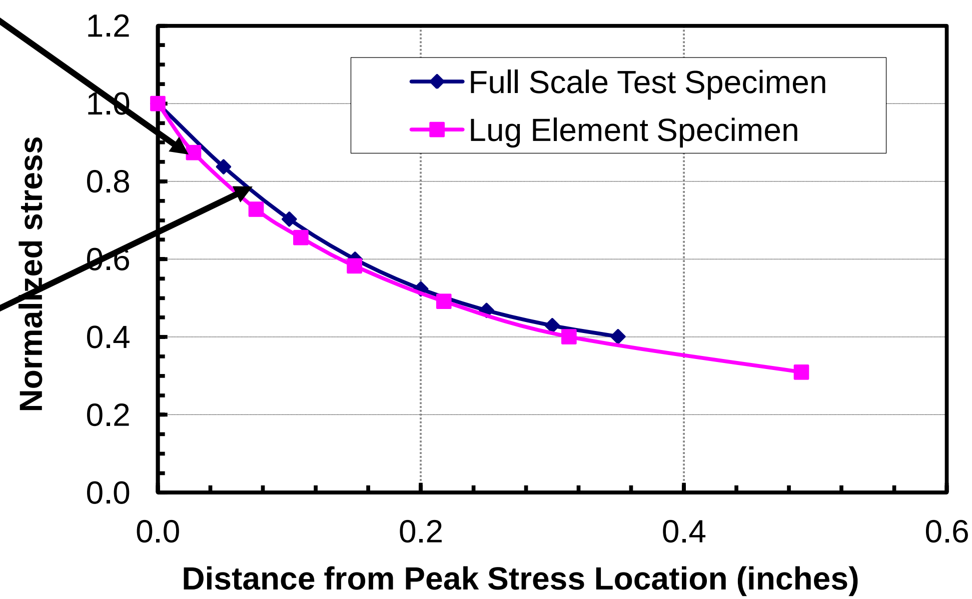
Test Specimen Configurations

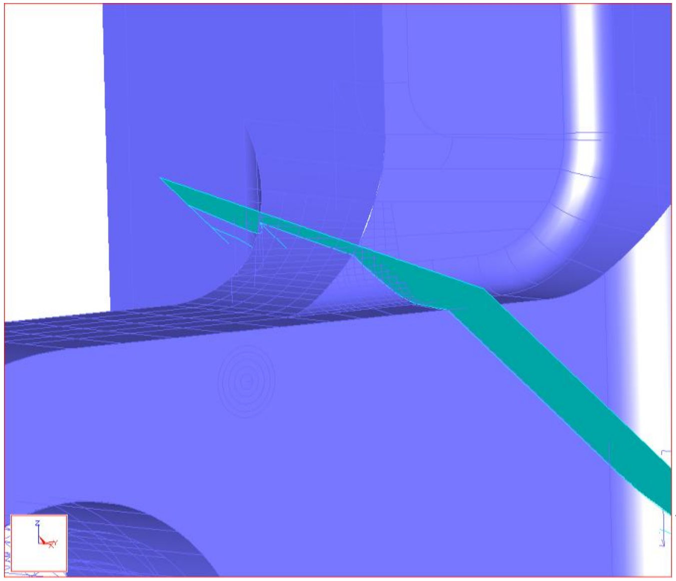
- **4 Full scale component frames test articles**
  - 2 configurations
    - Frame 2 upper fillet radius of lower lug
    - Frame 4 lower fillet radius of lower lug
  - 1 specimen each:
    - Naturally initiated crack
    - EDM notch
  - Cracks detected and monitored by multiple NDI techniques
    - Eddy current
    - Fluorescent Penetrant Inspection
    - Digital microscope (primary method to measure crack length)
  - All Frames produced to aircraft production standards

Test Specimen Configurations

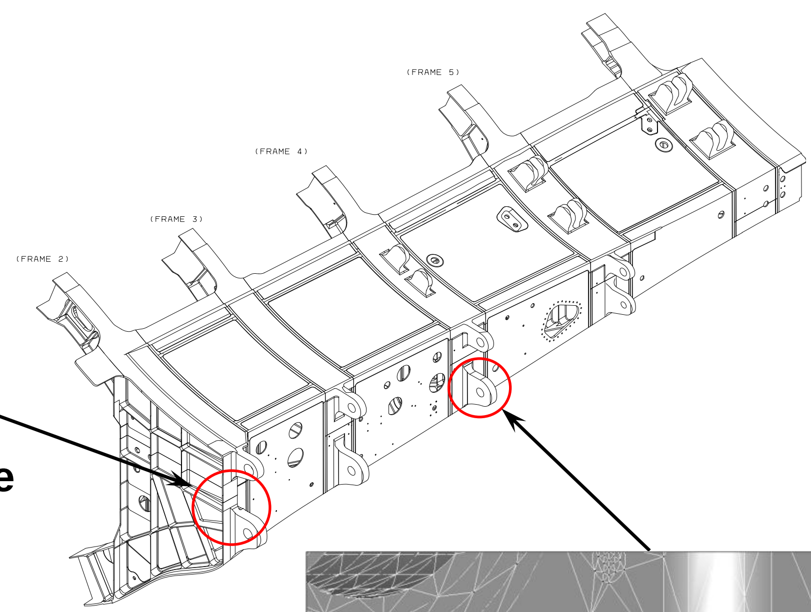
- The relative small size of the lug elements facilitated a larger test matrix and ease of handling and a
- Stress gradients in the critical zones were compared to full scale components to assure similarity between specimen configurations



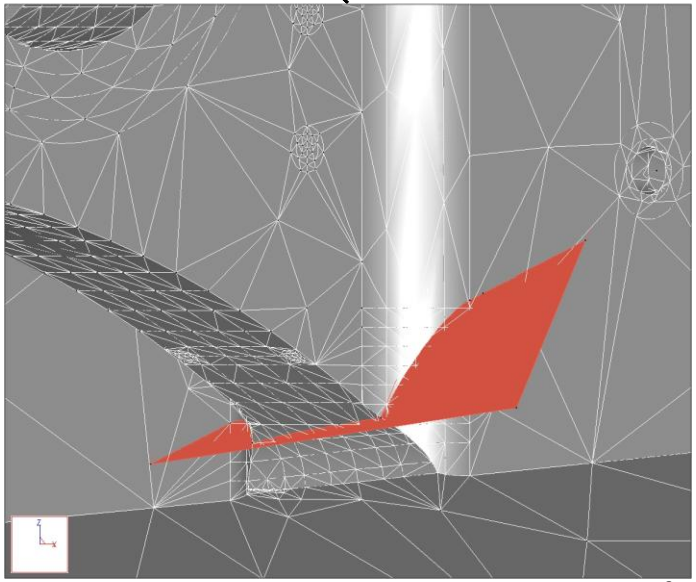




2 Full Scale Component Geometries tested



- **Upper fillet of Frame 2 provided unique critical detail and analysis challenge**
  - 1 specimen tested, naturally initiated crack monitored to obtain data
  - 1 specimen tested with edm notch to obtain damage tolerance data
- **Lower fillet of Frame 4 representative of all lower fillet radii**
  - 1 specimen tested from naturally intiated crack monitored to obtain crack growth data
  - 1 specimen tested with edm notch to obtain damage tolerance data

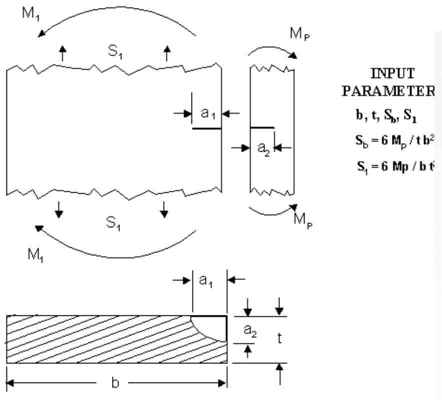


Test Matrix

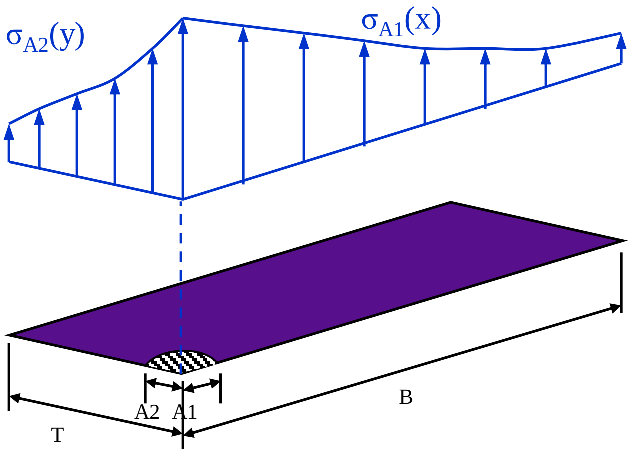
Test Type	Load Spectrum	Reference Stress	#	Data collected
Element	Constant Amplitude		3	Initiation and Growth
Element	Spectrum		6	Initiation and Growth
Element	Spectrum		6	Initiation and Growth
Element	Spectrum		6	Initiation and Growth
Frame 2 Component	Spectrum		1	Initiation and Growth
Frame 4 Component	Spectrum		1	Initiation and Growth
Frame 4 Component	Spectrum		1	Growth from EDM notch

Analysis: Crack Growth Program

- **In-House source code used to compute lives**
  - Retardation moded: Modified Generalized Willenborg model
  - da/dN equation: Tabular lookup of digitized da/dN curve
- **Program contains library of geometric details for computing stress intensity factors**
  - solutions based on accepted and validated sources (e.g. Kathirisen and Brussat, Newman and Raju, etc.)
  - Effects of stress gradient accounted for using Green's function to generate beta-modification factors

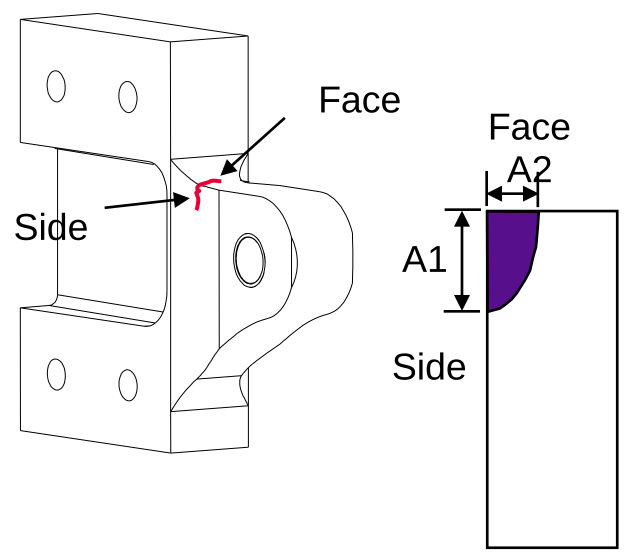


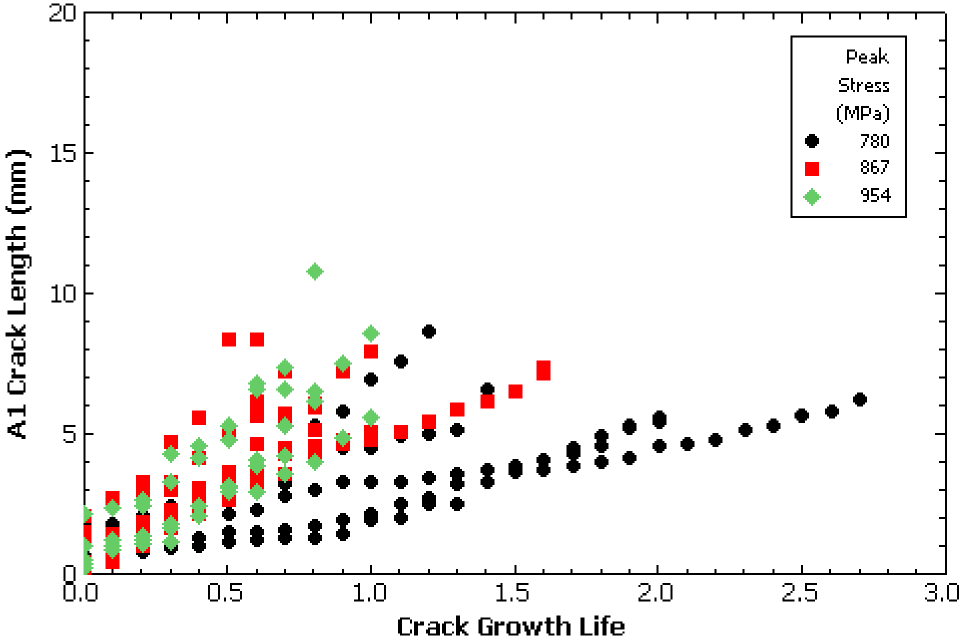
CASE 120. Single Corner-to-Corner Edge Crack, Strip Tension and Plate Bending

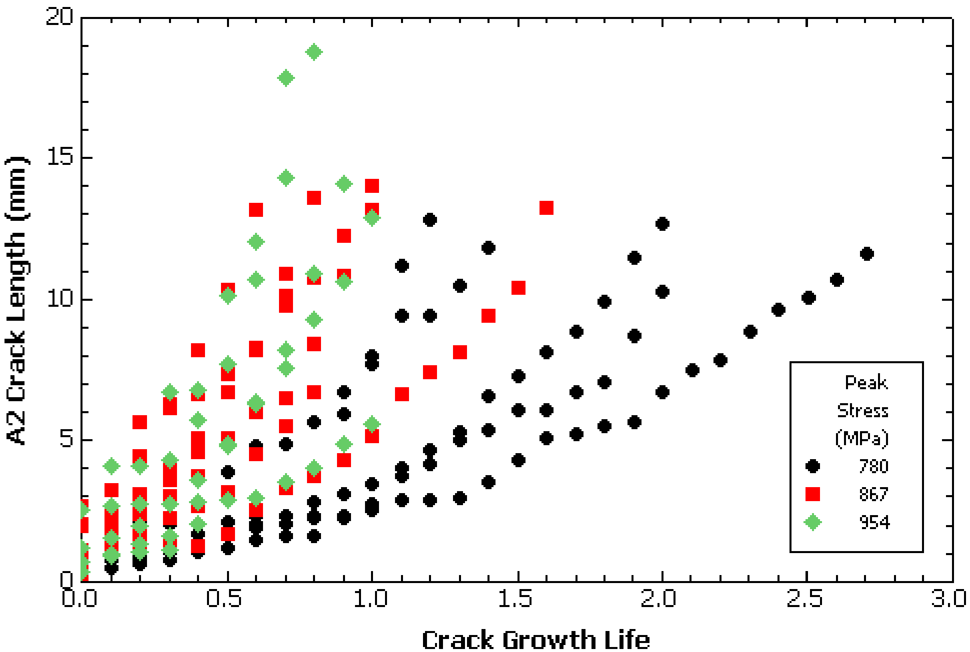


Lug Element Test Results

- Results for 18 specimens grouped by stress level
- Variability in crack size when naturally initiated cracks detected affect direct comparisons

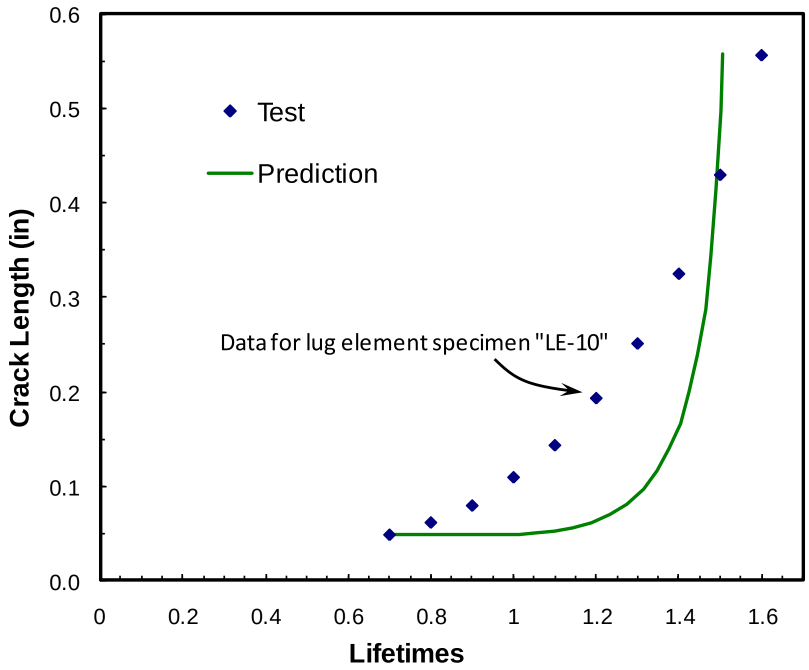






Test Results

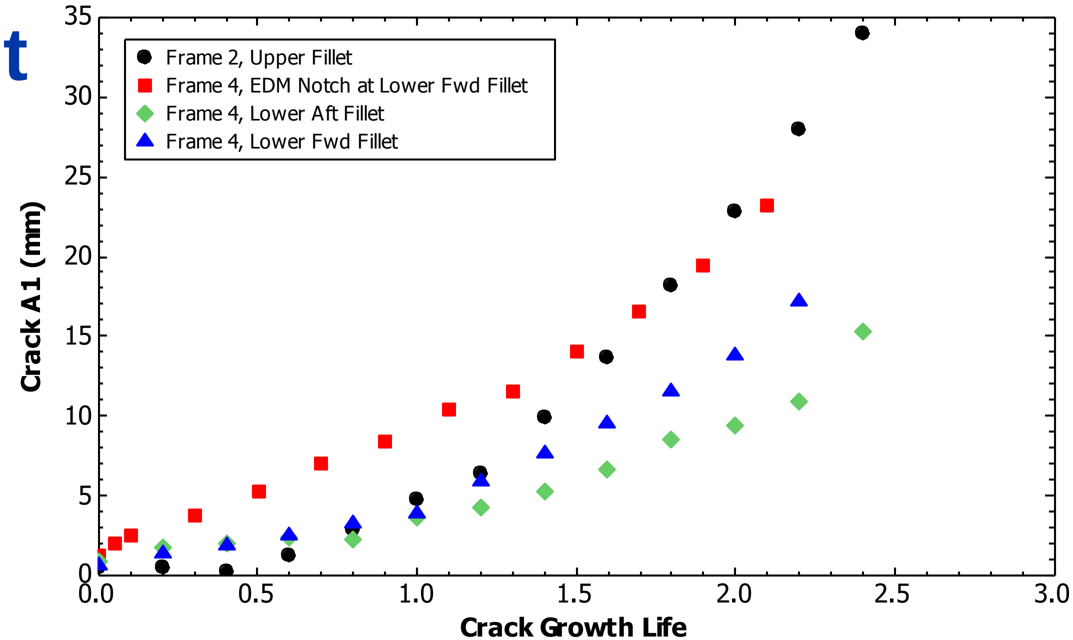
- Test results element tests typically did not match
- Neither the end point or the shape of the curve were accurately predicted

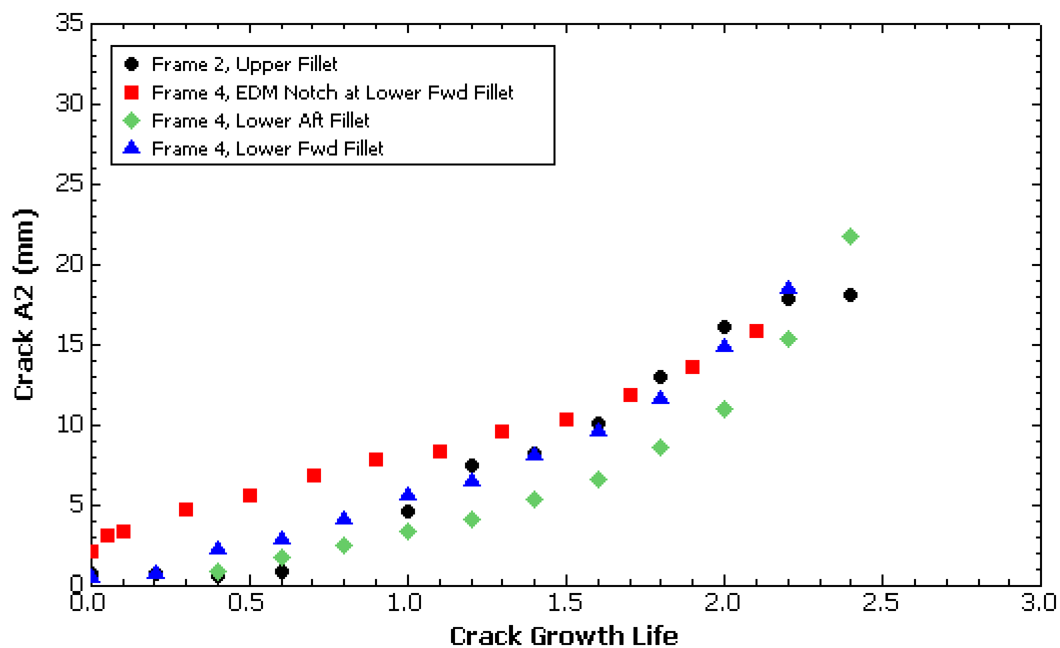


Analysis does not predict results

Full Scale Component Results

- **Full scale component results from 3 test articles**
  - Frame 4 crack initiation test article naturally initiated 2 cracks
  - Each crack monitored separately

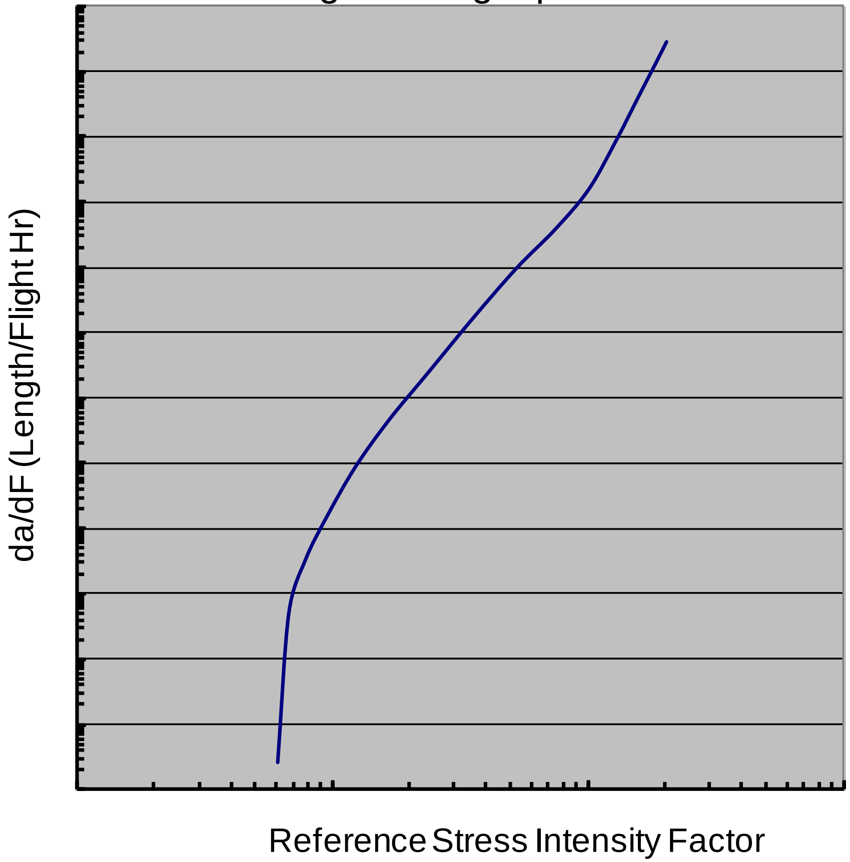




Analysis of Test Data

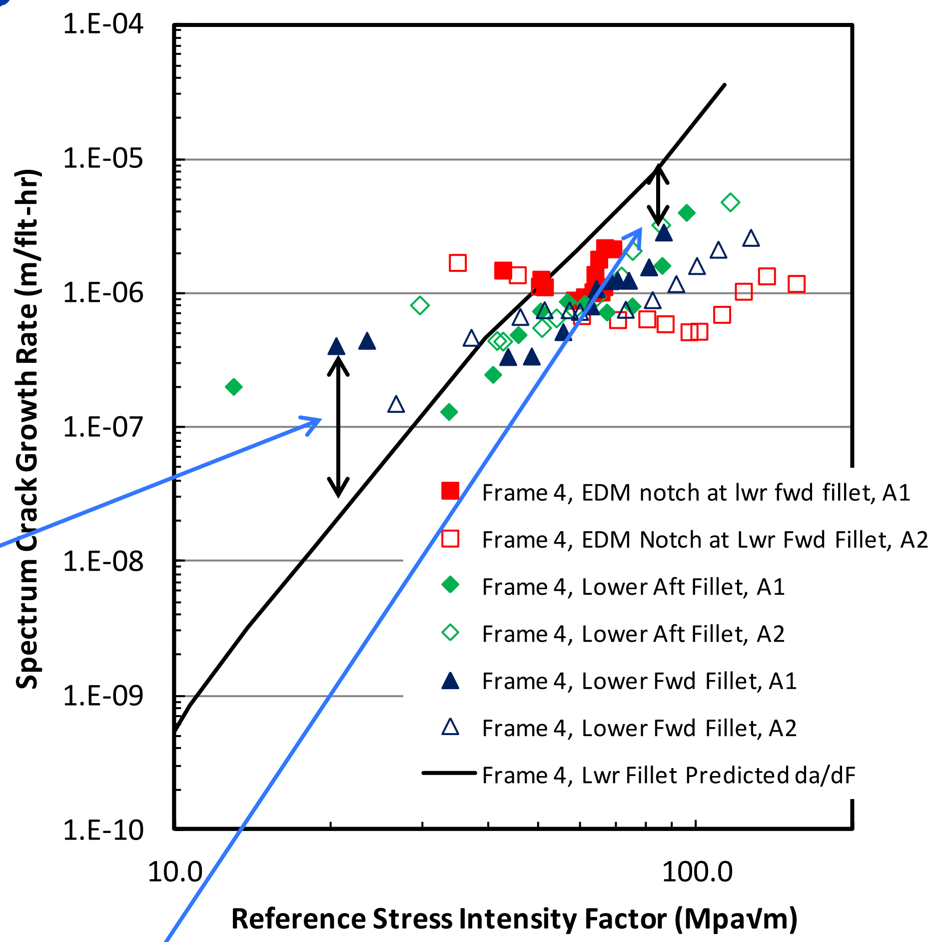
- **Data assessed by plotting growth rate per flight hour (da/dF) vs DK curves**
- **Analogous to da/dN curves**
  - Curves are specific to Material and load spectrum
  - Independent of test article geometry

Spectrum da/dF Curve
Ti-6Al-4V Beta Annealed Forging
Wing Bending Spectrum



Predicted crack growth curve shape does not match test results

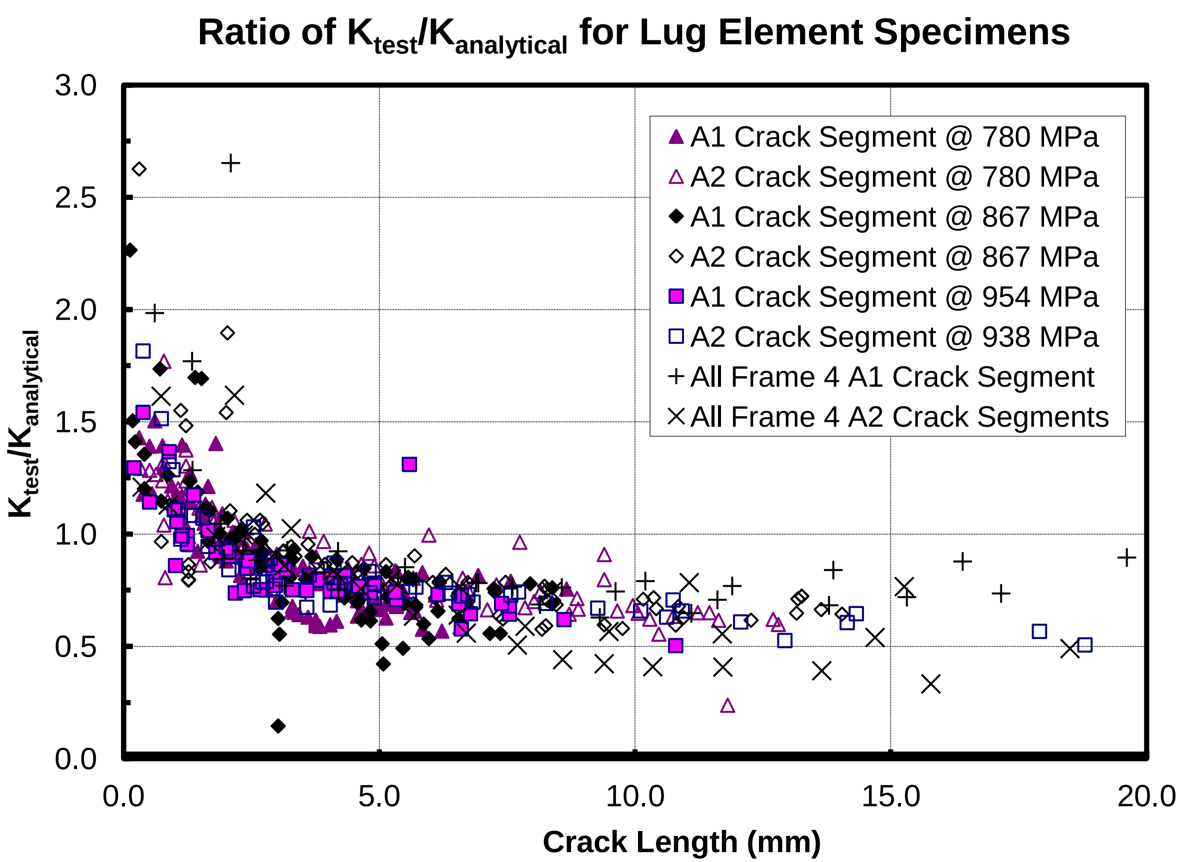
- **Consistent behavior observed for lug element and full scale test articles**



For given low value of stress intensity predicted growth rates are slower than test

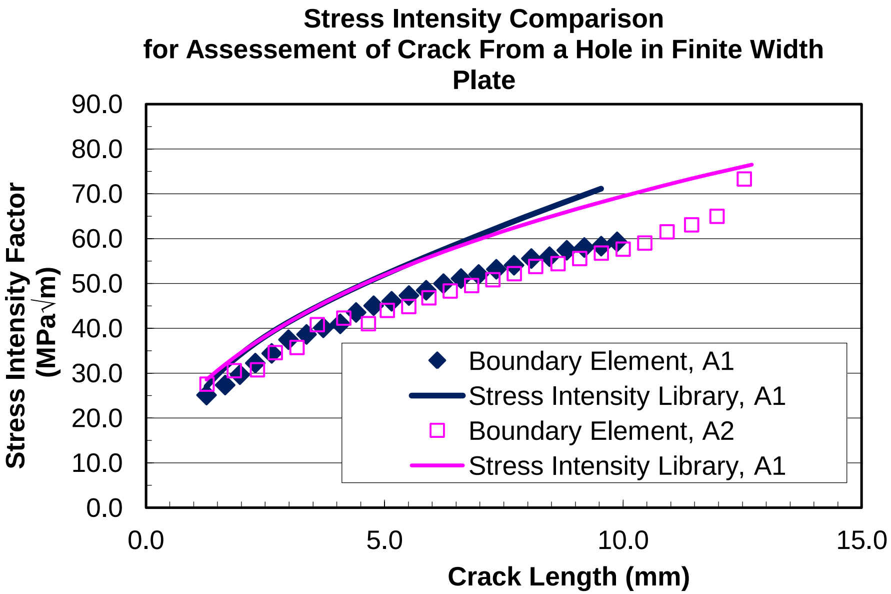
For larger stress intensities, predicted growth rates are faster than test.

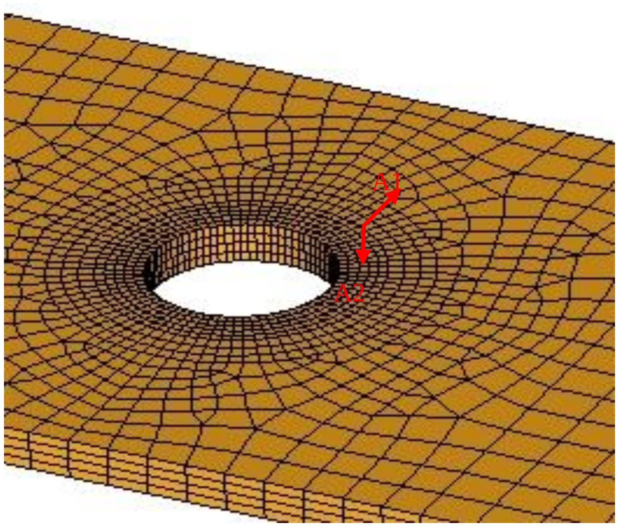
Ratio of Test Derived Stress Intensity Factors to analytical Stress Intensity Factors

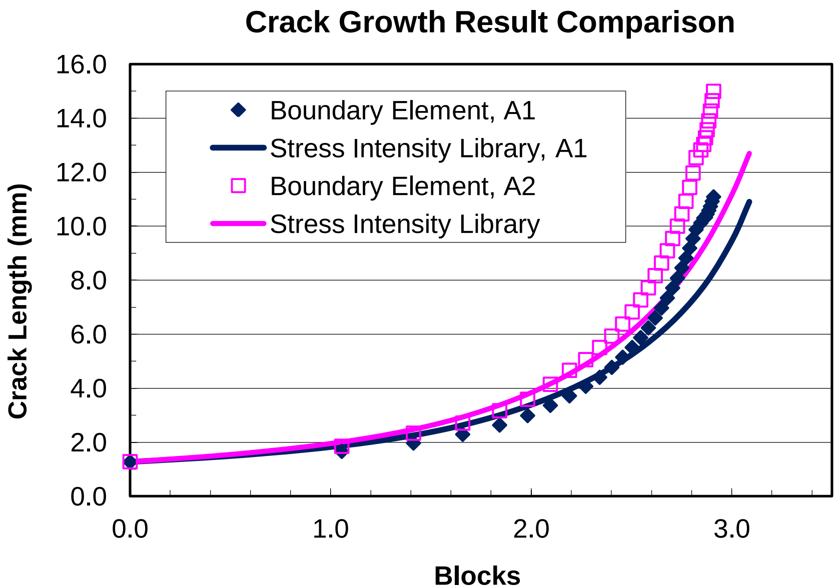


Comparisons with Simpler geometry Open hole specimen in uniaxial tensio

- **From previous tests and analysis of a common geometry and same material and similar load spectrum**
  - Good agreement between test and prediction
  - Basic stress intensity solutions are accurate
- Eliminates issues regarding retardation model

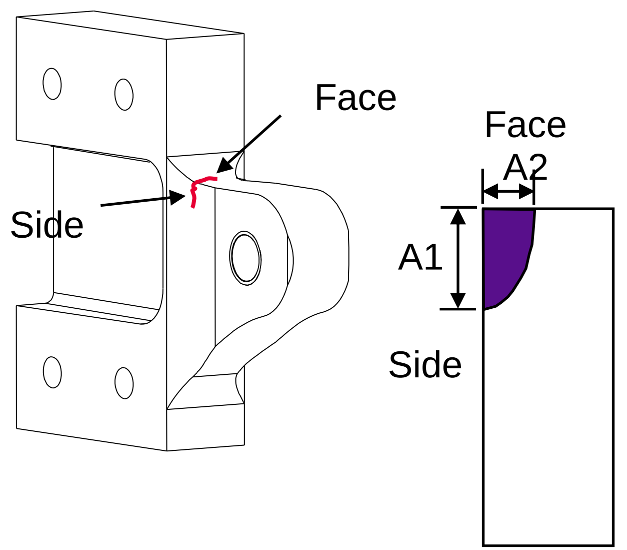


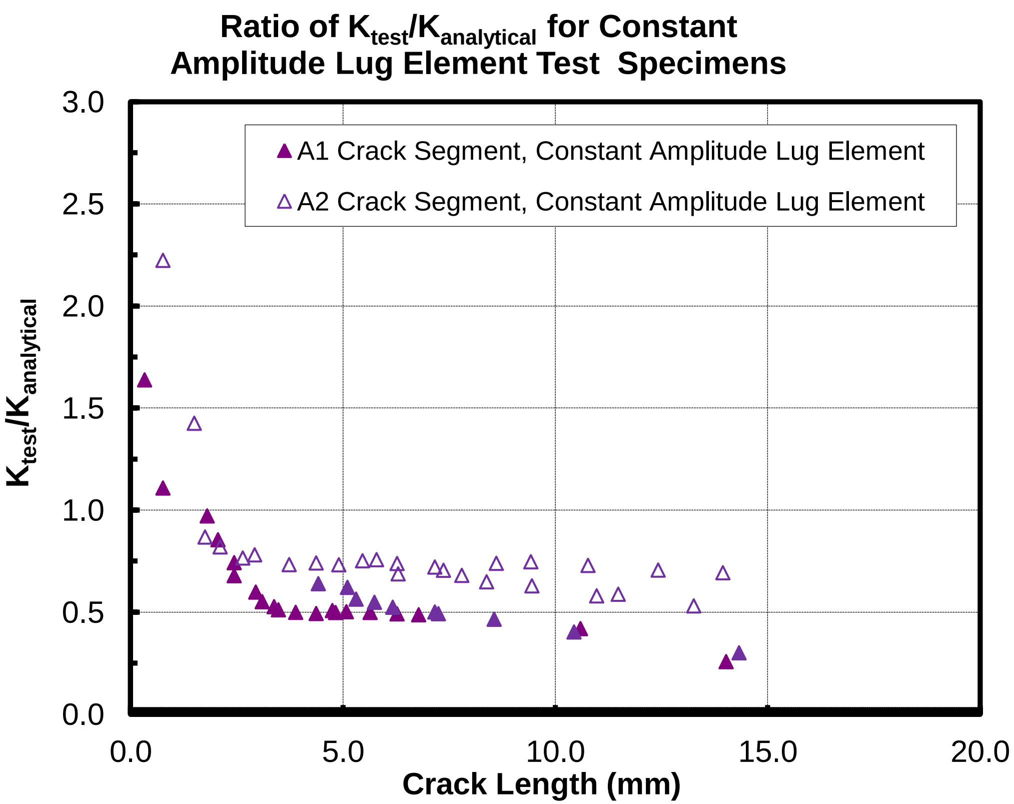




Lug Element Tests with Constant Amplitude Loading

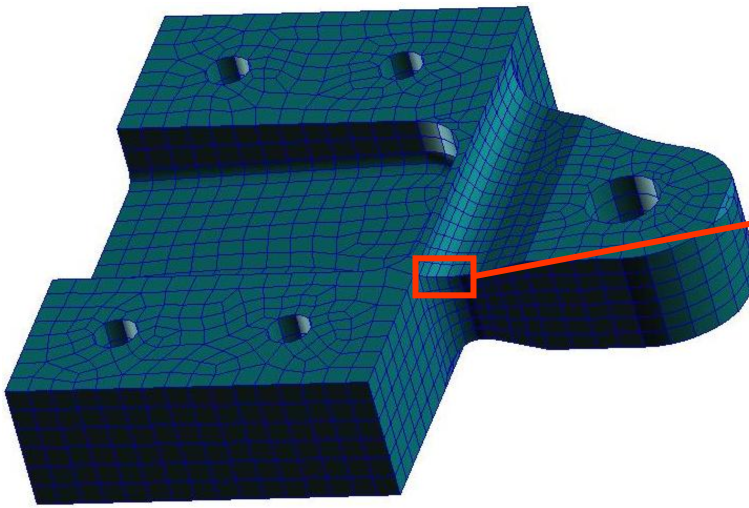
- Test derived Stress Intensity Factors for constant amplitude specimens follow same trend as for spectrum tests.



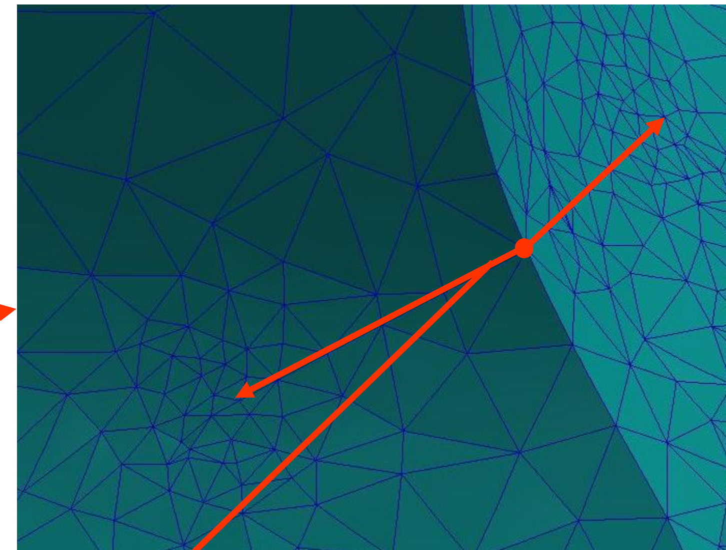


Boundary Element Model for Lug Element

Initial Mesh w/o crack

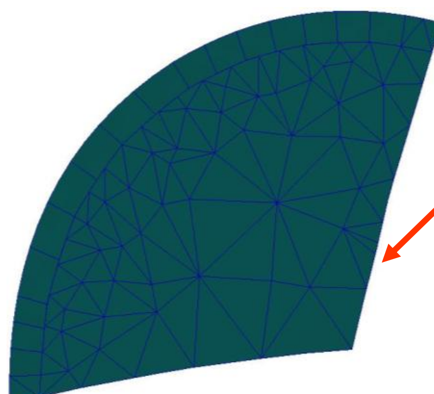


Mesh w/ crack
(local auto remesh)



(minimum mesh size ~0.005”)

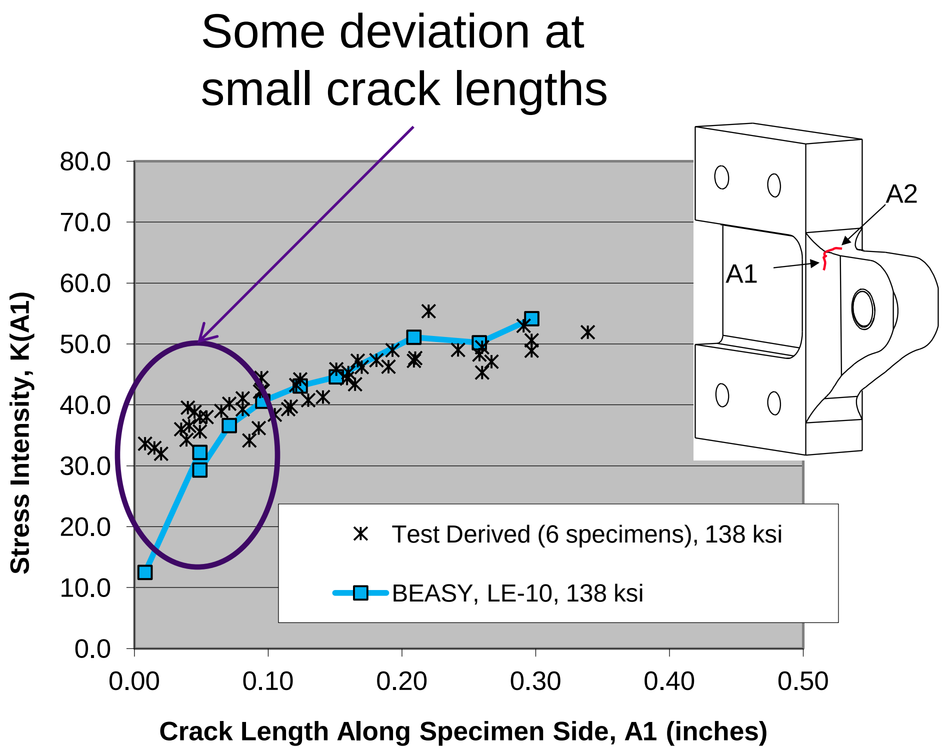
Boundary Condition: fix at the 4 clamping bolt locations
Loading: load in the lug bore

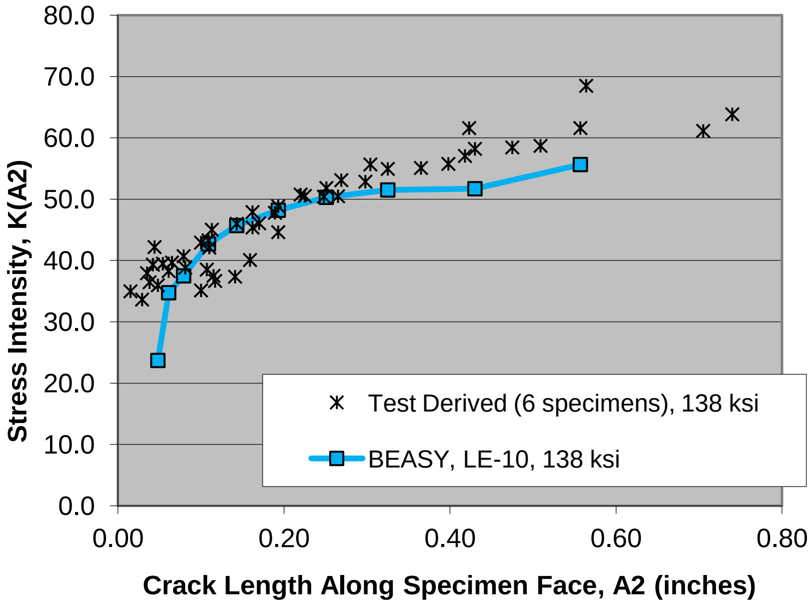


Mesh on the crack surface
(auto remesh)

Lug Element Test Results

- **Stress Intensity factors from Boundary Element Code Closely match test derived factors**

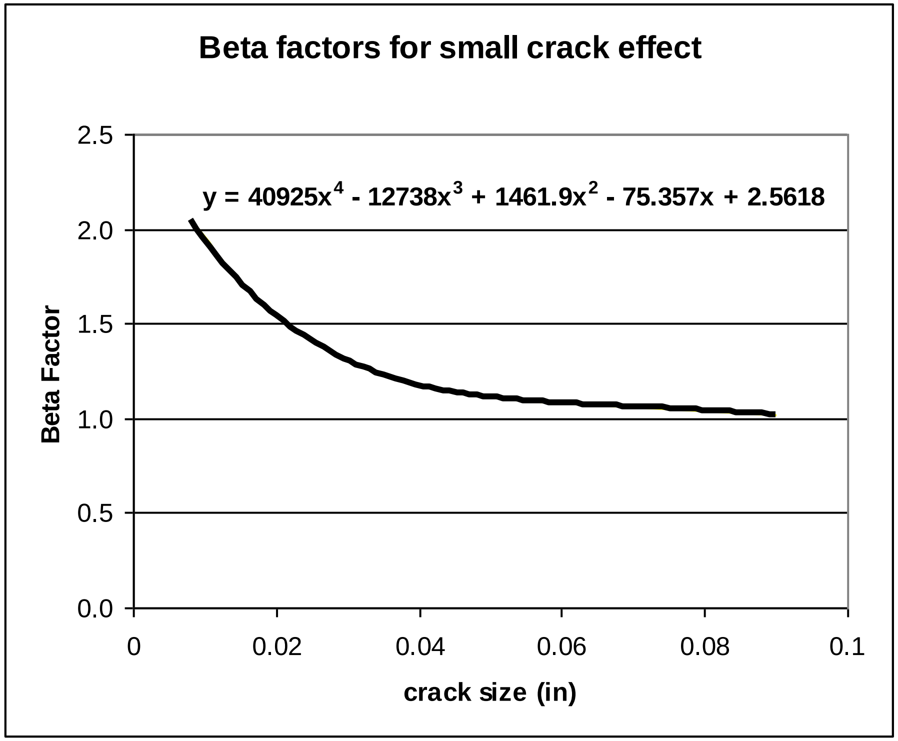




Similar results for tests conducted at 125 and 113 ksi

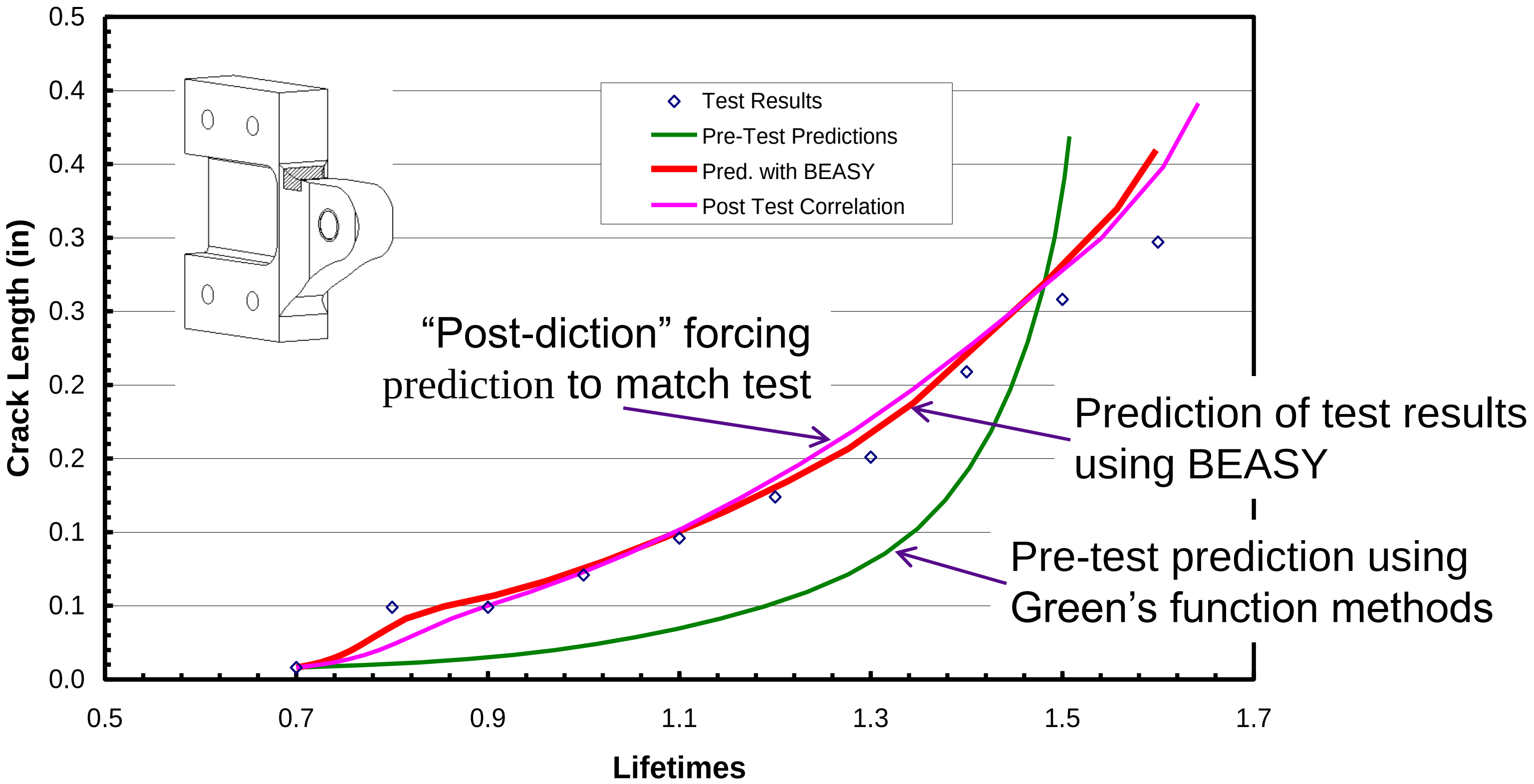
Empirical "Short Crack" Beta Test Factor Derived from Lug Element Tests

- **For cracks < 2.54 mm (0.1"), a correction was applied to account for short crack effects**
  - Necessary to match growth rates for cracks small cracks
  - Beta factors used to modify the stress intensity factor for small cracks derived from evaluation of lug element specimens



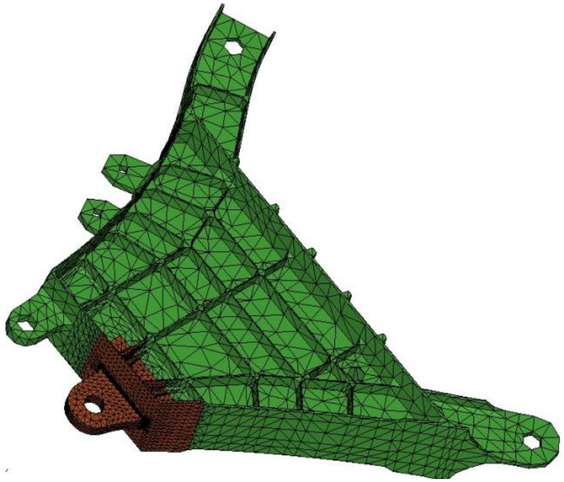
For Ti-6Al-4V Beta Annealed, 2.54 mm (0.1") is approximately 2 to 3 grain diameters. A range where microstructural features can strongly influence crack growth.

Results for Lug Element Test

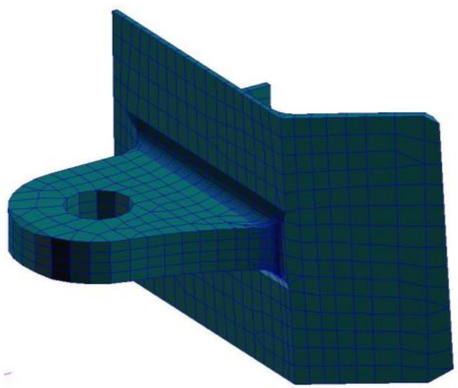


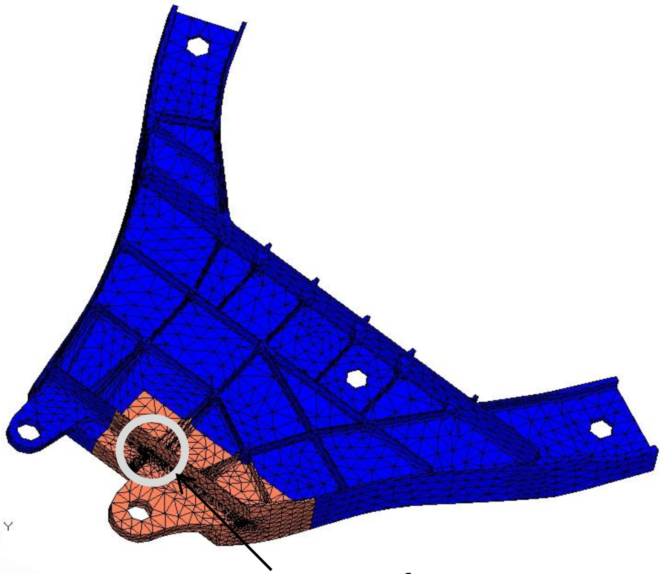
Crack growth predictions using stress intensity factors from the boundary element analysis match test results

Models for Full Scale Components



Frame 4

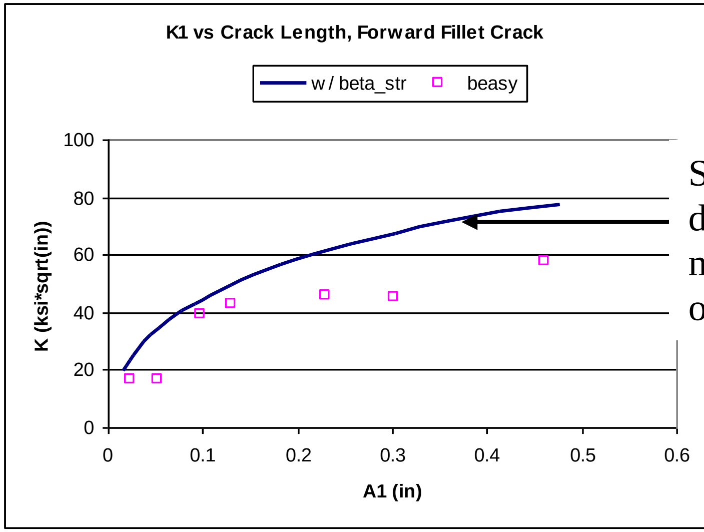




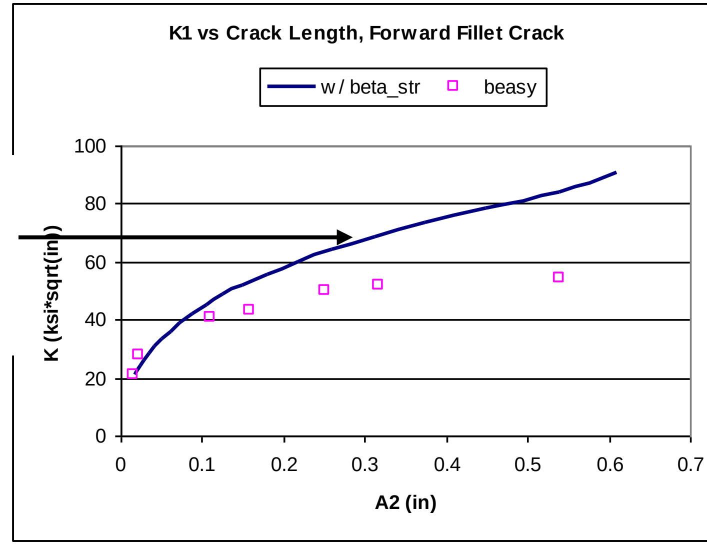
Area of concern

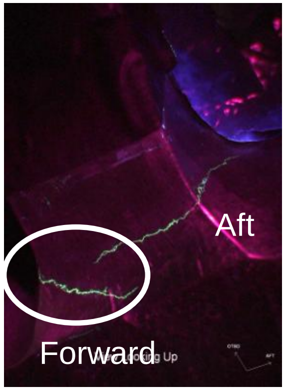
Frame 2

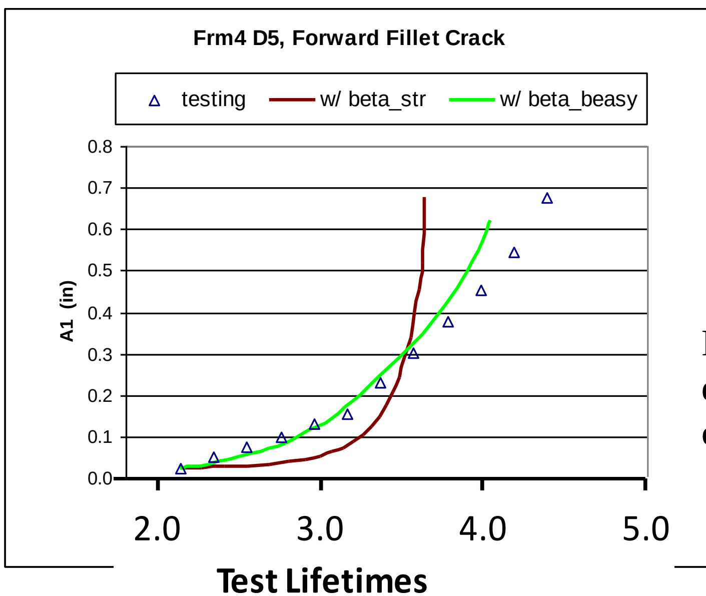
Frame 4 Component Test Results, Forward Crack



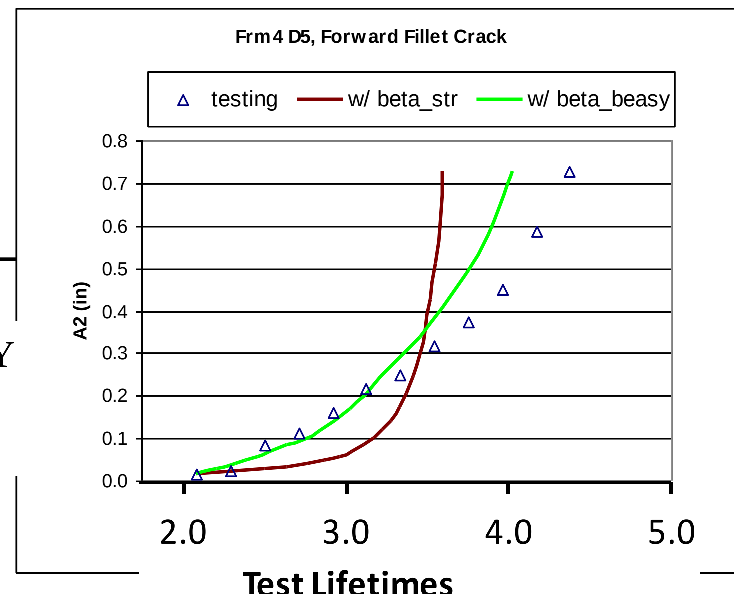
Stress intensity factors derived using current method higher than those obtained from BEASY



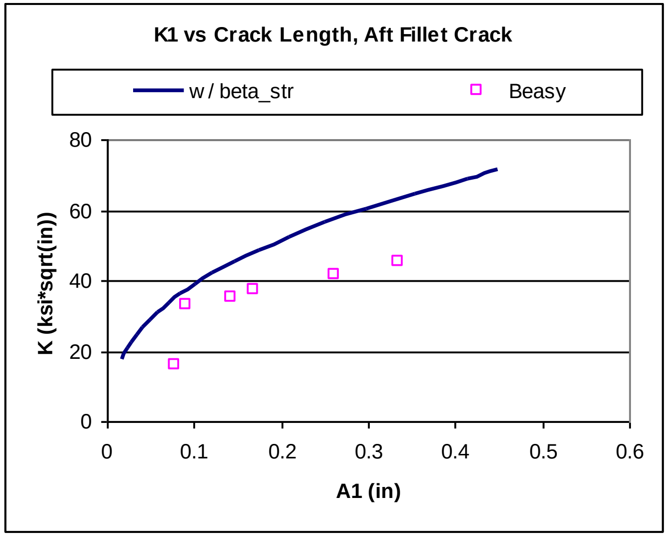


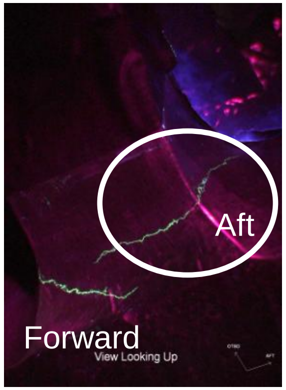


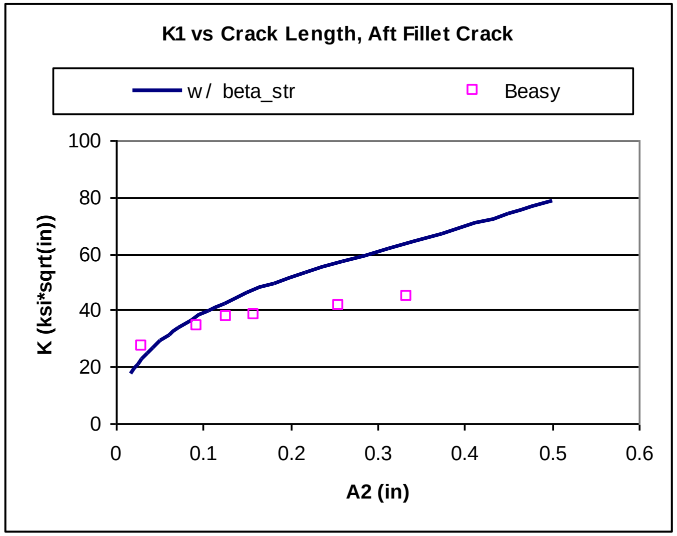
Predictions using BEASY derived stress intensities closely match test results

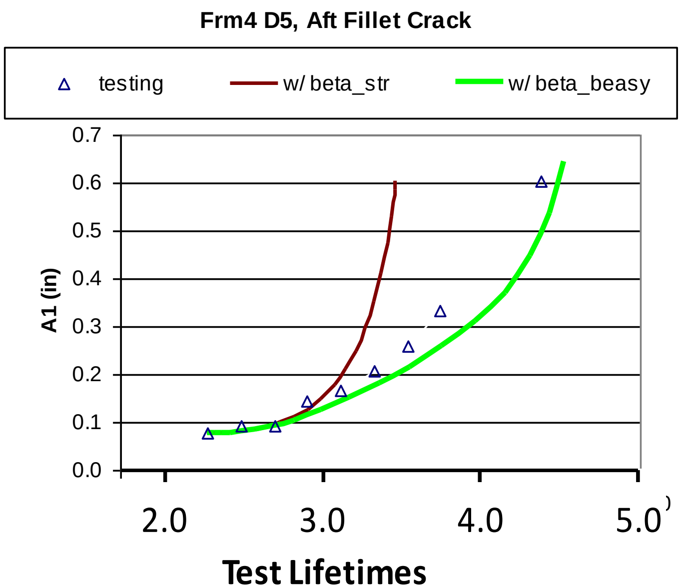


Frame 4 Component Test Results, Aft Fillet Crack

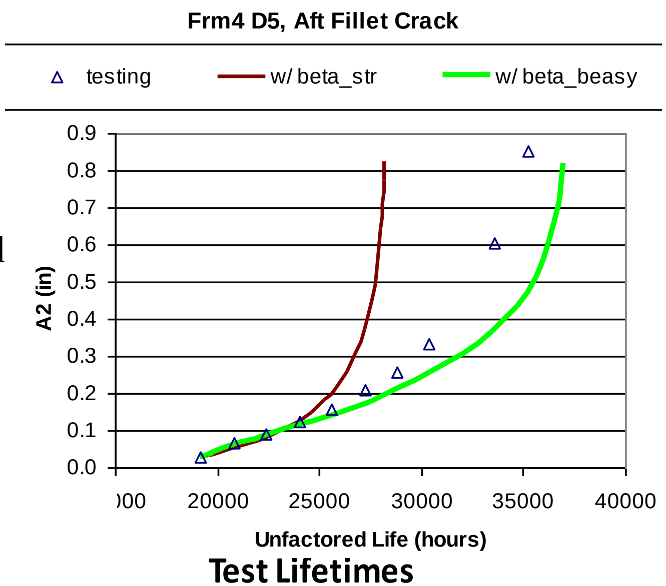




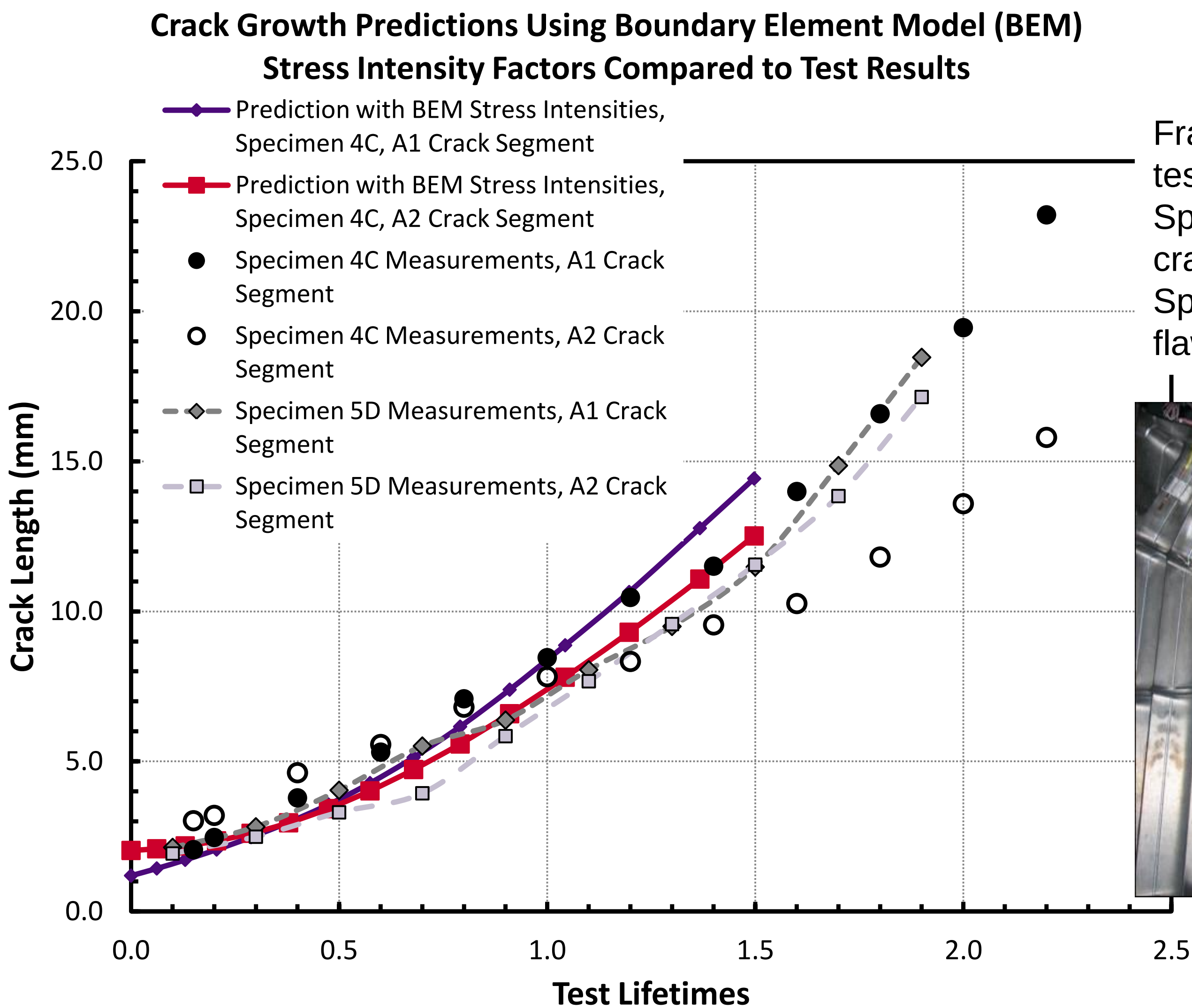




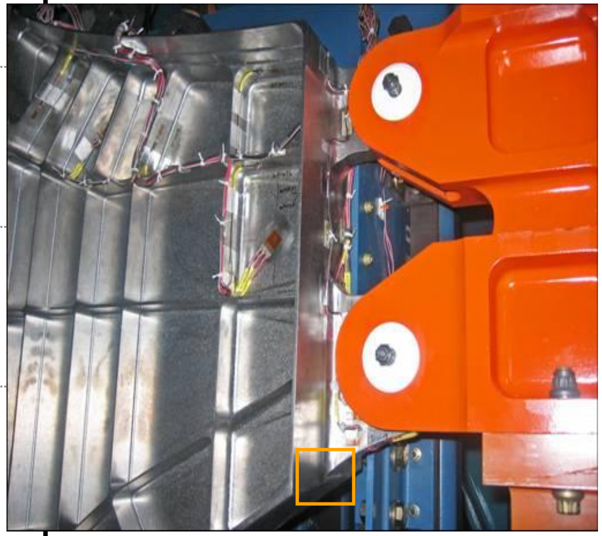
Analysis using BEASY Derived Beta Factors PREdict both the shape and the end point of the crack growth curve for the frame 4 specimen



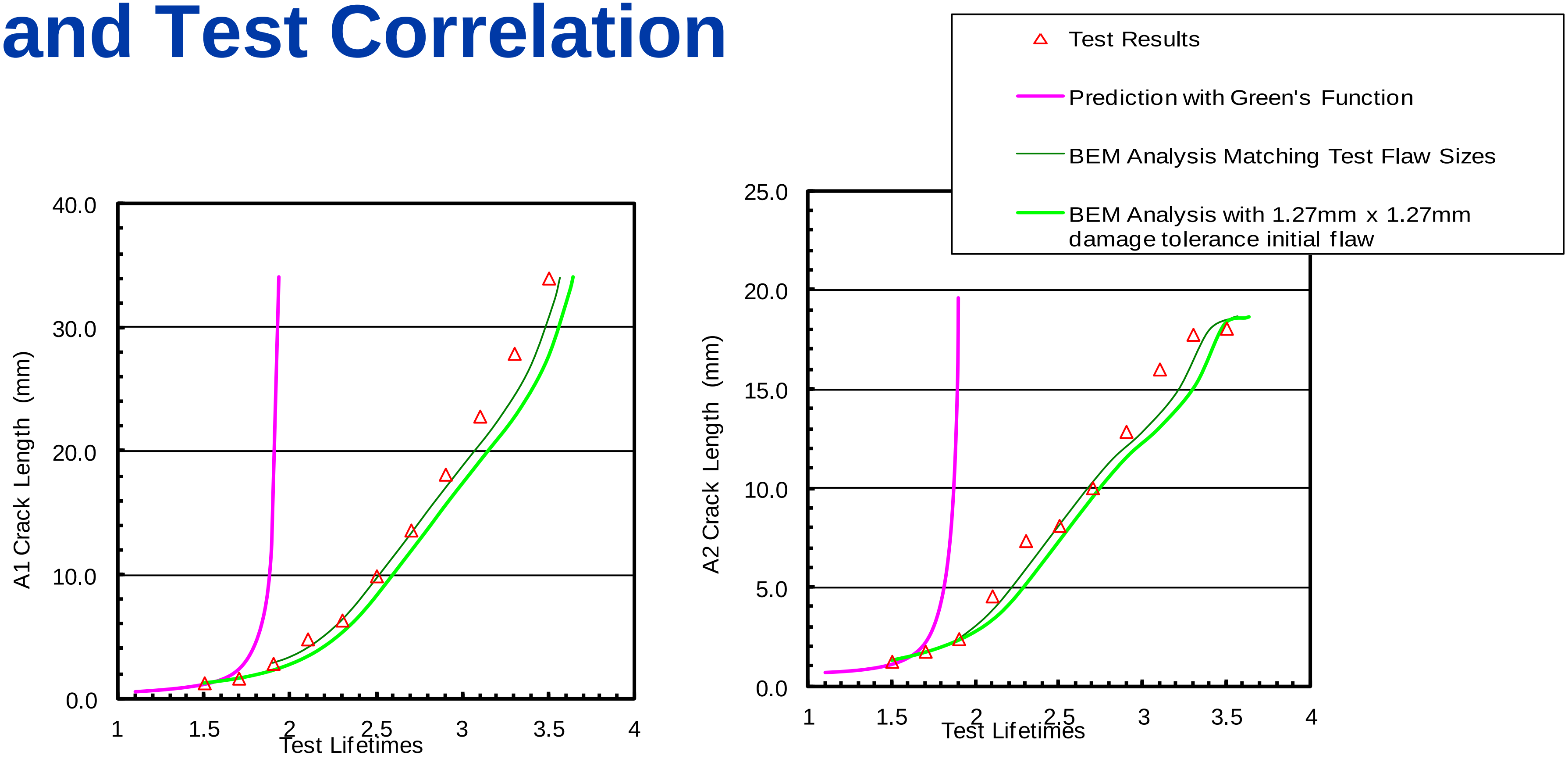
Comparison of Frame 4 Component Test Crack Growth Results



Frame 4 component crack growth test results.
Specimen 5D – naturally initiated crack
Specimen 4C – Crack from EDM flaw



Frame 2 Upper Fillet Analytical Results and Test Correlation

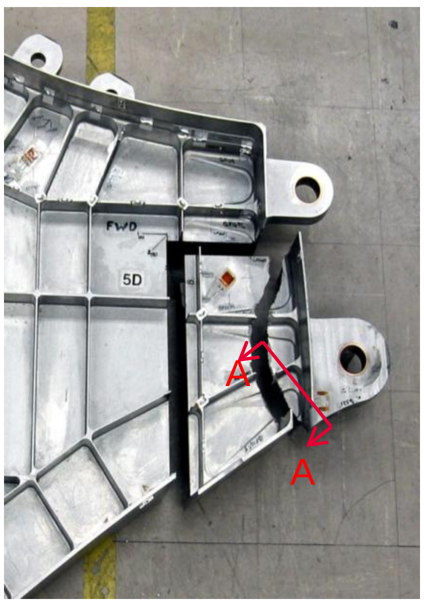


Analytical results are from crack growth analysis with different stress intensity solutions:

- Predictions using the original method with Green’s Function
- Predictions using stress intensities from boundary element analysis and a 1.27 mm x 1.27mm (0.05”x0.05”) initial flaw
- Predictions using stress intensities from boundary element analysis and a 2.84mm x 2.41 mm (0.112”x0.095”) initial flaw to match the initial observed flaw from test

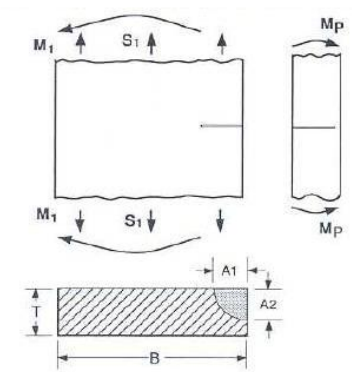
Full Scale Component Results

- **When the structure cross section geometry gets complex**
  - simplified stress intensity solutions unable to model full range of crack lengths
- **Boundary element tool accurately accounts for effects of geometric boundary and complex loading**



View A-A

Crack origins at lower corners



Cross section of fracture surface shows greater complexity than provided by simplified stress intensity solution

Stress intensity factors computed from boundary element tool improves crack growth "pre-"dictions in complex geometric details

Conclusion

- **A rigorous test program was executed to understand crack growth behavior in full scale structures**
- **Two sources of error were observed affecting model accuracy**
  - Incorrect stress intensity factors
  - Short crack effect for cracks less than 2.54 mm (0.1 in) or 2 to 3 grain diameters
- **FEM based approach validated against test data to improve stress intensity data**
- **Empirical modification implemented to account for short crack effect**

Observations

- **Properly designed element specimens that match stress gradient and material processing can match behavior of full scale structures**
- **Methods can be validated and verified utilizing the smaller less expensive element specimens**
- **Methods should be calibrated using specimens that look like the structures being modeled**
  - Previous methods calibration and validation tests focused on specimens that looked like standard stress intensity solutions (i.e. cracks growing from a round hole in a finite width plate)
  - Future emphasis on integral structures, larger forgings, etc, require verification and validation tests that represent details in the structure

Questions?