Incorporation of Load Redistribution in Analytical Correlation of Spectrum Crack Growth Test Data

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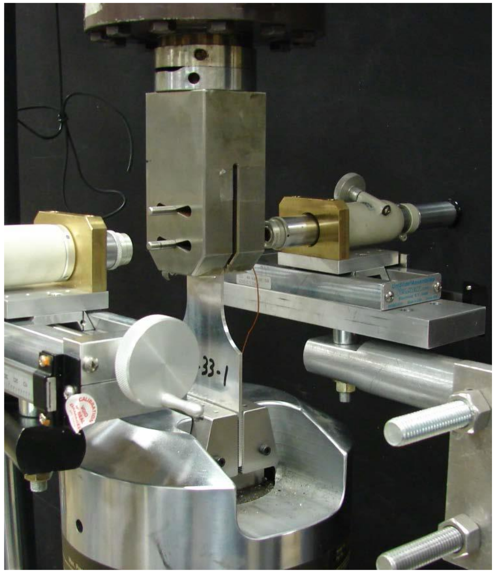
Introduction

- Very large loads in a load spectrum can cause crack growth to slow down, known as crack retardation
- Spectrum crack growth tests were performed to determine crack growth retardation parameters
- Two geometries – both with mixed tension and bearing load transfer

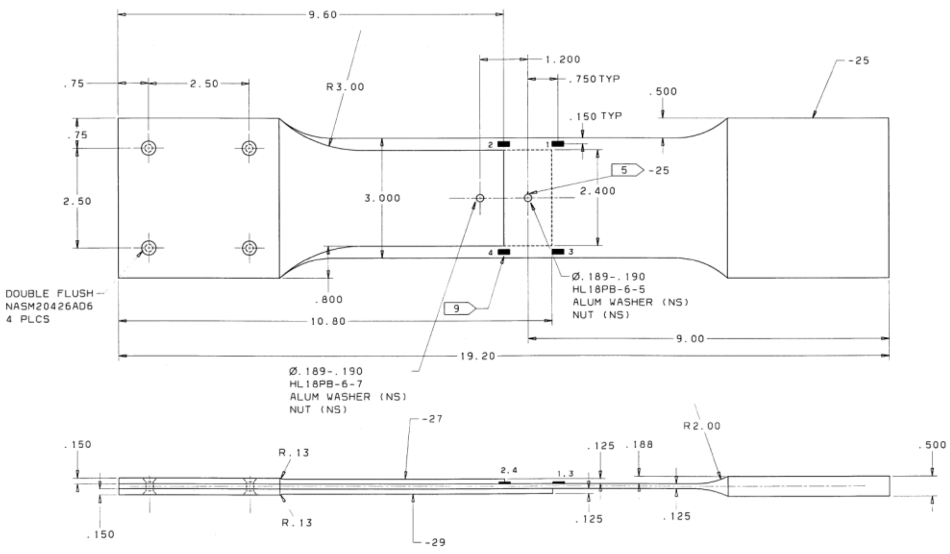


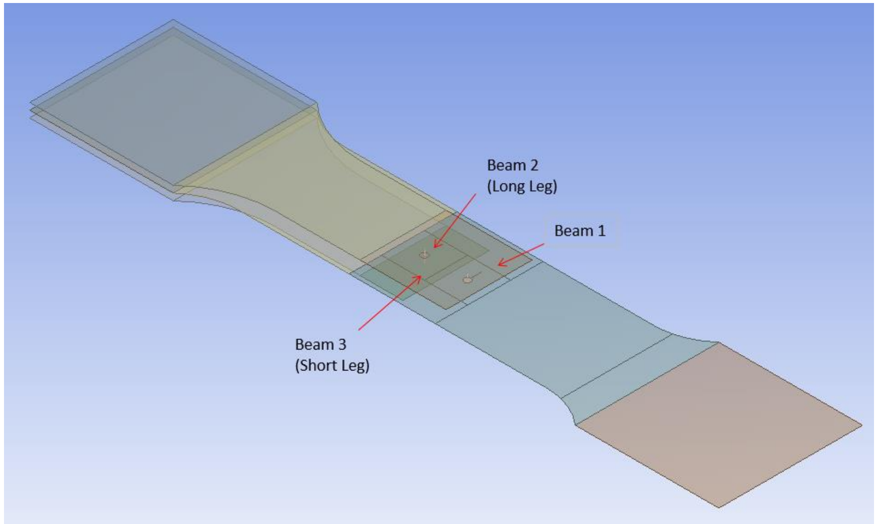
Objectives

- Primary question
  - As the cracks grew, how much did the fastener load change, and what effect did that have on stress intensities and crack growth?
- Approach
  - Through FEM, determine loads carried by each fastener as the crack grows
  - Using AFGROW, determine the effects on stress intensities and crack growth

Test Configuration – Specimen 1

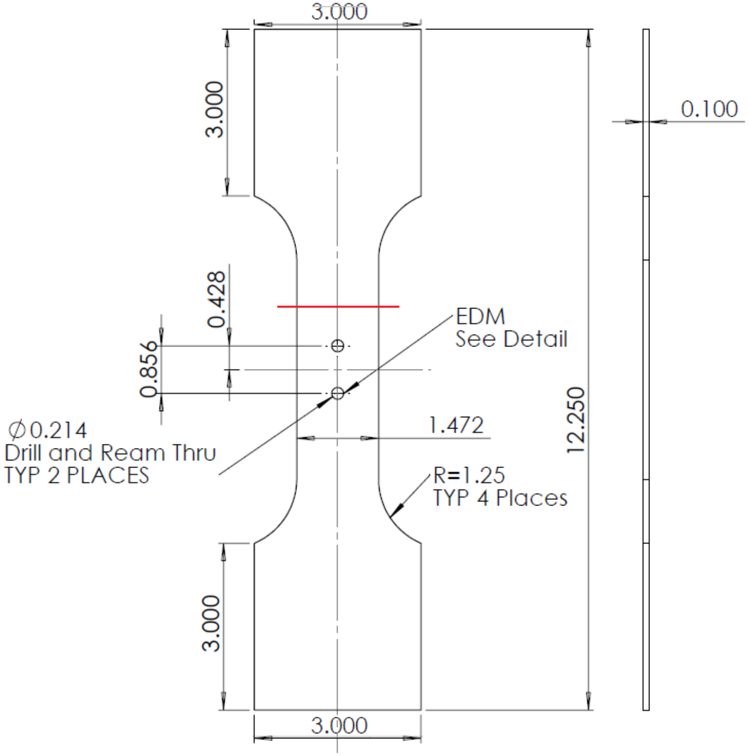
- Three part specimen:
  - Primary part is dog bone with two fastener holes
  - Secondary part on top mates to both fasteners
  - Secondary part on bottom mates only to uncracked fastener
- Neat fit Hi-Lok fasteners with hand-tight nuts

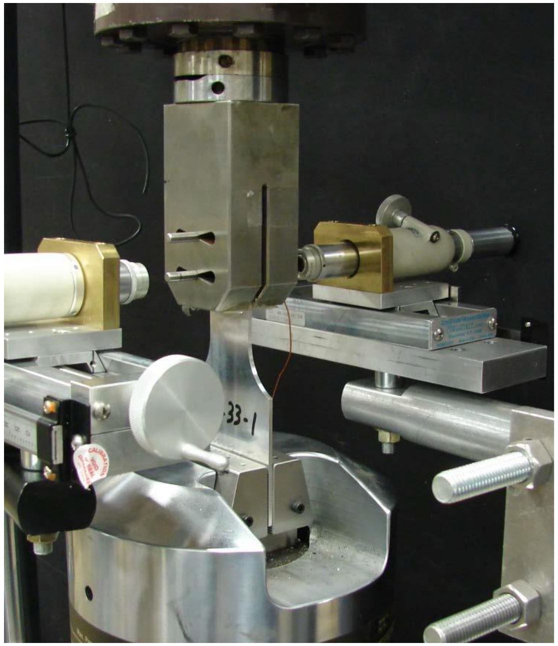




Test Configuration – Specimen 2

- Dog bone specimen with two fastener holes
  - After precracking in pure tension, specimen was cut at red line for spectrum loading in bearing
- Neat fit pins attached specimen to custom made clevis





Finite Element Modeling

- Thin plates should be modeled with either 2-D plate elements or non-linear elements to prevent locking
  - Whitman (2012) used non-linear tetrahedral (10-node) elements (3-7 nodes thru thickness)
  - Northrop in FEM of Specimen 1 used 2-D plate elements
- Fasteners can be modeled with springs or solid elements
  - Whitman used solid tet elements
  - Northrop used 1-D spring elements
- Friction, even on fastener head and nut, can have a large effect on results (Parks, 2009)
  - Frictionless conditions are used for model/test validation when possible

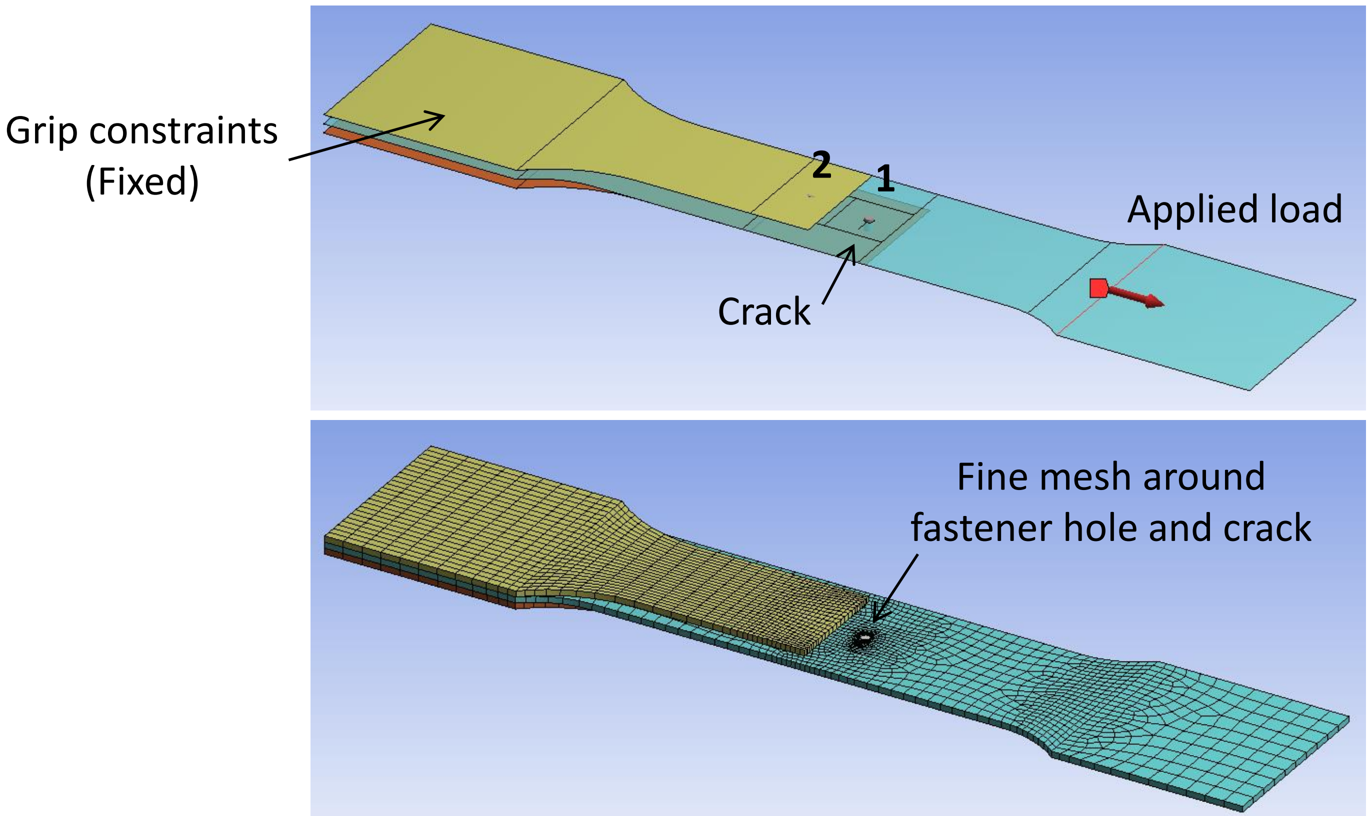
Out-of-plane bending behavior susceptible to locking (picture from Parks, 2009)

Finite Element Modeling

- **Specimen 1 modeling conditions**
  - Model was designed to replicate Northrop's FEA results
    - 2D plate elements and springs were used
  - Test specimens were Teflon coated
    - Multiple frictionless contact surfaces
- **Specimen 2 modeling conditions**
  - Custom high-strength steel clevis was modeled as a fixed support in the direction of loading
    - No global out-of-plane bending
  - Only contact is between pins and plate
    - Minimal contact allowed for non-linear 20-node solid elements (5-11 nodes thru plate thickness)
- Mesh refinement around fastener holes and crack tips until fastener load results converged to within 1%

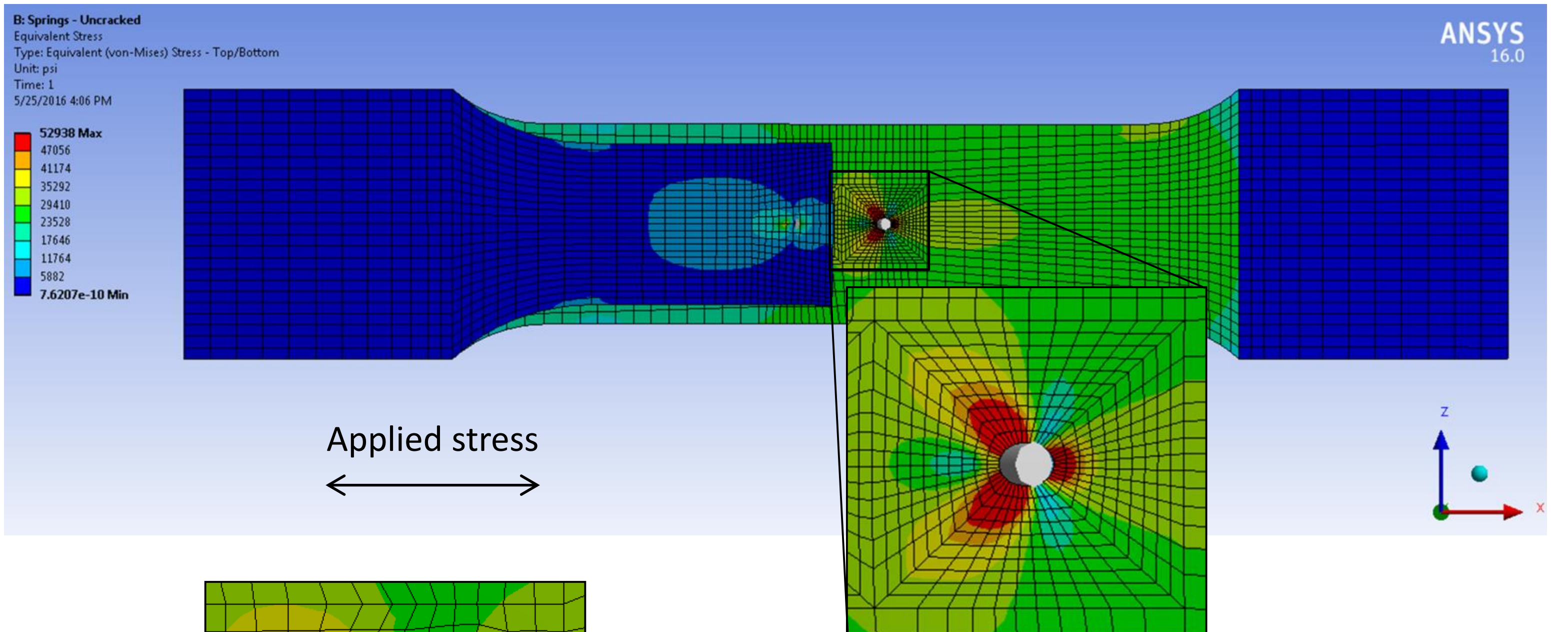
Specimen 1 FEM

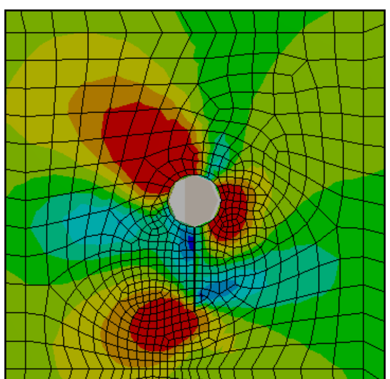
- Model was designed to replicate Northrop's FEA results
  - Plate elements for the coupon, beam elements for fasteners



Specimen 1 FEM Results

- Uncracked model, Von Mises stress profile

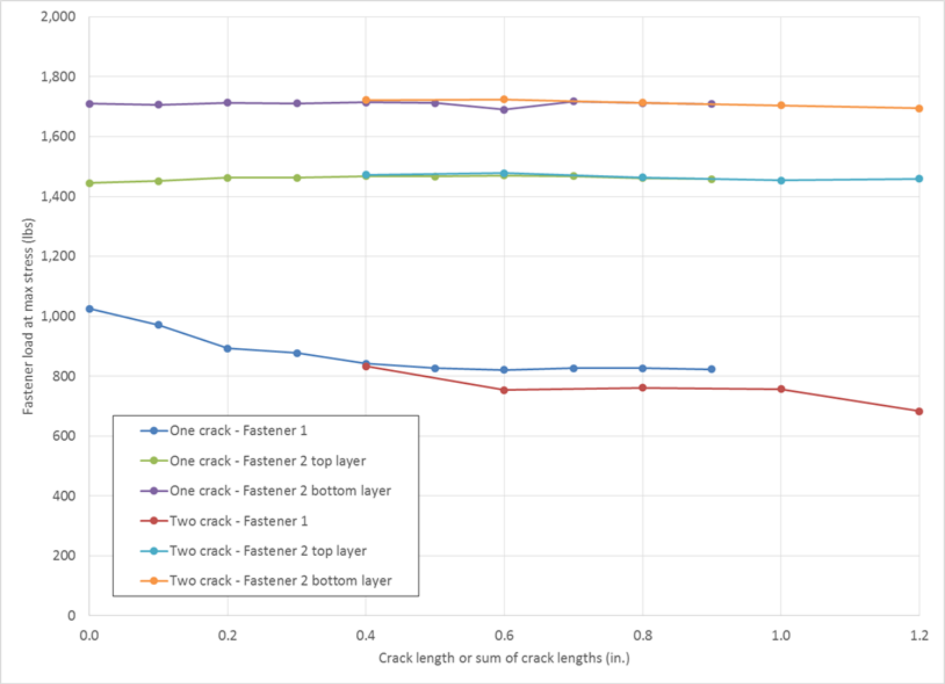




- Typical cracked stress profile

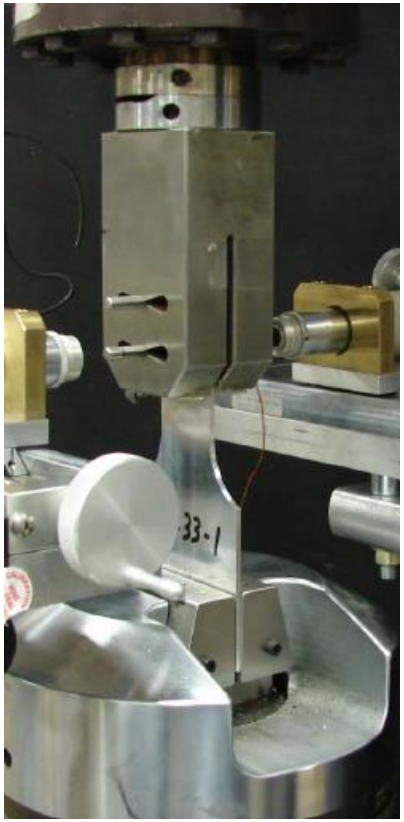
Specimen 1 FEM Results

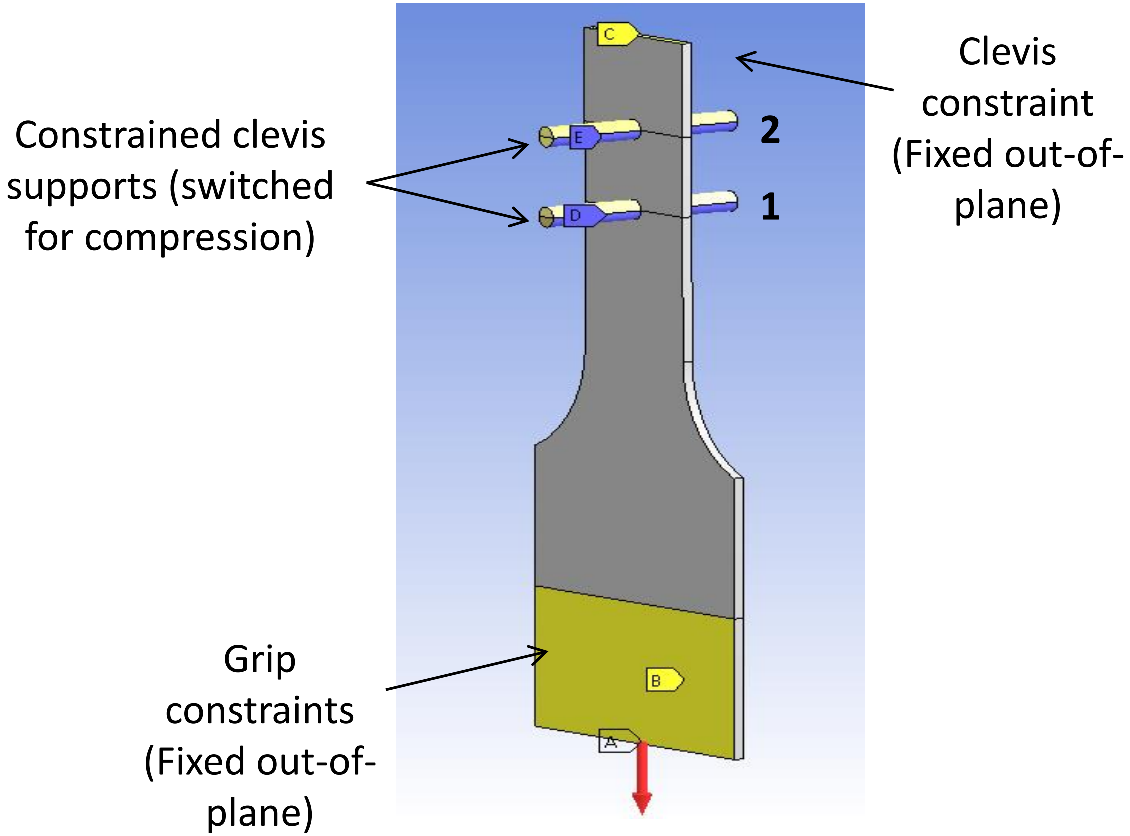
- Shear force on beam used to extract fastener loads
  - Loads were within 3% of Northrop's uncracked model results
- Fastener load at cracked hole decreases as crack grows
- Other fastener load largely unchanged



Specimen 2 FEM

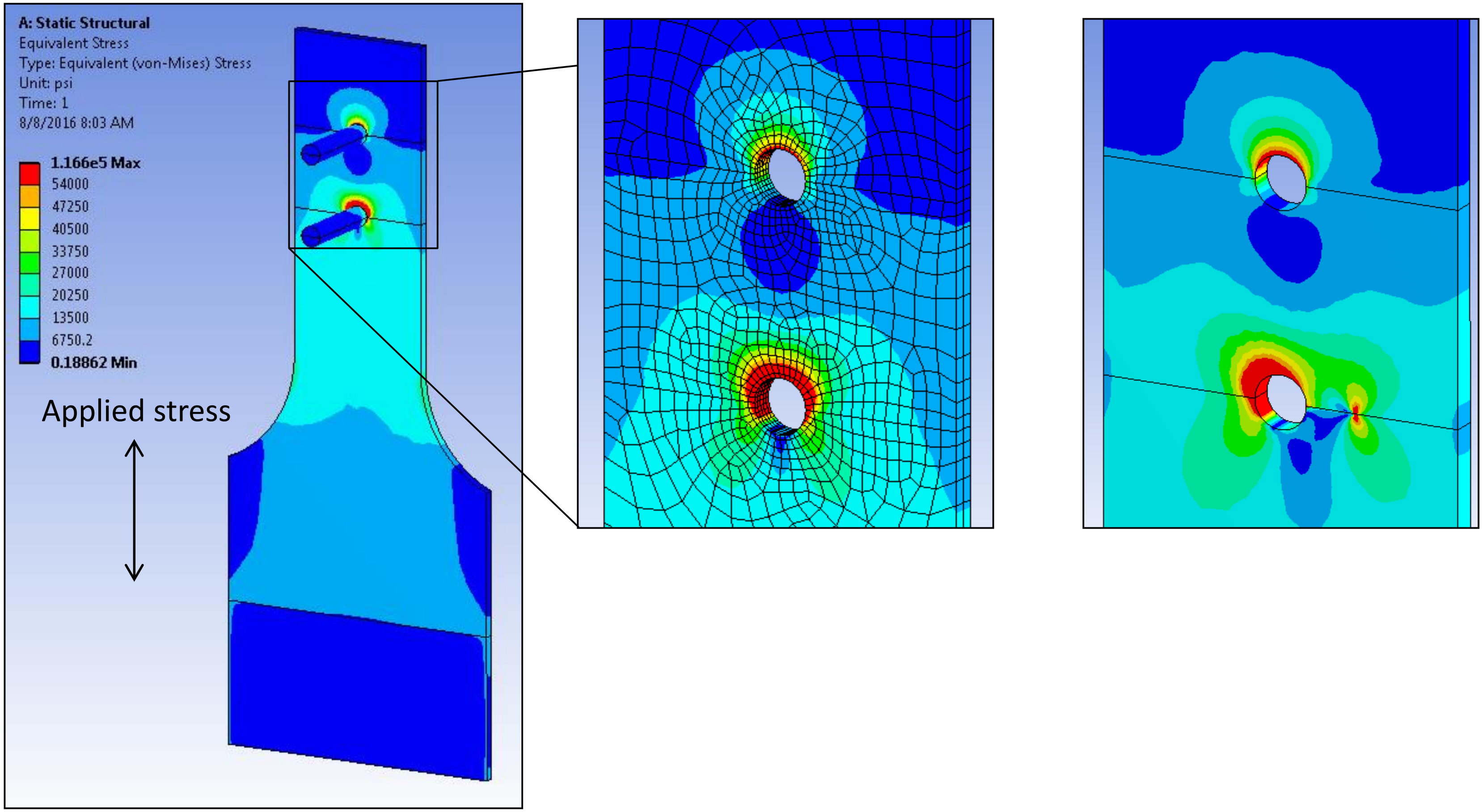
- Model was designed to replicate test conditions
- Fewer contact surfaces allowed for higher fidelity model





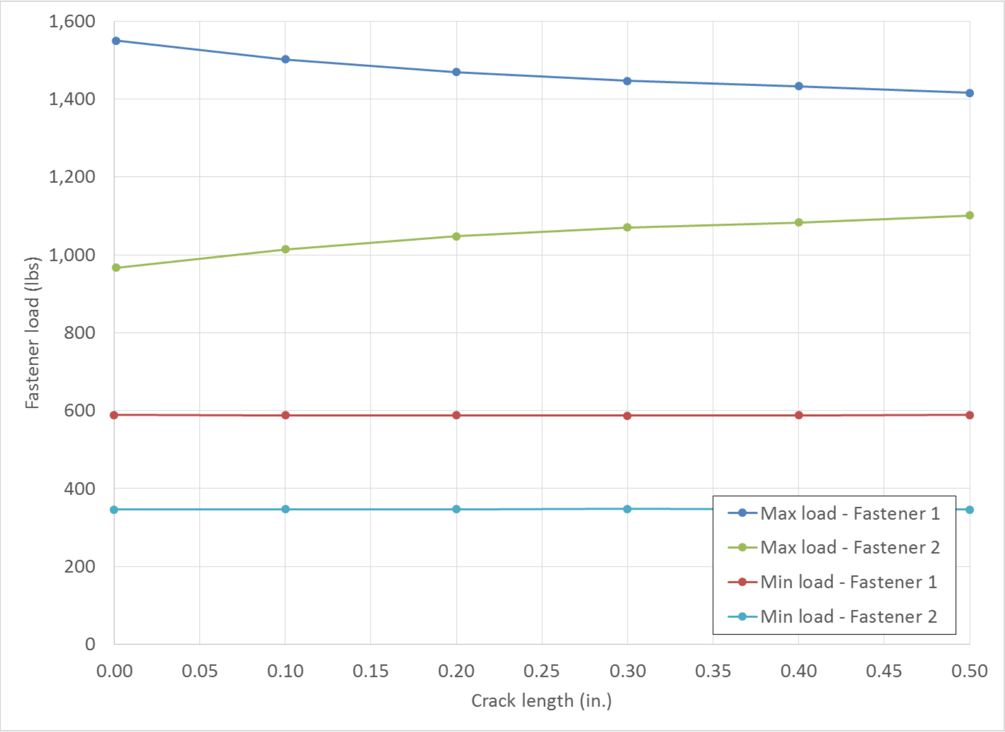
Specimen 2 FEM Results

- Von Mises stress profiles for uncracked and cracked models



Specimen 2 FEM Results

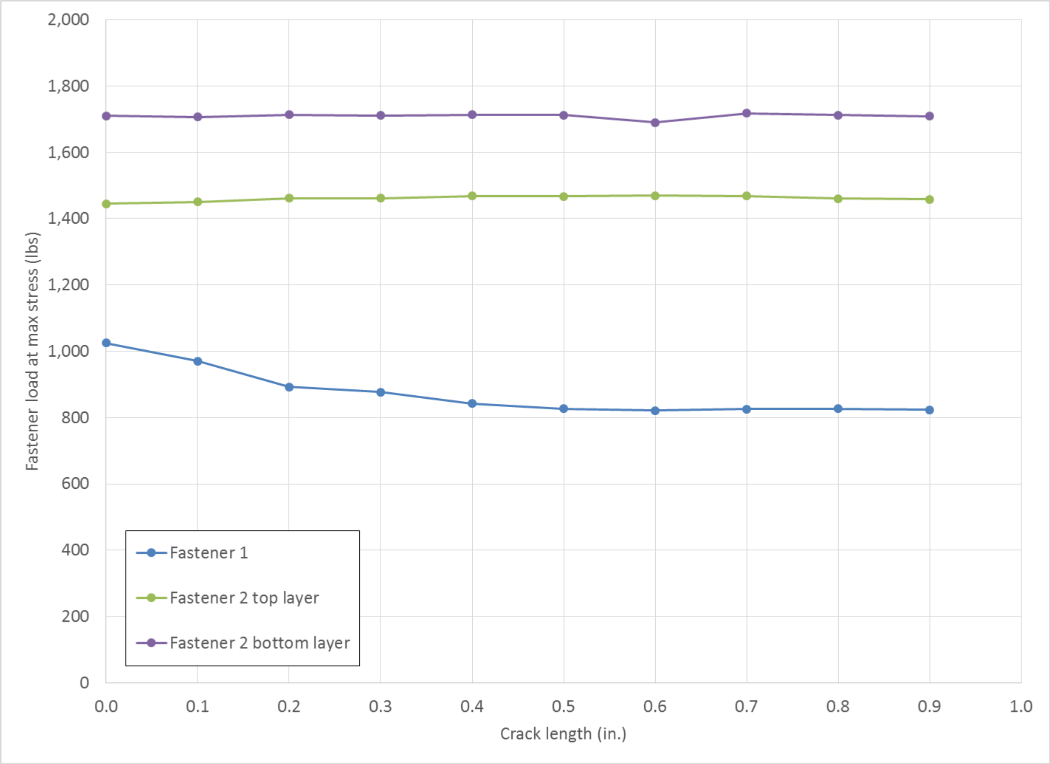
- Reaction force on each pin used to estimate fastener loads
- In tension, load shifts from cracked fastener hole (1) to uncracked hole (2) as the crack grows
- Crack length has no effect on fastener load distribution in compression



Incorporation of FEA Fastener Loads

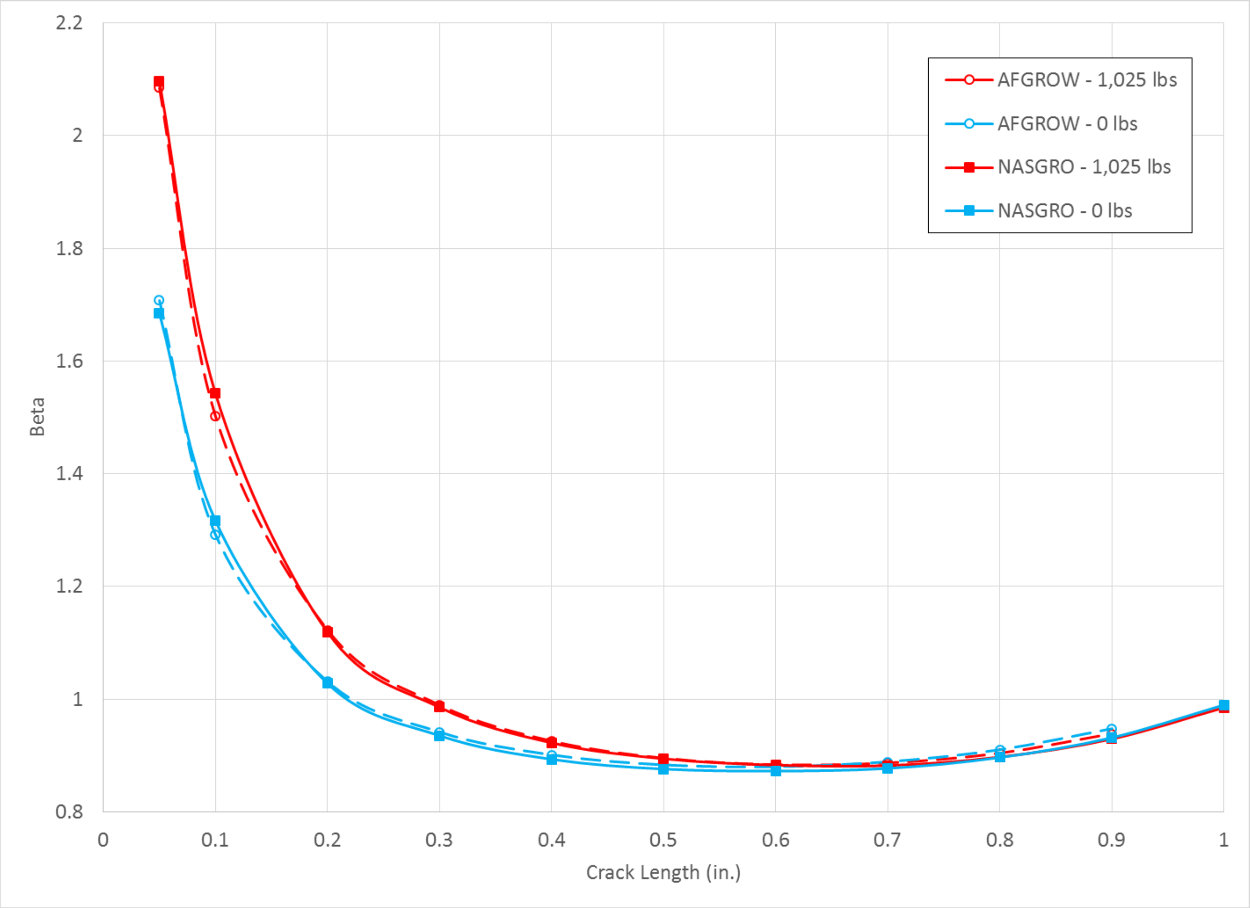
- Specimen 1 FEA fastener loads
  - $(\beta = TSF * \beta_{tension} + BSF * \beta_{bearing})$

crack length (in.)	Fastener 1 load at max stress (lbs)	Decrease from initial load	TSF at max stress	BSF at max stress
0.0	1025	0.0%	0.904	1.515
0.1	971	5.3%	0.909	1.435
0.2	893	12.9%	0.917	1.320
0.3	877	14.4%	0.918	1.296
0.4	842	17.9%	0.921	1.245
0.5	827	19.3%	0.923	1.223
0.6	821	19.9%	0.923	1.214
0.7	826	19.4%	0.923	1.221
0.8	827	19.3%	0.923	1.223
0.9	823	19.7%	0.923	1.217



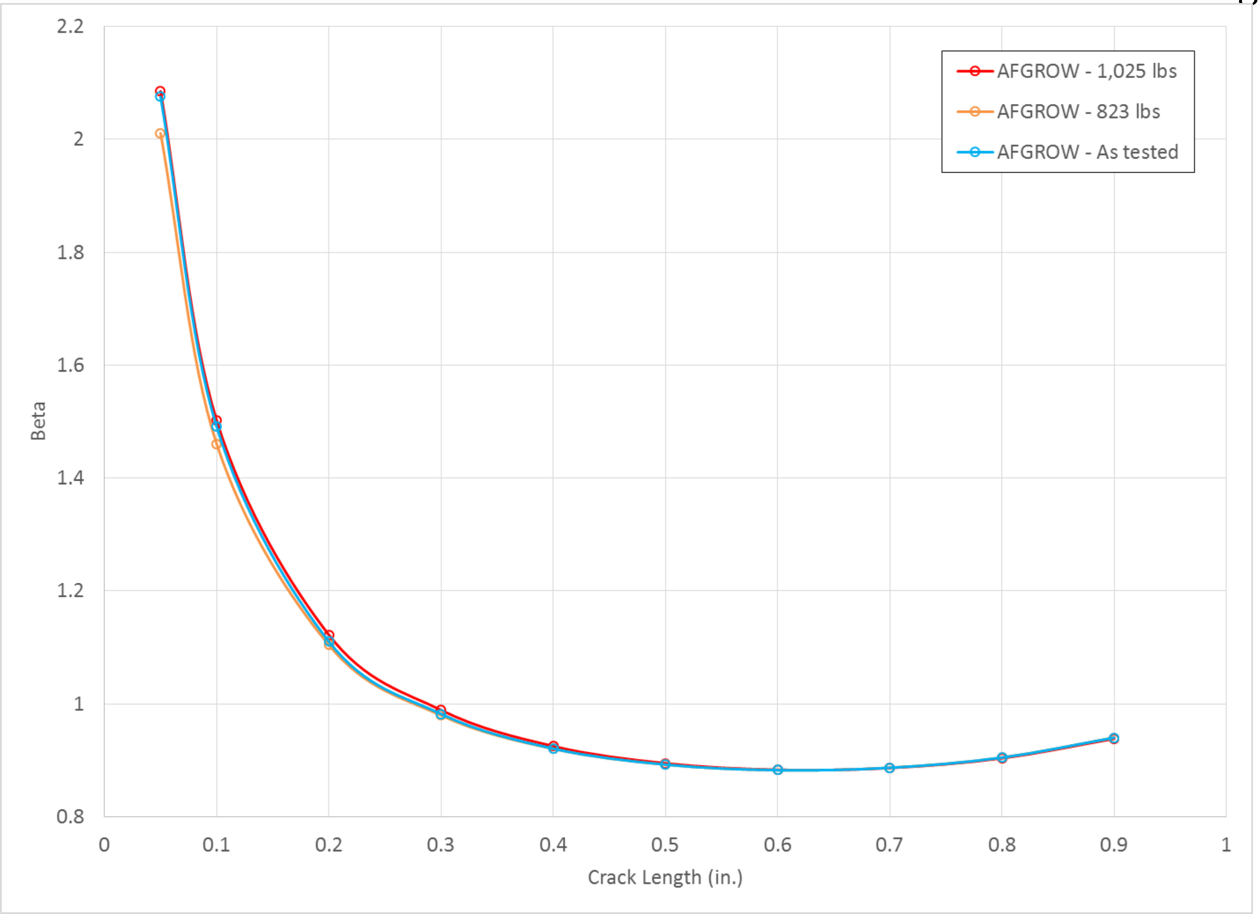
Incorporation of FEA Fastener Loads

- Development and verification of beta values at 0 and 1,025 lbs load transfer using AFGROW, NASGRO, and StressCheck



Incorporation of FEA Fastener Loads

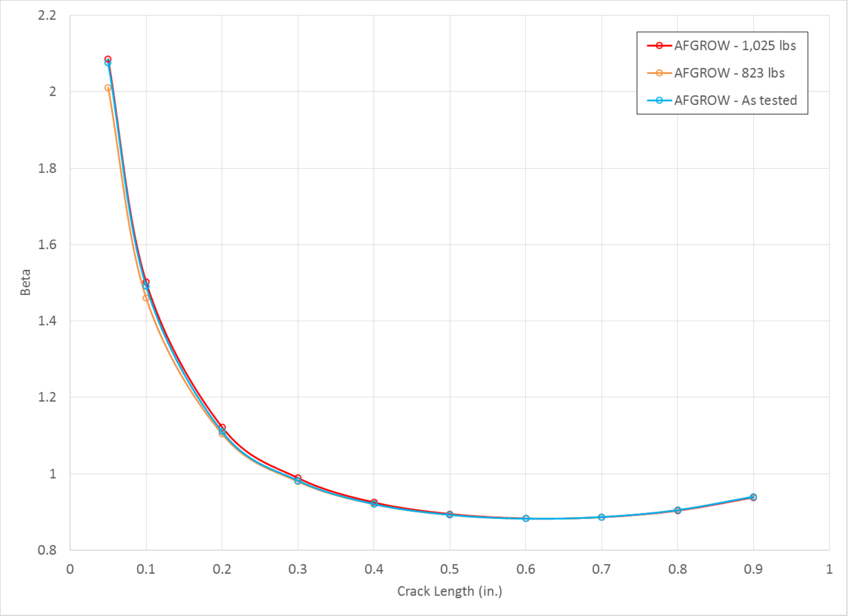
- Development of beta values at actual load transfer values for each crack increment ($\beta = TSF * \beta_{tension} + BSF * \beta_{bearing}$)



Incorporation of FEA Fastener Loads

- Development of beta correction values for compounding against AFGROW model betas

crack length (in.)	beta (1,025 lbs)	beta (actual loads)	beta correction
0.01	3.626	3.626	1.000
0.05	2.086	2.076	0.995
0.10	1.502	1.491	0.993
0.20	1.122	1.110	0.990
0.30	0.989	0.982	0.993
0.40	0.925	0.921	0.995
0.50	0.895	0.892	0.998
0.60	0.883	0.882	0.999
0.70	0.886	0.887	1.001
0.80	0.904	0.905	1.001
0.90	0.938	0.940	1.002



  - Max difference of 1.0%

Incorporation of FEA Fastener Loads

- Specimen 2 results give similar beta corrections

crack length (in.)	fastener load (lbs)	Decrease from initial load	TSF	BSF	beta (1,550 lbs)	beta (actual loads)	beta correction
0.005	1,550	0.0%	0.384	4.237	3.910	3.910	1.000
0.1	1,502	3.1%	0.403	4.106	1.874	1.860	0.992
0.2	1,469	5.2%	0.416	4.015	1.312	1.303	0.993
0.3	1,447	6.7%	0.425	3.954	1.144	1.141	0.997
0.4	1,434	7.5%	0.430	3.917	1.140	1.141	1.000
0.5	1,416	8.7%	0.438	3.869	1.328	1.331	1.002

  - Max difference of 0.8%

Incorporation of FEA Fastener Loads

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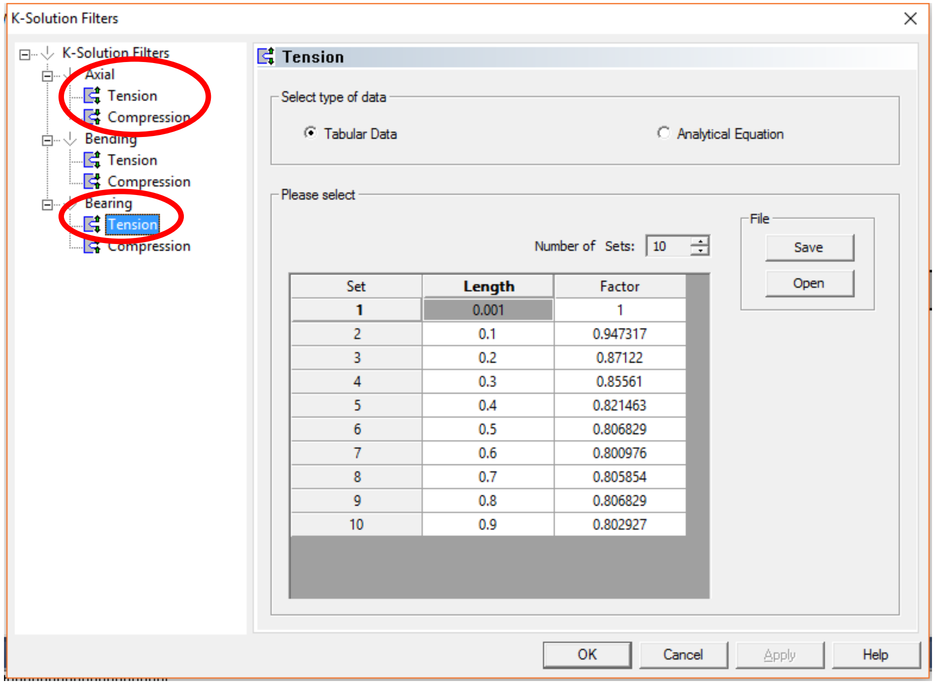
0.4	1,434	7.5%	0.430	3.917	1.140	1.141	1.000
0.5	1,416	8.7%	0.438	3.869	1.328	1.331	1.002

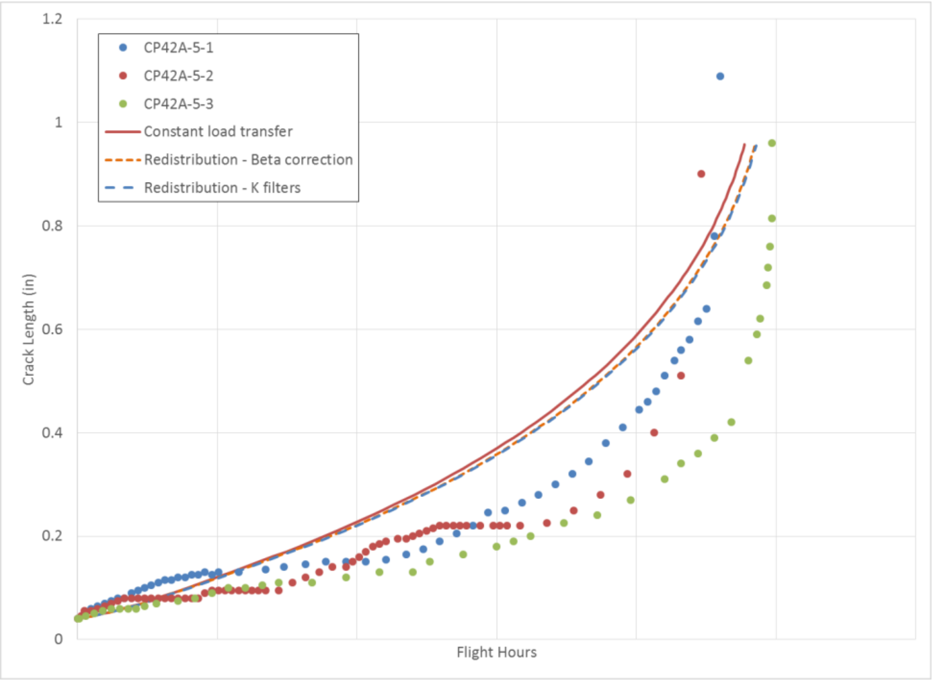
- Max difference of 0.8%

- Impact for both geometries is less than 2% increase in analytical life

Incorporation of FEA Fastener Loads

- Ran the same comparison using AFGROW K-Solution Filters
  - Allows user to change scaling of applied tension, bending, and bearing independently by crack length

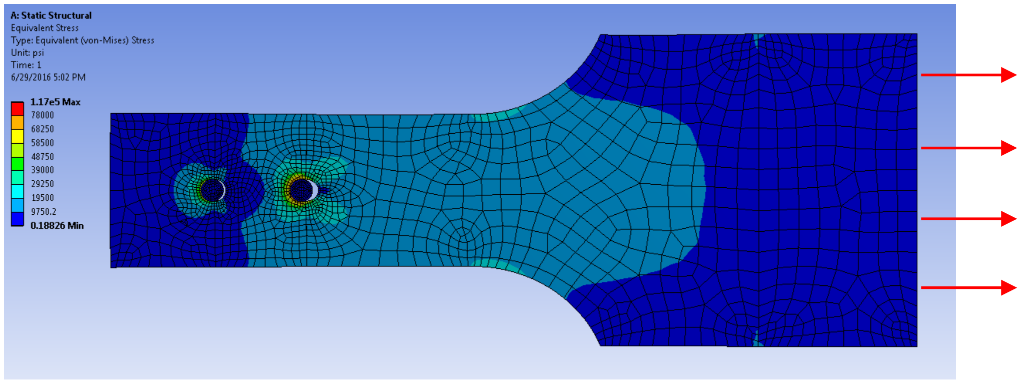




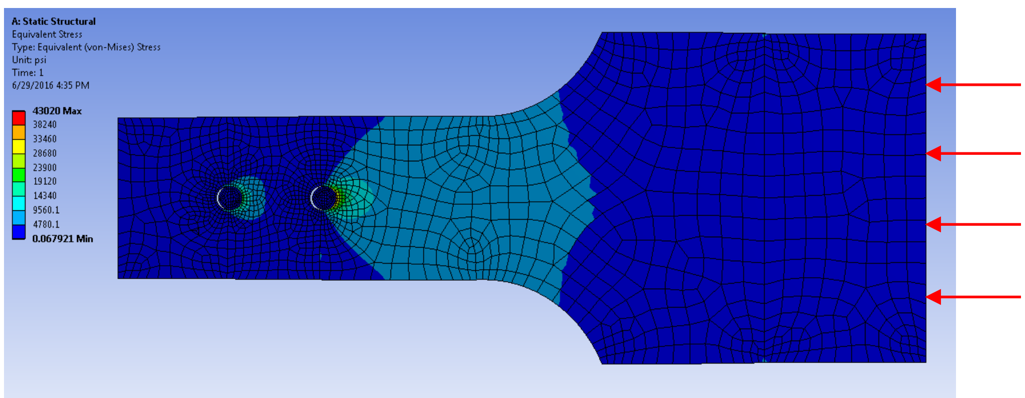
➢ Nearly identical results to Beta Correction for both geometries

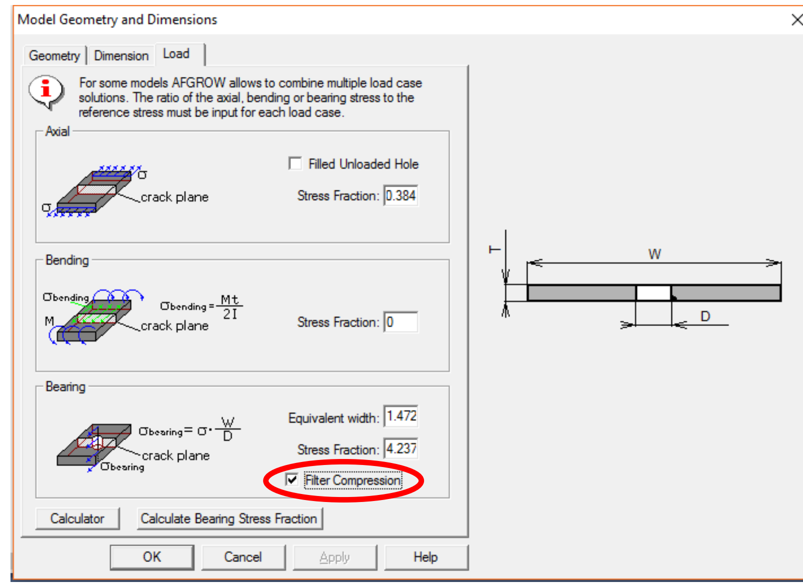
Load Transfer in Compression

- Tension:



- Compression:

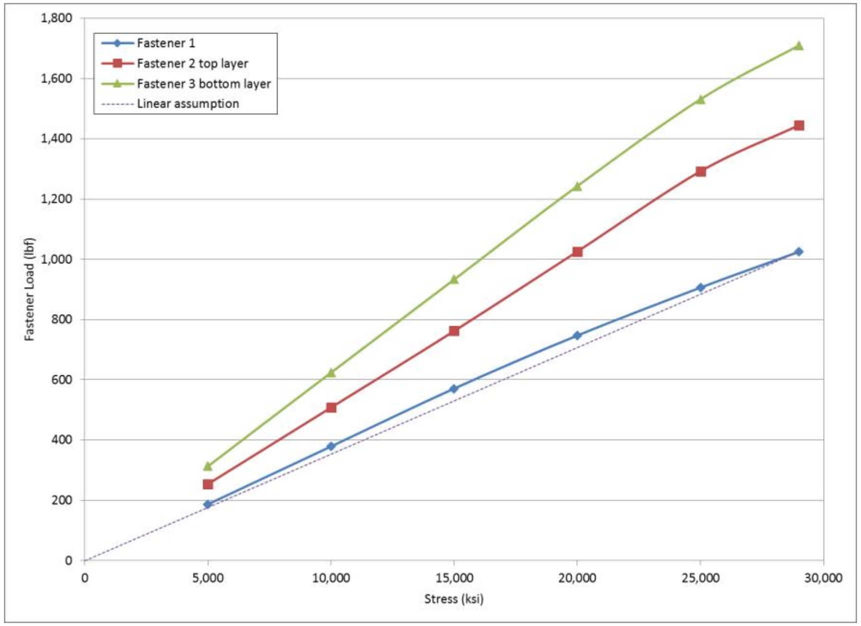




➢ Analytical life impact for these specimens less than 0.5%

Load Transfer at Max vs. Partial Load

- Max stress for Specimen 1 spectrum is ~29 ksi, but 80% of the cycles are below 14 ksi
- Looked at fastener loads at varying stress levels
  - Fastener 1 load is up to 8% higher than expected, assuming max stress load transfer percentage
- Specimen 2 much closer to linear
  - Applied stress not as high relative to material yield strength
  - Max nonlinearity <2%

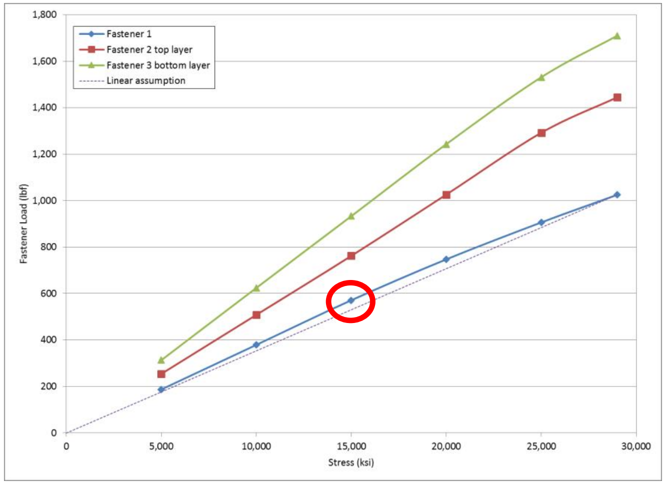


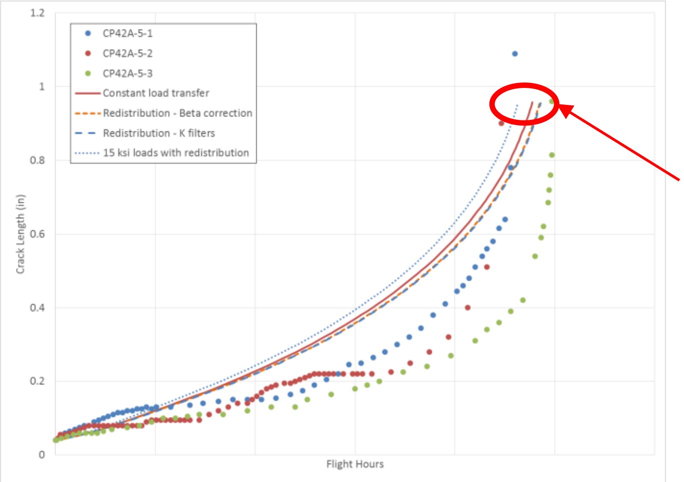
Load Transfer at Max vs. Partial Load

- LexTech developing a multichannel spectrum format for using different ratios of tension, bending, and bearing by loading cycle

Cycle	Ten max	Ten min	Bend max	Bend min	Bear max	Bear min	Cycles
1	0.31194	0.11648	0	0	0.34396	0.13117	1
2	0.30498	0.11511	0	0	0.33655	0.12964	1
3	0.11648	0.11511	0	0	0.13117	0.12964	1
4	0.30498	0.11648	0	0	0.33655	0.13117	1
5	0.62129	0.11648	0	0	0.65946	0.13117	1
6	0.36880	0.11511	0	0	0.40400	0.12964	1
7	0.36880	0.11511	0	0	0.40400	0.12964	1

  - Not yet implemented in current version
- Bounded problem by using maximum bearing stress fraction





Life decreased by 3% over redistributed analysis, and 2% over constant load transfer analysis

Conclusions and Recommendations

- Accurate modeling of fastener loads requires knowledge of test conditions
  - Modeling assumptions were applicable for these cases because of certain test conditions (Teflon coatings, custom clevis, etc.)
- Incorporation of load redistribution in this type of geometry is largely negligible
  - Fastener load differences grow as crack grows large, when impacts on stress intensities and lives are smallest
- In most geometries, bearing should not be included when load is negative
  - Minimal impact here because of tension-dominated loading
- Relationship between applied load and fastener load not necessarily linear
  - Impact is small, and offset by impact of load redistribution