B-2 and WU-402 Detail Analysis Using BAMpF

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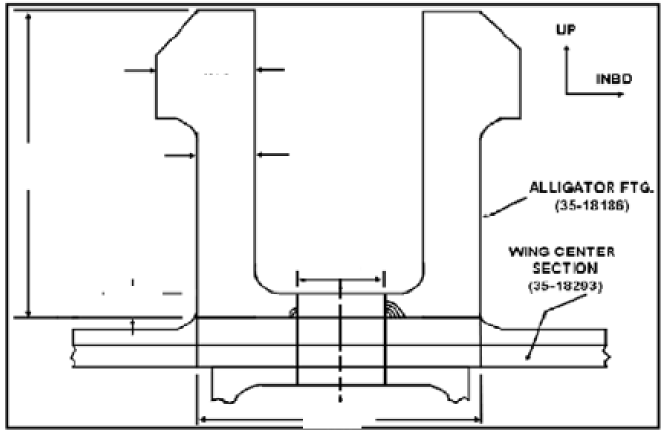
14 Sept 2022

Outline

- B-2 Detail Location
- Boeing Data and Model Development
- Loads and Constraints
- BAMpF Transitions
- Constraint Method Variance
- Refined Constraint Methods
- WU-402 Residual Stress Measurements
- RS Incorporation into BAMpF
- Pin Correction and Contact

B-2 Detail Location

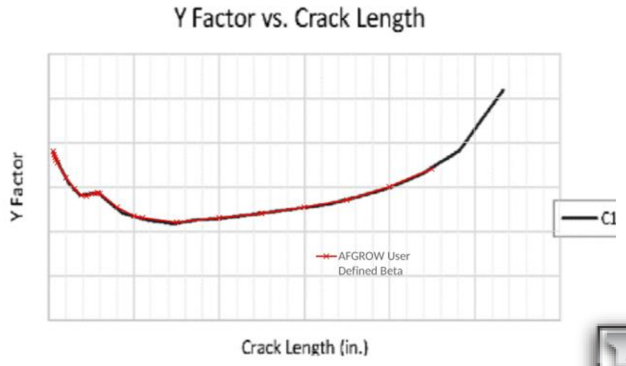
- **The B-2 detail is the primary upper longeron attachment to the fuselage**
- **Primary Concerns**
  - **Critical structure**
  - **Complex geometry**
  - **Short inspection interval**
  - **Difficult inspection process**

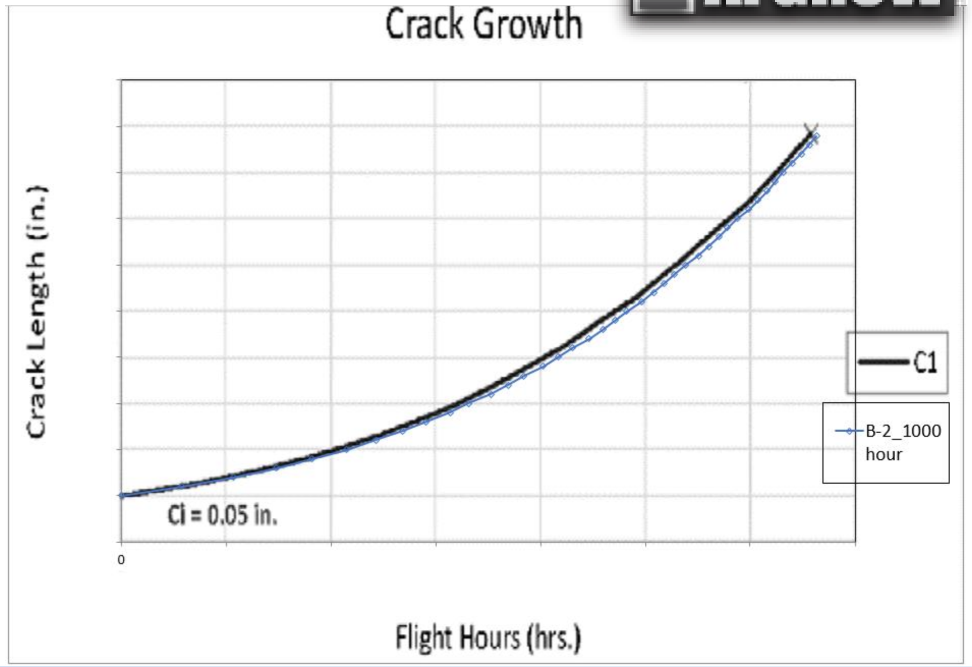


B-2 Detail

Boeing Data and Model Development

- Material: 4340 Steel Forging (180-200ksi)
  - Boeing walker
    - Rlo or Rhi
    - Y Factor = User Defined Beta
    - AFGROW parameters
- Geometry: 0.58in thick, 13.00in wide, 6.50” edge distance
- Initial flaw size .05”
  - Studied as corner crack in a flat plate
  - Initial AFGROW recreation studies correlated well with OEM DTA curves
- BAMpF selected to consider complex geometry





The Walker/Erdogan crack growth rate, $(dc/dN)_j$ in Eq. 4-1 is given as:

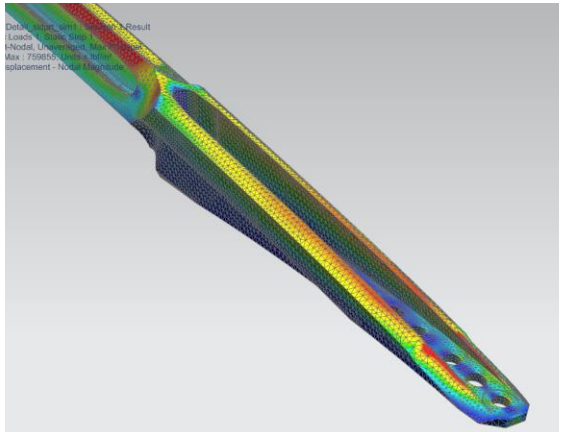
$$\frac{dc}{dN_j} = 10^{-4}\left(Z_j \frac{K_{maxj}}{M}\right)^p \quad \text{Eq. 4-2}$$

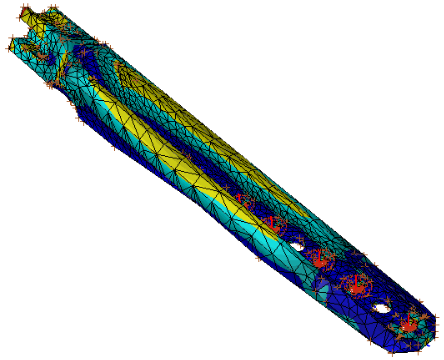
Where,

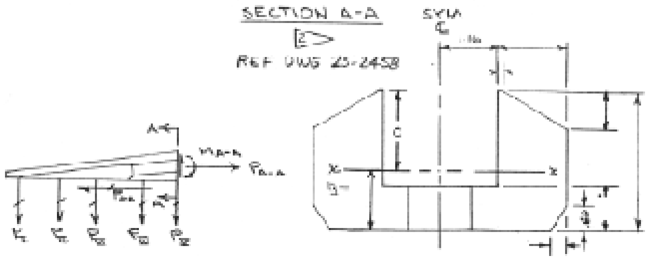
Z_j	minimum stress factor	
	$=(1-R_j)^q$	for $R_j \geq 0$
	$=1-uR_j$	for $R_j \leq 0$
R_j	stress ratio for the j[th] load event (f_{minj}/f_{maxj})	
K_{maxj}	stress intensity factor for the j[th] load event (ksi√in.)	

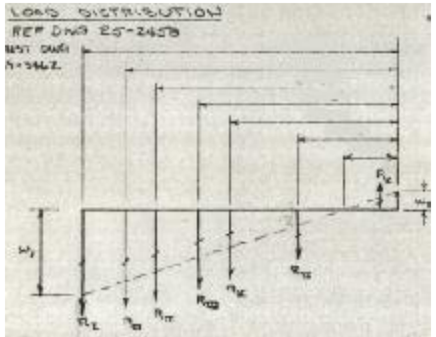
Load and Constraint M1

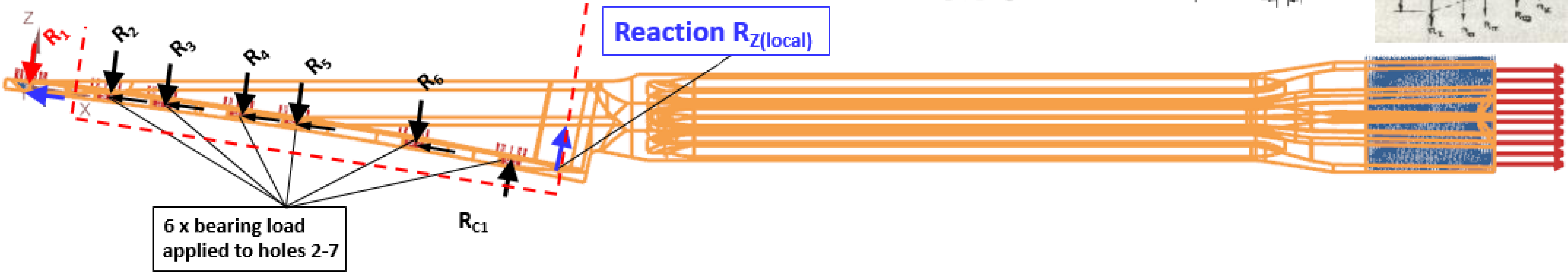
- Initial loads and constraints applied IAW OEM stress reports
- FEM developed based on OEM inputs
- Stress analysis used to determine reasonable locations to truncate model
  - Model size reduced to minimize element count and computational times







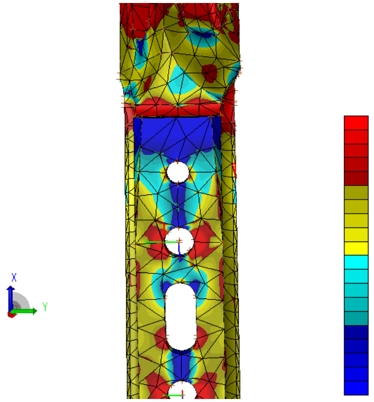




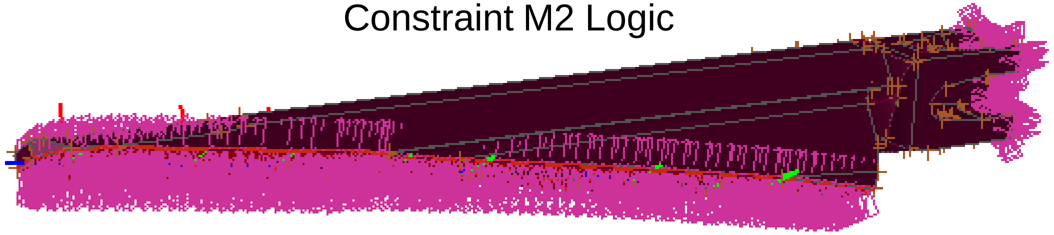
Z Constraint M2

- **Post analysis demonstrated excessive bending in the model.**
  - **Related to lack of realistic constraint logic at the lower interface.**

M2 Stresses

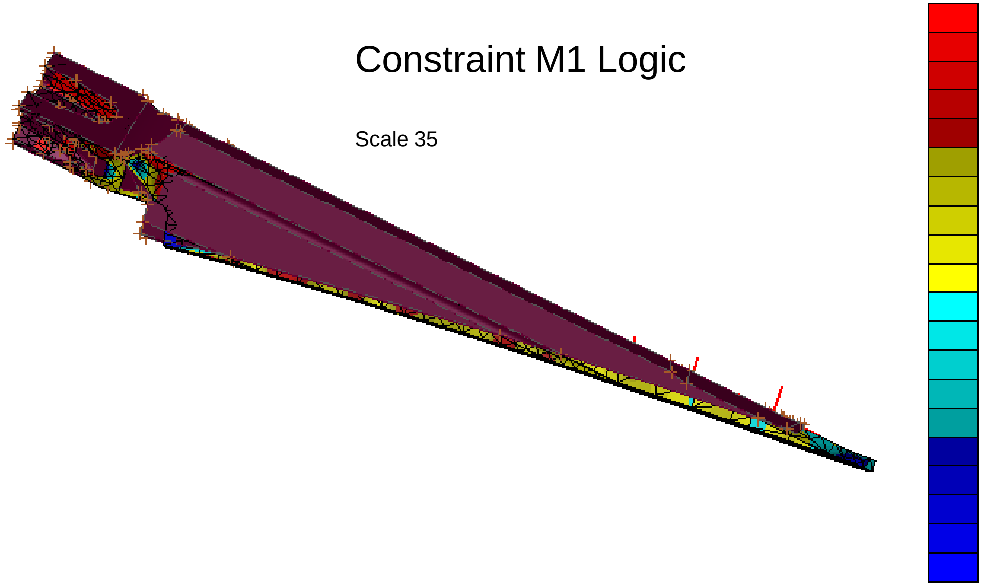


Constraint M2 Logic



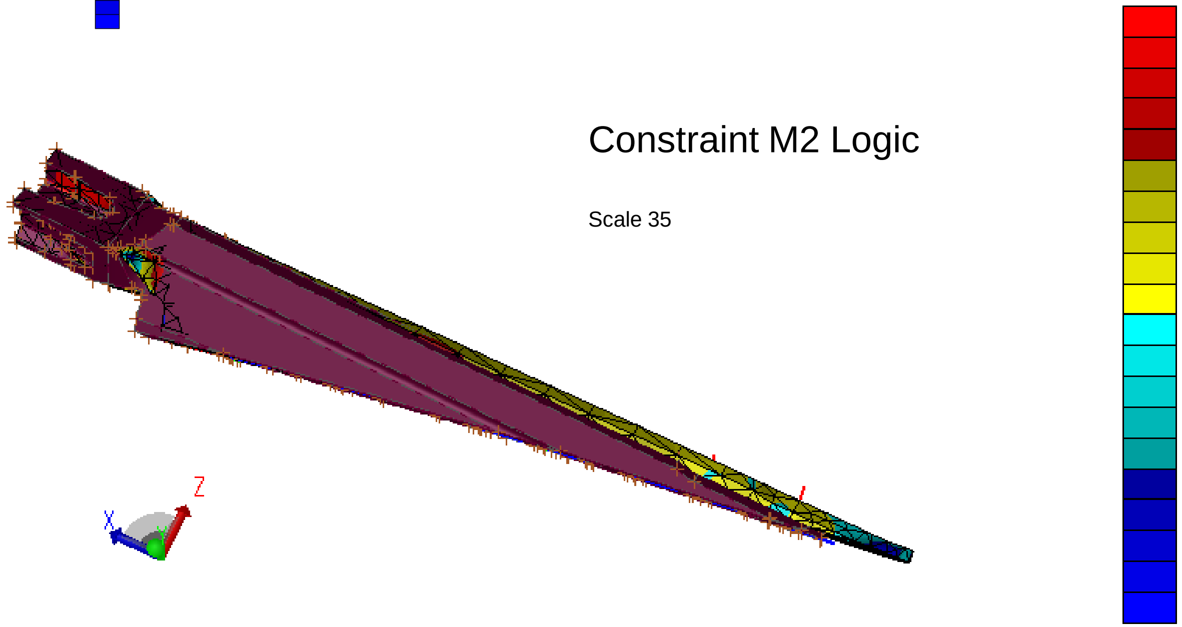
Constraint M1 Logic

Scale 35



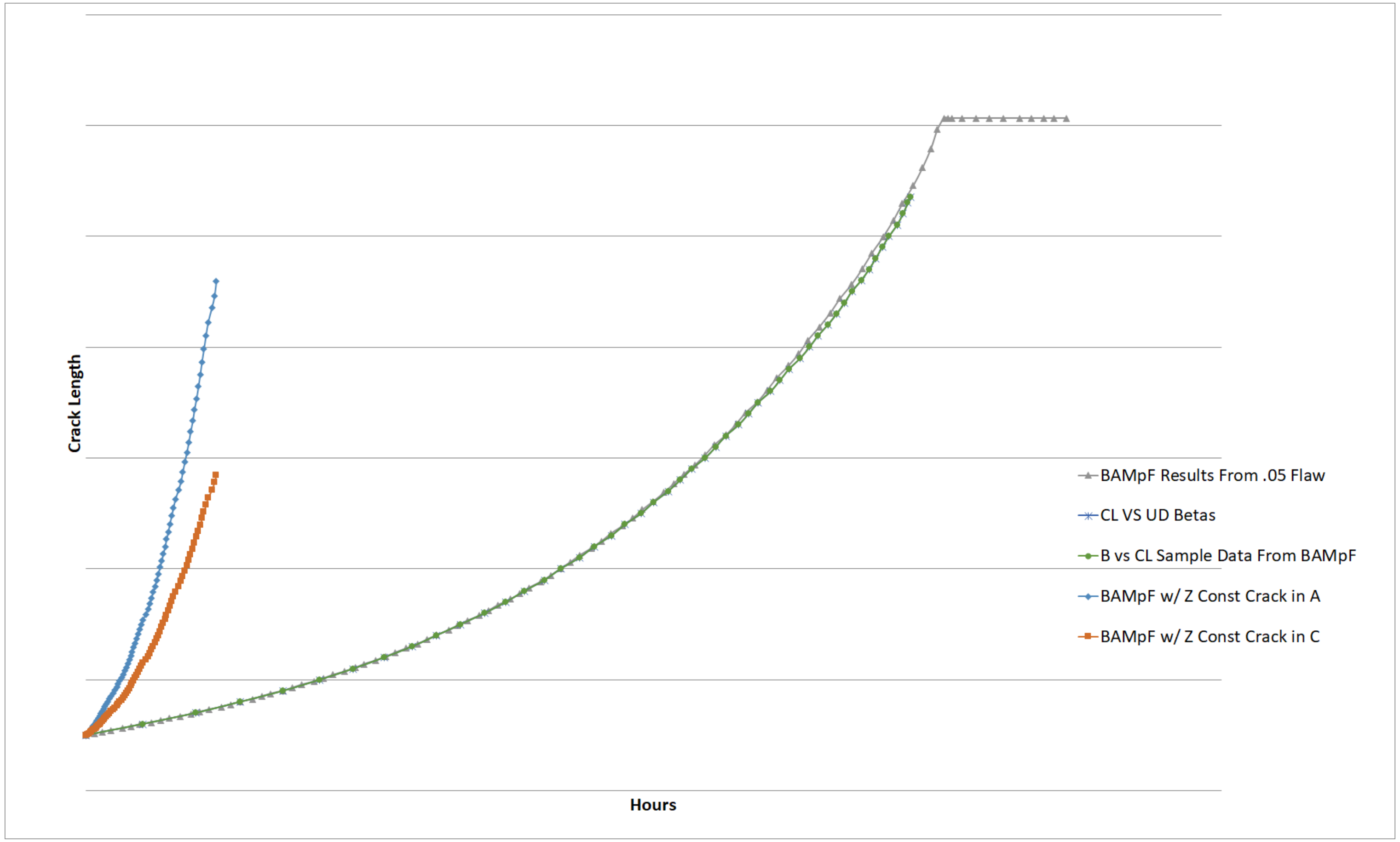
Constraint M2 Logic

Scale 35



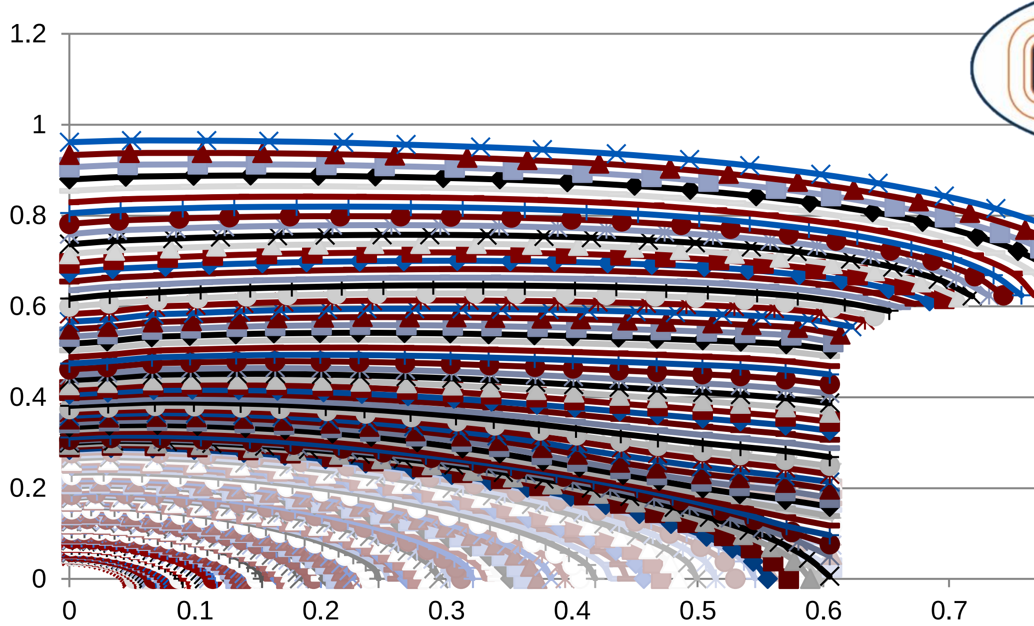
Constraint Method Variance

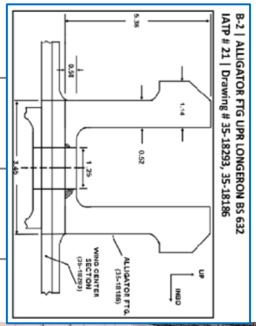
- **Model Variations**
  - **Run with different constraint methods**
    - Under constrained M1
    - Over constrained M2
    - The truth somewhere in the middle
- **More refined constraint methods required**

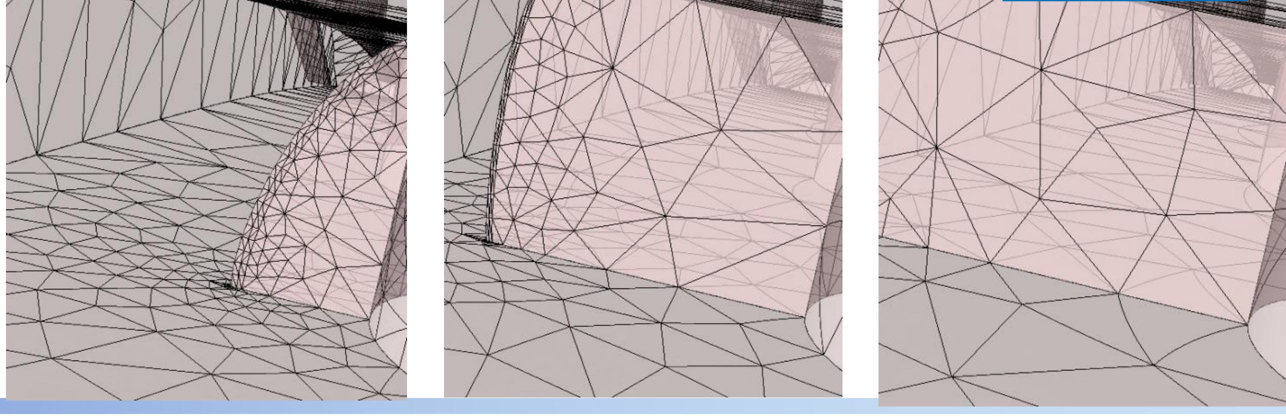


BAMpF Transitions

- **Multiple transition strategies**
  - **AFGROW Growth increment % decreased while approaching transitions**
  - **Crack-front refined above default**
  - **Applied new boundaries to reference points on the spline in the stress check model to ensure points track correctly through transitions**
    - **Points located slightly outside the body but on the crack front spline**

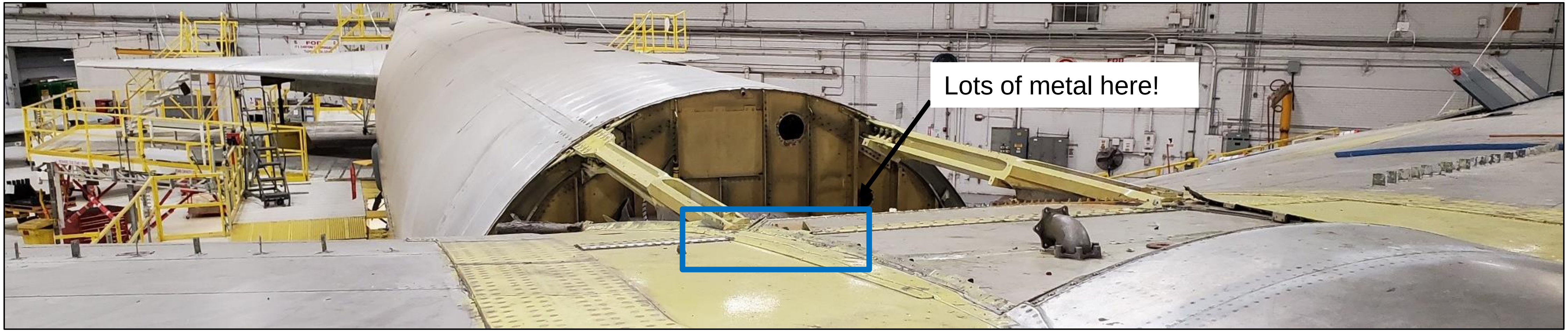






Refined Constraint Methods

- Actual structure is attached with 1.25” bolts to very stiff back-up structure
  - No models of attaching structure
  - Thickness of alligator fitting is about 0.6”, but bolt shank length is over 2”
    - Shows rest of stack-up is quite thick
  - Very large bolt preload (~52,000 lbs)
- An approximation of this setup was created in Simcenter



Simcenter Constraints

- **Surface created to mate with alligator fitting that was fixed**
- **CELAS springs created for fastener shear stiffness**
  - **CELAS are independent of spring length (unlike CBUSH)**
    - **Simplifies overall configuration**
    - **Spring stiffness determined using Huth fastener stiffness model**

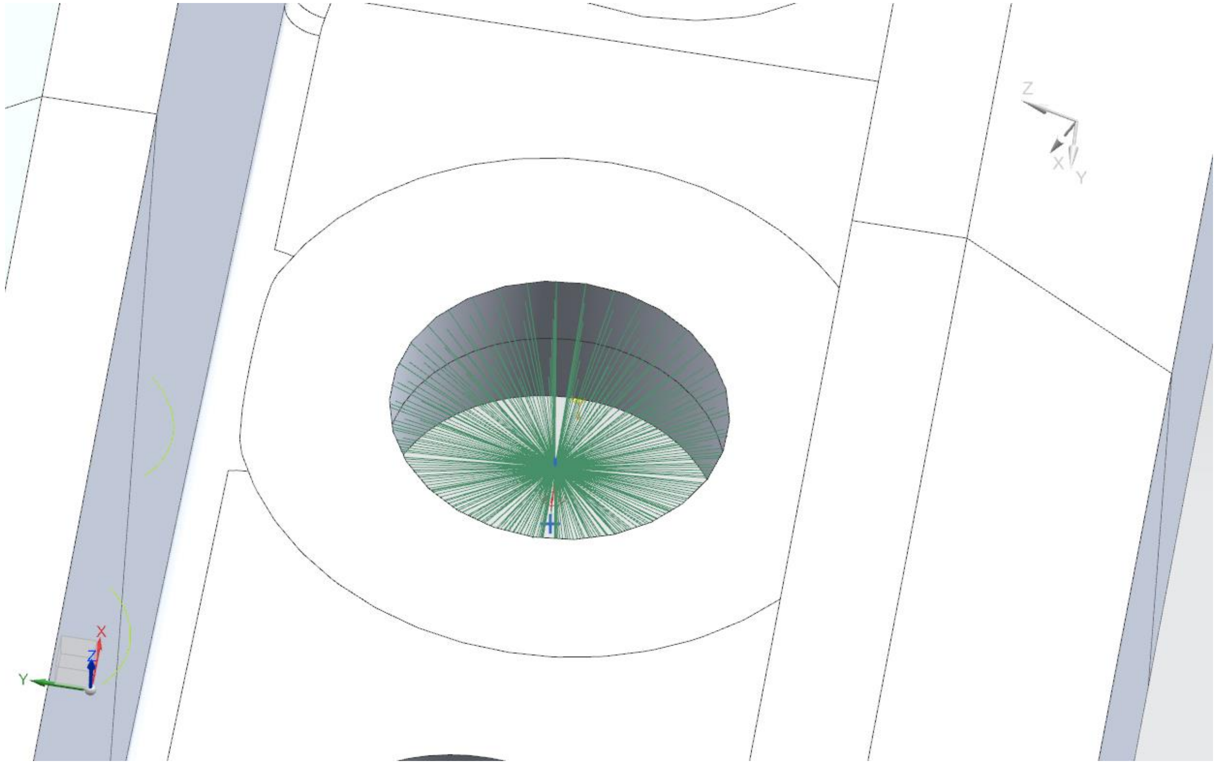
$$f = \left(\frac{t_1 + t_2}{2d}\right)^a * \frac{b}{n}\left(\frac{1}{t_1 E_1} + \frac{1}{n t_2 E_2} + \frac{1}{2 t_1 E_3} + \frac{1}{2 n t_2 E_3}\right)$$

a = .667 and b = 3.0
E_1 = steel modulus
E_2 = aluminum modulus
E_3 = fastener modulus
t_1 = thickness of alligator fitting
t_2 = bolt grip – thickness of alligator fitting

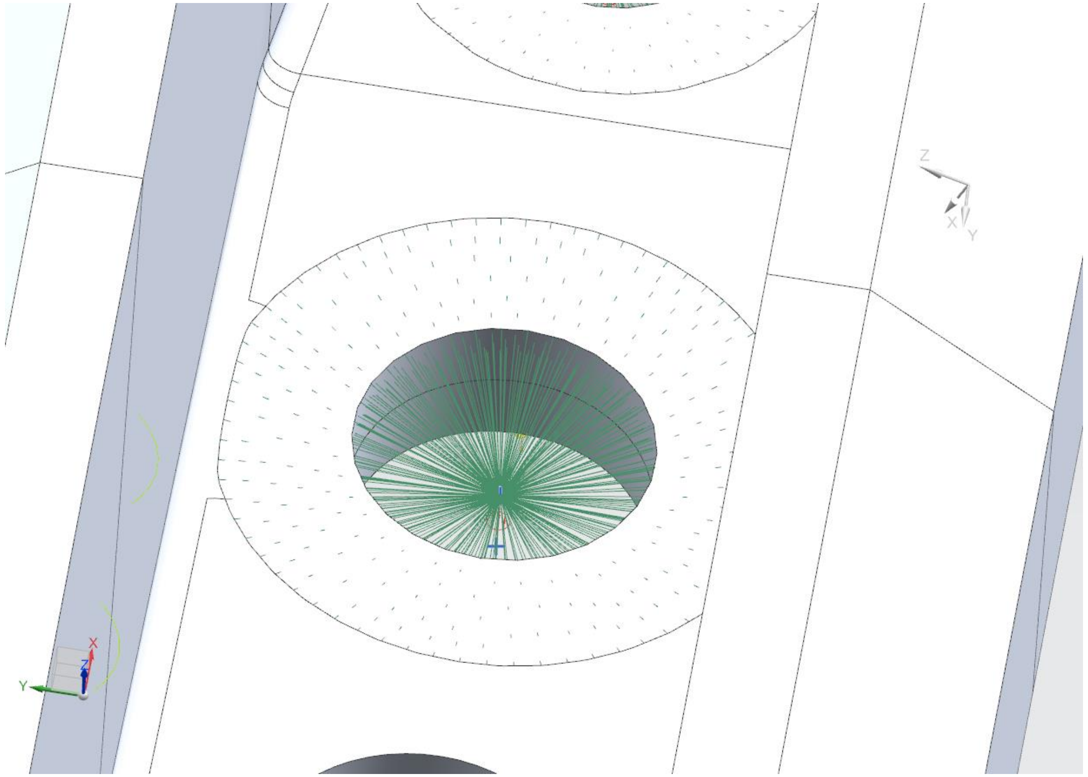
- **Beam elements used for tension and preload application**
- **Two versions for fastener attachment**
  - **Springs and beam attached to hole shank through RBE3 elements (fastener 1)**
  - **Springs attached to hole shank with RBE3 and Beam elements attached to fastener head area through RBE2 elements (fastener 2)**

Fastener Approximations

CELAS to hole shank with RBE3s (model 1)

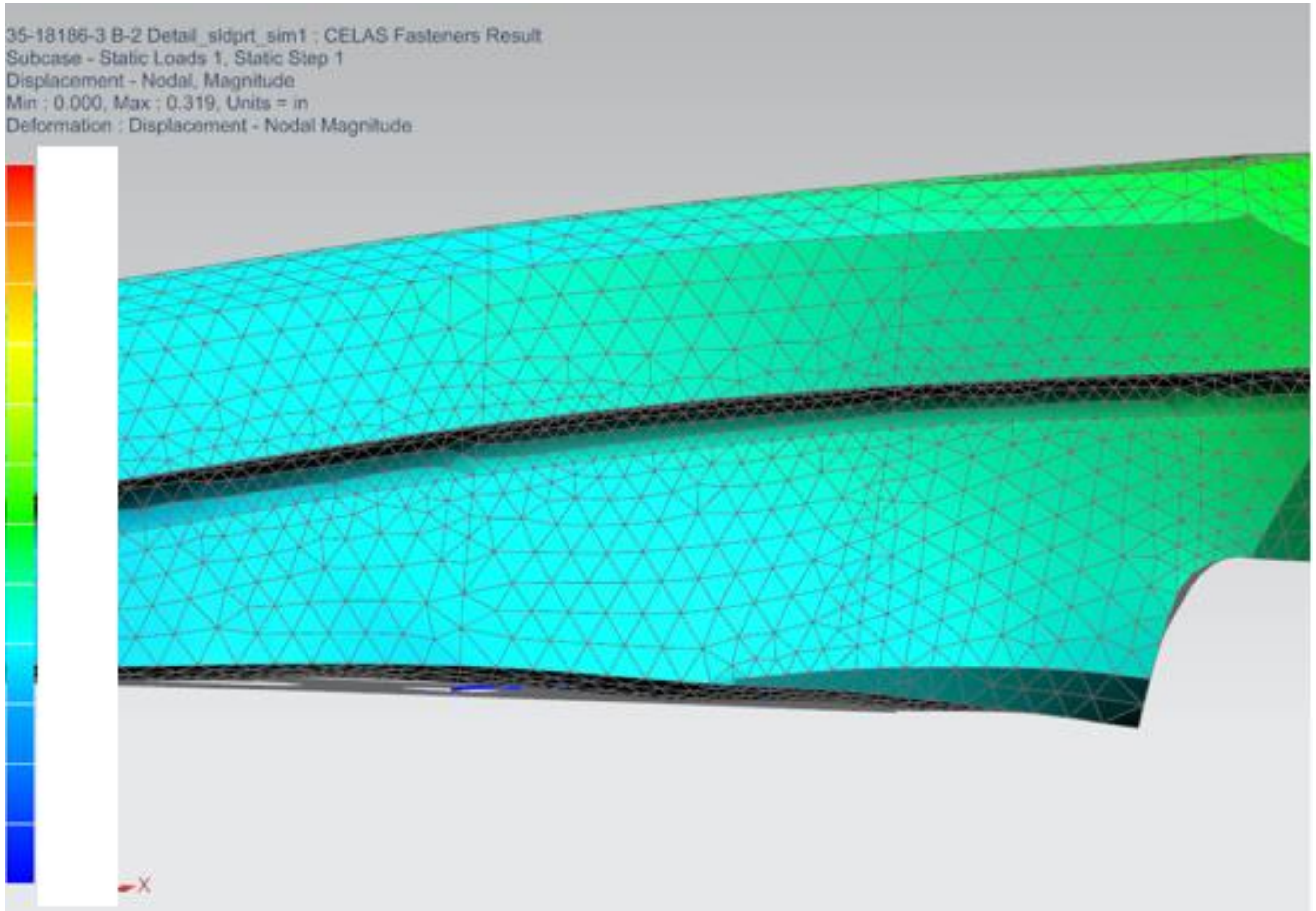


Beam to fastener head area with RBE2s (model 2)

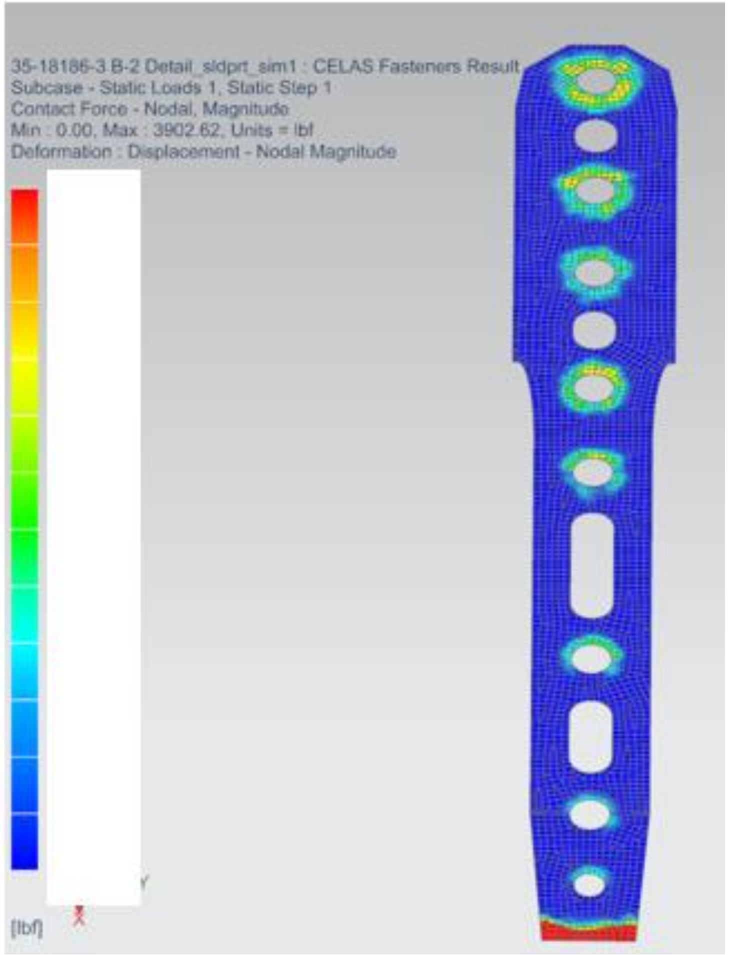


Contact and Displacement

Displacement Side View

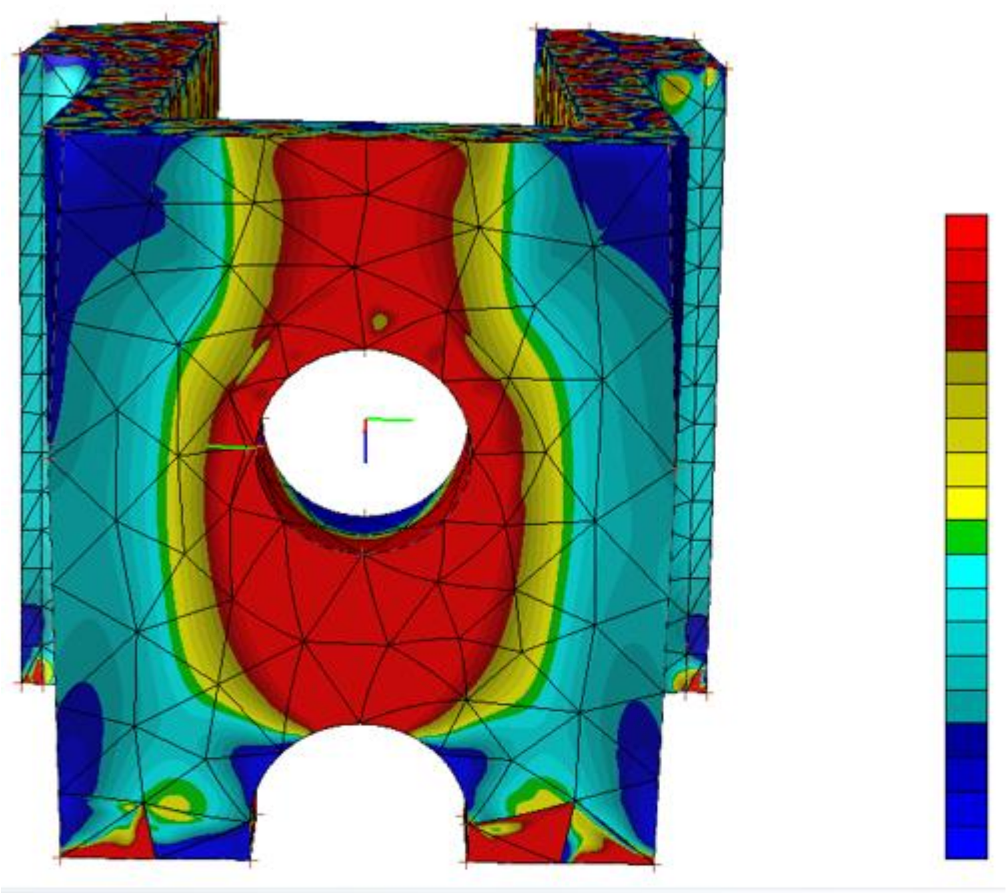


Contact Force

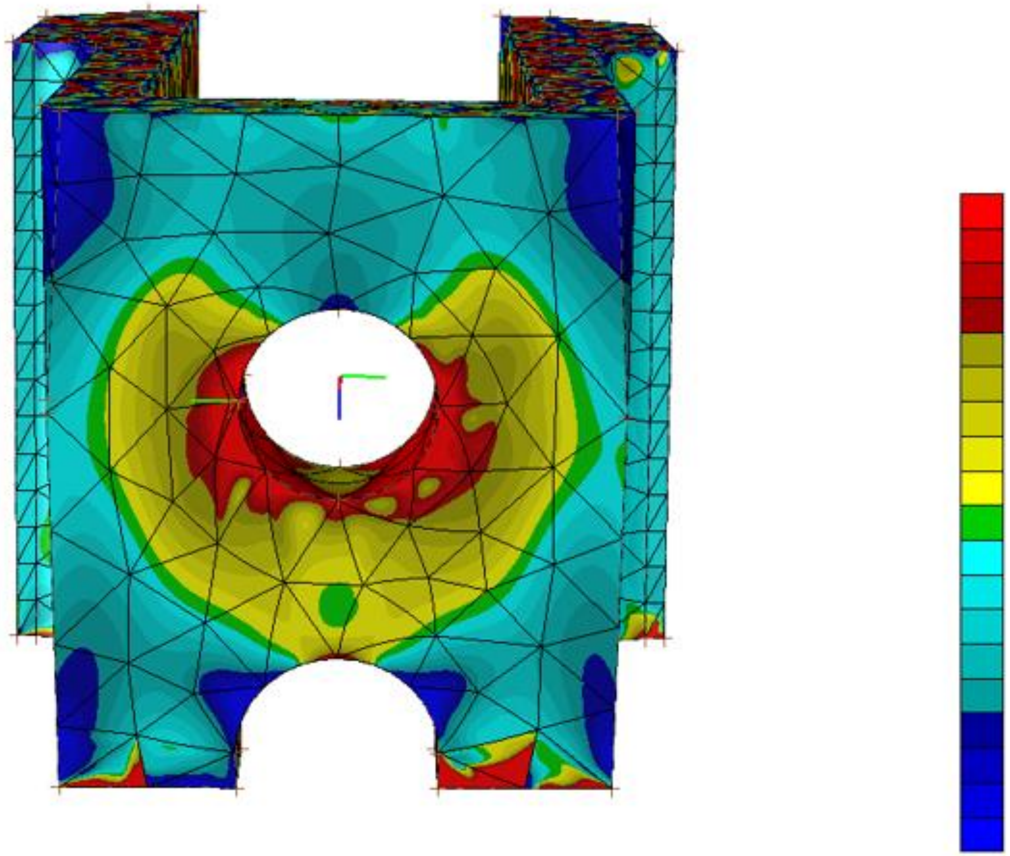


Stress Contour Differences

Fastener 1

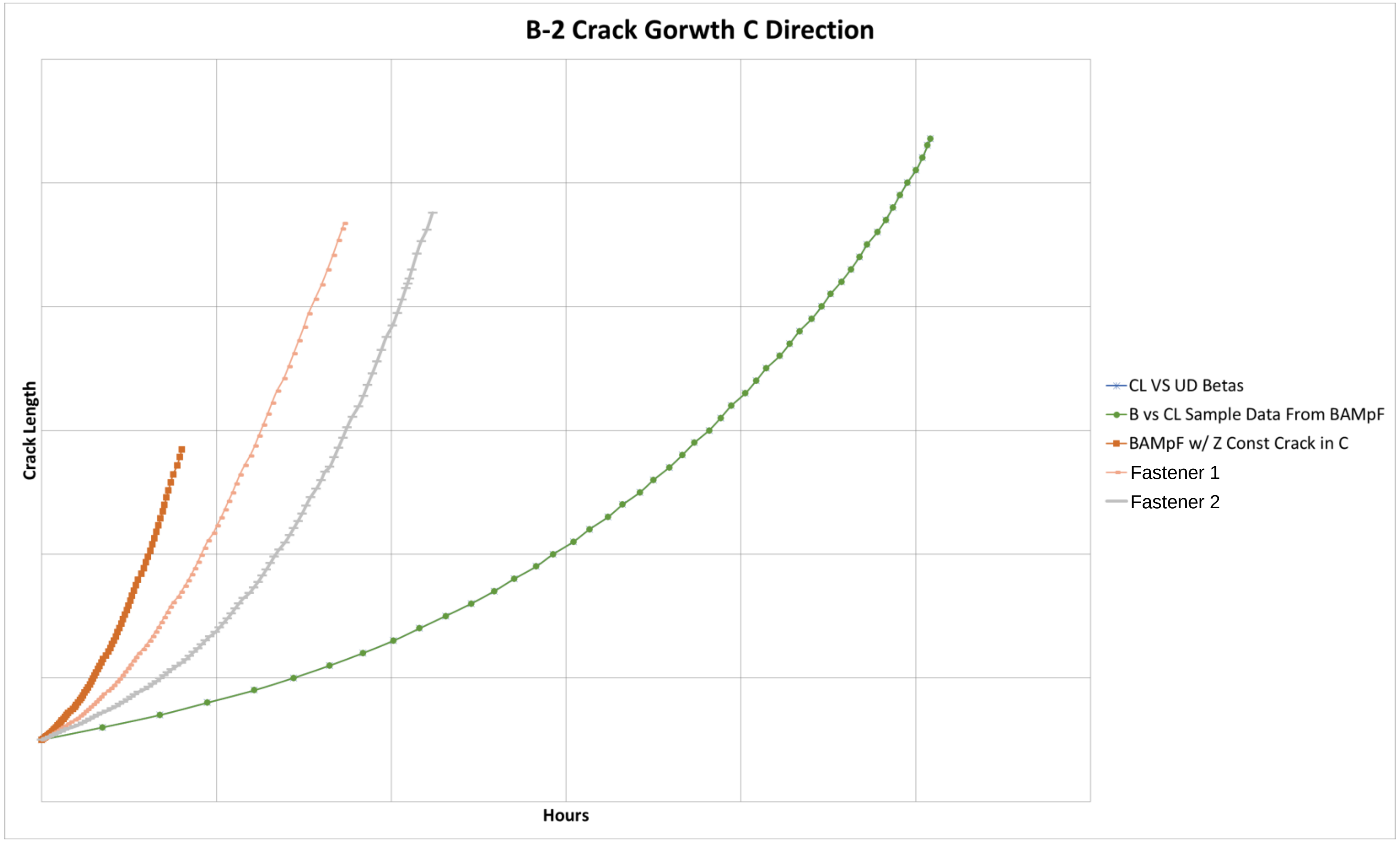


Fastener 2



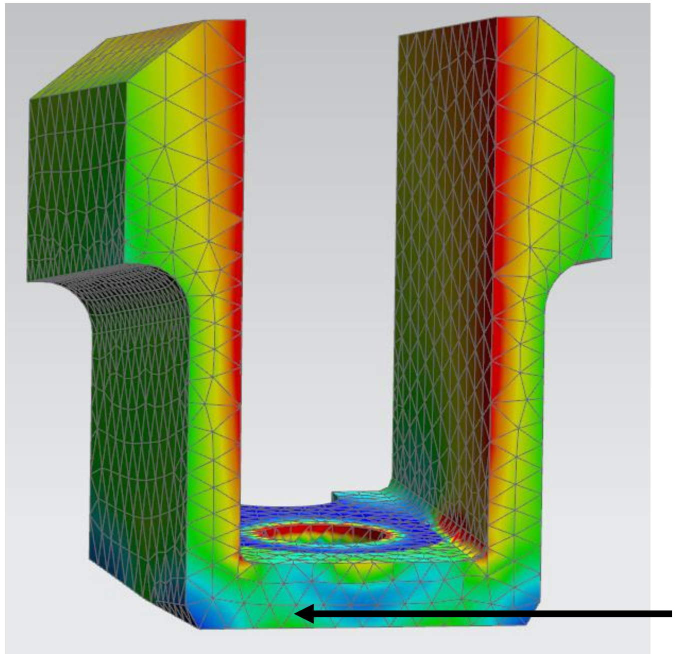
Crack Growth Curve Comparison

- Fastener 1 and Fastener 2 fell between first two constraint methods
- Even within contact modeling constraint method, approximation of fastener makes significant difference

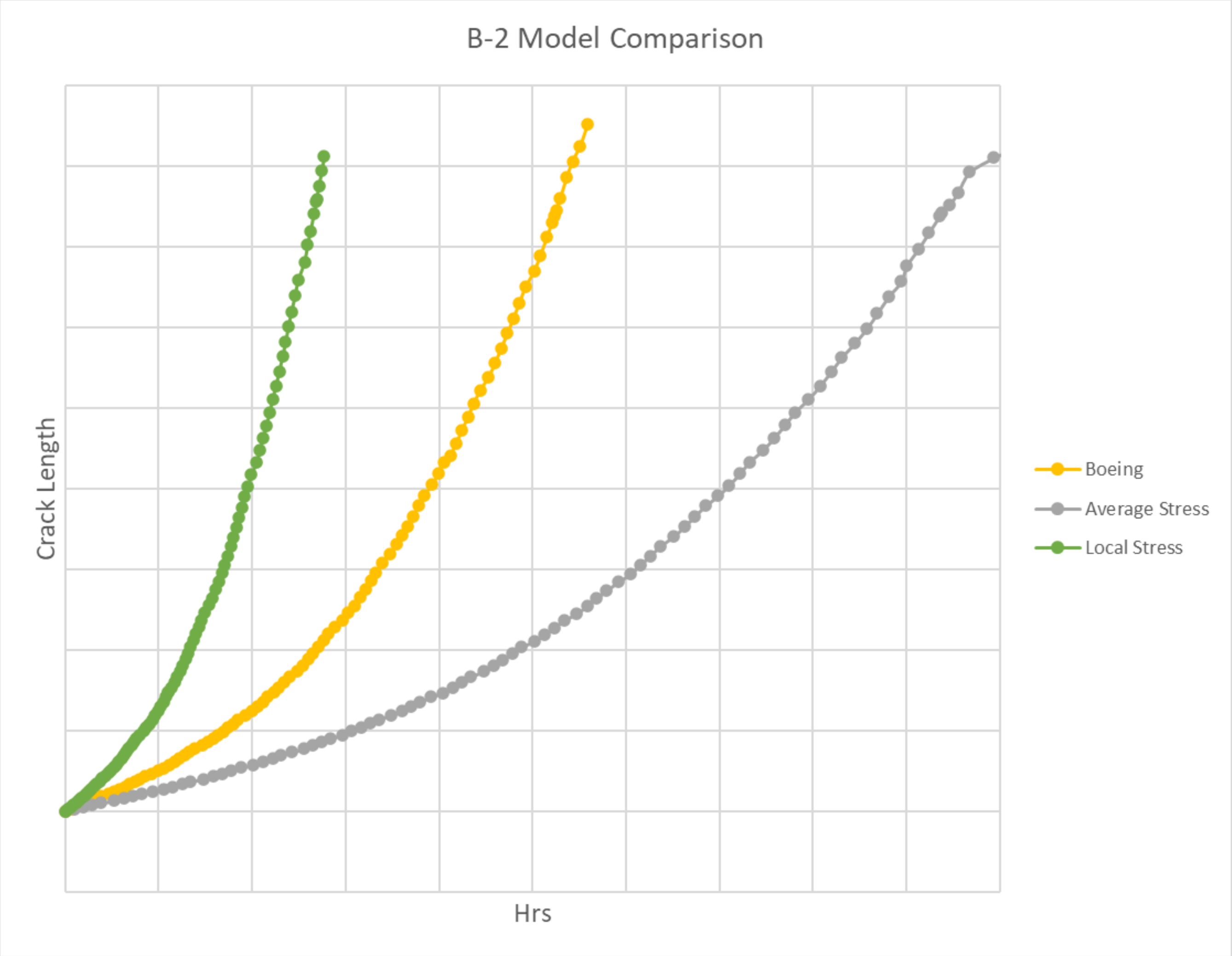


BAMpF Stress Parameter: Difference in CGC

- **Stress local to crack: baseline**
- **Boeing Limit Stress: ~2x baseline**
- **Average stress over section: ~3.5x baseline**
- **Very important to understand how your load condition relates to the peak stress in the spectrum and how the spectrum was created.**



Assumed crack origin

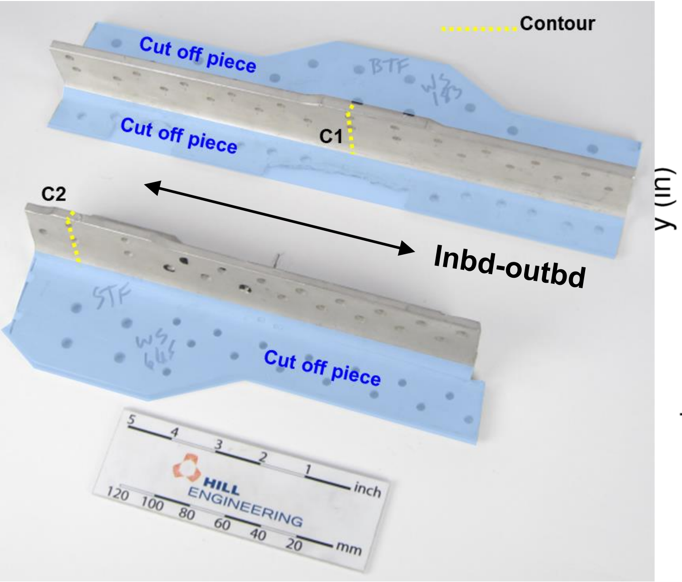


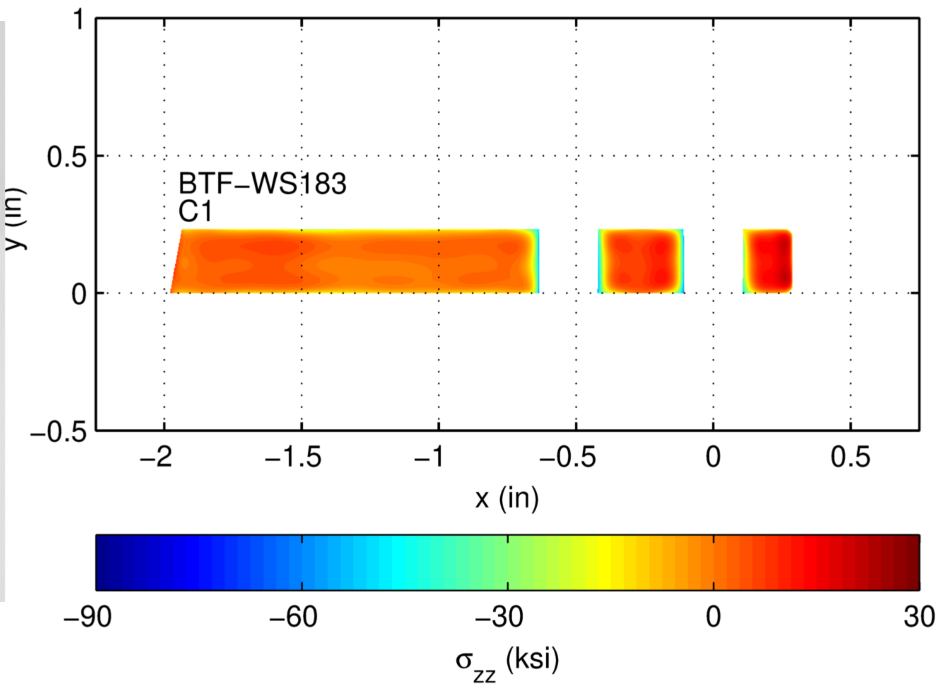
WU-402 Residual Stress

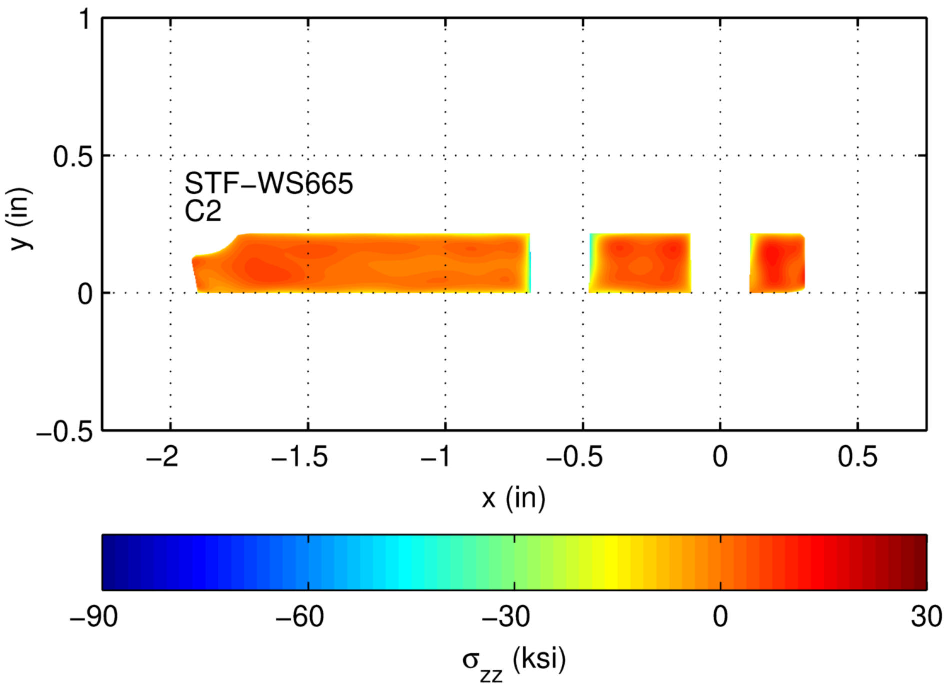
- **WU-402 was the focus of A-10 support for B-52 program**
- **Upper front spar critical location**
  - **Crack growth driven by high negative R cycles at takeoff and landing**
- **Taper-Loks installed where stiffeners intersect spar chord**
- **Analysis completed to attempt to take advantage of Taper-Lok Residual Stress (RS) field from installation**

Contour Measurement

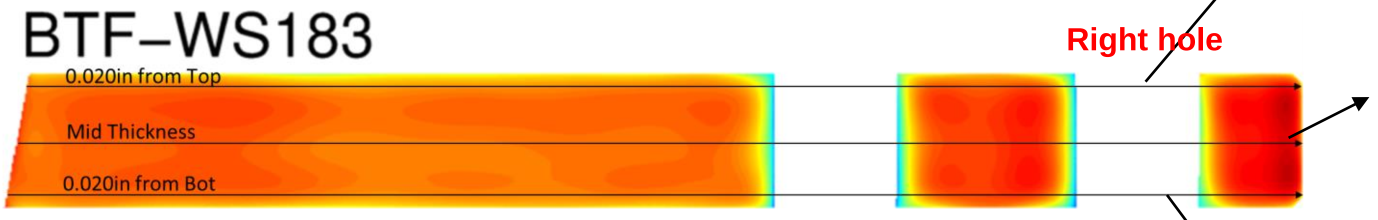
- Hill Engineering performed contour on multiple holes with Taper-Loks installed related to WU-402.
  - Significant variation, especially at hole closer to edge of part

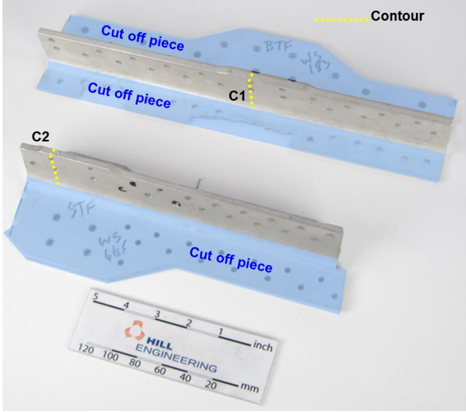


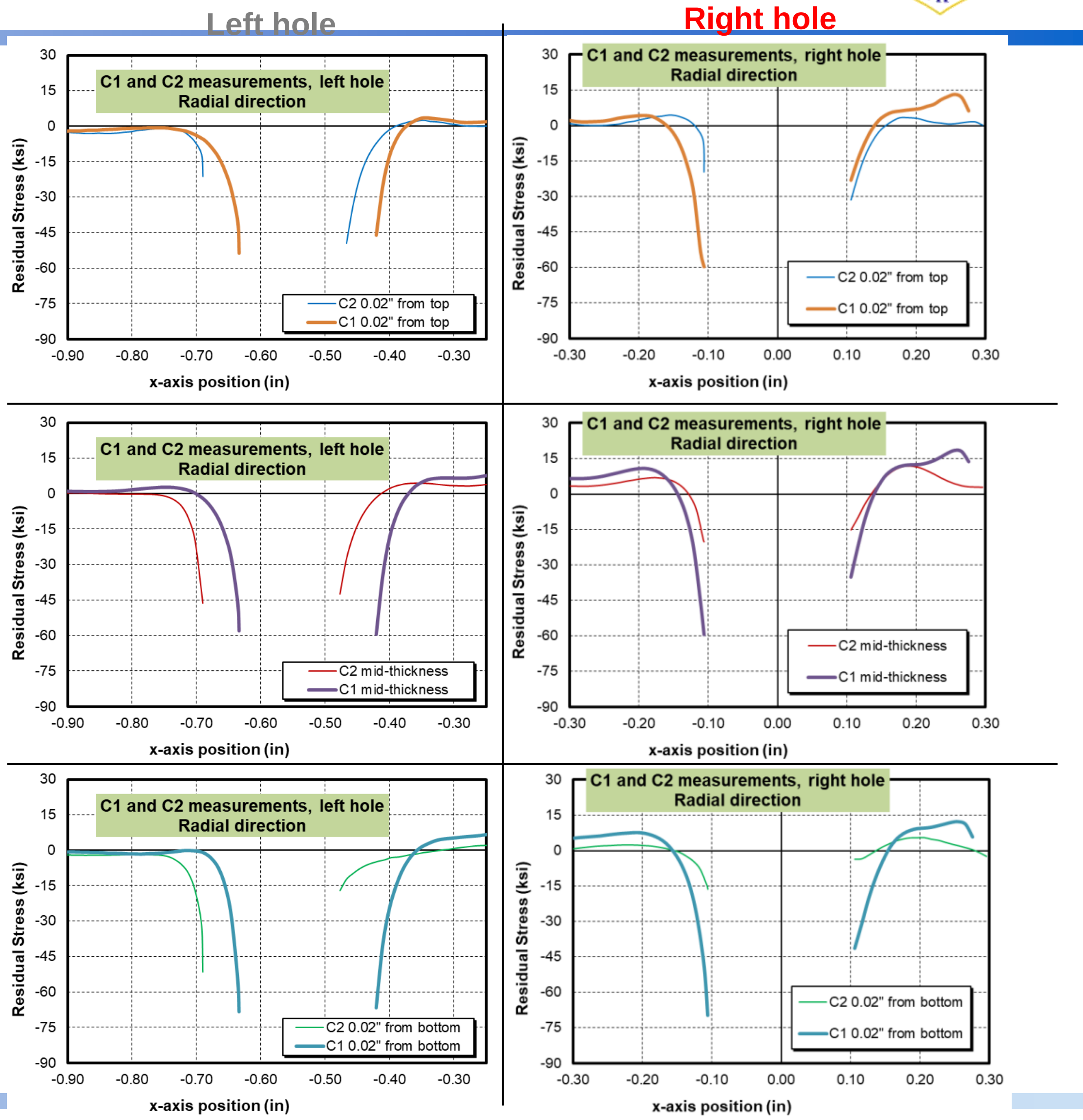




RS Measurements

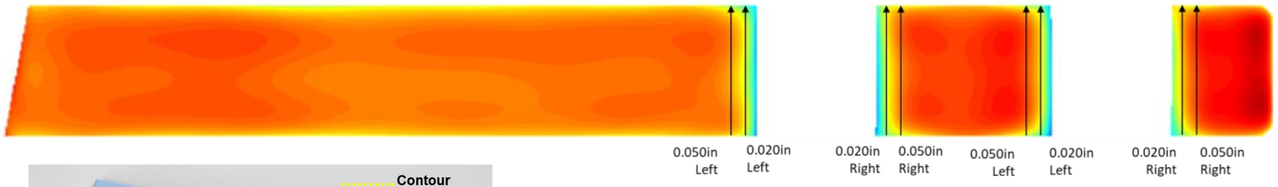


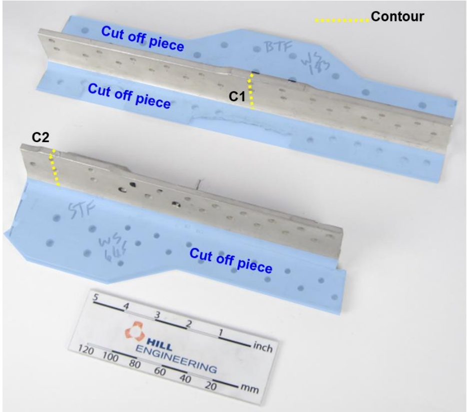




RS Measurements

BTF–WS183

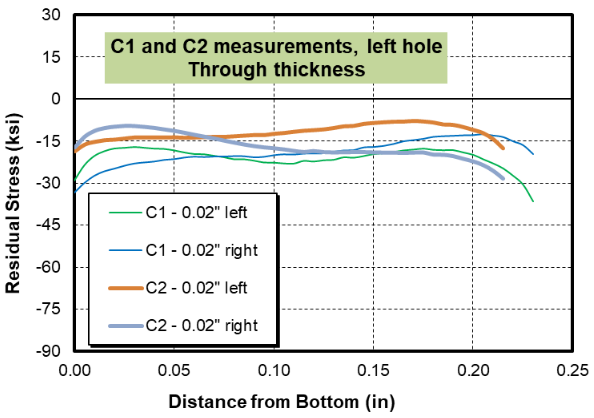


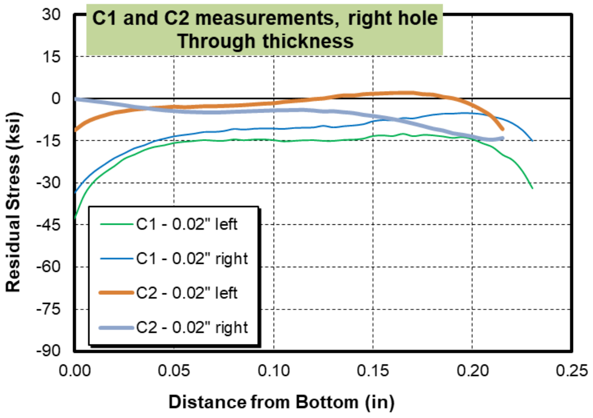


Left hole

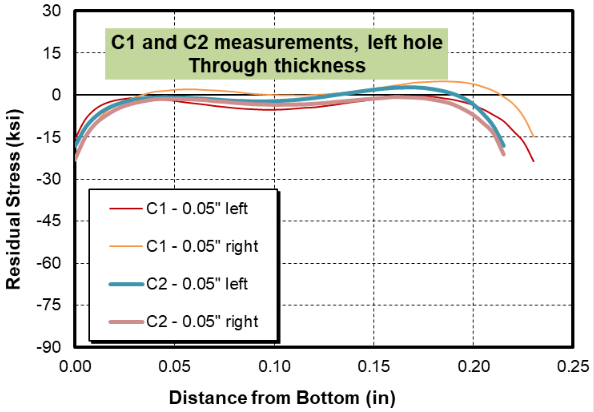
Right hole

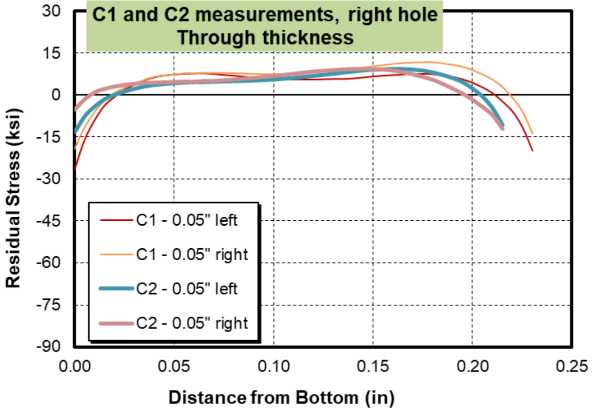
0.02” from hole edges





0.05” from hole edges





Neat Fit Pin Correction

For all cracked hole models, there is an axial load case option to add a filled hole (zero interference) correction. This correction was originally provided by Dr. Jack Lincoln (~1993), and was most likely developed by Lockheed under contract to the Air Force Research Laboratory in the 1980's. This correction factor (Ffill) is given below:

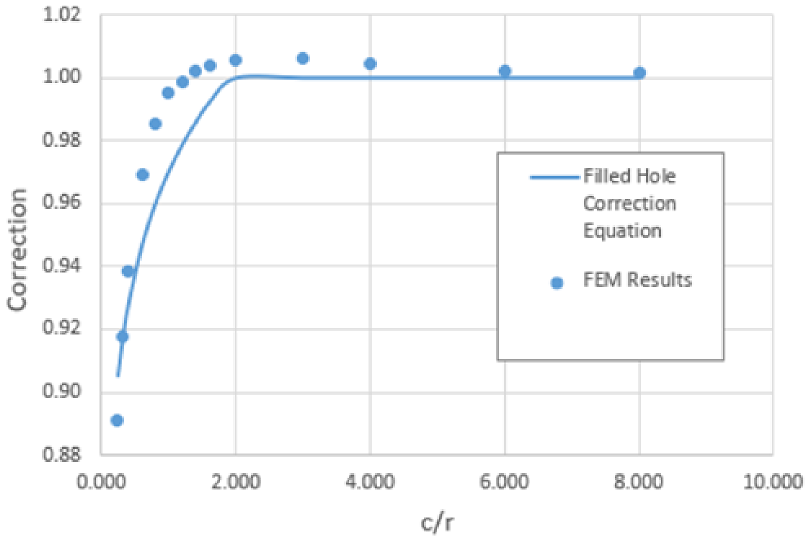
$F_{fill}=0.969831+0.10763Log_{10}(c/r+0.01)$

Where:

c = crack length in the c-direction
r = hole radius

Note: If $F_{fill} > 1$, $F_{fill} = 1$

This correction has more recently been compared to a correction based on finite element model results for a single through cracked hole as shown.



Kirsch equations

$$\sigma_{rr} = \frac{\sigma}{2}\left(1-\frac{a^2}{r^2}\right)+\frac{\sigma}{2}\left(1+3\frac{a^4}{r^4}-4\frac{a^2}{r^2}\right)\cos 2\theta$$

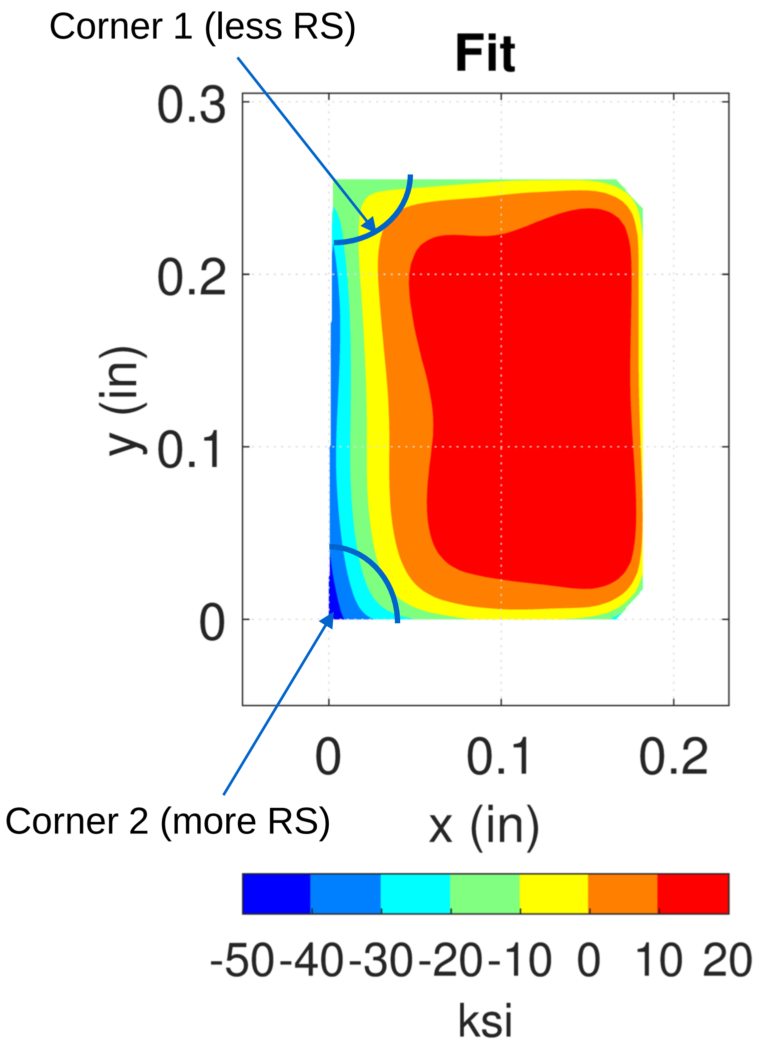
$$\sigma_{\theta\theta} = \frac{\sigma}{2}\left(1+\frac{a^2}{r^2}\right)-\frac{\sigma}{2}\left(1+3\frac{a^4}{r^4}\right)\cos 2\theta$$

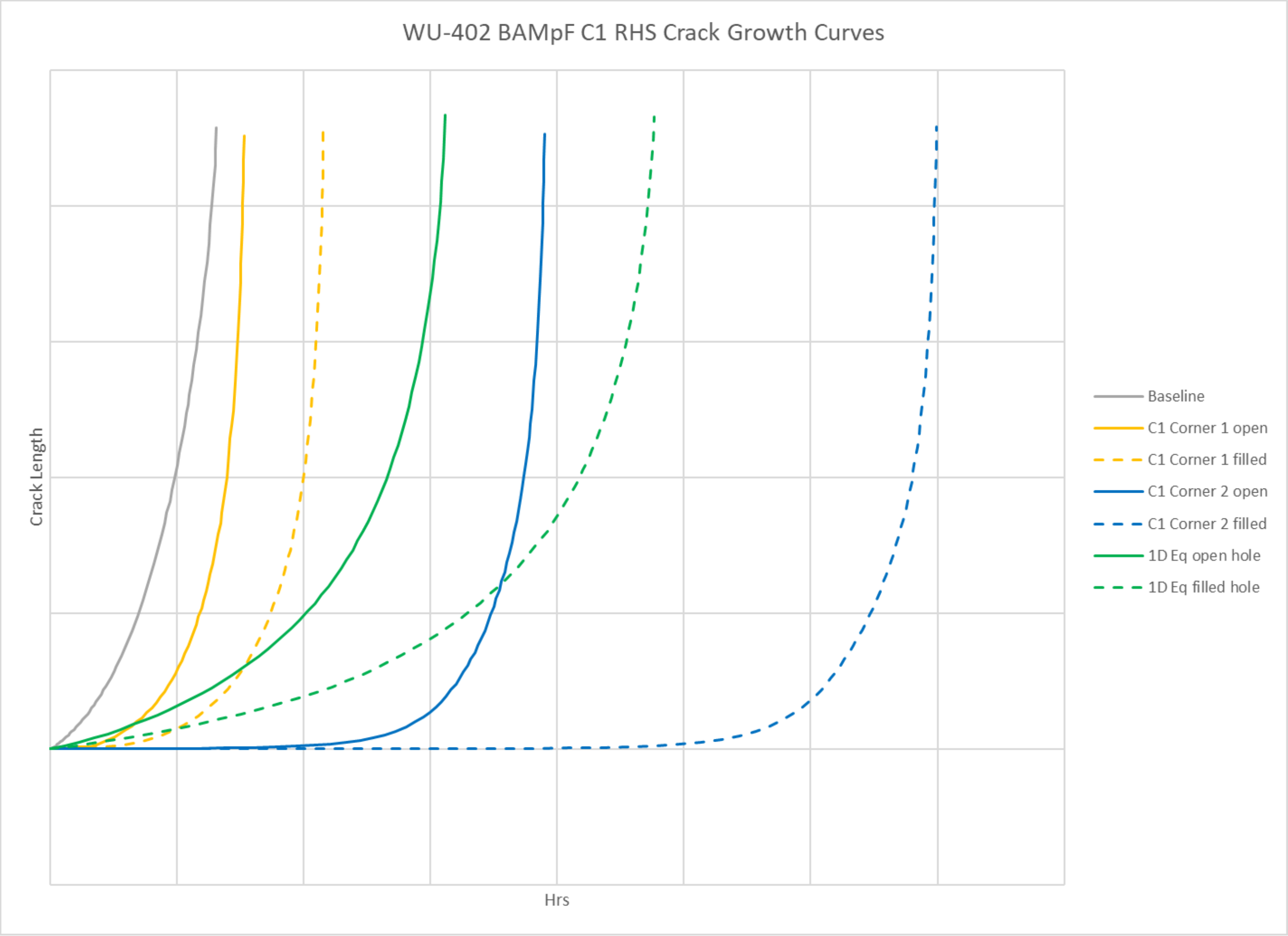
$$\sigma_{r\theta} = -\frac{\sigma}{2}\left(1-3\frac{a^4}{r^4}+2\frac{a^2}{r^2}\right)\sin 2\theta$$

Traction in StressCheck = $(1-F_{fill})*\sigma_{\theta\theta}$

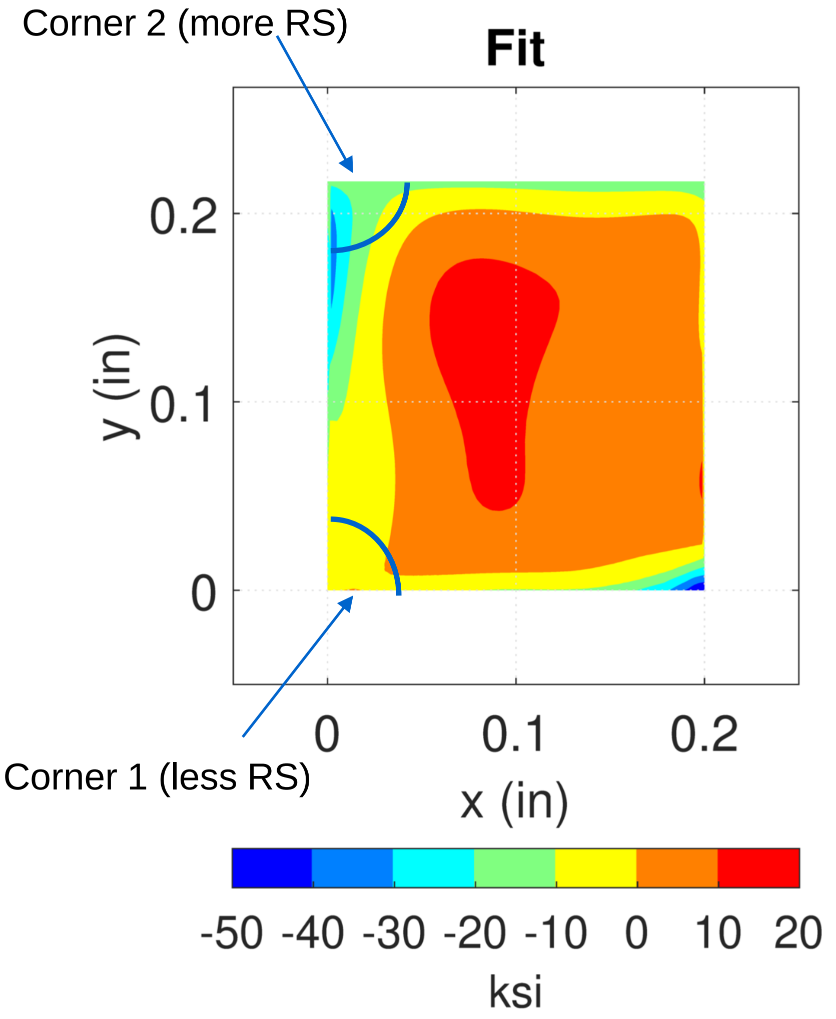
Essentially adds more compressive RS

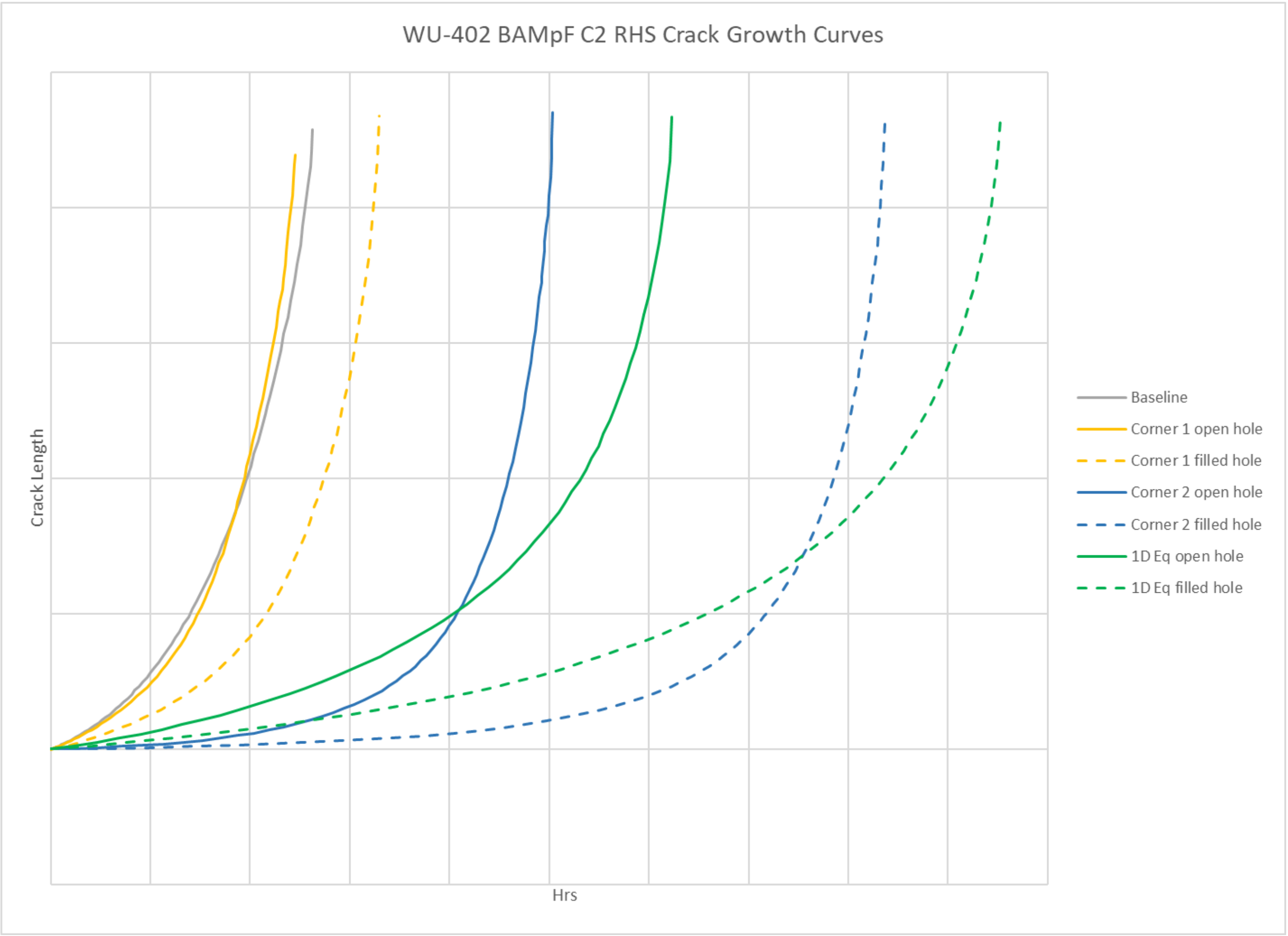
C1 Short Ligament Results





C2 Short Ligament Results





Interference Fit Modeling

- **Ensure contact pressure and stress in interference fit scenario are correct**
- **NASTRAN and Hand Calcs Correlate Well**
  - **Residual Stress Fields Significantly Impacted by Contact Stresses**
  - **Nastran shows a significant reduction in delta stress due to the presence of an interference fit pin.**

Stress in interference fit couple

$\delta_{if} := .0015in$ $\quad E_{hub} := 1.04 \cdot 10^{7} psi$ $\quad r_{0.hub} := .38in$ $\quad \nu_{hub} := .33$

$E_{shaft} := 3.0\,10^{7} psi$ $\quad r_{0.shaft} := .0937in$ $\quad \nu_{shaft} := .33$

$r_{i.shaft} := 0in$

$$p_{IF} := \frac{\delta_{if}}{2 \cdot r_{0.shaft} \cdot \left[\frac{1}{E_{hub}} \cdot \left(\frac{r_{0.hub}^{2} + r_{0.shaft}^{2}}{r_{0.hub}^{2} - r_{0.shaft}^{2}} + \nu_{hub}\right) + \frac{1}{E_{shaft}} \cdot \left(\frac{r_{0.shaft}^{2} + r_{i.shaft}^{2}}{r_{0.shaft}^{2} - r_{i.shaft}^{2}} - \nu_{shaft}\right)\right]}$$

$p_{IF} = 49206.342 \cdot psi$

$\sigma_{if} := 2 \cdot p_{IF} = 98412.684 \cdot psi$

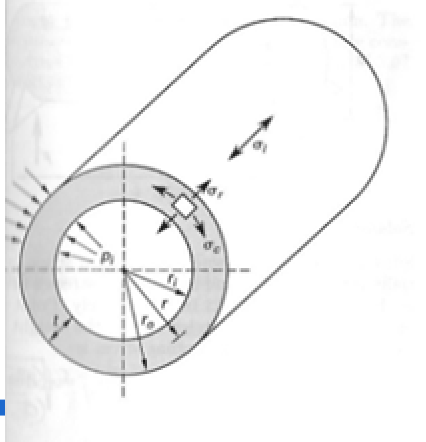


*Table 53.2 Stresses in Thick-Walled Cylinders**

stress	external pressure, p	internal pressure, p
$\sigma_{c,o}$	$\frac{-(r_o^2 + r_i^2)p_o}{r_o^2 - r_i^2}$	$\frac{2r_i^2 p_i}{r_o^2 - r_i^2}$
$\sigma_{r,o}$	$-p_o$	0
$\sigma_{c,i}$	$\frac{-2r_o^2 p_o}{r_o^2 - r_i^2}$	$\frac{(r_o^2 + r_i^2)p_i}{r_o^2 - r_i^2}$
$\sigma_{r,i}$	0	$-p_i$
τ_{max}	$\frac{1}{2}\sigma_{c,i}$	$\frac{1}{2}(\sigma_{c,i} + p_i)$

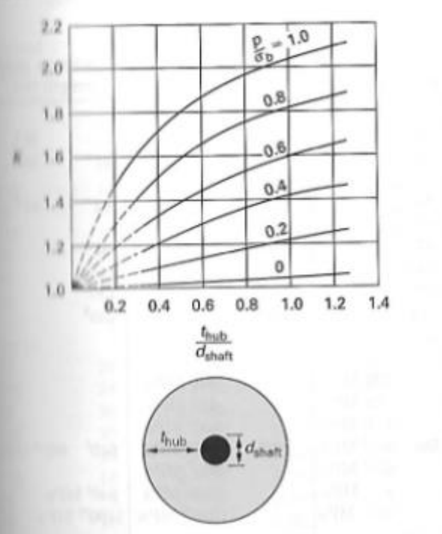
*Table 53.2 can be used with thin-walled cylinders. However, in most cases it will not be necessary to do so.

within the wall thickness, the strain can be evaluated at inner, outer, and any intermediate locations within the wall.

$$\epsilon = \frac{\Delta d}{} = \frac{\Delta C}{} = \frac{\Delta r}{}$$

$$I_{diametral} = 2I_{radial} = \left(\frac{2pr_{o,shaft}}{E_{hub}}\right)\left(\frac{r_{o,hub}^2 + r_{o,shaft}^2}{r_{o,hub}^2 - r_{o,shaft}^2} + \nu_{hub}\right) + \left(\frac{2pr_{o,shaft}}{E_{shaft}}\right)\left(\frac{r_{o,shaft}^2 + r_{i,shaft}^2}{r_{o,shaft}^2 - r_{i,shaft}^2} - \nu_{shaft}\right) \qquad 53.28$$

Figure 53.4 Stress Concentration Factors for Press Fits



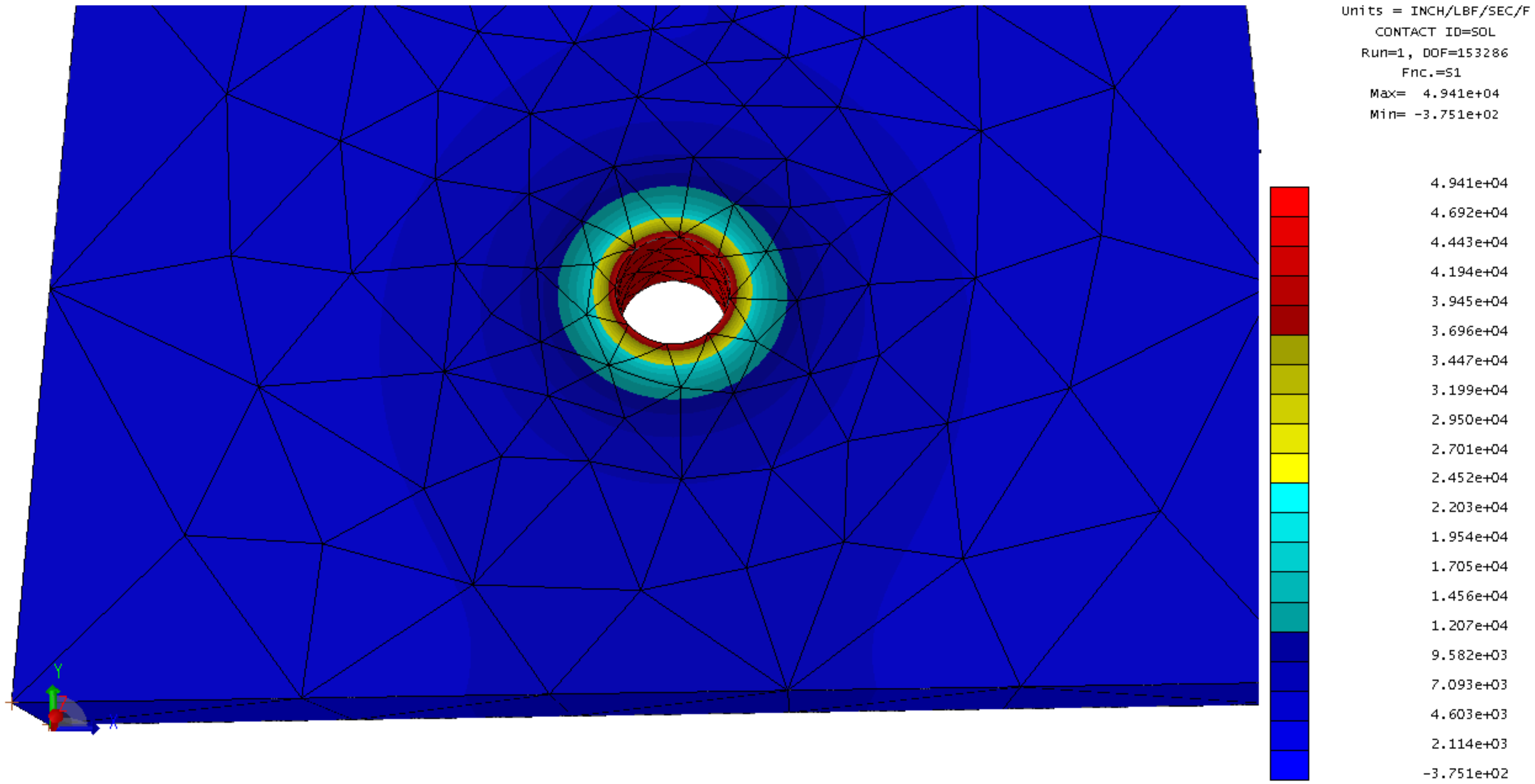
... of Shafts at Fitted Members, with a Related Photo... Analysis," reproduced from *Transactions of the ASME*, ... © 1935, and Vol. 58, © 1936, with permission of the ... Society of Mechanical Engineers.

**Figures From Mechanical Engineering Reference Manual: 53-7 Basic Machine Design

Task 2) Prioritization of analysis & test critical details

- StressCheck Max Contact Pressure Error sensitivity
  - Hand Calculation : 109 ksi (0.0015” radial interference, .187” diameter hole)
  - Pressure error = 1.83% (contact constant = 1e6, 40 iterations)

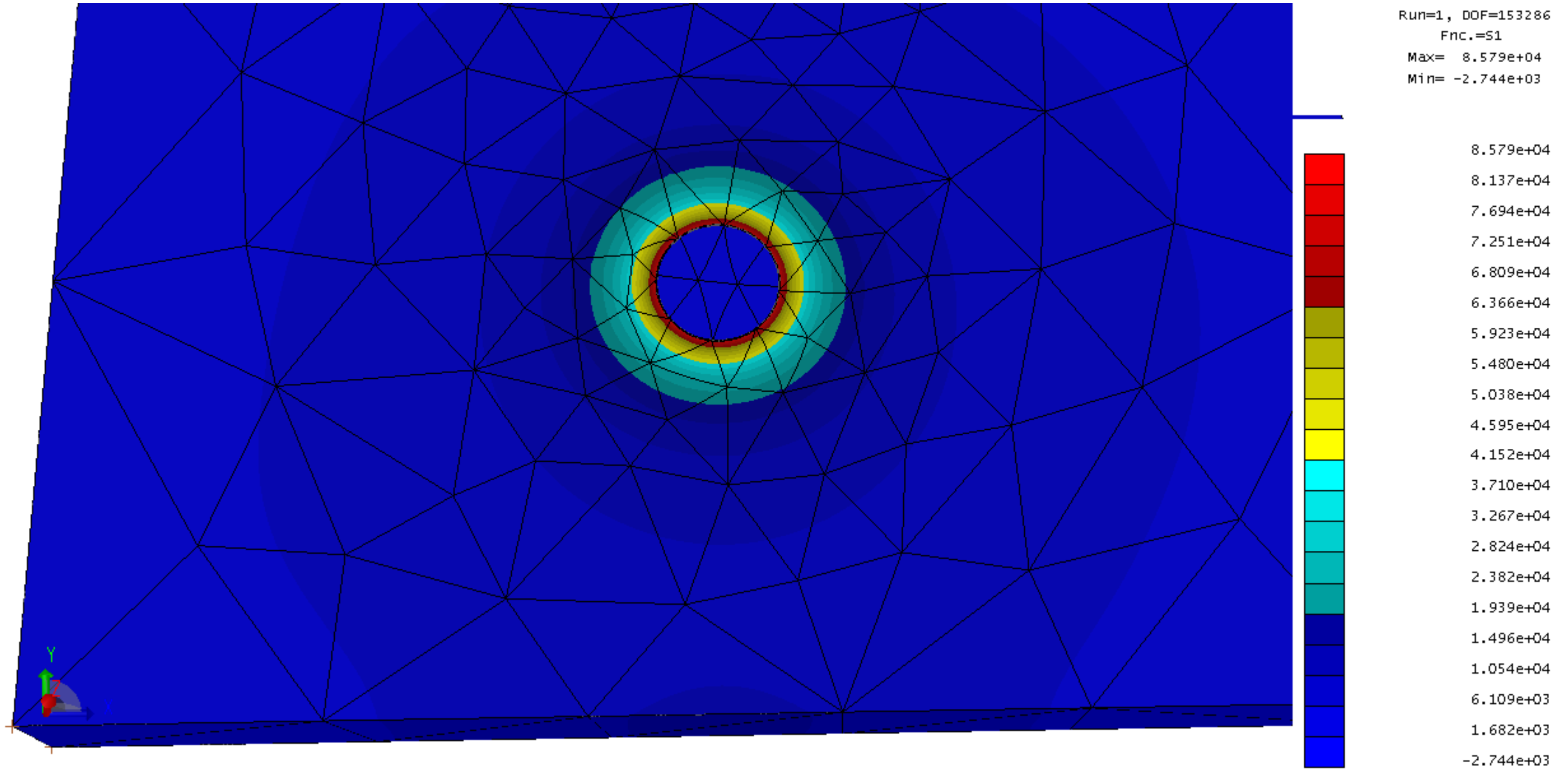
Max Stress: 49.4 ksi



Task 2) Prioritization of analysis & test critical details

- StressCheck Max Contact Pressure Error sensitivity
  - Hand Calculation : 109 ksi (0.0015" radial interference, .187" diameter hole)
  - Pressure error = 1.10% (contact constant = 2e6, 40 iterations)

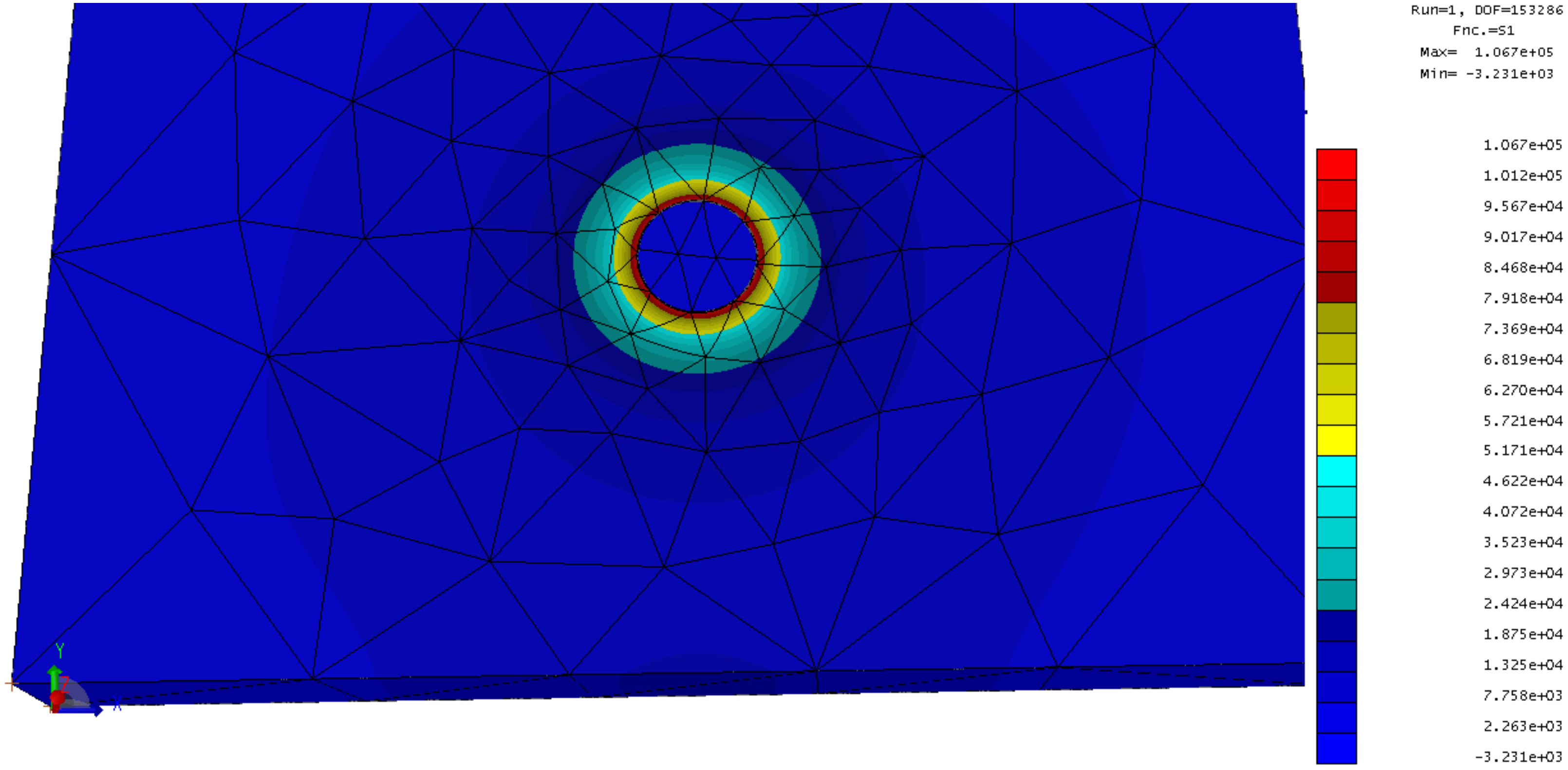
Max Stress: 85.8 ksi



Task 2) Prioritization of analysis & test critical details

- StressCheck Max Contact Pressure Error sensitivity
  - Hand Calculation : 109 ksi (0.0015” radial interference, .187” diameter hole)
  - Pressure error = 0.42% (contact constant = 5e6, 40 iterations)

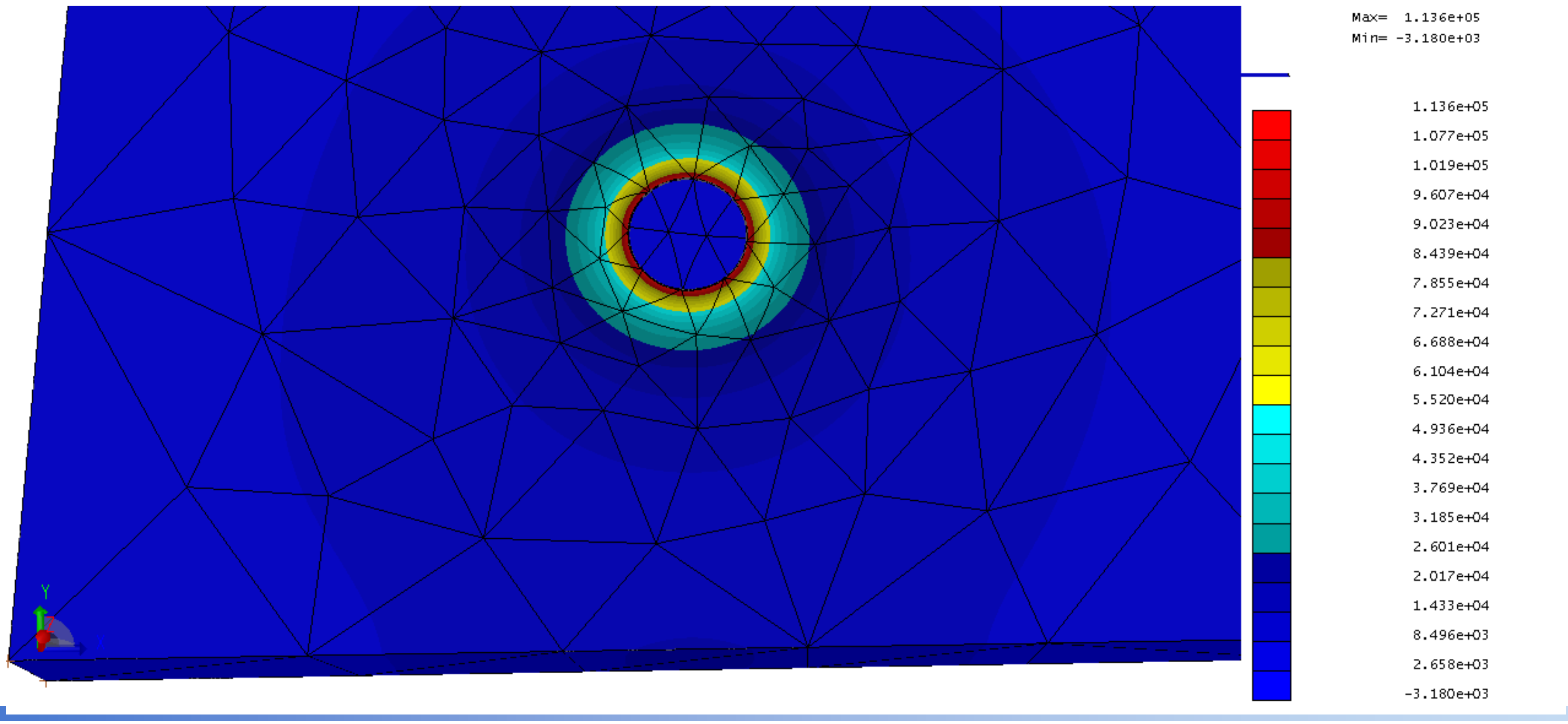
Max Stress: 106.7 ksi



Task 2) Prioritization of analysis & test critical details

- StressCheck Max Contact Pressure Error sensitivity
  - Hand Calculation : 109 ksi (0.0015” radial interference, .187” diameter hole)
  - Pressure error = 0.08% (contact constant = 10e6, 40 iterations)

Max Stress: 113.6 ksi



Questions?