NRC·CNRC

Analysis of a Lap Joint Including Fastener Hole Residual Stress Effects

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Aerospace Portfolio

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Outline

Introduction

Fastener Hole Residual Stress Analysis

- Hole Cold Expansion Simulation
- Interference Fit Fastener Installation Simulation
- Riveting Simulation

Example: Crack Growth in Riveted Lap Joint

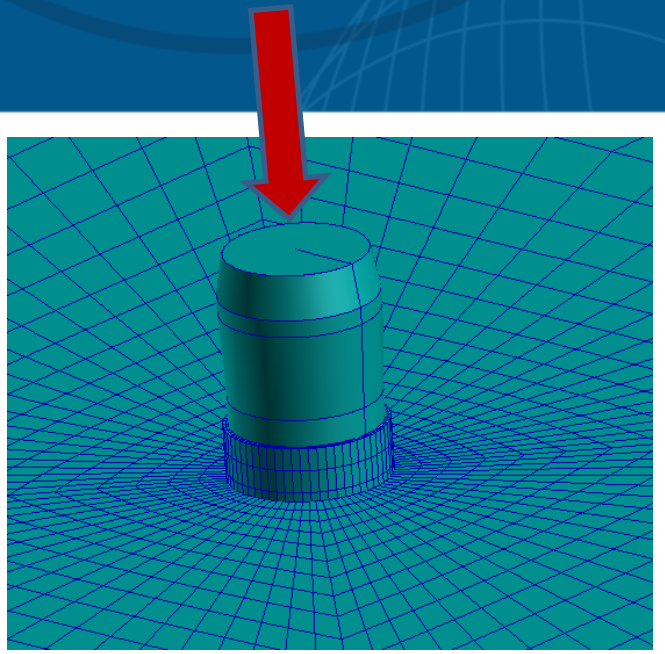
- Finite Element Analysis (MSC Marc)
- Crack Growth Analysis (AFGROW)
- Probabilistic Analysis (CanGROW)

Conclusion and Future Work

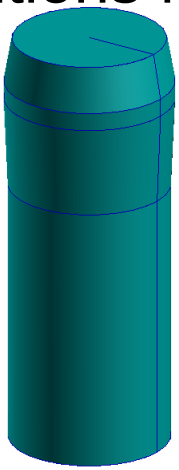
Hole Cold Expansion (Cx) Simulation

3D Simulations Using MSC Marc

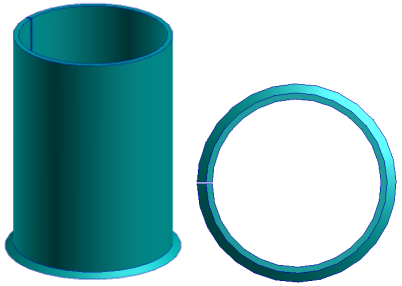
- PCL: Parameterization, Automation
- Contact assumed between nosecap and sleeve, and between sleeve and hole bore
- Boundary conditions representative of FTI process



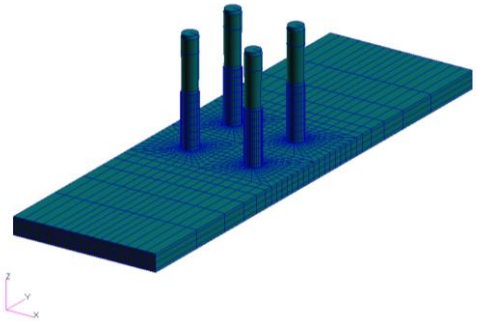
Mandrel entrance side (FTI process)



Mandrel



Sleeve



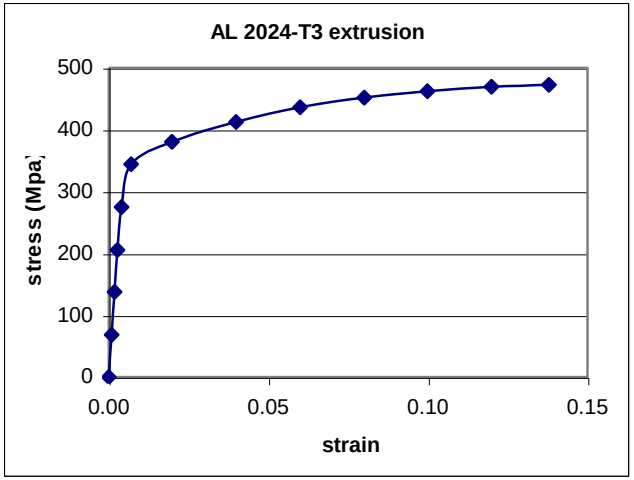
Multiple Cx hole interaction

Model Parameters

1. Plate geometry:
   - Length: L
   - Width: W
   - Plate thickness, Tp
   - Starting hole diameter: D
   - Edge margins: e/D
2. Applied expansion:
   - Cx range from 3 to 6% for aluminum and mild steels (80 ksi Fty max)
   - Cx range from 4.5 to 6.7 % for titanium and high strength steels (240 ksi Fty max)
3. Mandrel shape:
   - Length
   - Slope
   - Cross section shape
4. Sleeve configuration:
   - Split orientation: 0^0 – 360^0
   - Gap size
   - Sleeve thickness
5. Lubrication conditions (Friction)
   - Friction model type
   - Friction coefficient
6. Mesh density :
   - Mesh density on plate
   - Mesh density on sleeve
7. Process control
   - Cold expansion process
   - Mandrel contact release
   - Sleeve contact release
   - Sleeve removal
   - Tension load
8. Result data implementation :
   - Residual tangential stress curve on Entrance surface
   - Residual tangential stress curve on middle line
   - Residual tangential stress curve on Exit surface
   - Residual tangential stress curve along plate thickness

Baseline Configuration

- Tool selected: 8-0-N from Table 4.01-1 in FTI process specification 8101D, 2002
  - Original hole dia.: 0.235” (5.969 mm) min, 0.238” (6.045 mm) max
  - Mandrel diameter: Major: nom. 0.23” (5.842 mm)
  - Sleeve thickness: 0.008”(0.2032 mm)
- Plate geometry:
  - Dimensions: Thickness: 0.25” (6.35 mm); Length: 5.51” (140 mm); Width: 2.56” (65 mm)
- Plate material: 2024-T3 extrusion (MIL-HDBK-5H)
  - E = 10.8×10^3 ksi (74.4 GPa); $\mu = 0.33$
  - Fty = 40 ksi (275 MPa)
  - Futs = 68 ksi (470MPa)
- Sleeve material: elastic steel
  - E = 30.5×10^3 ksi (210 GPa); $\mu = 0.3$
- Mandrel: rigid body



Parametric Study Matrix

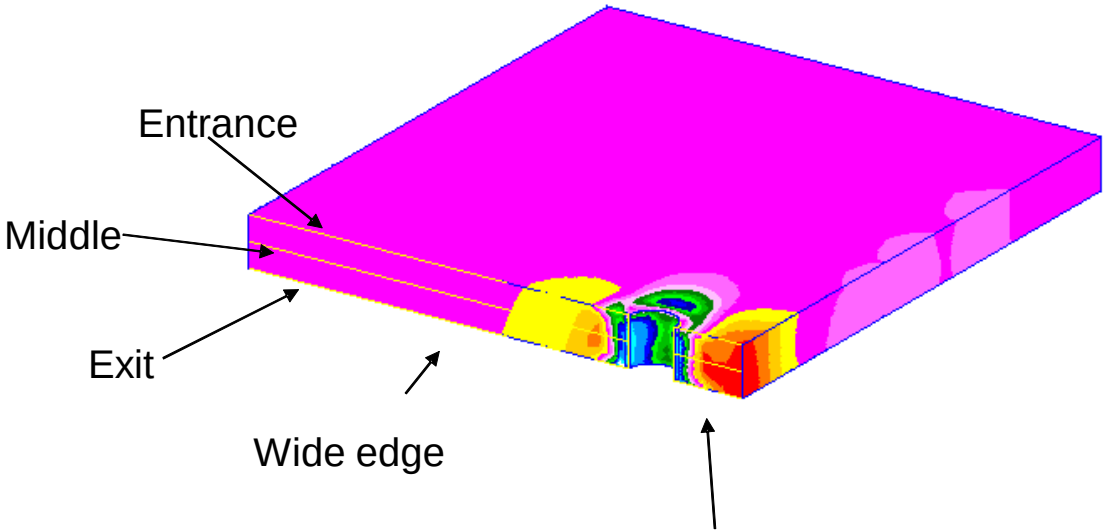
- 3D FE Models

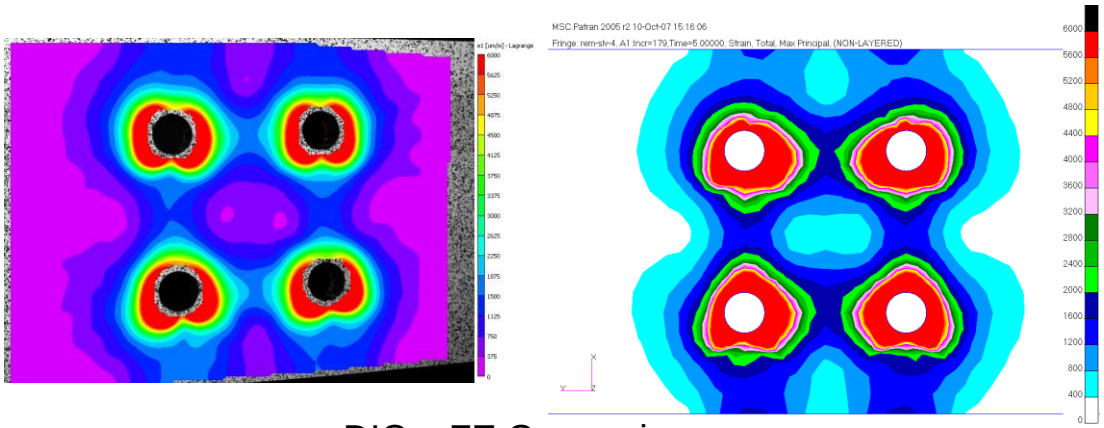
Sleeve split orientation	0^0, 45^0, 90^0, 135^0, 180^0
Sleeve thickness	0.006”, 0.008”, 0.012”, 0.018”
Plate thickness	0.063”, 0.125”, 0.25”
Friction coefficient	0.1, 0.3, 0.5, 0.8

Baseline: Cx = 4.0%, e/D = 2.0

	Cx % = $\frac{100\% \times (Dm + 2ts - D\ hole)}{D\ hole}$			
e/D	3.0	3.5	4.0	4.68
5.0	x	x	x	x
3.0			x	
2.0	x	x	x	x
1.75			x	
1.5			x	
1.2	x	x	x	x
0.8	x	x	x	x

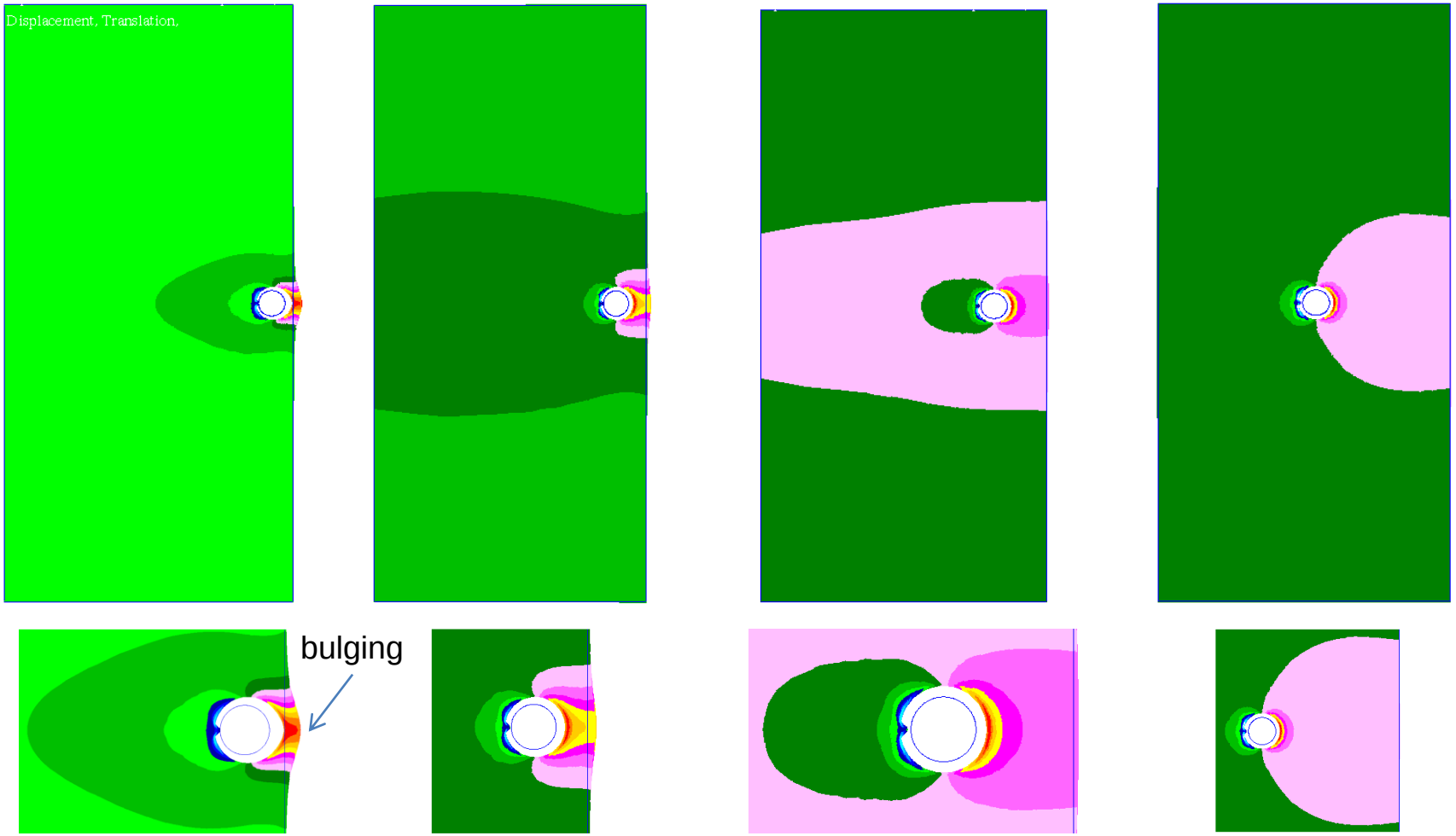
Example of Hole Cx Residual Stress Results





DIC – FE Comparison

Edge Margin Study: Deformations



Cx =4.68%, e/D=0.8

Cx =4.68%, e/D=1.2

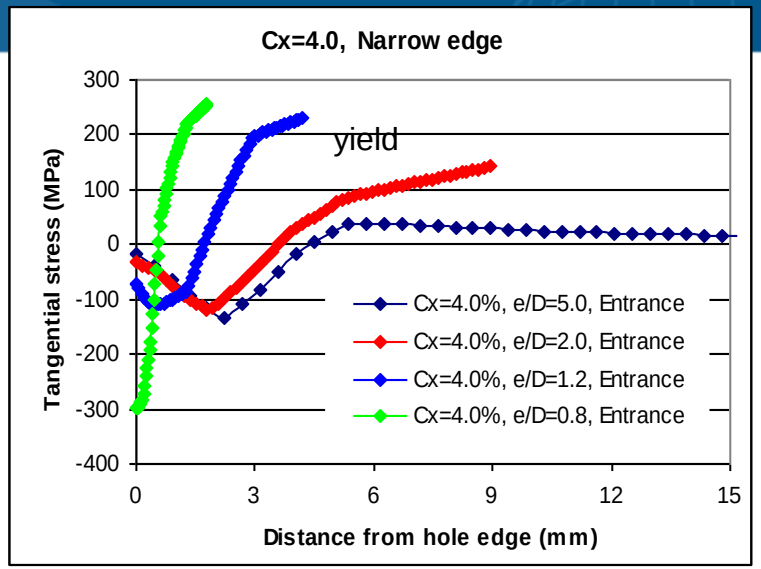
Cx =4.68%, e/D=2.0

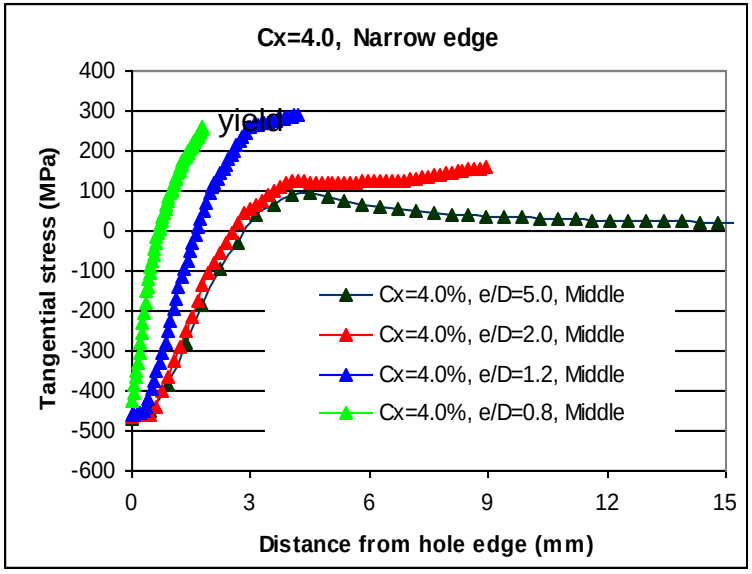
Cx =4.68%, e/D=5.0

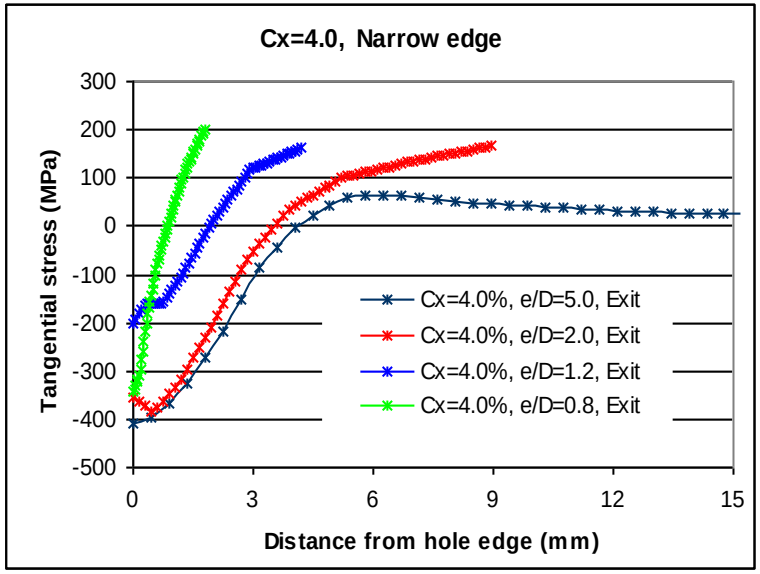
Edge Margin

- Effects on hoop (tangential) stress after cold expansion (narrow edge)

Compression at hole edge
e/D ↓ → $\sigma_{compression}$ ↑ at Entrance
e/D ↓ → $\sigma_{tensile}$ ↑





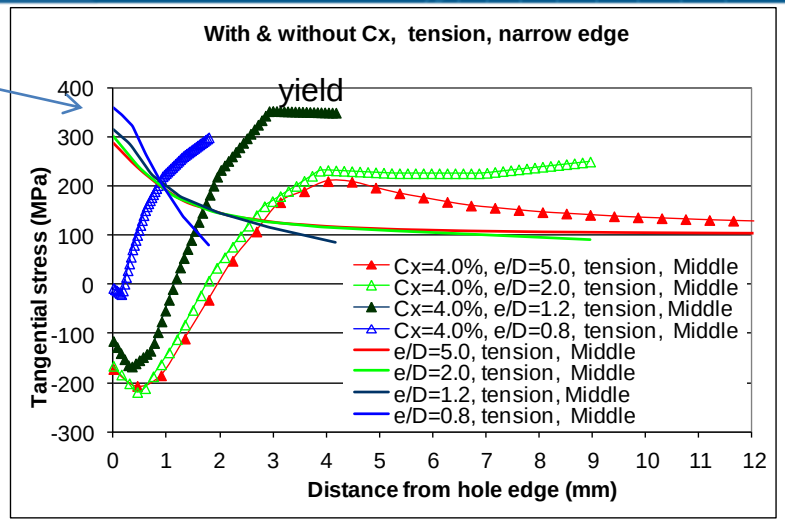


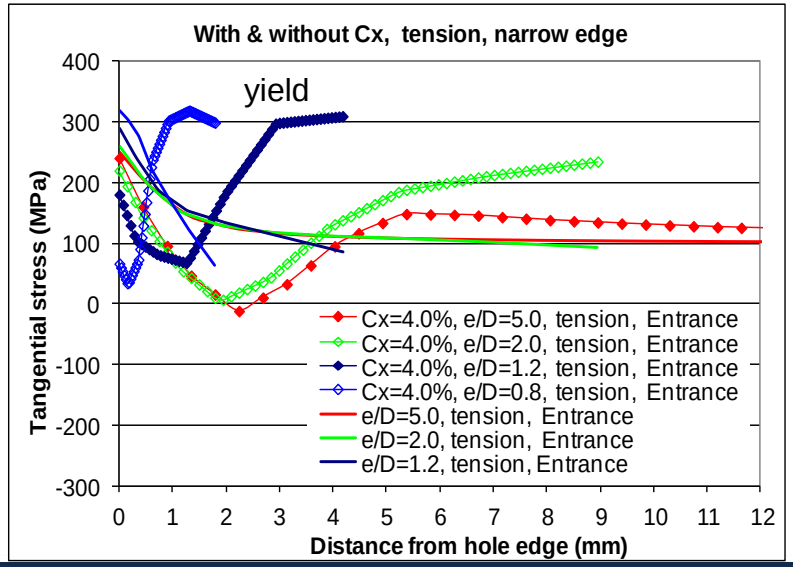
Edge Margin

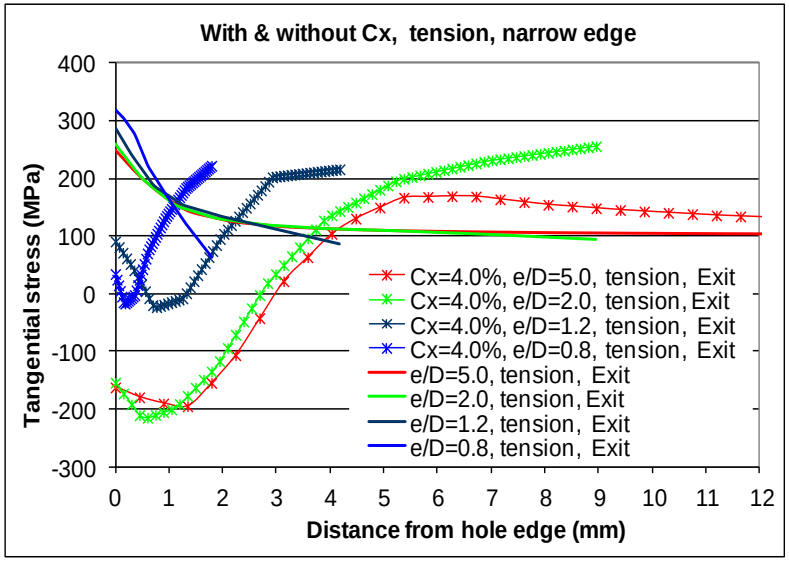
- Effects on hoop (tangential) stress under 100 MPa tension (narrow edge)

Low stress at hole edge
e/D ↓ → $\sigma_{tensile}$ ↑↑
e/D ↓ → $\sigma_{compression}$ ↓ at Entrance

Without Cx



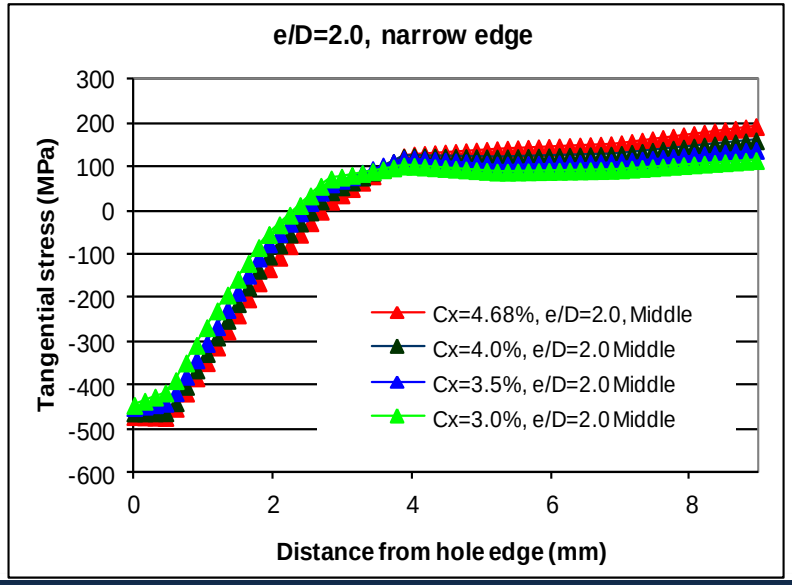


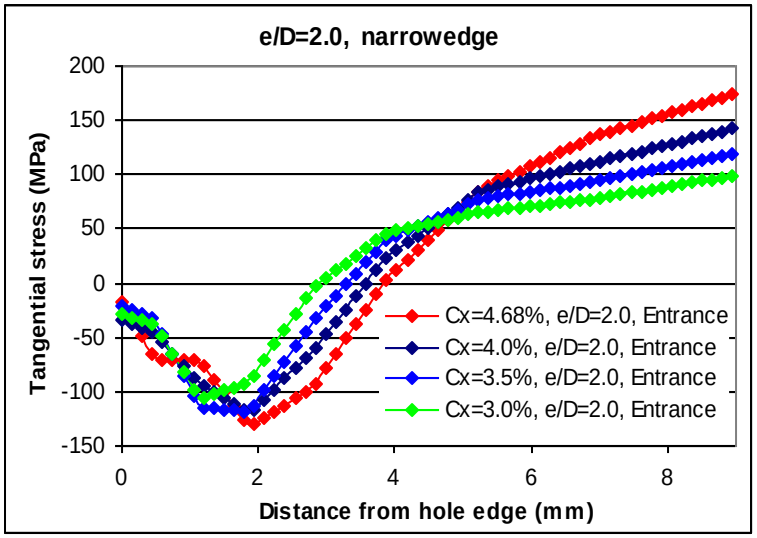


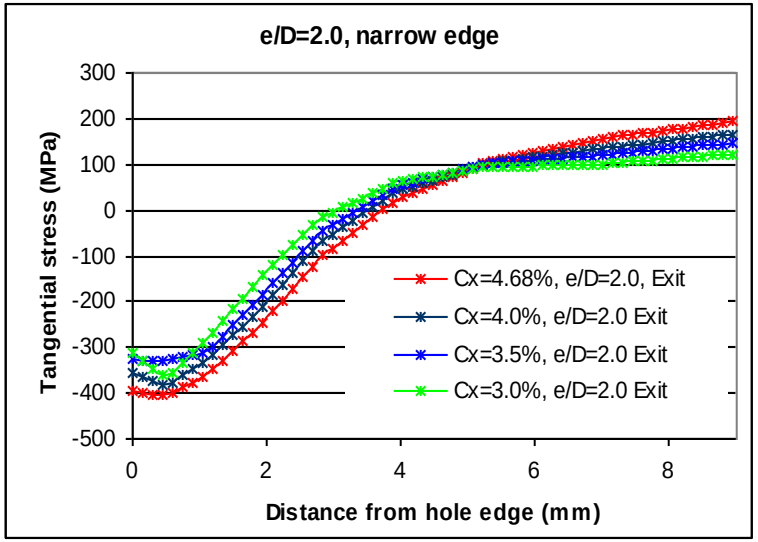
Cx Level

- Effects on hoop (tangential) stress after cold expansion (narrow edge)

Compression at hole edge
Cx ↑ → $\sigma_{tension}$ ↑
Cx ↑ → $\sigma_{compression}$ ↑



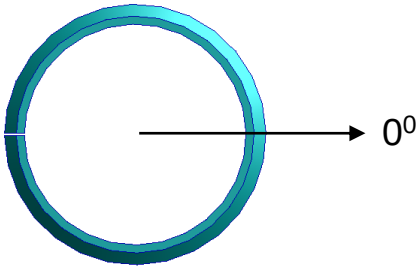


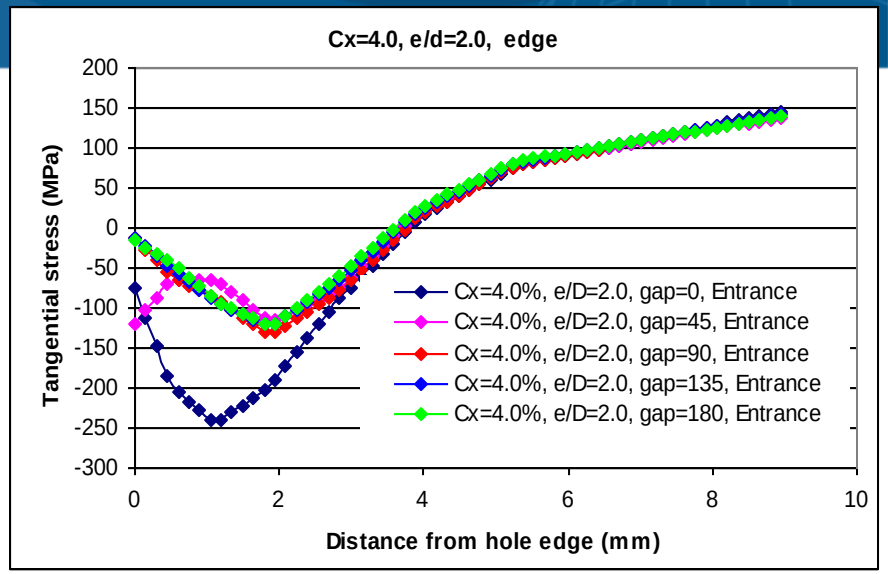


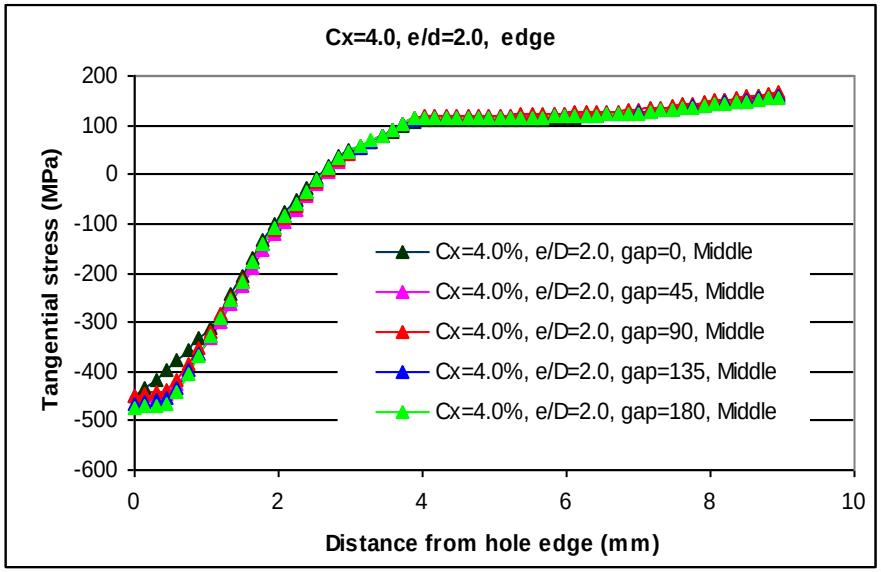
Sleeve Split Orientation

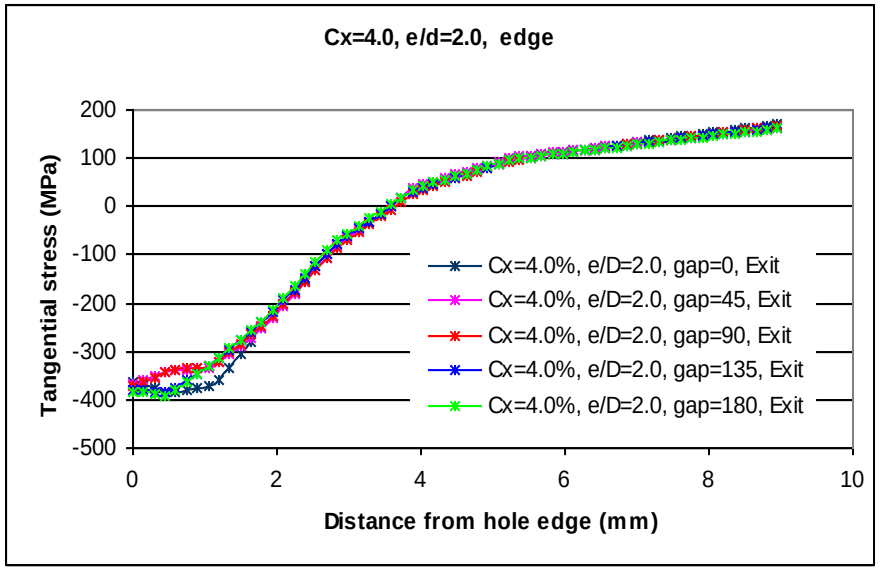
- Effects on hoop (tangential) stress after cold expansion (narrow edge)

Effect on Entrance side









Sleeve Split Orientation

- Effects on hoop (tangential) stress after cold expansion (narrow edge)

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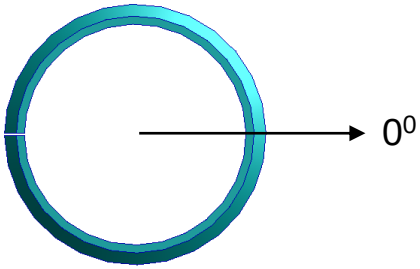
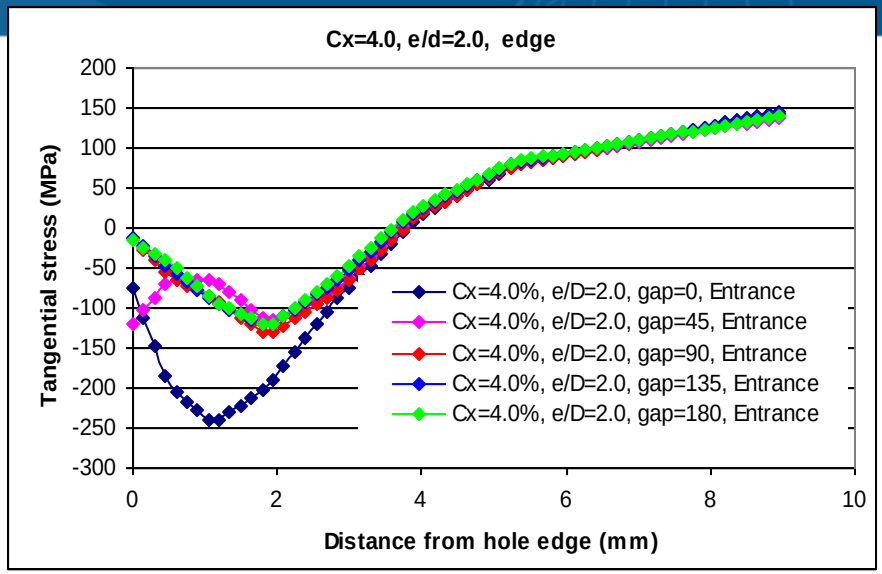
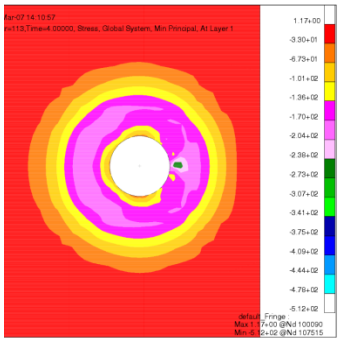
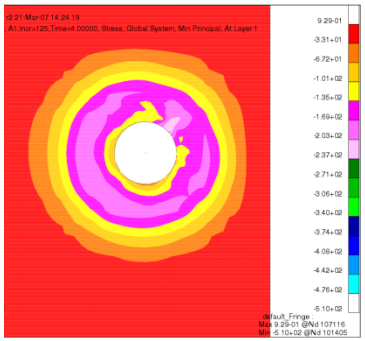


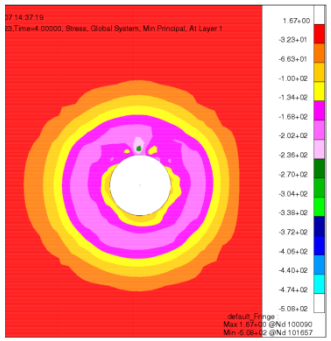




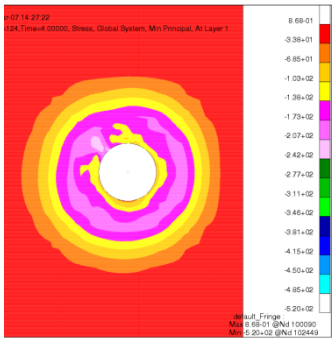
0⁰



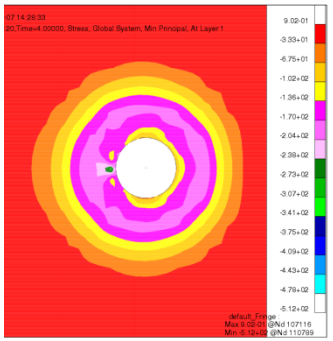
45⁰



90⁰



135⁰

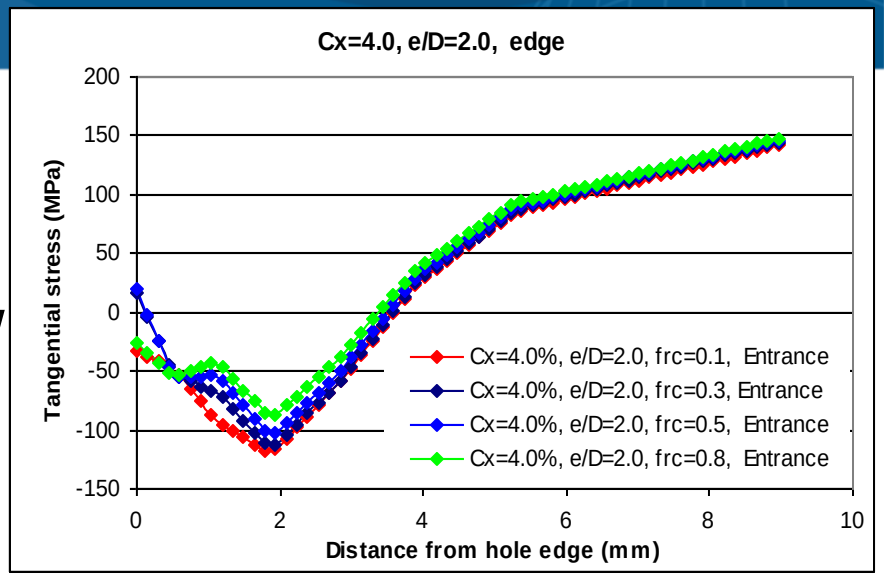


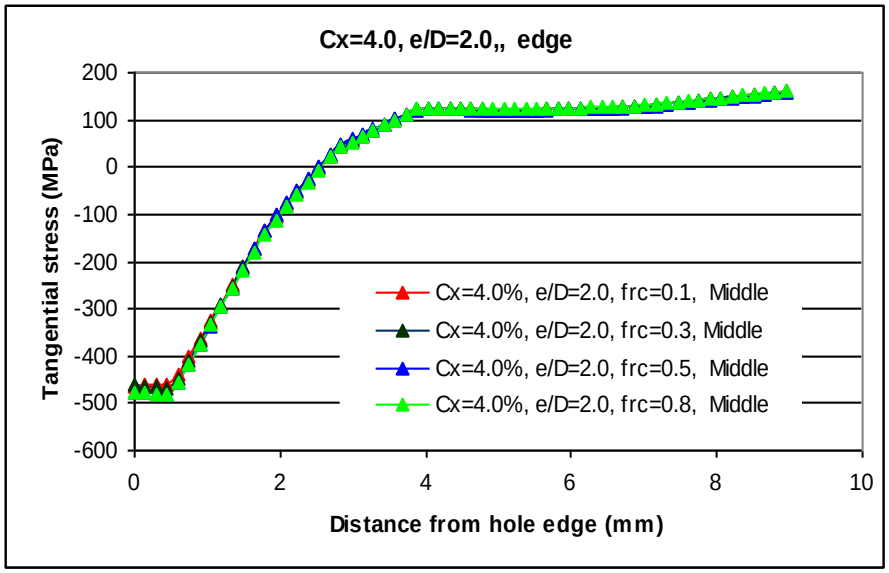
180⁰

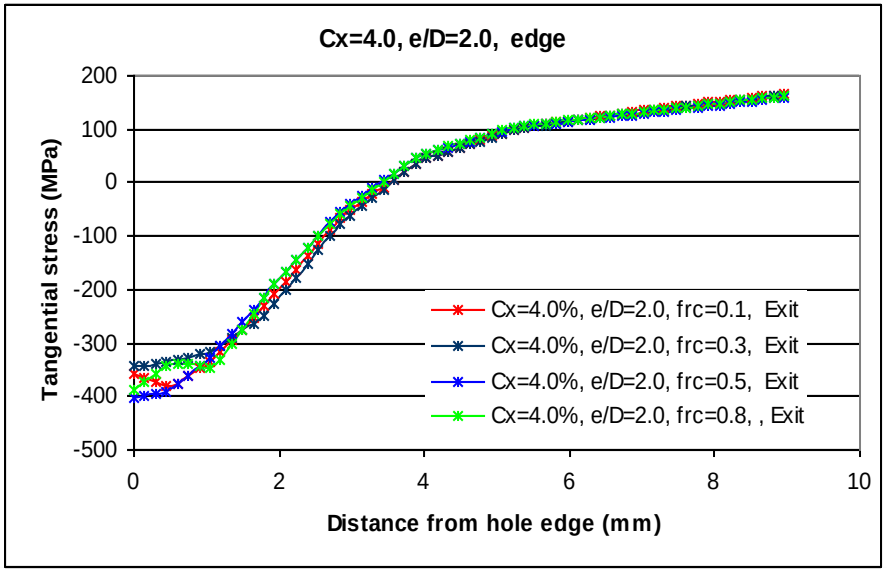
Friction (Lubrication)

- Effects on hoop (tangential) stress after cold expansion (between sleeve and mandrel / sleeve and hole bore) (narrow edge)

No significant effect



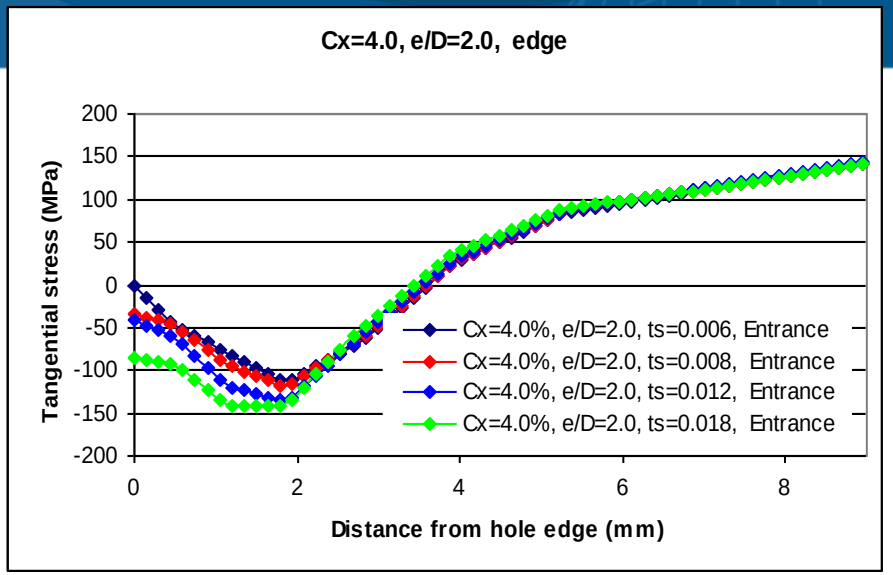


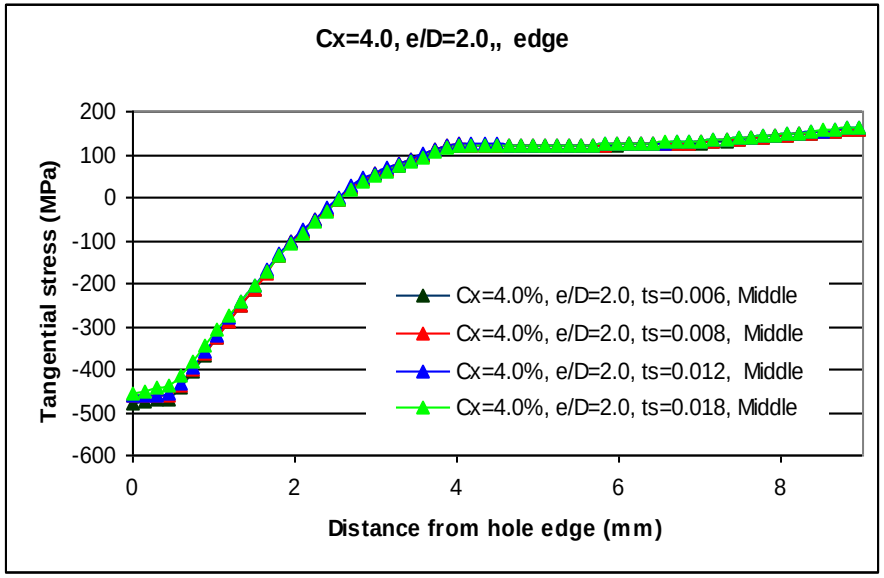


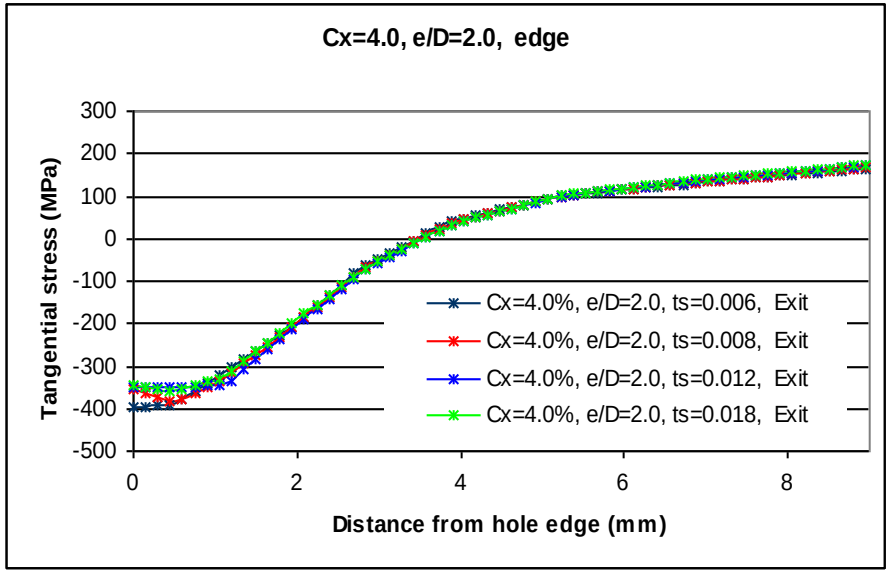
Sleeve Thickness

- Effects on hoop (tangential) stress after cold expansion (narrow edge)

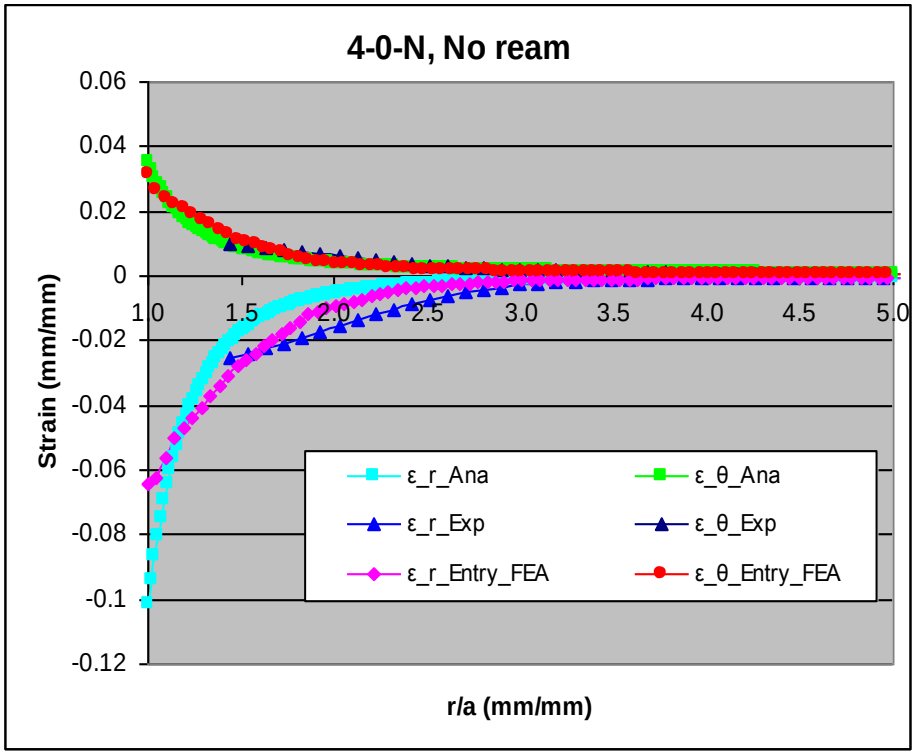
$t \uparrow \rightarrow \sigma_{compression} \uparrow$ at Entrance

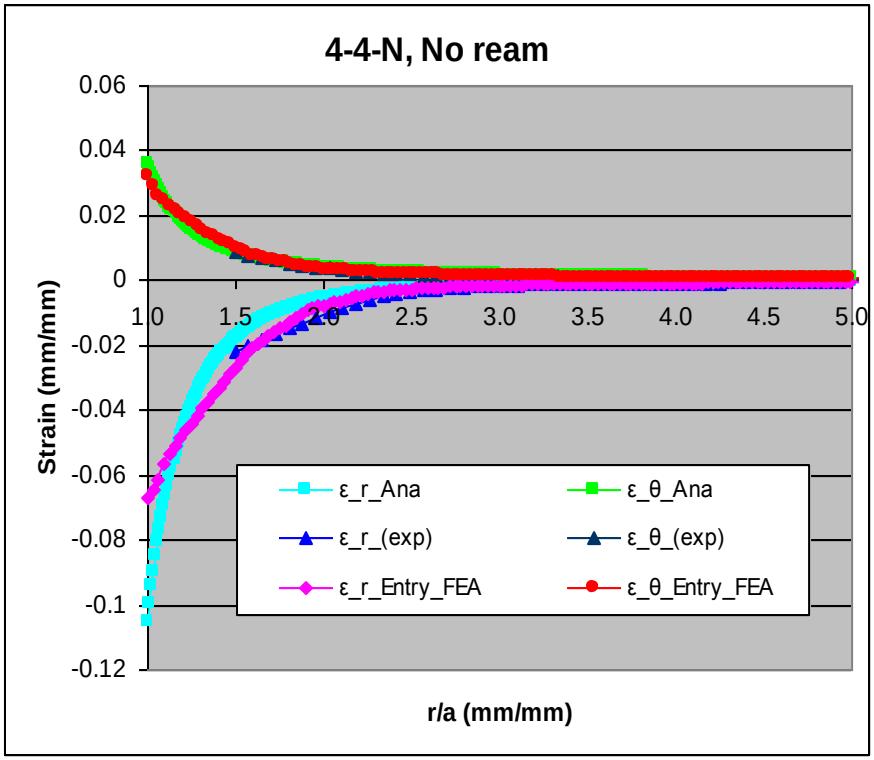






Comparison with Analytical Solutions and Digital Image Correlation (DIC) Test Strain Measurements





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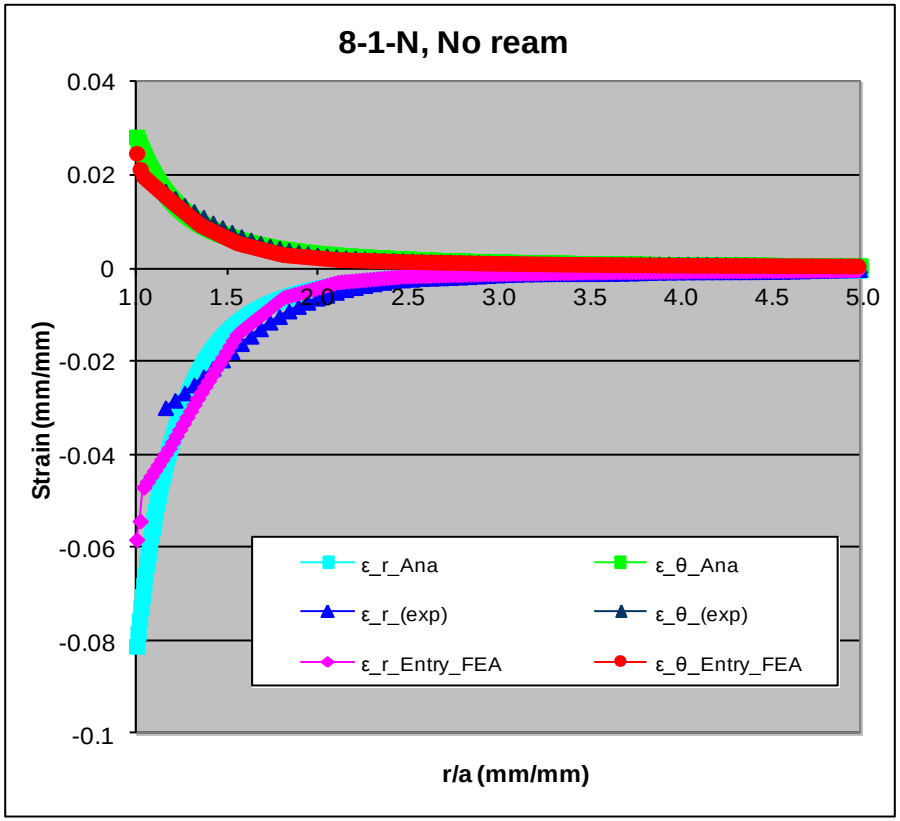
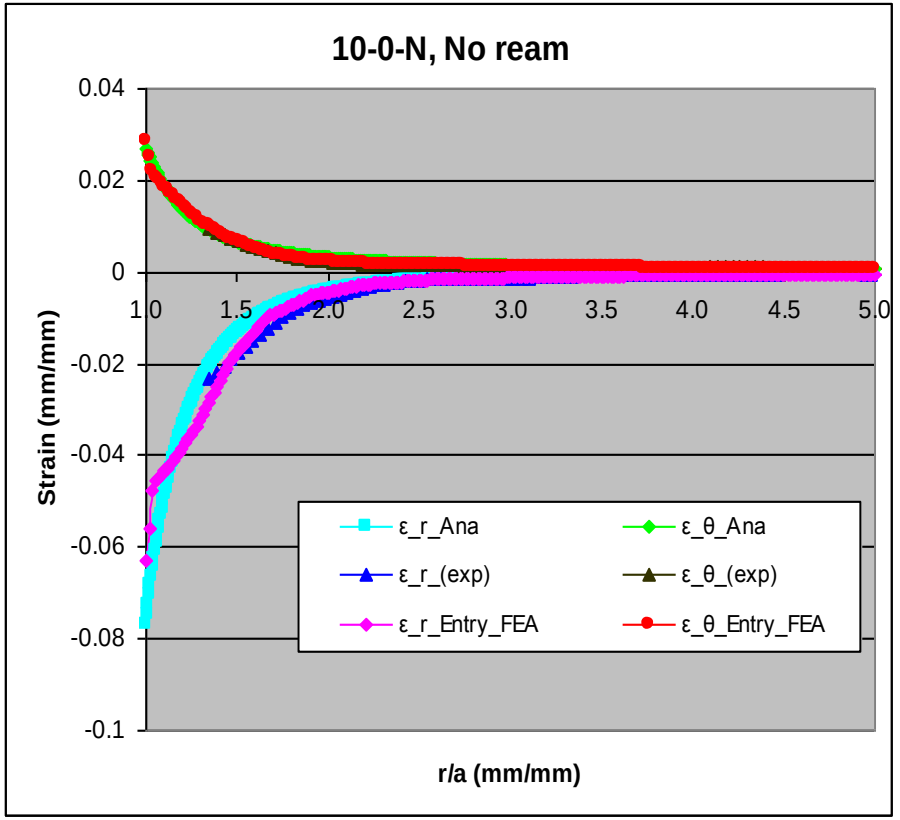




Brief Summary from parametric Study

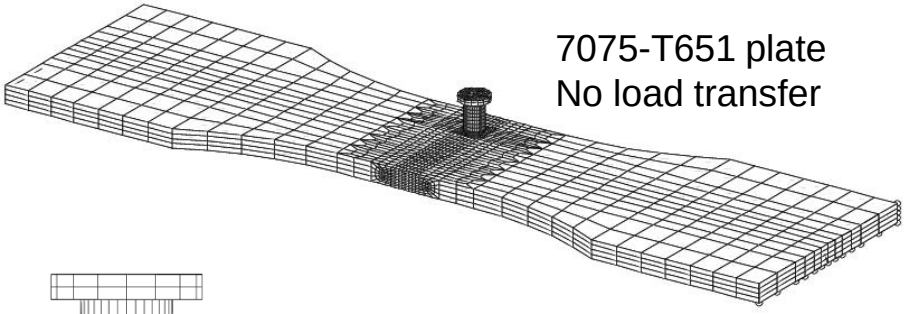
- Low edge margins can lead to high deformation and high edge tension
- Entrance side displayed the most variability and least amount of Cx benefit
- Middle displayed most consistency and greatest amount of Cx benefit
- Cx technology shows clear benefits; however, there are obvious limitations for low edge margins

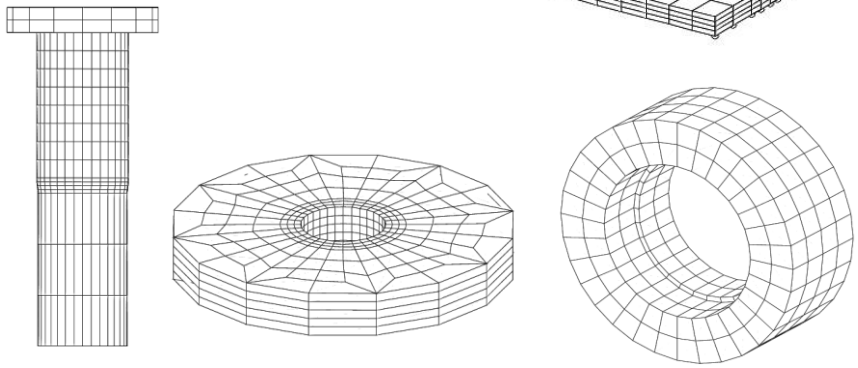
Residual Stresses Induced by Hole Cx Process

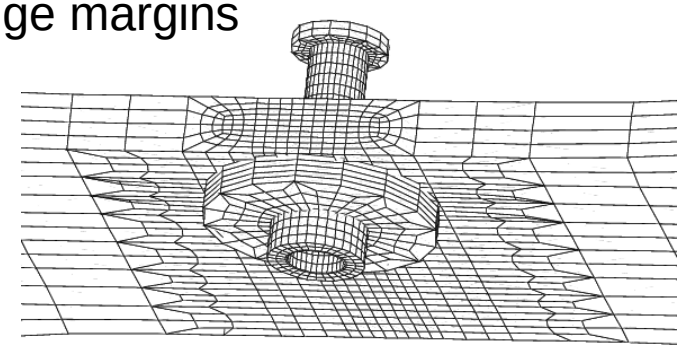
- Observations from FE Simulations:
  - Uniform radial expansion resulted in higher compressive radial and hoop stresses
  - A considerable through-the-thickness radial and hoop stress variation was observed
  - Compressive hoop residual stresses are larger at the exit face than at the entrance face, which contains the smallest compressive (or even tensile) hoop residual stresses
  - Fatigue tests show that early crack nucleation and growth tend to occur primarily and more extensively at the mendrel entrance face

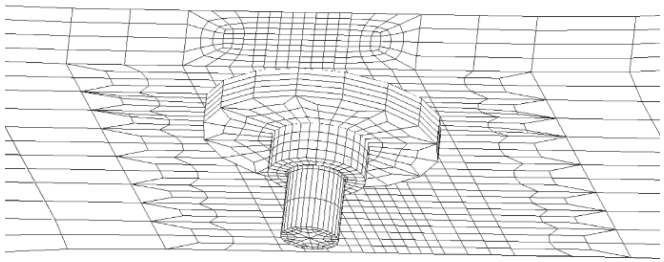
Interference Fit Fastener Modeling

- Hi-Lok fastener HL50-80-6 with HL90-8A collar
  - 1- Insert fastener / hold disk
  - 2- Release pusher
  - 2- Apply pre-tension (torque) to fastener / collar
- Parametric study:
  - Hole diameters (interference fits)
  - Edge margins

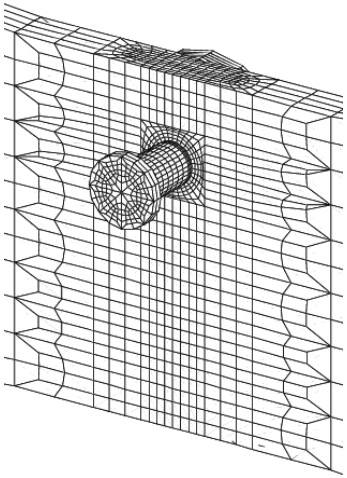




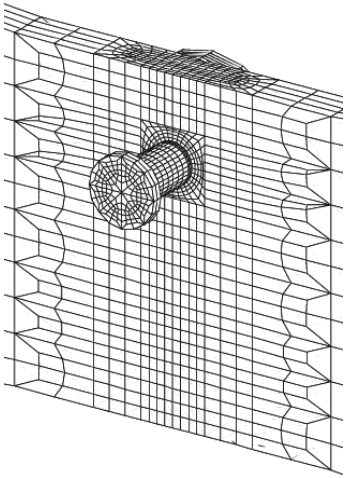




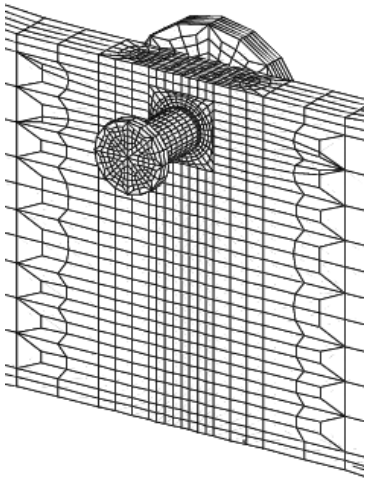
Interference Fit Fastener Modeling



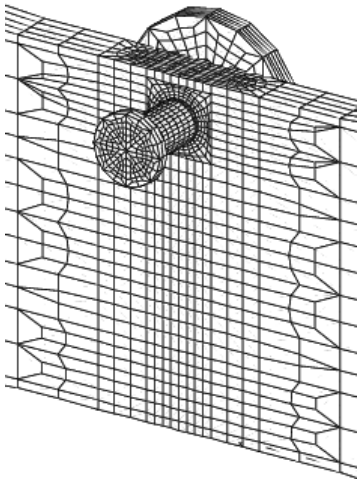
e/D = 2.0



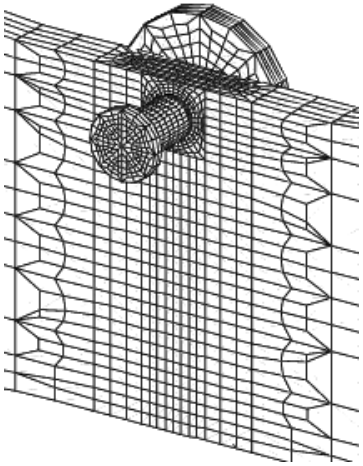
e/D = 1.5



e/D = 1.2



e/D = 1.0



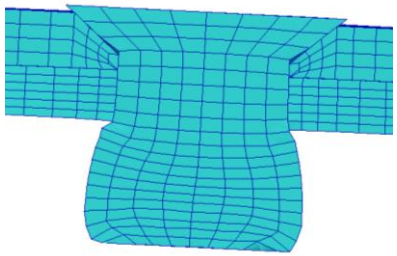
e/D = 0.8

Summary of Interference Fit Fastener Modeling

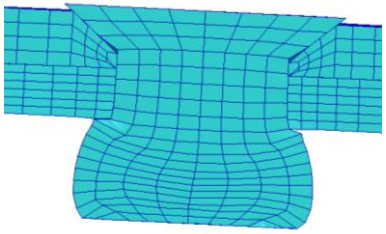
- Properly installed Hi-Lok fasteners will reduce the stress concentration effect at the hole edge by their clamping force and move the largest stressed areas from the surfaces to the mid-plane.
- A 0.0035” induced interference fit was the best of the four values investigated (0”, 0.001”, 0.0035”, 0.005”)
- Effect of the low edge margin e/D was significant. At a e/D value less than 1.2, a highly localized tensile stress occurred in the remaining ligament, independent of the degree of interference fit

Riveting Simulation

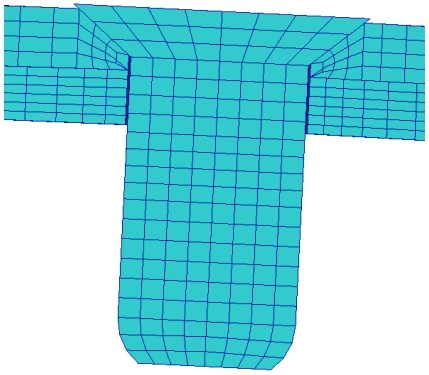
- Countersunk fastener
  - 1- Squeeze fastener
  - 2- Release pusher
- Parametric study:
  - Hole diameters (clearance)
  - Squeeze displacement (head deformation)



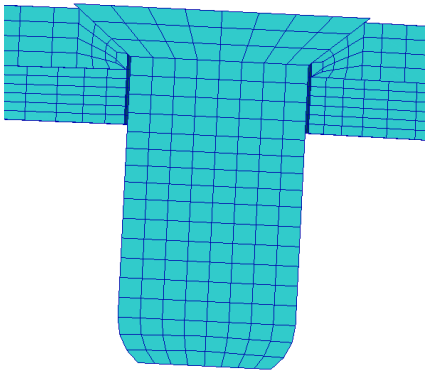
Def 1



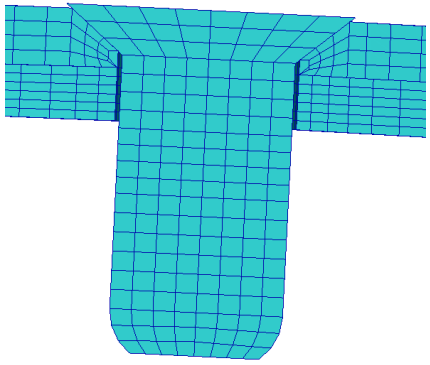
Def 2



Size 1



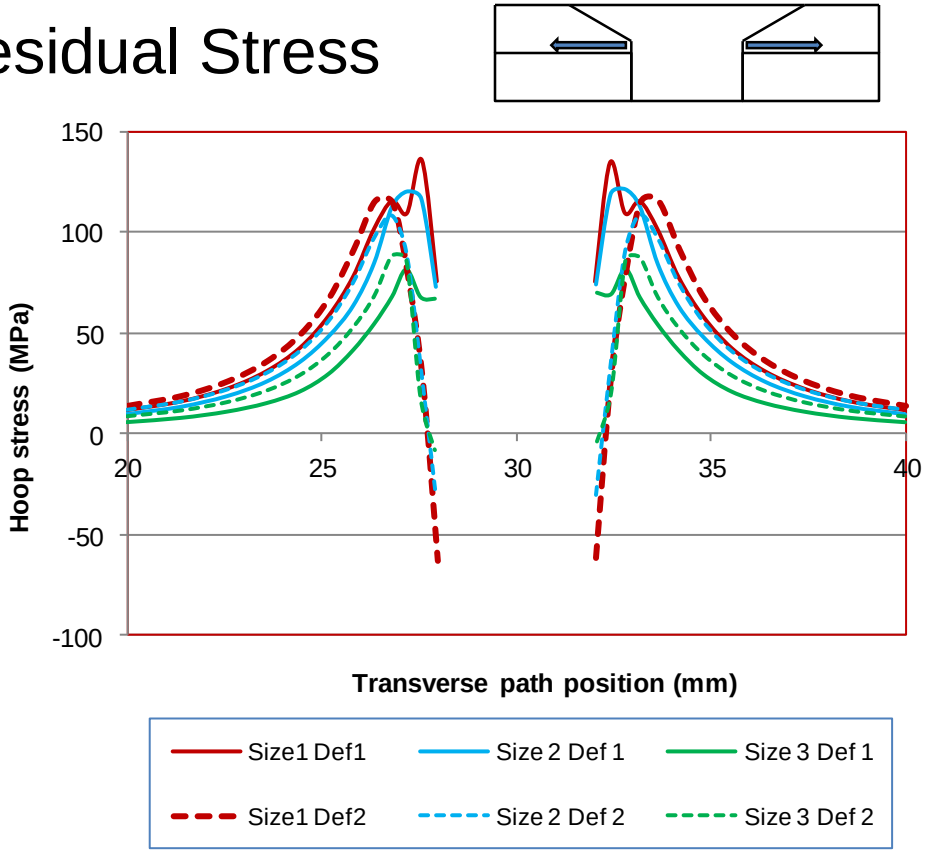
Size 2



Size 3 (largest clearance)

Riveting Simulation

- General Observations on Residual Stress
  - Smaller diameters / Larger deformation resulted in compression at hole edge
  - Larger compression is balanced by larger tension, at a larger distance from the hole
  - Results agreed well with Neutron Diffraction measurements



Post-Riveting Residual Stress

Example: Crack Growth in Riveted Lap Joint

Typical Lap Joint

- Geometry representative of a fuselage panel
- Three rows of countersunk rivets

Analysis Objective

- Calculate life to first link-up distribution

Analysis Strategy

Stress and Residual Stress Profiles

- Riveting simulation (MSC Marc)

Crack Growth Analysis

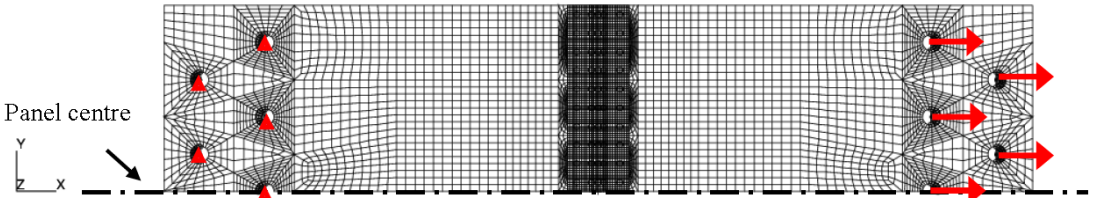
- Countersunk geometry correction factor ← AFGROW
- Riveting residual stress correction factor
  - Spectrum modification based on tip position ← AFGROW
  - Residual stress correction factor ← AFGROW

Monte Carlo Simulations (CanGROW)

- EIFS distribution calculation
- Life distribution calculation (to first link-up)

Riveting Simulation

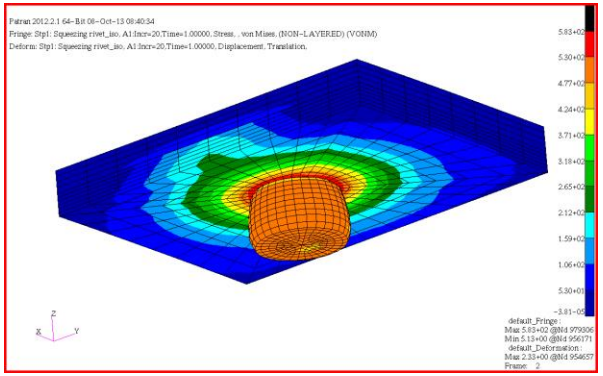
Global Model

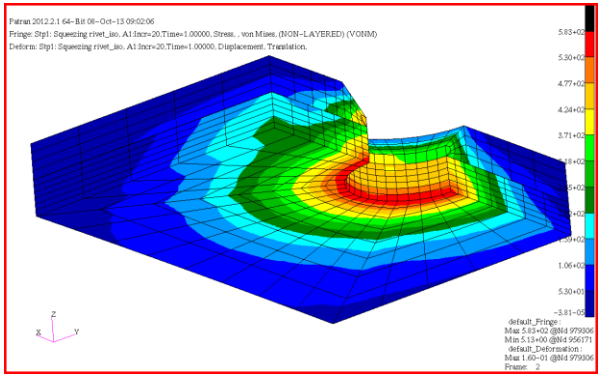


- Shell model
  - Displacements from applied loads

Local Model

- Central region / Nine rivets
- 3D model / Multi-Step Analysis
- Riveting simulation
  - Squeeze, release
  - Cyclic loading
  - 1 or 3 rivets

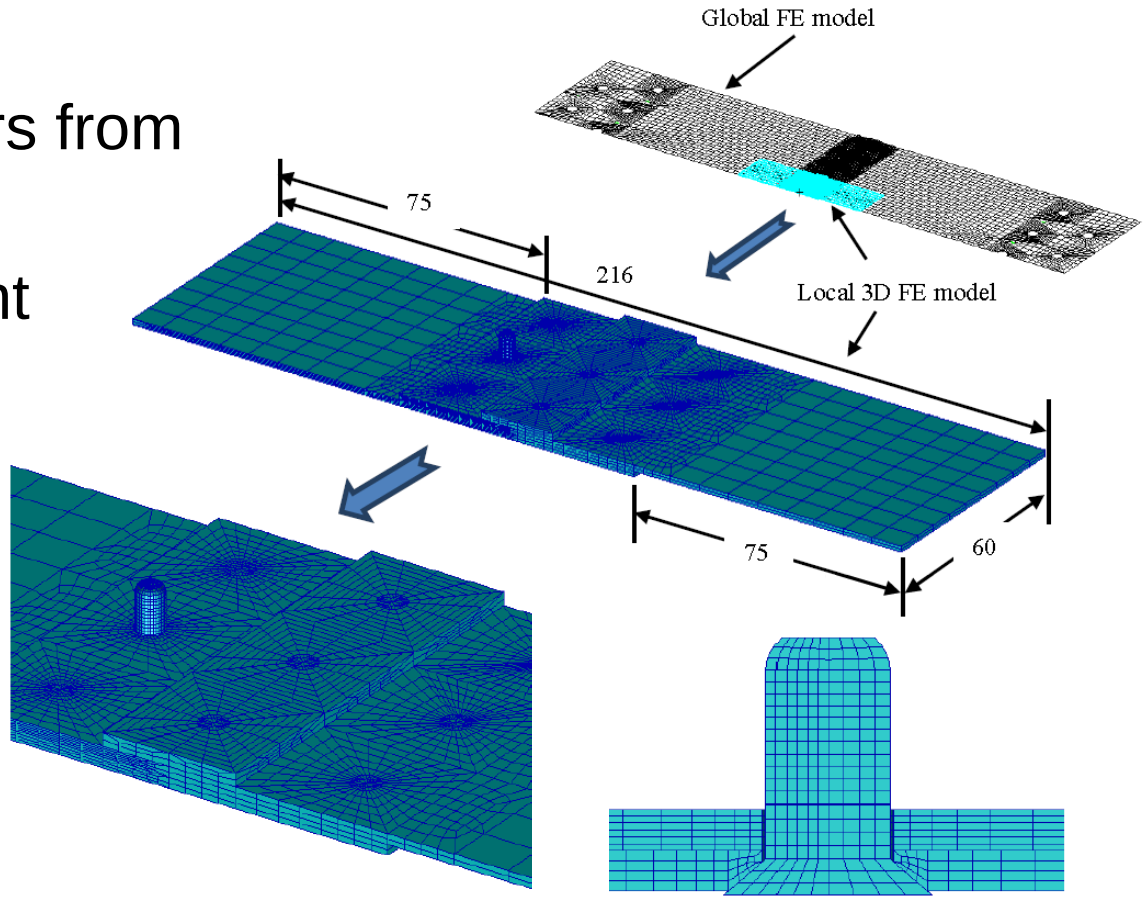




Finite Element Analysis

Input Parameters

- Several hole diameters from specifications
- Squeeze displacement derived from test measurements
- Material properties from published data
- Model validated with strain survey

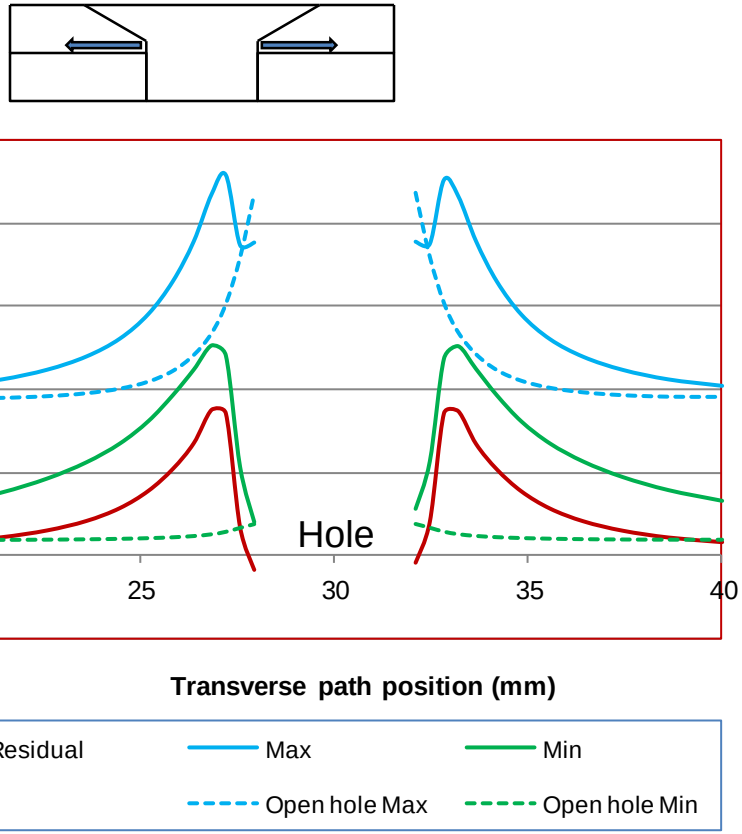


Finite Element Analysis

Local Model Analysis Results

- Post-riveting stress
  - No load
- Stress under applied loads
  - Max, min
- Open hole stress
  - Max, min

- Include nonlinear effects:
  - Material
  - Geometry
  - Contact



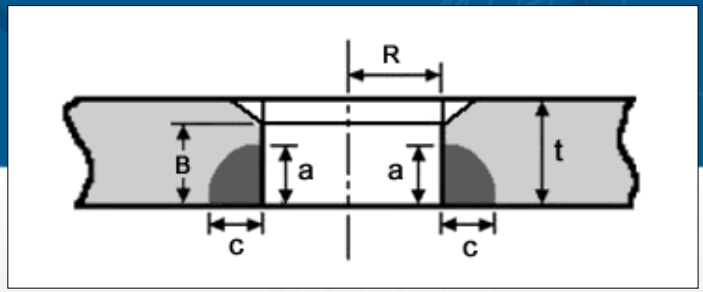
Size 3 Def 2
(low compression at hole edge)

Beta Solution – Riveting Residual Stress

- CanGROW:
  - Does not have CSK model or residual stress capabilities yet
  - Approach: Convert AFGROW's results to a Beta correction for constant amplitude loading (compounded with MSD factors)

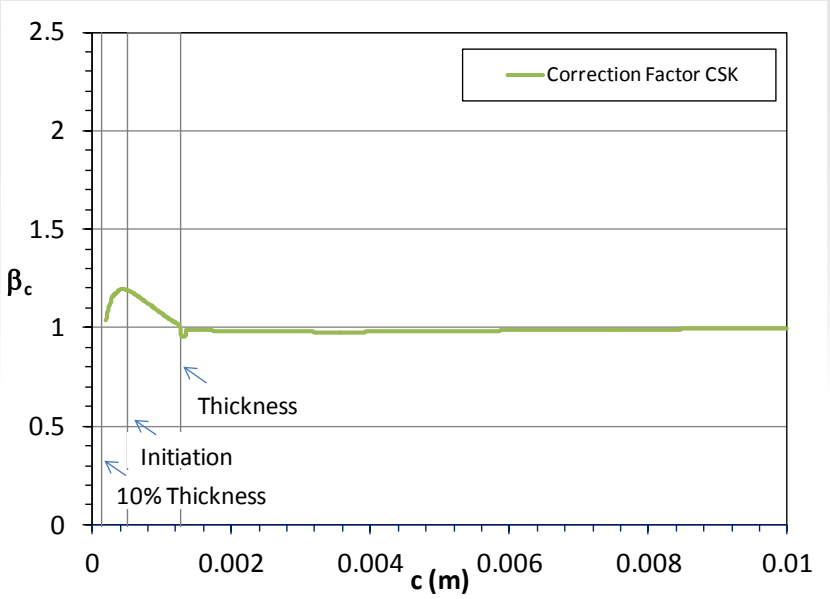
- AFGROW:
  - Approach 1: AFGROW CSK model
    - Residual Stress option not available for CSK model
    - Modify spectrum based on tip position (FE min and max stress)
  - Approach 2: AFGROW Straight Hole Model
    - Convert CSK Model to a Beta table
    - Add post-riveting residual stress from FE

Beta Correction for CSK Geometry

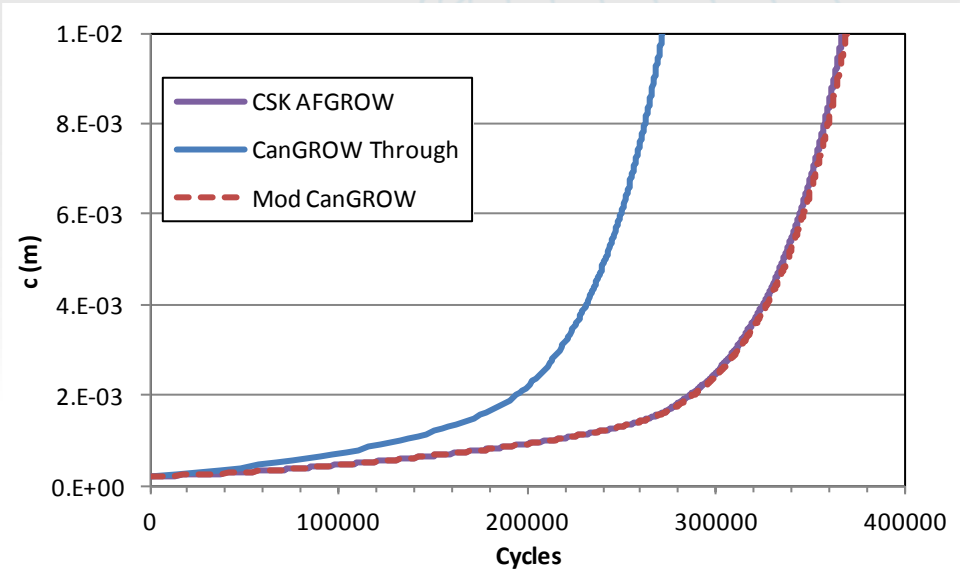


Countersunk Hole Solution

- Uses AFGROW's solution in CanGROW (through crack)
- Correction Factor (CF) = $\beta_{c\_AFGROW} / \beta_{c\_CanGROW}$



Correction Factor

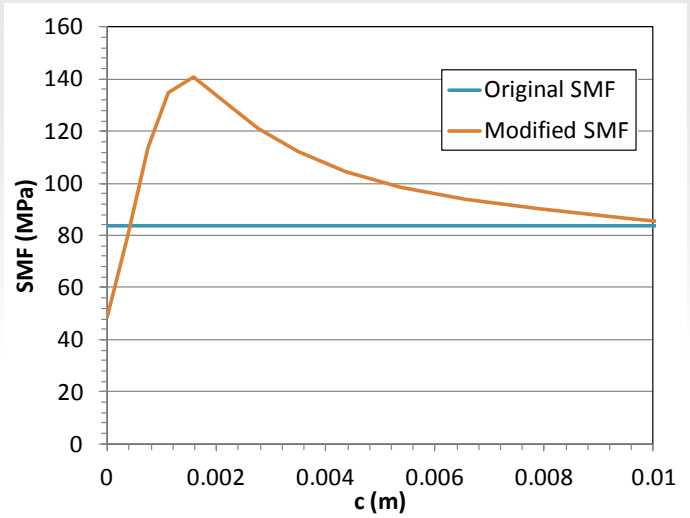


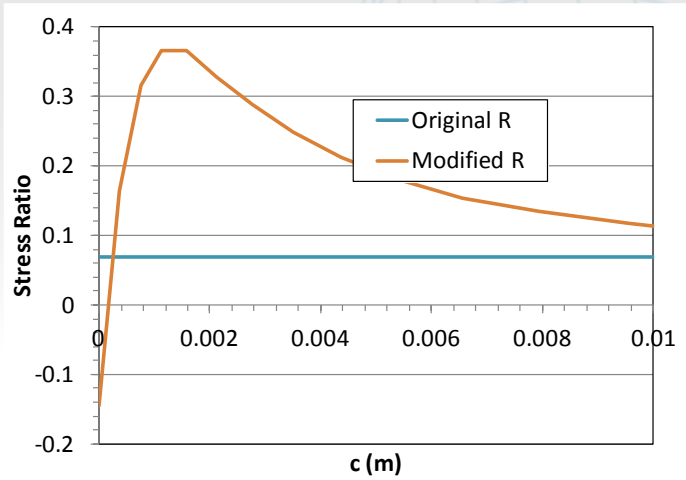
Crack Growth

NRC·CNRC

Approach 1: AFGROW CSK Model

- Calculate SMF and R based on tip position
  - Use FE min and max stress in AFGROW
  - Calculated using FE open CSK hole model
  - Incremental growth (VBA Program / COM interface)

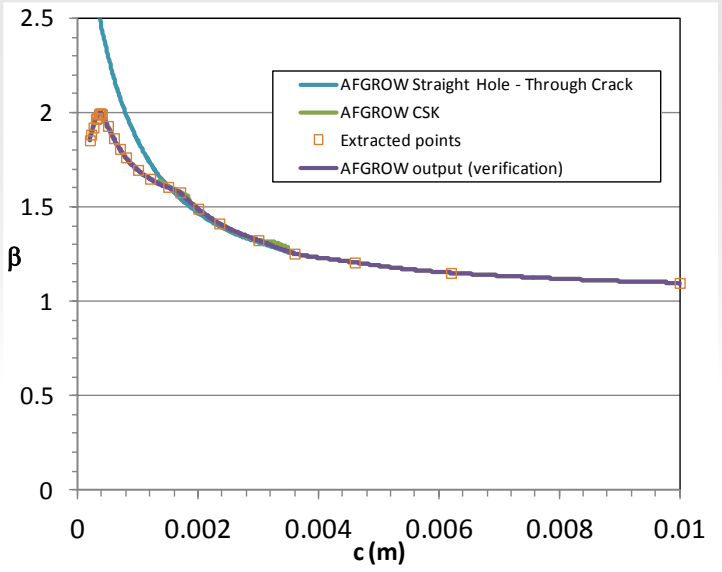


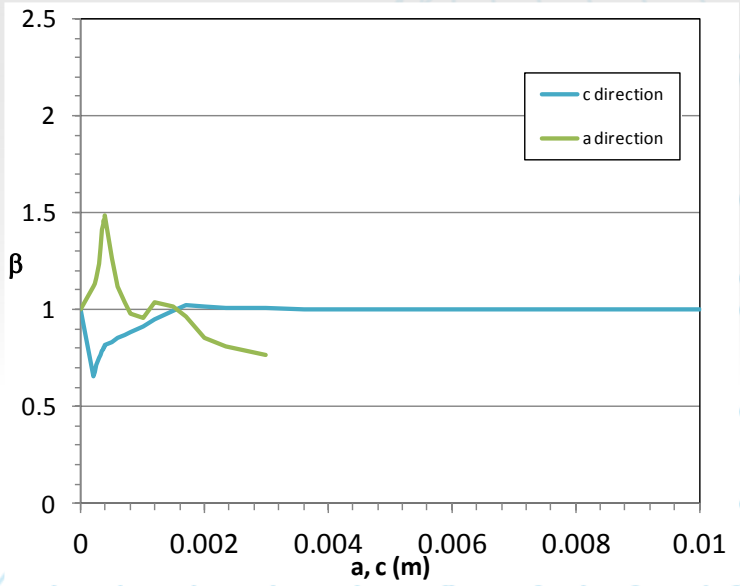


Size 3 Def 2
(low compression at hole edge)

Approach 2: AFGROW Straight Hole Model

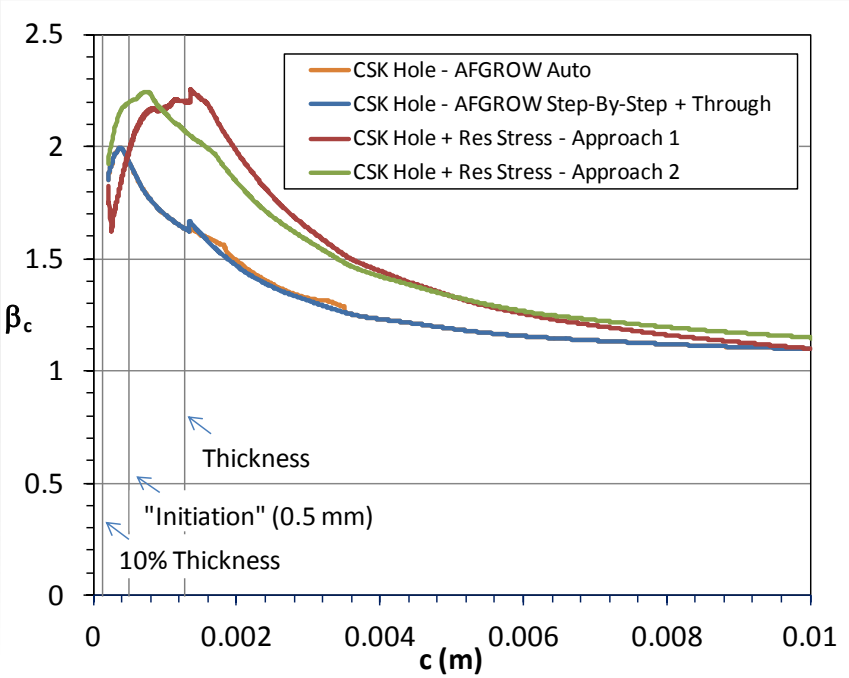
- Manual CSK Beta correction
- Residual stresses curve from FE
  - Constant $\Delta\sigma$ is assumed



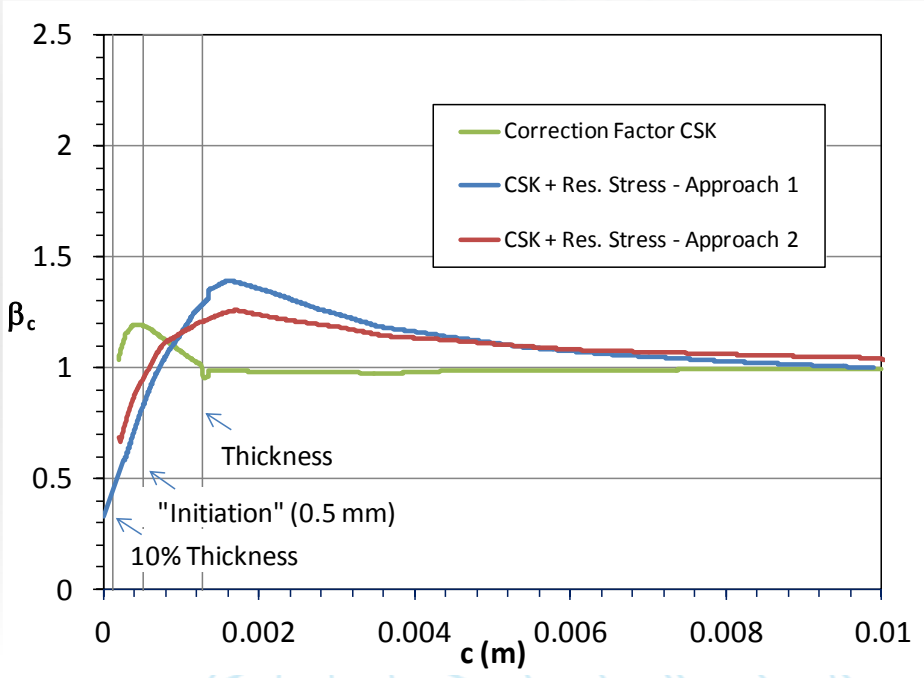


Size 3 Def 2
(low compression at hole edge)

Beta Solutions



Beta curve (AFGROW)

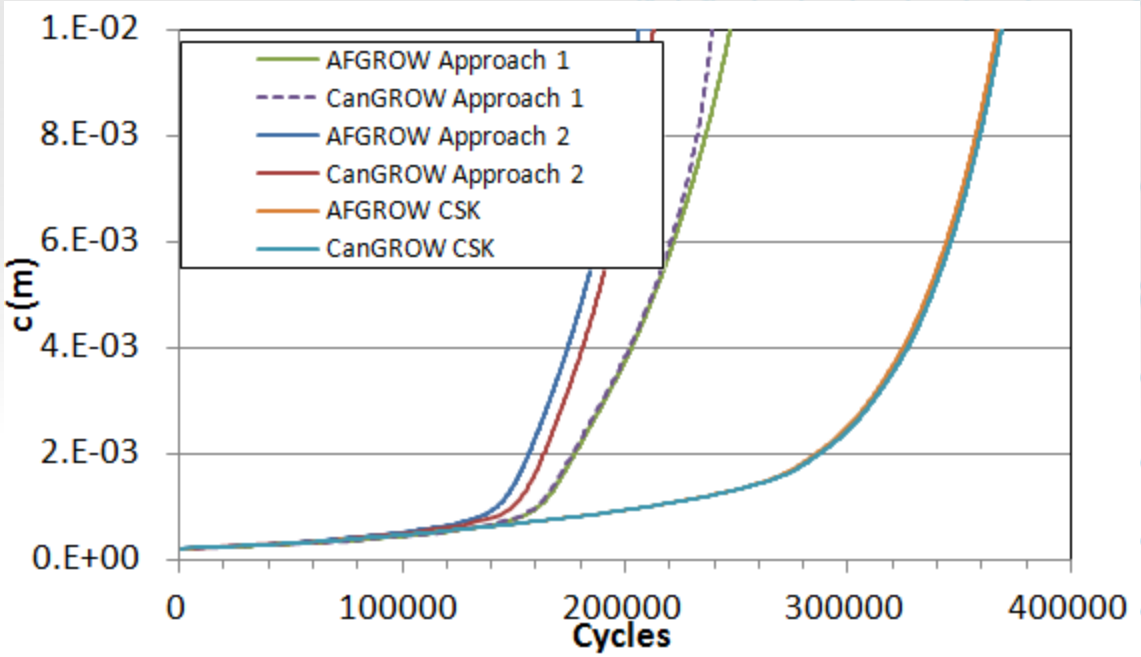


CanGROW Correction Factor

Size 3 Def 2
(low compression at hole edge)

Crack Growth

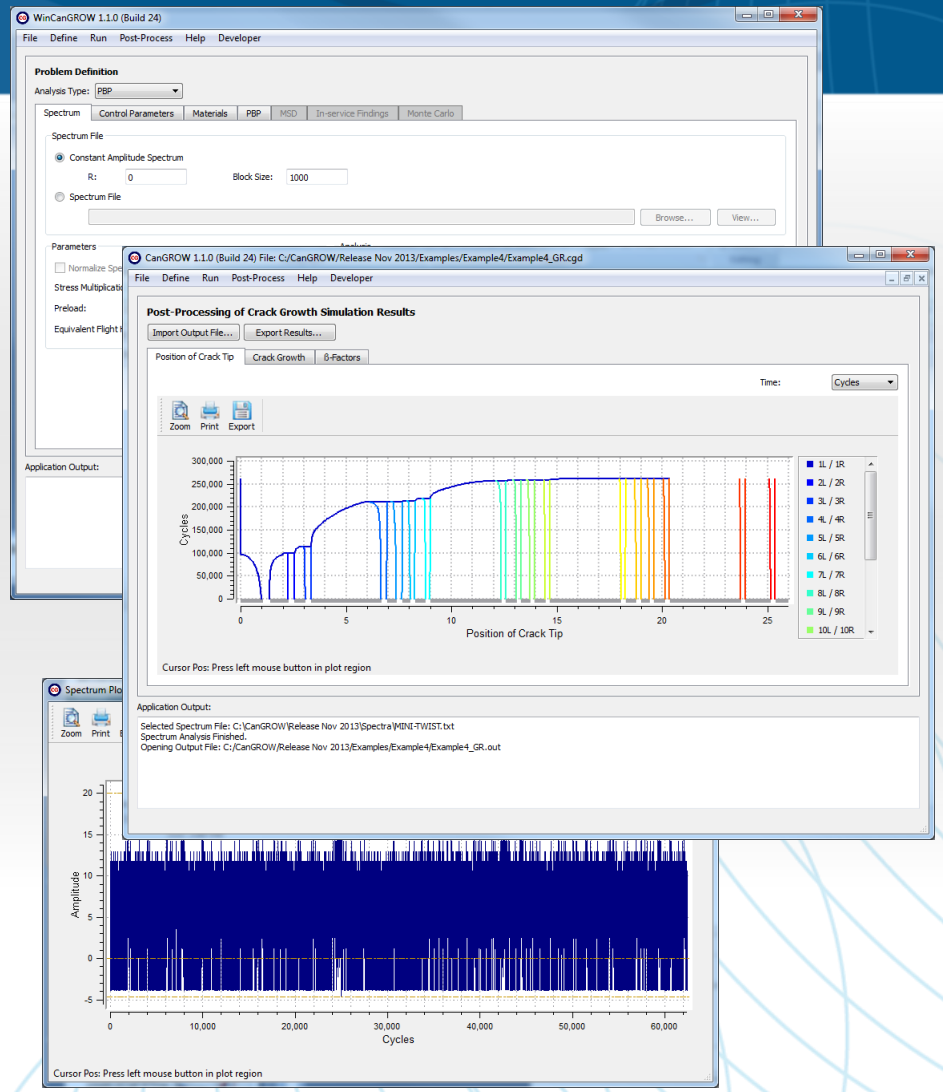
- Approach 2 more severe than Approach 1
  - $\Delta\sigma$ assumed constant in Approach 2
  - Nonlinearities in FE results



Size 3 Def 2 (low compression at hole edge)

Probabilistic Analysis

- Life to first link-up
  - Option 1: Probabilistic “initiation” life (strain life using FE results) + Crack Growth
  - Option 2: EIFS distribution based on in-service findings (including censored data) – Crack Growth only
  - CanGROW MSD analysis (crack interaction)
  - Monte Carlo simulation → life distribution (POF)



CanGROW

Conclusion

- An overview of NRC's work on the calculation of residual stresses using 3D finite element modeling was presented
- These simulations replicate as closely as possible the actual processes by using 3D multi-step nonlinear analysis
  - Hole cold expansion; Interference fit fastener installation; Riveting
- 3D and through-the-thickness effects were shown to be significant
- An example was presented, where life to first-linkup is to be calculated for a lap joint, using a series of three software tools:
  - MSC Marc to calculate post-riveting residual stresses
  - AFGROW to build a Beta factor for CSK geometry and FE stresses
  - CanGROW to perform MSD Monte Carlo simulations

Possible Future Work

- Possible verification and improvement steps:
  - Use StressCheck to develop Beta factors that includes the hole geometry and service and/or residual stresses determined by Cx or riveting simulation
  - Additional test validation using digital image correlation, X-ray diffraction, contour method, etc.

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Thank you

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