Residual Stress Process Simulation Subcommittee Progress Report

Engineered Residual Stress Implementation Workshop 2017

Layton, Utah, USA

September 21, 2017

Keith Hitchman - FTI

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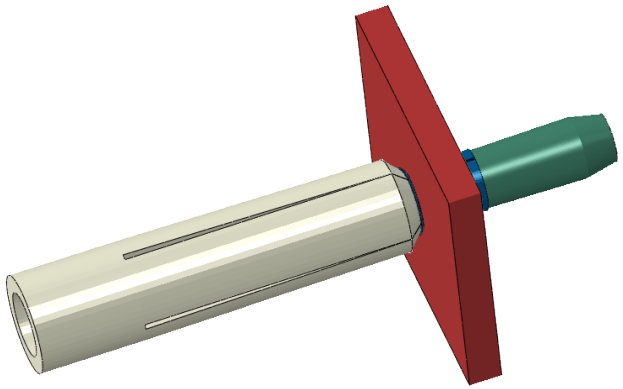
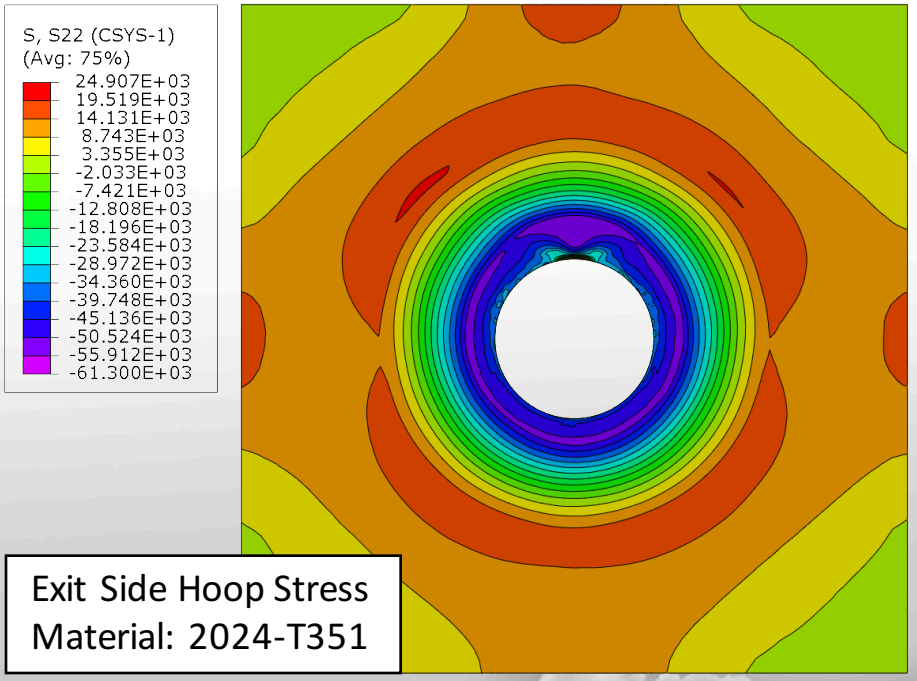
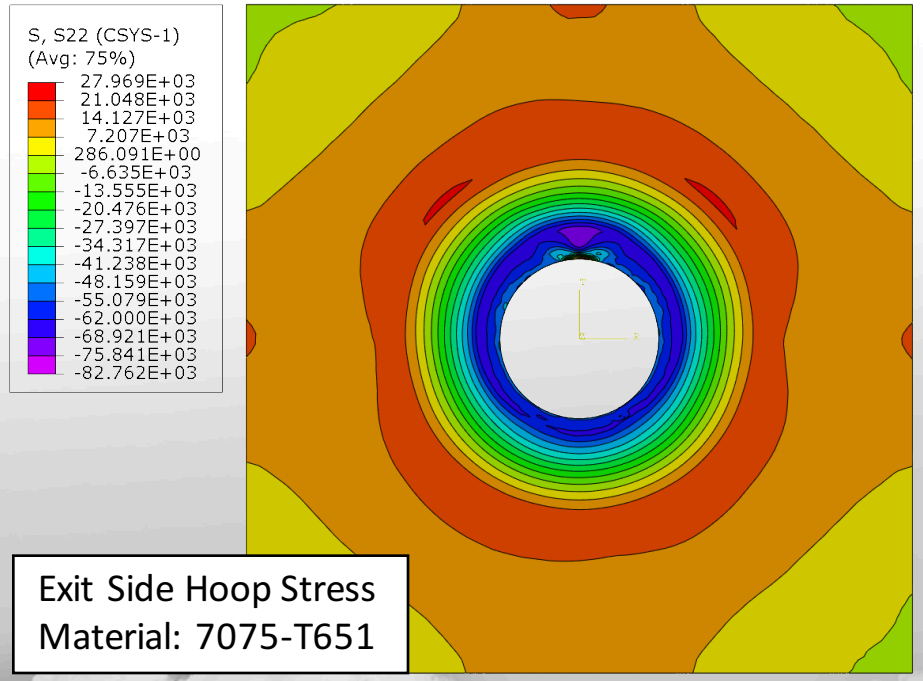
Outline

- RS Process Simulation Review
- Material Testing Progress
- RS Process Simulation Validation Progress





Exit Side Hoop Stress
Material: 2024-T351



Exit Side Hoop Stress
Material: 7075-T651

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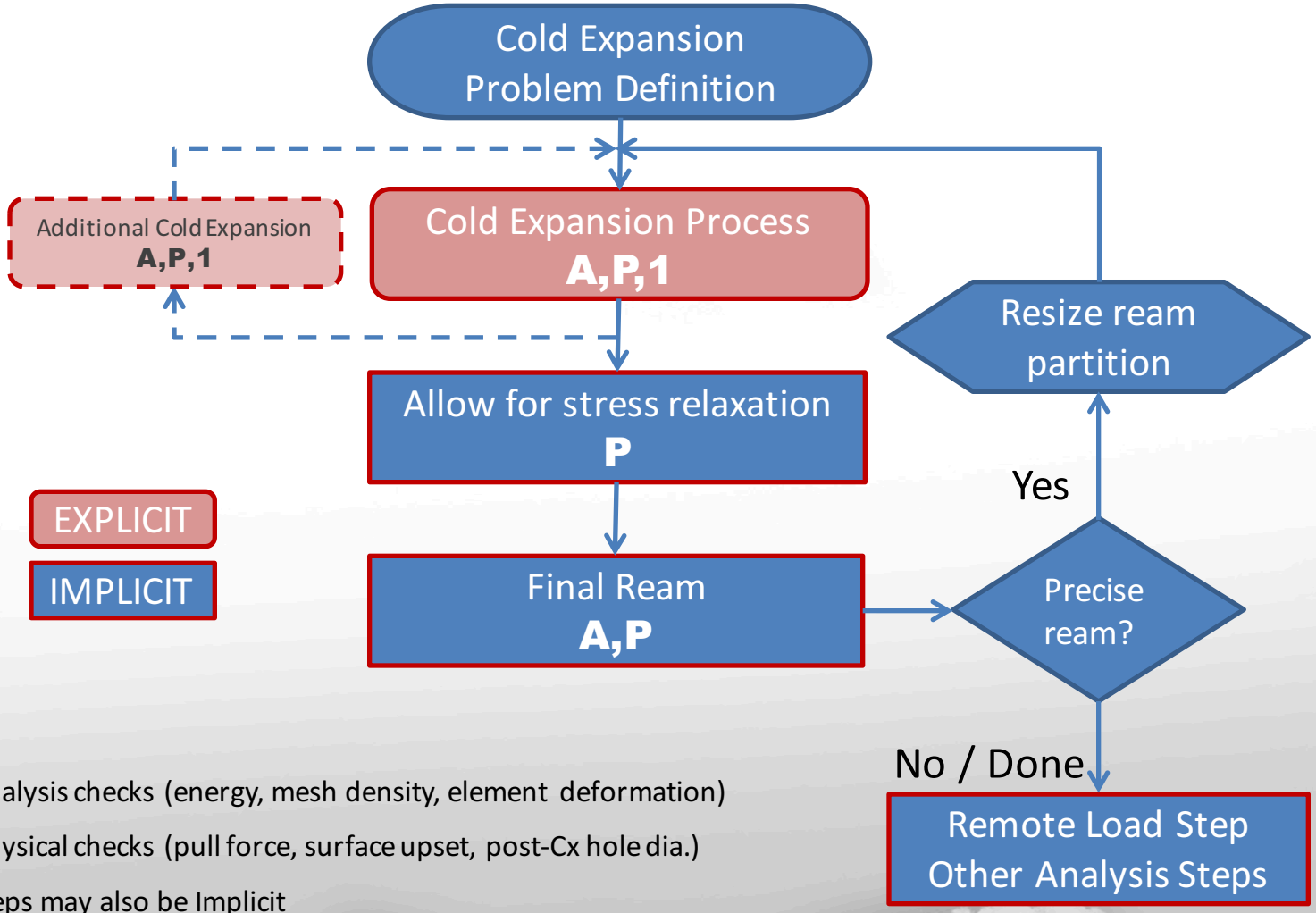
RS Process Simulation Review – Typical FEA Workflow



A: analysis checks (energy, mesh density, element deformation)

P: physical checks (pull force, surface upset, post-Cx hole dia.)

1: Steps may also be Implicit

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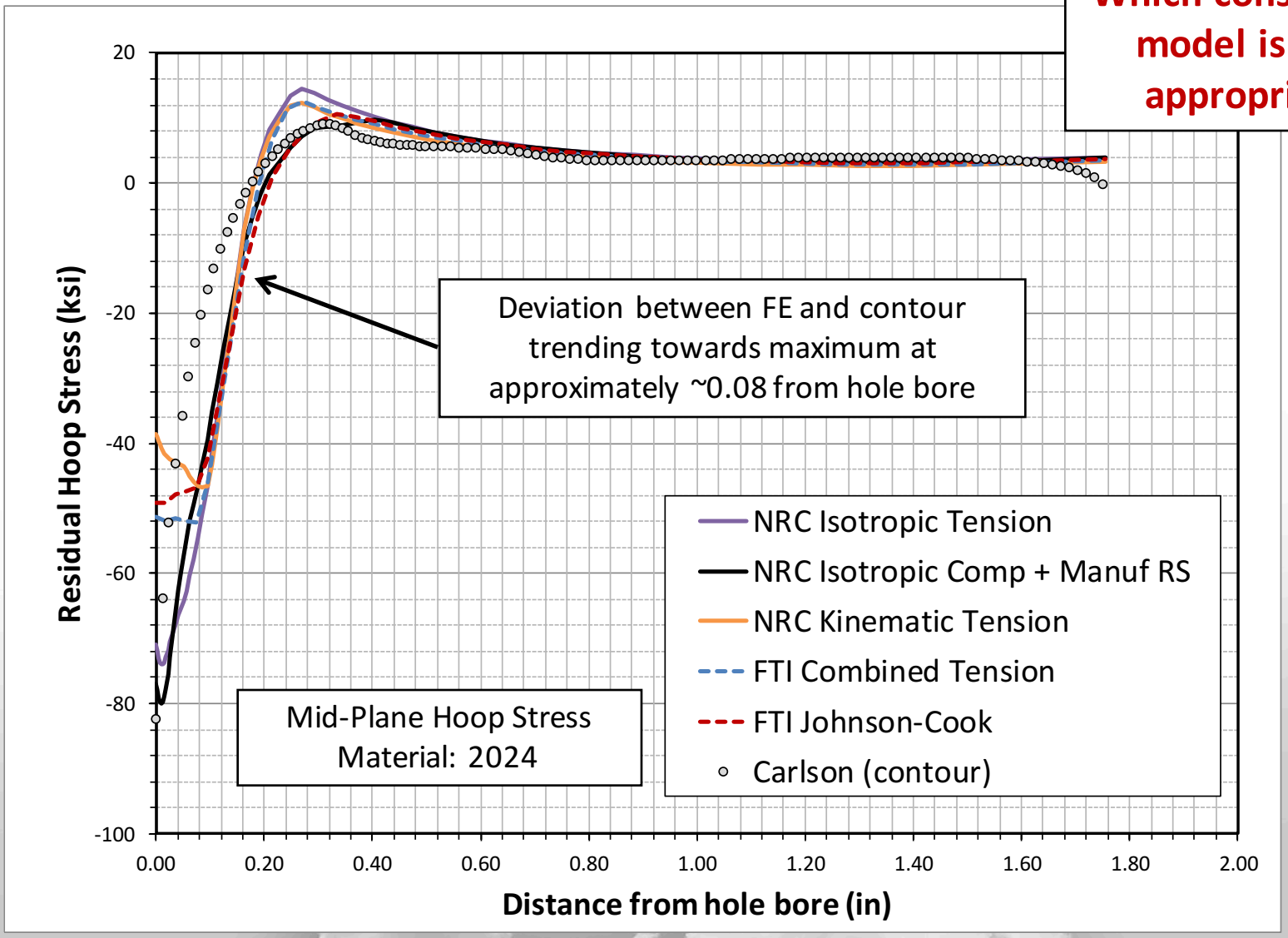
Material Model Testing
Purpose of Program

Which constitutive model is most appropriate?



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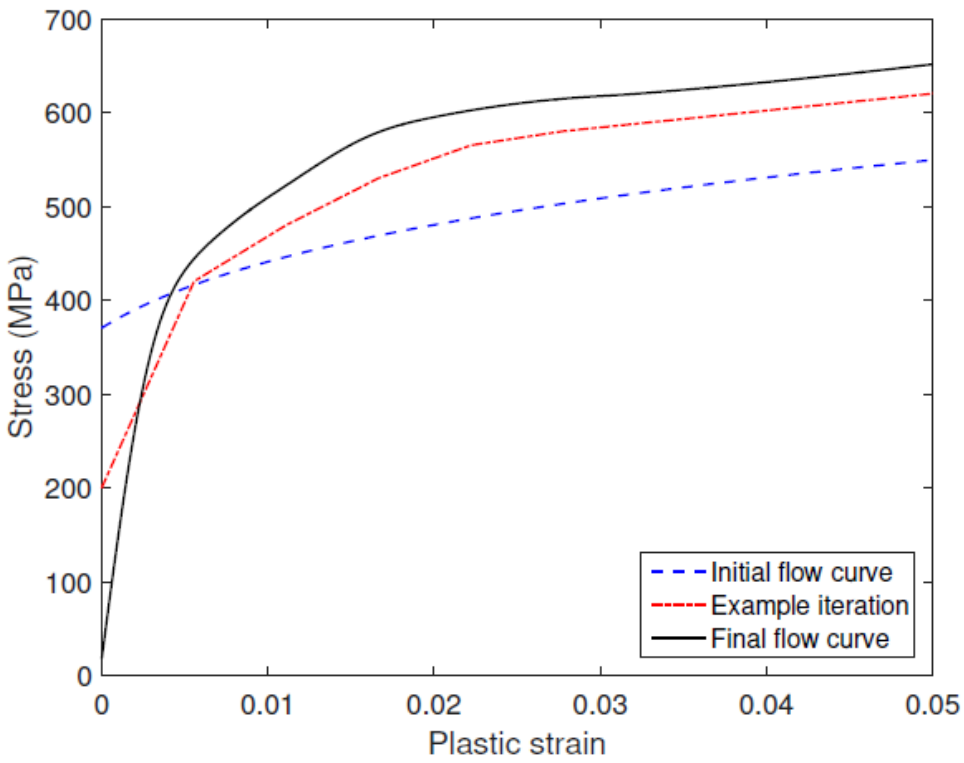
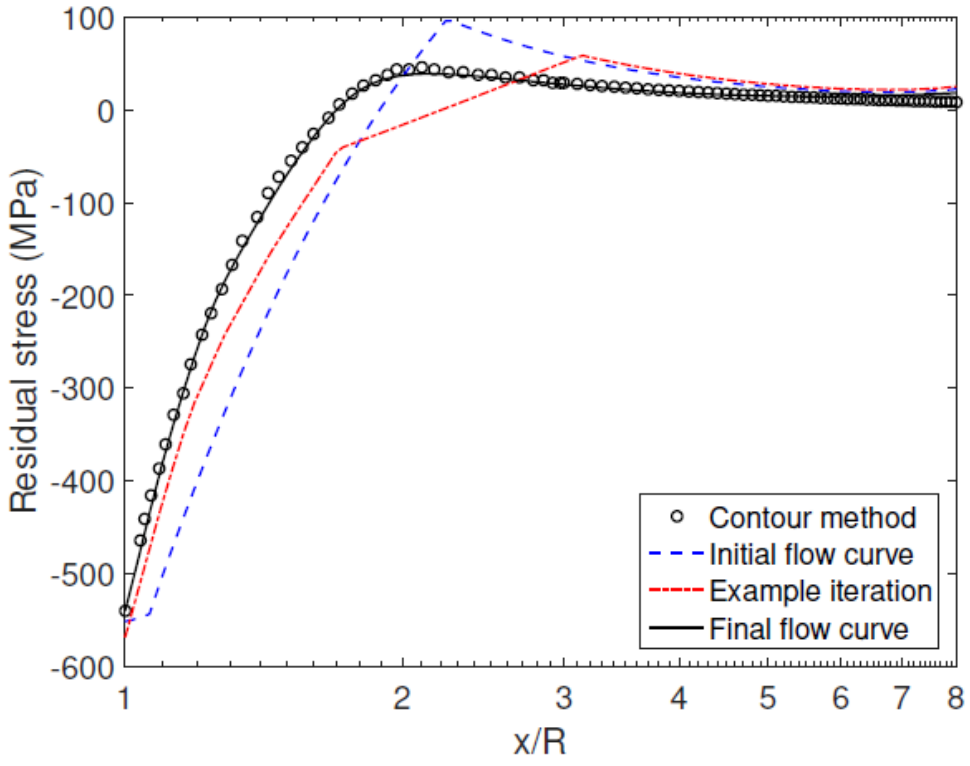
Material Model Testing

Purpose of Program – Example



(a)



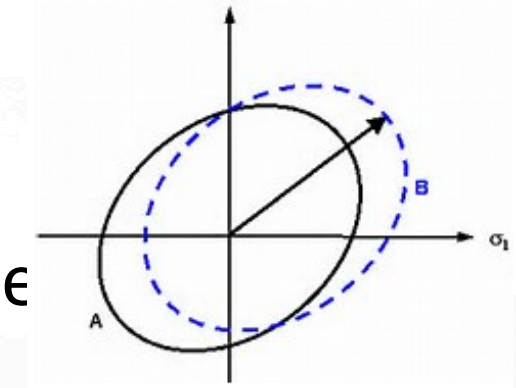
(b)

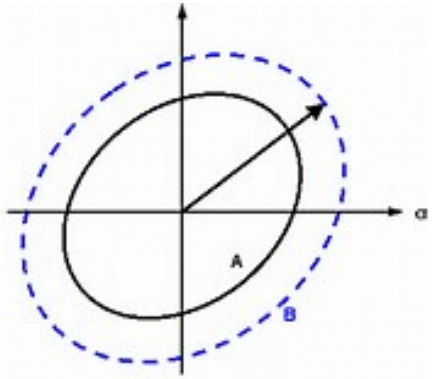
Figure 7 – (a) Flow curves tested, (b) resulting hoop residual stress ($\sigma_{\theta\theta}$); note log scale on x/R

Ribeiro, Renan L., and Michael R. Hill. "Residual Stress From Cold Expansion of Fastener Holes: Measurement, Eigenstrain, and Process Finite Element Modeling." Journal of Engineering Materials and Technology 139.4 (2017): 041012. https://doi.org/10.1115/1.4037021

Material Models To Consider

- Isotropic
- Kinematic
- Combined
- Johnson-Cook (rate dep.)
- Triax/pressure dependence
  - Drucker-Prager (FTI)
  - Triax look-up (UMAT
- Anisotropic
  - Hill
  - Barlat (pressure dep./NRC)





$$\sigma_{yield,effective} = \sigma_0 \left[1 - c_\eta \left(\eta - \eta_0\right)\right]$$

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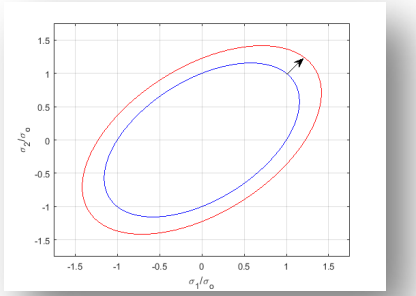
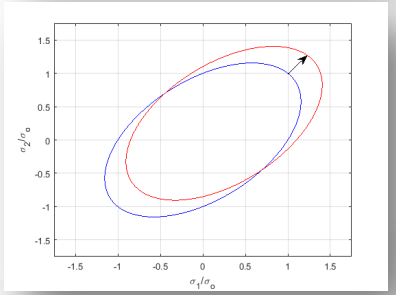
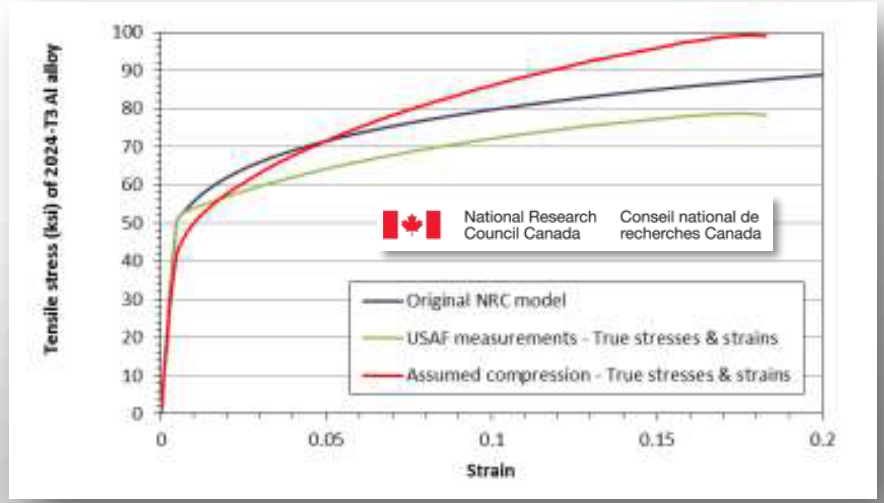
Material Model Testing

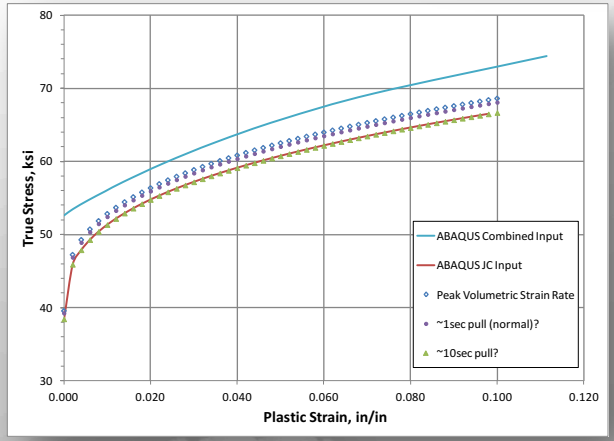
General Plan

- Based upon E606 LCF, up to ±4% in./in.
- Isolating current investigation to orthotropy
- Focusing on single-cycle reverse-yield behavior
- **Testing to be complete Fall 2017**









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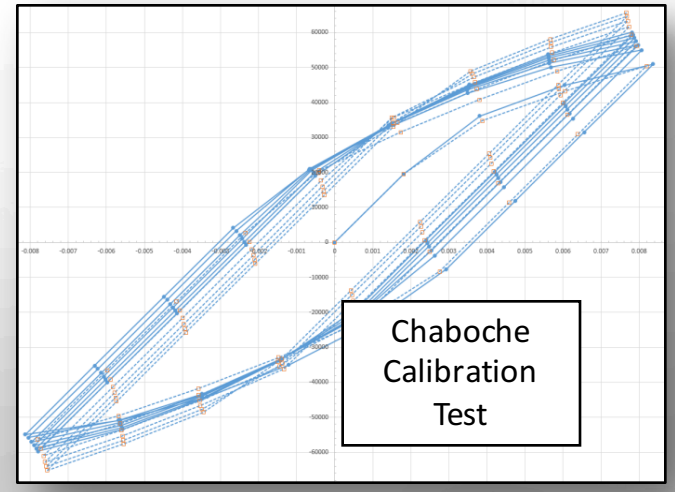
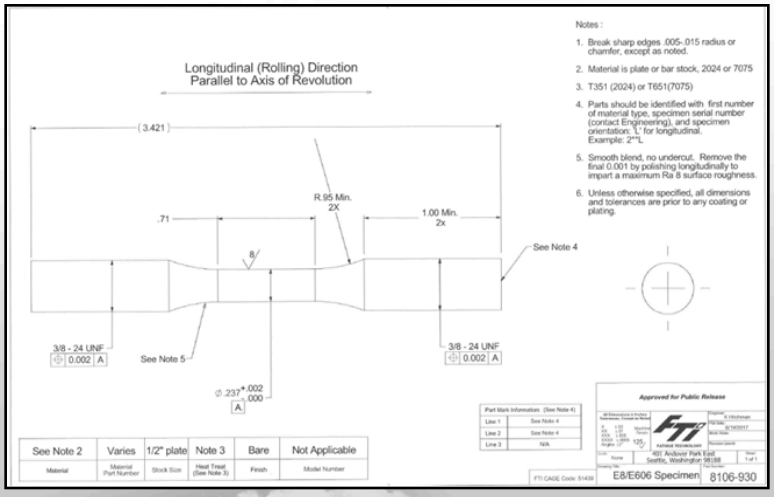
Material Model Testing

Experimental Matrix

Material and heat treat	Material Orientation	Specimens used for alignment + Spares	E8 specimens	E606 Specimens		
				R Ratio	Tension first	Compression first
2024-T351	L	4	2	-1	2	2
2024-T351	45-degrees	2	2	-1	2	2
2024-T351	LT	2	2	-1	2	2
7075-T651	L	4	2	-1	2	2
7075-T651	45-degrees	2	2	-1	2	2
7075-T651	LT	2	2	-1	2	2





RS Process Simulation Validation
Purpose of Program

- Perform Experiments to Capture Surface and Through-Thickness Strains for FEA Process Simulation Validation
  - Quantification of residual stresses through process simulation is a critical path for future ERSI realization
  - Perform Residual Stress Validation Through Comparison of Techniques
  - Limited open literature on cross-comparison of residual stress measurement methods for Cx holes
  - Potential to complement through-thickness techniques with surface techniques for a more accurate understanding of the complete residual stress field
  - Current work underway through Process Simulation Subcommittee, with the kind assistance of the ***Organization and Execution Group***:

- Dr. TJ Spradlin (AFRL)
- Keith Hitchman (FTI)
- Dr. Marcias Martinez (Clarkson U.)
- Marcus Stanfield (SwRI)
- Prof. Michael Fitzpatrick (Coventry U.)
- Scott Carlson (SwRI)
- Dr. Min Liao (NRC)
- Dr. Guillaume Renaud (NRC)
- Dr. Mike Hill (Hill Engineering)

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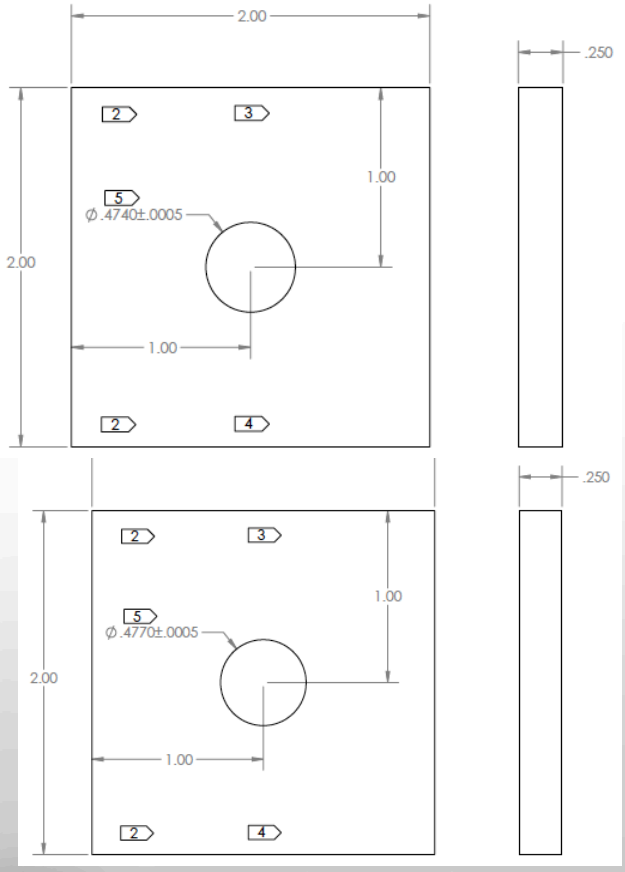
Experimental Matrix

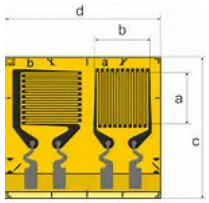
- Material: 2024-T351 & 7075-T651
- Applied Expansion Levels:
  - "Low" (3.16%)
  - "High" (4.16%)
- Center Hole Diameter: 16-O-N Tool Set
  - 0.50inch final diameter
  - Hole not reamed



Coupon Name	Geometry Outer Size (inch)	Defined Applied Cx Level	Material
2024-Cx-DIC/LUNA/XRD/CM/SG-01-L1	2x2	Low	2024-T351
2024-Cx-DIC/LUNA/XRD/CM/SG-02-L2			
2024-Cx-DIC/LUNA/XRD/CM/SG-03-H1		High	
2024-Cx-DIC/LUNA/XRD/CM/SG-04-H2			
7075-Cx-DIC/LUNA/XRD/CM/SG-01-L1		Low	7075-T651
7075-Cx-DIC/LUNA/XRD/CM/SG-02-L2			
7075-Cx-DIC/LUNA/XRD/CM/SG-03-H1		High	
7075-Cx-DIC/LUNA/XRD/CM/SG-04-H2			

Strain Measurement Techniques

- Surface Strain Measurement Techniques (Performed on Exit and Entrance Surfaces)
  - Digital Image Correlation (DIC)
  - Fiber Optics (LUNA)
  - Strain gages
- Through-Thickness Measurement Techniques
  - High Energy X-ray Diffraction (XRD)
    - Argonne National Labs
  - Neutron Diffraction
    - Coventry University (UK)
  - Contour Method
    - Hill Engineering, LLC.



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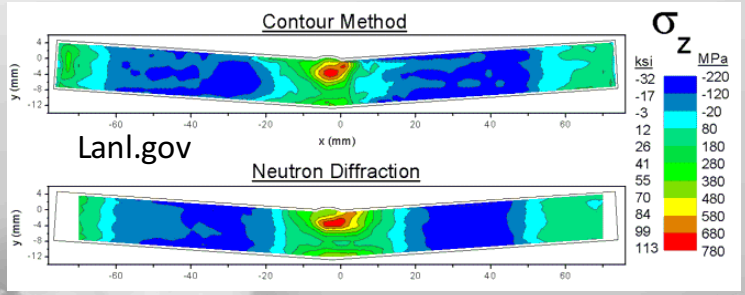
Argonne NATIONAL LABORATORY



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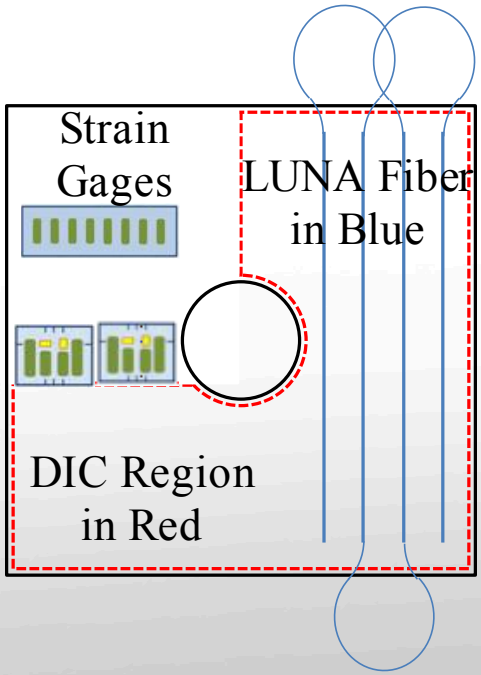
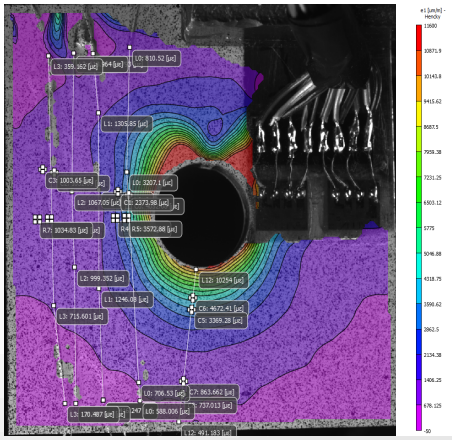
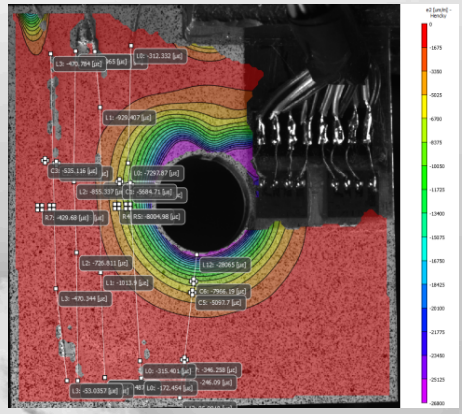
Surface Strain Measurements

- Measurements Performed at SwRI
- Both Entrance and Exit Surfaces Instrumented
- Able to Capture All Techniques Full-field Data for 6 of 8







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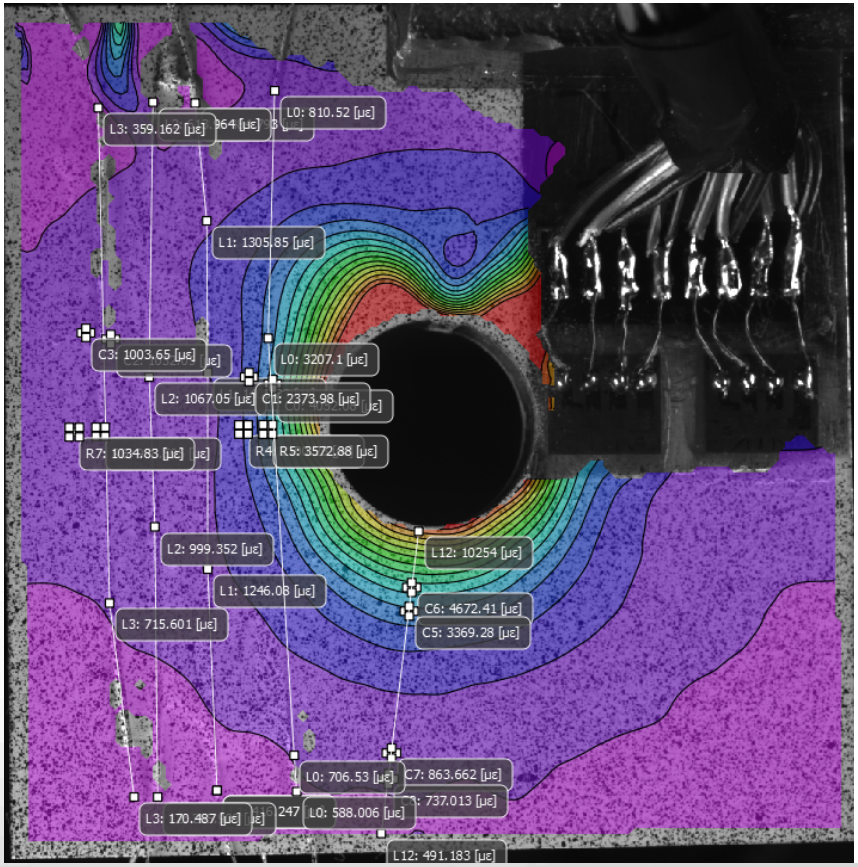
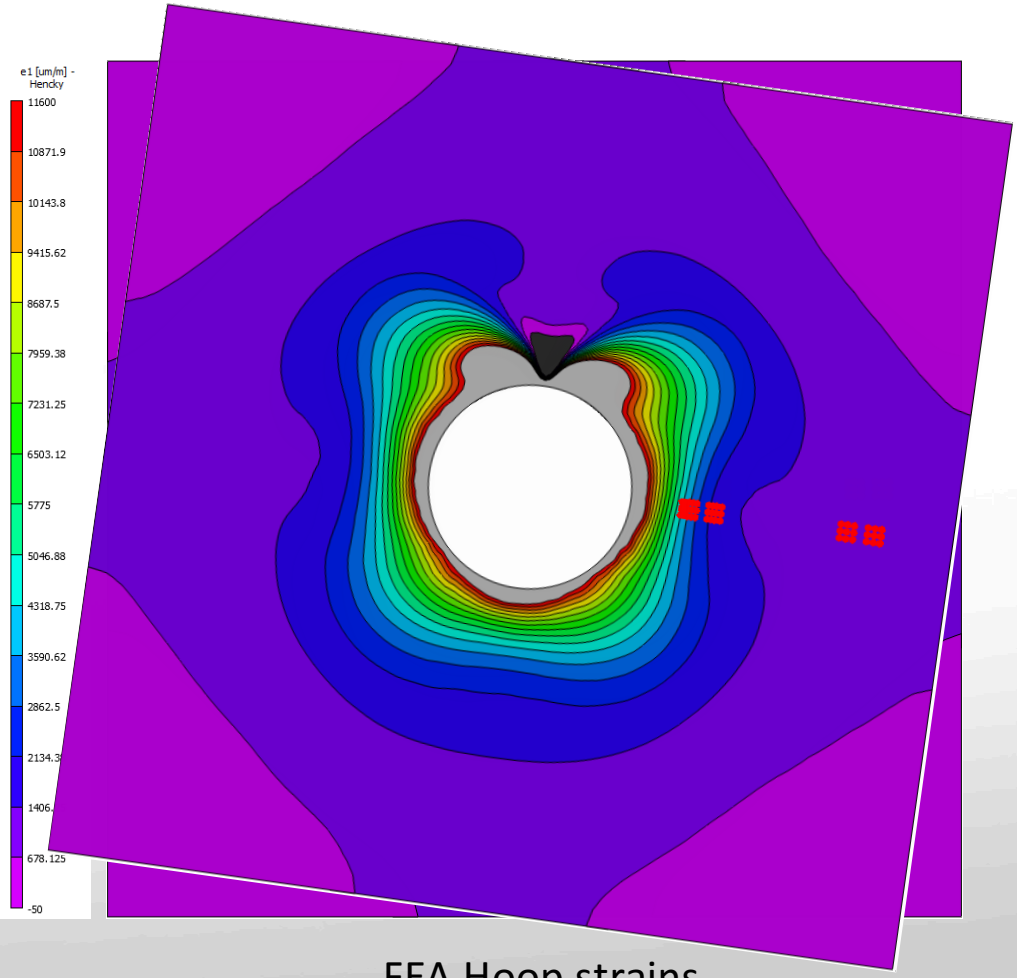
RS Process Simulation Validation

DIC vs Process Simulation Data





DIC Hoop strains

FEA Hoop strains
Combined Hardening

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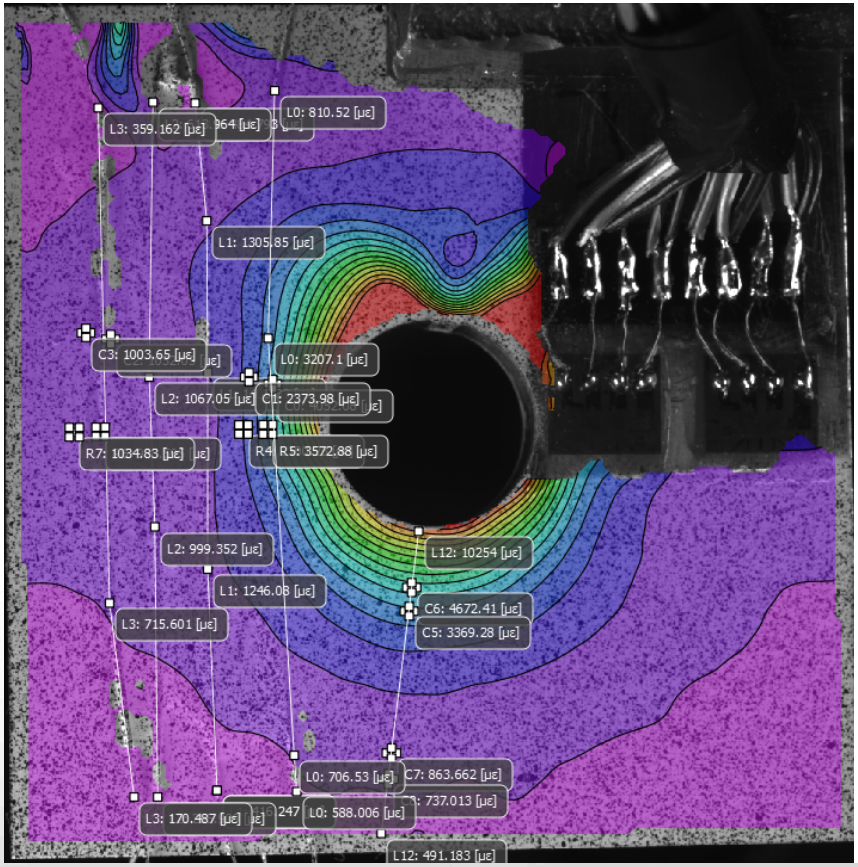
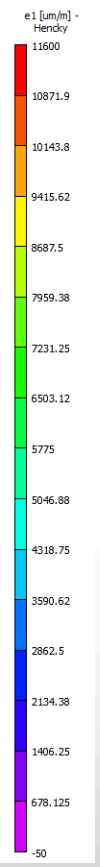
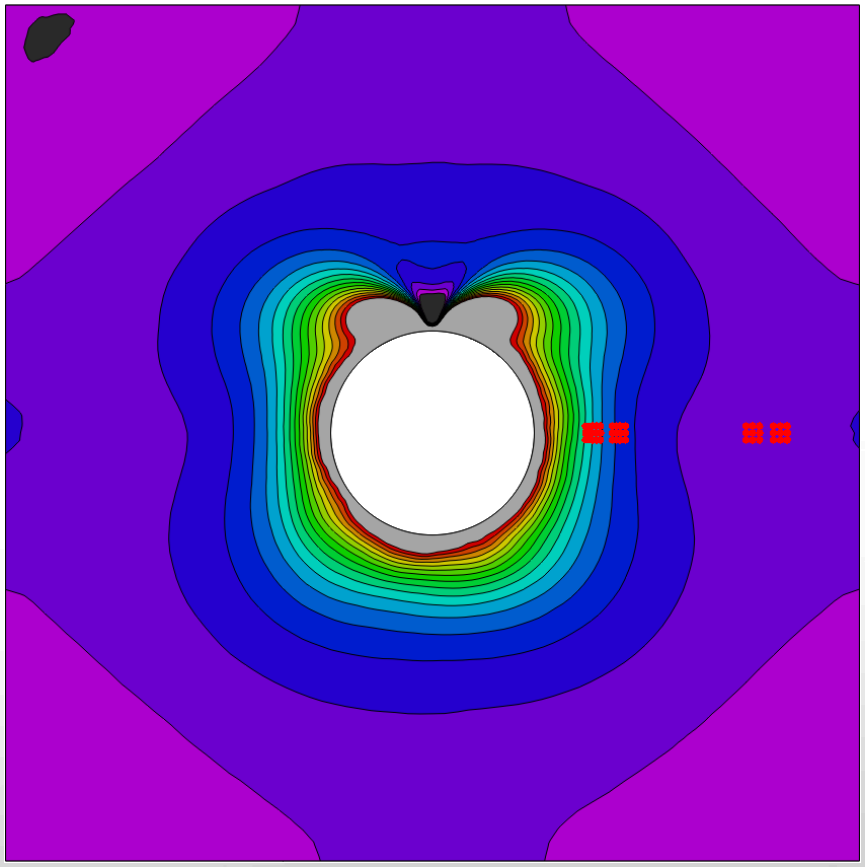
RS Process Simulation Validation

DIC vs Process Simulation Data







DIC Hoop strains

FEA Hoop strains
Chaboche Hardening

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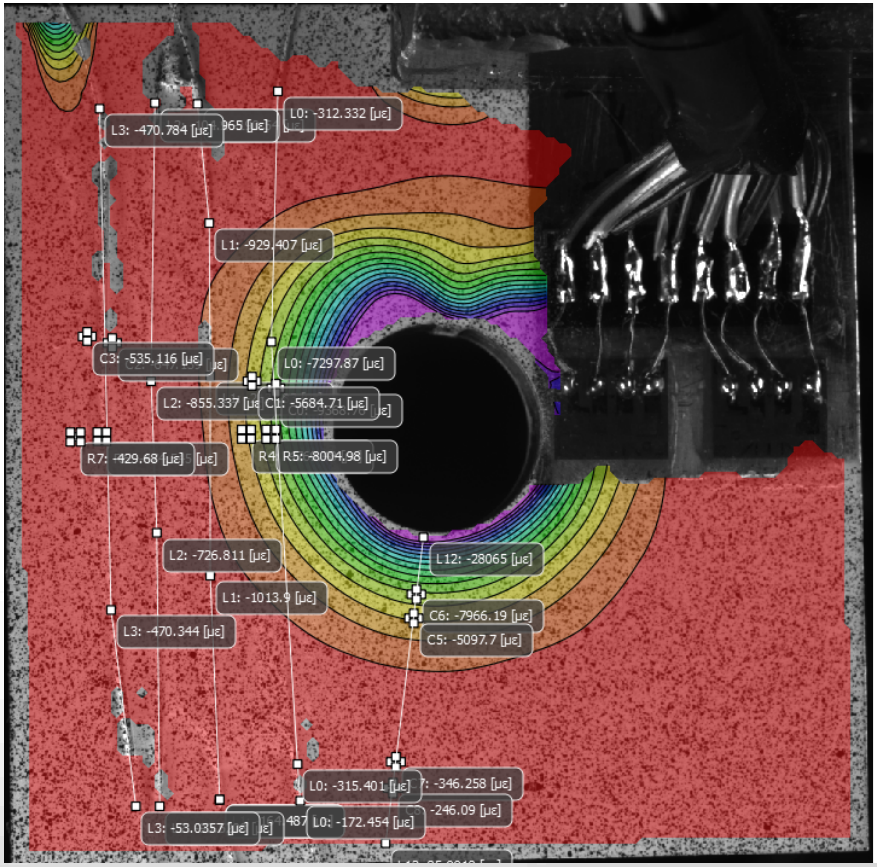
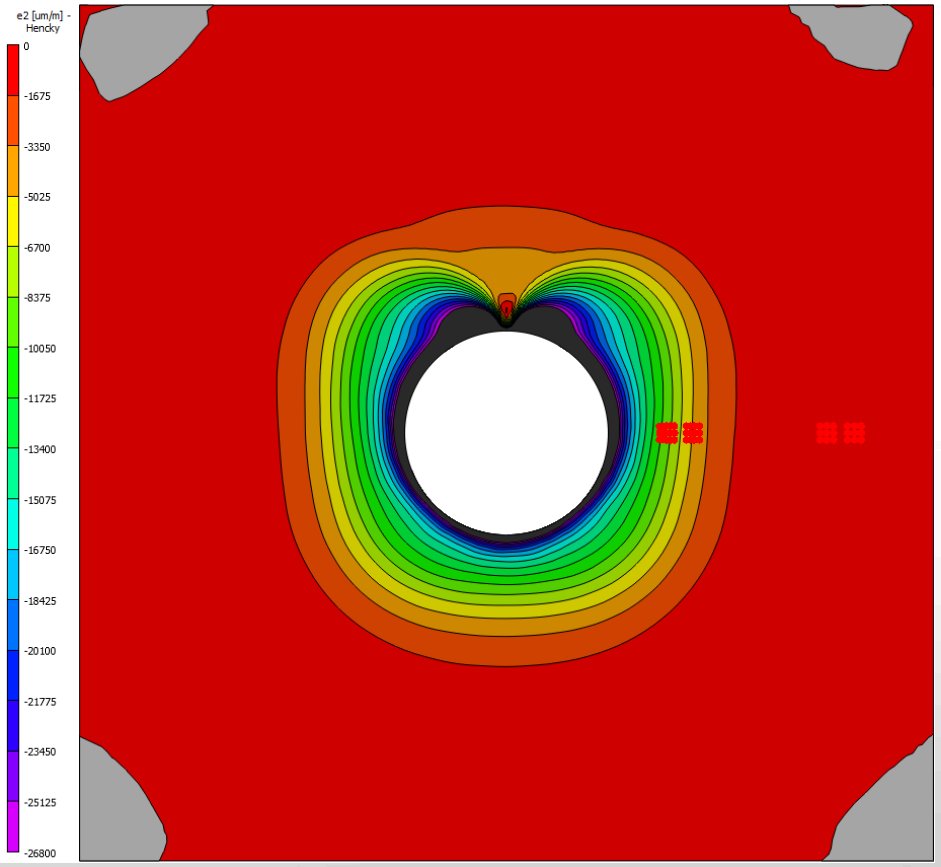
RS Process Simulation Validation

DIC vs Process Simulation Data



DIC Radial strains



FEA Radial strains
Combined Hardening

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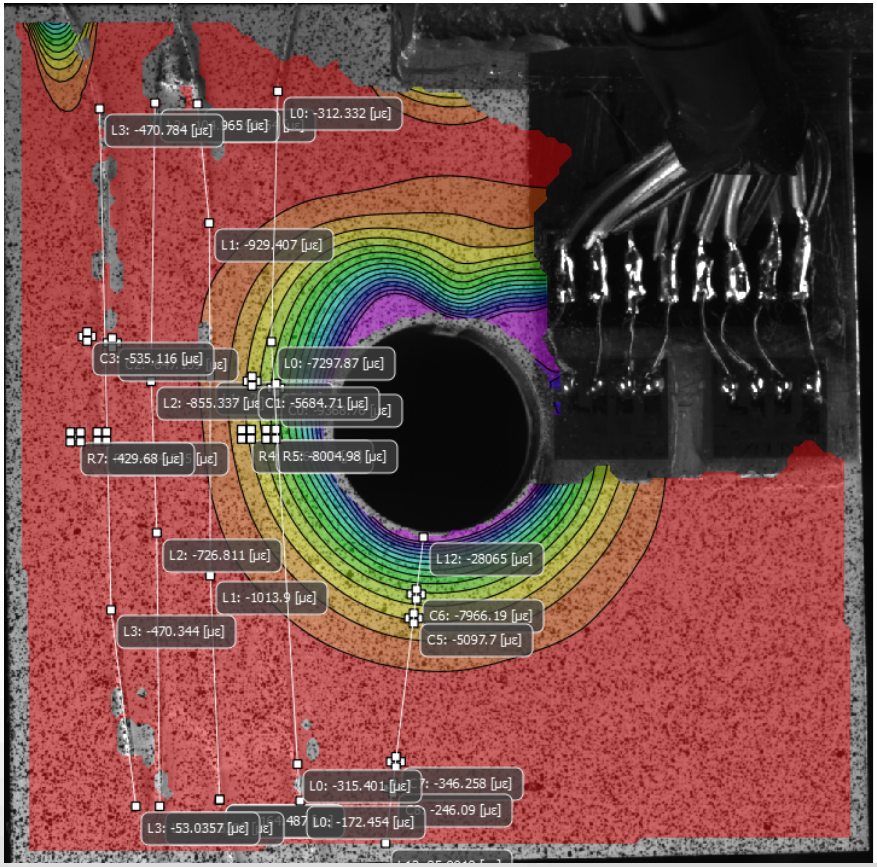
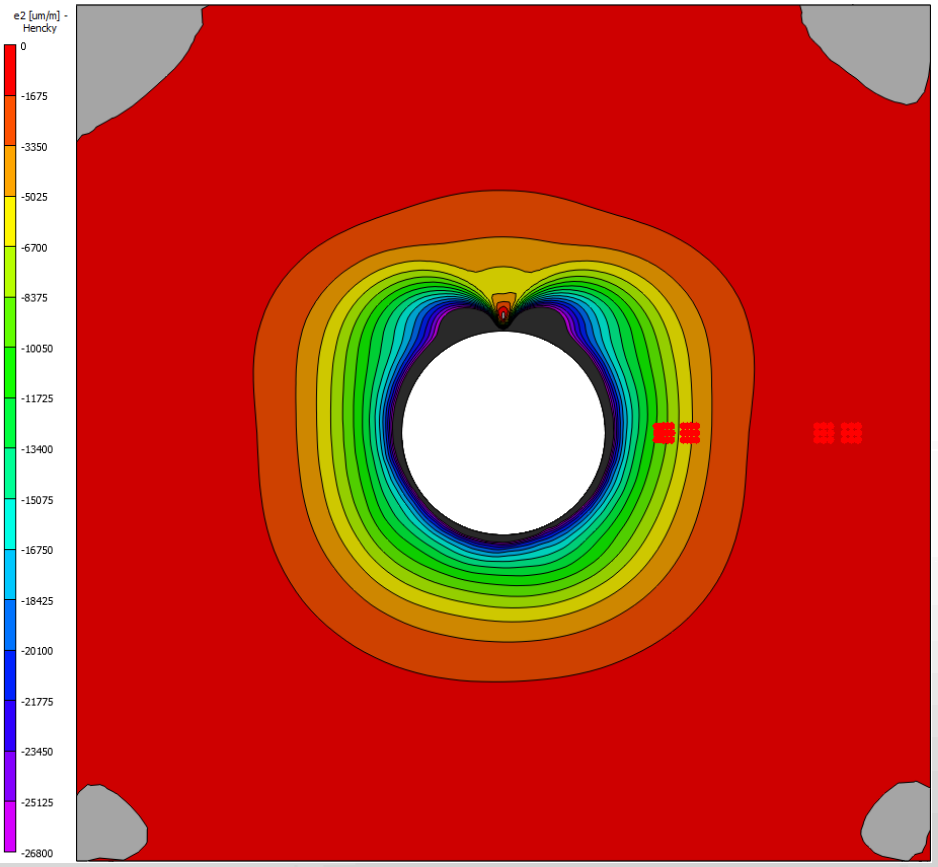
DIC vs Process Simulation Data



DIC Radial strains



FEA Radial strains
Chaboche Hardening

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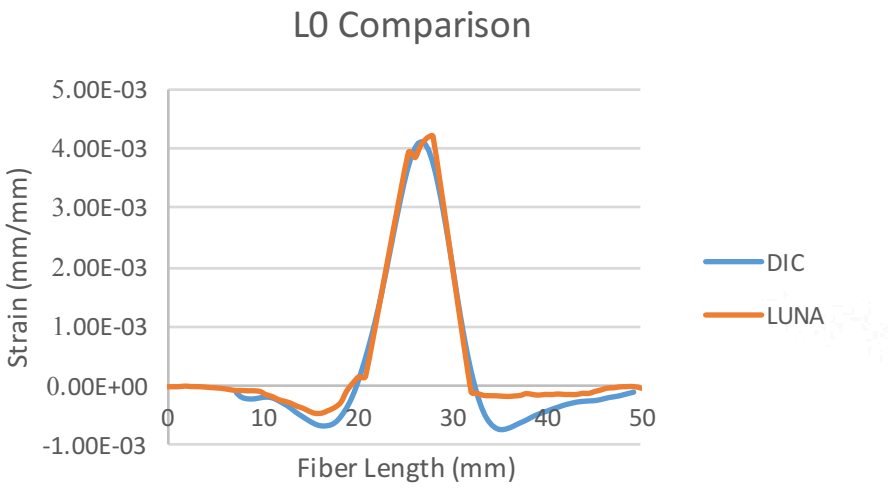
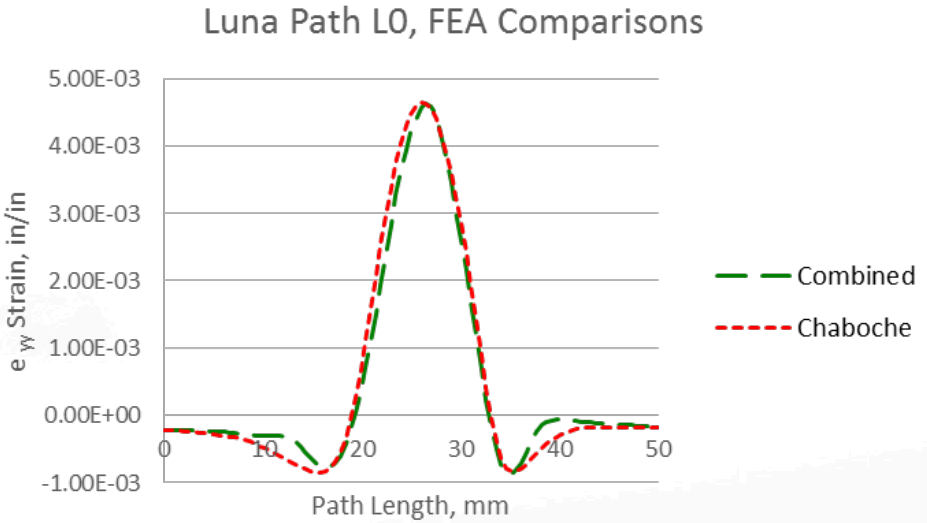
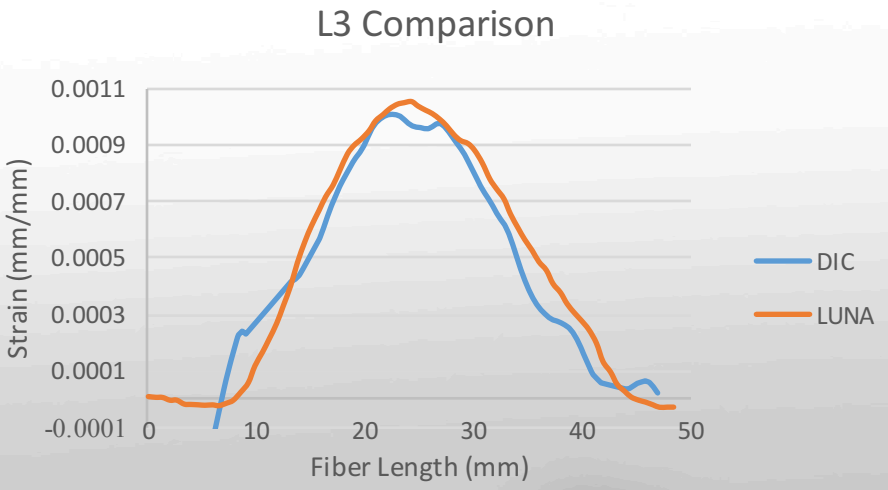
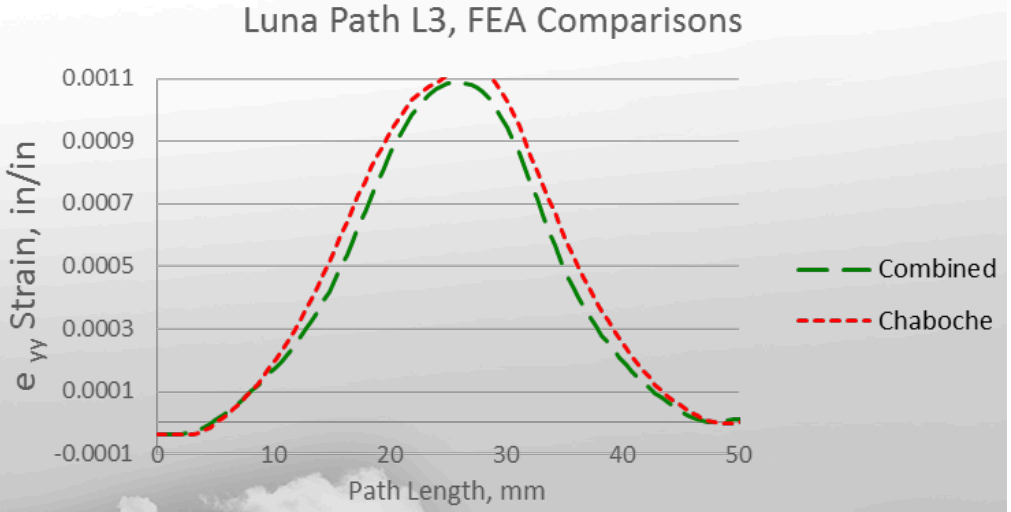
RS Process Simulation Validation

Luna/DIC vs Process Simulation Data









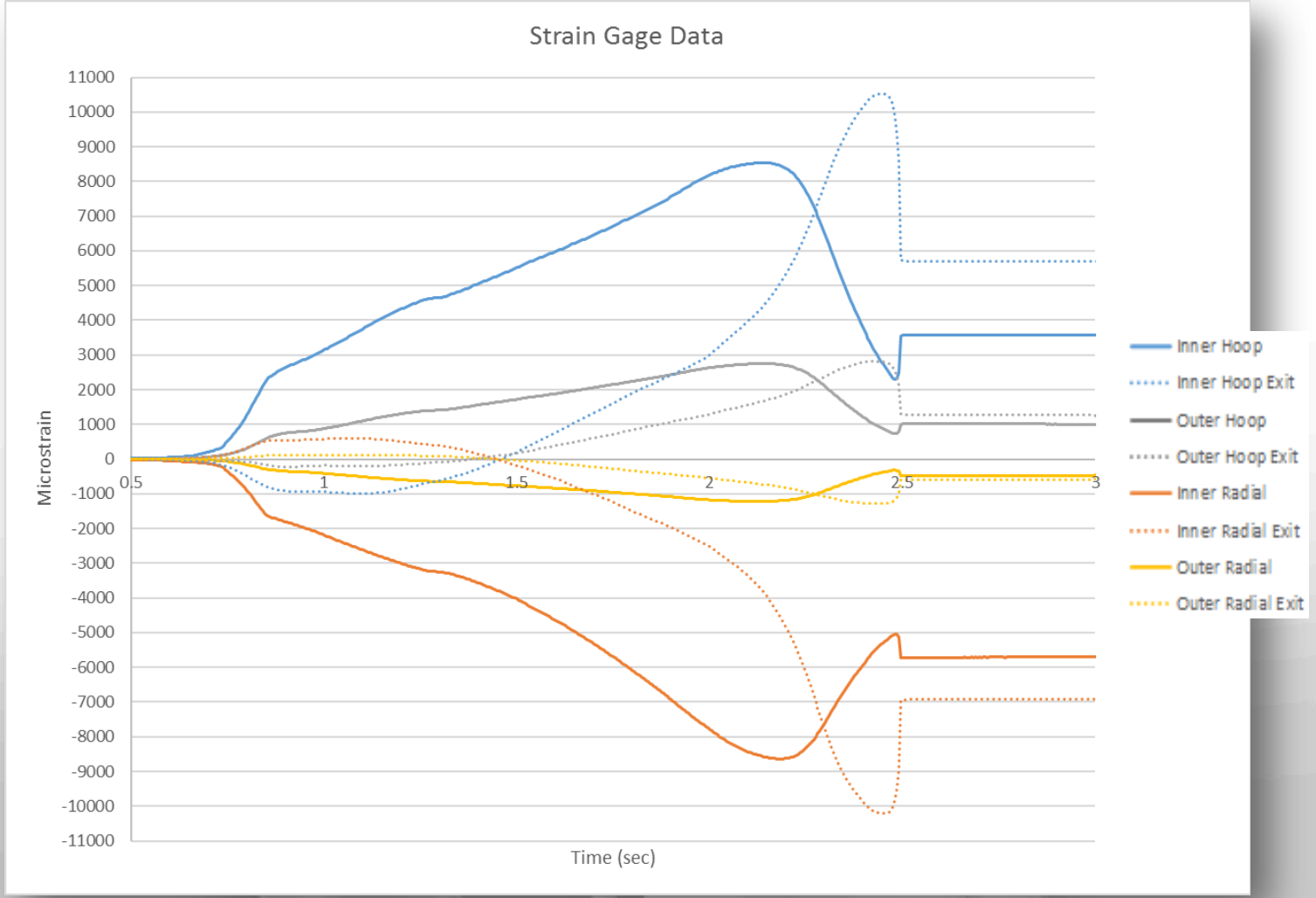
Luna/DIC e_{yy} strains

FEA e_{yy} strains

RS Process Simulation Validation

Strain Gage vs Process Simulation Data

Solid Lines – Entrance **Dotted Lines – Exit**



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RS Process Simulation Validation

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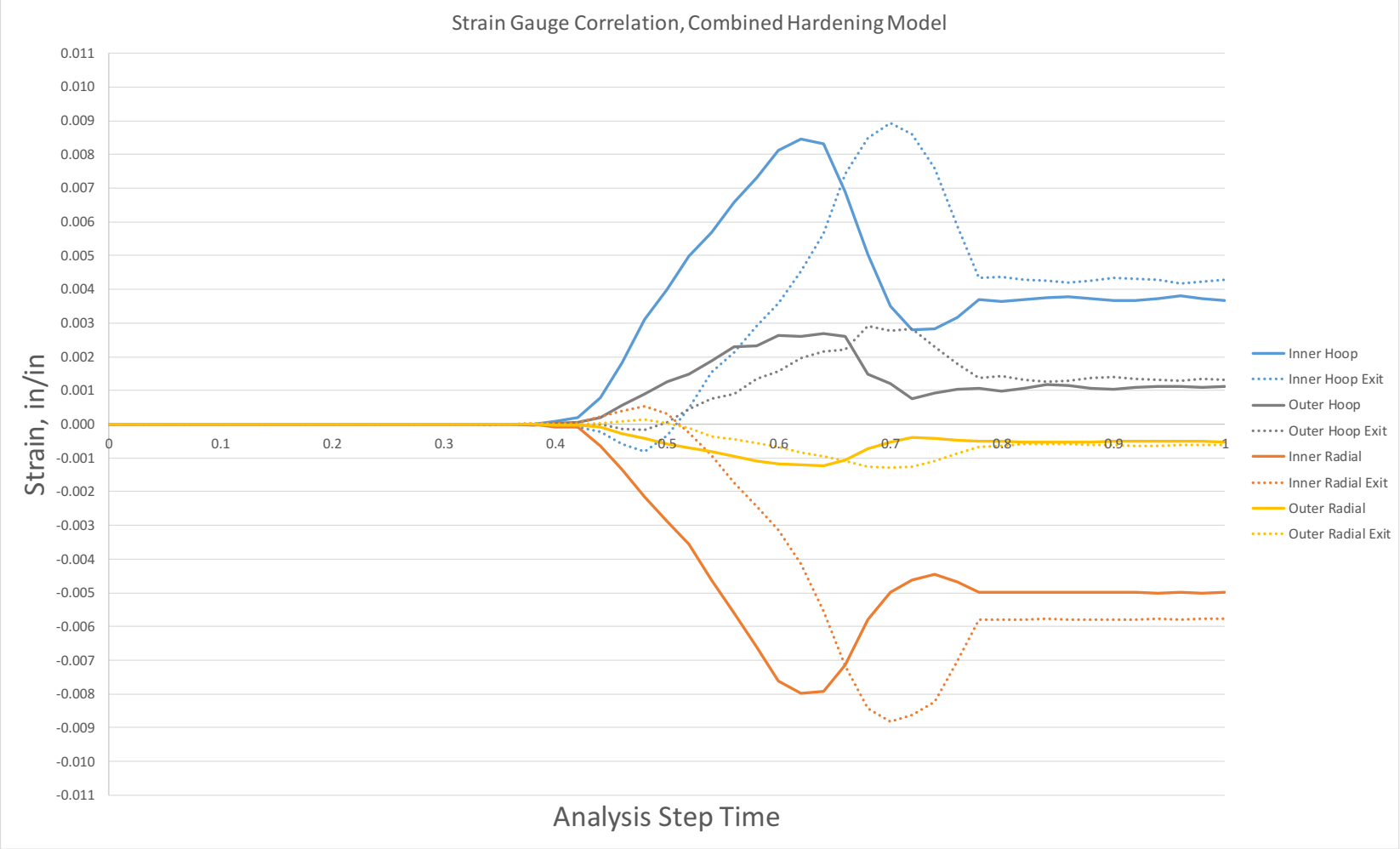

RS Process Simulation Validation

Strain Gage vs Process Simulation Data

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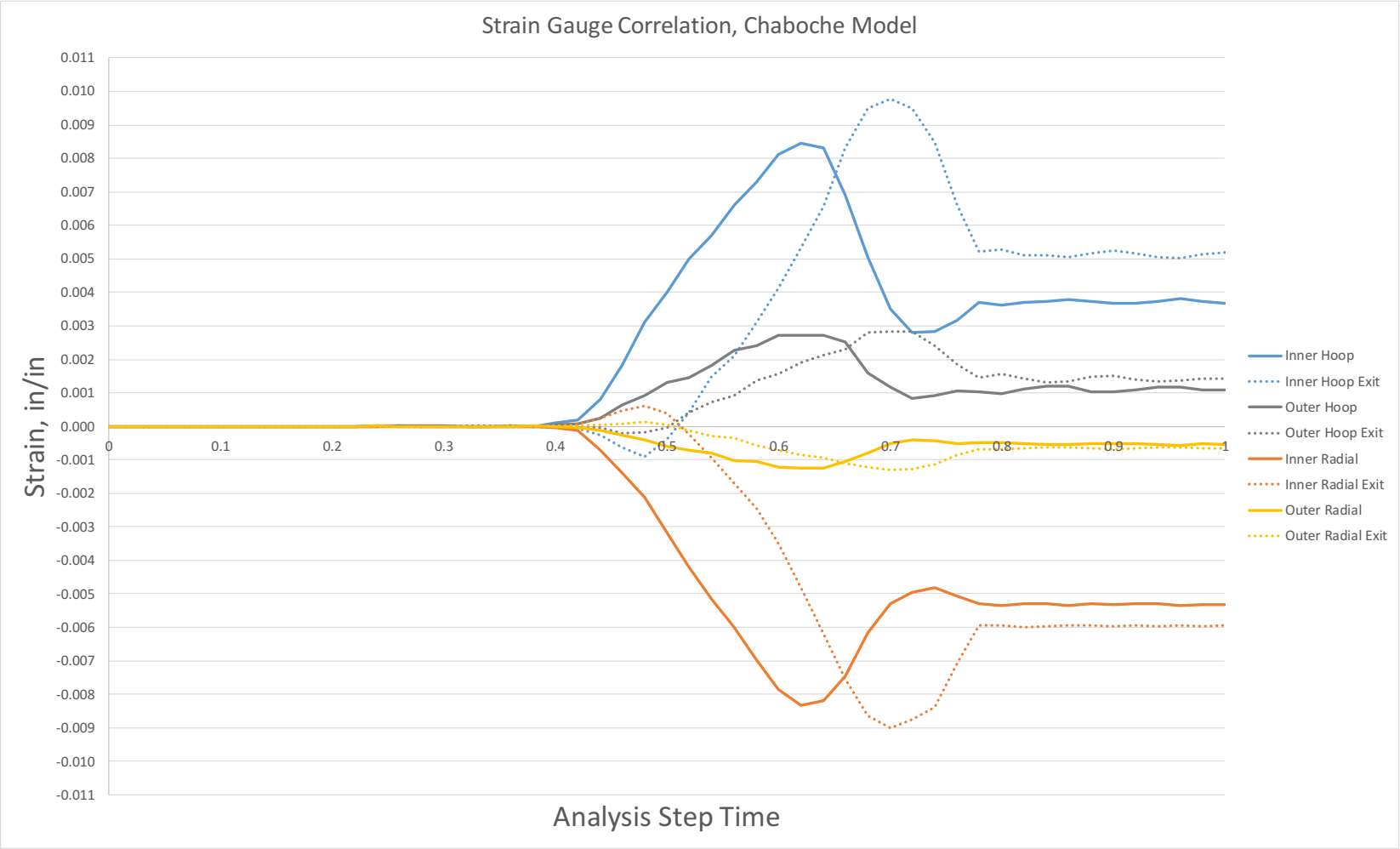
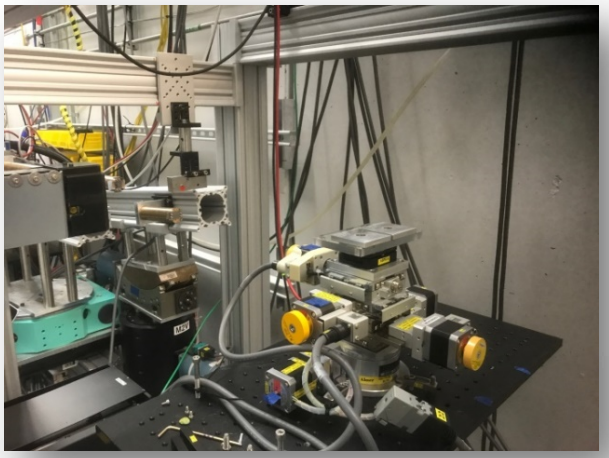
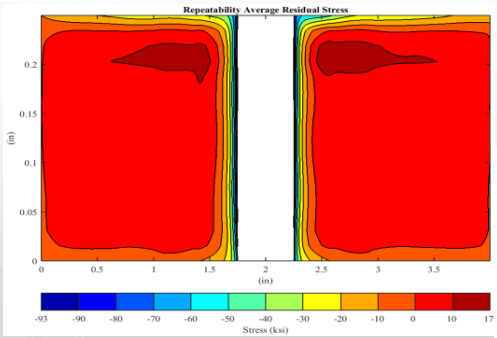
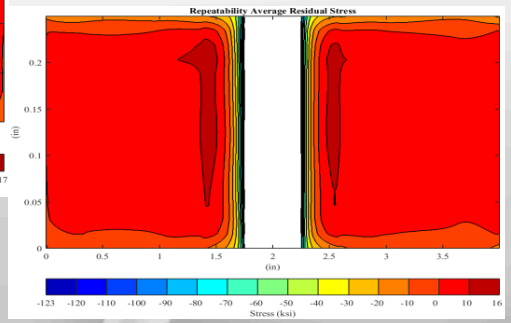


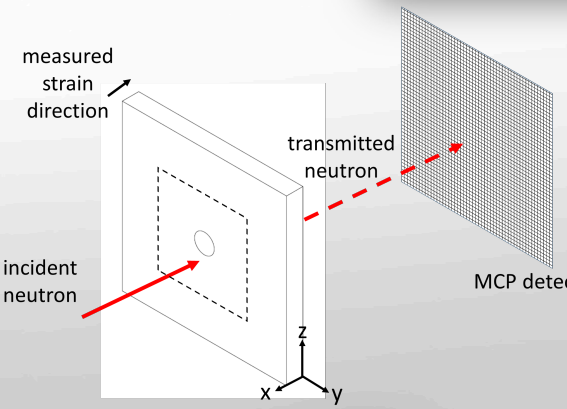
Next Steps: Thru-Thickness Measurements

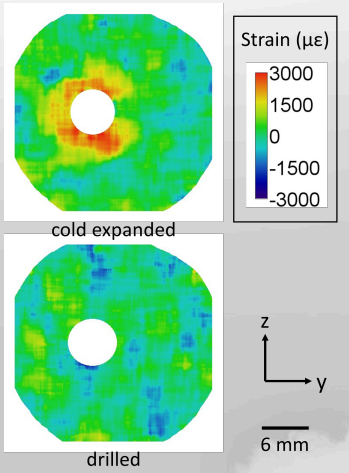
- Three Different Through-Thickness Techniques Planned:
  - High Energy X-ray Diffraction (HE-XRD); **Complete**
    - Argonne National Labs
  - Proto X-ray Diffraction; **October 2017**
    - NRC-Canada
  - Neutron diffraction; **December 2017**
    - Coventry University's IMAT
  - Contour Method; **February 2018**
    - Hill Engineering, LLC.











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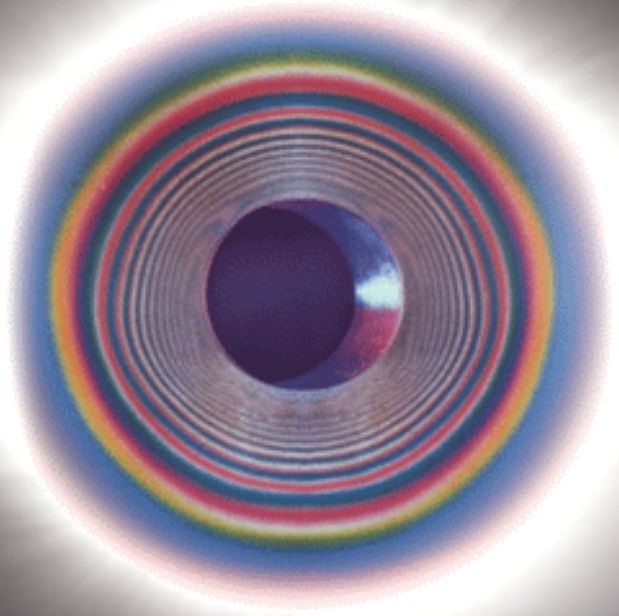
ERSI Residual Stress Process Simulation Sub Committee

Dr. Scott Prost-Domasky, Analytical Processes/Engineering Solutions (AP/ES), Inc.
Dr. Guillaume Renaud, National Research Council Canada
Dr. Ralph Bush, United States Air Force Academy
Marcus Stanfield, Southwest Research Institute
Dr. Min Liao, National Research Council Canada
Dr. Marcias Martinez, Clarkson University
Dr. Adrian DeWald, Hill Engineering, LLC
Dr. Keith Jones, Jones Engineering, LLC
Robert Pilarczyk, Hill Engineering, LLC
Dr. Mike Hill, Hill Engineering, LLC
Matt Shultz, Fatigue Technology



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Total Solar Eclipse
August 21, 2017
Culver, OR