Quantification of Residual Stress Fields via FEA Compared to Measurement

Engineered Residual Stress Implementation Workshop 2016
Ogden, Utah, USA
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OUTLINE

- Introduction
- Finite Element Analysis Methodologies
  - Analysis at FTI and a Case Study
  - Cold Expansion Analysis Best Practices
- FEA Benchmarking Introduction and Status
  - The Test Case
  - The Preliminary Results
- Conclusions and Future Work
- References

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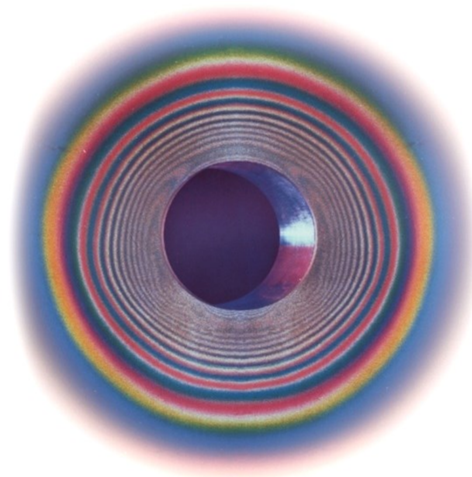
A little bit about FTI

- FTI is a wholly-owned subsidiary of Precision Castparts Corp. (PCC).
- Recognized as industry experts on RS field technology relative to fastened joints and holes.
- FTI utilizes finite element analysis (FEA) together with static and dynamic testing to validate solutions prior to implementation.
- FTI repeatedly lowers manufacturing and MRO installation costs and aircraft weight while enhancing structural performance.

FTI is committed to internal and collaborative research programs that enable continual improvements to the fidelity and accessibility of RS data for customer use

A little bit about FTI’s Split Sleeve Cold Expansion



- Generates large, controllable zone of residual stress surrounding the hole.
- Effective in nearly all aerospace materials.
- Typical applied expansion levels:
  - 3% to 5% for aluminum
  - 4% to 6% for Titanium and high strength steels
- Applicable in new production and rework for holes up to 6.0 inch in diameter.

- Numerous derivative products:
  - ForceMate
  - ForceTec
  - GromEx
  - RailTec
  - StopCrackEX
  - ForceLoc
  - TukLoc

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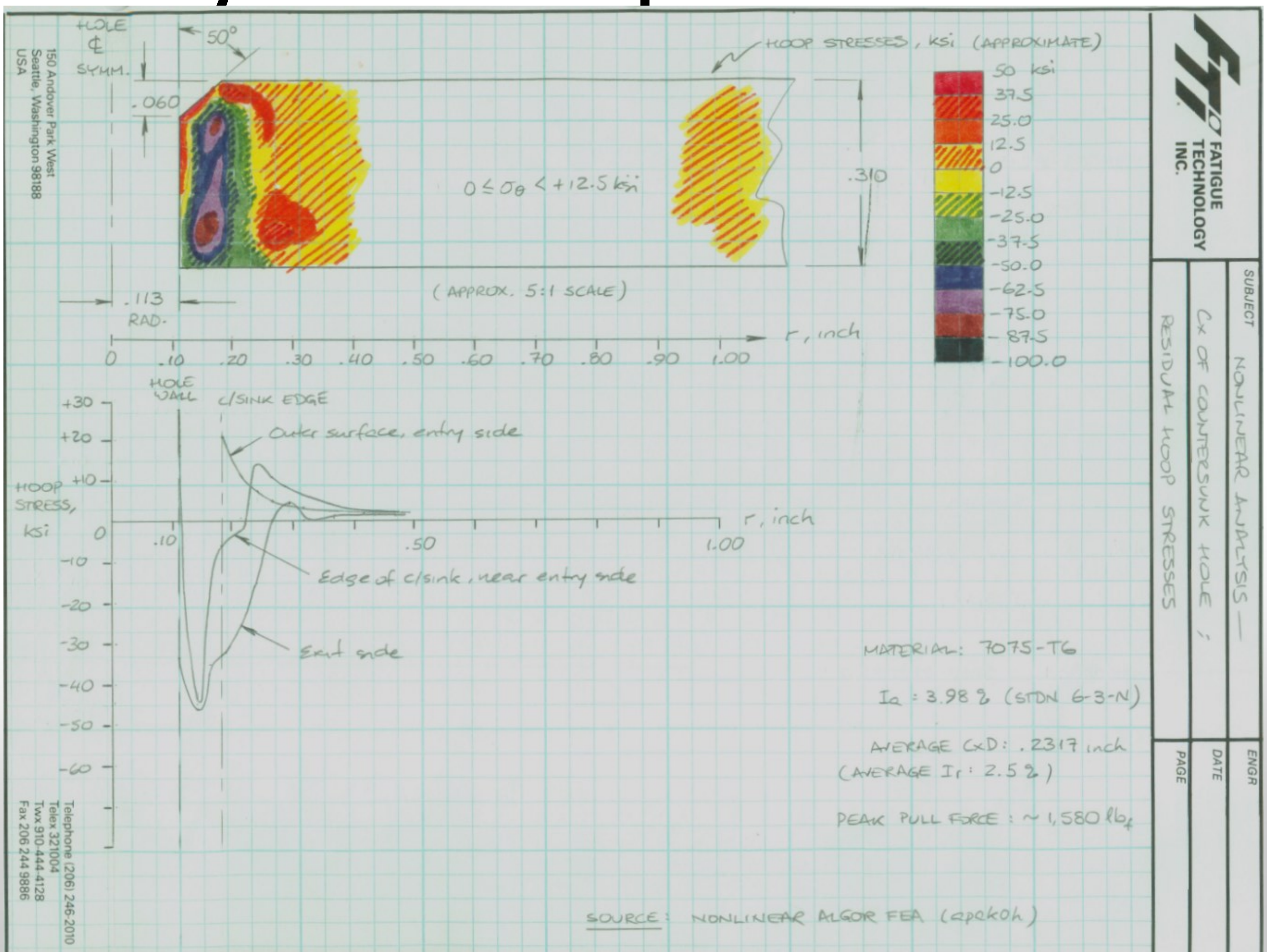
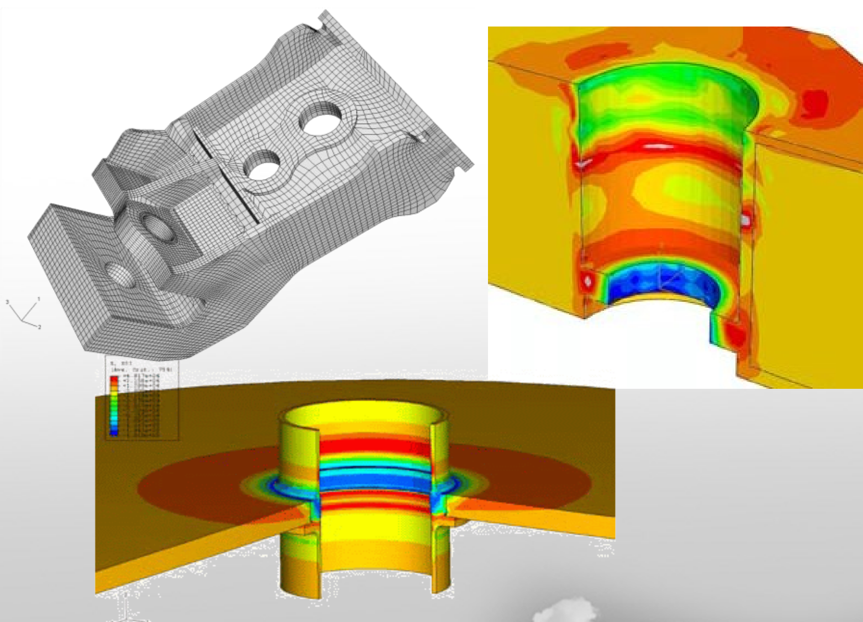
Analysis of Cold Expansion circa 1991

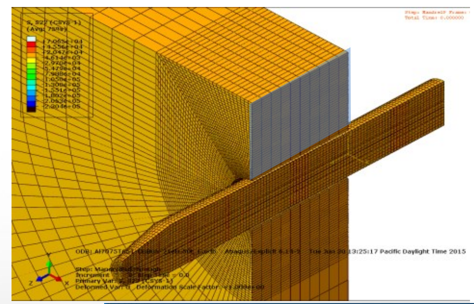


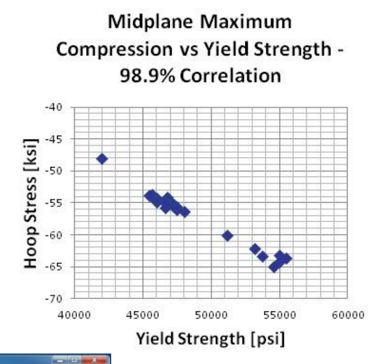
Analysis of Cold Expansion circa 2016

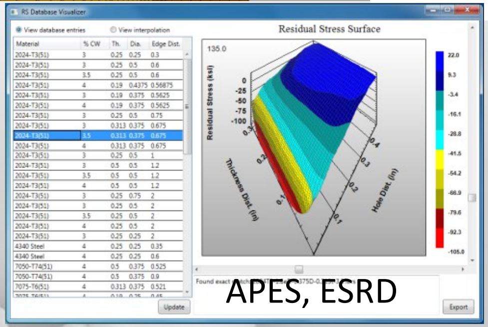
- Complex analyses:
  - Multiple FTI process steps
  - Refined correlation
  - All FTI processes

- Script driven 3D analysis:
  - Parametric studies
  - RS database population





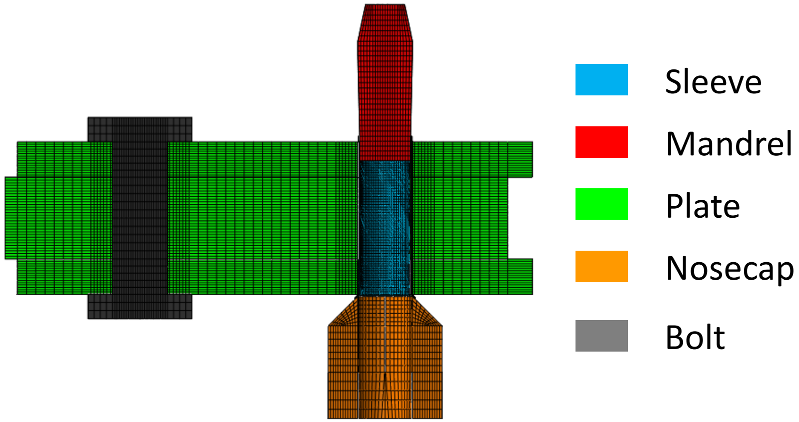


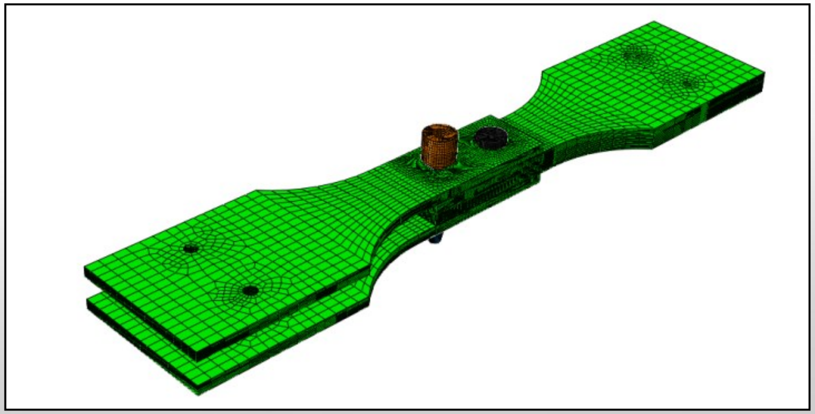


APES, ESRD

Complex Cx Analysis Case Study

- High Load Transfer Specimen:
  - 7000 series aluminum (MMPDS)
  - Multiple Steps
    - Cx (two holes, full specimen stack)
    - Ream
    - Fastener Clamp
    - Fastener Interference
    - Remote Load.
  - Not modeled: surface preparations
- Goals:
  - Understand specimen performance
  - Evaluate RS interactions
  - Evaluate RS differences that may affect fatigue life.





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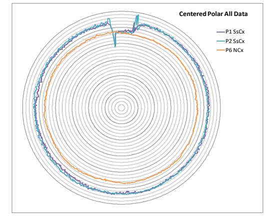
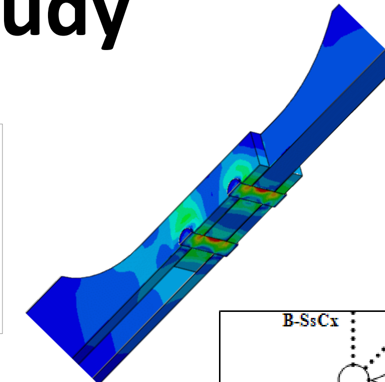
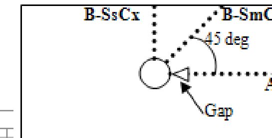
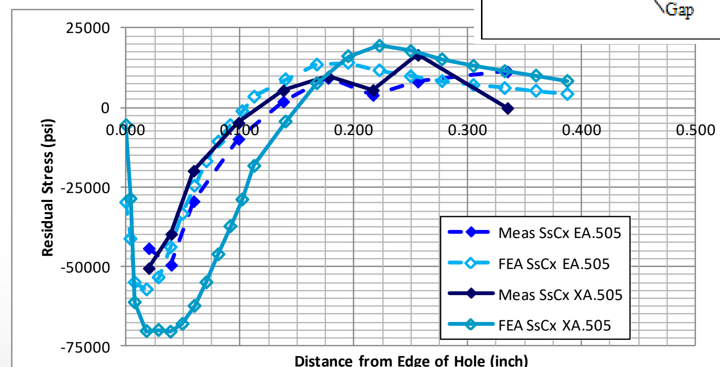
Complex Cx Analysis Case Study

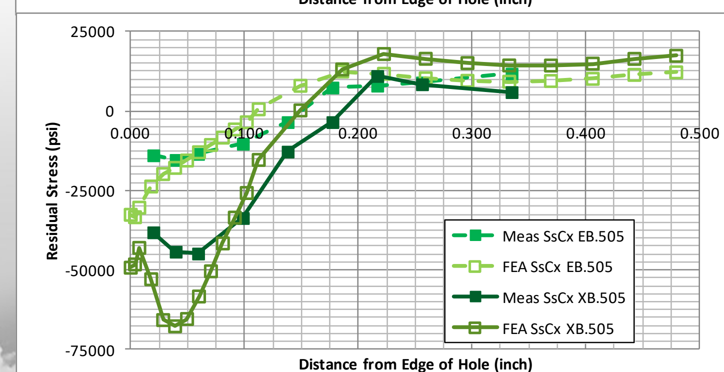
- Results:
  - RS states useful in predicting fatigue performance in bare specimens.
  - Repeated localized yielding may not be accurately represented by the assumed material model (combined hardening, half-cycle tensile data).
  - Fatigue performance impacted by the non-modeled surface preparation the highest remote loads ($S_{gross} \sim 0.3\ S_{yield}$).











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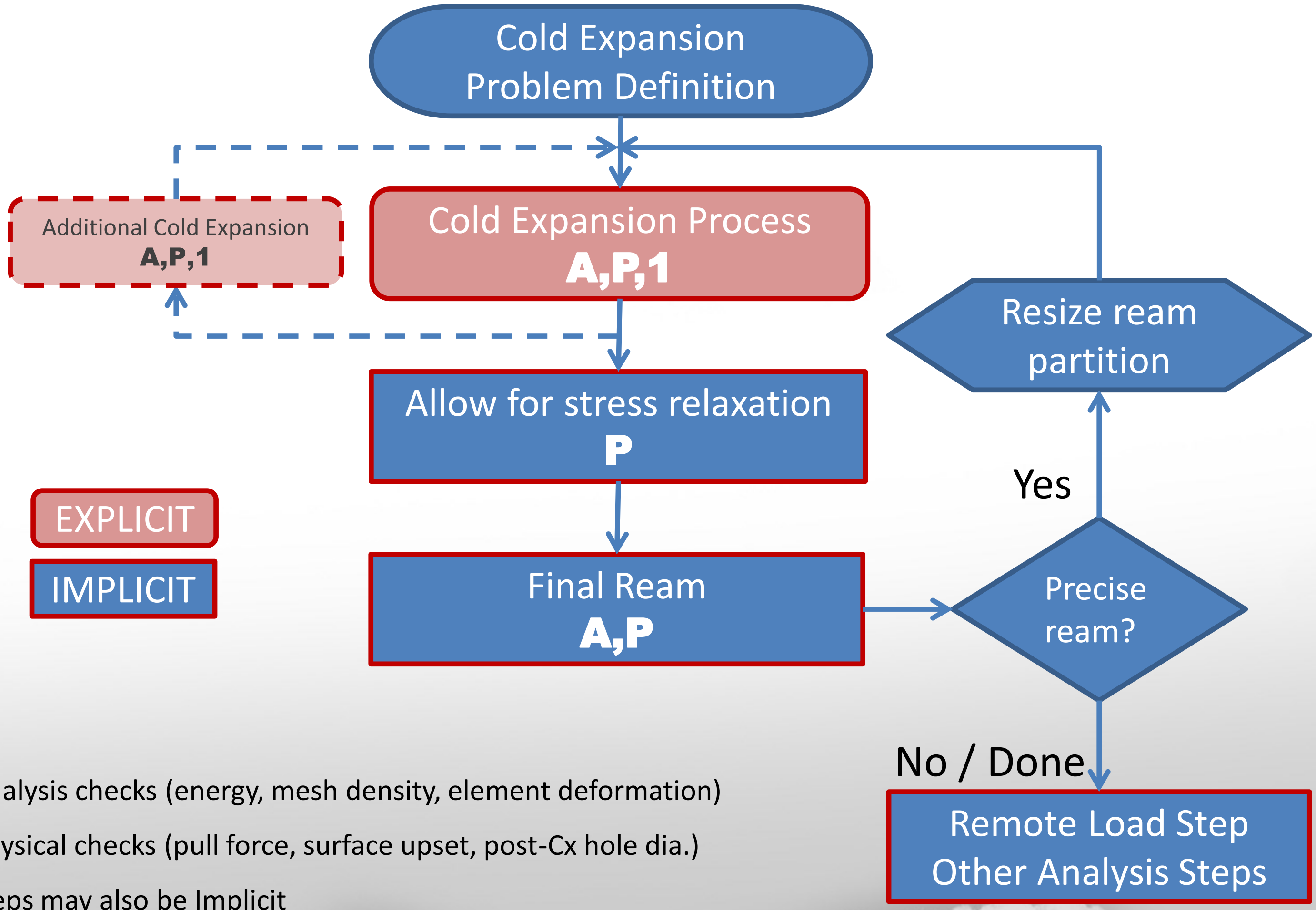
Typical Cold Expansion FE Workflow



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

Some Basic Analysis Setup Tips

- Geometry
  - Pay particular attention to tooling geometry, as residual stresses can be affected by tooling geometry.
  - Consider subsequent analysis steps when considering how to represent model changes (ream, c'bore, c'sink); additional analysis runs may be required.
- Constraints
  - Appropriate model fixity may require additional parts to be modeled (nosecap).
  - Avoid mismatches in contact pair mesh density, regardless of what the manual tells you.
- Material Behavior
  - Consider specifics of material constitutive model:
    - May impact element selection.
    - Desired endpoint (failure during expansion, or just RS).
  - Avoid rigid bodies for tooling; use of plasticity for tools can be useful.

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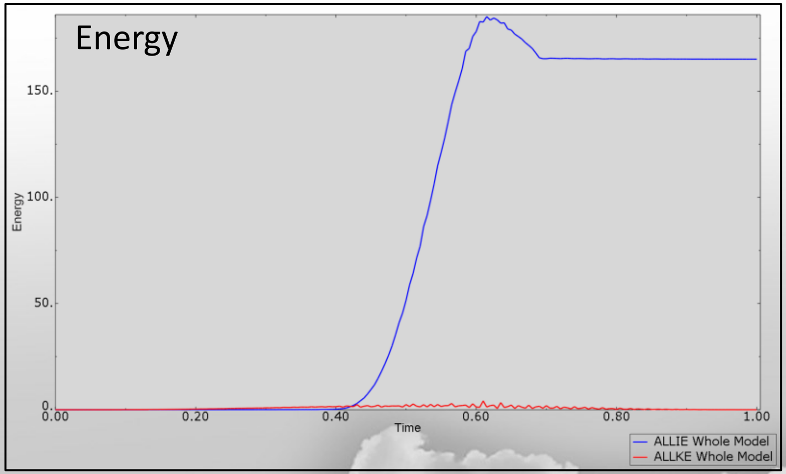
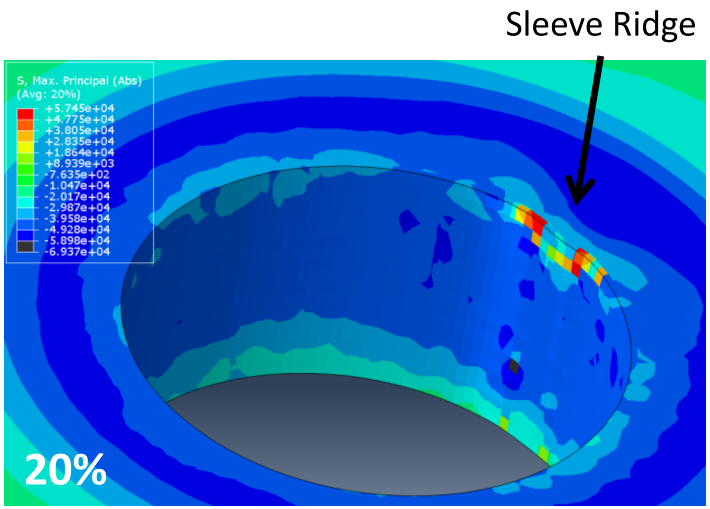
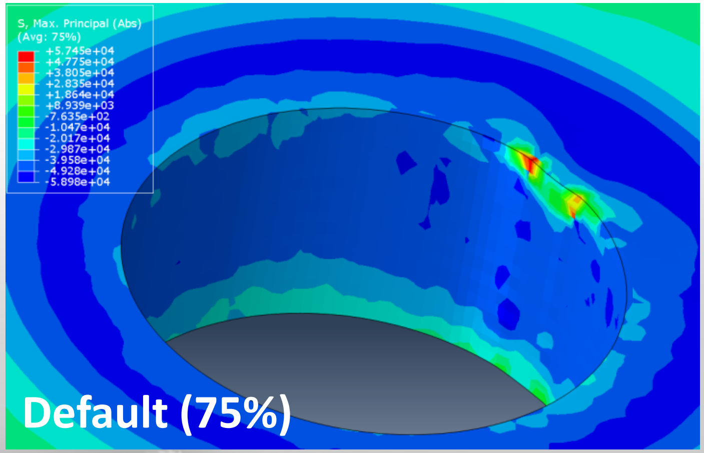
Quality Assurance

- Analysis Checks
  - Mesh refinement (via averaging checks, for example).
  - Contact penetration checks (penetration a possible factor in local mesh deformation).
  - KE checks to confirm quasi-static assumption remains valid (explicit).
  - Stabilization checks to confirm minimal influence (if used).
  - Closed form solutions (Lame, Grandt/Potter).

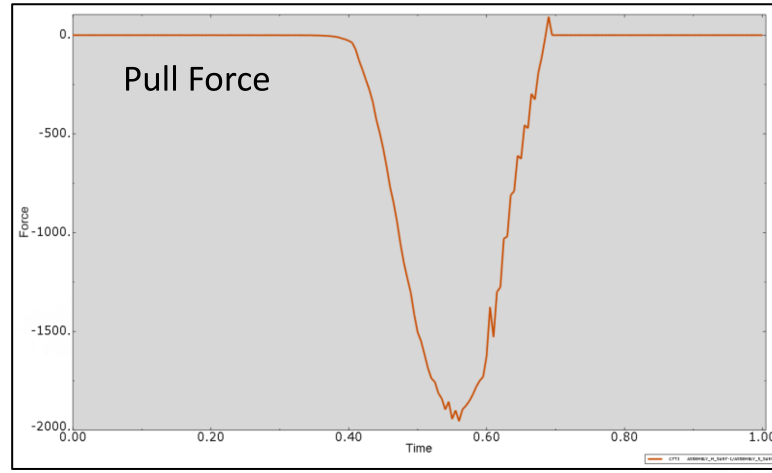


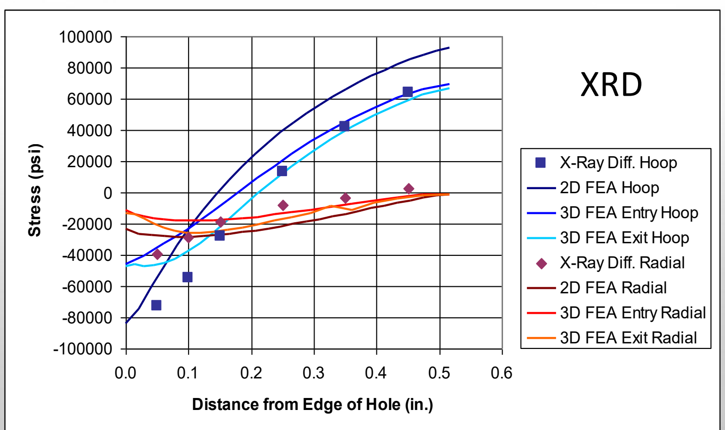


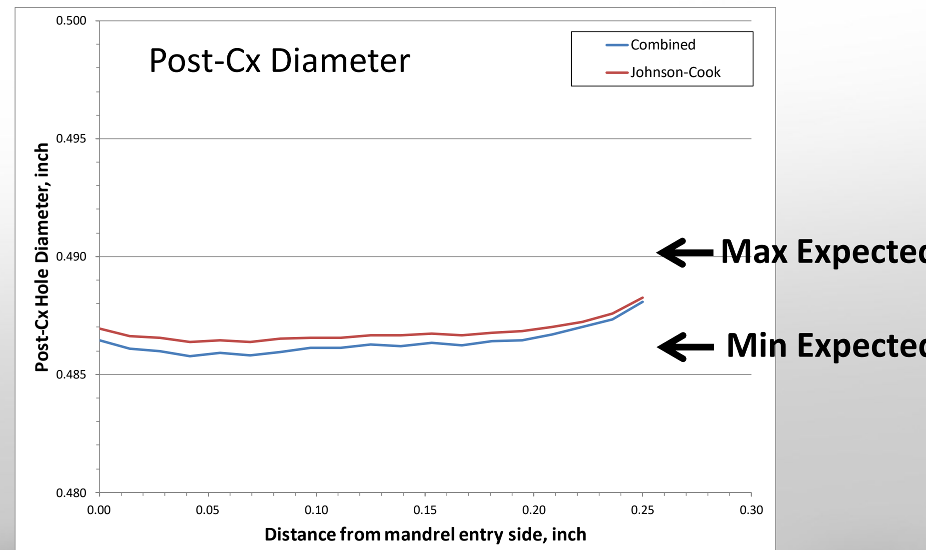


Quality Control

- Physical Checks
  - In-process measures:
    - Pull force
    - Deflection/deformation
    - Instrumented (strain gauges, DIC).
  - Post-process measures:
    - Hole diameters
    - Retention forces
    - Deflection/deformation
    - Instrumented (strain, XRD, etc.).







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FEA Benchmarking Exercise

Goal: To increase confidence in FE modeling of RS.

- Phase I
  - Compare RS distribution between NRC and FTI 3D analysis on selected Cx hole, using same geometry inputs.
  - Compare analytical RS with experimental measurements from SwRI and APES.
- Phase II (optional)
  - Compare crack growth and life predictions from the FE models and from experiments.

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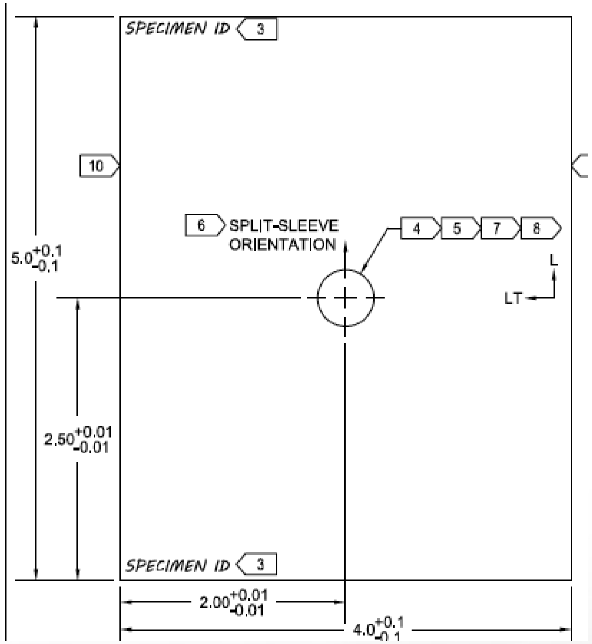
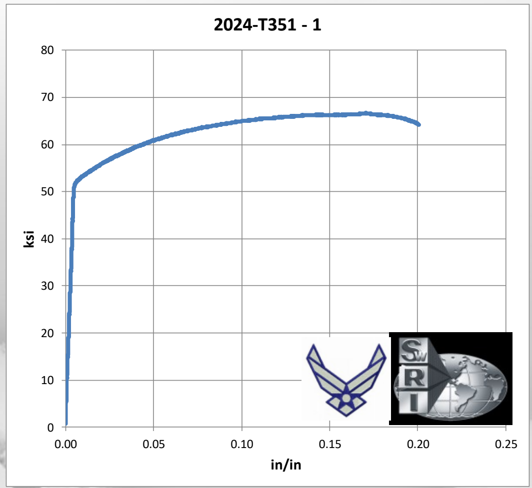
FEA Benchmarking Exercise

- 16-0-N tooling, low applied expansion
  - Mandrel just below bottom of tolerance: ∅0.4683”
  - Starting hole at top of tolerance: ∅0.4770”
  - Final hole: ∅0.5000”
- Previously tested plate geometry
  - Width: 4.00”
  - Thickness: 0.25”
  - e/D: 8
  - K_{tg} = 3.04, K_{tn} = 2.66
- Material properties from USAF uniaxial tensile tests; see next slide
  - 2024-T351 (current results)
  - 7075-T651 (for later)





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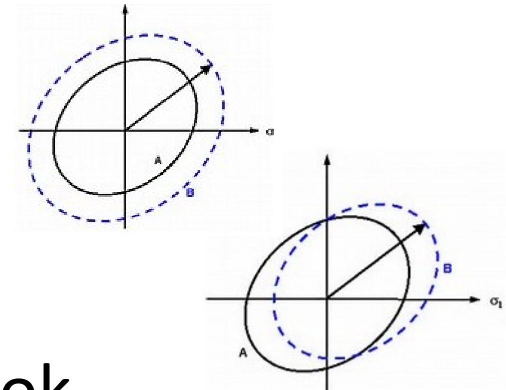
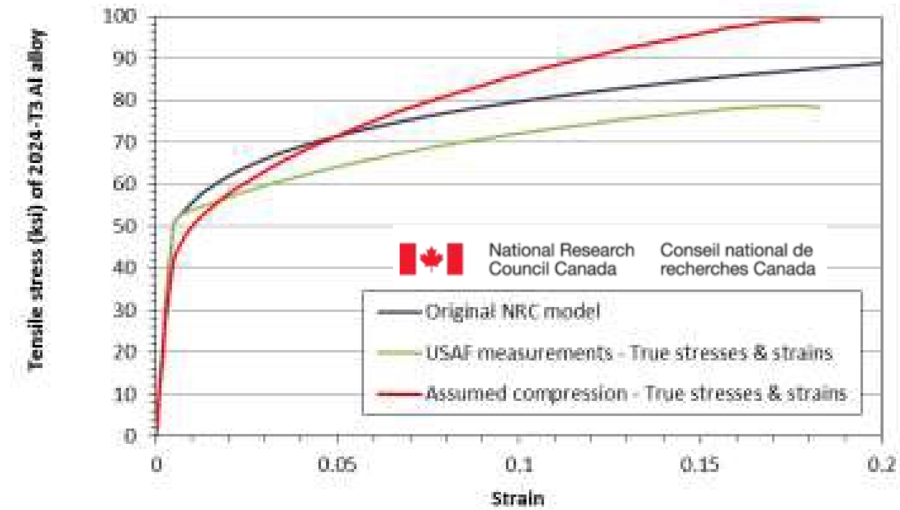
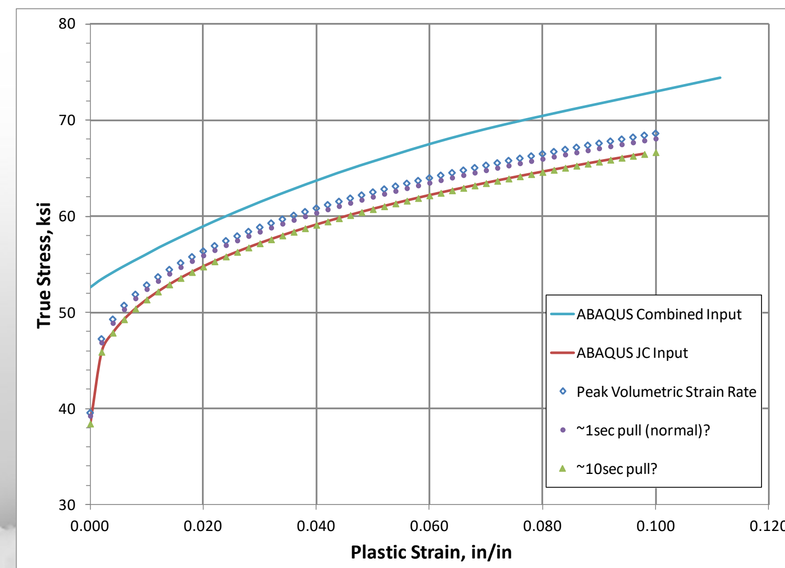
FEA Benchmarking – Material Models

- Isotropic
- Kinematic
- Combined
- Johnson-Cook
- Others not used in benchmark:
  - Drucker-Prager: may be appropriate for ultra-LCF metal response (P. Allen dissertation, 2002)
  - Hill
  - Barlat







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FEA Benchmarking Exercise Analyses

	Model ID	Material Curve	Material Model (hardening law)	Plate Manuf. Residual Stress?	Precise (re-sized) Ream?
NRC	1	Tension based	Isotropic	No	No
	2	Compression based (approximate)	Isotropic	Yes	No
	3	Tension based	Kinematic	No	No
FTI	Combined	Tension based	Combined	No	No
	Johnson-Cook	Tension based	Johnson-Cook	No	No

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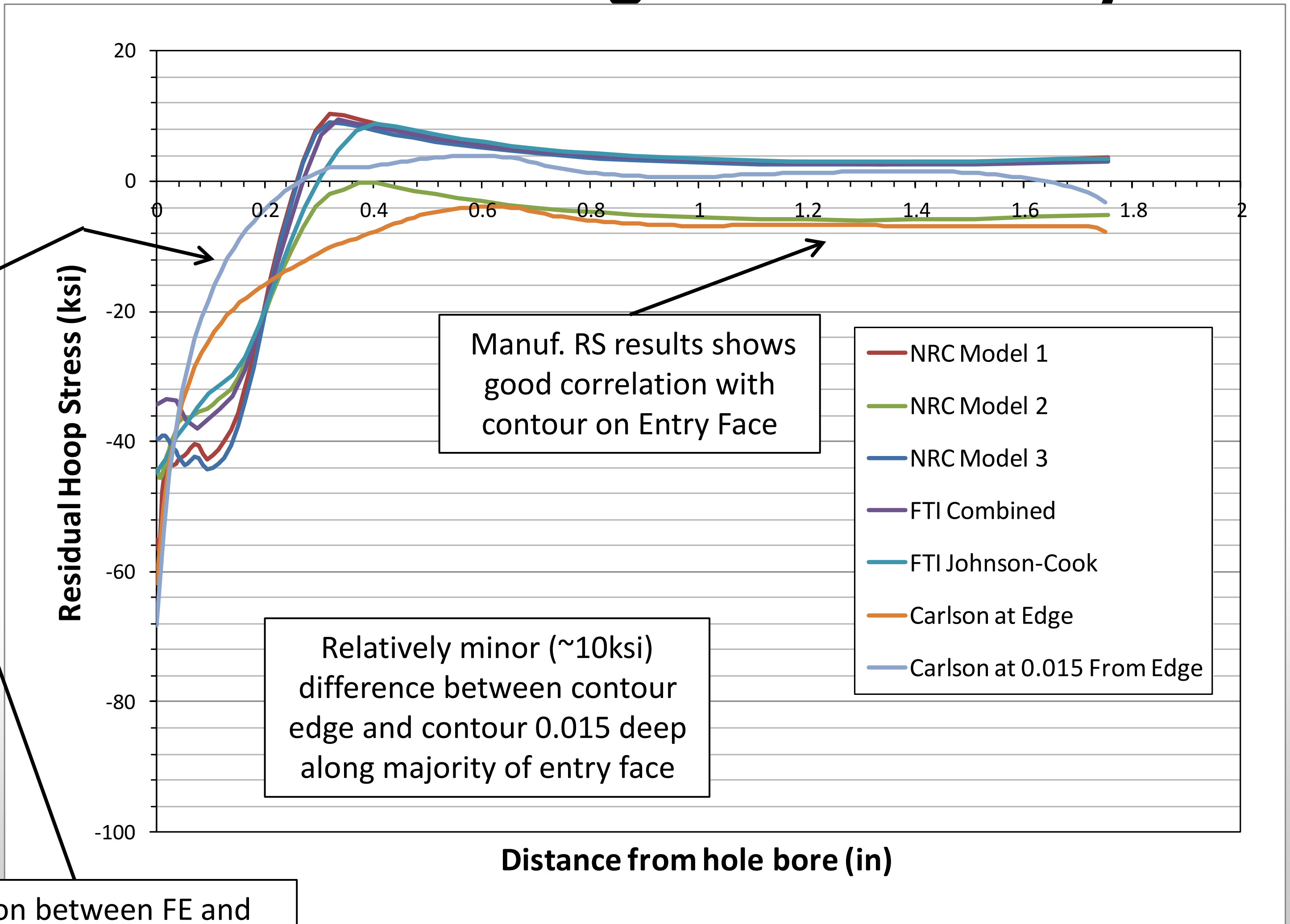
FEA Benchmarking Results – Entry Face



Deviation between FE and contour trending towards maximum at approximately ~0.15 from hole bore

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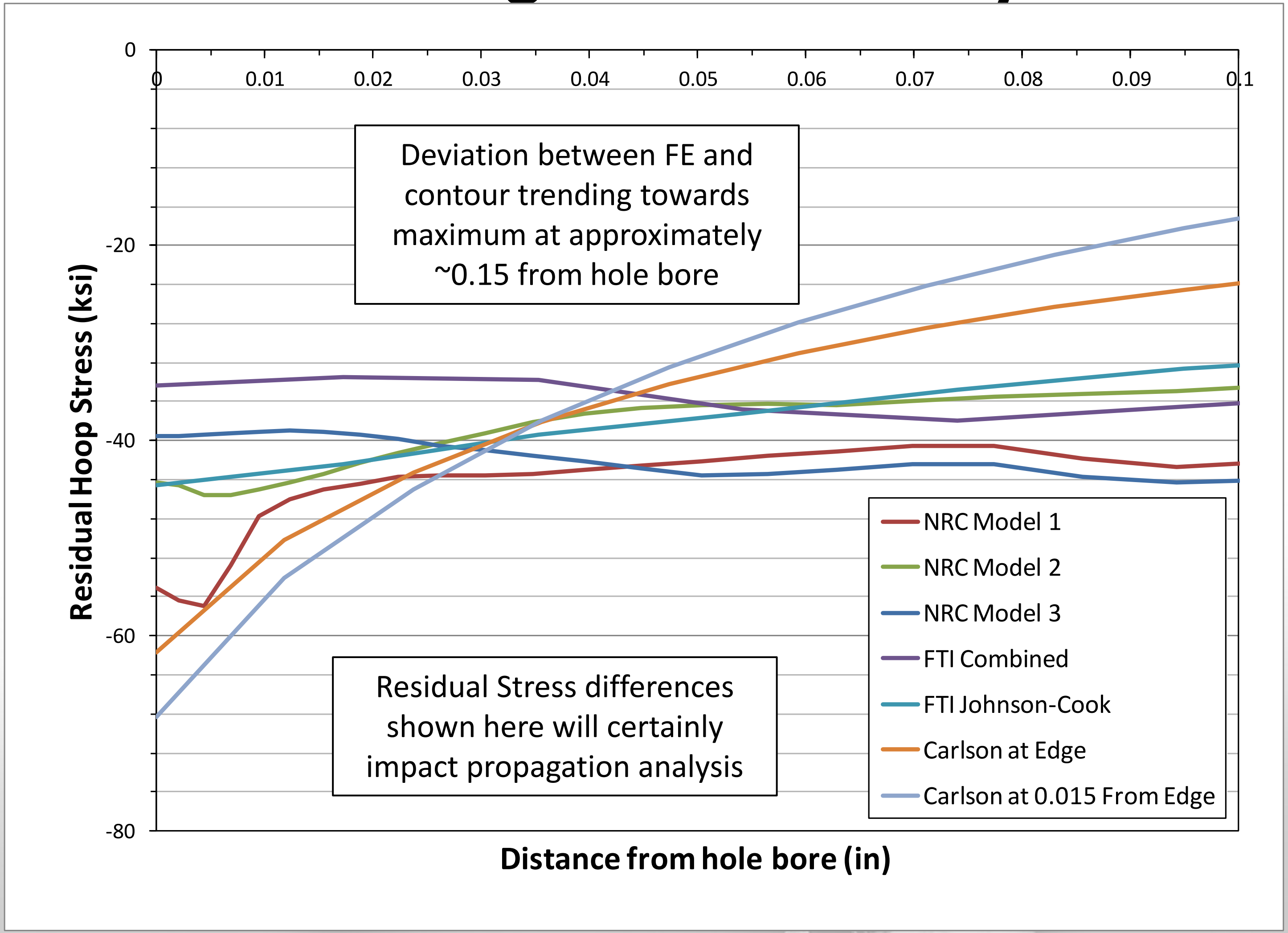
FEA Benchmarking Results – Entry Face Detail



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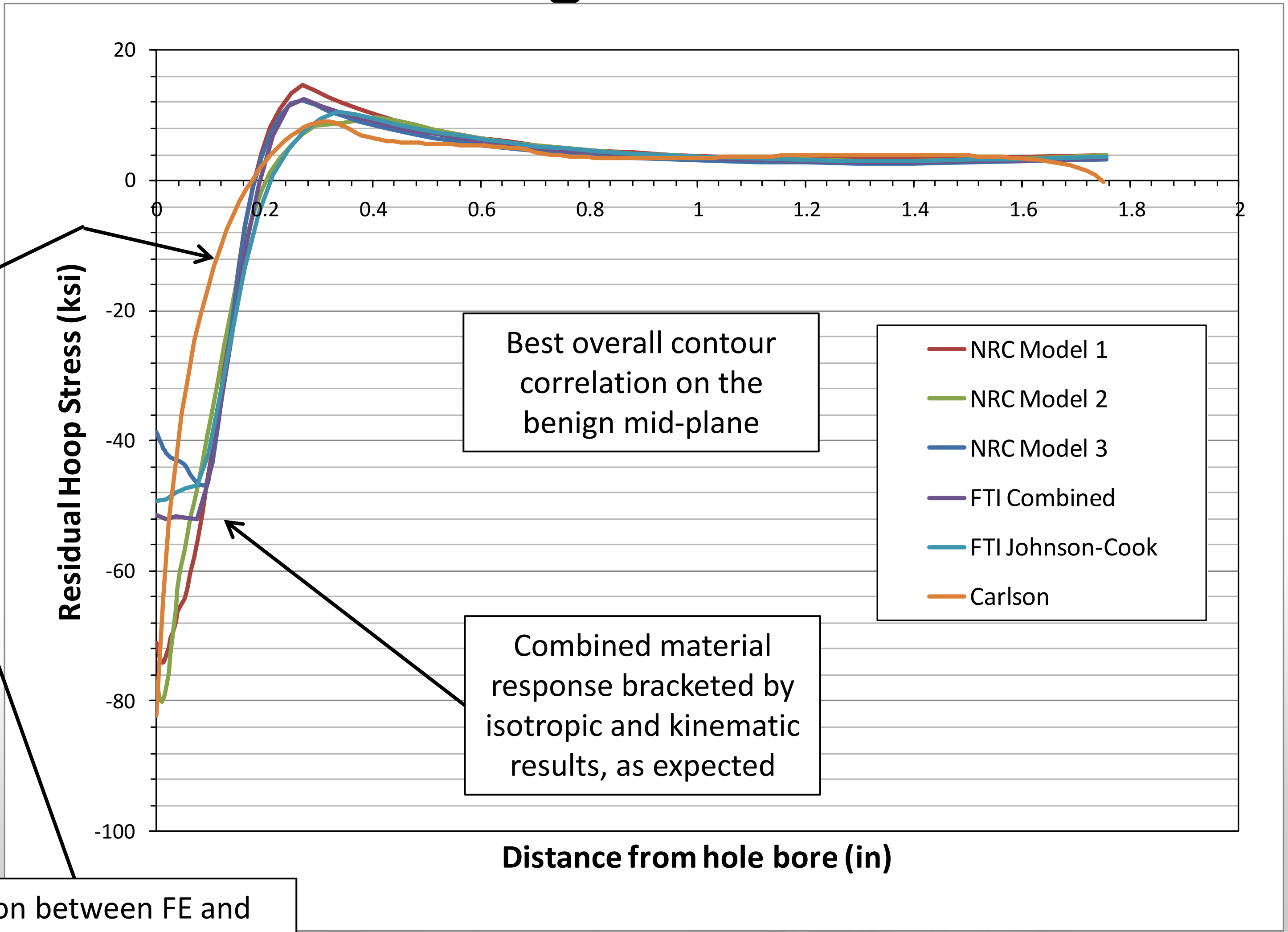
FEA Benchmarking Results – Mid-thickness



Deviation between FE and contour trending towards maximum at approximately ~0.15 from hole bore

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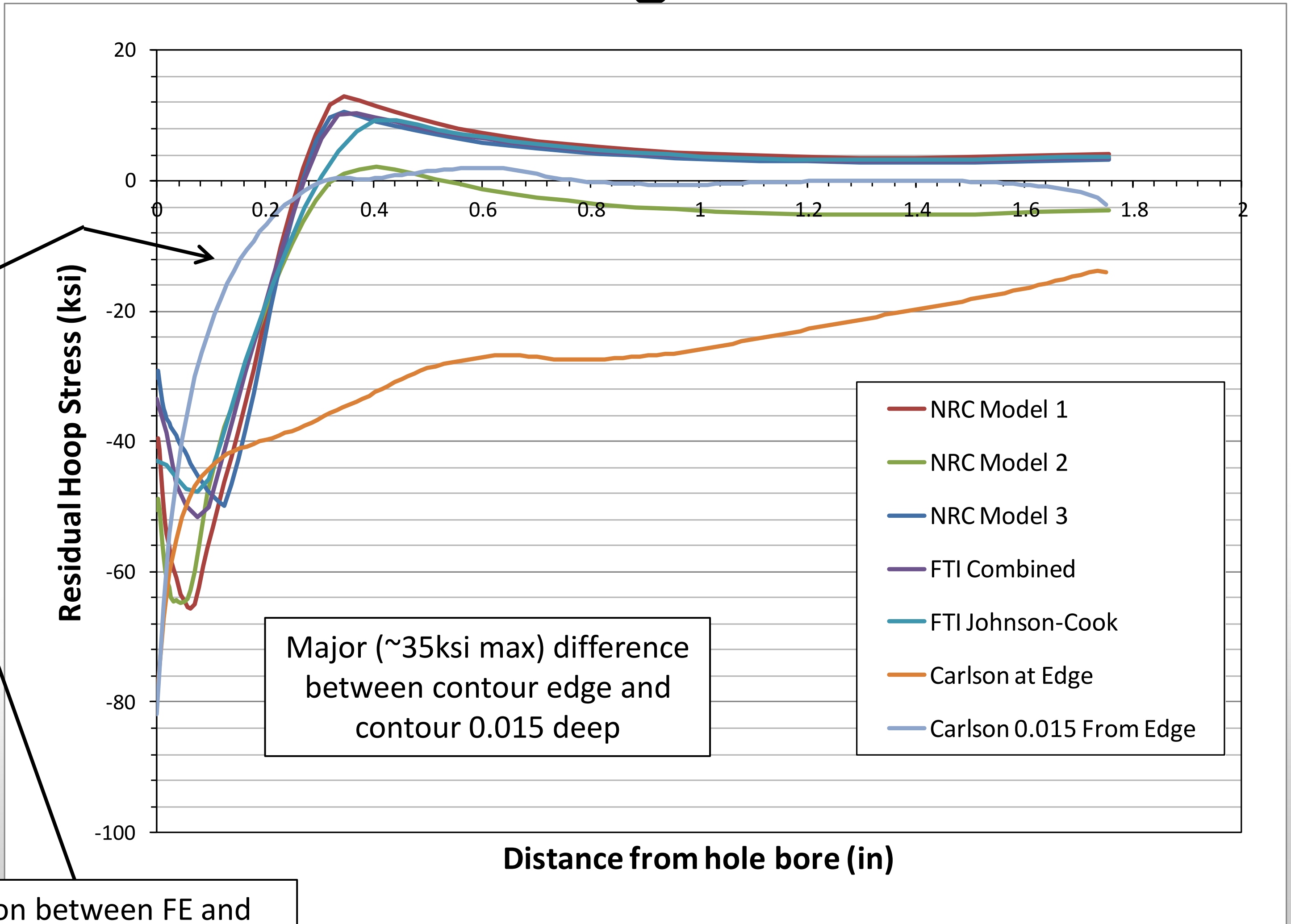
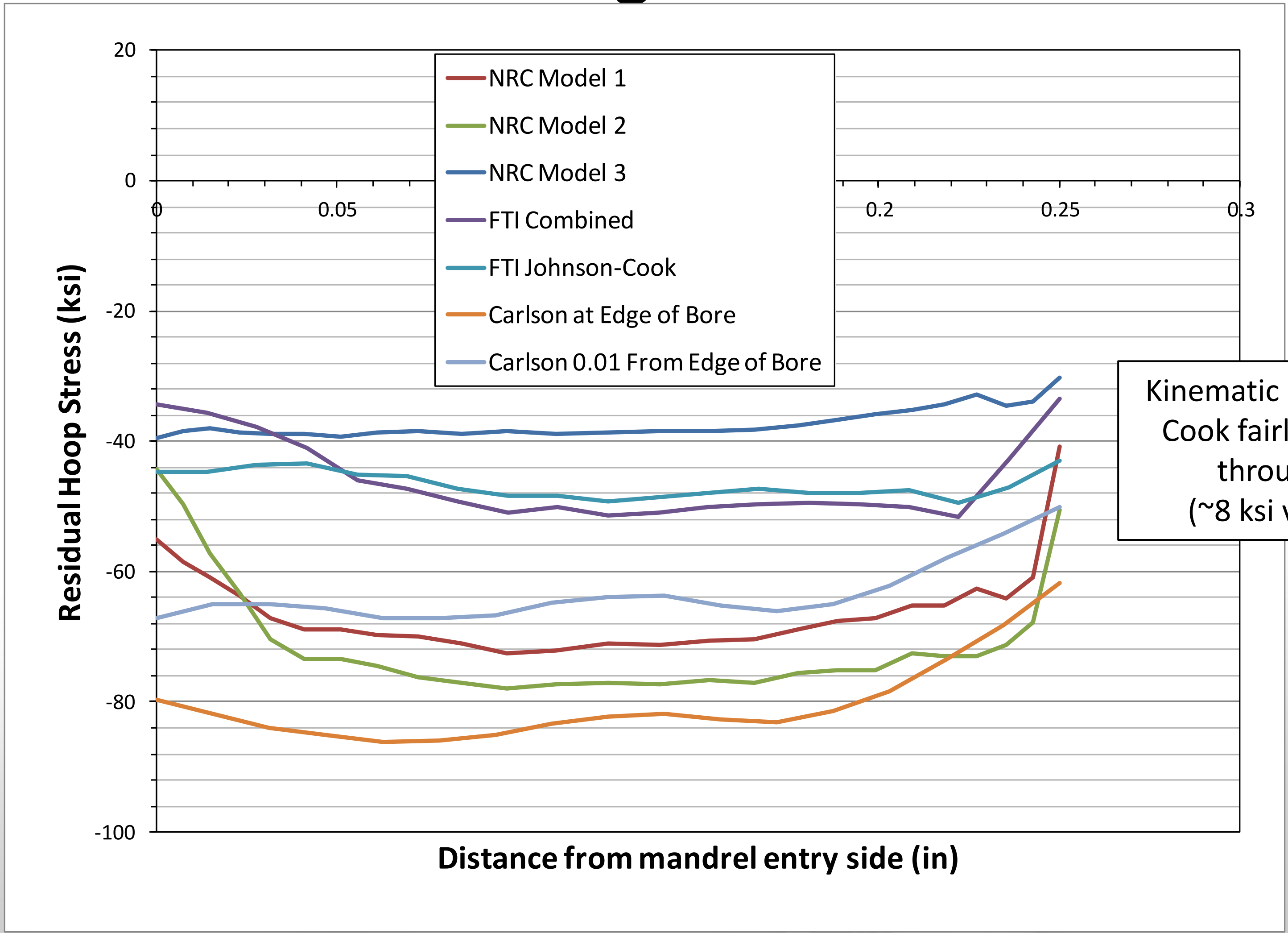
FEA Benchmarking Results – Exit Face



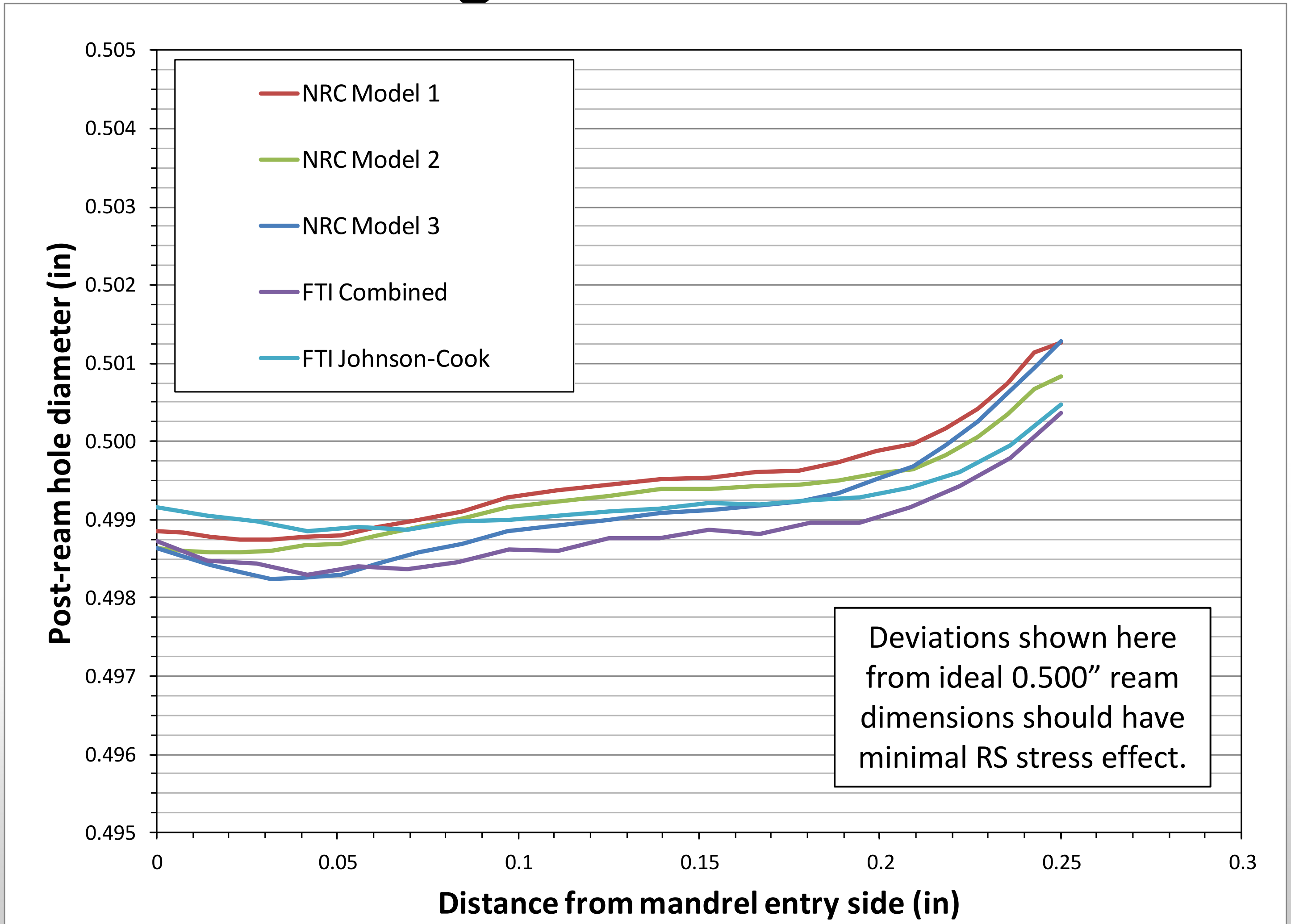
Deviation between FE and contour trending towards maximum at approximately ~0.15 from hole bore

FEA Benchmarking Results – Hole Bore



Kinematic and Johnson-Cook fairly consistent through bore (~8 ksi variability)

FEA Benchmarking Results – Post-ream Hole Dia.



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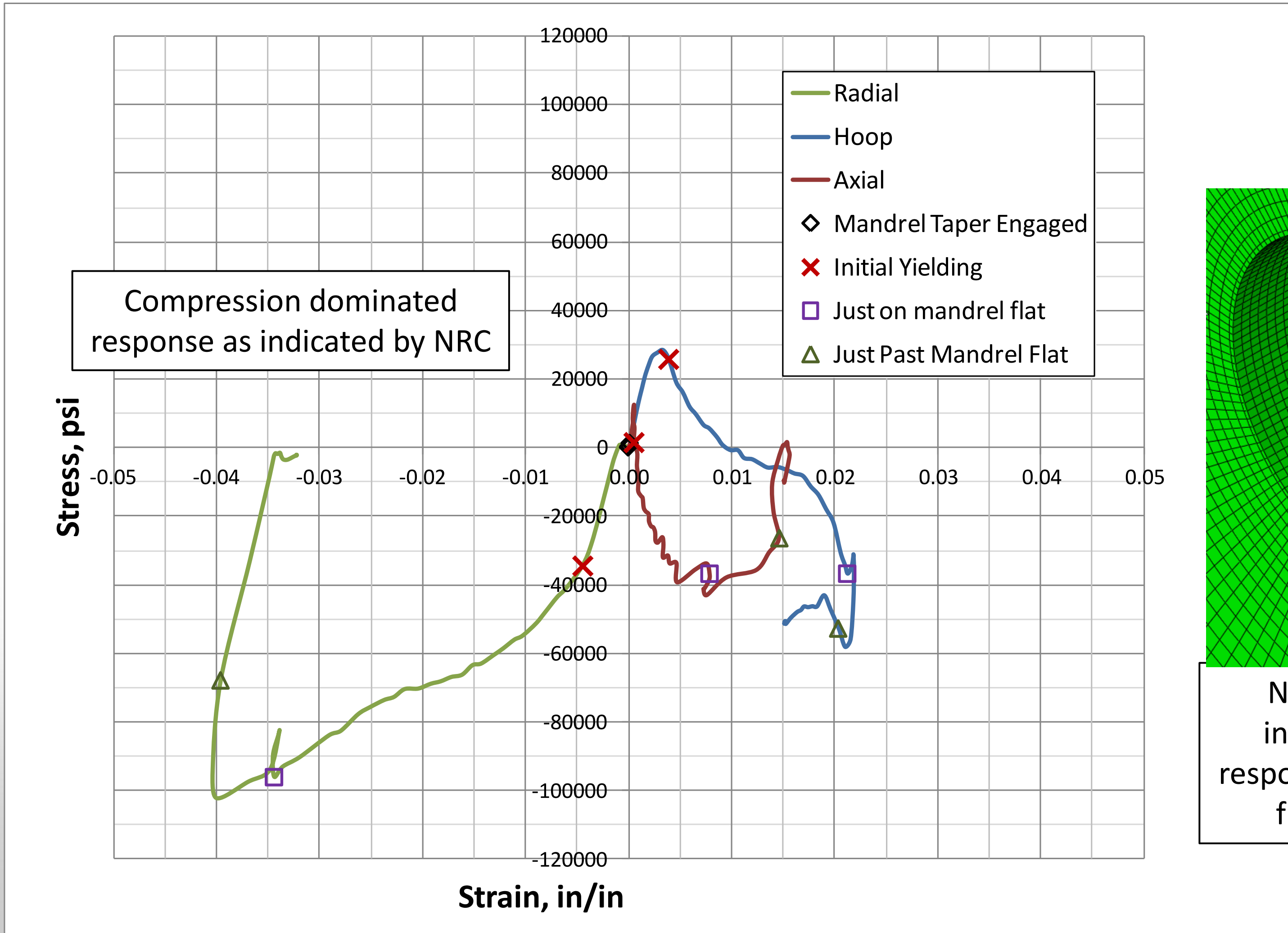
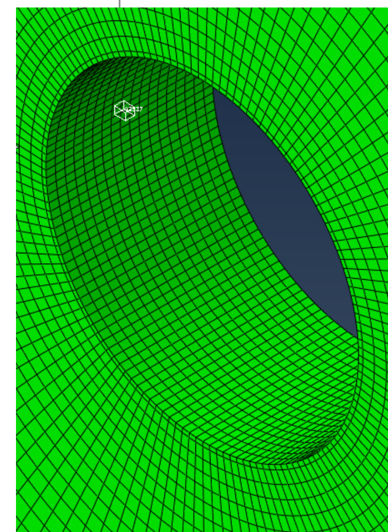
FEA Benchmarking – Stress/Strain Response





NOTE: Shown is integration point response two elements from hole bore

FEA Benchmarking – Conclusions

- Each group used their best practice, resulting in some differences:
  - Mesh Density/Solver/Convergence criteria.
  - Constraints (nosecap vs sleeve).
  - Deformable tooling.
  - Manufacturing RS.
  - Material models for plastic response.
- Correlation between NRC and FTI models seem to be generally comparable when considering the differences above, especially material model differences.
- Correlation with contour method mixed:
  - Isotropic models showed best correlation with contour along bore.
  - All models show less than ideal correlation with contour in compressive region, overall.
  - Maximum deviation between contour and FE occurs ~0.15” from hole bore.

FEA Benchmarking – Next Steps

- Identify and obtain better material data (USAF/SwRI to test):
  - Test to ASTM E606 (LCF), not ASTM E8 (tensile)
  - Obtain at least one full hysteresis loop w/representative total strain range
  - Tensile-compressive or compressive-tensile?
  - Appropriate strain rate?
- Unify model construction practices.
- Re-run and compare with contour (and other test data, as available) in greater detail.
- Begin drafting a cold expansion FE modeling “standard”.
- Phase II….

FTI would like to thank Scott Carlson, SwRI, and the USAF for the opportunity to participate in ERSI, and FTI looks forward to future collaborations with NRC, SwRI, APES and others enabling the full benefits of cold expansion residual stresses to be realized by our customers.

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