ERSI

ERSI RISK AND UQ SUBCOMMITTEE ACTIVITIES

Virtual ERSI Workshop

February 2022

Committee Overview

- **GOAL**: Investigate and implement UQ methods that enhance the overall understanding of how residual stress affects life prediction analyses
  - Uncertainty Quantification
    - How do we understand and describe the uncertainty and variability in the relevant parameters?
  - Sensitivity Analysis
    - What are the most significant variables in the ERS process?
    - How can we maximize/minimize the benefits/damages of these variables?

Committee Members

- Co-chairs: Juan Ocampo (StMU) and Laura Hunt (SwRI)
- Participating Organizations
  - Analytical Processes/Engineering Solutions (AP/ES)
  - Hill Engineering
  - Lockheed Martin
  - NRC Canada
  - SmartUQ
  - Southwest Research Institute
  - St. Mary's University (TX)
  - University of Pittsburgh
  - USAF

Statistics, UQ, and V&V References

- ASTM E739-10, "Standard Practice for Statistical Analysis of Linear or Linearized Stress-Life or Strain-Life Fatigue Data," American Society of Testing and Materials, 2015.
- ASTM E2586-19, "Standard Practice for Calculating and Using Basic Statistics," American Society of Testing and Materials, 2020 Revision.
- Efron, Hastie, *Computer Age Statistical Inference,* 2017 – Free PDF
- ASME V&V 10 – Standard for Verification and Validation in Computational Solid Mechanics

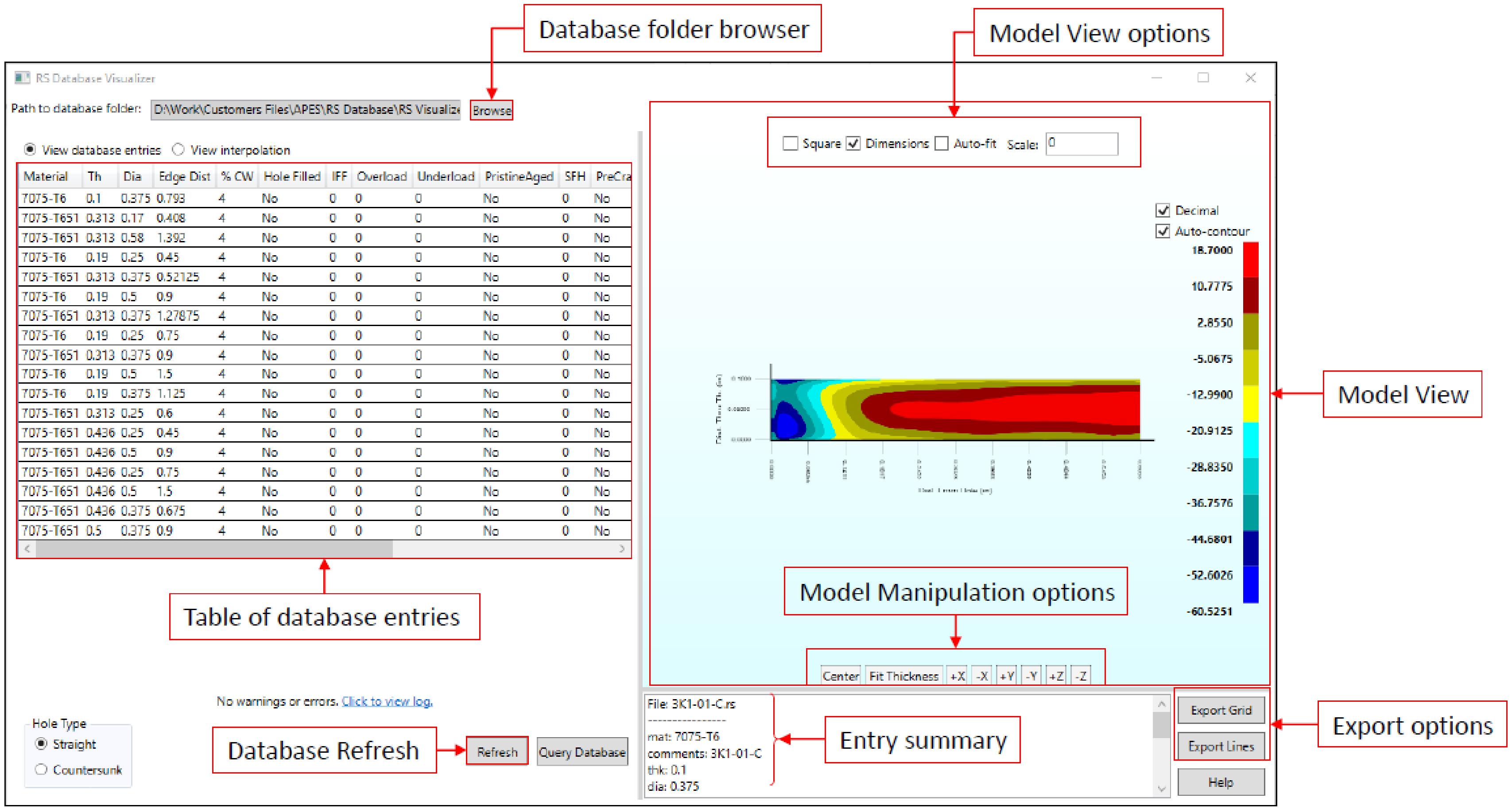
New Residual Stress Database

APES, Inc.

Residual Stress Database

- Old capabilities retained: visualization, library, search db, interpolations of multiple files.
- New capabilities
  - Filtering of over 15 new parameters (old (5): material, CX%, D, t, e/D. new (24): over/underload, pre-cycles, filled holes, pristine/aged, CX countersink process, etc.)
  - AFGROW .sd3 (Residual stress data) output (Export Lines)
  - Handles replicates

Residual Stress Database-Library & Visualization

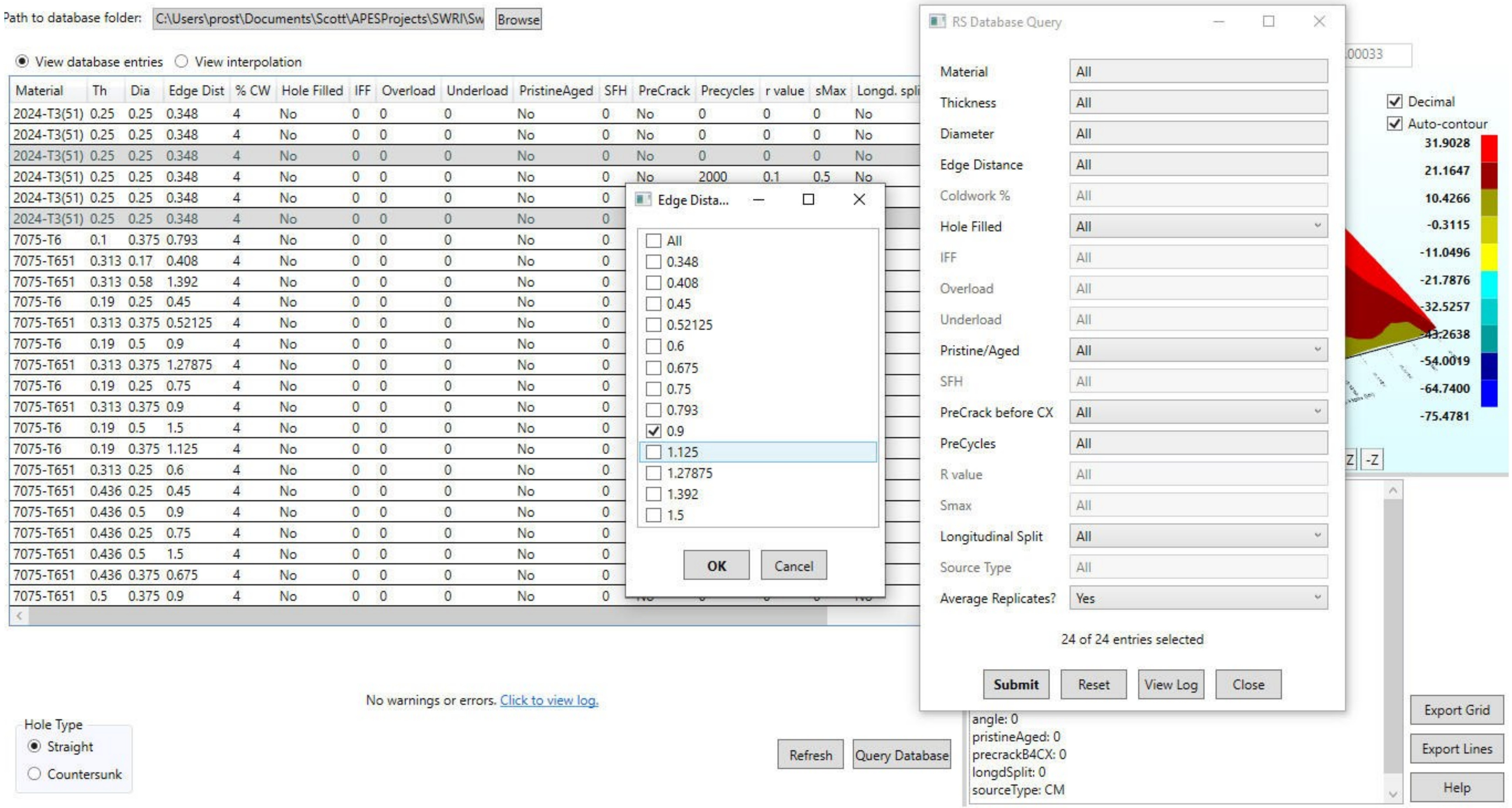


Over 15 unique parameters added

Entry Fields

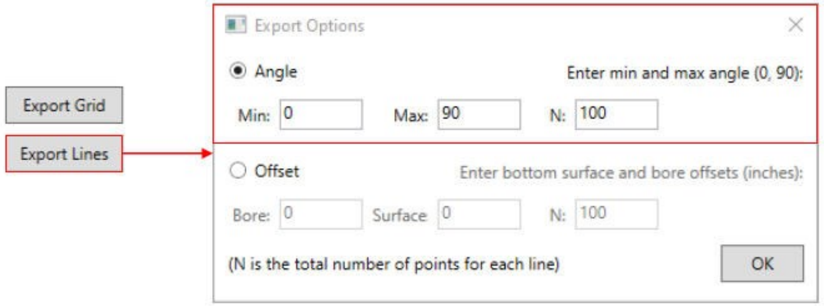
ID#	Parameter	Description	Type	Dependencies
1	mat	Material name	String	Required
2	comments	Coupon information or other	String	Required
3	thk	Thickness	Double	Required
4	Dia	Diameter	Double	Required
5	ed	Edge Distance	Double	Required
6	pctCX	Percentage Cold Work	Double	Required
7	cskProc1	Countersink process	String	10,11
8	angle	Countersink angle	Double	Required
9	depth	Countersink depth	Double	Required if 10 is not = 0, 7
10	precycles	Number of pre-cycles	Integer	20 must be Yes, 11,12
11	rvalue	R value	Double	20 must be Yes, 10,12
12	smax	Pre-cycle load	Double	20 must be Yes, 10,11
13	replicates	Replicate number out of a set	Integer.Integer	Required
14	holeFilled	Boolean	Boolean	Required
15	iff	Interference Fit during pre-cycle	Double	14 must be Yes
16	overload	Overload as percentage of Yield	Double	14 must be Yes
17	underload	Underload as a percentage of yield	Double	14 must be Yes
18	sfh	Spectrum Flight Hours	Integer	19 must be Yes
19	pristineAged	When cold work is performed on a pristine or aged material	Boolean	Required
20	precrackB4CX	Existing pre-crack on coupon	Boolean	Required
21	longdSplit	For specimens where longitudinal cut was made to compute RS	Boolean	Required
22	sourceType	FEA (Finite Element Analysis), CM (Contour Method), EC (Eddy Current), ND (Neutron Diffraction), etc.	String	Required

Filtering capability added



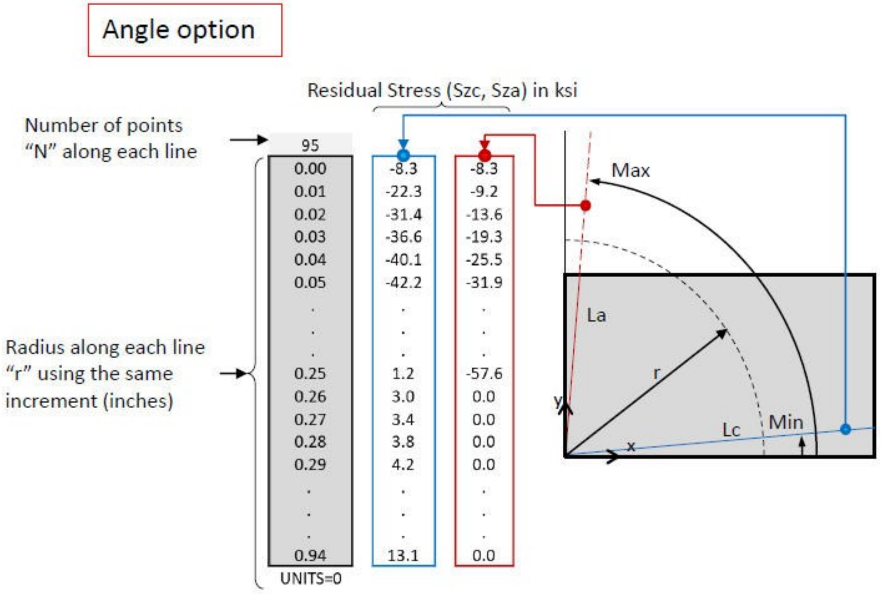
Export to AFGROW readable residual stress file

Export Lines option



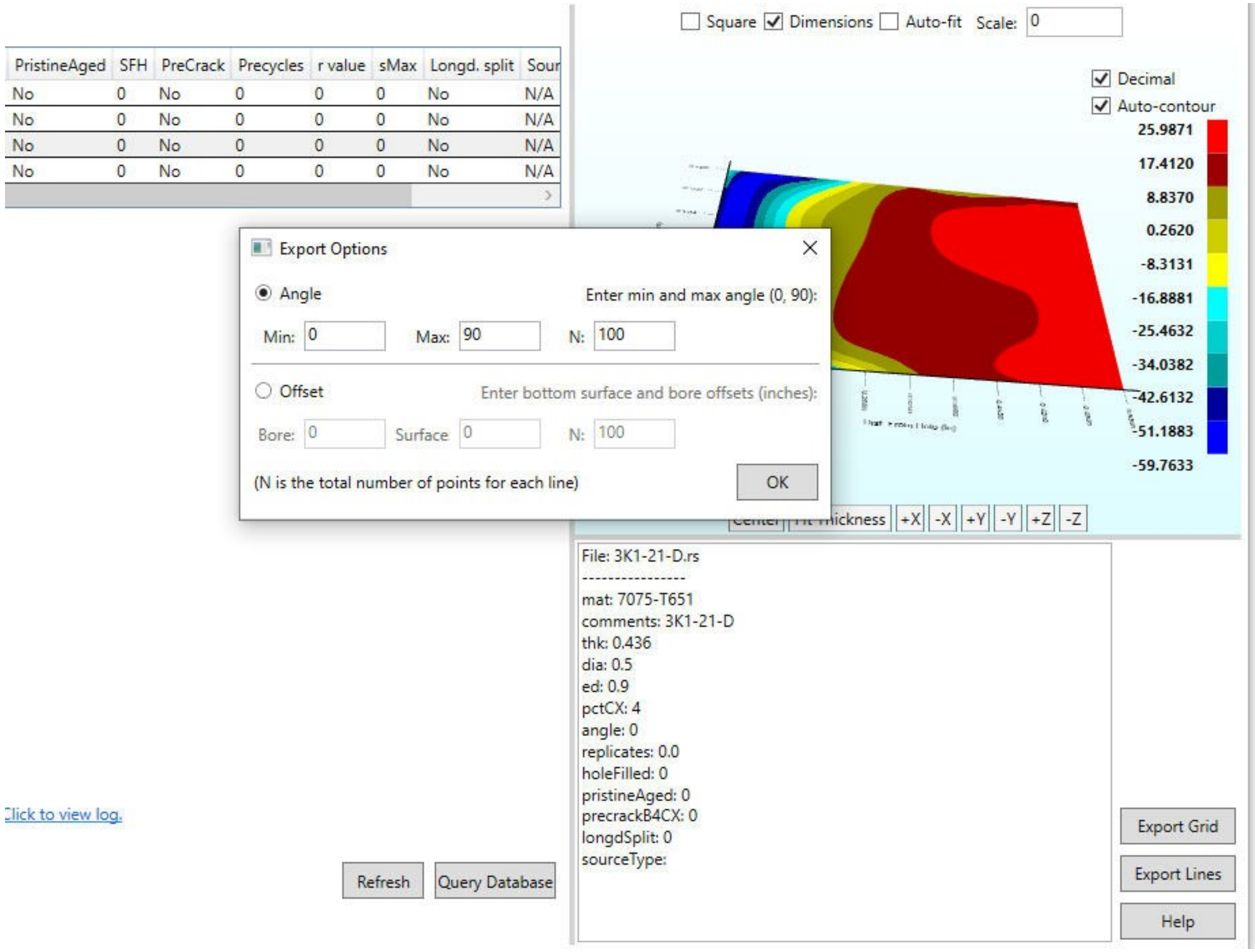
The Export Lines option can be used to output a file with interpolated residual stress in (x,y,Sz) columns in an ASCII file format with extension *.sd3:

N (integer)
r1 (double) Szc1 (double) Sza1 (double)
r2 (double) Szc2 (double) Sza2 (double)
...
rN (double) SzcN (double) SzaN (double)
UNIT=0 (string)



Increment = max(La,Lc)/(N-1)

Export along angles or offset distances



Available, Free!

- Original database had 47 RS profiles
- 2021 update includes 323 RS profiles
  - User can add profiles
- For access, contact Scott Prost-Domasky: prost@apesolutions.com

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Sensitivity Study on Cold Expanded Fastener Hole Damage Tolerance Life

A Collaborative ERSI Effort

Presented at the AFGROW Workshop 2021

Acknowledgements

- **Fatigue Technology Inc.**
  - Keith Hitchman
  - Sam Zimmerman
- **USAF**
  - Jake Warner
- **Hill Engineering**
  - Dallen Andrew
  - Josh Hodges
- **SwRI**
  - Matt Kirby

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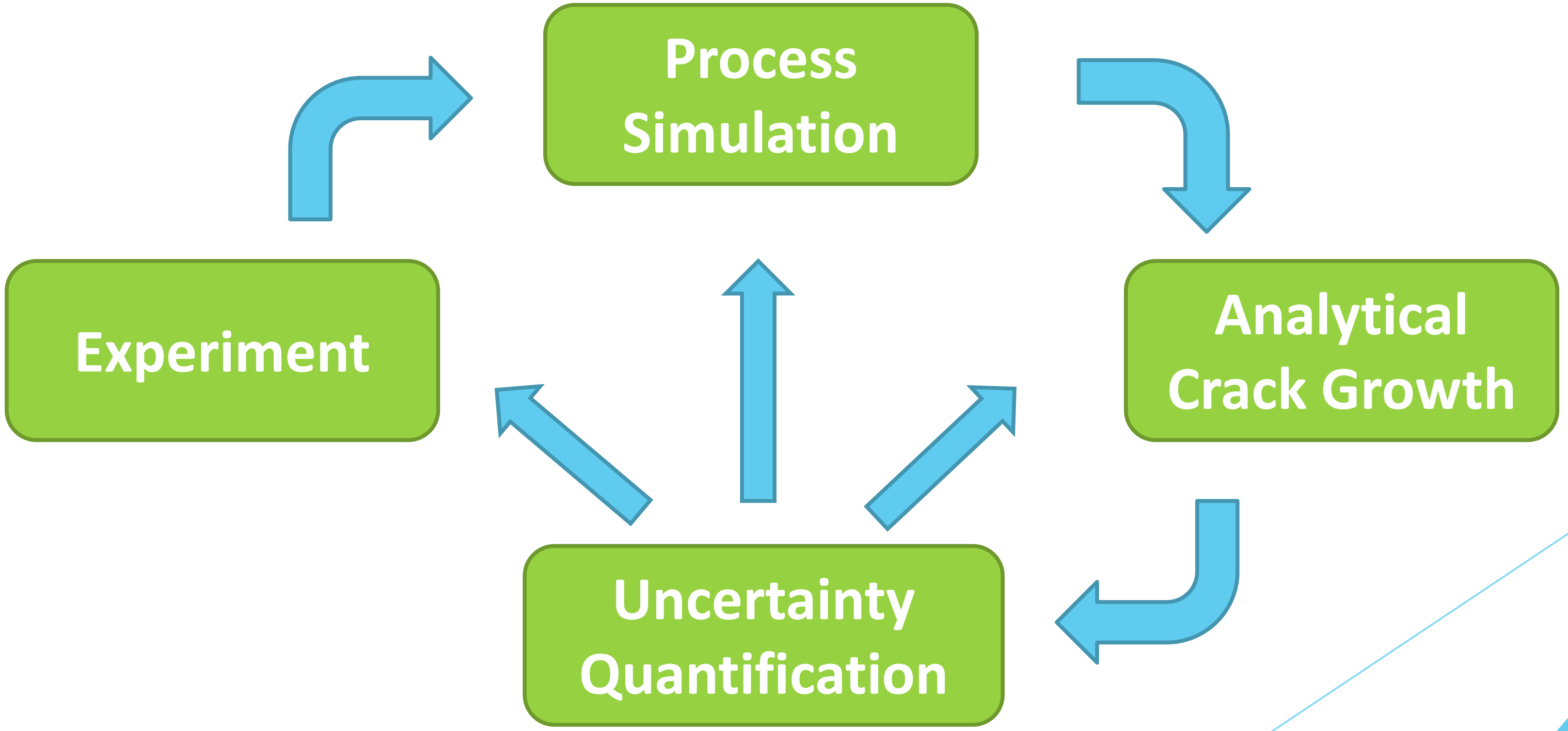
What is Sensitivity Analysis?

- Sensitivity methods are analyses complementary to risk and uncertainty quantification that can help determine the impact of an input variable
- Sensitivity methods can have a tangible impact on analysis and testing
  - Save time
  - Save money
  - Spend time and money on characterizing the most important inputs

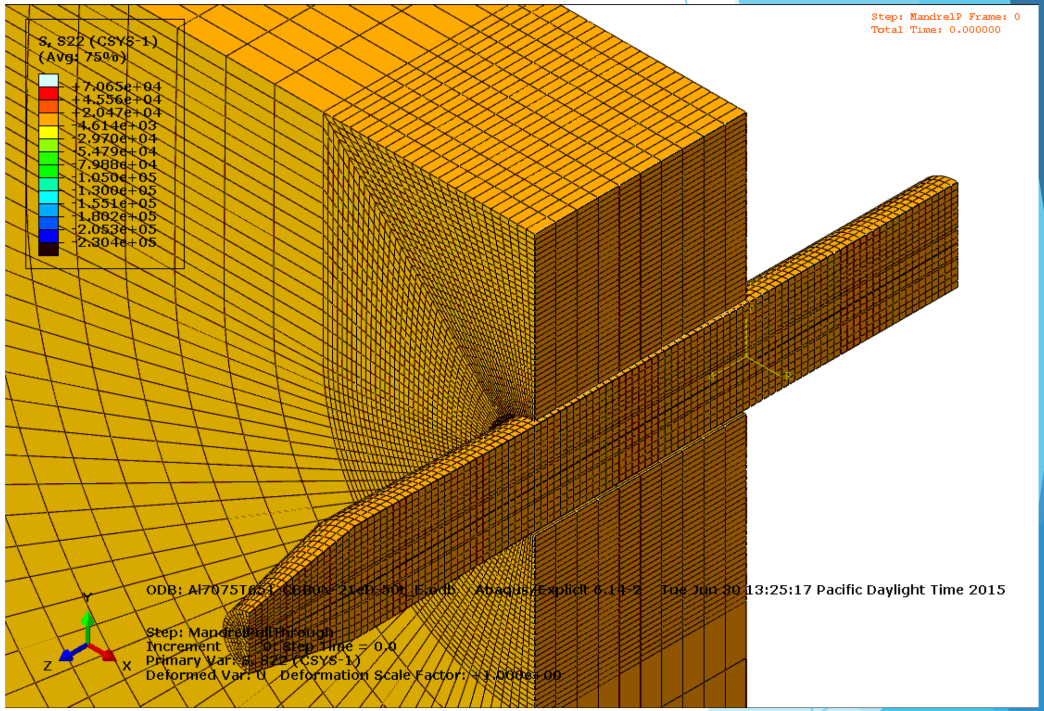
Data Flow

- Data flow through ERSI committees
  - Data gleaned from UQ/SA can inform all stages of the process



Specimen Geometry

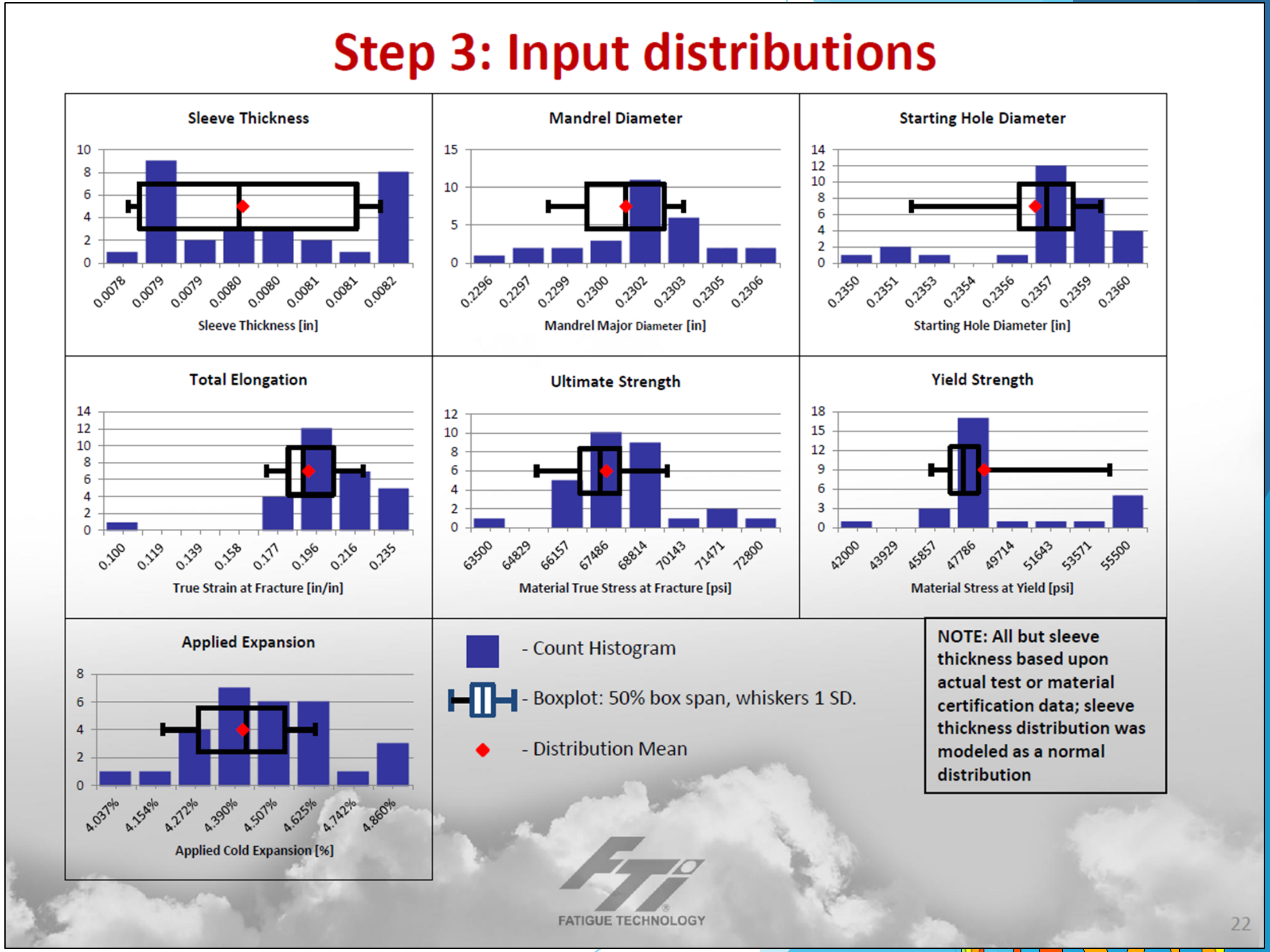
- FTI has an ABAQUS model of their cold expansion process
- Two load steps: mandrel pull-through and reaming
- 0.5” aluminum plate thickness



From Hitchman and Zimmerman, “Development and Use of an FEA Script for Variance and Correlation Studies of Analytical Predictions of Cold Expansion Residual Stress Fields,” HOLSIP 2016.

FTI Simulation Study

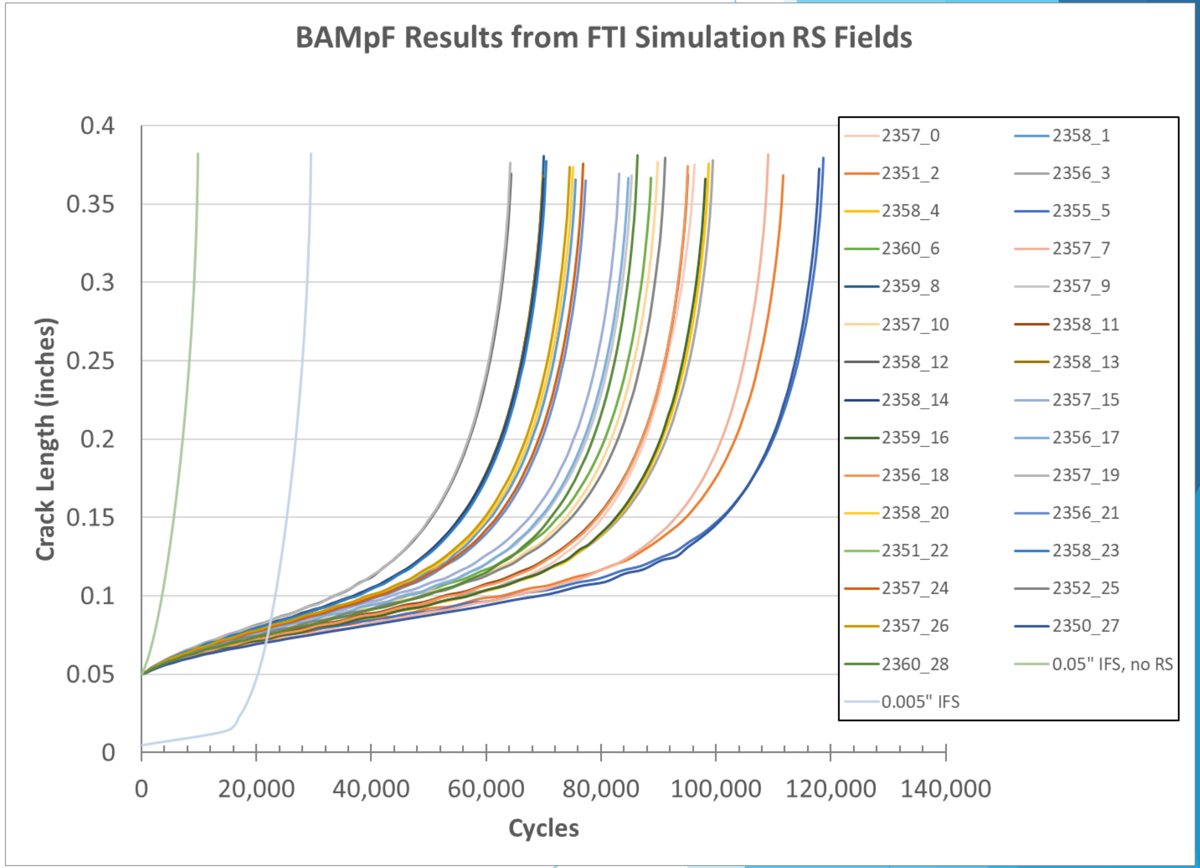
- FTI ran 29 samples of their cold expansion simulation ABAQUS model
- Results were provided to UQ and Analytical Methods Comms.
- Note that samples (except for sleeve thickness) were based on actual measurements, not from a distribution or DOE



BAMpF Crack Growth Simulation

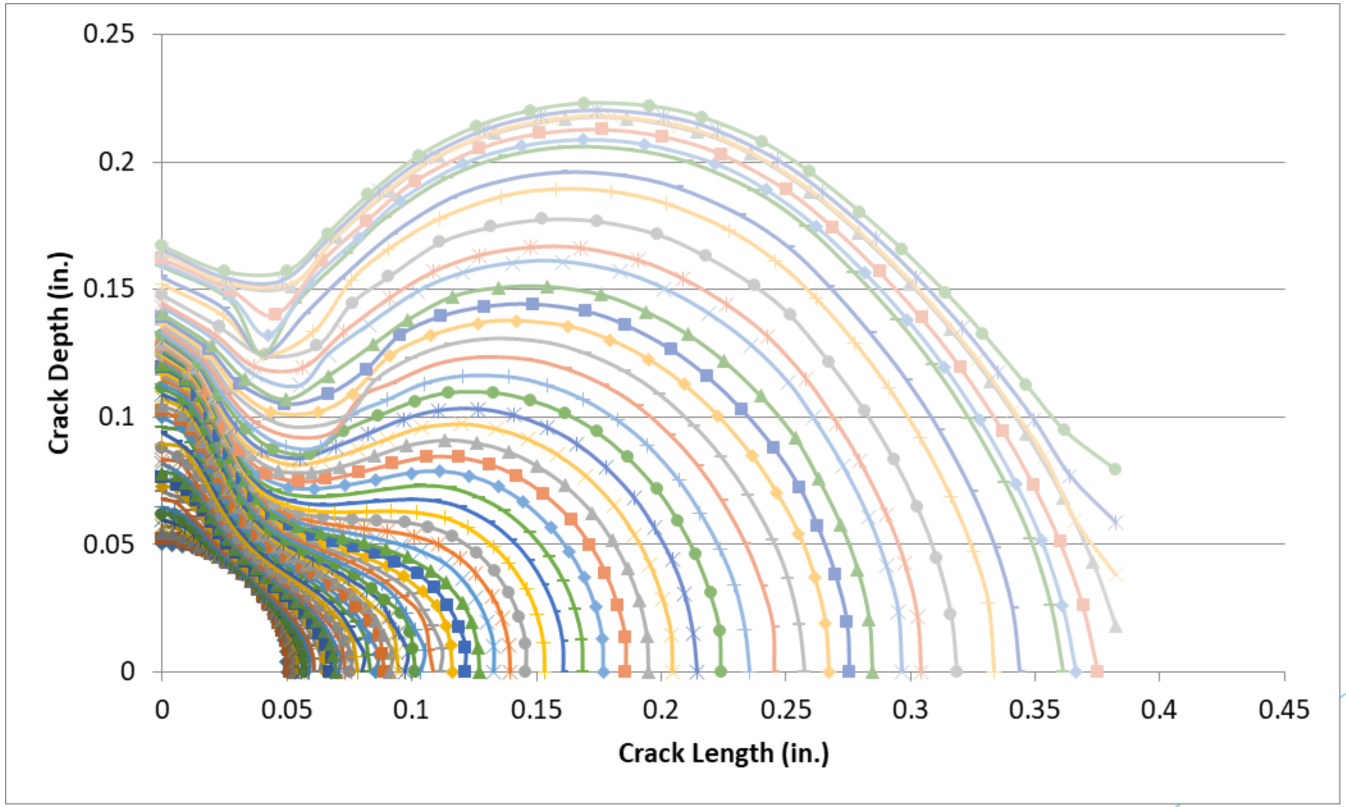
- Analytical Methods Committee used the resulting residual stress fields to grow a crack from an IFS of 0.05 in.
- Also ran cases with no RS from 0.05 and 0.005

- Note that most life benefit due to a compressive stress field happens below crack sizes of 0.05 inches
- However, since the initial flaw size of a DTA is associated with NDI capability, the initial flaw size remains the same despite the beneficial stress field



BAMpF Simulation

- Typical crack front with residual stress included



Correlation Matrix

	Starting D	Elongation	Mandrel Diameter	Sleeve Thickness	Applied Expansion	Ultimate Strength	Yield Strength	Life
Starting D	1.00	-0.02	0.02	-0.11	-0.61	0.15	0.09	-0.56
Elongation	-0.02	1.00	0.15	0.14	0.17	0.60	0.74	0.14
Mandrel Diameter	0.02	0.15	1.00	0.03	0.52	-0.22	-0.10	0.34
Sleeve Thickness	-0.11	0.14	0.03	1.00	0.67	-0.11	0.00	0.79
Applied Expansion	-0.61	0.17	0.52	0.67	1.00	-0.26	-0.10	0.95
Ultimate Strength	0.15	0.60	-0.22	-0.11	-0.26	1.00	0.80	-0.22
Yield Strength	0.09	0.74	-0.10	0.00	-0.10	0.80	1.00	-0.09
Life	-0.56	0.14	0.34	0.79	0.95	-0.22	-0.09	1.00

Applied Expansion (I_a) is given by the following formula:

$$I_a = \frac{(D + 2t - SHD)}{SHD} \times 100\%$$

Where:

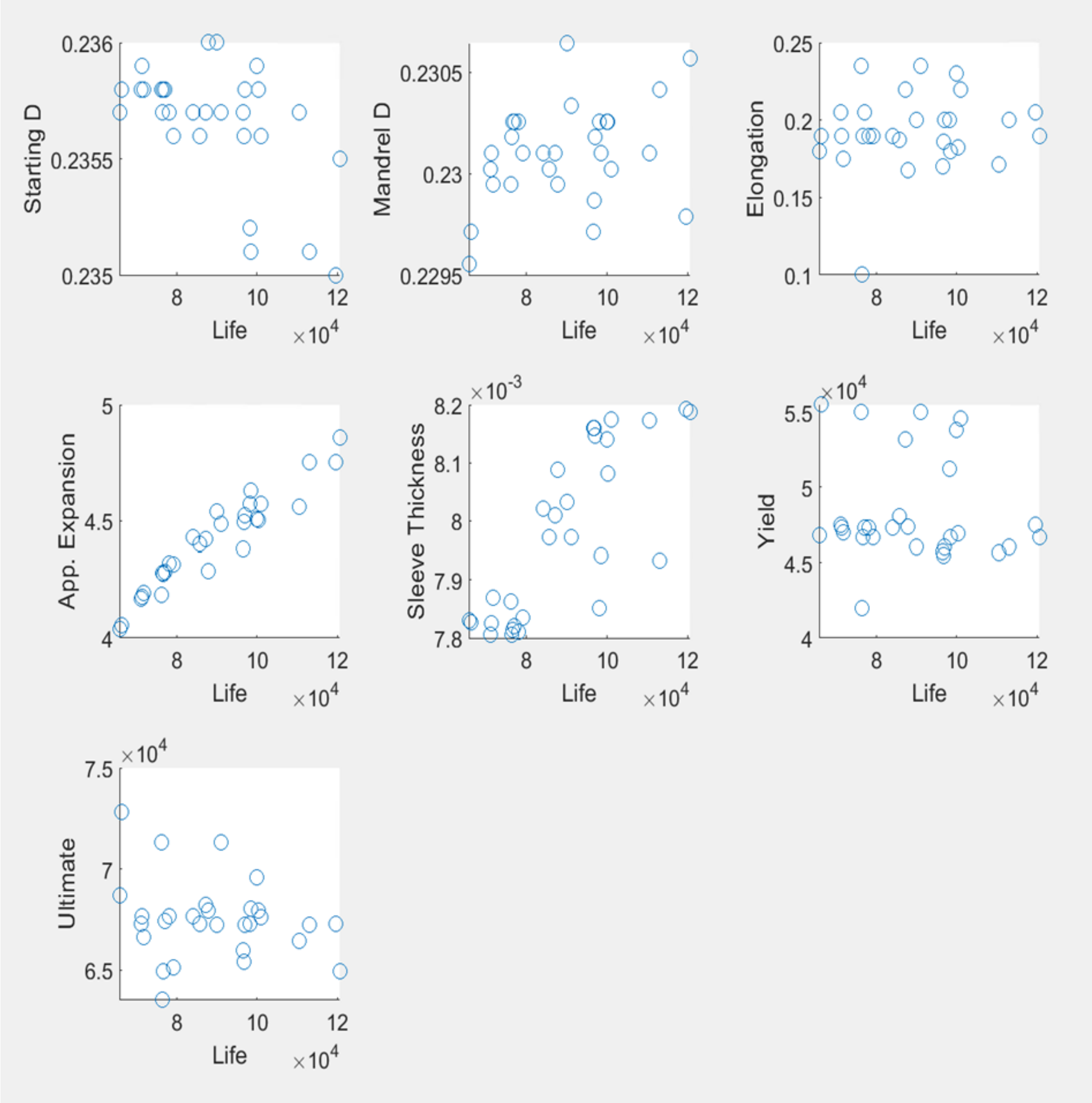
D = *Major Mandrel Diameter*
t = *Sleeve Thickness*
SHD = *Starting Hole Diameter*

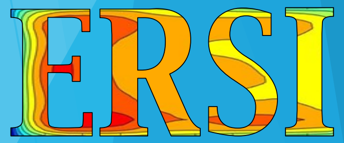
Reality Check

- Life is strongly correlated to applied expansion
- Yield is positively correlated to Ultimate
- Applied expansion is inversely correlated to starting hole diameter

Scatter Plots

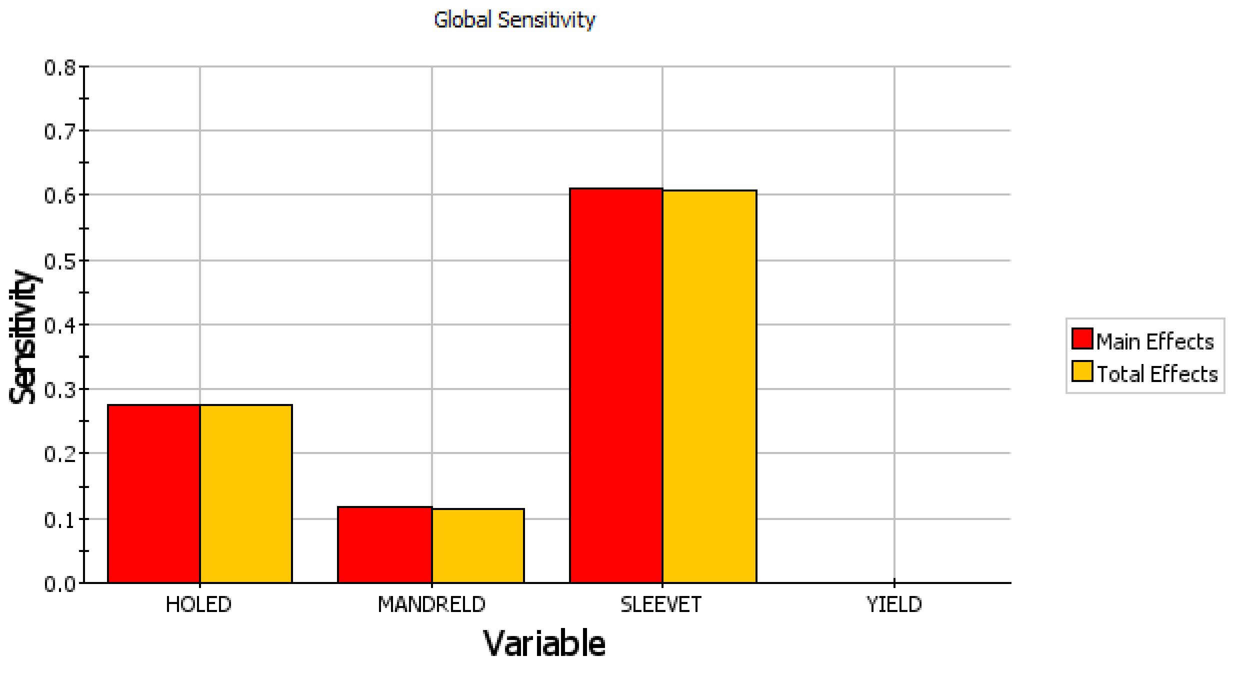
- All variables vs. Life
- High correlation between Applied expansion and Life
- Low correlation between Yield/Ultimate and Life
  - Sensitivity studies of RS fields found high correlation between material properties and outputs of interest
  - Emphasizes importance of defining the intended use of models





Global Sensitivities

- Calculated sensitivities on the linear reduced model using NESSUS
  - Note that main and total effects are the same due to linear model
- Sleeve thickness dominates, however,
  - small sensitivities could be due to unstructured sampling



Global Sensitivity

Recommended Future Studies

- Rerun FTI models using a structured sampling method, such as Latin Hypercube
- Do more detailed studies between RS fields and Life to determine a proper metric for RS fields
- Compare results of BAMpF vs. regular AFGROW 2-pt models

Activities for Upcoming Year

- Perform risk calculations for crack growth simulations in the presence of residual stresses.
- Sensitivity and parametric study
- Provide support to other subcommittees as needed.