Sensitivity Study on Cold Expanded Fastener Hole Damage Tolerance Life

ERSI Process Simulation, Analytical Methods, and Risk & UQ Committees

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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

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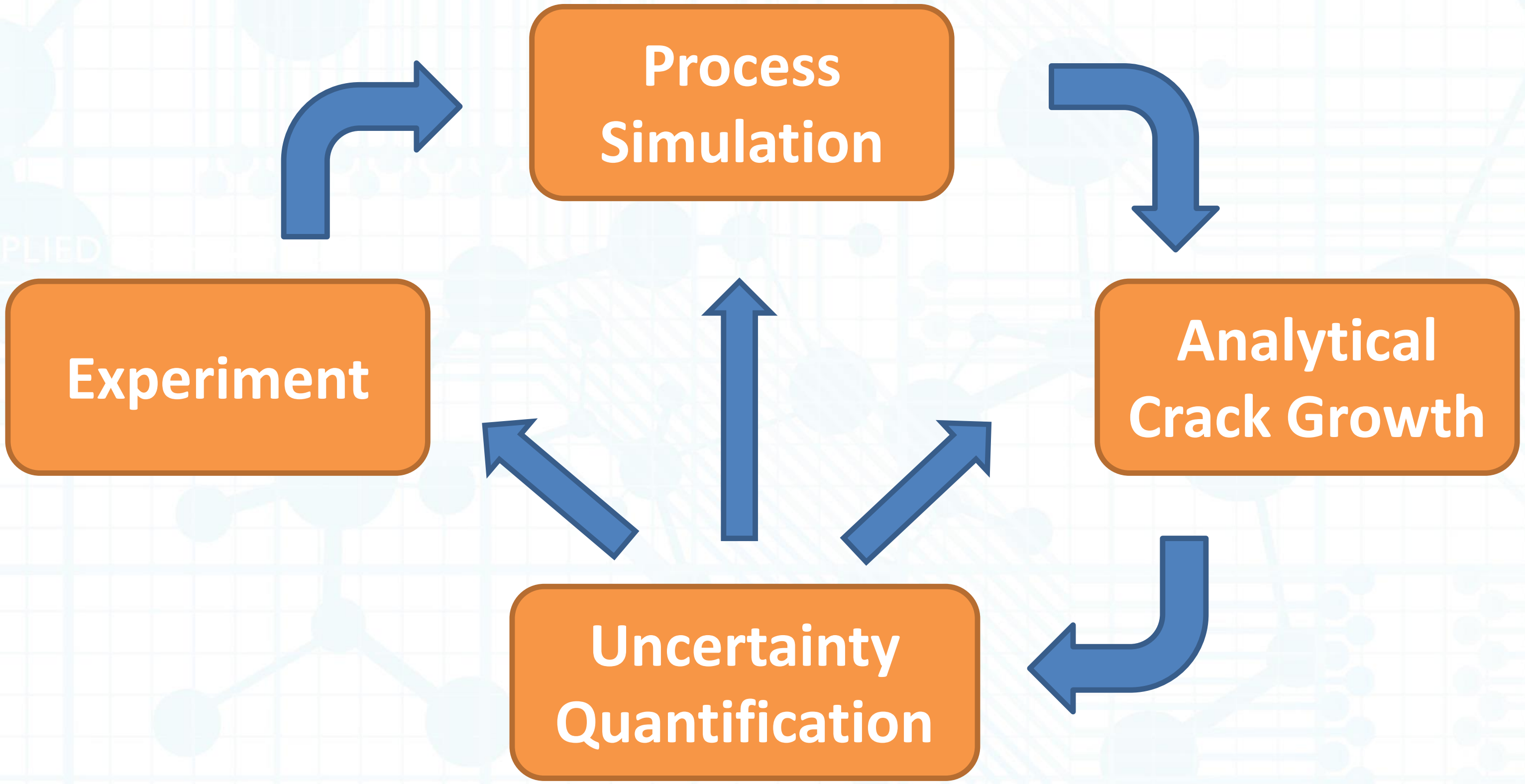
Data Flow

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



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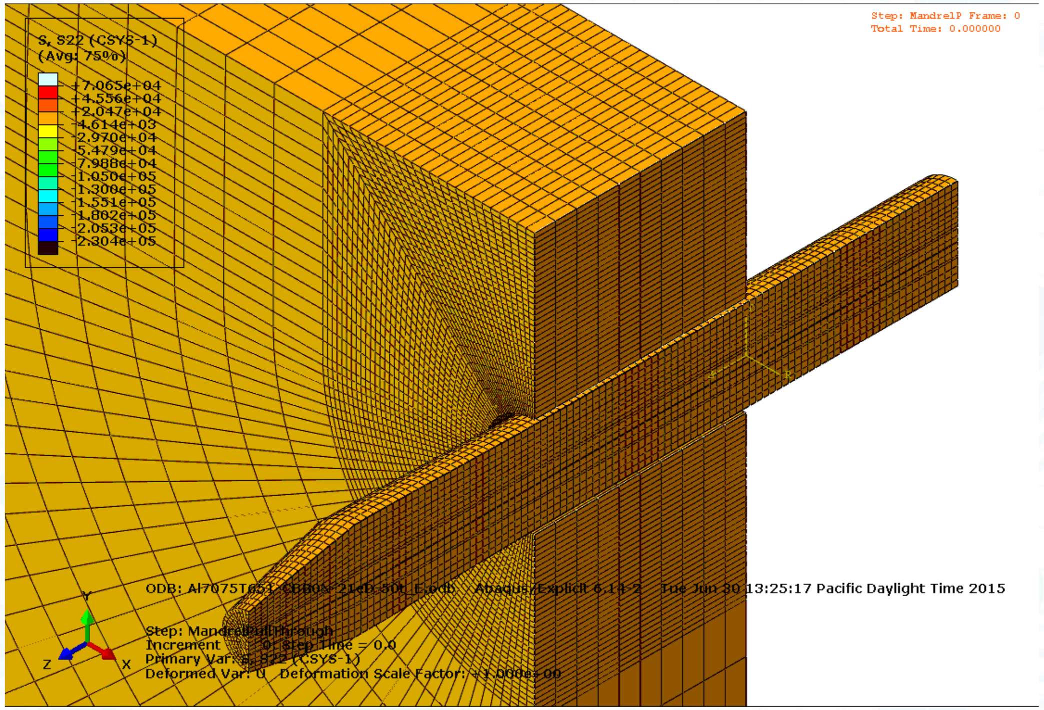
Specimen Geometry

- 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.

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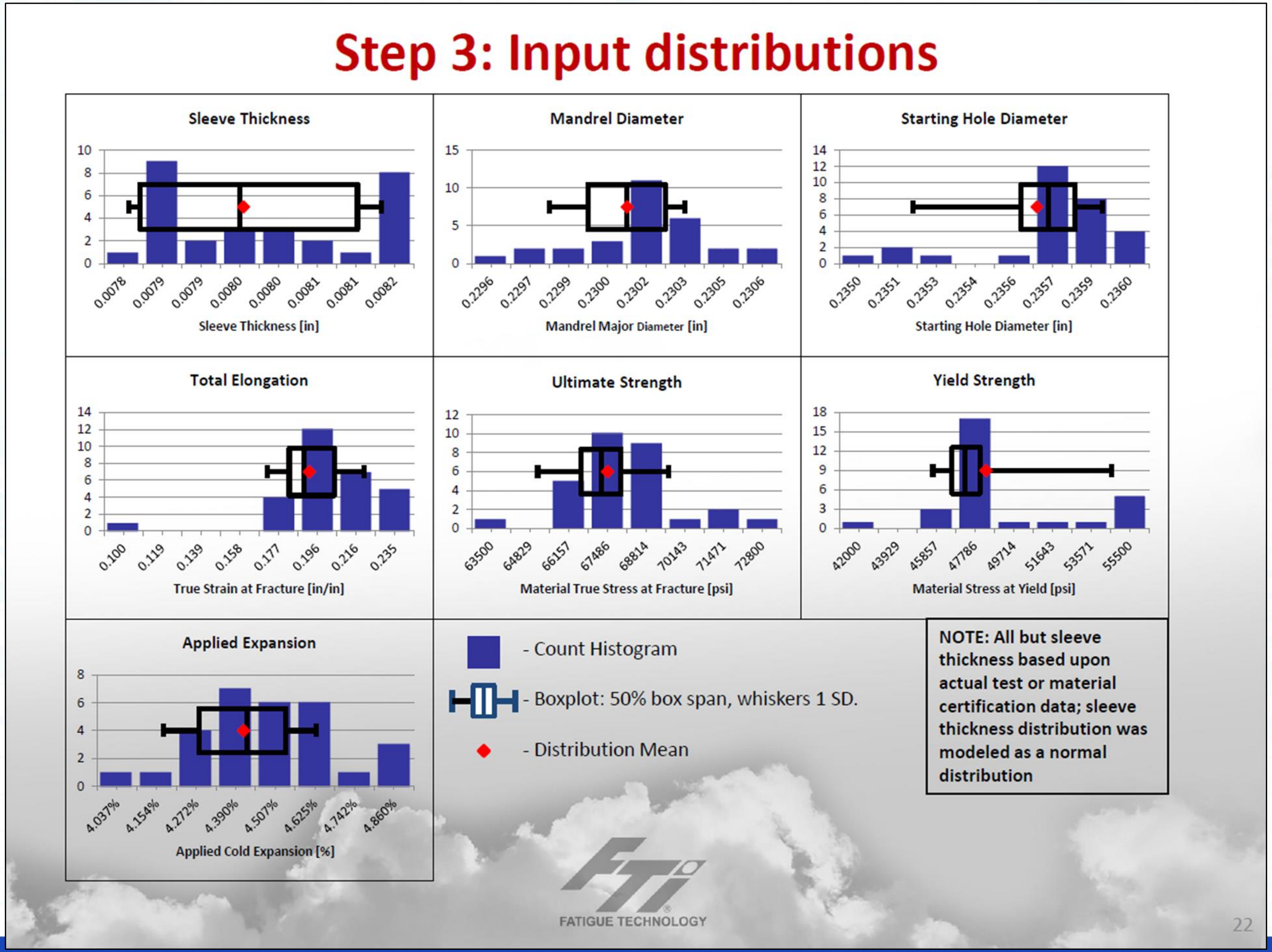
FTI Simulation Study

- 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



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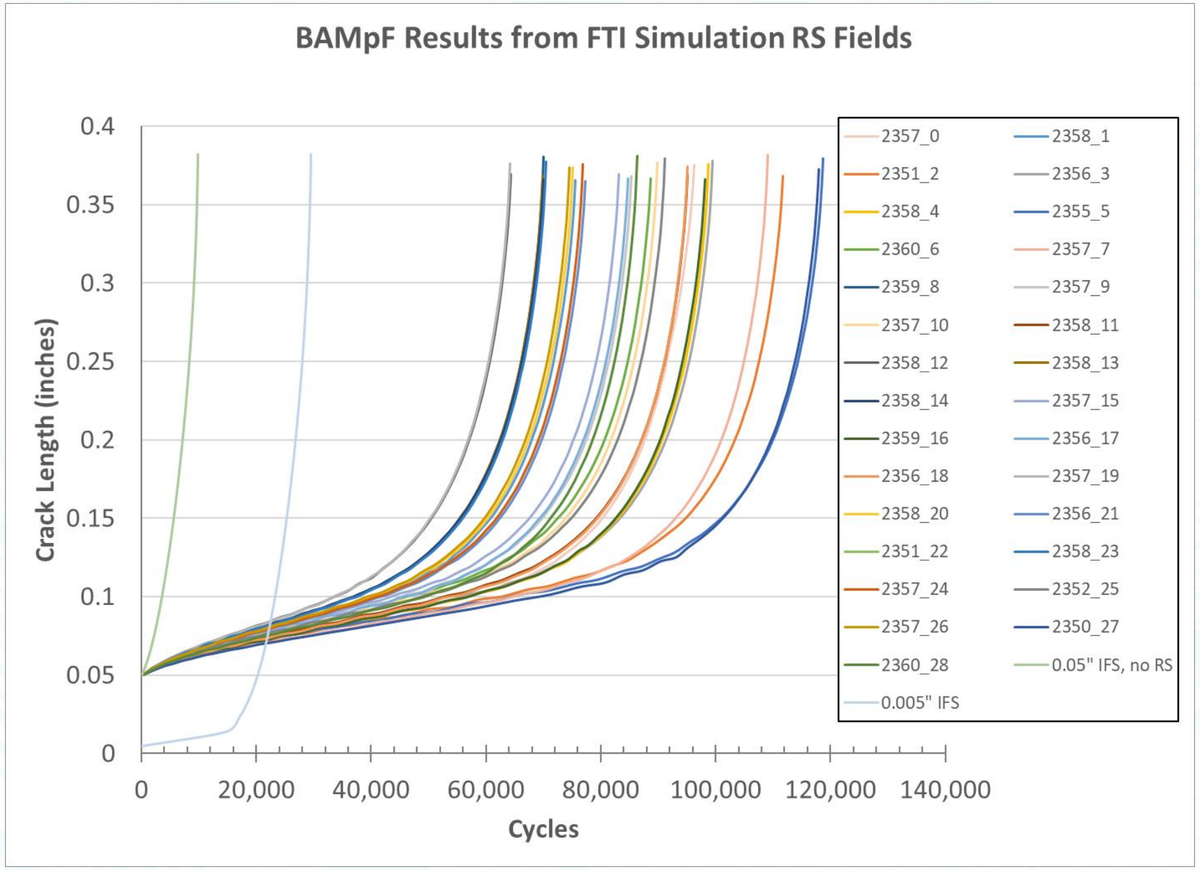
BAMpF Simulation

- 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



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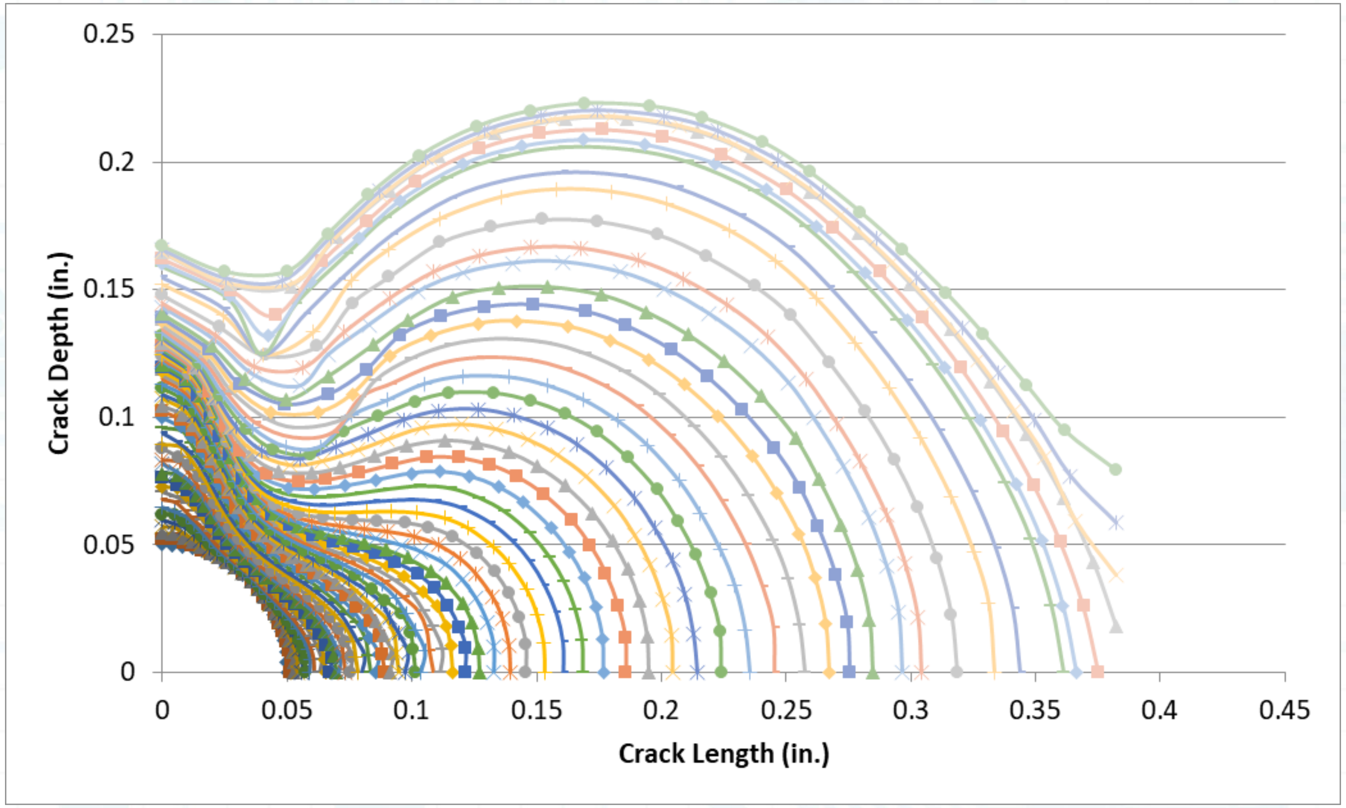
BAMpF Simulation

- Typical crack front with residual stress included



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Comments on DTA + Residual Stress

- 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

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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

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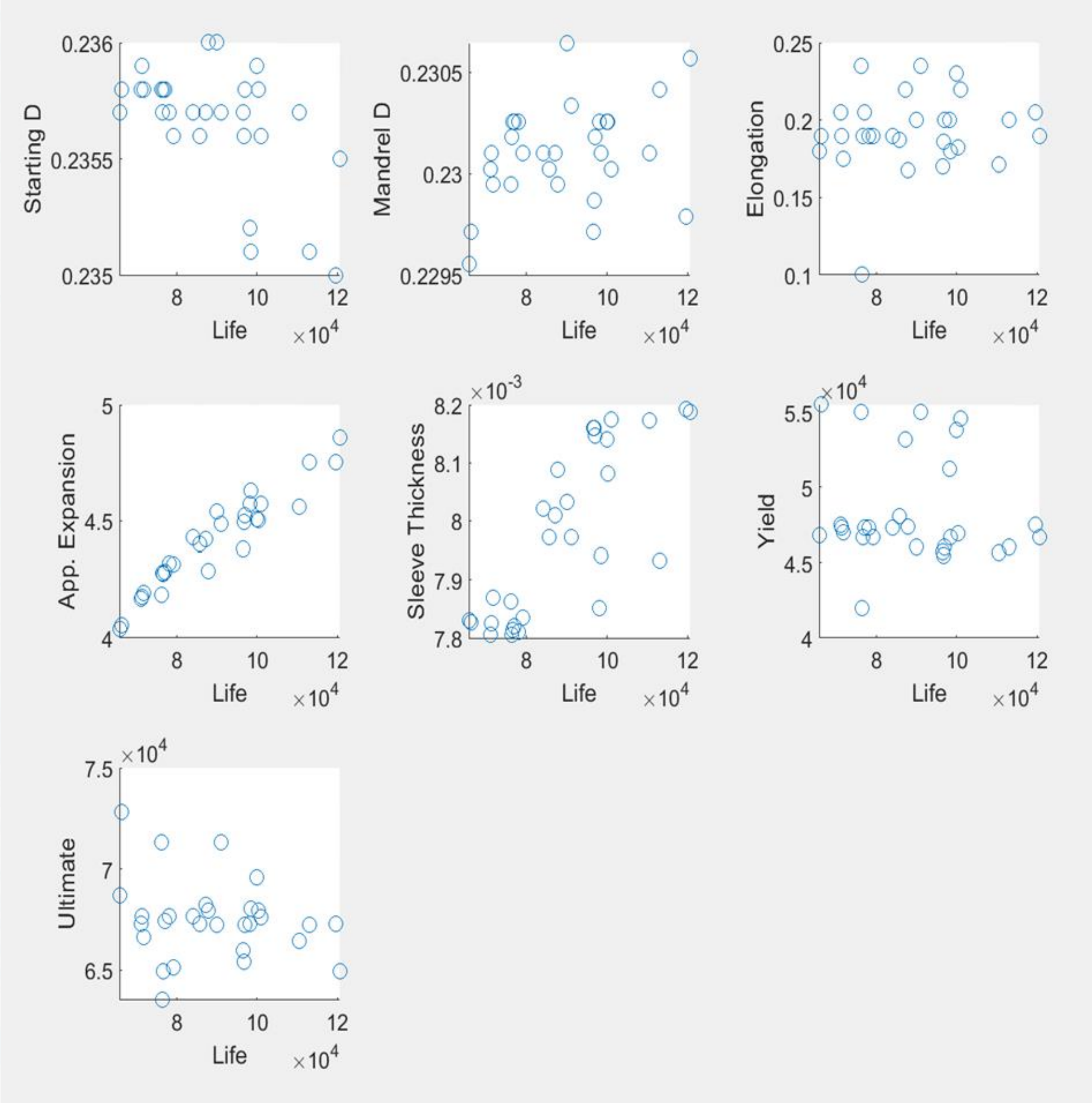
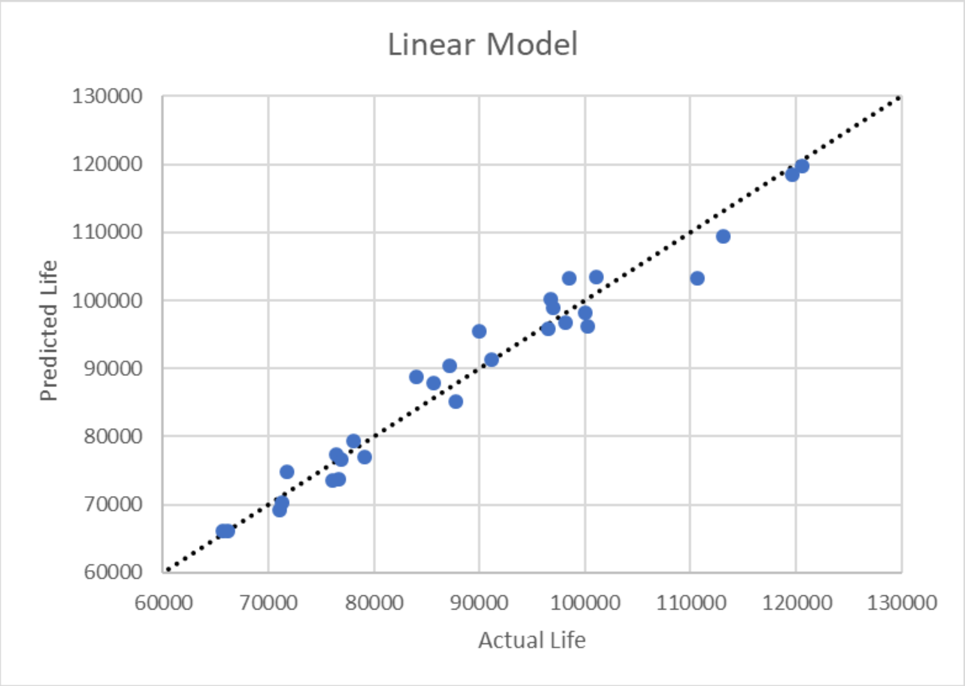
Scatter Plots

- 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



Linear Surrogate Model

- Surrogate model created by fitting inputs to output by linear regression
- R-squared = 0.96 => Pretty good



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Reduced Linear Model

- Remove dependent and insignificant variables from the model
- Elongation, Applied expansion, and Ultimate removed as variables
- R-squared goes from 0.96 to 0.94 => **still pretty good**
- Note that small sensitivities can be due to a poorly designed DOE
  – Since the FTI inputs were based on observed data and not a DOE, this could be the case for some variables

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Global Sensitivity Methods

- Global sensitivity is a variance-based method that pairs well with Monte Carlo Sampling
- First-order sensitivity uses the variance of the conditional expectation and represents the main effect of each input on the variance of the output

$$S_i = \frac{V[E(Y \mid X_i)]}{V(Y)}$$

Each index has a maximum value of 1

- The "total effect" sensitivity takes into account interaction effects between variables and is written as

$$S_{T_i} = 1 - \frac{V[E(Y \mid \mathbf{X}_{\sim i})]}{V(Y)}$$

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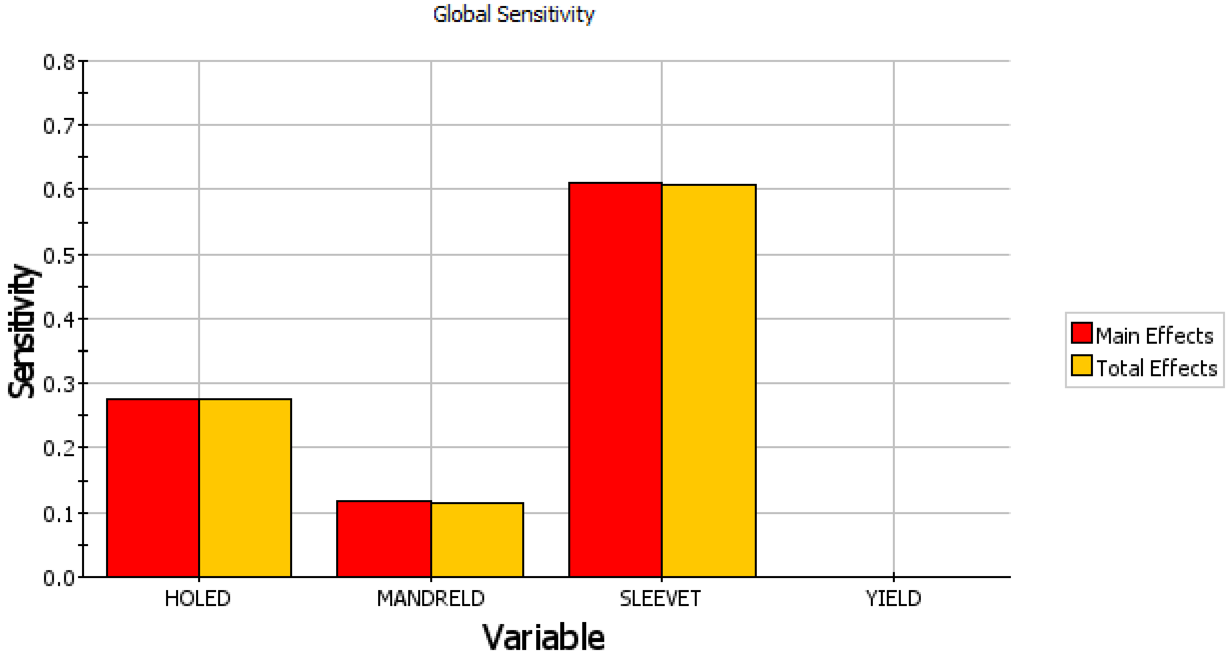
Global Sensitivities

- 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 can be due to un-designed sampling



Global Sensitivity

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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

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