ERSI RISK AND UQ SUBCOMMITTEE ACTIVITIES

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Outline

- Risk and UQ Subcommittee Overview

- Short Presentations of Current Activities
  - "**A spatial statistics approach for utilizing 2D residual stress fields in a fatigue crack growth analysis**," Dallen Andrew, Hill Engineering
  - **FTI Coldworking Simulation Data Analysis**
    - Gavin Jones, Smart UQ
    - Joseph Yurko, University of Pittsburgh

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?

A spatial statistics approach for utilizing 2D residual stress fields in a fatigue crack growth analysis

Dallen Andrew

Hill Engineering, LLC

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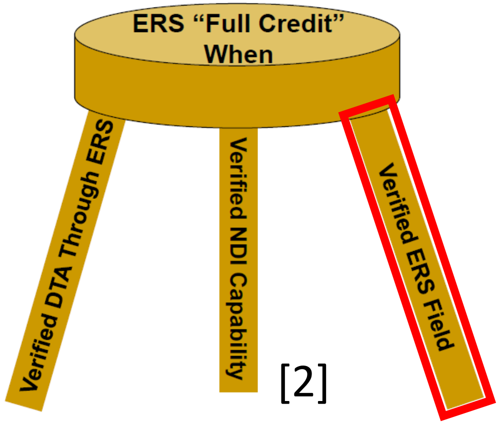
Objective



[2]

- Develop an analytical methodology to:
  - Characterize 2D spatial field of residual stresses from the Cx process using spatial statistical methods
    - Focus on determining the appropriate 'binning' method for the residual stresses in a model (i.e. is a 2 ksi to 3 ksi bin sufficient or should it be a 2.5 ksi to 2.6 ksi bin)
    - Focus on determining the appropriate filtering or sub-sampling method for the residual stress data prior to developing the response surface model, as the data density is essentially continuous
  - Utilize the characterized residual stress field in FCG analyses to meet airworthiness requirements
    - Perform deterministic FCG analysis that utilizes the statistically characterized residual stress field, analyzing both the mean response surface and the 5% lower bound "manage to" response surface (such as $RS_{90/95}$) [3]
      - Focus on method to ensure each response surface used still meets physical static equilibrium requirements
    - Perform probabilistic FCG analysis and risk assessment using the statistically characterized response surface
- Fatigue crack growth testing and residual stress measurements of Cx holes have been performed to verify and validate the analysis methodology

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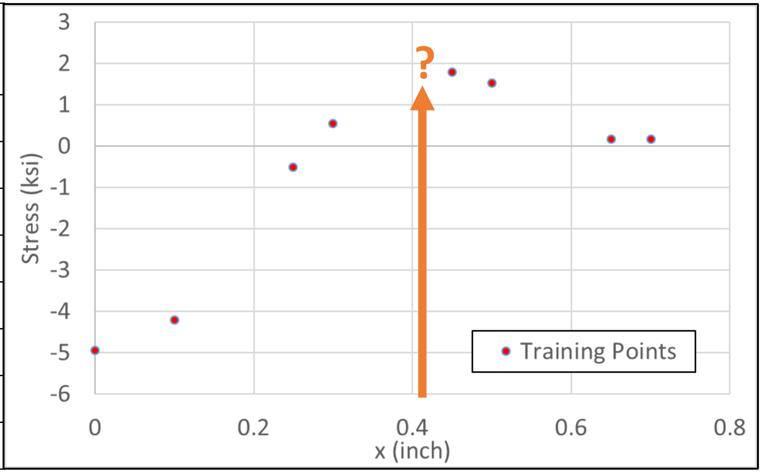
Preliminary Work

- Data is representative of RS field at Cx hole
  - Objective is to calculate the Kriging response at x=0.4

Training Point	x (inch)	Stress (ksi)
1	0	-4.95
2	0.1	-4.21
3	0.25	-0.52
4	0.3	0.54
5	0.45	1.78
6	0.5	1.53
7	0.65	0.17
8	0.7	0.16

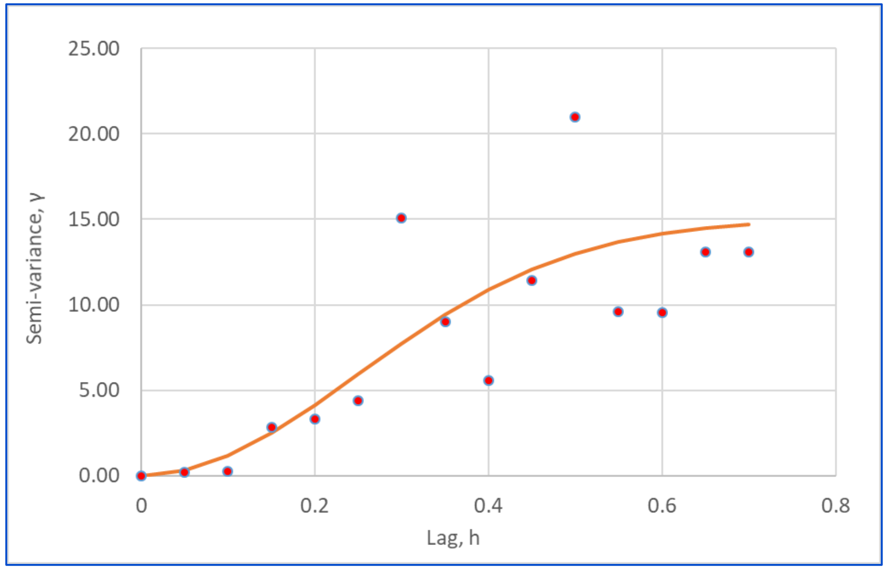


- Given the training points, the next step is to compute the experimental semivariogram γ(h)

$$\hat{\gamma}(h) = \frac{1}{2|N(\boldsymbol{h})|} \sum_{N(h)} \left[Z(s_i) - Z(s_j)\right]^2$$

- When experimental semivariogram is estimated a semivariogram model is selected

$$\gamma(h) = c \cdot \left(1 - exp\left(-\frac{h^2}{\theta^2}\right)\right)$$



- Having the semivariogram matrix and vector, the Kriging weights (λ) can be computed

$$\gamma\lambda_0 = \gamma_0$$

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Preliminary Work

- Response at $x = 0.4$ is:

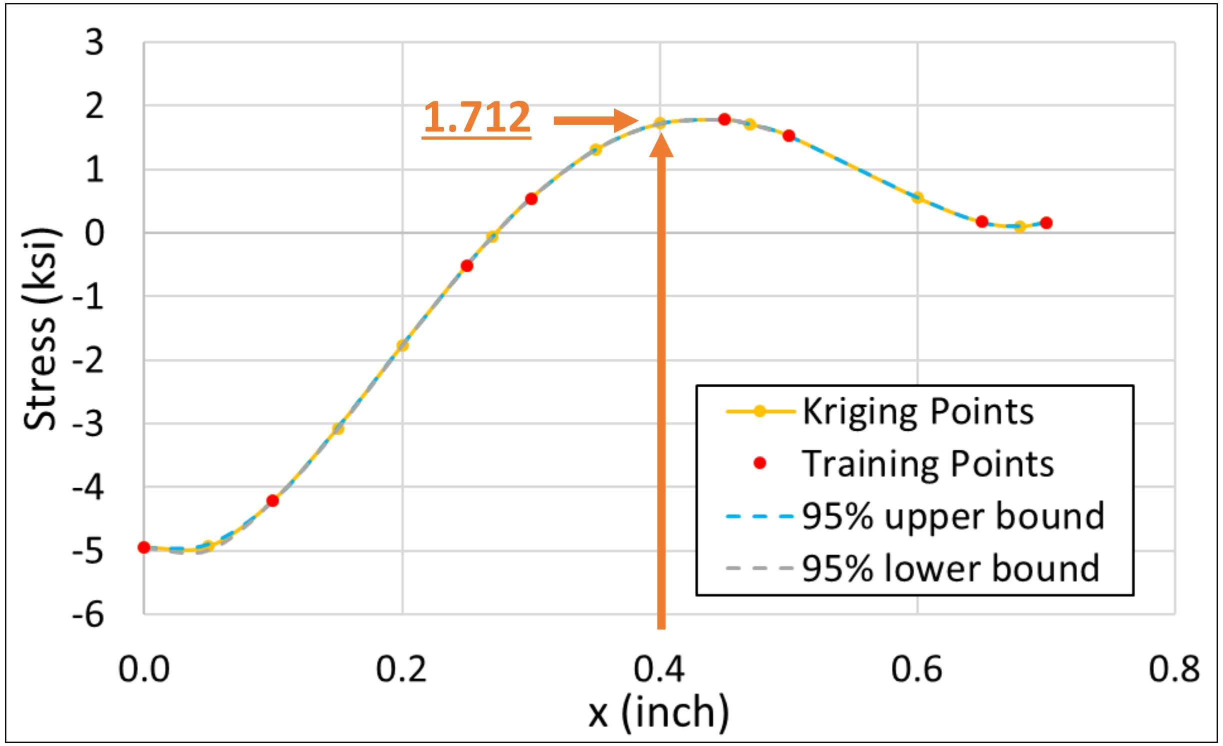
  $\hat{Z}(0.4) = \lambda^t Z = 1.712$

- Error in terms of the variance computed at x=0.4:

  $\sigma_e^2(x = 0.4) = \boldsymbol{\lambda}_0^t \cdot \boldsymbol{\gamma}_0 = 7.7\text{E-}7$

- The 95% confidence bound at x=0.4 from the prediction can be computed:

  $(Z(x_0) - 1.96\sigma_e(x_0),\ Z(x_0) + 1.96\sigma_e(x_0)) = (1.710, 1.714)$

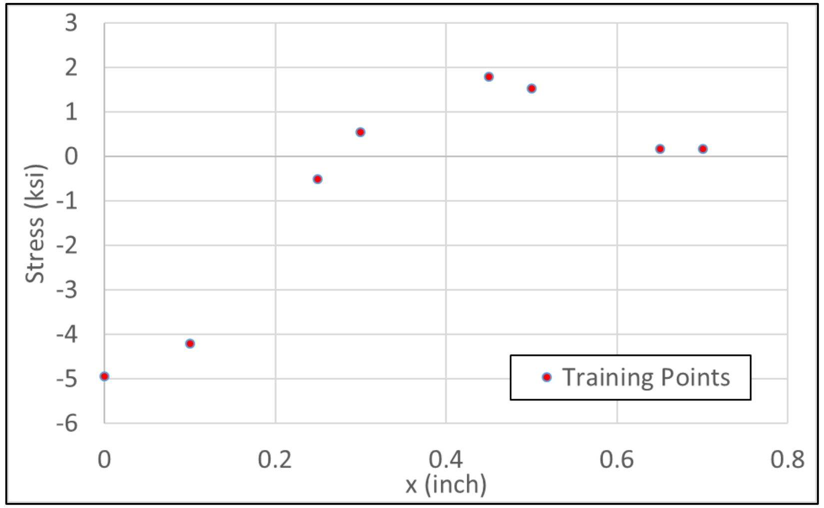


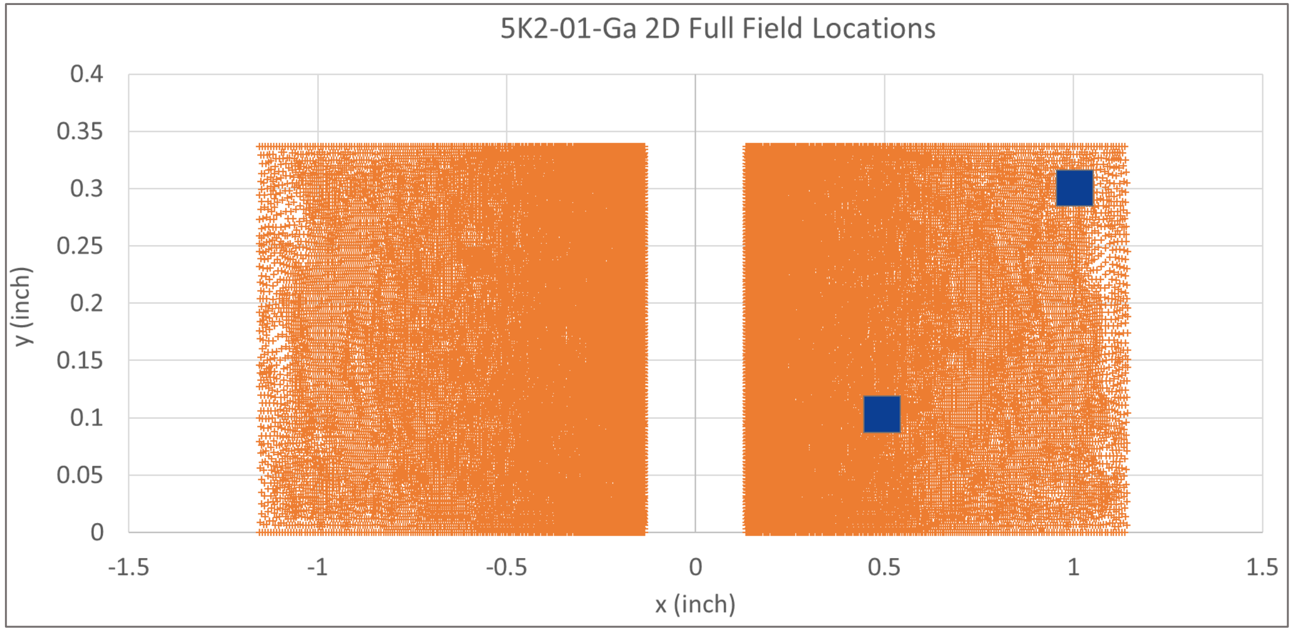
Methodology

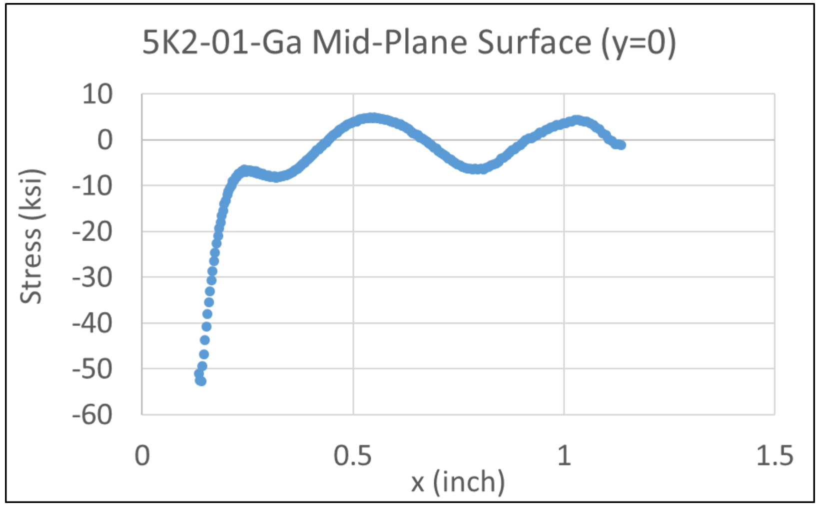
- The same process used for the simple 1D example will be implemented and expanded to apply to full 2D spatial residual stress field through the following steps:
  - Determine which fitting method is most appropriate for the 2D residual stress spatial data (i.e. polynomial, response surface model, etc.) then expand previous work for 1D line (single coupon) to 2D field (single coupon)
  - Develop method to incorporate multiple sample reps for 1D line (multi-coupon) then expand to 2D field (multi-coupon) using probabilistic methods
  - Determine and implement method for quantifying uncertainty and goodness of fit for 1D line then expand to 2D field and assess validity of static equilibrium of predicted response surface
  - Perform FCG analysis with predicted response surface

Methodology: RS Characterization

- Compute experimental semivariogram beginning with a 1D line then expand methodology for 2D surface, focusing on:
- - Binning Methods
- - Sub-sampling Methods
  - Output resolution of (x,y) coordinates is relatively high (# points >34,000)







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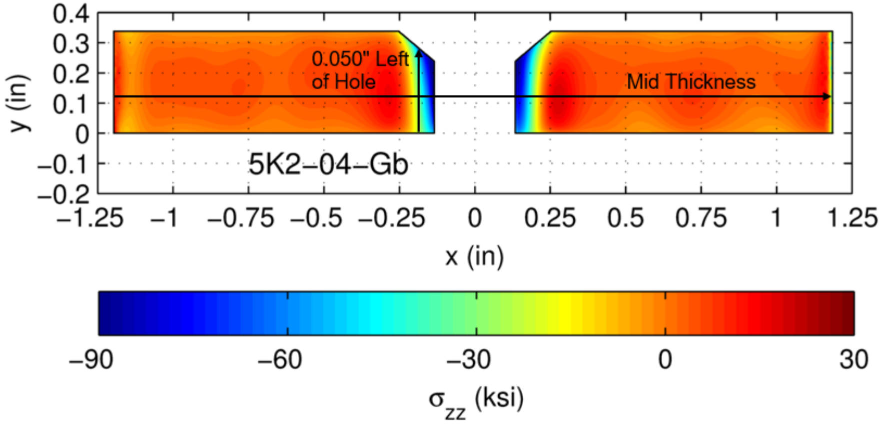
Methodology: RS Characterization

- \- Probabilistic Analysis
  - Use replicate samples to develop a distribution of response surfaces and Cumulative Distribution Function (CDF)
  - Available Cx hole test data from contour method has up to 5 replicate samples for a given Cx condition
  - RS process simulation data replicates from varying Cx parameters is also available

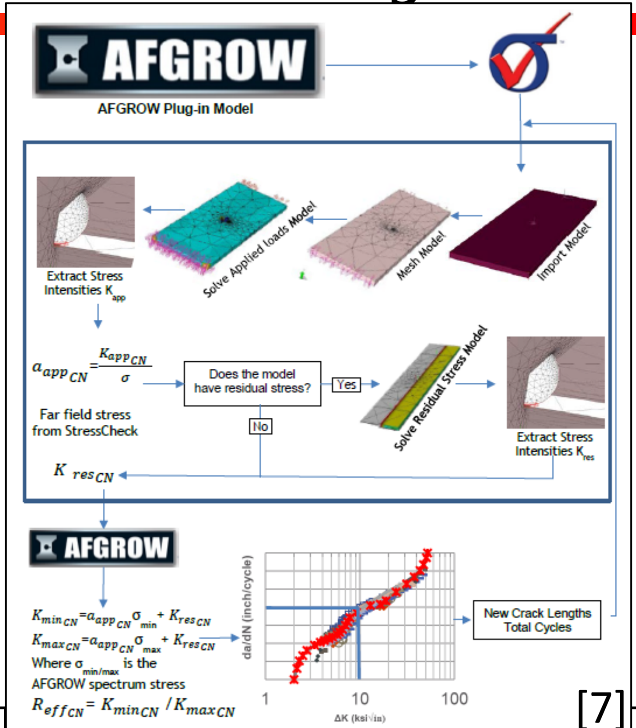
Coupon Type	Material	Loading	Hole Type	Thickness	CX method	Reps
Residual Stress	7075-T7351	N/A	Straight	0.34	CX Hole	3
			CSK		CX Hole	5
					CsCx	3
					CX Bore	3
			Straight	0.2	CX Hole	3
			CSK		CX Hole	3
					CsCx	3
					CX Bore	3
					TOTAL:	26

- \- Uncertainty Quantification
  - Uncertainty introduced by a response surface model
    - Can calculate variance with Kriging
  - Uncertainty of the RS from the contour method
    - Can use published UQ methods for
      - Repeatability uncertainty associated with Cx process variation [5]
      - Single measurement uncertainty from contour method [6]
  - Assess validity of static equilibrium of any predicted response surface



Methodology: Fatigue Crack Growth Analysis

- Perform deterministic FCG analysis with response surface
  - Mean surface & “manage to” surface [3], such as $RS_{90/95}$
  - Validate analytical method by comparing model predictions to countersunk Cx hole fatigue test data
- Perform probabilistic FCG analysis and risk assessment with predicted response surface
  - Using SMART [8] and/or PROF
  - Ocampo, AA&S 2017: “There is a need for a methodology…to model probabilistic residual stress [and] incorporate them into Probabilistic Damage Tolerance Analysis” [9]



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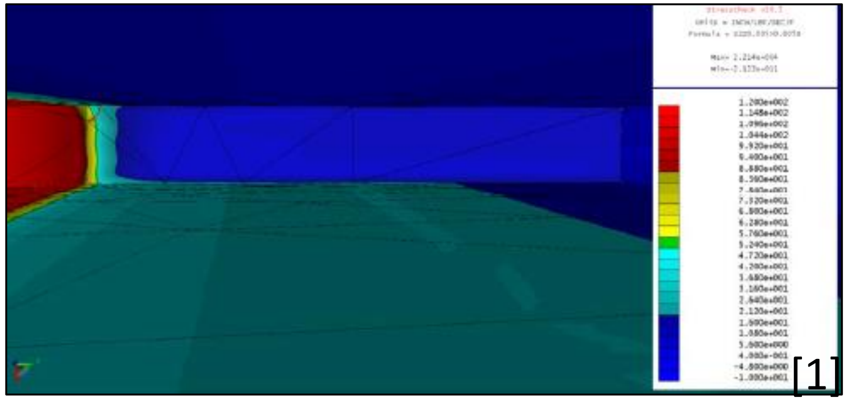
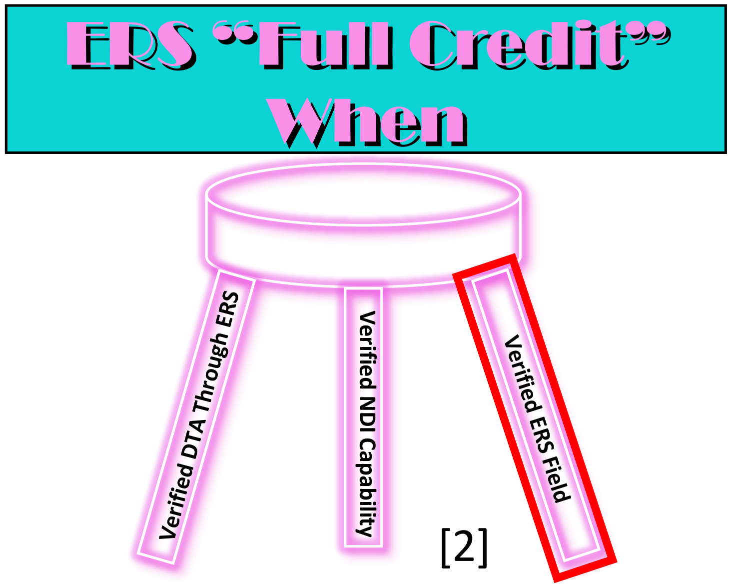

[1]

Coupon Type	Material	Loading	Hole Type	Thickness	CX method	Reps
Fatigue	7075-T7351	CA	CSK	0.34	NonCX	3
					CX Hole	5
					CsCx	3
					CX Bore	3
				0.2	NonCX	3
					CX Hole	3
					CsCx	3
					CX Bore	3
		CA + MB		0.34	NonCX	1
					CX Hole	1
					CsCx	1
					CX Bore	1
					Total:	30

Summary

- The main contribution of this research is to produce an allowables-based methodology for utilizing residual stress in FCG analyses
  - Enhances the current analysis method to match other aircraft structural methods that rely on the use of allowable values to ensure structural safety and certification requirements for "full credit" of the fatigue life benefit from the Cx process

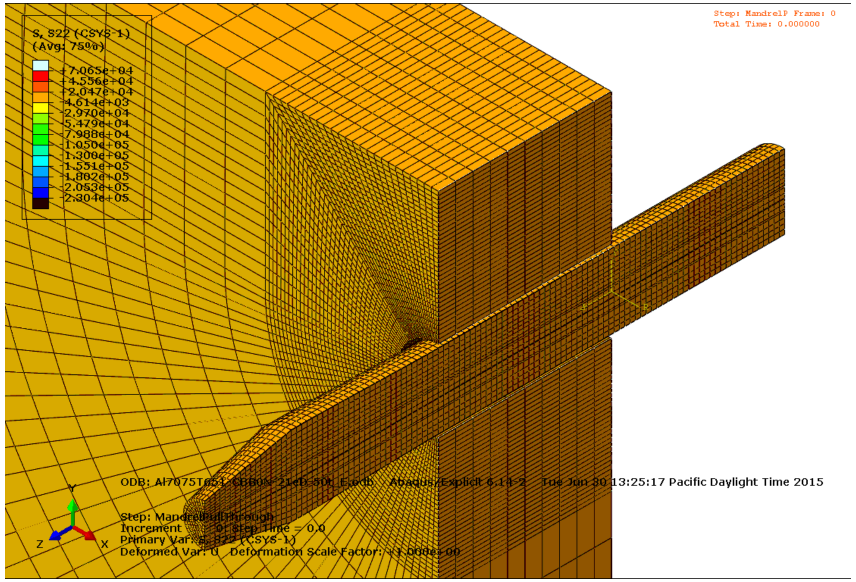


References

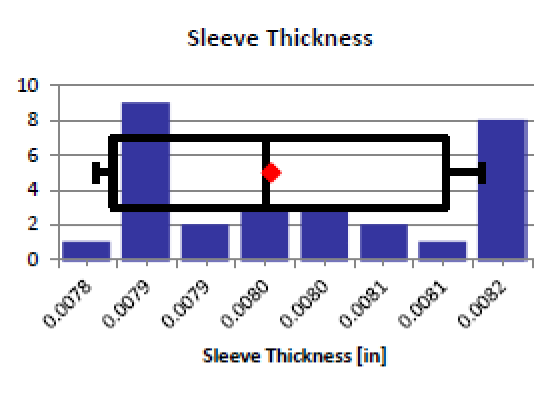
1. Carlson, S.S., “Quantifying the effect of a fatigue crack on the residual stress field induced by the split sleeve cold expansion process in 2024-T351 and 7075-T651 aluminum alloys,” Doctoral Dissertation, University of Utah, May 2018.
2. Babish, C., “ASIP Perspective on Accounting for Engineered Residual Stress in Damage Tolerance Analysis,” Proceedings of the Aircraft Structural Integrity Program Conference, Jacksonville, FL, November 2017.
3. Thomsen, M.L., “Incorporation of Residual Stresses into Aircraft Design and Sustainment: An ASIP Manager Perspective,” Proceedings of the Aircraft Structural Integrity Program Conference, Jacksonville, FL, November 2017.
4. Riha, D., McFarland, J., Thacker, B., Bichon, B., and Enright, M., “Short Course on Probabilistic Analysis and Uncertainty Quantification for Engineering Design – Methods and NESSUS® Training,” Southwest Research Institute, San Antonio, TX, September 2014.
5. Hill, M.R. and Olson, M.D., “Repeatability of the contour method for residual stress measurement,” Experimental Mechanics, Vol. 54, pgs. 1269-1277, 2014.
6. Olson, M.D., DeWald, A.T., Prime, M.B., Hill, M.R., “Estimation of Uncertainty for Contour Method Residual Stress Measurements,” Experimental Mechanics, 55, pgs. 577-585, 2014.
7. Hill Engineering, LLC., “Broad Application for Modeling Failure (BAMF) User’s Guide,” Release 5.0, Rancho Cordova, CA, January 2018.
8. Reyer, M., Millwater, H., Ocampo, J., Crosby, N., Gamble, B., Hurst, C., and Nuss, M., “Training using the SMART|DT software,” Proceedings of the Aircraft Airworthiness & Sustainment Conference, Grapevine, TX, March 2016.
9. Ocampo, J., Carlson, S., Smith, L., Millwater, H., and Crosby, N., “Incorporating residual stresses into Probabilistic Damage Tolerance Analysis,” Proceedings of the Aircraft Airworthiness & Sustainment Conference, Phoenix, AZ, May 2017.

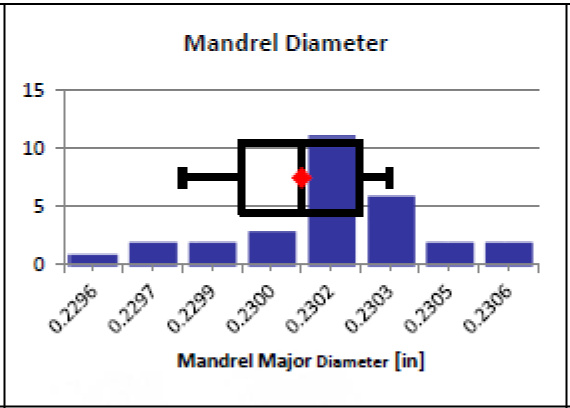
Preliminary FTI UQ Study

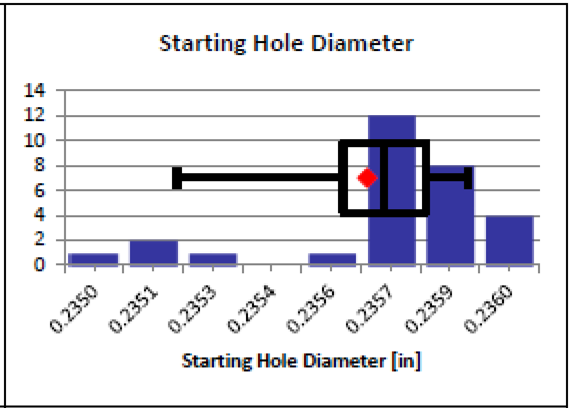
- FTI provided the committee access to stress results from their cold expansion process models
  - Hitchman and Zimmerman, “Development and Use of an FEA Script for Variance and Correlation Studies of Analytical Predictions of Cold Expansion Residual Stress Fields,” HOLSIP 2016.
- A total of 29 models with varying input parameters were provided (inputs on next slide)
- Stresses extracted from short ligament crack plane, after coldworking and reaming
- **Purpose of showing these preliminary results is to demonstrate available techniques, NOT necessarily to draw conclusions on RS process modeling**

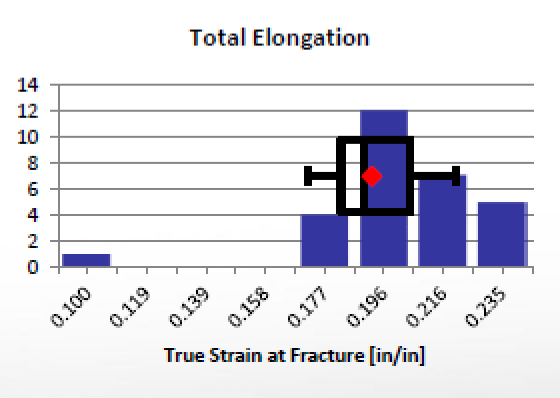


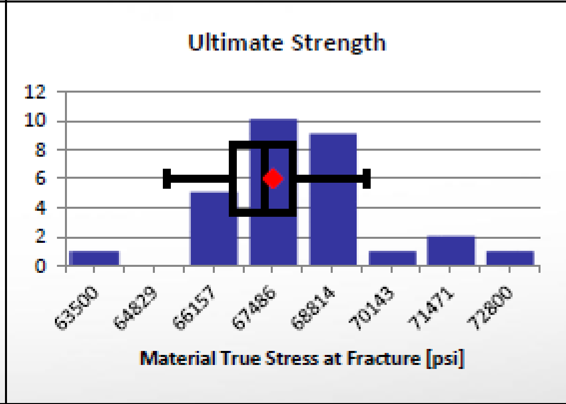
Step 3: Input distributions

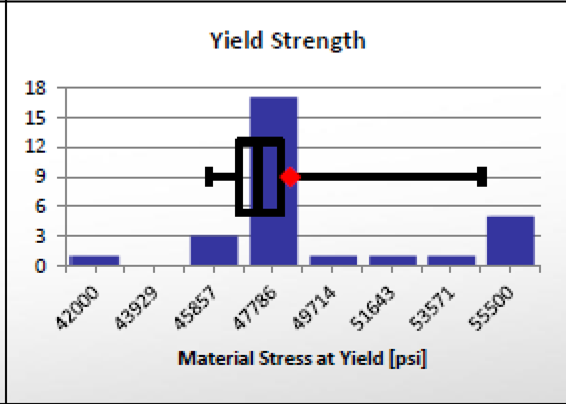


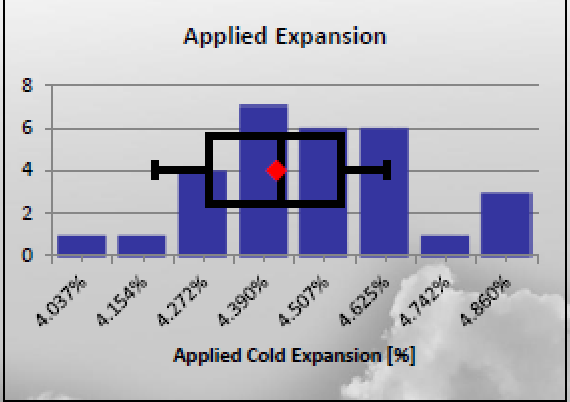












- Count Histogram

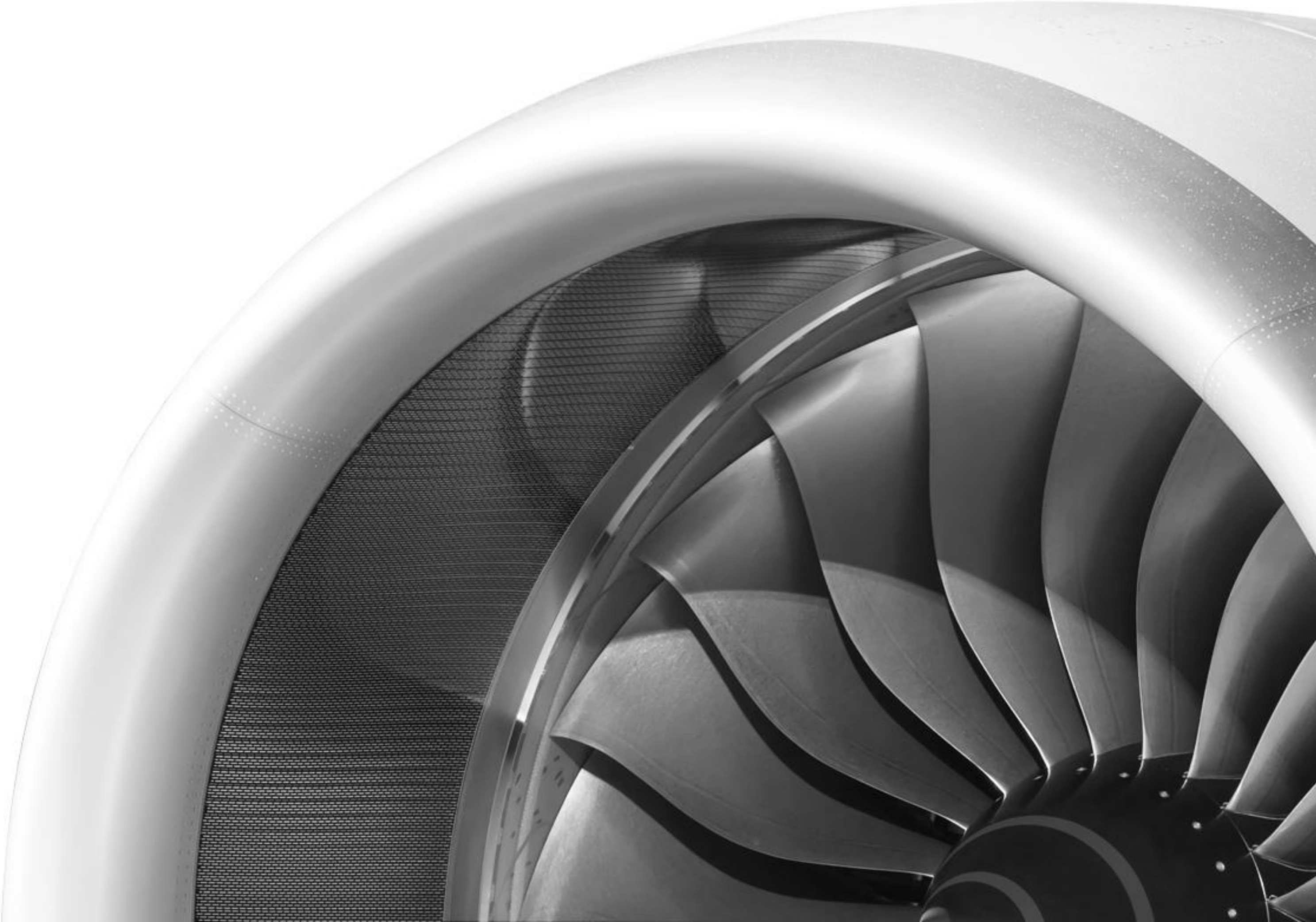
- Boxplot: 50% box span, whiskers 1 SD.

- Distribution Mean

NOTE: All but sleeve thickness based upon actual test or material certification data; sleeve thickness distribution was modeled as a normal distribution

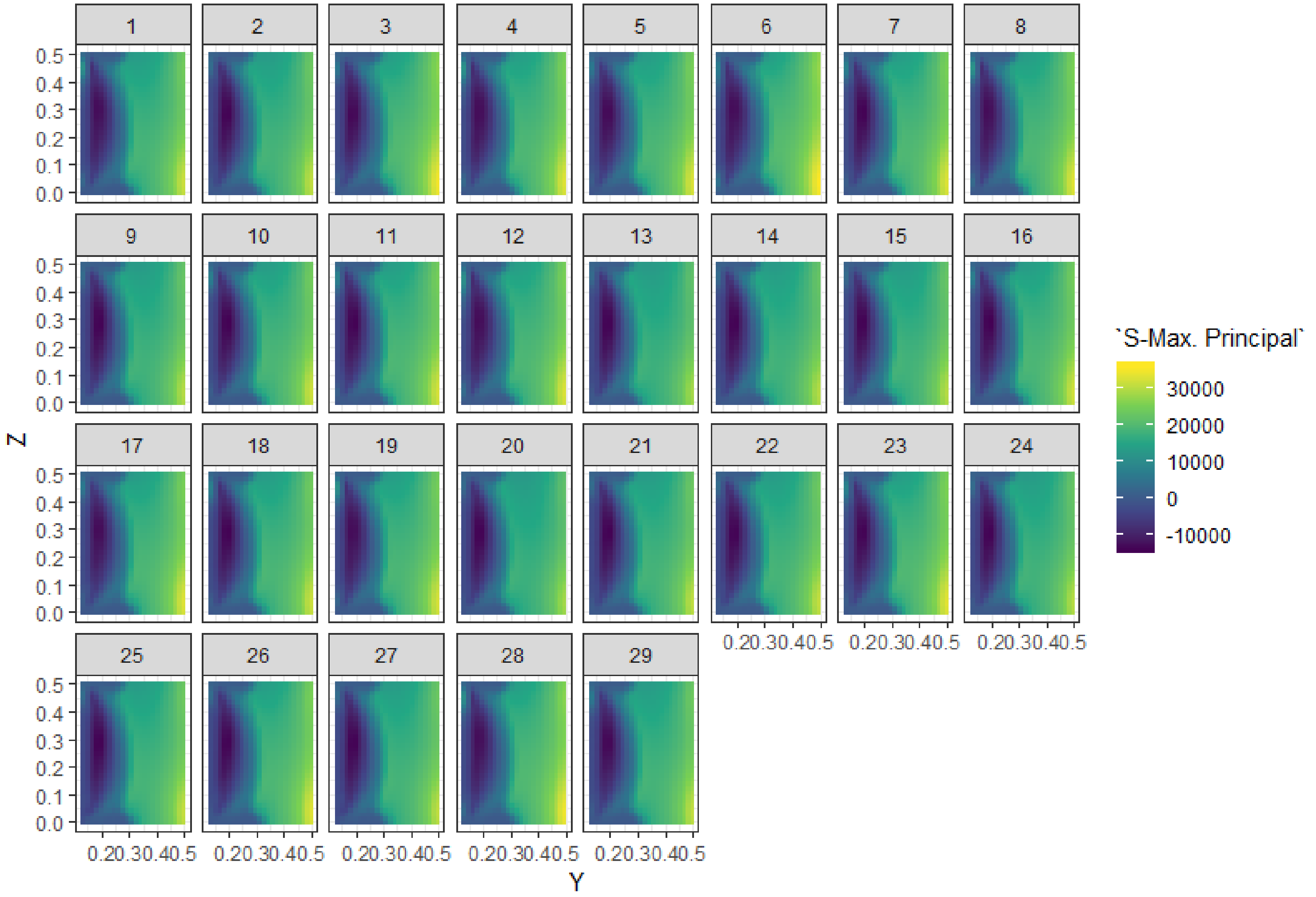
Ream Simulation EDA

Joe Yurko Arconic ATC

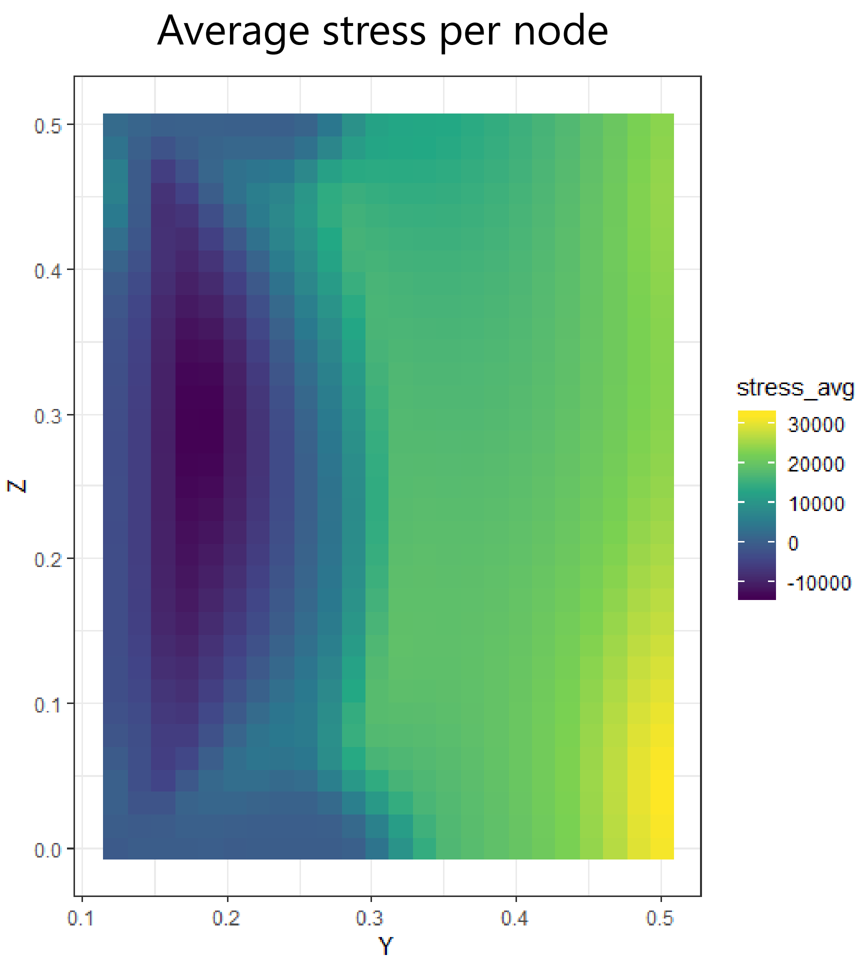


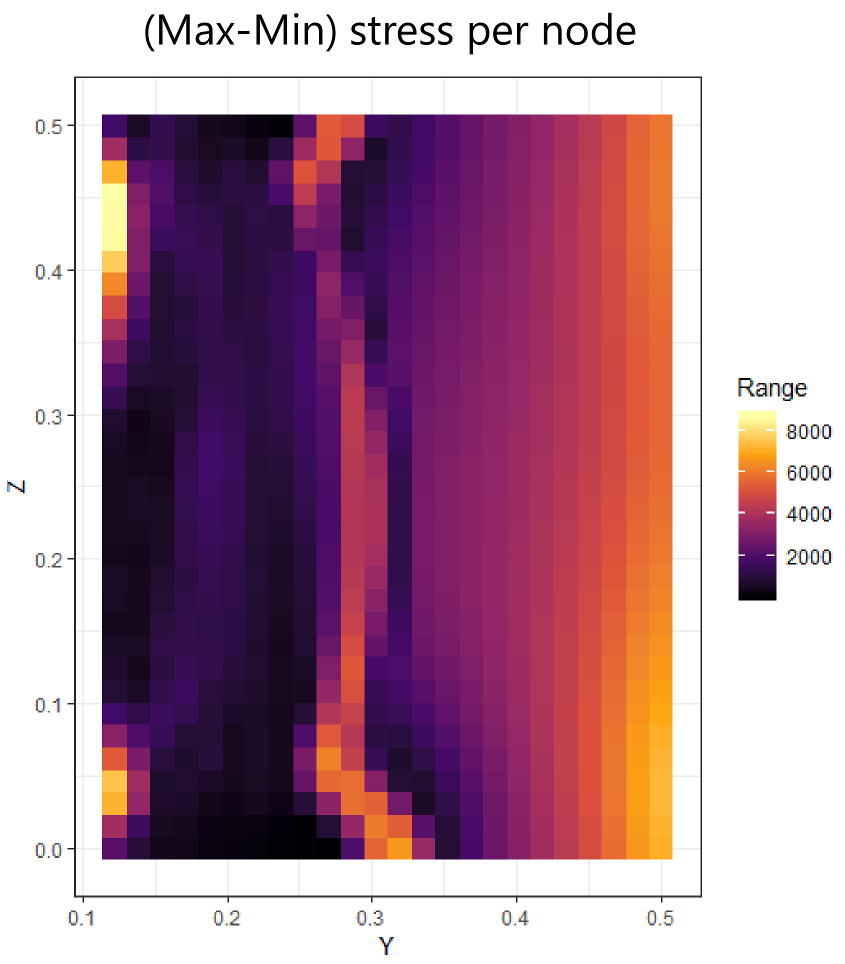
ARCONIC
Innovation, engineered.

Ream simulation results across all 29 runs

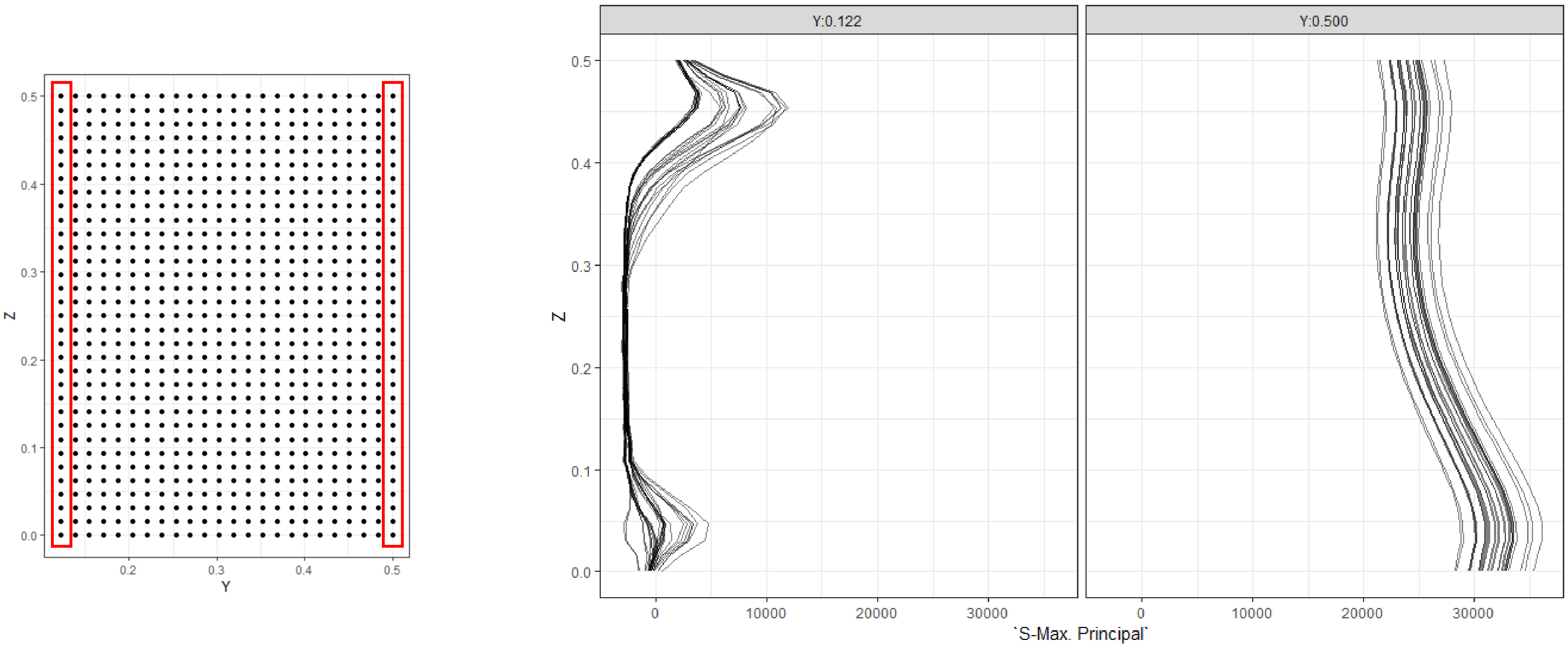


Summarize each stress at each node across the 29 runs

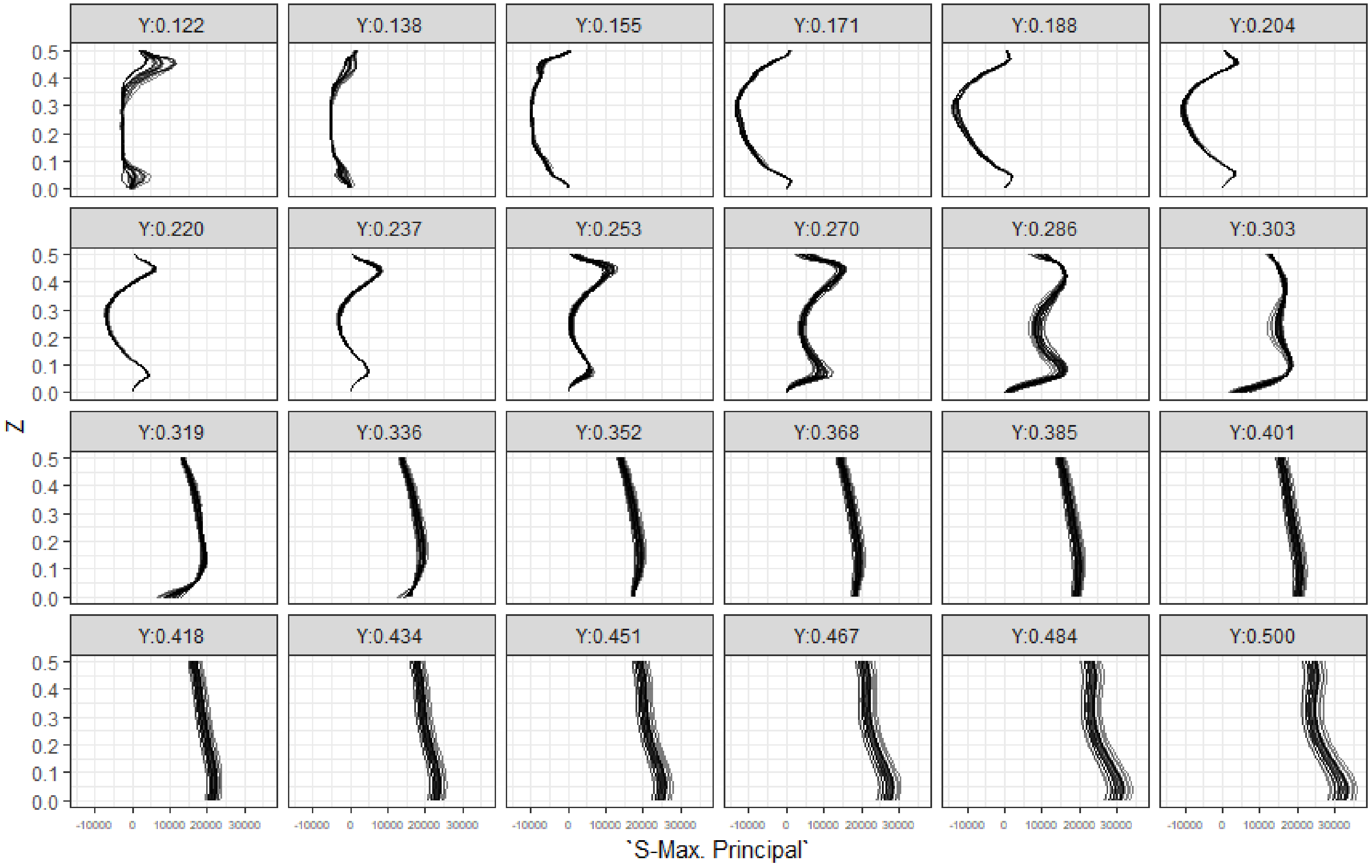




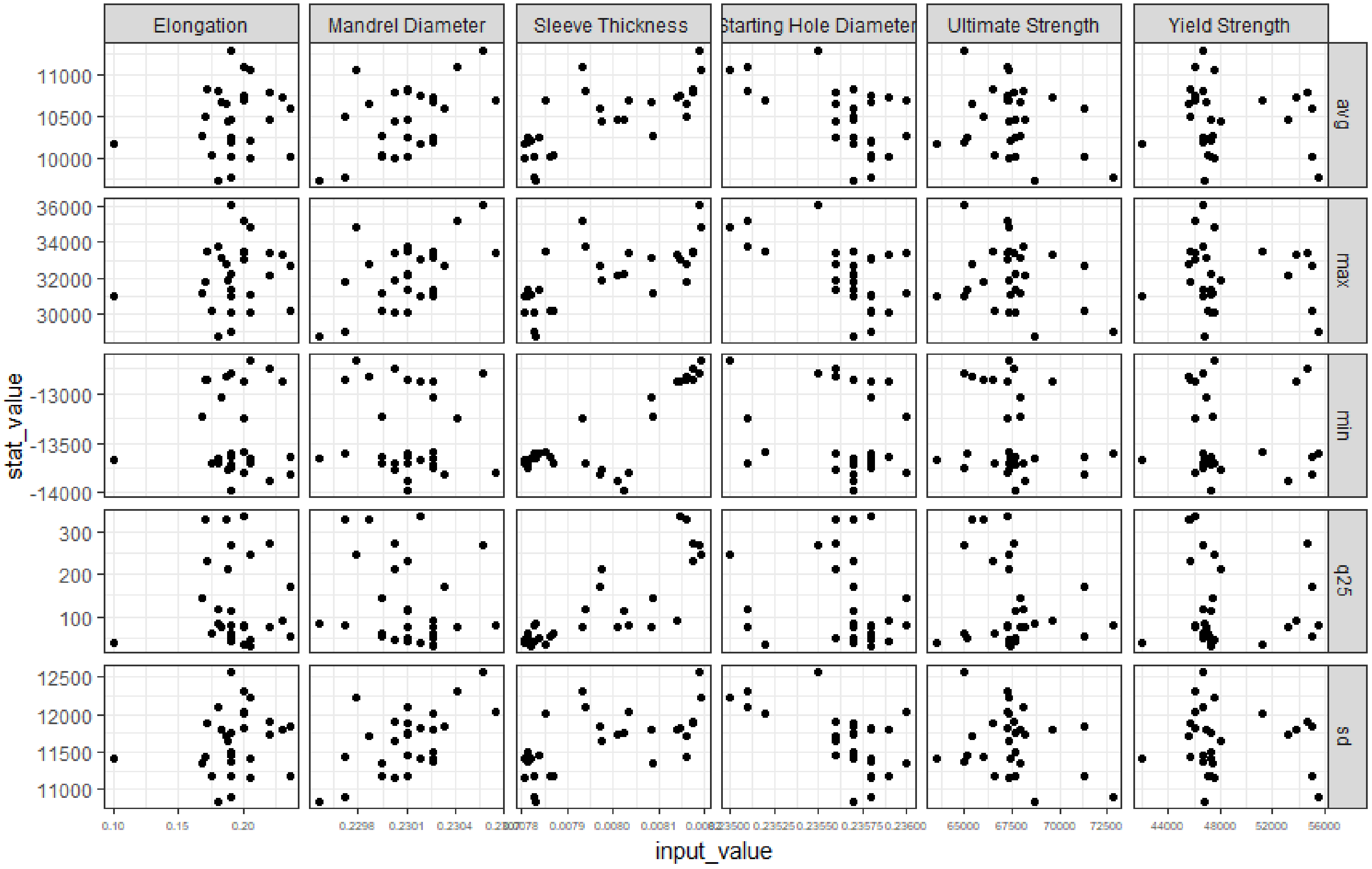
Line style plots for the `S-Max. Principal` wrt the z-direction at two y-locations, across all 29 runs



Line style plots at all y-locations across all runs

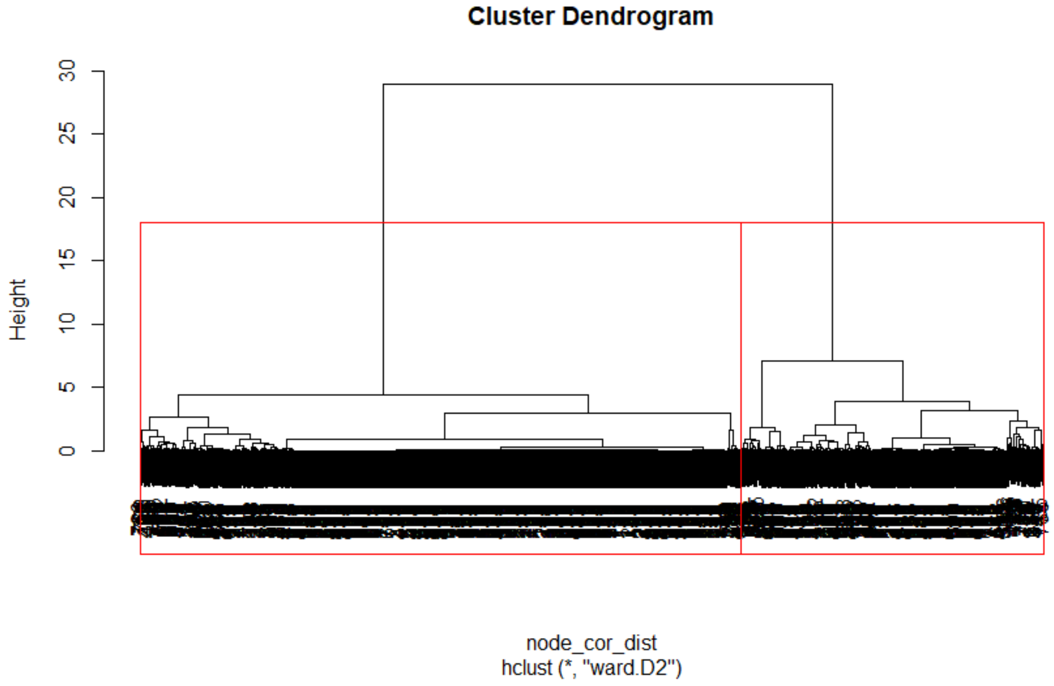


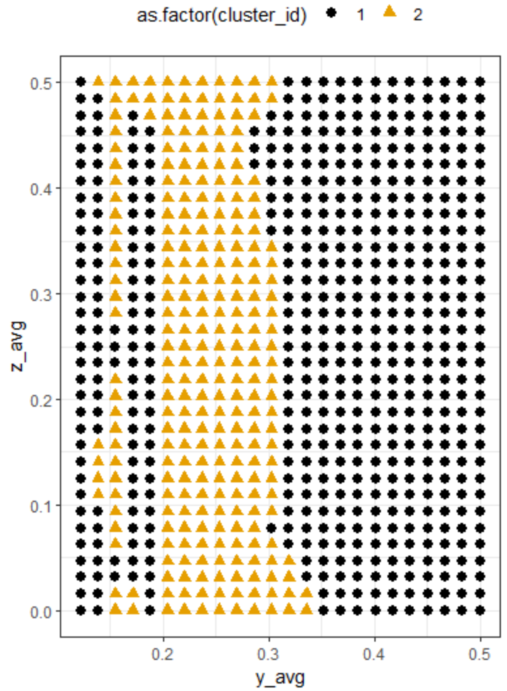
Scatter plots between the run summary stats and the inputs



Source/date last updated/contact person/mark as Confidential if appropriate Example: October QBR/October 12, 2016/John Smith/Confidential

Cluster nodes together based on their correlation





FTI Preliminary Data Analysis

ERSI Risk and UQ Subcommittee Teleconference
July 25, 2019

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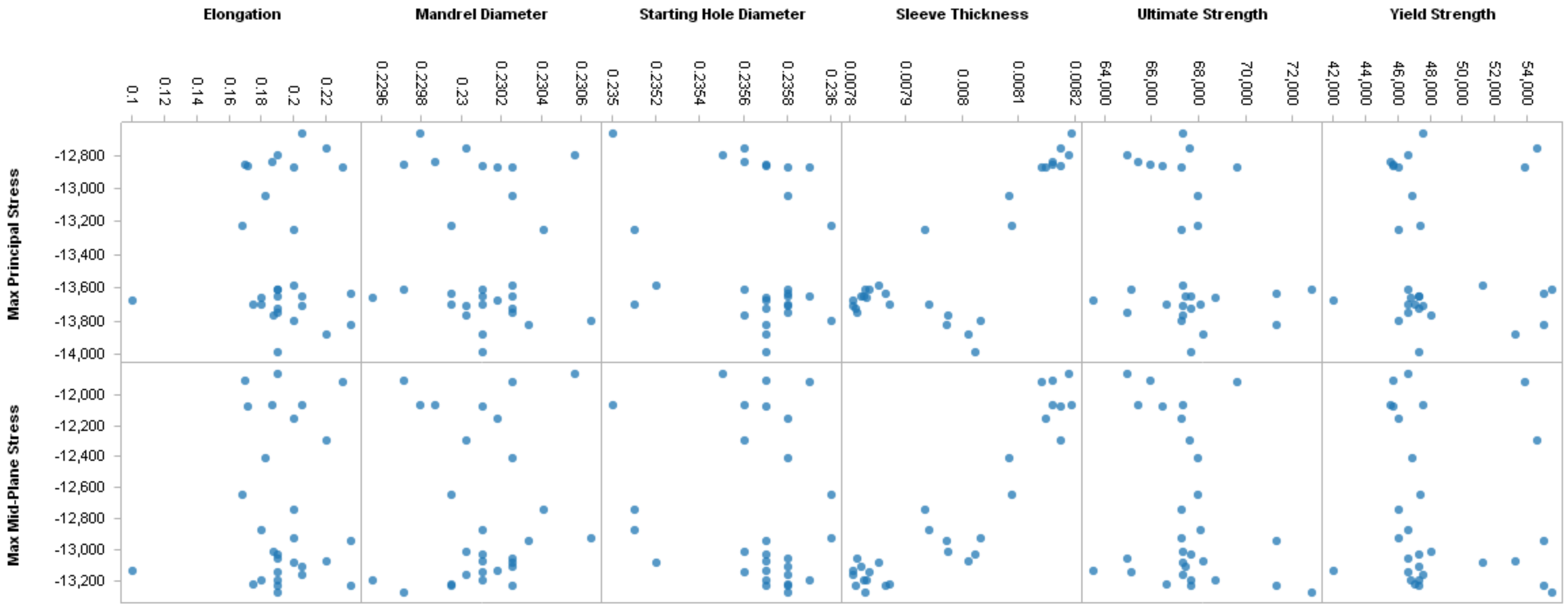
Data Preprocessing

- Python script to extract
  - Most negative stress value from each of the 29 Ream files, i.e. largest max compressive stress
  - Most negative stress value at thickness = 0.25 coordinate for max mid-plane stress
- Data looks very uncorrelated except for sleeve thickness

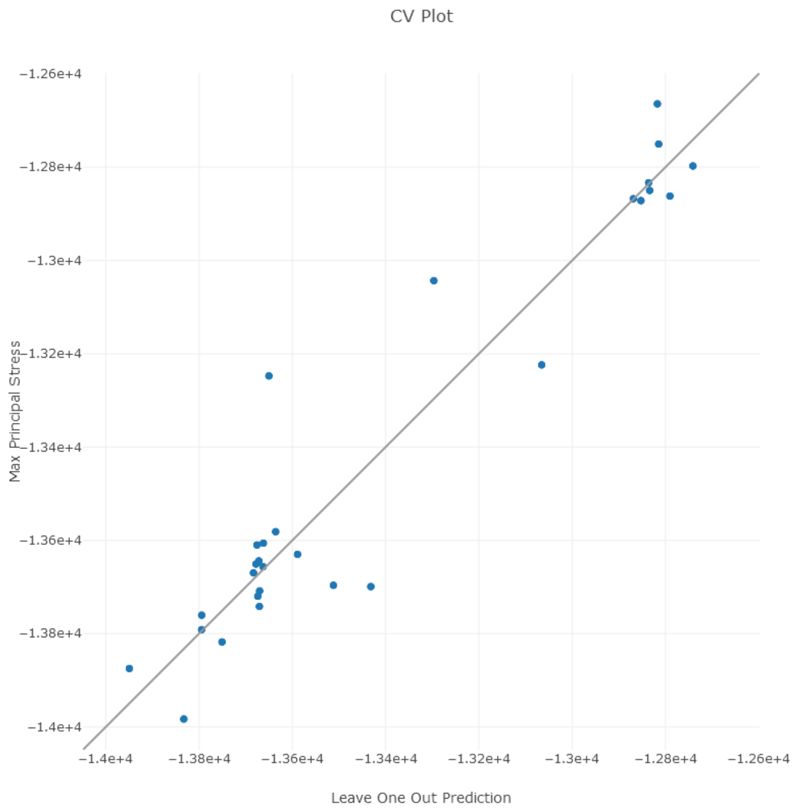


Initial Model Fitting

- Built Gaussian Process (GP) Surrogate Model for Maximum Principal Stress and Maximum Midplane Stress using all 29 data points (Ream Data)
- Built linear regression model for comparison

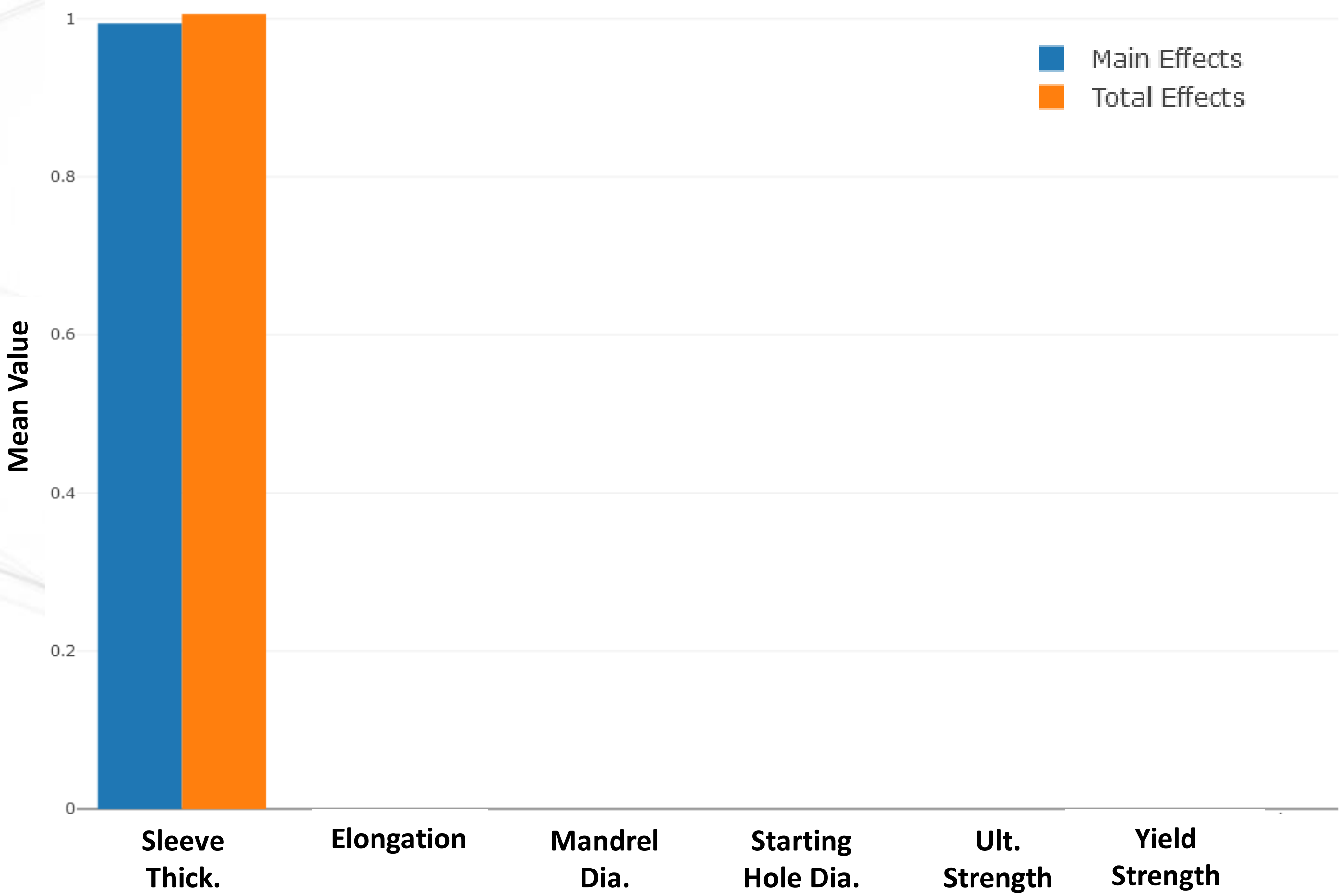
	Std CV (GP Model)	R^2 Equivalent	Linear Model R^2
Max Principal Stress	0.2968	0.9119	0.6887
Max Mid Plane Stress	0.2712	0.9265	0.8638

Maximum Principal Stress



Sensitivity Analysis

- Used GP Emulator for Global Sensitivity Analysis
- Sensitivity analysis shows response is completely dependent on sleeve thickness

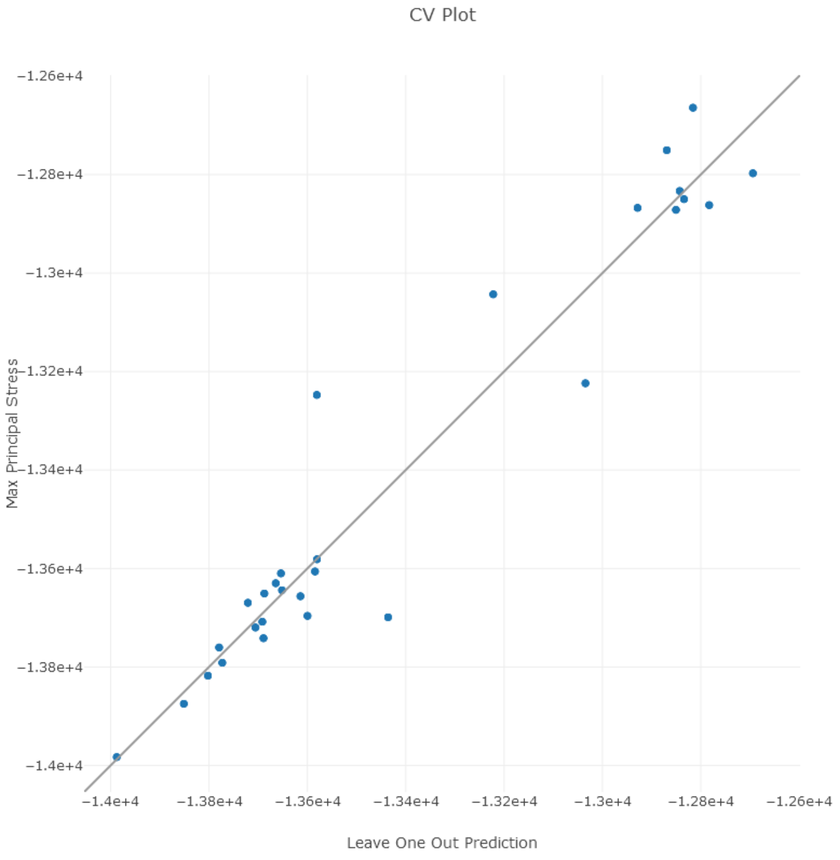


Reduced Input Set Model Fitting

- Rebuilt GP Surrogate Model only using the sleeve thickness input.
- Tried other input combinations, based on assumed correlations, e.g. yield and ultimate strength being correlated, but could not achieve better results.

	Std CV (GP Model)	R^2 Equivalent	Linear Model R^2
Max Principal Stress (All Inputs)	0.2968	0.9119	0.6887
Max Mid Plane Stress (All Inputs)	0.2712	0.9265	0.8638
Max Principal Stress (Sleeve Thickness Only)	0.2543	0.9353	0.6420
Max Mid Plane Stress (Sleeve Thickness Only)	0.2704	0.9269	0.8425

Maximum Principal Stress

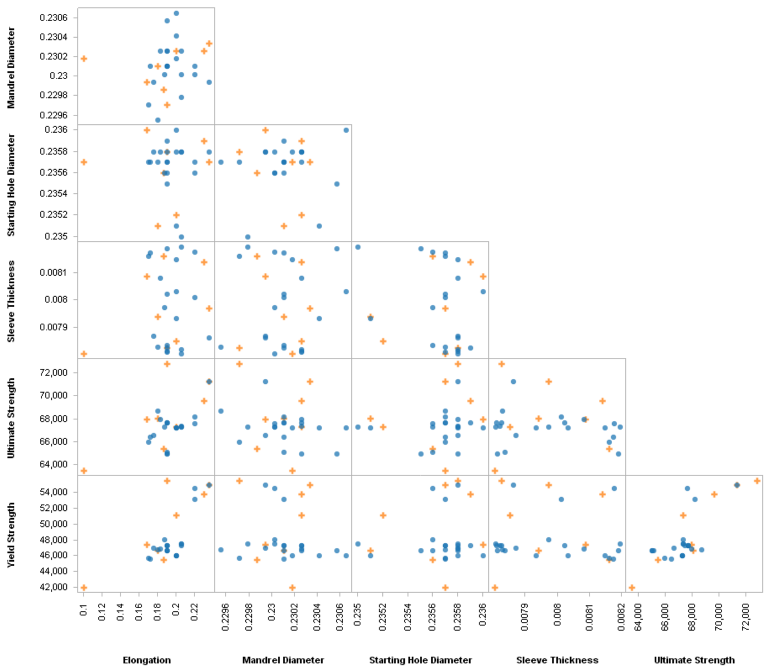


Model Validation

- Subsampled 8 points from original 29 to use as validation set via 2 separate methods
- Built GP emulators with remaining 21 points
- Results seem promising in suggesting an accurate GP model could be trained given more (and better space-filling) data. Making further conclusions or comparisons between Std CV and Std RMSE results is risky as the datasets are small and standard deviations will vary.

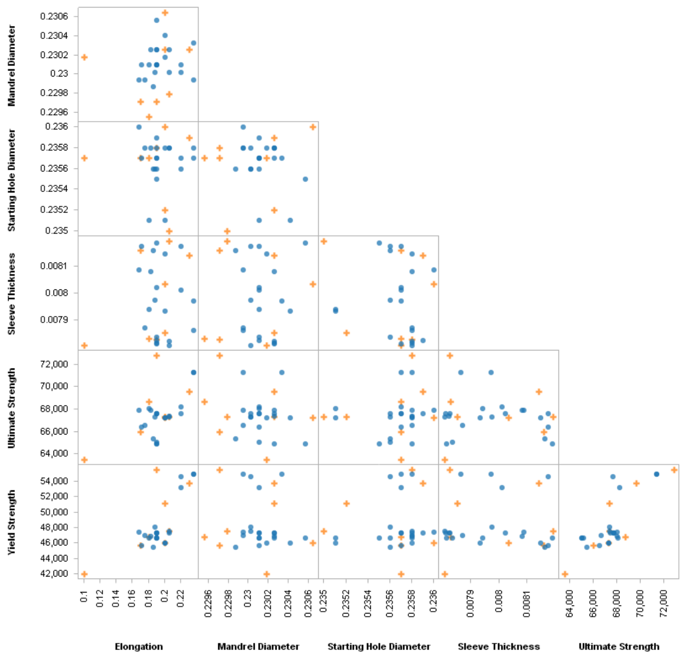
Subsample Method 1

	Std CV	Std CV Equivalent R^2	Std RMSE (Validation Set)	Std RMSE Equivalent R^2 (Validation Set)
Max Principal Stress (All Inputs)	0.4810	0.7687	0.4376	0.8085
Max Mid Plane Stress (All Inputs)	0.3193	0.8981	0.5562	0.6910
Max Principal Stress (Sleeve Thickness Only)	0.2402	0.9423	0.4324	0.8130
Max Mid Plane Stress (Sleeve Thickness Only)	0.2793	0.9220	0.2580	0.9334



Subsample Method 2

	Std CV	Std CV Equivalent R^2	Std RMSE (Validation Set)	Std RMSE Equivalent R^2 (Validation Set)
Max Principal Stress (All Inputs)	0.5244	0.7250	0.3272	0.8930
Max Mid Plane Stress (All Inputs)	0.2839	0.9194	0.3479	0.8790
Max Principal Stress (Sleeve Thickness Only)	0.3297	0.8913	0.1533	0.9765
Max Mid Plane Stress (Sleeve Thickness Only)	0.3282	0.8923	0.2120	0.9516



Set

- Training
- Validation

Questions?