# ERSI RISK AND UQ SUBCOMMITTEE ACTIVITIES

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# Outline

- Risk and UQ Subcommittee Overview
- Short Presentations of Current Activities
  - "**Probability of Cold Expansion (POCx) Variable**," Laura Hunt, SwRI
  - "**Some Observations on the Significance of Residual Stress Variability on Fatigue Crack Growth Life**," Craig McClung, SwRI
  - "**Residual Stress Sensitivity Analysis in Probabilistic DTA**," Juan Ocampo, St. Mary's U

# Committee Overview

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

# 2018 Workshop

- In the past year, the state of the art for UQ and sensitivity analysis methods were investigated
  - NASA UQ Challenge – 2014 AIAA SciTech Conference
  - Spatial statistics
  - Variance-based and local sensitivity analysis methods
  - What methods are useful for the group going forward?

- **We're here to help**
  - Our subcommittee doesn't generate data
  - We received one RS data set in the past year

# “PROBABILITY OF COLD EXPANSION” VARIABLE

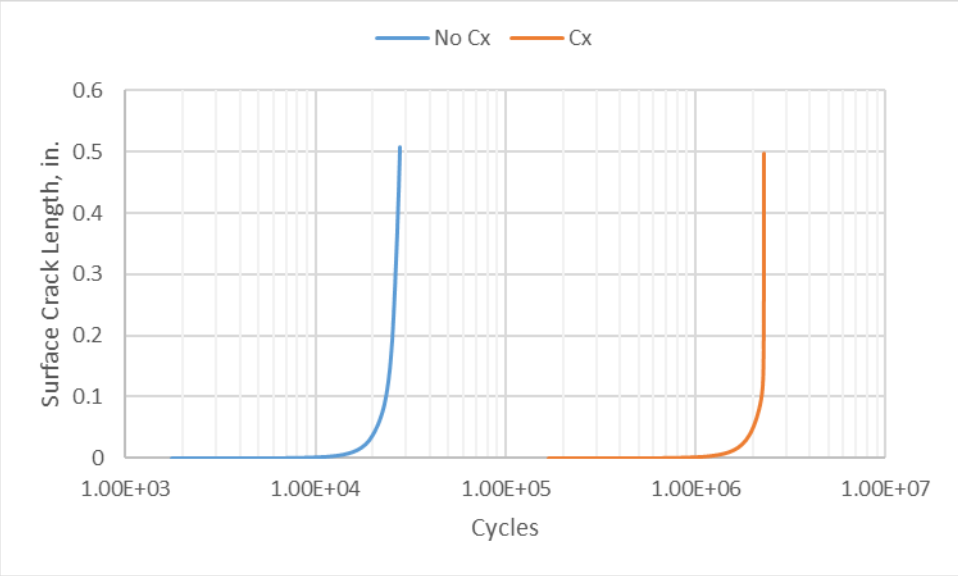
A-10 ASIP and Southwest Research Institute

# POCx

- **How can we incorporate cold expansion into a PROF-type risk analysis?**
- A-10 ASIP suggested a Probability of Cold expansion (POCx) variable that acts similarly to the Probability of Inspection (POI) variable that is currently in PROF
- POCx is a singular value that represents the probability that a hole was cold-worked correctly
  - "Correctly" is a loaded term
- **This is not a final methodology, but rather a very simplified way to incorporate coldworking into current methods**

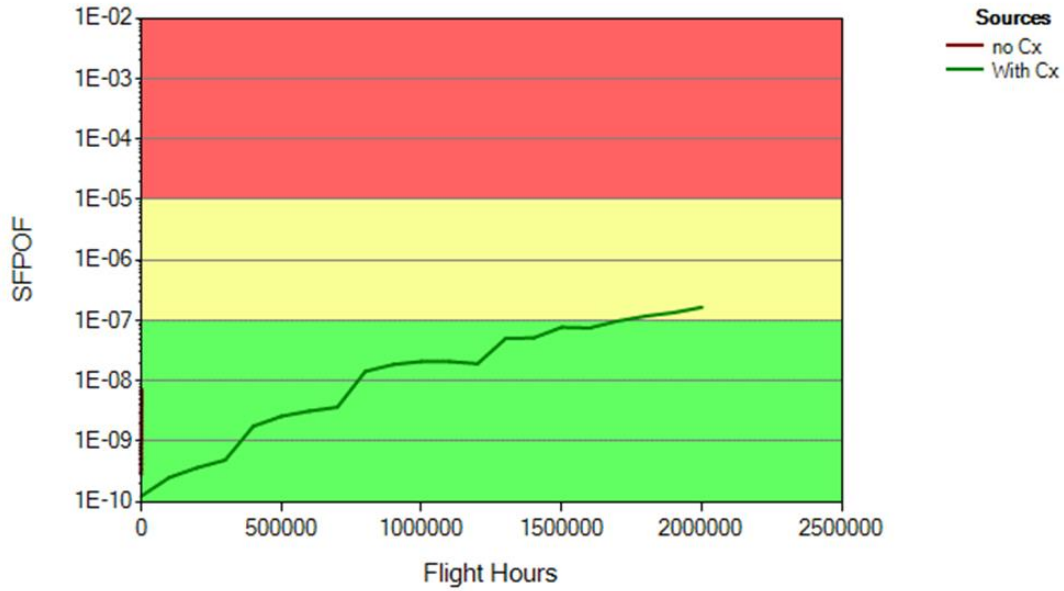
# Crack Growth Life Curves

- Results from the ERSI round-robin were used as an input for the cold expanded hole case
  - Benchmark 2, 25 ksi stress
- Residual stresses were removed from the AFGROW input to create results for a theoretical non-coldworked hole case



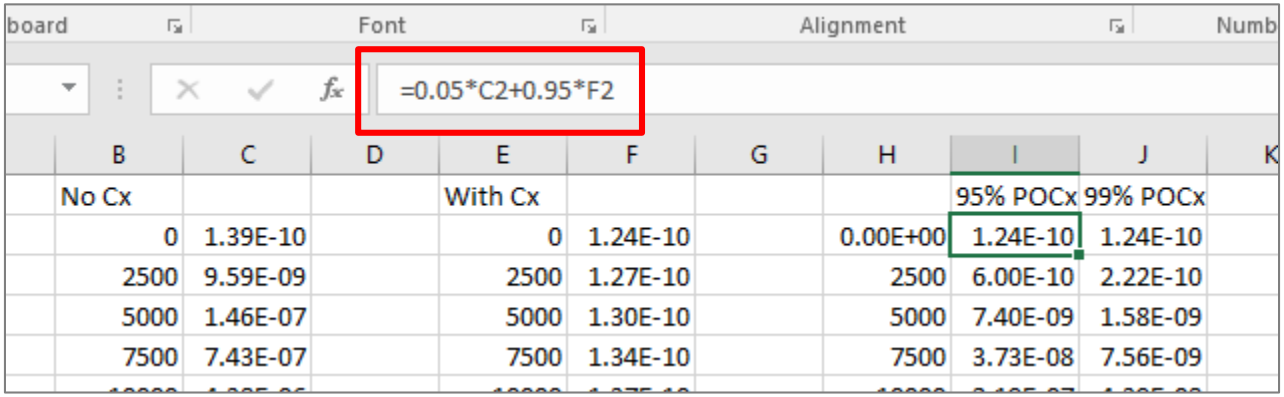
# PROF Results

- Separate PROF analyses were run for the Cx and non-Cx cases



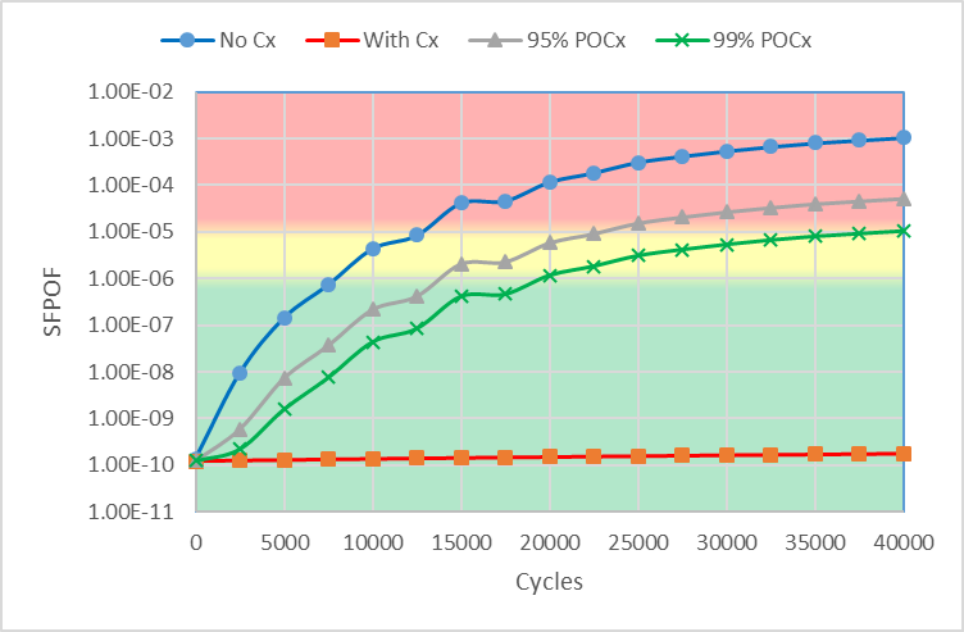
# Incorporating POCx

- The SFPOF results for both analyses were imported into Excel
- 95% and 99% POCx were incorporated by the formula below




| | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|
| | No Cx | | | With Cx | | | | 95% POCx | 99% POCx | |
| | 0 | 1.39E-10 | | 0 | 1.24E-10 | | 0.00E+00 | 1.24E-10 | 1.24E-10 | |
| | 2500 | 9.59E-09 | | 2500 | 1.27E-10 | | 2500 | 6.00E-10 | 2.22E-10 | |
| | 5000 | 1.46E-07 | | 5000 | 1.30E-10 | | 5000 | 7.40E-09 | 1.58E-09 | |
| | 7500 | 7.43E-07 | | 7500 | 1.34E-10 | | 7500 | 3.73E-08 | 7.56E-09 | |

# POCx Risk Results




- POCx is a simple knockdown factor to incorporate residual stresses
  - Danger of becoming a "thumb-in-the-air" variable
- UQ is required to actually quantify this variable

# Residual Stresses Sensitivity Analysis in Probabilistic Damage Tolerance Analysis

Juan D. Ocampo and Alexander Horwath

St. Mary's University

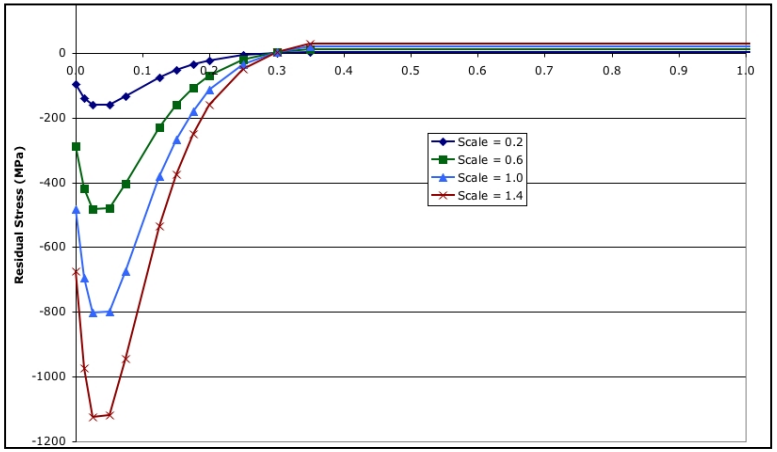
Luciano Smith and Laura Domyancic

Southwest Research Institute

Engineered Residual Stress Implementation Workshop 2018
Salt Lake City, UT, September 13–14, 2018.

# Outline

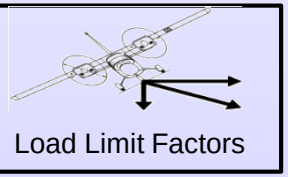
- ✓ SMART|DT AND Residual Stresses
- ✓ Residual Stresses Modeling Software (Update)
- ✓ Residual Stresses and Inspections
- ✓ Sensitivity Analysis
- ✓ Future Plans & Group Suggestions



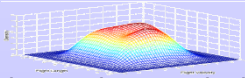
Smart | DT UTSA

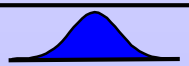
## Loading Data

### Internally Generated Loading

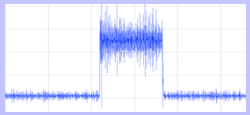

Load Limit Factors

Exceedance Curves

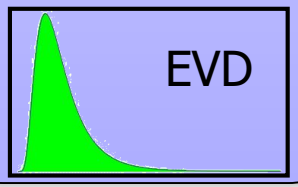

Flt Duration & Velocity Weight Matrix


Sink Rate

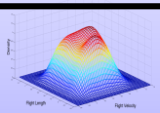
### User Loading


User Spectrum

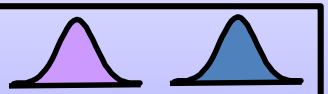
SMF


EVD

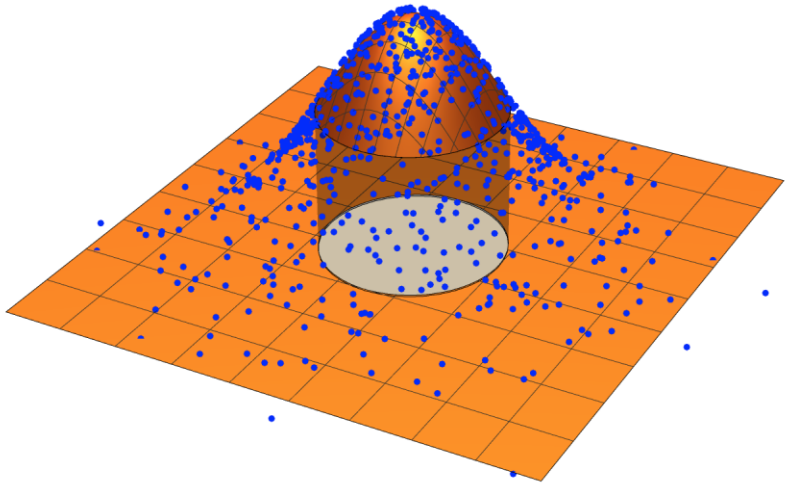
## Material Data


da/dN

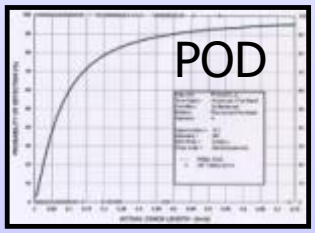
Fracture Toughness

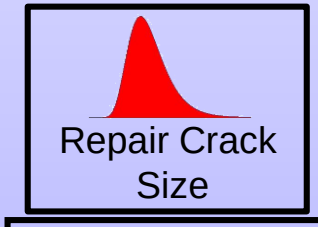

Yield and Ultimate Stress

## Monte Carlo Sampling



## Inspection Data





Repair Crack Size

Repair Scenarios

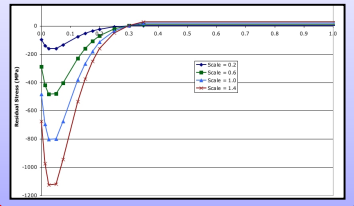
Inspection times

Prob. of Inspecting

## Fracture Models

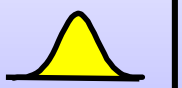
AFGROW

SMART-CG

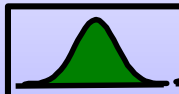


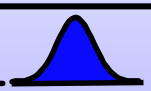
## Initial Crack Size

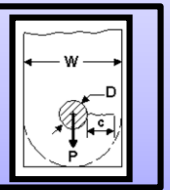
## Crack Aspect Ratio



## Geometry Data

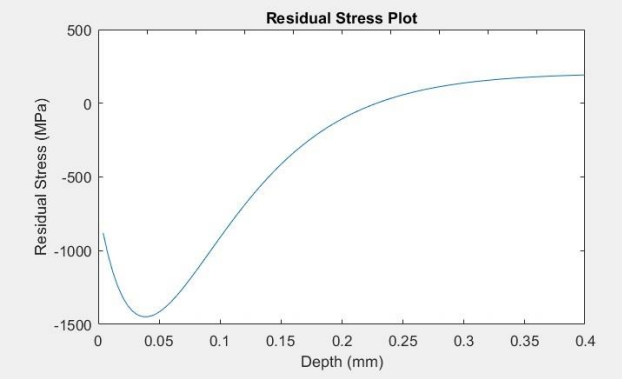

Hole Dia.


Hole Offset

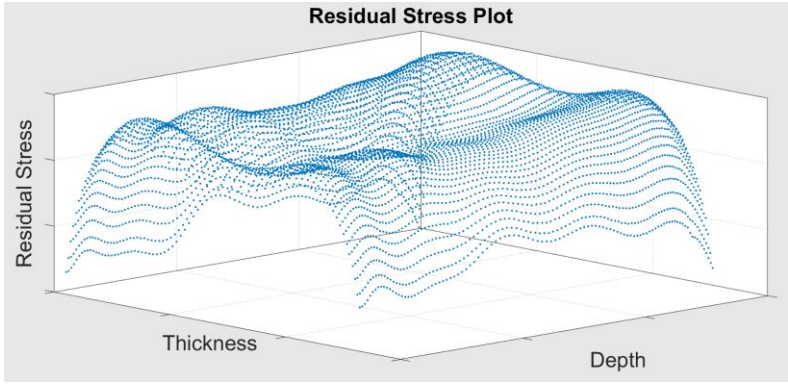


# Residual Stress Modeling Software

- Standalone executable to read experimental/ simulated data and find the best deterministic and probabilistic fit parameters.
  - 2 Models Available (Expandable)
  - 2D (Stress vs Depth) and 3D (Stress vs Depth vs Thickness).
  - Read input data in .txt & .csv format




2D




3D

# Models

- Model I*

$$\sigma(x) = (ss - si + C_1 x)Exp(-C_2 x) + si$$

$$C_1 = \frac{\{(ss - si)(1 - Exp(-C_2 B)) + siBC_2\}C_2}{(C_2 B + 1)Exp(-C_2 B) - 1}$$

- Model II**

$$\sigma(x) = Asin(Bx + C)Exp\left(-\frac{x}{\lambda}\right)$$

* *User Manual for ZENCRACK™ 7.1*, Zentech International Ltd., Camberley, Surrey, UK, September, 2003.

** R. VanStone, "F101-GE-102 B-1B Update to Engine Structural Durability and Damage Tolerance Analysis Final Report (ENSIP), Vol. 2," General Electric, p. 5-2-2.

# Single Profile Model I & II

IN100ResidualStressProfilesGUI

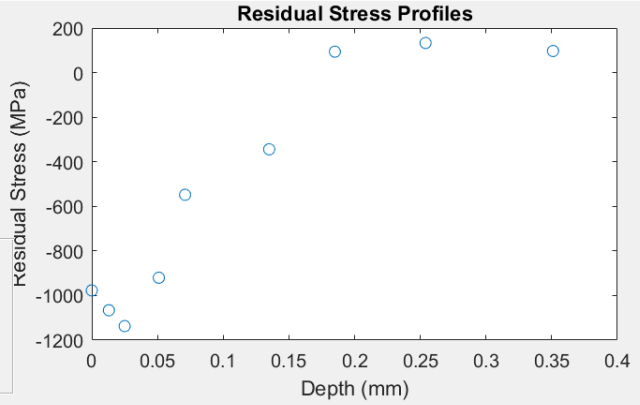
all
RS1.csv
RS2.csv
RS3.csv
RS4.csv
RS5.csv
RS6.csv

Profile Type
Single Profile
Multiple Profile

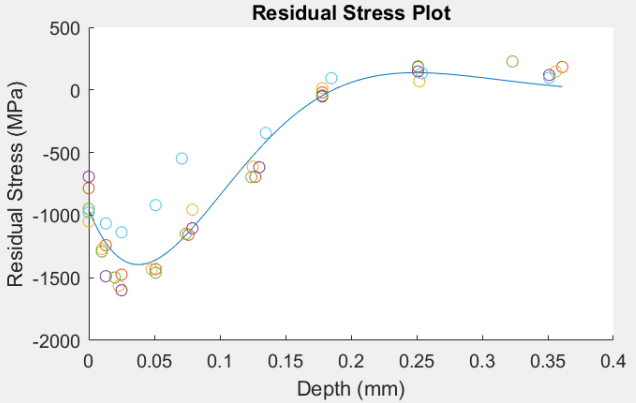
Options
Model 2
Width

Run

A 2621.44
B 14.8527
C -2.76741
lambda 0.0914038




< 0.0 >



# Mult. Profile Model I

IN100ResidualStressProfilesGUI

Listbox

Profile Type

Single Profile

Multiple Profile

Options

Model 1

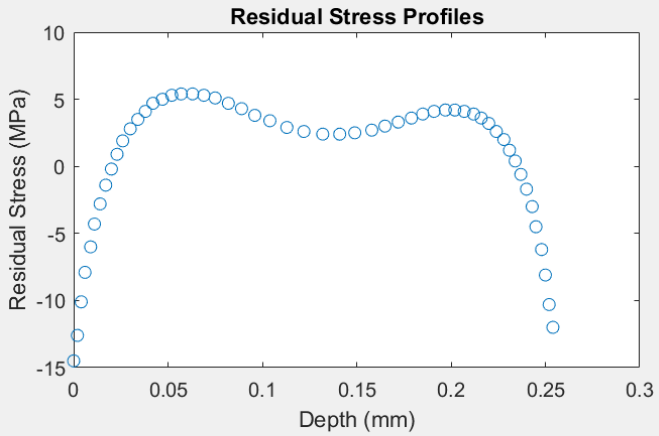
Width

Run

SS -13.6089

SI -0.696984

C1 23.7289

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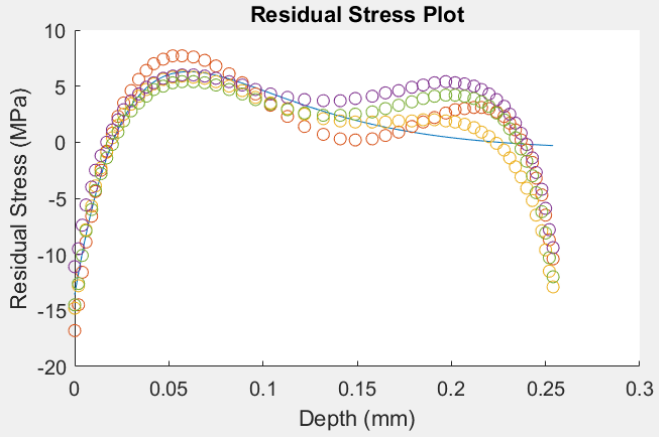


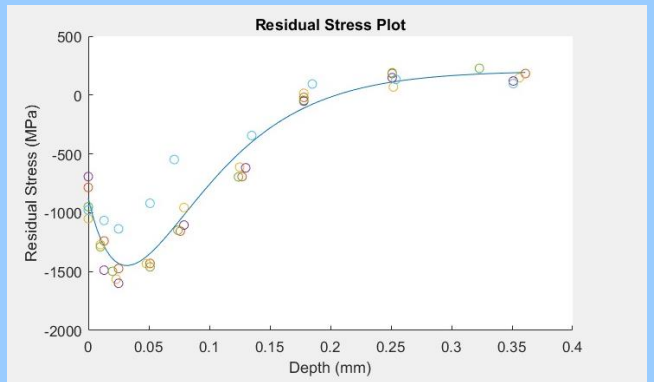
# Input/Output

A2-1_stress.txt - Notepad

File Edit Format View Help

| | | | |
|---|---|---|---|
| -1.928 | 0.254 | 0.000 | -10.4 |
| -1.928 | 0.000 | 0.000 | -16.8 |
| -1.928 | 0.252 | 0.000 | -8.7 |
| -1.928 | 0.250 | 0.000 | -6.5 |
| -1.928 | 0.248 | 0.000 | -4.7 |
| -1.928 | 0.245 | 0.000 | -3.2 |
| -1.928 | 0.243 | 0.000 | -1.8 |
| -1.928 | 0.240 | 0.000 | -0.7 |
| -1.928 | 0.237 | 0.000 | 0.2 |
| -1.928 | 0.234 | 0.000 | 1.1 |
| -1.928 | 0.231 | 0.000 | 1.7 |
| -1.928 | 0.228 | 0.000 | 2.3 |
| -1.928 | 0.224 | 0.000 | 2.7 |
| -1.928 | 0.220 | 0.000 | 3.0 |
| -1.928 | 0.216 | 0.000 | 3.1 |
| -1.928 | 0.212 | 0.000 | 3.1 |
| -1.928 | 0.207 | 0.000 | 3.0 |
| -1.928 | 0.202 | 0.000 | 2.9 |

RS Mod




Mean and Standard Deviation Parameters

| | Mean | St dev |
|---|---|---|
| ss | -879.16 | 58.58 |
| si | 205.68 | 9.448 |
| c2 | 20.872 | 1.050 |

Correlation Parameters

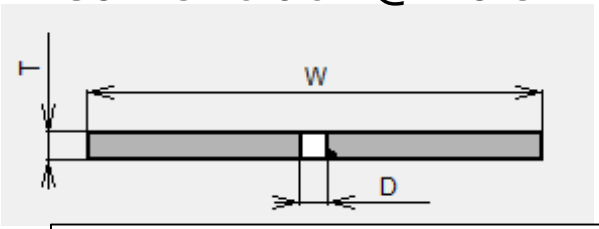
| | ss | si | c2 |
|---|---|---|---|
| ss | 1 | -0.214 | 0.402 |
| si | -0.214 | 1 | -0.796 |
| c2 | 0.402 | -0.796 | 1 |

ERSI

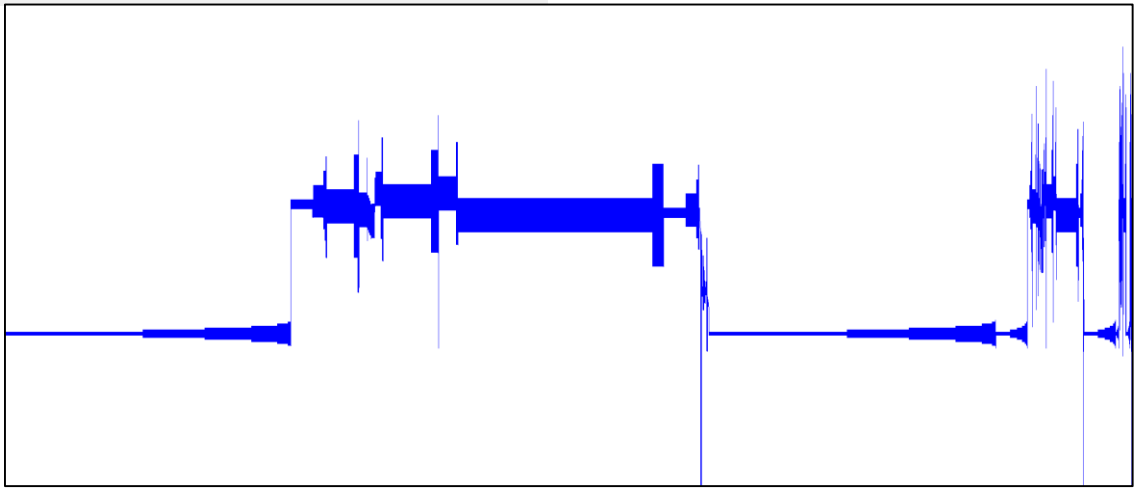
# Academic Example Problem

# Input Parameters

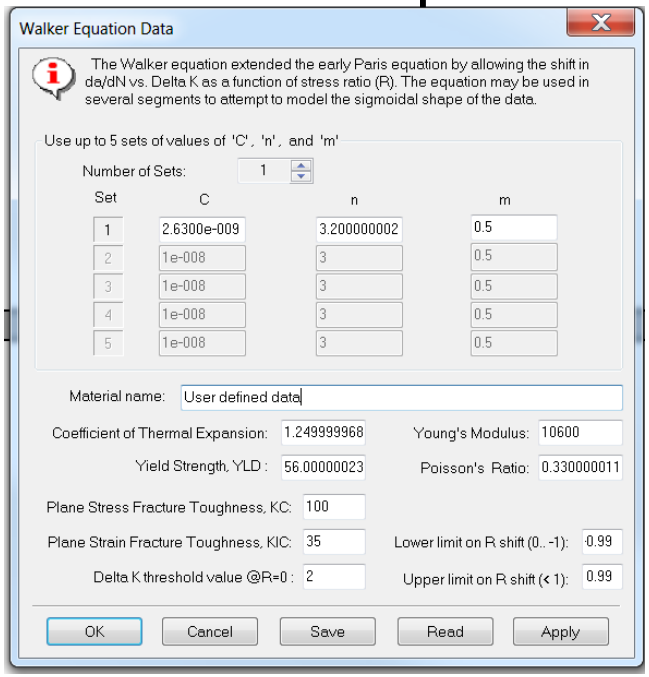
## Corner crack @ hole




| Parameter | Value |
|---|---|
| T | 0.09 in |
| W | 4.0 in |
| D | 0.25 in |



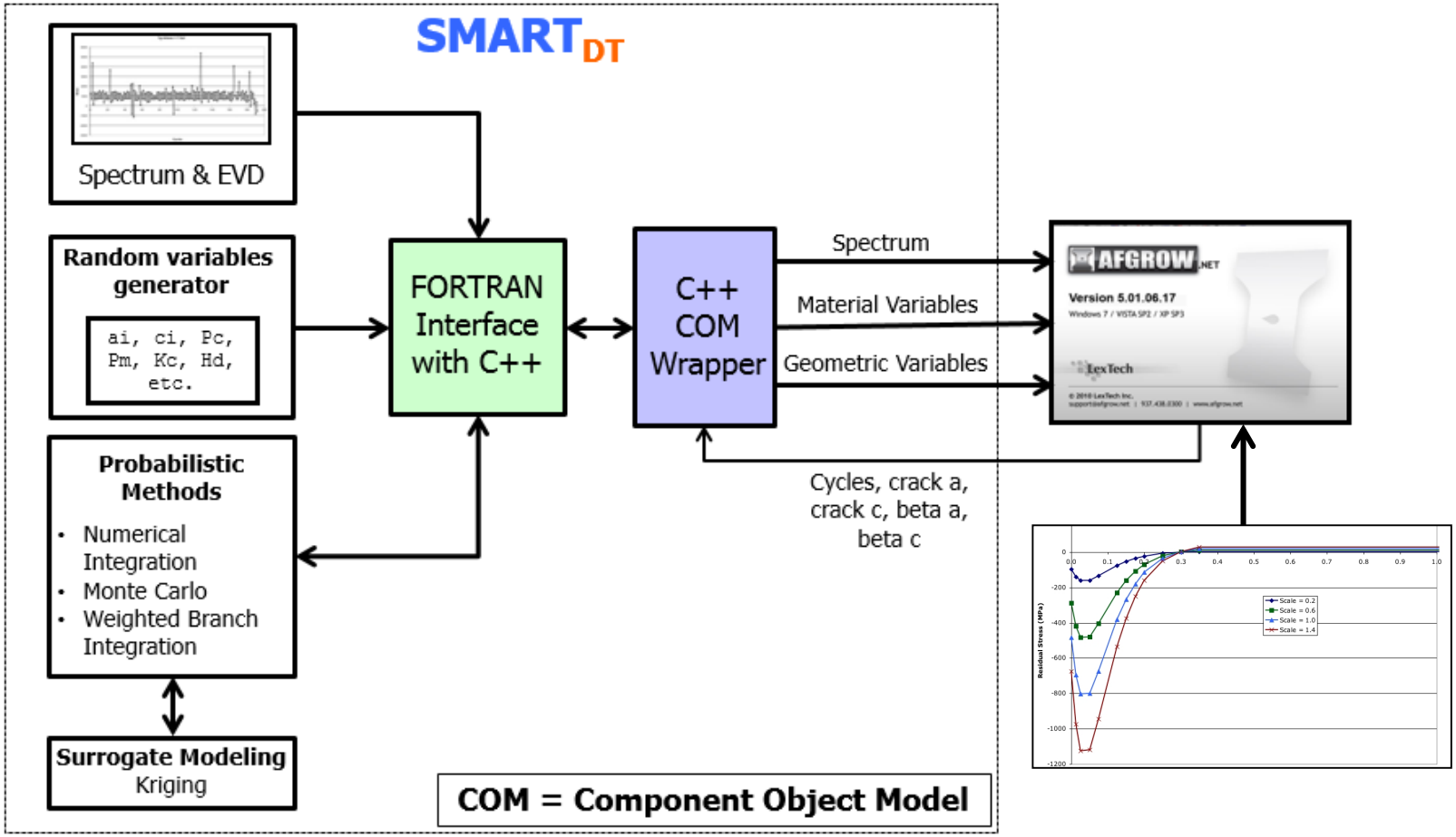
## Mat. Prop.




| Random Variables | Value |
|---|---|
| Fracture Toughness Distribution (Normal) | Mean = 34.5ksi√in, Standard Deviation = 3.8 ksi√in. |
| Initial & Repair Lognormal Size Distribution (a & c) (Lognormal) | Mean = 0.01 in, Standard Deviation = 0.001 in. |
| Extreme Value Distribution (Gumbel) | Location = 14.5, Scale = 0.8, and Shape = 0.0 |
| Inspections (5,000 & 10,000) | POD Lognormal<br>Mean = 0.07in, Standard Deviation = 0.06 |

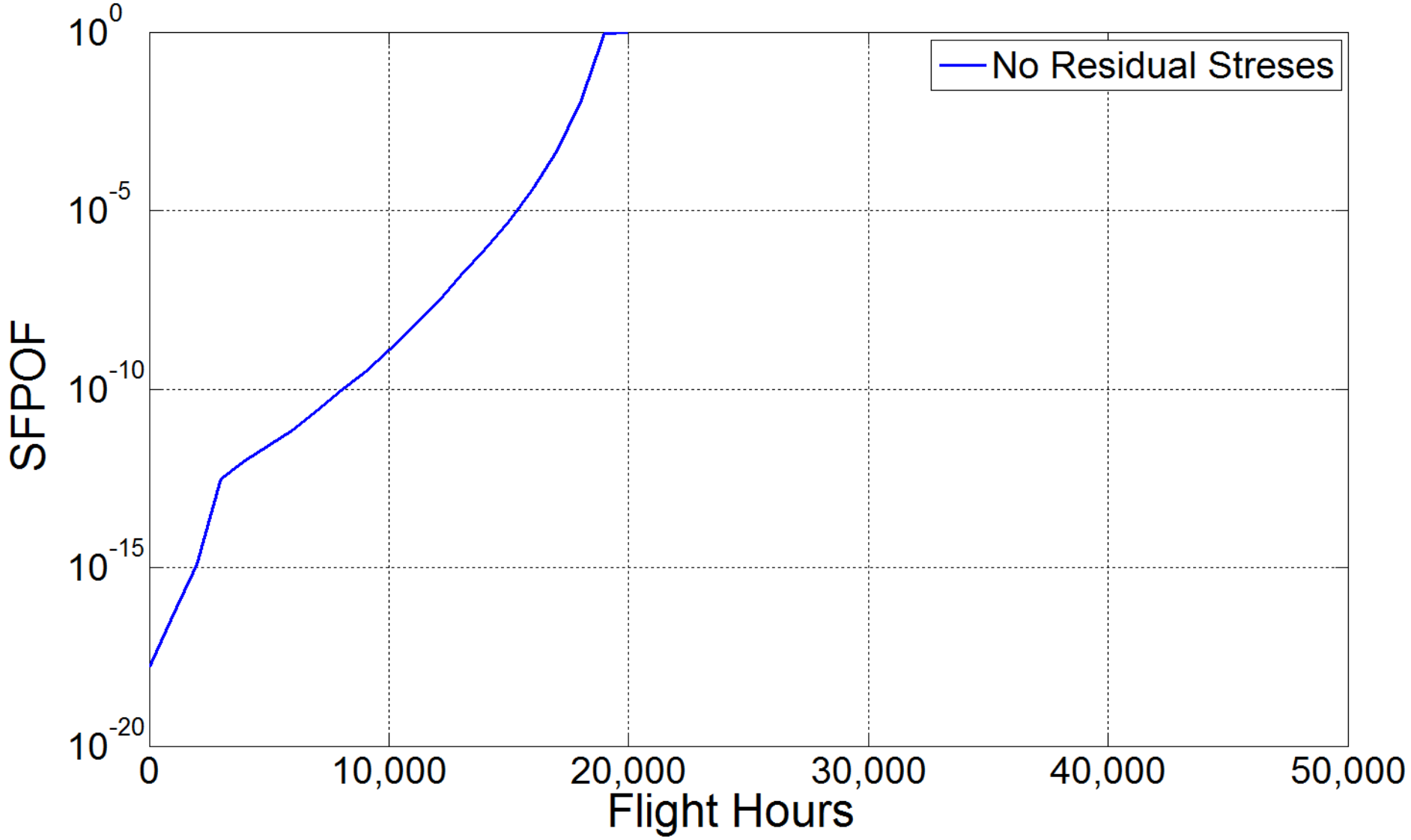
# Residual Stress Effect on SFPOF

- SMART-AFGROW interface.

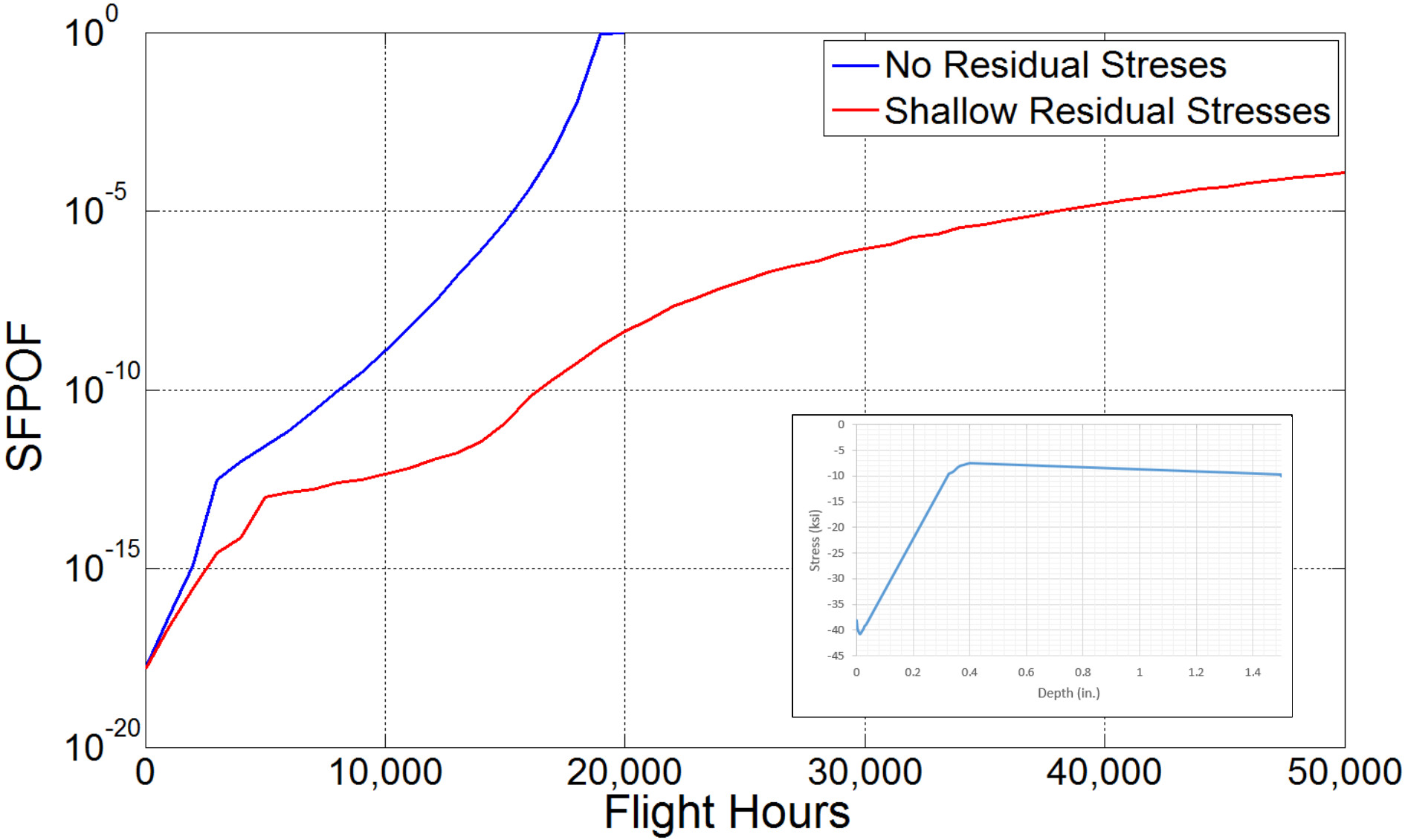


# Inpections

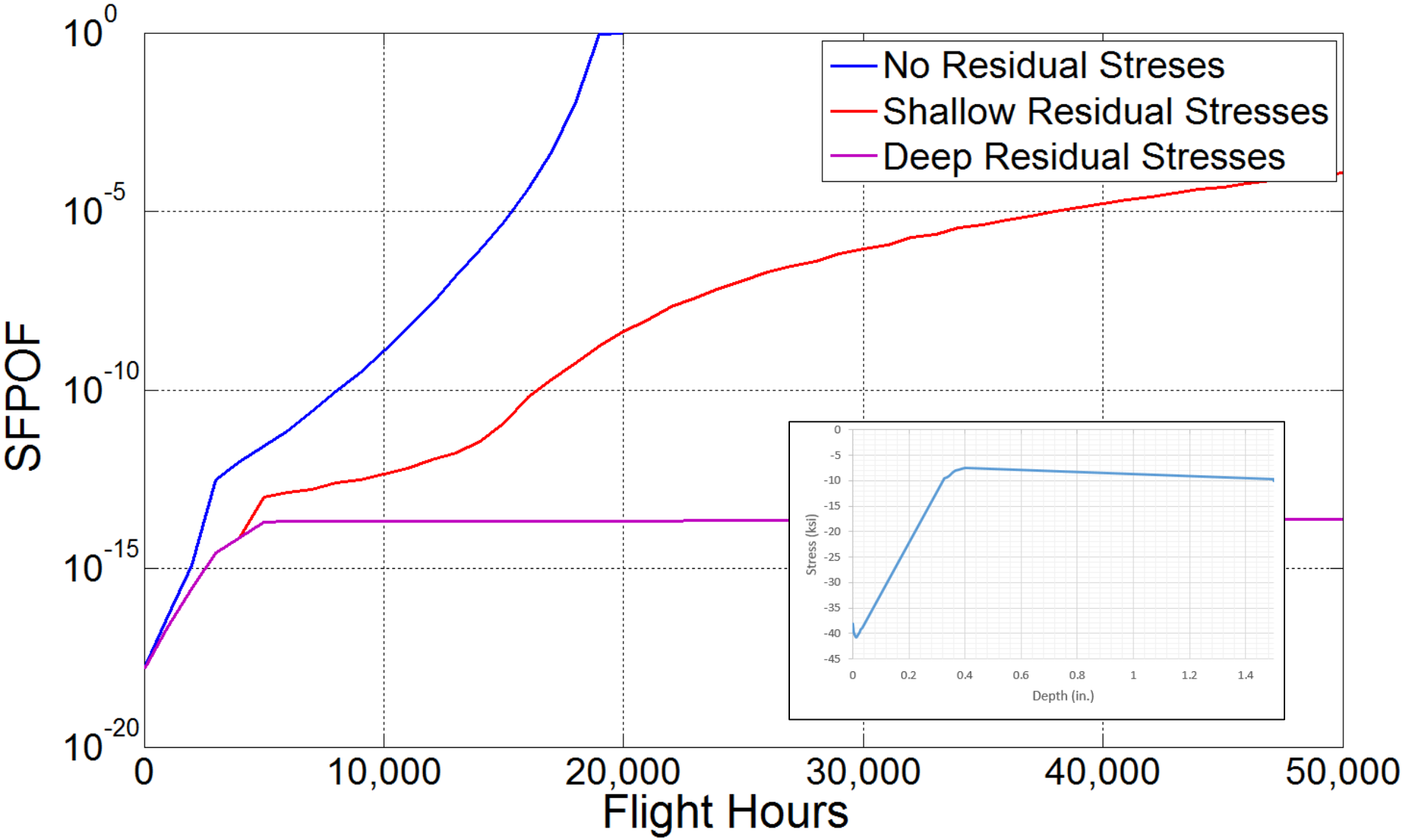
# Results without Inspections



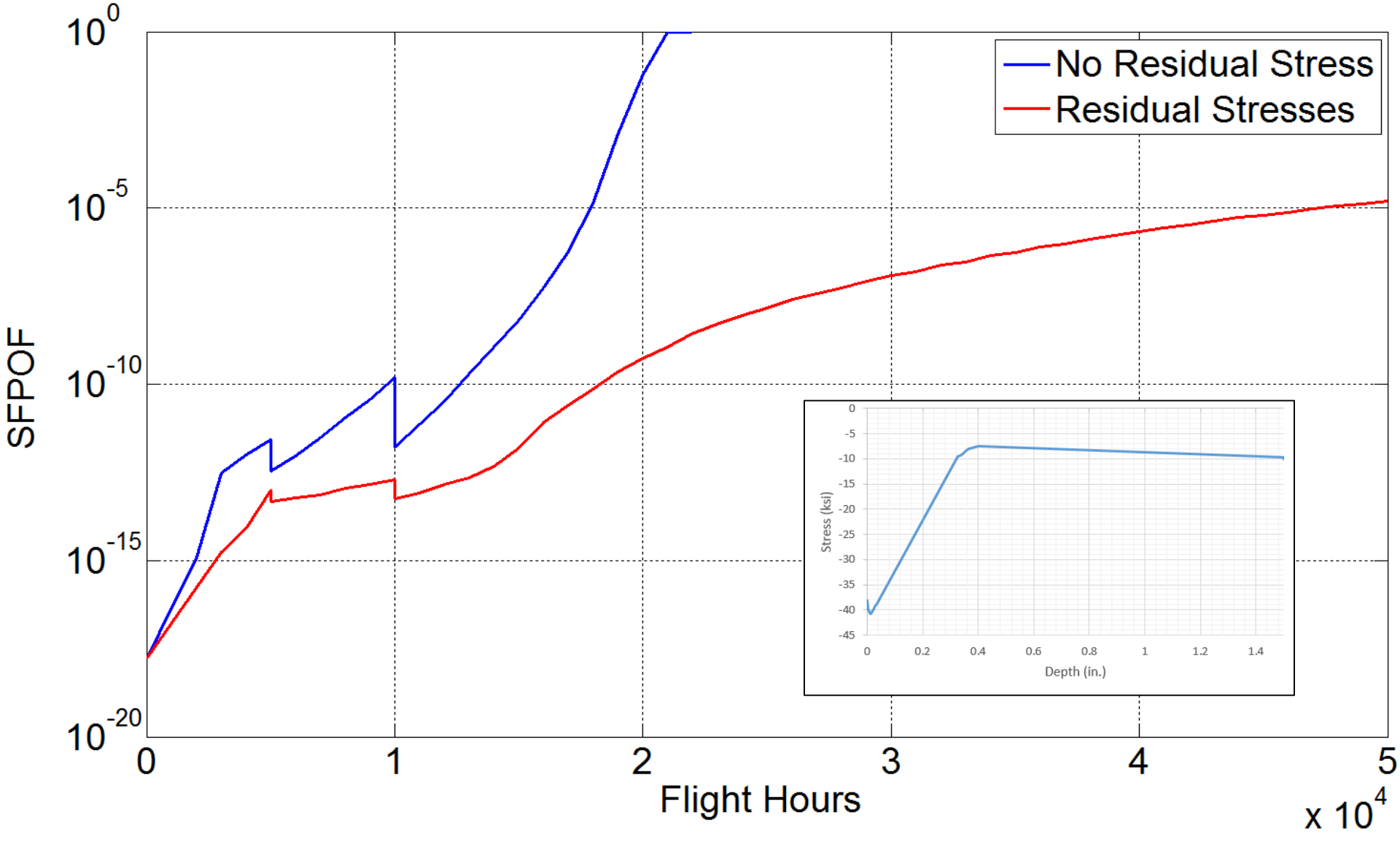
# Results without Inspections



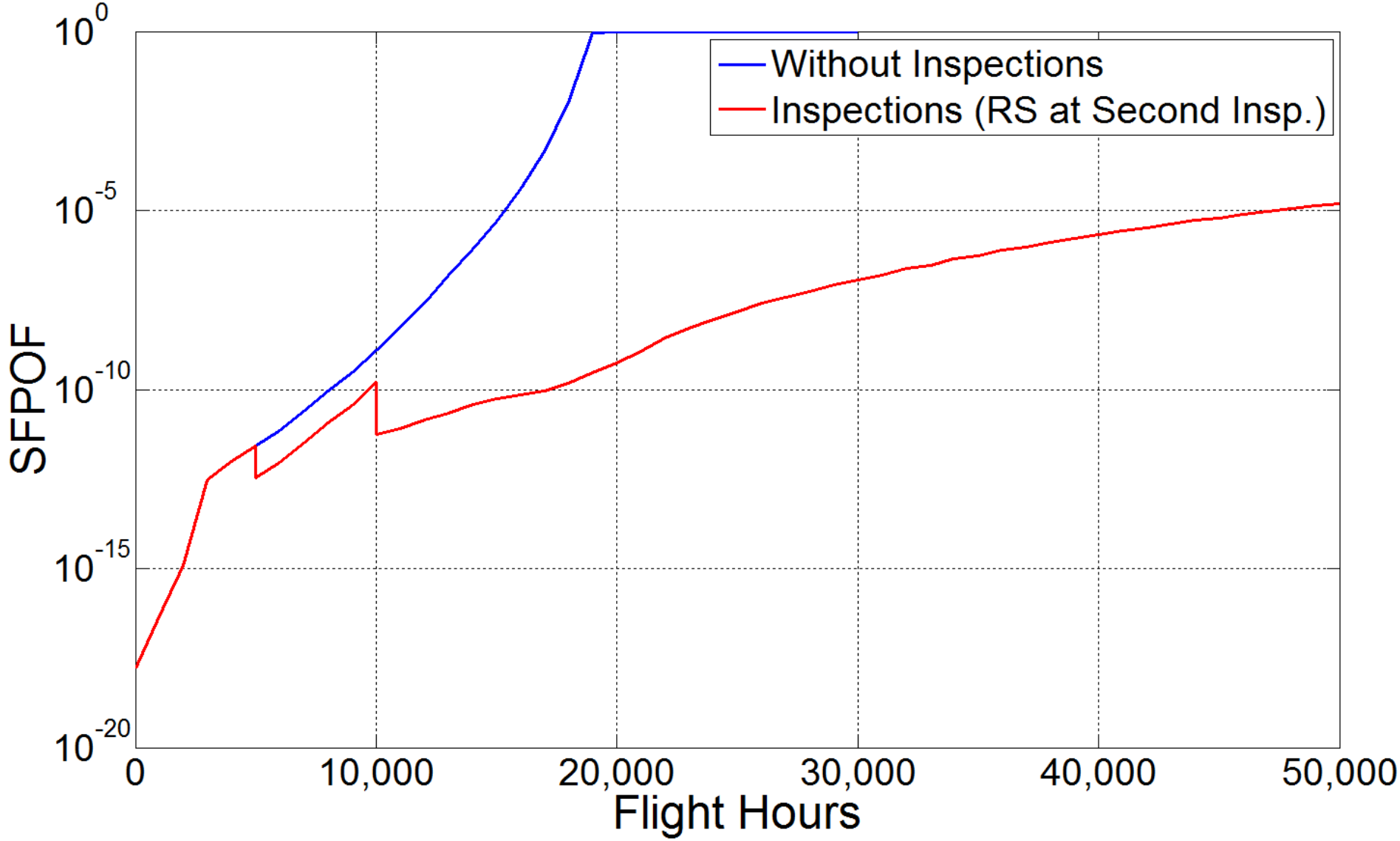
# Results without Inspections



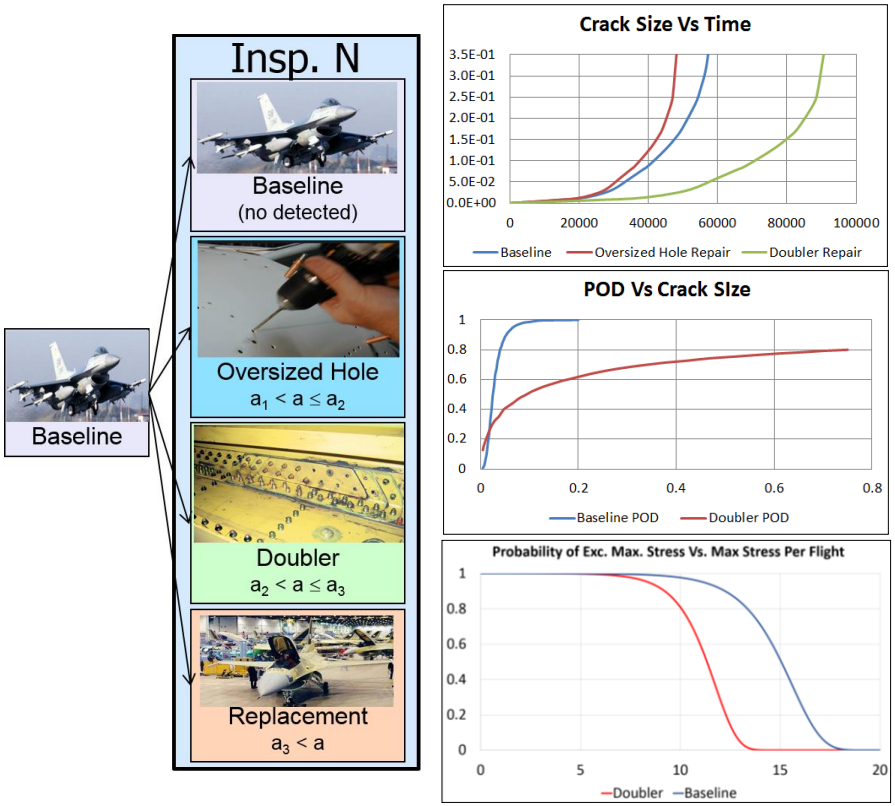
# Results with Inspections



# Inducing RS at the Second Inspections



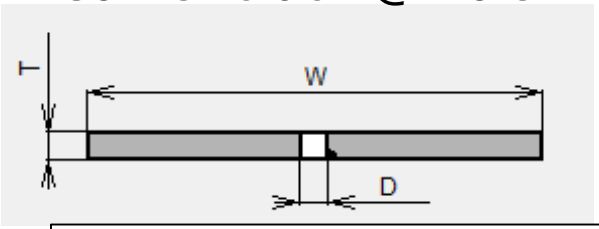
# Sensitivity Study



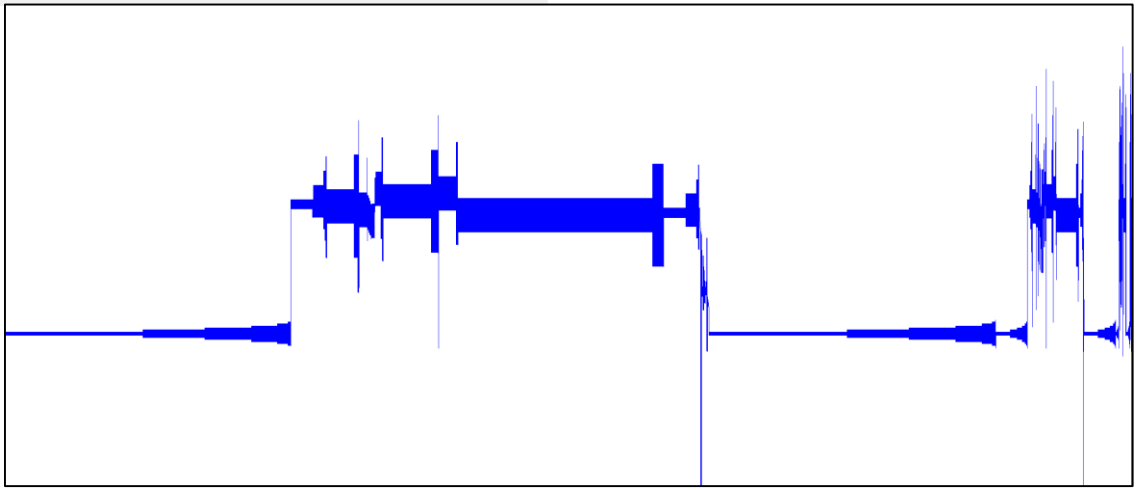

$$\bar{S}_\theta = \frac{\partial P}{\partial \theta} \cdot \theta$$

# Input Parameters

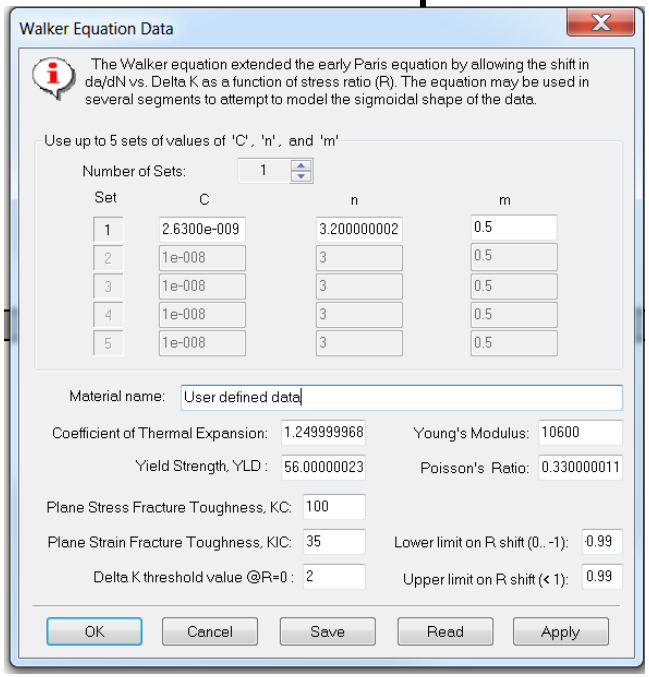
## Corner crack @ hole




| Parameter | Value |
|---|---|
| T | 0.09 in |
| W | 4.0 in |
| D | 0.25 in |



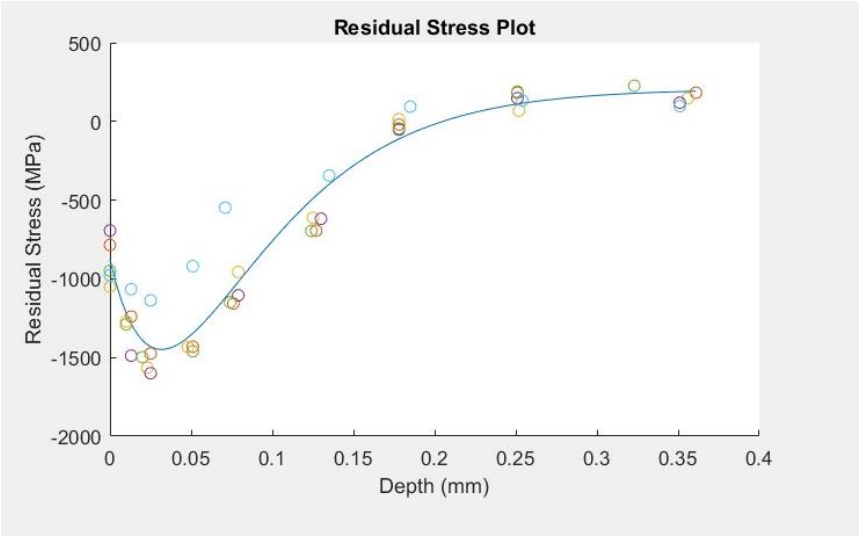
## Mat. Prop.




| Random Variables | Value |
|---|---|
| Fracture Toughness Distribution (Normal) | Mean = 34.5ksi√in, Standard Deviation = 3.8 ksi√in. |
| Initial & Repair Lognormal Size Distribution (a & c) (Lognormal) | Mean = 0.005 in, Standard Deviation = 0.001 in. |
| Extreme Value Distribution (Gumbel) | Location = 14.5, Scale = 0.8, and Shape = 0.0 |

# Residual Stress Profile

- Shot Peening Residual Stress Profile (Random)




$$\sigma(x) = (ss - si + c_1 x)Exp[-C_2 x] + si$$

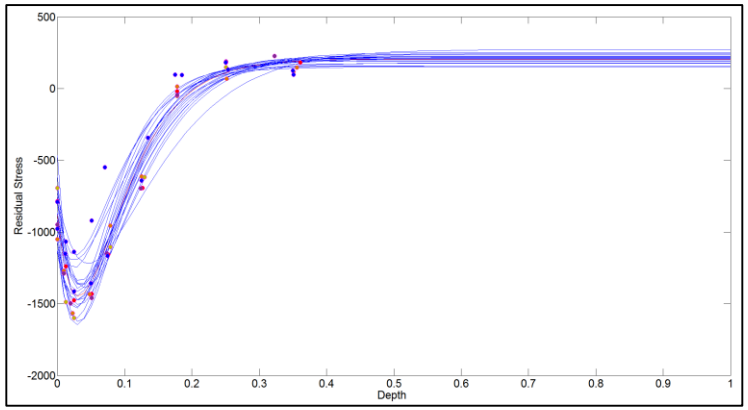
$$C_1 = \frac{\{(\sigma_s - \sigma_i)(1 - Exp[-C_2 B]) + \sigma_i B C_2\} C_2}{(C_2 B + 1)Exp[-C_2 B] - 1}$$

Mean and Standard Deviation Parameters

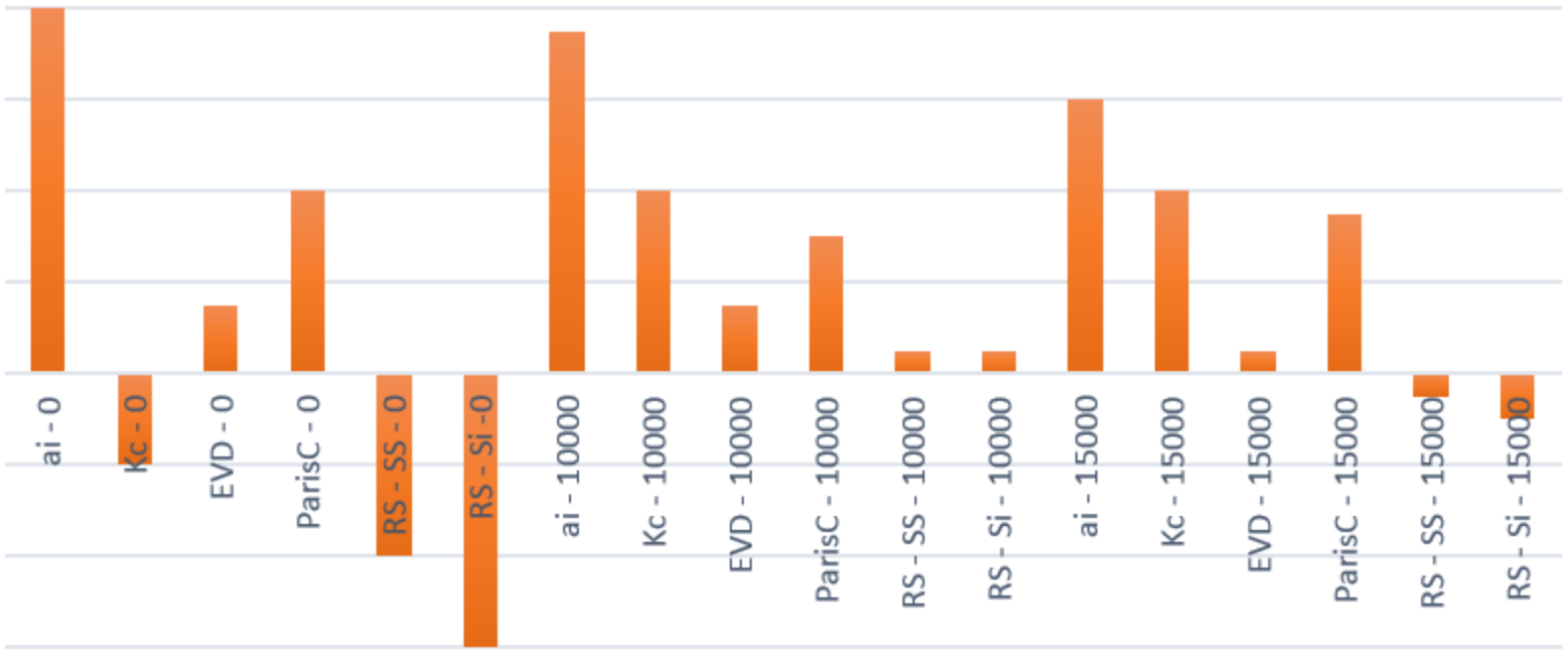
| | Mean (Mpa) | St dev |
|---|---|---|
| ss | -879.16 | 58.58 |
| si | 205.68 | 9.448 |
| c2 | 20.872 | 1.050 |

Correlation Parameters

| | ss | si | c2 |
|---|---|---|---|
| ss | 1 | -0.214 | 0.402 |
| si | -0.214 | 1 | -0.796 |
| c2 | 0.402 | -0.796 | 1 |



# Sensitivity



# Future Work

- Compute sensitivities wrt standard deviation.
- Define handbook example problems
  - Need help from the group

# Thank you!!

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# Some Observations on the Significance of Residual Stress Variability on Fatigue Crack Growth Life

ERSI Workshop
Layton, Utah
September 13-14, 2018

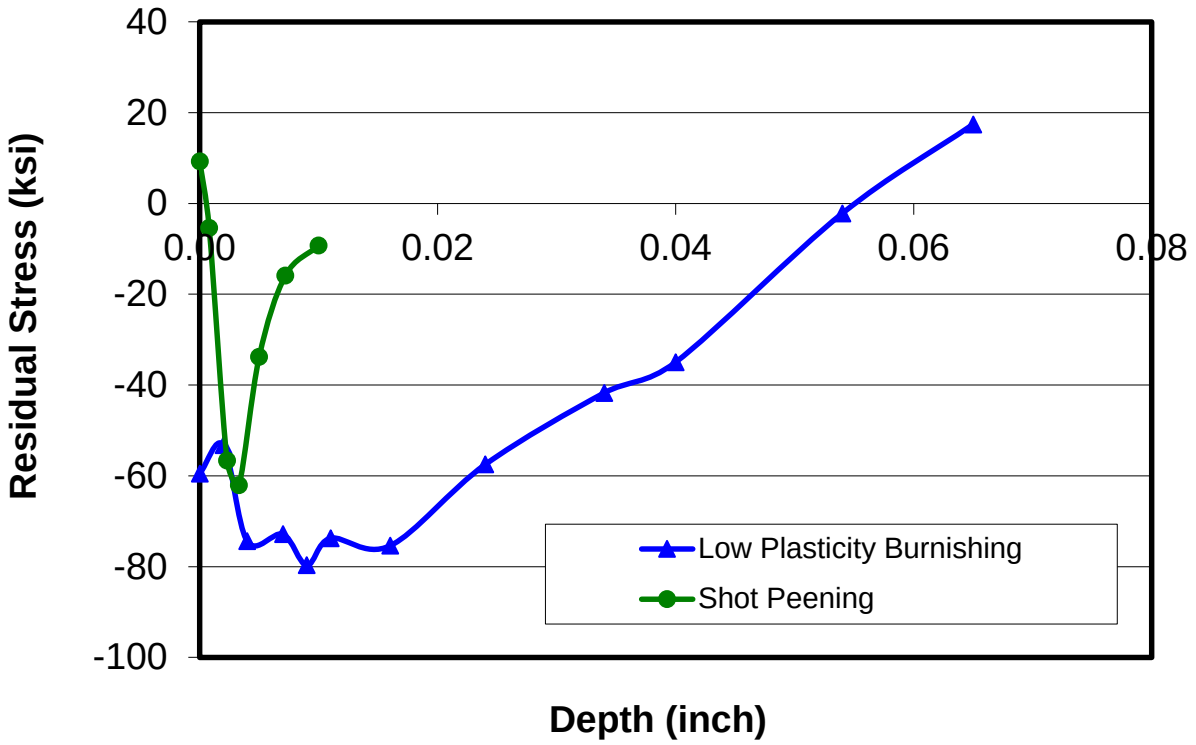
R. Craig McClung
Southwest Research Institute
San Antonio, Texas

# Overview

- A few anecdotal observations are offered on the significance of variability in residual stress on fatigue crack growth lifetime
- Example 1: Relaxed surface residual stress field created by surface enhancement (shot peening or laser peening) – *data courtesy Lambda Technologies (P. S. Prevéy)*
- Example 2: Bulk residual stress field created by heat treating – *data from MAI BA-11 project*

# Example 1: Surface Engineered RS

- Surface enhancement methods such as shot peening (SP) or low plasticity burnishing (LPB) can introduce significant near-surface compressive RS fields.
- FCG analysis can be used to predict the influence of the resulting stable RS fields on fatigue life.
- In this example, alpha-beta Ti-6Al-4V laboratory coupons were subjected to SP or LPB and then thermally exposed (425°C/10 hrs) before RS profiles were measured.

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# Example 1: Surface ERS
## Approach

- These RS profiles were inserted into a univariant weight function surface crack SIF solution.
- Hypothesizing that the surface enhancement could have introduced microscopic damage that would initiate fatigue cracks quickly, FCG analyses with small initial crack sizes were used to calculate total fatigue life.
- A simple El Haddad model was used to describe small-crack growth rate behavior.

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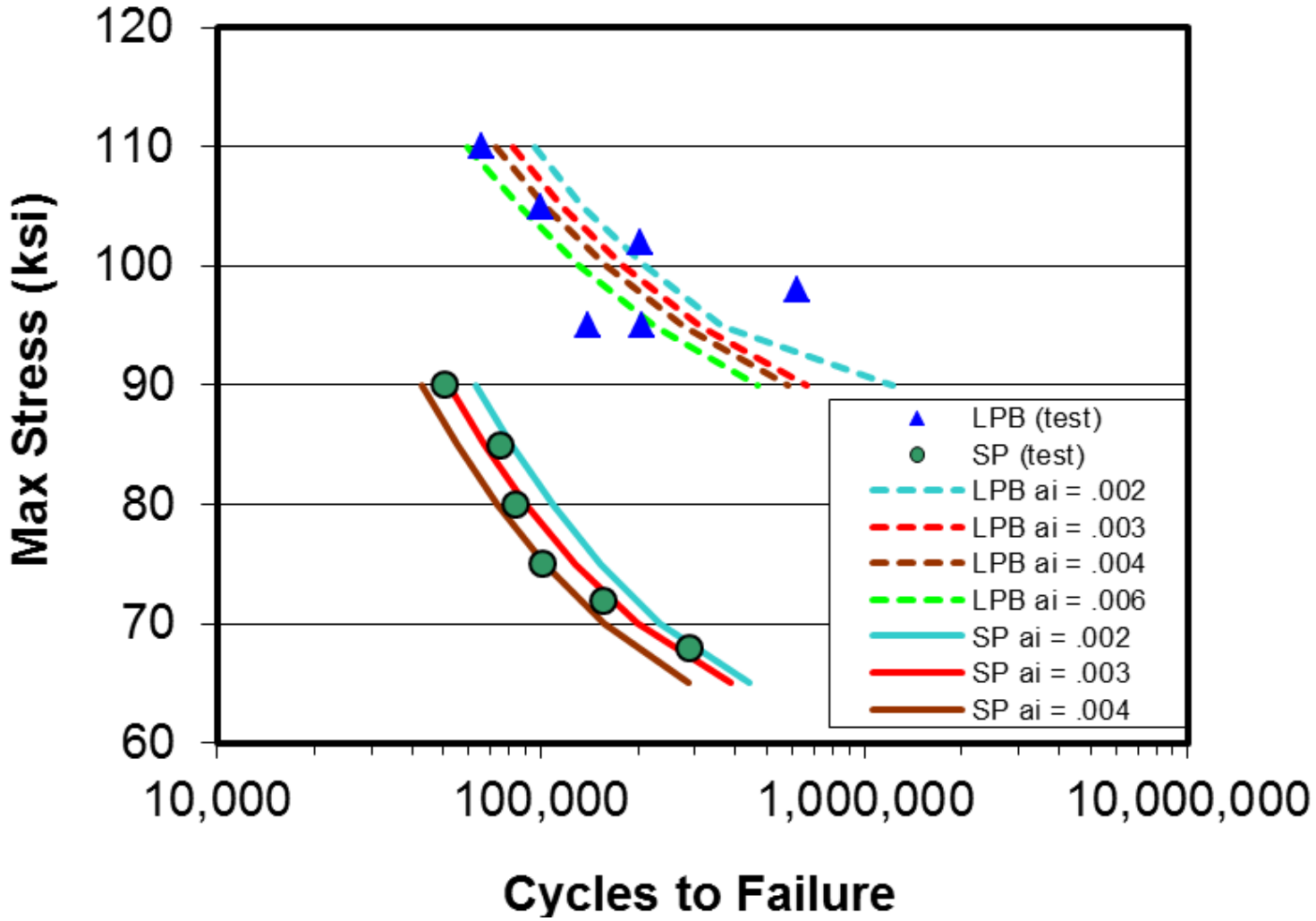
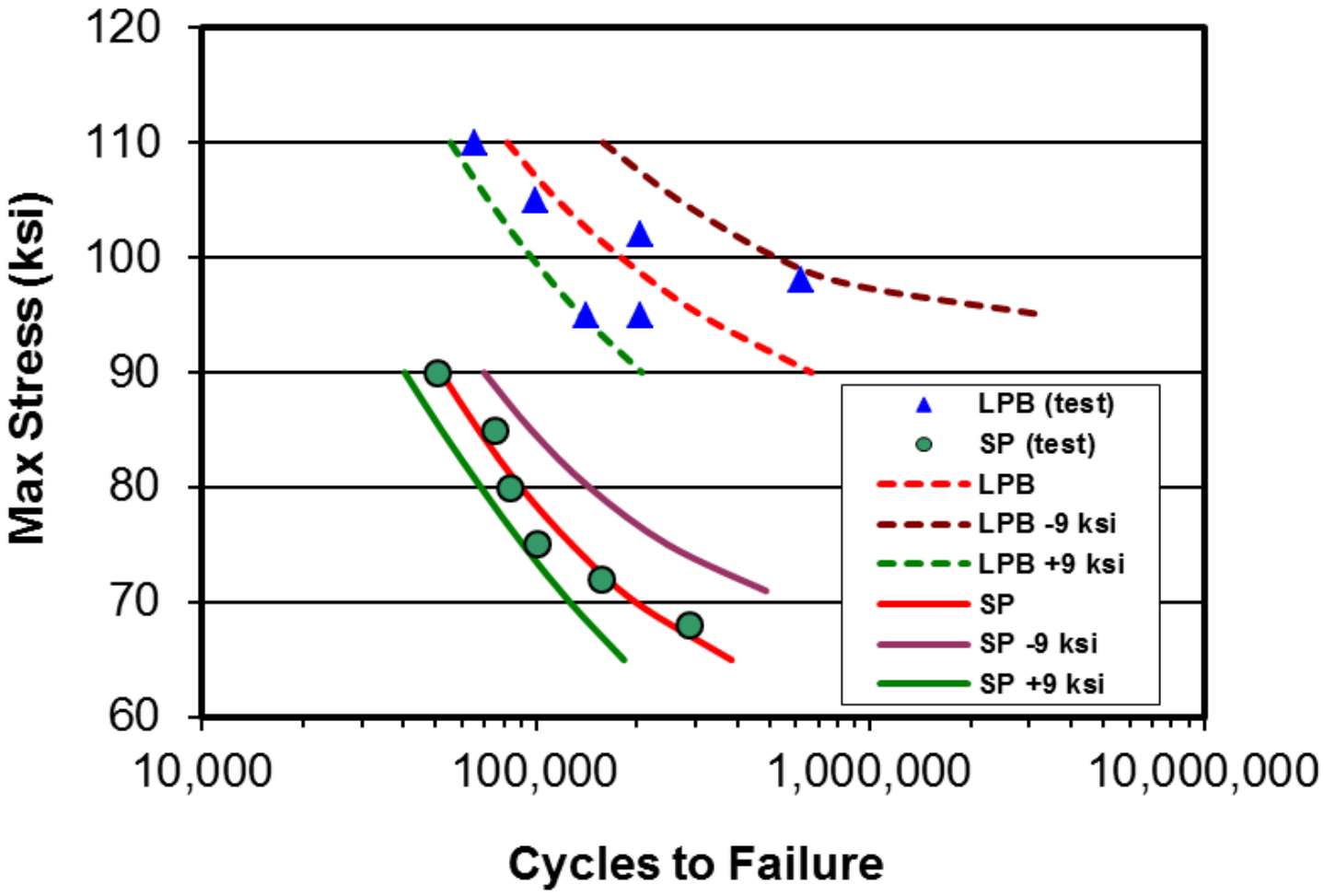
# Example 1: Surface ERS
## Effect of Initial Crack Size

- Variations in the assumed initial crack size had relatively little impact on calculated life (compare large scatter in fatigue lifetimes)



# Example 1: Surface ERS
## Effect of RS Variability

- Small shifts (±9 ksi) in the RS profiles, hypothetically arising from process variability or measurement uncertainty, had a much larger impact on calculated life and were consistent with limited data for life scatter

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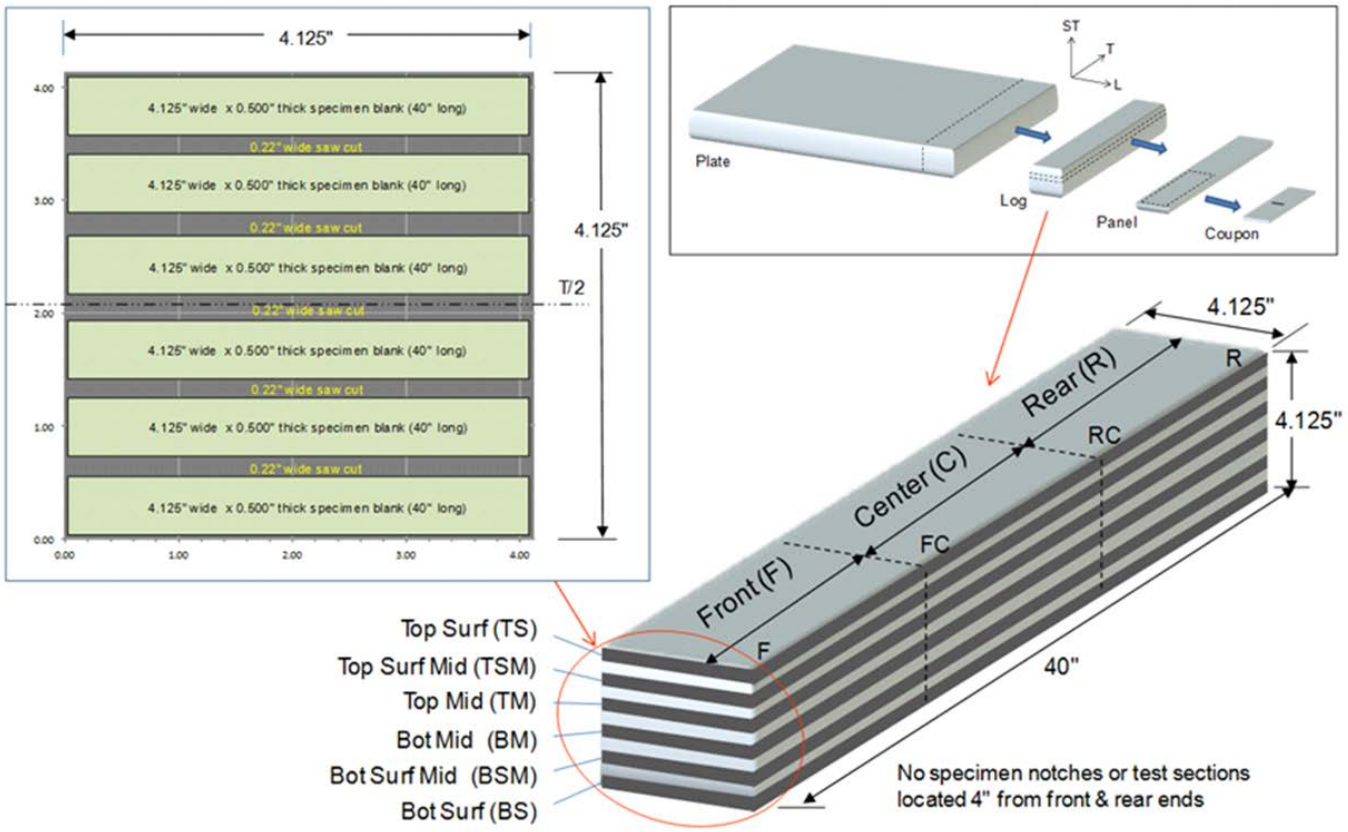
# Example 2: Bulk RS
## Billet, Logs, Coupons

- 7085-T74 billet cut into many ‘logs’ that were quenched and aged individually to intentionally leave significant residual stress
- Coupon blanks extracted from three longitudinal positions and six transverse positions (total of eighteen unique positions) within each log

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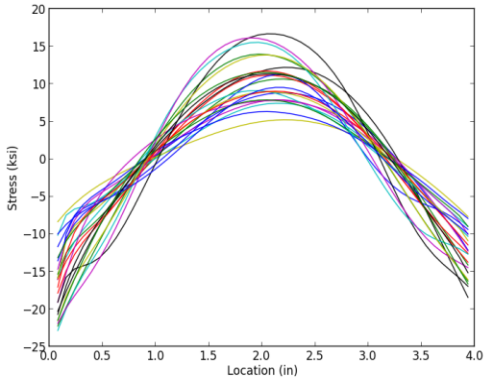
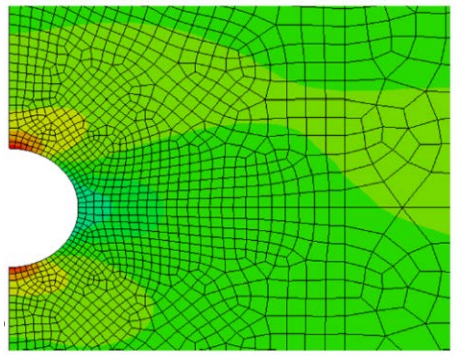
# Example 2: Bulk RS
## Approach Overview

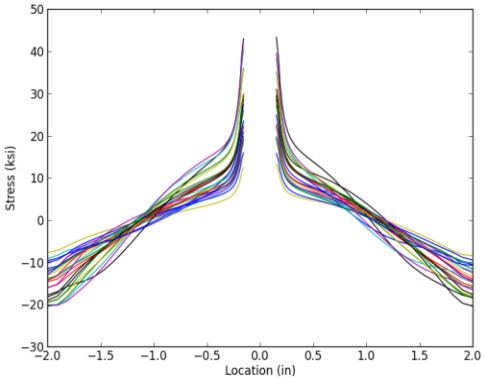
**Slitting RS measurements**



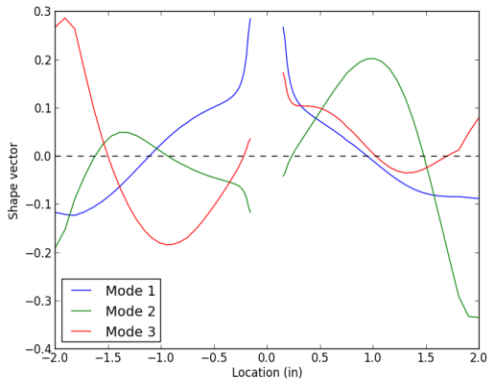

**Finite Element Analysis**



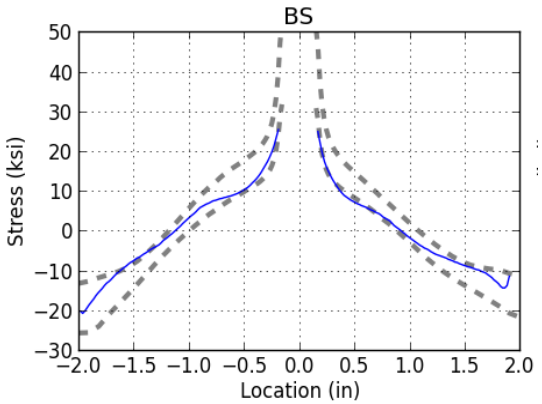
**Predicted DF Residual Stress**



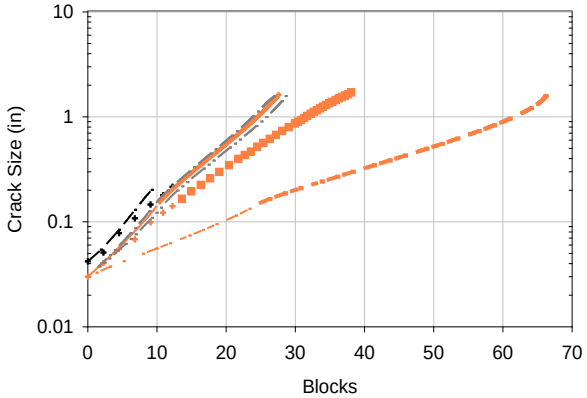

**Principal Components Analysis**




**Probabilistic RS Models**




**FCG predictions/comparisons**

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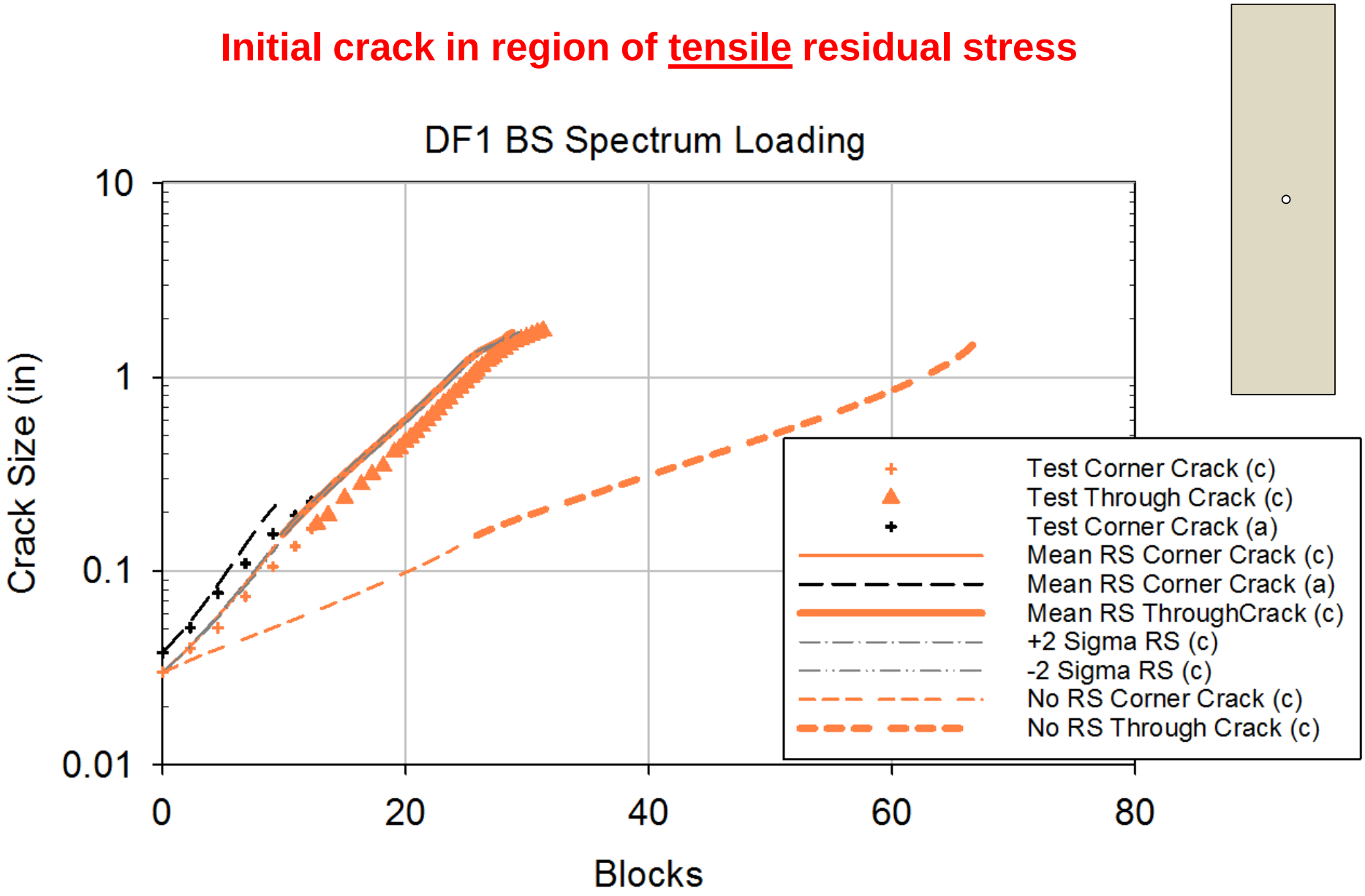
# Example 2: Bulk RS
## Spectrum Tests (Tensile RS)

**Initial crack in region of tensile residual stress**

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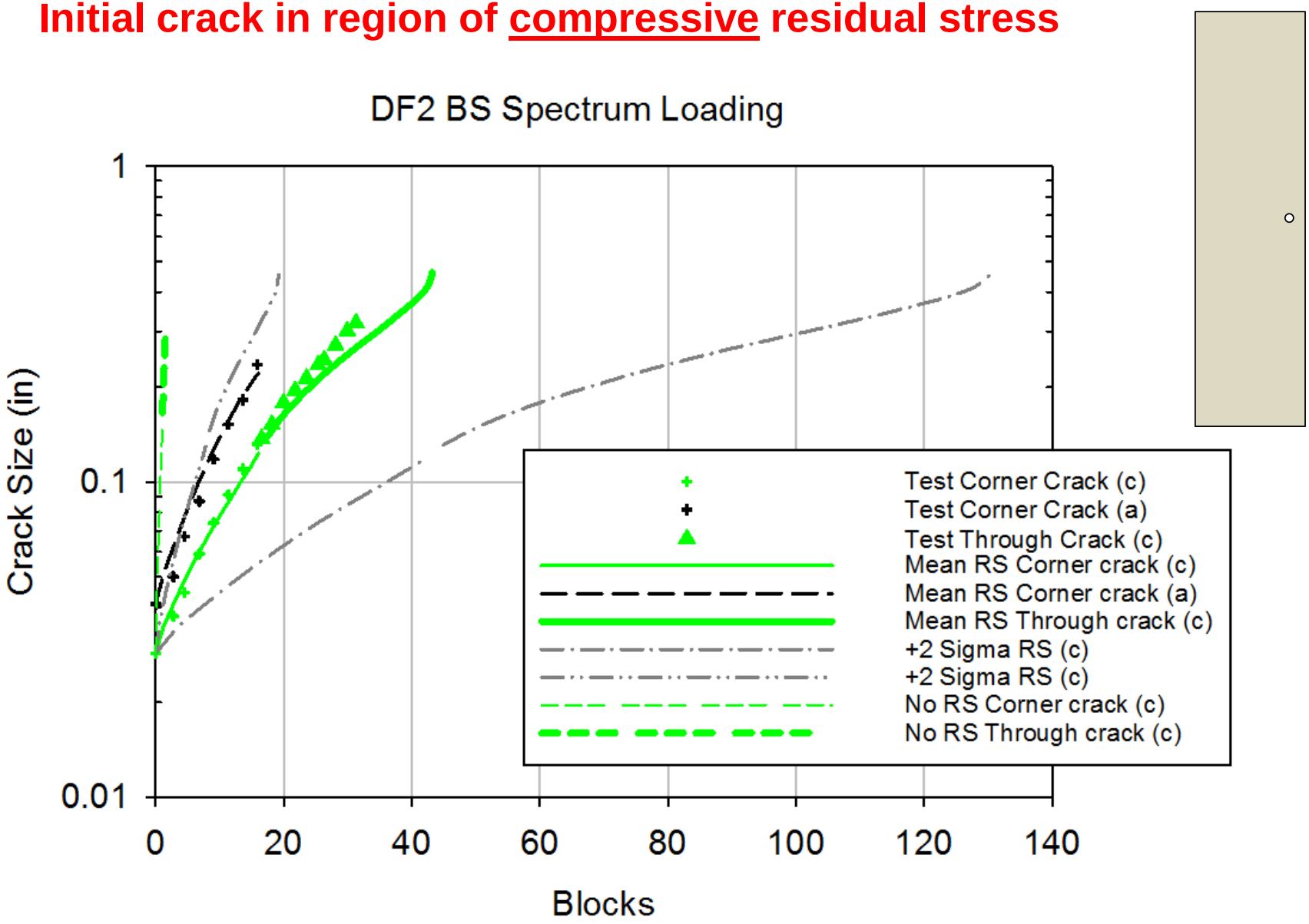
# Example 2: Bulk RS
## Spectrum Tests (Compressive RS)

**Initial crack in region of compressive residual stress**

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# Example 2: Bulk RS
## Observations

- In these tests, the RS had a significant impact on the predicted life, and predictions ignoring RS tended to be highly conservative or highly non-conservative.
- Predictions (32 tests) including mean value RS were generally accurate (±2x) with a conservative bias for constant amplitude loading, and accurate (±2x) with no bias for spectrum loading.
- How did RS scatter affect the predicted life in these tests?
  - Scatter in tensile RS generally had a very small effect
  - Scatter in compressive RS generally had a very large effect

# Possible Path Forward

- Use DARWIN probabilistic damage tolerance software
  - Current AFRL investment in DARWIN for AFLCMC
- Develop quantitative characterization of uncertainty in RS
  - Informed by RS models and RS measurements
- Use weight function SIF solutions to model effect of RS on crack driving force
- Perform probabilistic analysis of (uncertain) RS effects on FCG life and fracture risk

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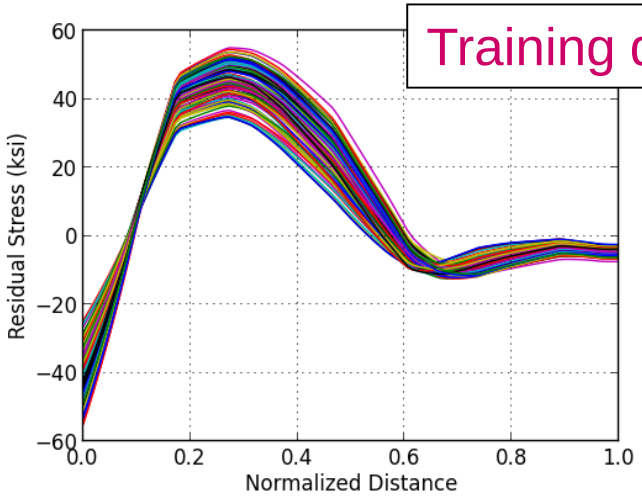
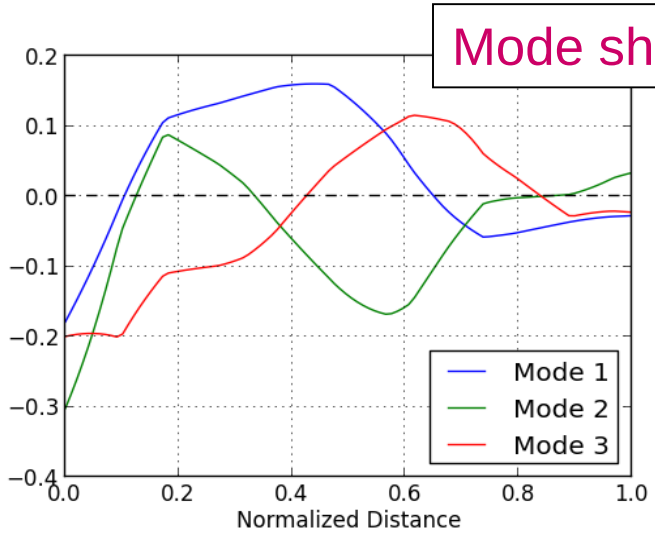
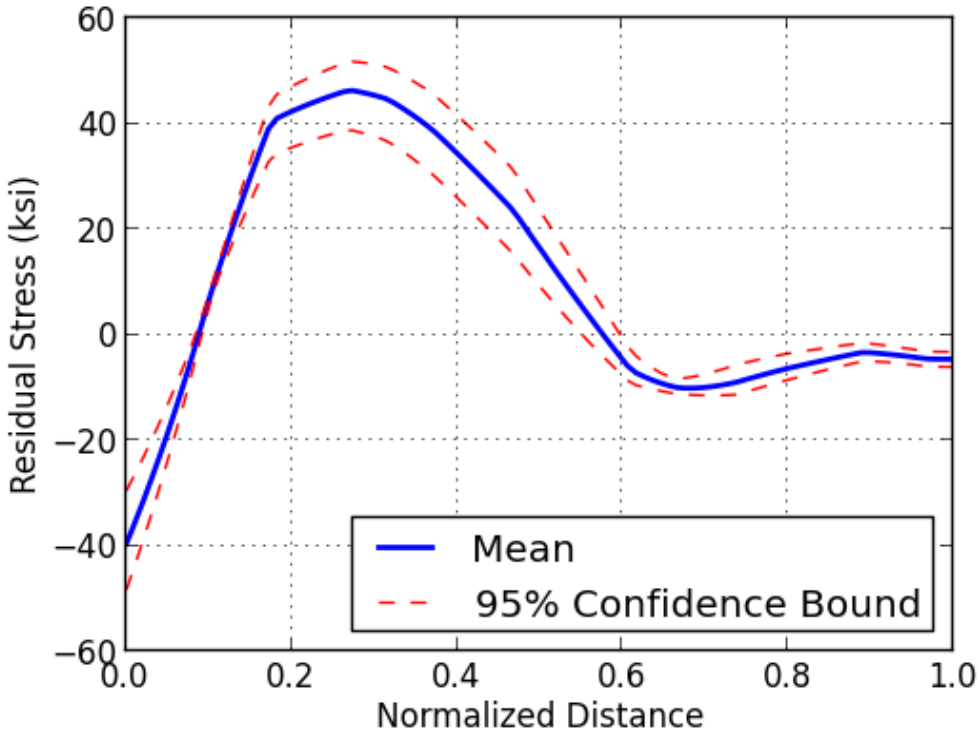
# Principal Components Analysis for Residual Stresses Along Crack Path

Training data




Mode shapes



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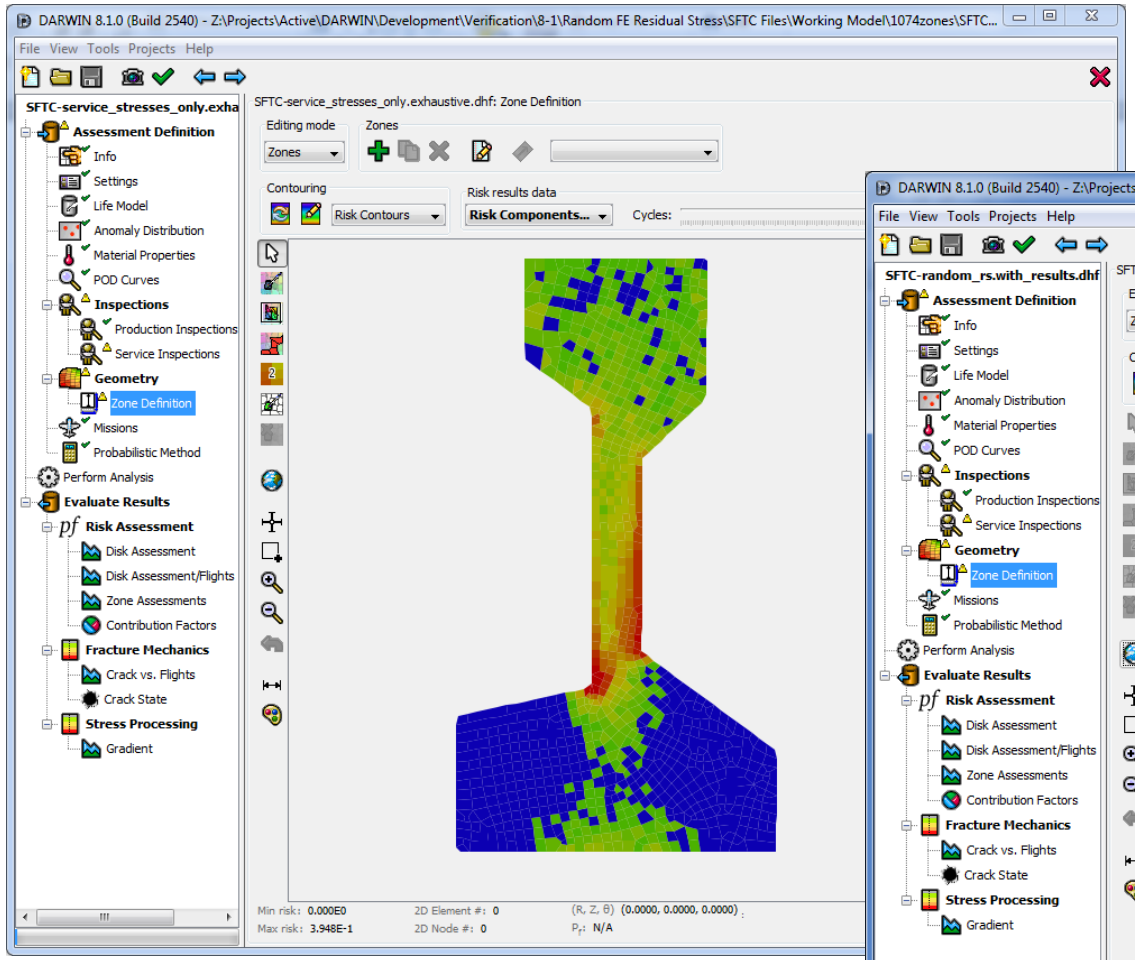
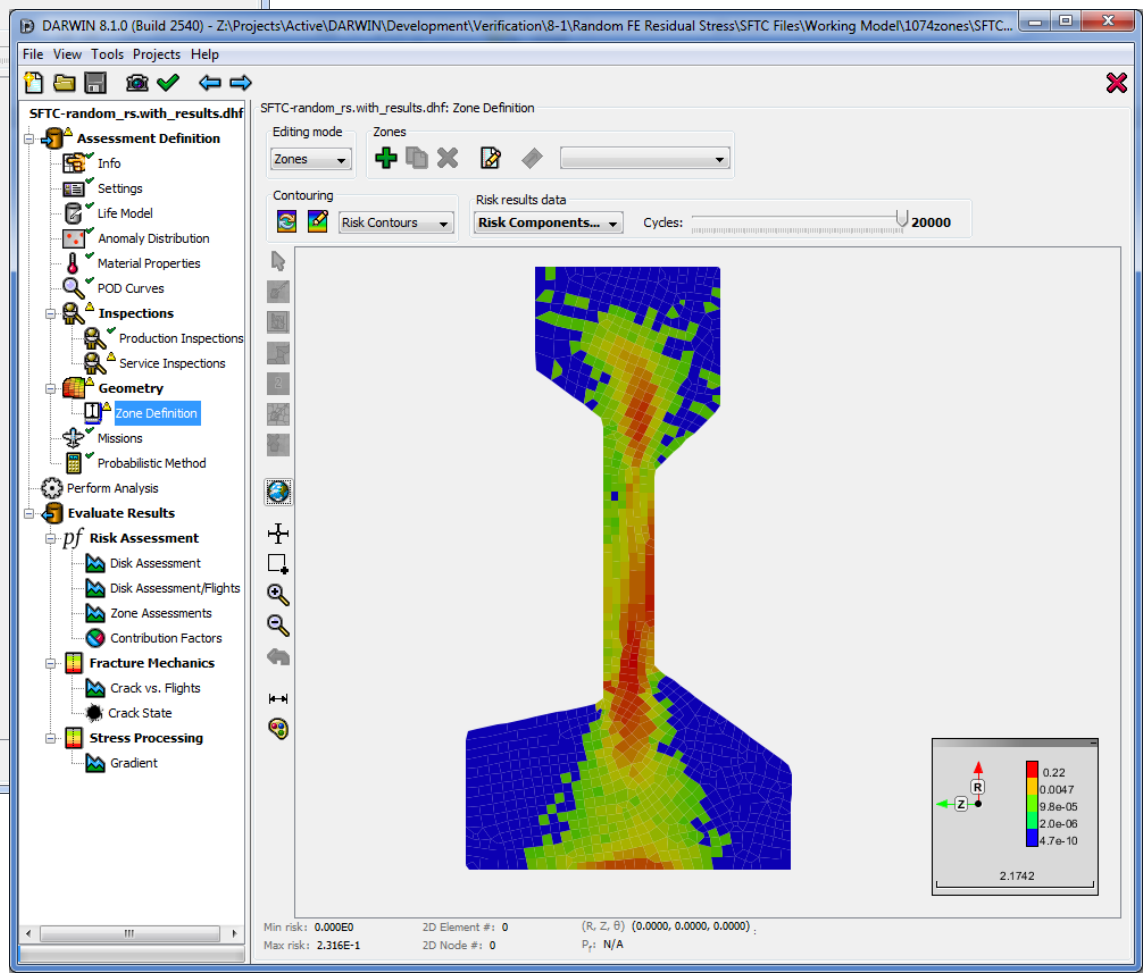
# Effect of Random Residual Stress on Risk

## Without Residual Stress




## With Random Residual Stress

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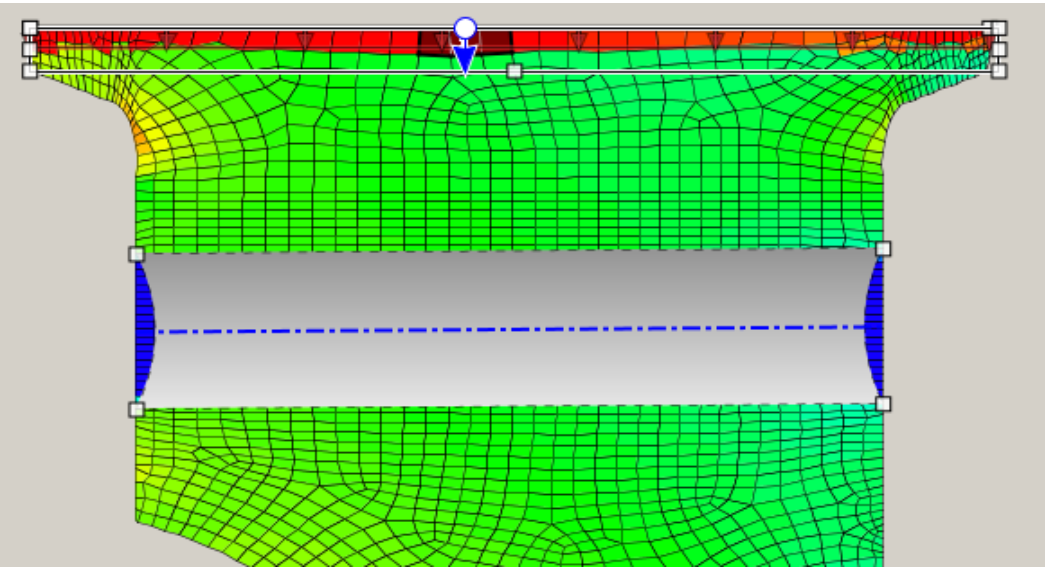
# DARWIN Status

- Framework available to superimpose local residual stresses (e.g., surface RS at holes) with service stresses
- Univariant & bivariant WF SIF solutions available for corner/ surface/thru cracks at holes, corner/surface cracks in plates
- Probabilistic treatment of residual stress uncertainty available for bulk residual stresses in 2D finite element models
- Random RS capabilities expandable to local RS in 3D models



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# Closing Comments

- Relatively small variations in residual stress can have a very large impact on predicted FCG lifetime when the residual stress is compressive
- Uncertainty in tensile residual stresses appears to have relatively less effect on life variability
- A more rigorous probabilistic treatment of RS uncertainty and its effect on fracture risk appears warranted
- DARWIN software provides a potential path forward, but some enhancements are needed

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