Incorporating Residual Stresses into Probabilistic Damage Tolerance Analysis

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Outline

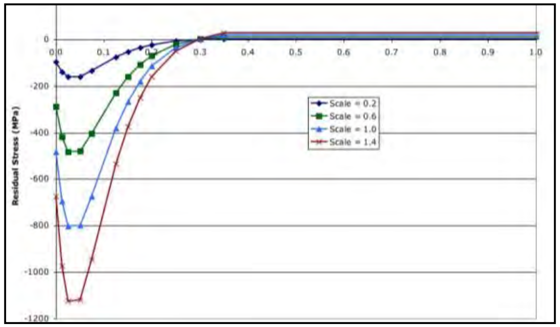
- ✓ SMART|DT Overview
- ✓ Residual Stresses Modeling Software
- ✓ Are RS needed in PDTA?
  - ✓ Sensitivity Study wrt. Remaining Useful Life

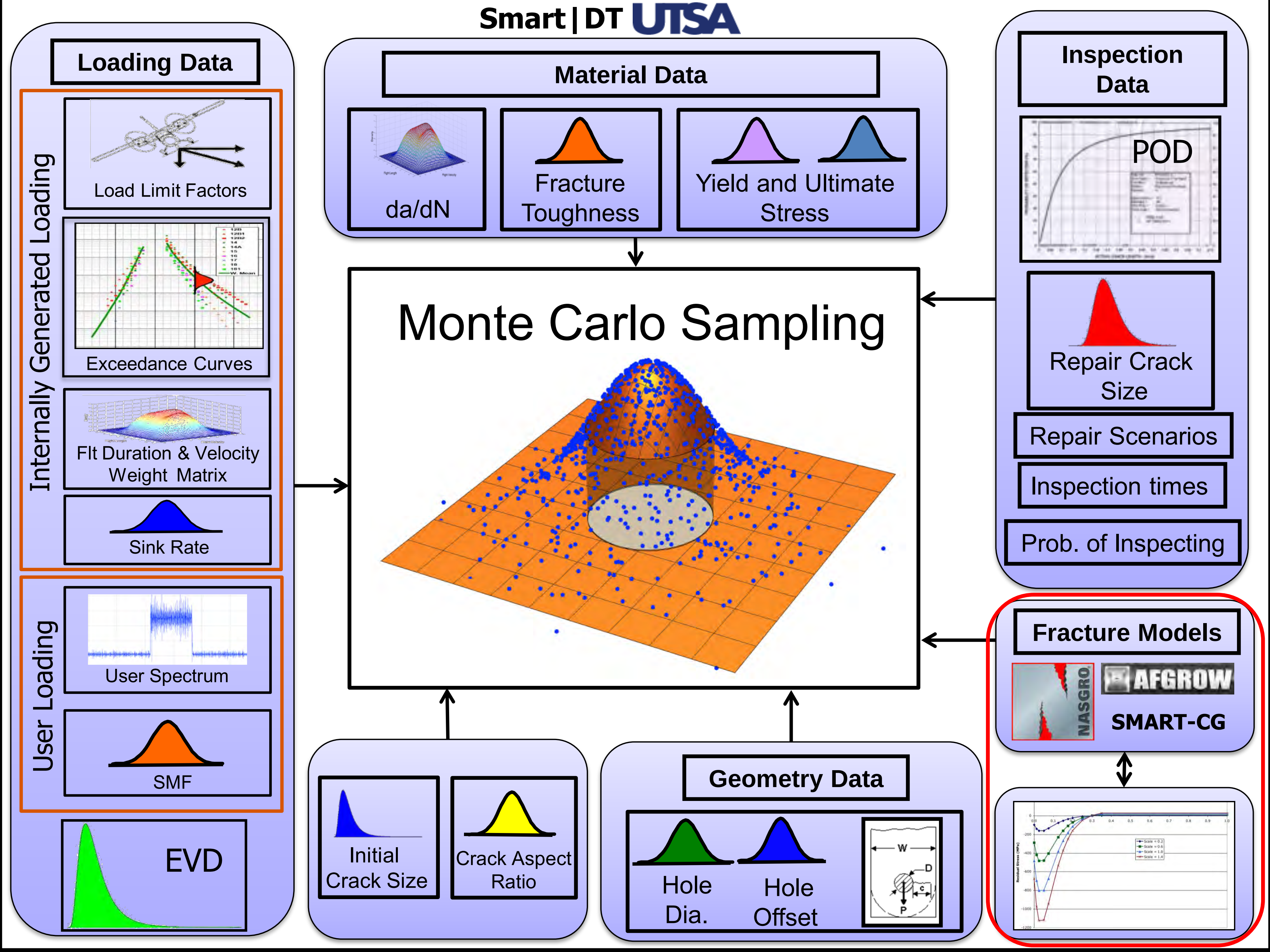
Probabilistic RS Profile

- ✓ Residual Stresses incorporated into PDTA
  - ✓ Deterministic Residual Stresses

Deterministic RS Profile

- ✓ Future Plans

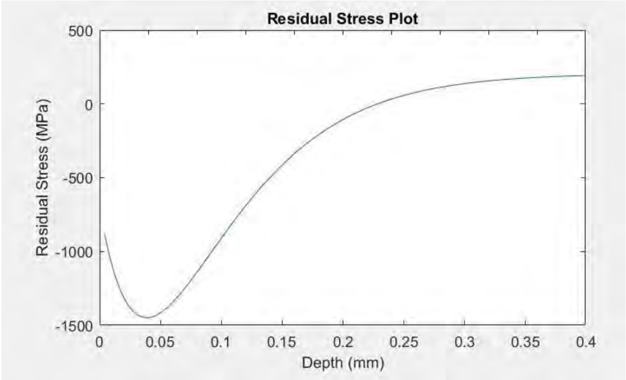




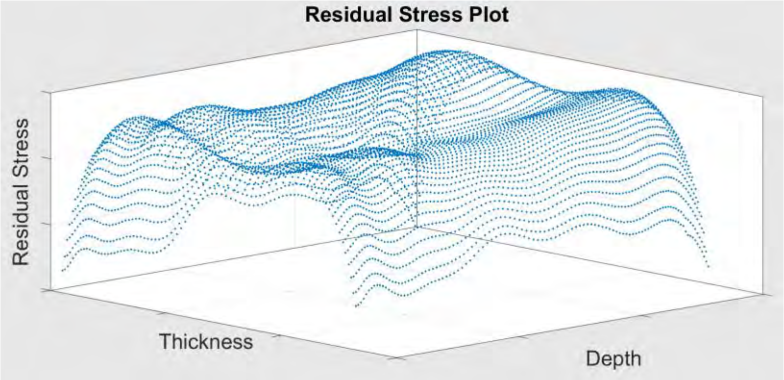
Smart | DT UTSA
Loading Data
Internally Generated Loading
Load Limit Factors
Exceedance Curves
Flt Duration & Velocity Weight Matrix
Sink Rate
User Loading
User Spectrum
SMF
EVD
Material Data
da/dN
Fracture Toughness
Yield and Ultimate Stress
Monte Carlo Sampling
Inspection Data
POD
Repair Crack Size
Repair Scenarios
Inspection times
Prob. of Inspecting
Fracture Models
NASGRO
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.
  - 3 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*

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

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

- Model II**

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

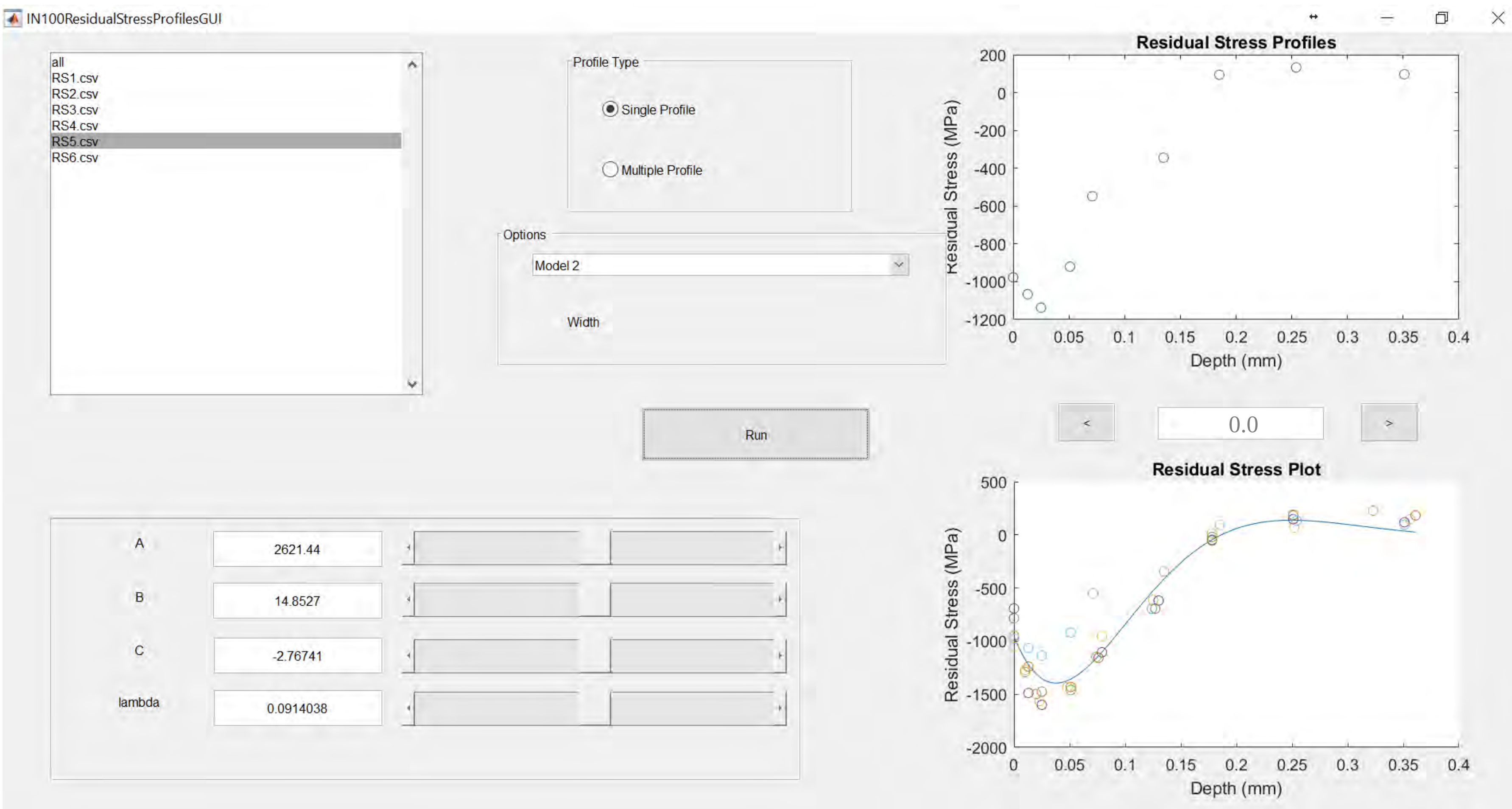
- Model III (Polynomial Fit – Under Development)

$$\sigma(x) = Ax^5 + Bx^4 - Cx^3 + Dx^2 - Ex - F$$

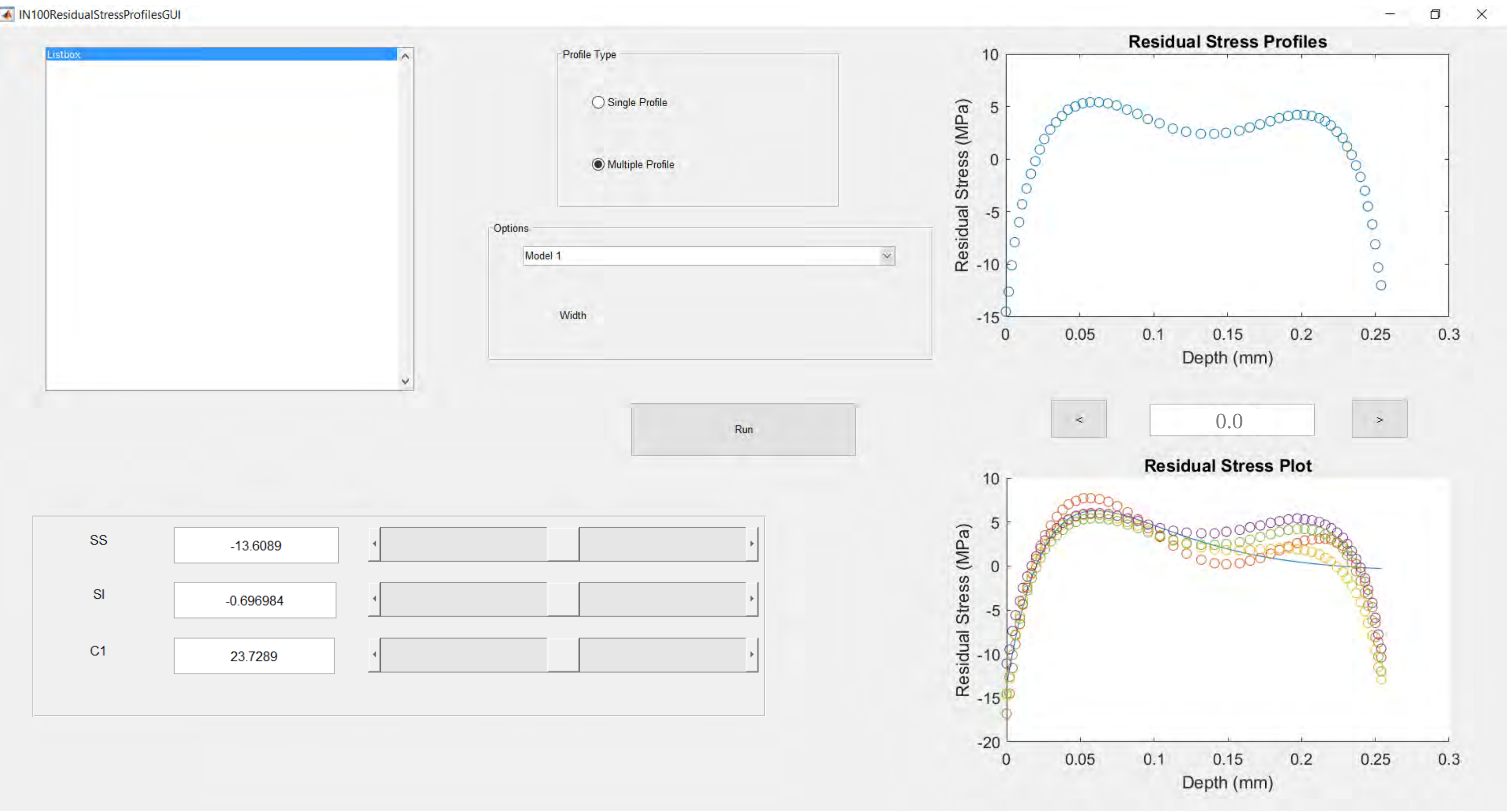
* *User Manual for ZENCRACK™ 7.1*, Zentech International Ltd., Camberley, Surrey, UK, September, 2003.

** 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



Mult. Profile Model I



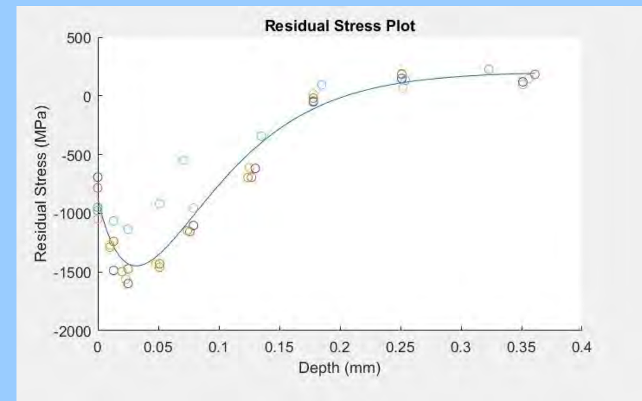
Input/Output

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

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Are probabilistic RS needed in PDTA?

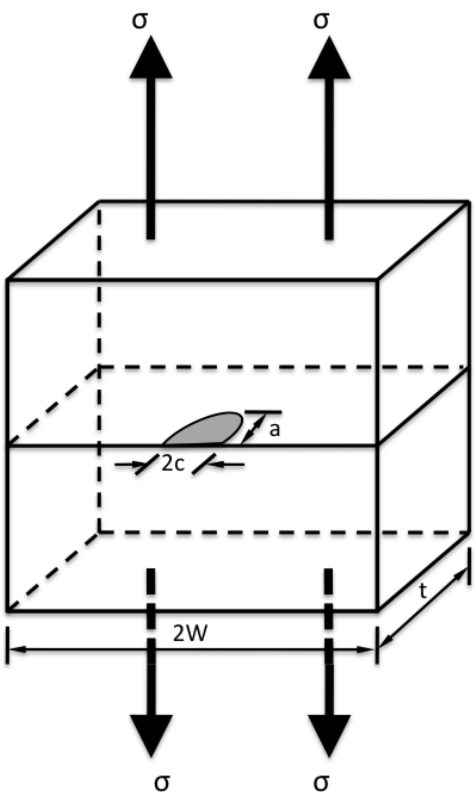
Sensitivity Study wrt Remaining Useful Life

Residual Stress Sensitivity Study

- Random variable sensitivity wrt remaining useful life

Variable Name	Type
Geometry (W)	Random
Geometry (t)	Random
Initial Crack Size (a)	Random
Initial Crack Size (c)	Random
Fracture Toughness (Kc)	Random
Residual Stress	Random
Paris Coefficients (C, m)	Random
Loading	Random
Walker m parameter	Deterministic
Stress Gradient (die out)	Deterministic
Threshold Kth	Deterministic

Residual Stress Sensitivity Study



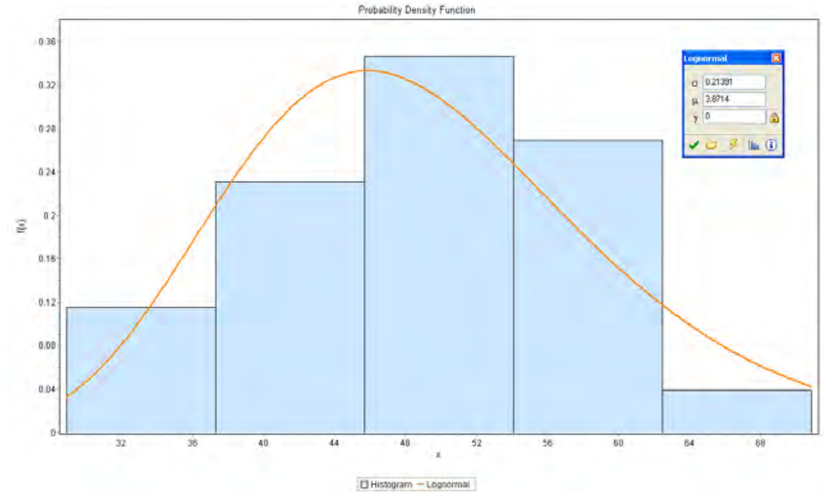
Parameter	Mean (m)	COV
W = 2t	0.5	10%
t	0.25	10%

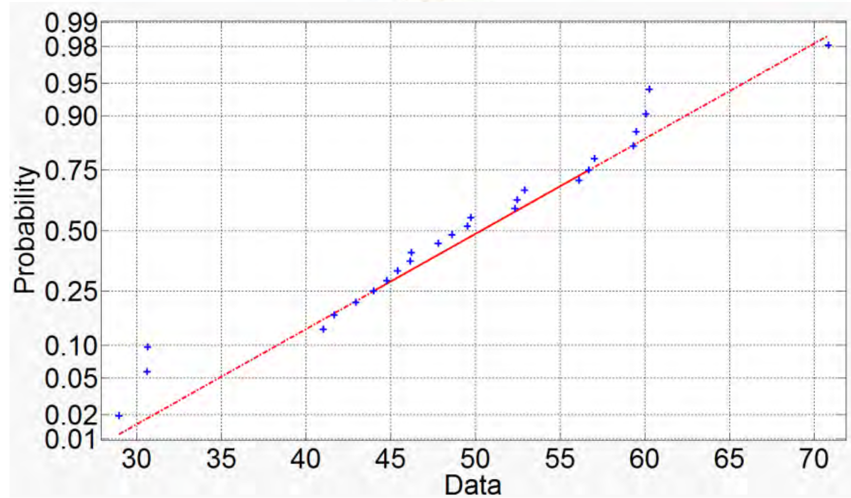
Residual Stress Sensitivity Study

Raw Data

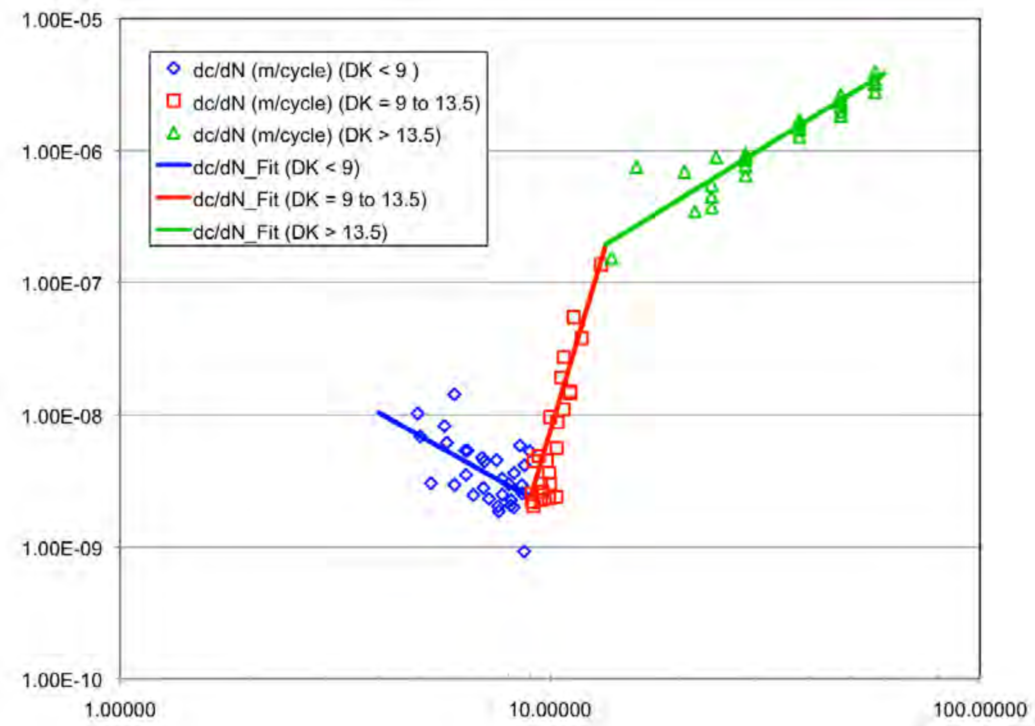
Equivalent Semi-elliptical Crack Depth (a/c=1) (um)
42.94
43.98
28.93
48.63
52.48
60.26
52.32
47.82
44.75
59.34
70.83
59.49
41.65
56.68
49.72
41.01
30.65
45.40
57.04
52.90
46.20
49.53
56.11
60.08
46.14
30.60

Lognormal distribution with histogram and lognormal probability plot LN~(3.871, 0.23)





Residual Stress Sensitivity Study



Curve Section	C	m
ΔK > 13	1.602E-09	1.8753
9 < ΔK < 13	2.425E-20	11.3580
ΔK < 9	1.306E-07	-1.8293

SAS Code to find the regression parameters and the variation on the parameters (Using simple linear regression)

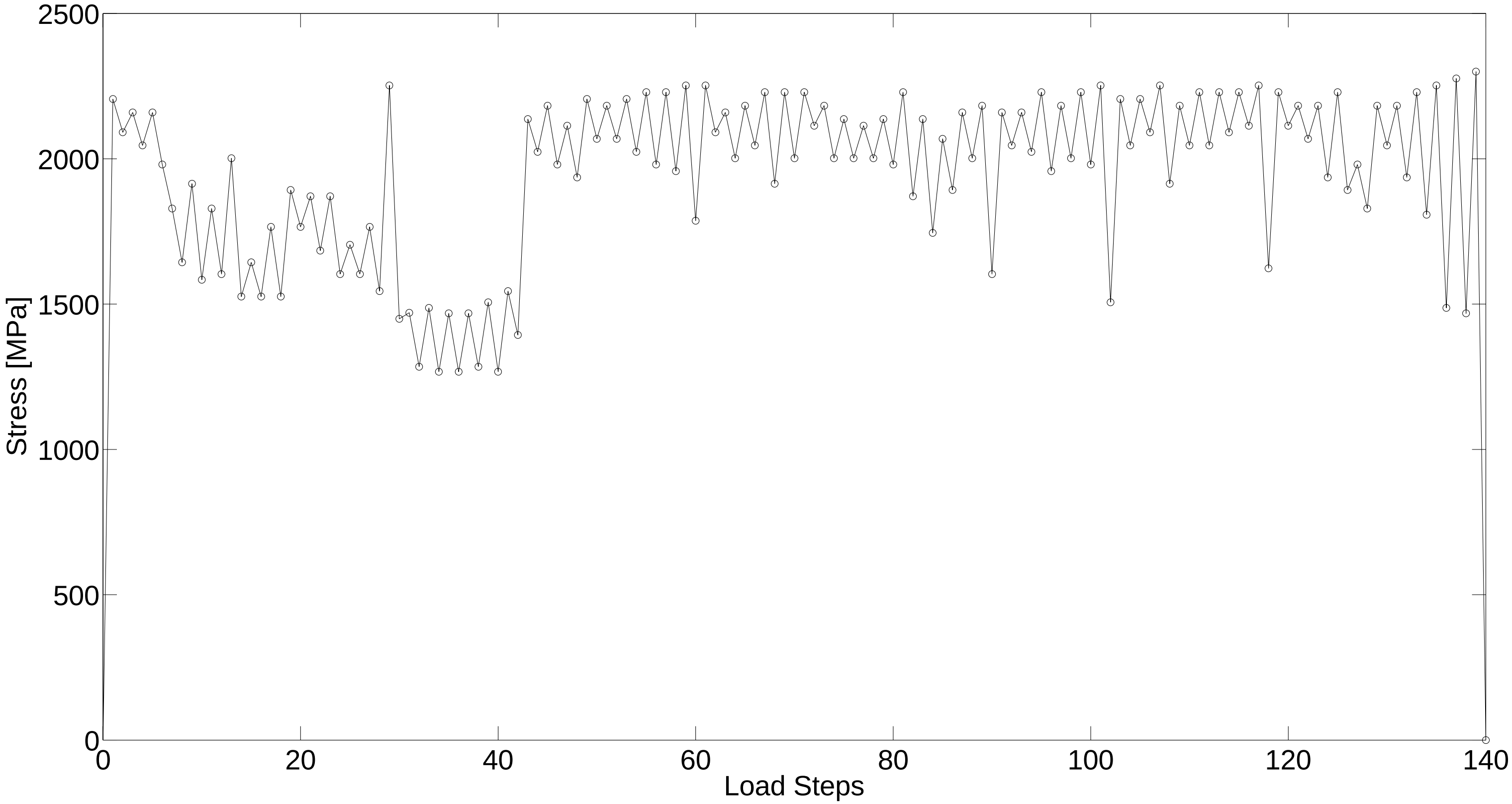
$$\frac{da}{dN} = C_1\left[(\mathrm{D}K)(1 - R)^{(m-1)}\right]^{n_1} \qquad \mathrm{D}K < b$$

$$\frac{da}{dN} = C_2\left[(\mathrm{D}K)(1 - R)^{(m-1)}\right]^{n_2} \qquad \mathrm{D}K \geq b$$

$$b = \frac{\log_{10}(C_1) - \log_{10}(C_2)}{n_2 - n_1}$$

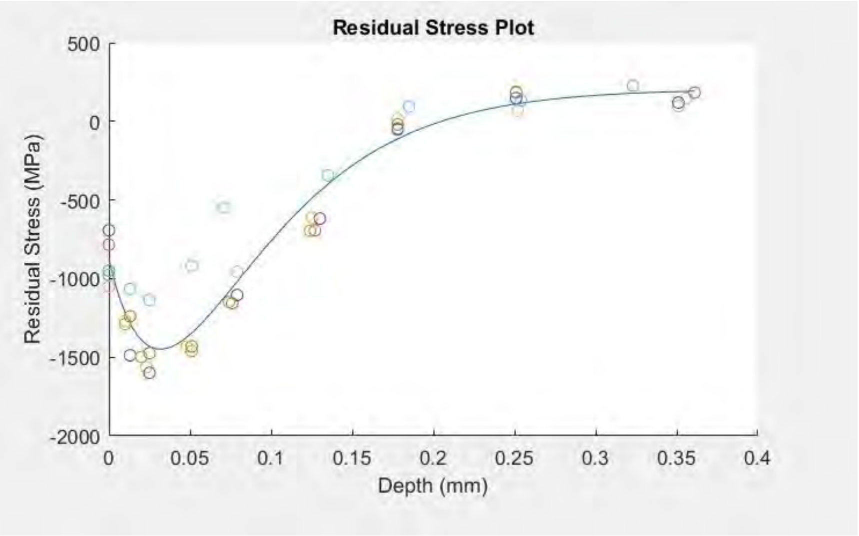
Residual Stress Sensitivity Study

Variable Amplitude Loading



Previous RS Sensitivity Study

➢ Shot Peening Residual Stress Profile (Random)



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

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

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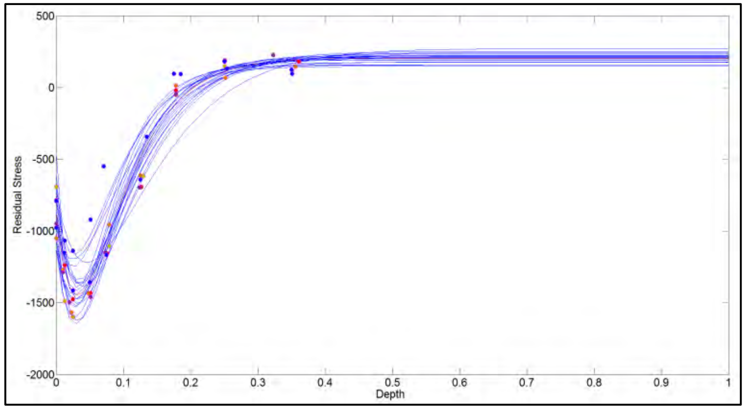
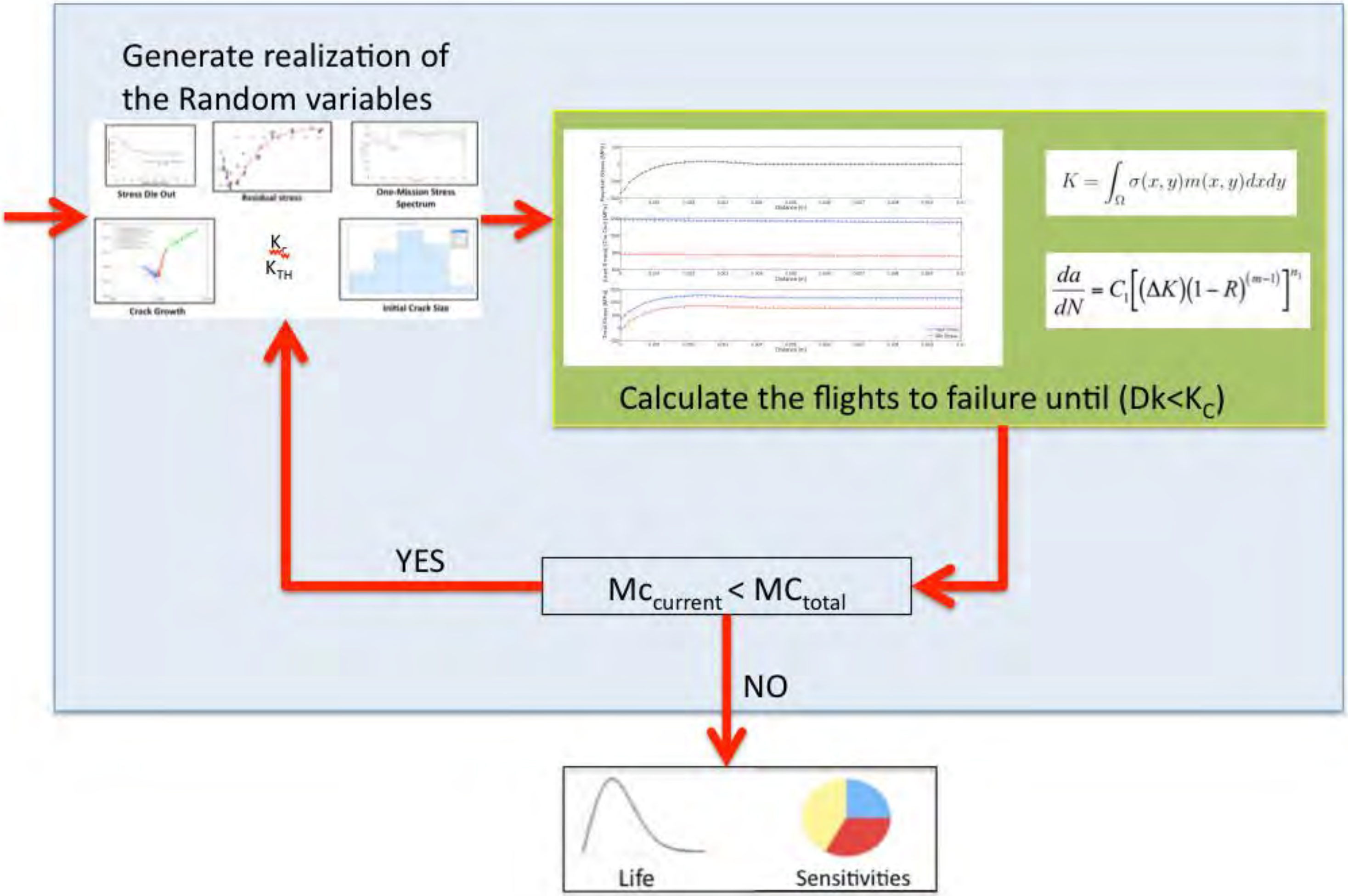


Residual Stress Sensitivity Study



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Sensitivity Results

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

$$S_i = \frac{V_{X_i}\left(E_{X\sim i}(Y/X_i)\right)}{V(Y)}$$

Input variable	Sensitivity Value	Importance	Sensitivity Value	Importance
C2	0.30	1	0.473479	1
Si	0.18	2	0.329348	2
Paris	0.16	3	0.150957	4
Ss	0.09	4	0.198532	3
ai	0.04	5	0.092150	5
Loading	0.01	6	0.014135	6
W	0.0026	7	0.003211	7
Kic	0.0009	8	0.001111	8
t	0.000009	9	1.11E-05	9

Results are problem dependent

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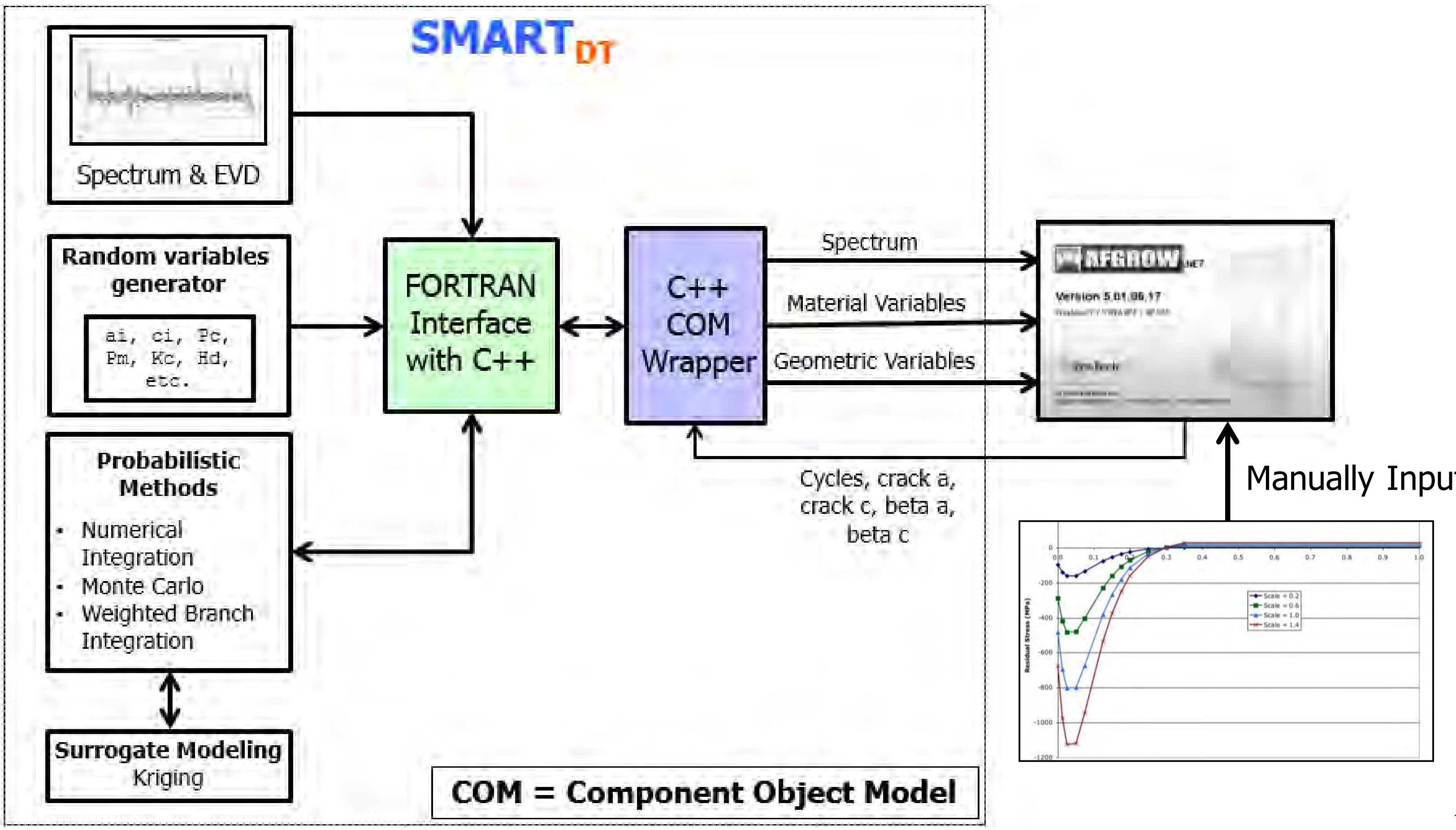
Residual Stress Effect on SFPOF Using Deterministic Residual Stress Profile

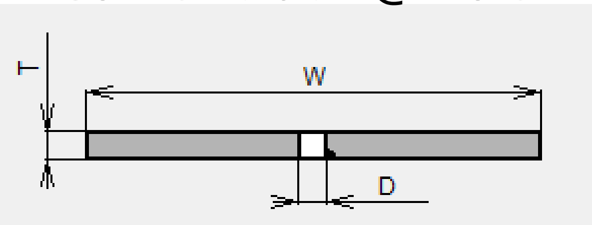
Residual Stress Effect on SFPOF

- SMART-AFGROW interface.

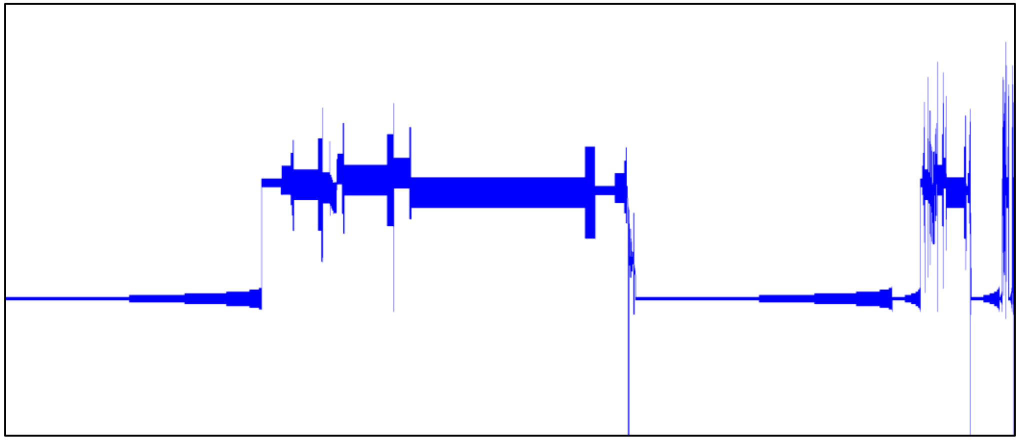


Input Parameters
Deterministic RS Example

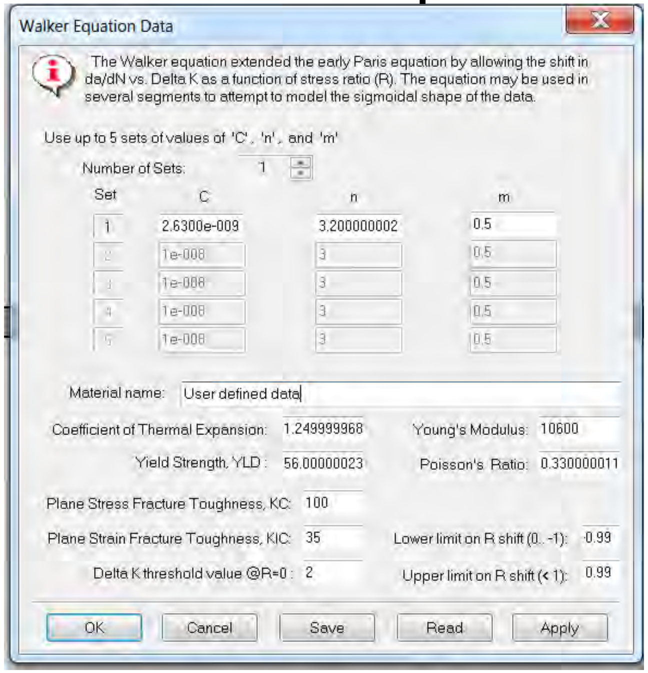
Corner crack @ hole



Parameter	Value
T	0.09 in
W	4.0 in
D	0.25 in

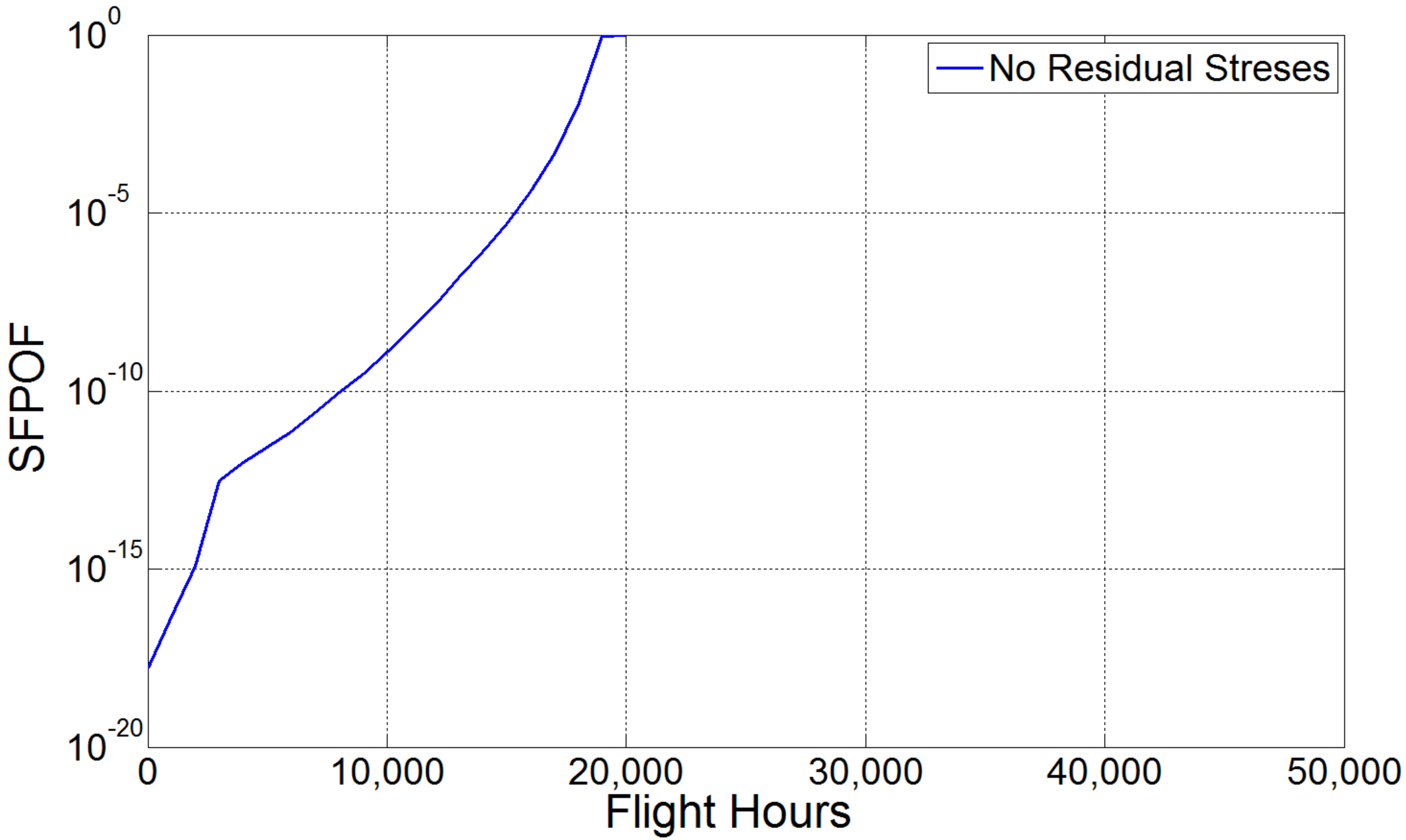


Mat. Prop.

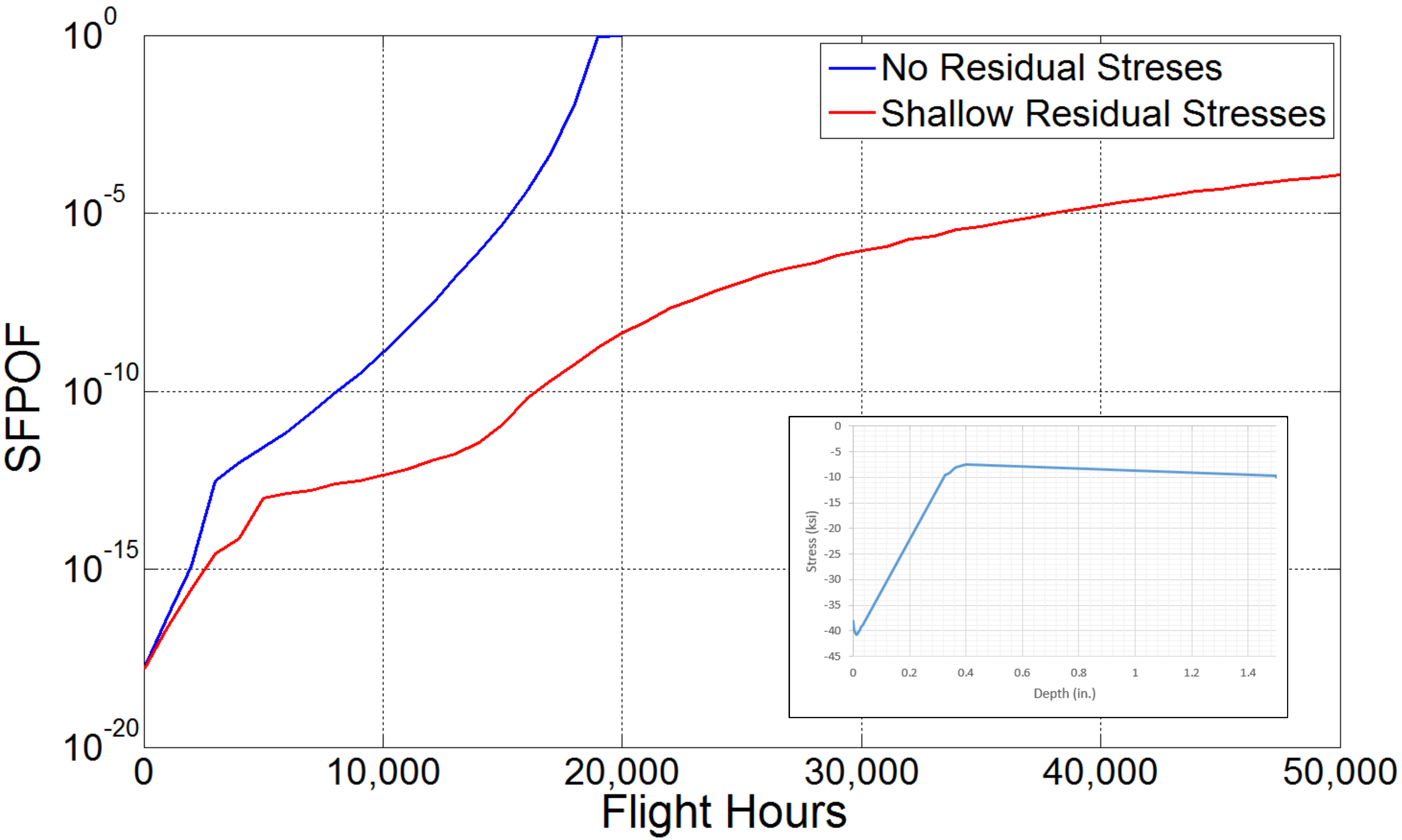


Random Variables	Value
Fracture Toughness Distribution (Normal)	Mean = 34.5ksi√in, Standard Deviation = 3.8 ksi√in.
Initial & Repair Lognormal Size Distribution (a & c) (Lognormal)	Mean = 0.01 in, Standard Deviation = 0.001 in.
Extreme Value Distribution (Gumbel)	Location = 14.5, Scale = 0.8, and Shape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

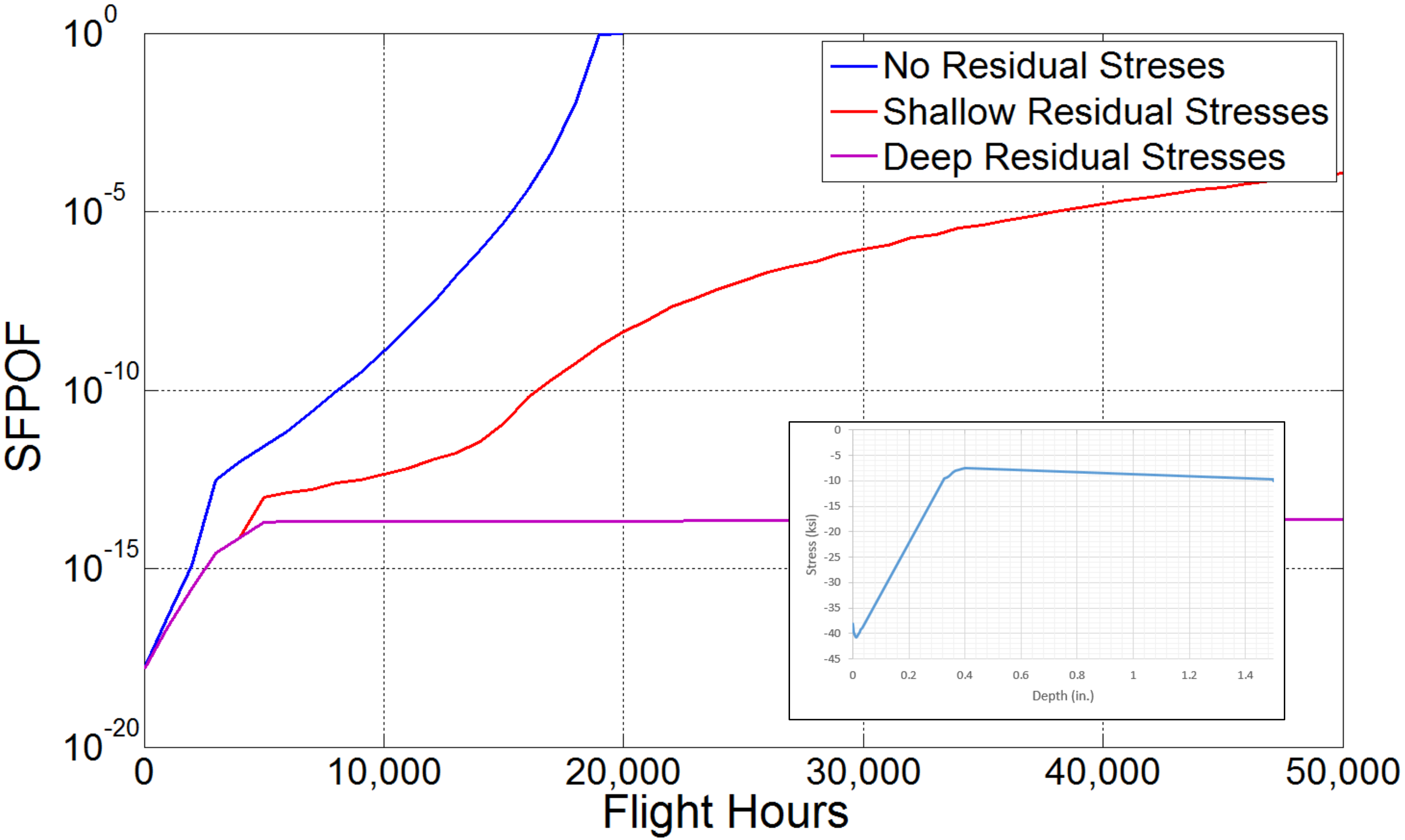
Results without Inspections



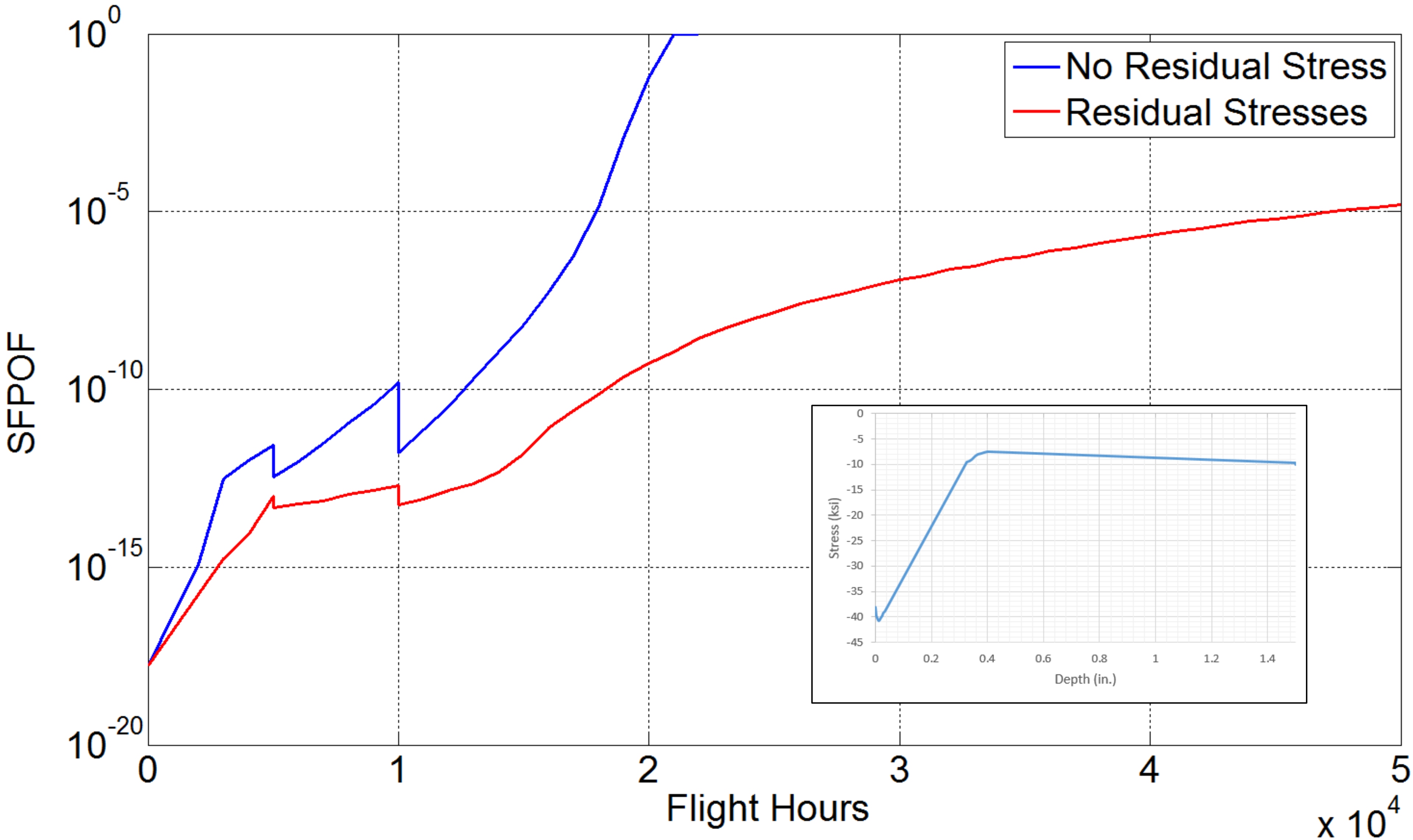
Results without Inspections



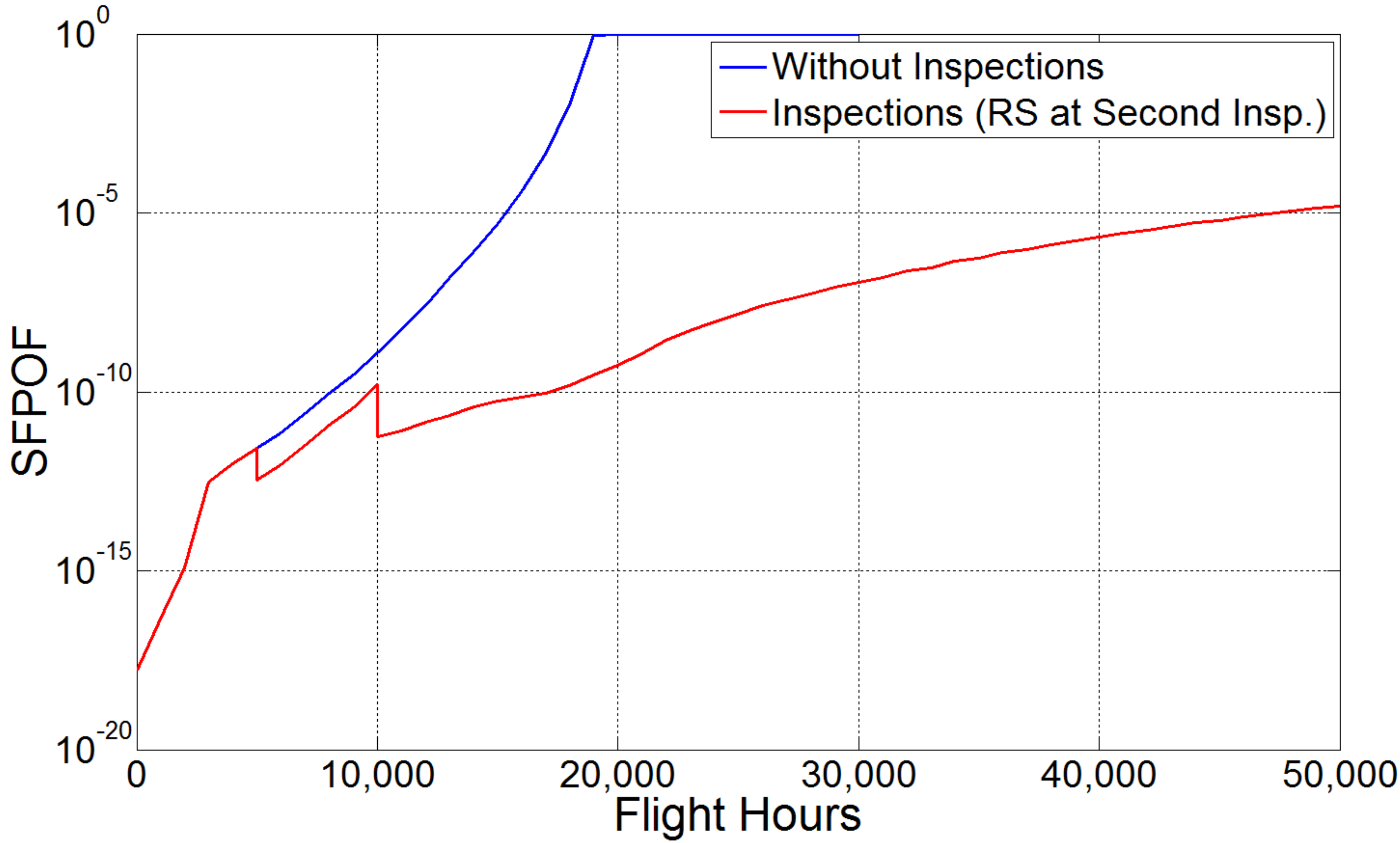
Results without Inspections



ERSI Results with Inspections



Inducing RS at the Second Inspections



SMART Internal Crack Growth Code

An Ultrafast Crack Growth Lifing Algorithm for Probabilistic Damage Tolerance Analysis

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The Aircraft Airworthiness & Sustainment (AA&S) Conference
Jacksonville, FL. May– 2018.

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Purpose

- Probabilistic damage tolerance analysis requires very small probabilities, e.g., 1E-9
- Previous methods allow for a deterministic crack growth curve and do not consider randomness in crack growth rate properties.
- Surrogate models, e.g., Kriging, can be used to speed up the analysis but are still very time consuming.
- Hence an ultrafast crack growth lifing code was developed.

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Ultrafast Approach

1) Create an equivalent constant amplitude from an arbitrary spectrum
2) Use an *internal* adaptive time stepping RK algorithm to grow the crack
3) Collect the top 100 (or so) damaging realizations for further examination and potential reanalysis

Thank you!!

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