Introduction to Probabilistic Methods with Applications to Probabilistic Damage Tolerance Analysis

Master Curve Fundamentals

Harry Millwater - University of Texas at San Antonio,
Juan Ocampo, St. Mary's University,
Nathan Crosby, AeroMatter Inc.
Beth Gamble, Chris Hurst, Textron Aviation (Cessna)
Marv Nuss, Nuss Sustainment Solutions

THE AIRCRAFT AIRWORTHINESS & SUSTAINMENT CONFERENCE






August 29, 2022

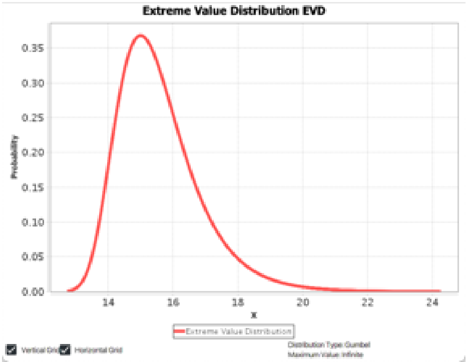
Outline

- ✓Probability of Failure review
- ✓Master Curve interpolation
  - ✓Excel exercises
    - ✓Simple crack growth interpolation to compute POF
      - ✓BasicPOF.smdt
      - ✓MasterCurveBasicsPOF.xlsx
      - ✓MasterCurveBasicsPOF.mp4
    - ✓Master Curve with Kc random to compute POF
      - ✓Kc_rnd.smdt
      - ✓MasterCurveRnd_Kc.xlsx
      - ✓MasterCurveRnd_Kc.mp4
- ✓External Crack Growth Link Options Review – Hypergrow
  - ✓Example using SMART
    - ✓MC_Hypergrow_NewmanRajuCorner.smdt
- ✓Supplemental Material
  - ✓Additional Example problem using SMART
    - ✓Test_Ex1.smdt

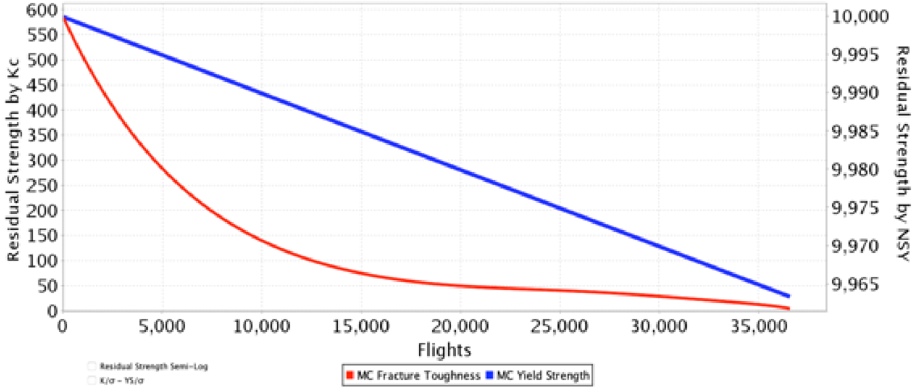
Probability of Failure

The probability-of-failure (POF) is the probability that maximum value of the applied stress (during the next flight) will exceed the residual strength σ_{RS} of the aircraft component

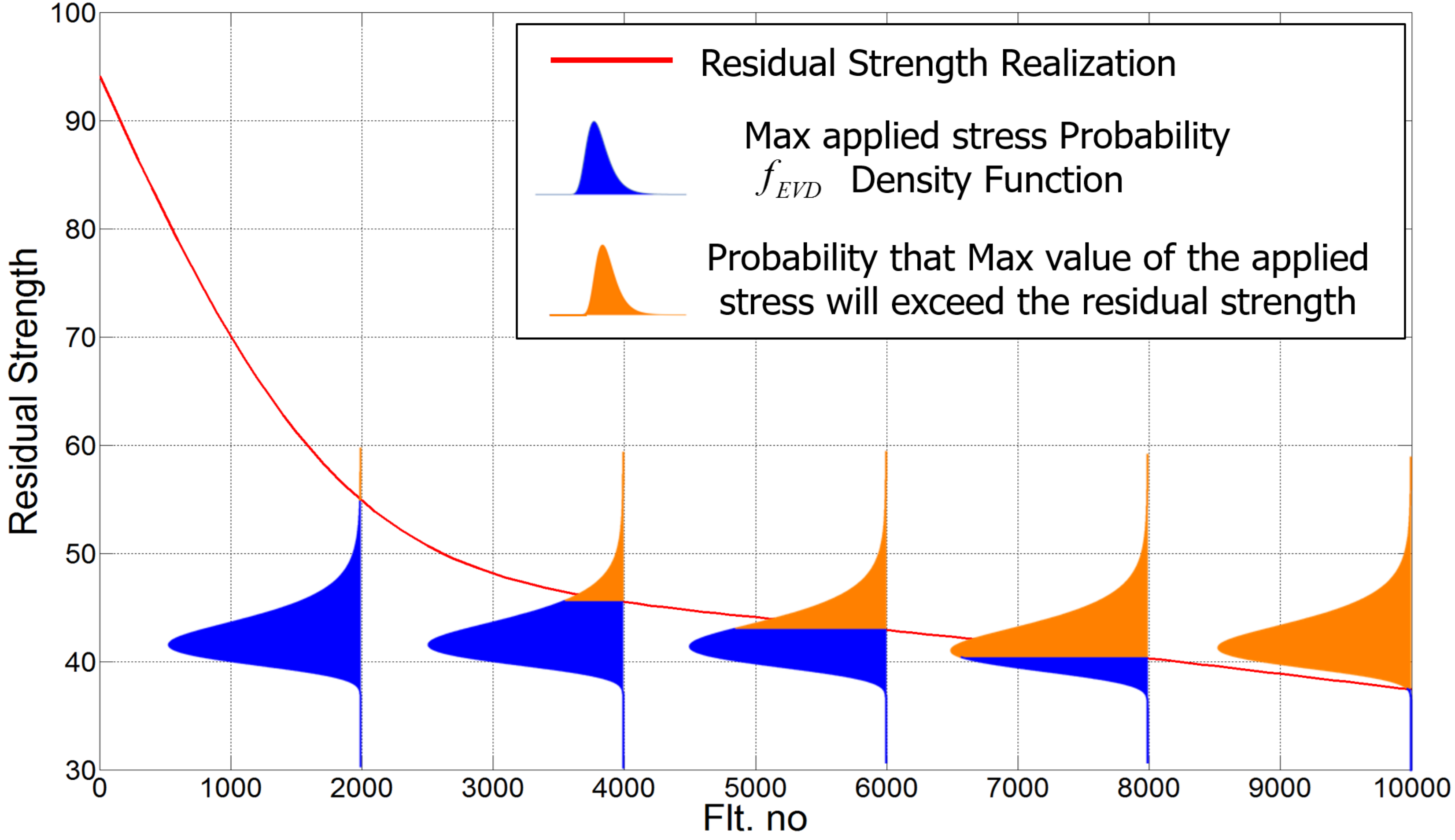
$$POF = P\left[\sigma_{Max} > \left(\frac{K_C}{\beta(a(a_o,t))\sqrt{\pi a(a_o,t)}}\right)\right] = P[\sigma_{Max} > \sigma_{RS}]$$



>



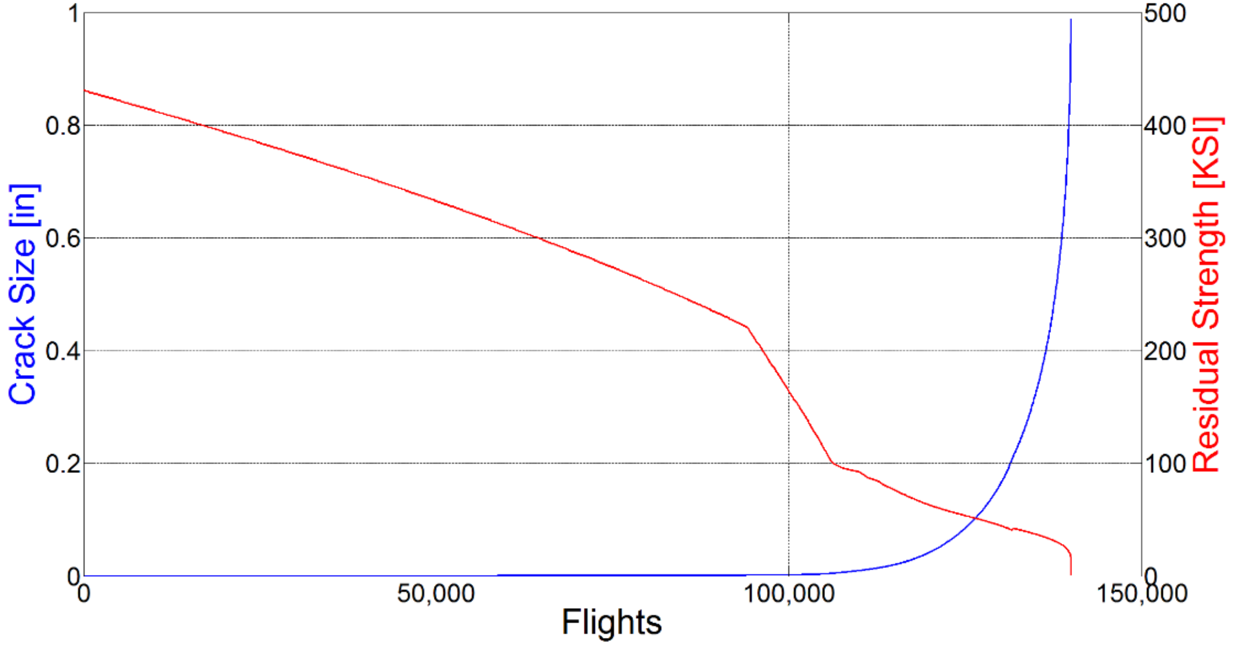
Probability of Failure

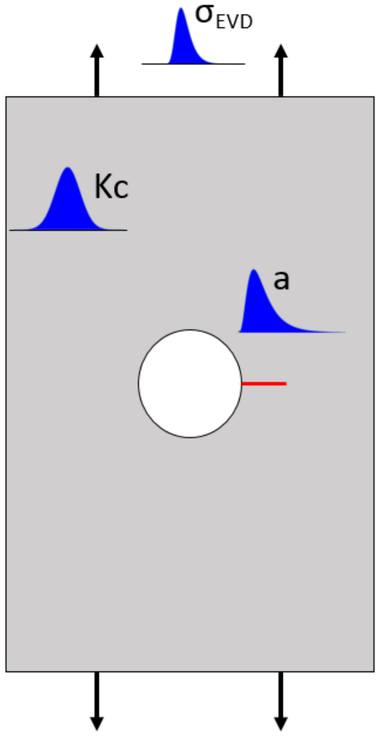


$$POF(t|a_i K_C) = 1 - F_{EVD}\left(\frac{K_C}{\beta(a(a_o,t))\sqrt{\pi a(a_o,t)}}\right)$$

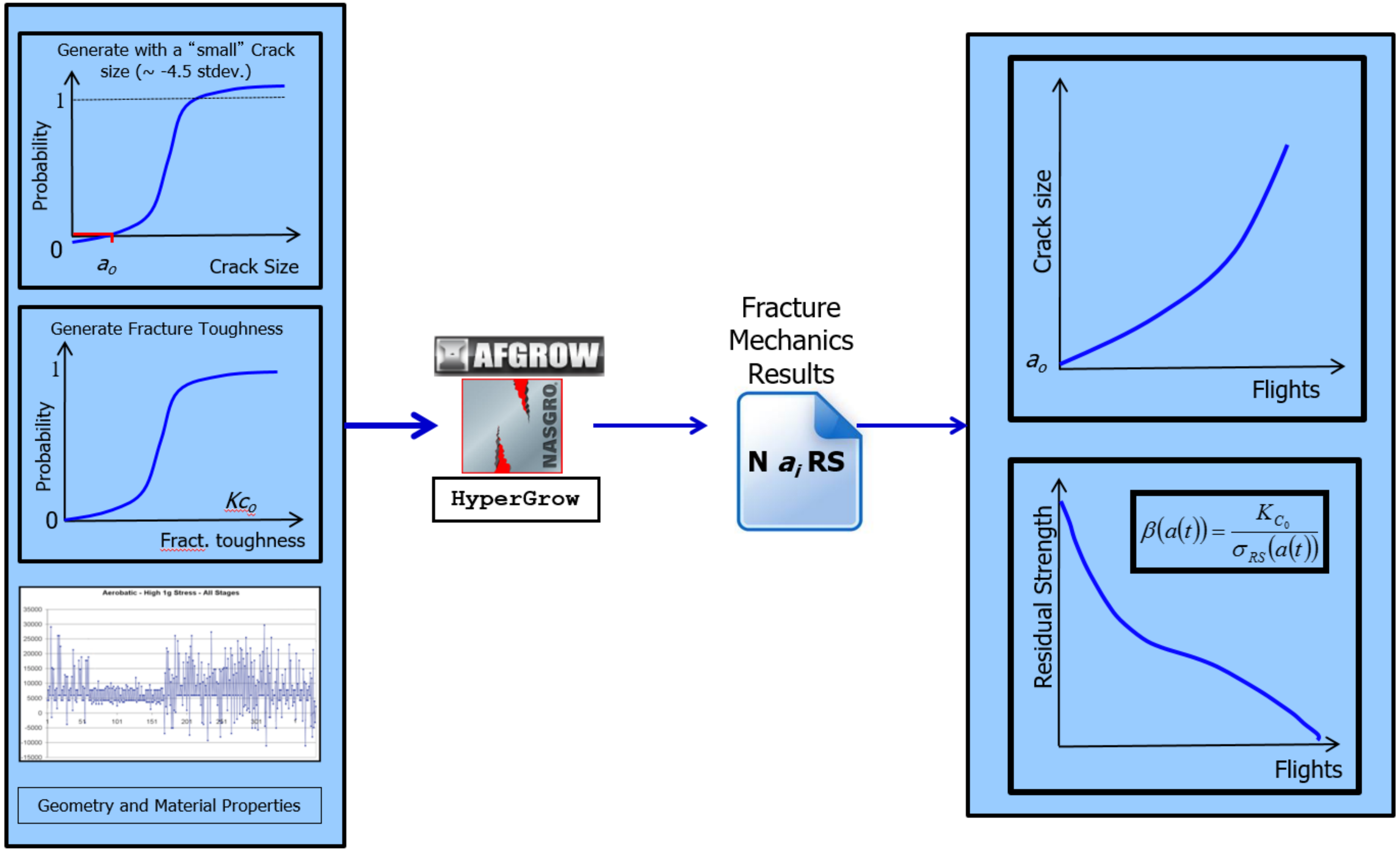
Master Curve Interpolation

- Assumptions:
  - One crack growth curve for the whole simulation.
    - **Only Kc, a_i and EVD can be random** - the structure has the same crack growth properties throughout the entire simulation.
    - One spectrum (representative) is used for the entire simulation.





Master Curve Approach



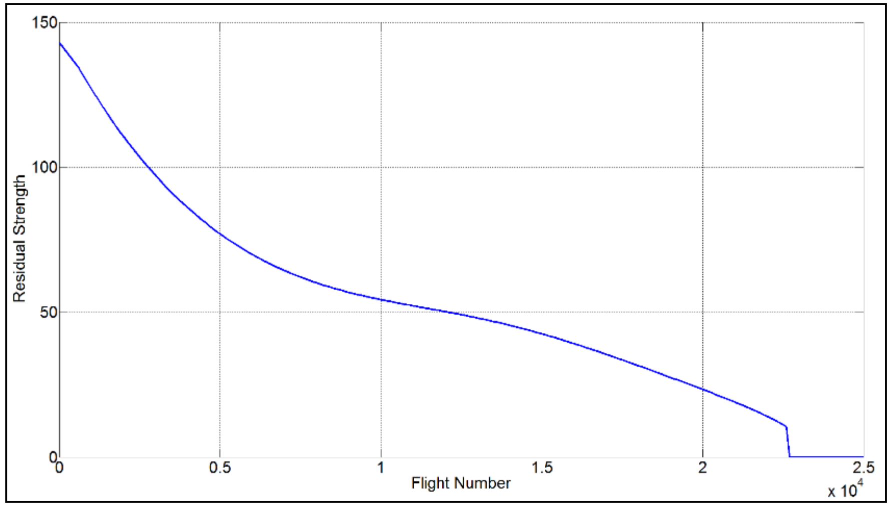
Residual Strength Interpolation

- From Fracture Mechanics we know:

$$K_C = \sigma_{RS}\beta(a(a_o,t))\sqrt{\pi a(a_o,t)}$$

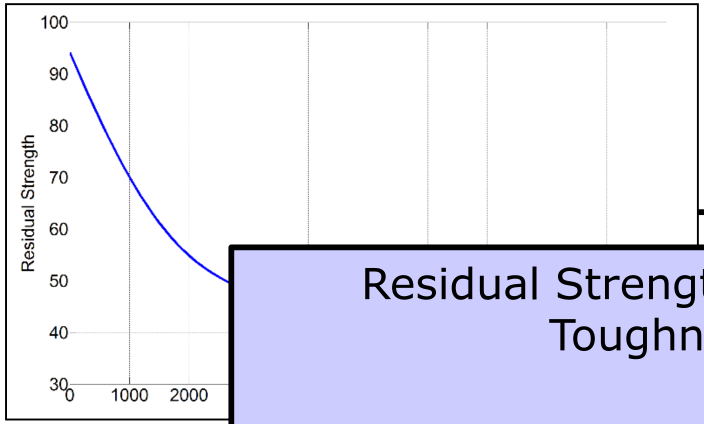
- Residual Strength can be defined as:

$$\sigma_{RS} = \frac{K_C}{\beta(a(a_o,t))\sqrt{\pi a(a_o,t)}}$$

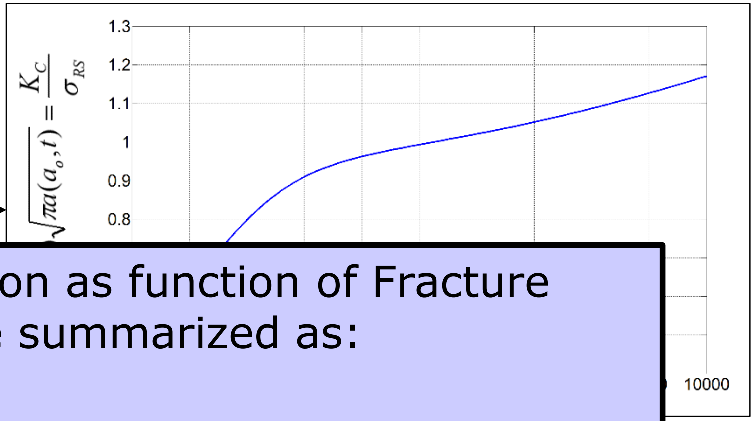


Residual Strength Interpolation

Get Residual Strength curve from Fracture Mechanics Analysis

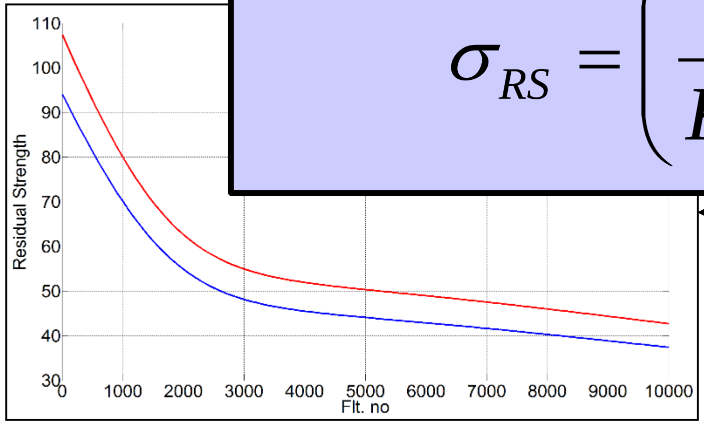


Normalize Residual Strength

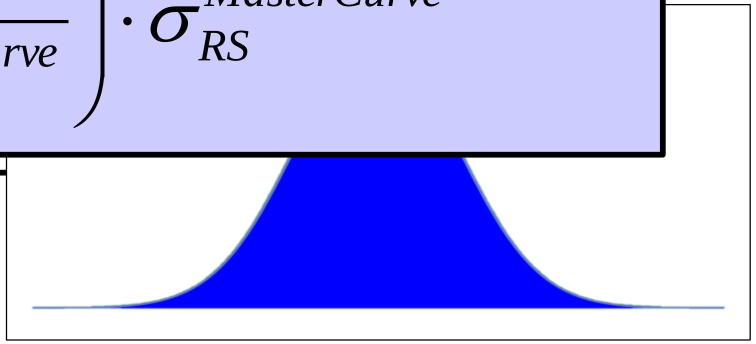


Residual Strength realization as function of Fracture Toughness can be summarized as:

$$\sigma_{RS} = \left(\frac{K_C^{Sample}}{K_C^{MasterCurve}} \right) \cdot \sigma_{RS}^{MasterCurve}$$



Generate Residual Strength given K_C^{Sample}



Generate Fracture Toughness realization (K_C^{Sample})

Excel Exercises

- Excel file:
  - MasterCurveBasicsPOF.xlsx
  - MasterCurveRnd_ai.xlsx
  - MasterCurveRnd_Kc.xlsx
- Excel files contained in:
  - \ Excel_Examples
- Videos contained in:
  - \ Videos

Master Curve Interpolation and POF Basics

E[POF] Calculation

- Integration:

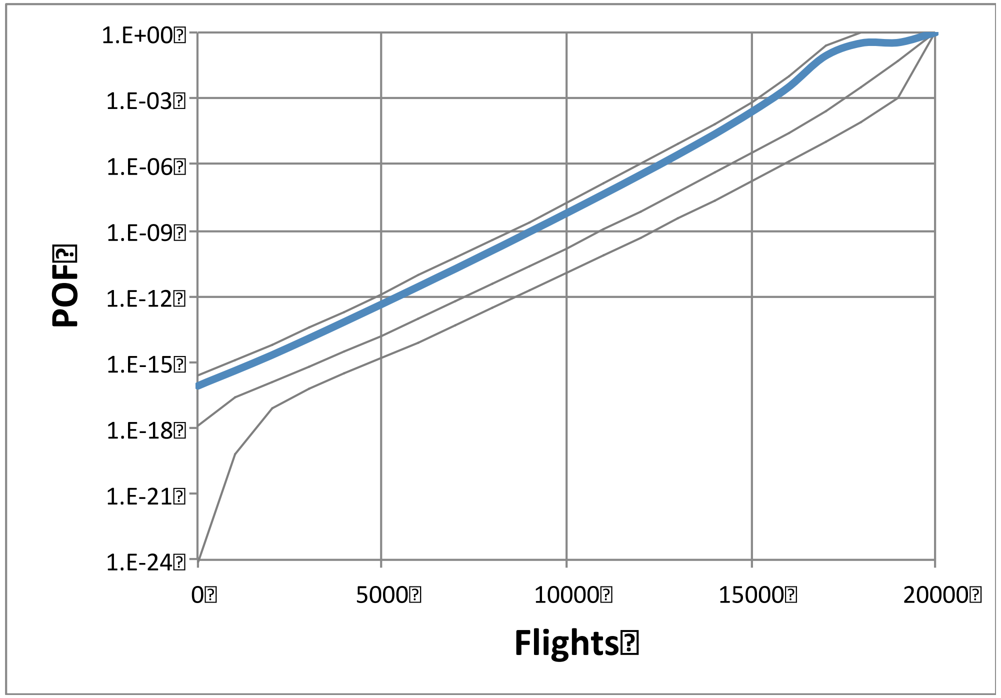
$$E[\mathrm{POF}]=\int_{0}^{\infty}\int_{-\infty}^{\infty}\left[1-F_{\mathrm{EVD}}\left(\frac{K_c}{\beta(a(a_i,t))\sqrt{\pi a(a_i,t)}}\right)\right]f_{a_i}\,f_{K_c}\,\mathrm{d}K_c\,\mathrm{d}a_i$$

- Sampling:

$$E[\mathrm{POF}]=\frac{1}{N}\sum_{i=1}^{N}\left[1-F_{\mathrm{EVD}}\left(\frac{K_{c_i}}{\beta(a(a_i,t))\sqrt{\pi a(a_i,t)}}\right)\right]$$

E[POF] Example

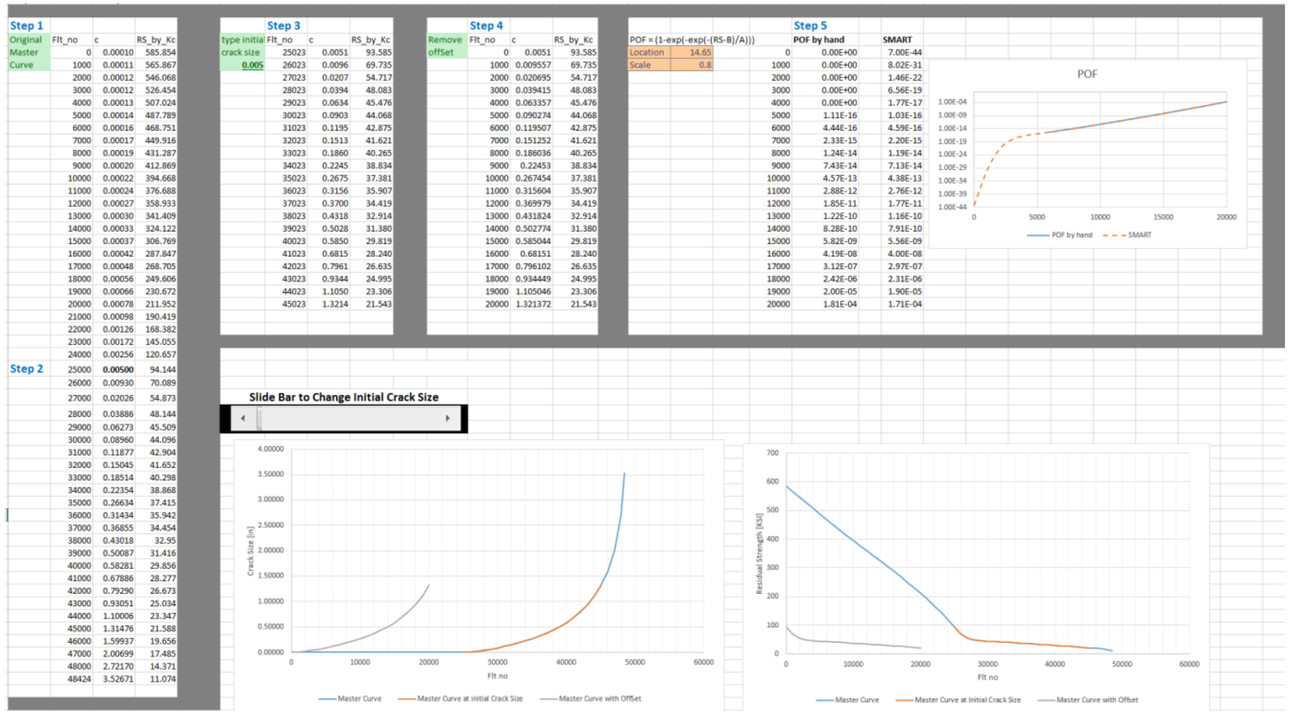
$$E[\text{POF}] = \frac{1}{3}\sum_{i=1}^{3} POF_i$$



	5000	10000	15000
POF_1	1.3 E-12	1.8 E-08	7.1 E-04
POF_2	1.6 E-14	1.6 E-10	3.3 E-06
POF_3	1.4 E-15	1.1 E-11	1.7 E-07
E[POF]	**4.4 E-13**	**6.0 E-09**	**2.3 E-04**

Excel Exercise

- ❑ Open the excel file:
  - ❑ MasterCurveBasicsPOF
- ❑ Contained in:
  - ❑\ Excel_Examples



Master Curve Steps

Step 1. Extract Flt. No., Crack Size, and Residual Strength from the fracture mechanics run.

Step 2. Find the value of your initial crack size on your crack growth curve.

Step 3. Extract the section of the curve from initial crack size to failure.

Step 4. Remove offset by subtracting the initial Flt. no. to all the Flt. no. values.

Let’s Compare with SMART (smdt file included)

Random Fracture Toughness Residual Strength Calculations

Excel Exercise

- Open the excel file:
  - MasterCurveRnd_Kc.xlsx
- Contained in:
  - \ Excel_Examples

	B	C	D	E	G	I	J	K	L	M	N	P	Q	R	S
1															
2	EVD Location (B)	14.65					POF = (1-exp(-exp(-(RS-B)/A)))								
3	EVD Scale (A)	0.8													
4	KC_{MC}	34.8					RS = $(KC_{SAMPLE}/KC_{MC})\ RS_{MC}$								
5	ai	0.005	Deterministic												
6															
7		Step 1			Step 2	Step 3						Step 3			
8	Original	Flt no.	c	Residual Strength	Samples	Sample 1	Master Curve flt no.	Sample flt no.	Residual Strength	Residual Strength Sample	POF	Sample 2	Master Curve flt no.	Sample flt no.	Residual Strength
9	Master	0	0.00010	585.85	12.62	Kc	25000	0	94.14	34.15	2.59E-11	Kc	25000	0	94.14
10	Curve	1000	0.00011	565.87	16.35	12.62	26000	1000	70.09	25.43	1.41E-06	16.35	26000	1000	70.09
11		2000	0.00012	546.07	14.63		27000	2000	54.87	19.91	1.40E-03		27000	2000	54.87
12		3000	0.00012	526.45	13.58		28000	3000	48.14	17.47	2.92E-02		28000	3000	48.14
13		4000	0.00013	507.02	15.35		29000	4000	45.51	16.51	9.32E-02		29000	4000	45.51
14		5000	0.00014	487.79			30000	5000	44.10	16.00	1.69E-01		30000	5000	44.10
15		6000	0.00016	468.75			31000	6000	42.90	15.56	2.73E-01		31000	6000	42.90
16		7000	0.00017	449.92			32000	7000	41.65	15.11	4.30E-01		32000	7000	41.65
17		8000	0.00019	431.29			33000	8000	40.30	14.62	6.46E-01		33000	8000	40.30
18		9000	0.00020	412.87			34000	9000	38.87	14.10	8.63E-01		34000	9000	38.87
19		10000	0.00022	394.67			35000	10000	37.42	13.57	9.79E-01		35000	10000	37.42
20		11000	0.00024	376.69			36000	11000	35.94	13.04	9.99E-01		36000	11000	35.94
21		12000	0.00027	358.93			37000	12000	34.45	12.50	1.00E+00		37000	12000	34.45
22		13000	0.00030	341.41			38000	13000	32.95	11.95	1.00E+00		38000	13000	32.95
23		14000	0.00033	324.12			39000	14000	31.42	11.40	1.00E+00		39000	14000	31.42

Using 5 Residual Strength samples compute the probability of failure

Exercise Steps

Step 1. Extract Flt no., Crack Size, and Residual Strength from the fracture mechanics run.

Step 2. Locate the five fracture toughness random samples *(Extracted from SMART).*

Step 3. Copy and paste each of the five fracture toughness samples.

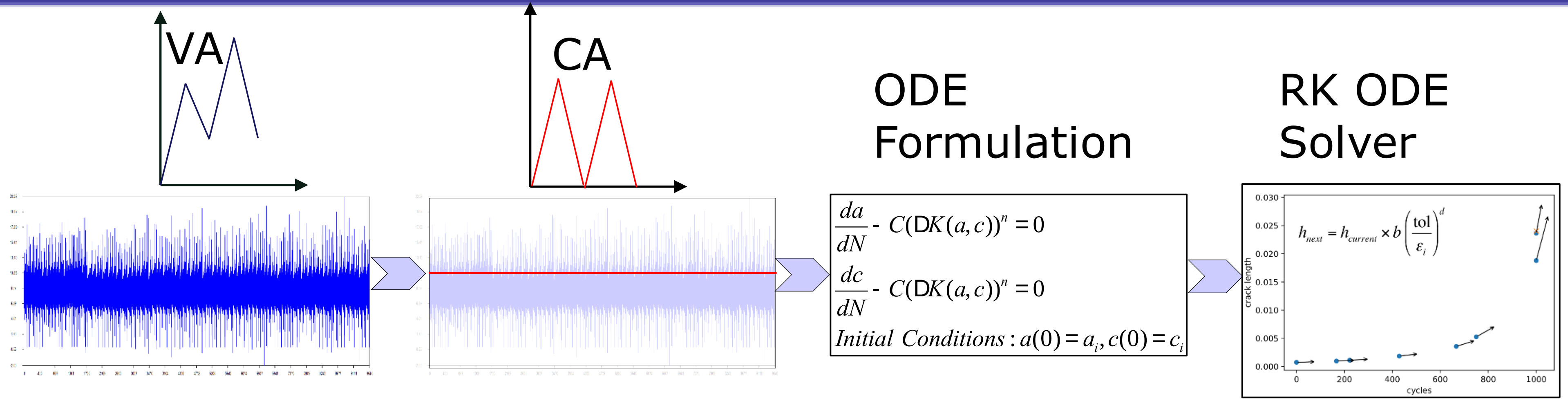
Step 4. Copy the POF value at 10,000 flights.

Step 5. Compute the average using the five POF values at 10,000.

Let's Compare with SMART (smdt file included)

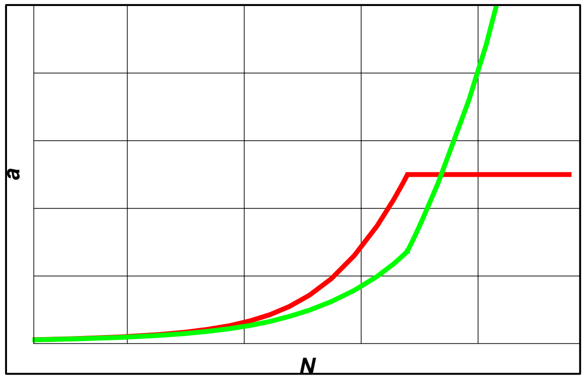
MasterCurve from Hypergrow

"Hypergrow" CG Code

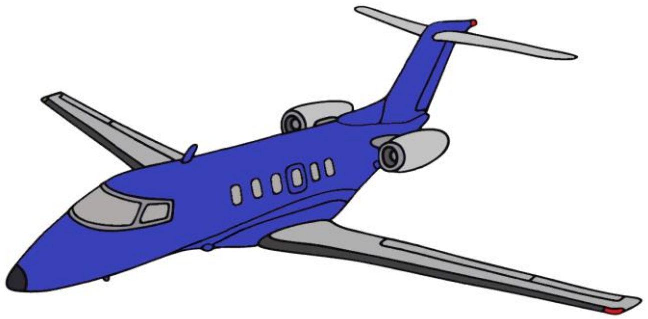


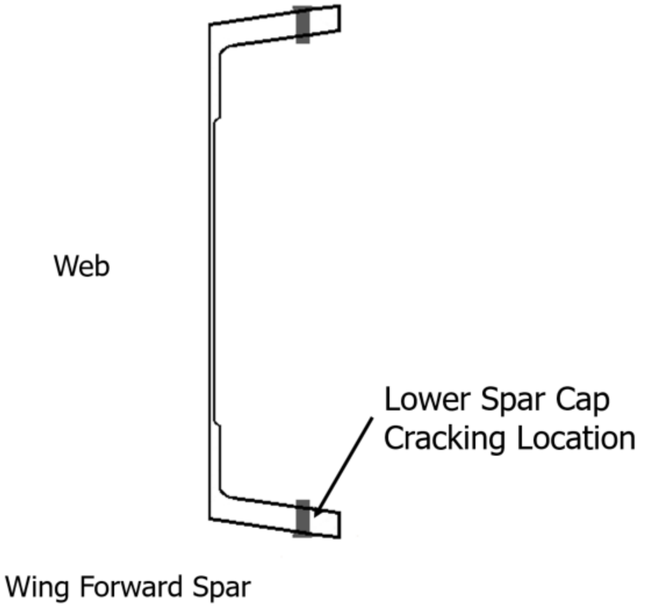
ICG Capabilities	
Method	4-5th order Runge-Kutta
Accuracy	Error controlled by user tolerance
Speed	~10,000/sec single proc.
Parallel	95% speedup on 8 proc.
K solutions	Newman-Raju, read beta tables

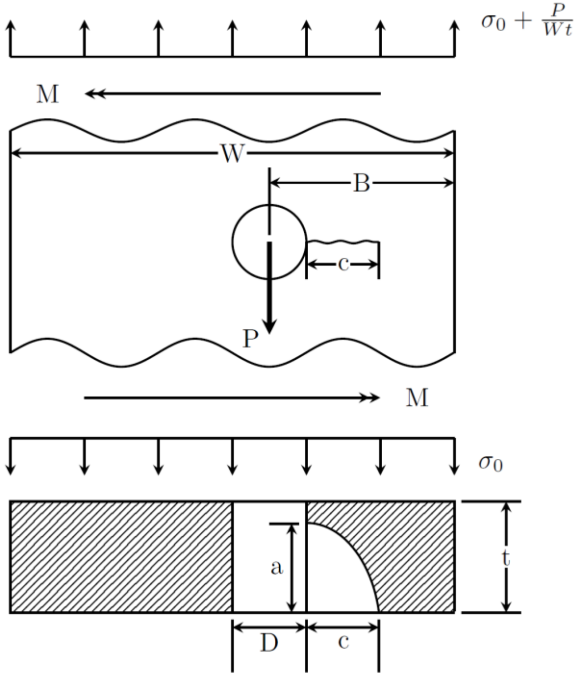
Crack Growth Result



Problem definition



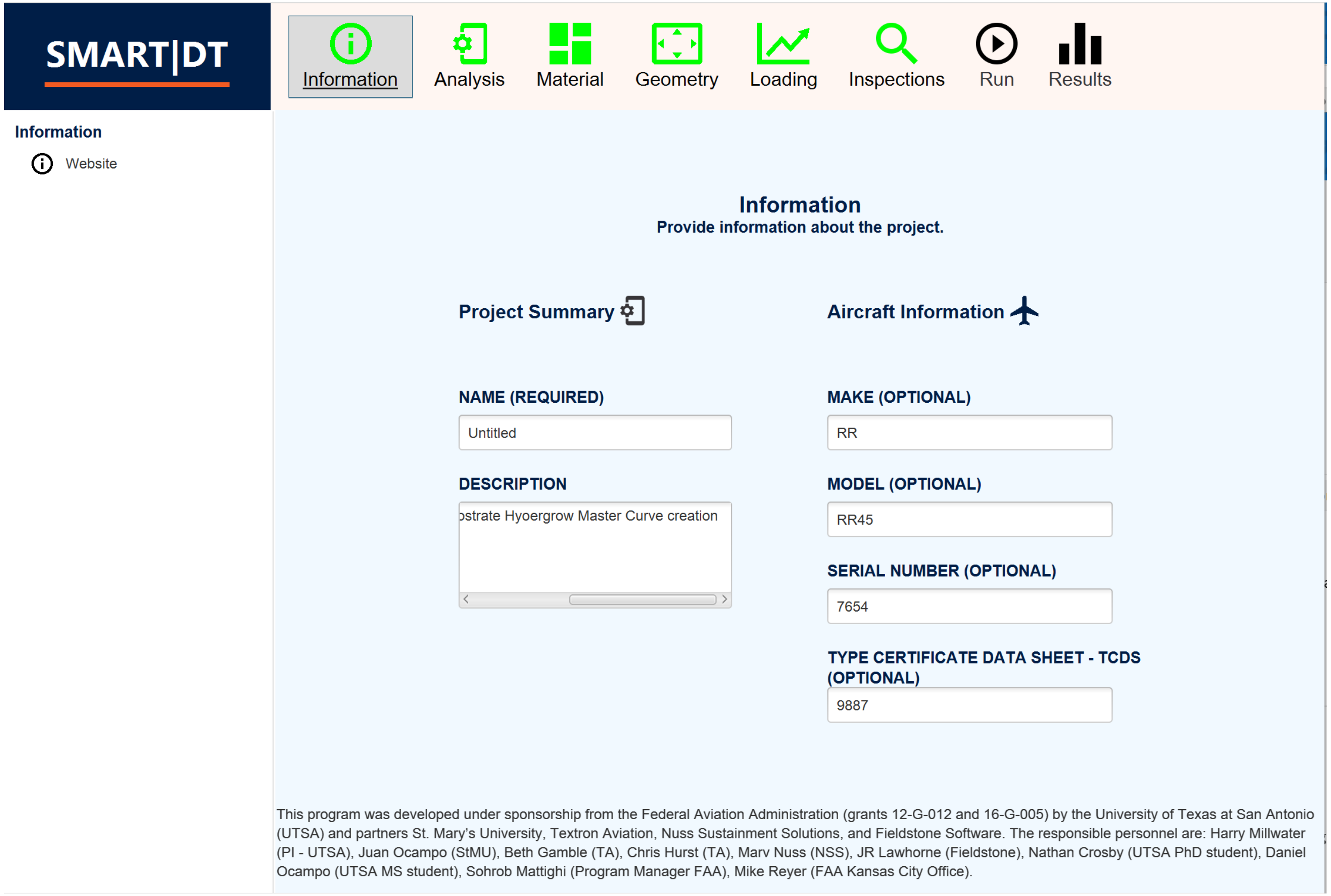




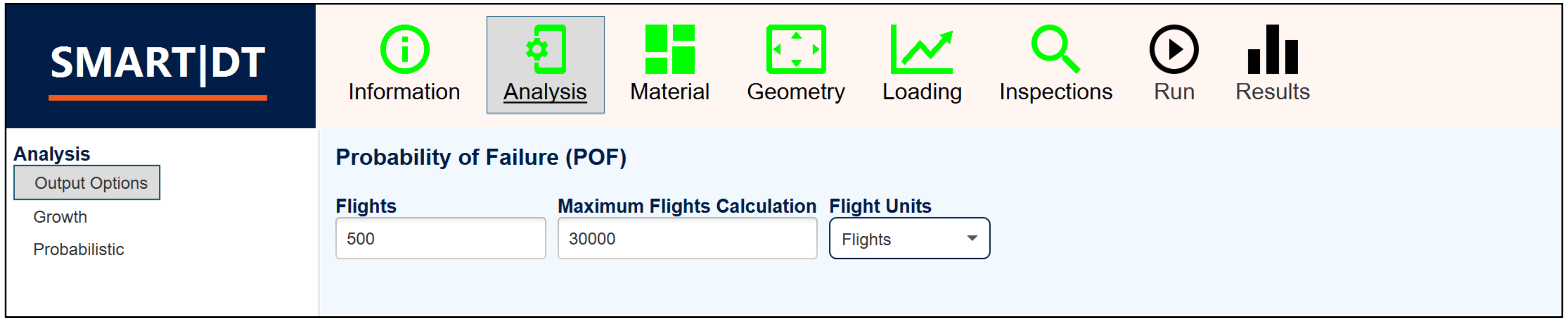
Geometric Variables	Value
Hole radius	0.164 in
Cap Thickness	0.175 in
Cap Width	1.80 in

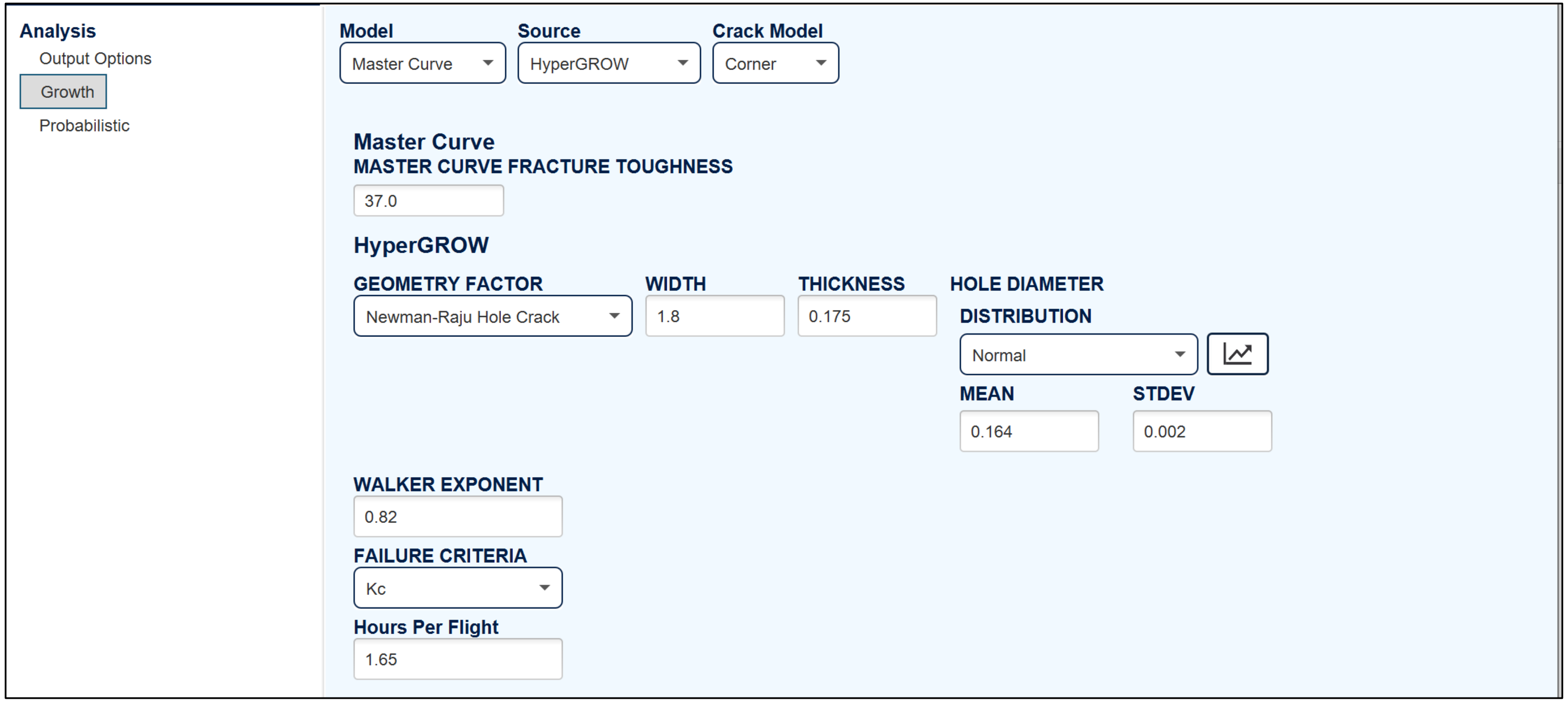
MC_Hypergrow_NewmanRajuCorner.smdt

GUI – Info

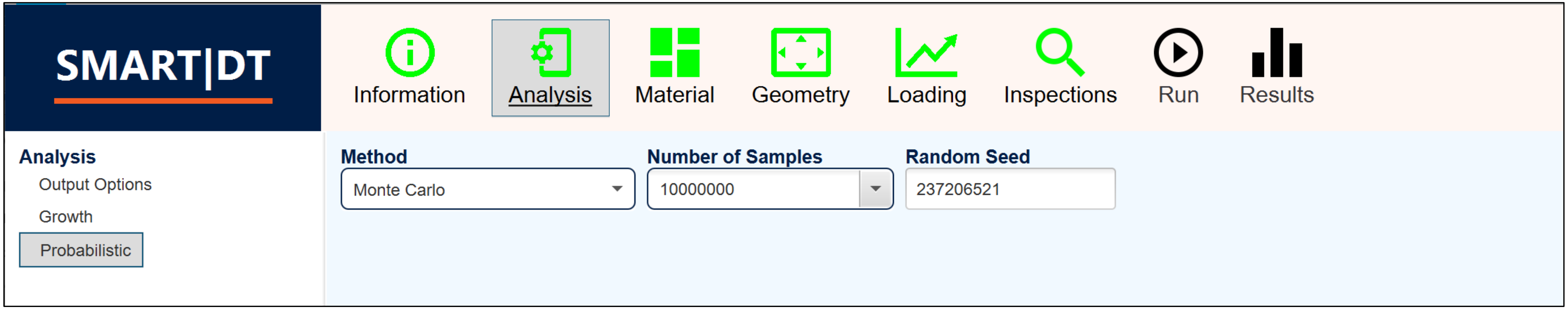

SMART|DT
Information
Analysis
Material
Geometry
Loading
Inspections
Run
Results
Information
Website
Information
Provide information about the project.
Project Summary
Aircraft Information
NAME (REQUIRED)
Untitled
DESCRIPTION
ɔstrate Hyoergrow Master Curve creation
MAKE (OPTIONAL)
RR
MODEL (OPTIONAL)
RR45
SERIAL NUMBER (OPTIONAL)
7654
TYPE CERTIFICATE DATA SHEET - TCDS (OPTIONAL)
9887
This program was developed under sponsorship from the Federal Aviation Administration (grants 12-G-012 and 16-G-005) by the University of Texas at San Antonio (UTSA) and partners St. Mary's University, Textron Aviation, Nuss Sustainment Solutions, and Fieldstone Software. The responsible personnel are: Harry Millwater (PI - UTSA), Juan Ocampo (StMU), Beth Gamble (TA), Chris Hurst (TA), Marv Nuss (NSS), JR Lawhorne (Fieldstone), Nathan Crosby (UTSA PhD student), Daniel Ocampo (UTSA MS student), Sohrob Mattighi (Program Manager FAA), Mike Reyer (FAA Kansas City Office).

GUI - Analysis (I)

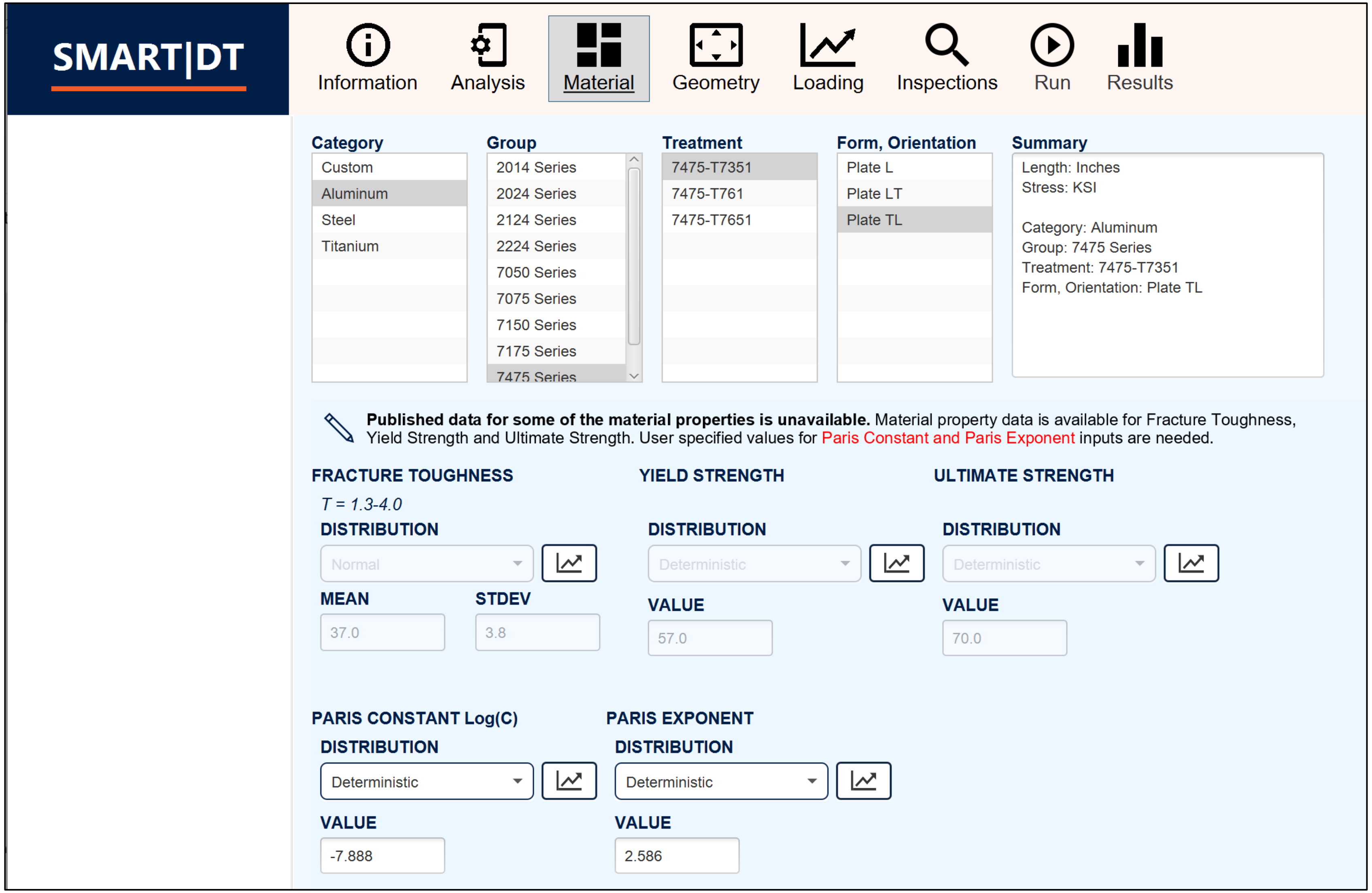




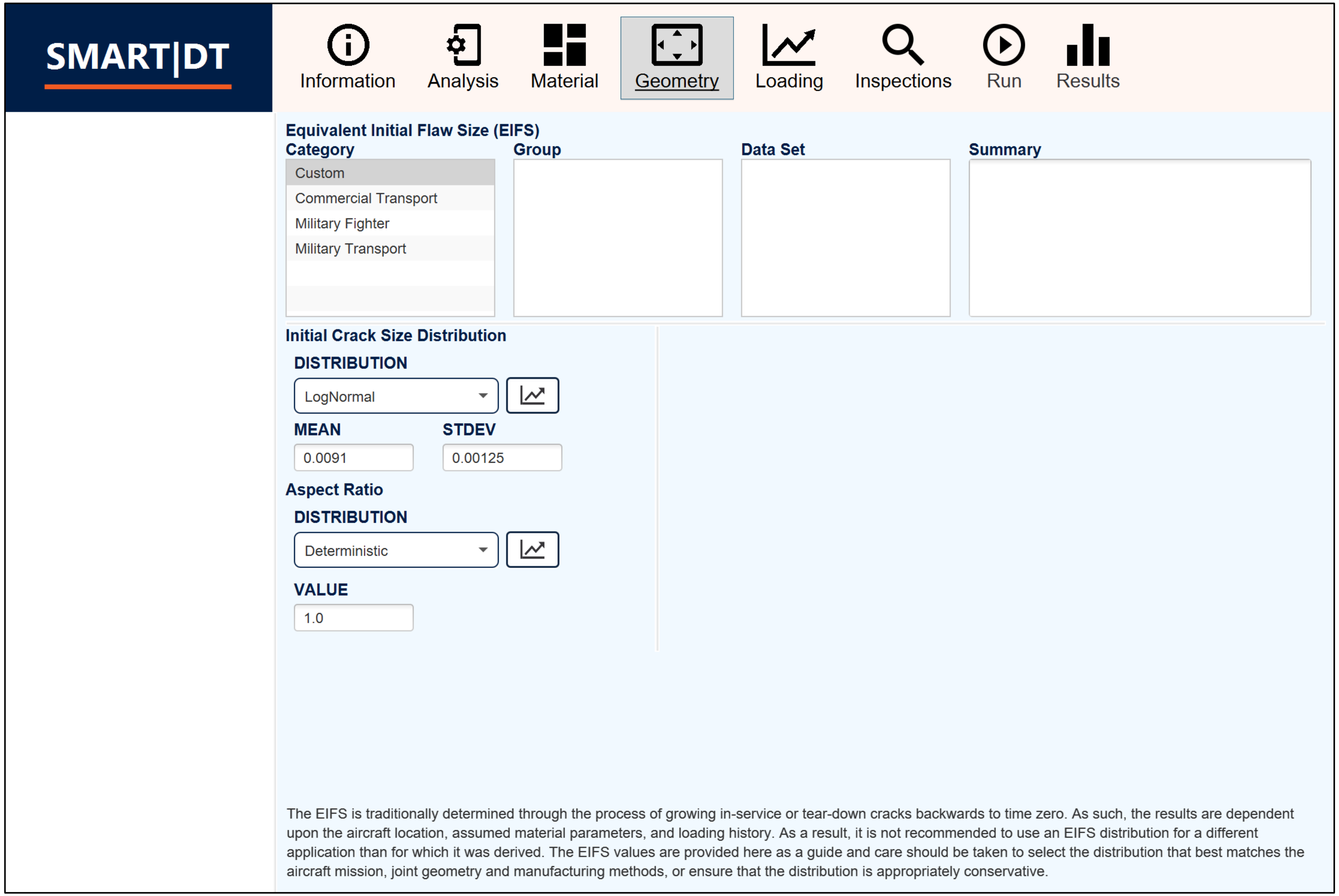
GUI - Analysis (II)



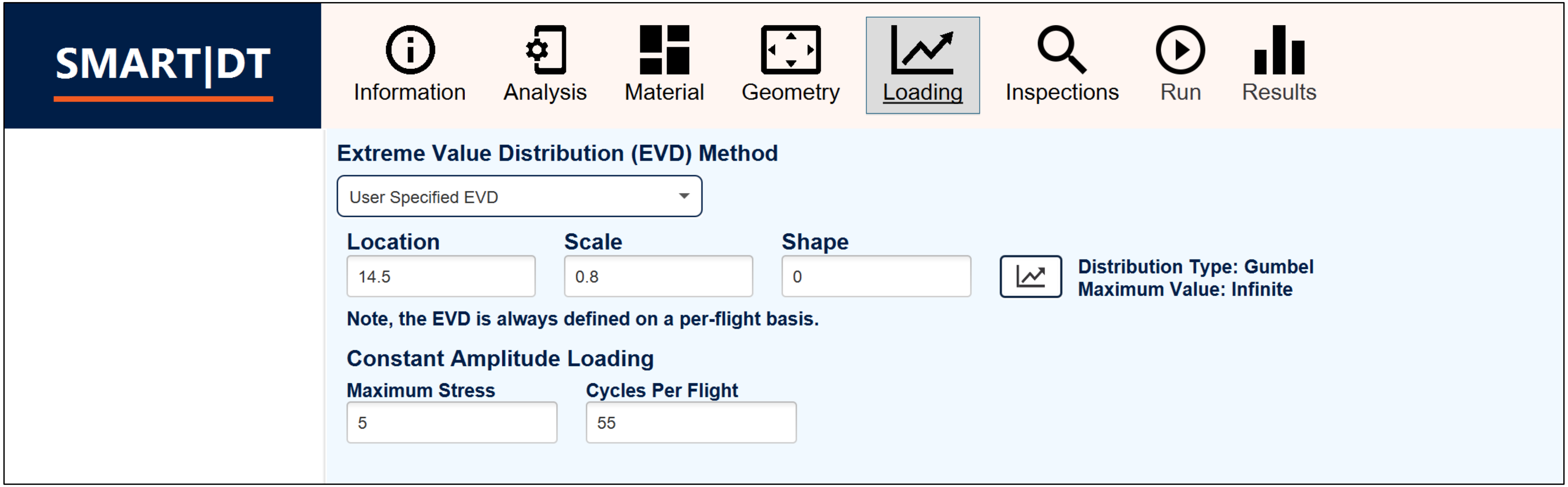
GUI - Material



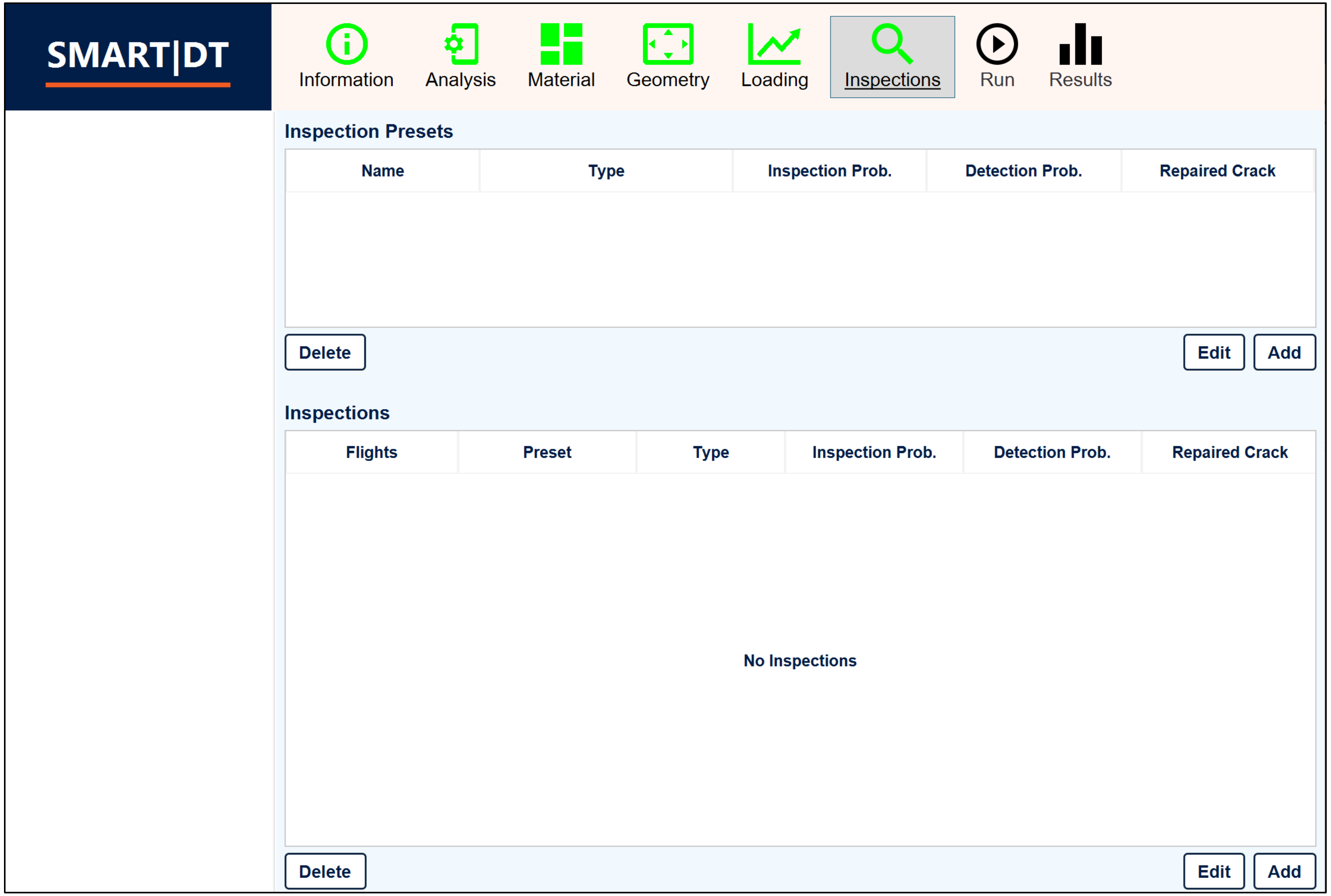
GUI – Geometry



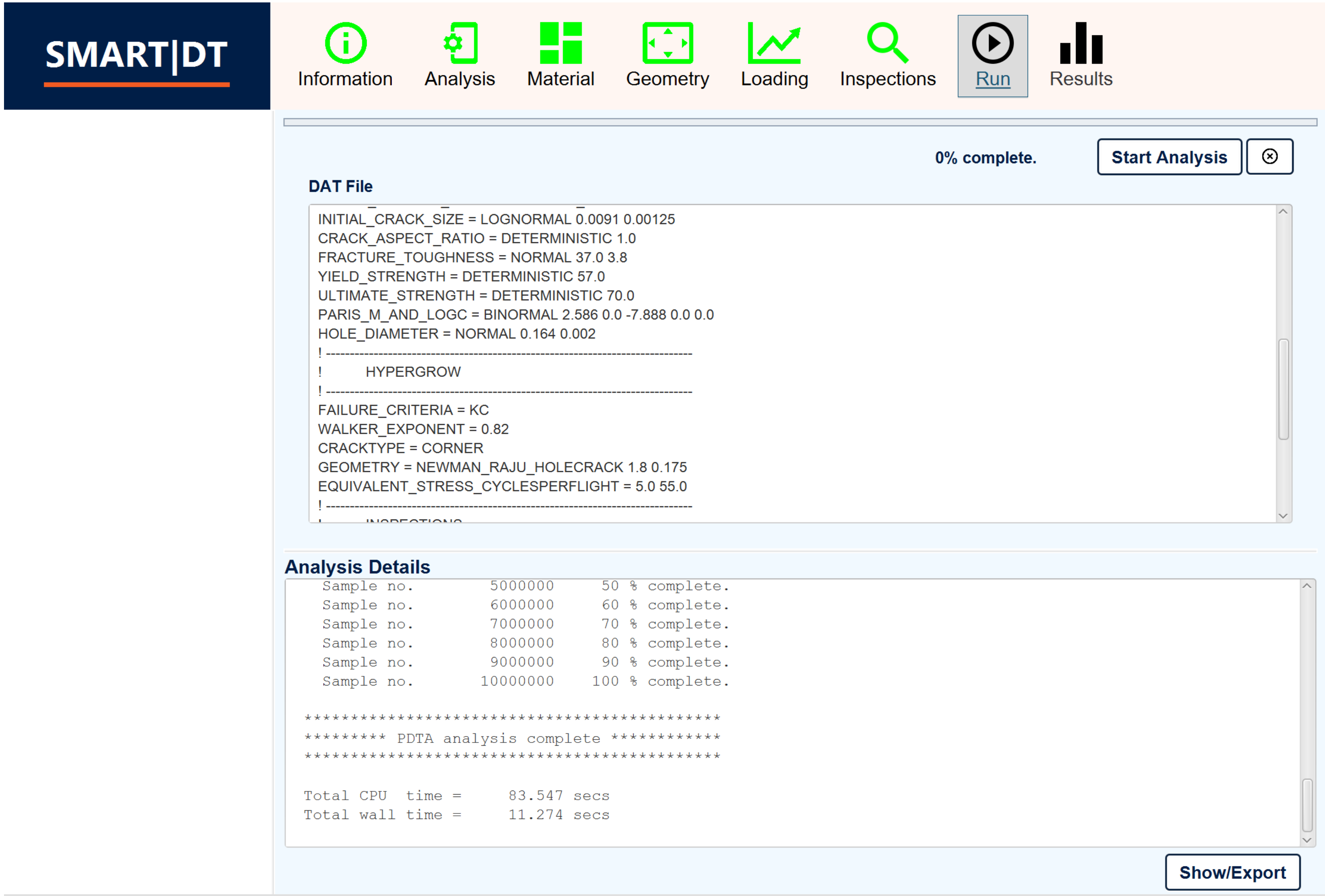
GUI – Loading


SMART|DT
Information
Analysis
Material
Geometry
Loading
Inspections
Run
Results
Extreme Value Distribution (EVD) Method
User Specified EVD
Location
14.5
Scale
0.8
Shape
0
Distribution Type: Gumbel
Maximum Value: Infinite
Note, the EVD is always defined on a per-flight basis.
Constant Amplitude Loading
Maximum Stress
5
Cycles Per Flight
55

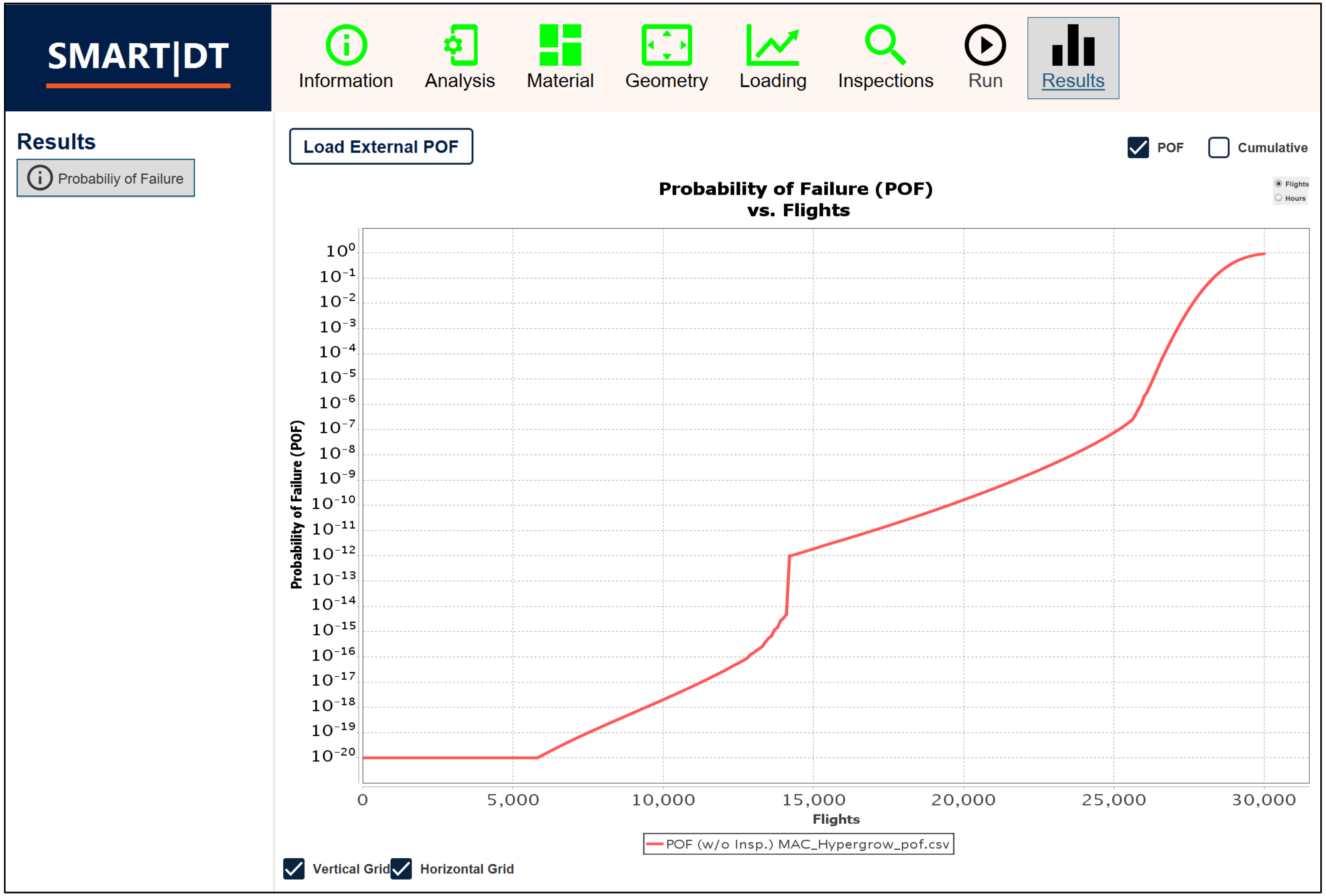
GUI – Inspections



GUI – Run

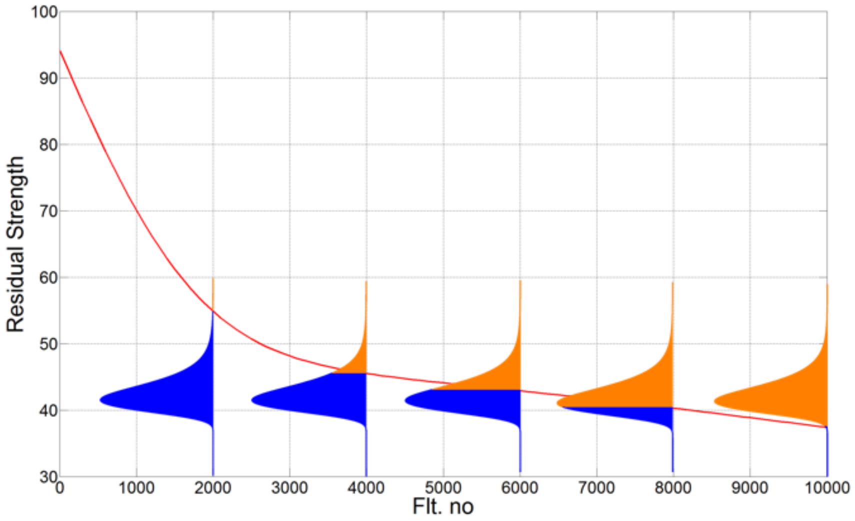

SMART|DT
Information
Analysis
Material
Geometry
Loading
Inspections
Run
Results
0% complete.
Start Analysis
DAT File
INITIAL_CRACK_SIZE = LOGNORMAL 0.0091 0.00125
CRACK_ASPECT_RATIO = DETERMINISTIC 1.0
FRACTURE_TOUGHNESS = NORMAL 37.0 3.8
YIELD_STRENGTH = DETERMINISTIC 57.0
ULTIMATE_STRENGTH = DETERMINISTIC 70.0
PARIS_M_AND_LOGC = BINORMAL 2.586 0.0 -7.888 0.0 0.0
HOLE_DIAMETER = NORMAL 0.164 0.002
! HYPERGROW
FAILURE_CRITERIA = KC
WALKER_EXPONENT = 0.82
CRACKTYPE = CORNER
GEOMETRY = NEWMAN_RAJU_HOLECRACK 1.8 0.175
EQUIVALENT_STRESS_CYCLESPERFLIGHT = 5.0 55.0
Analysis Details
Sample no. 5000000 50 % complete.
Sample no. 6000000 60 % complete.
Sample no. 7000000 70 % complete.
Sample no. 8000000 80 % complete.
Sample no. 9000000 90 % complete.
Sample no. 10000000 100 % complete.
****
********* PDTA analysis complete ************
****
Total CPU time = 83.547 secs
Total wall time = 11.274 secs
Show/Export

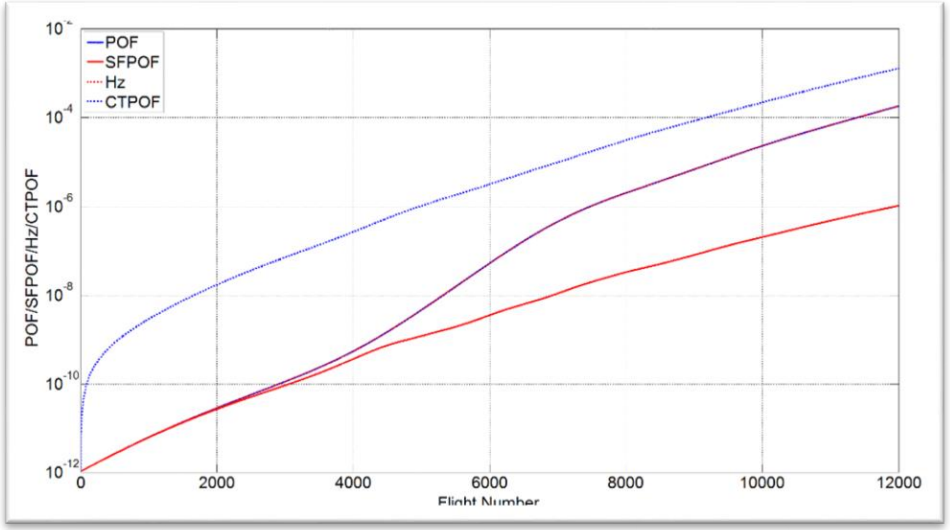
GUI – Results


SMART|DT
Information
Analysis
Material
Geometry
Loading
Inspections
Run
Results
Results
Probabiliy of Failure
Load External POF
POF
Cumulative
Flights
Hours
Probability of Failure (POF) vs. Flights
Probability of Failure (POF)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
0
5,000
10,000
15,000
20,000
25,000
30,000
Flights
POF (w/o Insp.) MAC_Hypergrow_pof.csv
Vertical Grid
Horizontal Grid

Summary

- Probability of Failure and EVD calculations were reviewed.
- Master Curve interpolation was reviewed.
  - Master curve can be user-generated (.avsn format) or generated using the HyperGrow/AFGROW/NASGRO SMART interface.





Questions

Supplemental Material

Random Crack Size
Probability-of-Failure Calculations

Excel Exercise

- **Open the excel file:**
  - MasterCurveRnd_ai.xlsx
- **Contained in:**
  - \ Excel_Examples

POF = (1-exp(-exp(-(RS-B)/A)))

Location	14.65		36.75482
Scale	0.8		

Step 1

Samples	Original Master Curve	Flt no.	c	Residual Strength
5.49E-02		0	0.00010	585.85
5.97E-02		1000	0.00011	565.87
6.50E-02		2000	0.00012	546.07
5.51E-02		3000	0.00012	526.45
3.54E-02		4000	0.00013	507.02
		5000	0.00014	487.79
		6000	0.00016	468.75
		7000	0.00017	449.92
		8000	0.00019	431.29
		9000	0.00020	412.87
		10000	0.00022	394.67
		11000	0.00024	376.69
		12000	0.00027	358.93
		13000	0.00030	341.41
		14000	0.00033	324.12
		15000	0.00037	306.77
		16000	0.00042	287.85
		17000	0.00048	268.71
		18000	0.00056	249.61
		19000	0.00066	230.67
		20000	0.00078	211.95
		21000	0.00098	190.42
		22000	0.00126	168.38
		23000	0.00172	145.06

Step 2

Sample 1 crack size	Master Curve flt no.	Sample flt no.	Residual Strength	POF
	26723	0	59.09	7.46E-25
1.72E-02	27723	1000	50.01	6.36E-20
	28723	2000	46.24	7.09E-18
	29723	3000	44.49	6.34E-17
	30723	4000	43.23	3.04E-16
	31723	5000	42.00	1.42E-15
	32723	6000	40.67	7.46E-15
	33723	7000	39.26	4.34E-14
	34723	8000	37.82	2.65E-13
	35723	9000	36.35	1.66E-12
	36723	10000	34.87	1.06E-11
	37723	11000	33.37	6.90E-11
	38723	12000	31.84	4.65E-10
	39723	13000	30.29	3.24E-09
	40723	14000	28.72	2.31E-08
	41723	15000	27.12	1.70E-07
	42723	16000	25.49	1.31E-06
	43723	17000	23.82	1.06E-05
	44723	18000	22.08	9.30E-05
	45723	19000	20.19	9.80E-04
	46723	20000	0.00	1.00E+00
	Extract POF @	10000	1.06E-11	

Step 2

Sample 2 crack size	Master Curve flt no.	Sample flt no.	Residual Strength	POF
	29001	0	45.51	0.00E+00
6.27E-02	30001	1000	44.10	1.11E-16
	31001	2000	42.90	4.44E-16
	32001	3000	41.65	2.22E-15
	33001	4000	40.30	1.20E-14
	34001	5000	38.87	7.13E-14
	35001	6000	37.41	4.39E-13
	36001	7000	35.94	2.77E-12
	37001	8000	34.45	1.78E-11
	38001	9000	32.95	1.16E-10
	39001	10000	31.42	7.92E-10
	40001	11000	29.86	5.57E-09
	41001	12000	28.28	4.01E-08
	42001	13000	26.67	2.98E-07
	43001	14000	25.03	2.31E-06
	44001	15000	23.35	1.90E-05
	45001	16000	21.59	1.71E-04
	46001	17000	19.65	1.92E-03
	47001	18000	17.48	2.86E-02
	48001	19000	14.37	7.60E-01
	49001	20000	0.00	1.00E+00
	Extract POF @	10000	7.92E-10	

Step 2

Sample 3 crack size	Master Curve flt no.	Sample flt no.	Residual Strength	POF
	29457	0	44.86	0.00E+00
7.50E-02	30457	1000	43.55	2.22E-16
	31457	2000	42.33	8.88E-16
	32457	3000	41.03	4.77E-15
	33457	4000	39.64	2.70E-14
	34457	5000	38.20	1.64E-13
	35457	6000	36.74	1.02E-12
	36457	7000	35.26	6.47E-12
	37457	8000	33.77	4.19E-11
	38457	9000	32.25	2.80E-10
	39457	10000	30.70	1.93E-09
	40457	11000	29.13	1.37E-08
	41457	12000	27.54	1.00E-07
	42457	13000	25.92	7.59E-07
	43457	14000	24.26	6.05E-06
	44457	15000	22.54	5.19E-05
	45457	16000	20.70	5.17E-04
	46457	17000	18.66	6.61E-03
	47457	18000	16.06	1.58E-01
	48457	19000	0.00	1.00E+00
	49457	20000	0.00	1.00E+00
	Extract POF @	10000	1.93E-09	

Step 2

Sample 4 crack size
5.31E-02

Using 5 Initial Crack Size samples compute the probability of failure

Exercise Steps

Step 1. Extract Flt no., Crack Size, and Residual Strength from the fracture mechanics run.
Step 2. Locate the five initial crack size random samples *(Extracted from SMART).*
Step 3. Copy and paste each of the five initial crack size samples.
Step 4. Copy the POF value at 10,000 flights.
Step 5. Compute the average using the five POF values at 10,000.

Let’s Compare with SMART (smdt file included)

SMART Example Problem

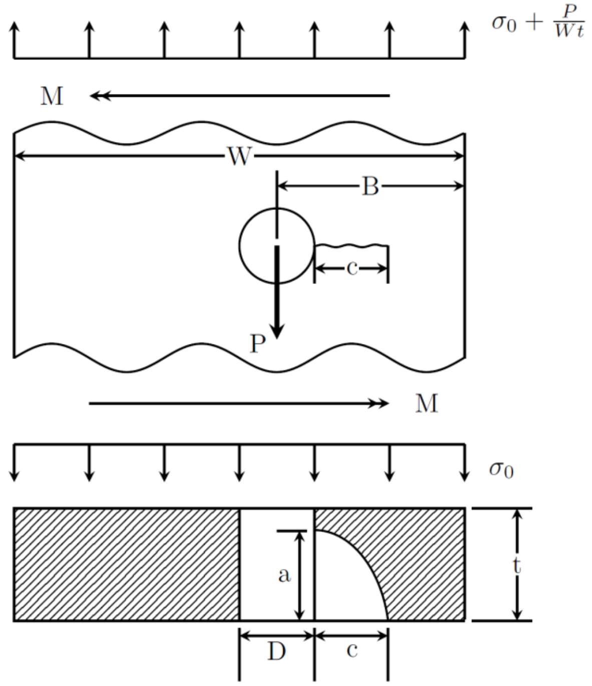
SMART$_{DT}$

SMall Aircraft Risk Technology - Damage Tolerance Analysis

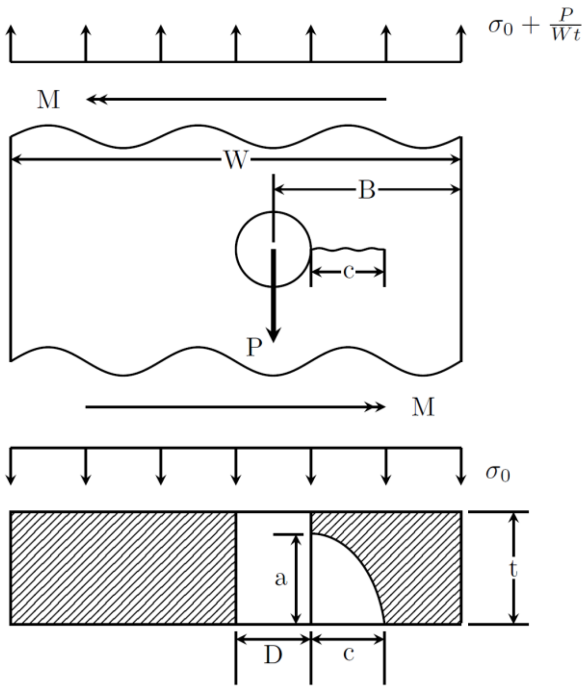
36

Problem Description

- ✓Master Curve (corner crack at a hole)
- ✓Random Initial Crack Size
- ✓Random Fracture Toughness
- ✓Random Loading (EVD)



Problem Overview



Geometric Variables	Value
Hole radius	0.156 in
Cap Thickness	0.250 in
Cap Width	2.50 in

Problem Overview

Loading Parameters	Value
Aircraft Usage	Twin Engine Unpressurized General Usage
Design Maneuver Load Factors	3.60 (high) -1.50 (low)
Design Gust Load Factors	4.50 (high) -2.50 (low)
Ground Stress	-50 psi (Flight 1) -70 psi (Flight 2)
One g Stress	5700 psi (Flight 1) 5280 psi (Flight 2)
Average Velocity	200 knots (Flight 1) 200 knots (Flight 2)
Number of Flight Times	1 (Flight 1) 1 (Flight 2)
Number of Velocities	5 (Flight 1) 5 (Flight 2)

Problem Overview

Random Variables	Distribution	Parameters
Initial Crack Size	Lognormal	Mean = 0.00196851 Standard deviation = 0.009055 in
Fracture Toughness	Normal	Mean = 50.0 $\text{ksi}\sqrt{\text{in}}$ Standard deviation = 3.4 $\text{ksi}\sqrt{\text{in}}$
Paris m	Binormal	Mean = 3.80 Standard deviation = 0.0
Paris c (log)	Binormal	Mean = -9.00 Standard deviation = 0.0
Ultimate Stress	Normal	Mean = 80.0 ksi Standard deviation = 0.0
Yield Stress	Normal	Mean = 65.0 ksi Standard deviation = 0.0
Hole Offset	Normal	Mean = 0.50 in Standard deviation = 0.0

Other Parameters	Distribution
Crack Growth Program	HyperGrow/AFGROW

SMART|DT
Generic Files Overview

File Type	Description
`jobname.dat`	Input file containing the keywords and run information
`jobname.err`	Runtime error file
`jobname.wrn`	Runtime warning file
`jobname.out`	File containing a summary of the inputs, probability of failure calculations, and inspection results (if applicable)
`jobname.pof`	File containing the probability of failure as a function of the flight number
`jobname.smdt`	File containing the GUI information

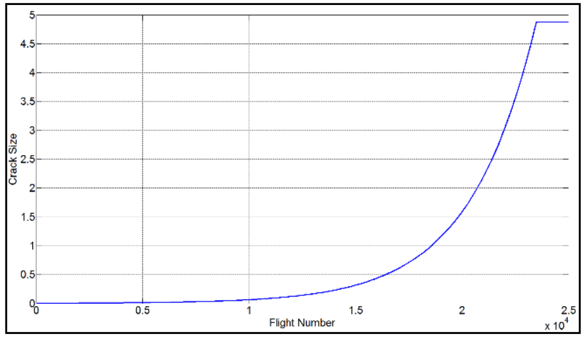
Input
output

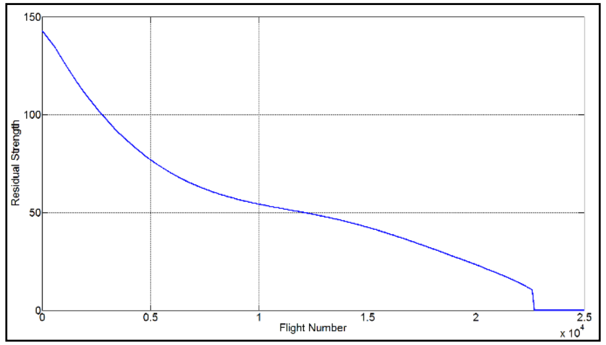
SMART .dat File

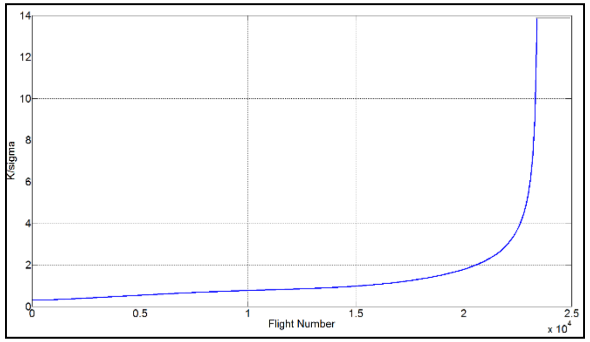

```
! ---------------------------------------------------------------------------
!            AIRCRAFT INFORMATION
! ---------------------------------------------------------------------------
TITLE = Wing_Spar
AC_MAKE = Acme
AC_MODEL = Sky Runner
AC_SERIAL_NUM = SR100
AC_TCDS = TCSR100
! ---------------------------------------------------------------------------
!            METHOD
! ---------------------------------------------------------------------------
INTEGRATION_METHOD = MC 1000000 2394
POF_MAX_INC = 40000 400
ANALYSIS_TIME_UNITS = flights
! ---------------------------------------------------------------------------
!            FRACTURE MECHANICS
! ---------------------------------------------------------------------------
CRACK_GROWTH_CODE = MASTERC_USER user_master_40pct_bearing.avsn
INITIAL_CRACK_SIZE = LOGNORMAL 0.009055 0.00196851
FRACTURE_TOUGHNESS = NORMAL 50.0 3.4
YIELD_STRENGTH = DETERMINISTIC 120.0
! ---------------------------------------------------------------------------
!            INSPECTIONS
! ---------------------------------------------------------------------------
INSPECTIONS = 0
! ---------------------------------------------------------------------------
!            LOADING AND EVD PARAMETERS
! ---------------------------------------------------------------------------
EVD_TYPE = USER 16.74 2.08 0.0
NUMBER_OF_USAGES = 0
! ---------------------------------------------------------------------------
!            DESCRIPTION
! ---------------------------------------------------------------------------
!  RUAG training June 29-30 - 2020
```

Master Curve Files Overview

File Type	Description
`anyname.avsn`	File containing the crack growth information (Flight number, crack size, and K/sigma or residual strength) File name specified in the input file (jobname.dat)







Avsn File Format

```
!Title: Example Problem
!             ICS          Kc           Pc           Pm           Sy           Sult         Hd           Hofs         aoci
!      5.0000E-04  3.5000E+01  1.0000E-09  3.8000E+00  6.5000E+01  8.0000E+01  1.5600E-01  5.0000E-01  1.0000E+00  5.0000E-01

Fracture_Toughness = 35.0
Yield_Strength = 1.0
Hours_Per_Flight = 1.0
Failure_Criteria = KC

flt_no  a       c               a1      c1              RS_by_Kc                RS_by_NSY
0       x       5.0000E-04      x       x               4.3091E+02              4.3091E+02
100     x       5.0041E-04      x       x               4.3074E+02              4.3074E+02
200     x       5.0083E-04      x       x               4.3056E+02              4.3056E+02
300     x       5.0124E-04      x       x               4.3038E+02              4.3038E+02
400     x       5.0166E-04      x       x               4.3020E+02              4.3020E+02
500     x       5.0207E-04      x       x               4.3002E+02              4.3002E+02
600     x       5.0249E-04      x       x               4.2985E+02              4.2985E+02
700     x       5.0291E-04      x       x               4.2967E+02              4.2967E+02
800     x       5.0333E-04      x       x               4.2949E+02              4.2949E+02
900     x       5.0374E-04      x       x               4.2931E+02              4.2931E+02
1000    x       5.0416E-04      x       x               4.2913E+02              4.2913E+02
1100    x       5.0458E-04      x       x               4.2895E+02              4.2895E+02
1200    x       5.0500E-04      x       x               4.2877E+02              4.2877E+02
1300    x       5.0542E-04      x       x               4.2860E+02              4.2860E+02
1400    x       5.0585E-04      x       x               4.2842E+02              4.2842E+02
1500    x       5.0627E-04      x       x               4.2824E+02              4.2824E+02
1600    x       5.0669E-04      x       x               4.2806E+02              4.2806E+02
1700    x       5.0712E-04      x       x               4.2788E+02              4.2788E+02
1800    x       5.0754E-04      x       x               4.2770E+02              4.2770E+02
1900    x       5.0797E-04      x       x               4.2752E+02              4.2752E+02
2000    x       5.0839E-04      x       x               4.2734E+02              4.2734E+02
2100    x       5.0882E-04      x       x               4.2716E+02              4.2716E+02
2200    x       5.0925E-04      x       x               4.2698E+02              4.2698E+02
2300    x       5.0967E-04      x       x               4.2681E+02              4.2681E+02
2400    x       5.1010E-04      x       x               4.2663E+02              4.2663E+02
2500    x       5.1053E-04      x       x               4.2645E+02              4.2645E+02
2600    x       5.1096E-04      x       x               4.2627E+02              4.2627E+02
2700    x       5.1139E-04      x       x               4.2609E+02              4.2609E+02
2800    x       5.1182E-04      x       x               4.2591E+02              4.2591E+02
2900    x       5.1226E-04      x       x               4.2573E+02              4.2573E+02
3000    x       5.1269E-04      x       x               4.2555E+02              4.2555E+02
3100    x       5.1312E-04      x       x               4.2537E+02              4.2537E+02
3200    x       5.1356E-04      x       x               4.2519E+02              4.2519E+02
3300    x       5.1399E-04      x       x               4.2501E+02              4.2501E+02
```

avsn File Format

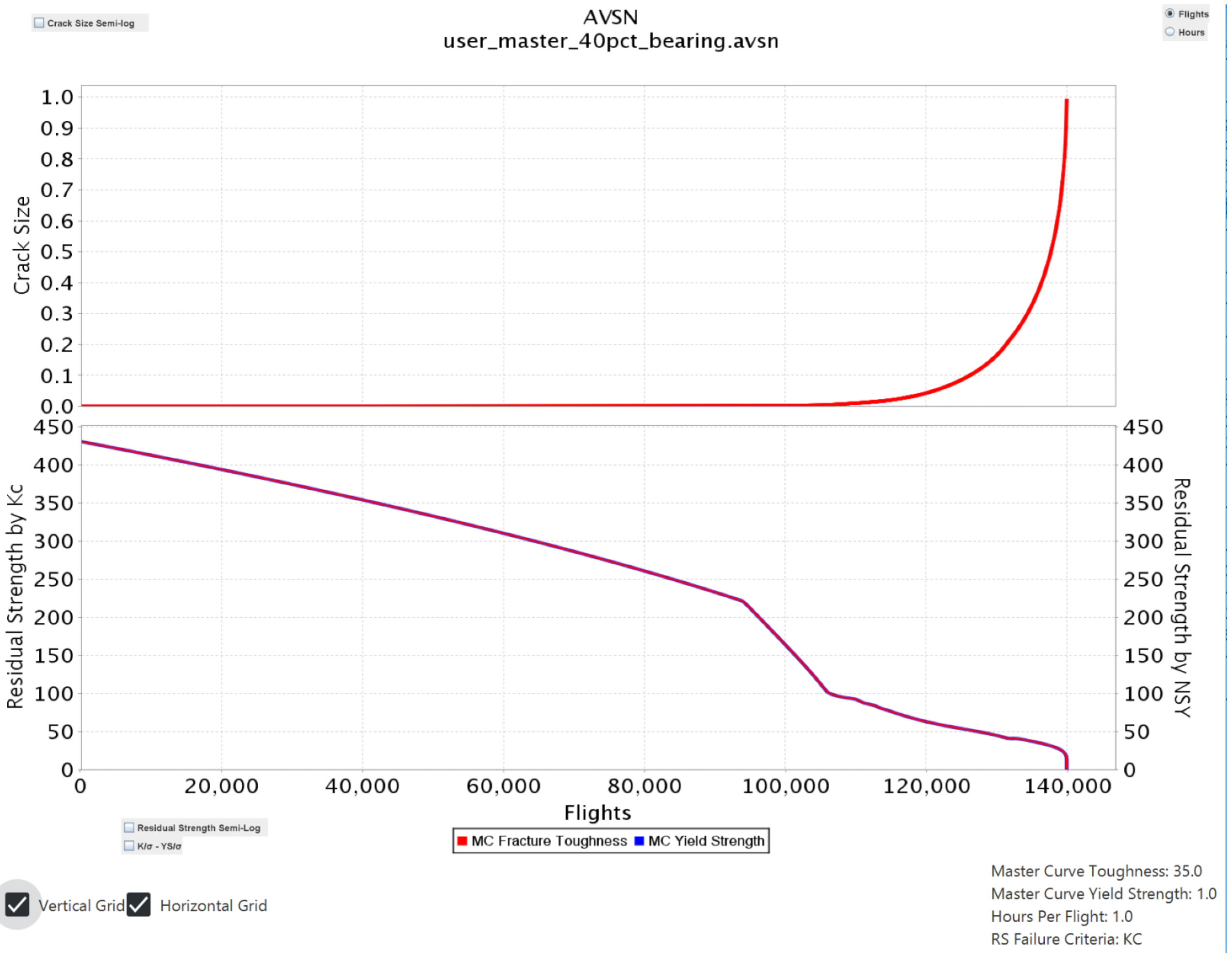
Flight Number

4 crack tips, only survival tip is used for the analysis.
If ‘x’ crack tip does not exist

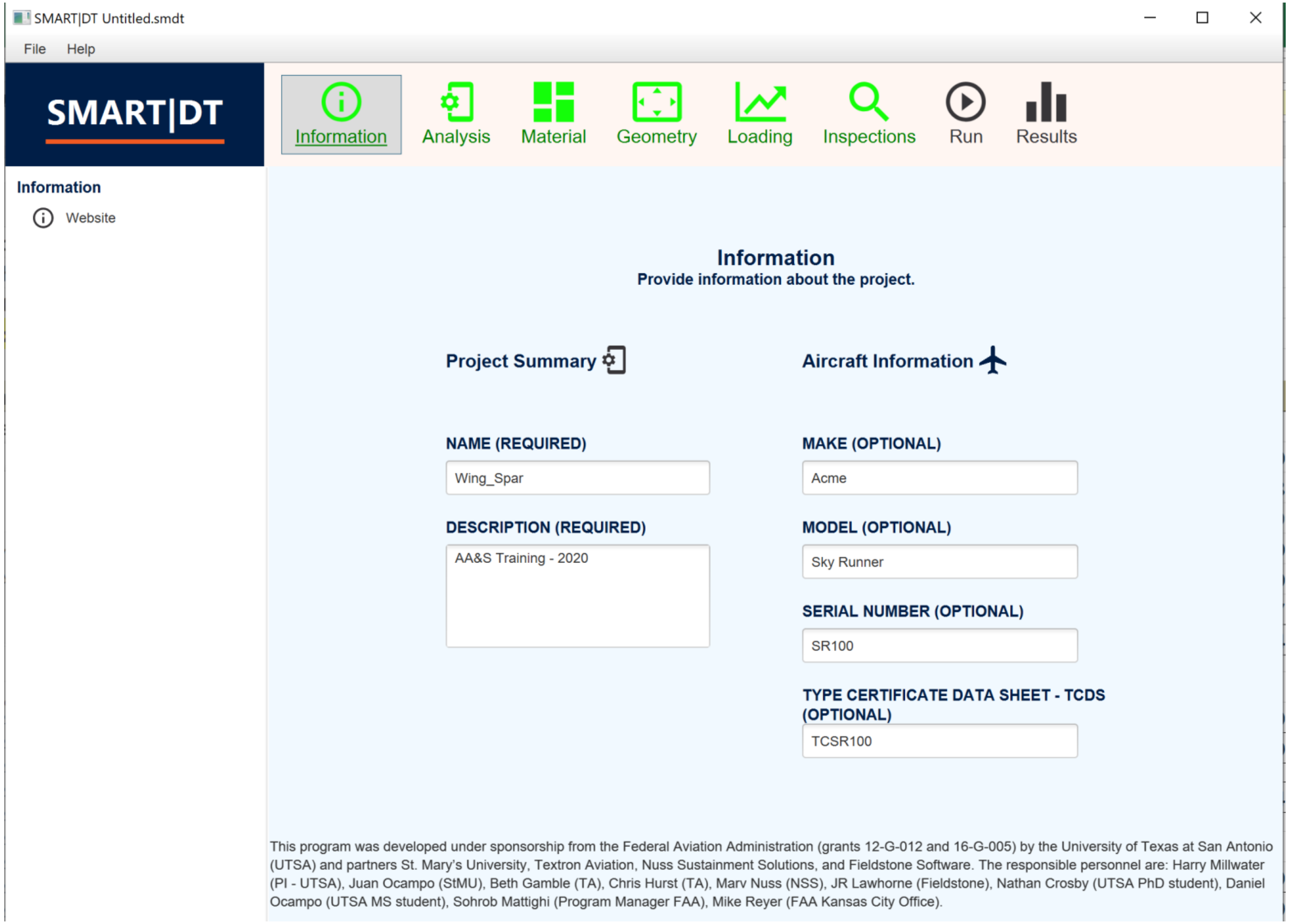
Residual Strength by Fracture and Net Section Yielding. User can select which one to use (not on the GUI yet) – Min. Default

Flt_no	a	c	a1	c1	RS_by_Kc	RS_by_NSY
0	0.00010	0.00010	x	x	585.85	585.85
1000	0.00011	0.00011	x	x	565.87	565.87
2000	0.00012	0.00012	x	x	546.07	546.07
3000	0.00012	0.00012	x	x	526.45	526.45
4000	0.00013	0.00013	x	`	507.02	507.02
5000	0.00014	0.00014	x	x	487.79	487.79
6000	0.00016	0.00016	x	x	468.75	468.75
7000	0.00017	0.00017	x	x	449.92	449.92
8000	0.00019	0.00019	x	x	431.29	431.29
9000	0.00020	0.00020	x	x	412.87	412.87
	… Lines were removed from this output …					
25000	0.00500	0.00500	x	x	94.14	94.14
26000	0.00930	0.00930	x	x	70.09	70.09
27000	x	0.02026	x	x	54.87	54.87
28000	x	0.03886	x	x	48.14	48.14
29000	x	0.06273	x	x	45.51	45.51
30000	x	0.08960	x	x	44.10	44.10

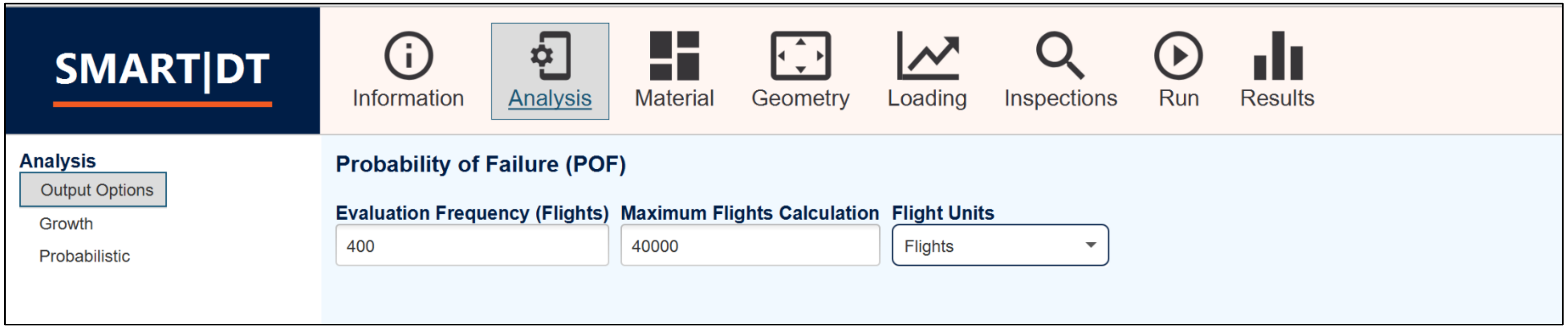
Visualize avsn in SMART



SMART GUI (Information Tab)

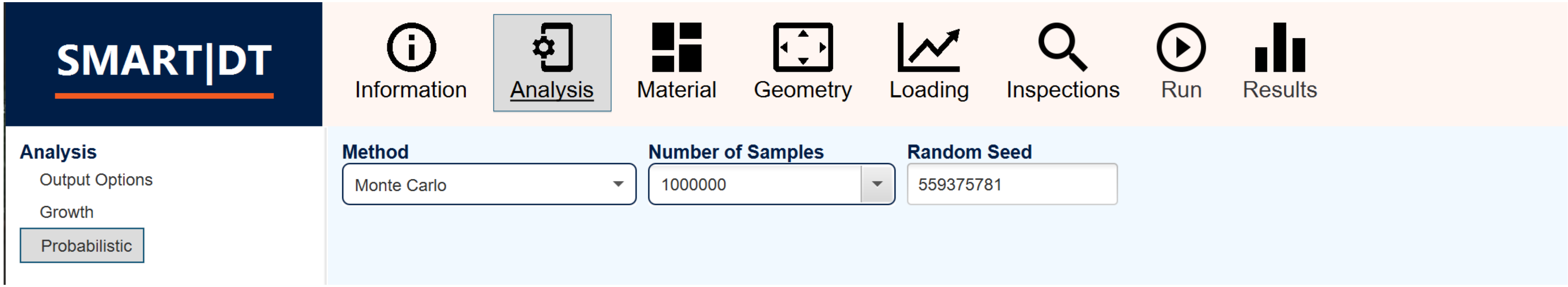


SMART GUI (Analysis Tab)

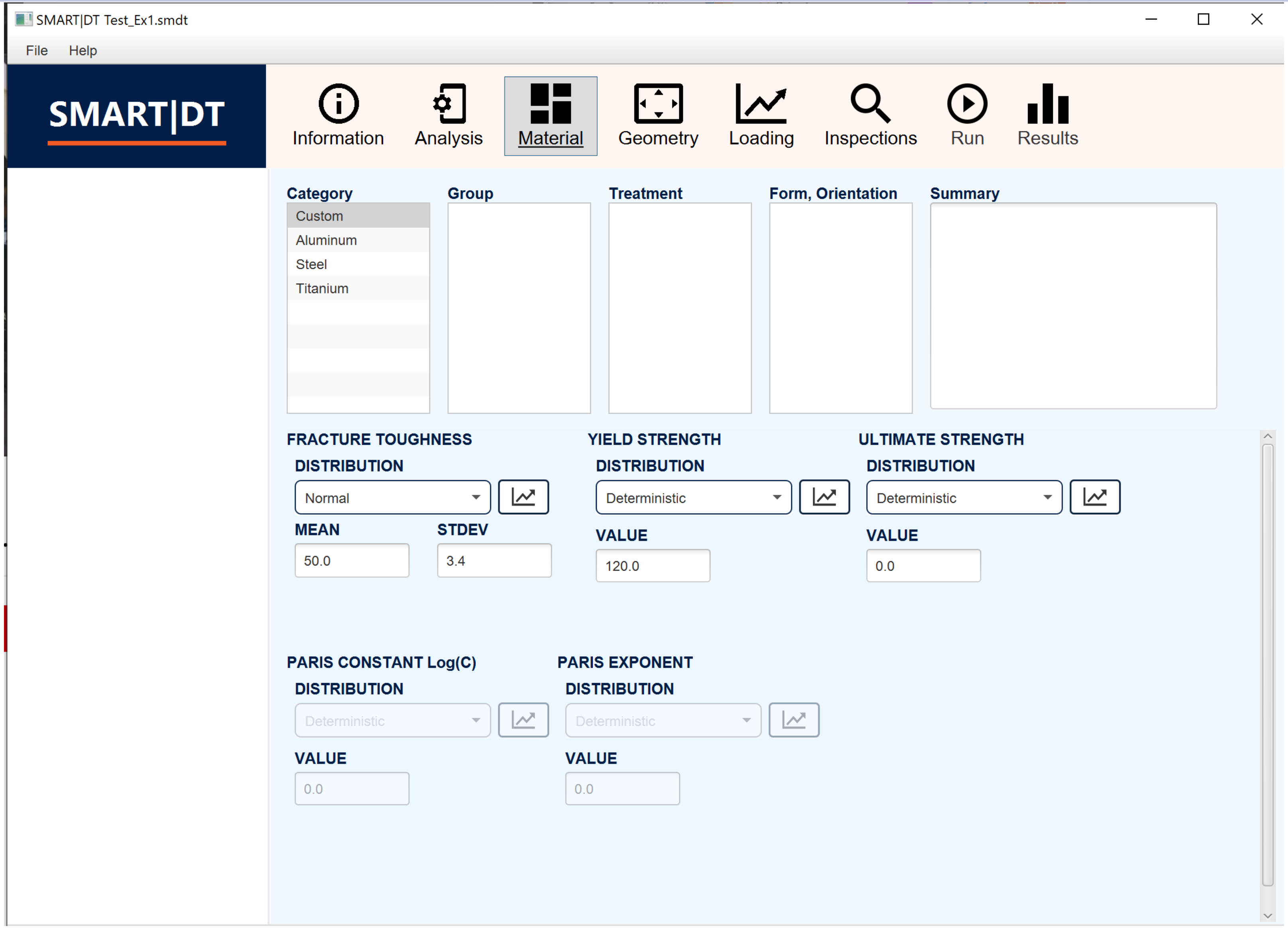


SMART GUI (Analysis Tab)

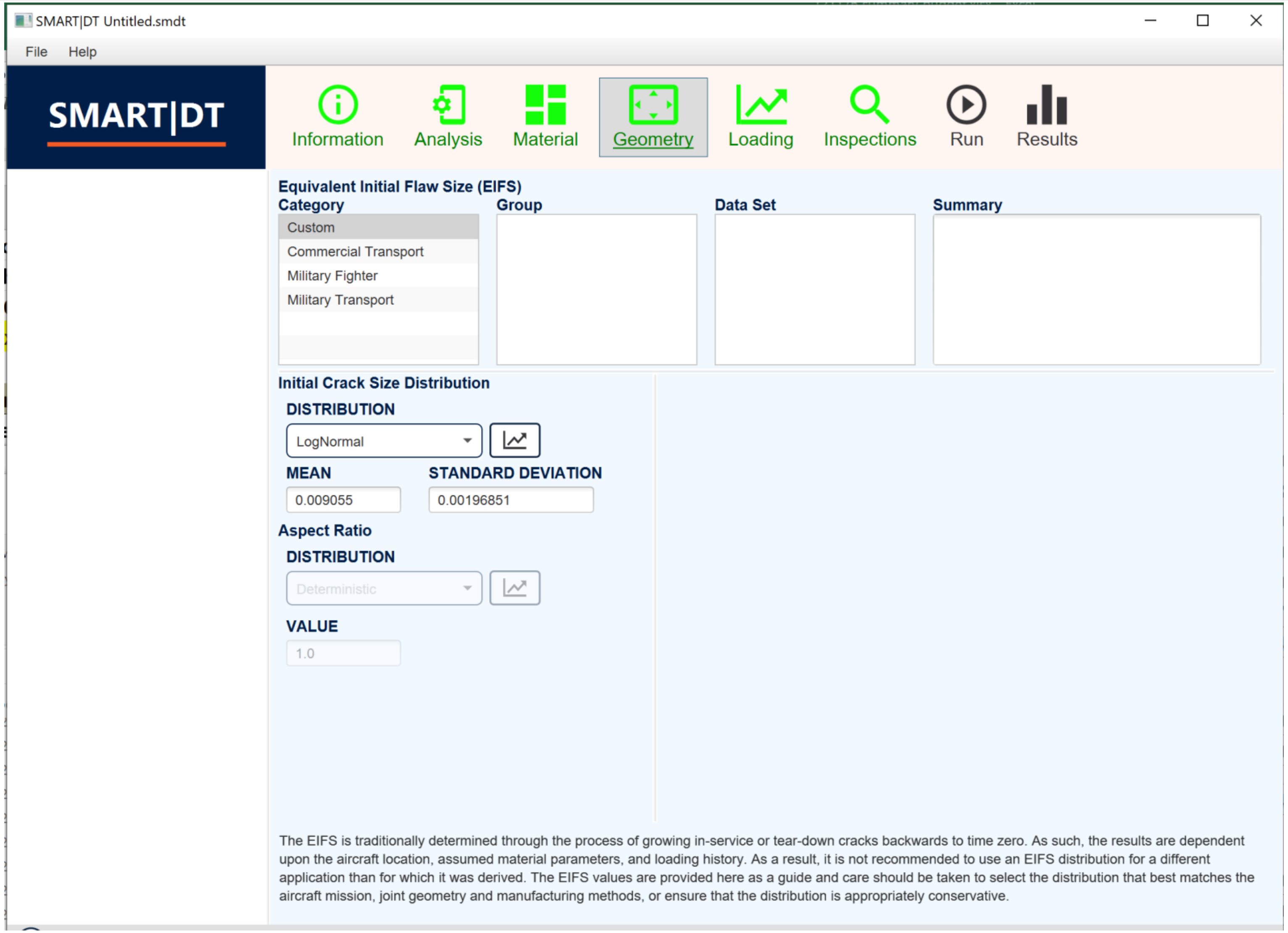
SMART GUI (Analysis Tab)



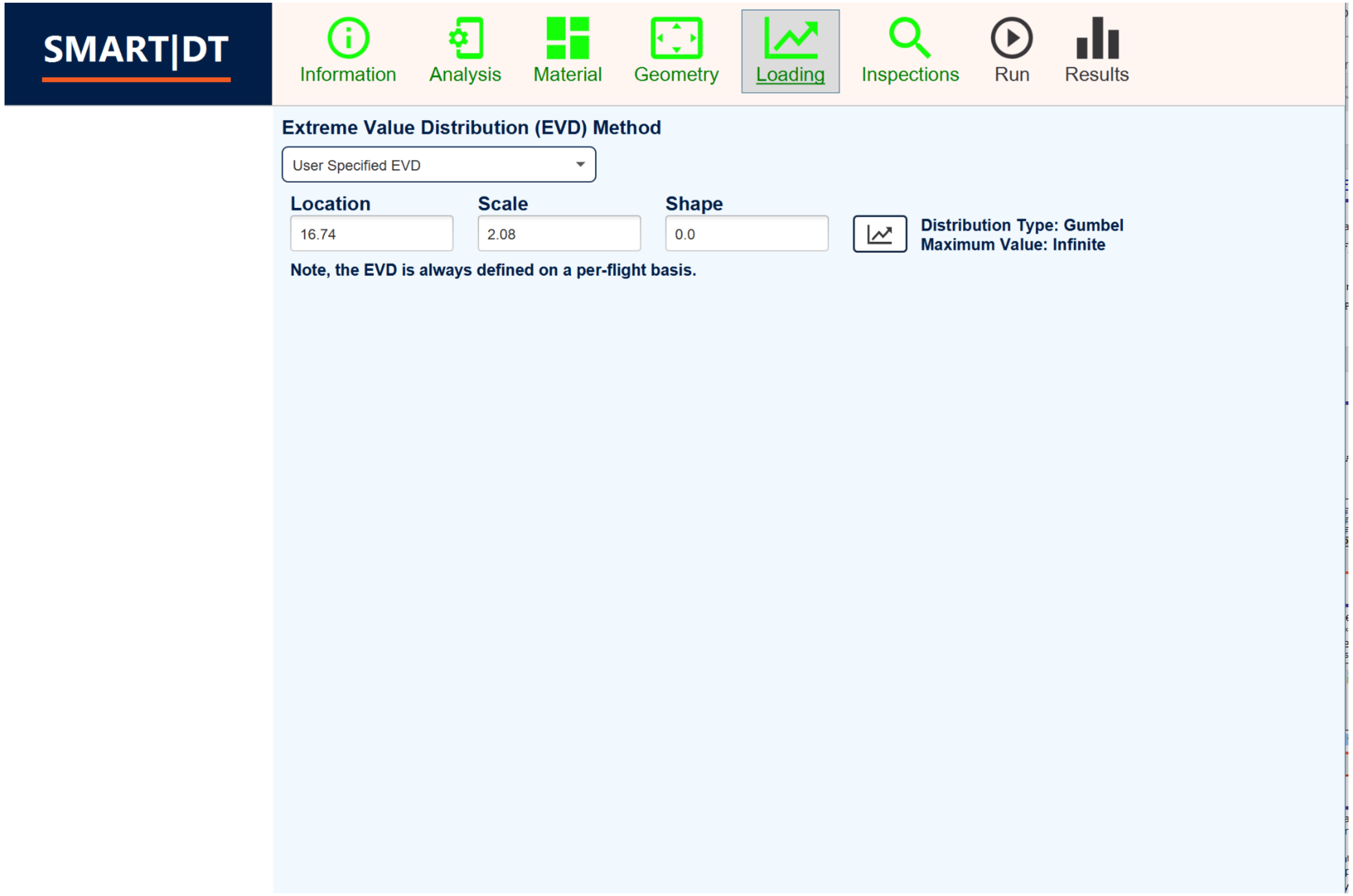
SMART GUI (Material Tab)



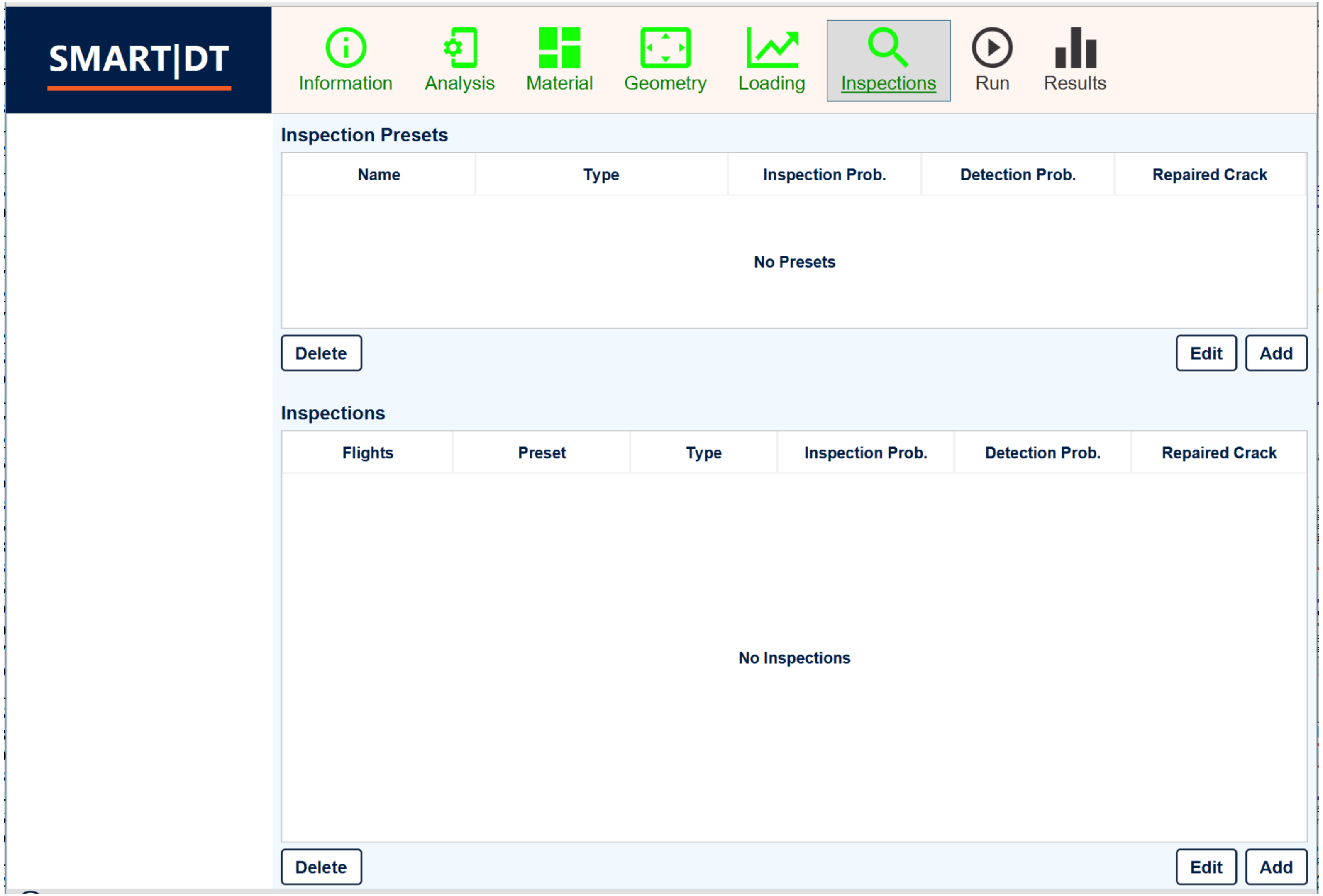
SMART GUI (Geometry Tab)



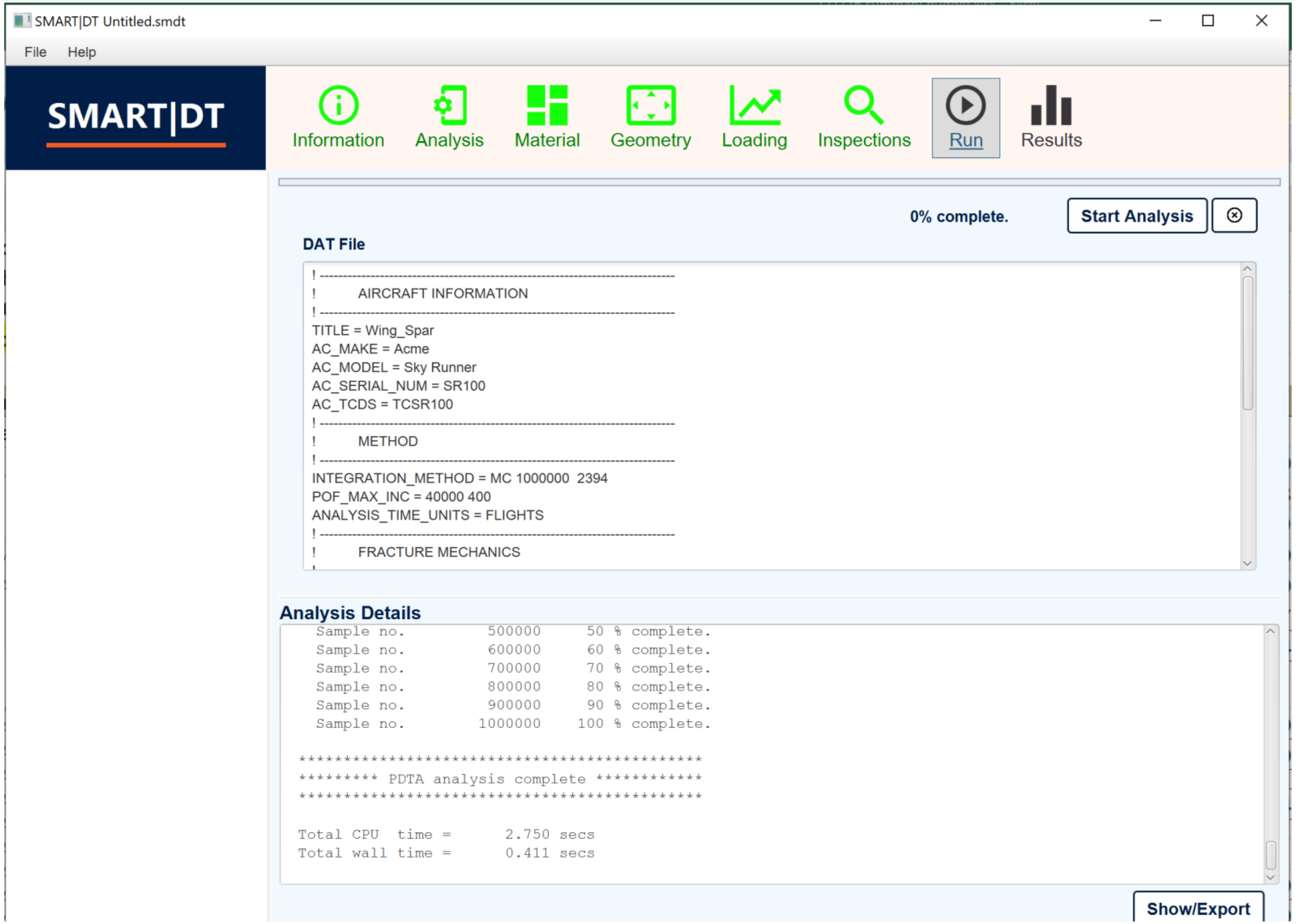
SMART GUI(Loading Tab)



SMART GUI (Inspections Tab)



SMART GUI (Run Tab)



SMART GUI (Results Tab)