Introduction to Probabilistic Methods with Applications to Probabilistic Damage Tolerance Analysis

PDTA Case Study

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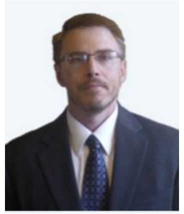
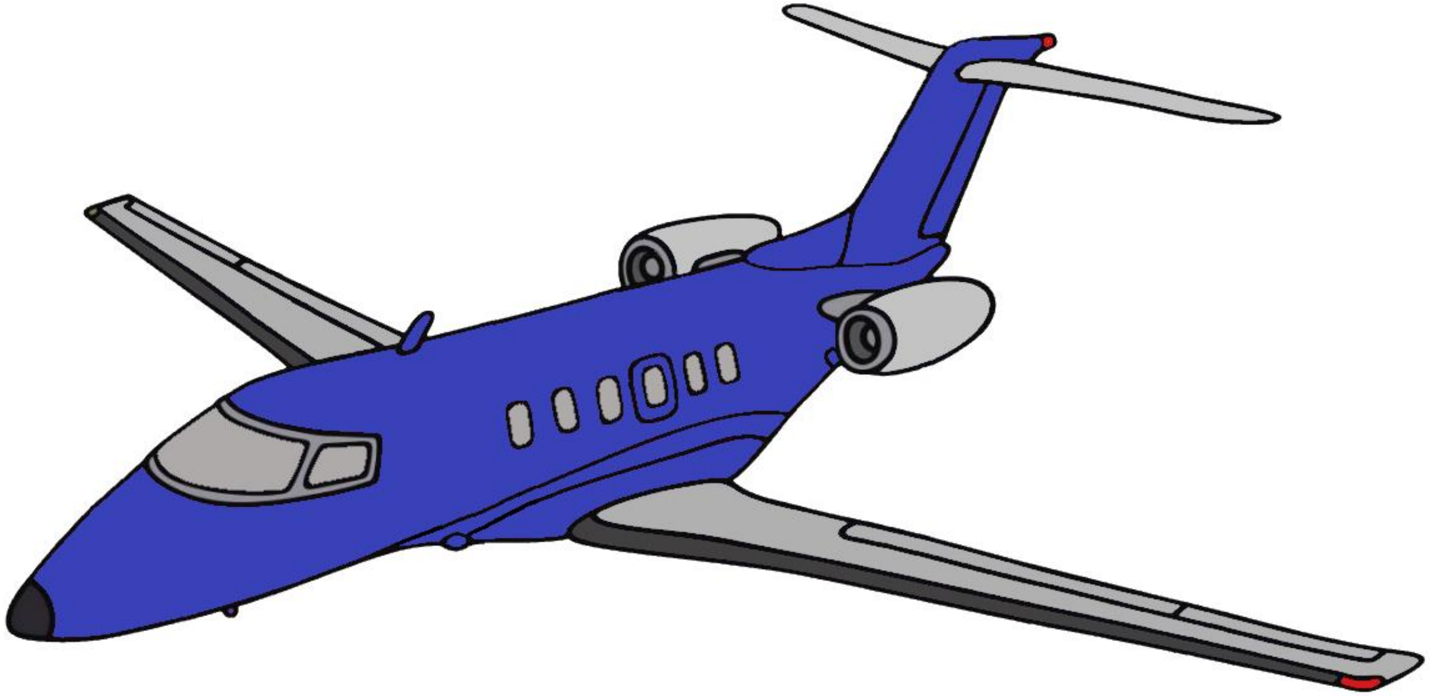
AA&S The Aircraft Airworthiness & Sustainment Conference






August 29, 2022

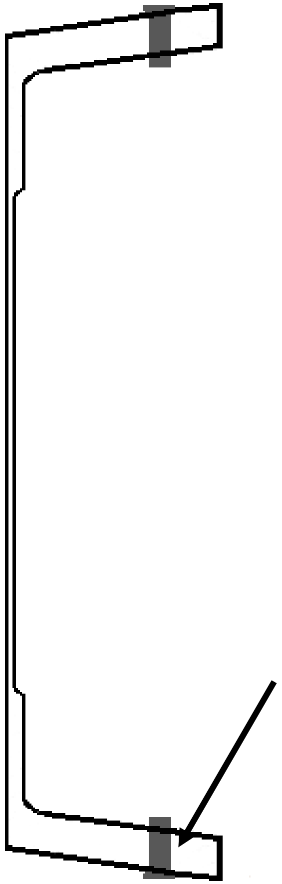
Problem Overview



General Aviation Corporate Jet With
Wing Forward Spar Cap Cracking

Problem Overview

Web

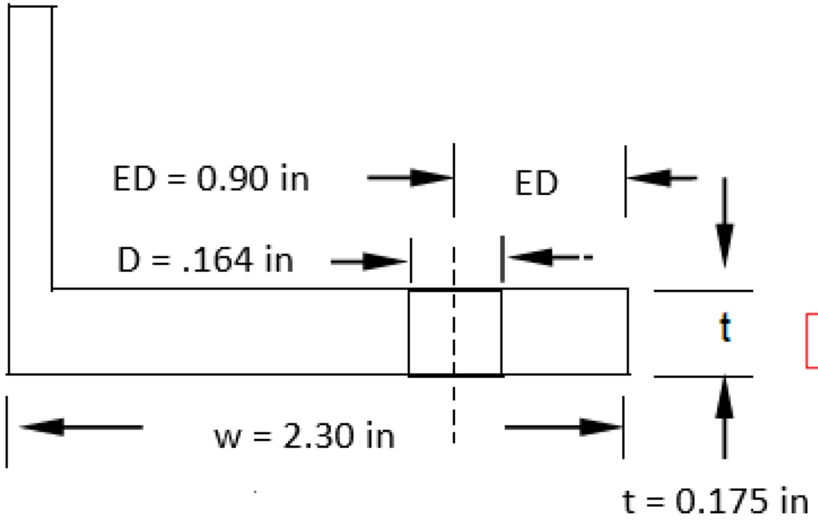


Lower Spar Cap
Cracking Location

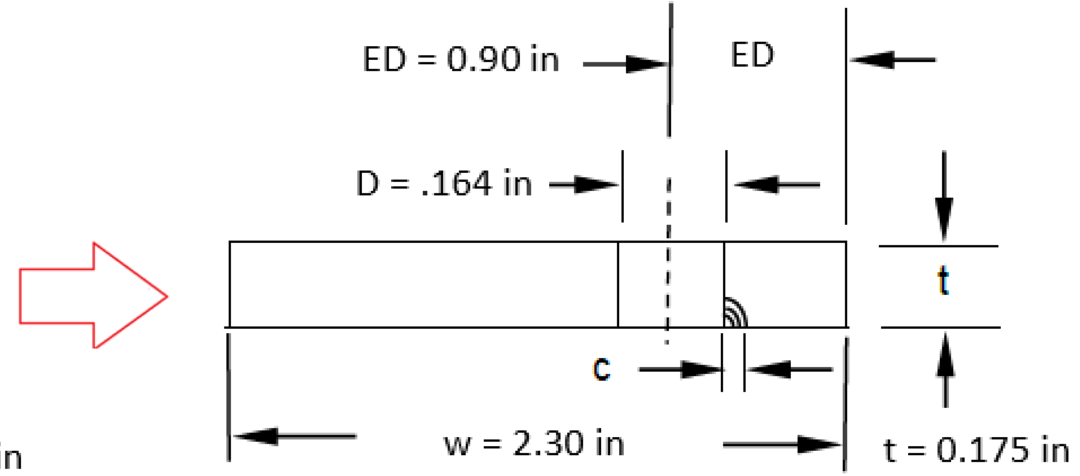
Wing Forward Spar

Problem Overview

Simplified Geometry



Idealized Geometry



$$\frac{\sigma_{bearing}}{\sigma_{bypass}} = .66$$

CLASSICAL CRACK GROWTH

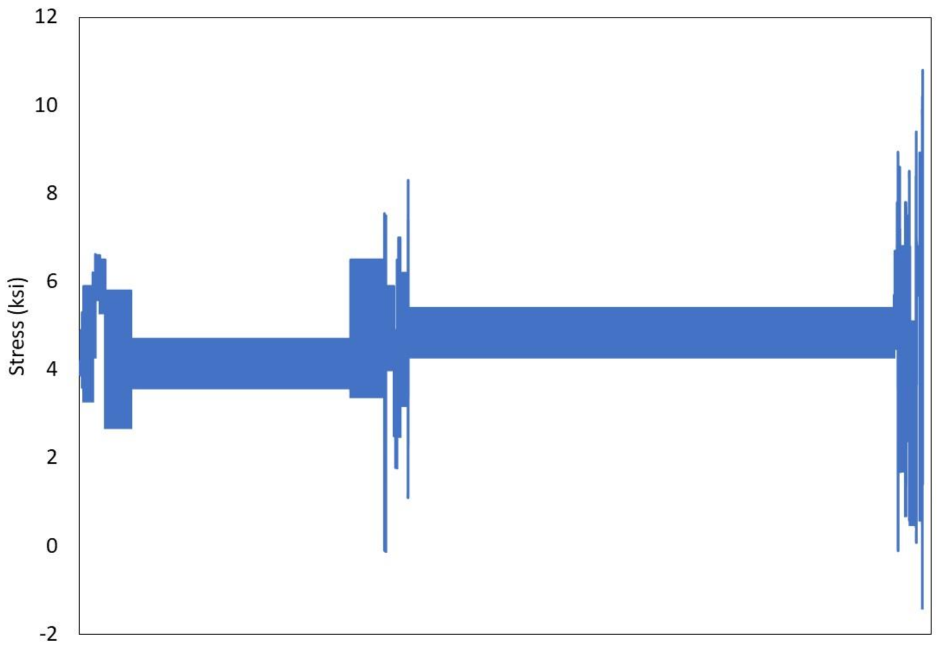
Classical Crack Growth

- Determine initial and recurring inspections using classical crack growth analysis from .05” flaw
  - AFGROW software used for crack growth
    - User defined spectrum
  - Detectable crack length = .20 in.
  - Inspections
    - Initial inspection $= \frac{\text{Life}}{2}$
    - Repeat inspection $= \frac{\text{Life} - \text{Life@detectable}}{2}$

TEXTRON AVIATION

User Stress Spectrum

- User defined spectra
  - Gust cycles are based on PSD continuous gust criteria in 14 CFR 25 Appendix G
  - Maneuver cycles are based on NASA measured data for business jets
  - Spectra is in AFGROW format (1,000 flight hours, 1 flight = 1.65 Flt. Hrs.)
  - Used SMART to create a simplified GAG spectrum with equivalent damage



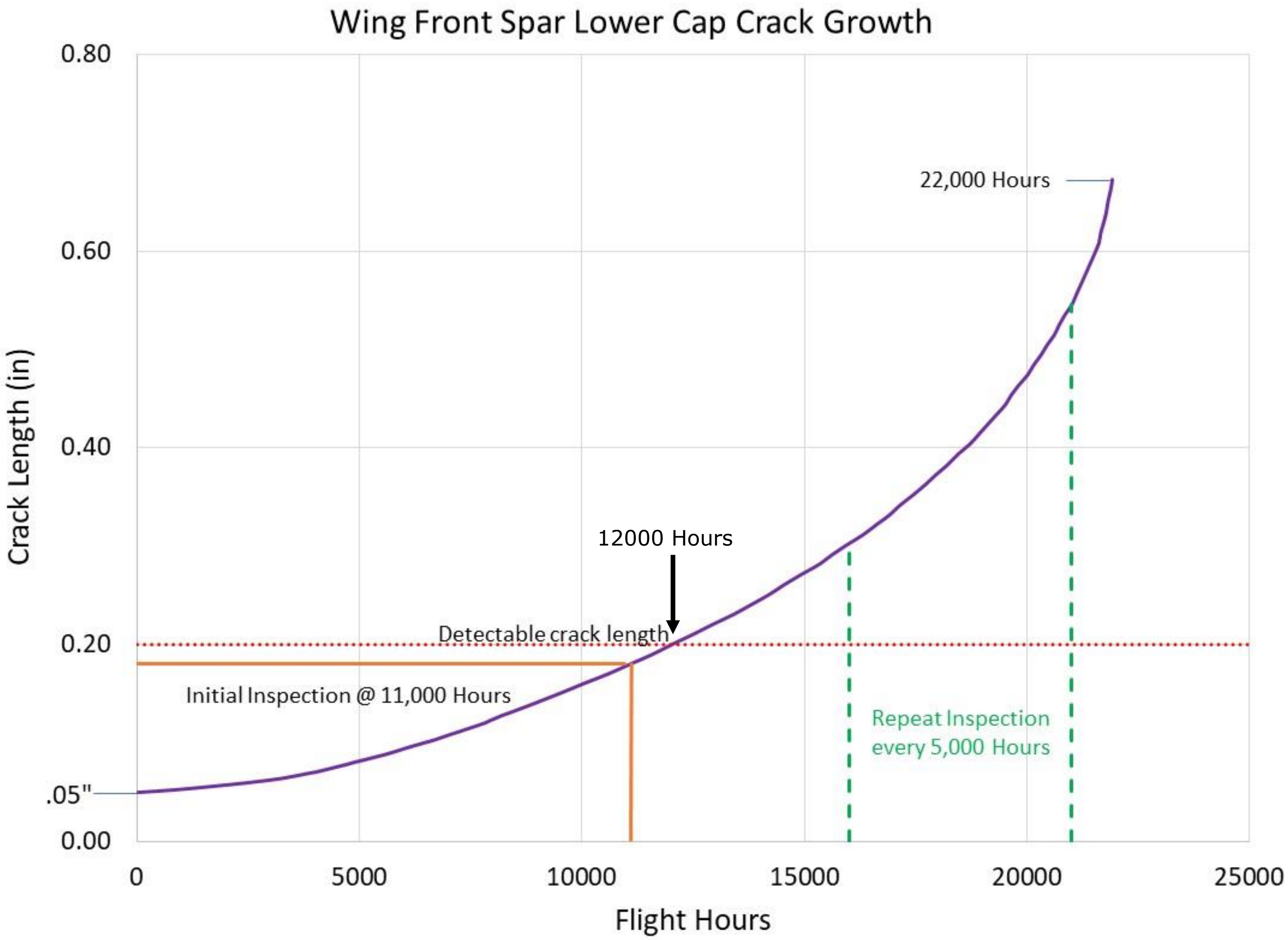
50 different max-min stress pairs, 33,600 total pairs

Classical Crack Growth

Variable	Parameter
Initial Crack Size	0.05 in
Fracture Toughness	37.0 ksi√in
Paris m	2.586
Paris c	1.29E-8
Walker exponent	.82
Ultimate Stress	69.0 ksi
Yield Stress	58.0 ksi
Hole Offset	0.90 in

AFGROW INPUT
Mean only

Classical Crack Growth



HYPERGROW WITH AFGROW AND ADAPTIVE MULTIPLE IMPORTANCE SAMPLING

Hypergrow and Adaptive Sampling

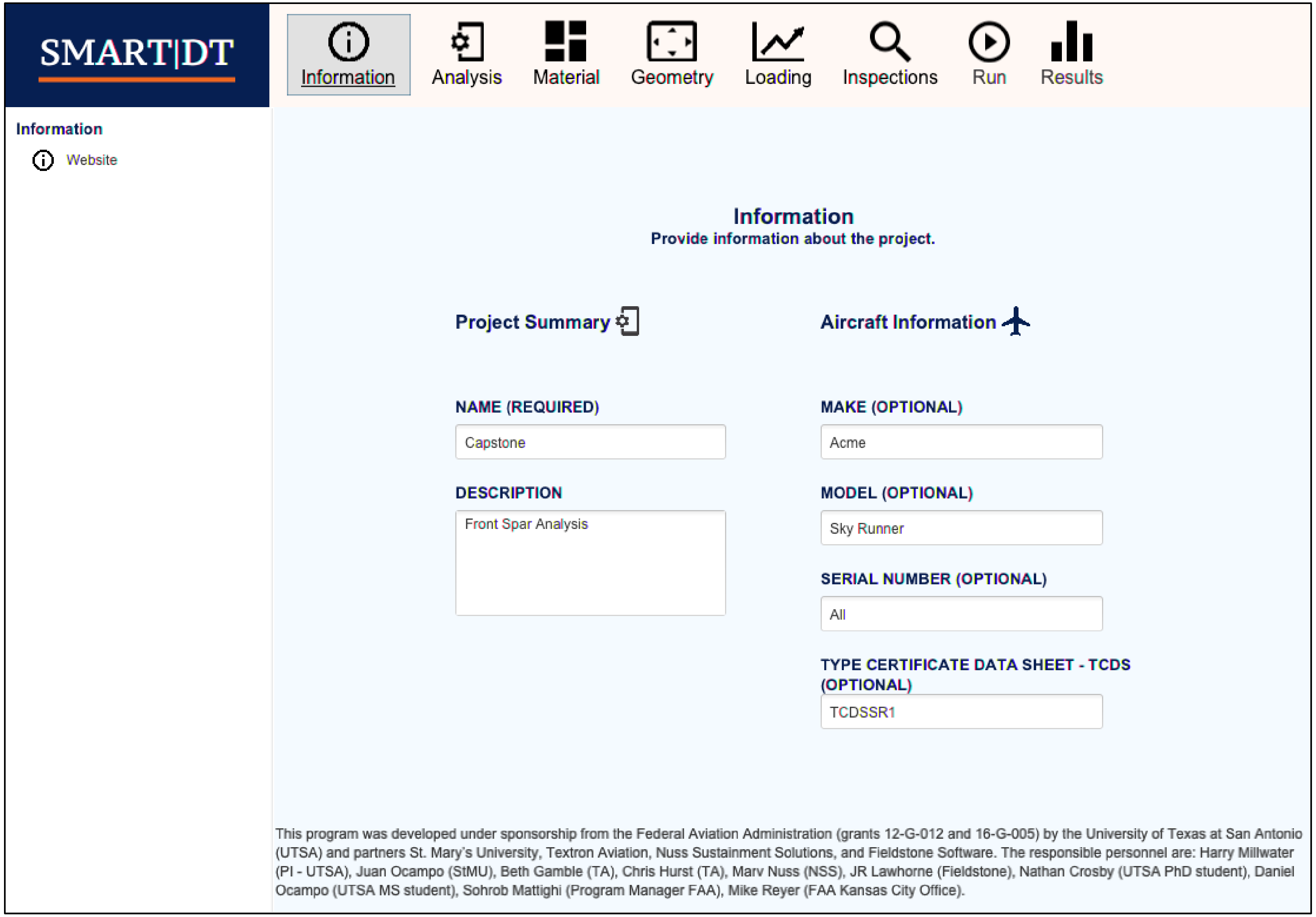
- Next, Hypergrow will be used for probabilistic analysis
- Hypergrow requires:
  - Probabilistic inputs for material properties
  - Probabilistic inputs for inspections
  - Beta solution generated by Afgrow and exported to .csv format
- Adaptive sampling used to evaluate POF with inspections
  - Adaptive sampling additional inputs:
    - Target coefficient of variation
    - Number of samples per iteration
- Example file provided: Capstone_hypergrow.smdt

Problem Overview

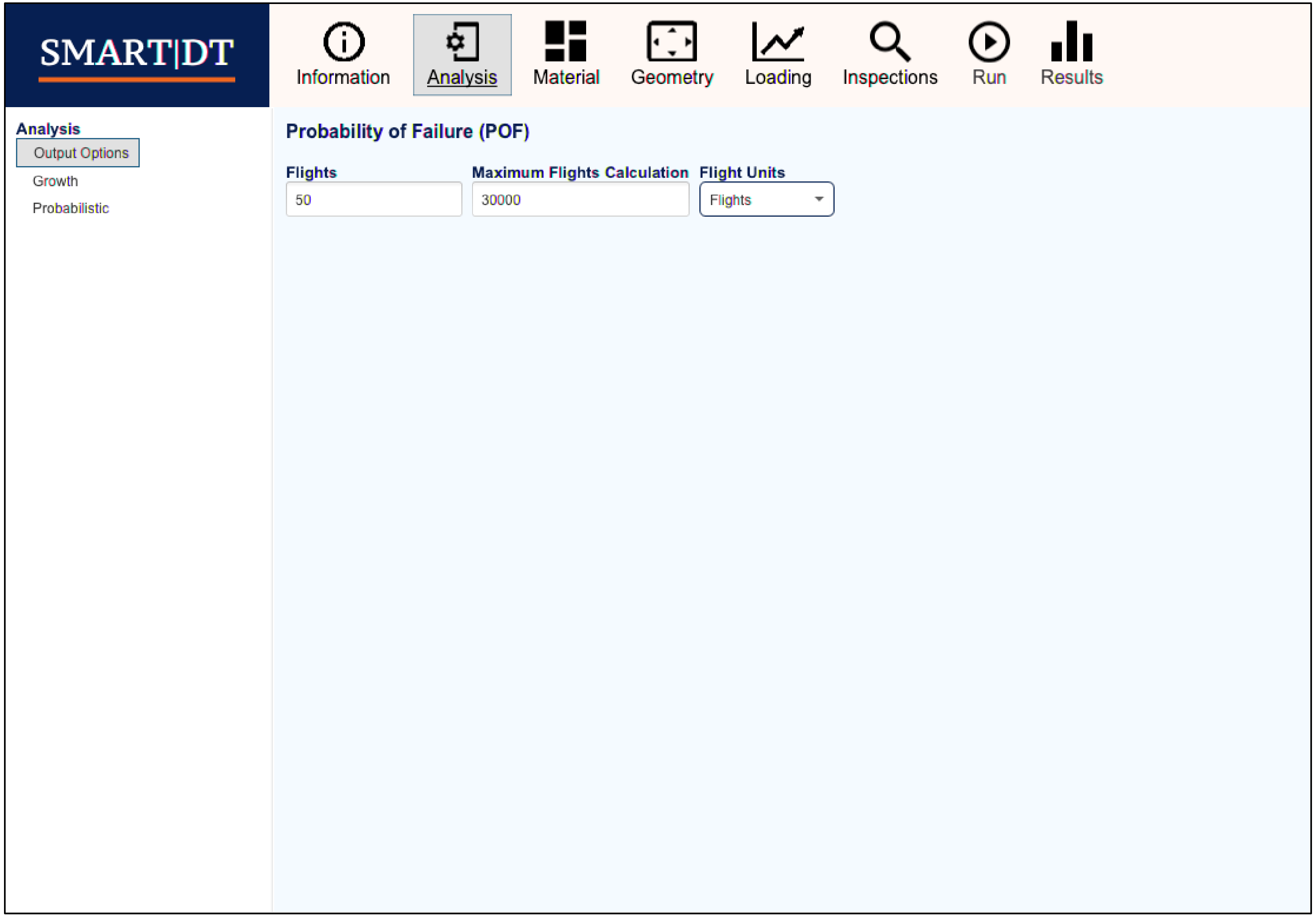
Random Variable	Distribution	Parameters
Initial Crack Size	Lognormal	Mean = 0.009055 in Standard Deviation =0.001252 in
Fracture Toughness	Normal	Mean = 37.0 ksi√in Standard Deviation = 3.8 ksi√in
Paris m	Binormal	Mean = 2.586 Standard Deviation = 0.0
Paris c (log)	Binormal	Mean = -7.888 Standard Deviation = 0.04
Coefficient of Variance		0.0
Walker exponent		.82
Ultimate Stress	Normal	Mean = 69.0 ksi Standard Deviation = 0.0 ksi
Yield Stress	Normal	Mean = 58.0 ksi Standard Deviation = 0.0 ksi
Hole Offset	Normal	Mean = 0.9000 in Standard Deviation = 0.0 in

SMART INPUT
Mean & StdDev

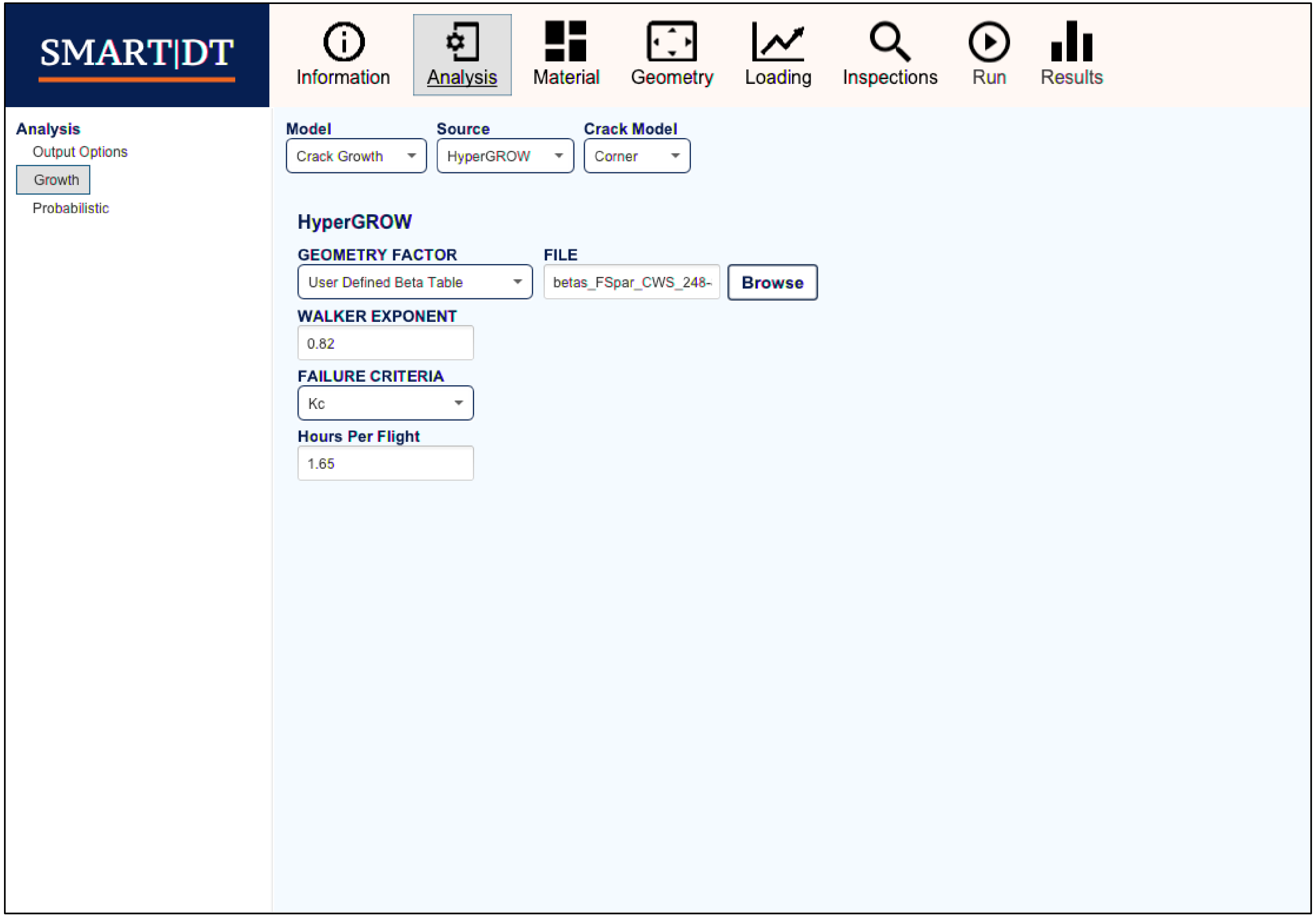
SMART|DT – Project Information



SMART|DT – Analysis Information (Output Options)



SMART|DT – Analysis Information (Growth)



Afgrow Beta Solution File

! Afgrow Model 1030 / 2030 - 0.6619 Bearing Load transfer
! Width = 2.30 in
! Thk = 0.175 in
! H Dia = 0.164 in
! H Ofs = 0.90 in
!

Thru crack Betas

! c	beta
0.0050	3.59907
0.0100	3.20130
0.0150	2.89657
⋮	⋮
0.8100	3.86109
0.8150	6.21646
0.8200	27.93956

!

Part-thru crack Betas

!beta c Crack Direction

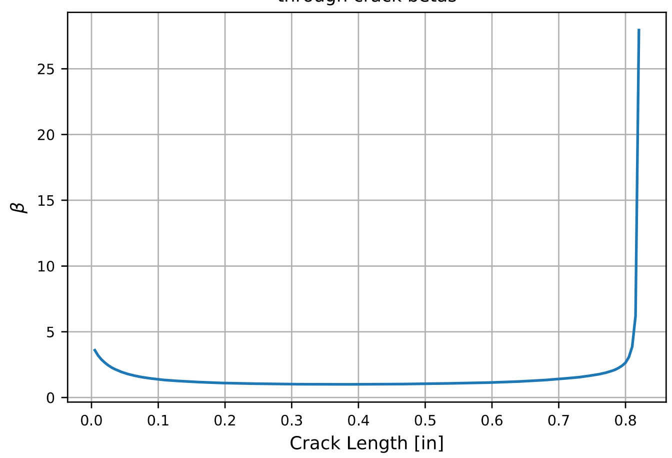
	0.0050	0.0125	0.0200	0.0275	0.0350	···	0.1475	0.1550	0.1625	0.1700	0.1750
0.0050	2.24485	3.19804	3.48930	3.62330	3.70123	···	3.99493	4.00368	4.01206	4.02010	4.02529
0.0125	1.00838	1.97282	2.45652	2.72711	2.89341	···	3.40218	3.41236	3.42193	3.43095	3.43671
0.0200	0.65282	1.21655	1.77304	2.07547	2.28183	···	2.97105	2.98348	2.99503	3.00581	3.01263
⋮	⋮	⋮	⋮	⋮	⋮	···	⋮	⋮	⋮	⋮	⋮
0.8000	0.02662	0.04209	0.05456	0.06696	0.08040	···	0.77079	0.90930	1.09491	1.36974	1.65756
0.8075	0.02630	0.04161	0.05398	0.06629	0.07965	···	0.80831	0.97114	1.20536	1.60190	2.12351
0.8150	0.02620	0.04147	0.05383	0.06615	0.07955	···	0.86325	1.06395	1.38532	2.08510	3.90826
0.8180	0.02616	0.04141	0.05377	0.06610	0.07952	···	0.88947	1.11091	1.48752	2.47098	2.17E+07

!

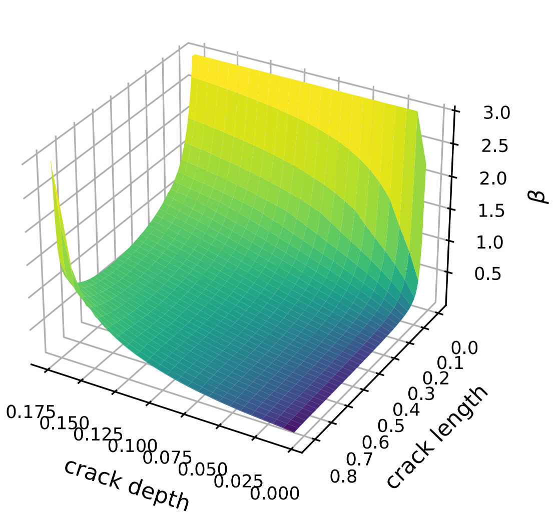
!beta a Crack Direction

	0.0050	0.0125	0.0200	0.0275	0.0350	···	0.1475	0.1550	0.1625	0.1700	0.1750
0.0050	2.38094	1.40933	1.01682	0.81909	0.70182	···	0.32664	0.31896	0.31184	0.30520	0.30101
0.0125	2.85559	2.26857	1.78653	1.46485	1.24436	···	0.49365	0.48046	0.46834	0.45714	0.45014
0.0200	3.07986	2.35492	2.15685	1.84767	1.60820	···	0.61072	0.59219	0.57526	0.55972	0.55005
⋮	⋮	⋮	⋮	⋮	⋮	···	⋮	⋮	⋮	⋮	⋮
0.8075	1.15054	1.14212	1.15544	1.18763	1.23595	···	3.66367	4.14637	4.85539	6.09787	7.79295
0.8150	1.14916	1.14142	1.15570	1.18912	1.23898	···	3.94530	4.58217	5.63174	8.01747	14.50856
0.8180	1.14861	1.14116	1.15584	1.18977	1.24025	···	4.07878	4.80130	6.07016	9.54257	8.14E+07

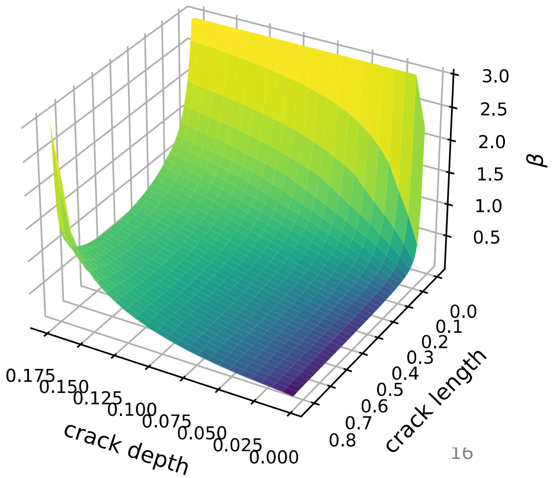
through crack betas



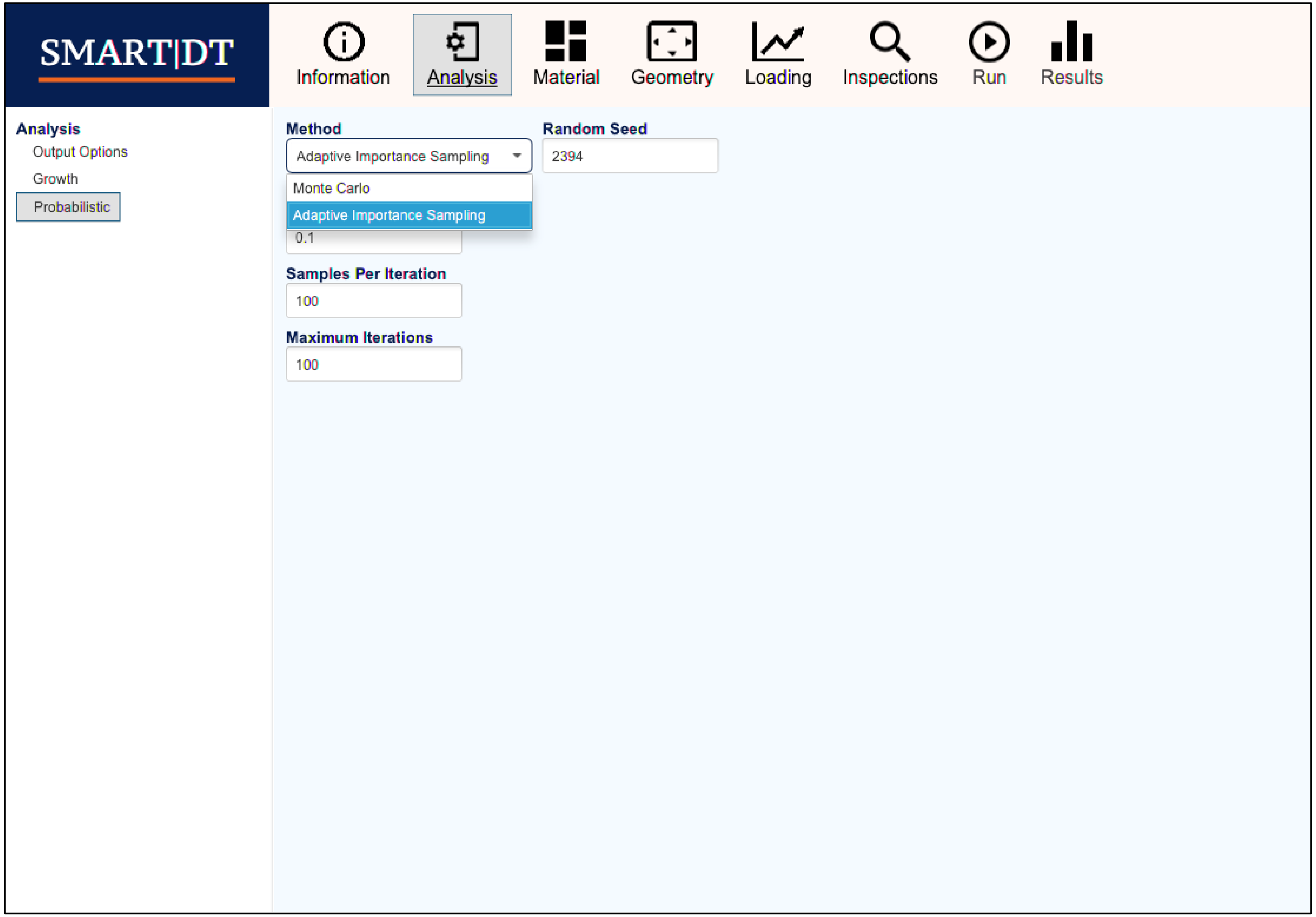
c-direction (along surface) betas



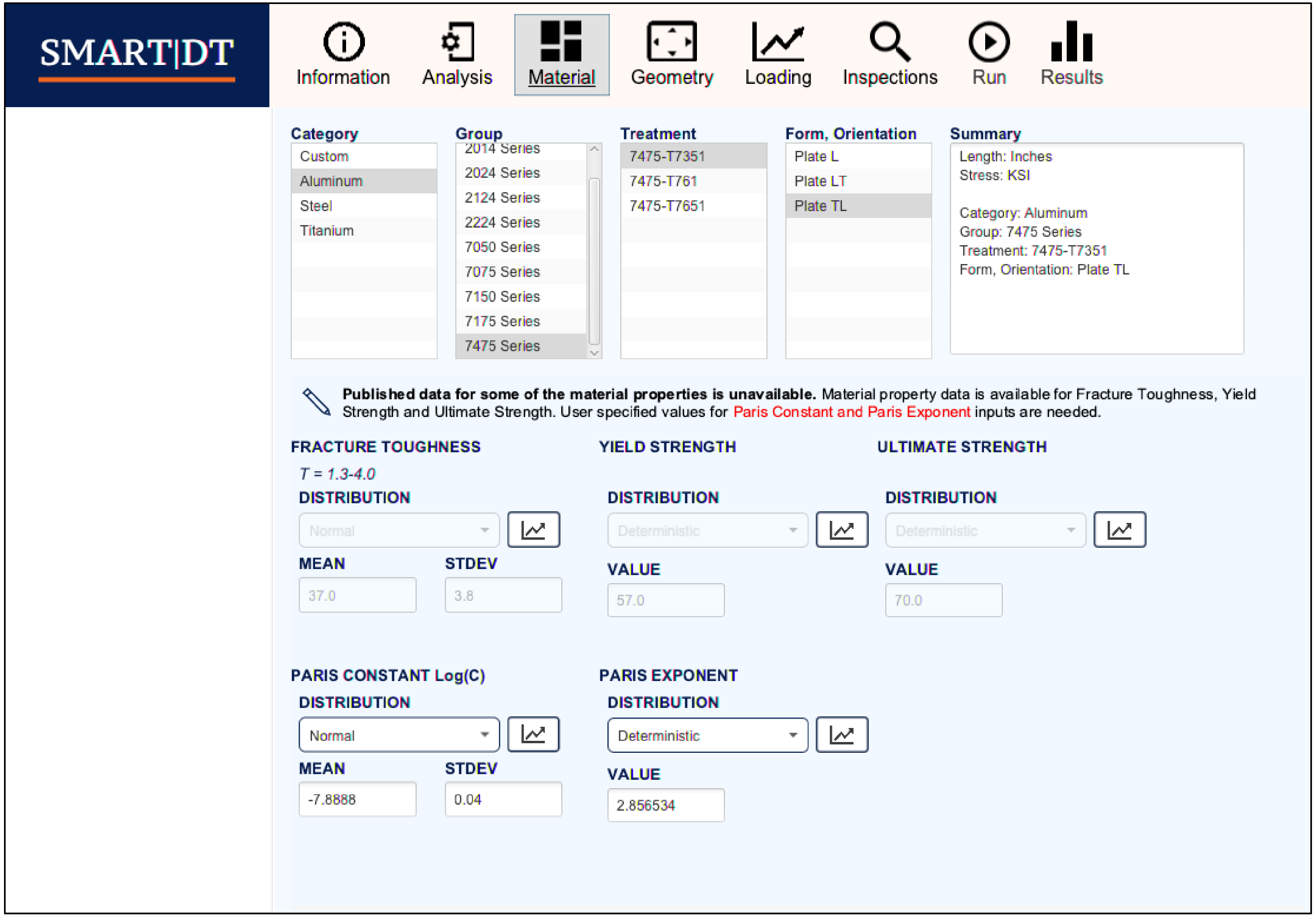
a-direction (through thickness) betas



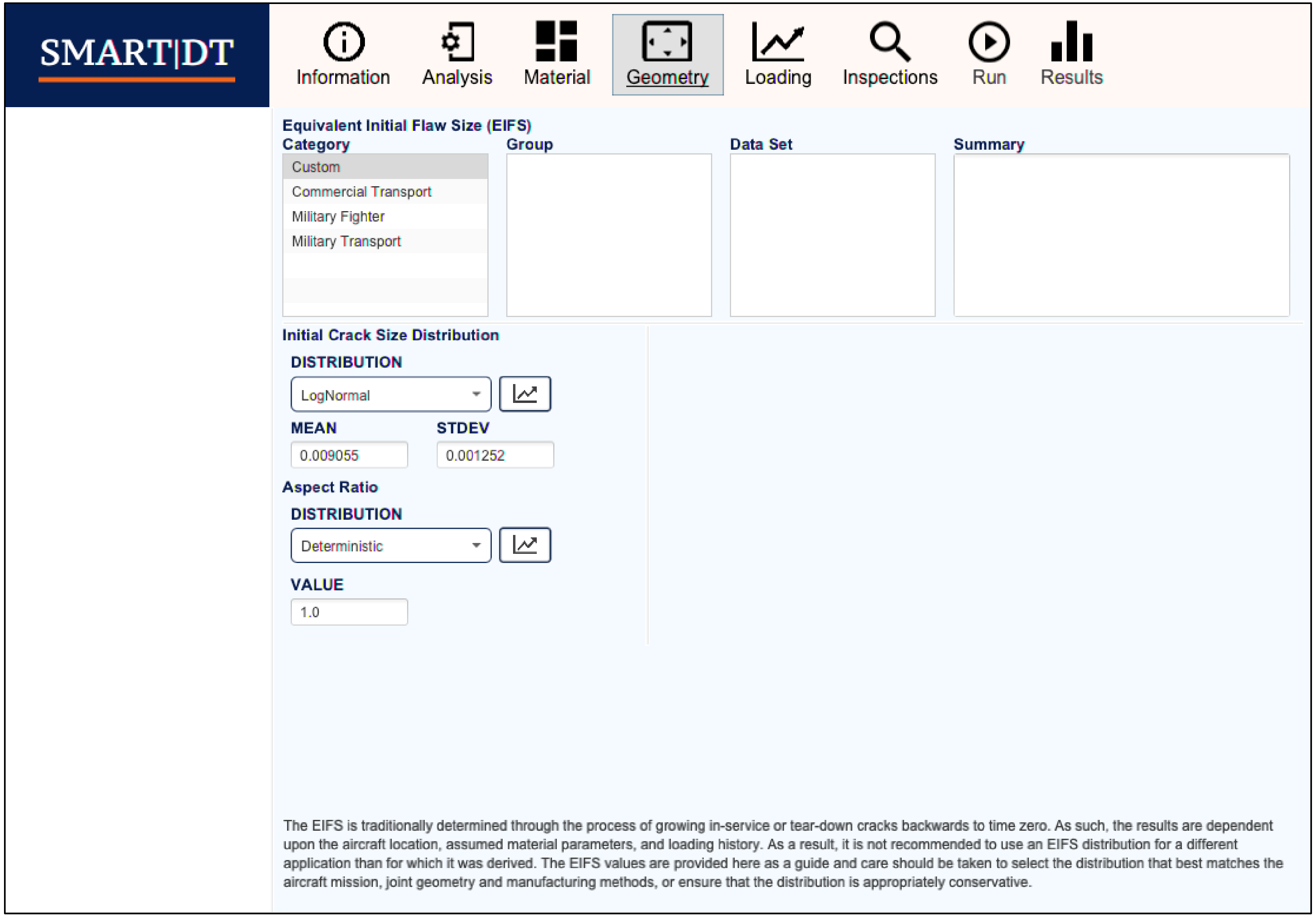
SMART|DT – Analysis Information (Probabilistic)



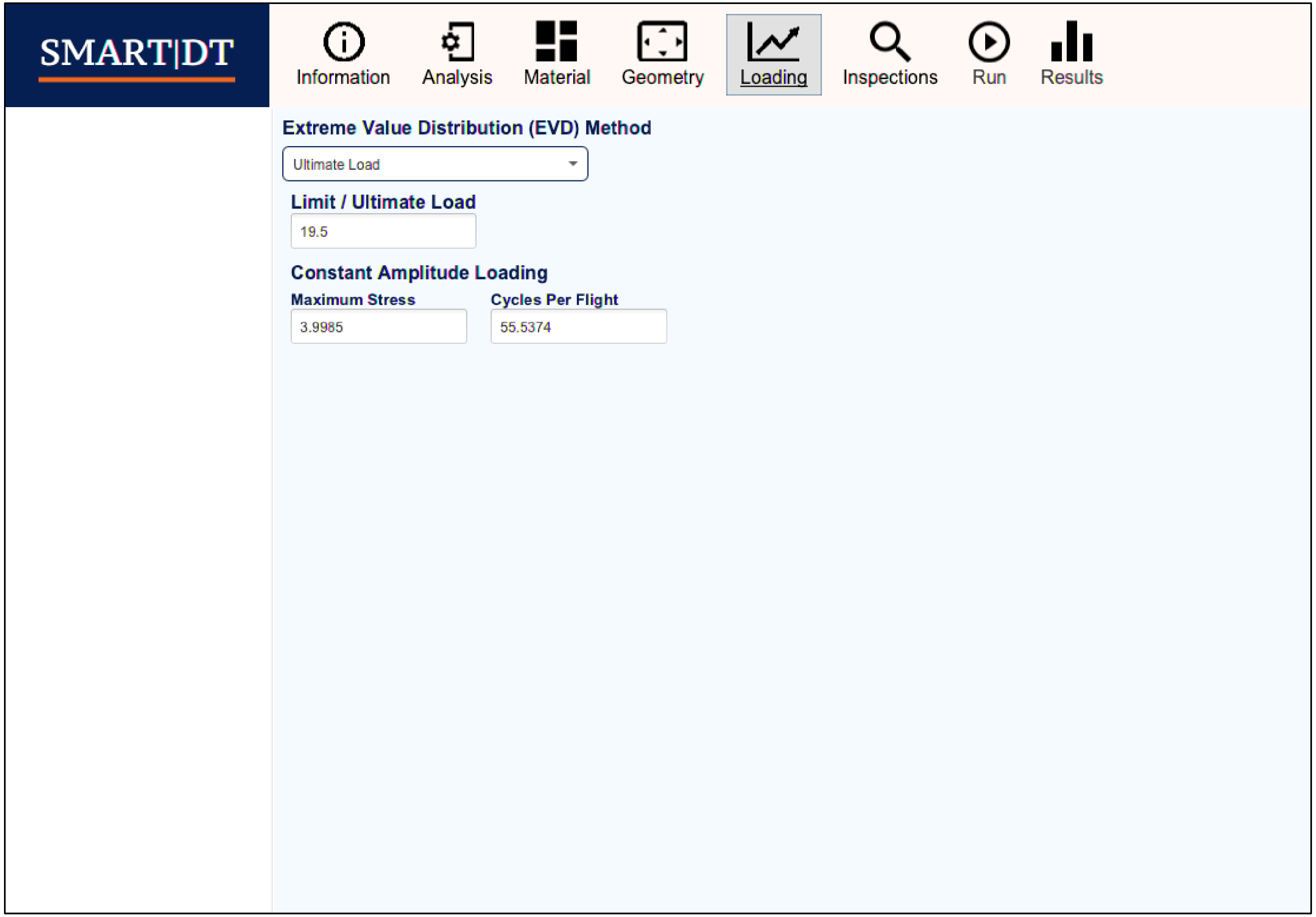
SMART|DT – Material Information



SMART|DT – Geometry Information



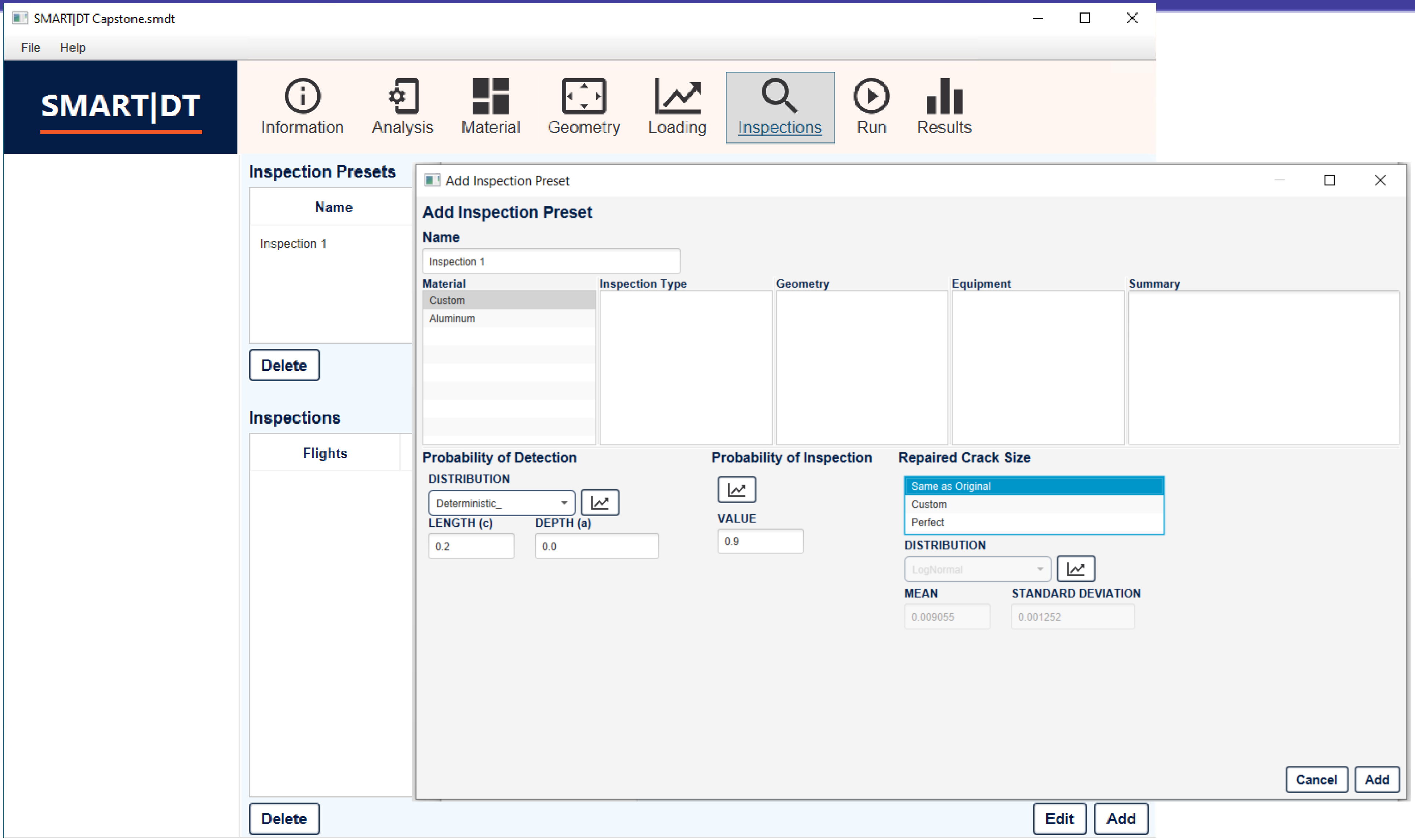
SMART|DT – Loading Information



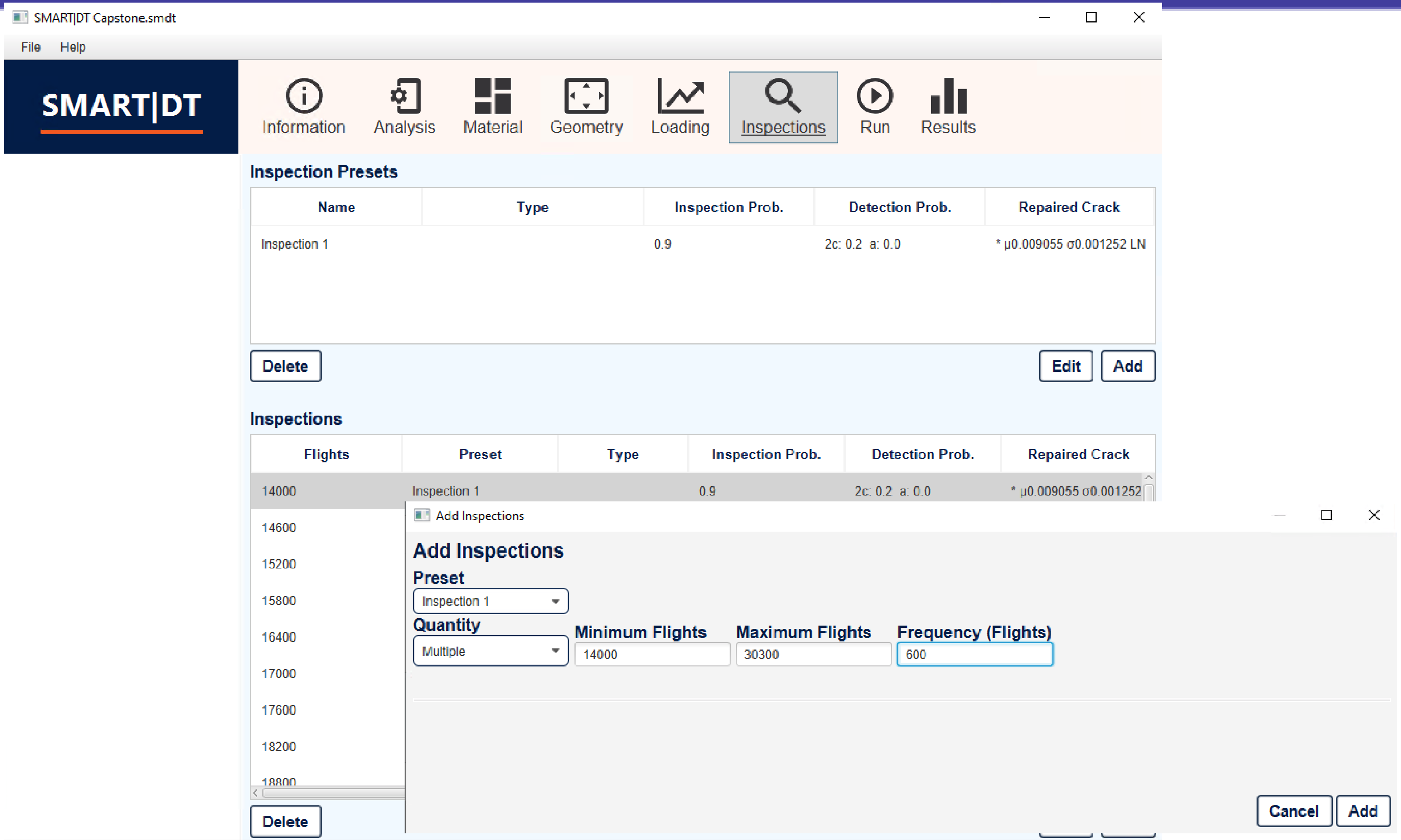
Analysis Inspection Parameters

Inspection Parameter	Value
Number of Inspection Types	One- Single Repair
Inspection Type	Sliding Probe – Eddy Current
Inspection Schedule	14,000 Flights (23,100 Hr) Initial 600 Flights (1,000 Hr) Repeat
Probability of Inspection	90%
Probability of Detection	Deterministic
Detectable Crack Size	.20 inch
Repair Crack POD	.20 inch
Repair Crack Size	Mean = 0.009055 in Standard Deviation = 0.001252 in

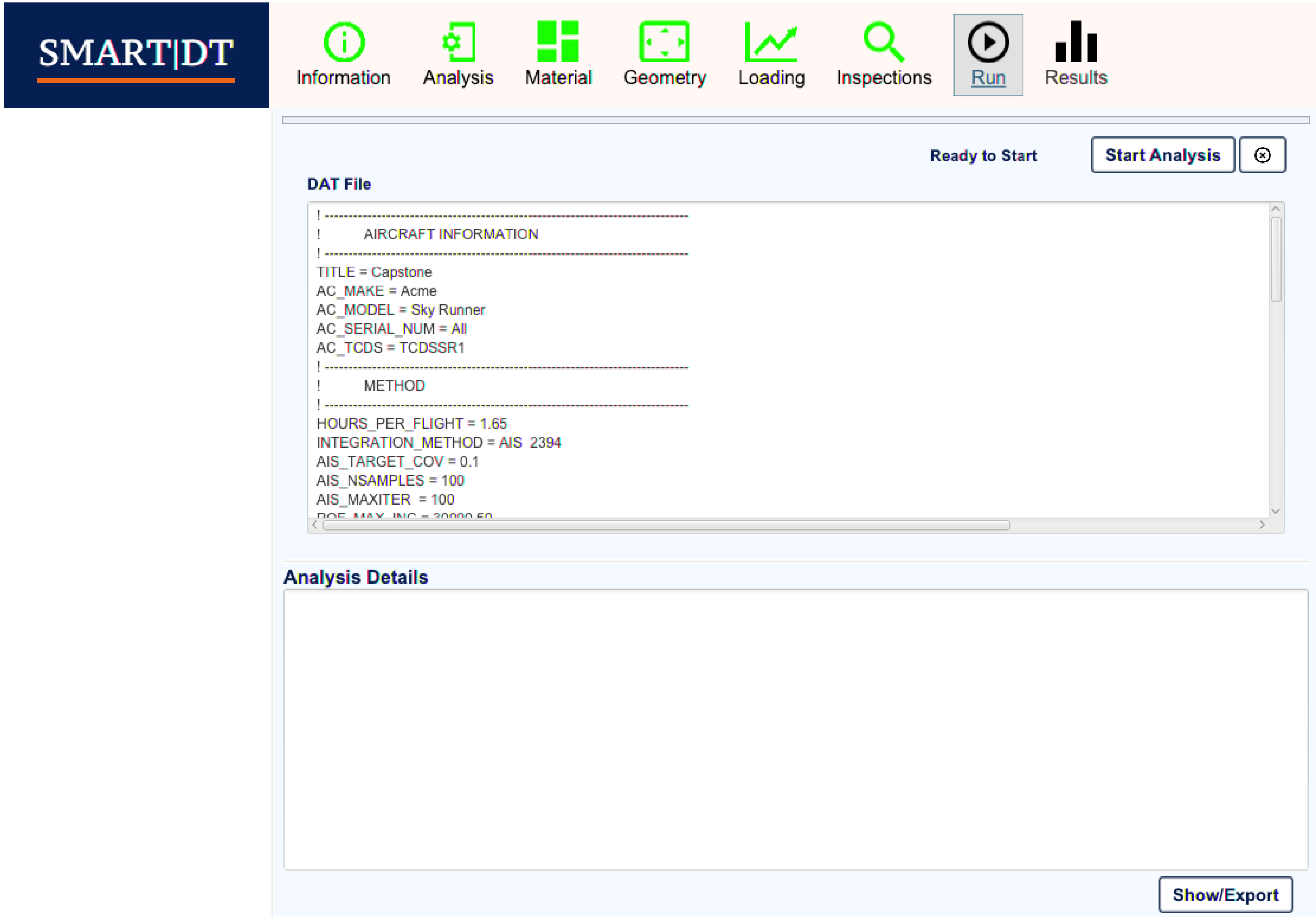
SMART|DT – Inspection Information



SMART|DT – Inspection Information



SMART|DT – Run



SMART|DT
Information
Analysis
Material
Geometry
Loading
Inspections
Run
Results
Ready to Start
Start Analysis
DAT File
! --
! AIRCRAFT INFORMATION
! --
TITLE = Capstone
AC_MAKE = Acme
AC_MODEL = Sky Runner
AC_SERIAL_NUM = All
AC_TCDS = TCDSSR1
! --
! METHOD
! --
HOURS_PER_FLIGHT = 1.65
INTEGRATION_METHOD = AIS 2394
AIS_TARGET_COV = 0.1
AIS_NSAMPLES = 100
AIS_MAXITER = 100
Analysis Details
Show/Export

Hypergrow Input

```
! -------------------------------------------------------------------------
!            AIRCRAFT INFORMATION
! -------------------------------------------------------------------------
TITLE = Capstone
AC_MAKE = Acme
AC_MODEL = Sky Runner
AC_SERIAL_NUM = All
AC_TCDS = TCDSSR1
! -------------------------------------------------------------------------
!            METHOD
! -------------------------------------------------------------------------
HOURS_PER_FLIGHT = 1.65
INTEGRATION_METHOD = MC 1000000000  2394
POF_MAX_INC = 30300 50
ANALYSIS_TIME_UNITS = FLIGHTS
! -------------------------------------------------------------------------
!            FRACTURE MECHANICS
! -------------------------------------------------------------------------
CRACK_GROWTH_CODE = HYPERGROW
INITIAL_CRACK_SIZE = LOGNORMAL 0.009055 0.001252
FRACTURE_TOUGHNESS = NORMAL 37.0 3.8
PARIS_M_AND_LOGC = BINORMAL 2.856534 0.0 -7.8888 0.04 0.0
CRACK_ASPECT_RATIO = DETERMINISTIC 1.0
YIELD_STRENGTH = DETERMINISTIC 57.0
```

Probabilistic Variables (INITIAL_CRACK_SIZE, FRACTURE_TOUGHNESS, PARIS_M_AND_LOGC)

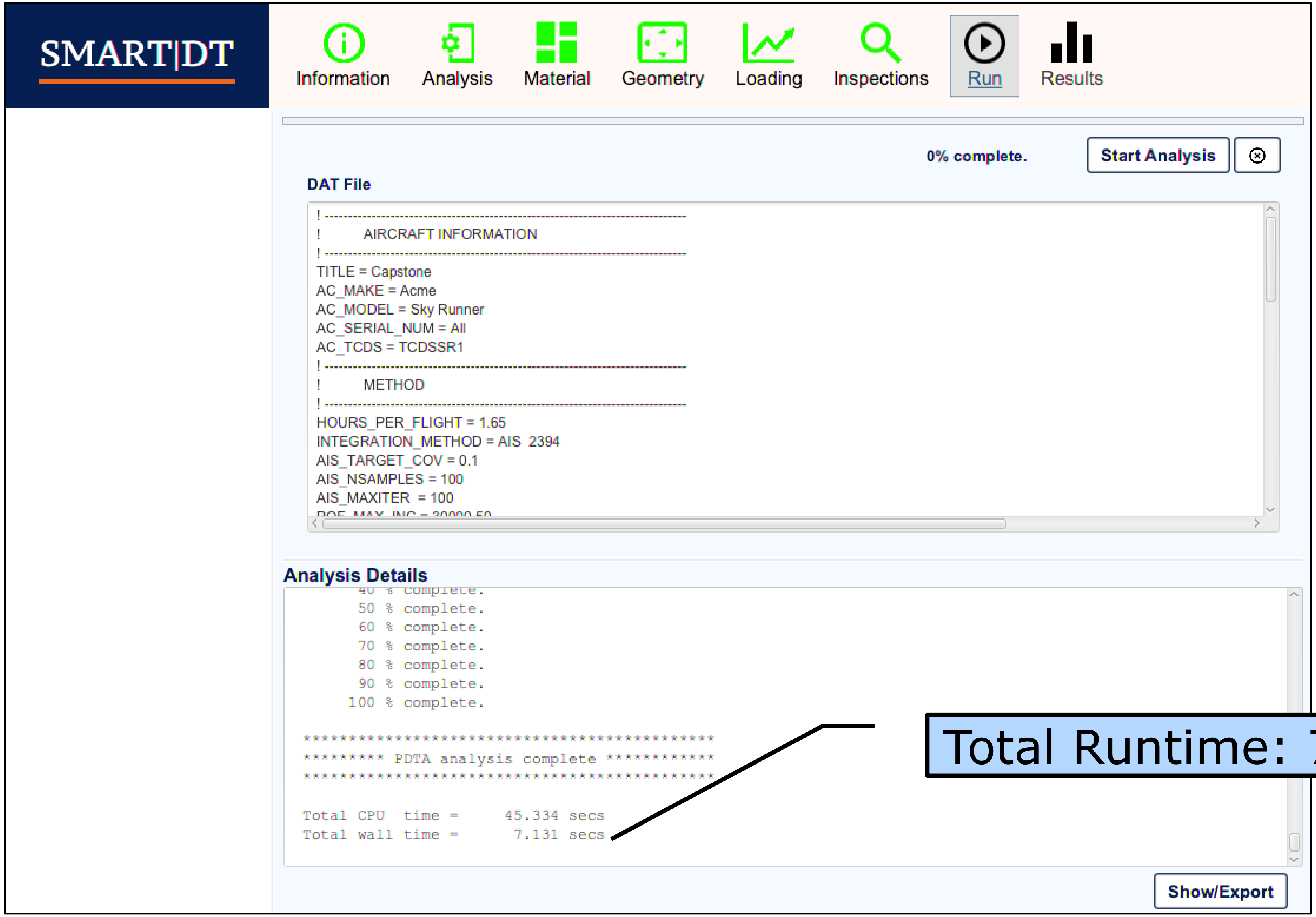
Hypergrow Input


```
! ---------------------------------------------------------------------------
!            HYPERGROW
! ---------------------------------------------------------------------------
FAILURE_CRITERIA = KC
WALKER_EXPONENT = 0.82
CRACKTYPE = CORNER
GEOMETRY = betas_FSpar_CWS_248-87.csv
EQUIVALENT_STRESS_CYCLESPERFLIGHT = 3.9985 55.5374
! ---------------------------------------------------------------------------
!            INSPECTIONS
! ---------------------------------------------------------------------------
INSPECTIONS = 14000 14600 15200 15800 16400 17000 17600 18200 18800 19400
              20600 21200 21800 22400 23000 23600 24200 24800 25400 26000
             27200 27800 28400 29000 29600 30200
INSPECTION_TYPE = 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
```

Inspection Parameters

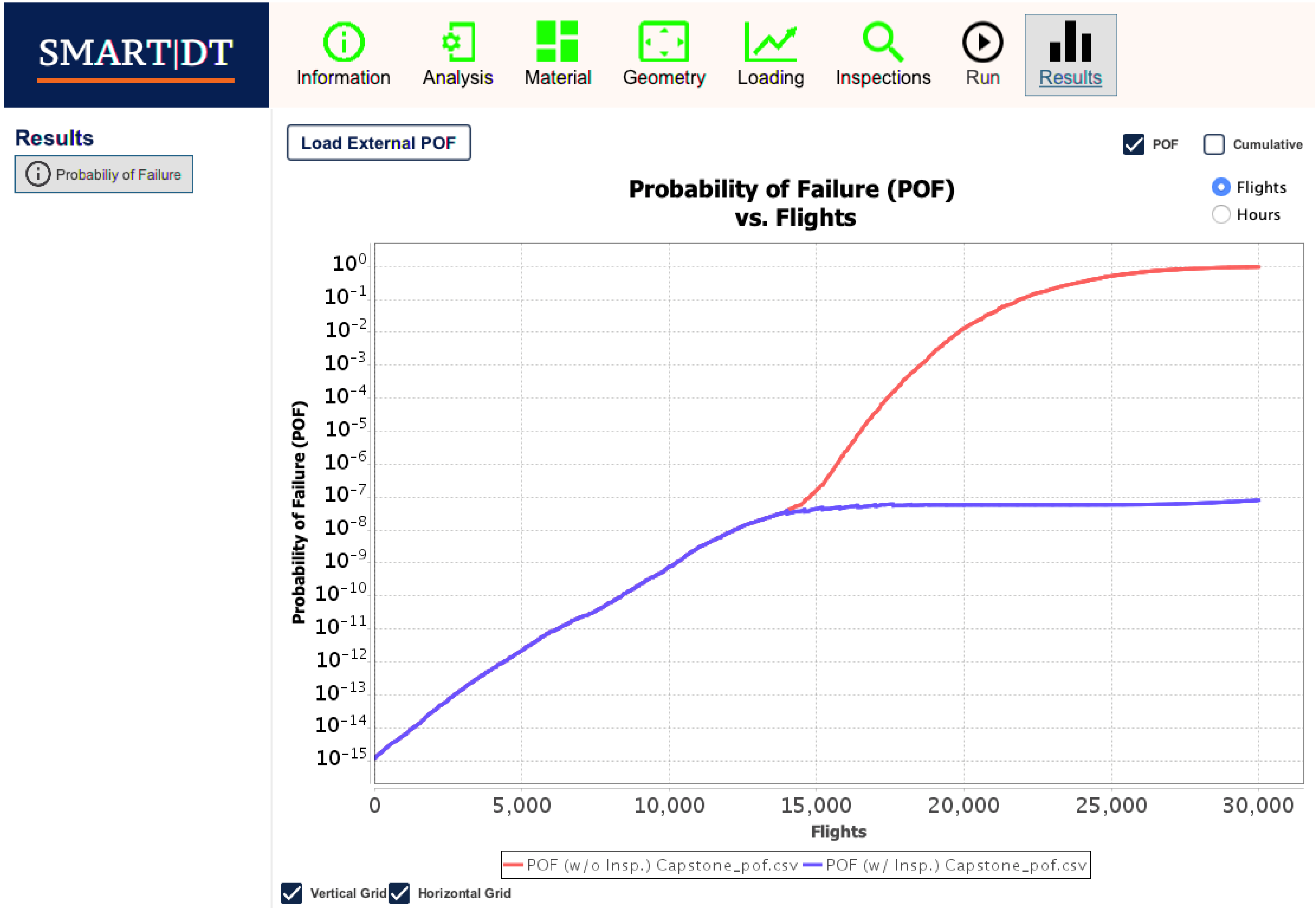
```
INSPECTION_ID = 1
PROB_OF_INSPECTION = DETERMINISTIC 0.9
POD = DETERMINISTIC 0.2 0.0
REPAIR_CRACK_SIZE = LOGNORMAL 0.009055 0.001252
! ---------------------------------------------------------------------------
!            LOADING AND EVD PARAMETERS
! ---------------------------------------------------------------------------
EVD_TYPE = LIMIT 19.5
! ---------------------------------------------------------------------------
!            DESCRIPTION
! ---------------------------------------------------------------------------
!  Front Spar Analysis
```

SMART|DT – Run



Total Runtime: 7 seconds

SMART|DT - Result



Initial Flaw Size
Lognormal
μ = .009055
σ = .001252

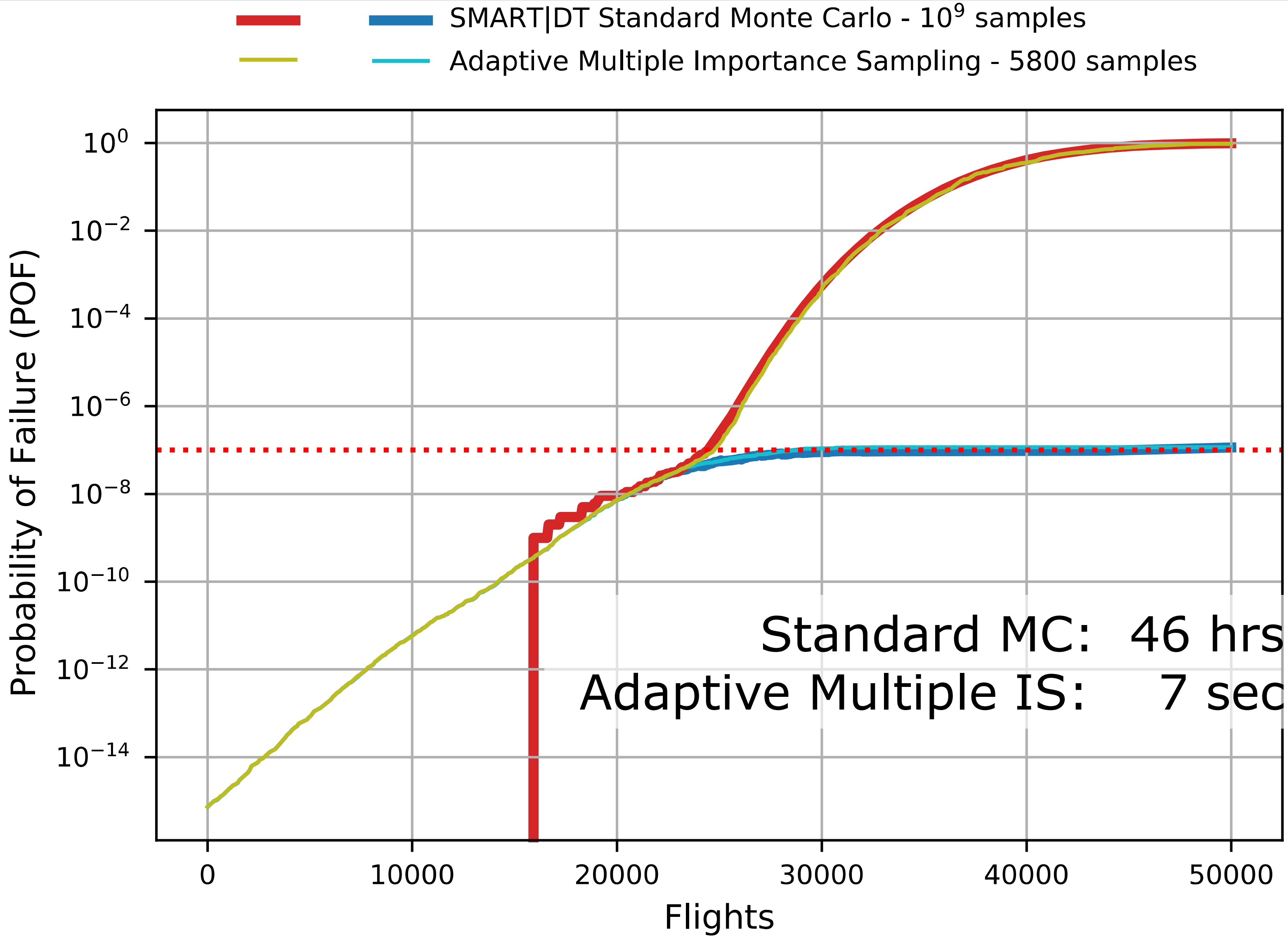
Fracture Toughness
μ = 37.0
σ = 3.8

da/dN Paris m
μ = 2.586
σ = 0.0

da/dN Log C
μ = -7.8888
σ = 0.04

Initial Inspection
23,100 Hours
Repeat Inspection
1,000 Hours

Compare AMIS with Standard Monte Carlo



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μ = -7.8888
σ = 0.04

Initial Inspection
23,100 Hours
Repeat Inspection
1,000 Hours

Questions