

SMART|LD Safe-Life



SMART Short Course
The Aircraft Airworthiness & Sustainment
Conference
Grapevine, Texas – March 21, 2016

Outline



- ✓ SMART|LD Files Overview
- ✓ Safe-Life Analysis
 - ✓ Required Elements Safe-Life Analysis
 - ✓ Loading
 - ✓ SN-Curves
 - ✓ Random Miner's D
 - ✓ Running Example Problem
 - ✓ Input File
 - ✓ GUI Inputs
 - ✓ Output Files
 - ✓ MonteCarlo Samples
 - ✓ Statistical Results
 - ✓ Hz Function Quick Look
 - ✓ SN Region Percentage Damage
- ✓ Summary

SMART Files Overview



SMART_{DT}

Small Aircraft Risk Technology - Damage Tolerance Analysis

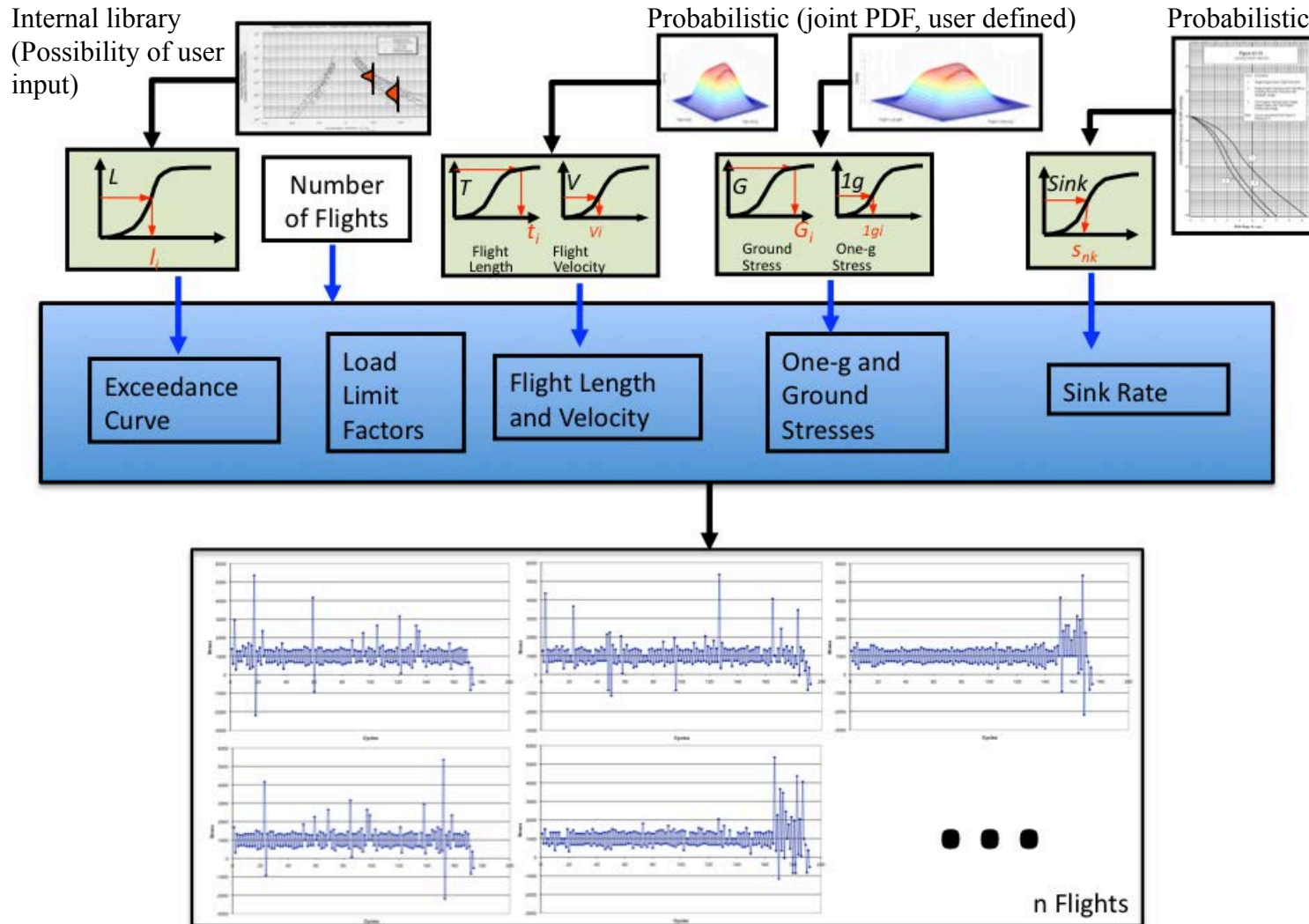
SMART|LD Files Overview



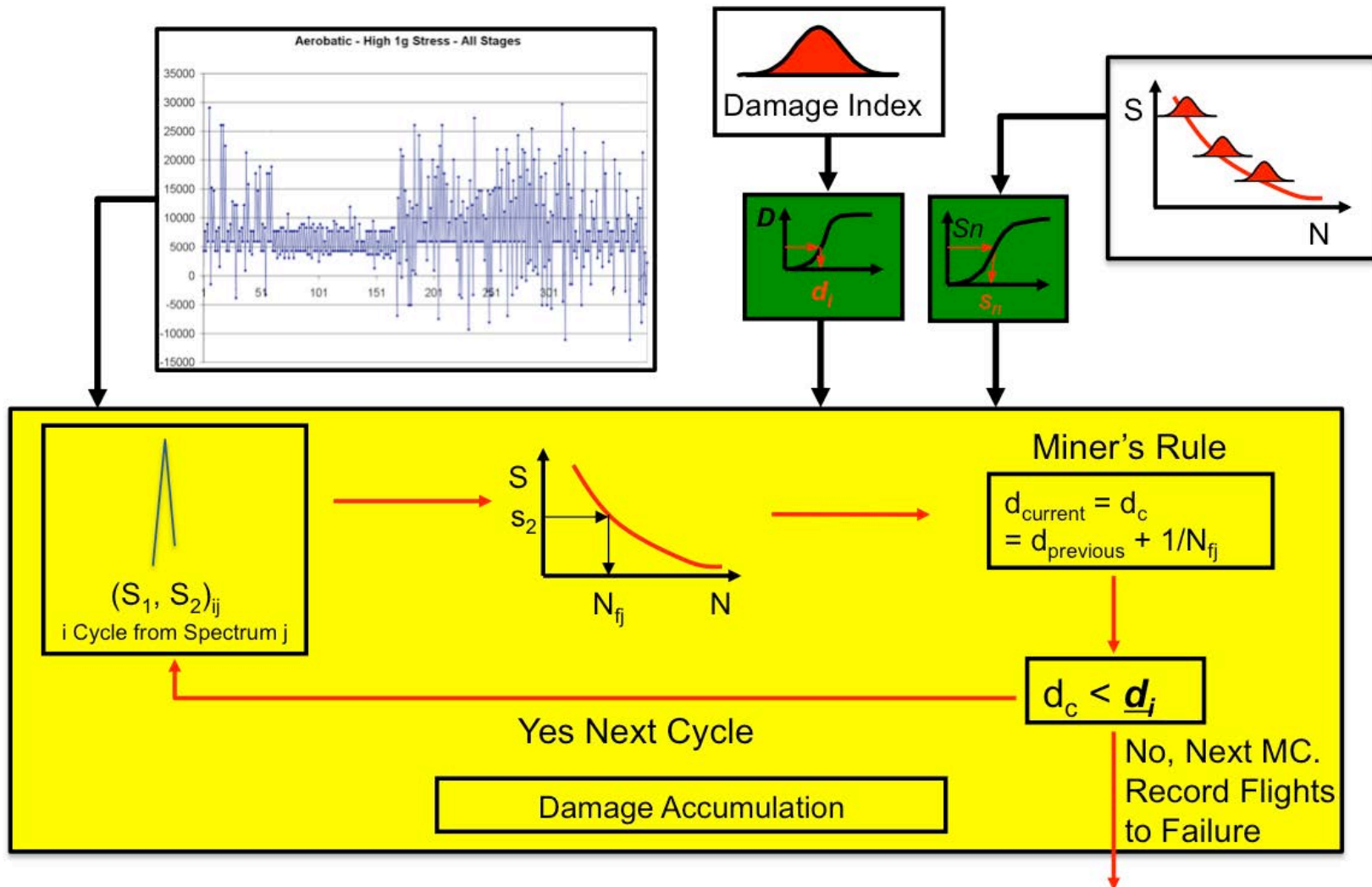
File Type	Description
<code>jobname.dat</code>	Input file containing the keywords and run information
<code>jobname.err</code>	Runtime error file
<code>jobname.wrn</code>	Runtime warning file
<code>jobname.out</code>	File containing a summary of the inputs and statistical results
<code>jobname.txt</code>	File containing the Monte Carlo realizations

Input
output

Loading Generation



Damage Methodology (Safe Life)





NuSS
Sustainment
Solutions

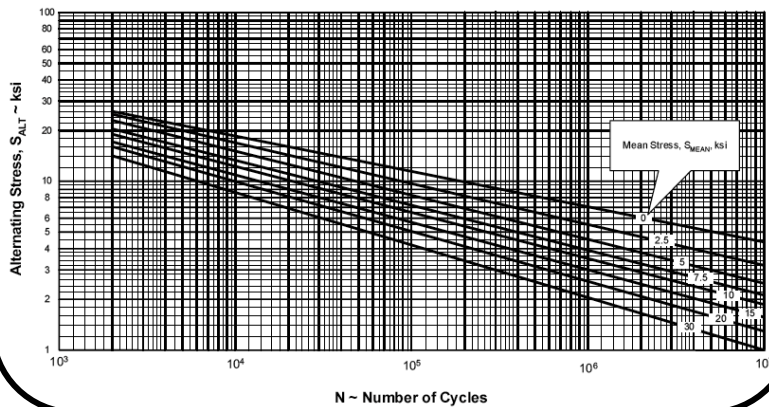
TEXTRON AVIATION

Stress Life Curves

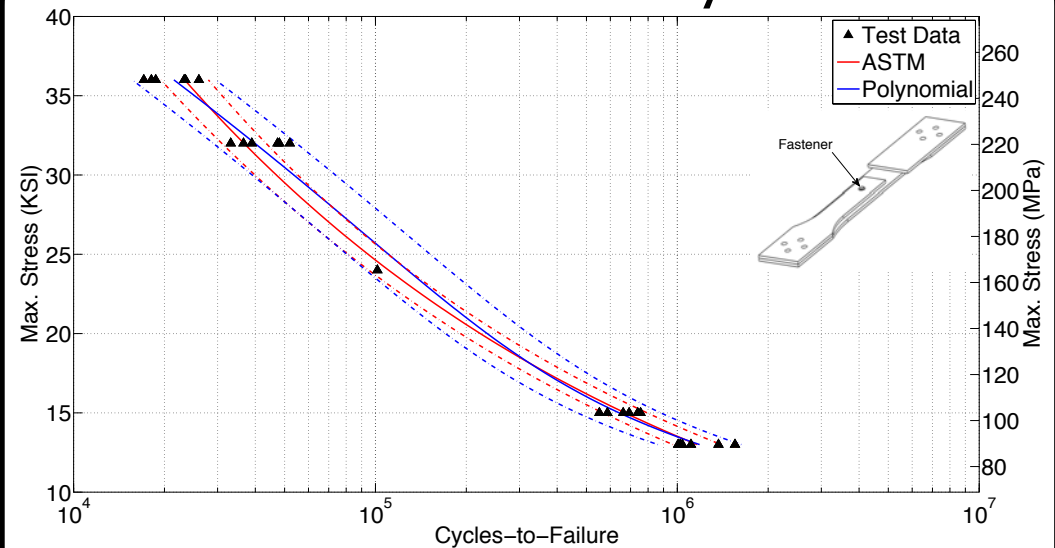
Risk Methodology



FAA AC-23-13A



ASTM E739-91 & Polynomial



```
AI6061-T6.sn
! LOG(N) = A + B * LOG (Seq + C) + Z*Stdev
! Seq = Smax*(1-R)^D
! E = Endurance limit
! Z ~ N(0,1)
```

*** SN PARAMETERS ***

```
A = 11.3196
B = -5.4083
C = 0.0
D = 0.0
E = 0.0
Stdev = 0.5
```

User-defined PSN

Testing
Data





Probabilistic SN

ASTM E739 Methodology



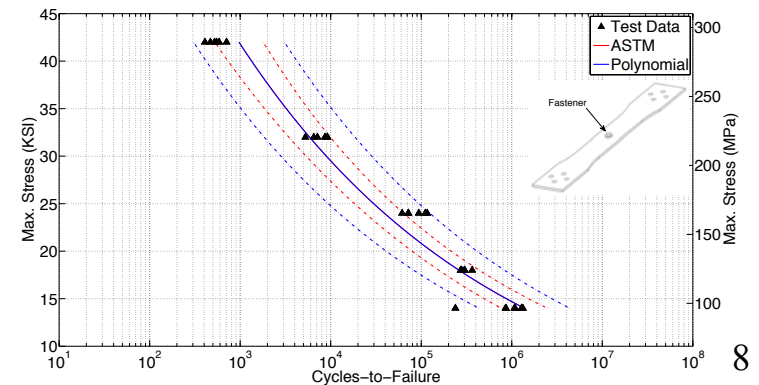
This practice relates only to S-N relationships that may be reasonably approximated by a straight line in log-log space.

Do not use runouts for fitting

$$\log N = A + B(\log S)$$

$$\hat{B} = \frac{\sum_{i=1}^k (X_i - \bar{X})(Y_i - \bar{Y})}{\sum_{i=1}^k (X_i - \bar{X})^2} ; \quad \hat{A} = \bar{Y} - \hat{B}\bar{X} \quad ; \quad \sigma^2 = \frac{\sum_{i=1}^k (Y_i - \hat{Y}_i)^2}{k-2}$$

$$\bar{Y} = \hat{A} + \hat{B}\bar{X} \pm \sqrt{2F_p} \sigma \left[\frac{1}{k} + \frac{(X - \bar{X})^2}{\sum_{i=1}^k (X_i - \bar{X})^2} \right]^{1/2}$$



Probabilistic SN

Polynomial Methodology



Polynomial Regression (Runouts were excluded for the fitting)

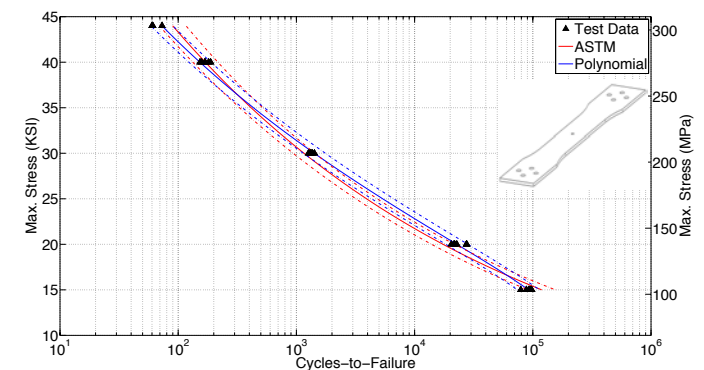
$$\log(N) = b + A(\log(\sigma_{center})) + B(\log(\sigma_{center}))^2 + C(\log(\sigma_{center}))^3 + D(\log(\sigma_{center}))^4$$

$$\sigma_{center} = \log(S) - \sum_{i=1}^n \frac{\log(S_i)}{n}$$

$$\log(N) = b + A(\sigma_{center}) + B(\sigma_{center})^2 + C(\sigma_{center})^3 + D(\sigma_{center})^4 + (Z\sigma_e)$$

Where σ_e is the residual standard deviation and $Z \sim N(0,1)$

Assumption: $e \sim N(0,\sigma)$



Probabilistic SN

MMPDS Methodology



$$\log(N) = A + B \cdot \log(\text{Seq} + C) + Z \cdot \text{stdev}$$

$$\text{Seq} = S_{\max} (1 - R)^D$$

$$Z \sim N(0,1)$$

$A, B, C,$ and D = Regression Parameters

N = Fatigue Life in cycles

Stdev = Standard deviation

Seq = Equivalent Stress

R = Stress Ratio (S_{\min}/S_{\max}),

$Z \sim N(0,1)$ = Standard normal

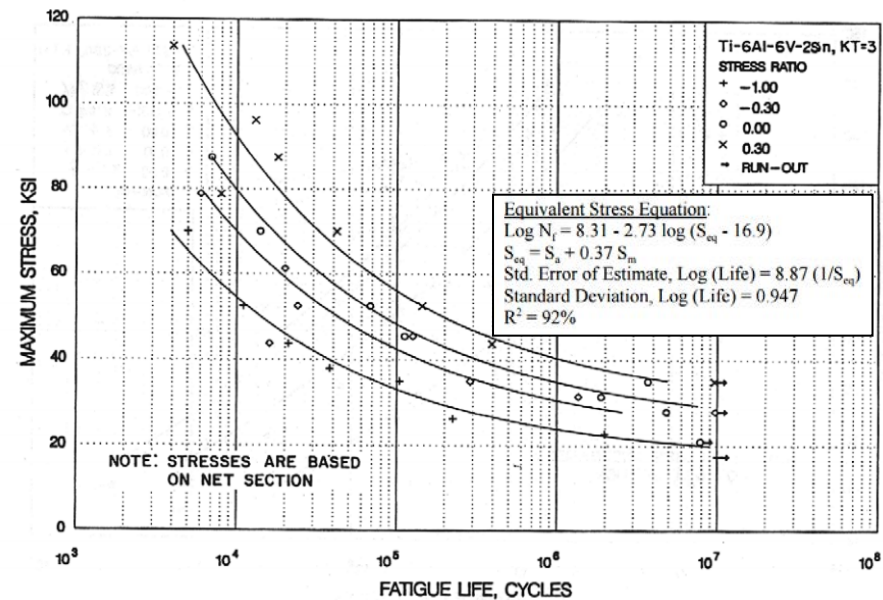
```

Al6061-T6.sn

! LOG(N) = A + B * LOG (Seq + C) + Z*Stdev
! Seq = Smax*(1-R)^D
! E = Endurance limit
! Z ~ N(0,1)

*** SN PARAMETERS ***
A = 11.3196
B = -5.4083
C = 0.0
D = 0.0
E = 0.0
Stdev = 0.5
    
```

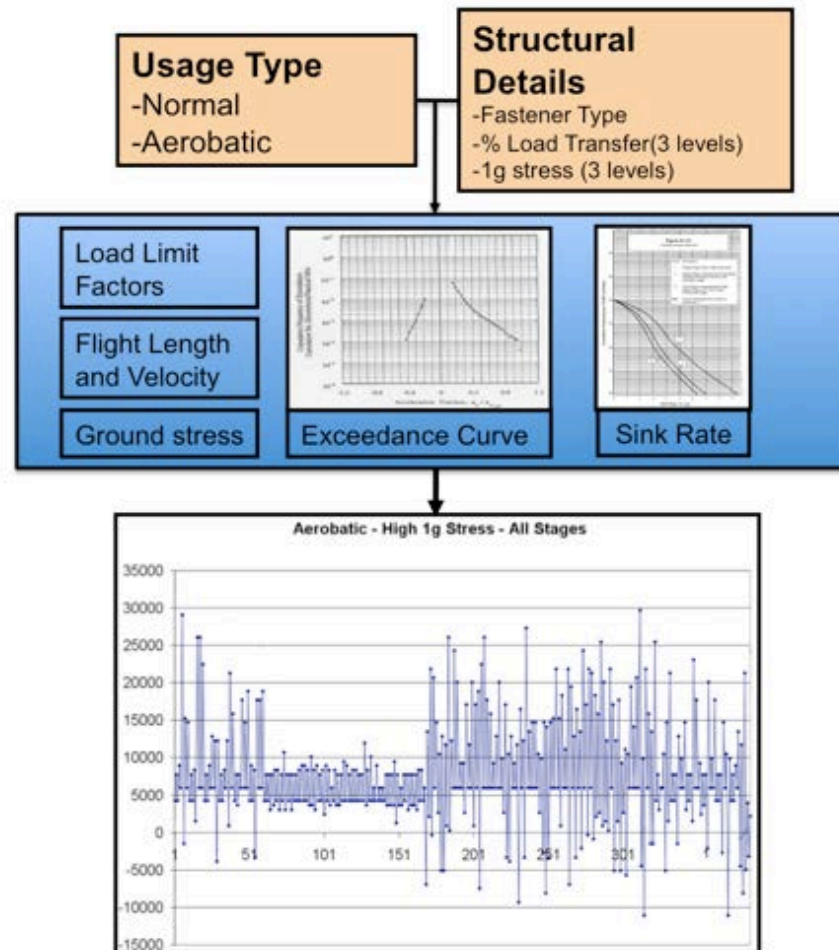
User-defined PSN



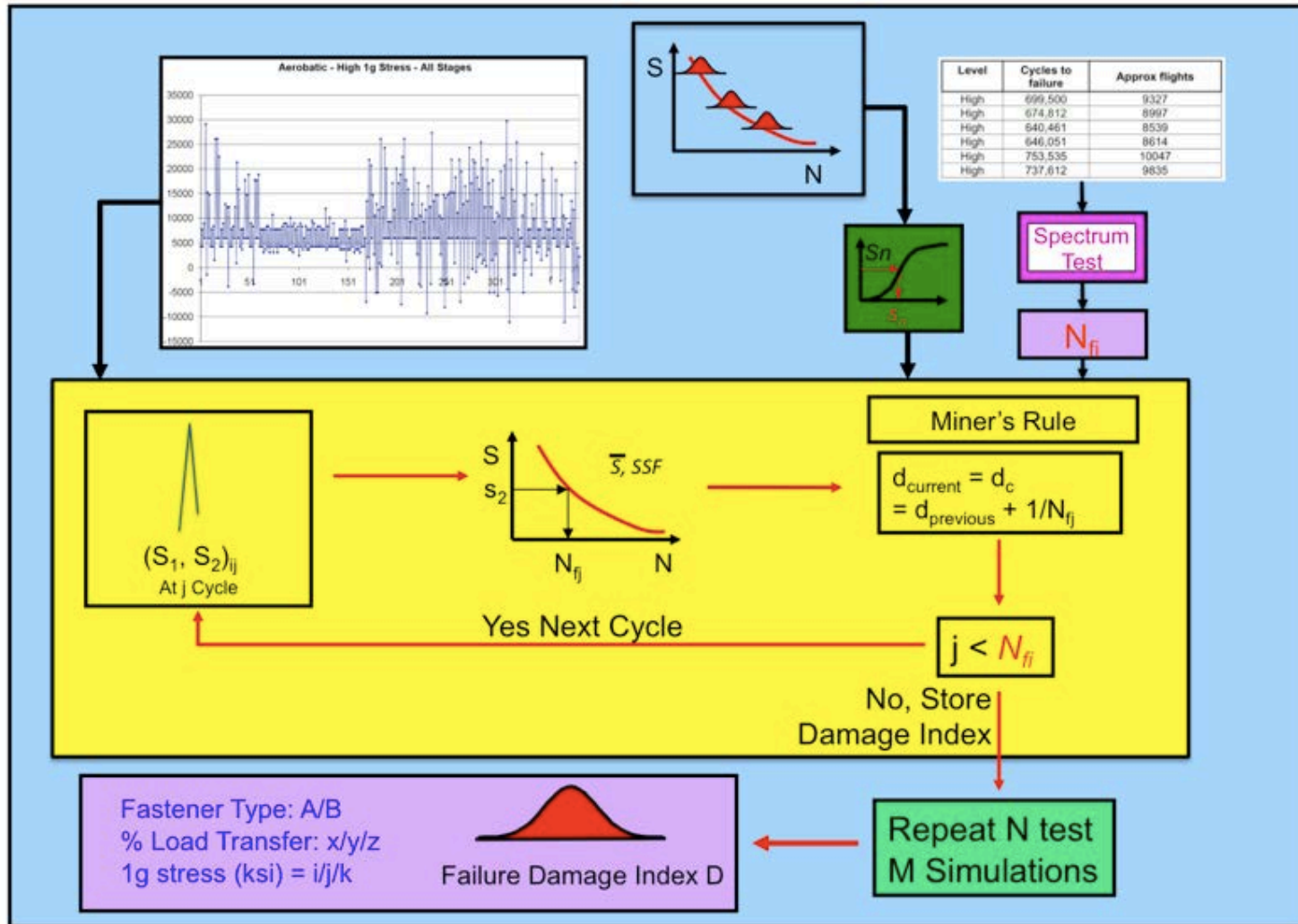
Random Damage Index Methodology



Variable Amplitude Spectrum Generation



Random Damage Index Methodology



Random Damage Index Examples



Spectrum	Severity	Coupon Configuration	Mean Damage Index	Coefficient of Variation
Normal	High (9 KSI)	Open Hole	0.7248	0.113
Normal	Medium (7 KSI)	Open Hole	0.8774	0.190
Normal	Low (5 KSI)	Open Hole	0.7281	0.228
Normal	High (9 KSI)	50% Load Transfer	5.7379	0.483
Normal	Medium (7 KSI)	50% Load Transfer	2.2056	0.437
Normal	Low (5 KSI)	50% Load Transfer	Coupon did not fail during testing	
Aerobatic	High (6 KSI)	Open Hole	0.8942	0.101
Aerobatic	Medium (4.5 KSI)	Open Hole	0.9151	0.131
Aerobatic	Low (3 KSI)	Open Hole	0.7495	0.135
Aerobatic	High (6 KSI)	50% Load Transfer	2.4138	0.225
Aerobatic	Medium (4.5 KSI)	50% Load Transfer	4.3957	0.468
Aerobatic	Low (3 KSI)	50% Load Transfer	Coupon did not fail during testing	

Example Problems



SMART_{LD}

Small Aircraft Risk Technology – Linear Damage Analysis

Example 1



Variable	Characteristics
Gust/Maneuver Load exceedances	Probabilistic exceedances curves for Single Engine Unpressurized Executive Usage
Sink Rate	Probabilistic sink rate
Design Maneuver Load Limit Factors	3.80, -1.52
Design Gust Load Limit Factors	3.41, -1.41
One g stress	+6,550
Ground Stress	-1,987
Aircraft Velocity	153
Damage Index	Normal distribution with mean 1.0 and standard deviation 0.1
SN Curve	AC23-13A

Example 1

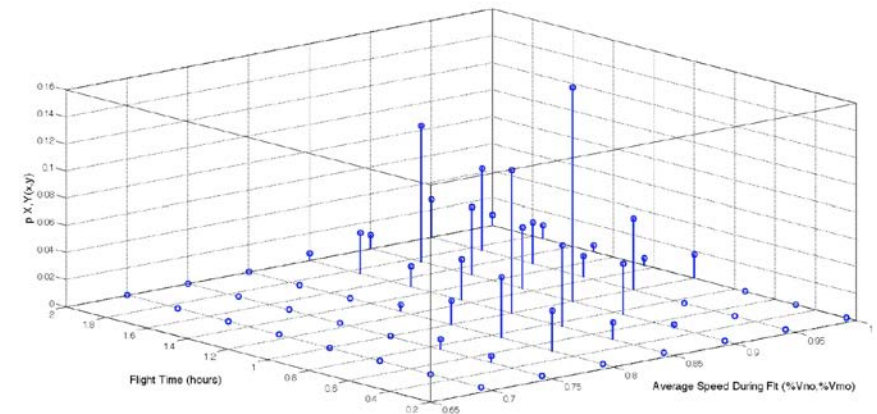


Flight Length and Velocity Matrix

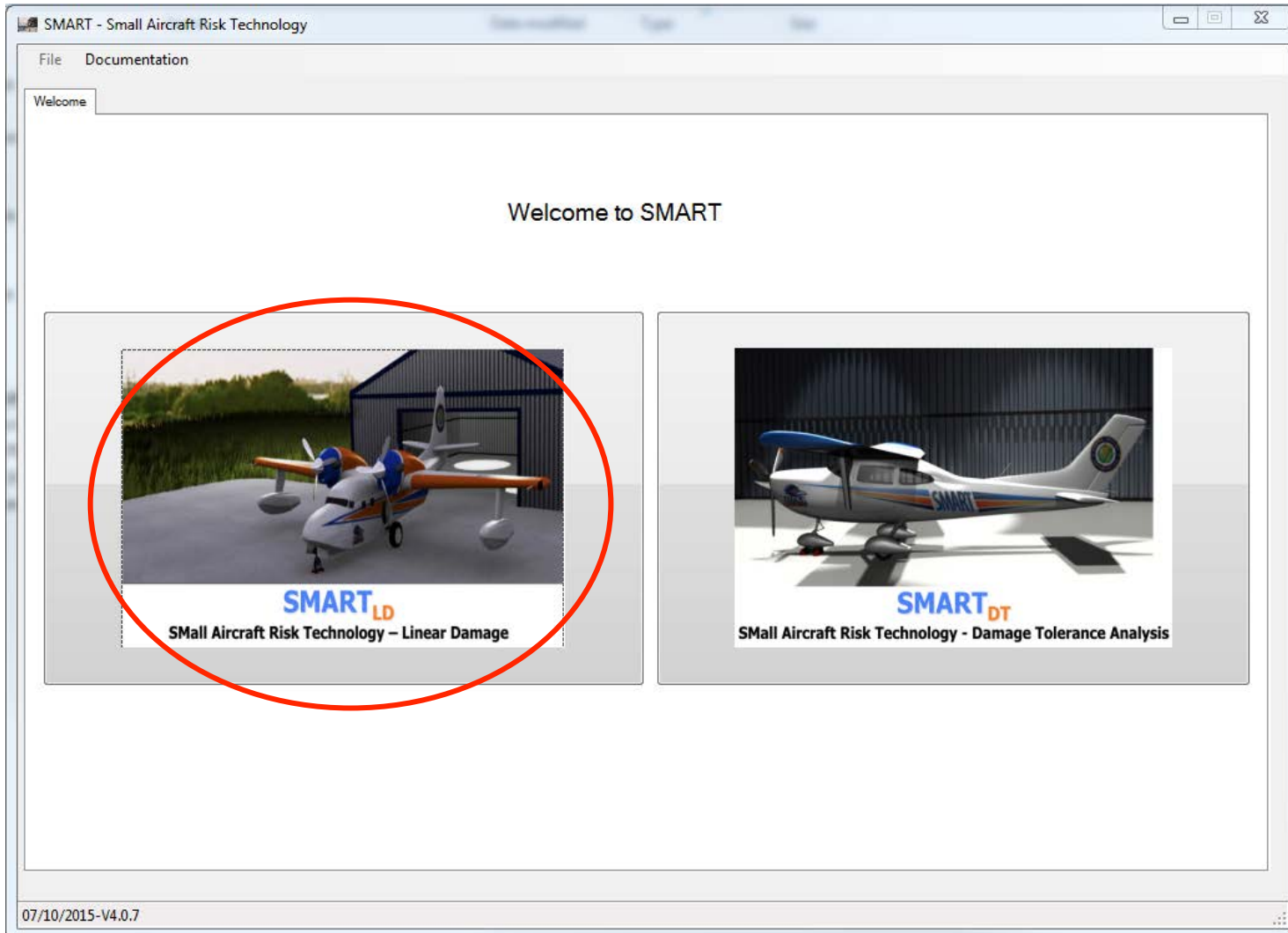
Flight time (Hours)	% of Flights	Average Speed During Flight, % Design Velocity						
		1.00	0.95	0.90	0.85	0.80	0.75	0.70
0.25	0.00	0	0	0	0	0	0	0
0.50	0.05	0	0	0.05	0.25	0.6	0.1	0
0.75	0.15	0	0	0.25	0.4	0.3	0.05	0
1.00	0.35	0.05	0.15	0.45	0.3	0.05	0	0
1.25	0.10	0.05	0.15	0.45	0.3	0.05	0	0
1.50	0.10	0.05	0.3	0.5	0.15	0	0	0
1.75	0.20	0.05	0.3	0.5	0.15	0	0	0
2.00	0.05	0.15	0.55	0.2	0.1	0	0	0

Flight Length and Weight Matrix

Flight time (Hours)	% of Flights	Weight (1g_stress and Ground_stress) Percentage						
		1.00	0.95	0.90	0.85	0.80	0.75	0.70
0.25	0.00	0	0	0	0	0	0	0
0.50	0.05	0	0	0.05	0.25	0.6	0.1	0
0.75	0.15	0	0	0.25	0.4	0.3	0.05	0
1.00	0.35	0.05	0.15	0.45	0.3	0.05	0	0
1.25	0.10	0.05	0.15	0.45	0.3	0.05	0	0
1.50	0.10	0.05	0.3	0.5	0.15	0	0	0
1.75	0.20	0.05	0.3	0.5	0.15	0	0	0
2.00	0.05	0.15	0.55	0.2	0.1	0	0	0



LD Example 1 (Select SMART|LD)



LD Example 1 (Begin Tab)



SMART - Small Aircraft Risk Technology

File Documentation

Begin Usage Spectra

Name:

Aircraft Make:

Aircraft Model:

Aircraft Serial No.:

Aircraft TCDS:

Use Previous Run

Description:

Miner's Rule Damage Factor:

Mean:

Std. Dev:

SN Curve:

Analysis Type:

No. Simulations:

Seed:

Stress Severity Factor Calculation

User Input PSN Curves Direct Input

Alpha:

Beta:

Theta:

Thickness:

Width:

Diameter:

Edge Distance:

Load Transfer:

SSF:

07/10/2015-V4.0.7

LD Example 1 (Usage Spectra Tab)



SMART - Small Aircraft Risk Technology

File Documentation

Begin Usage Spectra Launch Panel

Load Spectrum: Browse... Transfer Factor: 1.0

Flight Hours for this Spectrum: Flight Hours per Flight:

Load Usages:

- SEUE

Usage Spectra

Aircraft Usage: SINGLE_ENGINE_UNPRESS_EXEC_USAGE Plot Exceedances

Percent of Total Usage: 1.0 Exceedance NOV 12.0

Design Maneuver Load Factor High: 3.80 One G Stress (psi): 6550

Design Gust Load Factor High: 3.41 Average Velocity (Vno/Vmo/Kts): 153

Design Maneuver Load Factor Low: -1.52 Number of Flight Times: 13

Design Gust Load Factor Low: -1.41 Number of Velocities: 11

Ground Stress (psi): -1987 Load Matrices Matrix

File: Browse... Save Usage

Flight Variation Deleted Usages

07/10/2015-V4.0.7

Matrix

Flight Times vs. Velocity

Flt. Time (hrs)	% of Flts.	%Vno or %Vmo	%Vno or %Vmo	%Vno or %Vmo	%Vno or %Vmo
		0.75	0.80	0.85	0.90
0.6	0.2	0.2	0.3	0.3	0.2
0.7	0.2	0.2	0.3	0.3	0.2
0.8	0.3	0.2	0.2	0.2	0.4
0.9	0.3	0.25	0.25	0.25	0.25

Flight Times vs. Weight

Flt. Time (hrs)	% of Flts.	%Max. Wt.	%Max. Wt.	%Max. Wt.	%Max. Wt.
		0.75	0.80	0.85	0.90
0.6	0.2	0.2	0.3	0.3	0.2
0.7	0.2	0.2	0.3	0.3	0.2
0.8	0.3	0.2	0.2	0.2	0.4
0.9	0.3	0.25	0.25	0.25	0.25

LD Example 1 (Launch Panel Tab)



```
SMART - Small Aircraft Risk Technology
File Documentation
Begin Usage Spectra Launch Panel
!-----
! AIRCRAFT INFORMATION
!-----
TITLE = Example1_LD
AC_MAKE = None
AC_MODEL = None1
AC_SERIAL_NUM = None2
AC_TCDs = None3
!-----
! SN-CURVE, MINERS AND SSF
!-----
SN_CURVE = AC23
MINERS_D = NORMAL 1.0 0.1 0.0
!-----
! METHOD
!-----
MCSAMP = 20000
SEED = 7972210
INPUT_FILE = NO
ANALYSIS_TYPE = DAMAGE
!-----
! LOADING PARAMETERS
!-----
NUMBER_OF_USAGES = 1
USAGE = SINGLE_ENGINE_UNPRESS_EXEC_USAGE 1.0
LLF_MAN = 3.80 -1.52
LLF_GUST = 3.41 -1.41
GROUND_STRESS = -1987
ONEg_STRESS = 6550
AC_VEL = 153
FLT_VEL_MATRIX =
Run
07/10/2015-V4.0.7
```


LD Example 1 (Results Tab)



SMART - Small Aircraft Risk Technology

File Documentation

Results

Load Output File: C:\Users\pze593\Desktop\BenchmarkProblems\Example1_LD\Example1_LD_Damage.txt Load Output

Scatter Plots

Flights to Failure

VS

Flight Duration

Plot

2-D Line

Hours to Failure

VS

Hazard Function

Plot

Histograms

Flight Duration

Plot

Damage Pie Chart

Plot

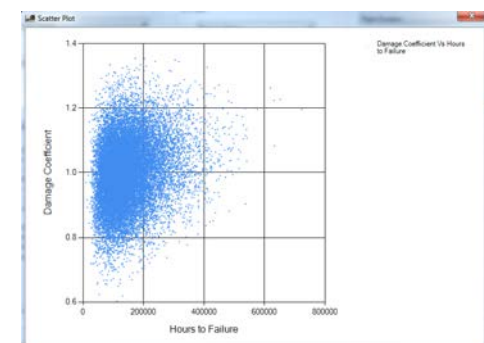
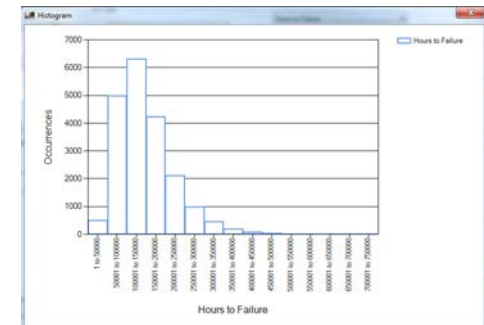
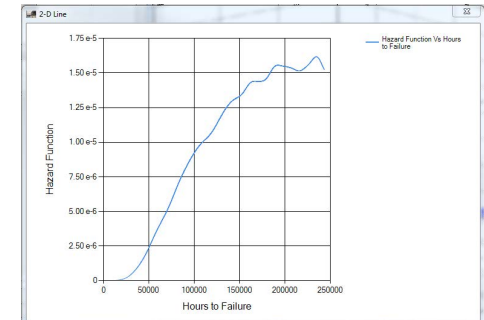
Samples Output Screen out Fleet Management

```

*SMART ANALYSIS*
DATE: 2/16/2016
TIME: 17:52:40
-----
Job Title: EXAMPLE1_LD
-----
SEED: 2133187540
SEED: 1328149471
SAMPLES: 20000
SN_CURVE_TYPE: AC23
ANALYSIS_TYPE: DAMAGE
USER_SPECTRUM: NO
Airplane Data

AC_MAKE: NONE
AC_MODEL: NONE1
AC_SERIAL_NUMBER: NONE2
    
```

07/10/2015-V4.0.7





Detailed Monte Carlo Info (.txt File)



Hours/
Flight Run no
Hz. Fn Failure

Run	Flight Duration	Percentage Gust Damage	Percentage Man Damage	Hours Fat	Hazard Function	Percentage Reb Damage	Percentage GAG Damage	Sample Usage
1	0.75	0.9400	0.0011	771	0.9378E-08	0.0004	0.0586	SEUE
2	0.90	0.9138	0.0120	1285	0.3691E-07	0.0006	0.0736	SEUE
3	0.90	0.8829	0.0150	1573	0.7663E-07	0.0011	0.1010	SEUE
4	0.55	0.8295	0.0200	1609	0.8261E-07	0.0025	0.1480	SEUE
5	0.80	0.8742	0.0133	1626	0.8559E-07	0.0014	0.1110	SEUE
6	0.70	0.8945	0.0028	1653	0.9042E-07	0.0012	0.1015	SEUE
7	0.75	0.8602	0.0170	1692	0.9738E-07	0.0020	0.1207	SEUE
8	0.70	0.8554	0.0161	1771	0.1124E-06	0.0018	0.1268	SEUE
9	0.65	0.8666	0.0048	1871	0.1329E-06	0.0020	0.1267	SEUE
10	1.00	0.8713	0.0067	1928	0.1455E-06	0.0021	0.1199	SEUE
11	0.65	0.8256	0.0113	1935	0.1469E-06	0.0030	0.1601	SEUE
12	0.80	0.8759	0.0083	1935	0.1455E-06	0.0016	0.1142	SEUE
13	0.60	0.7457	0.0962	1939	0.1469E-06	0.0026	0.1555	SEUE
14	0.70	0.8245	0.0341	1959	0.1479E-06	0.0024	0.1390	SEUE
15	0.85	0.8776	0.0092	1964	0.1526E-06	0.0015	0.1117	SEUE
16	0.85	0.8776	0.0092	1964	0.1526E-06	0.0015	0.1117	SEUE
17	0.90	0.3508	0.5007	2001	0.1536E-06	0.0024	0.1462	SEUE
18	0.70	0.8839	0.0144	2049	0.1628E-06	0.0011	0.1006	SEUE
19	0.85	0.8696	0.0140	2049	0.1752E-06	0.0017	0.1148	SEUE
20	0.90	0.8804	0.0068	2152	0.2054E-06	0.0016	0.1112	SEUE
21	0.95	0.8131	0.0024	2161	0.2087E-06	0.0016	0.1112	SEUE
22	0.55	0.8469	0.0419	2166	0.2102E-06	0.0035	0.1810	SEUE
23	0.75	0.8469	0.0419	2171	0.2102E-06	0.0014	0.1098	SEUE
24	1.10	0.8874	0.0068	2181	0.2120E-06	0.0012	0.1046	SEUE
25	0.95	0.8672	0.0217	2224	0.2151E-06	0.0015	0.1096	SEUE
26	0.60	0.8845	0.0065	2250	0.2307E-06	0.0014	0.1076	SEUE
27	1.10	0.8838	0.0040	2267	0.2407E-06	0.0016	0.1106	SEUE
28	0.70	0.8838	0.0040	2267	0.2407E-06	0.0016	0.1106	SEUE
29	0.90	0.8254	0.0129	2271	0.2478E-06	0.0026	0.1591	SEUE
30	0.95	0.8741	0.0116	2337	0.2493E-06	0.0018	0.1125	SEUE
31	0.60	0.8741	0.0116	2337	0.2493E-06	0.0018	0.1125	SEUE
32	1.10	0.8698	0.0069	2365	0.2789E-06	0.0022	0.1212	SEUE
33	0.90	0.8862	0.0078	2416	0.2926E-06	0.0011	0.1048	SEUE
34	0.95	0.8840	0.0047	2427	0.3193E-06	0.0014	0.1099	SEUE
35	0.95	0.8840	0.0047	2432	0.3254E-06	0.0014	0.1099	SEUE
36	0.95	0.8840	0.0047	2432	0.3284E-06	0.0014	0.1099	SEUE
37	0.95	137.7	1.5066	1.20	0.3284E-06	6419.00	-1947.26	SEUE

Hz. Fn

Run

Detailed output per MC run

Input & Output Summary .out File

```

... Lines were removed from this output ...
-----
User Spectrum: NO
-----
Summary of Input Data
-----
Flight Variation =          NO
-----
Analysis Type =          DAMAGE
-----
Number of Usages =          1
-----
Numb. of MC Samples: =      20000
Seed:                      7972210
-----
Usage:                      1
Usage name = SINGLE_ENGINE_UNPRESS_EXEC_USAGE
Percentage Usage = 1.00
-----
Stresses
Ground Stress:              -1987.00
One g Stress:               6550.00
-----
Design Load Limit Factors
Positive Gust:              3.410
Negative Gust:             -1.410
Positive Man:               3.800
Negative Man:              -1.520
-----
Flt Velocity and Duration Data
... Lines were removed from this output ...
-----
SN Curve = AC23      Deterministic
-----
***SMART RESULTS***
-----
Probability      Flights-to-Failure      Hours-to-Failure
0.500000         117050                   134646
0.100000         67662                    70690
0.010000         42116                    40804
0.001000         26187                    27889
0.000223         16942                    17350
-----
                          Mean Results
          Lower Bound      95%      99%      F-T-F Mean      90%      95%      Upper Bound      99%
126356.  126228.  125985.  127009.  127663.  127791.  128034.
-----
          Lower Bound      95%      99%      H-T-F Mean      90%      95%      Upper Bound      99%
147542.  147378.  147064.  148384.  149226.  149390.  149703.
-----
                          Stdev Results
          Lower Bound      95%      99%      F-T-F Stdev      90%      95%      Upper Bound      99%
55909.   55821.   55651.   56368.   56836.   56926.   57103.
-----
          Lower Bound      95%      99%      H-T-F Stdev      90%      95%      Upper Bound      99%
72008.   71896.   71676.   72600.   73203.   73319.   73547.
-----
... Lines were removed from this output ...
-----
          **** PEARSON CORRELATIONS ****
-----
          Flight      A/C      Sink      Damage      Gust      Man      One-g      Ground      PSN
          Duration    Velocity  Rate      Coefficient  Factor    Factor    Stress    Stress
-----
FTF      -0.24282  0.00573  -0.02277  0.23560    -0.56815  -0.11263  -0.45512  0.45508  0.00000
HTF      0.44856  -0.34164 -0.02118  0.21342    -0.51680  -0.10505  -0.74622  0.74616  0.00000
-----
Summary Results per Usage
-----
Usage = SINGLE_ENGINE_UNPRESS_EXEC_USAGE
Mean Flights to Failure = 127009.5
Mean Hours to Failure = 148383.7
... Lines were removed from this output ...

```



TEXTRON AVIATION

Safe-life Results

from .out File



Probability	Flights-to-Failure	Hours-to-Failure
0.500000	117050	134646
0.100000	67662	70690
0.010000	42116	40804
0.001000	26187	27889
0.000223	16942	17350

Mean Results

Lower Bound			F-T-F Mean	Upper Bound		
90%	95%	99%		90%	95%	99%
126356.	126228.	125985.	127009.	127663.	127791.	128034.

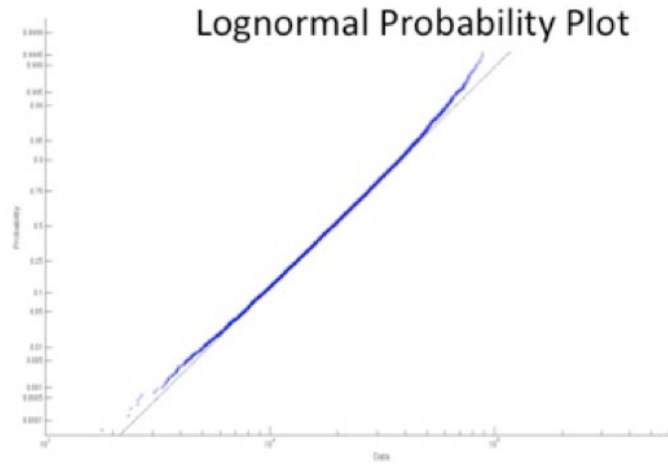
Lower Bound			H-T-F Mean	Upper Bound		
90%	95%	99%		90%	95%	99%
147542.	147378.	147064.	148384.	149226.	149390.	149703.

Stdev Results

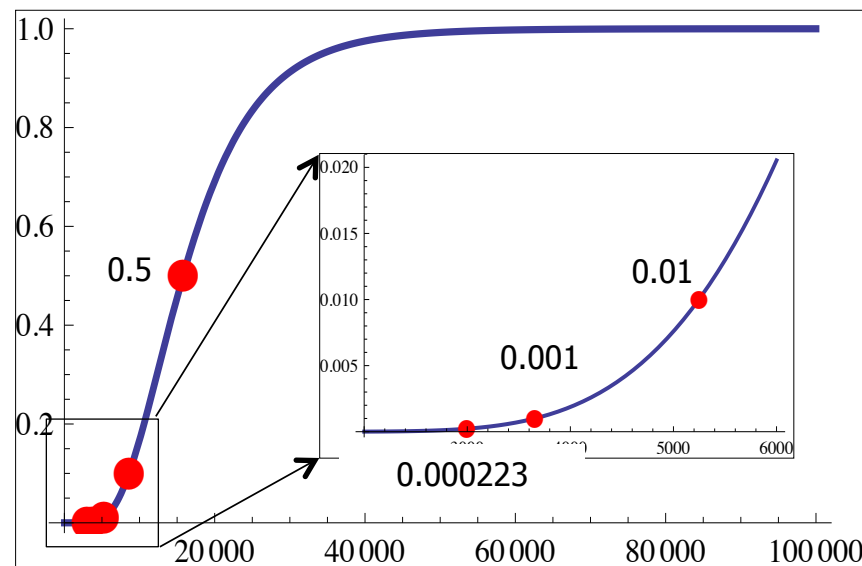
Lower Bound			F-T-F Stdev	Upper Bound		
90%	95%	99%		90%	95%	99%
55909.	55821.	55651.	56368.	56836.	56926.	57103.

Lower Bound			H-T-F Stdev	Upper Bound		
90%	95%	99%		90%	95%	99%
72008.	71896.	71676.	72600.	73203.	73319.	73547.

Safe-life Results



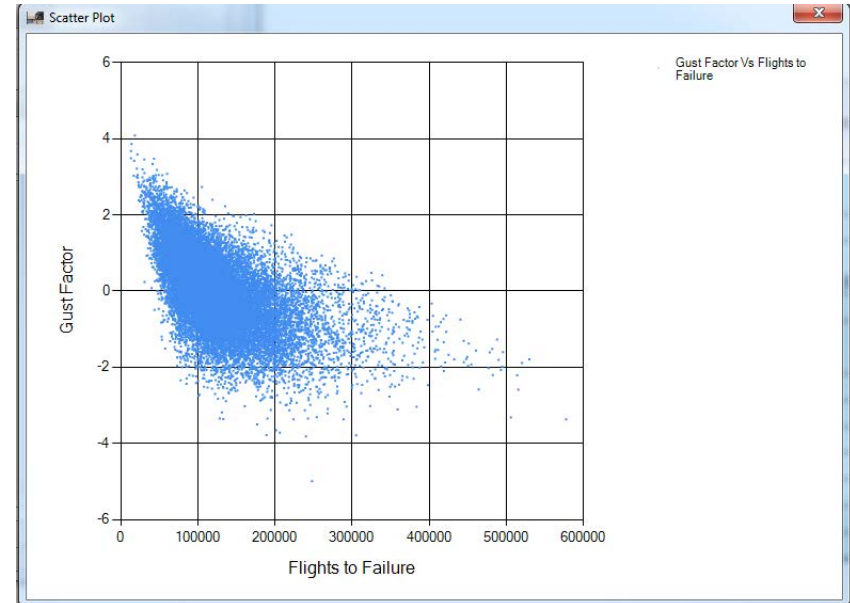
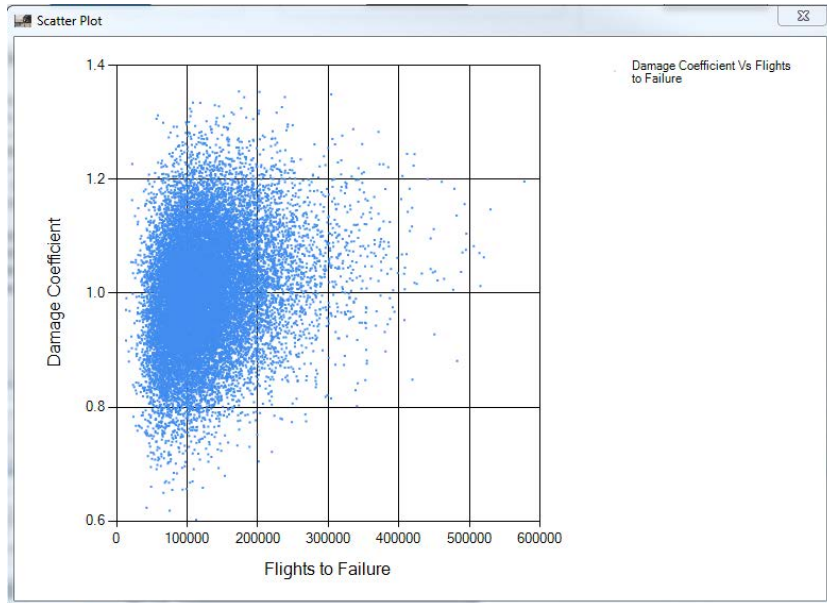
Probability	Hours-to-Failure AC23
0.5	134,646
0.1	70,690
0.01	40,804
0.001	27,889
0.000223	17,350



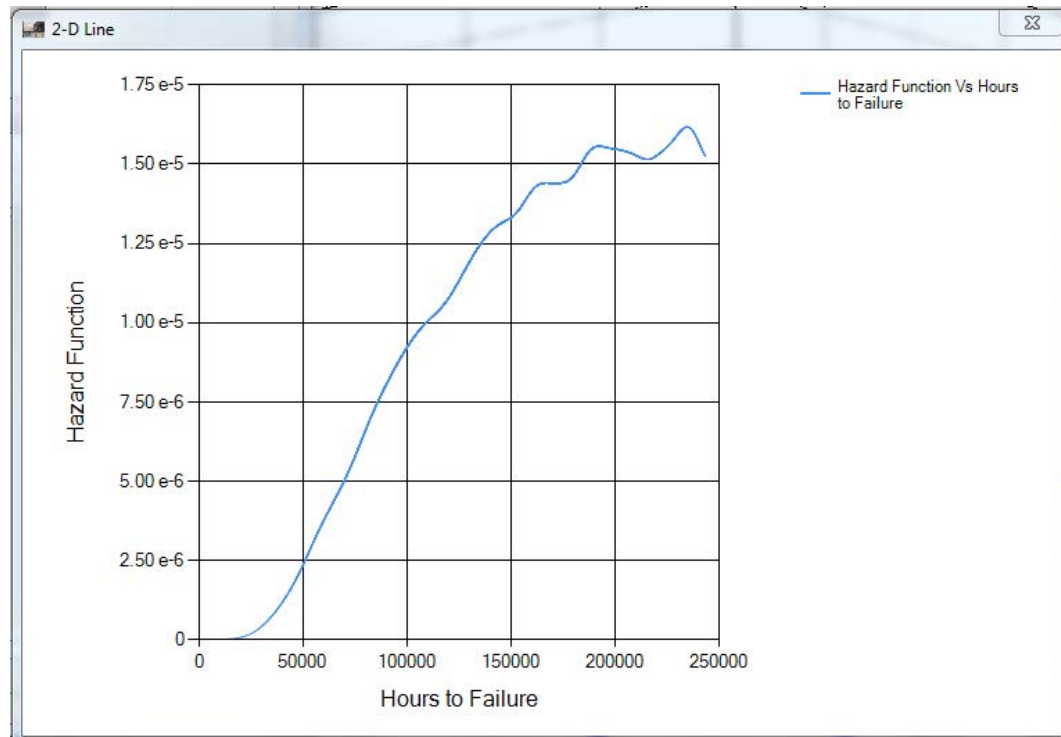
Correlation Sensitivity Analysis



	Flight Duration	A/C Velocity	Sink Rate	Damage Coefficient	Gust Factor	Man Factor	One-g Stress	Ground Stress	PSN
FTF	-0.24282	0.00573	-0.02277	0.23560	-0.56815	-0.11263	-0.45512	0.45508	0.00000
HTF	0.44856	-0.34164	-0.02118	0.21342	-0.51680	-0.10505	-0.74622	0.74616	0.00000



Hazard Function



The hazard rate is defined as the probability per time unit that a case that has survived to the beginning of the respective interval will fail in that interval

$$hz(t) = \frac{PDF(t)}{1 - CDF(t)}$$

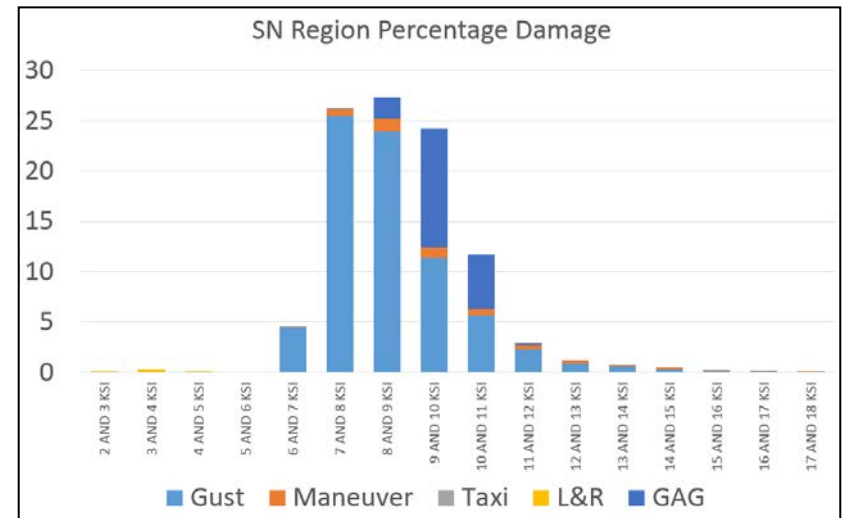


TEXTRON AVIATION

PSN Region Accumulated Damage



SN REGION	TOTAL	GUST	MAN.	TAXI	Land&Reb.	GAG
BELOW 1 KSI:	0.00	0.00	0.00	0.00	0.00	0.00
BETWEEN 1 AND 2 KSI:	0.00	0.00	0.00	0.00	0.00	0.00
BETWEEN 2 AND 3 KSI:	0.03	0.00	0.00	0.00	0.03	0.00
BETWEEN 3 AND 4 KSI:	0.30	0.00	0.00	0.00	0.30	0.00
BETWEEN 4 AND 5 KSI:	0.07	0.00	0.00	0.00	0.07	0.00
BETWEEN 5 AND 6 KSI:	0.00	0.00	0.00	0.00	0.00	0.00
BETWEEN 6 AND 7 KSI:	4.52	4.45	0.07	0.00	0.00	0.00
BETWEEN 7 AND 8 KSI:	26.19	25.42	0.75	0.00	0.00	0.02
BETWEEN 8 AND 9 KSI:	27.33	23.92	1.32	0.00	0.00	2.08
BETWEEN 9 AND 10 KSI:	24.26	11.43	0.98	0.00	0.00	11.85
BETWEEN 10 AND 11 KSI:	11.67	5.66	0.61	0.00	0.00	5.41
BETWEEN 11 AND 12 KSI:	2.88	2.25	0.45	0.00	0.00	0.18
BETWEEN 12 AND 13 KSI:	1.18	0.90	0.27	0.00	0.00	0.00
BETWEEN 13 AND 14 KSI:	0.76	0.58	0.17	0.00	0.00	0.00
BETWEEN 14 AND 15 KSI:	0.42	0.29	0.13	0.00	0.00	0.00
BETWEEN 15 AND 16 KSI:	0.19	0.13	0.05	0.00	0.00	0.00
BETWEEN 16 AND 17 KSI:	0.10	0.06	0.04	0.00	0.00	0.00
BETWEEN 17 AND 18 KSI:	0.05	0.03	0.02	0.00	0.00	0.00
BETWEEN 18 AND 19 KSI:	0.03	0.01	0.01	0.00	0.00	0.00
BETWEEN 19 AND 20 KSI:	0.01	0.01	0.01	0.00	0.00	0.00
BETWEEN 20 AND 21 KSI:	0.01	0.00	0.00	0.00	0.00	0.00
...
BETWEEN 39 AND 40 KSI:	0.00	0.00	0.00	0.00	0.00	0.00
ABOVE 40 KSI:	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL STAGE PERCENTAGE	100.00	75.15	4.90	0.00	0.40	19.55



Summary



- ✓ We Reviewed:
 - ✓ SMART|LD Files Overview
 - ✓ Safe-Life Analysis
 - ✓ Required Elements Safe-Life Analysis
 - ✓ Loading
 - ✓ SN-Curves
 - ✓ AC 23-13 (Deterministic)
 - ✓ ASTM & Polynomial (Probabilistic)
 - ✓ MMPDS (Deterministic or Probabilistic)
 - ✓ Random Miner's D
- ✓ Ran Safe Life Example Problem

Questions

