Probabilistic Risk Assessment in Small Airplanes

Harry Millwater, Juan Ocampo, Gulshan Singh

University of Texas at San Antonio

Herb Smith and Eric Meyer

Boeing Aircraft Company

Felix Abali, Michael Shiao, Marv Nuss,

Michael Reyer

Federal Aviation Administration

2010 Aircraft Airworthiness & Sustainment Conference

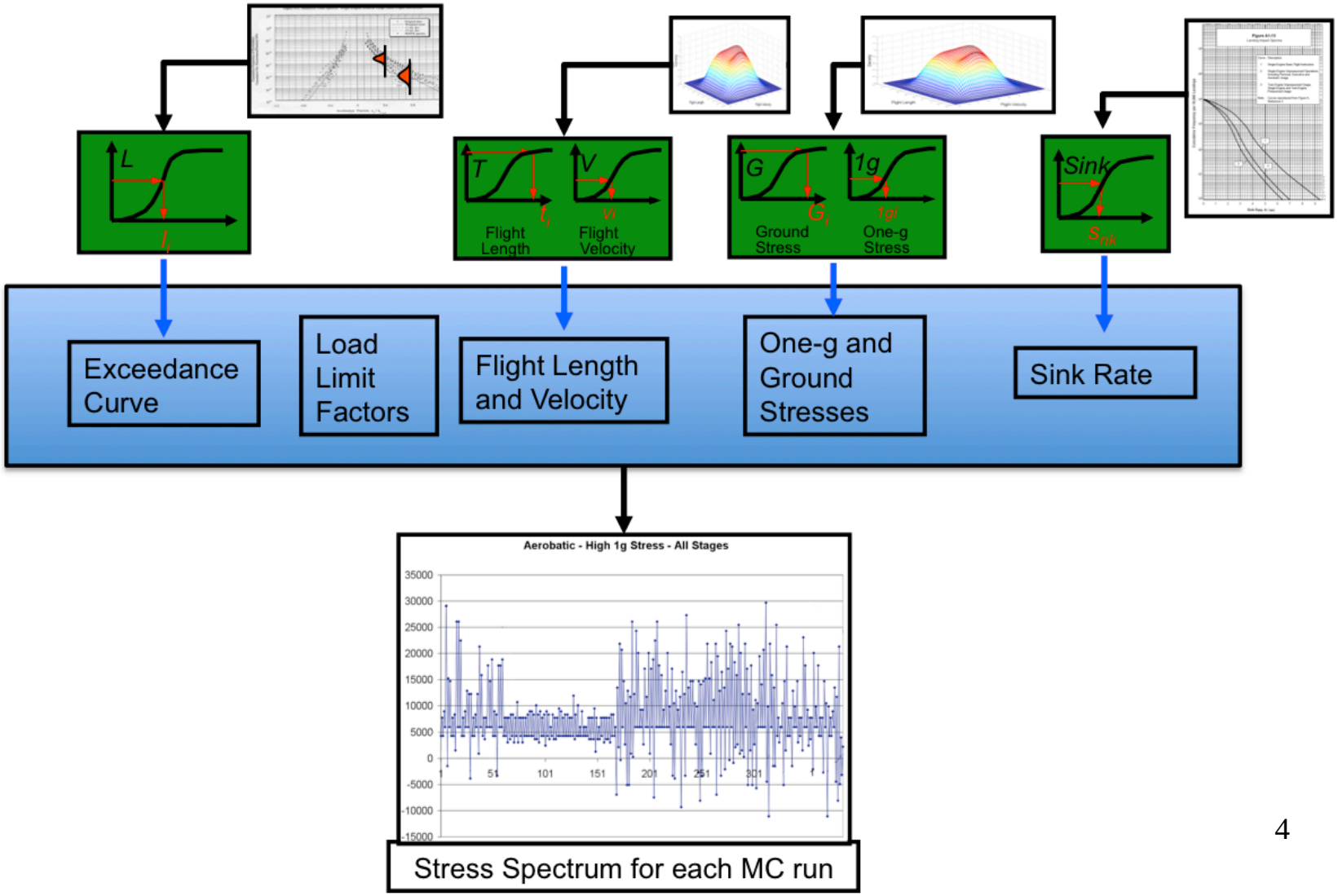
OUTLINE

- Motivation and Background
- Risk Assessment Methodology
- Example Problem
- Results
- Discussion & Conclusions
- Current Work

Objective

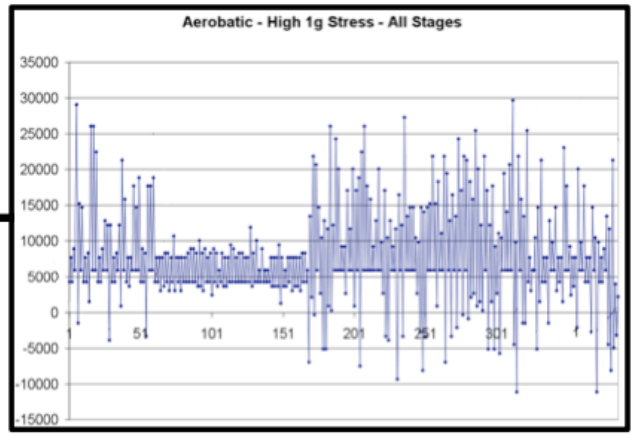
The objective is to develop a comprehensive probabilistic methodology to allow Federal Aviation Administration (FAA) engineers to conduct a risk assessment of general aviation (GA) structural issues in support of policy decisions

Spectrum Generation



Risk Methodology

Damage Methodology



Damage Index

D

d_i

Sn

s_n

S

N

$(S_1, S_2)_{ij}$

i Cycle from Spectrum j

S

s_2

N_{fj}

N

Miner's Rule

$d_{current} = d_c$
$= d_{previous} + 1/N_{fj}$

$d_c < d_i$

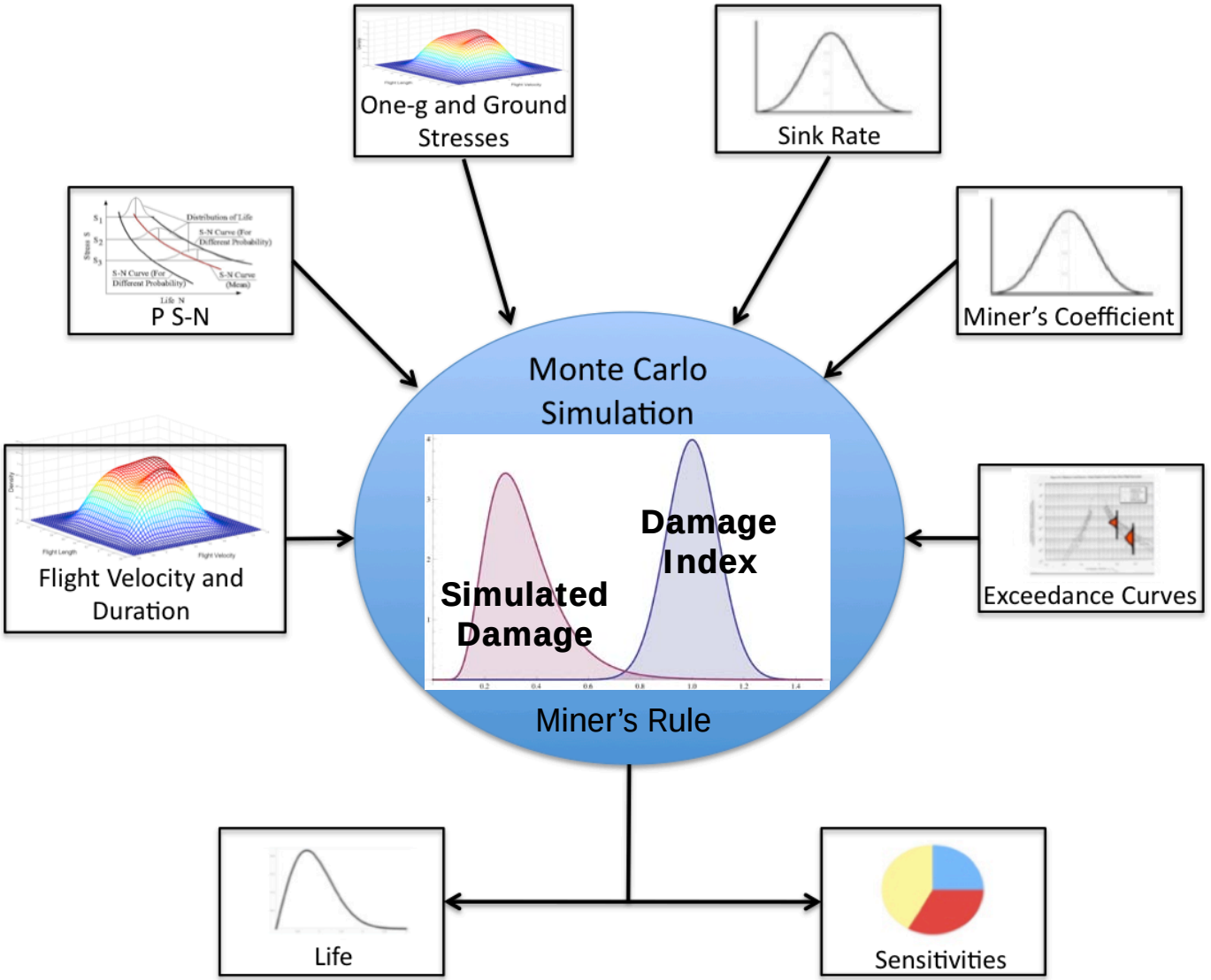
Yes Next Cycle

No, Next MC. Record Flights to Failure

Damage Accumulation

Risk Methodology

Methodology Summary



Risk Methodology

Variables Classification

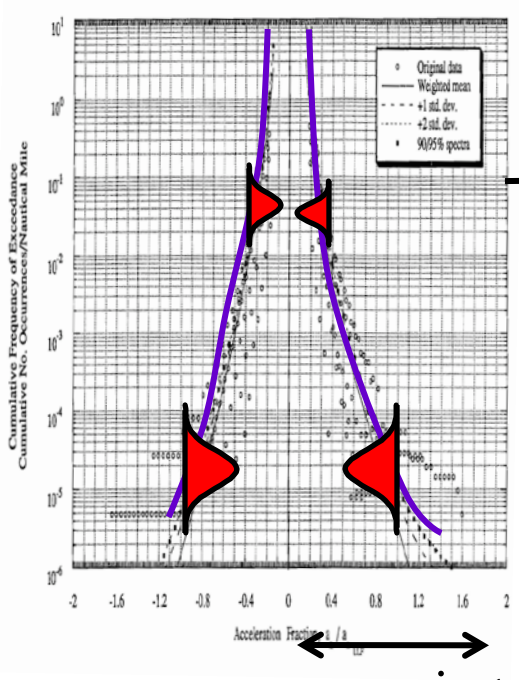
Variable	Type
Gust/Maneuver Load exceedances	Probabilistic: (lognormal distributions)
Aircraft Velocity and Flight Duration	Probabilistic: (Joint pdf with correlated variables)
Sink Rate	Probabilistic
Ground Stress	Probabilistic
One-g Stress	Probabilistic
Damage Index	Probabilistic: (normal or Weibull distribution)
Maneuver Load Limit Factors	Deterministic
Gust Load Limit Factors	Deterministic

Available Usages

Usages
Single-Engine Unpressurized Usage Basic Flight Instruction
Single-Engine Unpressurized Usage Personal Usage
Single-Engine Unpressurized Usage Executive Usage
Single-Engine Unpressurized Usage Aerobatic Usage
Twin-Engine Unpressurized Usage Basic Flight Instruction
Twin-Engine Unpressurized Usage General
Pressurized Usage
Agricultural Usage
User defined

Mix of weighted usages allowed

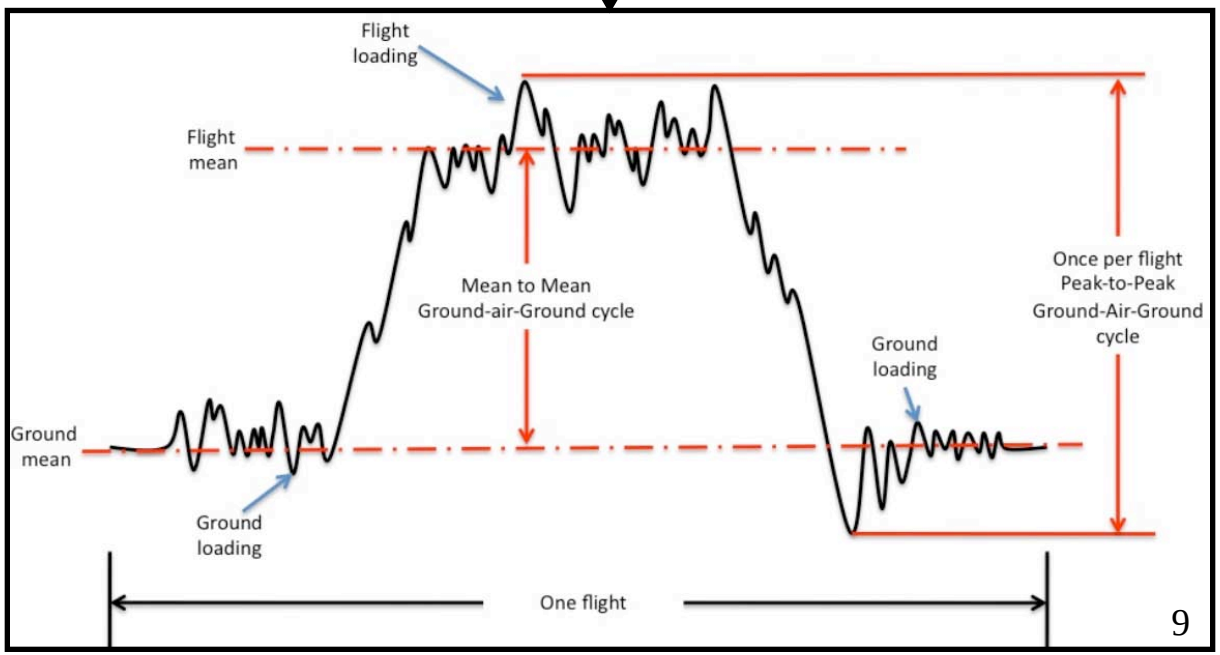
Exceedance Curve



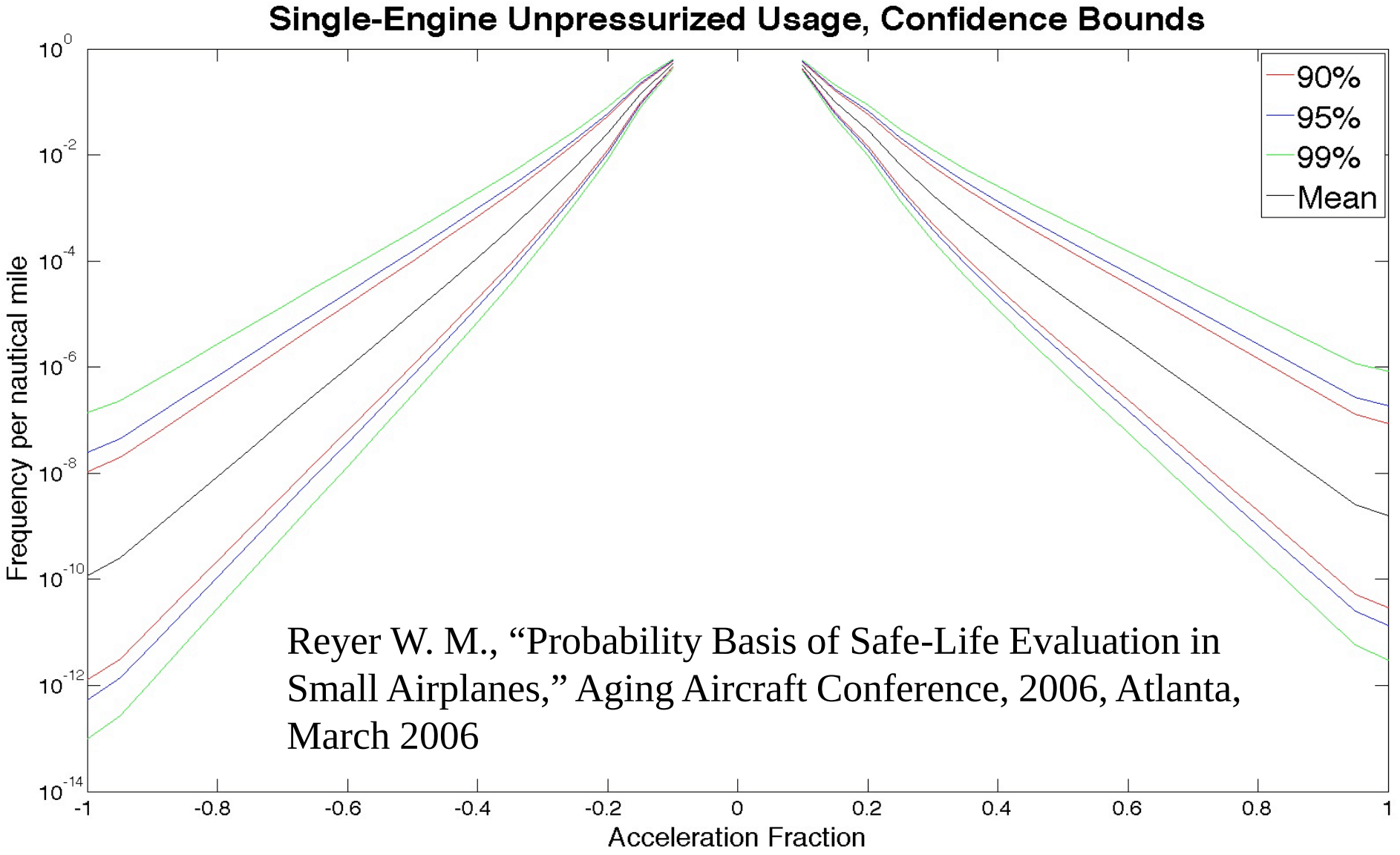
sweeping

+

Load Limit Factors
One-g Stress
Ground Stress
Sink Rate
Flight Velocity and Duration



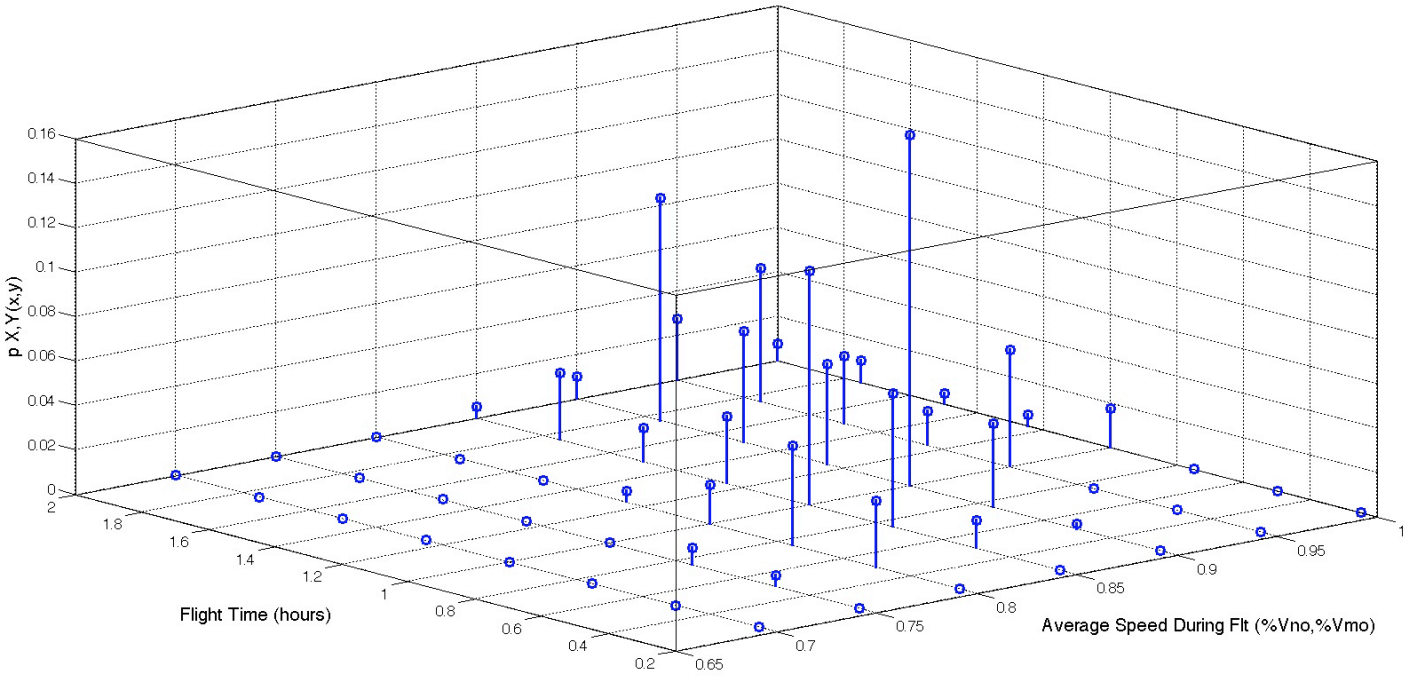
Exceedance Curve Variation



Reyer W. M., "Probability Basis of Safe-Life Evaluation in Small Airplanes," Aging Aircraft Conference, 2006, Atlanta, March 2006

Flight Velocity and Duration

- Joint pdf

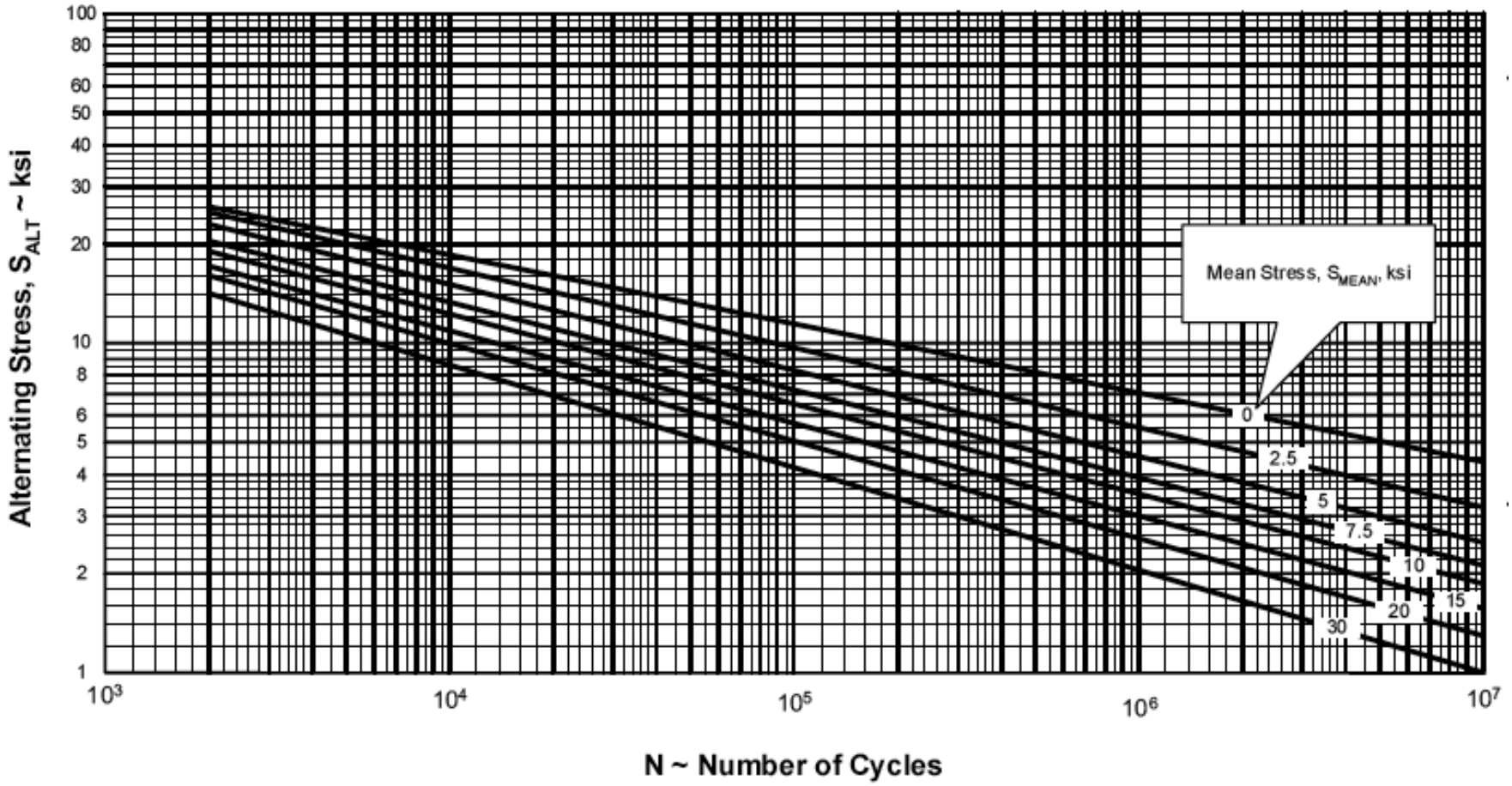


Flight Velocity and Duration

Velocity = 160

		Average Speed During Flight, % Design Velocity						
Flight time (Hours)	% of Flights	1.00	0.95	0.90	0.85	0.80	0.75	0.70
0.25	0	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	0.1	0.05	0.15	0.45	0.3	0.05	0	0
1.50	0.1	0.05	0.3	0.5	0.15	0	0	0
1.75	0.2	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

AC23-13A


Alternating Stress, S_{ALT} ~ ksi
100
80
60
50
40
30
20
10
8
6
5
4
3
2
1
10^3
10^4
10^5
10^6
10^7
N ~ Number of Cycles
Mean Stress, S_{MEAN}, ksi
0
2.5
5
7.5
10
15
20
30

Probabilistic S-N

Open Hole 3 KSI Mean Stress

$$SSF = \alpha\beta\left(K_{tb} \times \theta \times LT \times \frac{w}{d} + K_{tg}(1 - LT)\right)$$

42 KSI

32 KSI

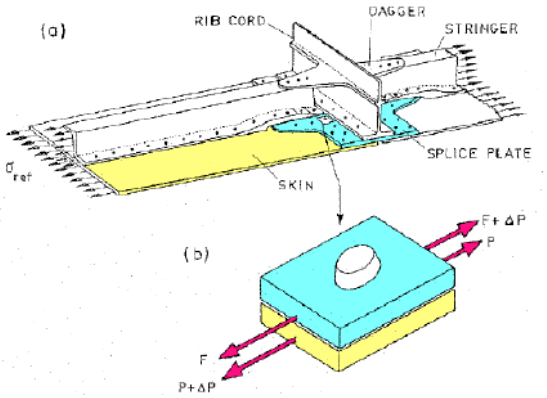
18 KSI

12 KSI

10 KSI

9.25 KSI

Testing conducted by Wichita State University



Log10 MaxStress(ksi)—Centered

0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4

1 2 3 4 5 6 7 8

log10(Cycles to Failure)

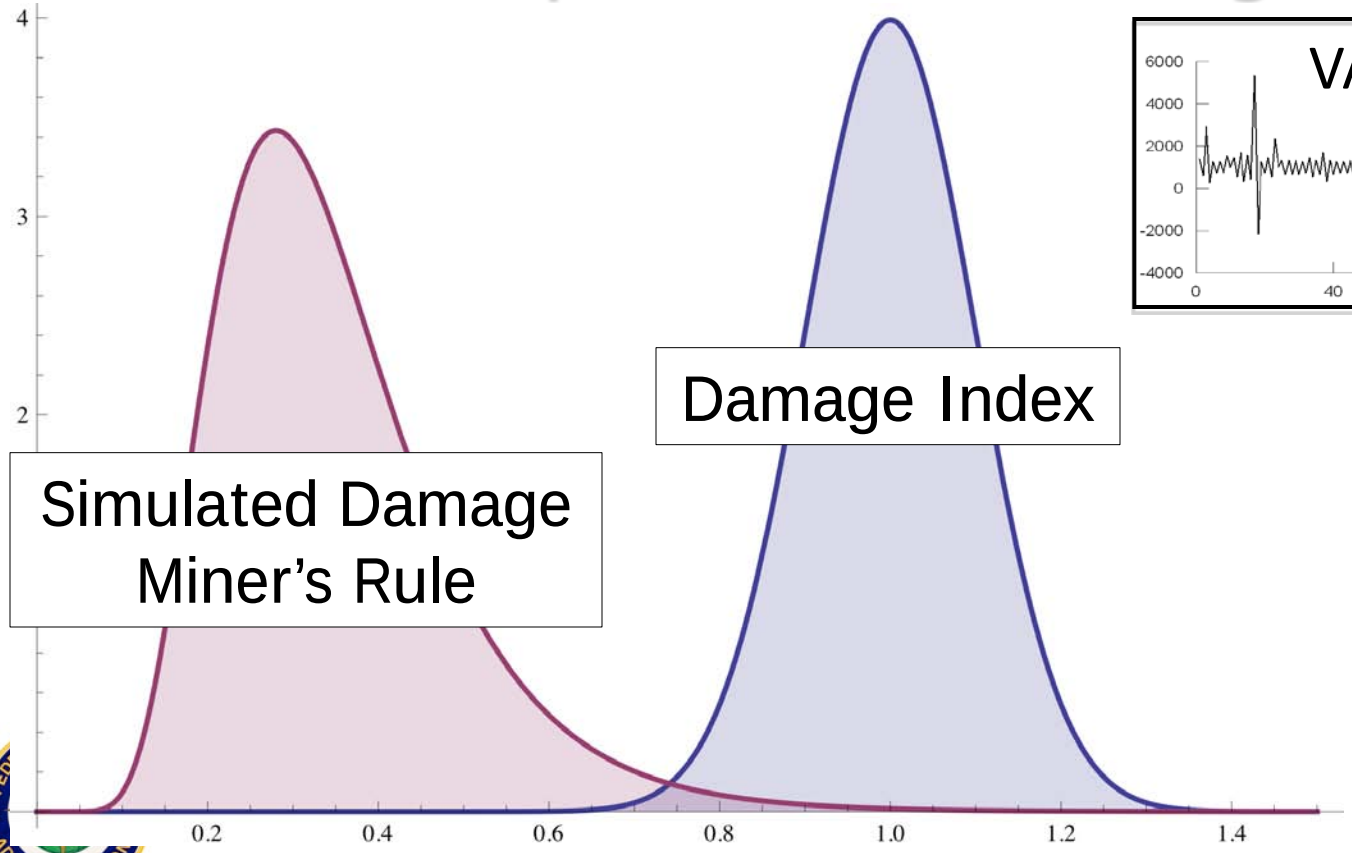
Constant Amplitude Data

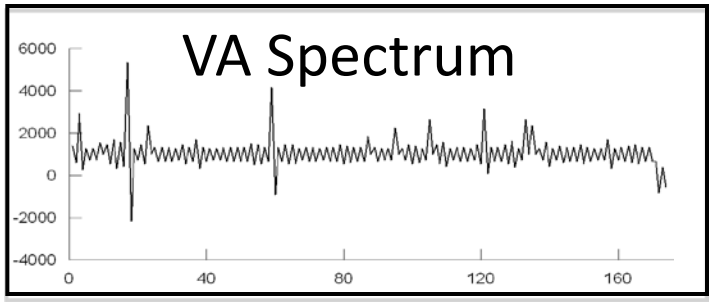
Coupon Configuration	Mean Stress [KSI]
Open Hole	3 and 6
Hilok Filled Hole	3 and 6
Hilok 6 % Load Transfer	3 and 6
Hilok 30 % Load Transfer	3 and 6
Hilok 50 % Load Transfer	3 and 6
Rivet Filled Hole	3 and 6
Rivet 6 % Load Transfer	3 and 6
Rivet 30 % Load Transfer	3 and 6
Rivet 50 % Load Transfer	3 and 6

Testing conducted by Wichita State Univ.

Random D

- Simulation of variable amplitude tests to determine probabilistic damage index

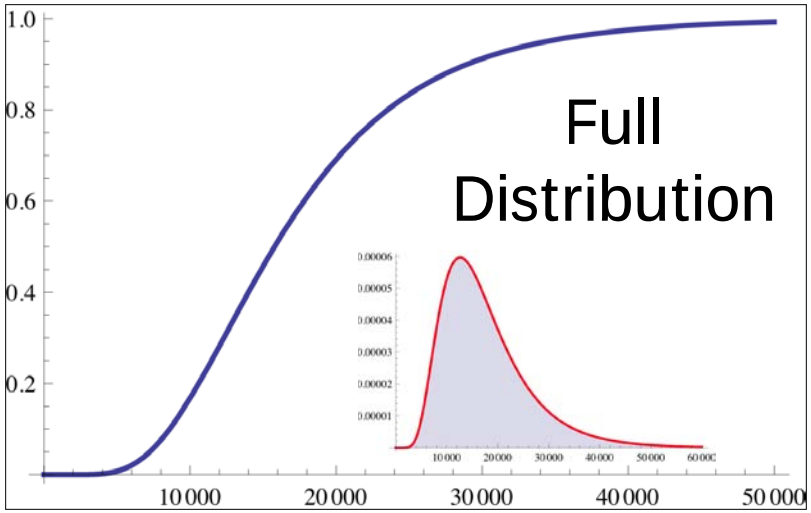




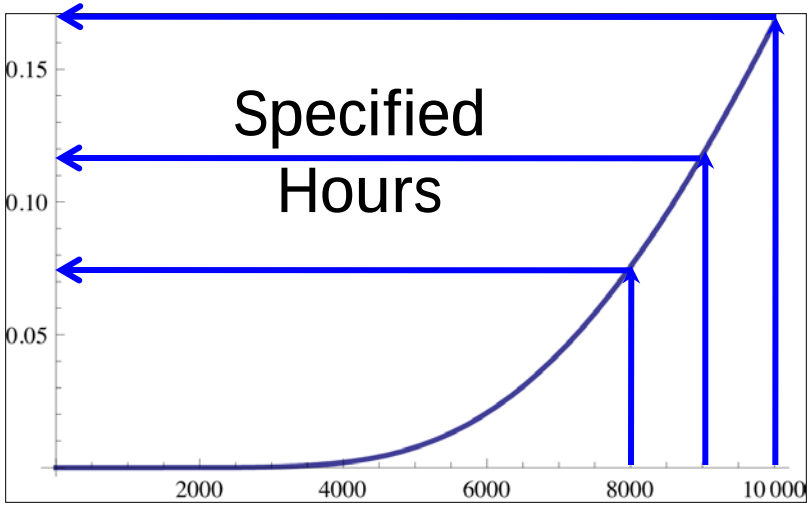
Example Problem

2 Analysis Modes

Damage Mode



Hours Mode



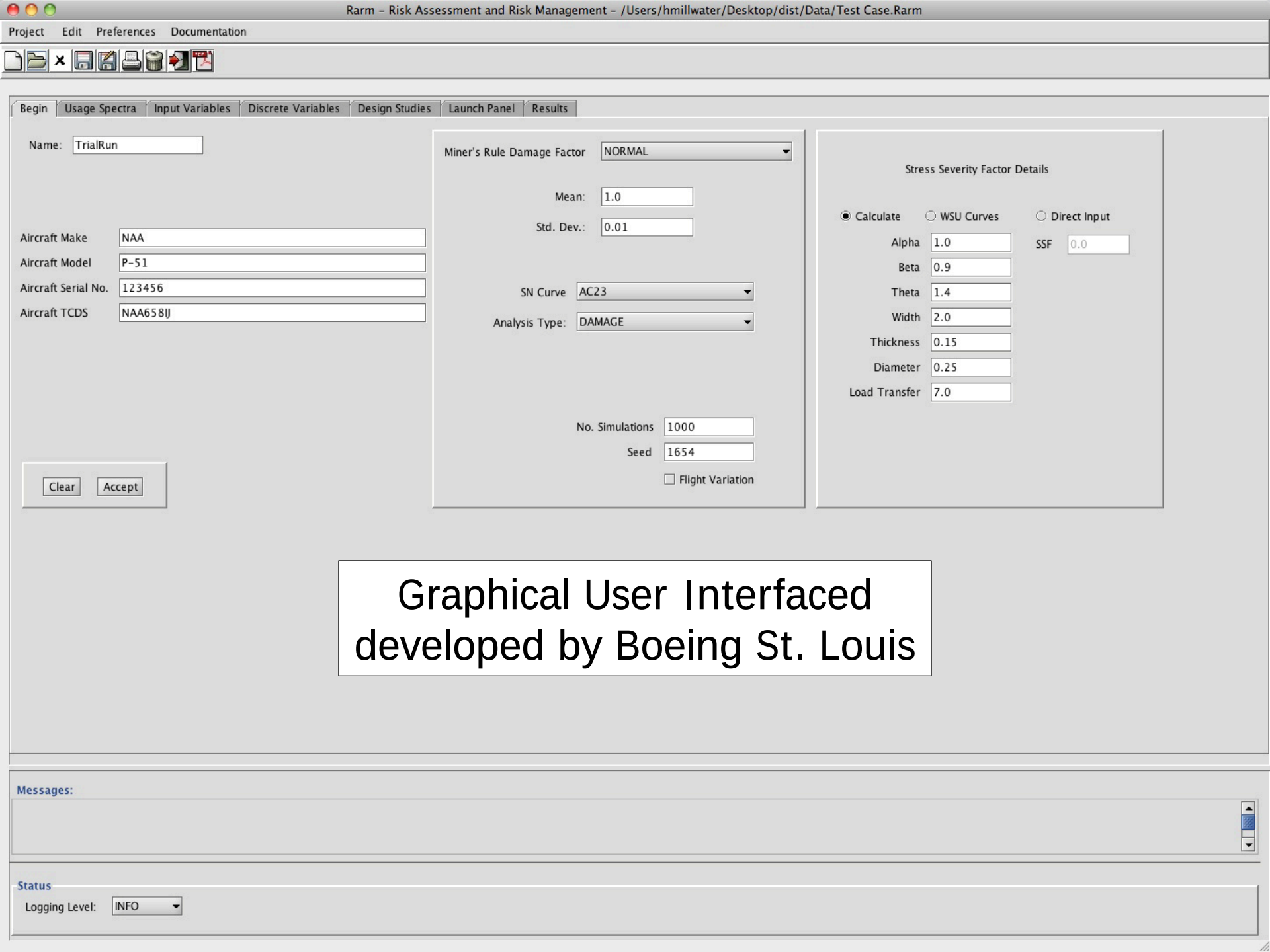
Example

Safe-life Analysis

Instructional usage – 50%
Personal usage – 50%
(up to 10 usages can be combined)

AC23-13A

Variable	Characteristics	
Gust/Maneuver Load exceedances	Probabilistic exceedances curves for Instructional and Personal usage	
Sink Rate	Probabilistic sink rate	
Maneuver Load Limit Factors	Instructional Usage	+2.80 -2.50
	Personal Usage	+2.40 -2.20
Gust Load Limit Factors	Instructional Usage	+2.15 -2.15
	Personal Usage	+2.30 -2.30
One g stress	Instructional Usage	+7410
	Personal Usage	+7900
Ground Stress	Instructional Usage	-4520
	Personal Usage	-4800
Aircraft Velocity	Instructional Usage	160
	Personal Usage	170
Damage Index	Normal distribution with mean 1.0 and standard deviation 0.2	


Rarm – Risk Assessment and Risk Management – /Users/hmillwater/Desktop/dist/Data/Test Case.Rarm
Project
Edit
Preferences
Documentation
Begin
Usage Spectra
Input Variables
Discrete Variables
Design Studies
Launch Panel
Results
Name: TrialRun
Aircraft Make NAA
Aircraft Model P-51
Aircraft Serial No. 123456
Aircraft TCDS NAA658IJ
Clear
Accept
Miner's Rule Damage Factor NORMAL
Mean: 1.0
Std. Dev.: 0.01
SN Curve AC23
Analysis Type: DAMAGE
No. Simulations 1000
Seed 1654
Flight Variation
Stress Severity Factor Details
Calculate
WSU Curves
Direct Input
Alpha 1.0
Beta 0.9
Theta 1.4
Width 2.0
Thickness 0.15
Diameter 0.25
Load Transfer 7.0
SSF 0.0
Graphical User Interfaced developed by Boeing St. Louis
Messages:
Status
Logging Level: INFO

Output Info

Input Variables

Percent Damage

Run	Flight Duration	A/C Velocity	Sink Rate	Damage Coefficient	Gust Factor	Man Factor	One-g Stress	Ground Stress	Percentage Gust Damage	Percentage Man Damage	Percentage Taxi Damage	Percentage Land & Reb Damage	Percentage GAG Damage	Flights to Failure	Hours to Failure
1	0.75	136.0	0.3012	0.7739	-0.0558	0.9208	7410.00	-4520.00	0.4274	0.2500	0.000026	0.0063	0.3163	27581	20685.75
2	1.00	136.0	4.1291	1.1522	-0.3292	-1.3313	7410.00	-4520.00	0.2237	0.5877	0.000009	0.0011	0.1875	14777	14777.00
3	1.50	144.0	0.2762	1.0920	-1.3183	0.3919	7410.00	-4520.00	0.5556	0.2906	0.000010	0.0025	0.1512	15229	22843.50
4	2.00	136.0	0.3657	1.1537	-0.4466	-1.3359	7410.00	-4520.00	0.2475	0.6278	0.000005	0.0012	0.1235	7873	15746.00
5	1.75	152.0	0.1154	1.2134	-0.4481	-0.1755	7410.00	-4520.00	0.4148	0.4409	0.000008	0.0021	0.1422	14183	24820.25
6	1.75	144.0	1.0801	0.8469	0.2611	0.4995	7410.00	-4520.00	0.4421	0.3718	0.000012	0.0029	0.1831	13896	24318.00
7	0.75	136.0	2.1213	1.1046	-0.5294	-0.9541	7410.00	-4520.00	0.2725	0.4984	0.000014	0.0033	0.2258	21522	16141.50
8	1.75	144.0	1.3556	0.9441	-0.8345	0.2723	7410.00	-4520.00	0.5021	0.3432	0.000009	0.0023	0.1524	12311	21544.25
9	0.75	128.0	2.3579	1.3223	1.2425	-0.9120	7410.00	-4520.00	0.1862	0.5483	0.000017	0.0038	0.2616	31103	23327.25
10	0.50	128.0	0.3661	0.7345	-0.6474	-0.5300	7410.00	-4520.00	0.3051	0.3901	0.000024	0.0059	0.2988	24509	12254.50

Hours/Flights-to-Failure

Run no.

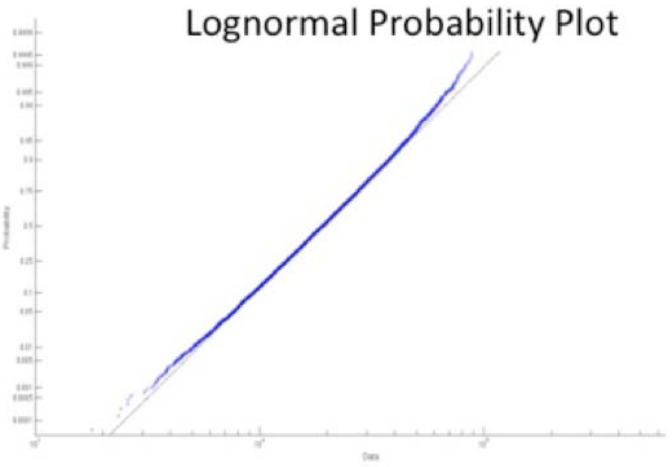
Detailed output per MC run

Safe-life Results

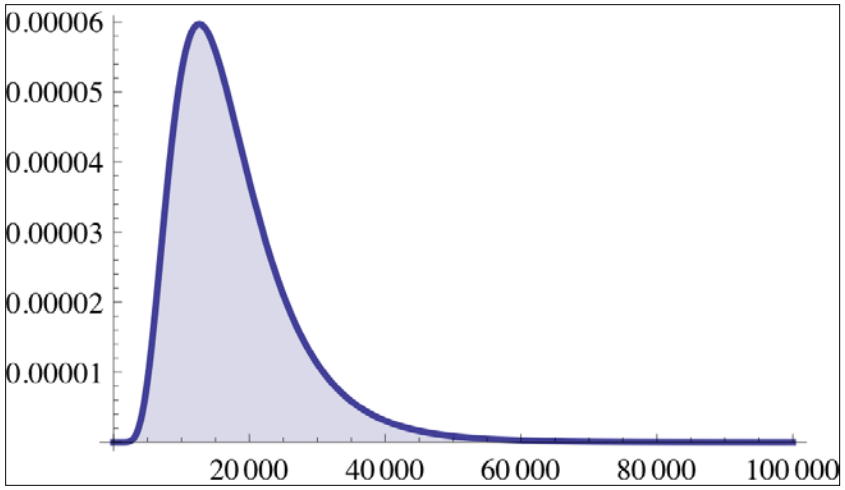
95% Confidence Interval	Flights-to-Failure Mean	95% Confidence Interval
17,537	17,659	17,782
95% Confidence Interval	Hours-to-Failure Mean	95% Confidence Interval
21,158	21,264	21,370
95% Confidence Interval	Flights-to-Failure Standard Deviation	95% Confidence Interval
8,871	8,853	8,926
95% Confidence Interval	Hours-to-Failure Standard Deviation	95% Confidence Interval
7609	7,672	7,735

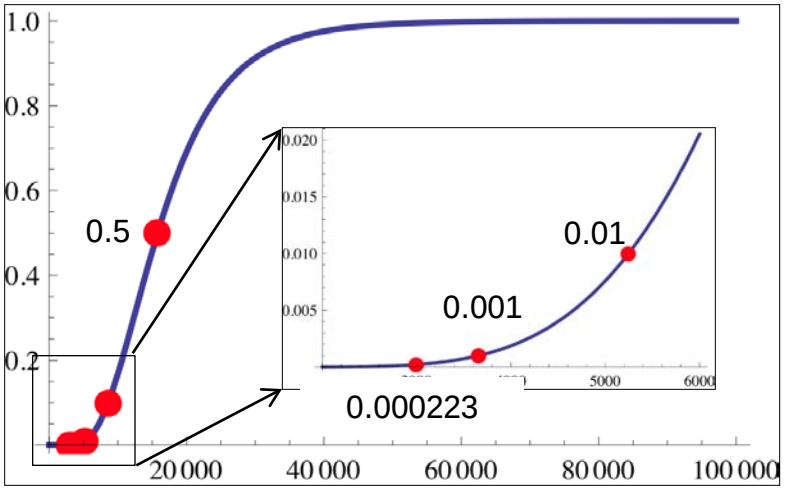
20,000 Monte Carlo Samples

Safe-life Results



Probability	Flights-to-Failure	Hours-to-Failure
0.5	15968	20472
0.1	8398	12043
0.01	4506	6665
0.001	2635	3729
0.000223	1909	2457





Correlation Sensitivity Analysis

Personal and Instructional

	Flight Length	Flight Speed	Sink Rate	Miner's Coefficient	Gust Factor	Maneuver Factor
Flights-to-Failure	-0.606	-0.426	-0.030	0.404	0.337	0.388

Personal

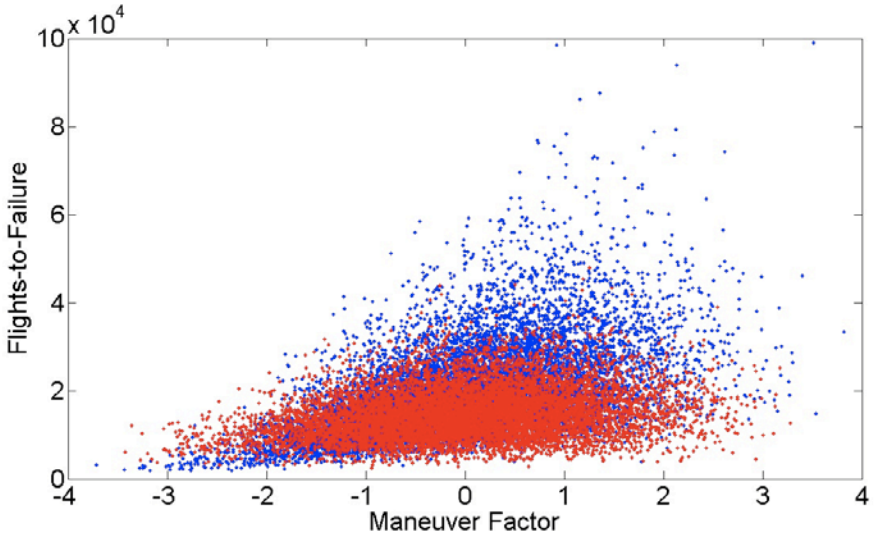
	Flight Length	Flight Speed	Sink Rate	Miner's Coefficient	Gust Factor	Maneuver Factor
Flights-to-Failure	-0.576	-0.265	-0.042	0.499	0.537	0.220

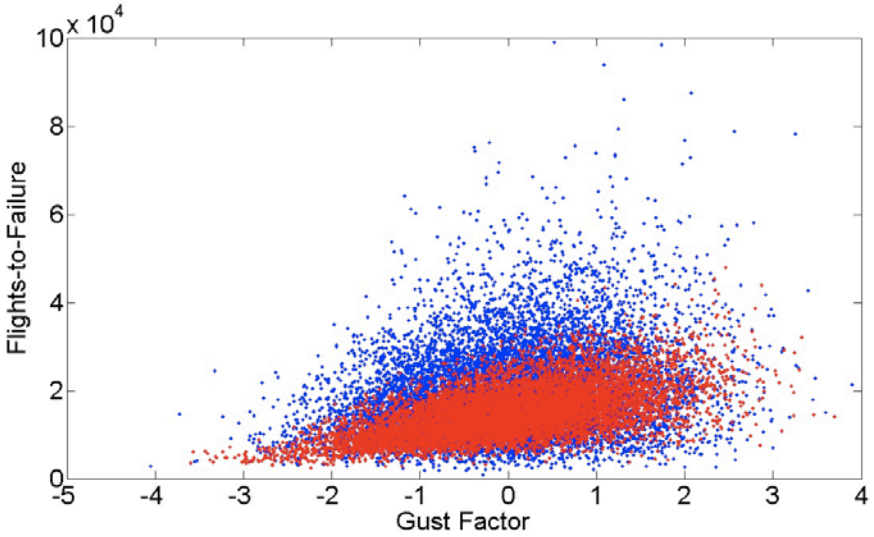
Instructional

	Flight Length	Flight Speed	Sink Rate	Miner's Coefficient	Gust Factor	Maneuver Factor
Flights-to-Failure	-0.595	-0.414	0.033	0.388	0.248	0.527

Correlation Sensitivity Analysis

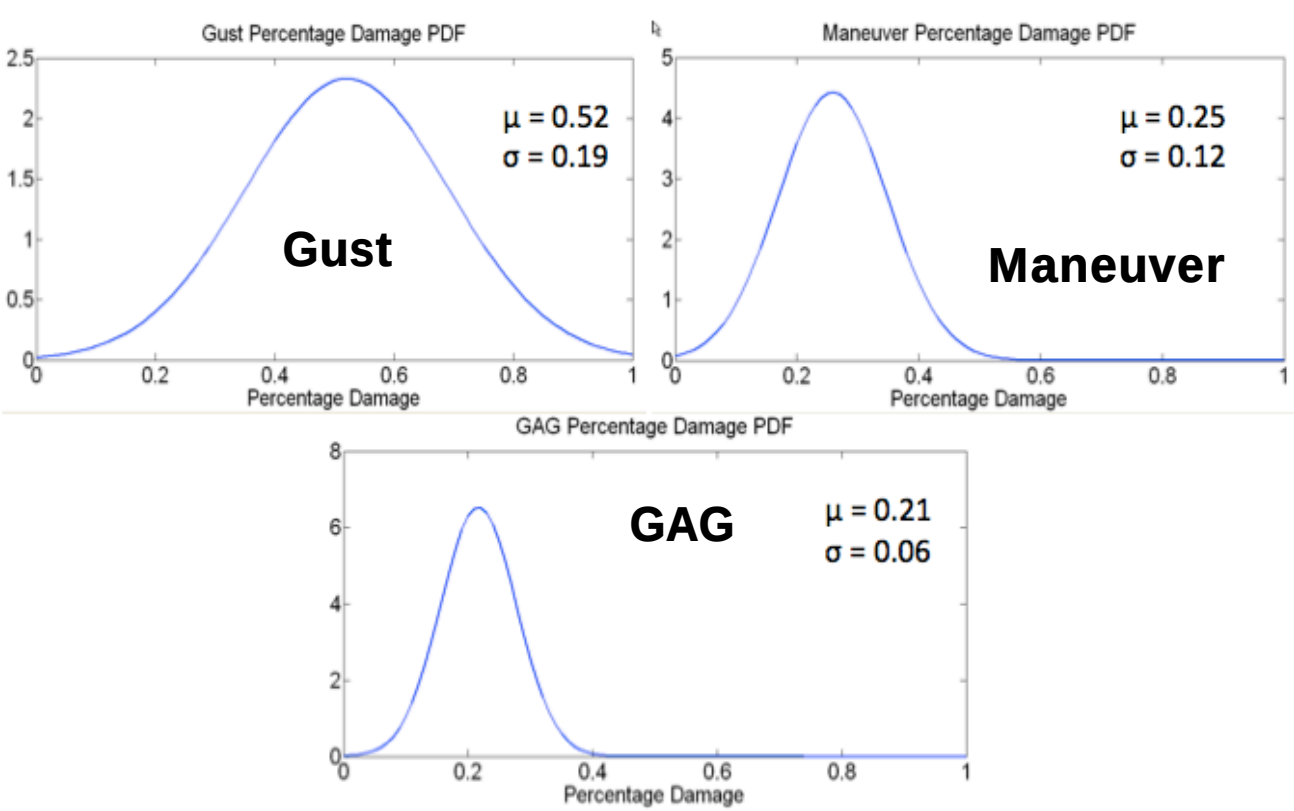
•Instructional •Personal



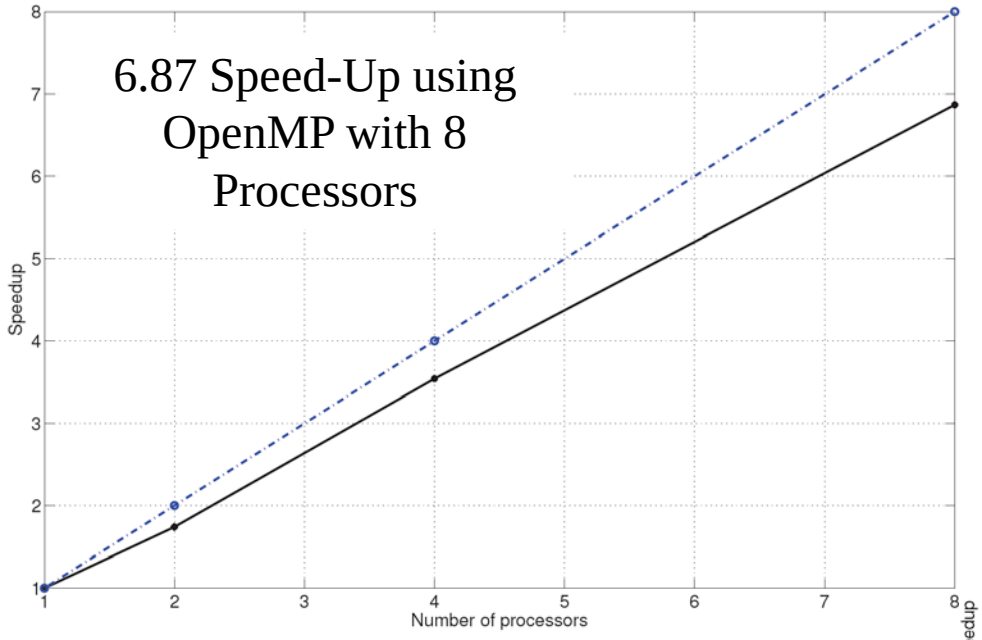


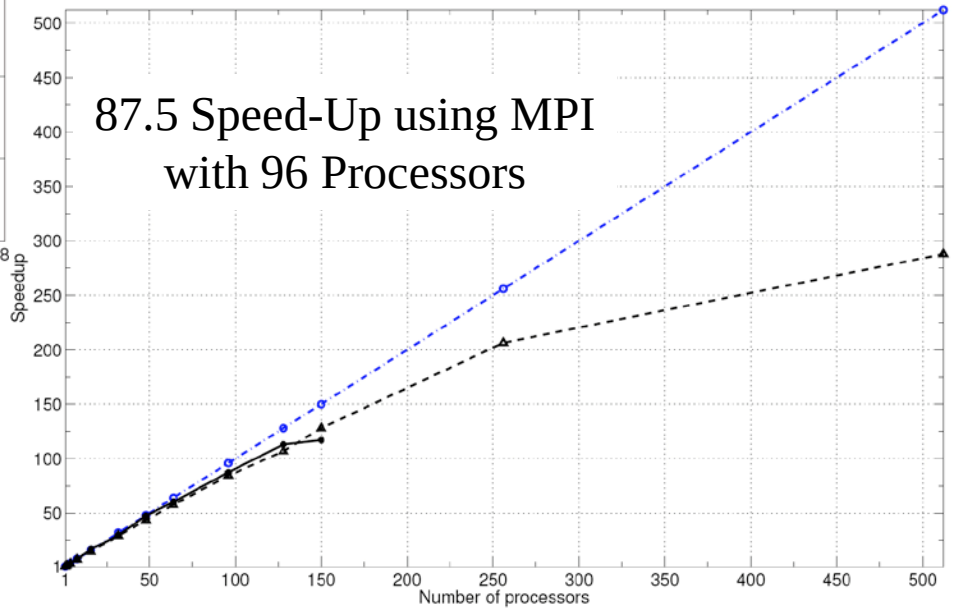
Damage Percentages

Mean Flight Stages Damage Percentage				
Gust	Maneuver	Taxi	Land. & Reb.	GAG
0.5231	0.2590	1.43E-05	0.0033	0.2144



High Performance Computing





Summary & Conclusions

- A probabilistic risk assessment methodology and computer software **(SMART)** was developed such that FAA engineers can perform a risk assessment of a structural issue.
- Probability density functions of the random variables were investigated and developed.
  - Variations in S-N modeled using constant amplitude tests from Wichita State University-> PSN curves developed
  - Variations in damage index determined from application of SMART to variable amplitude tests (Wichita State Univ.)

Summary & Conclusions

- Monte Carlo sampling used to determine probabilities using Miner's rule
- Sensitivity analysis available through correlation and scatter plots
- Parallel processing implementation for efficient analysis
- Graphical user interface developed (Boeing St. Louis)

SMART to be delivered to the FAA summer 2010.

Acknowledgements

The authors are grateful to the Federal Aviation Administration (FAA) for grant 07-G-011, Felix Abali program manager, which supports this research project.

Questions?