Probabilistic Structural Risk Assessment and Risk Management for Small Airplanes

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OUTLINE

- Background
- Deterministic Analysis
- Load Spectrum Generation
- Stress Severity Factor
- Damage Calculation
- Probabilistic Analysis
- Future Work

Background I

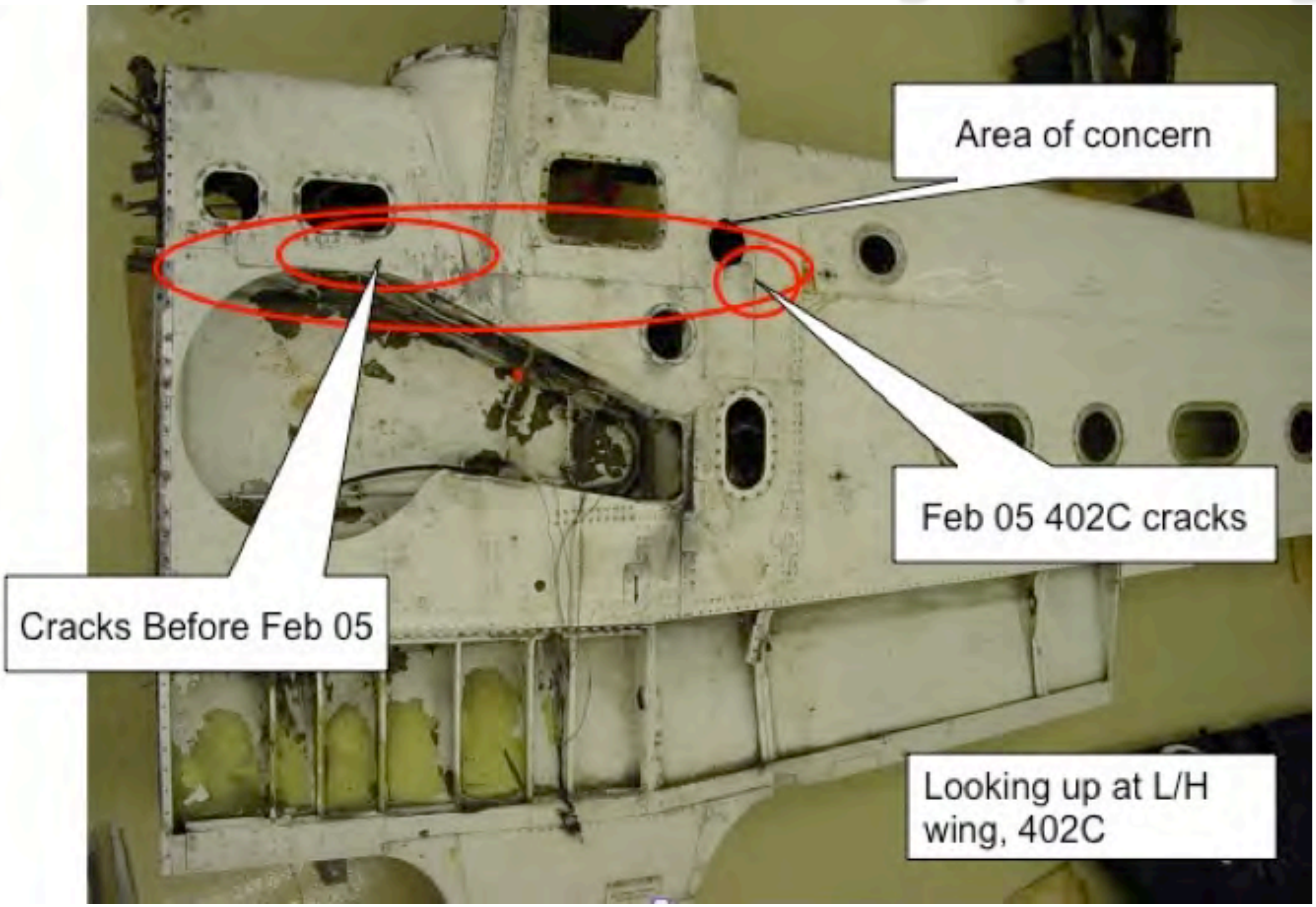
Fleet of twin Cessnas with unsafe condition

- Wing spar fatigue cracking

- **1973, 78: Service Incidents of cracked spars**
- **1990-92: Service Incidents of cracked spars**
- **1999: 402C fatal accident due to spar failure**
- **Feb. 2005: Two 402Cs found with cracked spars**

Background II

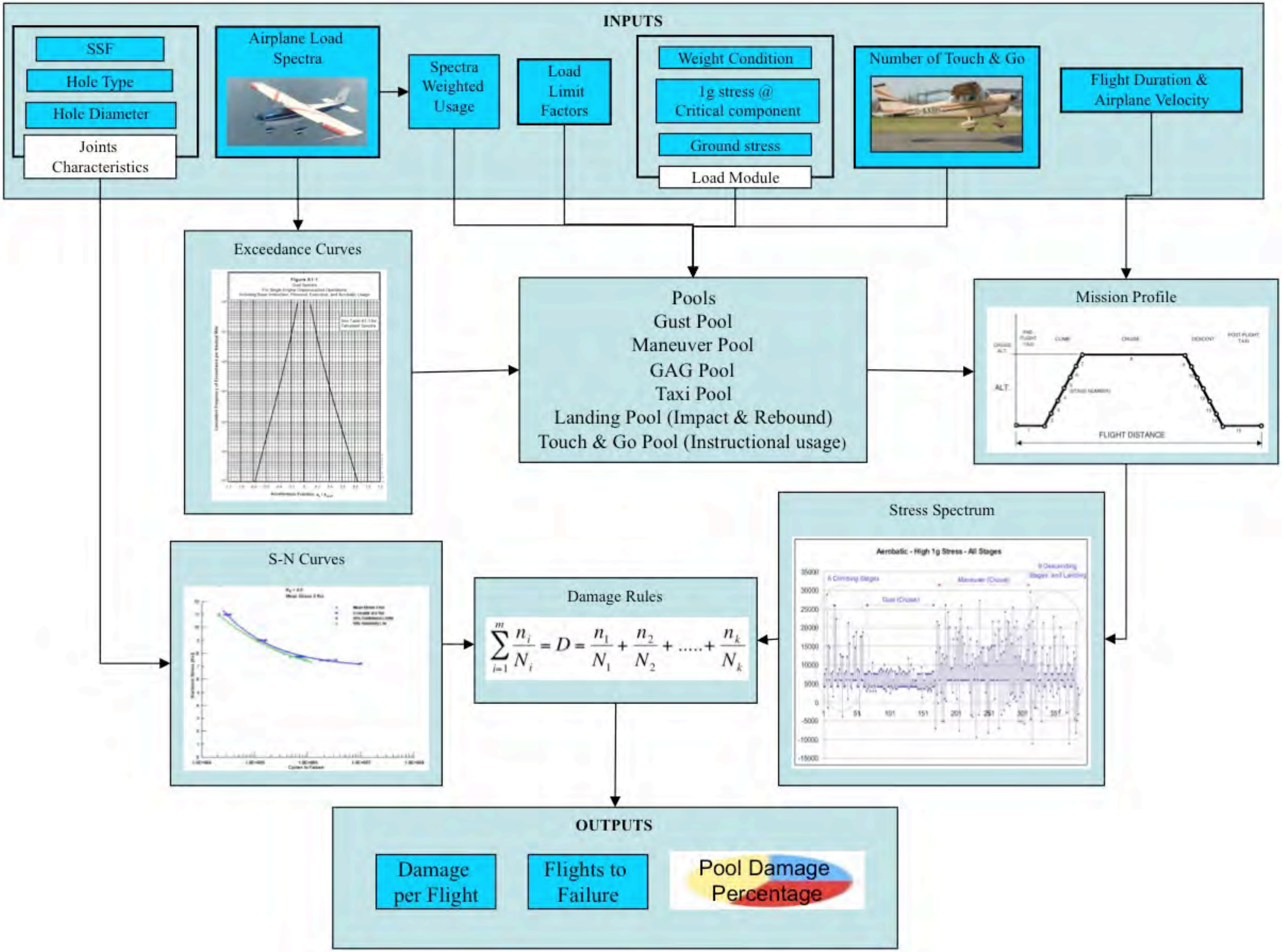
Cessna 400 Series Wing Spar Fatigue



Background III

- An assessment of the risk of future accidents was used to convince the pilots' association by the FAA of the need for remedial action.
- My research is to investigate a risk assessment methodology and tools for use by the FAA.

Deterministic Code


INPUTS
SSF
Hole Type
Hole Diameter
Joints Characteristics
Airplane Load Spectra
Spectra Weighted Usage
Load Limit Factors
Weight Condition
1g stress @ Critical component
Ground stress
Load Module
Number of Touch & Go
Flight Duration & Airplane Velocity
Exceedance Curves
Pools
Gust Pool
Maneuver Pool
GAG Pool
Taxi Pool
Landing Pool (Impact & Rebound)
Touch & Go Pool (Instructional usage)
Mission Profile
ALT.
FLIGHT DISTANCE
Stress Spectrum
Aerobatic - High 1g Stress - All Stages
S-N Curves
Damage Rules
$\sum_{i=1}^{m}\frac{n_i}{N_i}=D=\frac{n_1}{N_1}+\frac{n_2}{N_2}+.....+\frac{n_k}{N_k}$
OUTPUTS
Damage per Flight
Flights to Failure
Pool Damage Percentage

Load Spectrum Generation

Airplane type category selection

- ✓ SINGLE ENGINE UNPRESS BASIC INSTITUTIONAL USAGE
- ✓ SINGLE ENGINE UNPRESS PERSONAL USAGE
- ✓ SINGLE ENGINE UNPRESS EXECUTIVE USAGE
- ✓ SINGLE ENGINE UNPRESS ACROBATIC USAGE
- ✓ TWIN ENGINE UNPRESS BASIC INSTITUTIONAL USAGE
- ✓ TWIN ENGINE UNPRESS GENERAL USAGE
- ✓ SINGLE AND TWIN ENGINE PRESSURIZED GENRAL USAGE
- ✓ AGRICULTURAL OR AERIAL USAGE
- ✓ LOW LEVEL SURVEY OR PIPELINE PATROL USAGE

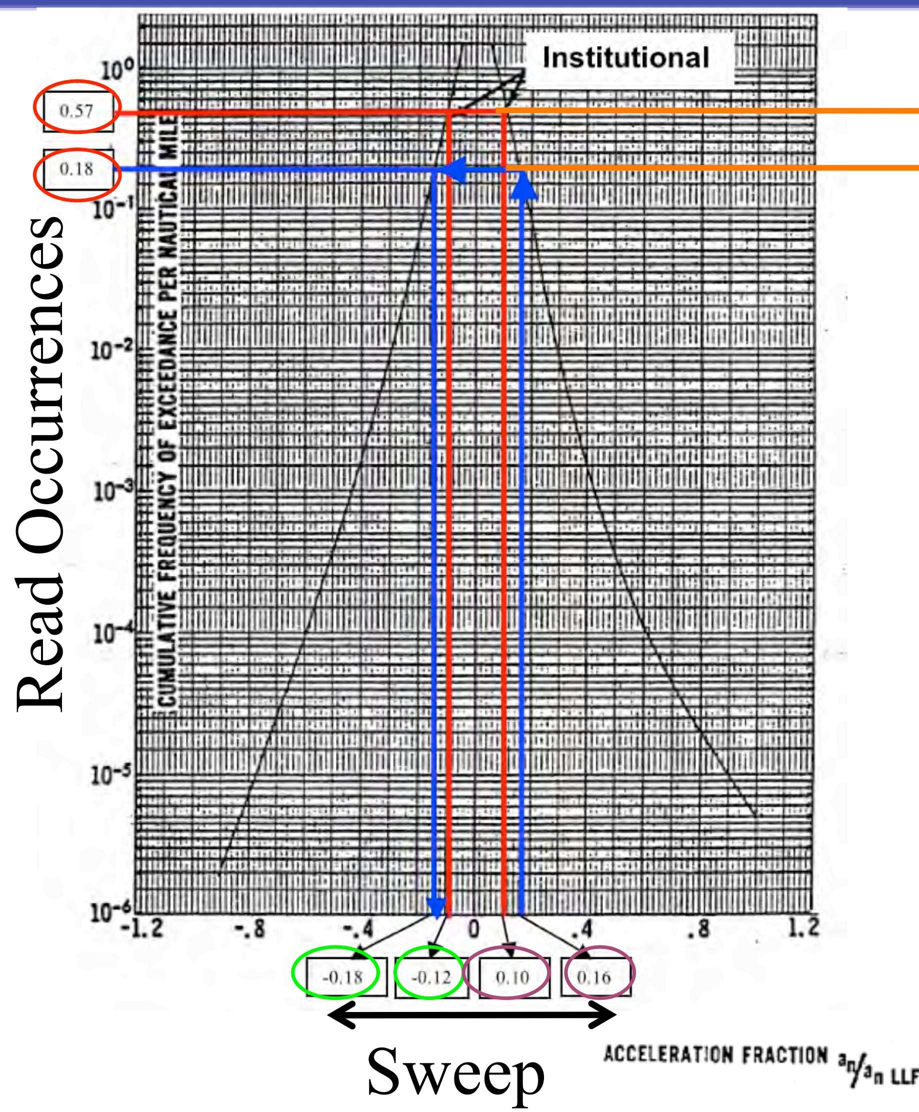
Load Spectrum Generation

Variables

Example

- ✓ SINGLE ENGINE UNPRESS BASIC INSTITUTIONAL USAGE
- ✓ FLIGHT DURATION = 50 min.
- ✓ FLIGHT PROFILE = Single
- ✓ GROSS WEIGHT = 4300 lb
- ✓ REFERENCE WING AREA = 55 s.f
- ✓ WING LIFT CURVE SLOPE (m) = 13.89 rad-1
- ✓ AIRPLANE VELOCITY = 165 kts
- ✓ NOMINAL GUST VELOCITY = 30 f.p.s
- ✓ STRESS AT CRITICAL COMPONENT = 7410 psi
- ✓ GROUND STRESS = -4520 psi
- ✓ SN CURVE = AC-23-13A
- ✓ NUMBER OF T&G = 0

Gust Occurrence-Damage Pool Calculation



0.57-0.18=0.39

Difference between two successive values, to convert from cumulative frequency to frequency

$$freq \cdot (0.9 \cdot vel.) = number\ of\ occurrences$$

0.39 x 0.9 (165Kts) = 57.8 (n, Damage rule)

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Stress/Occurrence Calculation (Gust)

$a_{NLLF} = \pm 2.155$
Acceleration load factor

Stress increment due to the gusts (a_n)

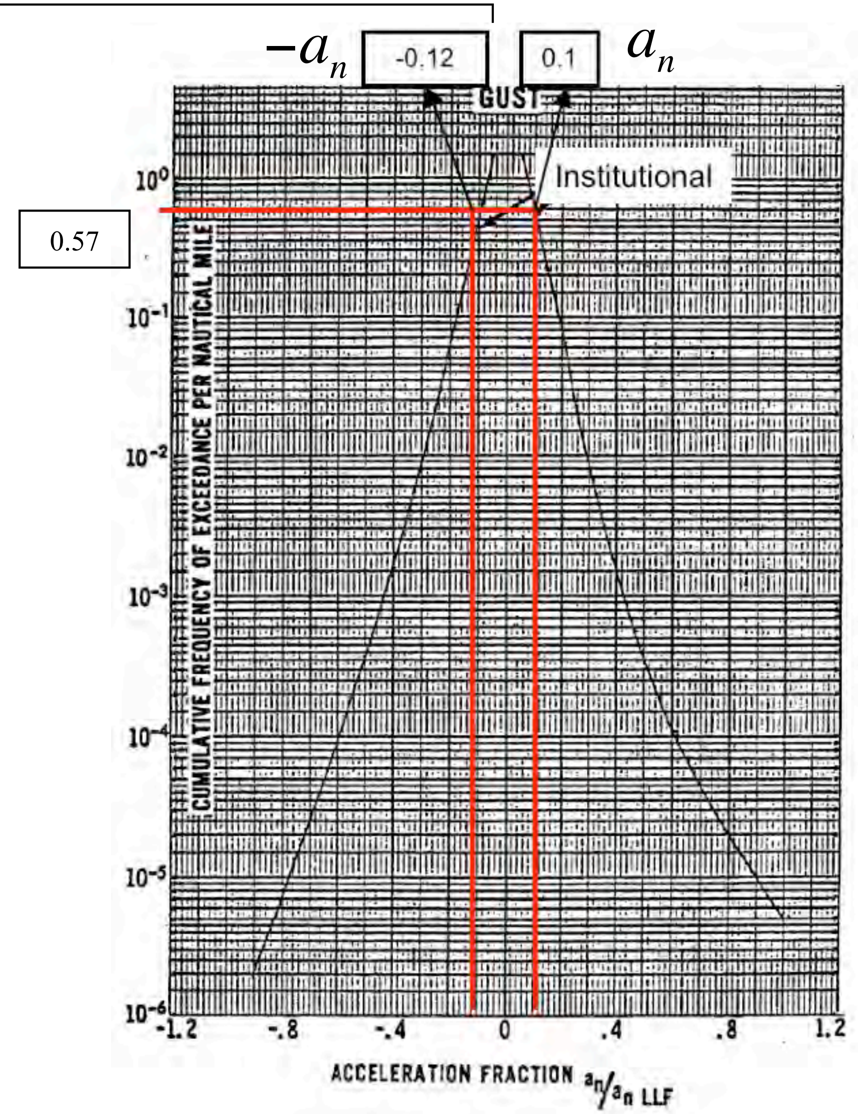
$(a_{nLLF}) \times (a_n/a_{nLLF})$

$a_n = -0.259$
$a_n = 0.28$

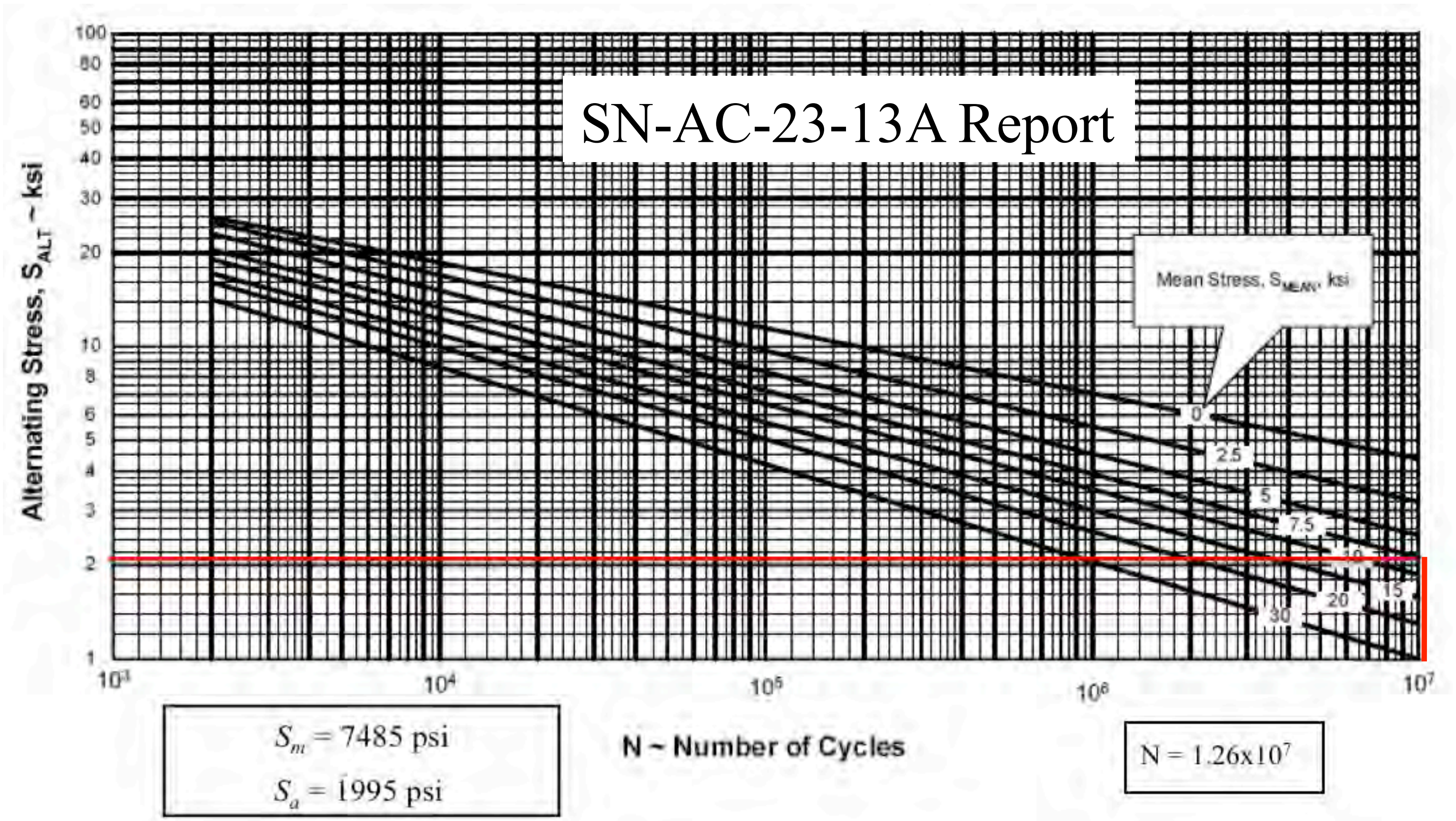
Stress = 7410 PSI @ Critical Component (1 g)

Maximum and minimum delta stress over and below the maximum stress @ the critical component

(+) Δ Max. Stress = 2070 psi (-) Δ Max Stress = -1920 psi



Life Calculation (Gust)



Damage Calculation (Gust)

N, Read from the S-N curve

n, Number of gust cycles accumulated per hour

Damage Rule (n/N)

Miner's

Damage per Hour

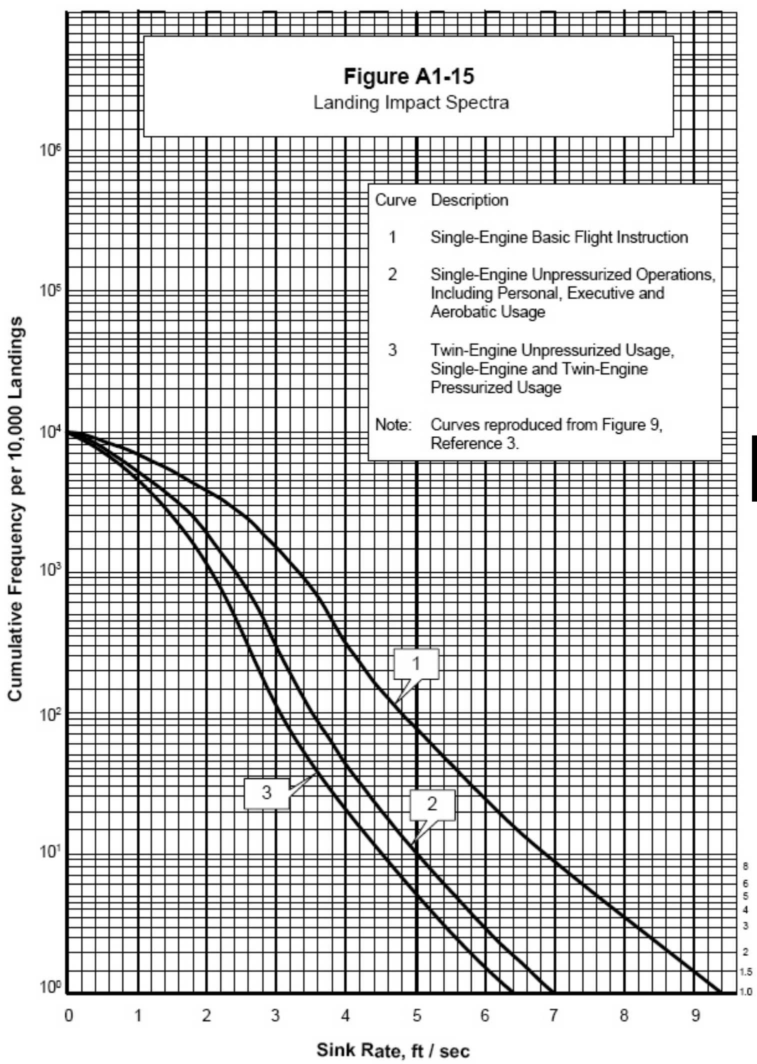
$(57.8/1.26 \times 10^{7}) = 1.39 \times 10^{-6}$

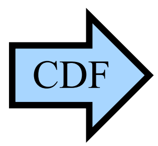
Damage for one stress level

Load Spectrum Generation

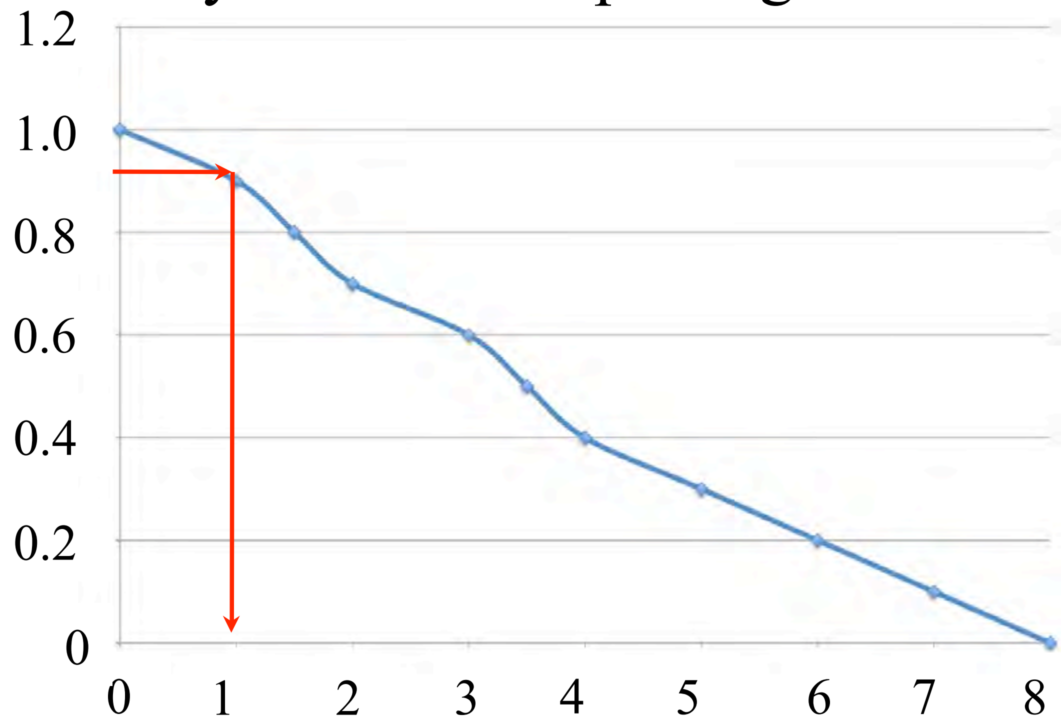
The same procedure is used to calculate the damage for Maneuver and Taxi

Sink rate Gen. (Landing and Rebound)





No sweeping because landing only occurs once per flight



Load Spectrum Generation

Load Factor Calculation (Landing and Rebound)

LANDING

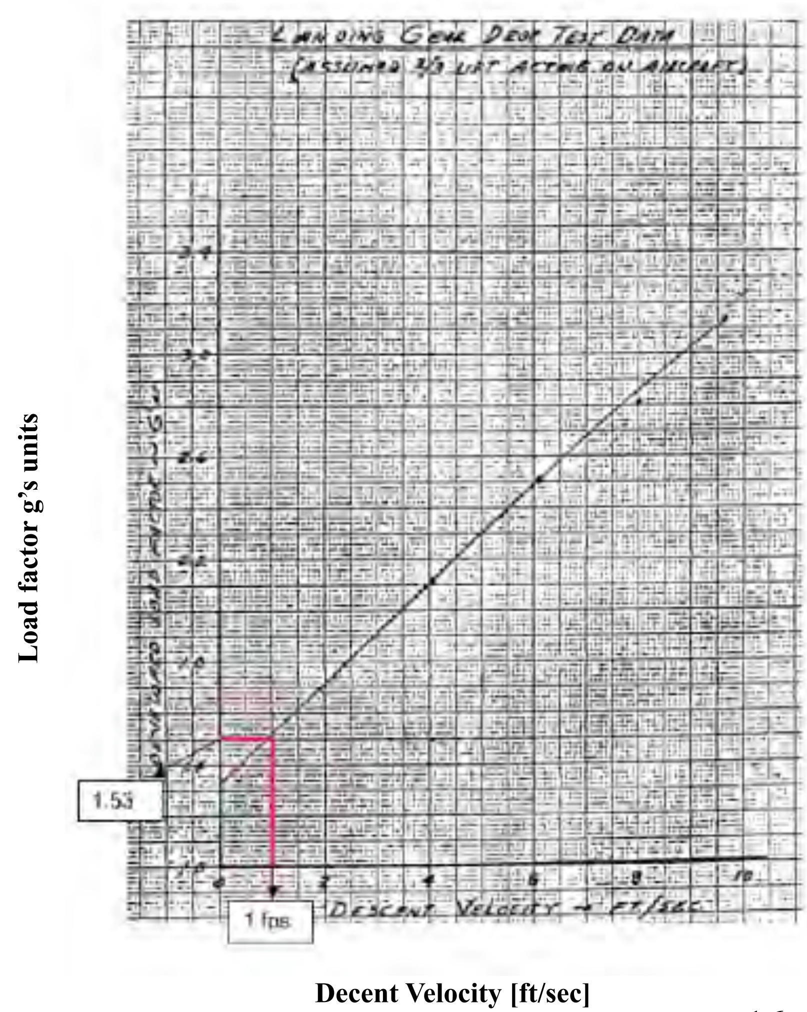
$$\sigma_{MAX\_LAND} = \frac{2}{3}\sigma_{1g}$$

$$\sigma_{MIN\_LAND} = \sigma_{ground} \cdot (Load\ factor)$$

REBOUND

$$\sigma_{MAX\_REB} = 0.6 \cdot \sigma_{MAX\_LAND}$$

$$\sigma_{MIN\_REB} = 0.6 \cdot \sigma_{MIN\_LAND}$$



Gust Damage Fortran Code

Number of Occurrences per hour	Max. Stress	Min. Stress	Damage
19.89594	9404.691	4938.486	2.25E-06
6.383856	10269.86	4019.402	2.56E-06
2.412624	11135.03	3589.076	2.06E-06
0.8268851	12000.2	2826.942	1.49E-06
0.2883785	12865.36	1963.539	9.92E-07
0.1121724	13730.53	1124.38	6.69E-07
4.69E-02	14595.7	319.4421	4.49E-07
2.06E-02	15460.87	-440.4744	2.98E-07
9.28E-03	16326.03	-1140.645	1.94E-07
4.25E-03	17191.2	-1862.795	1.25E-07
1.96E-03	18056.37	-2621.522	7.90E-08
9.01E-04	18921.53	-3384.746	4.87E-08
4.14E-04	19786.7	-4148.813	2.94E-08
2.24E-04	20219.29	-4531.846	1.82E-08
1.90E-04	20651.87	-4854.917	1.73E-08
8.67E-05	21517.04	-5405.45	9.94E-09
4.37E-05	21949.62	-6153.379	5.75E-09
3.96E-05	22382.2	-6199.305	5.72E-09
1.81E-05	23247.37	-6997.711	3.24E-09
8.52E-06	23679.96	-7777.103	1.72E-09
3.76E-06	24545.12	-8587.351	9.28E-10
3.76E-06	24977.71	-8587.351	1.01E-09

Load Spectrum Generation

Fortran Code

Taxi

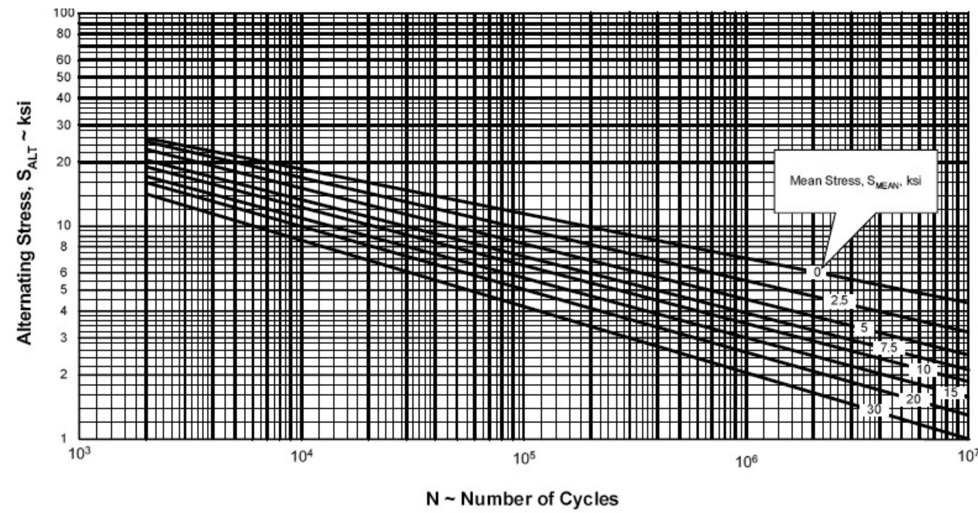
Number of Occurrences	Max. Stress	Min. Stress	Damage
147	-4633	-4407	7.73E-15
159	-4859	-4181	2.03E-12
140	-5085	-3955	2.30E-11
104	-5311	-3729	9.19E-11
61.9	-5537	-3503	1.92E-10
20.4	-5763	-3277	1.73E-10
6.61	-5989	-3051	1.29E-10
1.625	-6215	-2825	6.49E-11
0.3708	-6441	-2599	2.77E-11
7.37E-02	-6667	-2373	9.59E-12
1.63E-02	-6893	-2147	3.51E-12
3.33E-03	-7119	-1921	1.13E-12
6.75E-04	-7345	-1695	3.47E-13
1.27E-04	-7571	-1469	9.57E-14
2.32E-05	-7797	-1243	2.50E-14

Landing and Rebound

Number of Occurrences	Max. Stress	Min. Stress	Damage
1	4940	-8612.665	1.346303E-07
1	2964	-5167.596	1.046886E-08

Damage per Flight	7.437502E-05
Flights to Failure	13380.16

UTSA Stress Severity Factor (SSF)

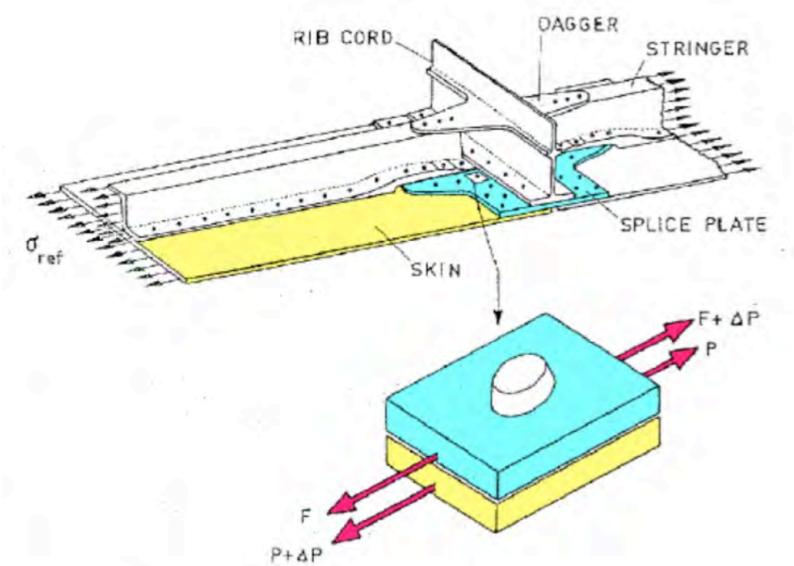


Old Fatigue life methodology:

- Fatigue data form full-scale wing tests (single Configuration).

-Does not account for differences in structural details between wings.

-Unrealistic fatigue life estimates.



Fatigue Failure is related with fastener joints

The SSF is a fatigue factor that accounts for:

•Fastener type, method of installation, interference, hole preparation, etc.

•Detail design

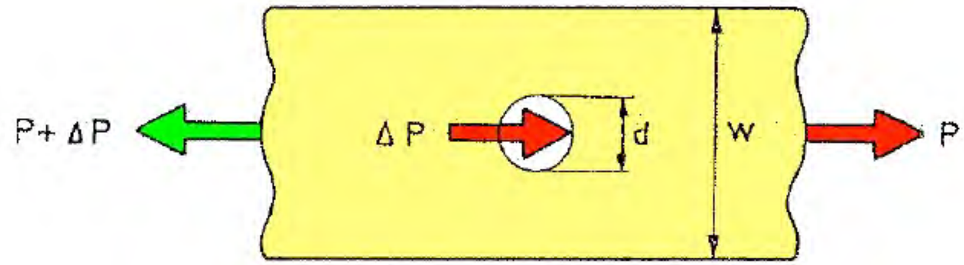
•Fastener load distribution

•And others

Stress Severity Factor

Equation

$$SSF = \frac{\alpha \cdot \beta}{\sigma_{ref}} \left(K_{TB} \cdot \frac{\Delta P}{d \cdot t} \cdot \Theta + K_{TG} \cdot \frac{P}{w \cdot t} \right)$$



α	A hole preparation factor, this effect can be determine by testing conventional fatigue coupons with various types of holes
β	A hole filling factor accounting for interference between fastener and hole
σ_{ref}	Reference (gross area stress)
K_{TB}	Stress concentration factor referred to nominal bearing stress
ΔP	Transfer load (by the fastener)
d	Fastener Diameter
t	Plate Thickness
Θ	Load transfer factor. This factor must be determined by testing specimens with variations in load transfer
K_{TG}	Stress concentration factor referred to gross area stress
P	Load, especially by-passing load
w	Plate Width

Stress Severity Factor

Example

Input Variables

- 1g Stress At Critical Location = 9410 psi
- Joint_Type = RIVET
- Joint_LT = 50%
- Joint_t = 0.09 in
- Joint_d = 0.322 in
- Joint_w = 3 in
- Mean Stress = 6 ksi

β

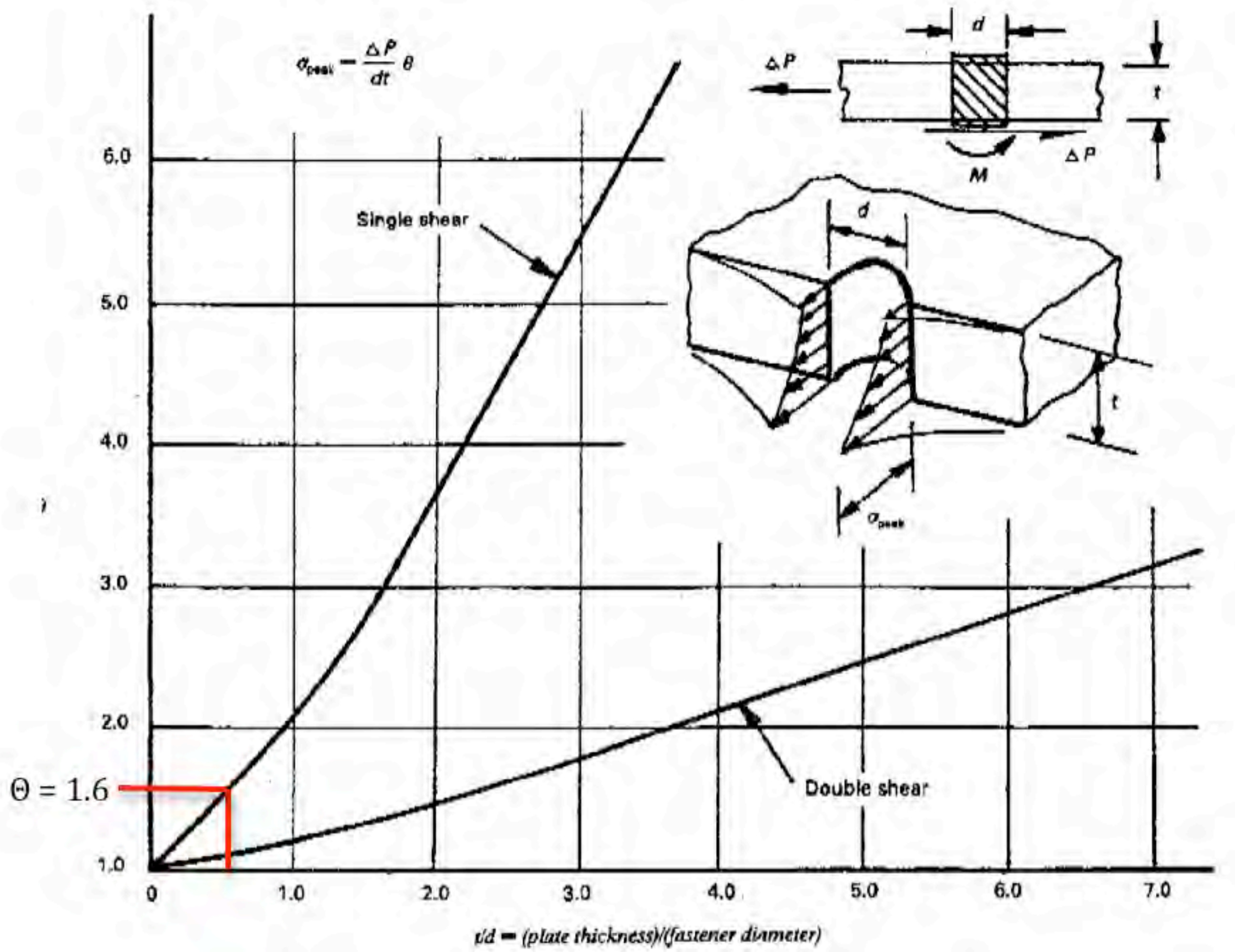
Fastener Type = Rivet

TABLE 2	β FACTORS	β
Open holes		1.0
Lock bolts steel (BAC5004)		0.75
Rivets 2117 (BAC5047)		0.75
Threaded bolts B30AB		0.75 - 0.9
Taperlocks		0.50

From Josef (Boeing)

θ

t/d = 0.2/0.322 = 0.621



Bearing distribution factor

Boeing and Michael C. Y. Niu, Airframe Structural Design

α

$\alpha = 1.0$ (std hole drilled)

TABLE 1	α FACTORS	α
Fillet radii		1.0 - 1.5
Standard hole drilled		1.0
Broached or reamed		0.9
Cold worked holes		0.7 - 0.8

Michael C. Y. Niu, Airframe Structural Design

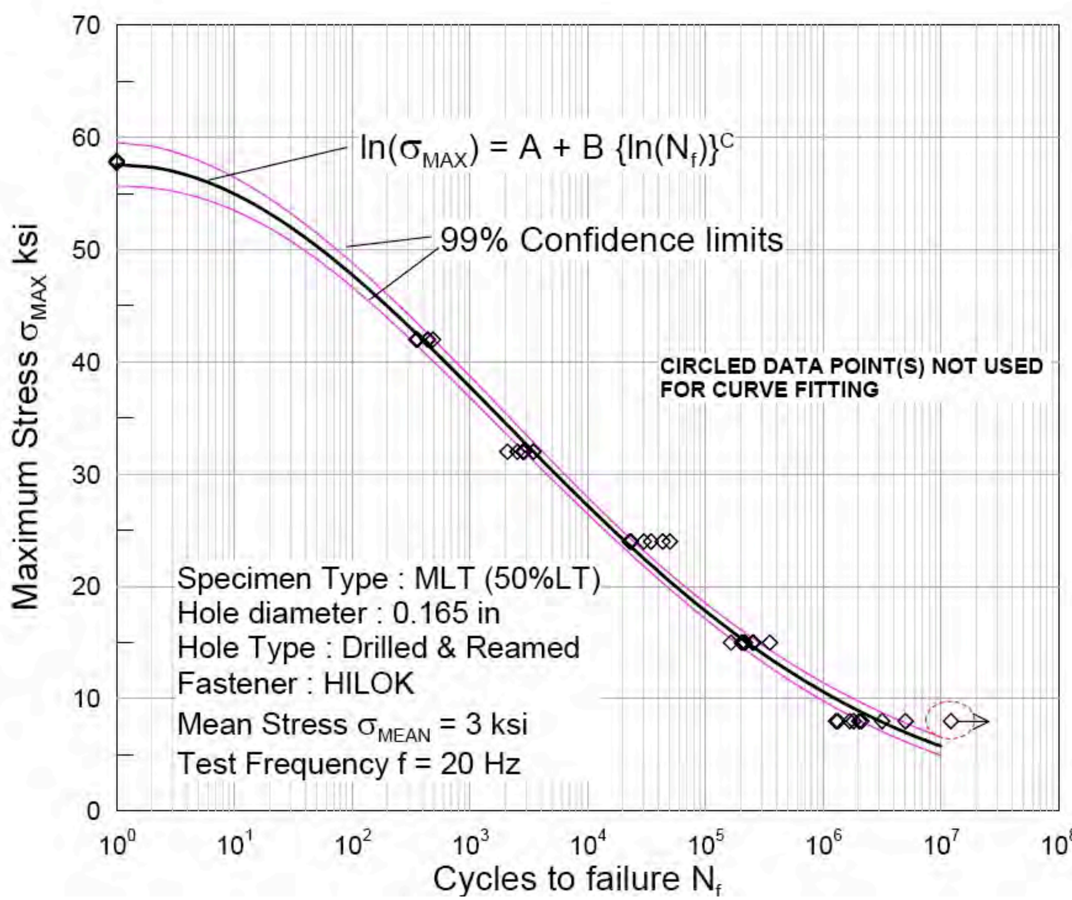
Solving for SSF

$$SSF = \frac{\alpha\beta}{\sigma_{ref}}\left(K_{tb}\theta\frac{\Delta P}{dt} + K_{tg}\frac{P}{wt}\right)$$

$$SSF = \frac{1.0 \times 0.75}{9410}\left(1.4 \times 1.6 \times \frac{635.175}{0.161 \times 0.09} + 3.02 \times \frac{1270.35}{1.5 \times 0.09}\right)$$

$$SSF = 8.07$$

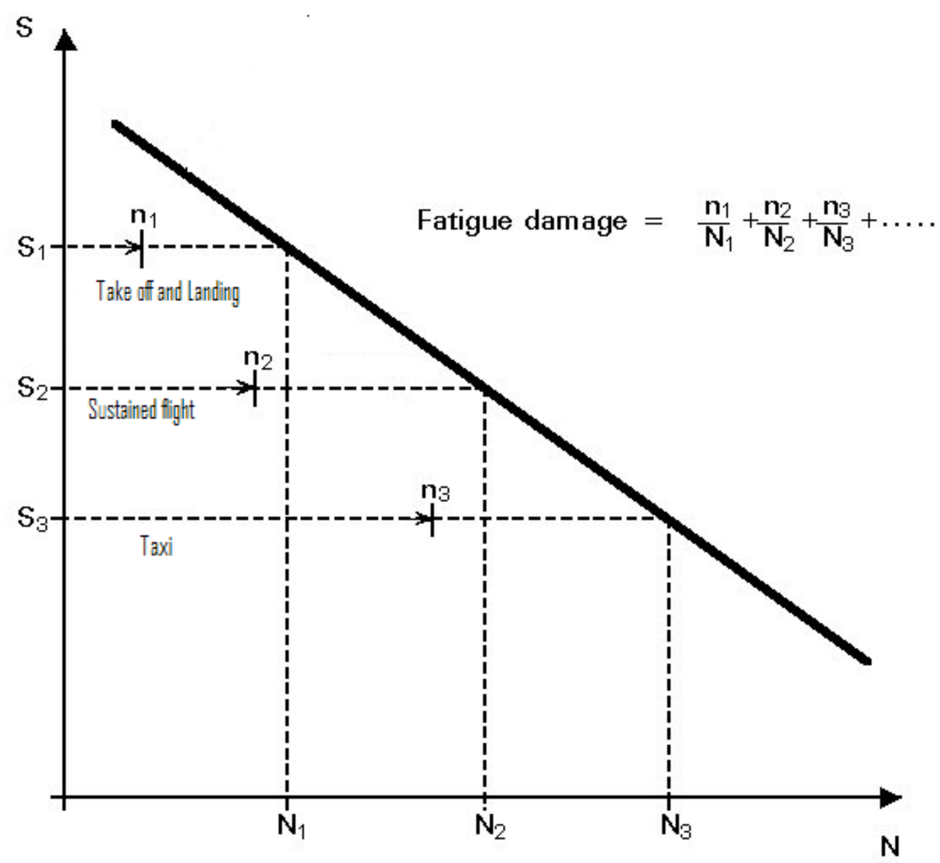
SSF & SN



70
60
50
40
30
20
10
0
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
Maximum Stress σ_{MAX} ksi
Cycles to failure N_f
$\ln(\sigma_{MAX}) = A + B\{\ln(N_f)\}^C$
99% Confidence limits
CIRCLED DATA POINT(S) NOT USED
FOR CURVE FITTING
Specimen Type : MLT (50%LT)
Hole diameter : 0.165 in
Hole Type : Drilled & Reamed
Fastener : HILOK
Mean Stress σ_{MEAN} = 3 ksi
Test Frequency f = 20 Hz

Damage Accumulation Models

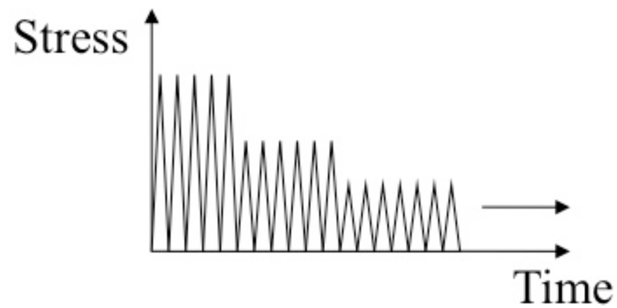
Fatigue damage increases with applied loading cycles in both constant amplitude loading and variable amplitude loading.



Damage Accumulation Models

Different damage models have been investigated:

- Palmgren-Miner's Rule
- Damage Curve Approach
- Double Linear Damage Rule
- Johannensson Method
- Liu and Mahadevan Method



$N_1 = 51{,}900$ $\quad n_1 = 95$

$N_2 = 414{,}140$ $\quad n_2 = 3990$

$N_3 = 13{,}800{,}000$ $\quad n_3 = 5415$

$S_1 > S_2 > S_3$

D.T.D. 683 Aluminum

UTSA

Damage Rules

Method	Damage[1]	Cycles to failure[2]	Testing C-T-F[3]	Ratio, Predicted/ Experimental
Miner's	0.0118	801,000	871,000	0.92
DLDR	0.13	672,000	871,000	0.77
DCA	0.002428	656,000	871,000	0.75
Johannensson	0.03	316,000	871,000	0.364[4]
Liu	0.0097	979,381	871,000	1.12

[1] First Three levels

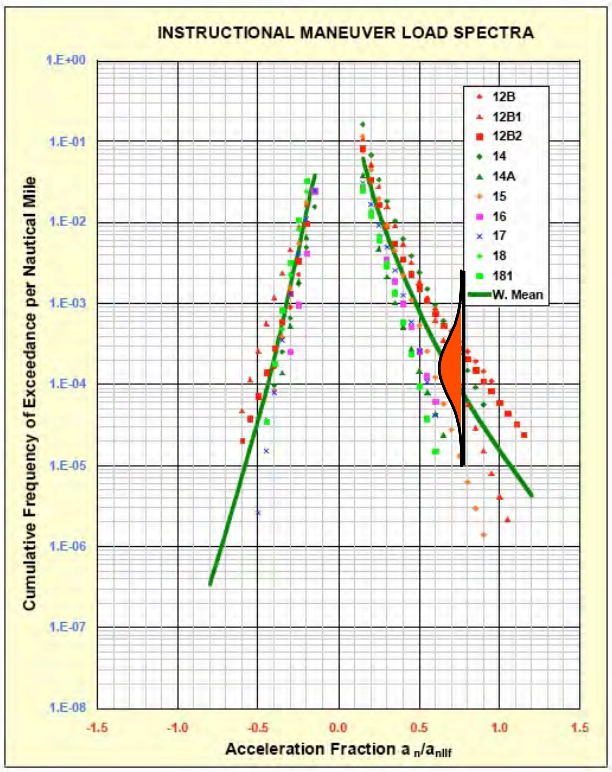
[2] When D =1

[3] From Testing, Manson 1981.

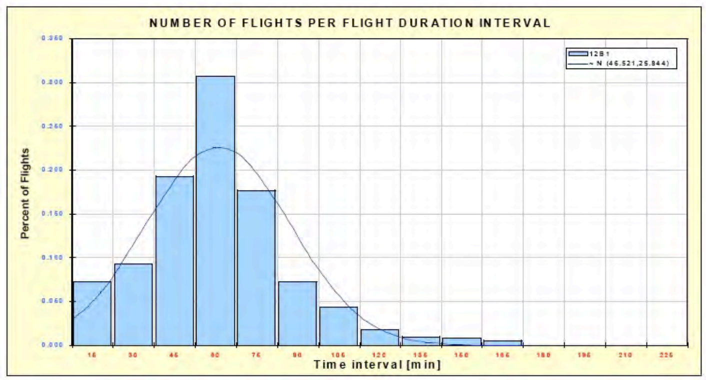
[4] We do not have in this moment enough information to compute the value

Probabilistic Code

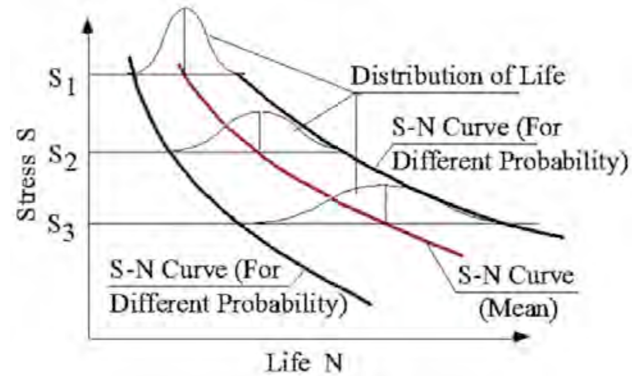
Random Variables



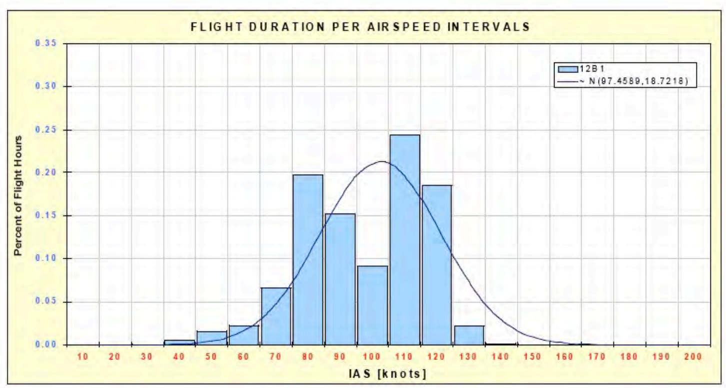
Exceedance Curves



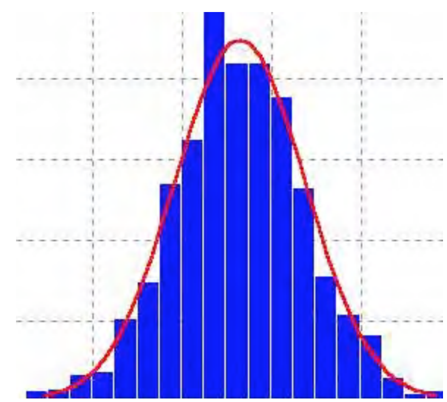
Flight Duration



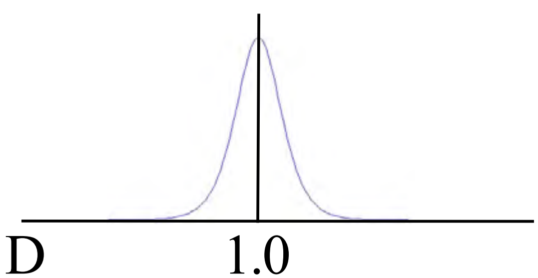
S-N Curves



A/C Velocity



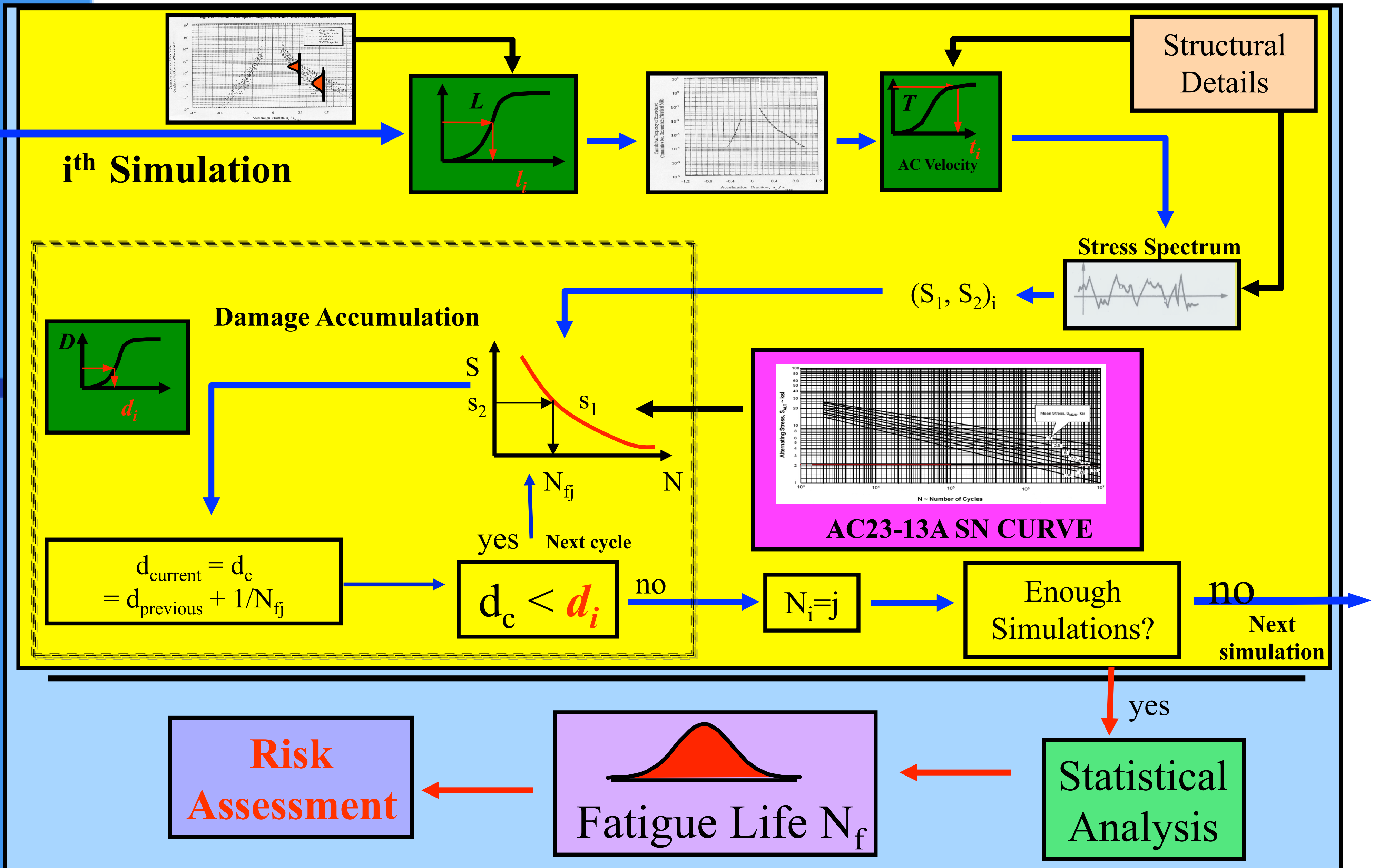
One g stress
Ground Stress



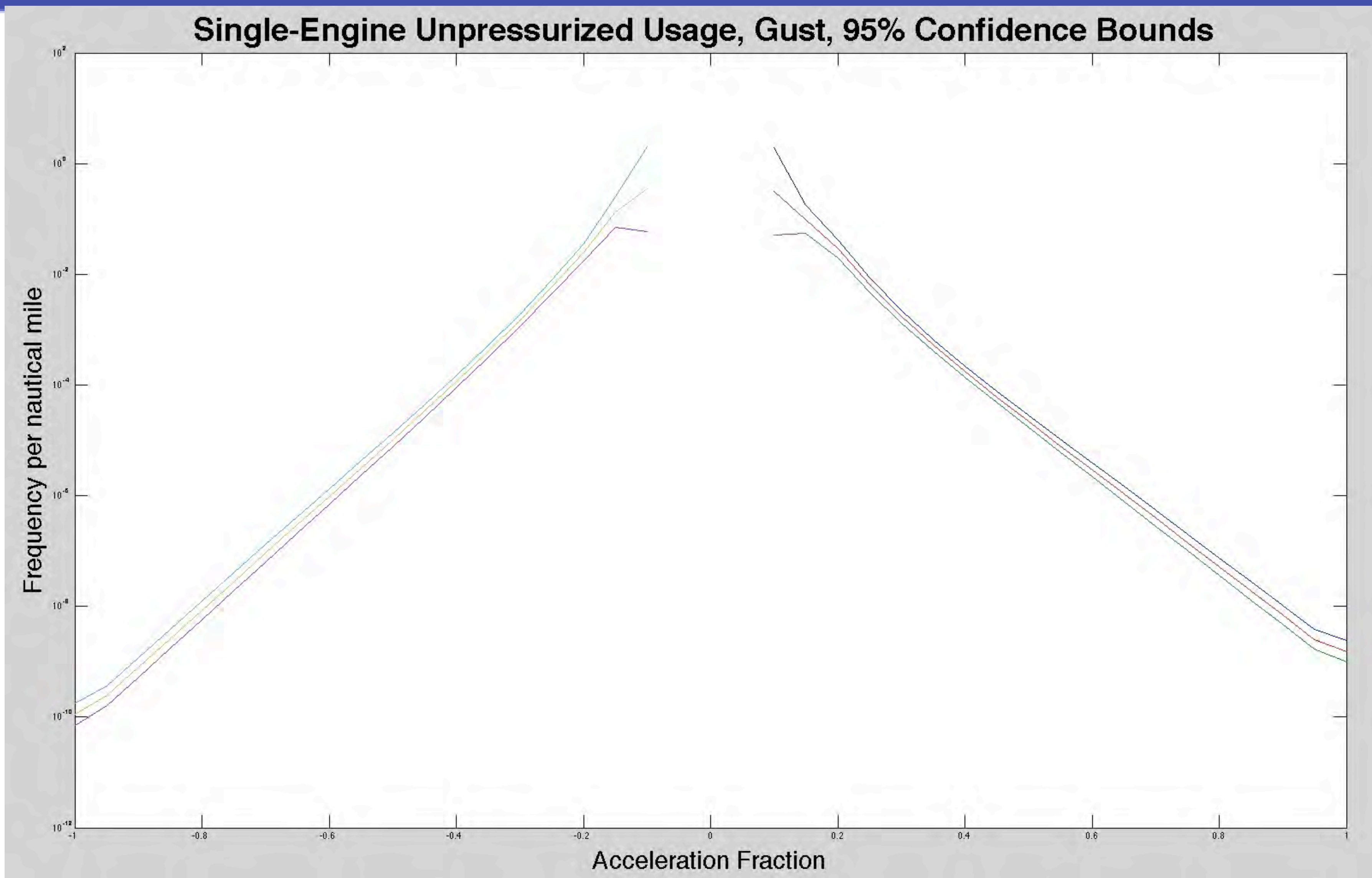
One possible approach

Risk Analysis and Risk Management (RARM) Methodology for Small Airplane Continued Operational Safety

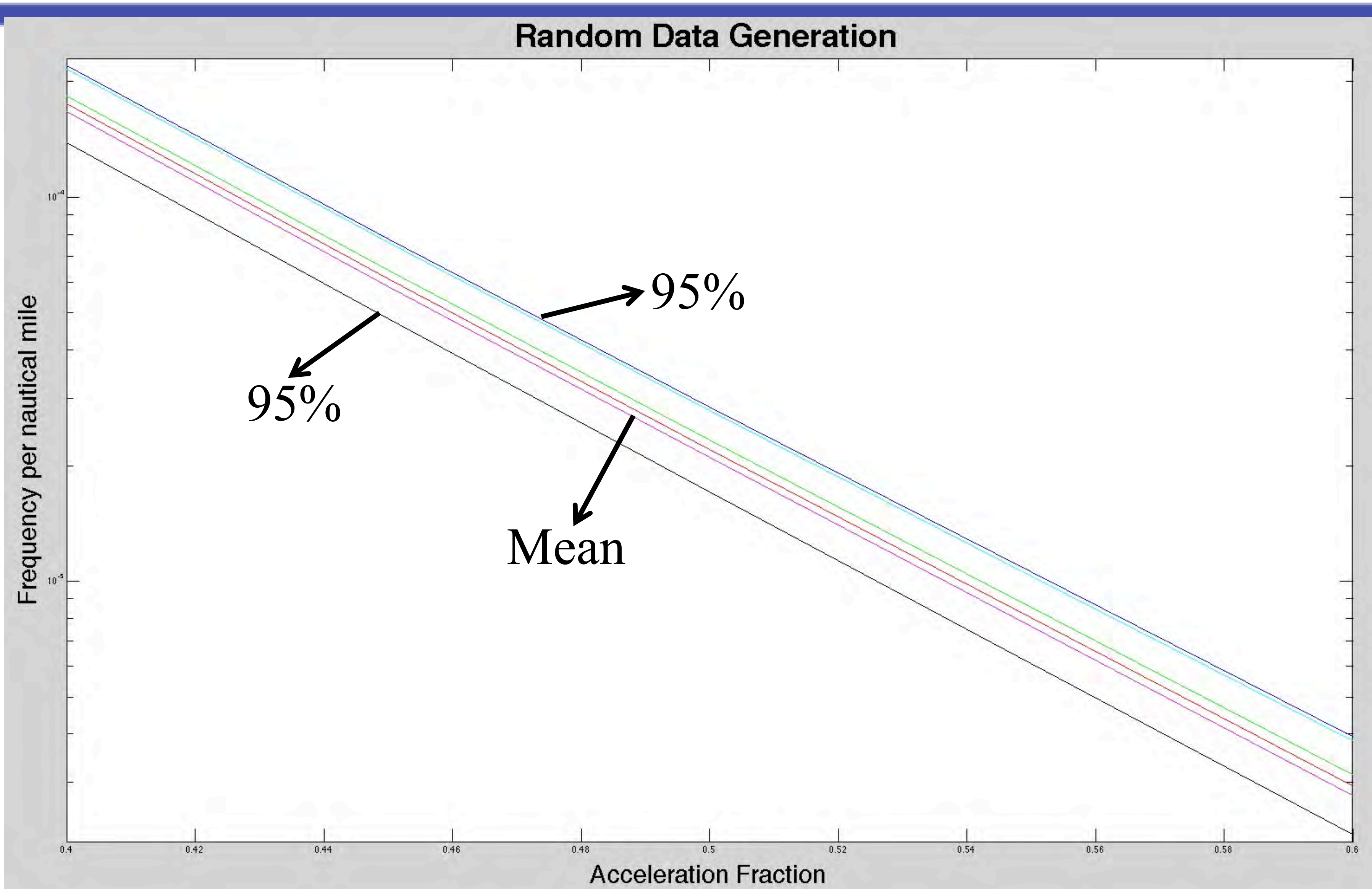
MONTE CARLO SIMULATION



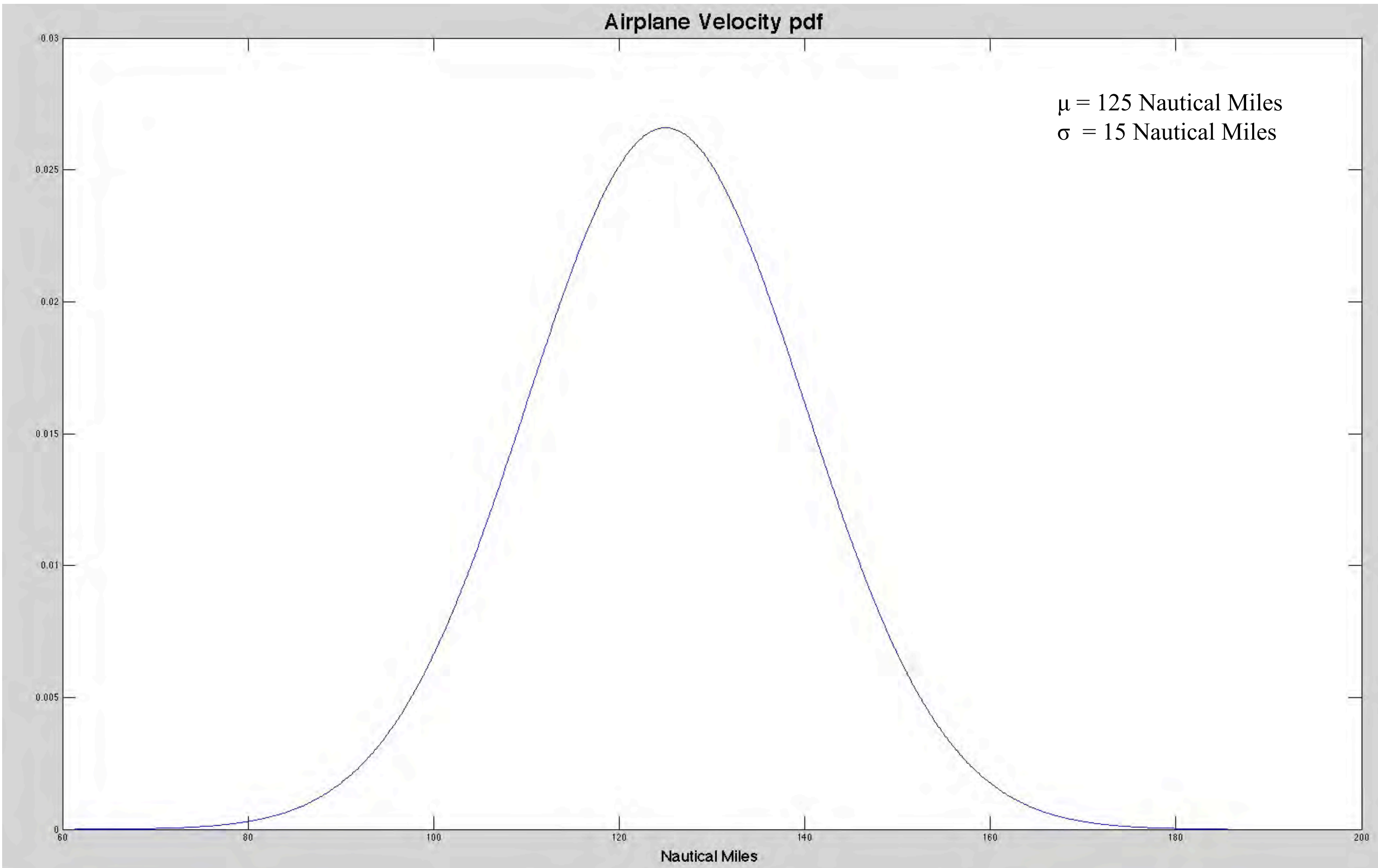
Random Exceedance



Random Exceedance

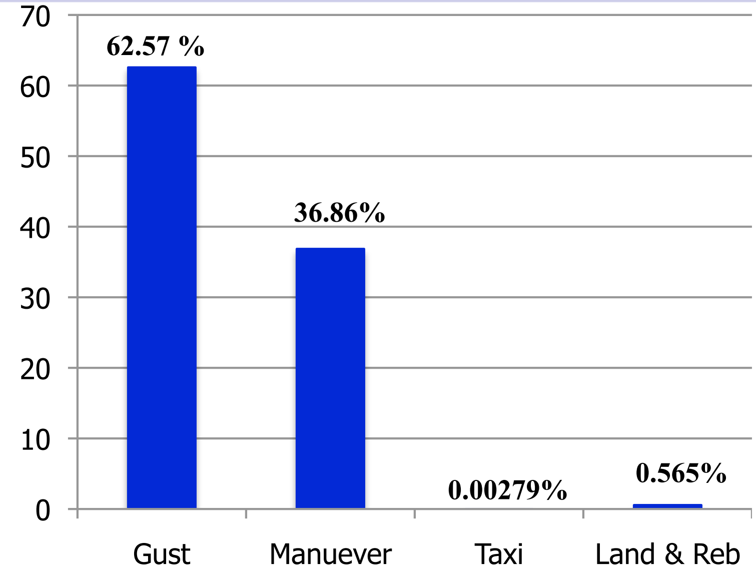


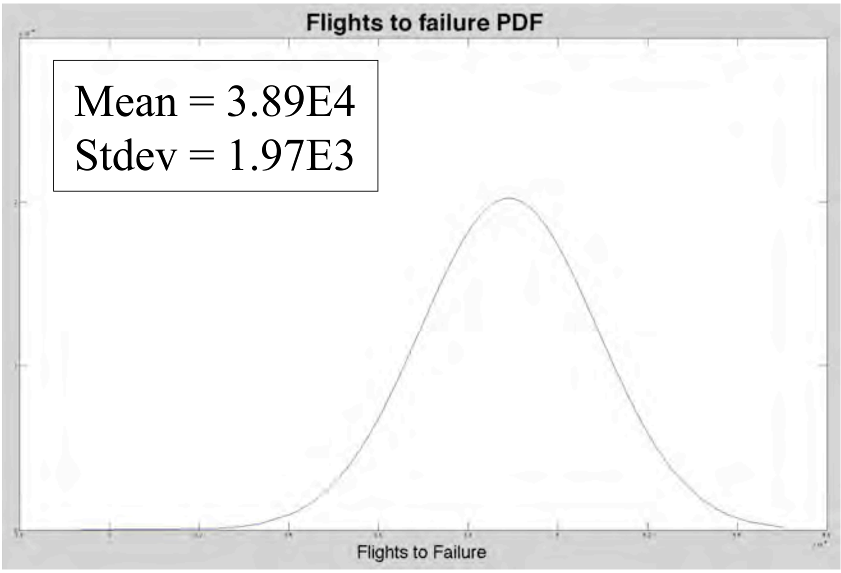
Airplane Velocity

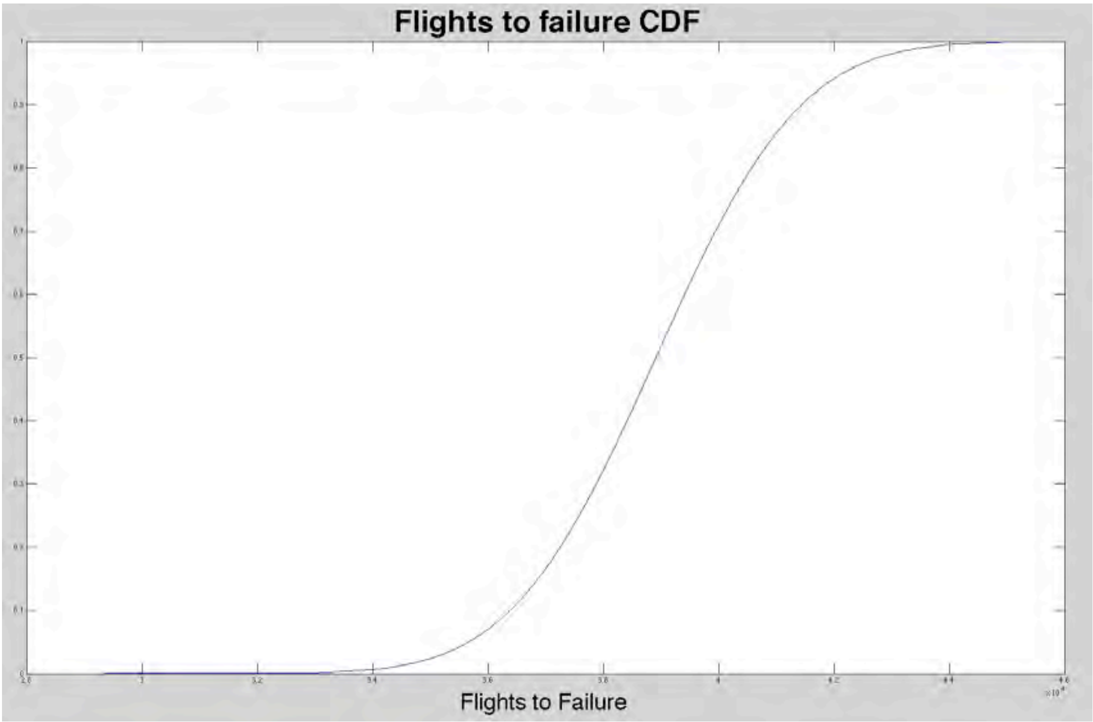


Probabilistic Code

Preliminary Results







Parallel Processing
OpenMP

What is OpenMP?

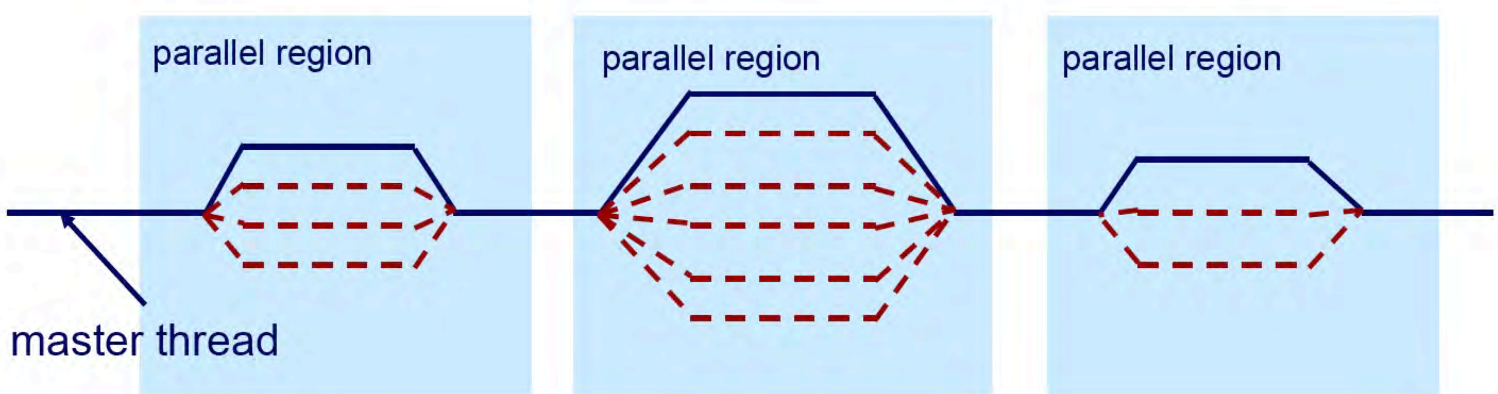
-Standard for Scientific Parallel Programming on Symmetric Multiprocessor (SMP) Systems.
-Implemented by compiler directives.
-Standard specifies Fortran and C/C++

Some advantages:

-Shared Memory Parallelism is easier to learn (compared with MPI).
-Parallelization can be incremental.
-Widely available, portable.

Some disadvantages:

- Scalability limited by memory



http://www.openmp.org/ (Tutorials and description)

Future Work

- Sensitivities
- Weibull Analysis
- Parallel Processing
- Hazard curve

UTSA

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