JAMS

Development of Reliability-Based Damage Tolerant Structural Design Methodology

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Outline

- Background and Objective
- Probabilistic Structural Design
  - Approach
  - Formulations
- Program Capabilities
  - Monte Carlo Simulation
  - Software Architecture
- SDR Data Mining
  - Damage Maps
  - PDF of Detected Damage
- Results
  - Sample Problems
  - Parametric Studies
- Summary

Development of Reliability-Based Damage Tolerant Structural Design Methodology

- ***Motivation and Key Issues:*** Composite materials are being used in aircraft primary structures such as 787 wings and fuselage. In these applications, stringent requirements on weight, damage tolerance, reliability and cost must be satisfied. Although currently there are MSG-3 guidelines for general aircraft maintenance, an urgent need exists to develop a standardized methodology specifically for composite structures to establish an optimal inspection schedule that provides minimum maintenance cost and maximum structural reliability.

- ***Objective:*** Develop a probabilistic method for estimating structural component reliabilities suitable for aircraft design, inspection, and regulatory compliance.

Contributors

- **Principal Investigator:**
  - Dr. Kuen Y. Lin, Aeronautics and Astronautics, UW
- **Research Scientist:** Dr. Andrey Styuart, UW
- **Research Assistants:** Chi Ho “Eric” Cheung, UW
- **FAA Technical Monitor:** Peter Shyprykevich
- **Other FAA Personnel:** Dr. Larry Ilcewicz, Curtis Davies
- **Industry Participants:** Dr. Cliff Chen, Dr. Hamid Razi, Mr. Gerald Mabson, Dr. Alan Miller (All from Boeing)

Example of Impact: Hail Damage

Fatigue Damage vs. Impact Damage

	Fatigue damage, *metals*	Impact damage, *composites*
Type of uncertainty	Quite certain: fatigue crack	3-5 damage types should be considered for any particular structure type
Location of uncertainty	Quite certain: high stress concentration locations	All surface: relative damage frequency is known
Size of uncertainty	For good designs, grows slowly from initial crack size. Can be stopped.	Created instantly, then usually doesn't grow.
Predictive methods	Well developed. Good prediction of fatigue life	Poor prediction due to lack of appropriate statistical data

Present Approach

- The present study is based on a probabilistic failure analysis with the consideration of parameters such as inspection intervals, statistical data on damages, loads, temperatures, damage detection capability, residual strength of the new, damaged and repaired structures.
- The inspection intervals are formulated based on the probability of failure of a structure containing damage and the quality of a repair.
- The approach combines the "Level of Safety" method proposed by Lin, et al. and "Probabilistic Design of Composite Structures" method by Styuart, at al.
- No damage growth is assumed in the present model.

Probabilistic Approach

Various Failure Modes

Strength/Stiffness vs. Temperature

Moisture Content vs. Time

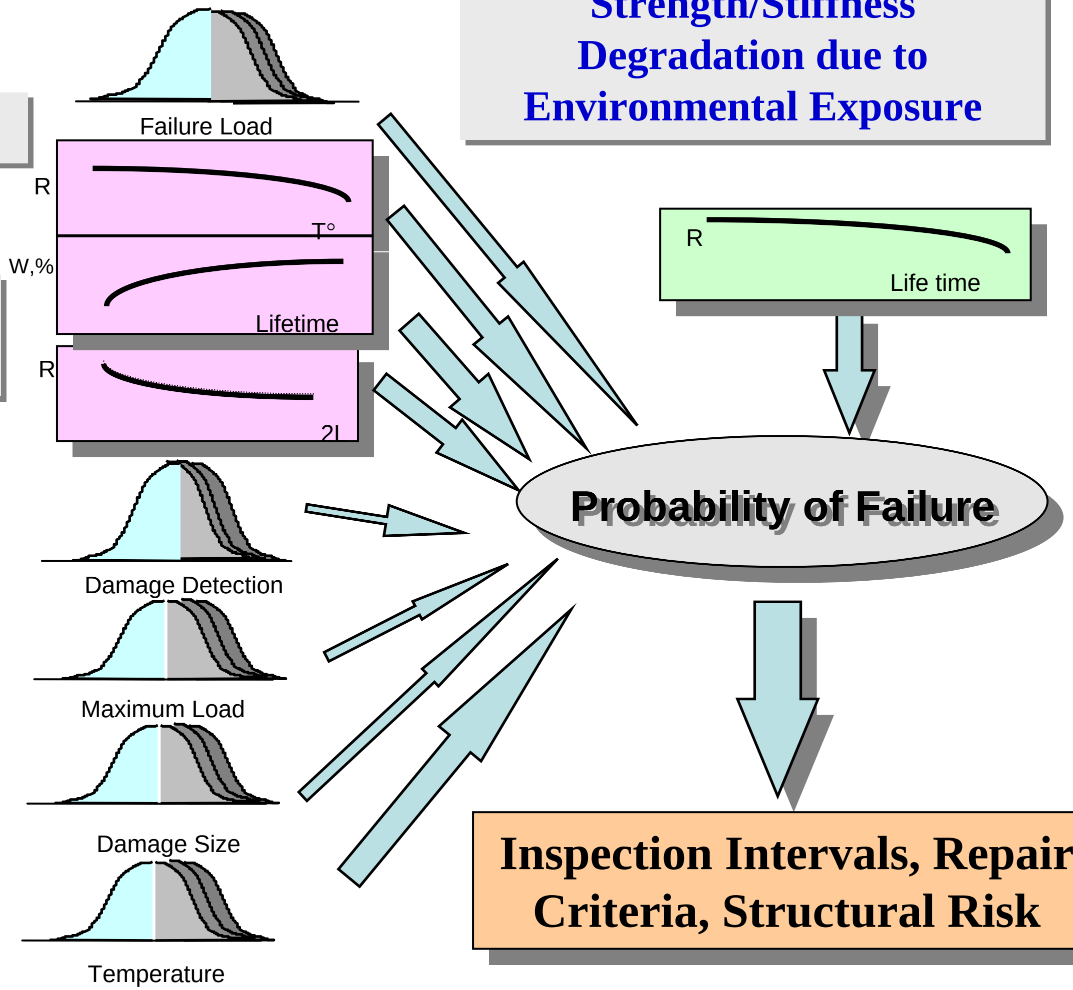
Residual Strength/Stiffness vs. Damage Size & Damage Type

Probability of Detection vs. Damage Size & Damage Type

Maximum Load vs. Time of Damage Existence

Damage Size & Damage Type Spectra

Structural Temperature Spectra



Strength/Stiffness Degradation due to Environmental Exposure

Probability of Failure

Inspection Intervals, Repair Criteria, Structural Risk

Probability of Failure Formulation

Deterministic Input Parameters:

- Type of damage T_D
- Failure mode/ load case FM
- Inspection intervals T_1, T_2, …

$$P_f = \int_{\Omega} f(N, \vec{D}, \vec{R}, t, td, \vec{L}, \vec{T}^{\circ} \,|\, T_D, FM, T_1, T_2, T_3 \ldots)\, d\vec{v}$$

$$d\vec{v} = dN\ d\vec{D}\ d\vec{R}\ dt\ d(td)\ d\vec{L}\ dT^{\circ}; \quad \Omega = \textit{failure domain}$$

Probabilistic Input Parameters:

- Failure load (initial strength) R^J_0
- Number of damages per life N^J
- Damage size D^J
- Time of damage initiation t_i^J
- Time of damage detection td_i^J
- Residual strength R^J_i
- External load L_i^J
- Structural temperature $T°_i^J$
- Effects of environmental aging and chemical corrosion

Piecewise random history method:

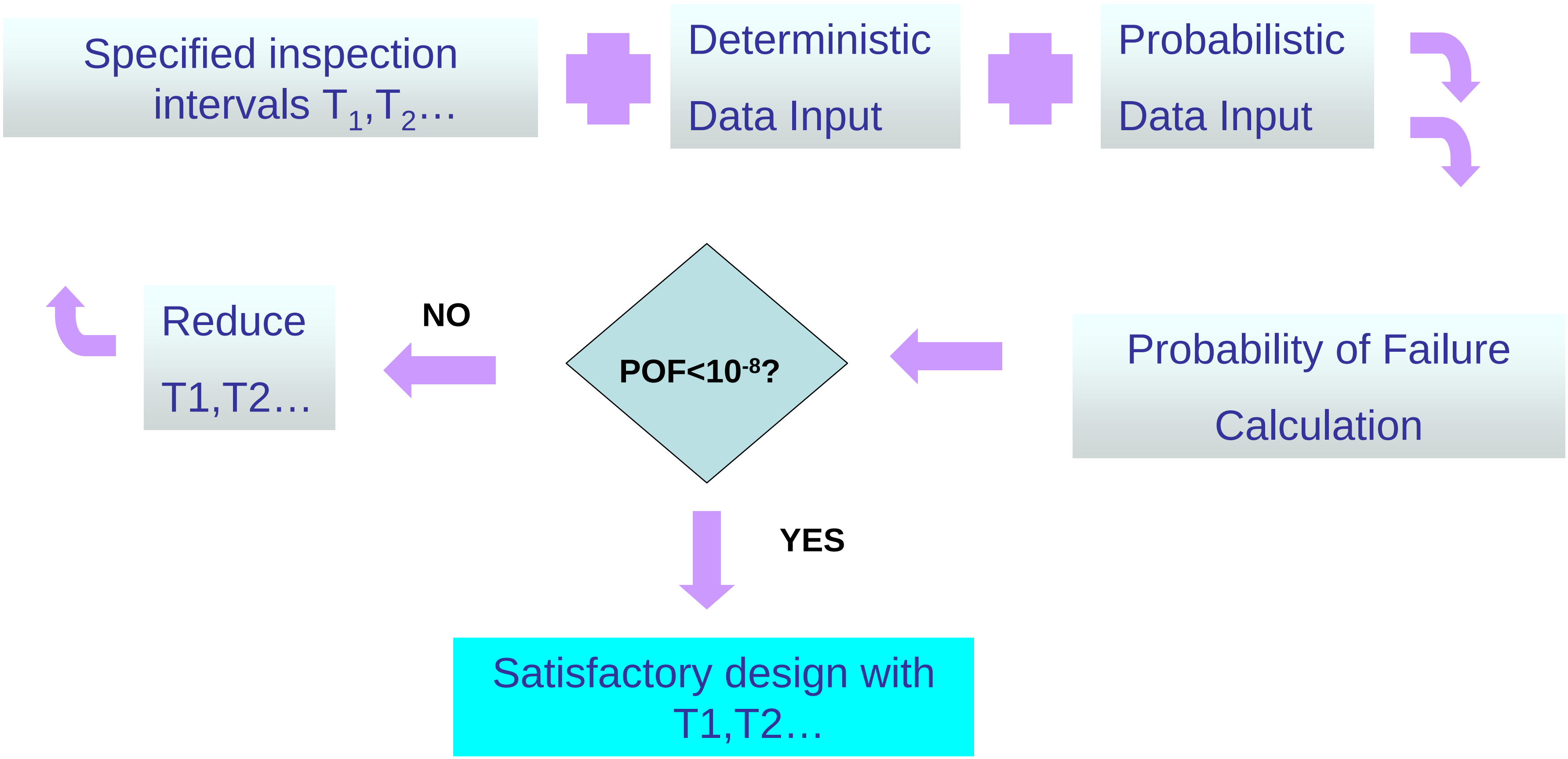
Relations for one type of damage and failure mode/ load case

$$P^j = 1 - \prod_{i=1}^{N_J} [1 - P_i^j(R_i^j, (td_i^j - t_i^j)]; \quad P_f = \frac{1}{N} \sum_{j=1}^{N} P_j; \quad N = f(\Delta);$$

$$P_i^j = 1 - \{F_L[R_i^j(D_i^j) \,|\, \mu_L, \sigma_L]\}^{\frac{(td_i^j - t_i^j)}{Life}}; \quad F_L = CPF\ of\ \max\ load\ \ per\ life$$

$$td_i^j = f[P_{Detect}(D_i^j), t_i^j]$$

Finding Inspection Intervals



Specified inspection intervals T_1,T_2…

Deterministic Data Input

Probabilistic Data Input

Probability of Failure Calculation

POF<10^{-8}?

NO

Reduce T1,T2…

YES

Satisfactory design with T1,T2…

Probabilistic Model

Probabilistic Input Parameters:

- **Type of damage T**
- **Number of damages per life**
- **Initial failure load (initial strength)**
- **Damage size**
- **Time of damage initiation**
- **Time to detect Damage**
- **External load**
- **Structural Temperature *T°***
- **Effects of environmental aging and chemical corrosion**

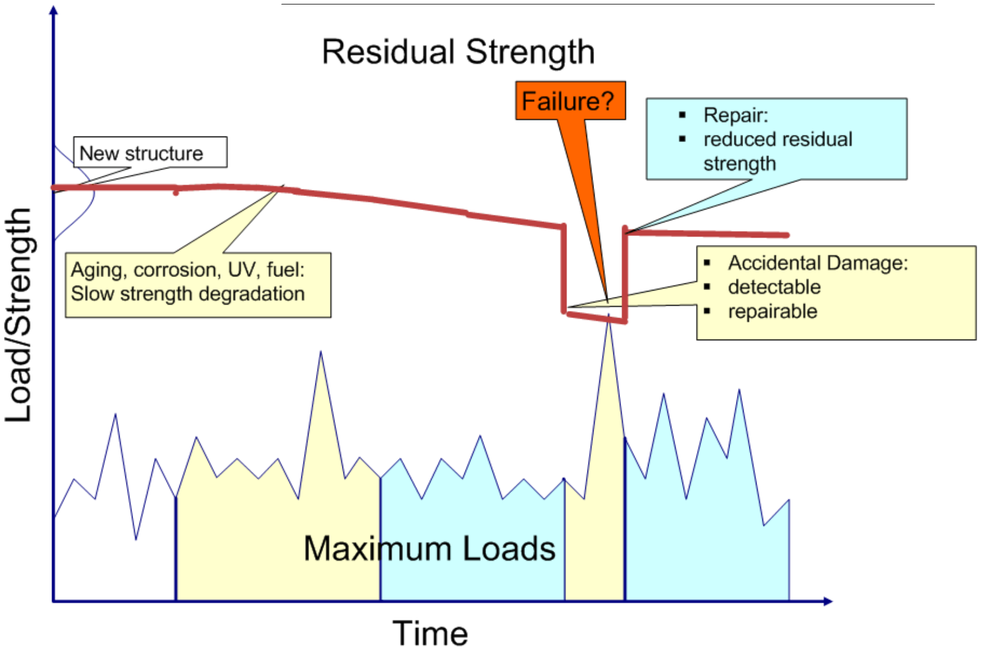
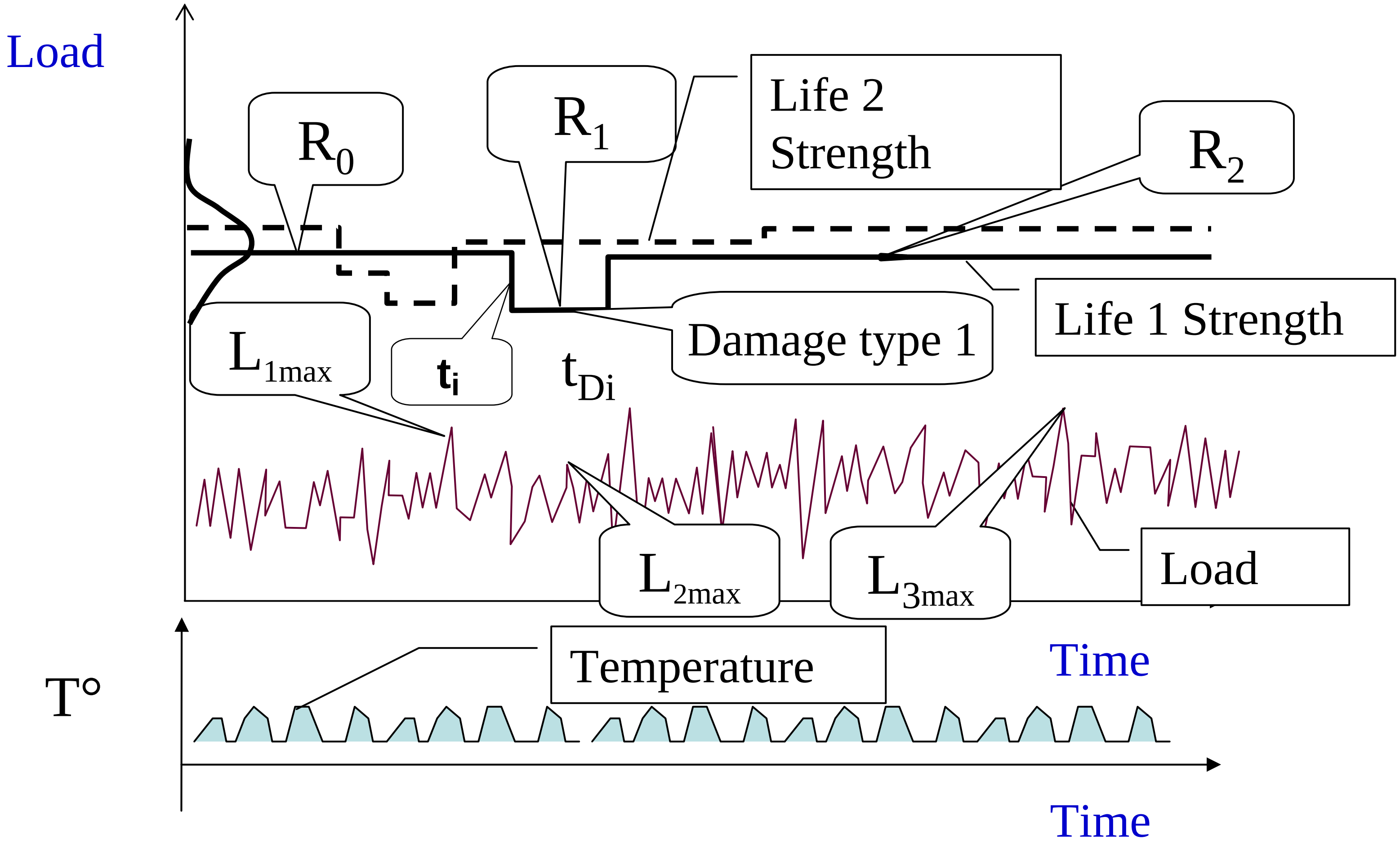


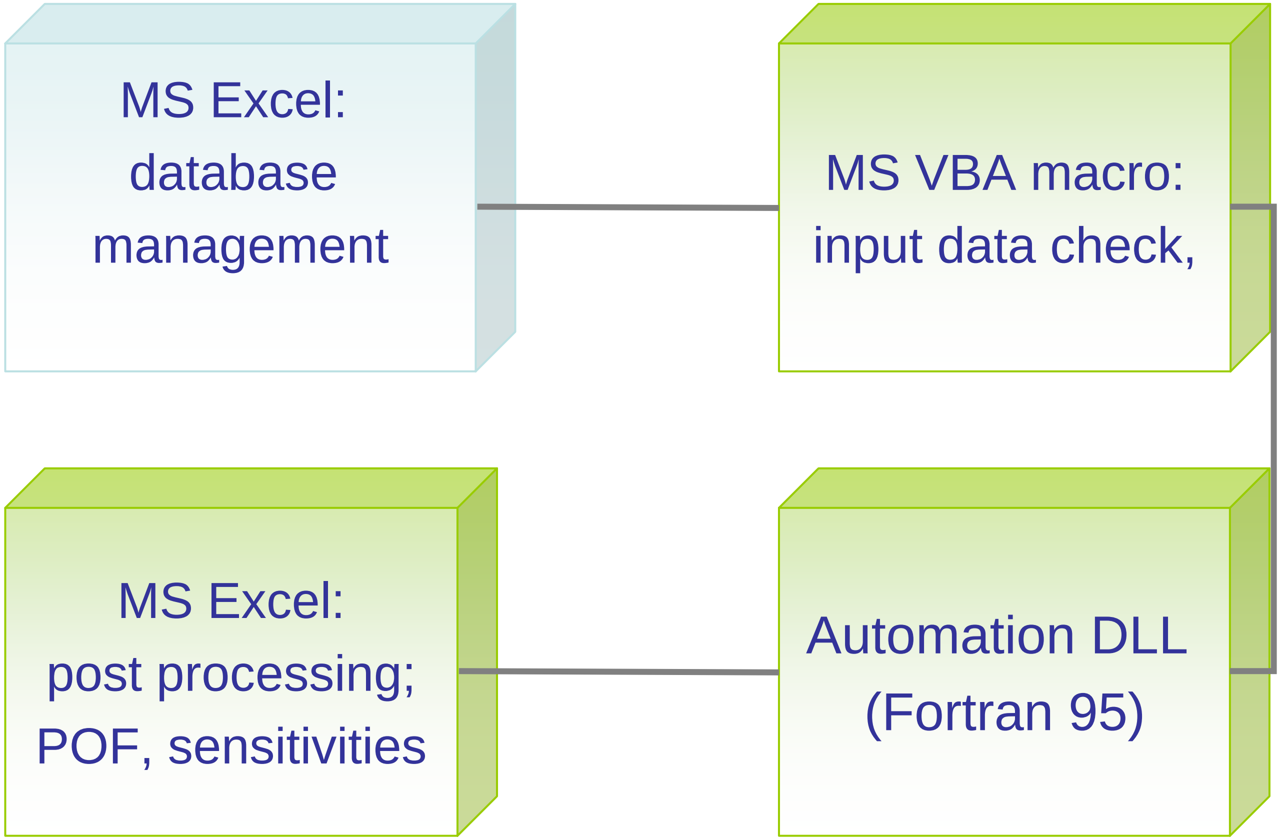
Fig.1

First, we simulate random time histories of residual strength as a sequence of intervals between damage initiation and detection/repair. The probability of failure (POF) can then be evaluated as the sum of POF for all intervals.

Probabilistic Model



Software Architecture



MS Excel:
database
management

MS VBA macro:
input data check,

MS Excel:
post processing;
POF, sensitivities

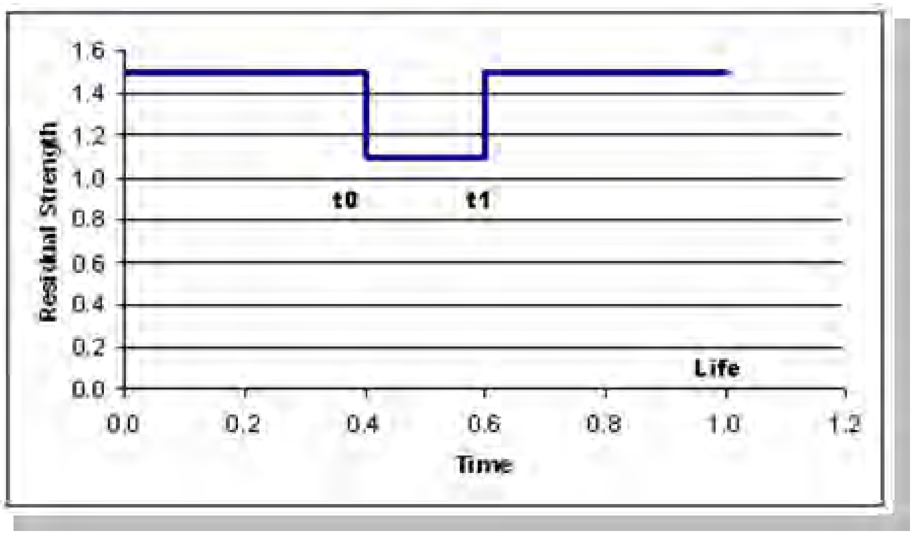
Automation DLL
(Fortran 95)

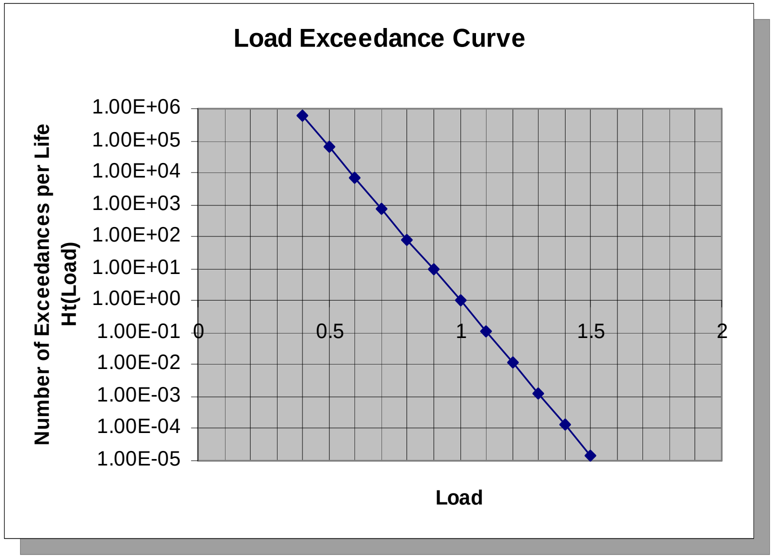
Program Capabilities

- “Static” failure: load exceeds the strength of damaged structure
- Excessive deformations
- Flutter: airspeed exceeds the flutter speed of damaged structure*
- High amplitude limit cycle oscillations: the acceptable level of vibrations is exceeded*

**See the FAA Grant “Combined Local ->Global Variability and Uncertainty in the Aeroservoelasticity of Composite Aircraft”*

Example of POF Calculation for One Structure



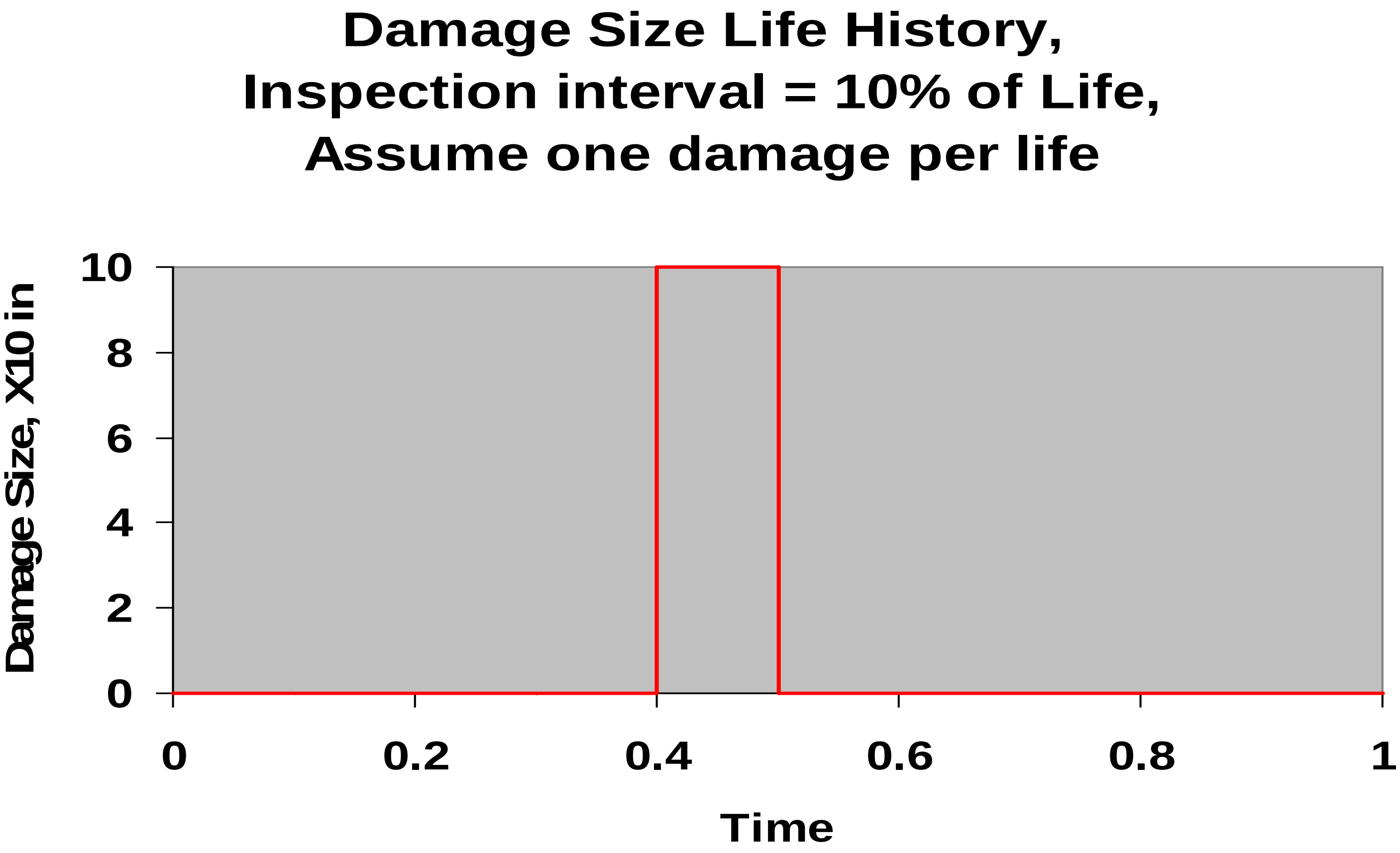


$$P_f = 1 - \prod_{i=1}^{N=3} [1 - P_f(R_i, t_i)]$$

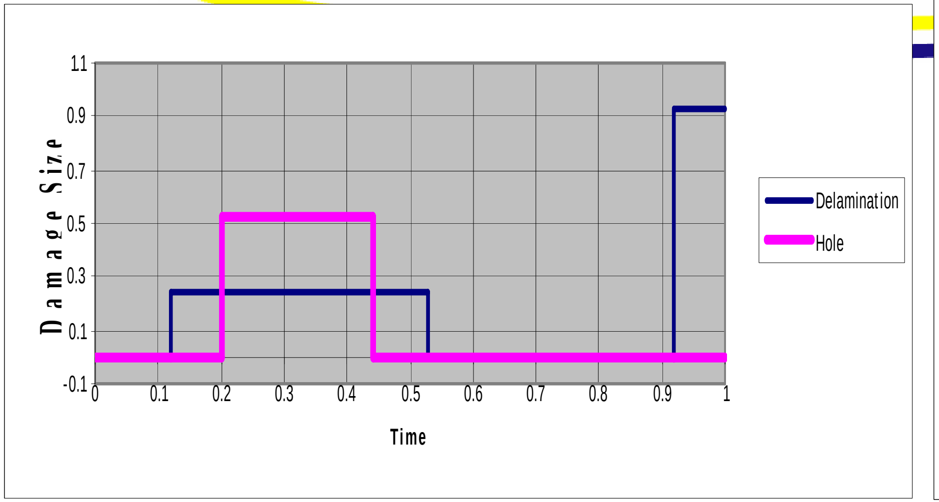
$$P_f(R,t) = 1 - \exp\{-H_t(R)t\}$$

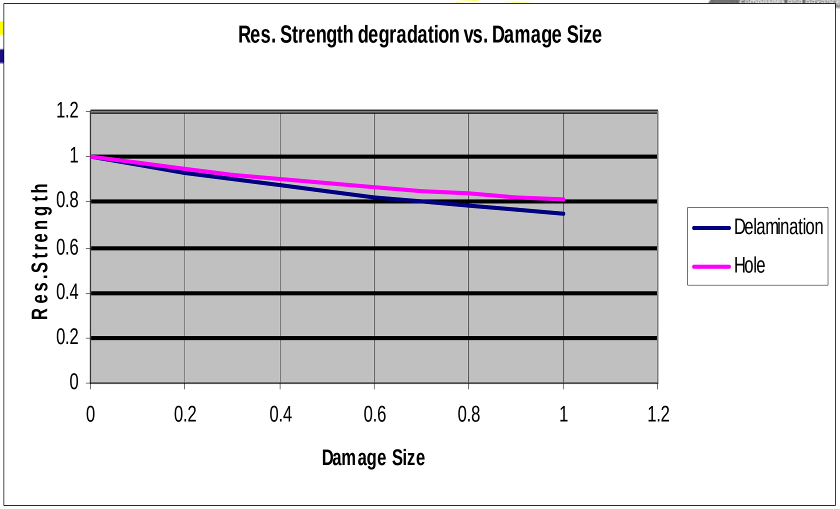
Interval #	**Probability of Failure**
1 (new structure); R=1.5	**6.12E-06**
2 (damaged structure); R=1.1	**4.26E-02**
3 (repaired structure)); R=1.5	**6.12E-06**
Total POF =	**4.26E-02**

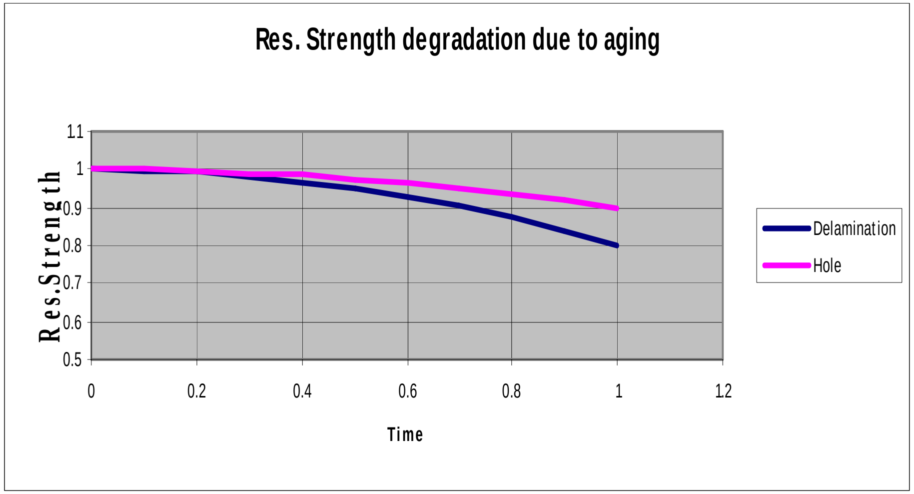
Damage Size History Simulation

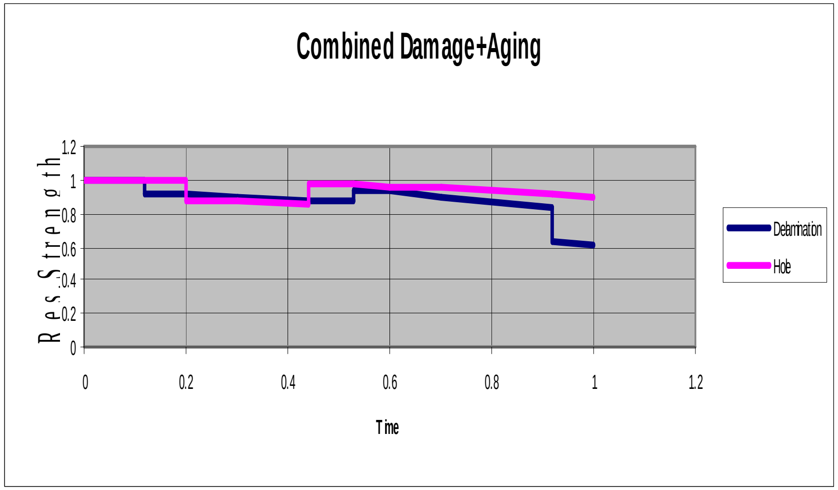


Residual Strength History Simulation

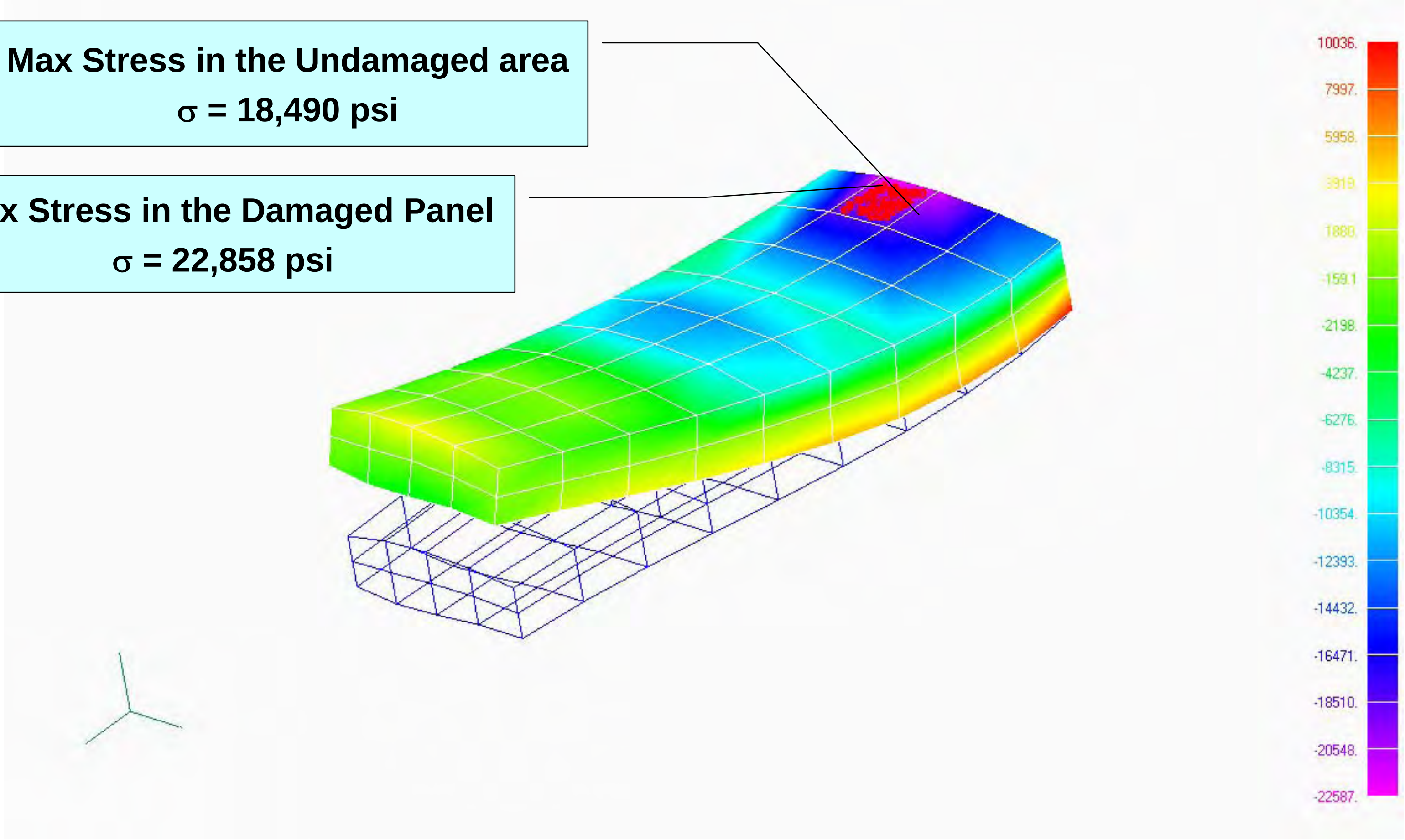



Res. Strength degradation vs. Damage Size


Res. Strength degradation due to aging


Combined Damage+Aging

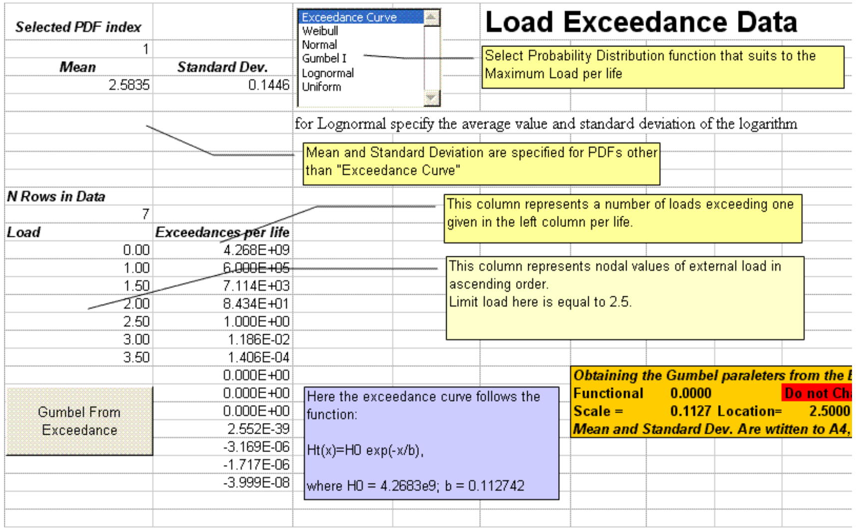
Residual Strength Analysis of a Simple Wing Box



Max Stress in the Undamaged area
σ = 18,490 psi

Max Stress in the Damaged Panel
σ = 22,858 psi

Input Data Management



Load Exceedance Data

Selected PDF index

1

Mean	**Standard Dev.**
2.5835	0.1446

Select Probability Distribution function that suits to the Maximum Load per life

for Lognormal specify the average value and standard deviation of the logarithm

Mean and Standard Deviation are specified for PDFs other than "Exceedance Curve"

N Rows in Data

7

Load	**Exceedances per life**
0.00	4.268E+09
1.00	6.000E+05
1.50	7.114E+03
2.00	8.434E+01
2.50	1.000E+00
3.00	1.186E-02
3.50	1.406E-04
	0.000E+00
	0.000E+00
	0.000E+00
	2.552E-39
	-3.169E-06
	-1.717E-06
	-3.999E-08

This column represents a number of loads exceeding one given in the left column per life.

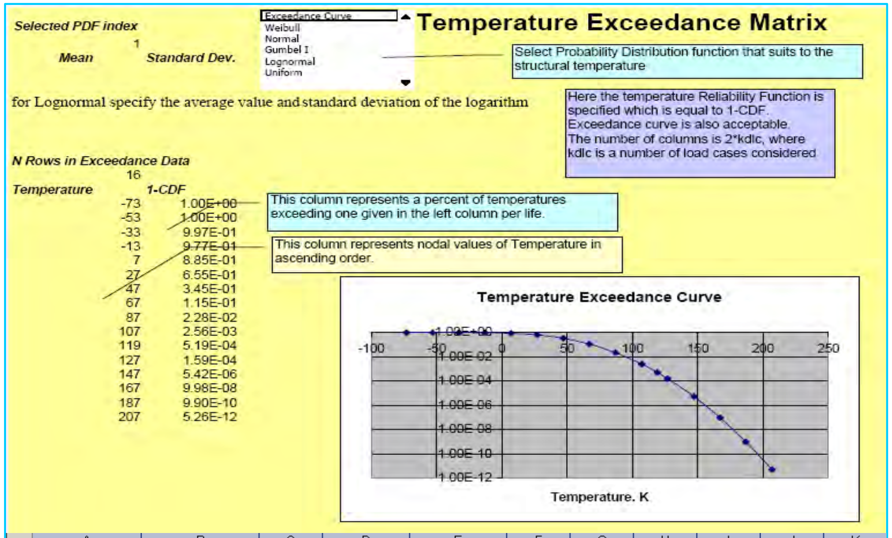
This column represents nodal values of external load in ascending order.
Limit load here is equal to 2.5.

Here the exceedance curve follows the function:

Ht(x)=H0 exp(-x/b),

where H0 = 4.2683e9; b = 0.112742

Obtaining the Gumbel paraleters from the E
Functional **0.0000** **Do not Ch**
Scale = **0.1127** **Location=** **2.5000**
Mean and Standard Dev. Are wtitten to A4,



Temperature Exceedance Matrix

Selected PDF index

1

Mean ***Standard Dev.***

Select Probability Distribution function that suits to the structural temperature

for Lognormal specify the average value and standard deviation of the logarithm

Here the temperature Reliability Function is specified which is equal to 1-CDF.
Exceedance curve is also acceptable.
The number of columns is 2*kdlc, where kdlc is a number of load cases considered

N Rows in Exceedance Data

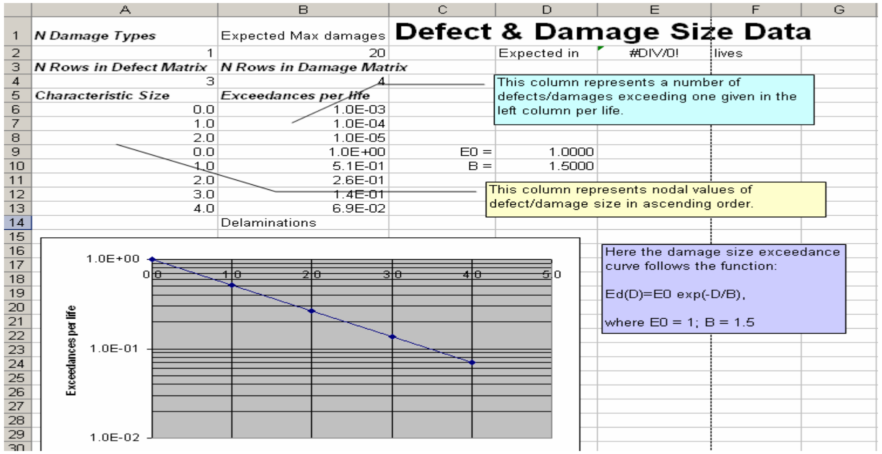
16

Temperature	***1-CDF***
-73	1.00E+00
-53	1.00E+00
-33	9.97E-01
-13	9.77E-01
7	8.85E-01
27	6.55E-01
47	3.45E-01
67	1.15E-01
87	2.28E-02
107	2.56E-03
119	5.19E-04
127	1.59E-04
147	5.42E-06
167	9.98E-08
187	9.90E-10
207	5.26E-12

This column represents a percent of temperatures exceeding one given in the left column per life.

This column represents nodal values of Temperature in ascending order.

Temperature Exceedance Curve



Defect & Damage Size Data

	A	B	C	D	E	F
1	***N Damage Types***	Expected Max damages				
2	1	20		Expected in	#DIV/0!	lives
3	***N Rows in Defect Matrix***	***N Rows in Damage Matrix***				
4	3	4				
5	***Characteristic Size***	***Exceedances per life***				
6	0.0	1.0E-03				
7	1.0	1.0E-04				
8	2.0	1.0E-05				
9	0.0	1.0E+00	E0 =	1.0000		
10	1.0	5.1E-01	B =	1.5000		
11	2.0	2.6E-01				
12	3.0	1.4E-01				
13	4.0	6.9E-02				
14		Delaminations				

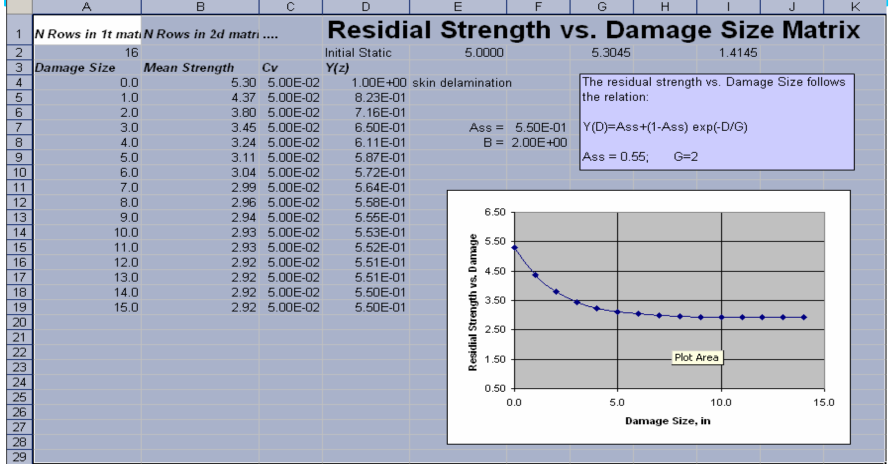
This column represents a number of defects/damages exceeding one given in the left column per life.

This column represents nodal values of defect/damage size in ascending order.

Here the damage size exceedance curve follows the function:

Ed(D)=E0 exp(-D/B),

where E0 = 1; B = 1.5



Residial Strength vs. Damage Size Matrix

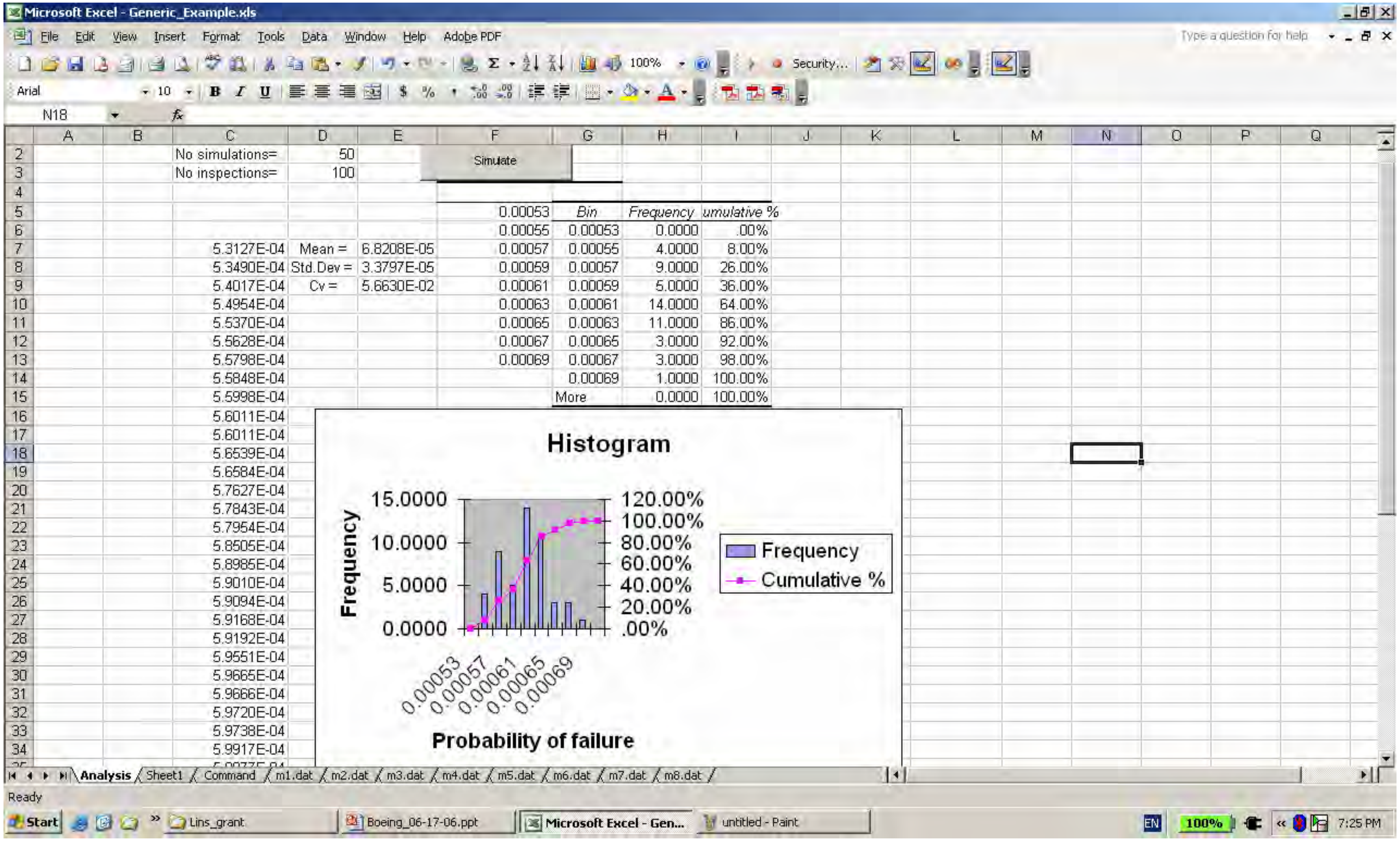
	A	B	C	D	E	F	G	H	I
1	***N Rows in 1t mat***	***N Rows in 2d matr***	....						
2	16			Initial Static	5.0000		5.3045		1.4145
3	***Damage Size***	***Mean Strength***	***Cv***	***Y(z)***					
4	0.0	5.30	5.00E-02	1.00E+00	skin delamination				
5	1.0	4.37	5.00E-02	8.23E-01					
6	2.0	3.80	5.00E-02	7.16E-01					
7	3.0	3.45	5.00E-02	6.50E-01	Ass =	5.50E-01			
8	4.0	3.24	5.00E-02	6.11E-01	B =	2.00E+00			
9	5.0	3.11	5.00E-02	5.87E-01					
10	6.0	3.04	5.00E-02	5.72E-01					
11	7.0	2.99	5.00E-02	5.64E-01					
12	8.0	2.96	5.00E-02	5.58E-01					
13	9.0	2.94	5.00E-02	5.55E-01					
14	10.0	2.93	5.00E-02	5.53E-01					
15	11.0	2.93	5.00E-02	5.52E-01					
16	12.0	2.92	5.00E-02	5.51E-01					
17	13.0	2.92	5.00E-02	5.51E-01					
18	14.0	2.92	5.00E-02	5.50E-01					
19	15.0	2.92	5.00E-02	5.50E-01					

The residual strength vs. Damage Size follows the relation:

Y(D)=Ass+(1-Ass) exp(-D/G)

Ass = 0.55; G=2

Results on POF

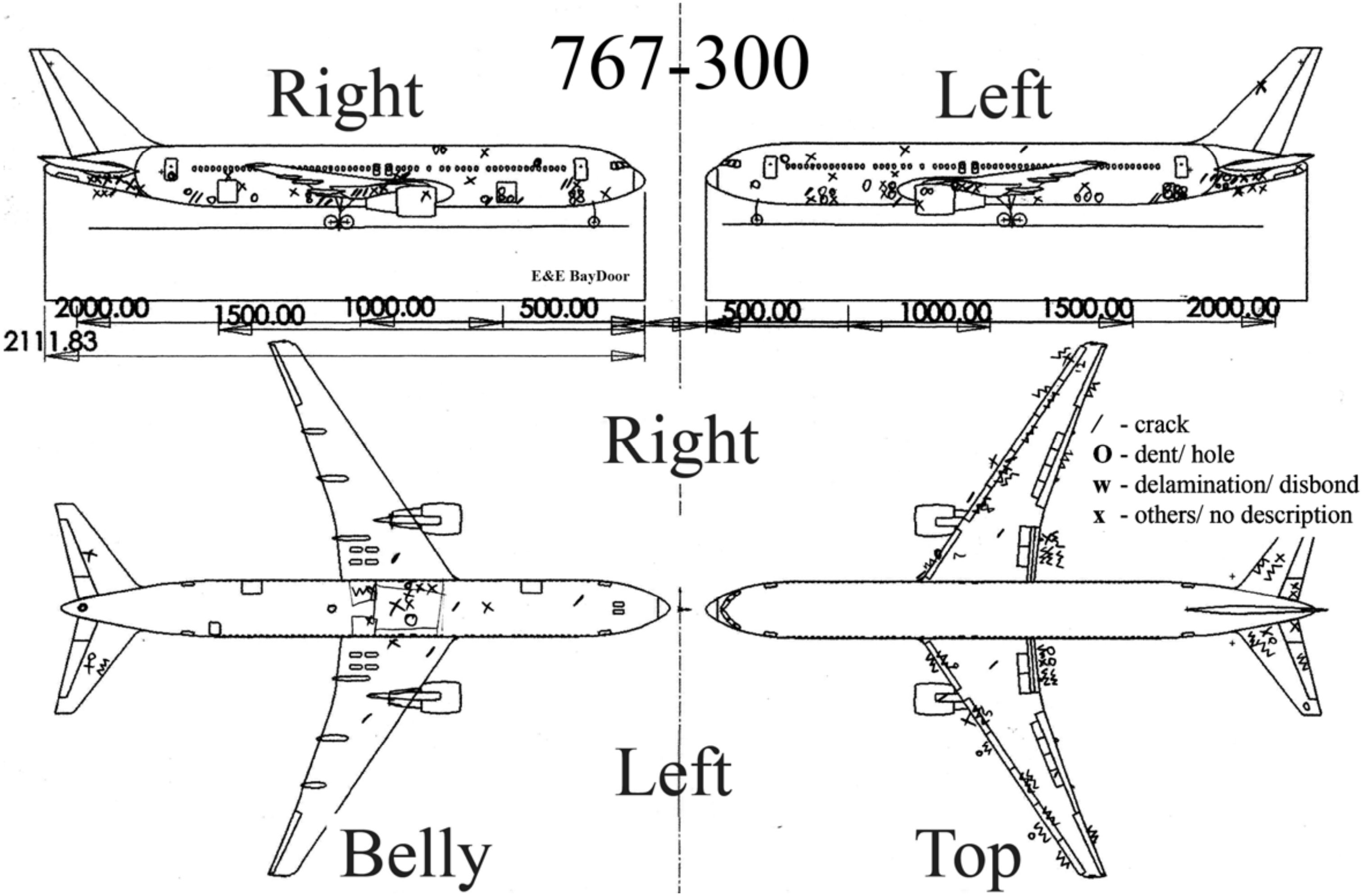


	A	B	C	D	E	F	G	H	I
2			No simulations=	50					
3			No inspections=	100					
4									
5						0.00053	*Bin*	*Frequency*	*umulative %*
6						0.00055	0.00053	0.0000	.00%
7			5.3127E-04	Mean =	6.8208E-05	0.00057	0.00055	4.0000	8.00%
8			5.3490E-04	Std.Dev =	3.3797E-05	0.00059	0.00057	9.0000	26.00%
9			5.4017E-04	Cv =	5.6630E-02	0.00061	0.00059	5.0000	36.00%
10			5.4954E-04			0.00063	0.00061	14.0000	64.00%
11			5.5370E-04			0.00065	0.00063	11.0000	86.00%
12			5.5628E-04			0.00067	0.00065	3.0000	92.00%
13			5.5798E-04			0.00069	0.00067	3.0000	98.00%
14			5.5848E-04				0.00069	1.0000	100.00%
15			5.5998E-04				More	0.0000	100.00%
16			5.6011E-04						
17			5.6011E-04						
18			5.6539E-04						
19			5.6584E-04						
20			5.7627E-04						
21			5.7843E-04						
22			5.7954E-04						
23			5.8505E-04						
24			5.8985E-04						
25			5.9010E-04						
26			5.9094E-04						
27			5.9168E-04						
28			5.9192E-04						
29			5.9551E-04						
30			5.9665E-04						
31			5.9666E-04						
32			5.9720E-04						
33			5.9738E-04						
34			5.9917E-04						

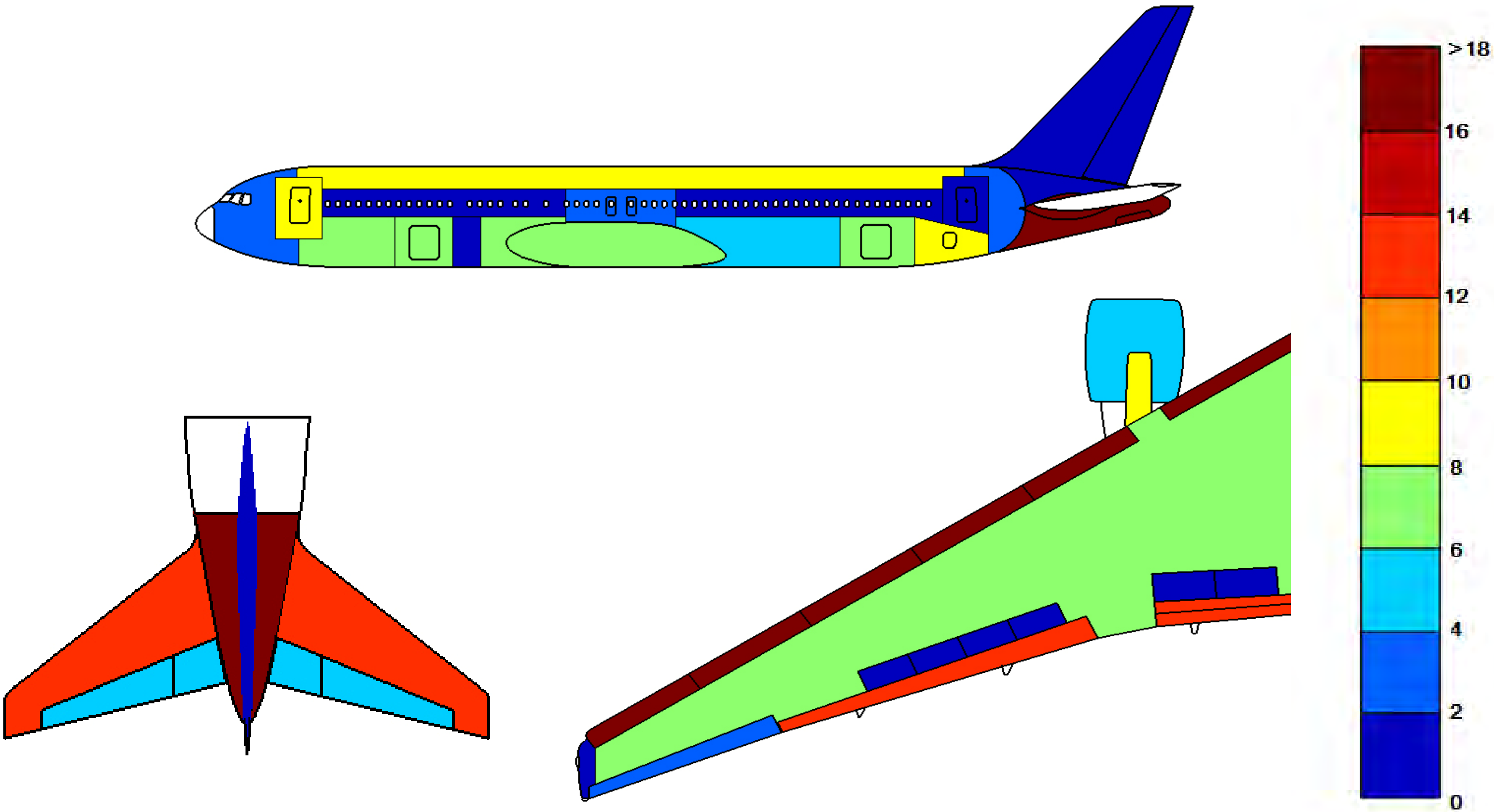
Service Difficulty Report (SDR)

- The Service Difficulty Report (SDR) is a database that contains damage reports almost exclusively from line and base maintenance in the U.S.
- A typical SDR is like a mechanics report on an inspection/ maintenance task, details including aircraft type and registration, damage type, damage location, sometimes a brief description of the damage itself
- SDRs containing external skin damage may be used to help determining the frequency and severity of impact damage occurrence in different part of the aircraft
- The SDRs for Boeing 767 from year 01/2002 to 03/2006 have been compiled as examples shown in the next couple pages

SDR: External Damage Map



SDR: External Damage Map



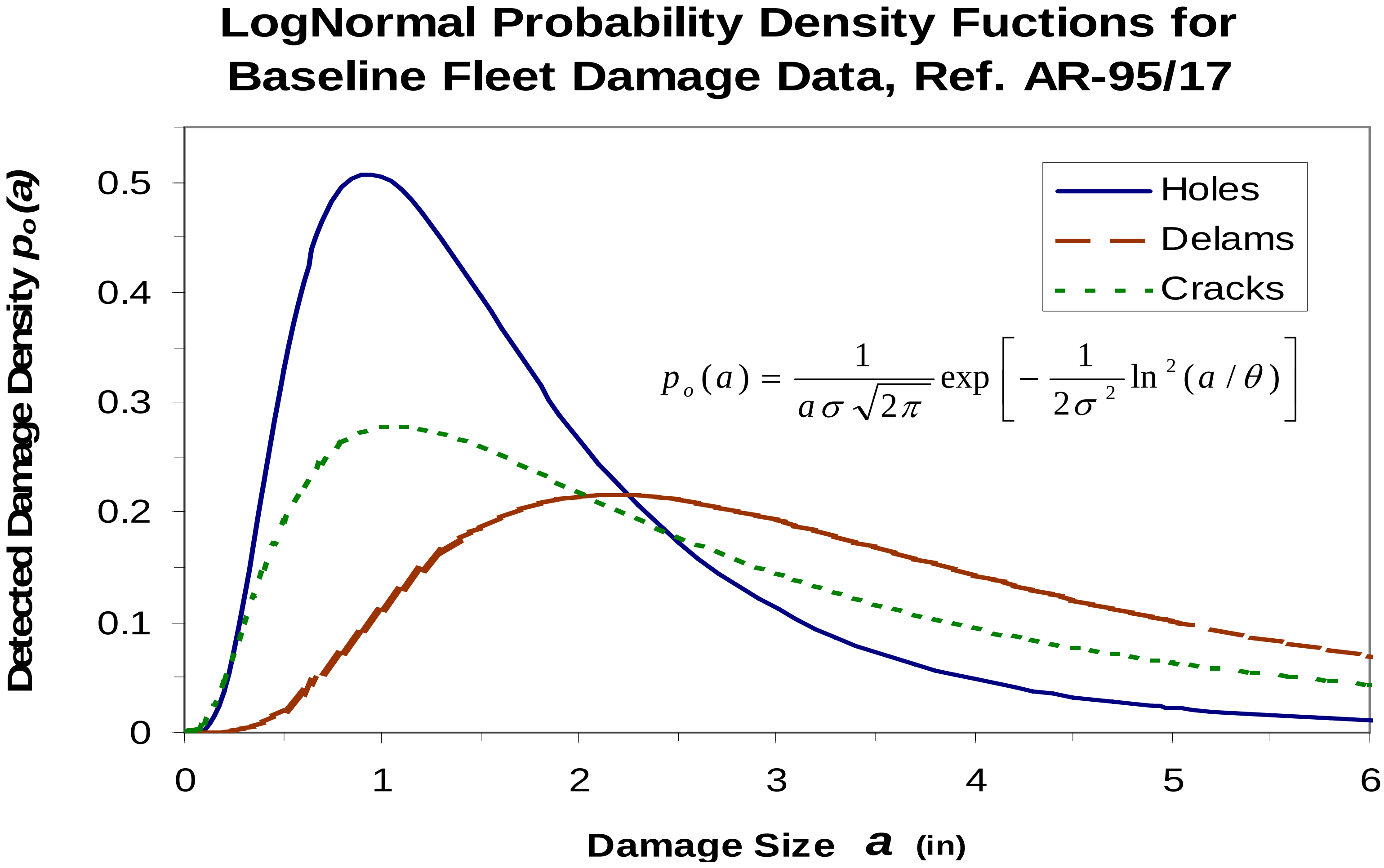
SDR Summary

- Aluminum-Honeycomb sandwich delamination is a reoccurring problem – slats, flaps and stabilizers on 767s shows large number of delamination occurrences
- Nearly all dents, holes and gouges are on the lower fuselage and are caused by ground activities, e.g. trucks and operation staff
- Majority of the damages on the upper fuselage are caused by lightning strikes
- Large number of cracks and fatigue damages occurred near the horizontal stabilizer cutout region
- Although the wings have very large areas, relatively few major damages are recorded

SDR Data Source Limitations

- Scarce description of the source of damage, thus hard to evaluate the effect of the same impact event to a composite structure, i.e. what kind of damage will result in cracks, delamination or even no damage at all?
- Composite vs. metal – a drunk catering truck driver causing a dent in the metal fuselage, may now causes a crack (or other forms of damage)
- Since reports are generated during line and base maintenances, the time of event is mostly lost, thus it is hard to know if damage occurred in-flight or on ground, and under what kind of loads
- No information about repair quality, which could greatly affects the residual strength and modulus of the composite structures

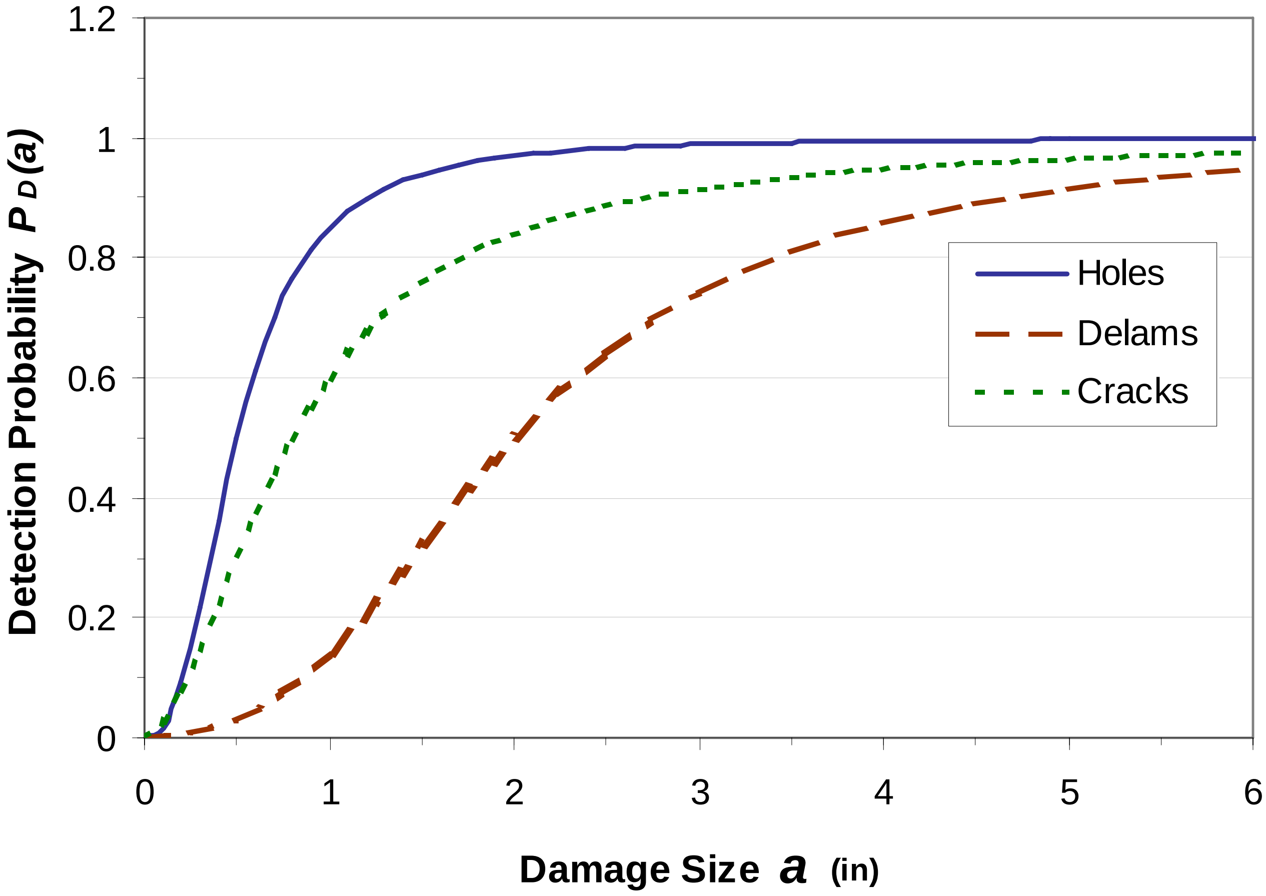
PDF of Detected Damages



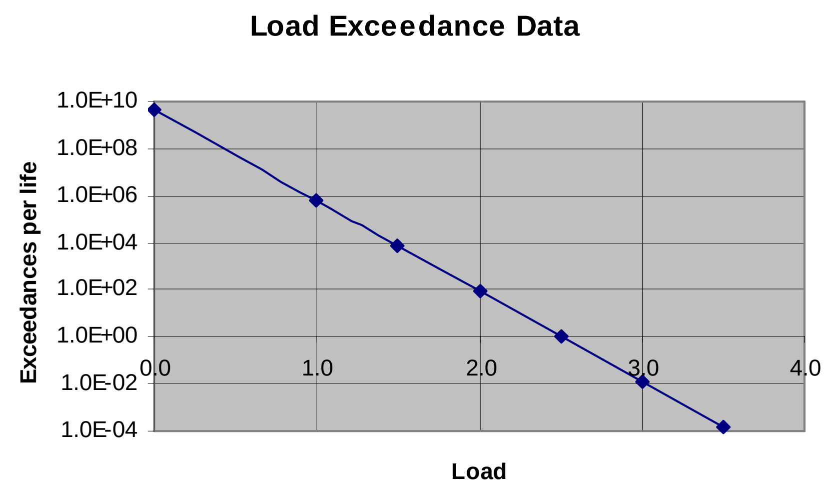
$$p_o(a) = \frac{1}{a\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2\sigma^2}\ln^2(a/\theta)\right]$$

Probability of Detection

Log-Odds Detection Probability Functions



Sample Problem 1: Input Data

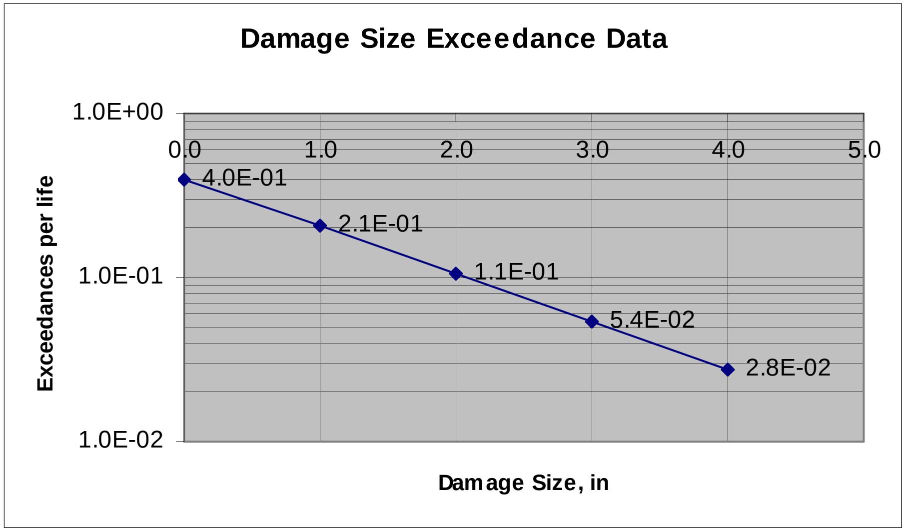


$$H_t(x) = H_0 \exp(-\frac{x}{b});$$

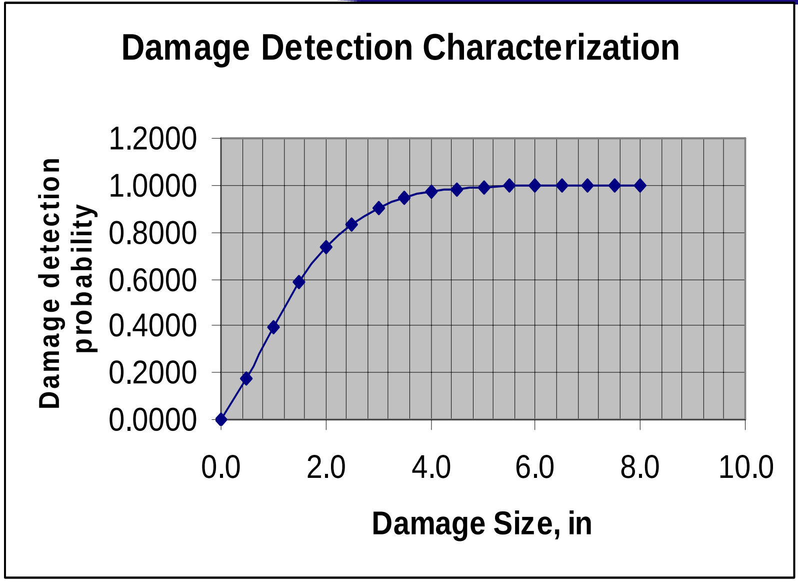
$$H_0 = 4.268e9; \quad b = 0.1127$$

$$E_t(D) = E_0 \exp(-\frac{D}{B});$$

$$E_0 = 0.4; \quad B = 1.5$$



Sample Problem 1: Input Data

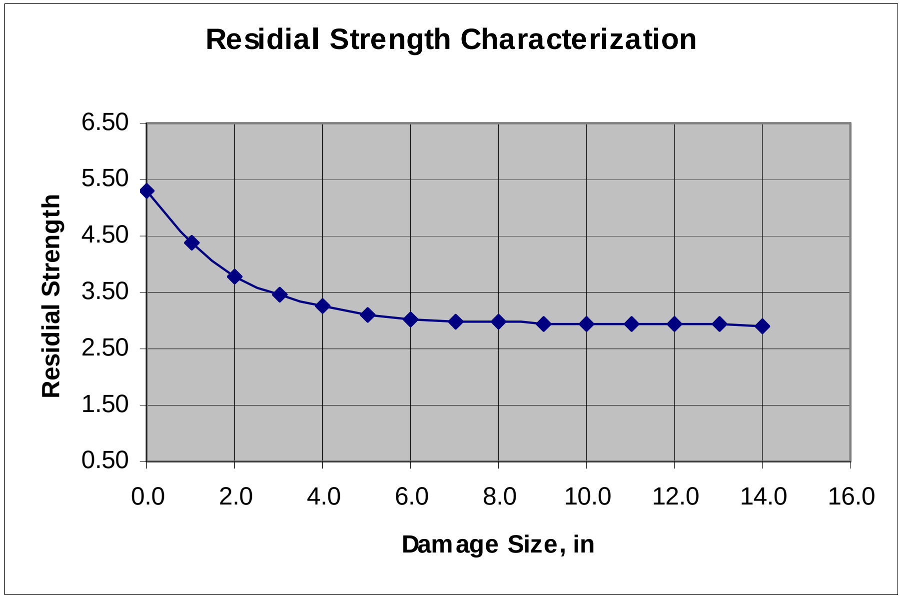


$$P_D(D) = 1 - \exp\left(-\frac{D}{\beta}\right)^{\alpha};$$

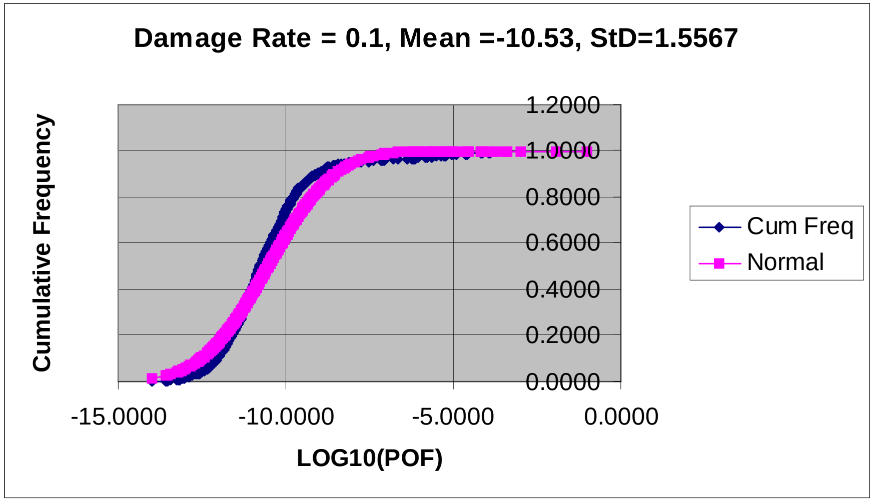
$$\beta = 2.0; \ \alpha = 1.4$$

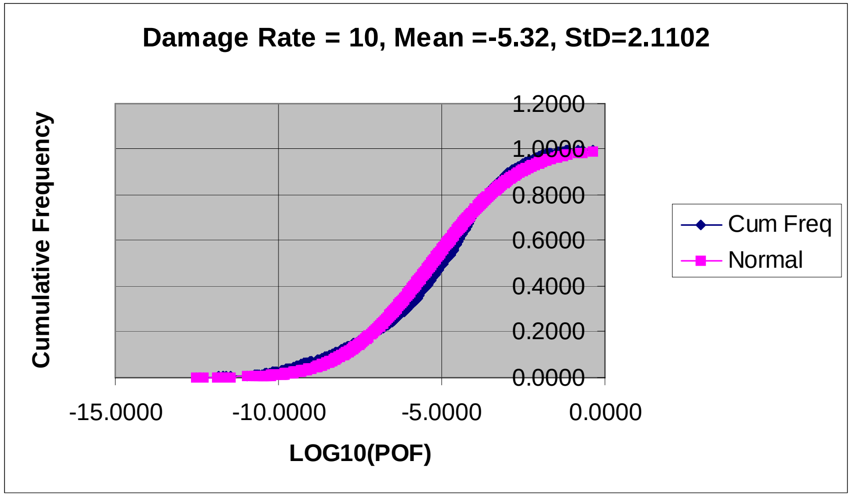
$$Y(D) = A + (1 - A)\exp(-\frac{D}{G});$$

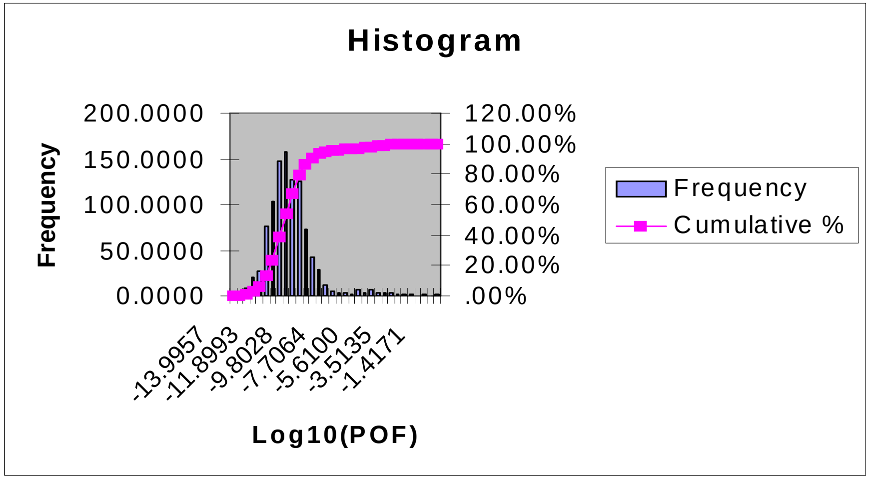
$$A = 0.55; \quad G = 2.0$$

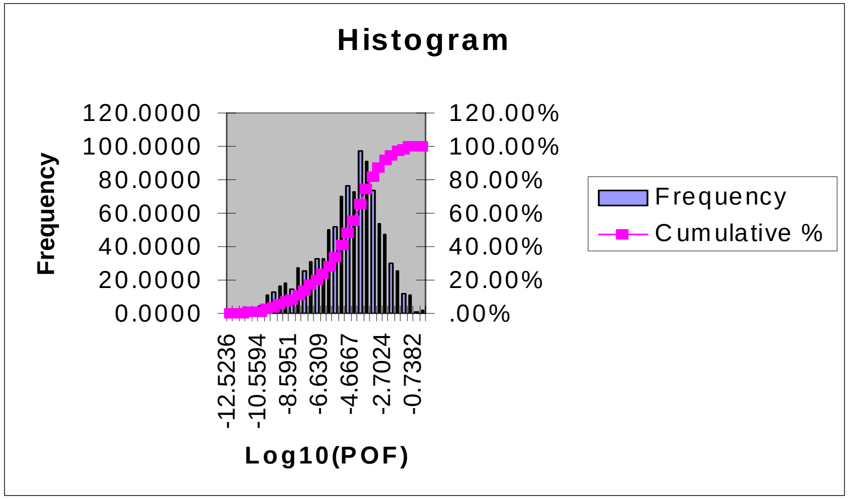


Sample Problem 1: Output on POF


Damage Rate = 0.1, Mean =-10.53, StD=1.5567


Damage Rate = 10, Mean =-5.32, StD=2.1102


Histogram


Histogram

Probabilistic Sensitivities: Classical S-R model

Probability of Failure: Classical S-R model: $POF = P(s > r) = 1 - P(s < r)$

$$P_f = \int_0^\infty f_s(x)F_r(x)dx = 1 - \int_0^\infty f_r(x)F_s(x)dx$$

Sensitivity Coefficients: $C_\mu = (\partial P_f / \partial \mu)(\sigma / P) \quad C_\sigma = (\partial P_f / \partial \sigma)(\sigma / P)$

Stress: Normal; Resistance: Weibull

$$\mu_s = 1; \quad \sigma_s = 0.08; \quad \mu_R = 1.5; \quad \sigma_R = 0.12;$$

$$C_{\mu s} = 1.134; \quad C_{\sigma s} = 1.206; \quad C_{\mu R} = -1.628; \quad C_{\sigma R} = 4.448$$

Stress: Extreme Value I; Resistance: Weibull

$$\mu_s = 1; \quad \sigma_s = 0.08; \quad \mu_R = 1.5; \quad \sigma_R = 0.12;$$

$$C_{\mu s} = 1.025; \quad C_{\sigma s} = 1.617; \quad C_{\mu R} = -1.509; \quad C_{\sigma R} = 4.072$$

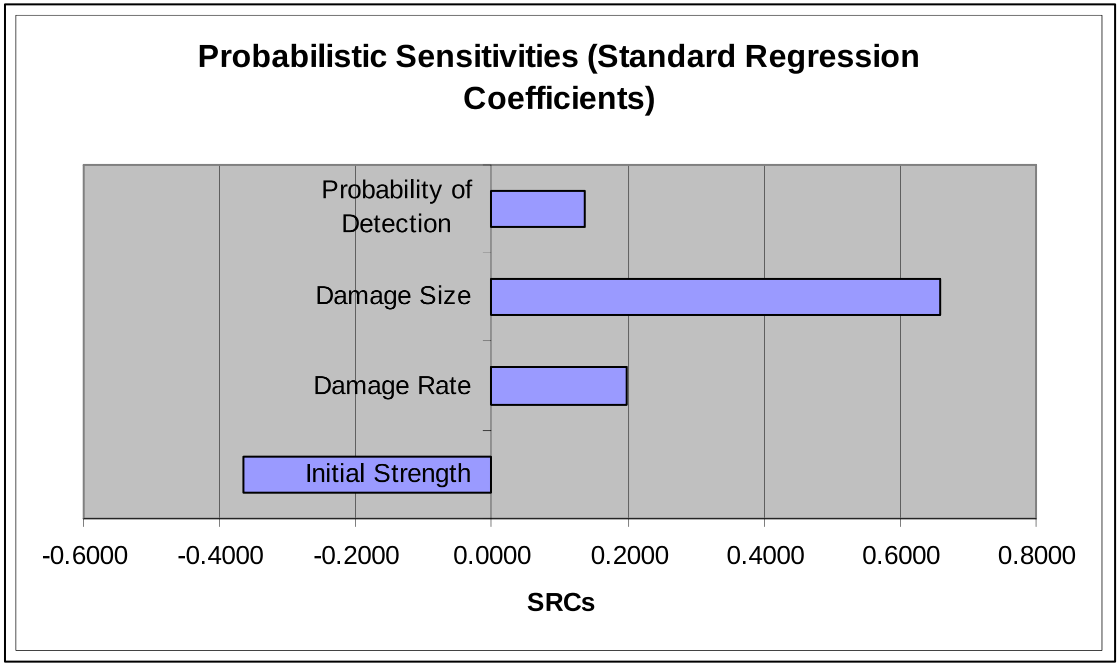
Sample Problem 1: Probabilistic Sensitivities

Sensitivity coefficients for load

$$C_\mu = (\partial P_f / \partial \mu)(\sigma / P) \approx \frac{1}{N} \sum_{j=1}^{N} \sum_{i=1}^{N_j} \frac{(td_i^j - t_i^j)}{Life} (\partial F_L / \partial \mu)^{\frac{(td_i^j - t_i^j)}{Life} - 1};$$

$$C_\sigma = (\partial P_f / \partial \sigma)(\sigma / P) \approx \frac{1}{N} \sum_{j=1}^{N} \sum_{i=1}^{N_j} \frac{(td_i^j - t_i^j)}{Life} (\partial F_L / \partial \sigma)^{\frac{(td_i^j - t_i^j)}{Life} - 1}$$

Sample Problem: Sensitivity coefficients (disturbance method)



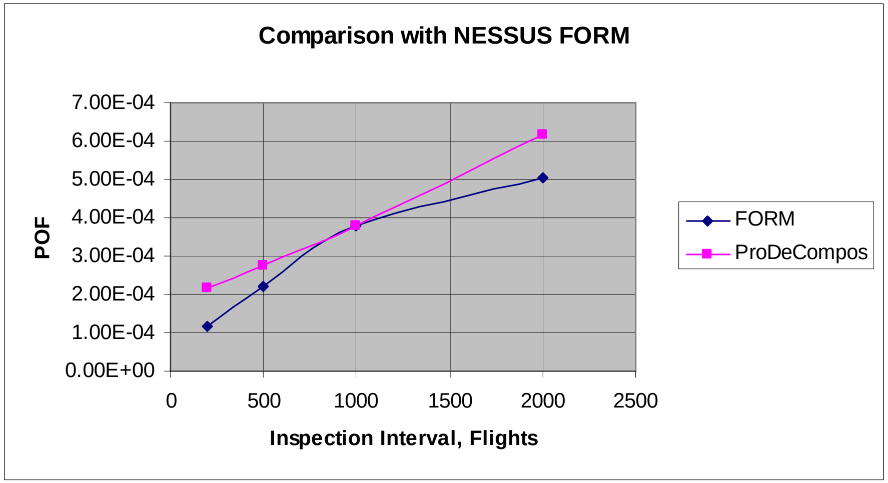
Sample Problem 1: Comparison With NESSUS

NESSUS Model feature: Exactly one damage per life

Random variables:

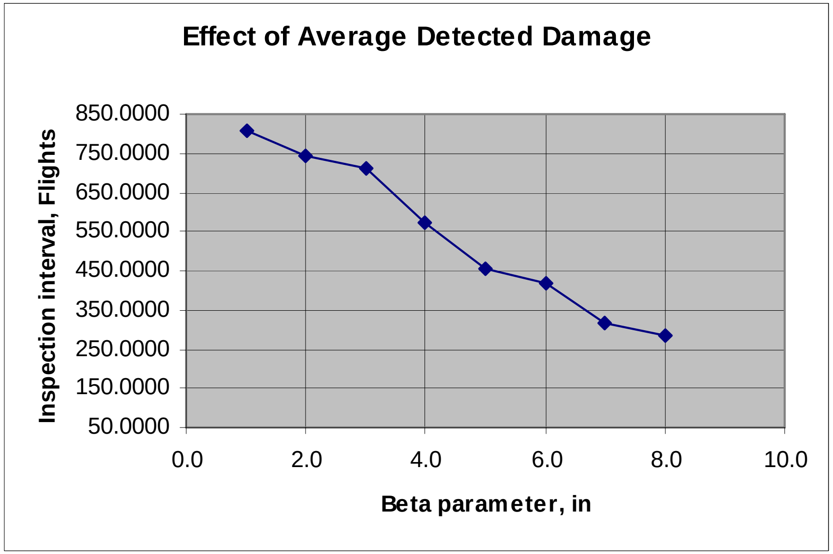
1. **Load Lmax, LmaxD, LmaxR for undamaged, damaged and repaired item; Gumbel distribution**
2. **Initial Strength Rini; Normal distribution**
3. **Damage size D; Exponential distribution;**
4. **Random inspection Interval Cv=10%**

Satisfactory comparison with NESSUS



Sample Problem 1: Parametric Study

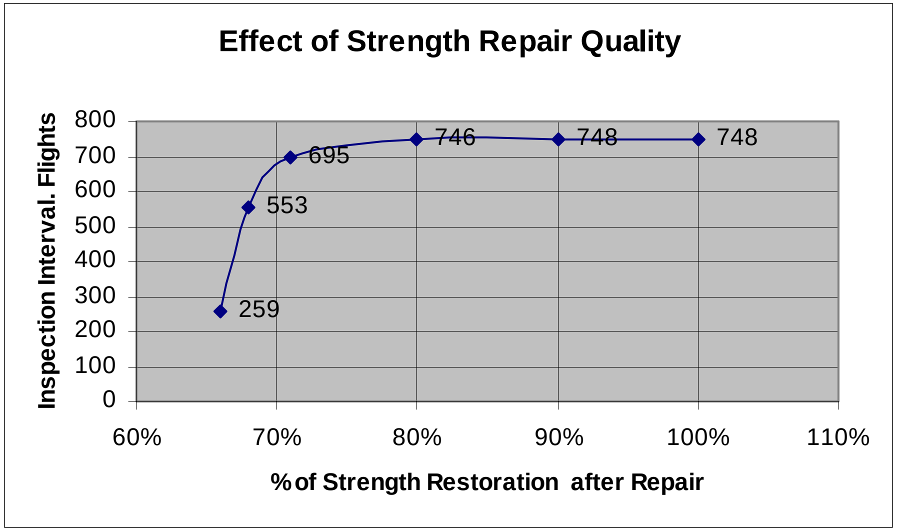
Inspection Interval determined corresponds to Probability of Failure = 1e-4 per life



$$P_D(D) = 1 - \exp\left(-\frac{D}{\beta}\right)^{\alpha};$$

$$\alpha = 1.4; \quad \beta = Variable$$

Variable Strength Recovery Percent

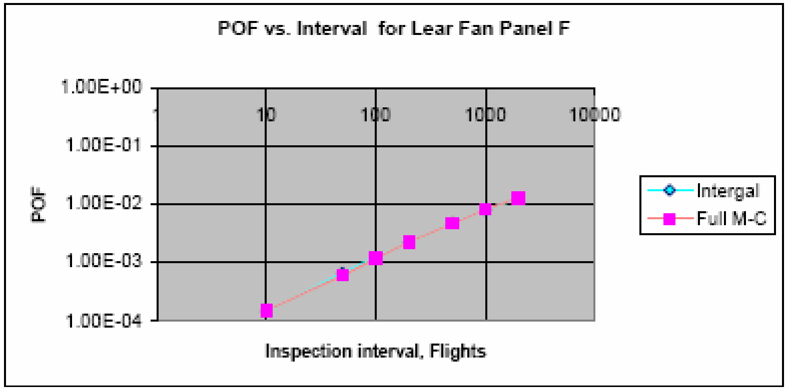


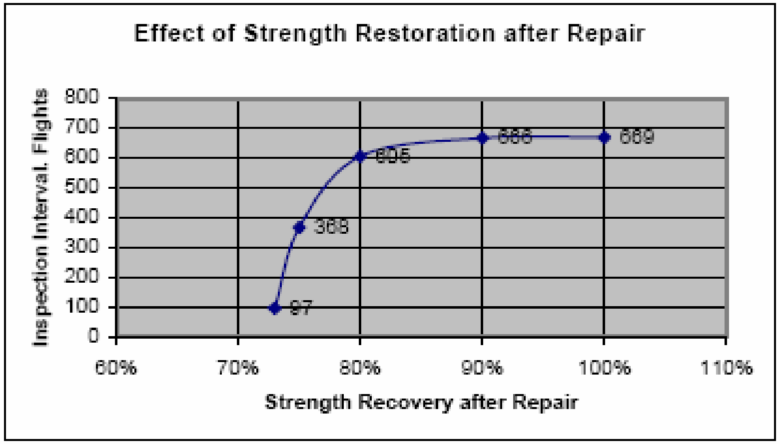
Sample Problem 2:
Lear Fan 2100 Composite Wing Panels

- **Structural Component:** Lear Fan 2100 composite wing panels
- **Source of Data:** Report DOT/FAA/AR-01/55, Washington DC, January 2002
- **Output:** Inspection schedule over the life-cycle of a structure for maximum safety

Features:

- Two Damage Types: Delamination and Hole/Crack
- Two Inspection Types: Post Flight and Regular Maintenance
- Two Repair Types (Field and Depot)
- Relatively Low Damage Sensitivity
- Temperature Effects Included
- Relatively Low Output Reliability



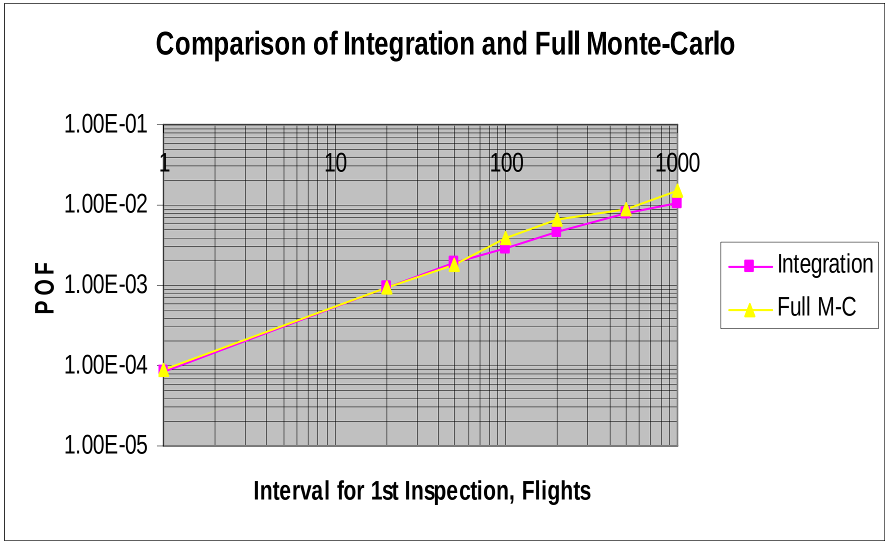


Sample Problem 3:
TU-204 Composite Aileron

- **Structural Component:** TU-204 commercial aircraft composite aileron
- **Source of Data:** Report DOT/FAA/AR-01/55, Washington DC, January 2002
- **Output:** Inspection schedule over the life-cycle of a structure for maximum safety and optimum cost

Features:

- Two Damage Types: Delamination and Hole/Crack
- Two Inspection Types: Post Flight and Regular Maintenance
- Two Repair Types (Field and Depot)
- Relatively Low Damage Sensitivity
- Temperature Effects Included
- Relatively Low Output Reliability



A Look Forward

- **Benefit to Aviation**
  - The present method allows engineers to design damage tolerant composite structures for a predetermined level of reliability, as required by FAR 25.
  - The present study makes it possible to determine the relationship among the reliability level, inspection interval, inspection method, and repair quality to minimize the maintenance cost and risk of structural failure.
- **Future needs**
  - A standardized methodology for establishing an optimal inspection schedule for aircraft manufacturers and operators.
  - Enhanced damage data reporting requirements regulated by the FAA.