

Development of Reliability-Based Damage Tolerant Structural Design Methodology

Presented

by

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Mr. Gerald Mabson, Dr. Alan Miller (All from Boeing)

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.

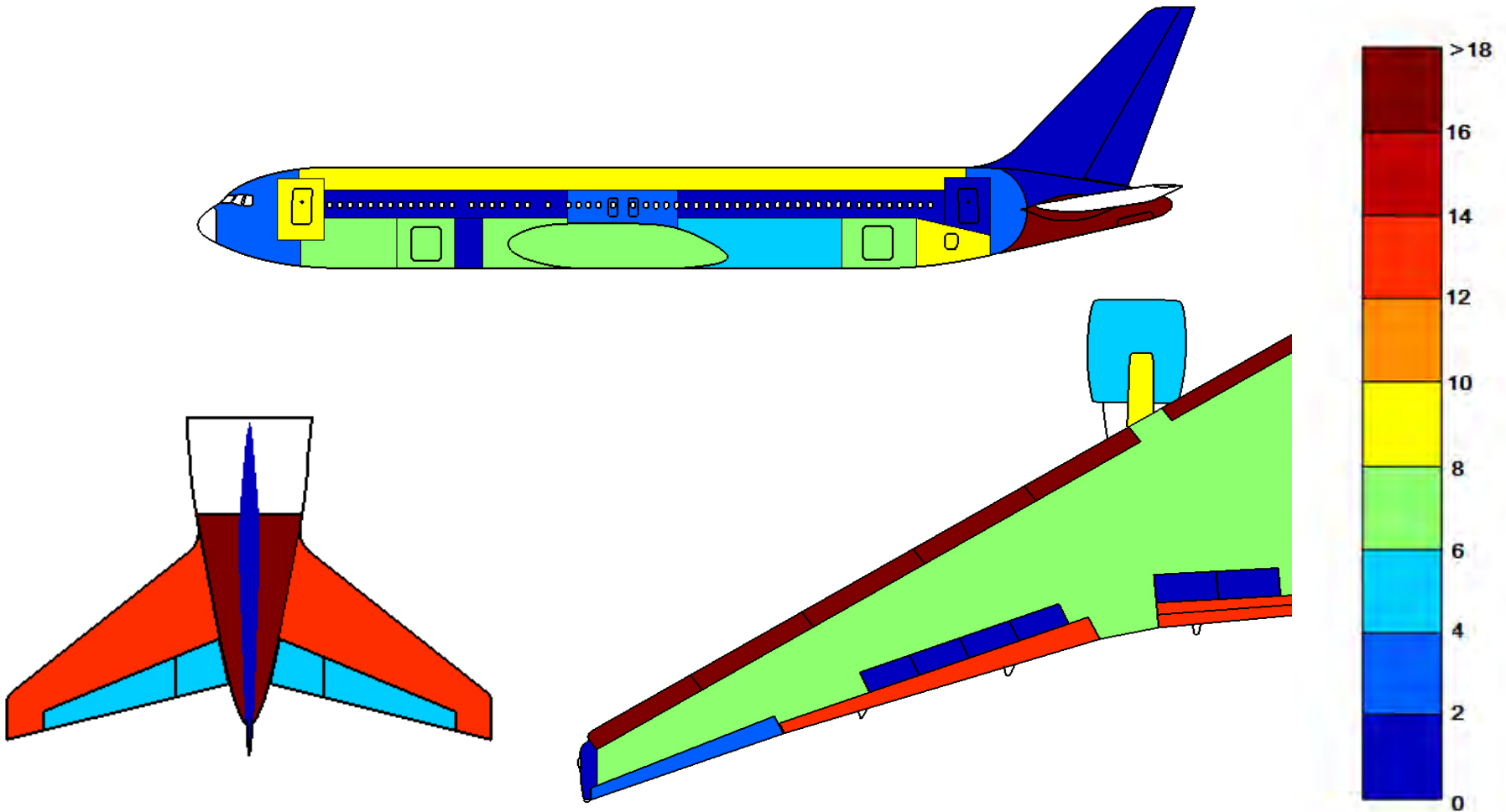
Critical Damage Types in Metals vs. Composites

	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 zero. Can be stopped.	Created instantly, then usually doesn't grow.
Predictive methods	Well developed. Combined with fatigue tests give quite good idea of fatigue life	Poor prediction due to lack of appropriate statistical data
Inspection interval	Quite certain: should be long enough to detect growing crack	Uncertain: no deterministic criteria to follow

Example of In-service Damage: Hail Damage



External Damage Map from the FAA Service Difficulty Report



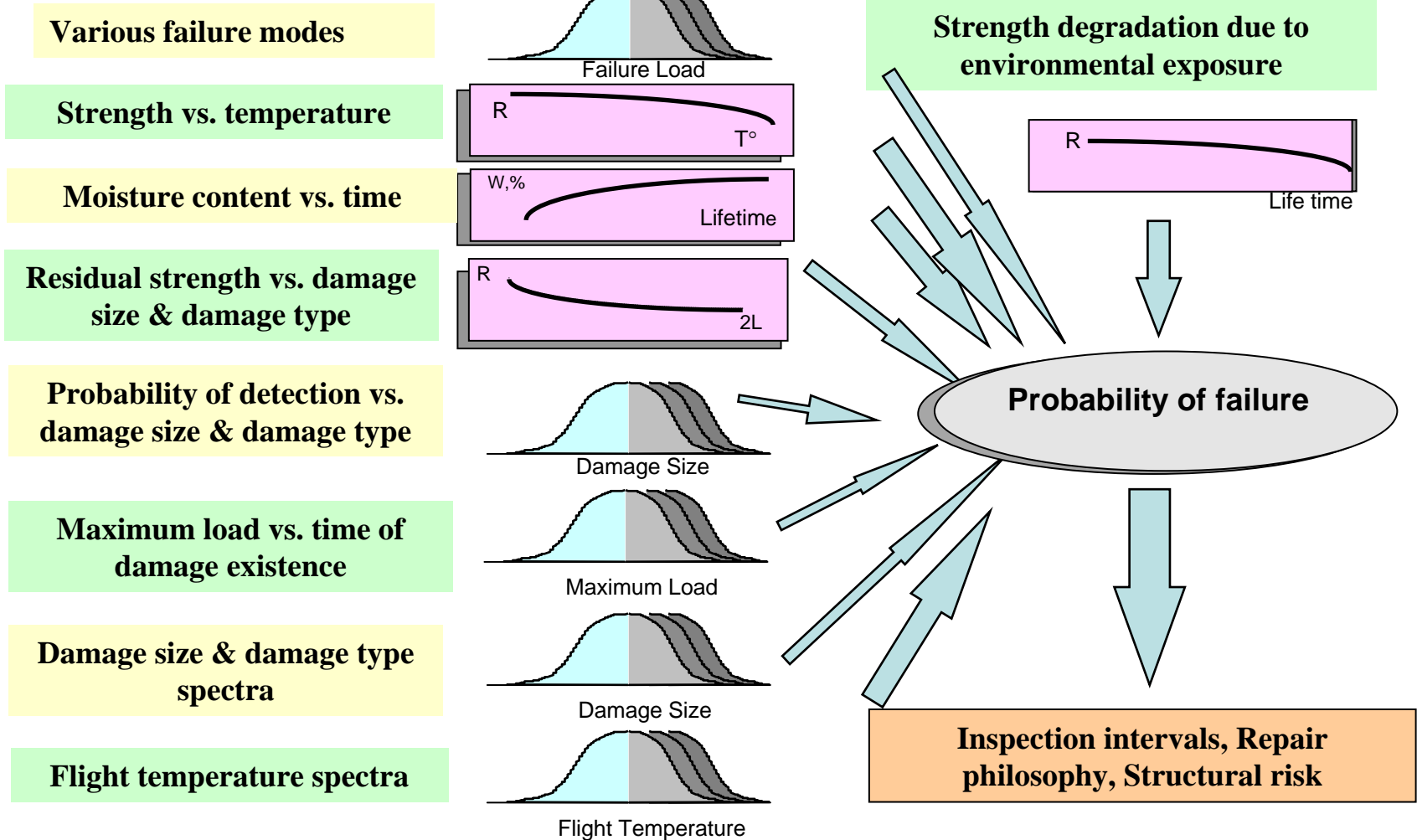
SDR Summary

- 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

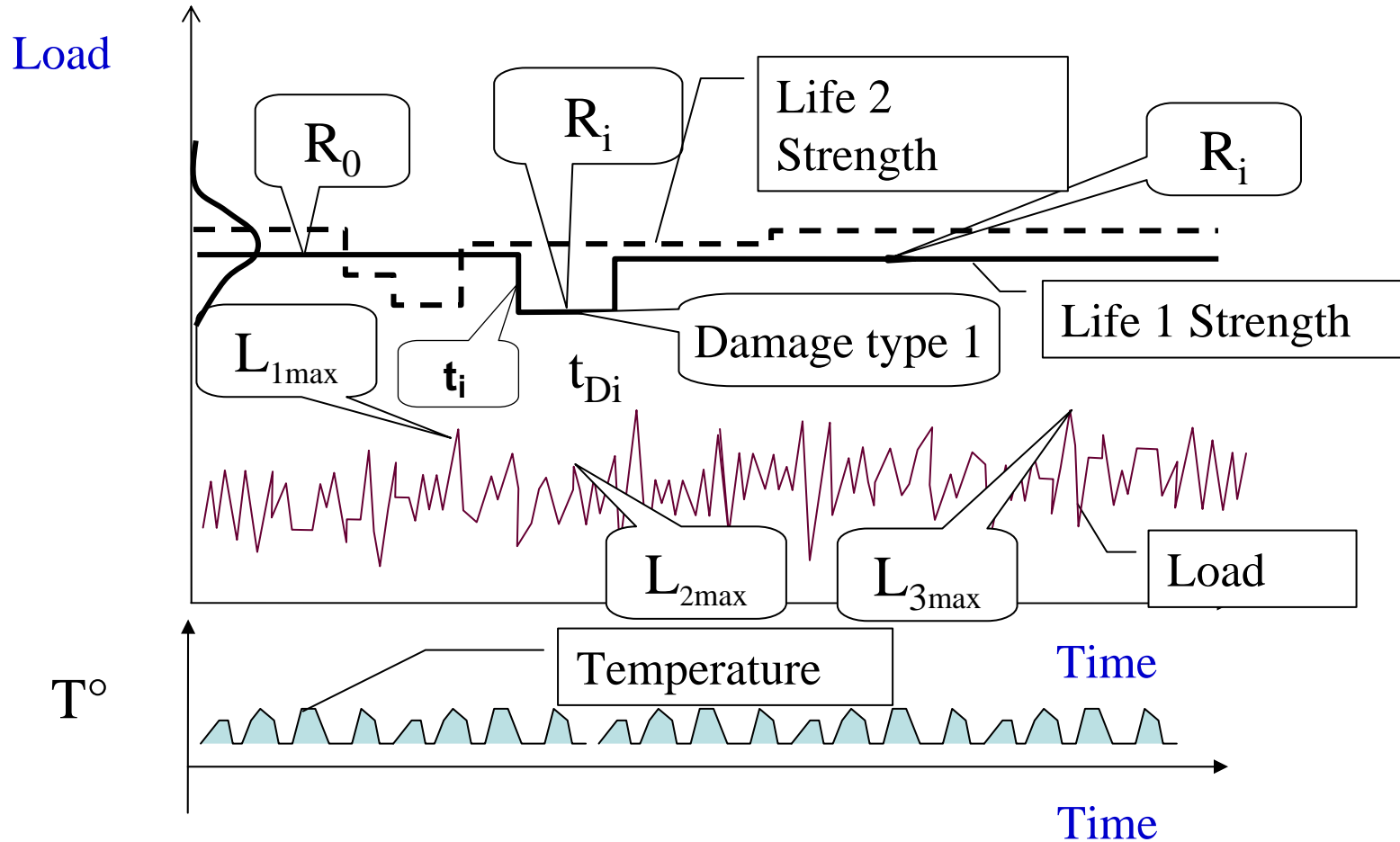
Technical Approach

- 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



Probabilistic Model



Probability of Failure Formulation

Deterministic Input Parameters:

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

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^J_i
- Structural temperature $T^{\circ J}_i$
- Effects of environmental aging and chemical corrosion

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

$$d\overset{r}{v} = dN \overset{r}{dD} \overset{r}{dR} dt d(td) \overset{r}{dL} dT^{\circ}; \quad \Omega = \text{failure domain}$$

Piecewise random history method:

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

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

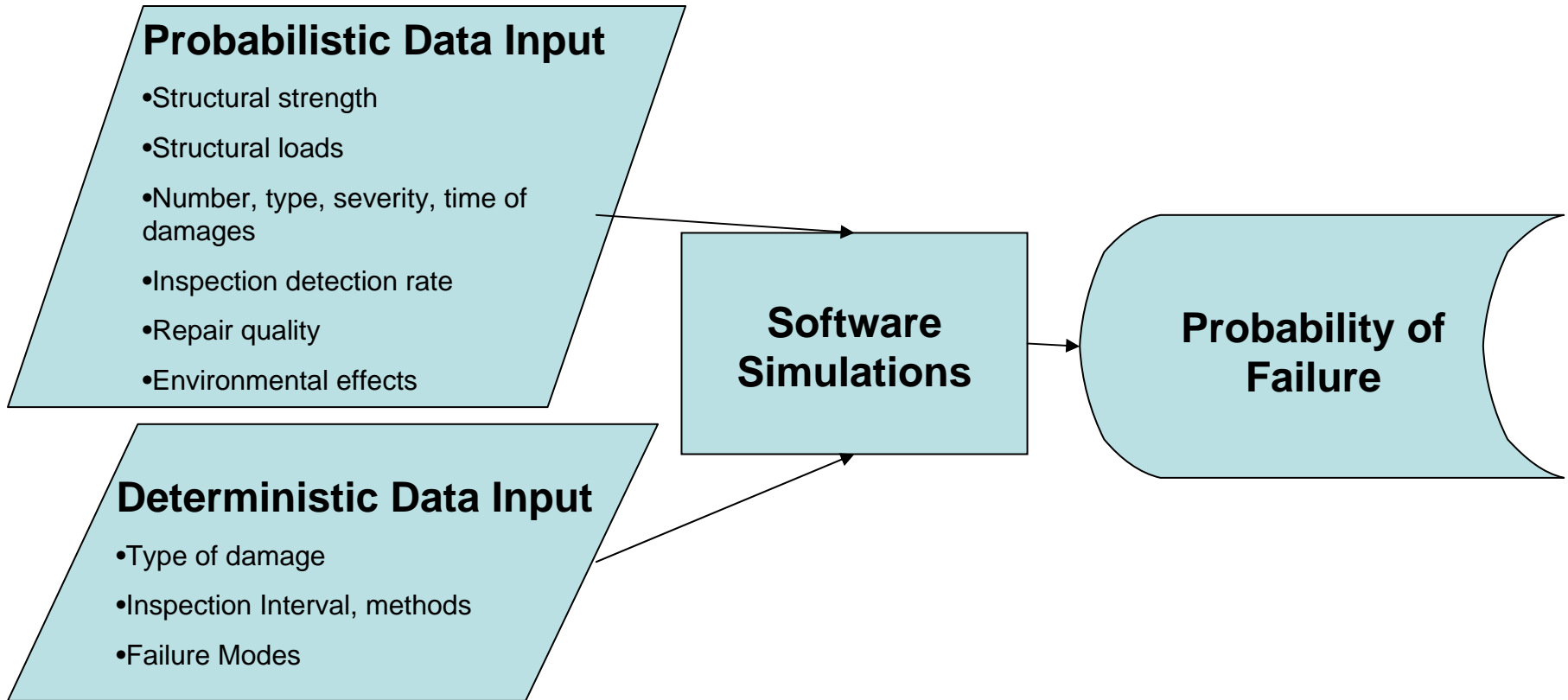
$$P_i^j = 1 - \{F_L[R_i^j(D_i^j) | \mu_L, \sigma_L]\}^{\frac{(td_i^j - t_i^j)}{Life}}; \quad F_L = \text{CPF of max load per life}$$

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

Work Accomplished

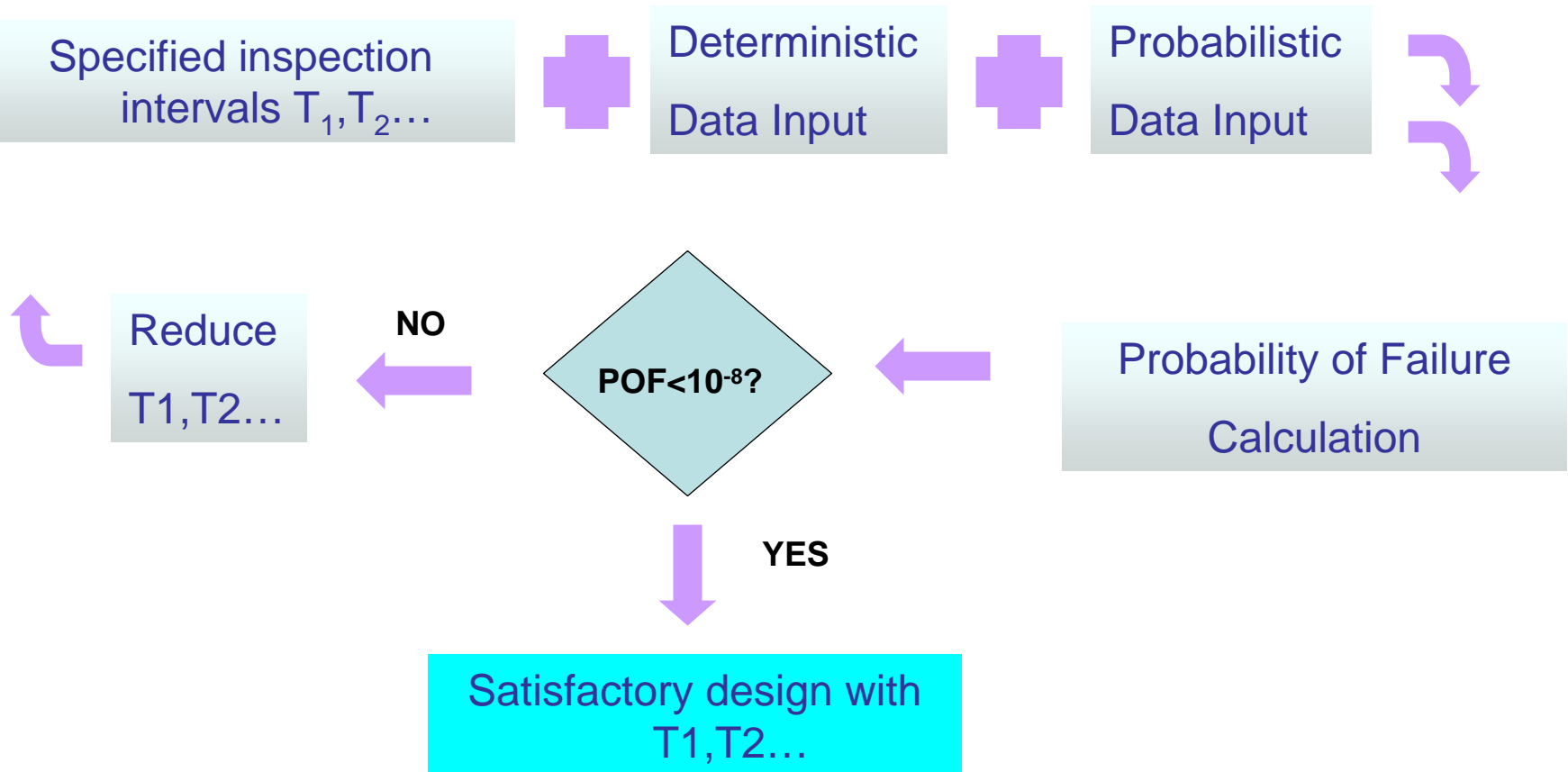
- Developed a Probabilistic Method for Determining the Probability of Failure and Inspection Interval for Aircraft Structures (from sub-structure level to airframe level)
- Implemented the Developed Probabilistic Method in the Form of Computer Software for the Probabilistic Analysis
- Demonstrated the Developed Method on Existing Structural Components (Lear Fan 2100 Composite Wing and TU-204 Composite Aileron)
- Demonstrated Cost Optimization Capability using the Developed Method
- Established Major Damage History on Aluminum Airframes from FAA SDR as a Baseline for Data Extrapolation

Software Architecture



The immediate output is the Probability of Failure of a fleet with given engineering and operational statistics. The method can then be adapted to calculate the inspection interval, repair quality, etc. needed to ensure a sufficiently low probability of failure or safety benchmark.

Finding Inspection Intervals

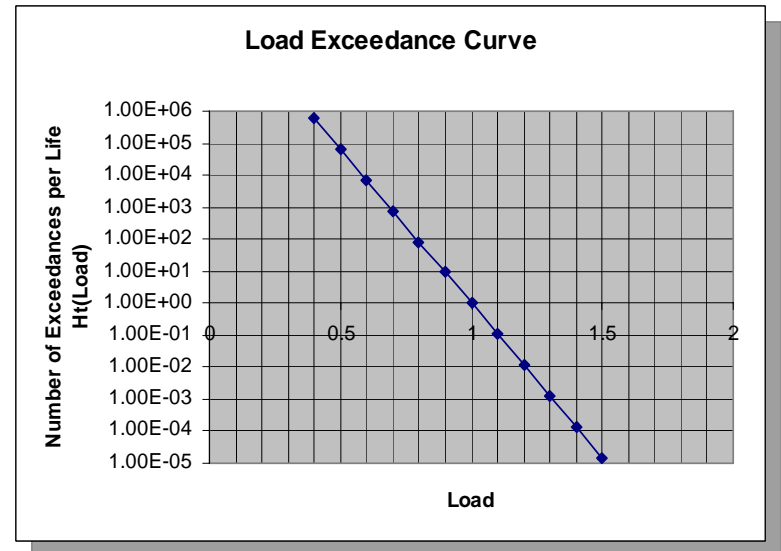
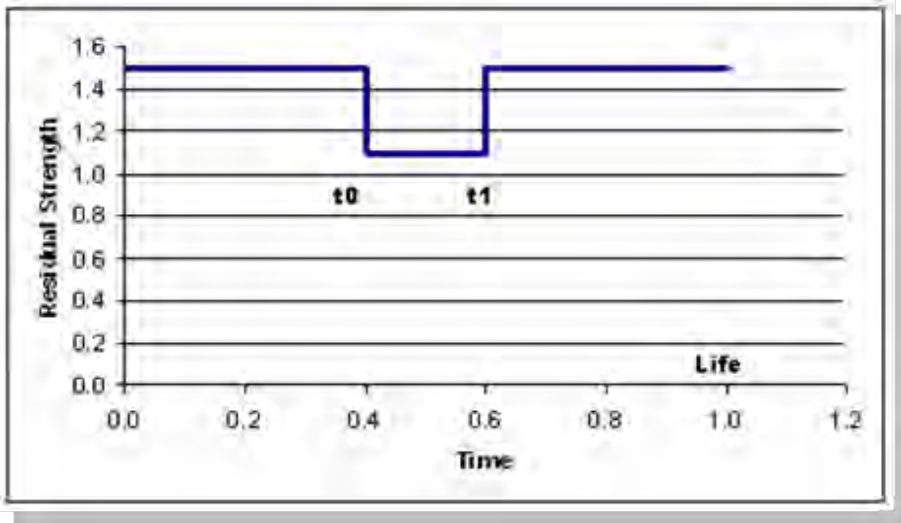


Program Capabilities

- “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

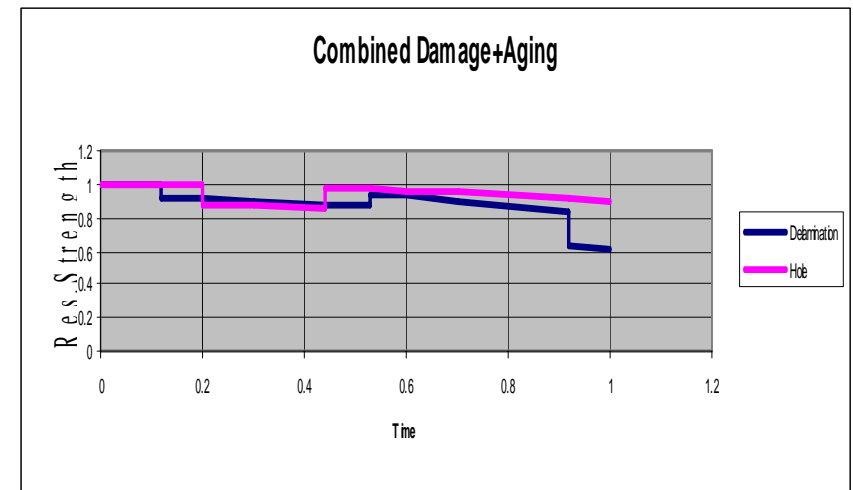
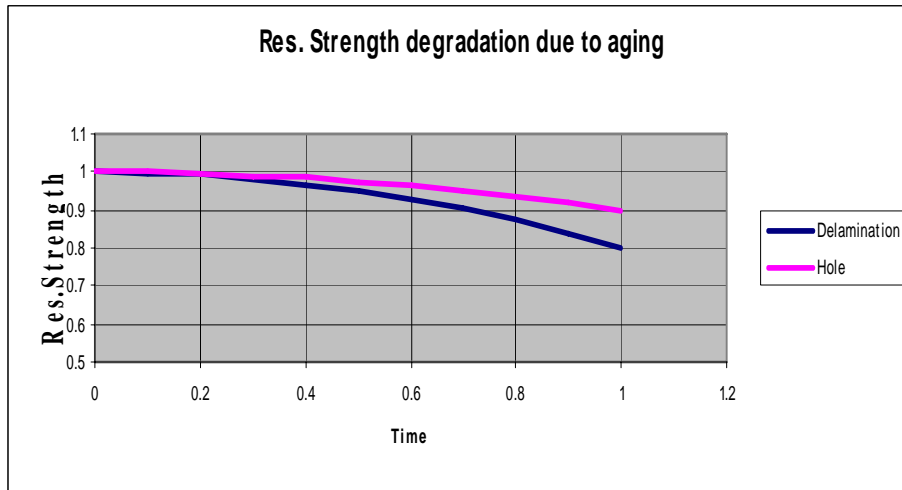
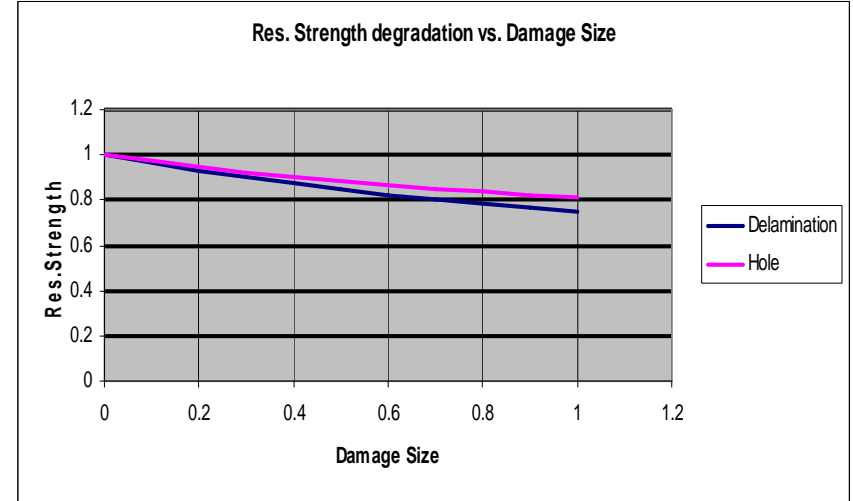
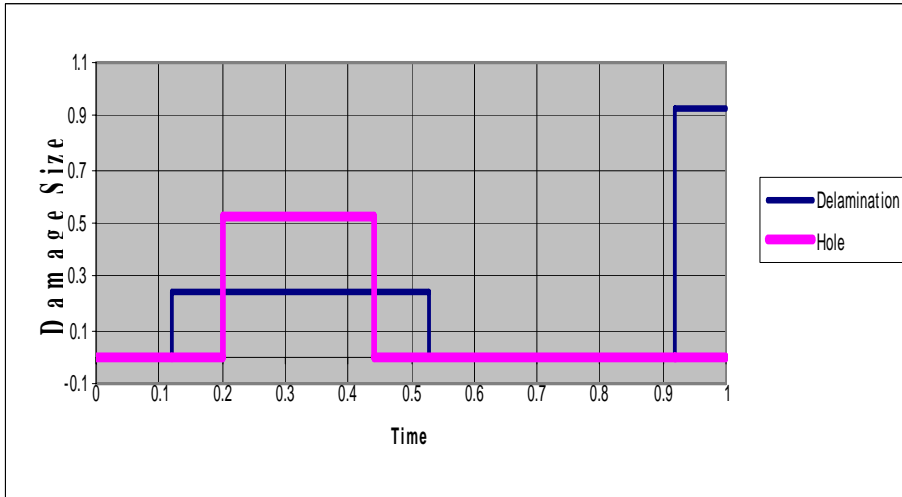


$$P_f = 1 - \prod_{i=1}^{N=3} [1 - P_f(R_i, t_i)]$$

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

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

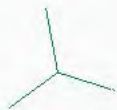
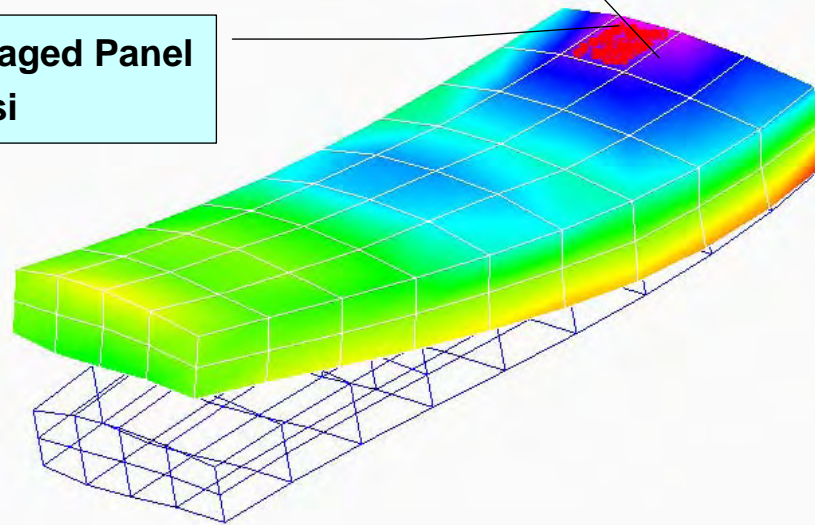
Residual Strength History Simulation



Residual Strength Analysis of a Simple Wing Box

Max Stress in the Undamaged area
 $\sigma = 18,490$ psi

Max Stress in the Damaged Panel
 $\sigma = 22,858$ psi



Input Data Management

Load Exceedance Data

Selected PDF index	Mean	Standard Dev.
1	2.5835	0.1446

Exceedance Curve: Weibull, Normal, Gumbel I, Lognormal, Uniform

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.

Obtaining the Gumbel parameters from the Functional 0.0000 Do not Ch Scale = 0.1127 Location = 2.5000 Mean and Standard Dev. Are written to A4.

Here the exceedance curve follows the function:
 $Ht(x) = H_0 \exp(-x/b)$,
 where $H_0 = 4.2683e9$; $b = 0.112742$

Temperature Exceedance Matrix

Selected PDF index	Mean	Standard Dev.
1		

Exceedance Curve: Weibull, Normal, Gumbel I, Lognormal, Uniform

Select Probability Distribution function that suits to the structural temperature

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

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

Defect & Damage Size Data

N Damage Types	Expected Max damages	Expected in #DIV/0!	lives
1	20		

N Rows in Defect Matrix: 3

N Rows in Damage Matrix: 4

Characteristic Size	Exceedances per life
0.0	1.0E-03
1.0	1.0E-04
2.0	1.0E-05
3.0	1.0E-06
4.0	5.1E-01
	2.6E-01
	1.4E-01
	6.9E-02

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.

EO = 1.0000
B = 1.5000

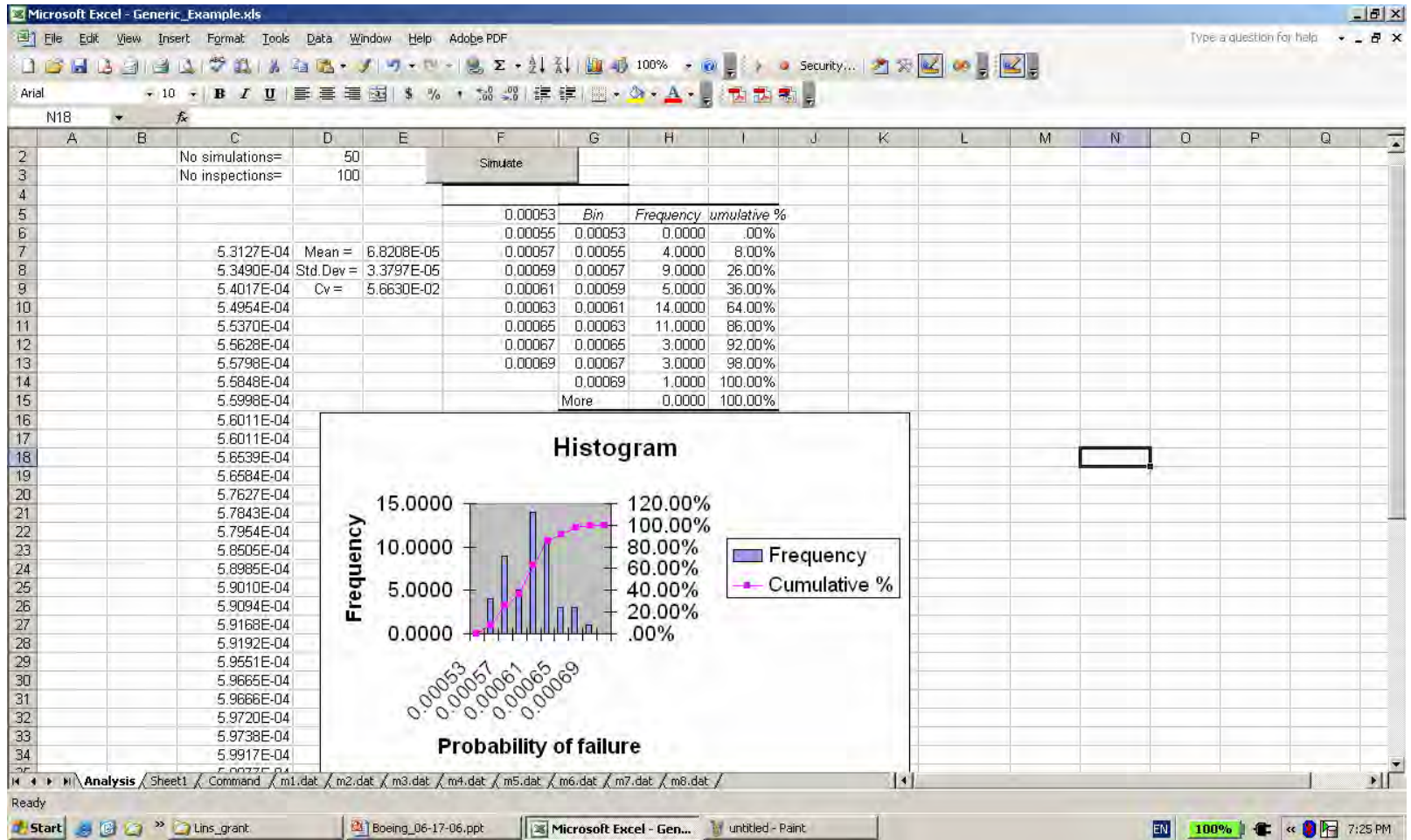
Here the damage size exceedance curve follows the function:
 $Ed(D) = E_0 \exp(-D/B)$,
 where $E_0 = 1$; $B = 1.5$

Residual Strength vs. Damage Size Matrix

N Rows in 1st mat	N Rows in 2d mat	Initial Static	5.0000	5.3045	1.4145
1	16				
2					
3	Damage Size	Mean Strength	Cv	Y(2)	
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	
8	4.0	3.24	5.00E-02	6.11E-01	
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	5.56E-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:
 $Y(D) = Ass + (1 - Ass) \exp(-D/G)$
 $Ass = 5.50E-01$
 $B = 2.00E+00$
 $Ass = 0.55$; $G = 2$

Probability of Failure Predictions



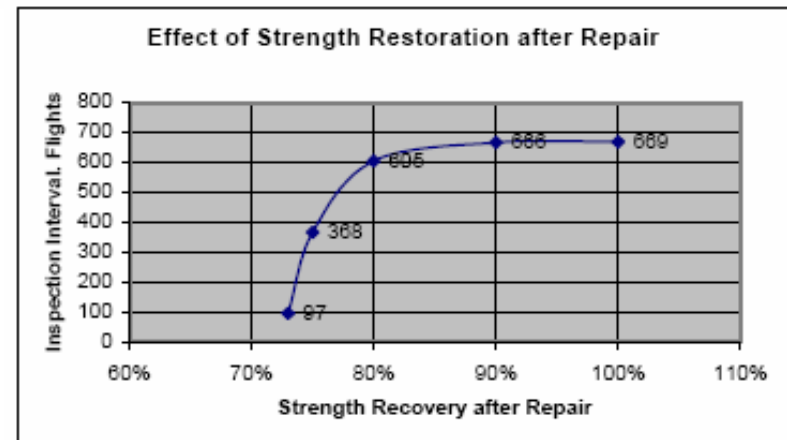
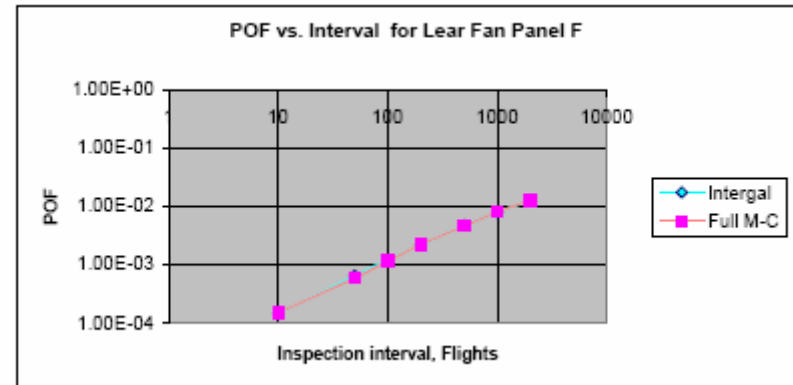
Sample Problem

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



Work in Progress

(September 1, 2006 – August 31, 2007)

The primary objective of this year's study is to demonstrate the potential benefit of the currently developed methodology in composite aircraft maintenance and certification.

Major tasks to be accomplished are:

- Task 3.1 Analysis Method Enhancement**
- Task 3.2 Methodology Implementation**
- Task 3.3 Method Demonstration and Documentation**

Future Developments

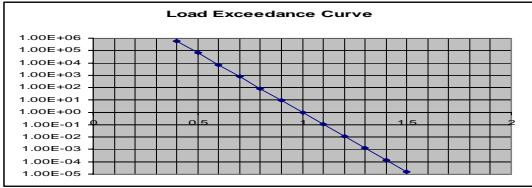
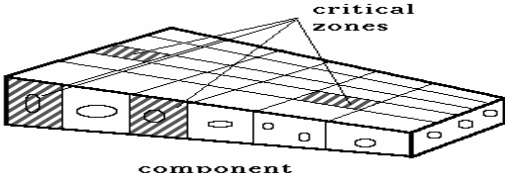
Progressive failure considerations:

- Fatigue damage accumulation
- Delamination propagation

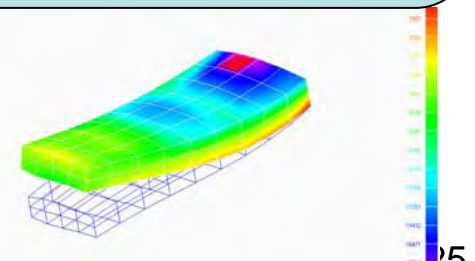
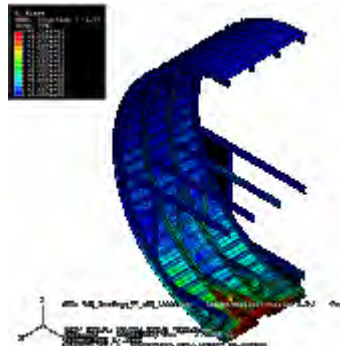
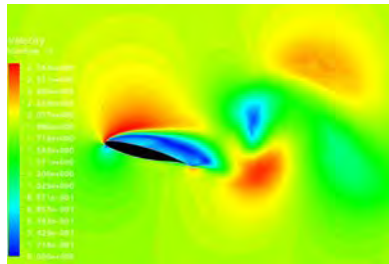
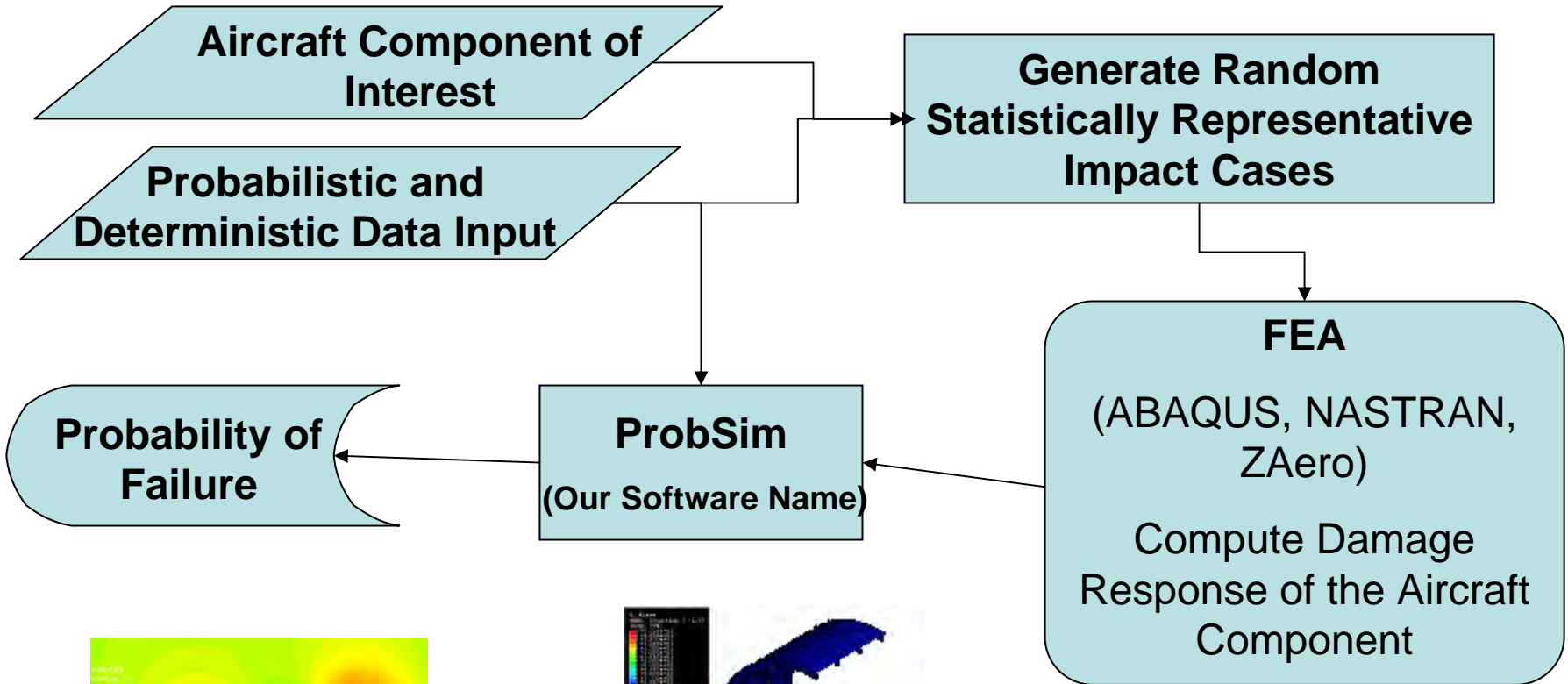
Extend software capability:

- Simulate environments as time-dependent multidimensional random functions
- Stochastic Finite Element Model: FE Model with statistical properties
- Full spectra of impact conditions to predict the type and size of expected damage vs. frequency through FE impact simulation

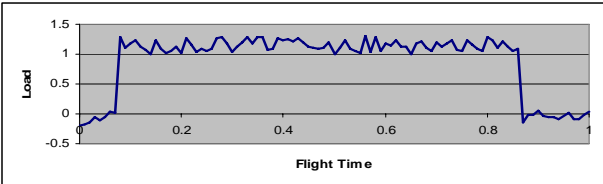
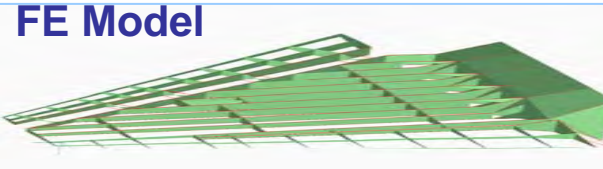
The Probabilistic Model We will have in 2007

Input	Presentation Format	Factors Considered
Operational Environments: <ul style="list-style-type: none"> • Mechanical loads • Temperature • Time in operation 	Exceedance data for finite set of “design cases”  <p>The graph is titled 'Load Exceedance Curve'. The y-axis represents load level on a logarithmic scale from 1.00E-05 to 1.00E+06. The x-axis represents exceedance probability on a logarithmic scale from 0.5 to 1.0. A blue line with circular markers shows a downward trend, indicating that as the load level increases, the probability of exceedance decreases.</p>	<ul style="list-style-type: none"> • Extreme values for static strength, stiffness, aeroelasticity using finite set of “design cases” • Material aging in empirical form
Stochastic Structure: <ul style="list-style-type: none"> • Static strength/stiffness • Aging • Flutter, LCO 	Residual properties for finite set of “design cases” for each structural subcomponent (panel)  <p>The diagram shows a 3D perspective view of a rectangular structural component with several circular holes. A grid is overlaid on the top surface. Two specific areas on the grid are highlighted with diagonal hatching and labeled 'critical zones' with arrows. The word 'component' is written below the diagram.</p>	Empirical residual properties (strength/stiffness) as a function of damage type/size and aging time
Impact conditions: <ul style="list-style-type: none"> • hail, birds, stones, debris • tools, ladders, trucks, etc 	Probabilistic description for resulting damage: <ul style="list-style-type: none"> • Size/type • Frequency 	Damage size exceedance data for finite set of damage types obtained on existing components in operations
Maintenance plan: <ul style="list-style-type: none"> • Inspection interval • Inspection method • Repair method • Repair decision logic 	Probabilistic description of each condition: <ul style="list-style-type: none"> • Probability of damage detection • Strength/stiffness recovery • Decision-making rules 	All formalized features of maintenance plan

Look into the Future: Integration with FEA Software



Required Capabilities

Input	Presentation Format	Factor Considered
Operational Environments: <ul style="list-style-type: none"> • Mechanical loads • Temperature • Humidity • Time in operation 	Simulated as time-dependent multidimensional random function 	<ul style="list-style-type: none"> • Extreme values for static strength, stiffness, aeroelasticity • Fatigue damage accumulation • Crack propagation • Material aging as a function of environmental history
Stochastic Structure: <ul style="list-style-type: none"> • Static strength/stiffness • Geometry • Aging • Fatigue • Flutter, LCO 	Stochastic Finite Element Model: FE Model with random properties FE Model 	Randomized structural properties with characteristic size of finite element
Impact conditions: <ul style="list-style-type: none"> • hail, birds, stones, debris • tools, ladders, trucks, etc 	Probabilistic description of each condition: <ul style="list-style-type: none"> • Frequency • Size, density • Velocity, angle 	Full spectra of impact conditions to predict the type and size of expected damage vs. frequency through FE impact simulation
Maintenance plan: <ul style="list-style-type: none"> • Inspection interval • Inspection method • Repair method • Repair decision logic 	Probabilistic description of each condition: <ul style="list-style-type: none"> • Probability of damage detection • Scatter of inspection time • Strength/stiffness recovery • Decision-making rules 	All formalized features of maintenance plan

- **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.

THANK YOU

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 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

Summary

What we have:

- Developed the method for determining POF and the inspection intervals.
- Developed the preliminary computer software for calculating POF and the inspection intervals.
- Mined statistical data on damage and other probabilistic parameters.

What we will have:

- An enhanced method for determining POF and the inspection intervals.
- A user friendly computer code for public use in probabilistic design of composite structures.