JAMS

Development of Reliability-Based Damage Tolerant Structural Design Methodology

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Outline

- Motivation and Objectives
- RELACS software
- Damage Growth Modeling
- Case Study- Fuselage Skin-stringer Disbond
- Summary

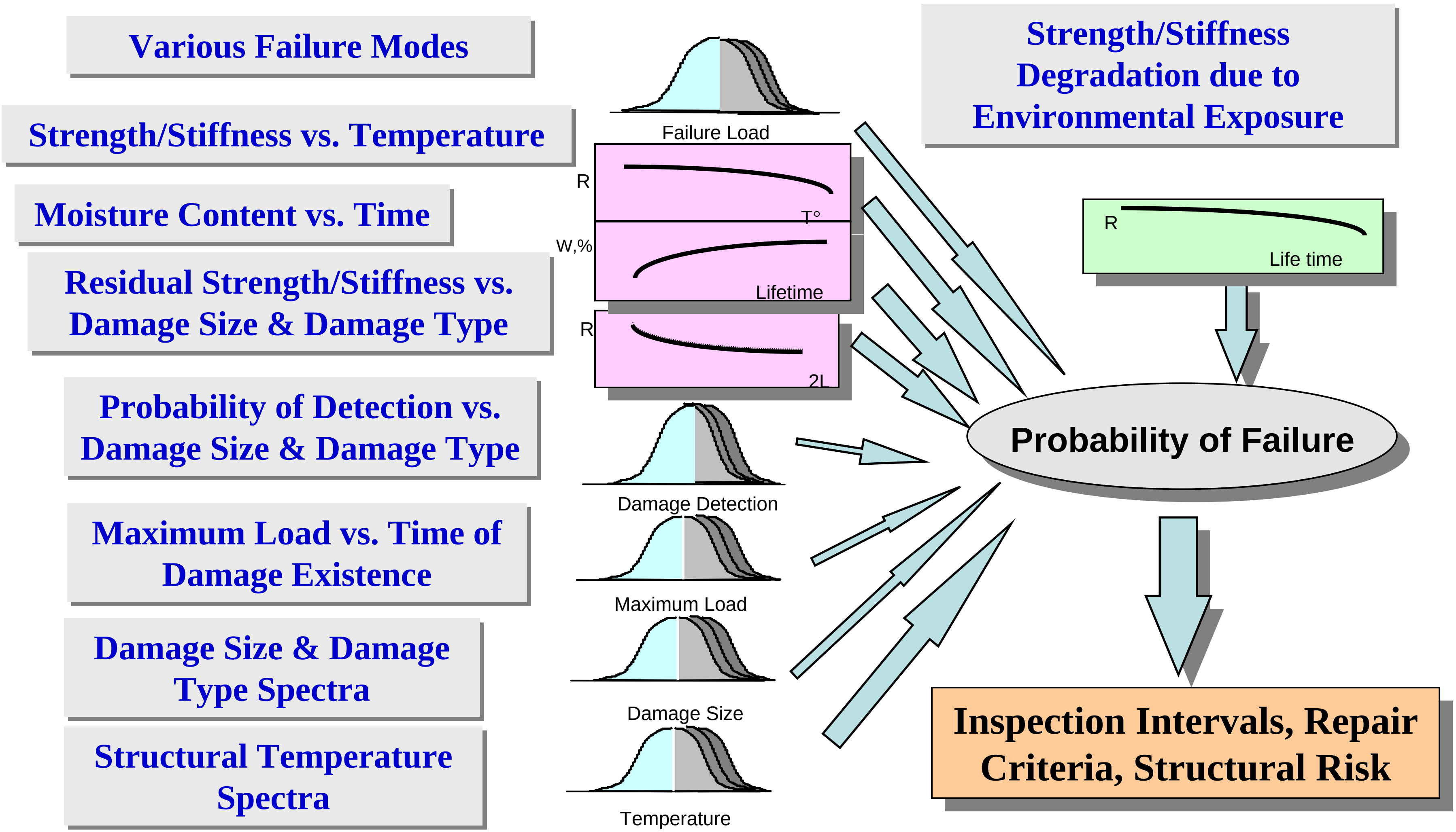
Reliability-Based Damage Tolerant Structural Design Methodology

- ***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.

Technical Approach

- The approach 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.

The Probabilistic Model



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

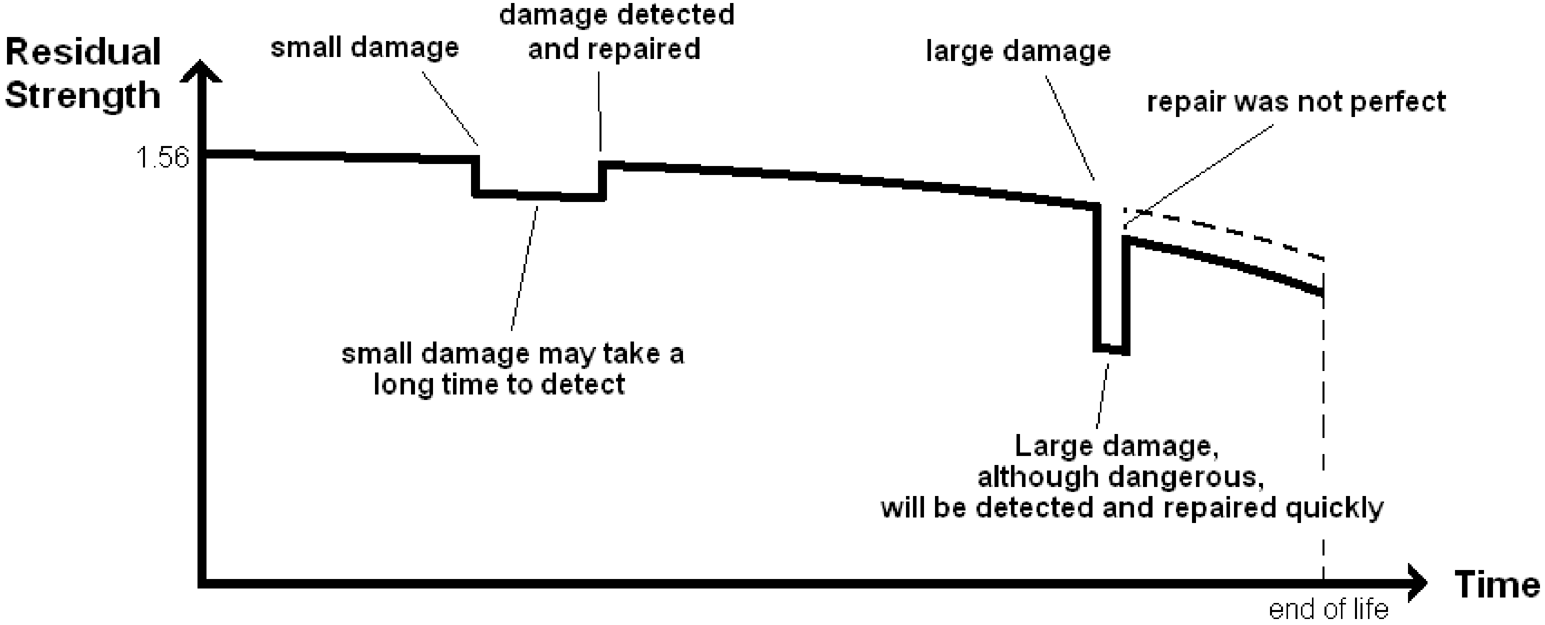
Structural Temperature Spectra

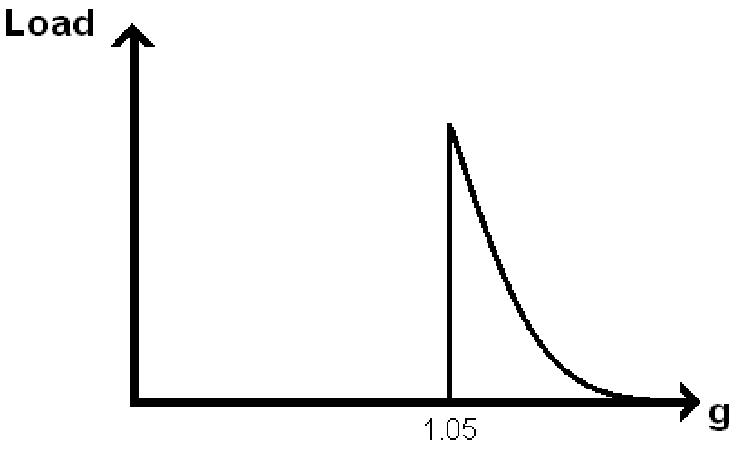
Strength/Stiffness Degradation due to Environmental Exposure

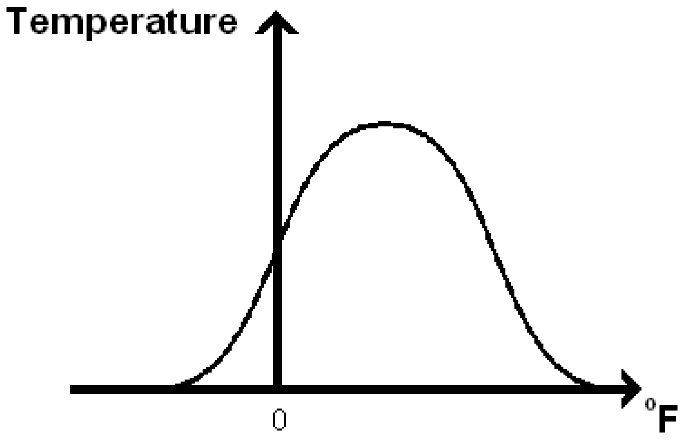
Probability of Failure

Inspection Intervals, Repair Criteria, Structural Risk

The Probabilistic Model





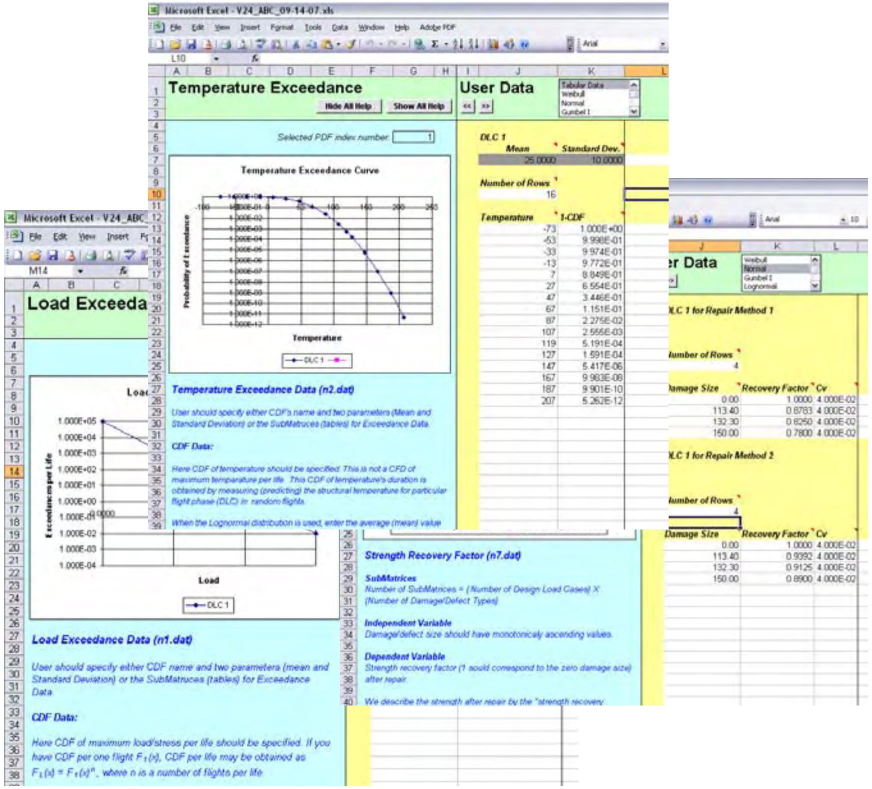


Input Data Requirements

- **Necessary**
  - Loads Exceedance
  - Damage Exceedance
  - Residual Strength
  - Inspection Interval
  - Detection Probability
  - Repair Quality
- **Additional**
  - Temperature
  - Aging
  - Damage Growth

RELACS: Reliability-based Lifecycle Analysis of Composite Structures

1st release of RELACS has been completed



Temperature Exceedance

Selected PDF index number: 1

User Data

DLC 1

Mean	*Standard Dev.*
25.0000	10.0000

Number of Rows: 16

Temperature	*1-CDF*
-73	1.000E+00
-53	9.998E-01
-33	9.974E-01
-13	9.772E-01
7	8.849E-01
27	6.554E-01
47	3.446E-01
67	1.151E-01
87	2.275E-02
107	2.555E-03
119	5.191E-04
127	1.591E-04
147	5.417E-06
167	9.983E-08
187	9.901E-10
207	5.262E-12

Temperature Exceedance Data (n2.dat)

User should specify either CDF's name and two parameters (Mean and Standard Deviation) or the SubMatrices (tables) for Exceedance Data.

CDF Data:

Here CDF of temperature should be specified. This is not a CFD of maximum temperature per life. This CDF of temperature's duration is obtained by measuring (predicting) the structural temperature for particular flight phase (DLC) in random flights.

When the Lognormal distribution is used, enter the average (mean) value

Load Exceeda

Load Exceedance Data (n1.dat)

User should specify either CDF name and two parameters (mean and Standard Deviation) or the SubMatrices (tables) for Exceedance Data.

CDF Data:

Here CDF of maximum load/stress per life should be specified. If you have CDF per one flight $F_1(x)$, CDF per life may be obtained as $F_L(x) = F_1(x)^n$, where n is a number of flights per life

Strength Recovery Factor (n7.dat)

SubMatrices
Number of SubMatrices = (Number of Design Load Cases) X (Number of Damage/Defect Types)

Independent Variable
Damage/defect size should have monotonicaly ascending values.

Dependant Variable
Strength recovery factor (1 sould correspond to the zero damage size) after repair.

We describe the strength after repair by the "strength recovery

User Data

DLC 1 for Repair Method 1

Number of Rows: 4

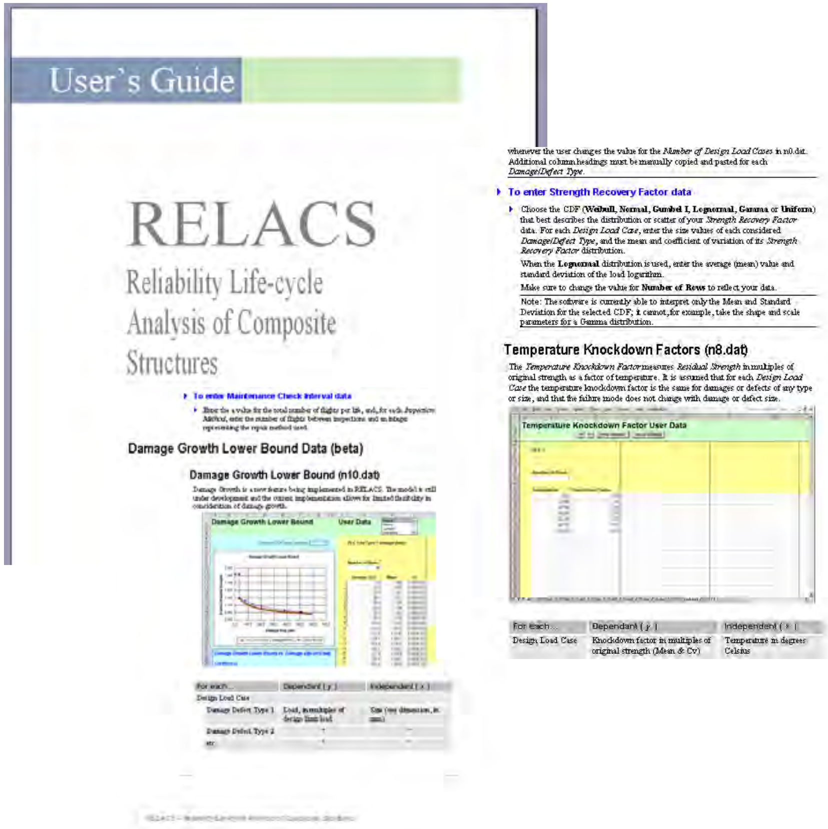
Damage Size	*Recovery Factor*	*Cv*
0.00	1.0000	4.000E-02
113.40	0.8783	4.000E-02
132.30	0.8250	4.000E-02
150.00	0.7800	4.000E-02

DLC 1 for Repair Method 2

Number of Rows: 4

Damage Size	*Recovery Factor*	*Cv*
0.00	1.0000	4.000E-02
113.40	0.9392	4.000E-02
132.30	0.9125	4.000E-02
150.00	0.8900	4.000E-02

RELACS User Manual has been completed



User's Guide

RELACS

Reliability Life-cycle Analysis of Composite Structures

- **To enter Maintenance Check Interval data**

Damage Growth Lower Bound Data (beta)

Damage Growth Lower Bound (n10.dat)

whenever the user changes the value for the *Number of Design Load Cases* in n0.dat. Additional column headings must be manually copied and pasted for each *Damage/Defect Type*.

- **To enter Strength Recovery Factor data**
  - Choose the CDF (**Weibull, Normal, Gumbel I, Lognormal, Gamma** or **Uniform**) that best describes the distribution or scatter of your *Strength Recovery Factor* data. For each *Design Load Case*, enter the size values of each considered *Damage/Defect Type*, and the mean and coefficient of variation of its *Strength Recovery Factor* distribution.

    When the **Lognormal** distribution is used, enter the average (mean) value and standard deviation of the load logarithm.

    Make sure to change the value for **Number of Rows** to reflect your data.

    Note: The software is currently able to interpret only the Mean and Standard Deviation for the selected CDF; it cannot, for example, take the shape and scale parameters for a Gamma distribution.

Temperature Knockdown Factors (n8.dat)

The *Temperature Knockdown Factor* measures *Residual Strength* in multiples of original strength as a factor of temperature. It is assumed that for each *Design Load Case* the temperature knockdown factor is the same for damages or defects of any type or size, and that the failure mode does not change with damage or defect size.

Temperature Knockdown Factor User Data

For each...	Dependant (*y*)	Independent (*x*)
Design Load Case	Knockdown factor in multiples of original strength (Mean & Cv)	Temperature in degrees Celsius

RELACS: Reliability-based Lifecycle Analysis of Composite Structures

Failure Modes Considered in RELACS:

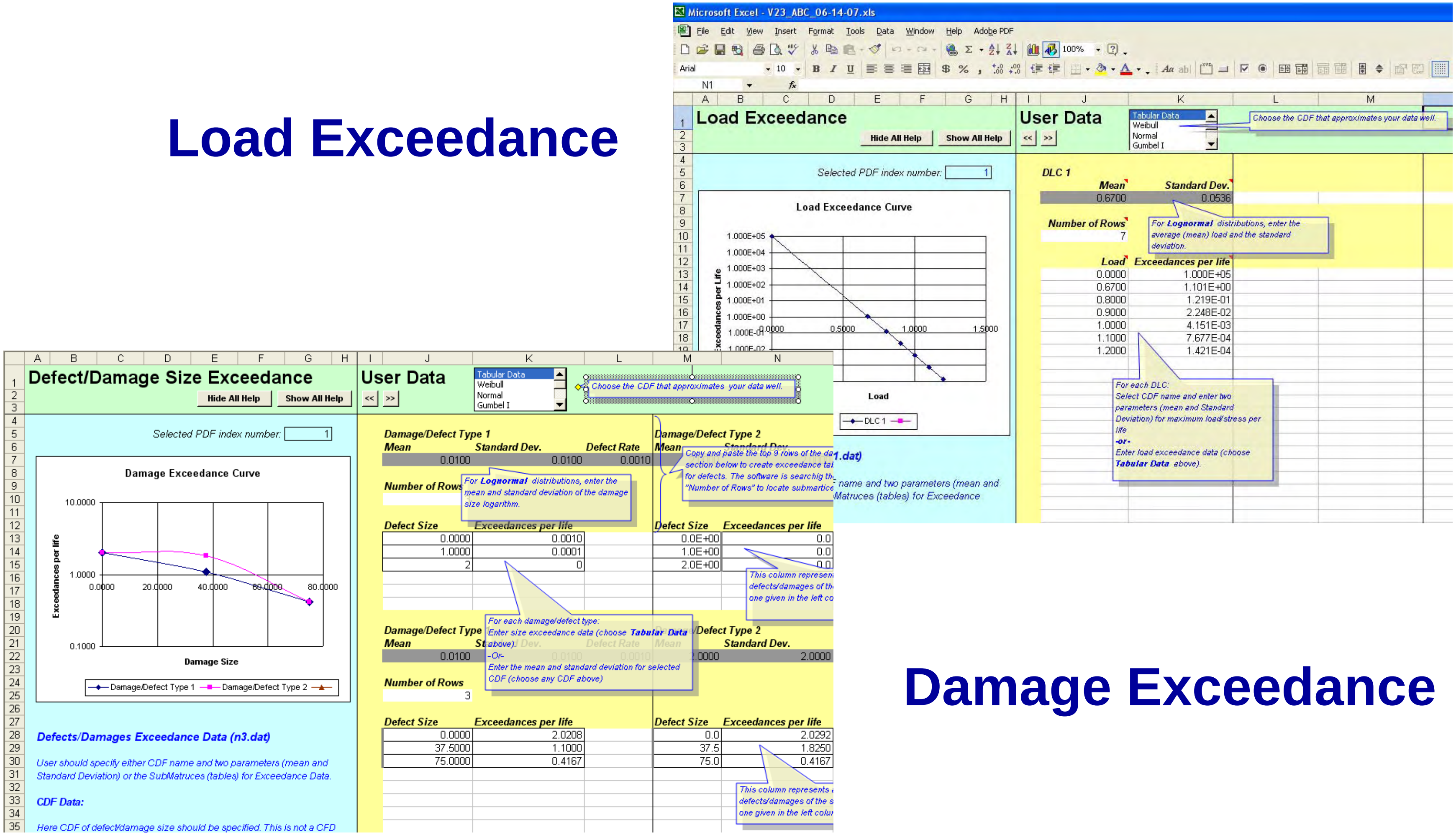
- “Static” failure: load exceeds the strength of damaged structures
- Deformation exceeds acceptable level
- Flutter: airspeed exceeds the flutter speed of damaged or repaired structure*
- High amplitude limit cycle oscillations: the acceptable level of vibrations is exceeded*
- Other single dimension failure criteria…

**See Livne and Styuart, “Combined Local-Global Variability and Uncertainty in the Aeroservoelasticity of Composite Aircraft”*

Input Data Management

Load Exceedance

Damage Exceedance



Load Exceedance

Selected PDF index number: 1

User Data

Choose the CDF that approximates your data well.

DLC 1

Mean	Standard Dev.
0.6700	0.0536

Number of Rows: 7

For **Lognormal** distributions, enter the average (mean) load and the standard deviation.

Load	Exceedances per life
0.0000	1.000E+05
0.6700	1.101E+00
0.8000	1.219E-01
0.9000	2.248E-02
1.0000	4.151E-03
1.1000	7.677E-04
1.2000	1.421E-04

For each DLC:
Select CDF name and enter two parameters (mean and Standard Deviation) for maximum load/stress per life
-or-
Enter load exceedance data (choose **Tabular Data** above).

Defect/Damage Size Exceedance

Selected PDF index number: 1

Defects/Damages Exceedance Data (n3.dat)

User should specify either CDF name and two parameters (mean and Standard Deviation) or the SubMatruces (tables) for Exceedance Data.

CDF Data:

Here CDF of defect/damage size should be specified. This is not a CFD

User Data

Choose the CDF that approximates your data well.

Damage/Defect Type 1

Mean	Standard Dev.	Defect Rate
0.0100	0.0100	0.0010

Number of Rows

For **Lognormal** distributions, enter the mean and standard deviation of the damage size logarithm.

Defect Size	Exceedances per life
0.0000	0.0010
1.0000	0.0001
2	0

Damage/Defect Type 2

Mean Standard Dev.

Copy and paste the top 9 rows of the da section below to create exceedance tal for defects. The software is searchig th "Number of Rows" to locate submartice

Defect Size	Exceedances per life
0.0E+00	0.0
1.0E+00	0.0
2.0E+00	0.0

This column represen defects/damages of th one given in the left co

For each damage/defect type:
Enter size exceedance data (choose **Tabular Data** above).
-Or-
Enter the mean and standard deviation for selected CDF (choose any CDF above)

Damage/Defect Type

Mean	Standard Dev.	Defect Rate
0.0100	0.0100	0.0010

Number of Rows: 3

Defect Size	Exceedances per life
0.0000	2.0208
37.5000	1.1000
75.0000	0.4167

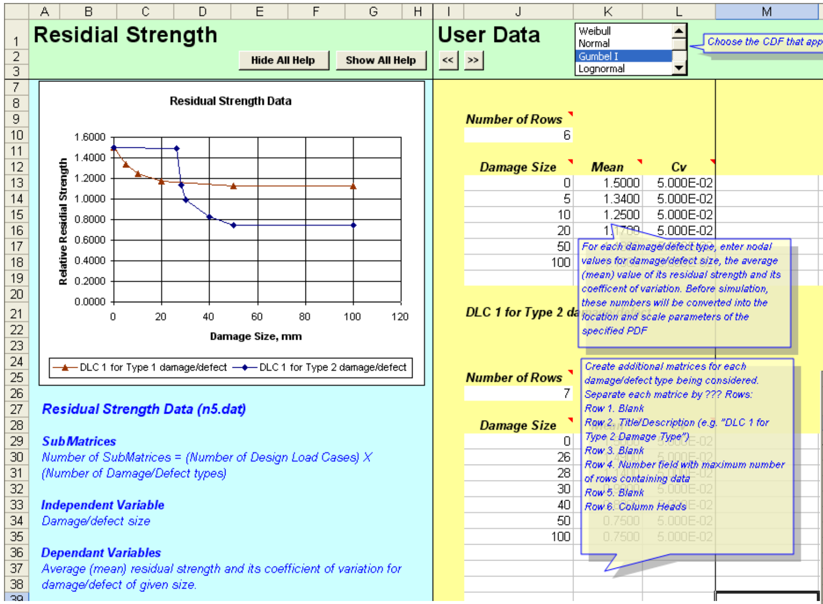
Damage/Defect Type 2

Mean	Standard Dev.
2.0000	2.0000

Defect Size	Exceedances per life
0.0	2.0292
37.5	1.8250
75.0	0.4167

This column represents defects/damages of the s one given in the left colu

Input Data Management



Residial Strength

User Data

Weibull
Normal
Gumbel I
Lognormal

Choose the CDF that approximates your data wel

Residual Strength Data (n5.dat)

SubMatrices
Number of SubMatrices = (Number of Design Load Cases) X (Number of Damage/Defect types)

Independent Variable
Damage/defect size

Dependant Variables
Average (mean) residual strength and its coefficient of variation for damage/defect of given size.

Number of Rows
6

Damage Size	***Mean***	***Cv***
0	1.5000	5.000E-02
5	1.3400	5.000E-02
10	1.2500	5.000E-02
20	1.1700	5.000E-02
50	[illegible]	[illegible]
100	[illegible]	[illegible]

For each damage/defect type, enter nodal values for damage/defect size, the average (mean) value of its residual strength and its coefficent of variation. Before simulation, these numbers will be converted into the location and scale parameters of the specified PDF

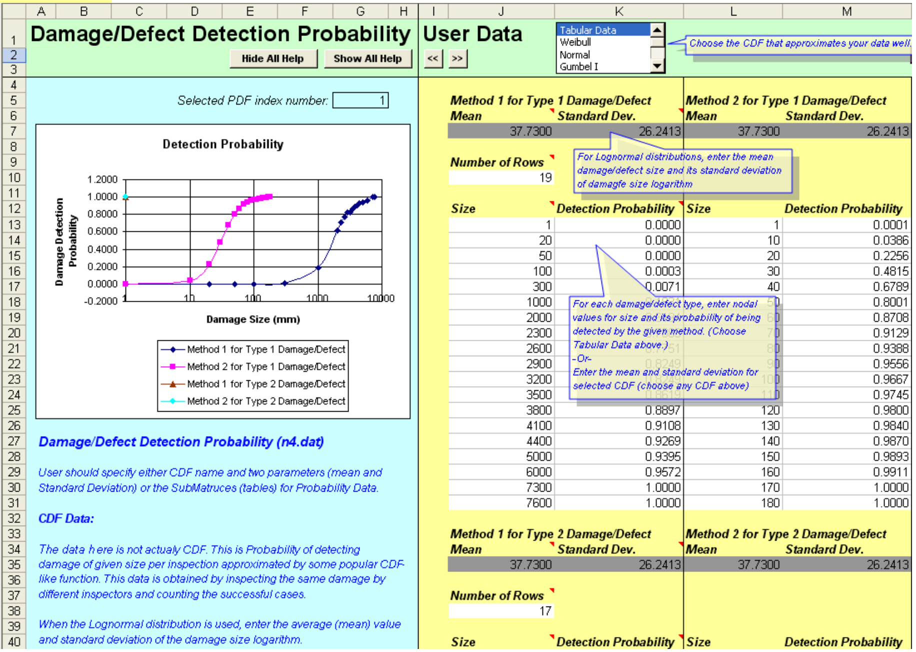
DLC 1 for Type 2 damage/defect

Number of Rows
7

Damage Size	***Mean***	***Cv***
0	1.5000	5.000E-02
26	1.4900	5.000E-02
28	1.1400	5.000E-02
30	0.9900	5.000E-02
40	0.8200	5.000E-02
50	0.7500	5.000E-02
100	0.7500	5.000E-02

Create additional matrices for each damage/defect type being considered.
Separate each matrice by ??? Rows:
Row 1. Blank
Row 2. Title/Description (e.g. "DLC 1 for Type 2 Damage Type")
Row 3. Blank
Row 4. Number field with maximum number of rows containing data
Row 5. Blank
Row 6. Column Heads

Residual Strength



Damage/Defect Detection Probability

Selected PDF index number: 1

Damage/Defect Detection Probability (n4.dat)

User should specify either CDF name and two parameters (mean and Standard Deviation) or the SubMatruces (tables) for Probability Data.

CDF Data:

The data here is not actualy CDF. This is Probability of detecting damage of given size per inspection approximated by some popular CDF-like function. This data is obtained by inspecting the same damage by different inspectors and counting the successful cases.

When the Lognormal distribution is used, enter the average (mean) value and standard deviation of the damage size logarithm.

User Data

Tabular Data
Weibull
Normal
Gumbel I

Choose the CDF that approximates your data well.

Method 1 for Type 1 Damage/Defect		***Method 2 for Type 1 Damage/Defect***	
Mean	***Standard Dev.***	***Mean***	***Standard Dev.***
37.7300	26.2413	37.7300	26.2413

For Lognormal distributions, enter the mean damage/defect size and its standard deviation of damagfe size logarithm

Number of Rows
19

Size	***Detection Probability***	***Size***	***Detection Probability***
1	0.0000	1	0.0001
20	0.0000	10	0.0386
50	0.0000	20	0.2256
100	0.0003	30	0.4815
300	0.0071	40	0.6789
1000	[illegible]	50	0.8001
2000	[illegible]	60	0.8708
2300	[illegible]	70	0.9129
2600	0.7751	80	0.9388
2900	0.8249	90	0.9556
3200	0.8249	100	0.9667
3500	0.8619	110	0.9745
3800	0.8897	120	0.9800
4100	0.9108	130	0.9840
4400	0.9269	140	0.9870
5000	0.9395	150	0.9893
6000	0.9572	160	0.9911
7300	1.0000	170	1.0000
7600	1.0000	180	1.0000

For each damage/defect type, enter nodal values for size and its probability of being detected by the given method. (Choose Tabular Data above.)
-Or-
Enter the mean and standard deviation for selected CDF (choose any CDF above)

Method 1 for Type 2 Damage/Defect		***Method 2 for Type 2 Damage/Defect***	
Mean	***Standard Dev.***	***Mean***	***Standard Dev.***
37.7300	26.2413	37.7300	26.2413

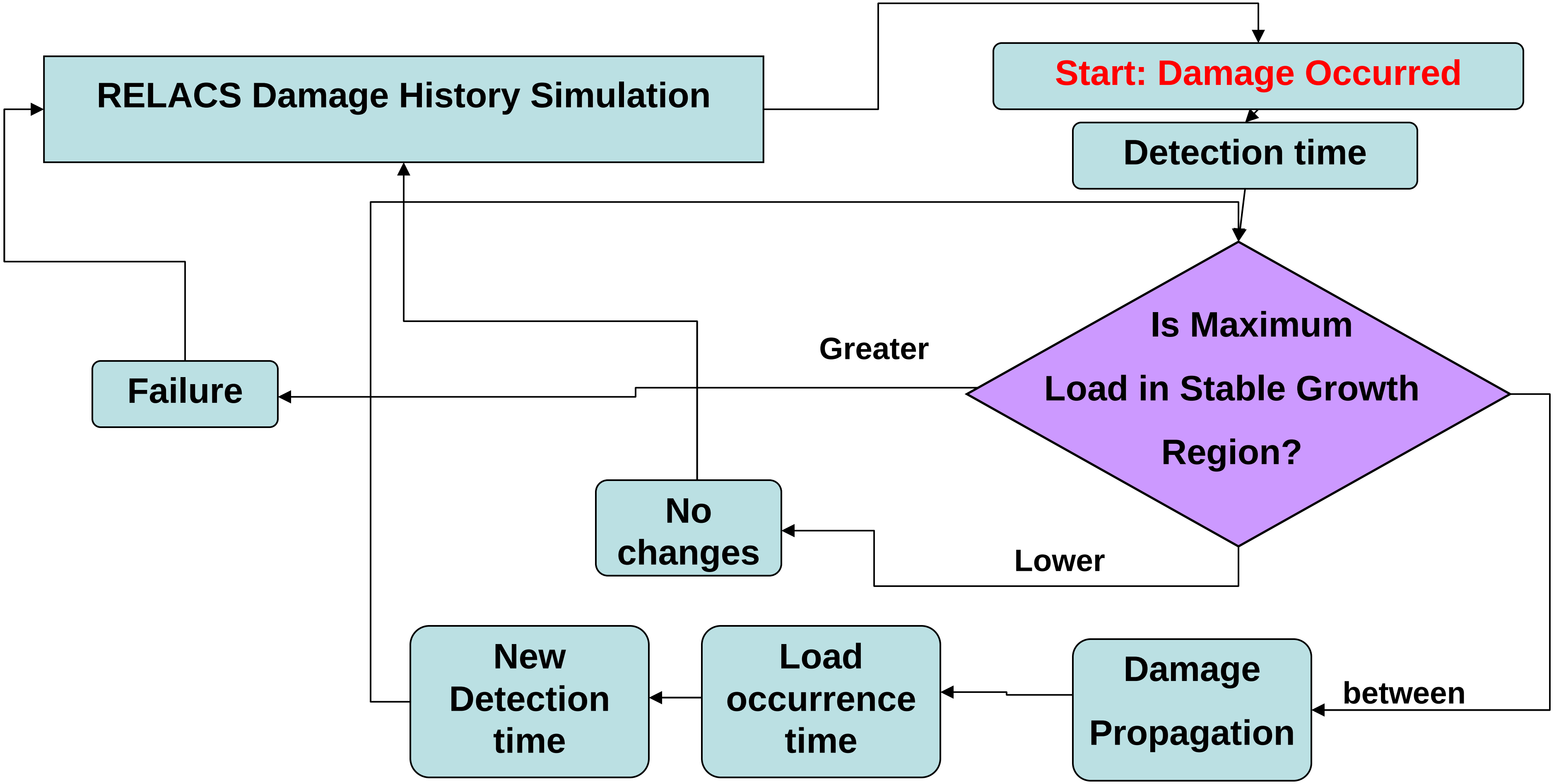
Number of Rows
17

Size	***Detection Probability***	***Size***	***Detection Probability***

Damage Detection Probability

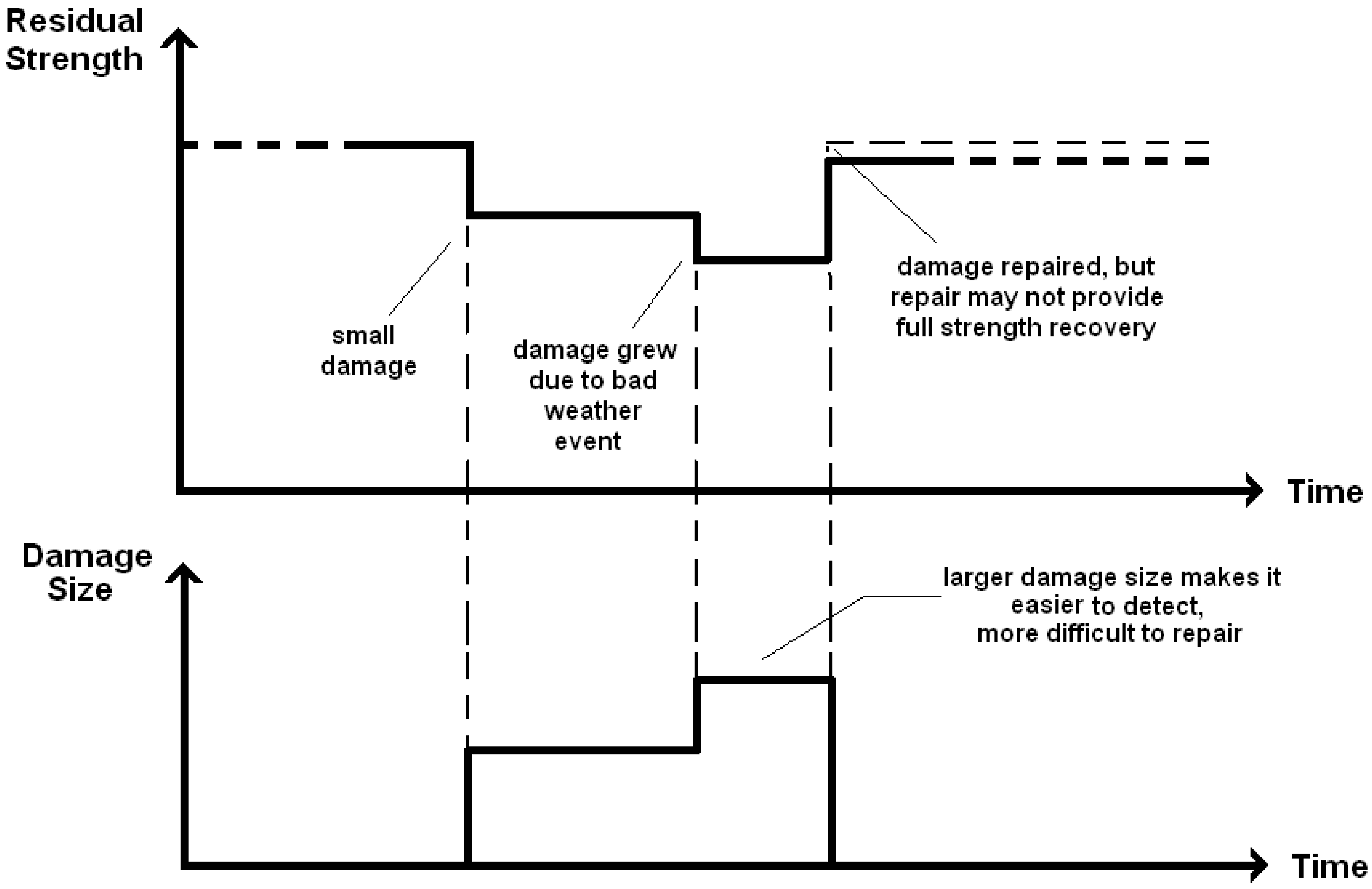
Damage Growth Consideration

Integration into RELACS



Damage Growth Consideration

Integration into RELACS

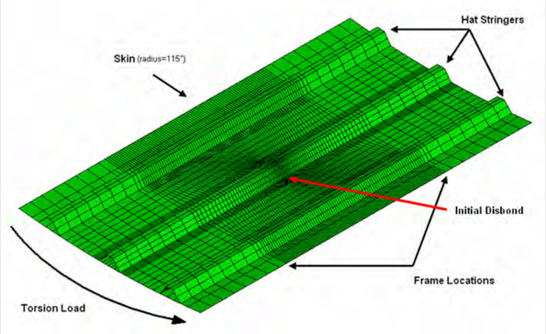


Damage Growth Analysis with RELACS

Problem Definition

Structure under investigation

Initial damage



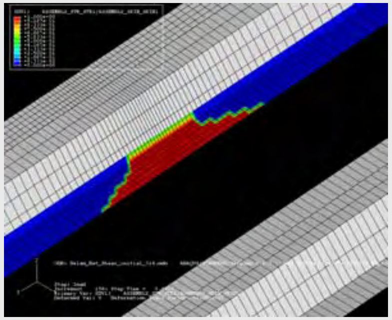
Analysis

Residual Strength/ Fatigue Life

VCCT

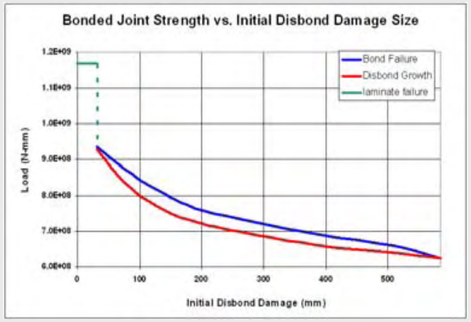
(or other damage growth and assessment mechanism)

Damage Growth



Input Data

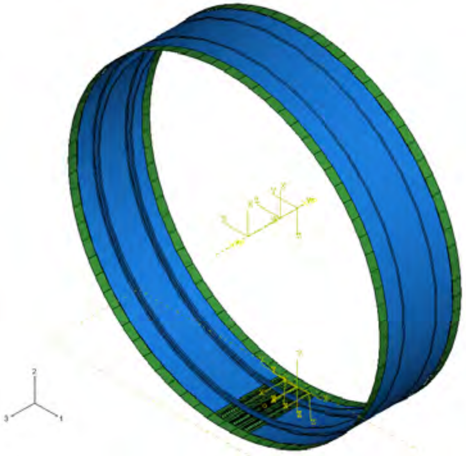
Input for RELACS

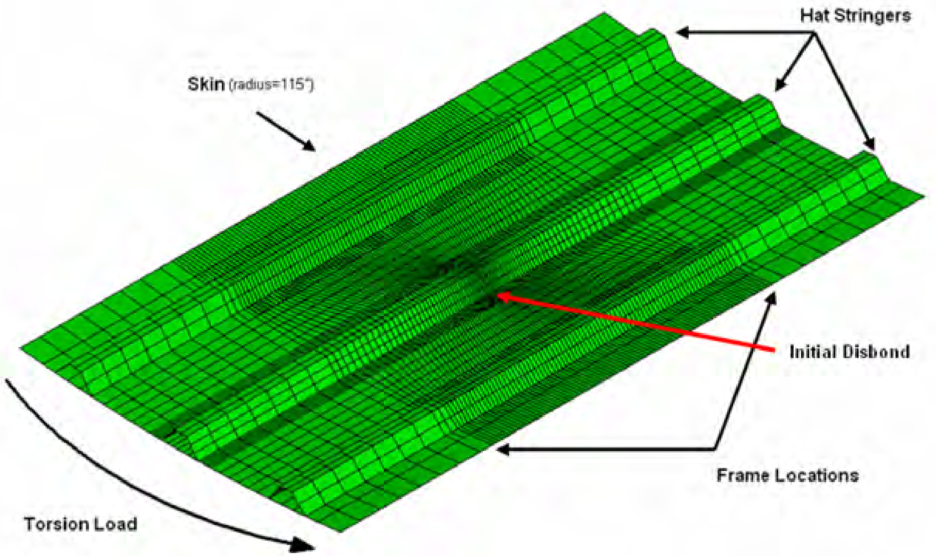


Damage Growth Scenario

Crack in Fuselage Skin-Stringer Bond

- A generic composite fuselage sub-section (24-ply quasi-isotropic) with hat stringer (8-ply quasi-isotropic) reinforcement is modeled in ABAQUS (r = 115”; one frame bay is considered)
- Disbonding of various sizes are implanted at the center of the stringer, on one legs of the hat stringer
- Skin-stringer debonding under shear is considered
- Frames spacing at 24” (debonding cannot penetrate frame locations)
- Disbond growth analysis took advantage of the commercially available ABAQUS with VCCT (Virtual Crack Closure Technique)





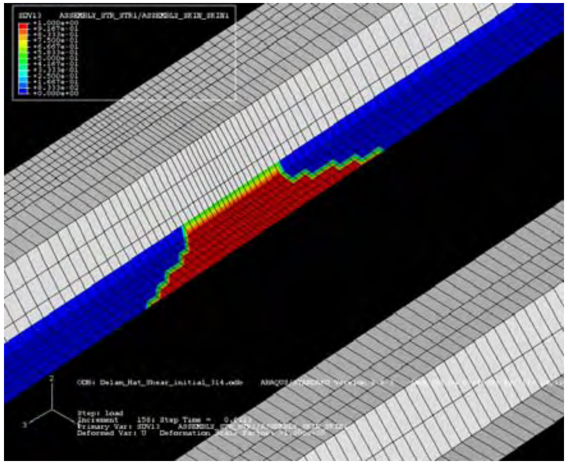
Damage Growth Consideration

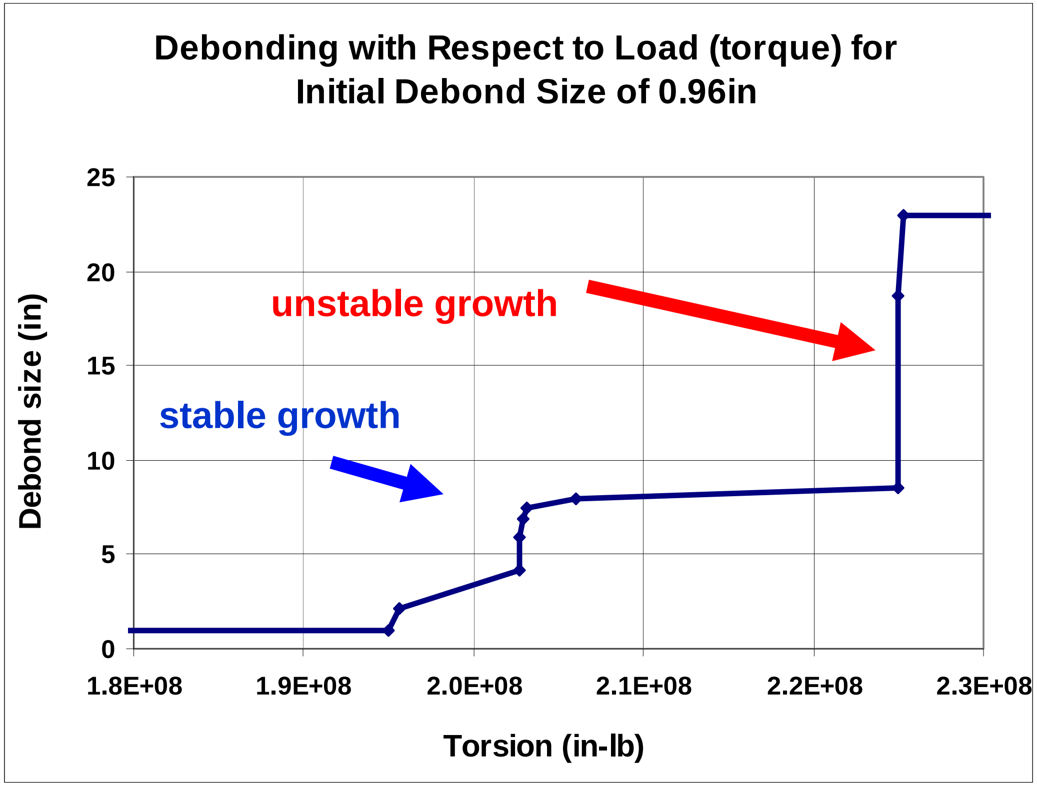
Example of Disbond Growth Results

Initial flaw = 0.96in

- Torsion load on fuselage is ramped from 0 in-lb to 3.0 x10^8 in-lb
- Crack front is not perpendicular to stringer

  as it propagates



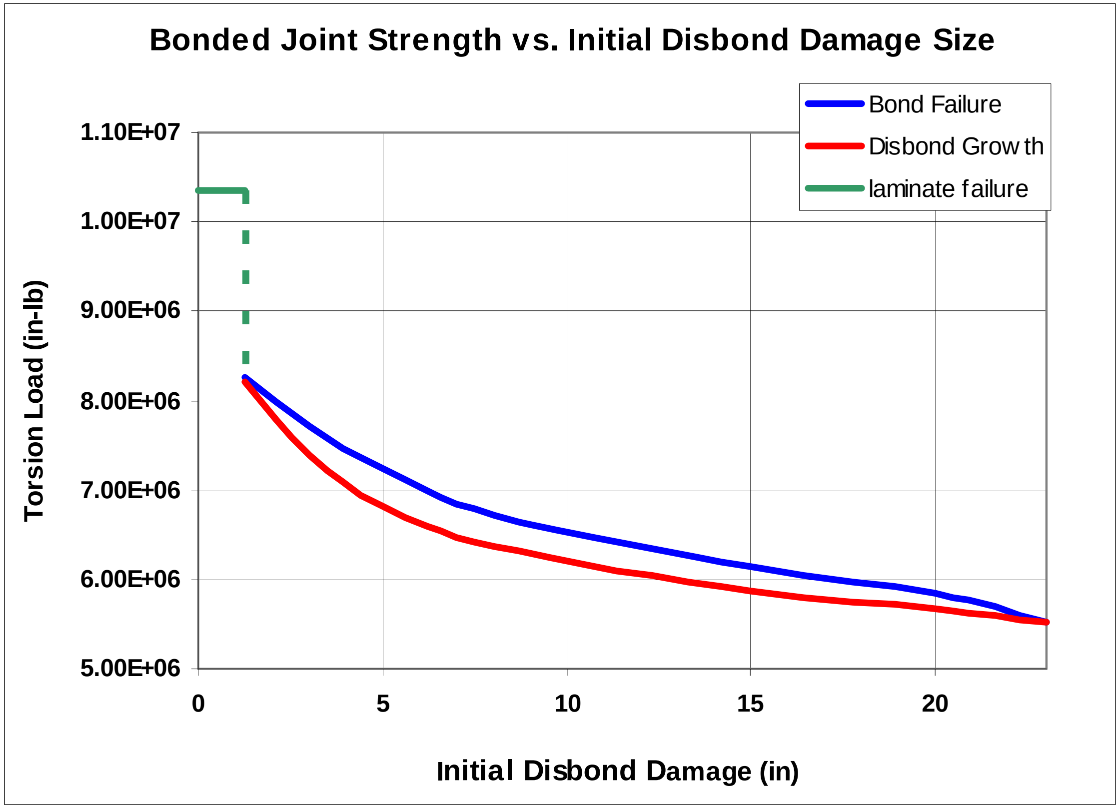


click for movie

Damage Growth Consideration

Results for Various Initial Damage Size

- Ultimate load capability reduction of the fuselage due to completed debonding of one stringer is minimal.
- There is a significant difference between stable and unstable growth load levels.
- Sub-structure is considered “completely failed” when unstable growth load level is reached and the stringer completely separately from the skin for the entire frame bay.

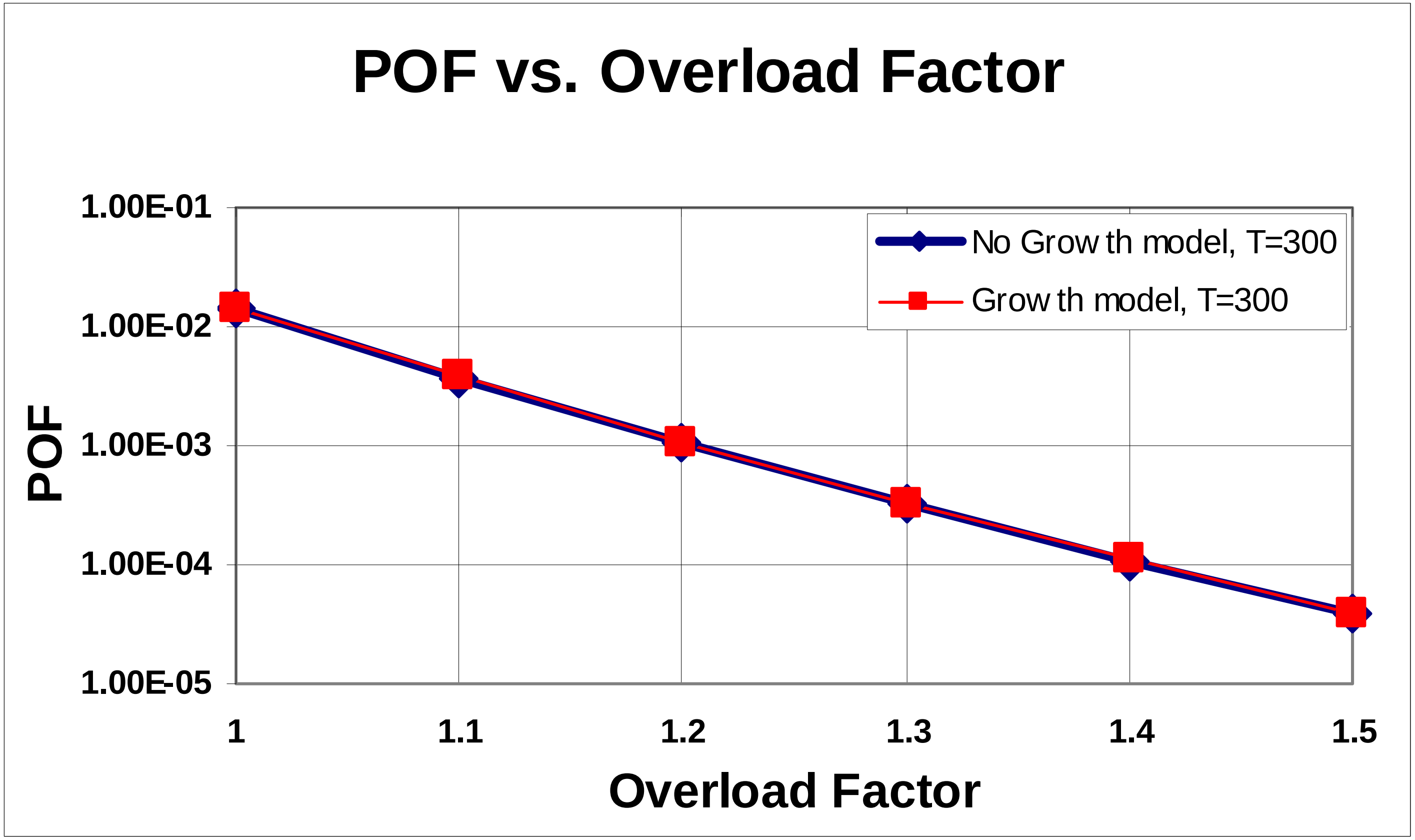


Probabilistic Inputs: External Loads

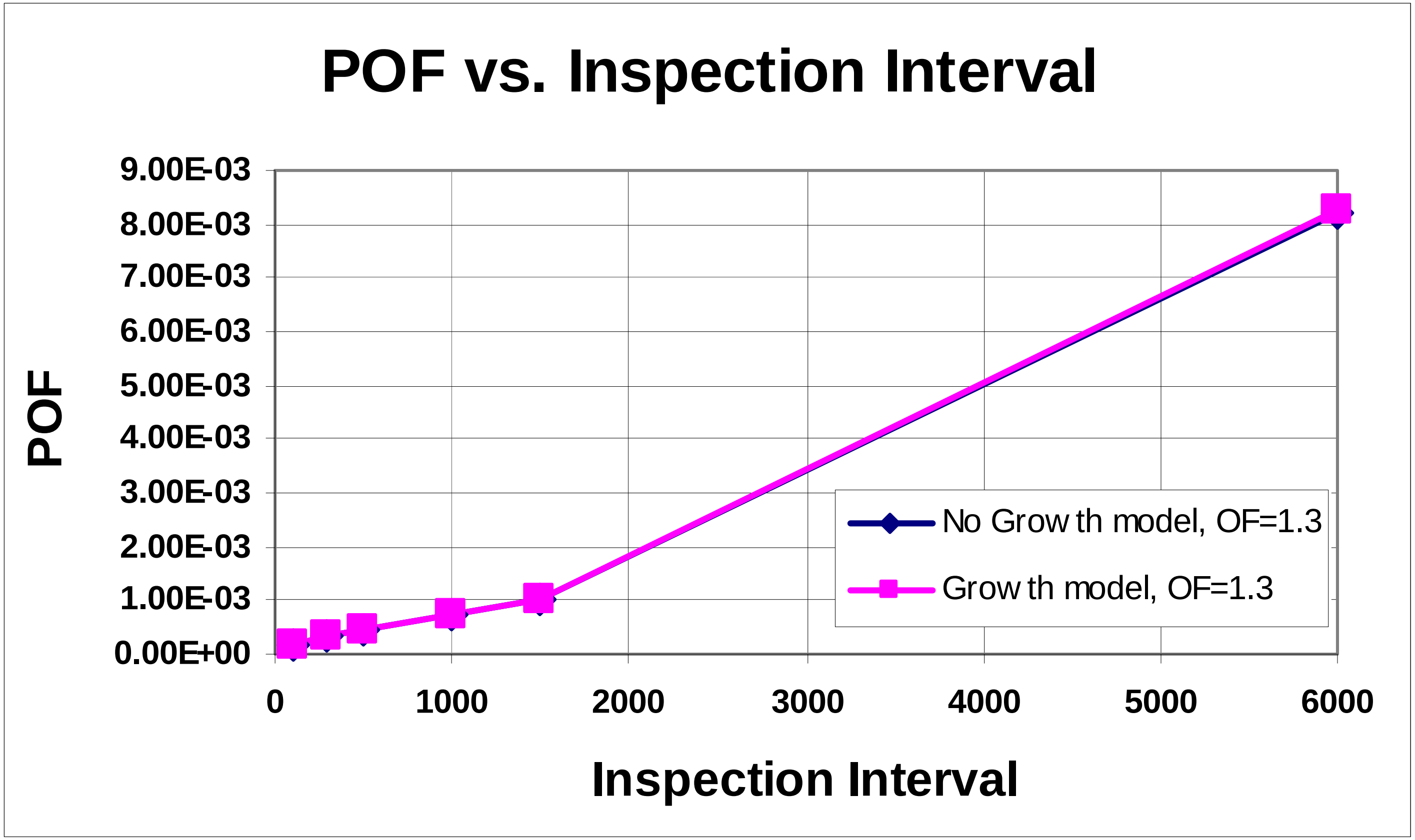
- Inversely determined using the static strength of the fuselage skin
- "Overload factors" are used for providing safety over the wider scatter of material properties
  - Limit load × 1.5 × overload factor = overall strength
- Distribution of peak load is taken from atmospheric turbulence, which is approximately exponential

* *FAA Static Strength Substantiation of Composite Airplane Structure (Policy Statement PS-ACE100-2001-006)*

Results on Overload Factor



Results on Inspection Interval



Effects of Damage Growth

- Detrimental effect on residual strength due to damage growth is small compared to original strength
- The effect of higher risk associated with larger damages after growth is offset by the increase in probability of detection by inspection
- The load range in which a damage could grow is very small, thus the probability of a damage growth event is also very small. The differences fall within noise of random simulation.

… consideration of damage growth in damage tolerance of composites is very much different from that of metallic structures

Work Plan:
More Complex Structural Models

Current Capabilities:

- Fixed Set of Random Variables
- Failure Criteria (one of the following):
  - **Stress > Allowable**
  - **Load > Strength**
  - **Temperature > Allowable**
  - **Debond Area > Allowable**
  - **Airspeed > Flutter Speed**
- Post-primary- Failure Criteria
- Non-random Aging-Humidity Infiltration Model
- Simplified Utility Equations

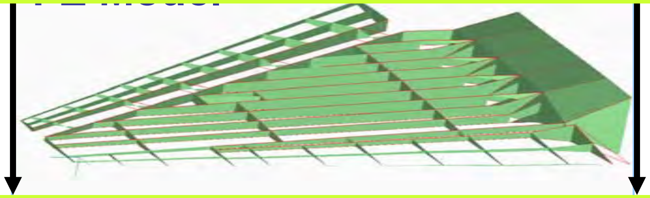
Desired Capabilities:

- More user-defined random variables

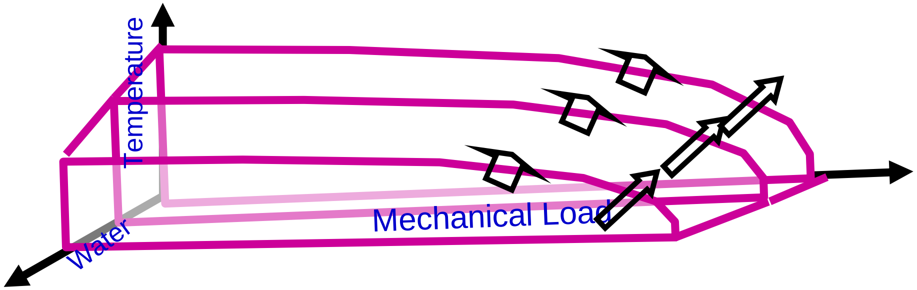
Damage-dependent Variables

Damage-independent Variables

- More complex structural model



- User-defined failure criteria



Summary

Work Accomplished:

- Developed a probabilistic method for determining POF and the inspection intervals
- Developed a computer code (RELACS) for calculating POF and the inspection intervals
- Mined statistical data on damage and other probabilistic parameters.
- Complete a user manual for RELACS
- Develop an example with FEA ABAQUS software for damage growth analysis

Work in Progress:

- Work with engineers at Boeing to apply RELACS to design and maintenance of composite aircraft
- Develop more complex structural model, e.g. stochastic FE models
- Add user-defined parameters, e.g. damage growth under fatigue loads

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.