Development of Reliability-Based Damage Tolerant Structural Design Methodology

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Reliability-Based Damage Tolerant Structural Design Methodology

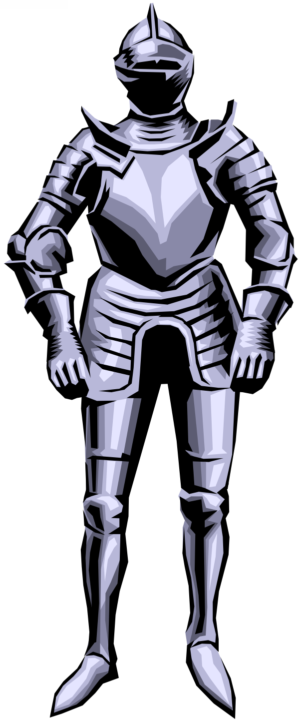
- ***Motivation and Key Issues:*** Composite materials are being used in aircraft primary structures such as 787 wings and fuselage. In these applications, stringent requirements on weight, damage tolerance, reliability and cost must be satisfied. Although currently there are MSG-3 guidelines for general 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.

Many Ways to Design a Damage Tolerant Structure

Damage-Tolerant Structure	= -	Additional skin thickness/weight/cost	+	Cheaper maintenance
Damage-Tolerant Structure	= -	Frequent checks/repairs	+	Structural weight/cost Savings
Damage-Tolerant Structure	= -	More thorough expensive checks	+	Less Frequent checks/repairs
Damage-Tolerant Structure	= -	Temporary field repair + final hangar repair	+	No revenue losses from diverted flights

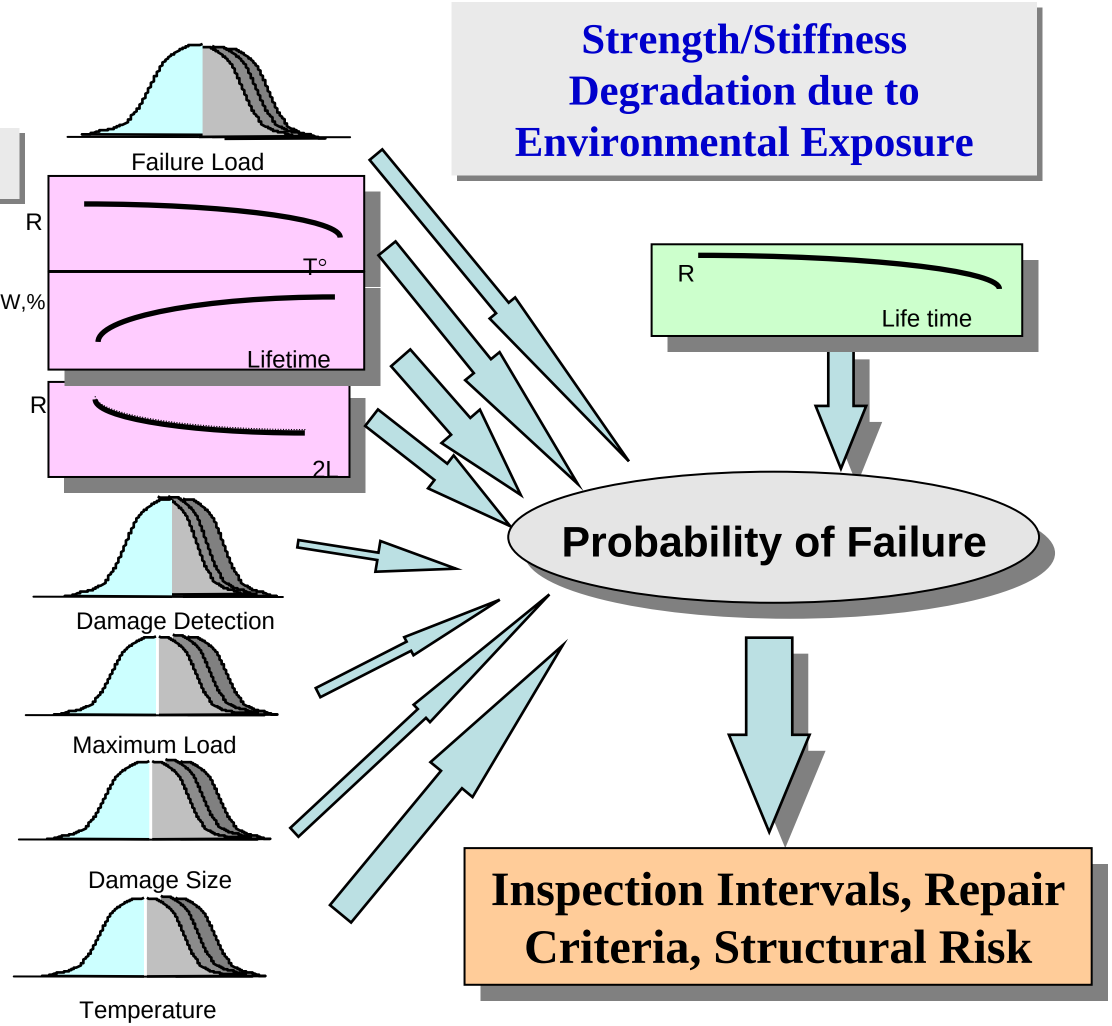


ARMOR

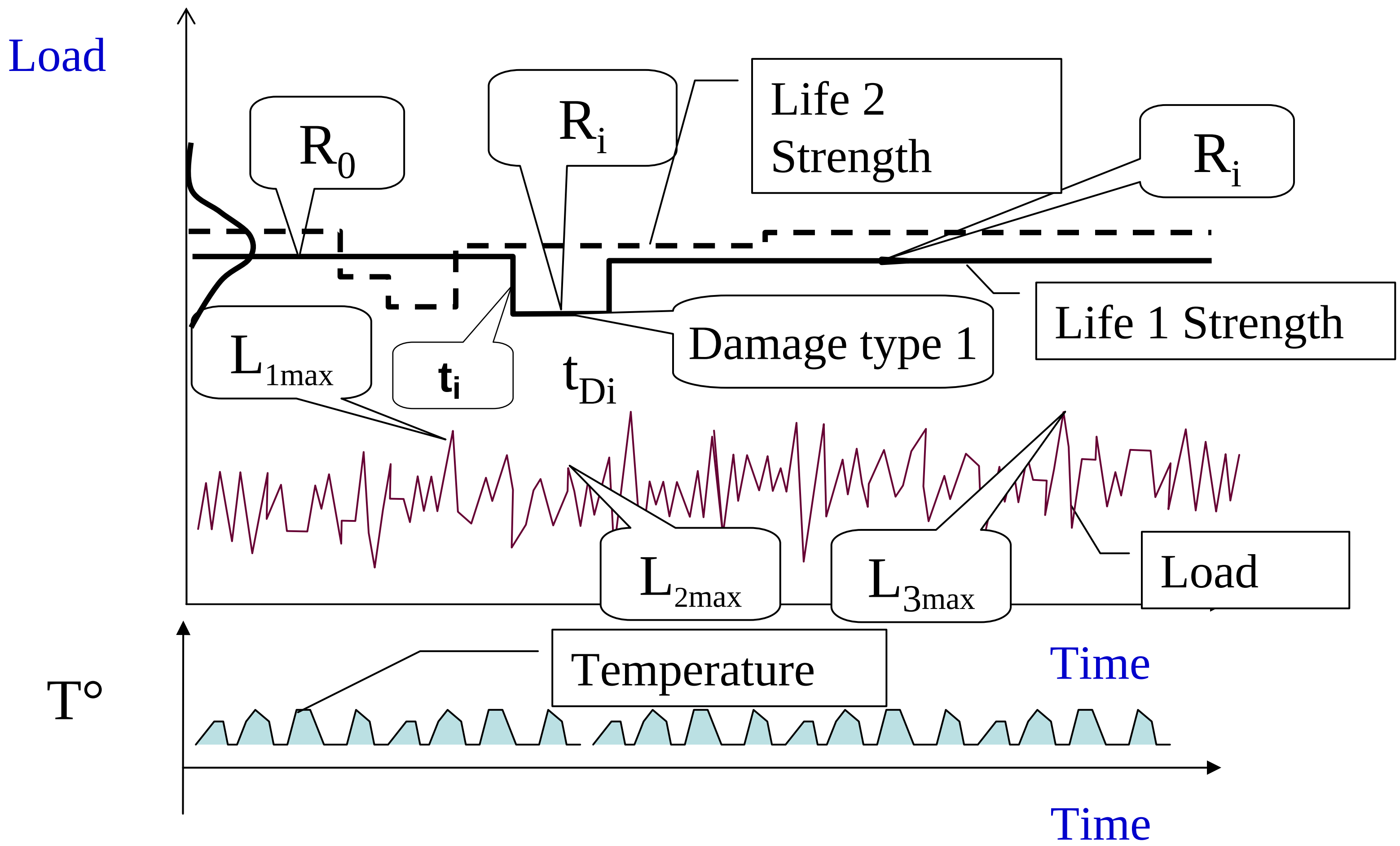
There is a need to evaluate the risk associated with each scenario: probability of failure evaluation is required

The 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



The 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, …

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

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

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 $T°_i^J$
- Quality of repair (recovery %)
- Effects of environmental aging and chemical corrosion

Piecewise random history method:

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

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

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

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

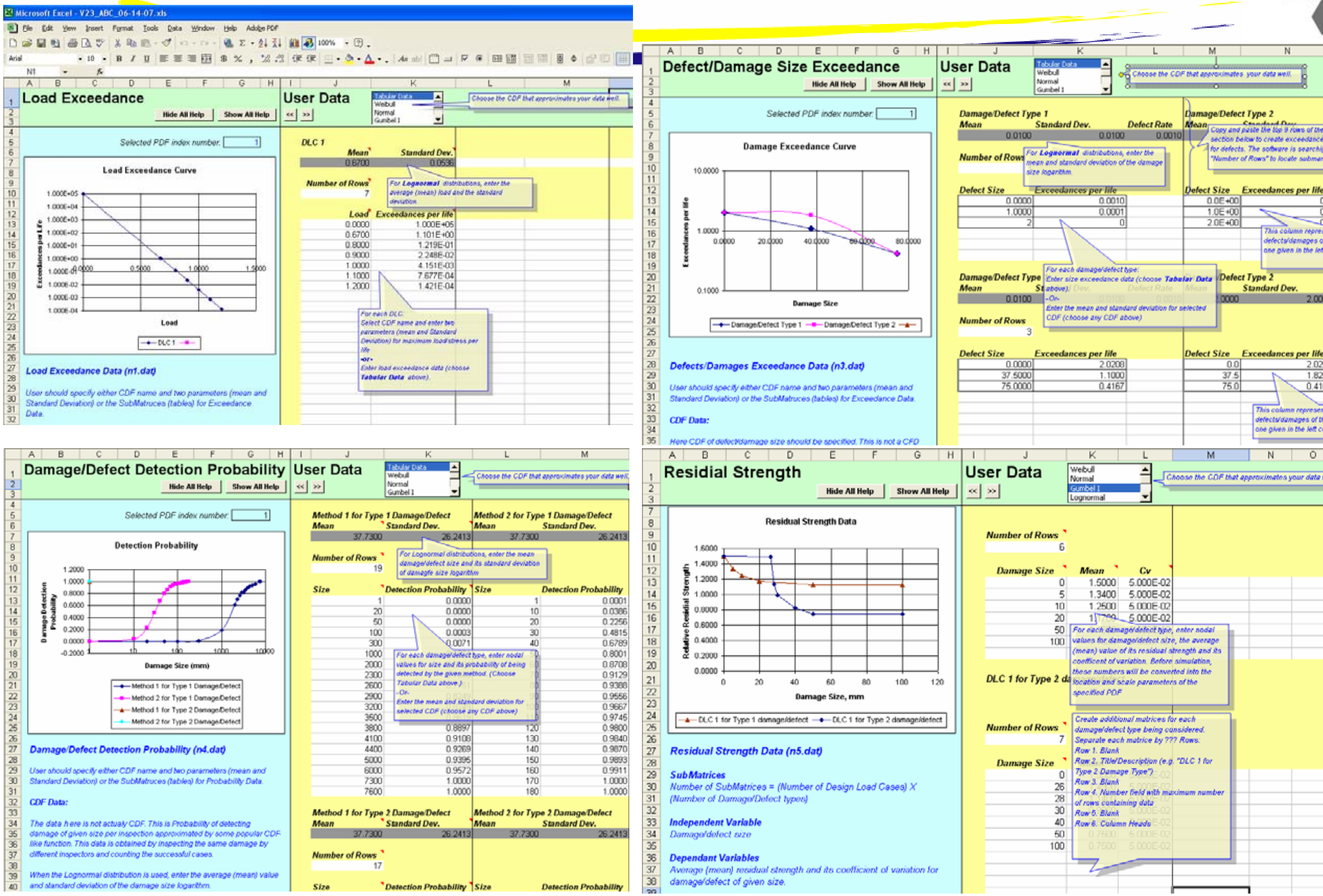
RELACS: Reliability Lifecycle Analysis of Composite Structures

Failure Modes Considered in RELACS:

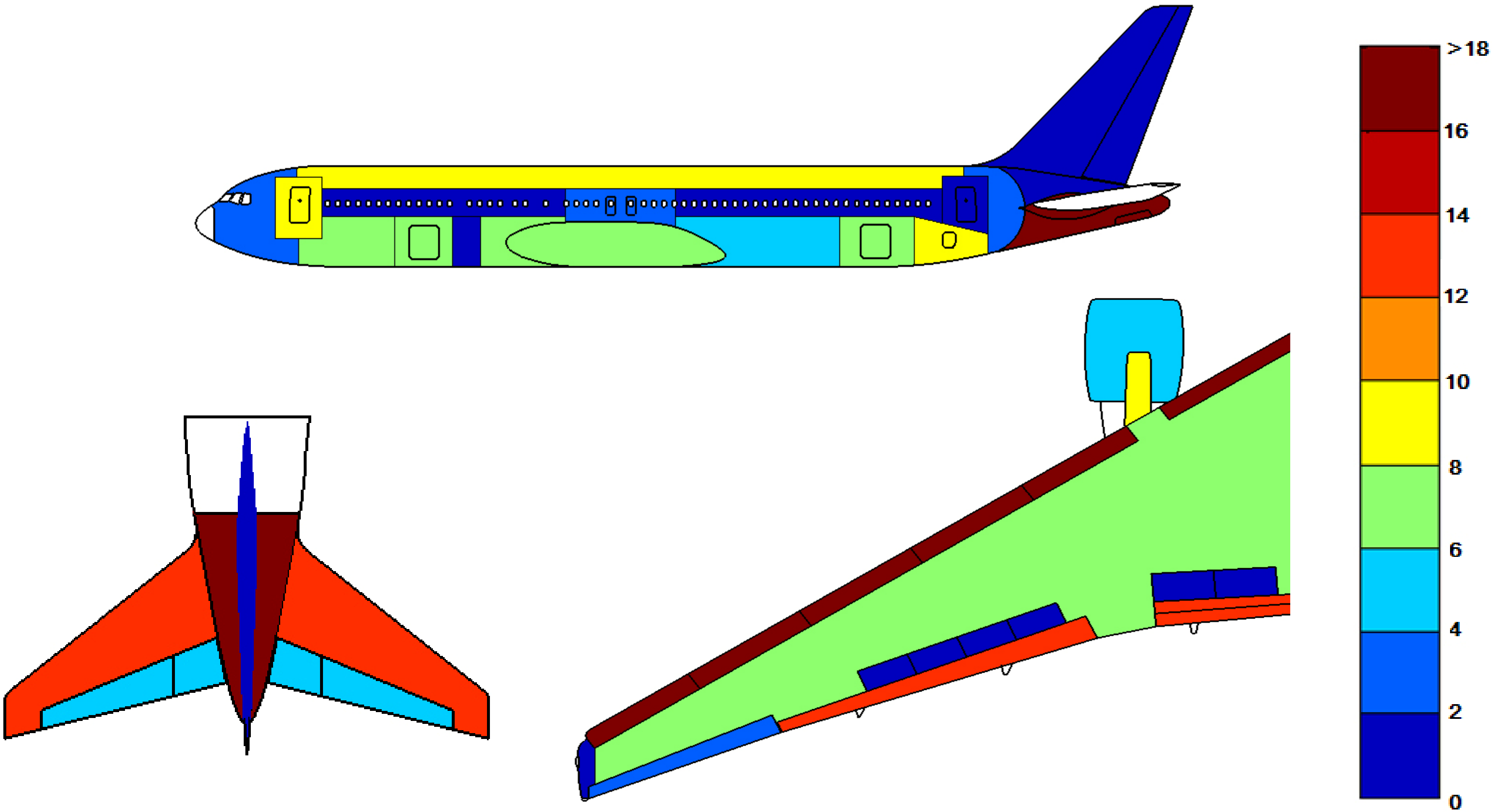
- “Static” failure: load exceeds the strength of damaged structures
- Deformation exceeds acceptable level
- Flutter: airspeed exceeds the flutter speed of damaged or repaired structure*
- High amplitude limit cycle oscillations: the acceptable level of vibrations is exceeded*

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

Input Data Management

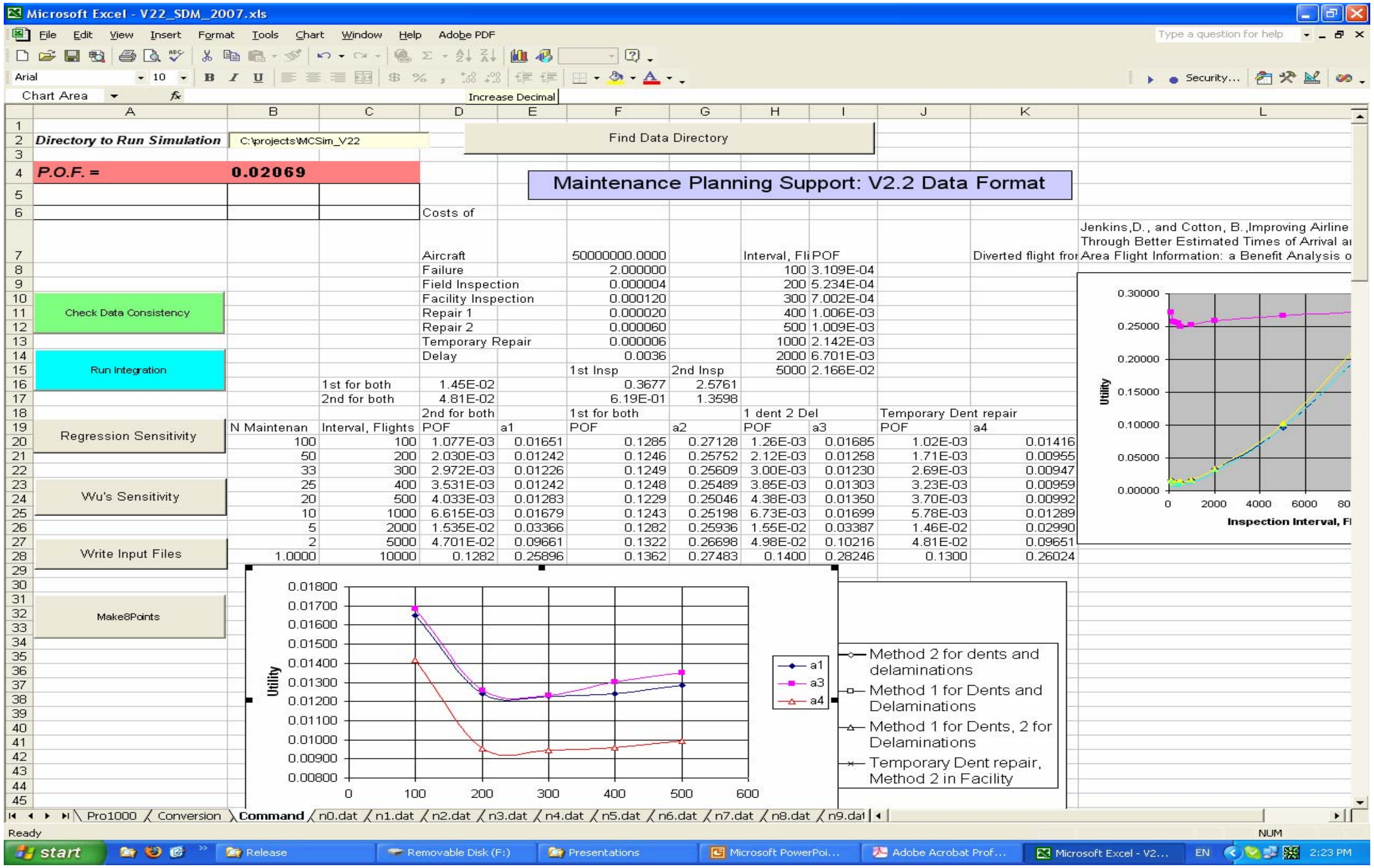


Example of SDR External Damage Map



RELACS OUTPUT:

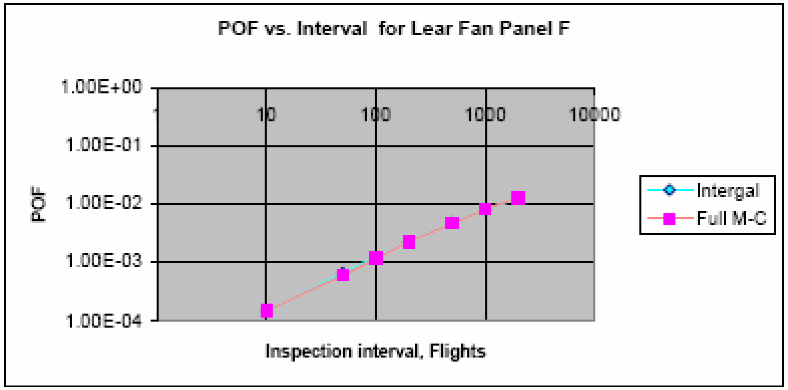
Minimum Risk Maintenance Planning



	A	B	C	D	E	F	G	H	I	J	K	L
2	*Directory to Run Simulation*	C:\projects\MCSim_V22										
4	*P.O.F. =*	**0.02069**										
6				Costs of								
7				Aircraft		50000000.0000		Interval, Fli	POF		Diverted flight fror	Jenkins,D., and Cotton, B.,Improving Airline Through Better Estimated Times of Arrival ai Area Flight Information: a Benefit Analysis o
8				Failure		2.000000		100	3.109E-04			
9				Field Inspection		0.000004		200	5.234E-04			
10				Facility Inspection		0.000120		300	7.002E-04			
11				Repair 1		0.000020		400	1.006E-03			
12				Repair 2		0.000060		500	1.009E-03			
13				Temporary Repair		0.000006		1000	2.142E-03			
14				Delay		0.0036		2000	6.701E-03			
15						1st Insp	2nd Insp	5000	2.166E-02			
16			1st for both	1.45E-02		0.3677	2.5761					
17			2nd for both	4.81E-02		6.19E-01	1.3598					
18				2nd for both		1st for both		1 dent 2 Del		Temporary Dent repair		
19		N Maintenan	Interval, Flights	POF	a1	POF	a2	POF	a3	POF	a4	
20		100	100	1.077E-03	0.01651	0.1285	0.27128	1.26E-03	0.01685	1.02E-03	0.01416	
21		50	200	2.030E-03	0.01242	0.1246	0.25752	2.12E-03	0.01258	1.71E-03	0.00955	
22		33	300	2.972E-03	0.01226	0.1249	0.25609	3.00E-03	0.01230	2.69E-03	0.00947	
23		25	400	3.531E-03	0.01242	0.1248	0.25489	3.85E-03	0.01303	3.23E-03	0.00959	
24		20	500	4.033E-03	0.01283	0.1229	0.25046	4.38E-03	0.01350	3.70E-03	0.00992	
25		10	1000	6.615E-03	0.01679	0.1243	0.25198	6.73E-03	0.01699	5.78E-03	0.01289	
26		5	2000	1.535E-02	0.03366	0.1282	0.25936	1.55E-02	0.03387	1.46E-02	0.02990	
27		2	5000	4.701E-02	0.09661	0.1322	0.26698	4.98E-02	0.10216	4.81E-02	0.09651	
28		1.0000	10000	0.1282	0.25896	0.1362	0.27483	0.1400	0.28246	0.1300	0.26024	

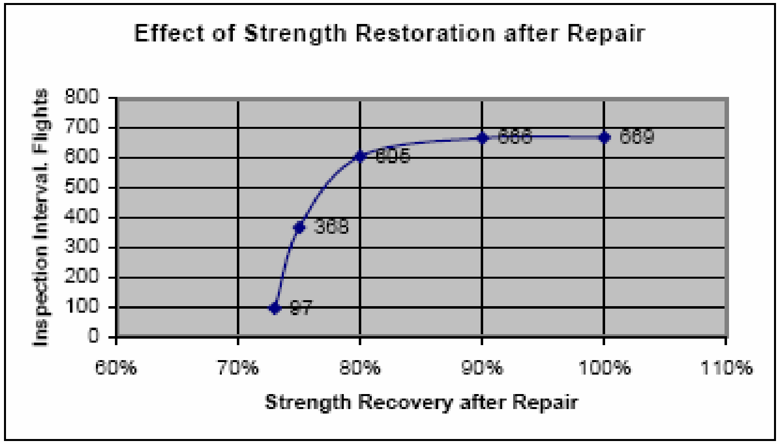
Sample Problem:
Lear Fan 2100 Composite Wing Panels

- **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 in Residual Strength
- Temperature Effects Included
- Relatively Low Reliability



* Assume POF=10e-4 per life →

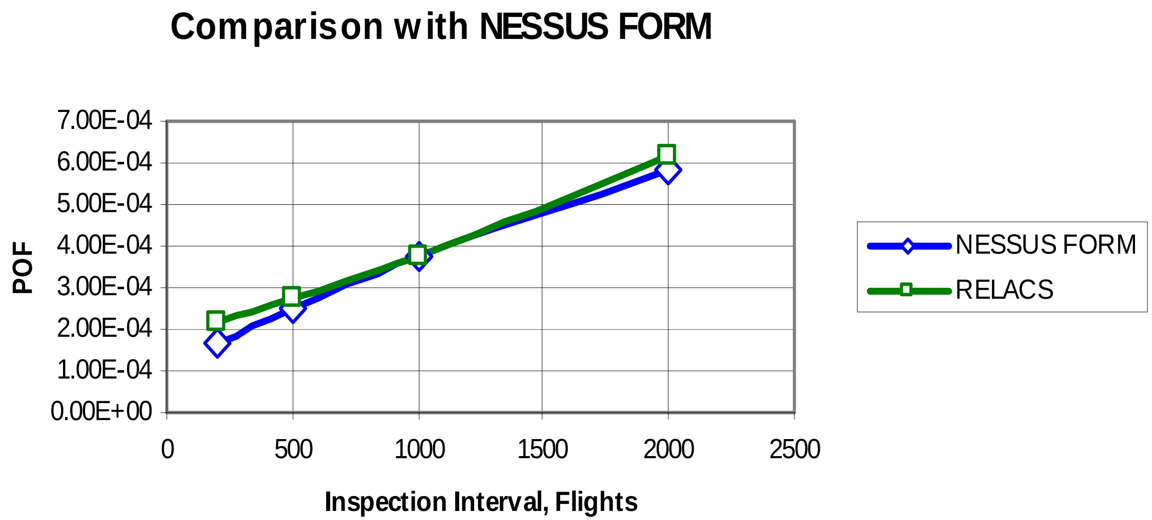
Validation of RELACS: Comparison with NESSUS

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%**

RELACS results agree well with output from NESSUS



Maintenance Planning Based on Risk Assessment

- Maintenance optimization is one of the most important design tools to manage damage-induced risk.
- Variability exists in many key parameters for damage tolerance analysis with inspections/repairs.
- An efficient reliability-based damage-tolerance analysis with inspections is urgently needed for general damage and maintenance scenarios.

Minimum Risk Maintenance Planning using Optimal Statistical Decisions

Family of Experiments (Inspection selection) E = {e}

- e_1, e_2 = Various Combinations of Inspection Methods and Intervals
- e_3 = No Inspections

Space of Experiment Outcomes (Inspection results) Z = {z}

- z_1, $z_{2...}$ = Various Damages Observed

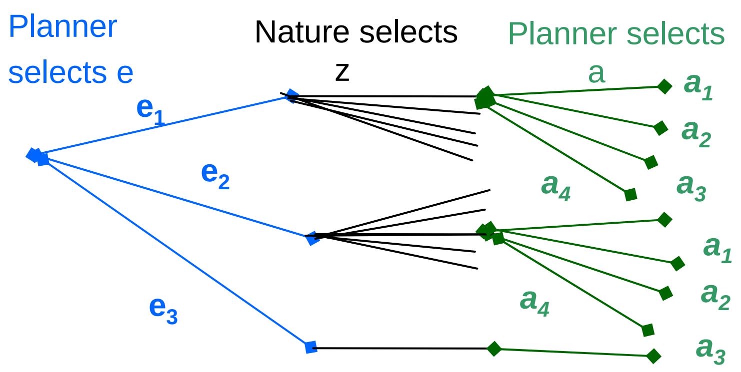
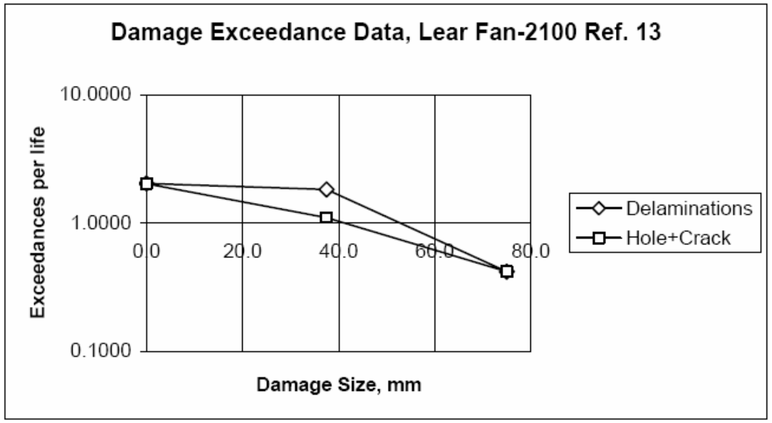


Figure Decision-making tree for inspections

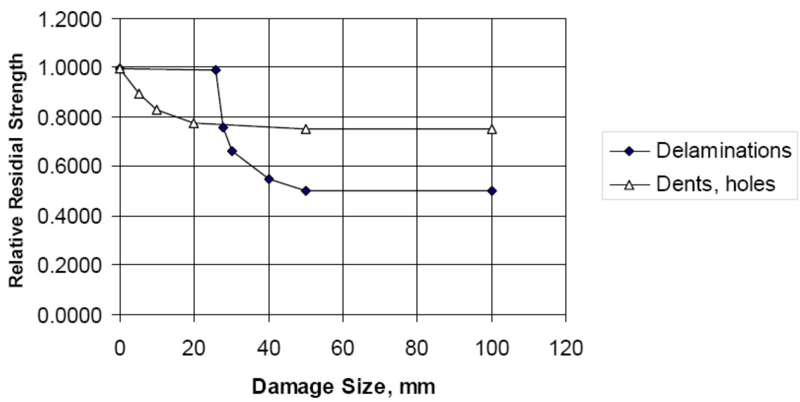
Space of Acts (Repair selection) A = {a}, e.g.

- a_1 = Method 1 (higher cost repair) for Field and Facility repair of all damages
- a_2 = Method 2 (lower cost repair) for Field and Facility repair of all damages
- a_3 = Method 2 for holes/dents, Method 1 for delaminations
- a_4 = Temporary repair for small damages that were detected in pre-flight Inspections. Method 1 for all damages repair during the regular scheduled maintenance

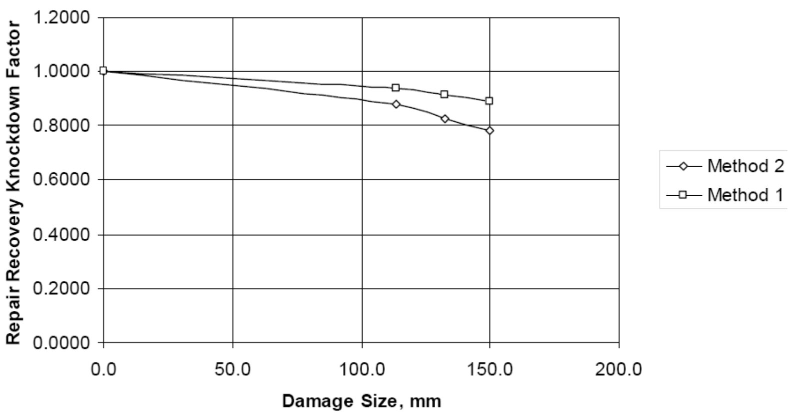
Minimum Risk Maintenance Planning
Input data for POF evaluation



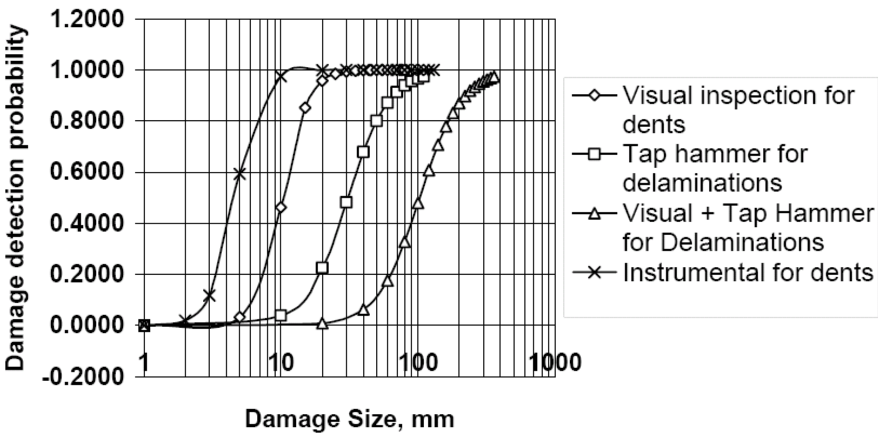
Residual Strength Data



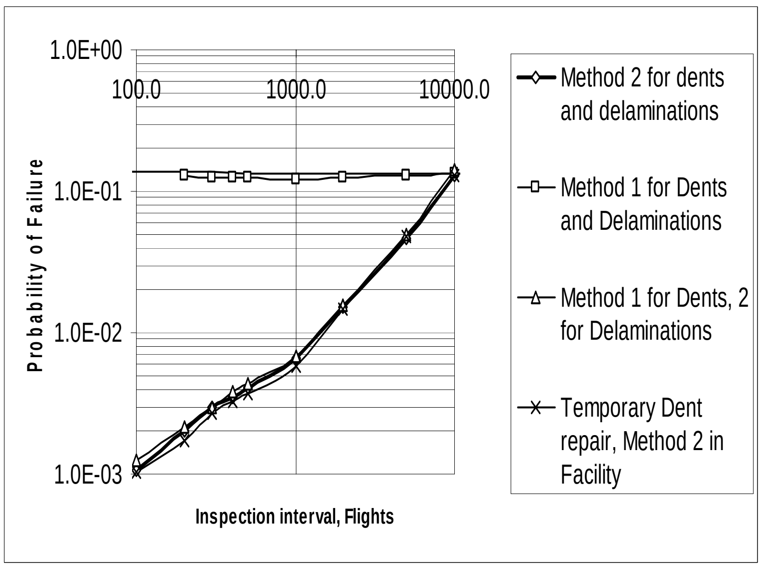
Repair Recovery Knockdown Factor versus Damage Size



Damage Detection Probability



Minimum Risk Maintenance Planning
Optimal Statistical Decision Output



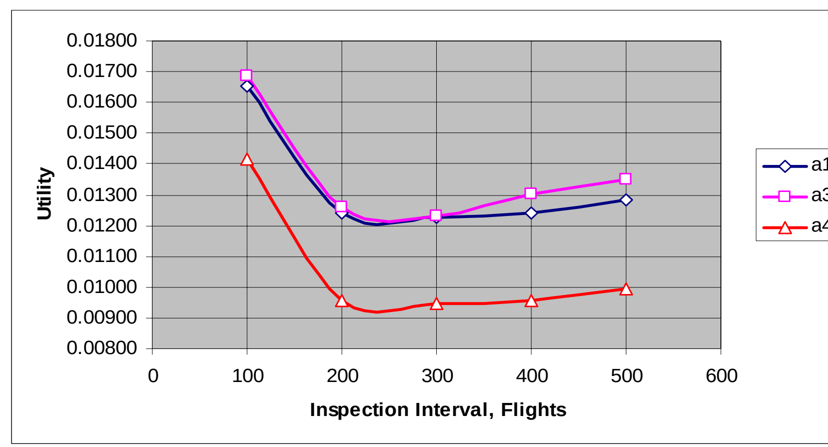
Utility Equations:

$$a_1: \quad u(e,z,a_1,\theta) = 2P_f + 0.0012N_m + (0.0036 + 6\cdot 10^{-5})N_{rep1} + 6\cdot 10^{-5} N_{rep2}$$

$$a_2: \quad u(e,z,a_1,\theta) = 2P_f + 0.0012N_m + (0.0036 + 2\cdot 10^{-5})N_{rep1} + 2\cdot 10^{-5} N_{rep2}$$

$$a_3: \quad u(e,z,a_1,\theta) = 2P_f + 0.0012N_m + (0.0036 + 2\cdot 10^{-5})N_{rep1} + 6\cdot 10^{-5} N_{rep2}$$

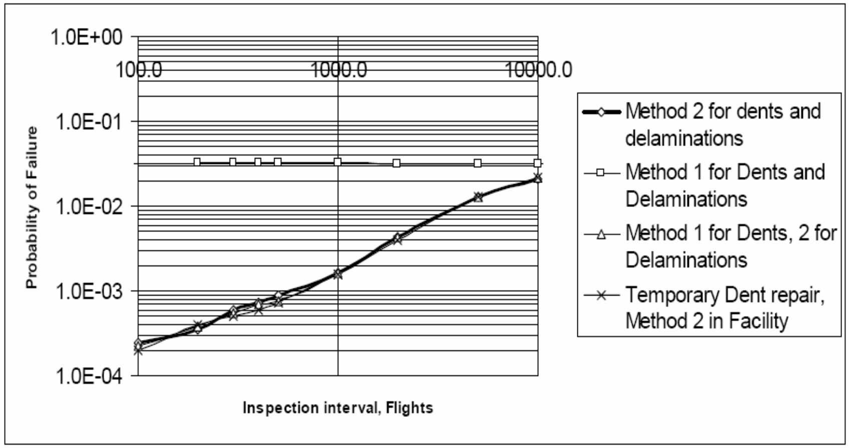
$$a_4: \quad u(e,z,a_1,\theta) = 2P_f + 0.0012N_m + 2\cdot 10^{-6} N_{rep1} + 6\cdot 10^{-5} N_{rep2}$$

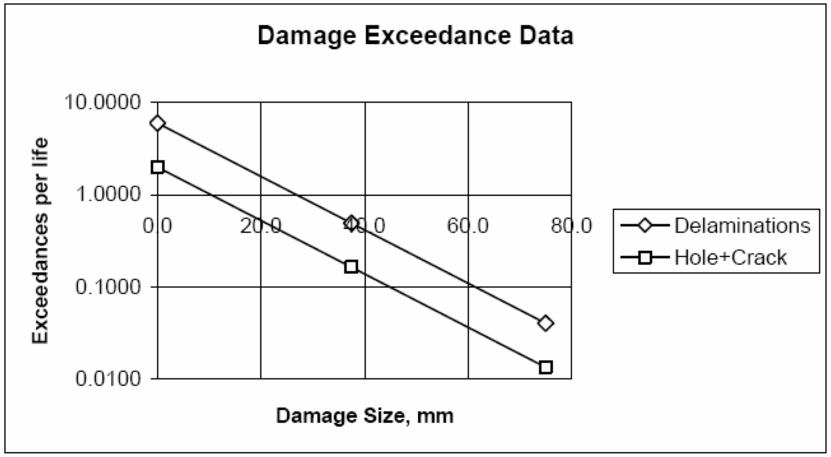


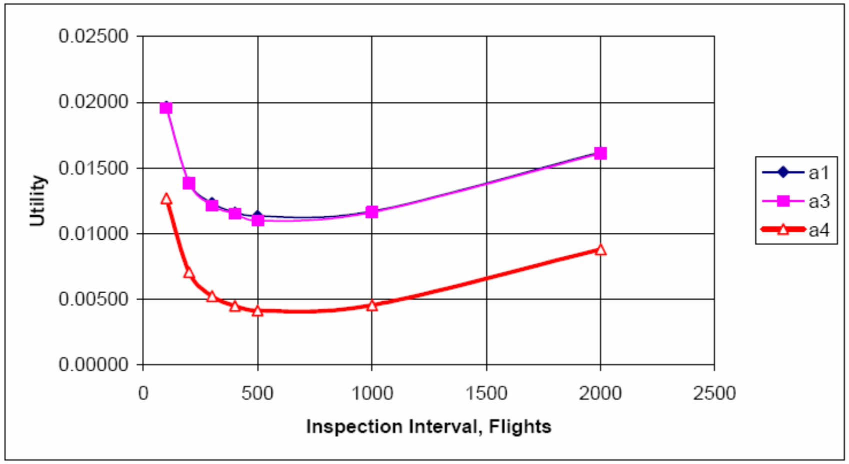
For large damage that will be repaired within a few flights: key factor is repair quality

Minimum Risk Maintenance Planning 2

Optimal Statistical Decisions







For small damages that will remain undetected for a long tome: Key factors are repair quality + POD

Practical Applications of RELACS

- Currently, the reliability analysis allows continuously adjustable inspection intervals, this is not realistic in the real world as many “maintenance tasks” are grouped together and performed in “maintenance checks (A,B,C,D checks)”.
- Inspection scheduling and maintenance are influenced by other technical factors: availability of certified technician and equipments, environmental and operational limitations (deferred repairs), etc.
- Maintenance planning is also influenced by costs, reliability and safety, damage statistics from service history, etc.
- Collaborations with specialists in the life-cycle management area could help define many variables and guide the development of the software towards industrial application.

Damage Growth Consideration
VCCT from ABAQUS

- Commercial FEM code ABAQUS has been used to explore the feasibility of including a damage growth model – delamination and debonding
- The code implements Virtual Crack Closure Technique (VCCT) to predict delamination/ debonding growth

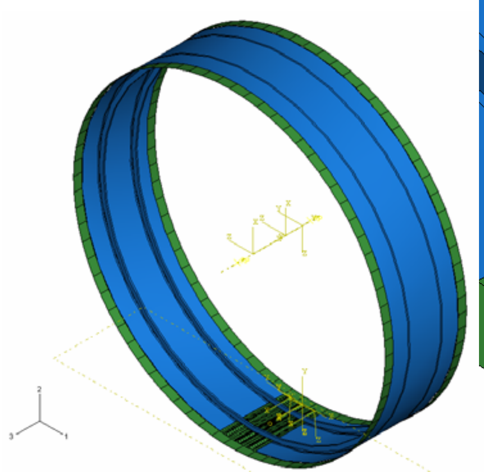
  The total strain energy released when a crack is extended by a certain amount is the same as the energy required to close the crack surface by the same amount. When the energy release rate reaches the critical energy release rate value for the corresponding mode, a pair of “bonded nodes” are separated and the crack extends.

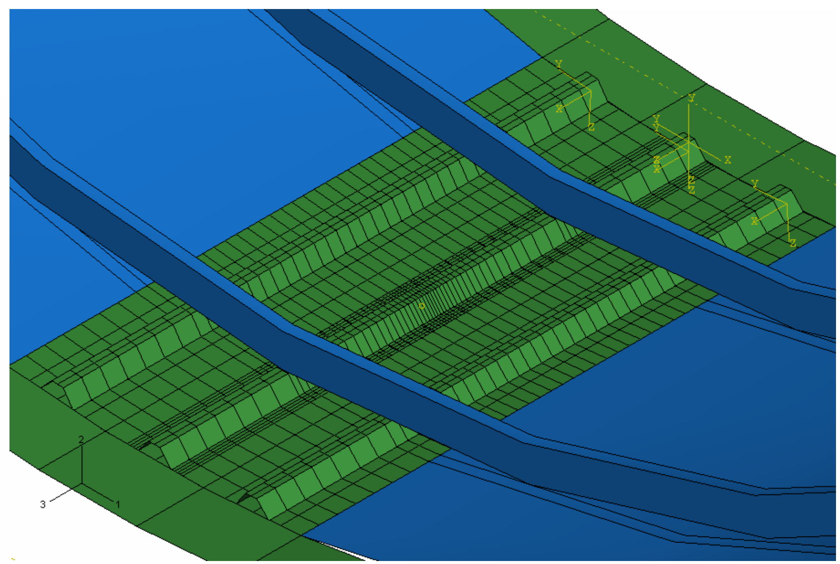
- Damage growth analysis does not require re-meshing after each crack extension

Damage Growth Consideration

A Preliminary Study

- 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)
- Debonding of various sizes are implanted at the center of the stringer, on both legs of the hat stringer
- Skin-stringer debonding under shear is considered
- Frames spacing at 24” (debonding cannot penetrate frame locations)



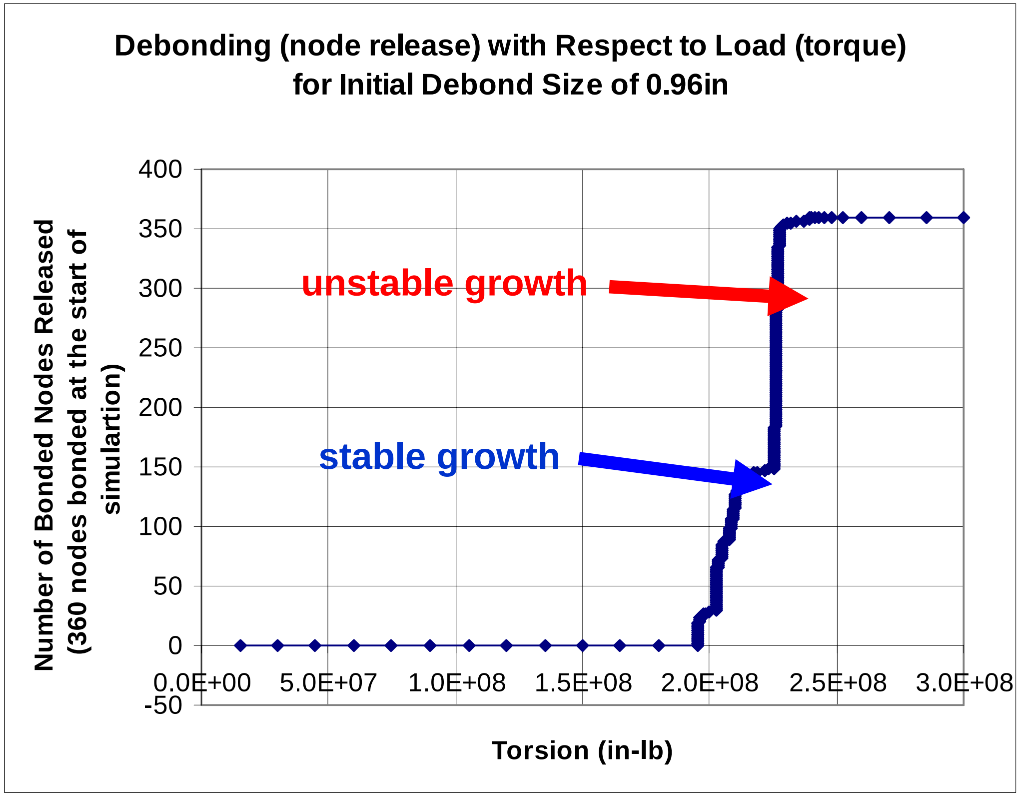


Damage Growth Consideration

Example of Debonding Growth Results

Initial flaw = 0.96”

- Initial debonding means the 30 nodes at the mid-point between two frames are not connected; the remaining 360 nodes are bonded.
- Torsion load on fuselage is ramped from 0 in-lb to 3×10^8 in-lb.
- Nodes released represent the extension of debonding somewhere along the crack front.

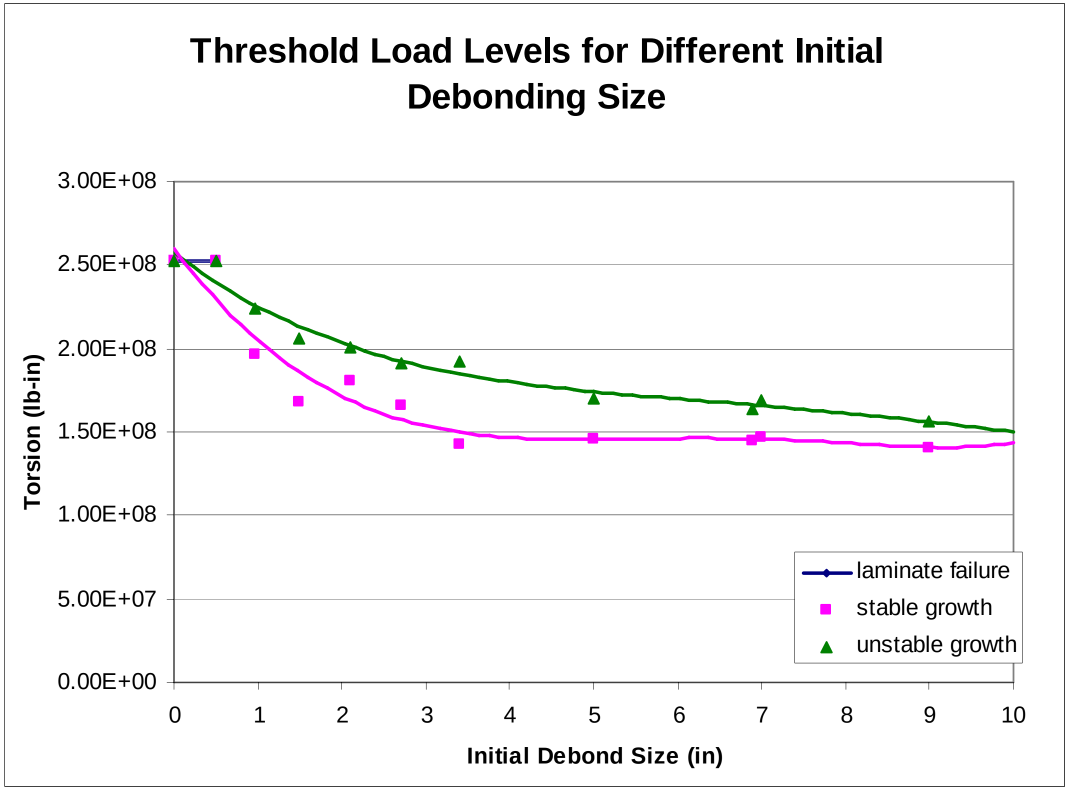


click for movie

Damage Growth Consideration

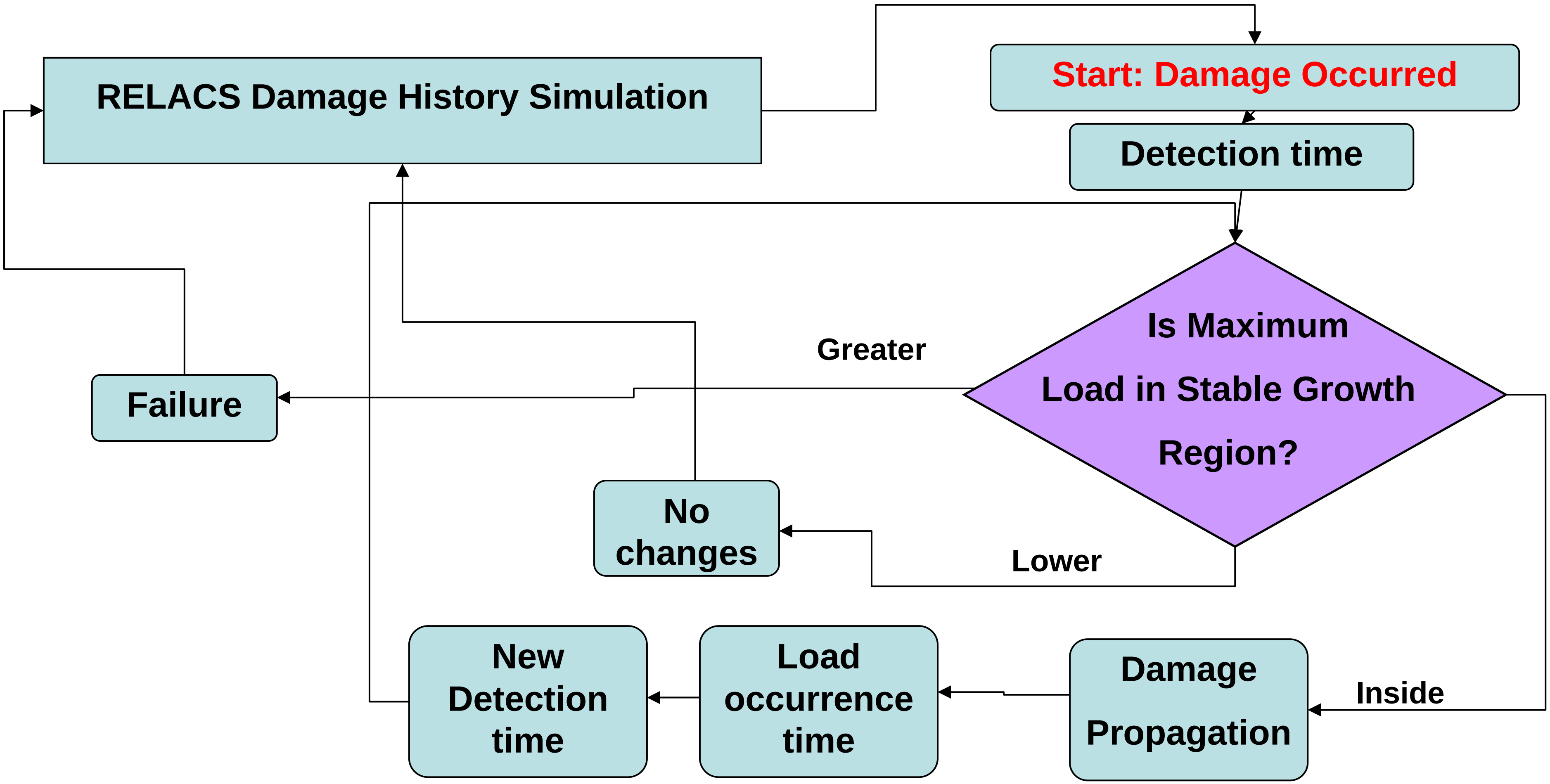
Results for Various Initial Damage Size

- Ultimate load capability reduction 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.



Damage Growth Consideration

Integration into RELACS



Work Plan: Enhance RELACS Core Capabilities

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

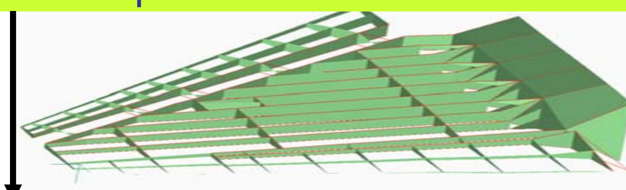
Desired Capabilities:

- More user-defined random variables

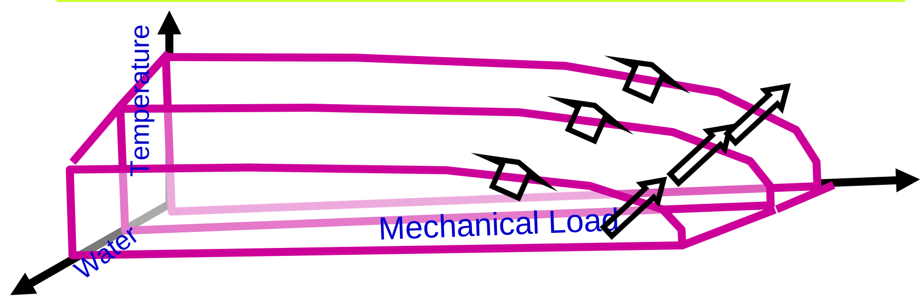
Damage-dependent Variables

Damage-independent Variables

- More complex structural model



- User-defined failure criteria



The RELACS Code- 2007

- A simulation-based approach
- Based on a few realistic assumptions
- Results are easily verifiable
- All key factors are taken into account
- Reasonably fast computations
- The worst-case scenario can be simulated

However, some input data need to be obtained through expensive tests. Alternately, analytical methods can be used for predicting these data:

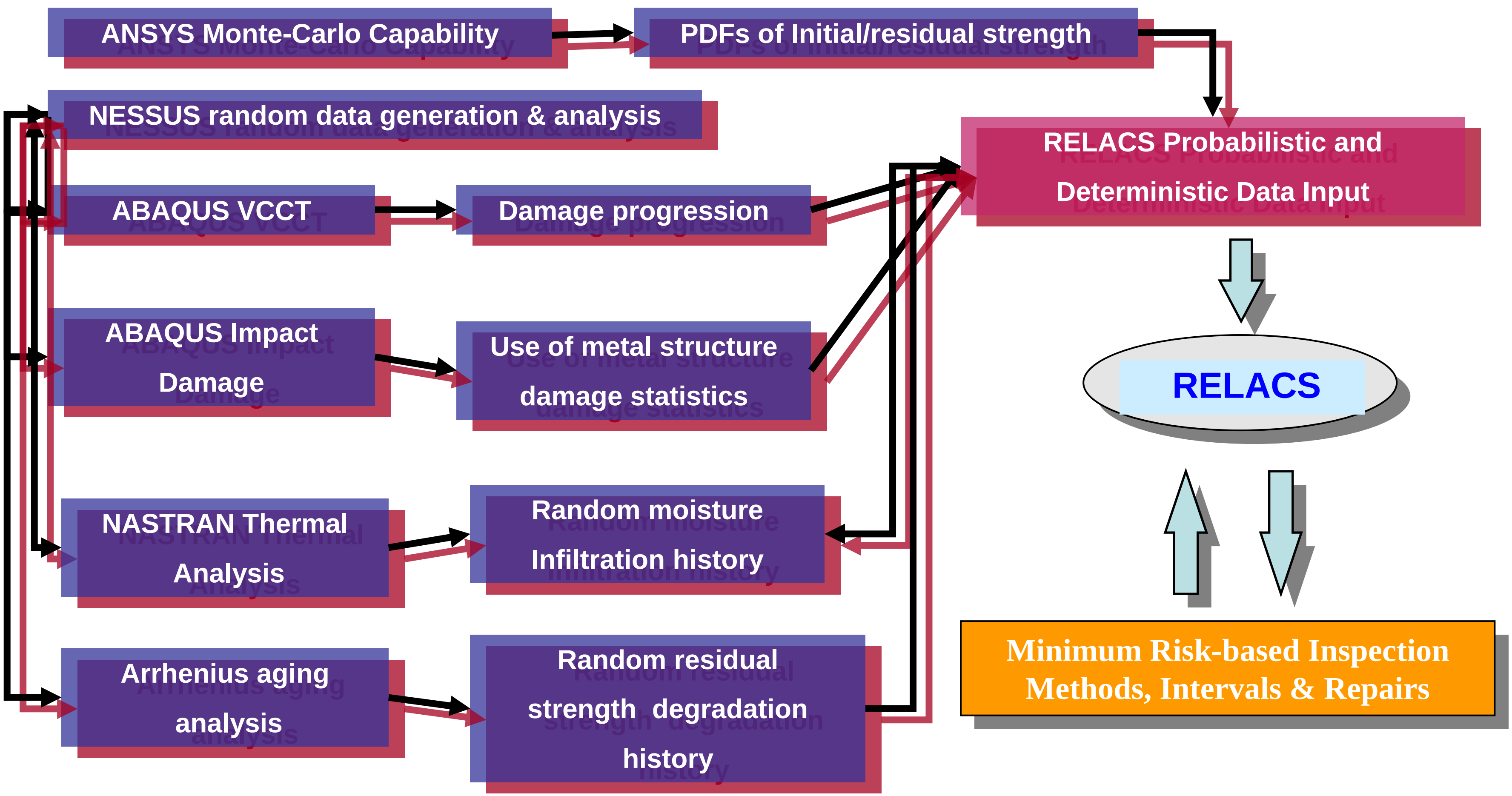
- Initial/residual strength
- Aging degradation
- Damage Growth
- Moisture absorption

Work Plan: Probabilistic Input Data Generation

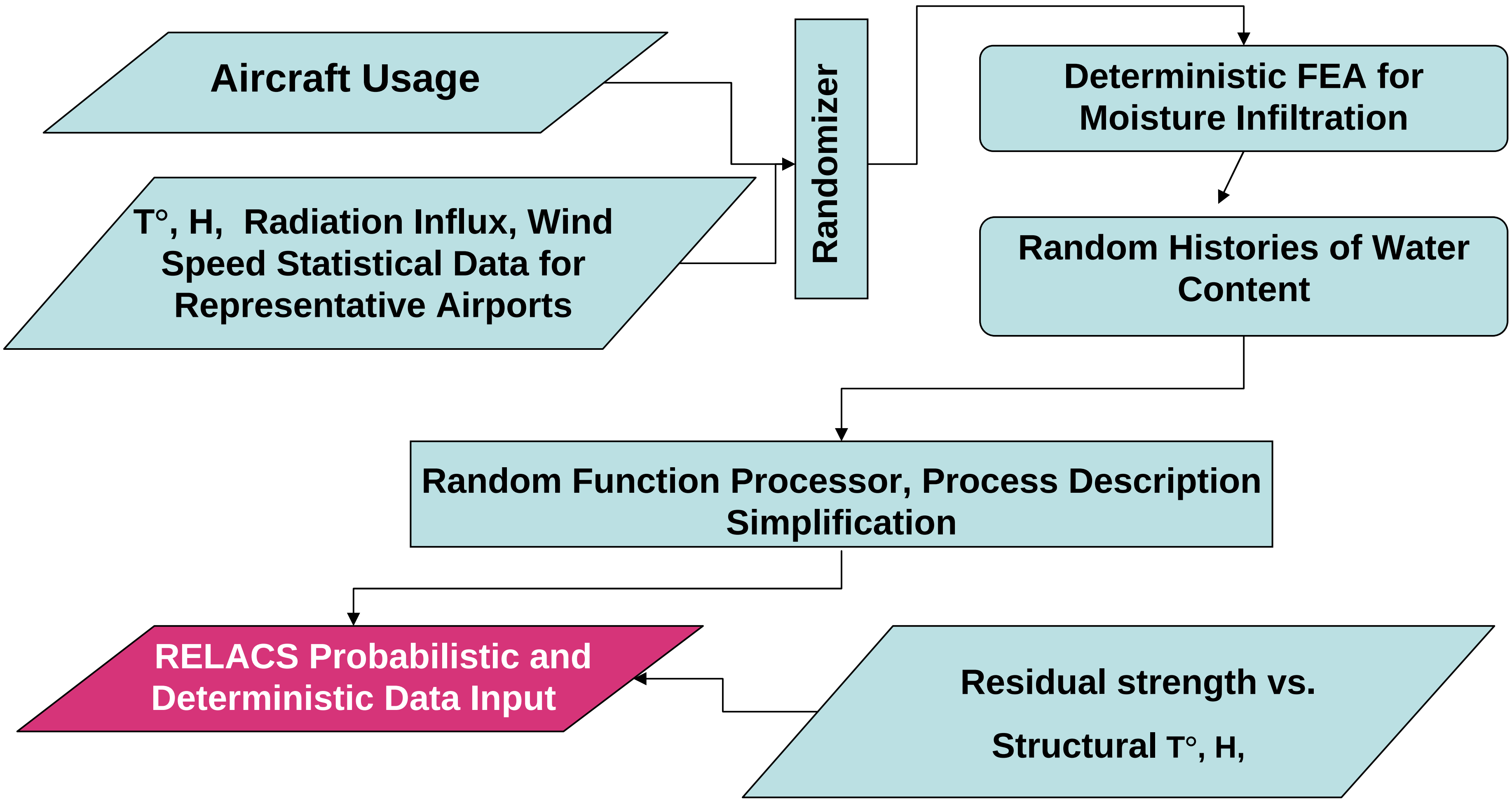
The main goal of the next step study is to alleviate data mining work using the available deterministic models for probabilistic analyses:

- Use ANSYS and ABAQUS to obtain the initial and residual strength variance
- Use ABAQUS to characterize impact damage and residual strength
- Use ABAQUS for predicting damage propagation
- Use the thermal FEA method for predicting moisture infiltration
- Use the available aging degradation models for composites

Work Plan: Software Integration



Moisture Infiltration Random Generator



Summary

Work Accomplished:

- Developed a probabilistic method for determining POF and the inspection intervals.
- Developed a preliminary computer code (RELACS) for calculating POF and the inspection intervals.
- Mined statistical data on damage and other probabilistic parameters.

Work in Progress:

- Complete a user manual for RELACS.
- Develop an example interface with FEA ABAQUS software for damage growth analysis.
- Work with engineers at Boeing to apply RELACS to design and maintenance of composite aircraft.

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.