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.

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

Research Accomplishments

- Developed a Probabilistic Method for Determining the Inspection Intervals for Aircraft Composite Structures.
- Developed Computing Tools and Algorithms for the Probabilistic Analysis.
- Established In-service Damage Database from FAA SDR and Other Sources.
- Demonstrated the Developed Method on Existing Structural Components.

Probabilistic Approach

Various Failure Modes

Strength/Stiffness vs. Temperature

Moisture Content vs. Time

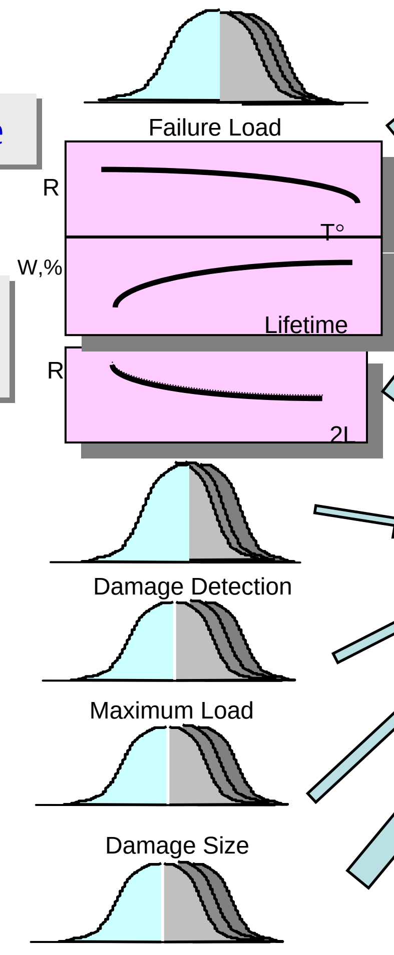
Residual Strength/Stiffness vs. Damage Size & Damage Type

Probability of Detection vs. Damage Size & Damage Type

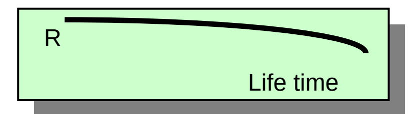
Maximum Load vs. Time of Damage Existence

Damage Size & Damage Type Spectra

Structural Temperature Spectra



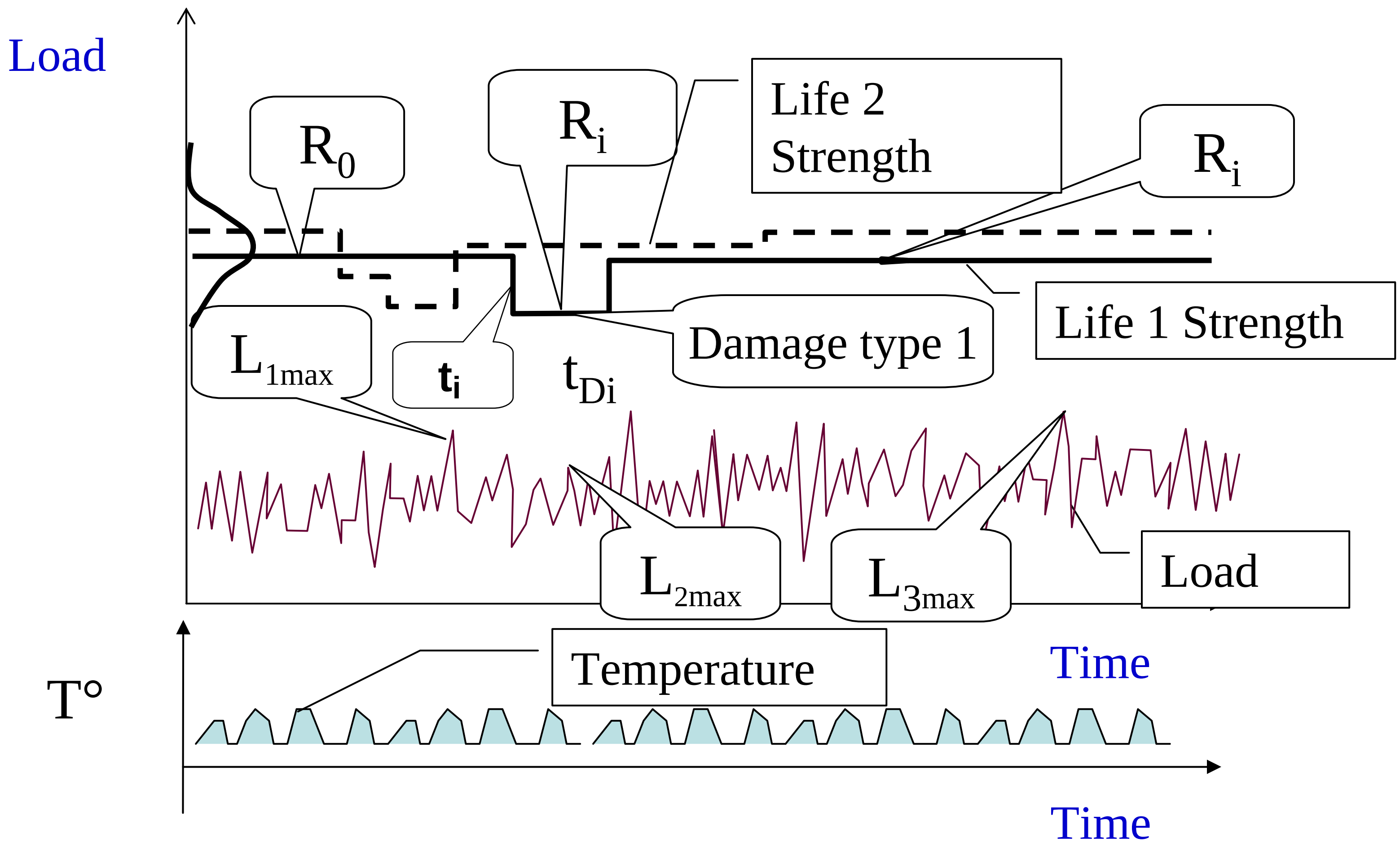
Strength/Stiffness Degradation due to Environmental Exposure



Probability of Failure

Inspection Intervals, Repair Criteria, Structural Risk

The Probabilistic Model



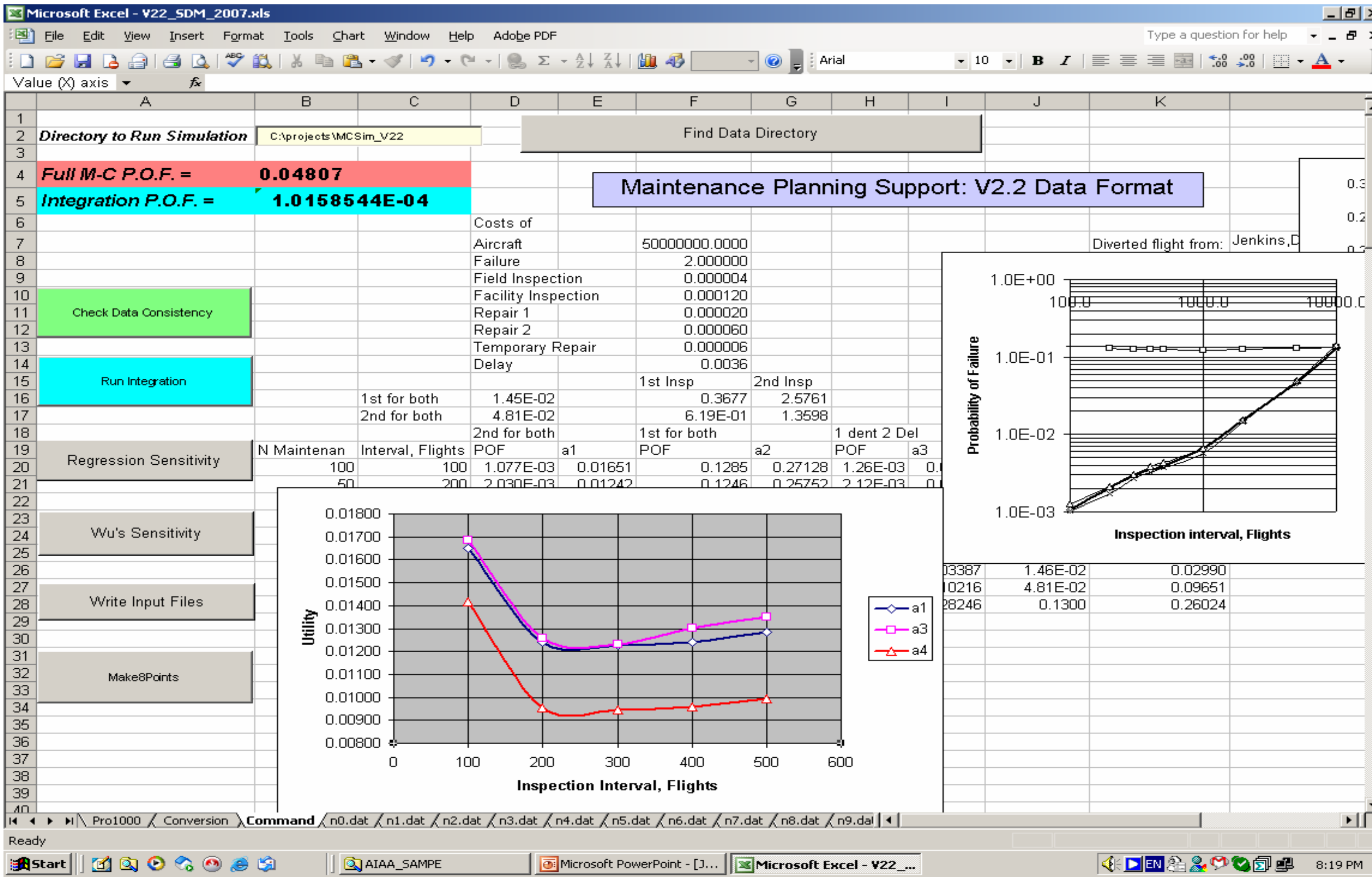
Program Capabilities: Various Failure Modes

- “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*

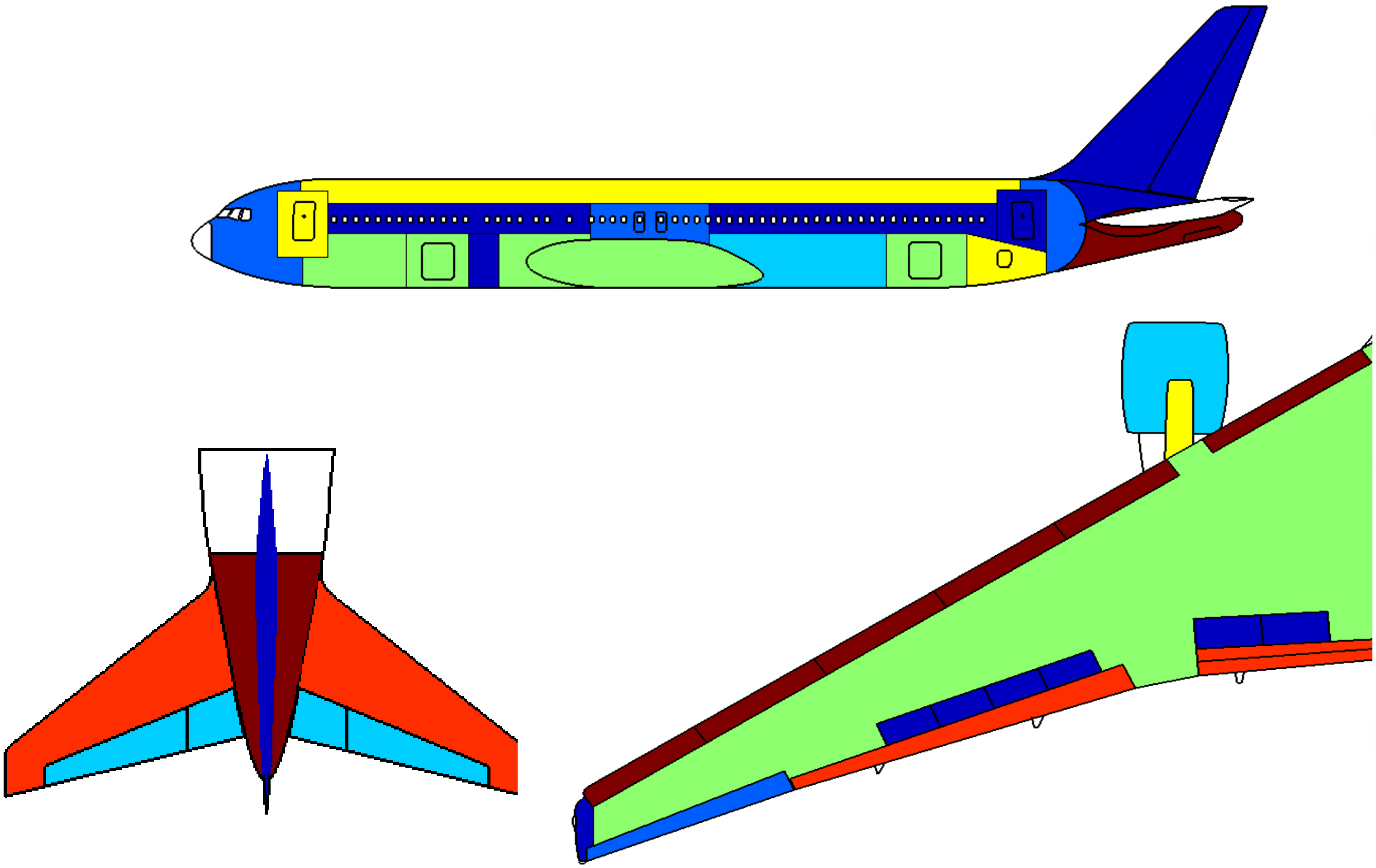
**See the FAA Grant “Combined Local-Global Variability and Uncertainty in the Aeroservoelasticity of Composite Aircraft”*

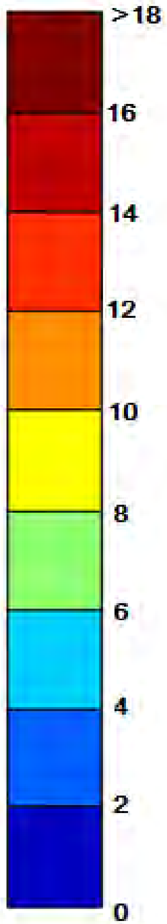
Program Capabilities:

Minimum Risk Maintenance Planning



SDR: External Damage Map





Minimum Risk Maintenance Planning

Theory of 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**

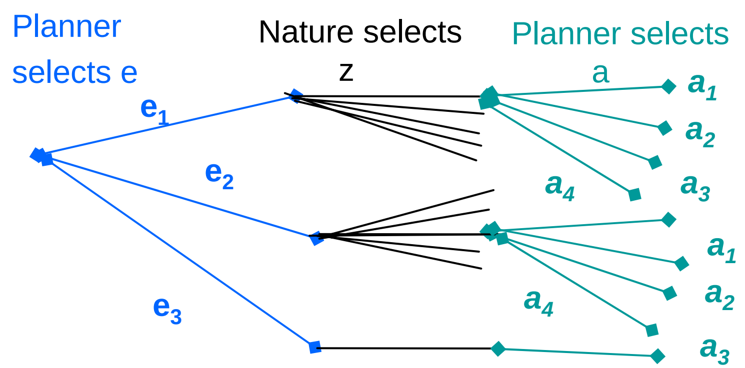


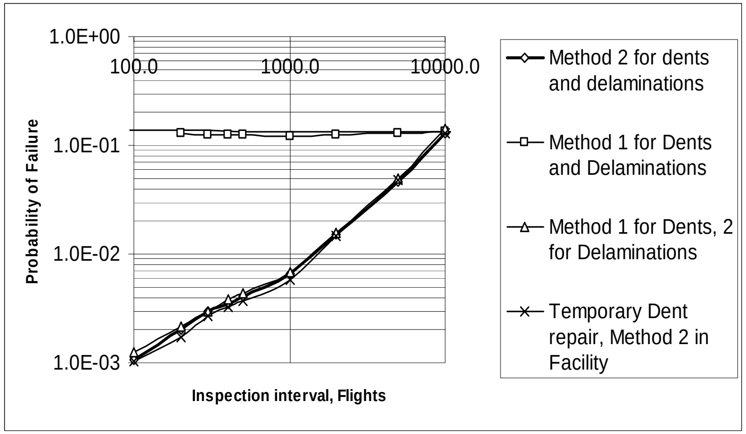
Figure Decision-making tree for inspections

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

- **a_1 = Method 1 for Field and Facility repair of all damages**
- **a_2 = Method 2 for Field and Facility repair of all damages**
- **a_3 = Method 1 for holes/dents, Method 2 for delaminations**
- **a_4 = Temporary repair for holes/dents, detected in pre-flight Inspections, Method 2 for holes/dents, delaminations in Facility**

Minimum Risk Maintenance Planning 1

Optimal Statistical Decisions



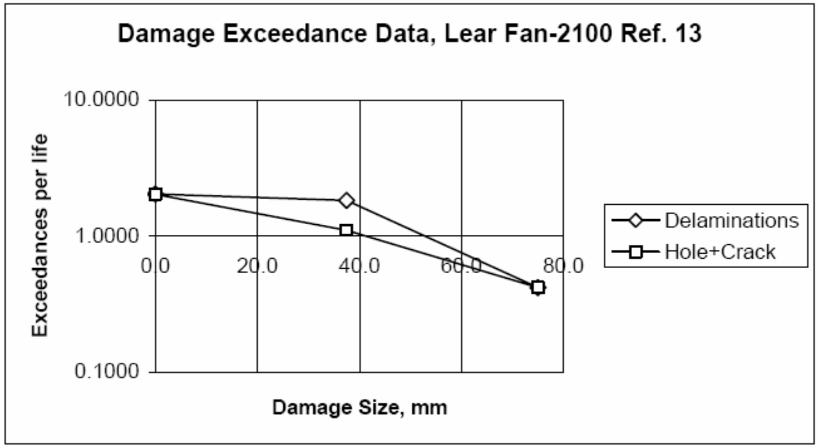
Utility Equations:

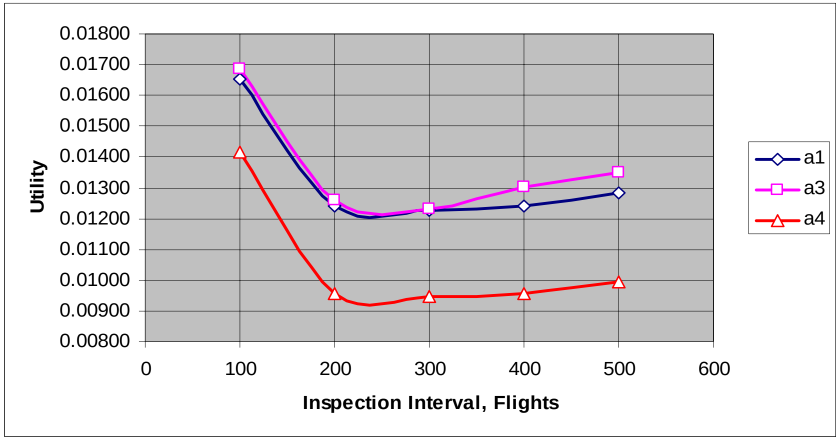
$$a_1: \quad u(e,z,a_1,\theta) = 2P_f + 0.0012N_m + (0.0036 + 6\cdot10^{-5})N_{rep1} + 6\cdot10^{-5}N_{rep2}$$

$$a_2: \quad u(e,z,a_1,\theta) = 2P_f + 0.0012N_m + (0.0036 + 2\cdot10^{-5})N_{rep1} + 2\cdot10^{-5}N_{rep2}$$

$$a_3: \quad u(e,z,a_1,\theta) = 2P_f + 0.0012N_m + (0.0036 + 2\cdot10^{-5})N_{rep1} + 6\cdot10^{-5}N_{rep2}$$

$$a_4: \quad u(e,z,a_1,\theta) = 2P_f + 0.0012N_m + 2\cdot10^{-6}N_{rep1} + 6\cdot10^{-5}N_{rep2}$$





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

Composite Structure Risk Assessment and Damage-Tolerance Maintenance Planning

Current State:

- Fixed set of Random Variables
- 1D Failure Criteria:
  - **Stress > Allowable**
  - **Load > Strength**
  - **Temperature > Allowable**
  - **Disbond Area > Allowable**
  - **Airspeed > Flutter Speed**
- Post-primary-failure 1D Criteria
- Simple Equation-Style Maintenance-Risk Cost Model

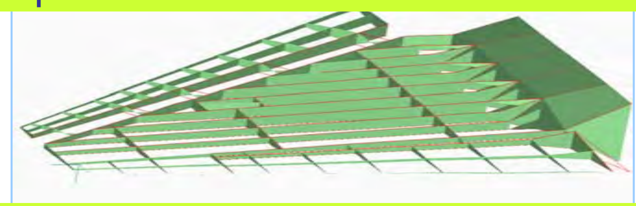
Demanded State:

- User-defined Set of Random Variables

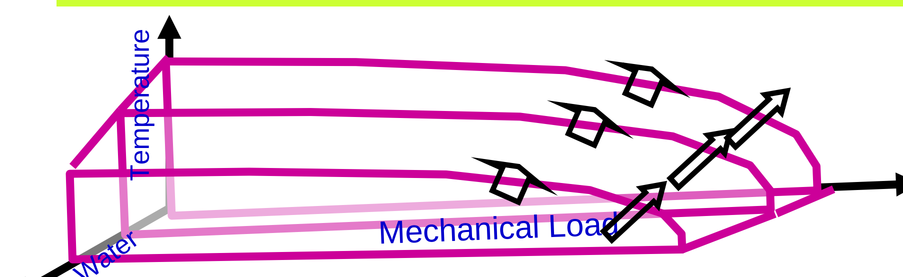
Damage-dependent Variables

Damage-independent Variables

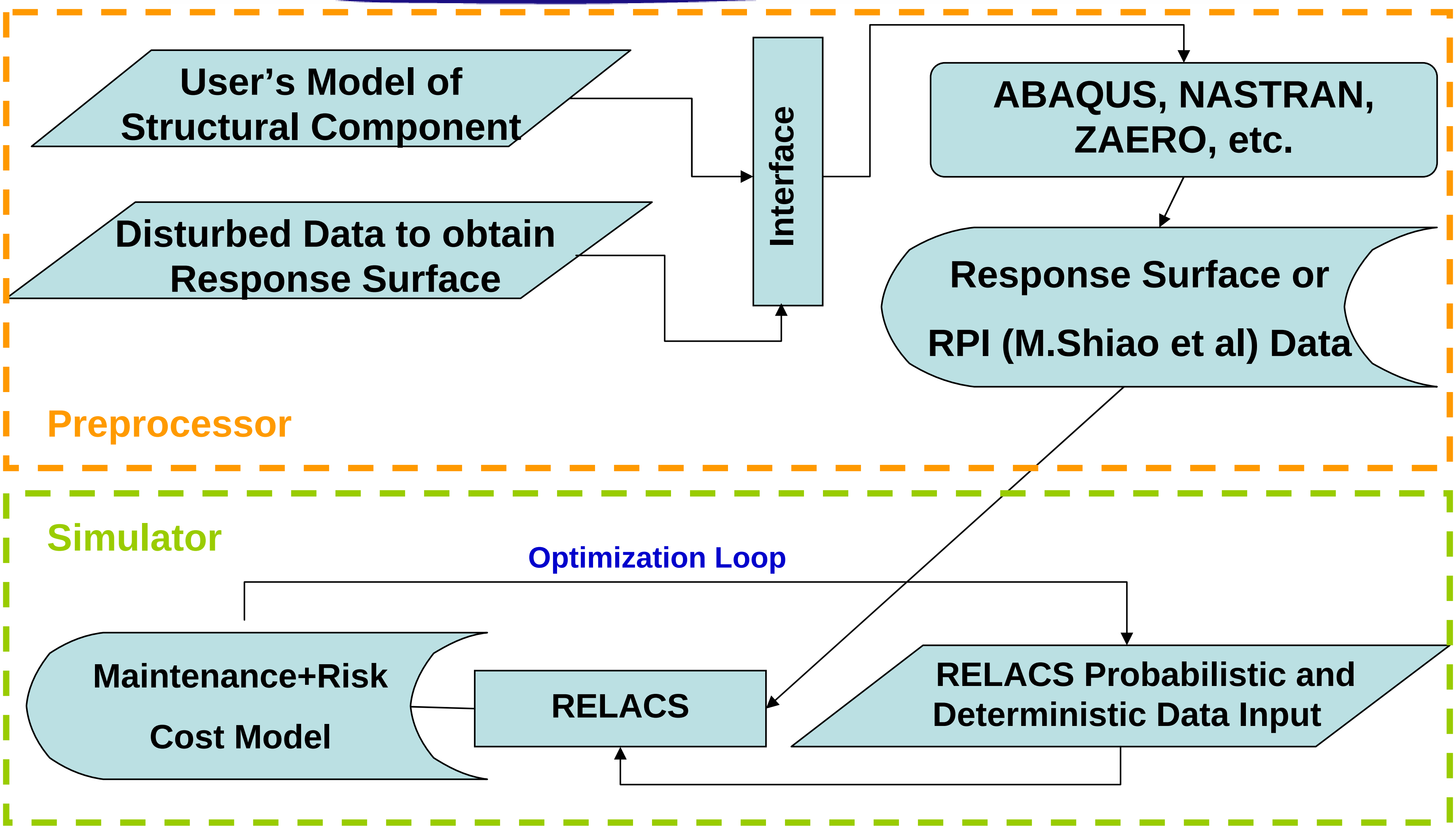
- Complex User-defined Structural Model



- Complex User-defined Failure Criteria

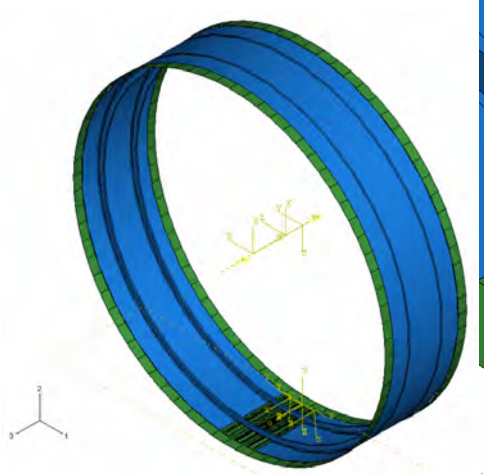


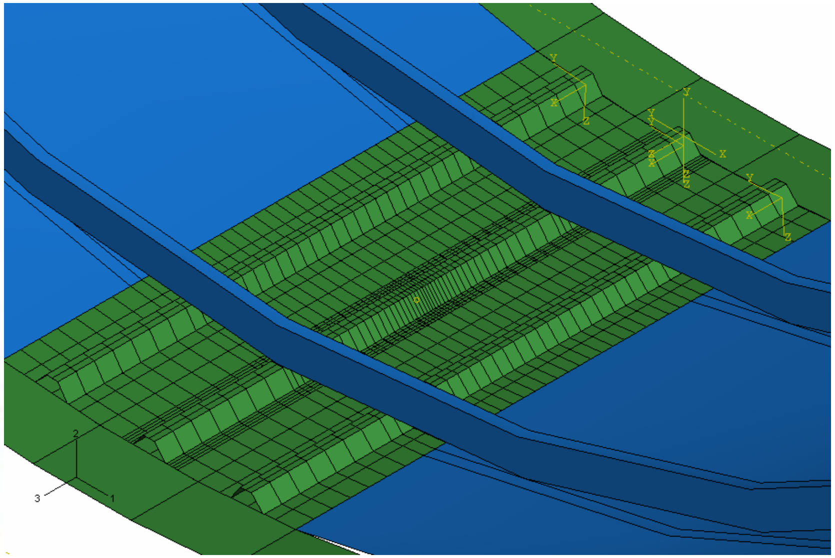
A Potential Tool: Integration with FEA Models



Damage Growth Consideration
A Preliminary Study

- A generic composite fuselage sub-section (24-ply isotropic) with hat stringer (8-ply 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)



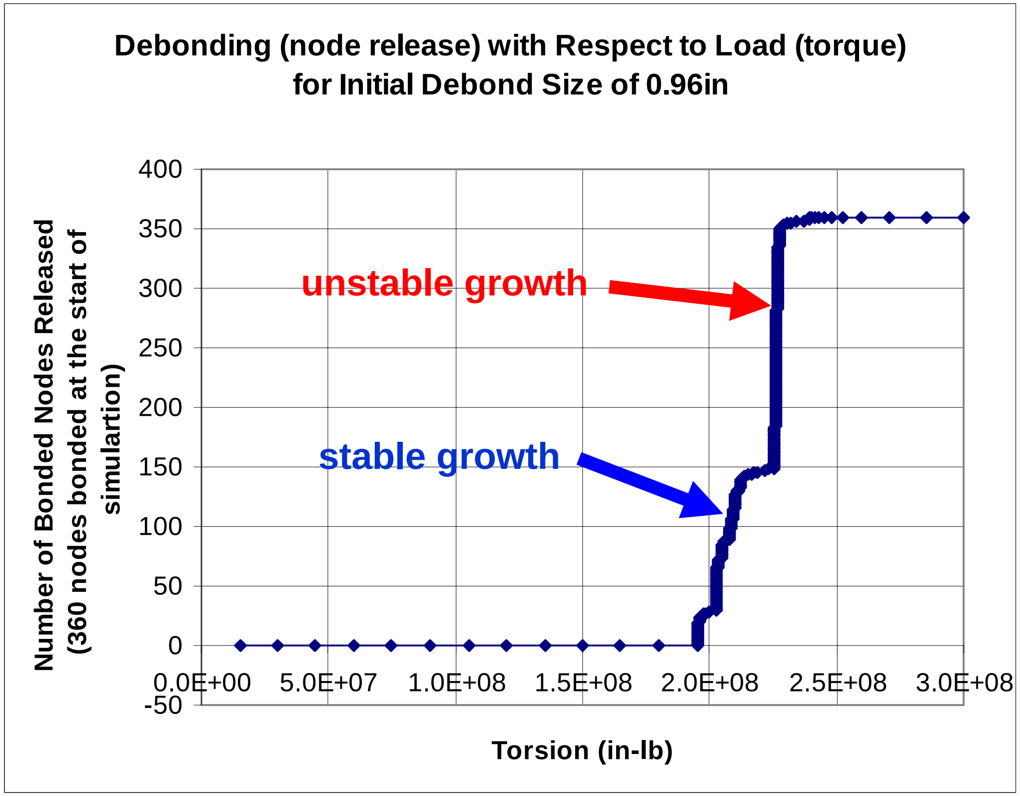


Damage Growth Consideration

Example of Debonding Growth Results

Initial flaw = 0.96”

- Initial debonding means the 30 nodes at the center of the stringer 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.

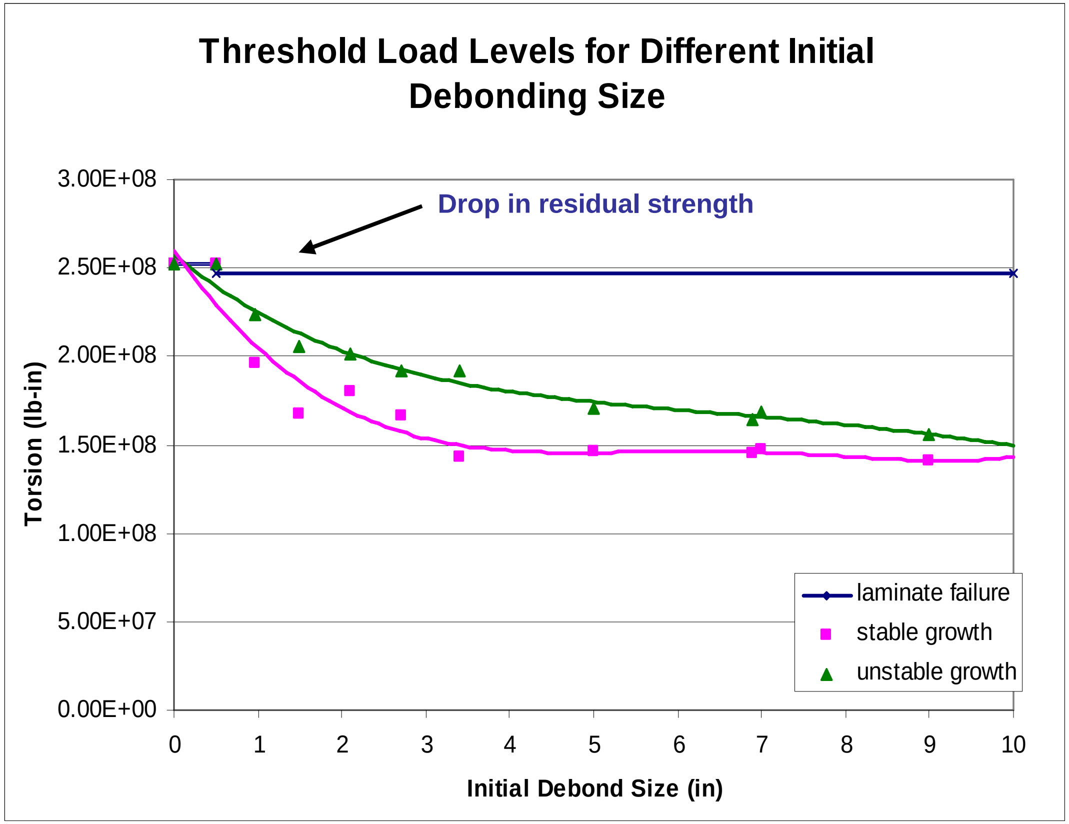


click for movie

Damage Growth Consideration

Results for Various Initial Damage Sizes

- 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.



Practical Applications of the Present Code, “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 applications.

Summary

Work Accomplished:

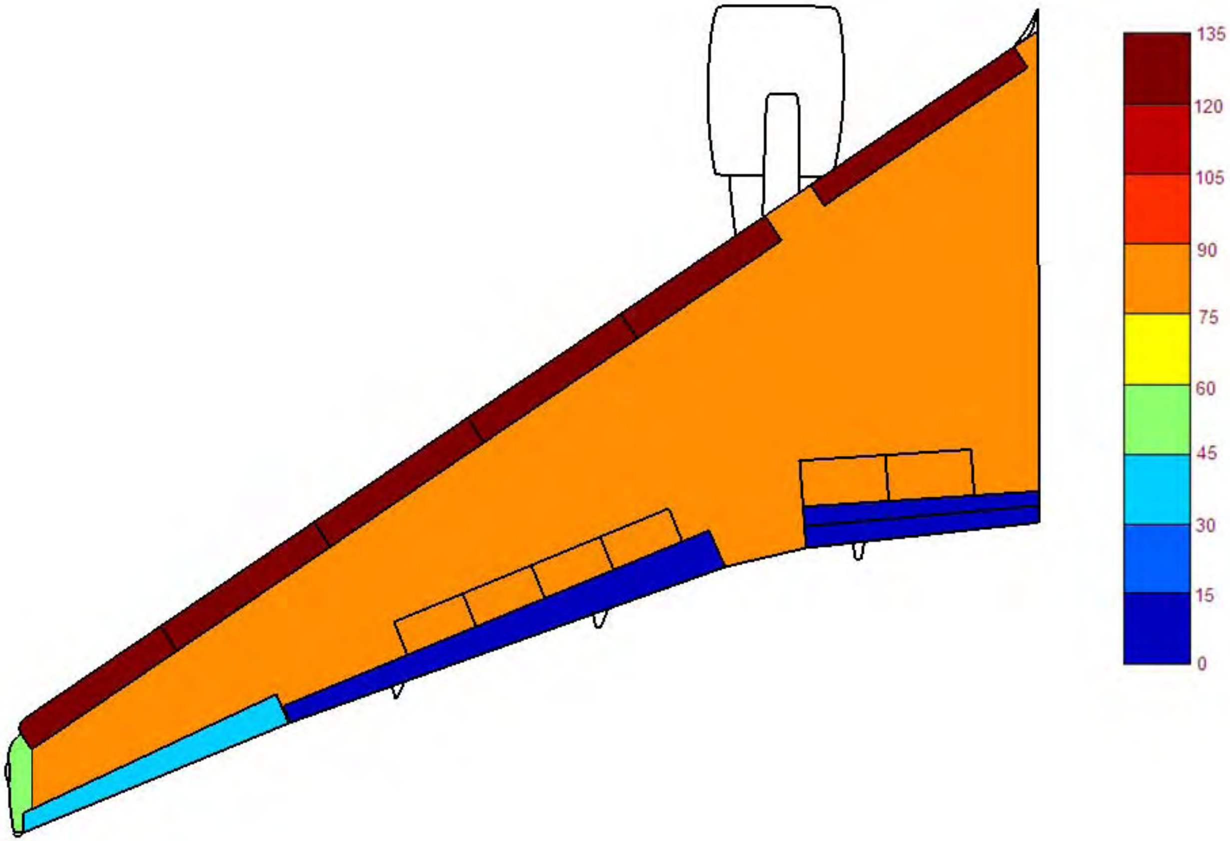
- Developed a method for determining POF and the inspection intervals.
- Developed a preliminary computer program for calculating POF and the inspection intervals.
- Mined statistical data on damage and other probabilistic parameters.

Work in Progress:

- Enhance the current method for POF and the inspection intervals.
- Complete a user friendly computer code and a user's manual for the probabilistic design of damage-tolerant composite structures.

THANK YOU

Example of Damage Mapping (767)



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.