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.

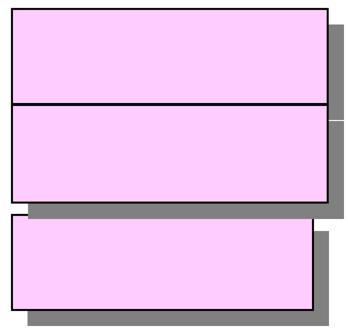
The approach combines the “Level of Safety” method proposed by Lin, et al. and “Probabilistic Design of Composite Structures” method by Styuart, at al.

Many Ways to Design a Damage Tolerant Structure

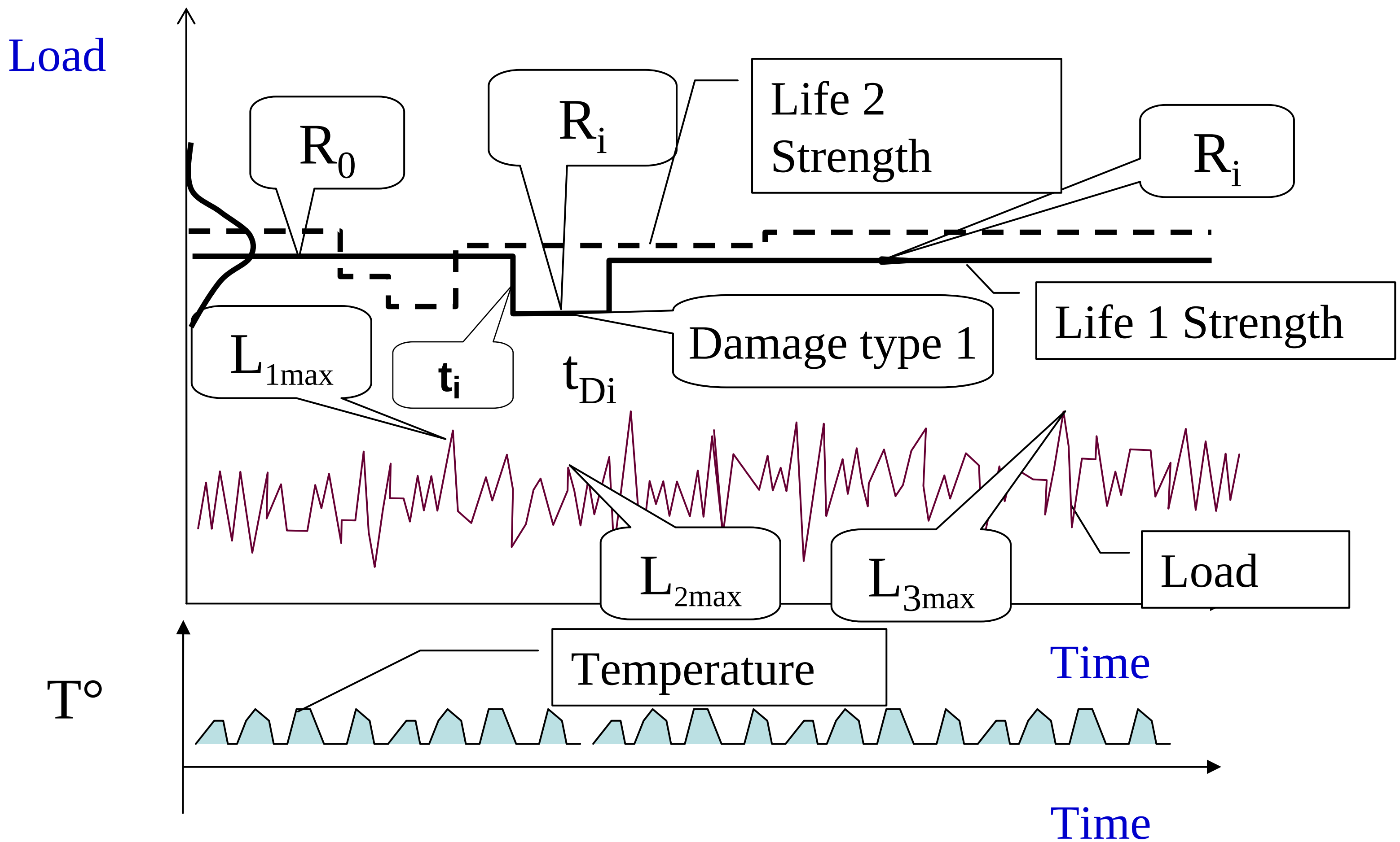
Damage-Tolerant Structure	= -	Additional skin thickness/weight/cost	+	Cheaper maintenance
Damage-Tolerant Structure	= -	Frequent checks/repairs	+	Structural weight/cost Savings
Damage-Tolerant Structure	= -	More thorough expensive checks	+	Less Frequent checks/repairs
Damage-Tolerant Structure	= -	Temporary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

There is a need

The Probabilistic Approach



The Probabilistic Model



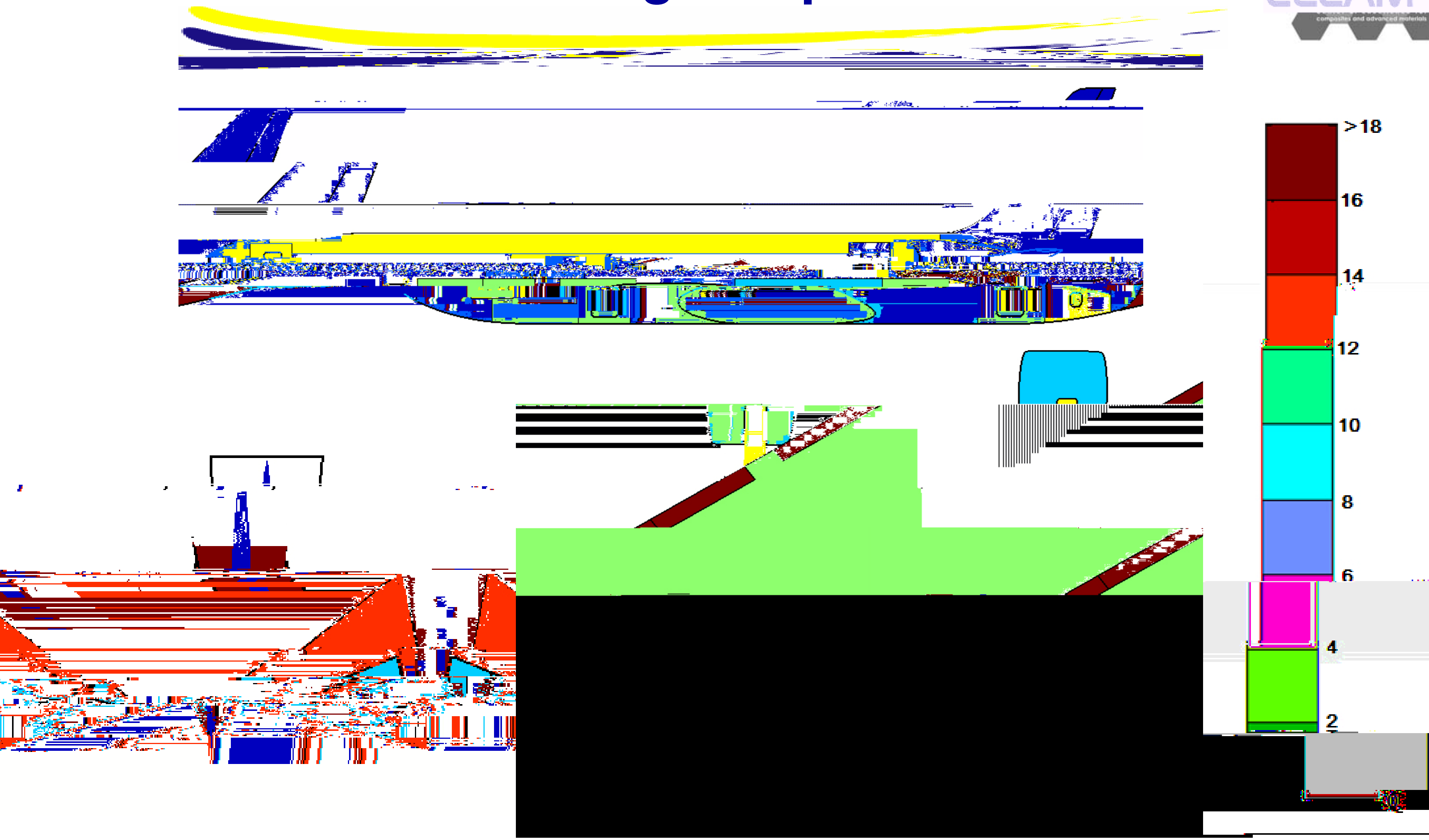
RELACS: Reliability Lifecycle Analysis of Composite Structures

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”*

Example of SDR External Damage Map



RELACS OUTPUT:

Minimum Risk Maintenance Planning

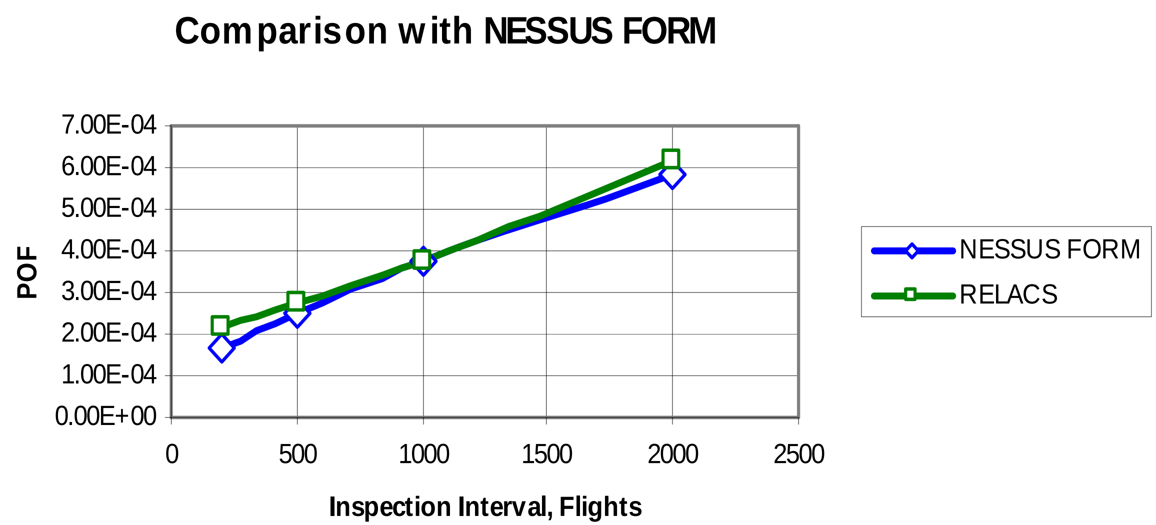
Validation of RELACS: Comparison with NESSUS

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.

Minimum Risk Maintenance Planning 2

Optimal Statistical Decisions

For small damages that will remain undetected for a long tome: K

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

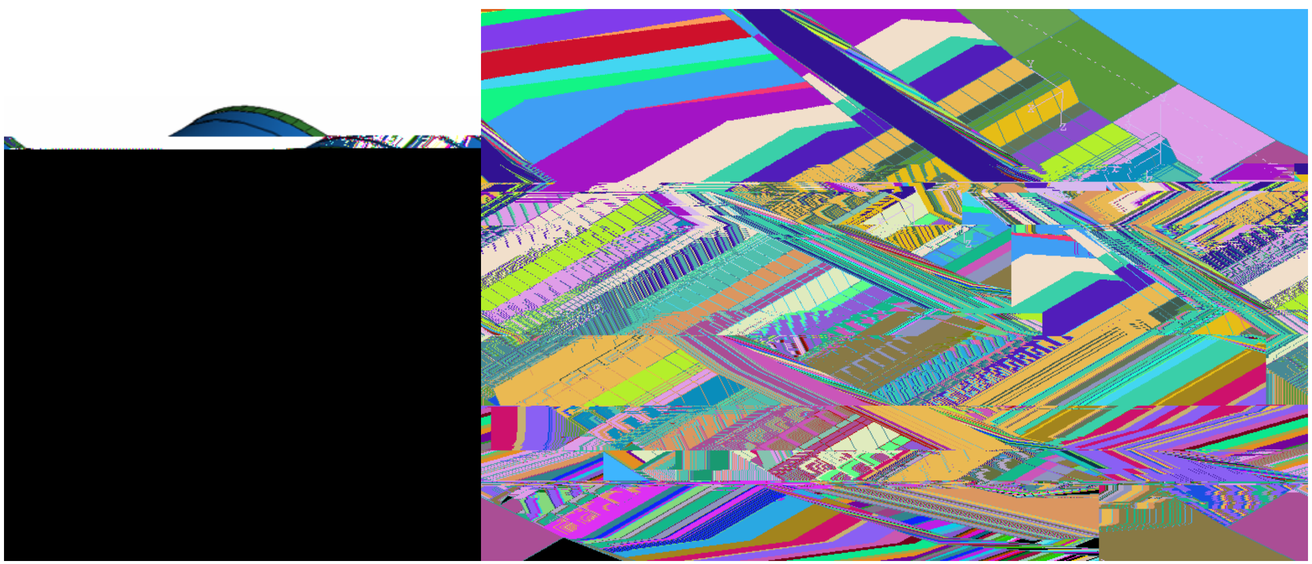
VCCT from ABAQUS

Commercial FEM code ABAQUS has been used to explore the feasibility of including a damage growth model – delamination and

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)

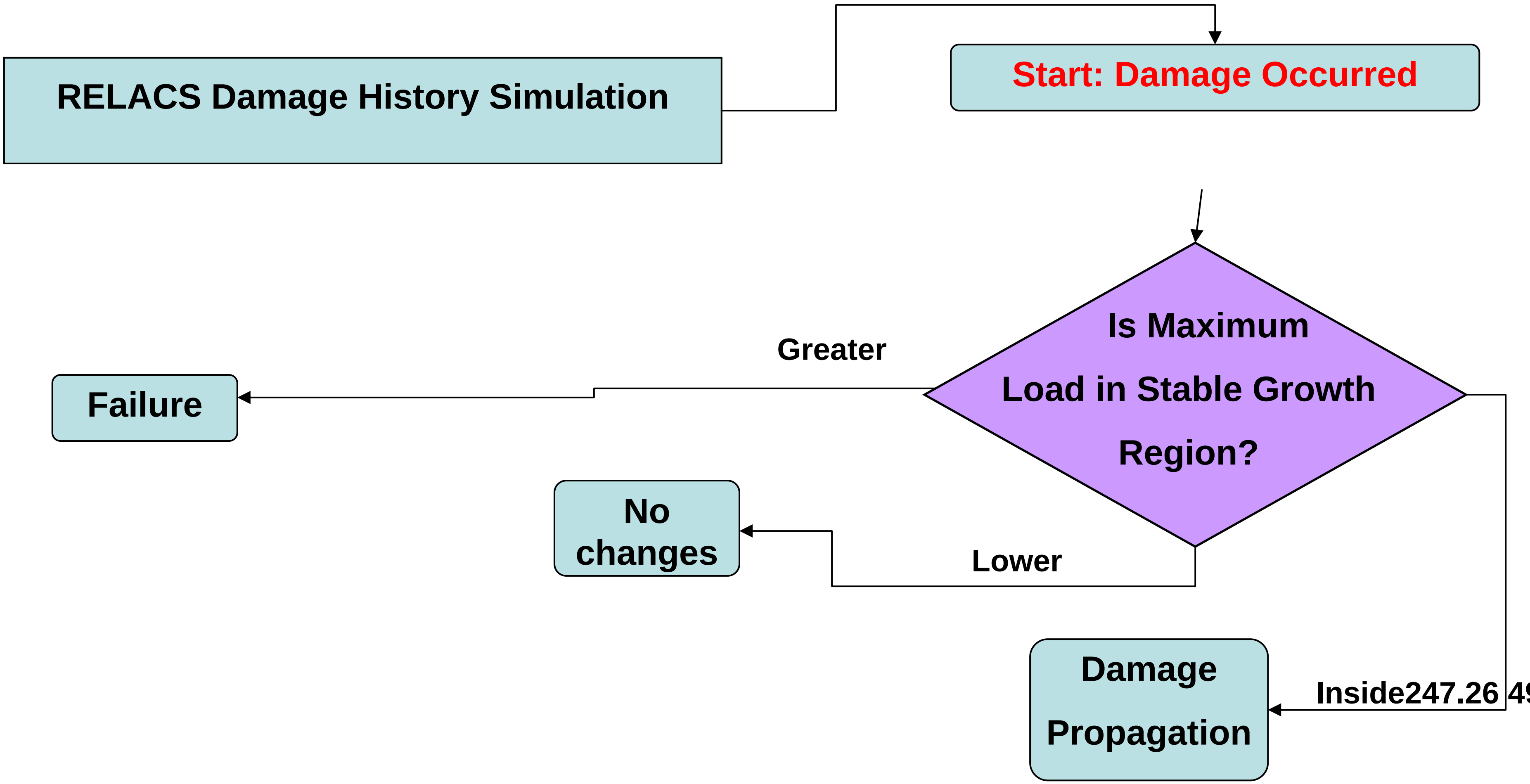


Damage Growth Consideration

Results for Various Initial Damage Size

Damage Growth Consideration

Integration into RELACS



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

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.