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.
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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.

Major Factors in Damage Tolerant Design

- Design Margins
- Analysis Tools
- Manufacturing Techniques

- Inspection Frequency
- Inspection Methods
- Repair Methods
- Rules on Repair Deferral

vs.

Cost
UW Virtual Test Lab (VTL)

Virtual Aeroelastic Test Module (VATM)
Virtual Strength Test Module (VSTM)
Statistical Inputs and Operational Inputs

Reliability Life-Cycle Analysis of Composite Structure (RELACS)

Probability of Failure

Inspection Intervals, Repair Criteria, Structural Reliability

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Stochastic Modeling of Structure via VSTM

Deterministic FEA Model of the Structure

Stochastic Model of the Structure

Failure Mode Prediction

Statistical Description of Structural Properties (mean, variance), Response Surface

Damages (size, location)

Manufacturing Defects

Correlation between Different Material Properties

Panel-to-panel Properties Variability

Spatial Properties Variability

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Software Architecture: VSTM with Excel Interface

MS Excel: Post processing, POF, Sensitivities

Interface with NASTRAN

MS Excel: Stochastic Modeling

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Example: Realistic Aero-Structure under Tuned Gust

Empirical CDF of Failure Load in Virtual Static Tests

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RELACS – Reliability Life-Cycle Analysis of Composite Structures

Environmental Physics:
1. External Loads
2. Temperatures
3. Damage Source

Operations:
1. Detection Probability
2. Repair Quality

Damage Physics:
1. Damage size and Occurrence
2. Residual Strength
3. Damage Growth or Fatigue after Damage

Quantified Safety
Better Design
Optimized Maintenance

Experiments
FEA
(CAI, progressive damage model, VCCT, etc)

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Simulation of Structure Life

- Residual Strength
- Small damage
- Large damage
- Damage detected and repaired
- Repair was not perfect
- Small damage may take a long time to detect
- Large damage, although dangerous, will be detected and repaired quickly

Load vs. Time

Temperature vs. Time
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”
Software Architecture: RELACS with Excel Interface

MS Excel: database management

MS Excel: cost optimization

MS VBA macro:
check input data, make exchange files, run MC module

MC module:
automation DLL (Fortran 95)

MS Excel:
post processing, POF, sensitivities

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Input Data Management

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Optimal Statistical Decisions
Minimum Risk Maintenance Planning

- Maintenance planning is one of the most important tools to manage damage-induced risks
- Flexibility exists in maintenance planning
- Variability exists in many key parameters for inspections and repairs
- The cost of any potential maintenance plan can be evaluated in terms of utility and the best decision can be identified with a quantitative basis

**Utility** = Inspection Costs + Repair Costs + Service Interruption Costs + Failure Costs
For large damage that will be repaired within a few flights:  
Key factor is repair quality

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

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Optimal Statistical Decisions
Selection of Certification Tests

- e1 (upper) – Analytical Substantiation Supported by Tests up to Limit Load/Stress
- e2 (lower) – Substantiation Primarily by Ultimate Load Tests with Minimal Analysis
- Reliability and risk associated with different static strength substantiation procedures can be quantified
- Manufacturers and certification authorities can optimize substantiation procedure on the basis of production and lifecycle costs

Figure 6: Prior and Posterior Empirical CDF for composite structures.

Figure 8: Prior and posterior CDFs for e1 substantiation method
Deterministic Damage Growth Analysis
ABAQUS with VCCT

- Virtual Crack Closure Technique (VCCT) is used to analyze delamination damage
- Establish delamination failure load curve
- Simulate damage growth (static)
- Analyze effect of damage growth on failure load
- Can be modeled stochastically
Deterministic Damage Growth Analysis

ABAQUS with VCCT

- Results from skin-stringer analysis shows damage growth under static loading is possible -> but does it affect failure load?
- Increased damage size would affect damage tolerance because inspection and repair will be influenced by damage size.
- Some parameters become important when lifecycle reliability is considered.
The unreliability due to repair quality scatter must be made up with reducing inspection interval (assumed case).

Depending on sensitivity of POF to inspection interval, the level of compromise will be different.
Summary

Work Accomplished

- Developed the methodology to determine the reliability and maintenance planning of damage tolerant structures.
- Developed a user-friendly software (RELACS) for calculating POF and inspection intervals.
- Developed software interface (VSTM) with Nastran to facilitate stochastic FEA.
- Mined statistical data on damage and other probabilistic parameters.
- Implemented stochastic FEA to obtain initial/damaged residual strength variance.
- Used FEA to characterize delamination progression and delamination damage failure load.

Future Research

- Employ the stochastic FEA capability to systematically study the effects of variability of composite materials and integrated structures.
- Develop analytical methods for interlaminar and disbond fracture of composites to enable stochastic modeling, design optimization and sensitivity study.
Future Research:
Systematic Study of the Variability of Composite Materials and Structures

- Use stochastic FEA to systematically study the effect of material variability in composite structures.
- A number of uncertainties are identified as crucial to the evaluation of structural reliability:
  - Panel-to-panel and batch-to-batch variability for typical failure modes
  - Manufacturing control and rejection criteria
  - Correlation between different material properties (e.g. stiffness vs. strength)
  - Spatial characteristics of material properties
  - Effect of BVID on structural properties
  - Method for variance prediction for various failure modes
  - Understand of processing and manufacturing environments
- A comprehensive way of test data processing, that includes information on batches, panels, coupons, etc, is proposed.
Future Research:

Systematic Study of the Variability of Composite Materials/Structures

Empirical CDF in Normal Scale:

- No checks
- Rejection

Normal scale index

Strength

POF

1 0.1 0.01 0.001

0.0001

0 5 10 15 20 25

N Elements per Panel

Empirical CDF in Normal Scale:

POF=0.66E-2 (no correlation); POF=1.26E-7 (full correlation)

Period of damage return

POF

0.1

0.01

0.001

0.0001

10 150 1000

Empirical CDF in Normal Scale:

Normal scale index

0.6 0.7 0.8 0.9 1

0.6 0.65 0.7 0.75 0.8 0.85 0.9 0.95 1.05

Strength

Full ES Correlation

No ES Correlation

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Future Research:
Analytical Methods for Interlaminar Fracture and Disbond of Composites

• Uncertainties in interlaminar fracture disbond are large and require probabilistic considerations for design and certification
• The number of variables in this type of problem is large (e.g. delamination location, ply thickness and orientation, spatial variation in material properties, damage geometry, etc)
• Pure FEM based approaches to interlaminar fracture are very time consuming
• Industry is interested in the development of a more efficient and reliable analysis tool for this type of problem
Future Research:
Analytical Methods for Interlaminar Fracture and Disbond of Composites

- Analytical approach promises computational efficiency and flexibility that would allow probabilistic analysis, design optimization and sensitivity study.
- Develop methods that can address delamination as well as disbond problems.
- Analytic modeling of damage growth mechanisms, such as fatigue, viscoelastic behavior, moisture infiltration, etc.
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.
– A comprehensive system of characterizing variability of material properties.