Development of Reliability-Based Damage Tolerant Structural Design Methodology

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FAA Sponsored Project Information

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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

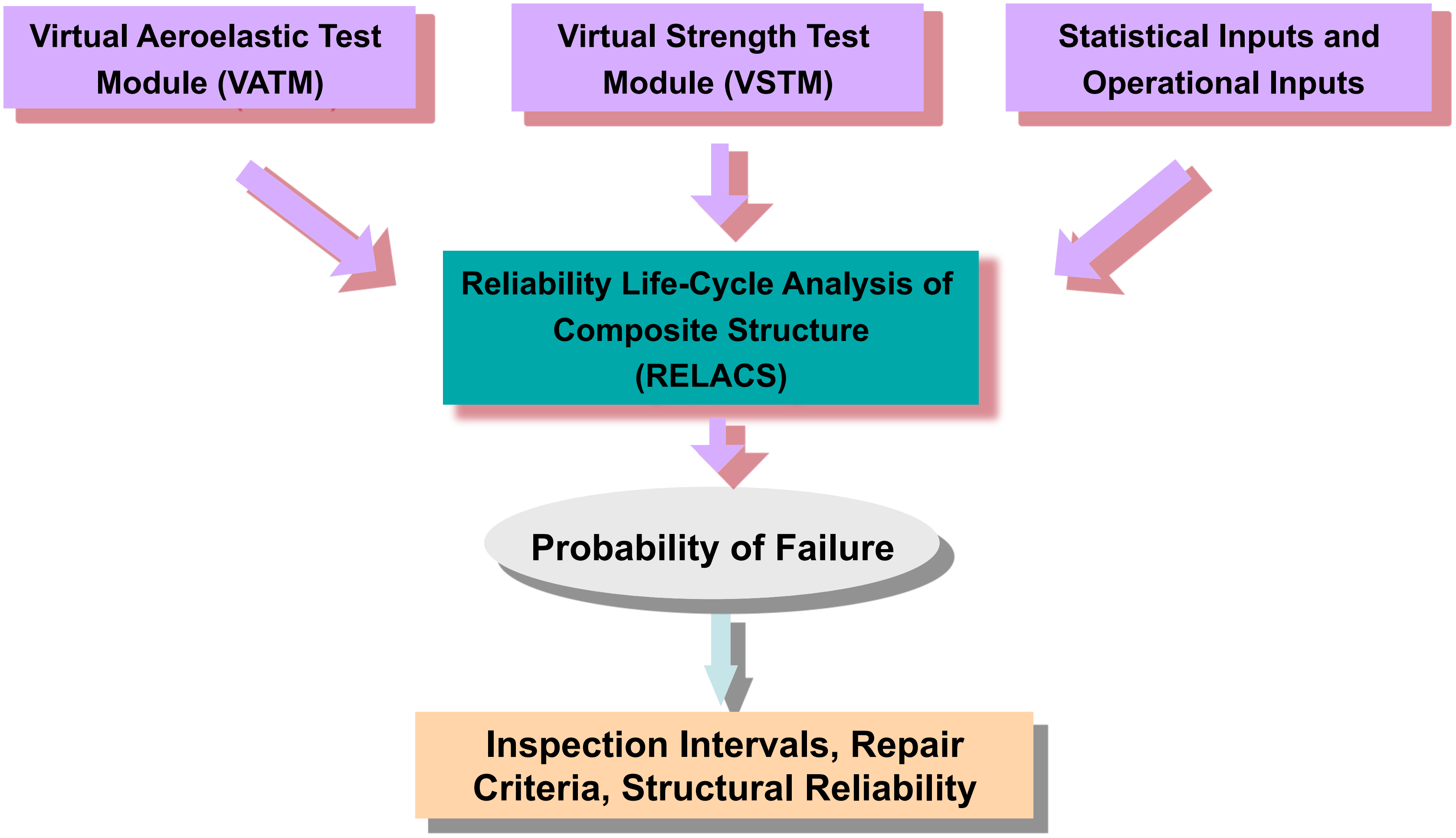
- The approach is based on a probabilistic failure analysis with the consideration of parameters such as inspection intervals, statistical data on damages, loads, temperatures, damage detection capability, residual strength of the new, damaged and repaired structures.

- The inspection intervals are formulated based on the probability of failure of a structure containing damage and the quality of a repair.

Work Accomplished

- Methodology for determining the life cycle reliability of composite structures has been developed and implemented as RELACS software.
- A reliability-based method to optimize inspection schedule of damage tolerant composite structures has been developed.
- A Virtual Strength Test Module (VSTM) has been developed to facilitate stochastic Finite Element Analysis to obtain the strength distributions of undamaged and damaged structures.
- The methodology and software have been demonstrated with examples of aircraft structures.

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)

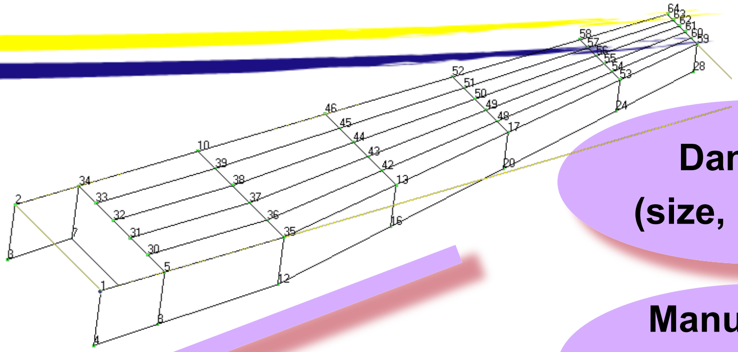
Probability of Failure

Inspection Intervals, Repair Criteria, Structural Reliability

Required Input

- **Maintenance Details**
  - Inspection Interval
  - Inspection/ Detection Capabilities
  - Repair Quality
- **Structural Component Definition**
  - Finite Element Model
  - Stochastic Structural parameters
    - Stiffness
    - Strength
    - Fracture properties
    - Thickness
- **Stochastic Environment Parameters**
  - Mechanical Load
  - Temperature
  - Humidity
  - Wind/ Gust
- **Impact/ Damage Event Descriptions**
  - Damage Types
  - Damage Occurrence Frequency
  - Damage Size
  - Residual Structural Properties after damage

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)

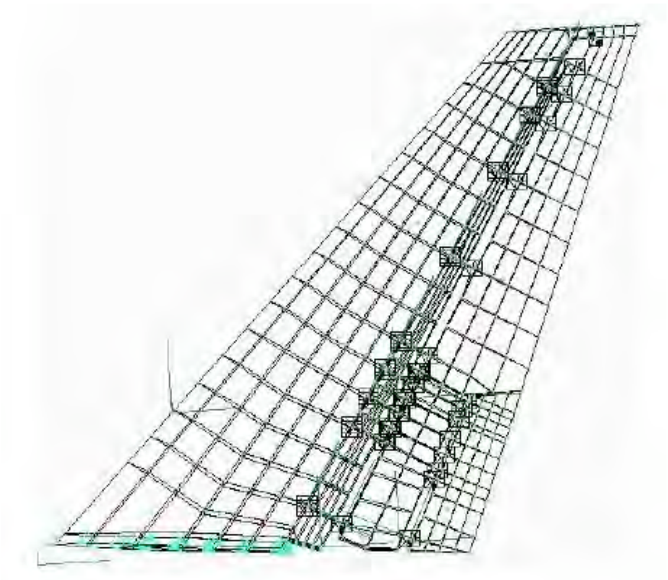
Manufacturing Defects

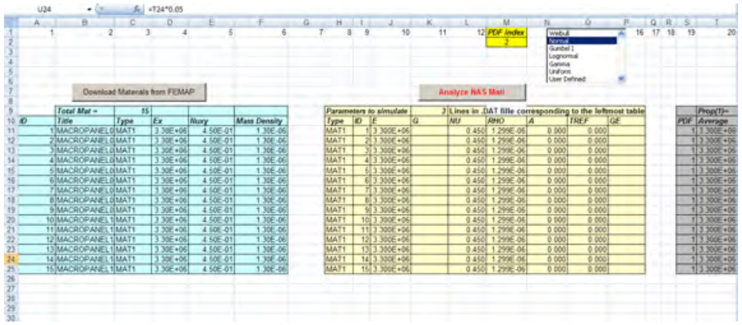
Correlation between Different Material Properties

Panel-to-panel Properties Variability

Spatial Properties Variability

Software Architecture: VSTM with Excel Interface





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3	MACROPANEL0	MAT1	3.30E+06	4.50E-01	1.30E-06
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Parameters to simulate			2	Lines in .DAT file corresponding to the leftmost table				
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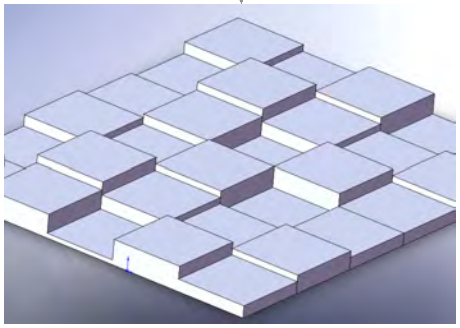
MS Excel:
Stochastic Modeling



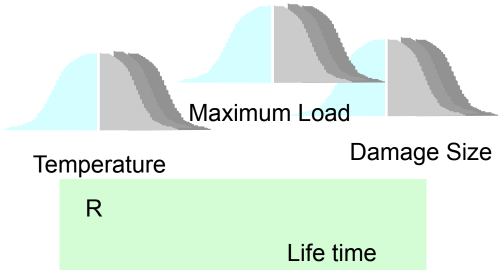
Interface
with
NASTRAN

MS Excel:
Post processing,
POF, Sensitivities

RELACS – Reliability Life-Cycle Analysis of Composite Structures

Environmental Physics:

1. External Loads
2. Temperatures
3. Damage Source



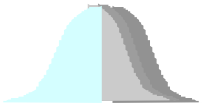
Damage Physics:

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

RELACS

Operations:

1. Detection Probability
2. Repair Quality



Quantified Safety

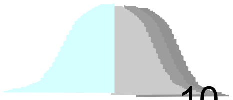
Better Design

Optimized Maintenance

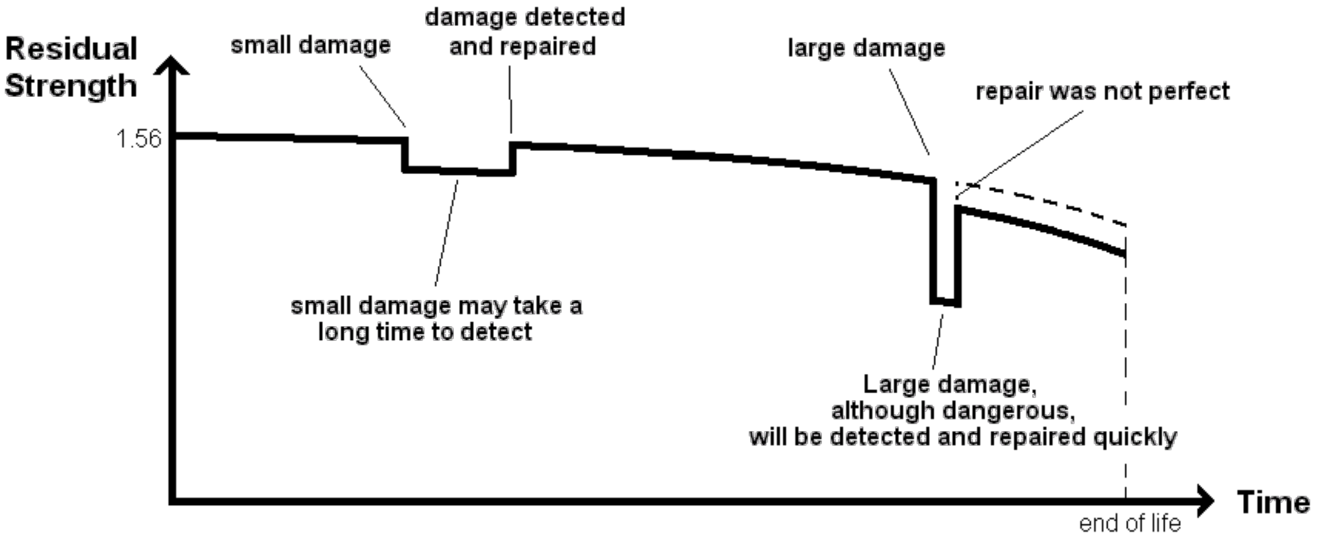
Experiments

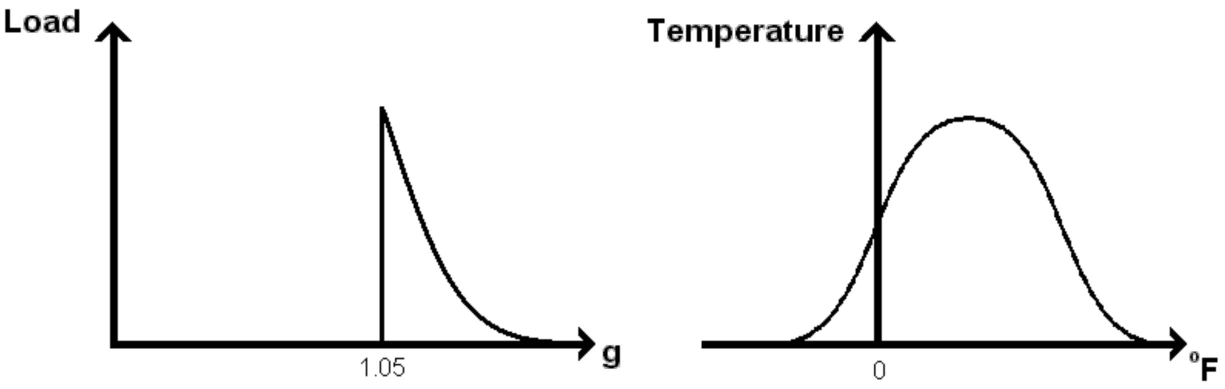
FEA

(CAI, progressive damage model, VCCT, etc)



Simulation of Structure Life





RELACS 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”*

Example 1

Optimal Statistical Decisions
Minimum Risk Maintenance Planning

- Maintenance planning is one of the most important tool 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 quantitative basis

Utility = Inspection Costs +

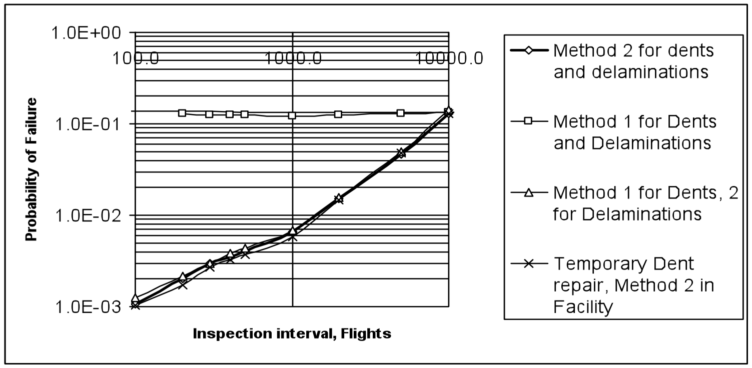
Repair Costs +

Service Interruption Costs +

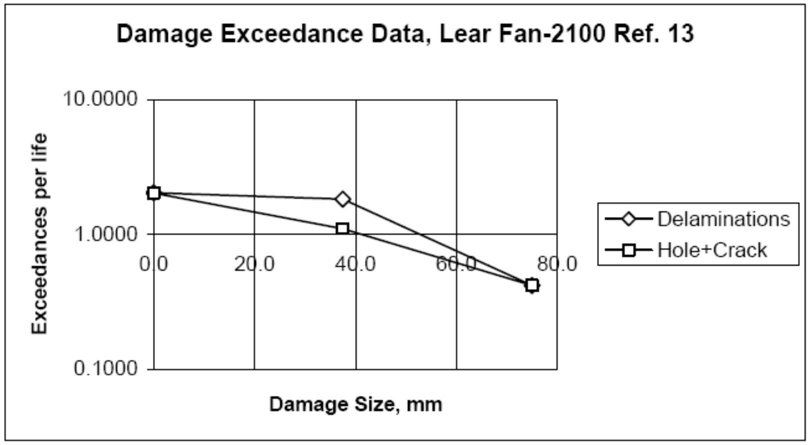
Failure Costs

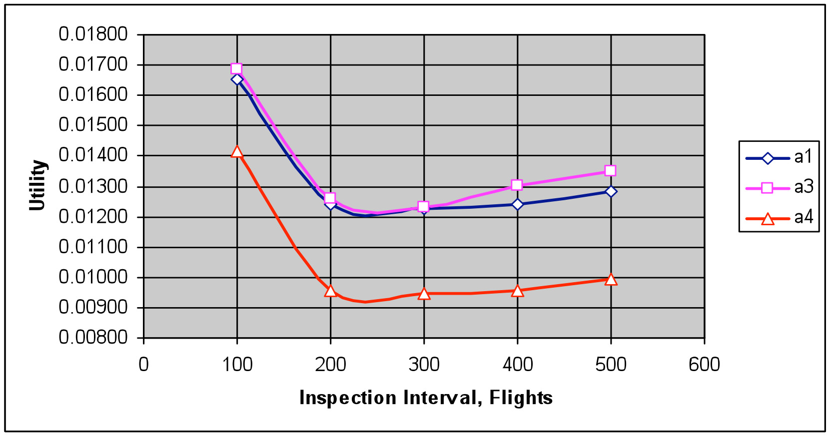
Example 1

Optimal Statistical Decisions
Minimum Risk Maintenance Planning



- Utility is defined as physical costs + risk costs
- Flexibility exists in maintenance planning, many combinations to choose from
- 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 quantitative basis





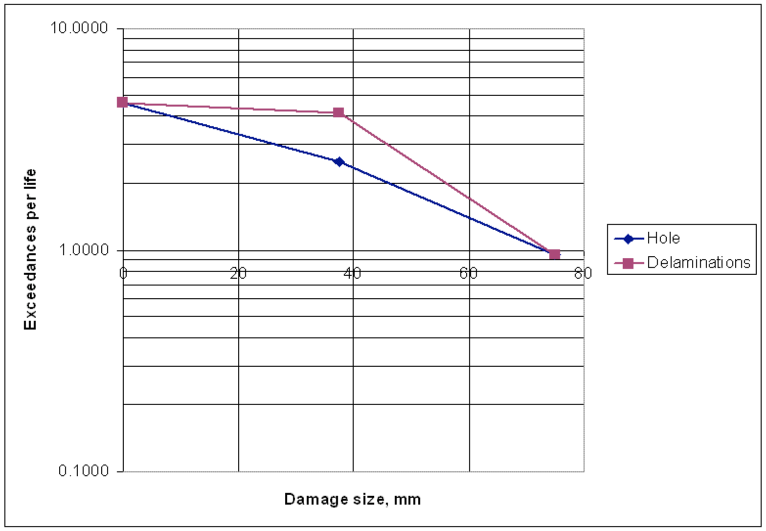
For large damage that will be repaired within a few flights: key factor is repair quality

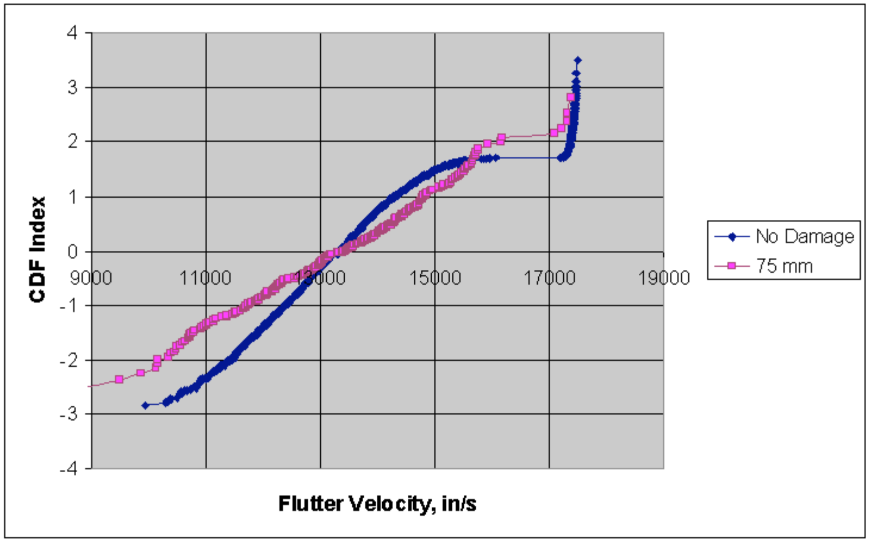
Example 2
Vertical Tail: Damage Analysis

Residual stiffness based upon a rule-of-mixtures for constant thickness panel

$$\kappa_T = \left(\frac{W - W_D}{W}\right)\kappa_{T(U)} + \left(\frac{W_D}{W}\right)\kappa_{T(D)};$$

$$\kappa_C = \left(\frac{W - W_D}{W}\right)\kappa_{C(U)} + \left(\frac{W_D}{W}\right)\kappa_{C(D)}$$





Locations of damaged elements have been chosen randomly with uniform distribution over the tail box skin area.

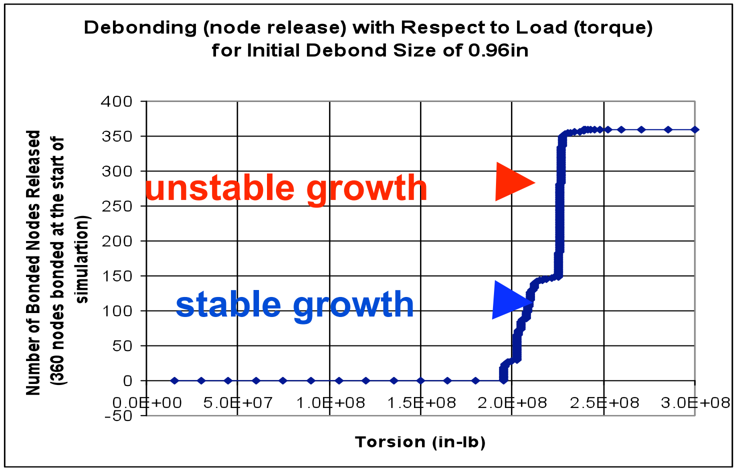
Example 2

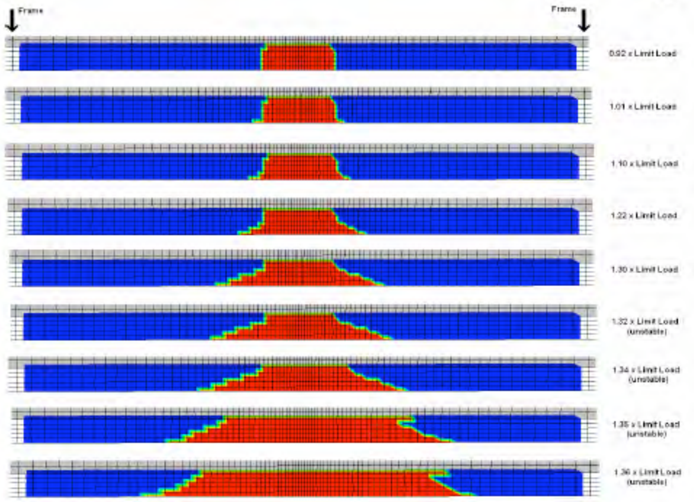
Vertical Tail: Effect of Damage on Probability of Failure

Example 3

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



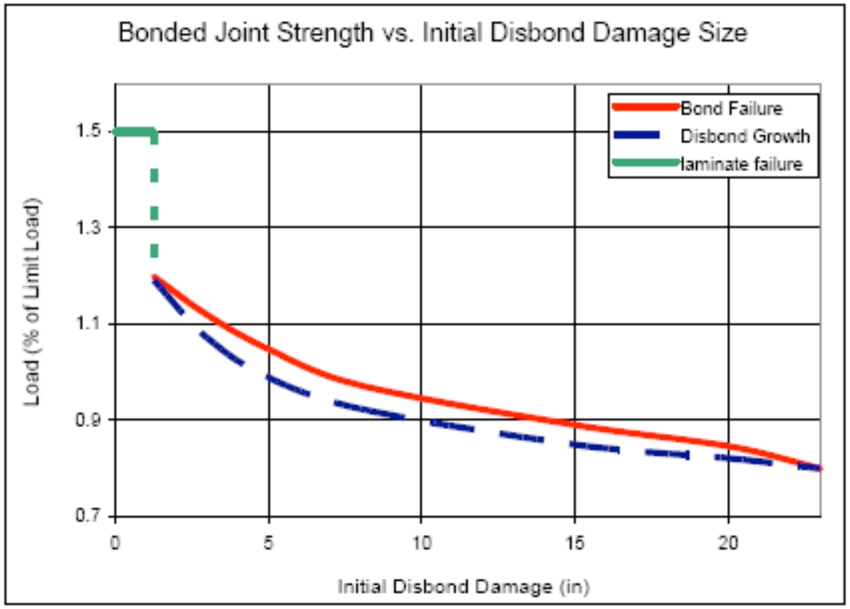


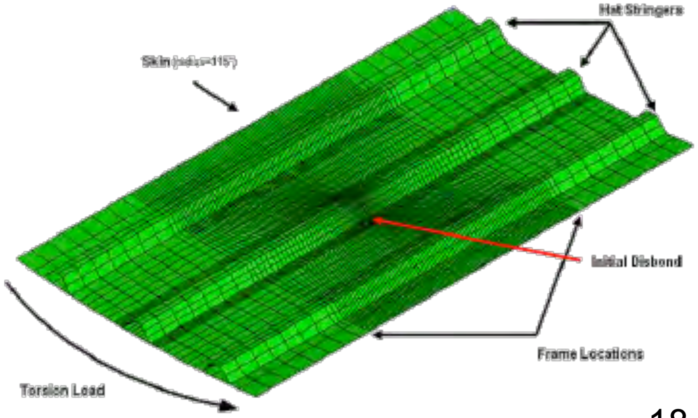
Example 3

Deterministic Damage Growth Analysis

ABAQUS with VCCT

- Results from skin-stringer analysis shows damage growth under static loading is possible
- 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





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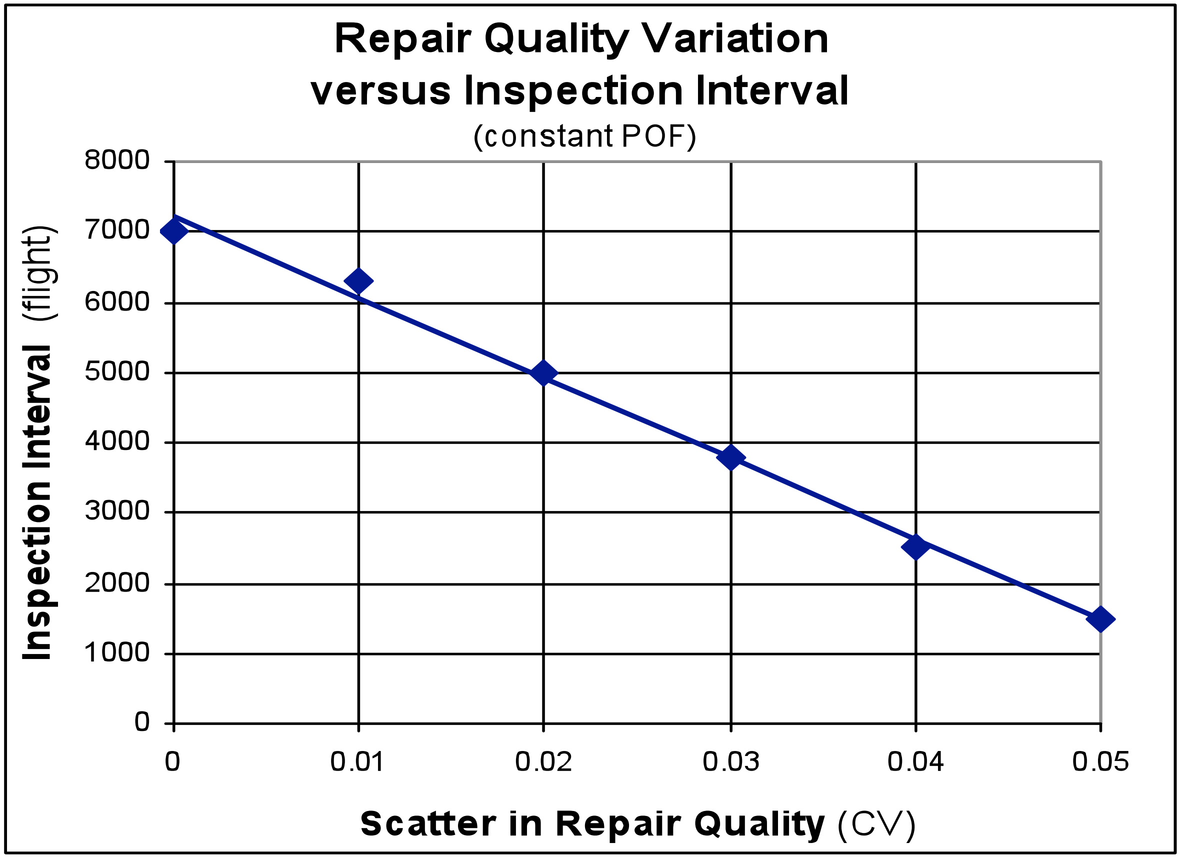
Example 3

Deterministic Damage Growth Analysis
Effect of Repair Quality Scatter

- 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



Current Research-

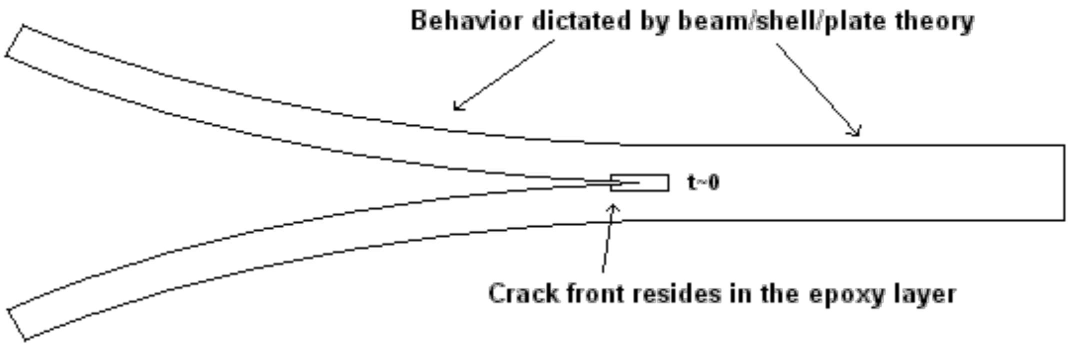
Probabilistic Progressive Failure Modeling of Composite Delamination

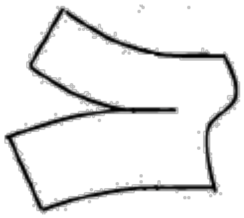
- Employ the stochastic FEA capability to systematically study the effects of variability of composite materials and integrated structures.
- Develop analytical methods for interlaminar and disbond fracture of composites to enable stochastic modeling, design optimization and sensitivity study.
- The specific tasks include the following components:
  - Elasticity solution of crack-tip stress field
  - Specialized progressive-failure FEA elements and routines
  - Probabilistic analysis capabilities

Current Research:

1. Elasticity Solution of the Crack-Tip Stress Field

- Obtain elasticity solution for crack-tip stress field
- Identify “what” causes crack to propagate
- Develop crack-tip-element that solves for SIF/SERR from plate model results
- The crack-tip-element will be designed for progressive failure and probabilistic analysis from conception
- A software package that units the crack-tip-element, progressive failure modeling and probabilistic analysis will be developed

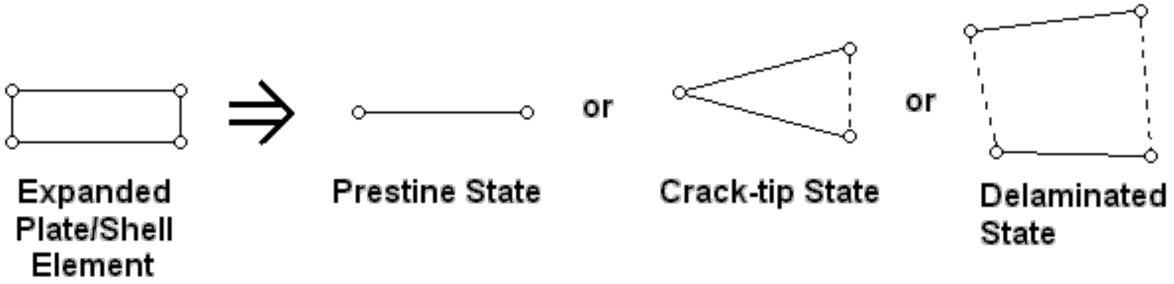




Future Research:

2. Specialized Progressive Failure FEA Routines

- FE modeling of progressive delamination failure based on two splitting plates is “incorrect”
- FE modeling that requires re-meshing for each propagation is impractical
- XFEM provides inspiration for an approach that solved both problems
- A plate/shell element can be developed that adapts from a single plate to two separate plates depending on damage state
- A FE routine that manages the progressive failure model will be developed
- Any plate model can be used, e.g. higher order shear deformable plate theories, layer-wise plate theories
- Any crack-tip solution can be used, e.g. stress-based solution, split-beam model, VCCT



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Future Research:

3. Probabilistic Analysis Capabilities

- Analysis model will be designed for probabilistic analysis from conception
- Model can take on random materials properties and geometric parameters, e.g. G_I, G_{II}, G_{III}, E, t
- Ability to model correlation between different material properties and between material properties and geometry
- Virtual experiment capability and extended statistical analysis

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.