

JAMS

# Development of Reliability-Based Damage Tolerant Structural Design Methodology

Chi Ho Eric Cheung, Andrey Styuart, Kuen Y. Lin  
Department of Aeronautics and Astronautics  
University of Washington



- **Principal Investigator:**
  - Dr. Kuen Y. Lin, Aeronautics and Astronautics, UW
- **Research Scientist:** Dr. Andrey Styuart, UW
- **PreDoctoral Research Assistant:** Chi Ho “Eric” Cheung, UW
- **FAA Technical Monitor:** Curtis Davies
- **Other FAA Personnel:** Dr. Larry Ilcewicz
- **Industry Participants:** Mr. Gerald Mabson, Dr. Cliff Chen, Dr. Hamid Razi, Dr. Lyle Deobald, Dr. Alan Miller (All from Boeing)

# 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.

# Major Factors in Damage Tolerant Design

**Damage Tolerant**

**Design/  
Manufacturing**

- Design Margins
- Analysis Tools
- Manufacturing Techniques

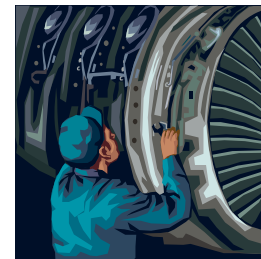


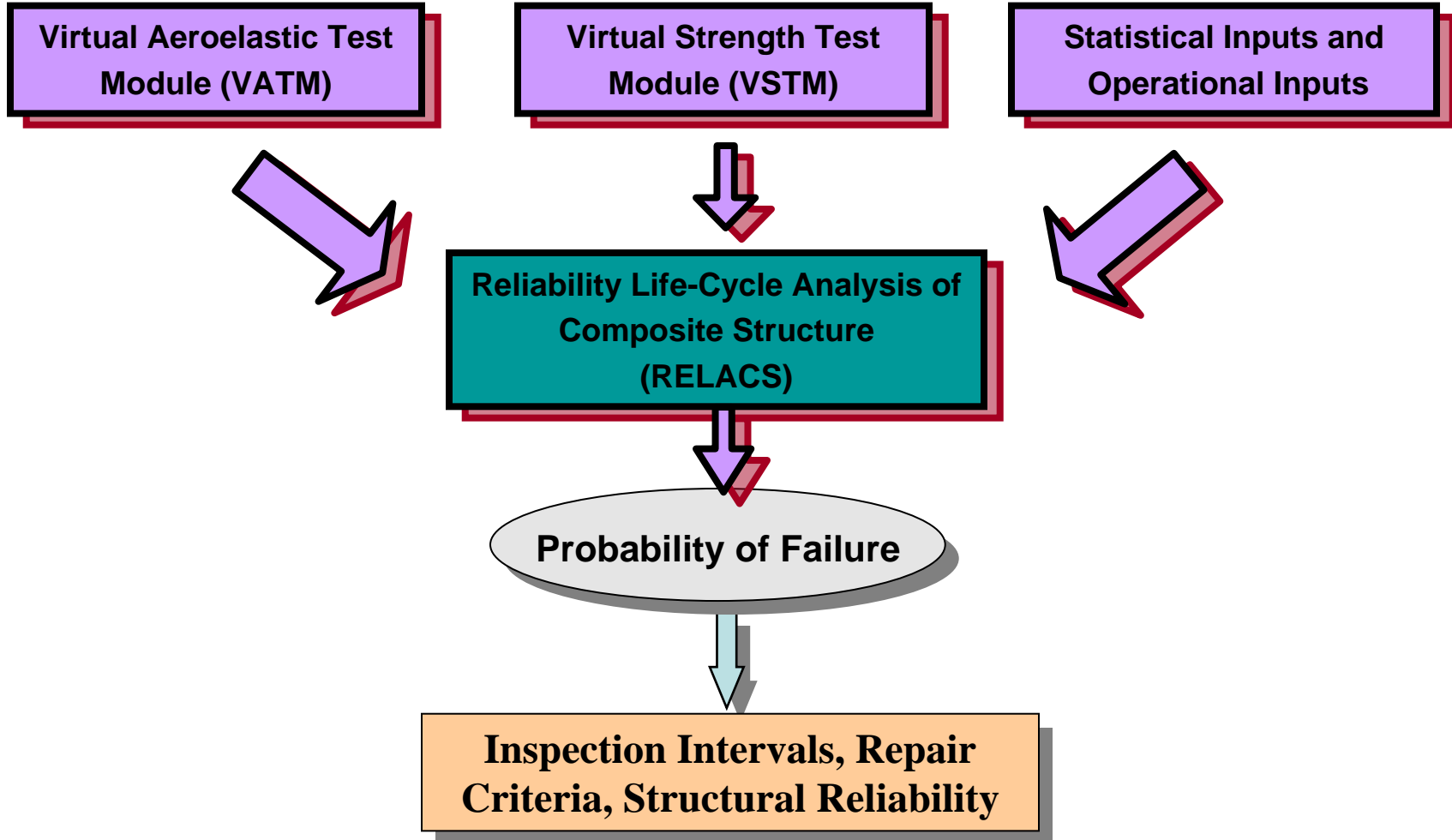
**Service**

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

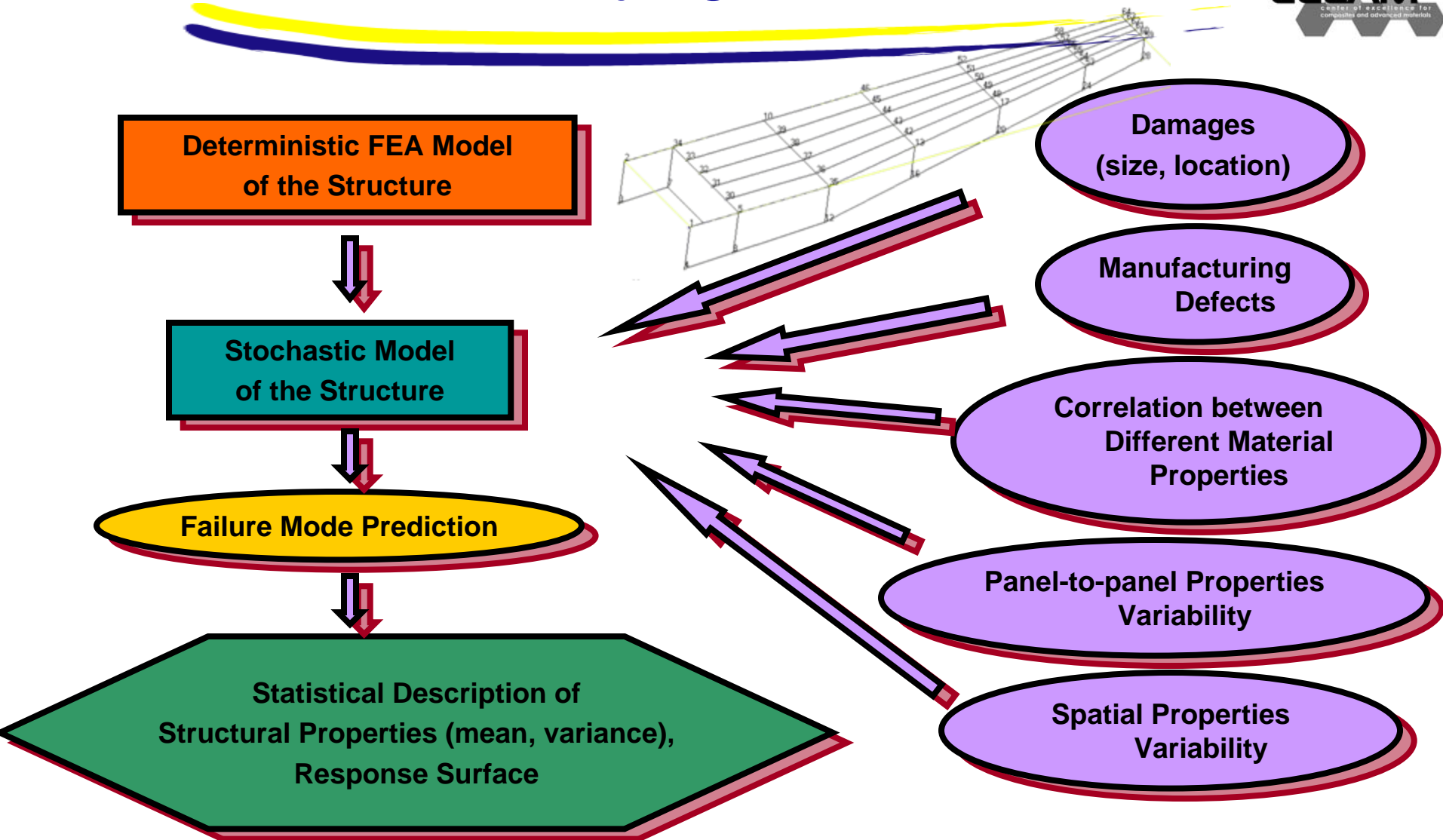
vs.

**Cost**

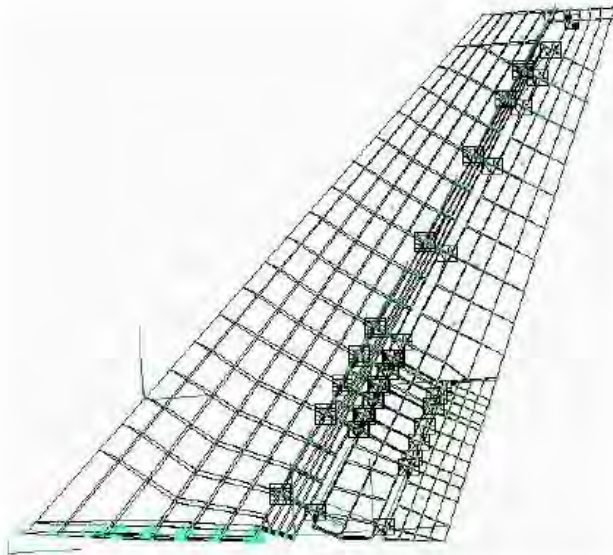




# Stochastic Modeling of Structure via VSTM

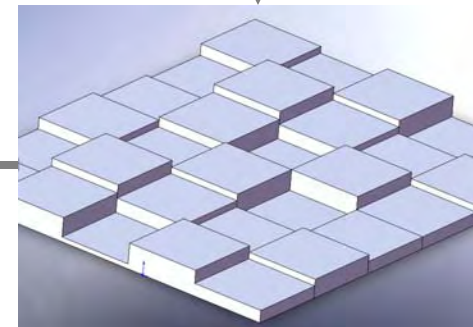


# Software Architecture: VSTM with Excel Interface



Download Materials from FEMAP					Analyze NASTRAN											
ID	Title	Type	Ex	Nuay	Mass Density	3/3 lines in .DAT file corresponding to the leftmost table										PropID
						Type	ID	E	G	MU	RHO	A	TREF	CE	PER	
11	11MACROPANEL	LMAT1	3.30E+06	4.50E-01	1.30E-05	MAT1	11	3.00E+09	0.450	2.99E-06	0.000	0.000	0.000	0.000	11	
12	12MACROPANEL	LMAT1	3.30E+06	4.50E-01	1.30E-05	MAT1	11	3.00E+09	0.450	2.99E-06	0.000	0.000	0.000	0.000	11	
13	13MACROPANEL	LMAT1	3.30E+06	4.50E-01	1.30E-05	MAT1	11	3.00E+09	0.450	2.99E-06	0.000	0.000	0.000	0.000	11	
14	14MACROPANEL	LMAT1	3.30E+06	4.50E-01	1.30E-05	MAT1	11	3.00E+09	0.450	2.99E-06	0.000	0.000	0.000	0.000	11	
15	15MACROPANEL	LMAT1	3.30E+06	4.50E-01	1.30E-05	MAT1	11	3.00E+09	0.450	2.99E-06	0.000	0.000	0.000	0.000	11	
16	16MACROPANEL	LMAT1	3.30E+06	4.50E-01	1.30E-05	MAT1	11	3.00E+09	0.450	2.99E-06	0.000	0.000	0.000	0.000	11	
17	17MACROPANEL	LMAT1	3.30E+06	4.50E-01	1.30E-05	MAT1	11	3.00E+09	0.450	2.99E-06	0.000	0.000	0.000	0.000	11	
18	18MACROPANEL	LMAT1	3.30E+06	4.50E-01	1.30E-05	MAT1	11	3.00E+09	0.450	2.99E-06	0.000	0.000	0.000	0.000	11	
19	19MACROPANEL	LMAT1	3.30E+06	4.50E-01	1.30E-05	MAT1	11	3.00E+09	0.450	2.99E-06	0.000	0.000	0.000	0.000	11	
20	20MACROPANEL	LMAT1	3.30E+06	4.50E-01	1.30E-05	MAT1	11	3.00E+09	0.450	2.99E-06	0.000	0.000	0.000	0.000	11	
21	21MACROPANEL	LMAT1	3.30E+06	4.50E-01	1.30E-05	MAT1	11	3.00E+09	0.450	2.99E-06	0.000	0.000	0.000	0.000	11	
22	22MACROPANEL	LMAT1	3.30E+06	4.50E-01	1.30E-05	MAT1	11	3.00E+09	0.450	2.99E-06	0.000	0.000	0.000	0.000	11	
23	23MACROPANEL	LMAT1	3.30E+06	4.50E-01	1.30E-05	MAT1	11	3.00E+09	0.450	2.99E-06	0.000	0.000	0.000	0.000	11	
24	24MACROPANEL	LMAT1	3.30E+06	4.50E-01	1.30E-05	MAT1	11	3.00E+09	0.450	2.99E-06	0.000	0.000	0.000	0.000	11	
25	25MACROPANEL	LMAT1	3.30E+06	4.50E-01	1.30E-05	MAT1	11	3.00E+09	0.450	2.99E-06	0.000	0.000	0.000	0.000	11	

MS Excel:  
Stochastic Modeling



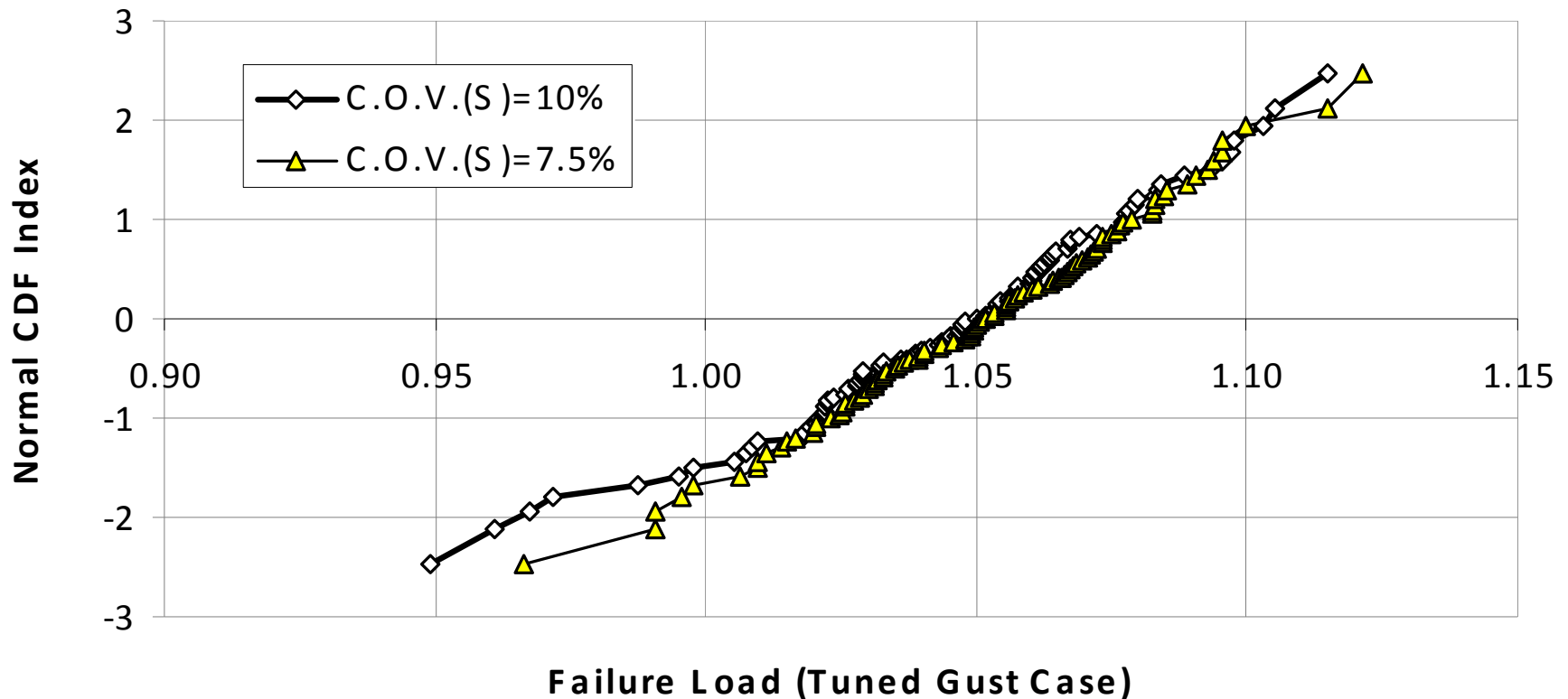
Interface  
with  
NASTRAN

MS Excel:  
Post processing,  
POF, Sensitivities

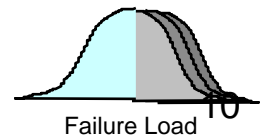
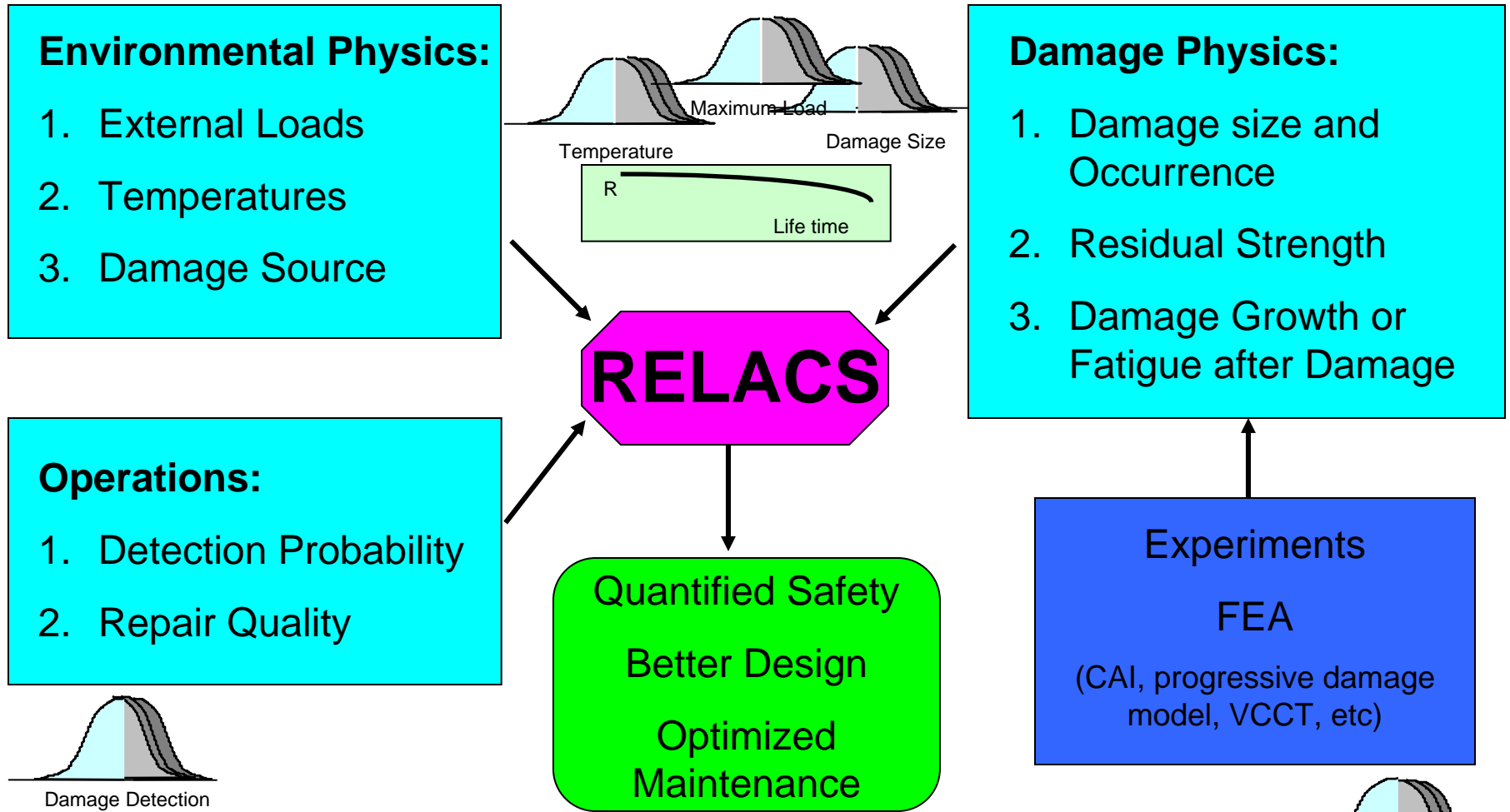


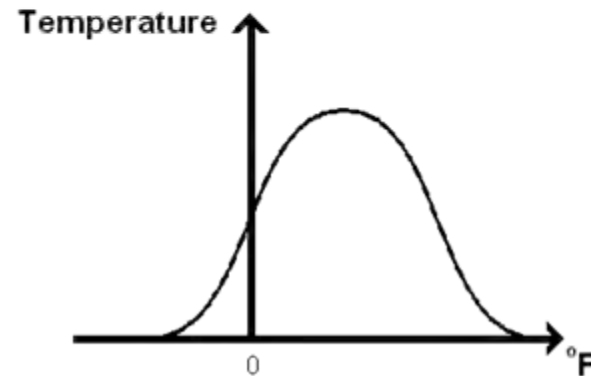
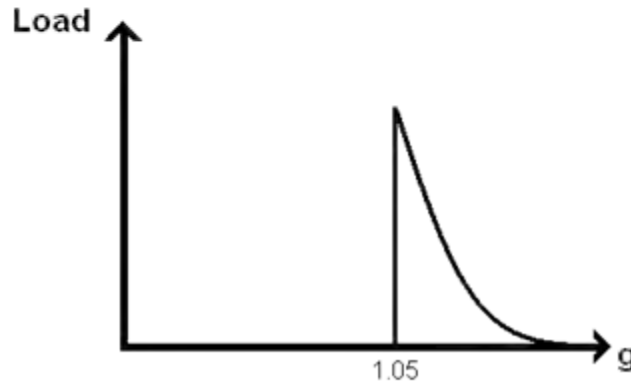
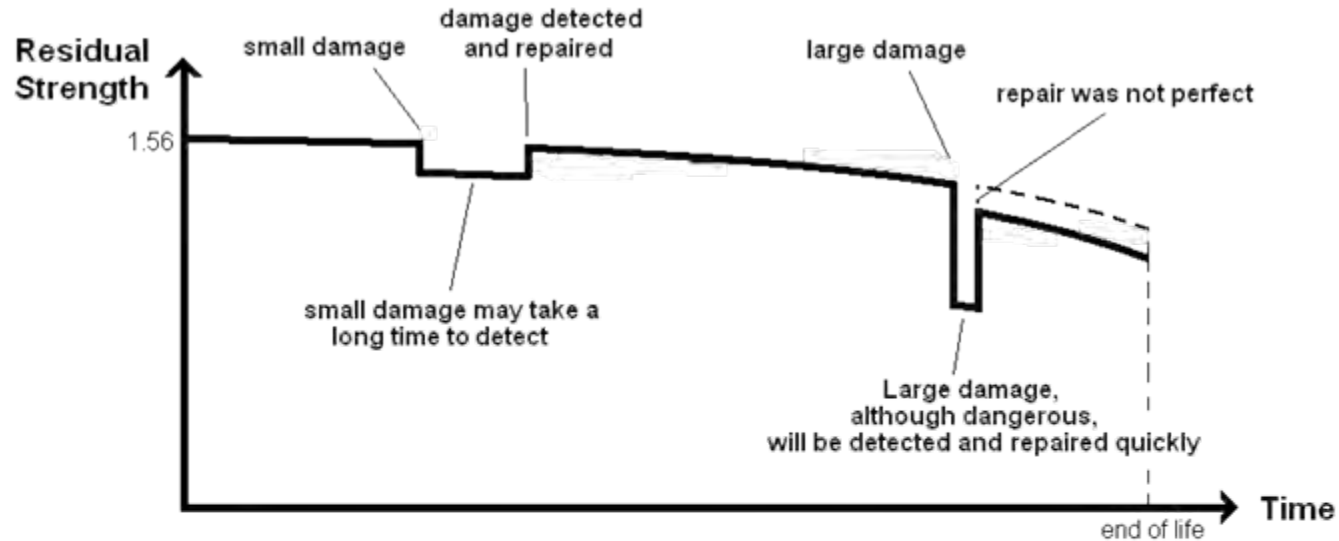
# Example: Realistic Aero-Structure under Tuned Gust

**Empirical CDF of Failure Load in Virtual Static Tests**



# RELACS – Reliability Life-Cycle Analysis of Composite Structures





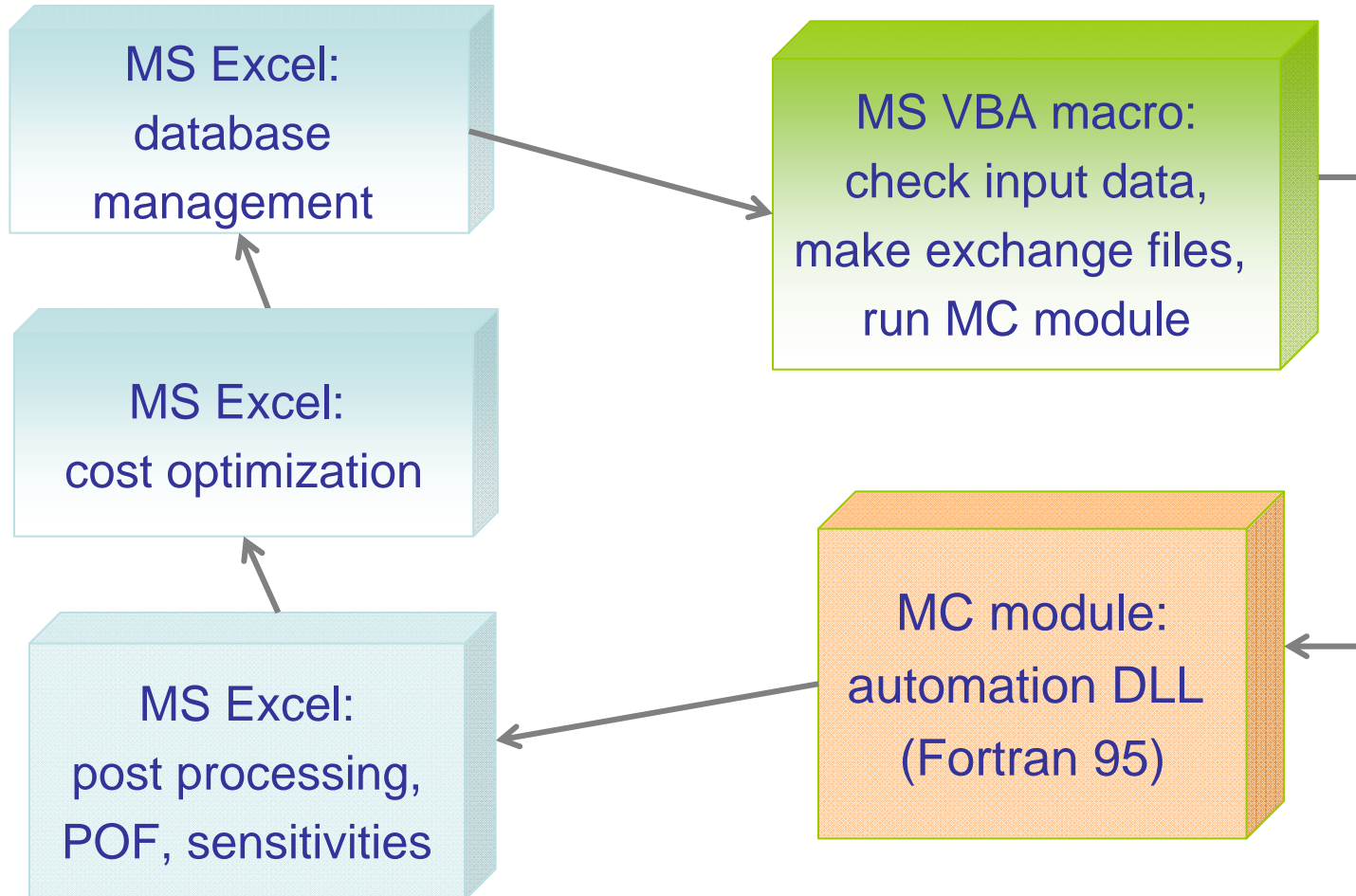
# Program Capabilities: Various Failure Modes

- “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\*

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

# Software Architecture: RELACS with Excel Interface



Microsoft Excel - V23\_ABC\_06-14-07.xls

### Load Exceedance

Selected PDF index number: 1

**Load Exceedance Data (n1,d4)**

User should specify either CDF name and two parameters (mean and Standard Deviation) or the SubMatrices (table) for Exceedance Data.

### User Data

Choose the CDF that approximates your data well.

Tabular Data: Weibull, Normal, Lognormal

**DLC 1**

Mean	Standard Dev.
0.6700	0.0536

Number of Rows: 7

For Lognormal distributions, enter the average (mean) load and the standard deviation.

For each DLC: Select CDF name and enter two parameters (mean and Standard Deviation) for maximum loadness per life.

Enter load exceedance data (choose Tabular Data above).

### Defect/Damage Size Exceedance

Selected PDF index number: 1

**Defects/Damages Exceedance Data (n3,d4)**

User should specify either CDF name and two parameters (mean and Standard Deviation) or the SubMatrices (table) for Exceedance Data.

### User Data

Choose the CDF that approximates your data well.

Tabular Data: Weibull, Normal, Lognormal

**Damage/Defect Type 1**

Mean	Standard Dev.	Defect Rate
0.0100	0.0010	0.0010

Number of Rows: 2

Defect Size: 0.0000, 1.0000, 2.0000

Exceedances per life: 0.0000, 0.0001, 0

**Damage/Defect Type 2**

Mean	Standard Dev.
0.0100	2.0000

Number of Rows: 3

Defect Size: 0.0000, 37.5000, 75.0000

Exceedances per life: 2.0292, 1.8250, 0.4167

For each damage/defect type: Enter size exceedance data (choose Tabular Data above). Enter the mean and standard deviation for selected CDF (choose any CDF above).

For Lognormal distributions, enter the average (mean) load and the standard deviation.

Copy and paste the top 4 rows of the data section below to create exceedance data for defects. The software is searching for "Number of Rows" to locate submatrix.

This column represents defect/damage sizes of one given in the left column.

This column represents defect/damage sizes of one given in the left column.

Here CDF of defect/damage size should be specified. This is not a CDF.

### Damage/Defect Detection Probability

Selected PDF index number: 1

**Damage/Defect Detection Probability (n4,d4)**

User should specify either CDF name and two parameters (mean and Standard Deviation) or the SubMatrices (table) for Probability Data.

### User Data

Choose the CDF that approximates your data well.

Tabular Data: Weibull, Normal, Lognormal

**Method 1 for Type 1 Damage/Defect**

Mean	Standard Dev.
37.7333	26.2412

Number of Rows: 19

Size: 1, 20, 50, 100, 300, 1000, 2000, 3000, 3600, 3800, 4100, 4400, 5000, 6000, 7300, 7600

Detection Probability: 0.0000, 0.0000, 0.0000, 0.0003, 0.0074, 0.0129, 0.0909, 0.0956, 0.5667, 0.9745, 0.9800, 0.9840, 0.9870, 0.9893, 0.9911, 1.0000, 1.0000

**Method 2 for Type 1 Damage/Defect**

Mean	Standard Dev.
37.7300	26.2412

Number of Rows: 17

Size: 1, 20, 50, 100, 300, 1000, 2000, 3000, 3600, 3800, 4100, 4400, 5000, 6000, 7300, 7600

Detection Probability: 0.0001, 0.0386, 0.2259, 0.4815, 0.6175, 0.8001, 0.8708, 0.9129, 0.9567, 0.9745, 0.9800, 0.9840, 0.9870, 0.9893, 0.9911, 1.0000, 1.0000

For Lognormal distributions, enter the mean, damage/defect size and its standard deviation of damage size logarithm.

For each damage/defect type, enter initial values for size and its probability of being detected by the given method (Choose Tabular Data above).

Enter the mean and standard deviation for selected CDF (choose any CDF above).

The data here is not actually CDF. This is Probability of detecting damage of given size per inspection approximated by some popular CDF-like function. This data is obtained by inspecting the same damage by different inspectors and counting the successful cases.

When the Lognormal distribution is used, enter the average (mean) value and standard deviation of the damage size logarithm.

### Residual Strength

Selected PDF index number: 1

**Residual Strength Data (n5,d4)**

User should specify either CDF name and two parameters (mean and Standard Deviation) or the SubMatrices (table) for Residual Strength Data.

### User Data

Choose the CDF that approximates your data well.

Tabular Data: Weibull, Normal, Lognormal

**DLC 1 for Type 1 Damage/Defect**

Mean	Cv
1.5000	5.000E-02

Number of Rows: 6

Damage Size: 0, 5, 10, 20, 50, 100

Relative Residual Strength: 1.4000, 1.3400, 1.2500, 1.1700, 1.0000, 0.8000

**DLC 1 for Type 2 Damage/Defect**

Mean	Cv
37.7300	26.2412

Number of Rows: 7

Damage Size: 0, 26, 28, 30, 32, 40, 50, 100

Relative Residual Strength: 1.4000, 1.3400, 1.2500, 1.1700, 1.0000, 0.8000, 0.6000

For each damage/defect type, enter initial values for damage/defect size, the average (mean) value of its residual strength and its coefficient of variation. Before simulation, these numbers will be converted into the location and scale parameters of the specified PDF.

Create additional instances for each damage/defect type being considered. Separate each matrix by ??? Rows.

Row 1: Blank

Row 2: Title/Description (e.g. "DLC 1 for Type 2 Damage Type")

Row 3: Blank

Row 4: Number field with maximum number of rows containing data

Row 5: Blank

Row 6: Column Header

SubMatrices: Number of SubMatrices = (Number of Design Load Cases) X (Number of Damage/Defect types)

Independent Variable: Damage/Defect size

Dependant Variables: Averages (mean) residual strength and its coefficient of variation for damage/defect of given size.

# Optimal Statistical Decisions

## Minimum Risk Maintenance Planning

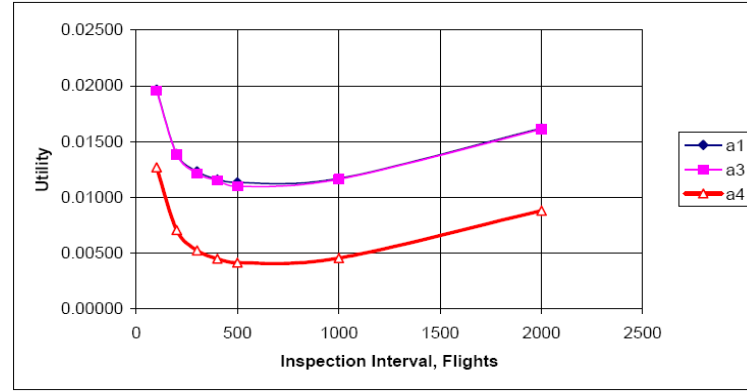
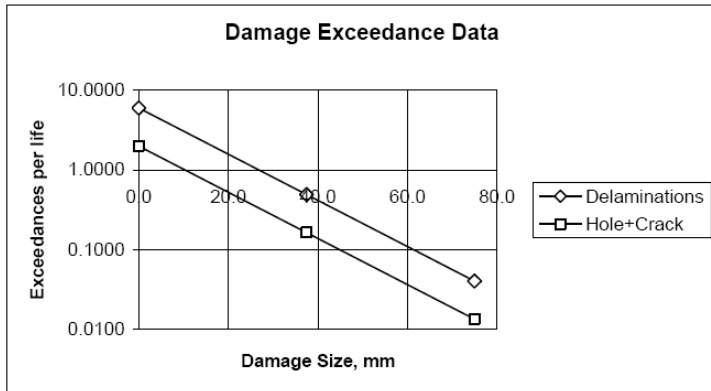
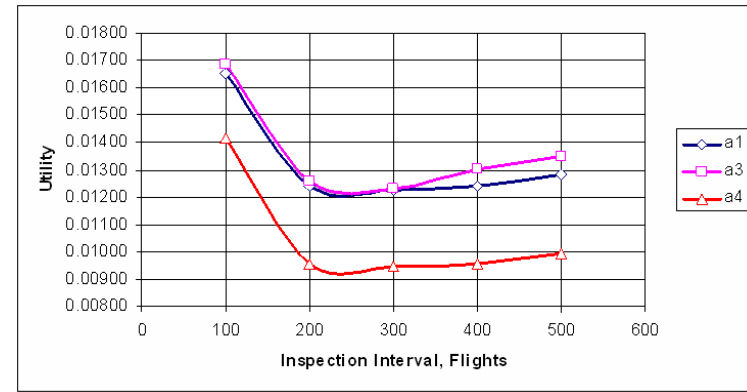
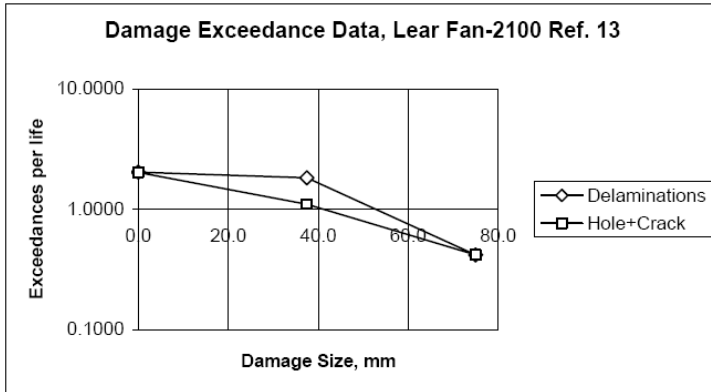
- Maintenance planning is one of the most important tool to manage damage-induced risks
- Flexibility exists in maintenance planning
- Variability exists in many key parameters for inspections and repairs
- The cost of any potential maintenance plan can be evaluated in terms of utility and the best decision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



**Utility** = Inspection Costs +  
Repair Costs +  
Service Interruption Costs +  
**Failure Costs**

# Optimal Statistical Decisions

## Minimum Risk Maintenance Planning



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



# 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

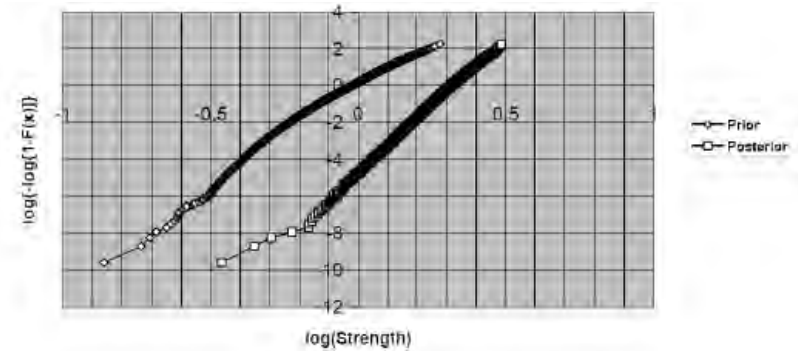


Figure 8: Prior and posterior CDFs for e1 substantiation method

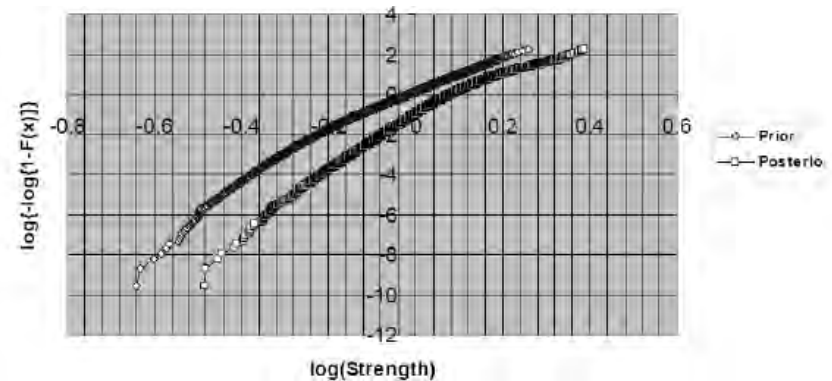
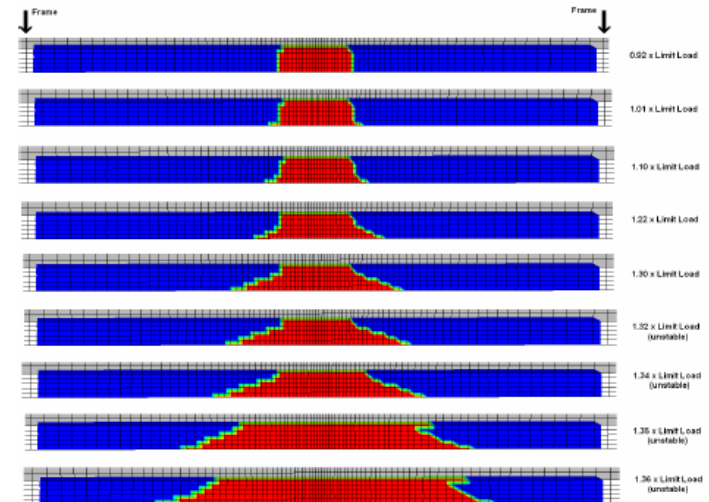
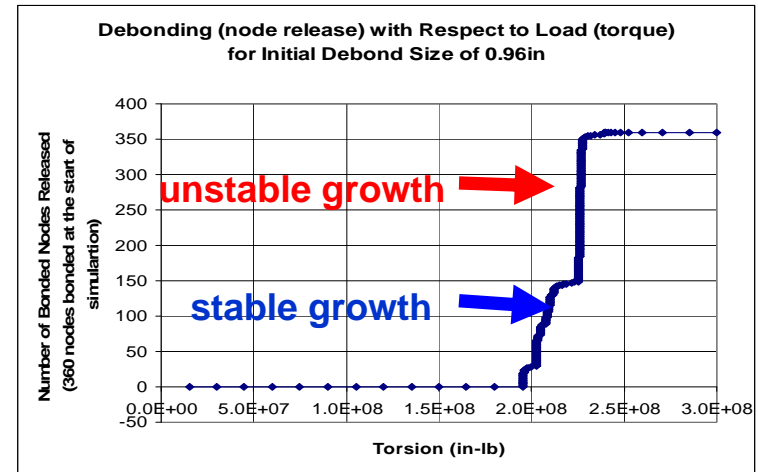


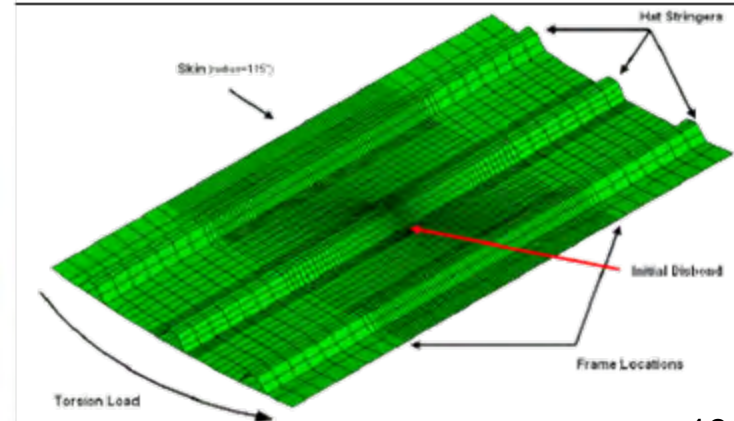
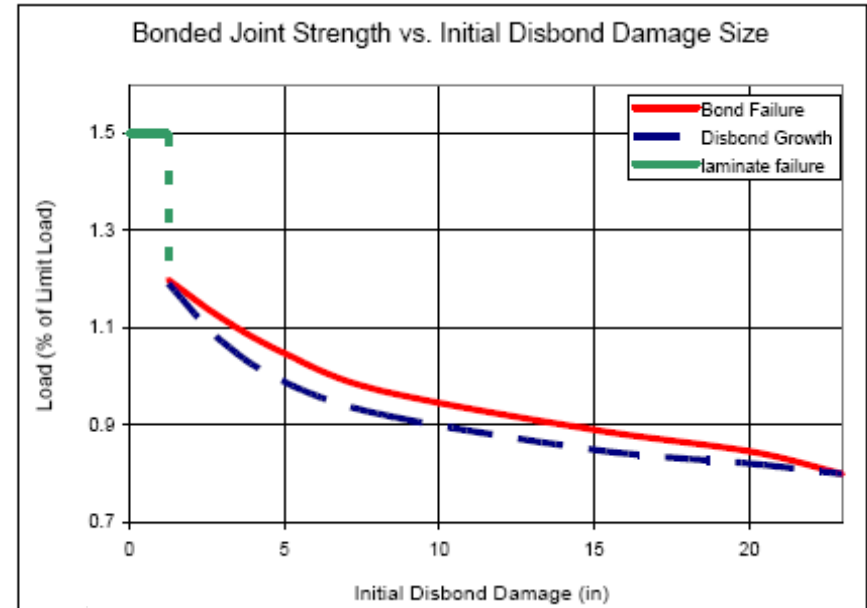
Figure 6: Prior and Posterior Empirical CDF for composite structures.

- 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



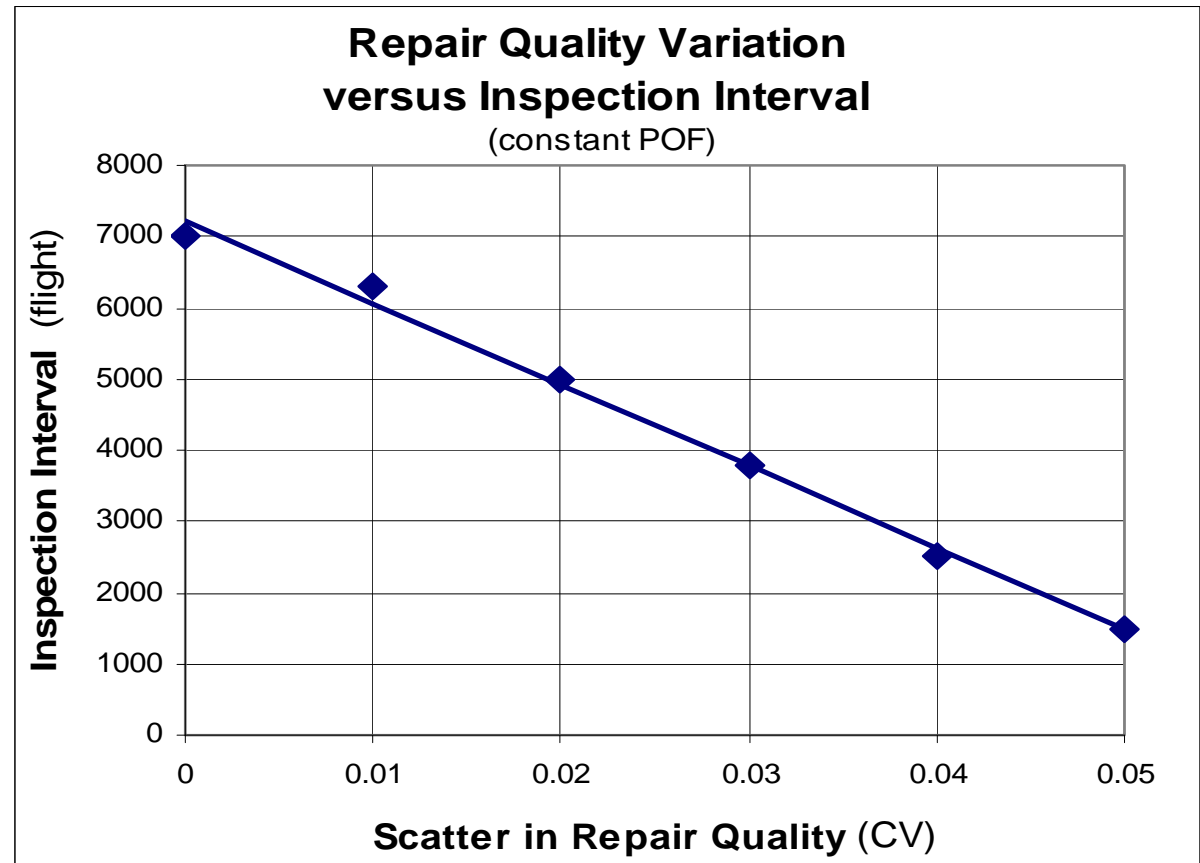
## ABAQUS with VCCT

- 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.



## 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.



## Work Accomplished

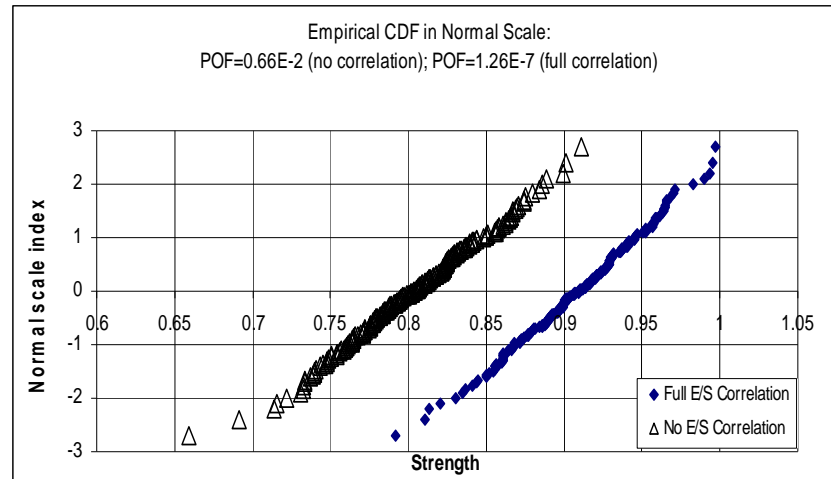
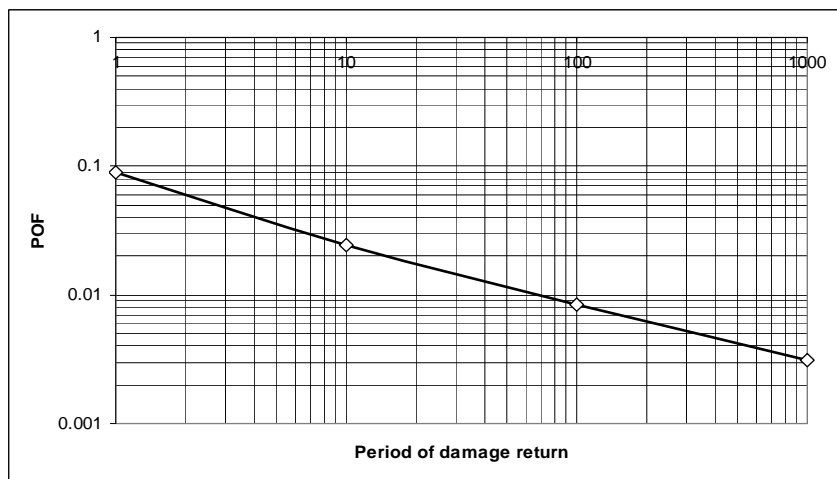
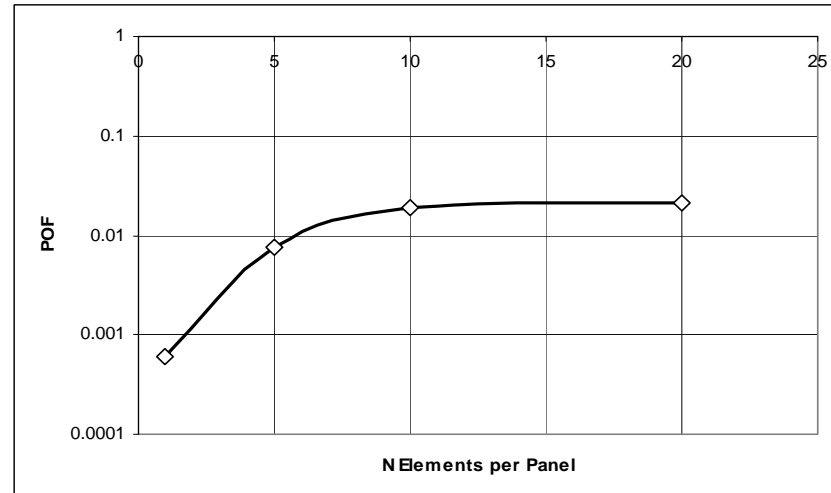
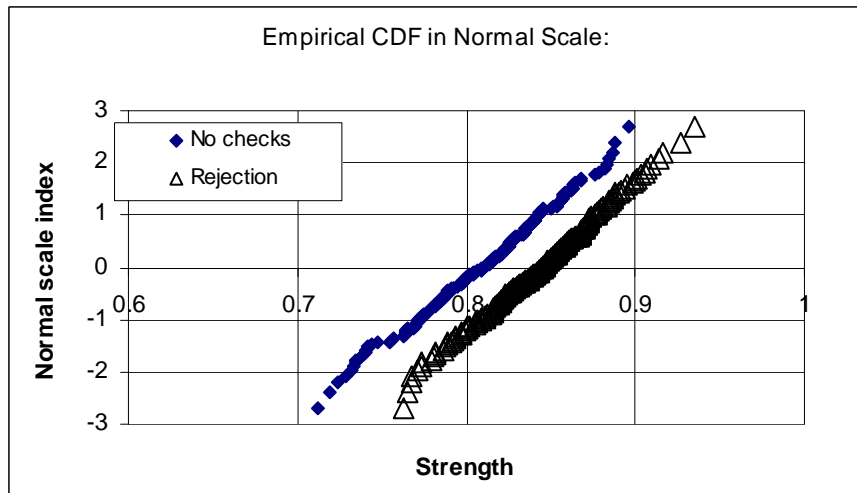
- Developed the methodology to determine the reliability and maintenance planning of damage tolerant structures.
- Developed a user-friendly software (RELACS) for calculating POF and inspection intervals.
- Developed software interface (VSTM) with Nastran to facilitate stochastic FEA.
- Mined statistical 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.

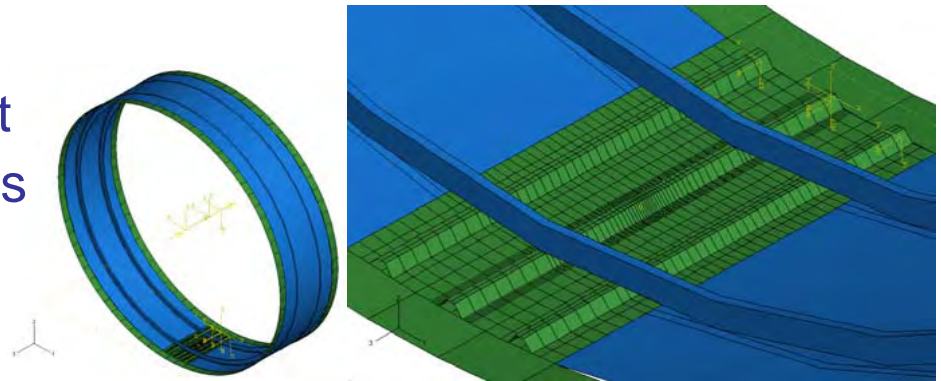
# Future Research: Systematic Study of the Variability of Composite Materials and Structures

- 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: Analytical Methods for Interlaminar Fracture and Disbond of Composites

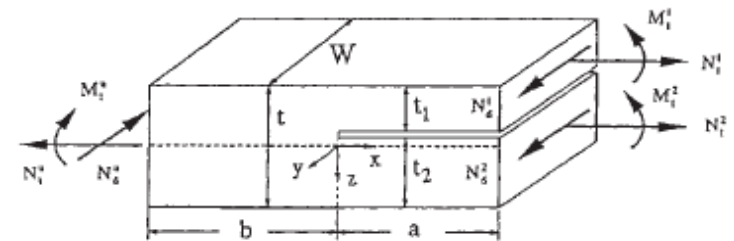
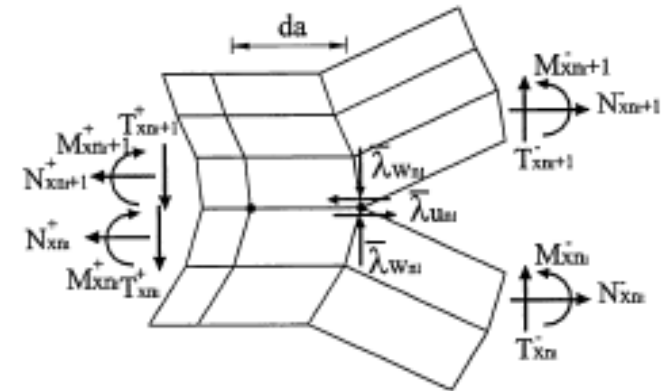
- Uncertainties in interlaminar fracture disbond are large and require probabilistic considerations for design and certification
- The number of variables in this type of problem is large (e.g. delamination location, ply thickness and orientation, spatial variation in material properties, damage geometry, 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.



## ■ 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.