Development of Reliability-Based Damage Tolerant Structural Design Methodology:

Progress Report

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- **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. Presently there is no industry-wide standard to establish appropriate inspection intervals for a damage-tolerant structure based on the consideration of structural reliability, inspection methods, and quality of repair. An urgent need exists to develop a standardized methodology for establishing an optimal inspection schedule that provides minimum maintenance cost and maximum structural reliability.

- **Objective:** Develop a probabilistic method to estimate structural component reliabilities suitable for aircraft design, inspection, and regulatory compliance.

Research Team

- **Principal Investigator:**
  Dr. Kuen Y. Lin, Aeronautics and Astronautics

  Research Scientist: Dr. Andrey Styuart

  Research Assistants: Cary Huang, Crystal Simon

- **FAA Technical Monitor:** Peter Shyprykevich

- **Other FAA Personnel:** Dr. Larry Ilcewicz, Curtis Davies

- **Industry Participants:** Dr. Alan Miller, Dr. Cliff Chen, Dr. Hamid Razi (Boeing)

Approach

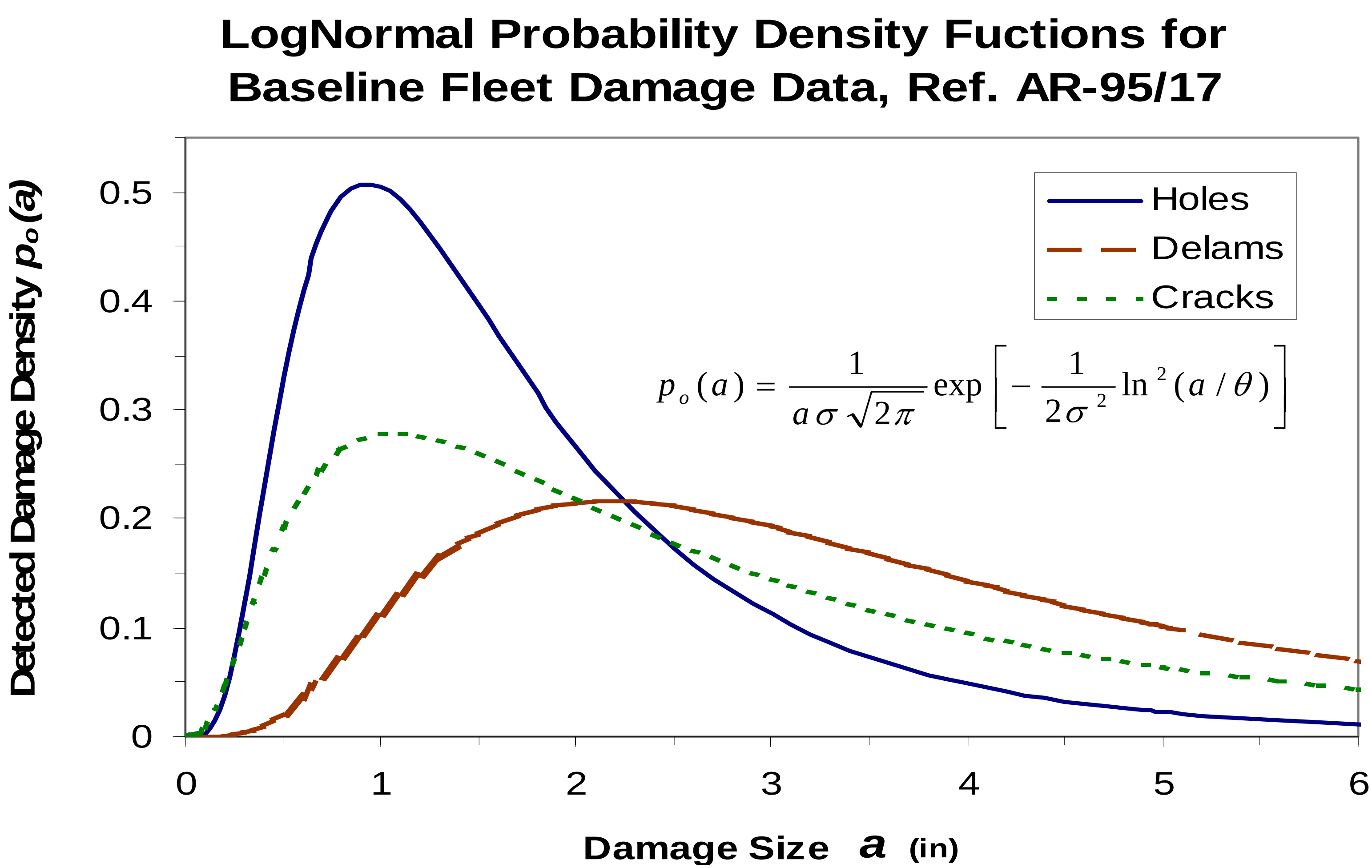
- The present study is based on a probabilistic failure analysis with the consideration of parameters such as inspection intervals, statistical data on damages, loads, temperatures, damage detection capability, residual strength of the new, damaged and repaired structures.
- The inspection intervals 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.
- No damage growth is assumed in the present model.

Phase I Research Tasks

- Develop a Probabilistic Method to Determine Inspection Intervals for Composite Aircraft Structures
- Develop Computing Tools and Algorithms for the Probabilistic Analysis
- Establish In-service Damage Database from FAA SDR and Other Sources
- Demonstrate the Developed Method on an Existing Structural Component

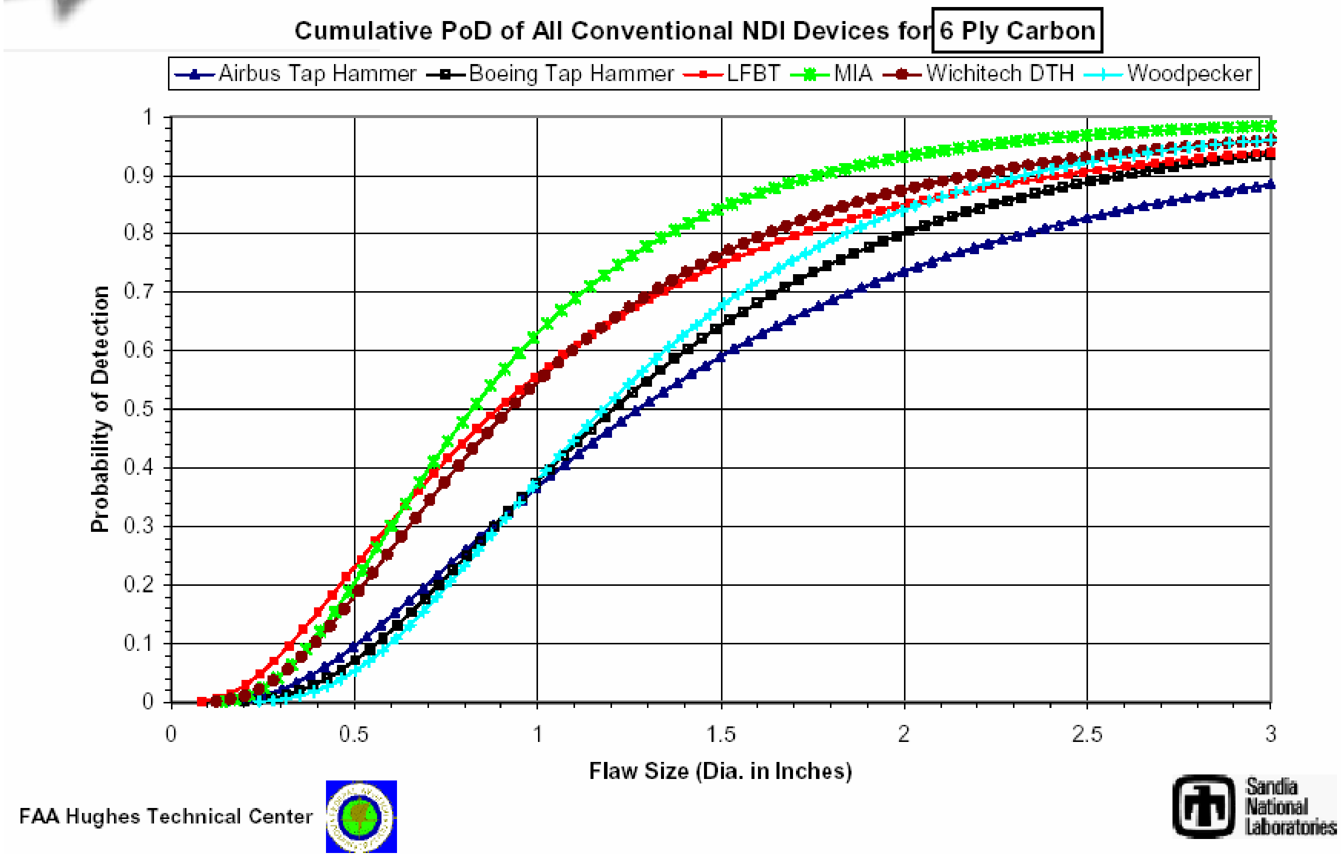
Typical In-service Damage– Hail Damage

PDF of Detected Damages

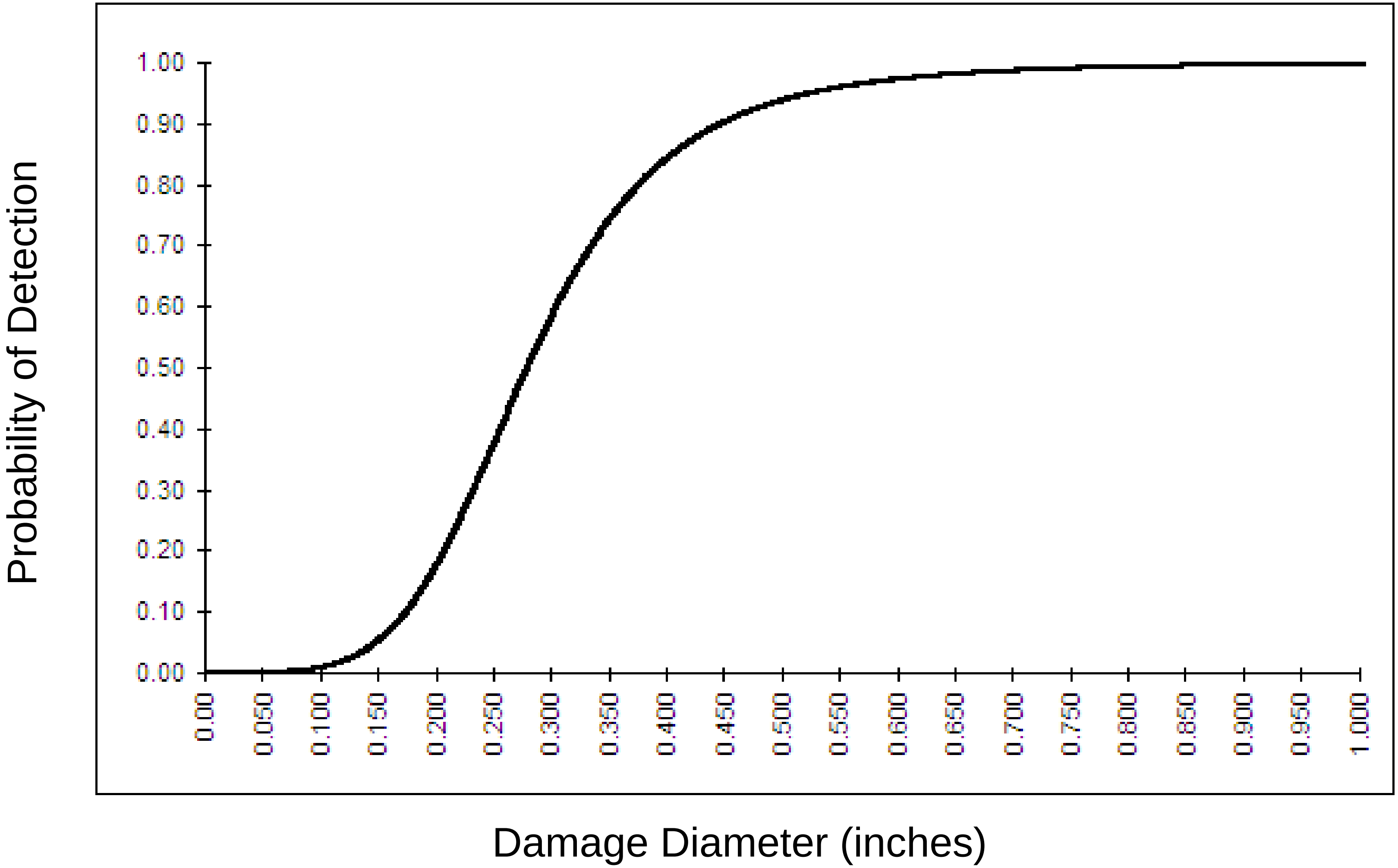


PDF of Detected Damages

Performance of Multiple Devices for A Single Type of Test Specimen



Visual Inspection POD for Shiny Surface at 20 ft Distance



Identification of Critical Parameters

Various Failure Modes

Strength vs. Temperature

Moisture Content vs. Time

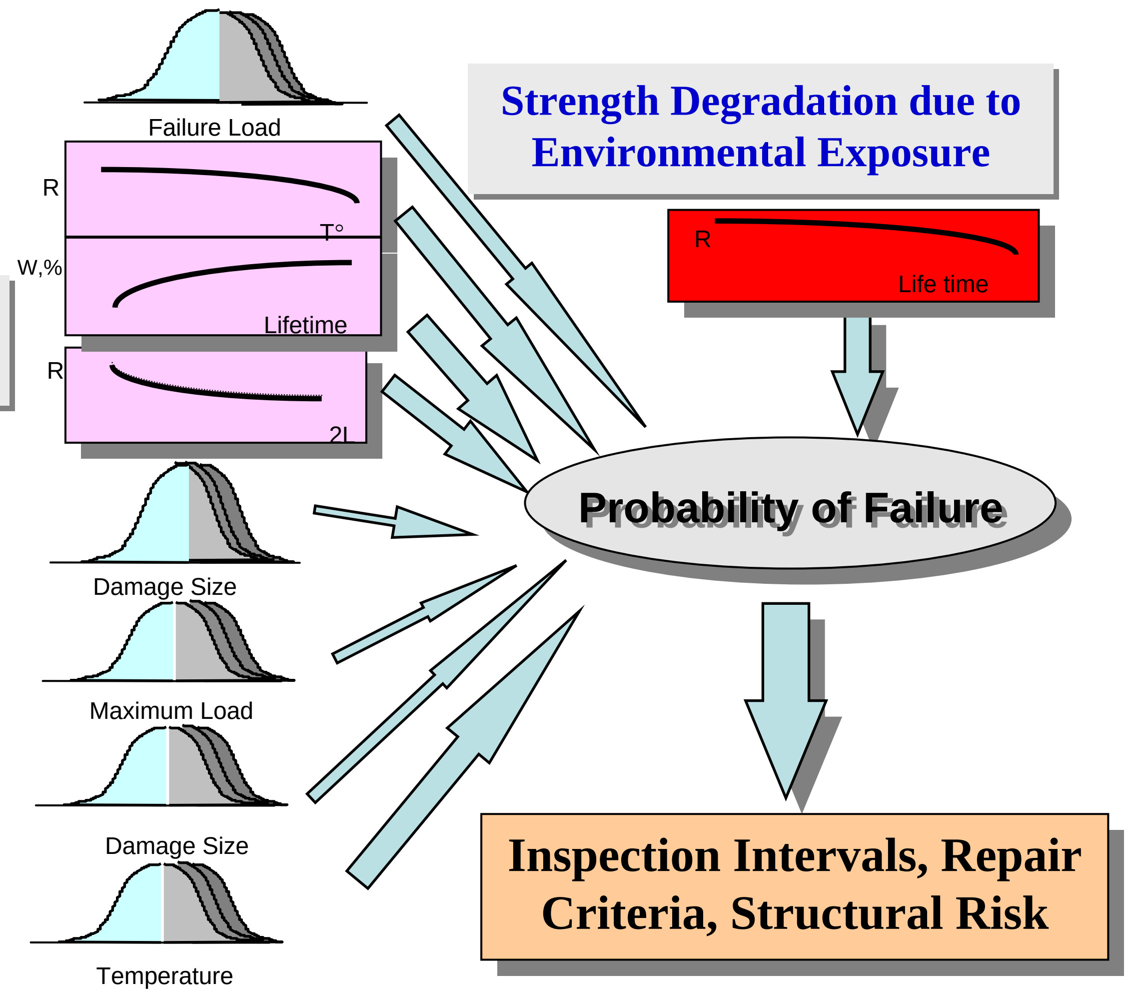
Residual Strength vs. Damage Size & Damage Type

Probability of Detection vs. Damage Size & Damage Type

Maximum Load vs. Time of Damage Existence

Damage Size & Damage Type Spectra

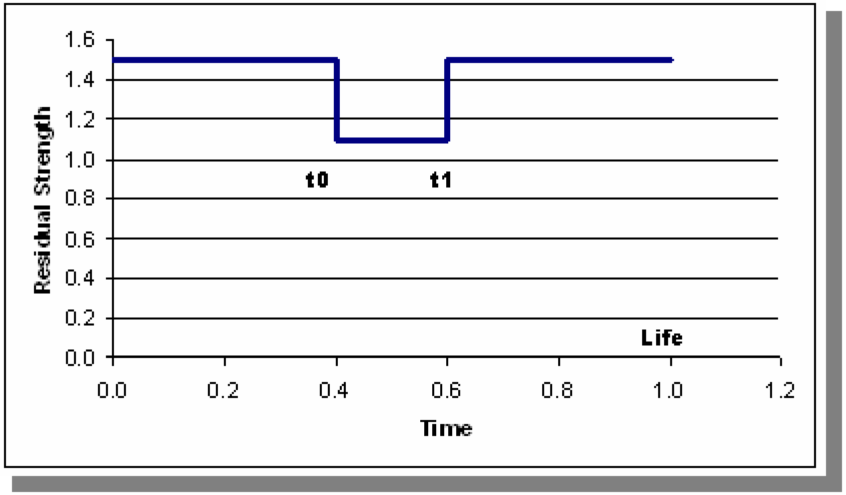
Structural Temperature Spectra

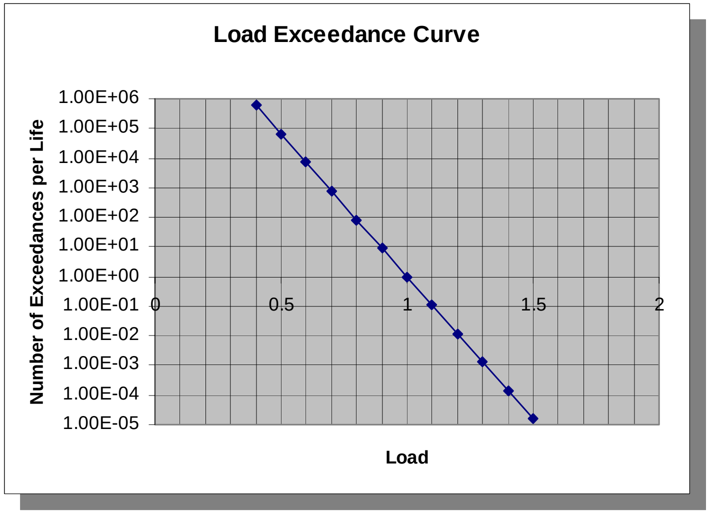


Work Accomplished

- Two methods, based on Importance Sampling and Monte-Carlo Simulation, have been developed for determining the inspection intervals.
- Computer software (Version 1.2) for calculating the inspection intervals has been completed.
- Database for Reliability-Based Damage Tolerance Analysis has been established.
- Three sample problems with parametric studies have been demonstrated on existing structural components.
- Results from the present study have been compared with those obtained by other methods and software (NESSUS).
- Effect of environmental aging and chemical corrosion added

Reliability Formulation 1





$$P_f = 1 - \prod_{i=1}^{N=3} [1 - P_f(R_i, t_i)]$$

Interval #	Probability of Failure
1 (new structure)	6.12E-06
2 (damaged structure)	4.26E-02
3 (repaired structure)	6.12E-06
Total POF =	4.26E-02

Reliability Formulation 2

Probabilistic Input Parameters:

- **Type of damage TD**
- **Number of damages per life**
- **Initial failure load (initial strength)**
- **Damage size**
- **Time of damage initiation**
- **Time to detect Damage**
- **External load**
- **Structural Temperature *T*°**
- **Effects of environmental aging and chemical corrosion**

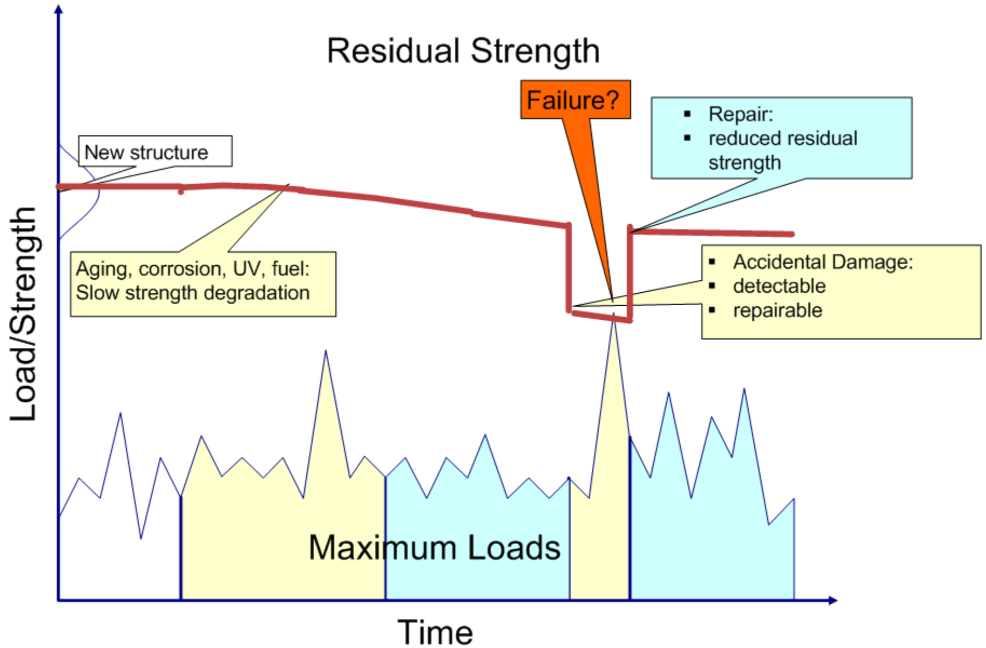
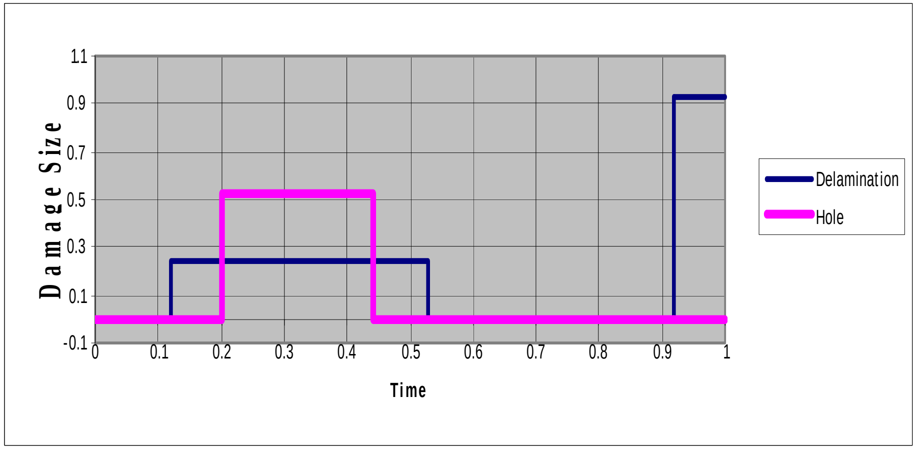
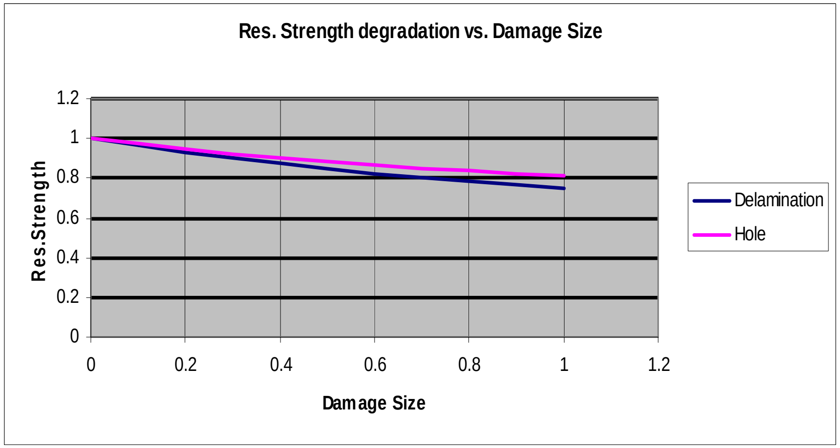


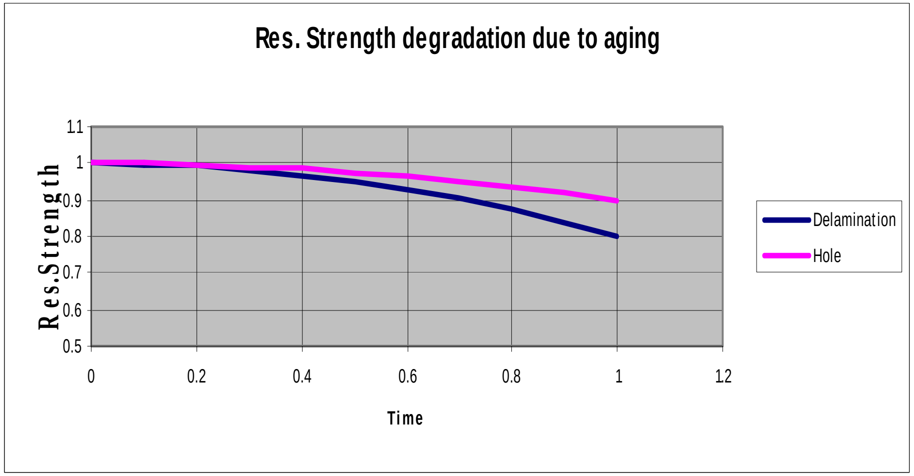
Fig.1

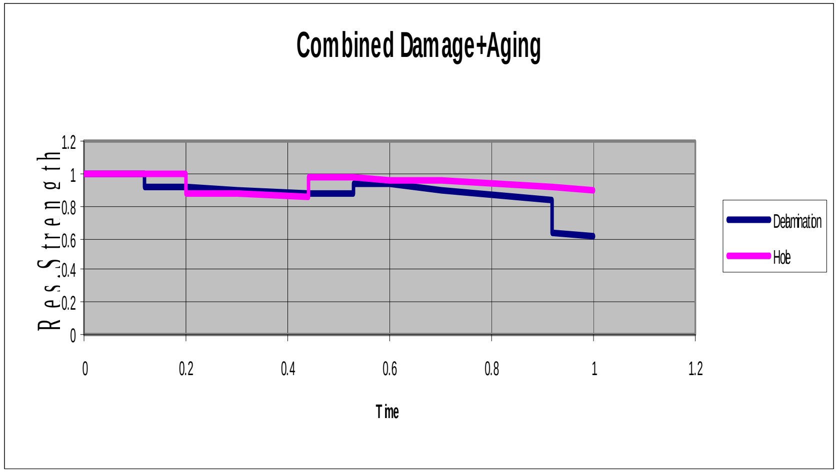
First, we simulate random time histories of residual strength as a sequence of intervals between damage initiation and detection/repair. The probability of failure (POF) can then be evaluated as the sum of POF for all intervals.

Reliability Formulation 3

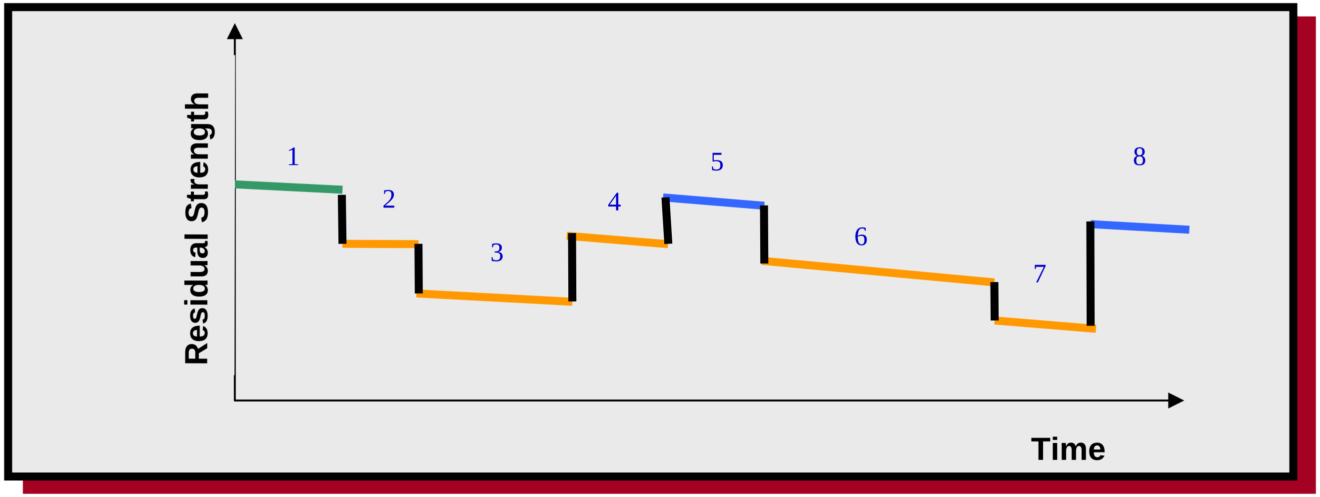








The Integration Model



$$POF_{fixed} = 1 - \prod_{i=1}^{N} F_{L\max}(S_i, t_i) = 1 - \prod_{i=1}^{N} \exp[-H_t(S_i)t_i]$$

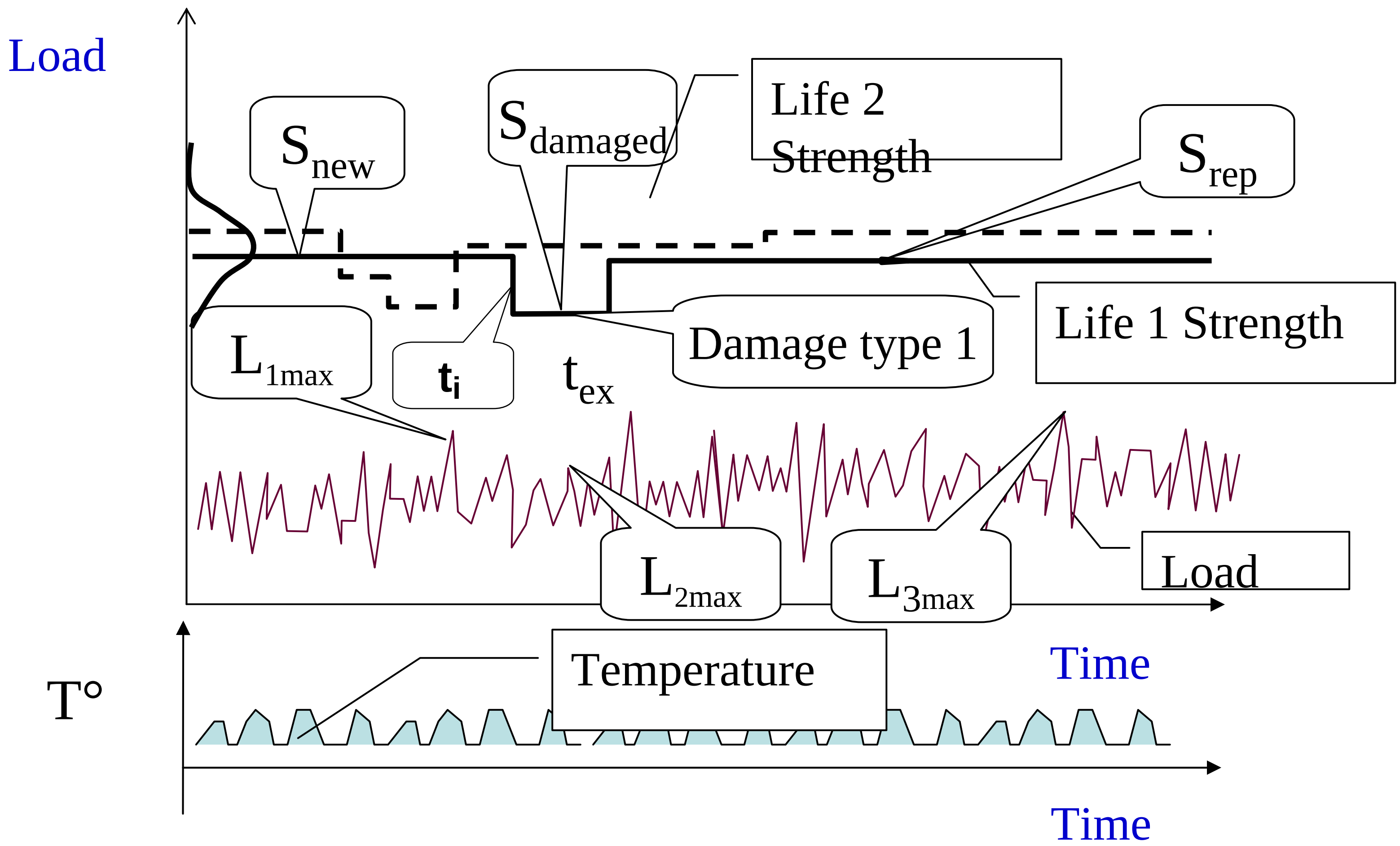
$$POF(T_1, T_2, \ldots) = \int_{\Omega} POF_{fixed}(N_I, S_1, S_2 \ldots, t_1, t_2 \ldots, TD_1, TD_2, \ldots, T^{\circ}) f(N_I, S_1, S_2 \ldots, t_1, t_2 \ldots, TD_1, TD_2, \ldots, T^{\circ}) d\vec{v}$$

$$d\vec{v} = dN_I dS_1 dS_2 \ldots dt_1 dt_2 \ldots dTD_1 dTD_2 \ldots dT^{\circ}$$

The Integration Technique:

- **Monte-Carlo Integration + Importance Sampling**

Simulation Algorithm



The Integration and Full Monte-Carlo Models

Integration -> Features Covered:

Random External Load ___	✓
Random Damage Sizes & Number	✓
Random Failure Load ____	✓
Random Damage Detection Time vs. Damage Size ___	✓
Random Properties Degradation due to Temperature ___	?
Multiple Load Cases _____	✓
Multiple Damage Types __	✓
Multiple Inspection Types __	✓
Various Repair Types & Repair Logic	✓
Multiple Damage Interaction _____	?
Effects of environmental aging	✓

Full M-C -> Features Covered:

Random External Load ___	✓
Random Damage Sizes & Number	✓
Random Failure Load ____	✓
Random Damage Detection Time vs. Damage Size ___	✓
Random Properties Degradation due to Temperature ___	✓
Multiple Load Cases _____	✓
Multiple Damage Types __	✓
Multiple Inspection Types __	✓
Various Repair Types & Repair Logic	✓
Multiple Damage Interaction _____	?
Effects of environmental aging	?

Integration -> Advantages:

- High Speed
- High Accuracy

Full M-C -> Advantages:

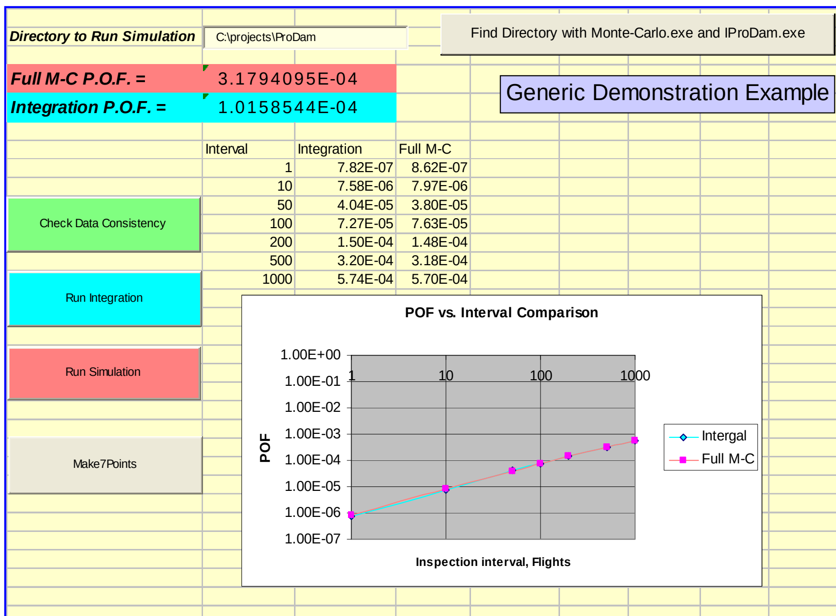
- Consistent Temperature Presentation
- Detailed Failure Data Output

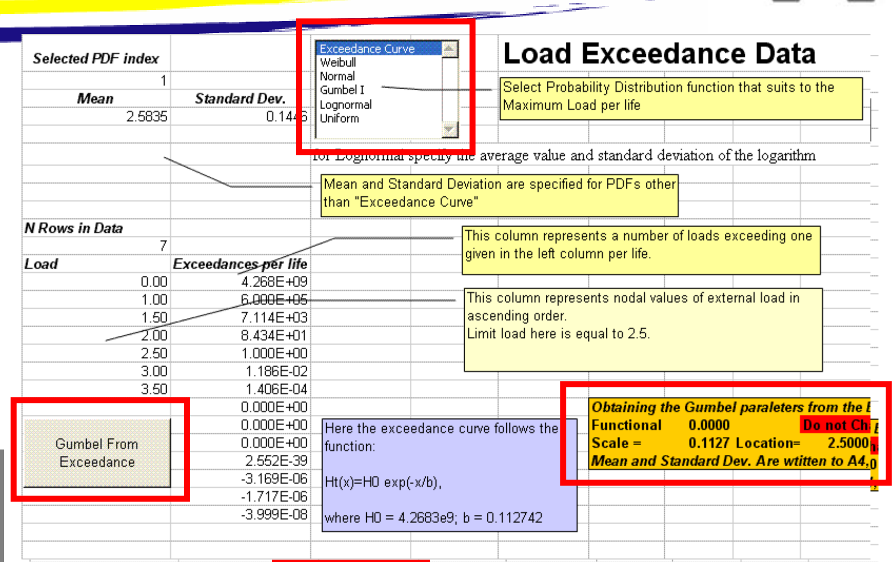
Algorithm Implementation

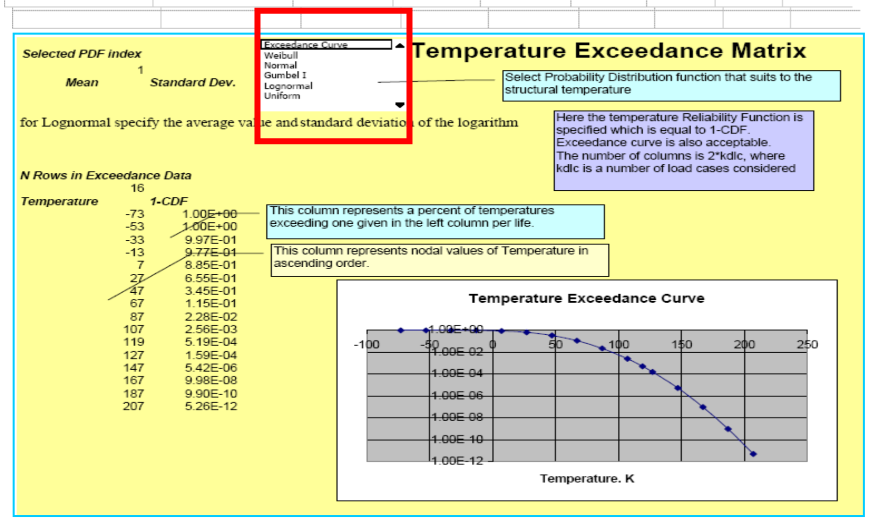
MS Excel (Data) +

Excel Macro (VBA) +

Automation DLL (Fortran 95)

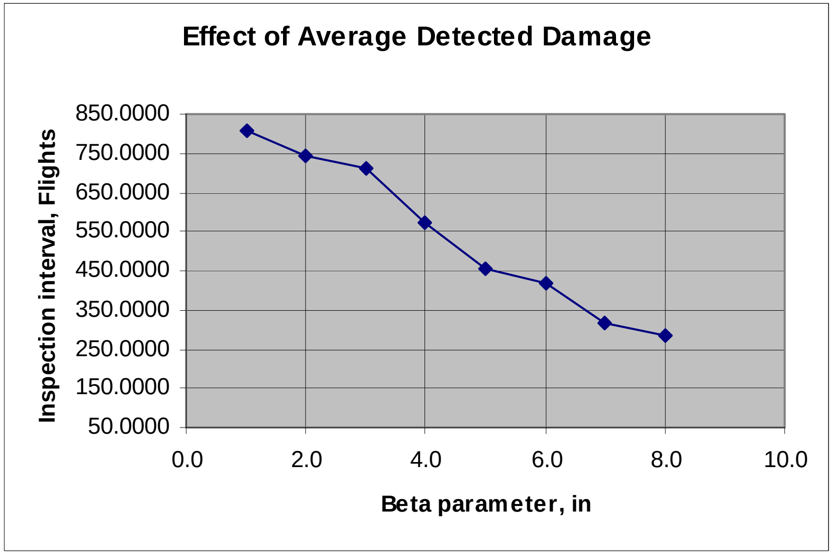






Results of Parametric Study

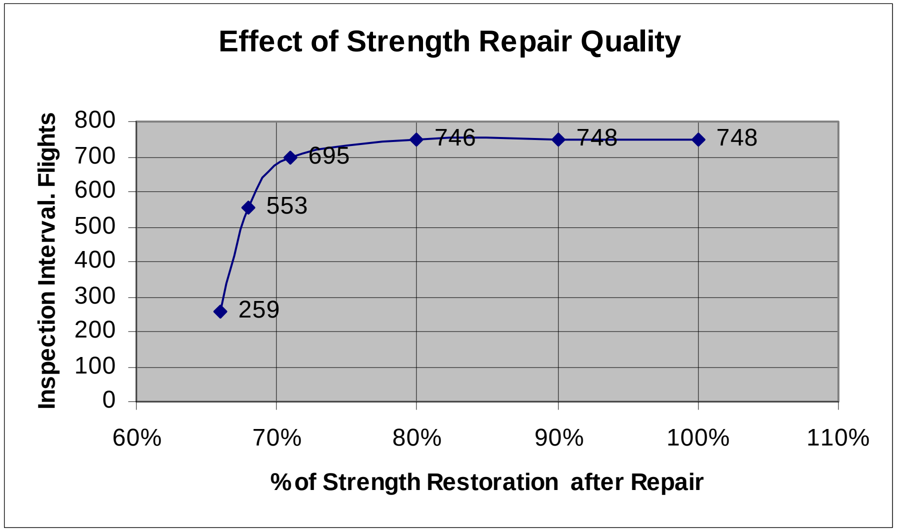
Inspection Interval determined corresponds to Probability of Failure = 1e-4 per life



$$P_D(D) = 1 - \exp\left(-\frac{D}{\beta}\right)^{\alpha};$$

$$\alpha = 1.4; \quad \beta = Variable$$

Variable Strength Recovery Percent



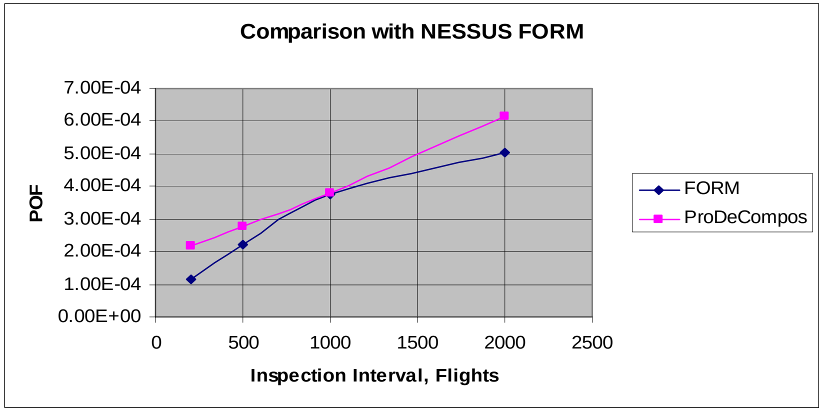
Sample Problem 1: Comparison With NESSUS

NESSUS Model feature: Exactly one damage per life

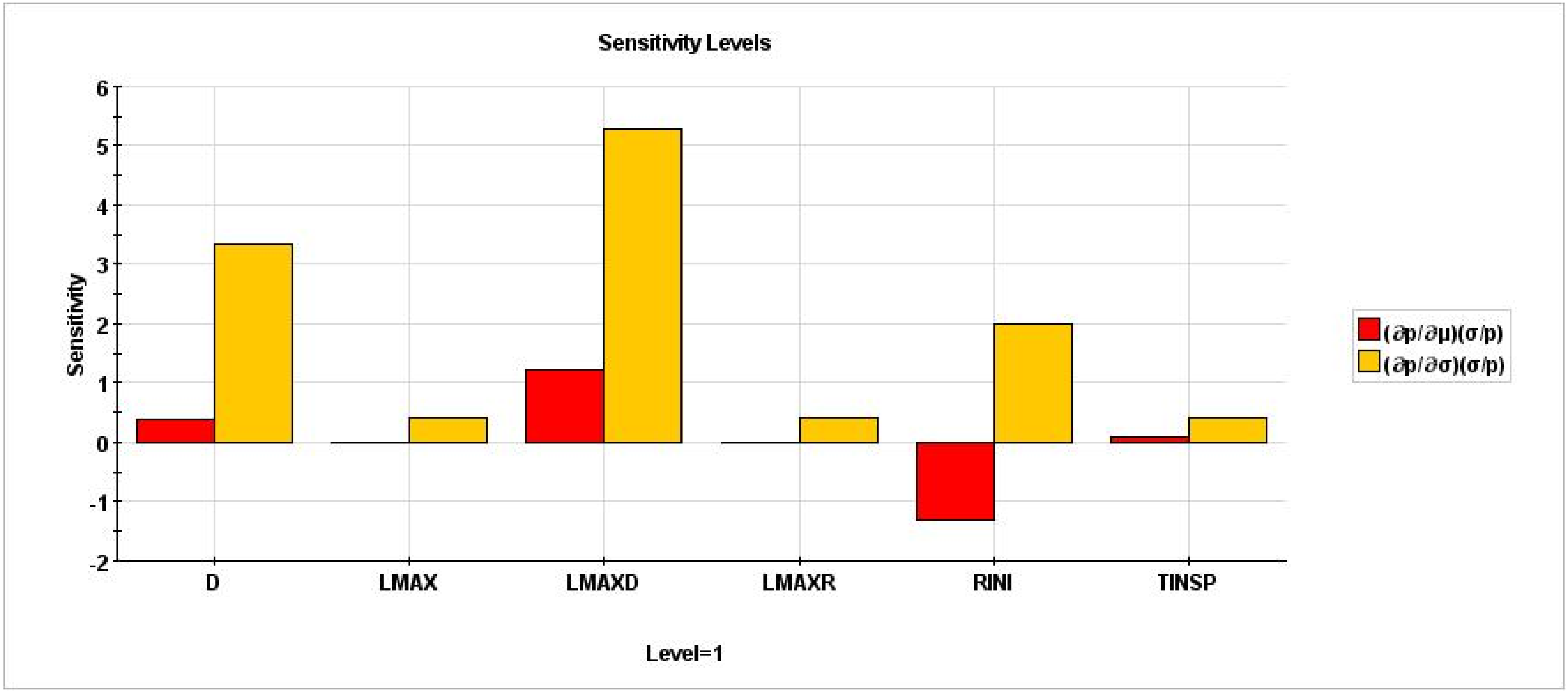
Random variables:

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%

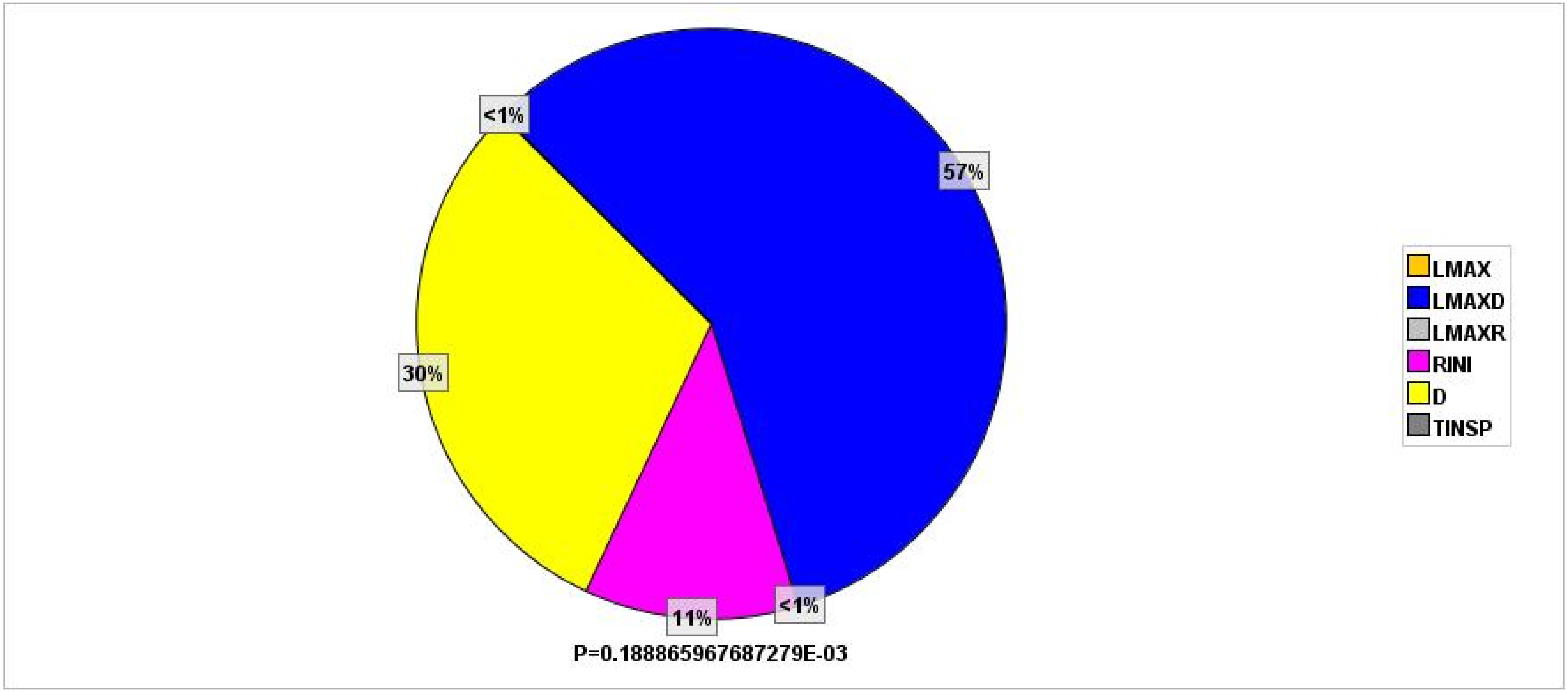
Satisfactory comparison with NESSUS



Sample Problem 1:
Sensitivity Study from NESSUS



Sample Problem 1:
Probabilistic Sensitivity Factors from NESSUS



Summary

What we have:

- The preliminary method for determining POF and the inspection intervals for no growth concept.
- Basic computer software for calculating POF and and the inspection intervals.
- Some restricted database for Reliability-Based Damage Tolerance Analyses.

What we will have:

- The established method for determining POF and the inspection intervals including material degradation.
- User friendly computer software for commercial use in probabilistic design.
- Acceptable database for Reliability-Based Damage Tolerance Analyses.

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.

Phase 2: Analysis Refinement and Methodology Implementation

(September 1, 2005 – August 31, 2007)

The primary objective of Phase 2 is to apply the developed methodology to the maintenance of current fleet and design of future aircraft.

Major tasks to be accomplished in Phase 2:

- **Analysis Method Enhancement**
- **Analysis Method Implementation**

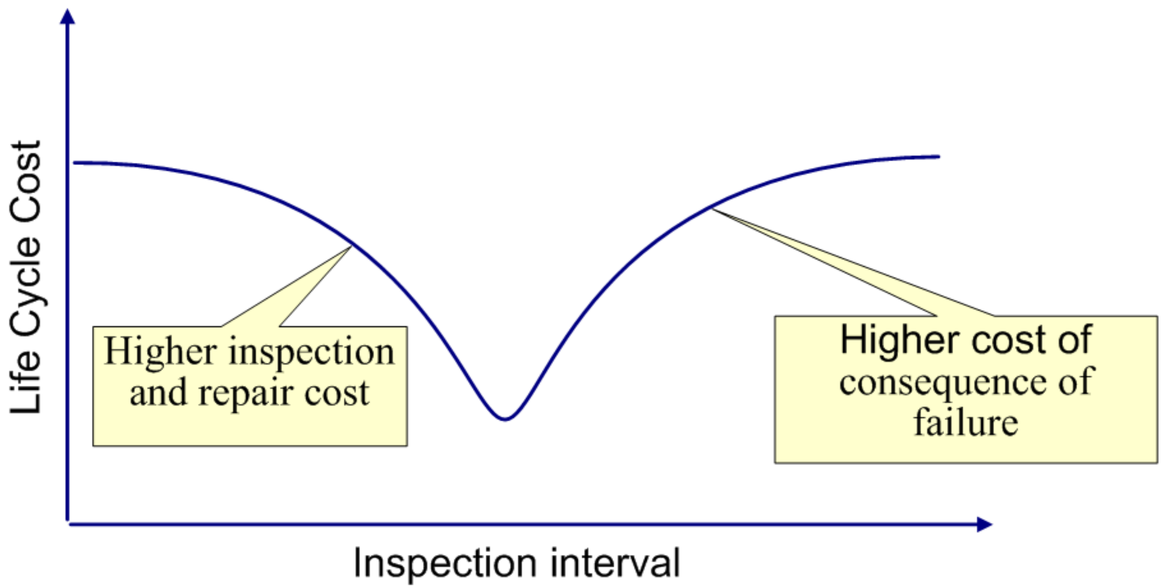
Task 2.1: Analysis Method Enhancement

The analysis method developed in Phase I will be enhanced to include:

1. **Effects of environmental aging and chemical corrosion. The mathematical model of aging will be represented by an Arrenius type equation to include the empirical UV and fuel degradation. The aging effects will be incorporated into computer software and algorithm that help designers to compare various aging environments and impact of aging/corrosion on the structural reliability.**

Task 2.1: Analysis Method Enhancement

2. Development of optimum inspection schedule to minimize maintenance cost and risk. Typical algorithms for minimum LCC design will be studied and incorporated into the software. The developed computer program will take into account the factors such as inspection cost and associated repair and downtime costs, cost of consequence of failure and possibly acquisition and operating costs.



Task 2.1: Analysis Method Enhancement

3. Development of database and tools to automate the entire evaluation process. Such tools may be used as production tools for maintenance planning.

Database on impact damage condition: The goal is to establish a set of standard design damage types along with their frequencies. Each of them has distinct characteristics such as geometry, energy (or any invariant metric), and density. The specific work items for this task may include:

(1) Data mining and grouping,

(2) Reverse engineering to estimate impact energy with known or best assumed geometry and density,

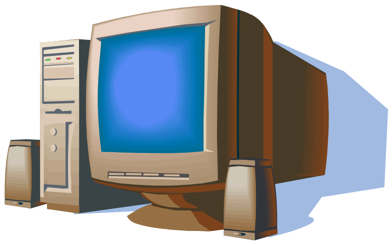
(3) Establishment of frequencies or exceedances.

These tasks need to be performed for each primary structural locations. Engineering judgment and assumptions will play a big role here; nevertheless, it should be acceptable as long as we take every measure conservatively. To do reverse engineering, we may try to simplify the process by making some parametric analyses for both metal and composite structures based on a conservative representative configuration for each structural area (e.g., fuselage skin-stringer panels). As such, for a given damage record, we may do interpolation to get an energy estimate based on the descriptions of the reported damage.

Task 2.1: Analysis Method Enhancement

3. Development of database and tools to automate the entire evaluation process. Such tools may be used as production tools for maintenance planning.

Tools: In order to conveniently apply the developed reliability method to industry, we need to develop "self-explanatory" software with built-in initial data sets, "transparent" simplified solutions, expert help system and clear sample results. Ideally, the tool should be applicable not only to maintenance but also to design as well.



With full characterization of damage, loads, environments, materials and costs available, the developed code can be used as a single design tool for a unified design (i.e., combining static strength, damage tolerance, inspections and fail-safety). The developed reliability code can be integrated into standard structural analysis and design optimization programs.

Task 2.2:
Methodology Implementation and Regulatory Compliance

This task will focus on the application of the developed methodology. Key to the implementation of the reliability methods is the development of an accidental damage rating system (ADR) that is compatible with the methodology and complies with MSG-3 guidelines.

The developed reliability method may help the industry in two ways:

- **Finding rational inspection intervals.**
- **Establishing more reasonable design requirements compared to the present requirements derived from AC-107 and so on. In fact, AC-107 regulates the residual strength curve depending on the probability of damage detection only. It seems that Boeing's approach is also based on the assumption that composite design is primarily driven by damage detectability. There is no connection with real impact conditions. Using results of this research, we can demonstrate to the FAA that in some cases the AC-107 requirements are too conservative, but in other cases they may be inadequate.**

Phase 2 Milestones
(September 1, 2005 – August 31, 2007)

	9/1/05-11/30/05	12/1/05-2/28/06	3/1/06-5/31/06	6/1/06-8/31/06
Task 2.1				
Subtask 1				
Subtask 2				
Subtask 3				
Task 2.2				