Development of Reliability-Based Damage Tolerant Structural Design Methodology

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By

Kuen Y. Lin
Department of Aeronautics and Astronautics
University of Washington, Box 352400
Seattle, WA 98195-2400

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UW/FAA/Boeing Team

- UW Aeronautics & Astronautics
  - Principal Investigator:
    - Prof. Kuen Y. Lin
- FAA CoE
  - Technical Monitors:
    - Curtis Davies, Peter Shyprykevich, Larry Ilcewicz
- Boeing
  - Administrative Contacts:
    - Alan G. Miller, Steve Coe, Gerald Roe
  - Technical Contacts:
    - Cliff Chen, Hamid Razi, Jay Hopper, Gary Oakes

Objective

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

Background

Designer's Objective:

Maximize Performance while Minimizing Risk

- Randomness Introduces Uncertainty (Risk)

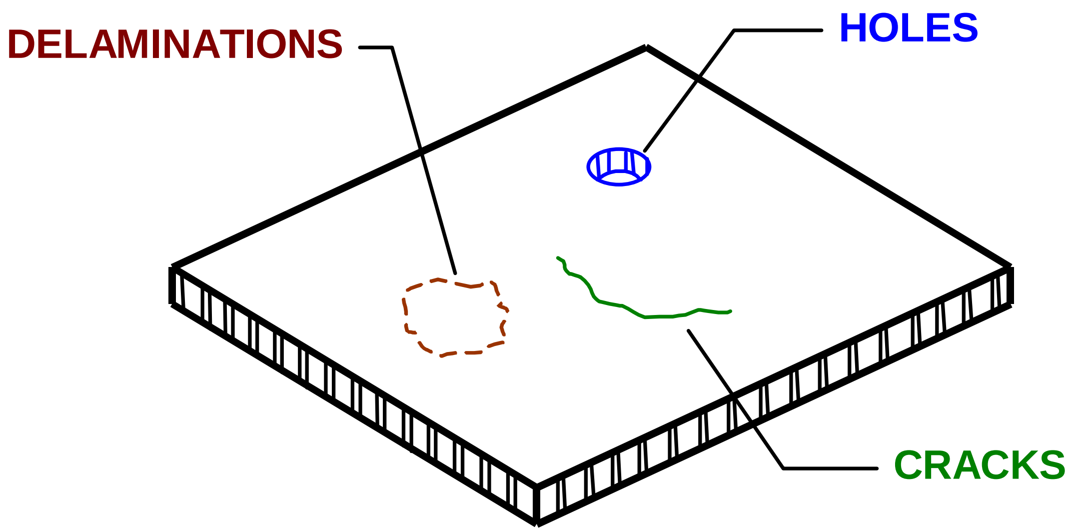
Variables:

» Environment
» Utilization
» Damage Threat
» Materials
» Loads
» Geometry

Damage Threat, Environment $\Rightarrow$ **High Variability, <u>High Risk</u>**

— Need a Probabilistic Approach —

Composite Structural Damage



- Data on Damage Sizes and Detection Capability are required
- Published data from Gray and Riskalla, *Development of Probabilistic Design Methodology for Composite Structures*, DOT/FAA/AR-95/17, August 1997
- High payoff in using the Probabilistic Method

Approach

1. Develop a reliability-based design method to quantify the safety level of aircraft structural components based on past fleet service data
2. Define a “Level of Safety” based on damage type and size, frequency of occurrence, damage location, detection method and probability of reporting
3. Develop methods for establishing an optimum inspection program for composite structures subjected to accidental damage

“Level of Safety” Formulation

Compliment of Probability that a flaw size larger than the critical flaw size for residual strength of the structure and that the flaw will not be detected.

$$LOS = 1 - PF$$

$$where\ PF = P(a \geq a_c, D = d_2)$$

a_c – Design Critical Damage Size

d_2 – Damage is Not Detected

- Single Detection Event
- Single Flaw Present
- No growth with Time

"Level of Safety" Formulation

$$LOS = 1 - \frac{\displaystyle\int_{a_c}^{\infty} \frac{p_o(a)}{P_D(a)}\left[1 - P_D(a)\right] da}{\displaystyle\int_{0}^{\infty} \frac{p_o(a)}{P_D(a)}\, da}$$

$p_o(a)$ = PDF of *Detected* Damage Size

$P_D(a)$ = Probability of Detection (POD)

- A General Formula for Safety of Aircraft Structures
- Independent of Materials & Damage Type or Configuration
- Enables Safety Comparisons Between Different Structures

"Level of Safety" for Multiple Damages

$$R = \prod_{i=1}^{N_L} \prod_{j=1}^{N_T} \left\{1 - PF_{ij}\right\}^{\mu_{ij}}$$

PF -- Probability of Failure

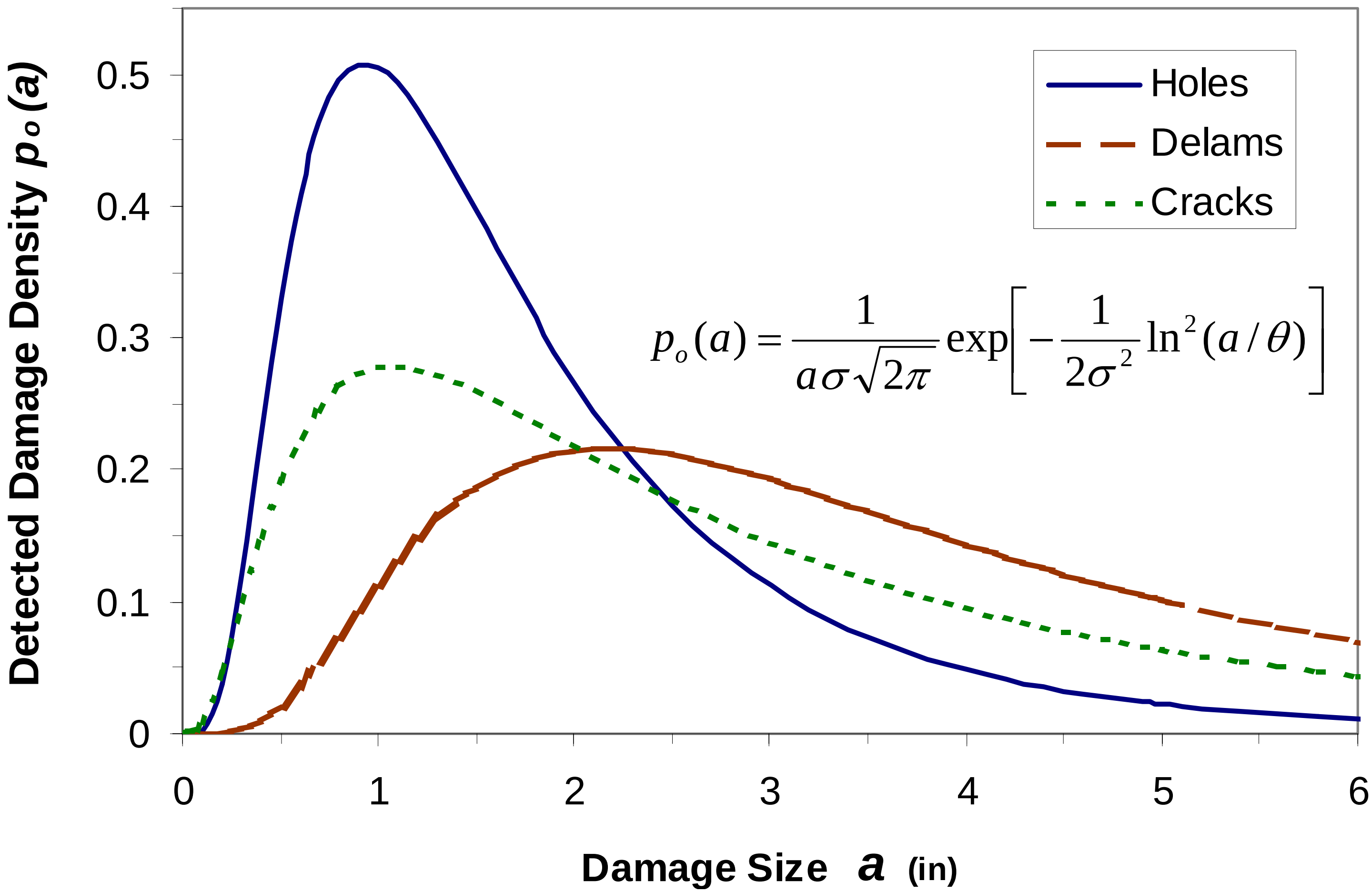
N_L -- Total Number of Different Damage Locations

N_T -- Total Number of Damage Types

μ -- Total Number of Identical Damages

- Multiple Detection Event
- Multiple Flaws Present
- Reliability at a Fixed Time

LogNormal Probability Density Fuctions for Baseline Fleet Damage Data, Ref. AR-95/17

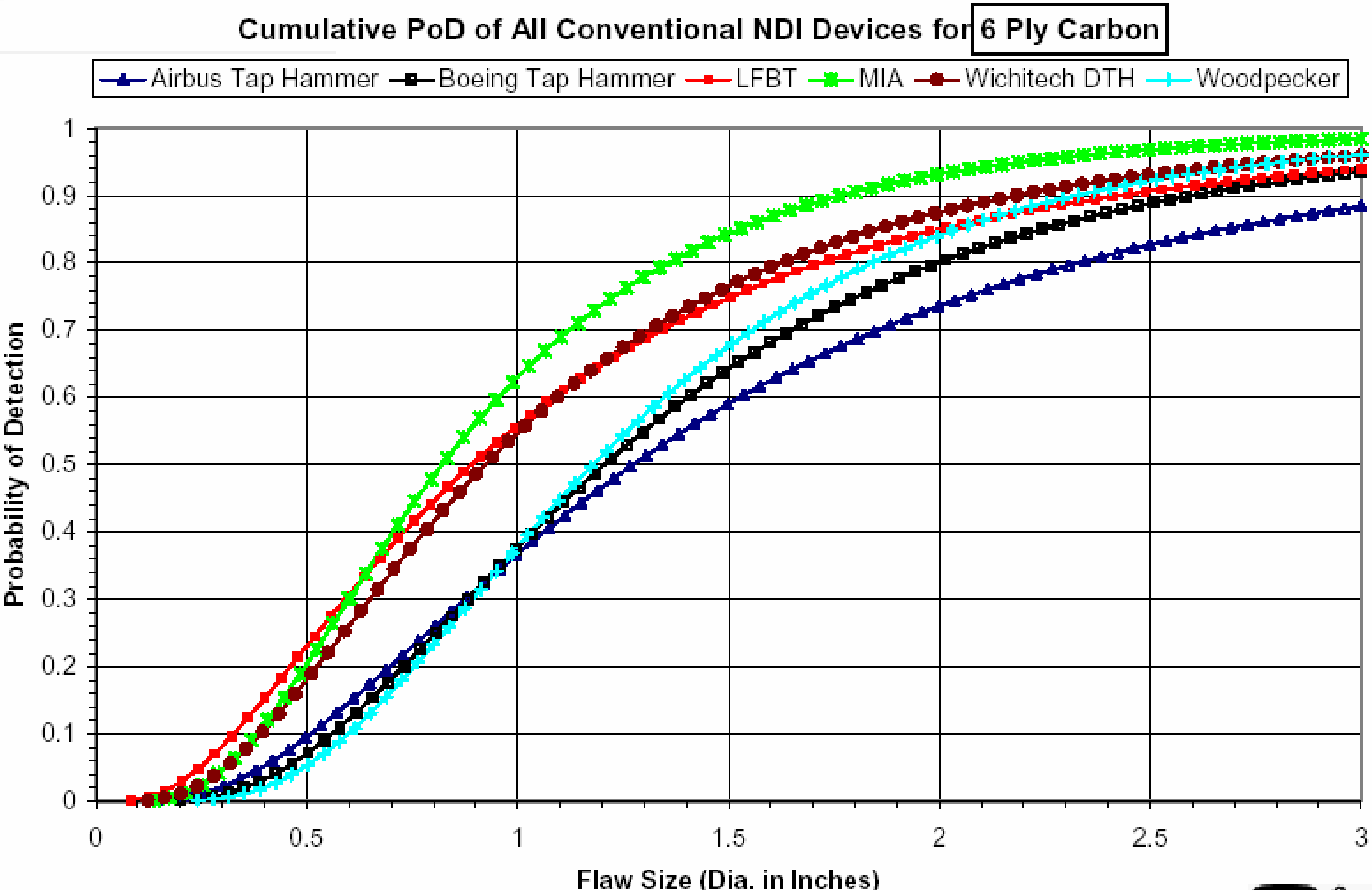


Probability of Detection

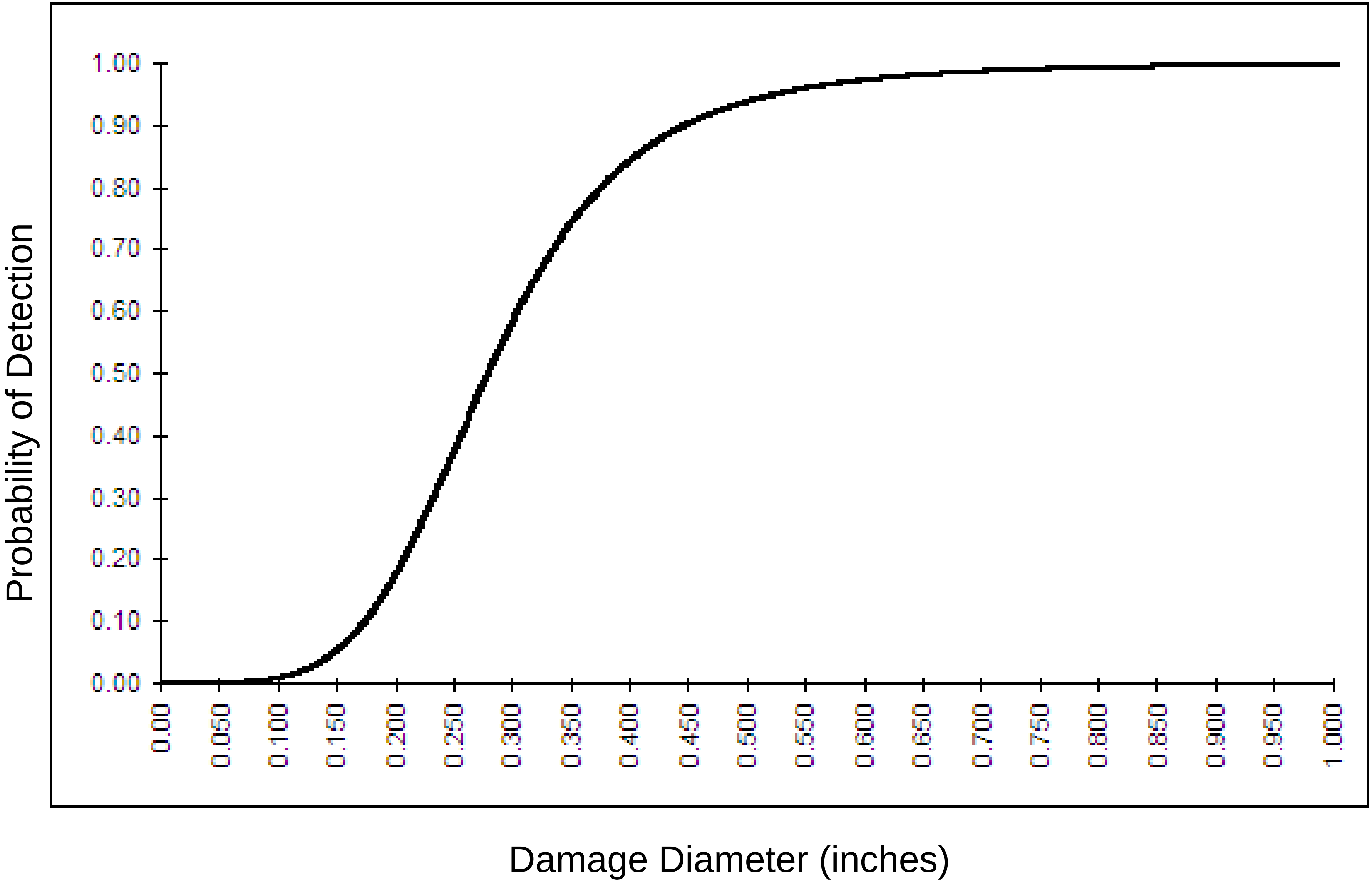
- Probability of detection (POD) curves for various non-destructive inspection (NDI) methods have been obtained by FAA/Sandia and Boeing

- FAA/Sandia Study on POD:
  - Honeycomb core sandwich panels of different ply thickness
  - Variability of device performance over the set of inspectors
  - Improvement in detection capability using advanced NDI methods

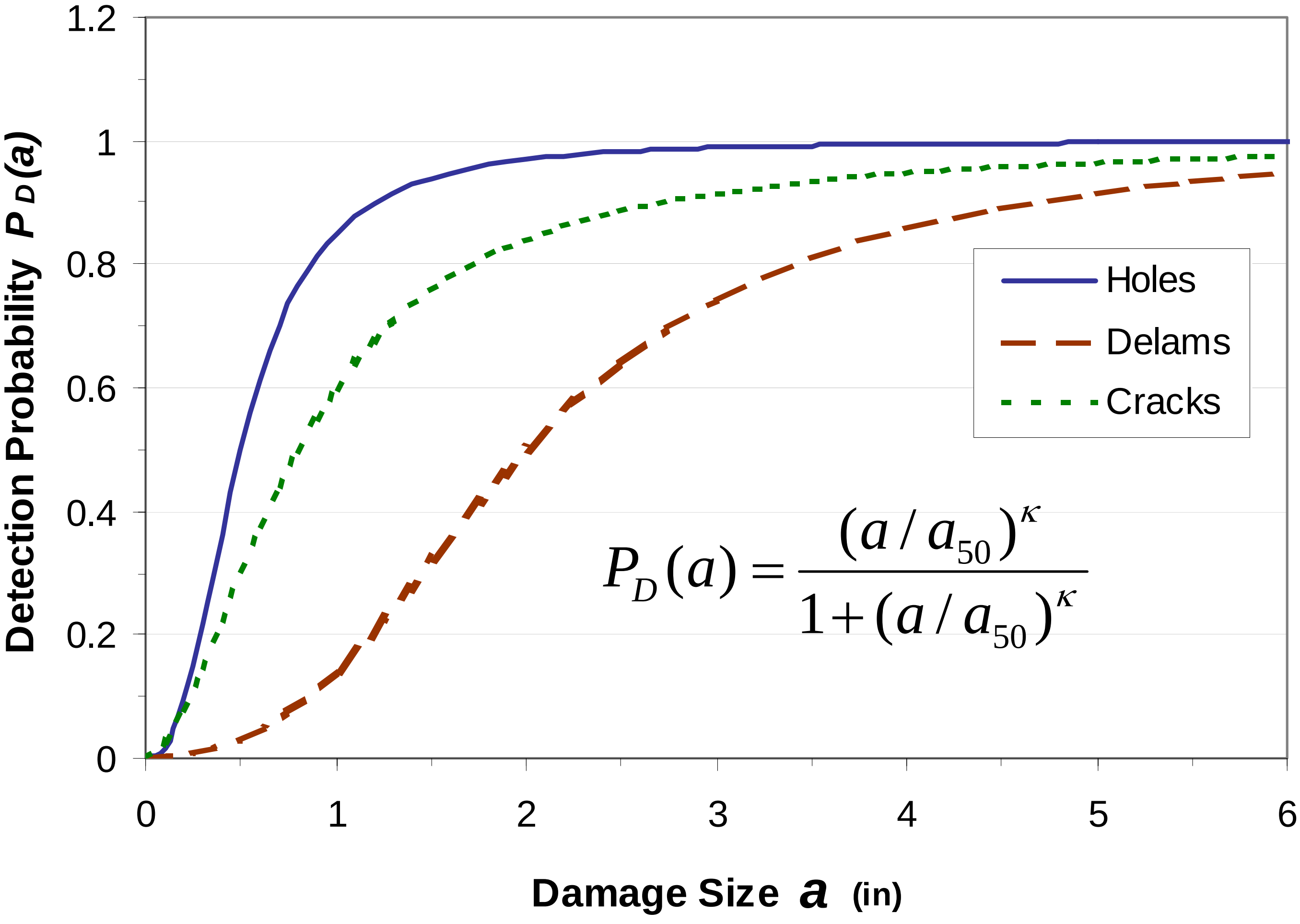
Performance of Multiple Devices for A Single Type of Test Specimen



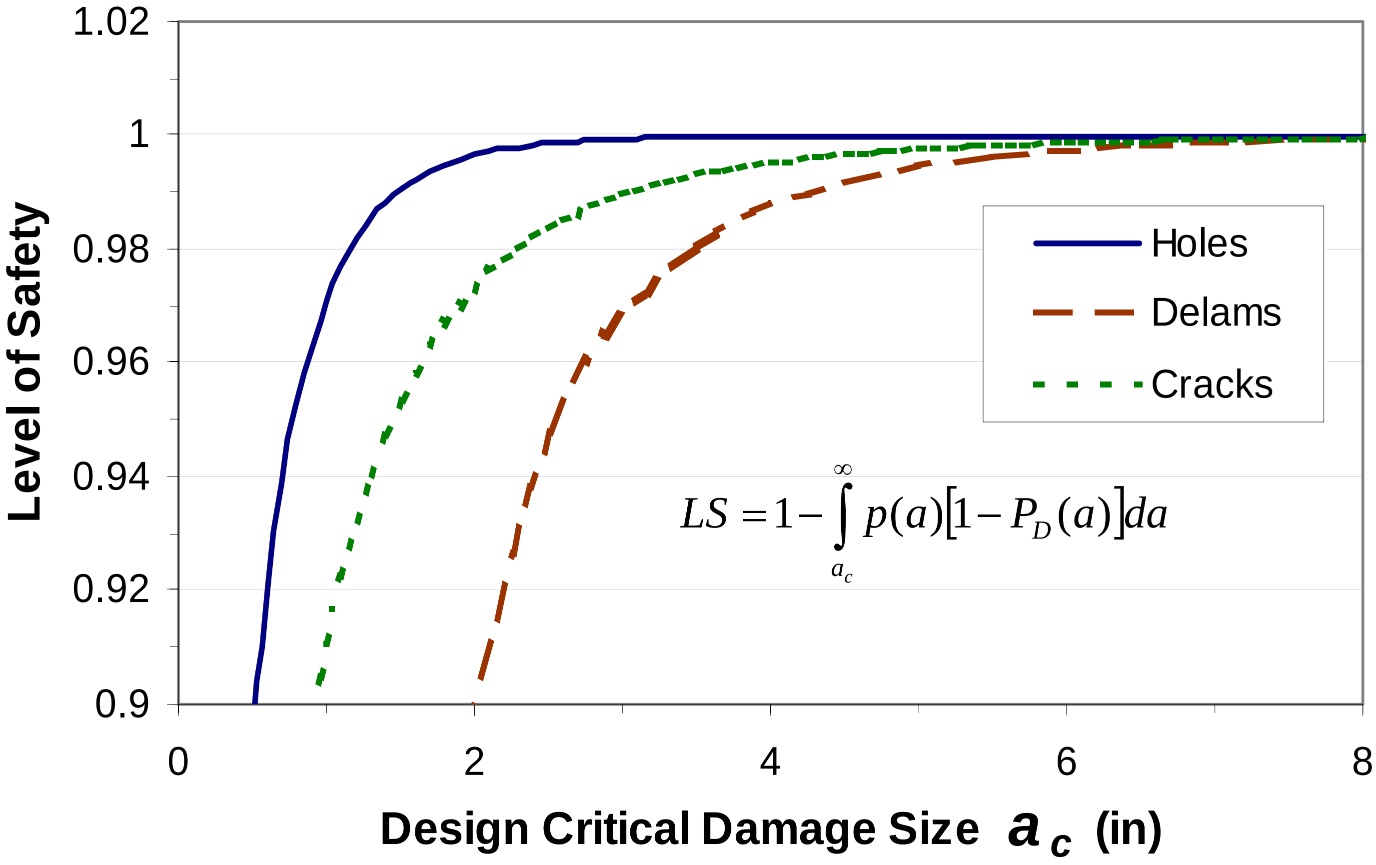
Visual Inspection POD for Shiny Surface at 20 ft Distance



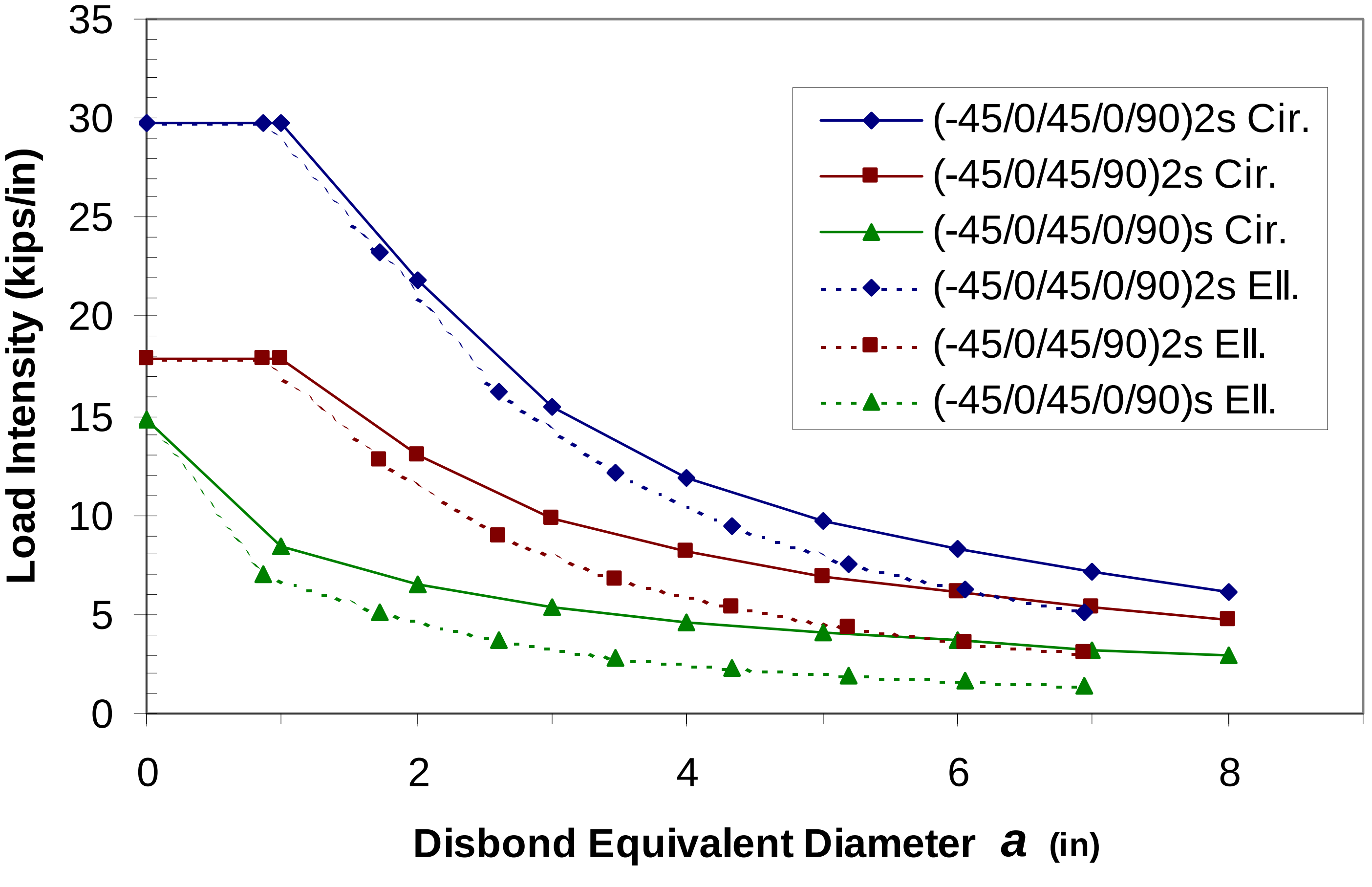
Log-Odds Detection Probability Functions



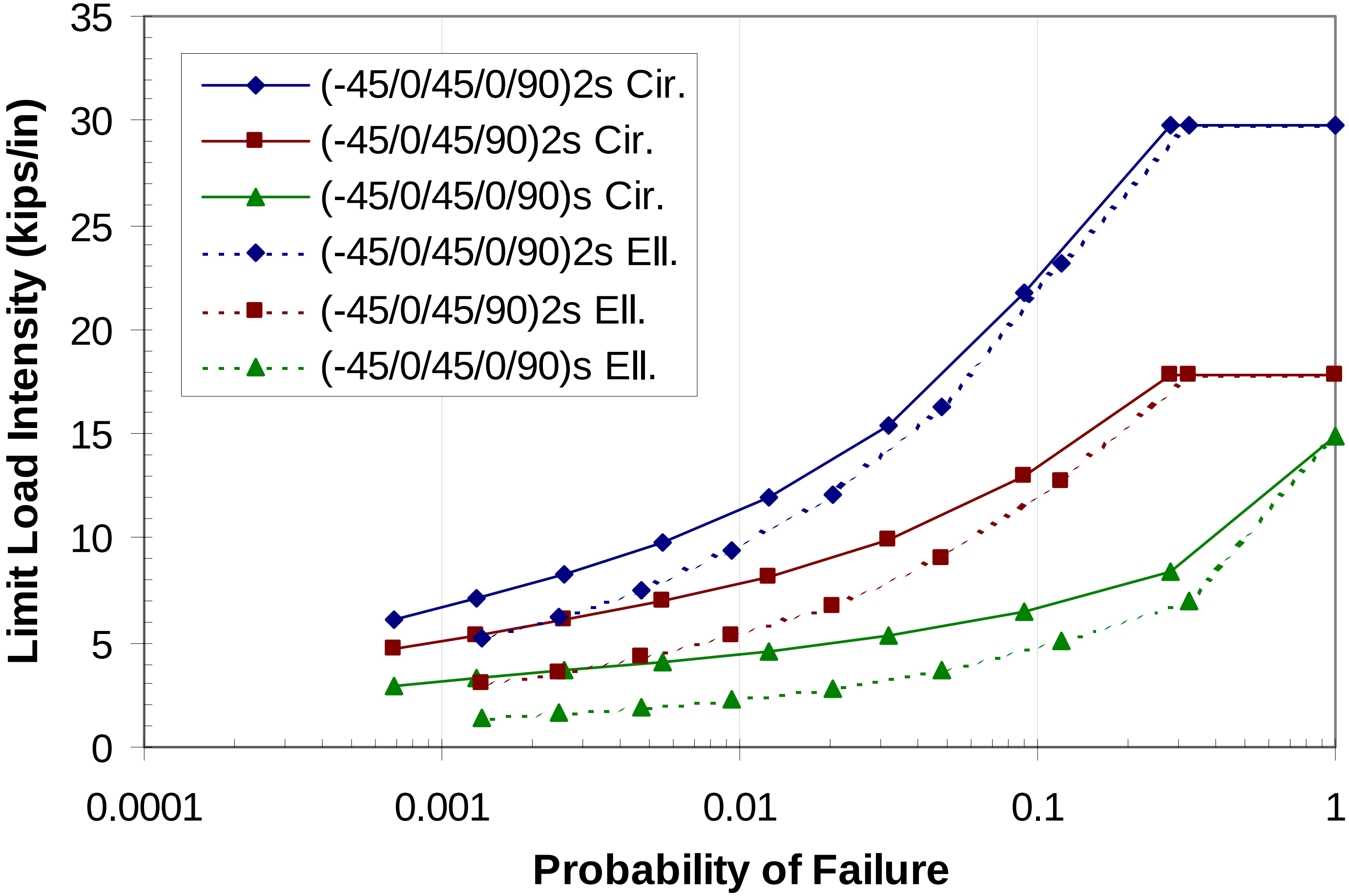
Level of Safety vs. Critical Damage Size for Composite Damage Types



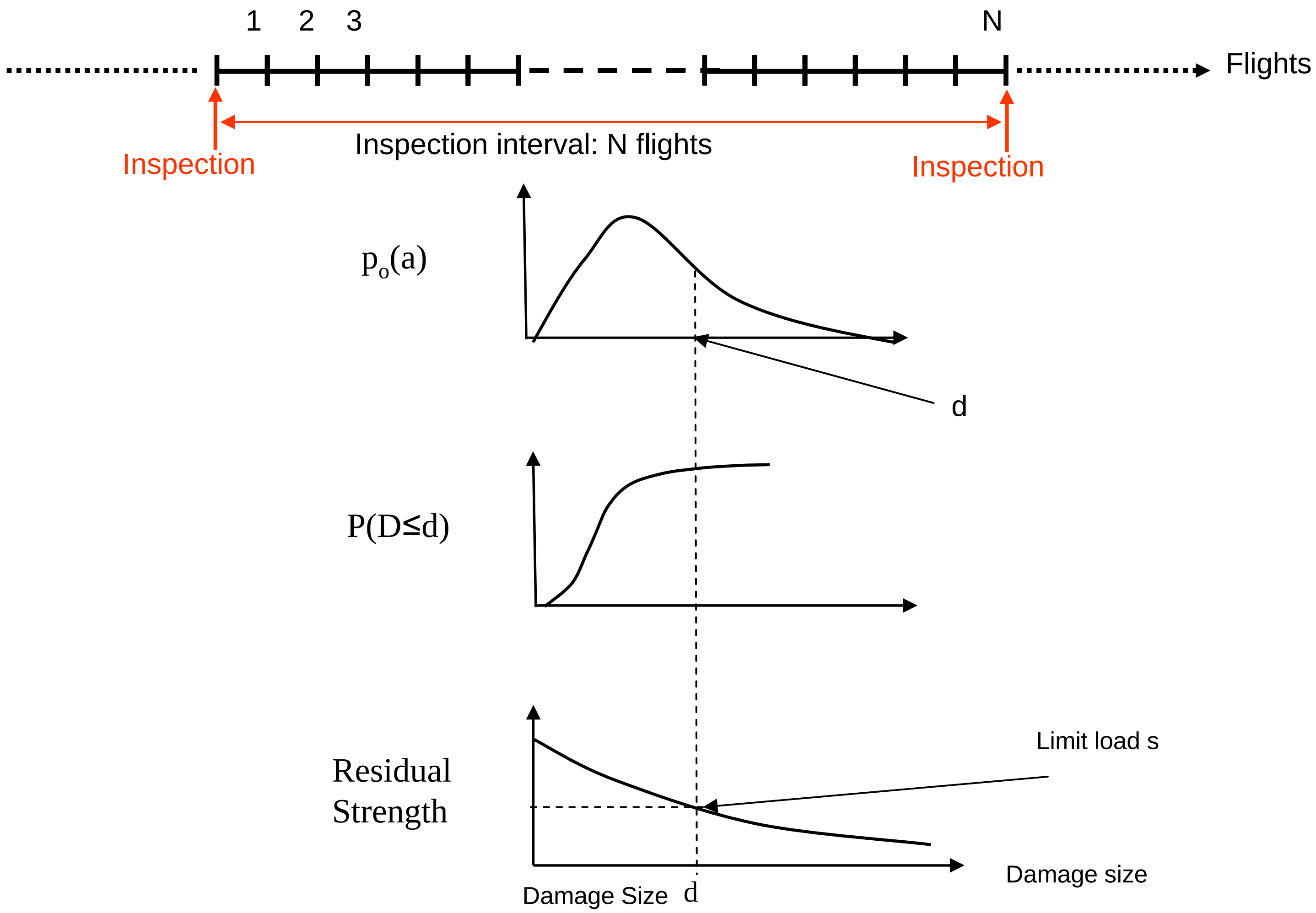
Postbuckled Compressive Strength vs. Damage Size for Disbonded Sandwich Panel



Compressive Failure Probability for Disbond Damaged Sandwich Panel



Inspection Interval for Accidental Damage



Formulation of Inspection Interval for Accidental Damage

The probability that a maximum accidental damage size D_{max} will be less than or equal to damage size d in m occurrences after N flights is:

$$\textbf{P}(\textbf{D}_{\textbf{max}}\ \textbf{after N flights} \leq \textbf{d}) = P(D_{insp} \leq d) \times \left[1 - p + p \times P(D \leq d)\right]^N$$

$$\textbf{P}(\textbf{D}_{\textbf{insp}} \leq \textbf{d}) \approx \int_0^{\infty} PoD(x)\, f_{D_{\max}}(x)\, dx + \int_0^{d} \left(1 - PoD(x)\right) f_{D_{\max}}(x)\, dx$$

The failure probability for a structure to encounter loads greater than its residual strength is:

$$\begin{aligned} P_f &= \int_0^{\infty} P(RS \text{ after N flights } \leq \text{s})\;\; f_{L\max}(s)\;\; ds \\ &= 1 - \int_0^{\infty} P(RS \text{ after N flights } \geq \text{s})\;\; f_{L\max}(s)\;\; ds \\ &= \int_0^{\infty} [1 - P(D_{\max} \text{ after N flights } \leq \text{d(s)})]\;\; f_{L\max}(s)\;\; ds \end{aligned}$$

The inspection interval N for an accidental damage can then be determined through an iterative process by setting the overall P_f to a target number (10^{-8}).

2004-2005 Research Tasks

- Develop a Probabilistic Method to Determine Inspection Intervals for Composite Aircraft Structures

- Develop Computing Tools and Algorithms or the Probabilistic Analysis

- Establish In-service Damage Database from FAA SDR and other sources

- Demonstrate the Developed Method on an Existing Structural Component

2005-2006 Research Plan

- Analysis Method Enhancement
- Methodology Implementation and Regulatory Compliance

Summary

- The background, approach and research tasks for the "Reliability-based Damage Tolerant Design of Aircraft Composite Structures" have been presented.

The End

THANKS

2004-2005 Research Plan

- Establish Method to assist in ADL Determination
  - Map damage by size and frequency on selected composite primary structures
  - Develop a flexible analysis method to accommodate various structures, locations, damage types, and damage threats
  - Results will assist engineers in determining ADL's in consideration of maintenance cost, damage detection capability, and regulatory compliance

Probability of Failure

$$PF = \int_{a_c}^{\infty} p(a)\left[1 - P_D(a)\right] da$$

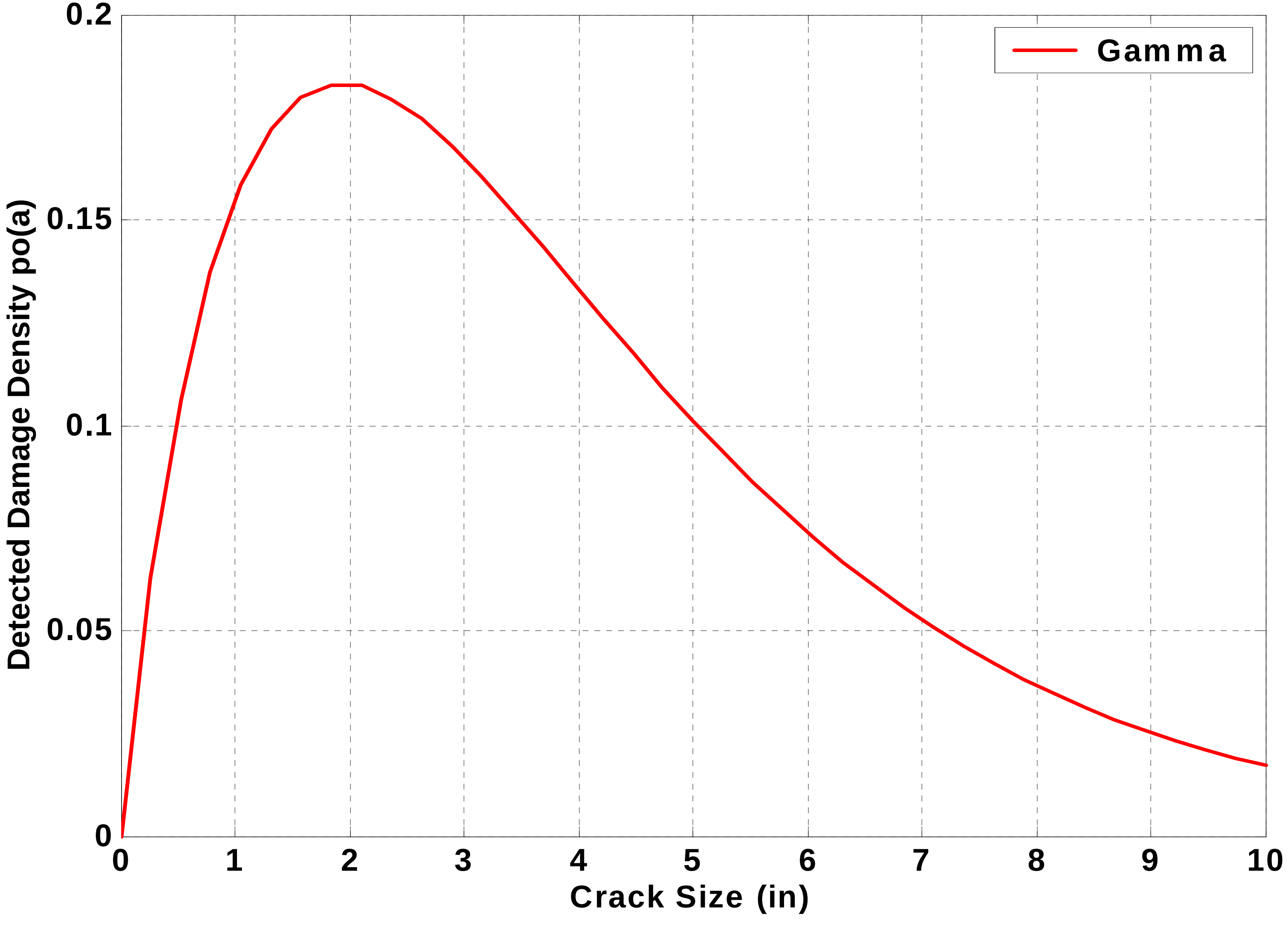
p(a) – PDF of *Actual* Damage Size (Unknown)

$P_D(a)$ – Probability of Detection (POD) (Known)

Time-Dependent Approach

- Continuous Time Reliability Model
- Formulation incorporates damage growth over time
- Incorporates Damage Initiation Model
- Quantitative Measures of Structural Reliability
- Calculates Reliability at Any Time Instant

Detected Crack Size Distributions
(composites 0-10 in)



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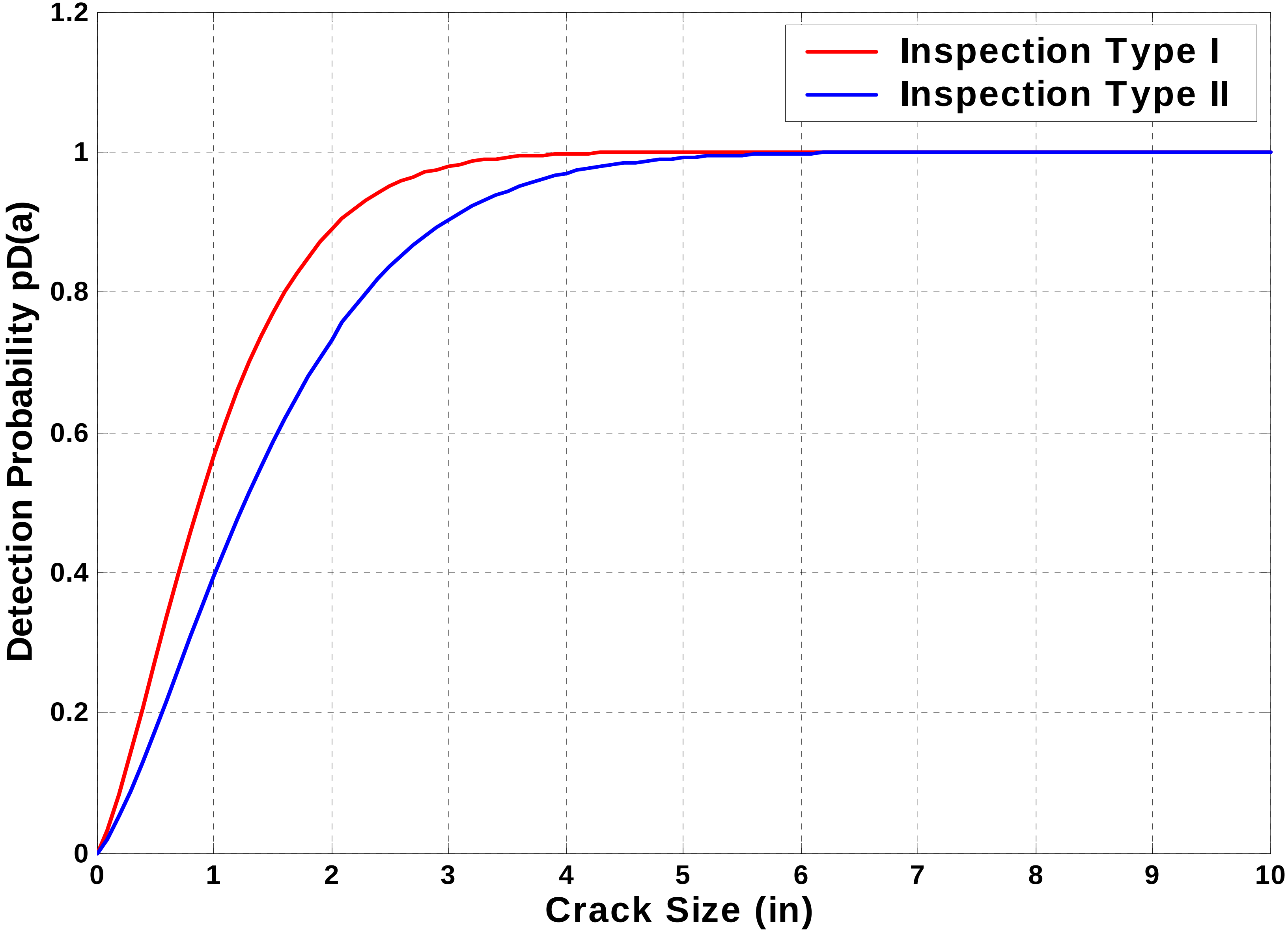

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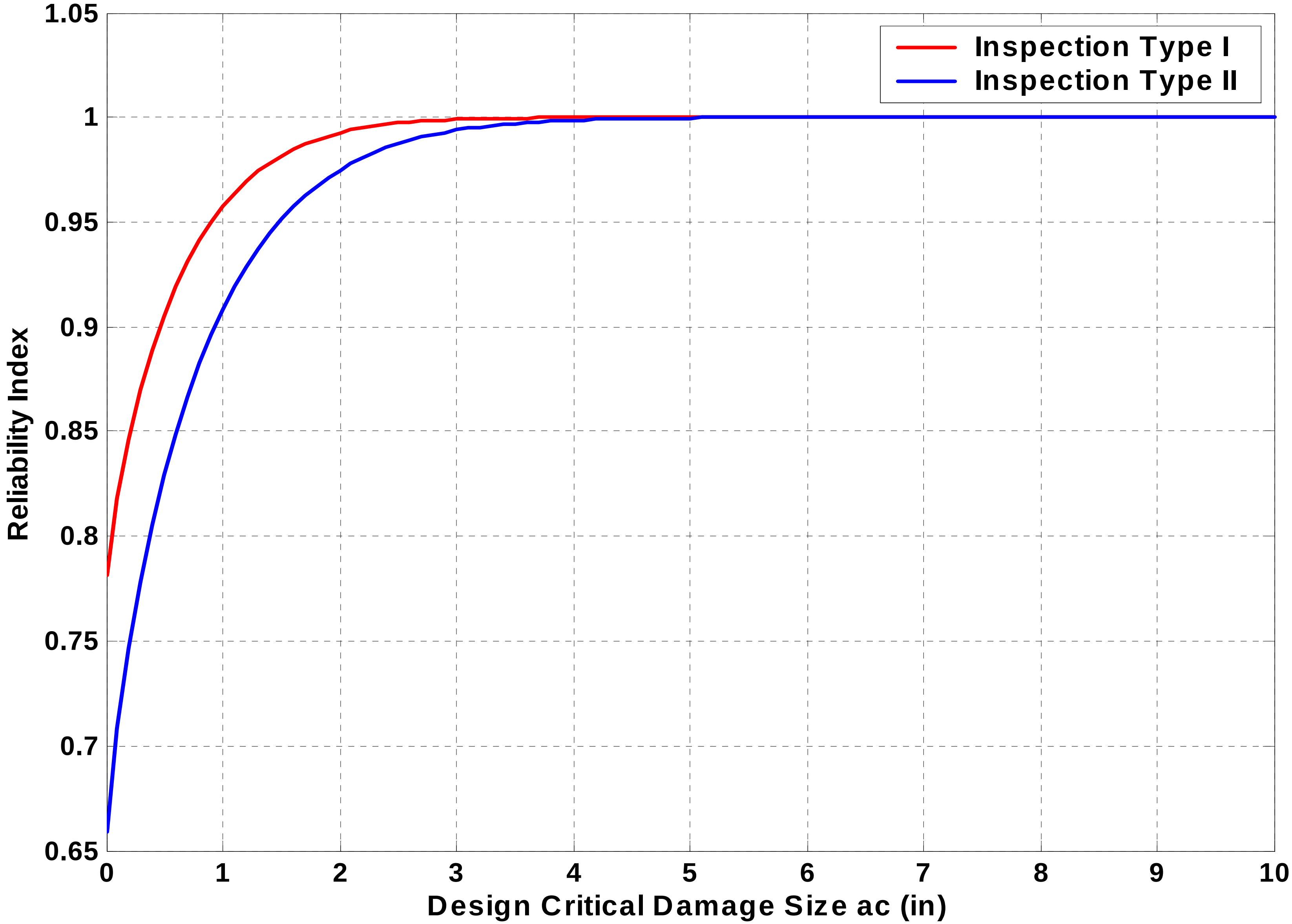
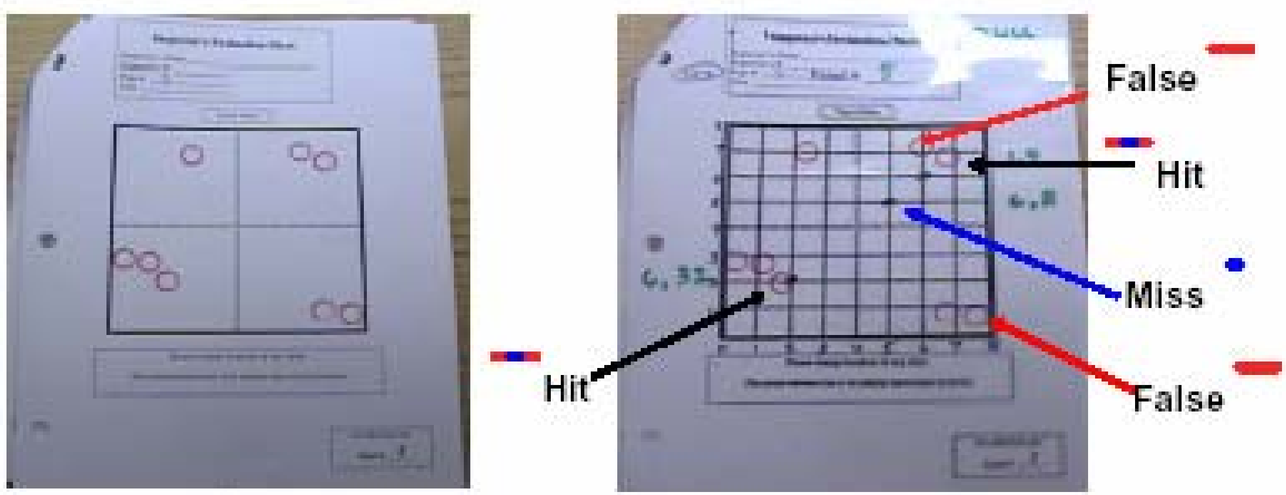


Probability of Detection

- Boeing Study:
  - Visual inspection of impacted composite panels
  - Dull and Shiny Surfaces
  - Distances of arms length, 5 feet and 20 feet



(a) (b)

Figure 6: (a): Inspector Data and 6(b) Inspector Data with True Dent Locations Overlaid