Reliability-based Design, Development and Sustainment

NDIA's 2007 T&E Conference:

T&E in Support of Operational Suitability, Effectiveness and Sustainment of Deployed Systems

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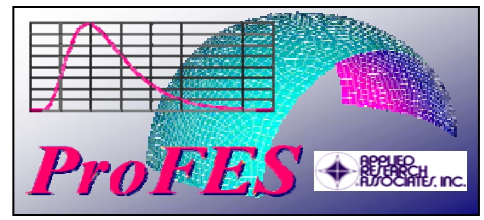
APPLIED RESEARCH ASSOCIATES, INC.
An Employee-Owned Company

Briefing Overview

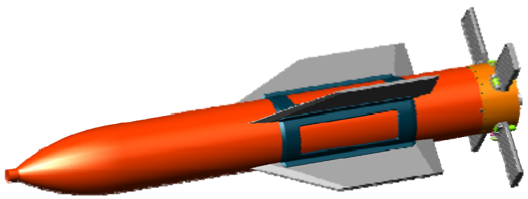
- Description of reliability-based methods
- Applications and results
- Implications of reliability-based methods for T&E
- Challenges
- Path ahead

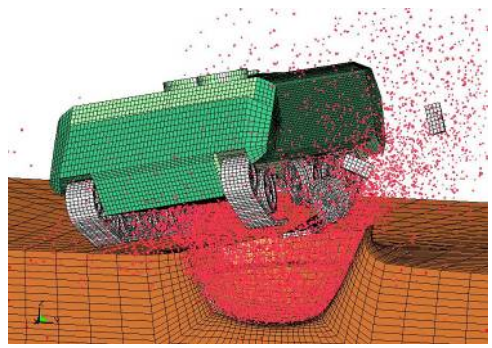
ARA BUSINESS AREAS

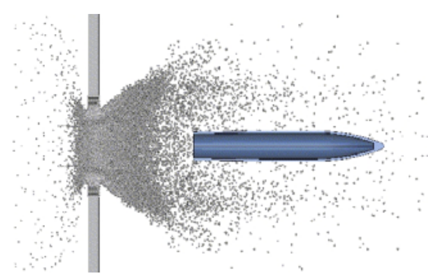
- National Defense
- Transportation
- Security Risk & Disaster Management
- Geotechnical & Environmental Technologies
- Computer Software & Supporting Technologies

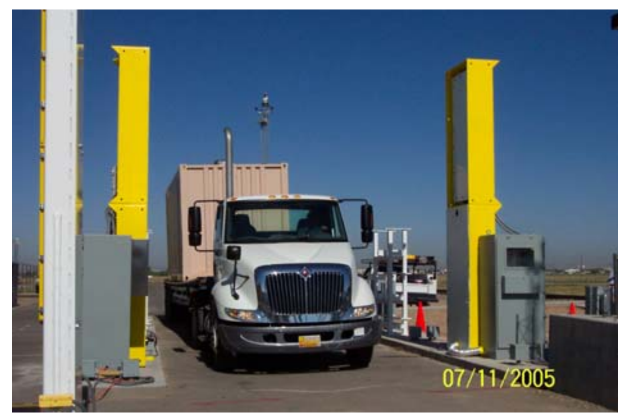


Probabilistic Function Evaluation System









Introduction

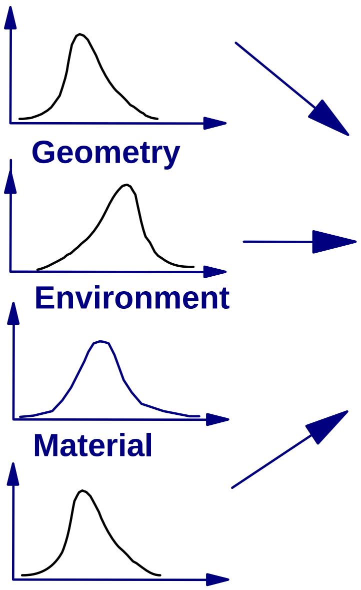
- Reliability-based methods are those that
  - Use the probability of failure as a criterion in the design process
- These methods contribute to suitability, effectiveness and sustainability by
  - Improving system performance
  - Increasing operational readiness
  - Reducing unnecessary intervention or maintenance
  - Managing spare parts inventories
  - Reducing technical and operational risk
- Other benefits of these methods
  - Provide predicted performance across a range of metrics
  - Support decision-makers by highlighting trade-offs in performance and RAM

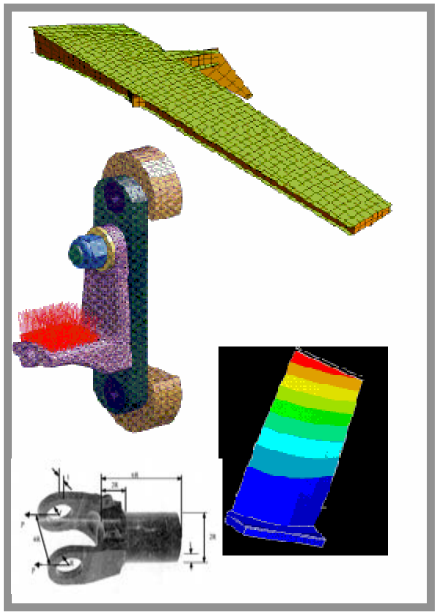
The "Magic" behind the Methods

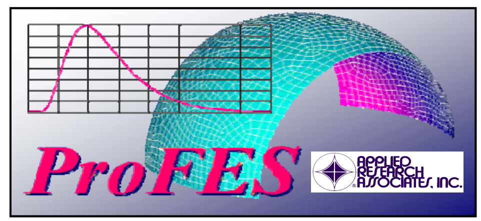
- These methods involve
  - Applying probability distributions to uncertainties
  - Using physics-based modeling to assess the impact of these uncertain factors on system performance
  - Balancing system design features and inspection intervals against risk

Physics-based Probabilistic Analysis

PRObabilistic Function Evaluation System

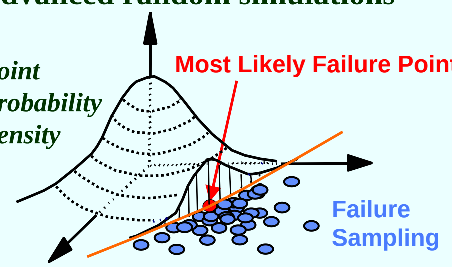






Compute:
- Risk
- Reliability
- Reliability sensitivities
- Response probability distributions
- Failure samples for maintenance simulation

Uncertainty analysis based on *fast probability integration* and advanced random simulations



Optimize:
- Risk and Reliability
- Maintenance Plan
- Test Plan

Model Uncertainties and Variability

Develop High Fidelity Computational Models

Apply State-of-the-Art probabilistic methods

Focus on “Weakest Links” and Most Likely Causes for Failures

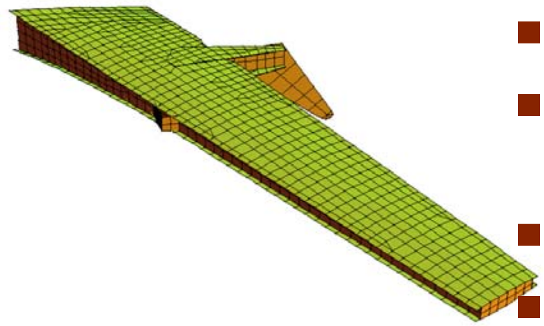
Reliability-based Methods that support Suitability, Effectiveness and Sustainability

- Reliability-based multidisciplinary optimization (RBMDO)
- Reliability-based damage tolerance (RBDT)

Reliability-based Multi-disciplinary Optimization (RBMDO)

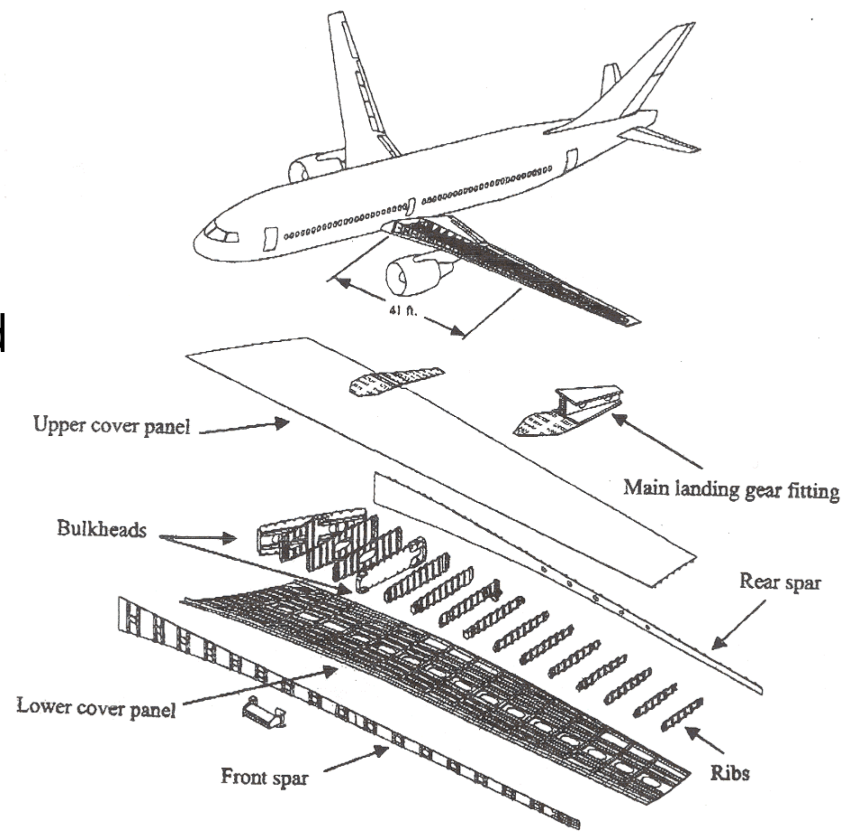
- Optimizes performance subject to multiple reliability-based constraints
- Incorporates multi-disciplinary objectives/models (e.g., payload, aerodynamics, shape parameters, weight,…)
- Accomplishes higher performance over independent optimization of each discipline

RBMDO Application – Aircraft Wing Design

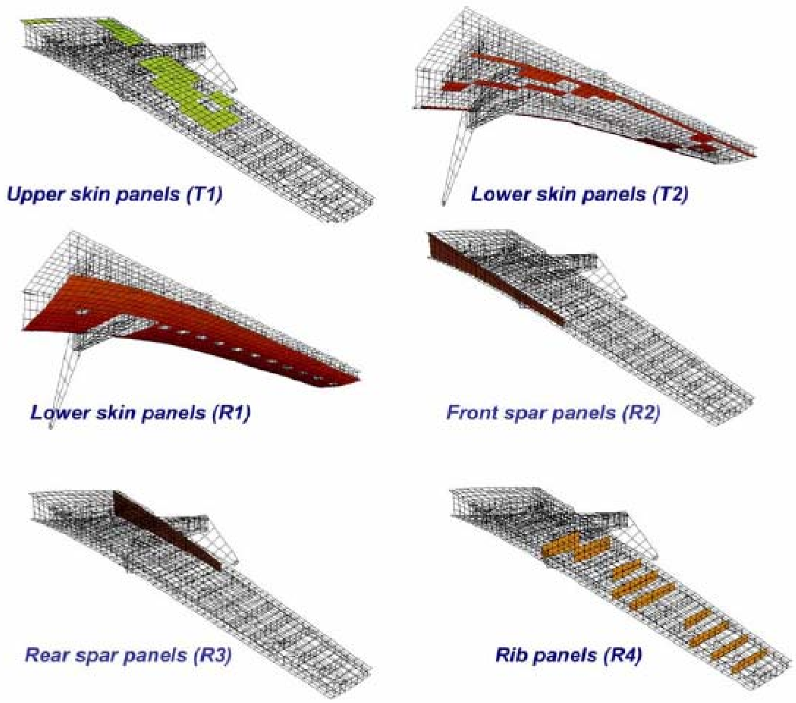


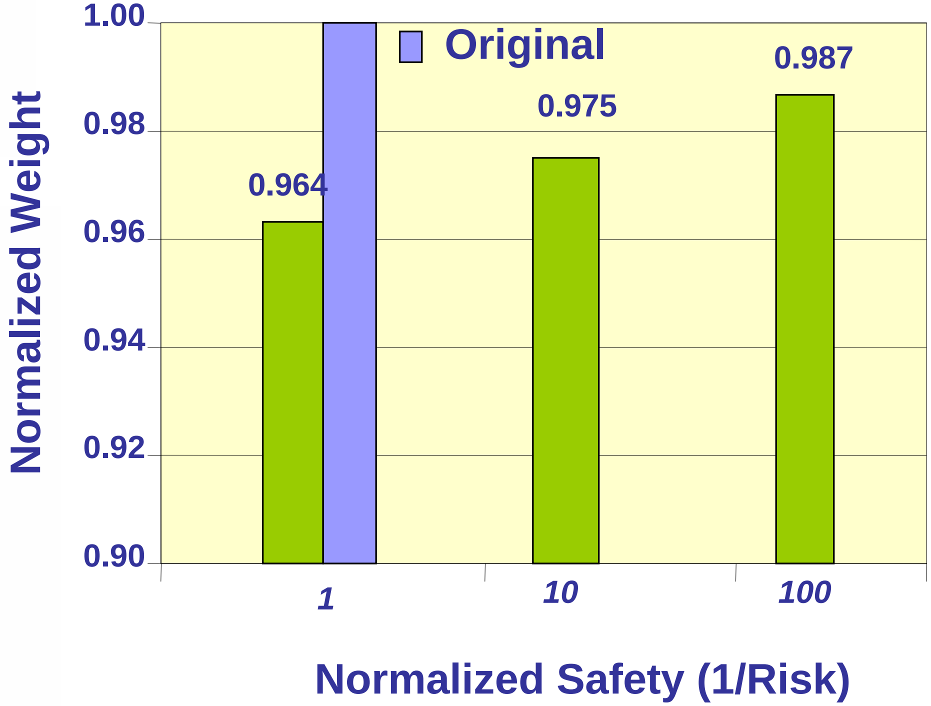
- 3804 finite element nodes
- 3770 finite elements (2222 shells + 1548 beams)
- 22 material properties
- 47 shell element properties

- NASTRAN model of Advanced Composite Technology (ACT) wing
- Baseline aircraft: proposed 190-passenger, two-class, transport aircraft
- Critical Design conditions derived from DC-10-10 and MD-90-30



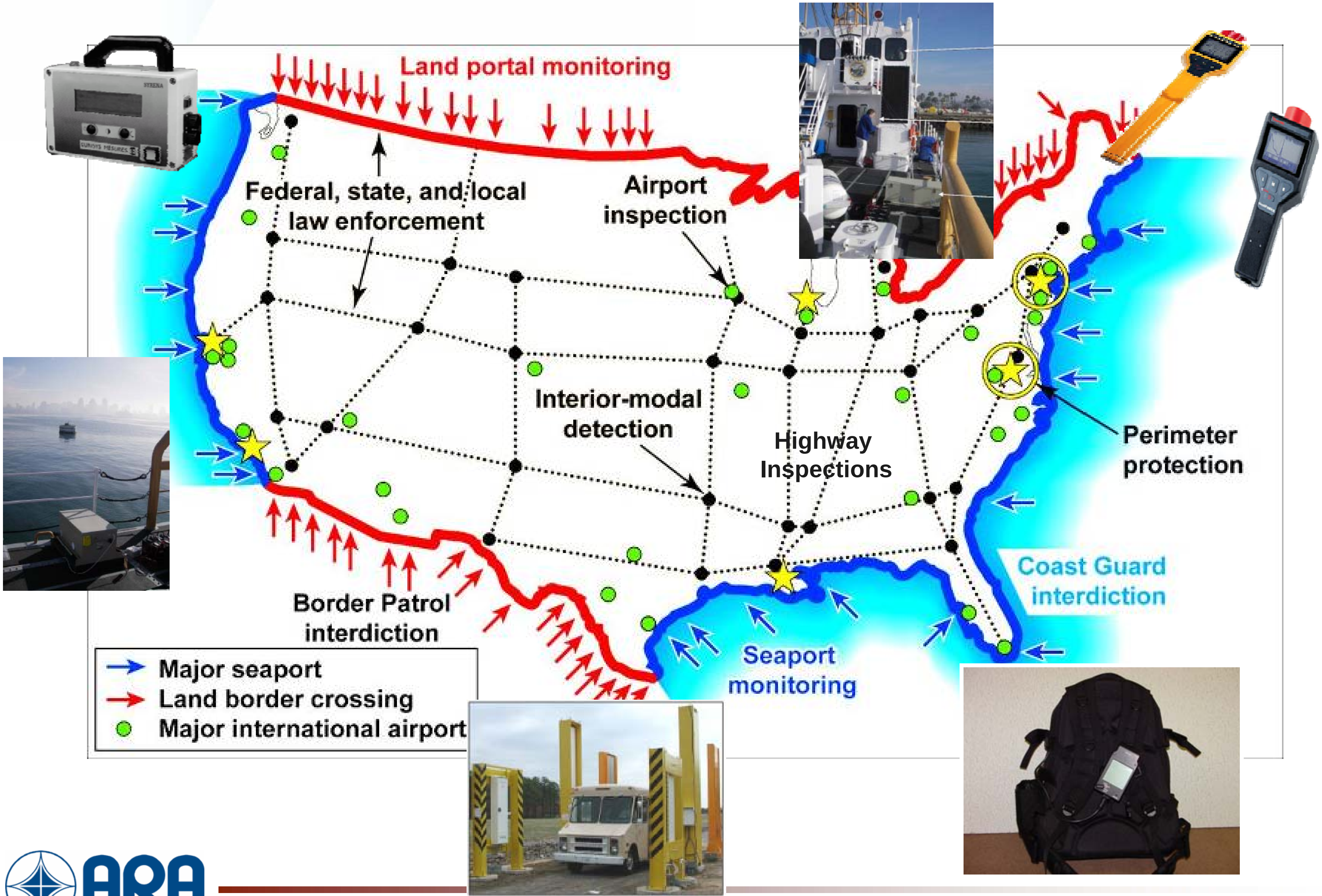
Performance-based objective and reliability-based constraints





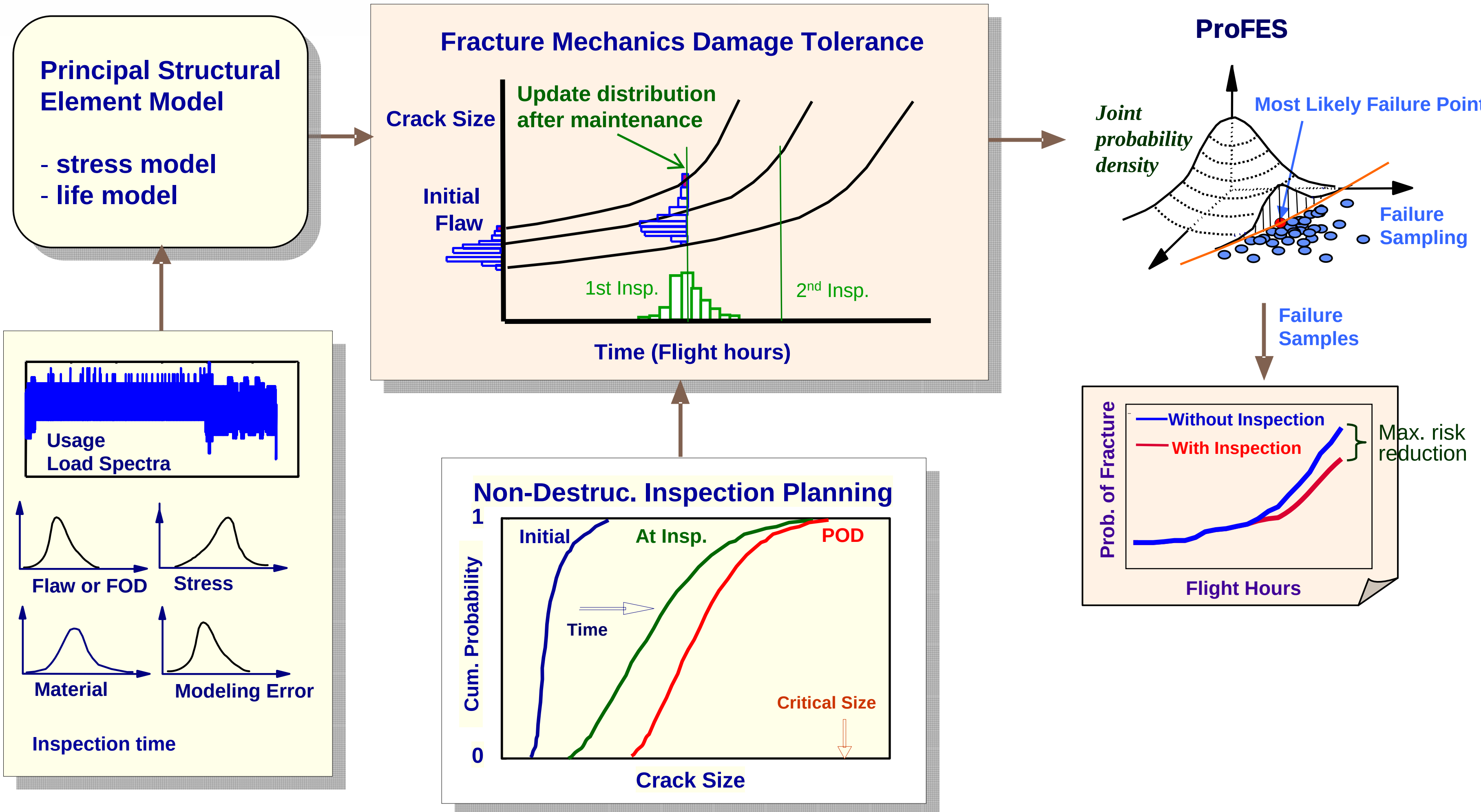
Weight is reduced while reliability is improved

Another Application – Radiation Detector Sustainment



Reliability-Based Damage Tolerance (RBDT) Framework

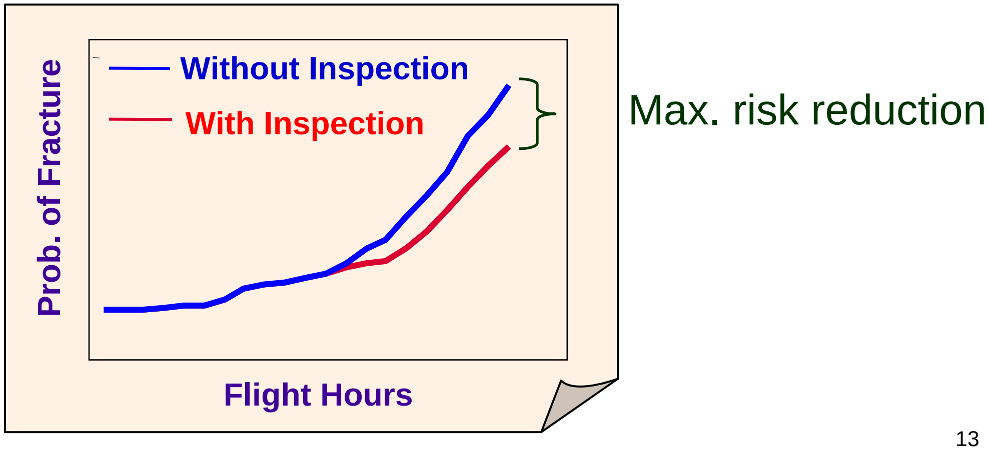
Fully Integrated Finite Element stress, Fracture Mechanics life and ProFES analyses



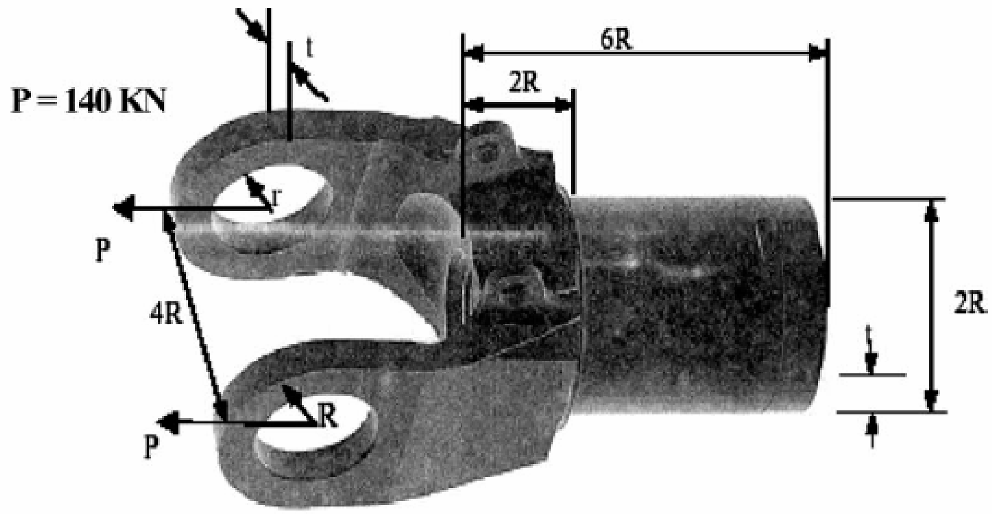
Reliability-Based Damage Tolerance (RBDT) Methodology for Rotorcraft Structures

- Project sponsored by FAA
- Critical structures must maintain very small probability of failure
- Supplement current "safe-life" design approach (which tends to be too conservative)
- Systematically treat variability/uncertainty in:
  - usage, load, flaw, material, geometry, modeling error, defect detection capability
- Maintenance planning for:
  - Non-Destructive Inspection, inspection frequencies, repair/replacement
- Has wide applicability to structures with material or manufacturing flaws
  - Select appropriate NDI interval
  - Optimize sustainment strategies

	Deterministic	Probabilistic
Underlying Principles	Bounds or Safety Factors	Probability & confidence
Flaw/Defect size	A given crack size	Probabilistic distribution
Flaw Existence	Certain (Safe-Life)	0 < Probability < 1
Inspection Schedule	Life/No. of inspections	Optimized schedules for max. risk reduction
Safety Measure	Safety margin	Reliability
Other Variables	Bounds or Safety Factors	Distributions



RBDT Application -- Rotorcraft Spindle Lug Model



Reference R = 0.25m, Thickness = 67 mm, Initial flaw size = 0.4 mm

Random variables for the lug model

	Distribution	Mean	SD	Cov (%)
Thickness, t (mm)	LN	28	0.14	0.50
Max. load (N)	LN	145000	10000	6.9
Initial flaw size (mm)	User-defined	0.074	0.0224	30.2
Delta K_{th}	LN	48	4	8.33
Life scatter	LN	1	0.1	10.0

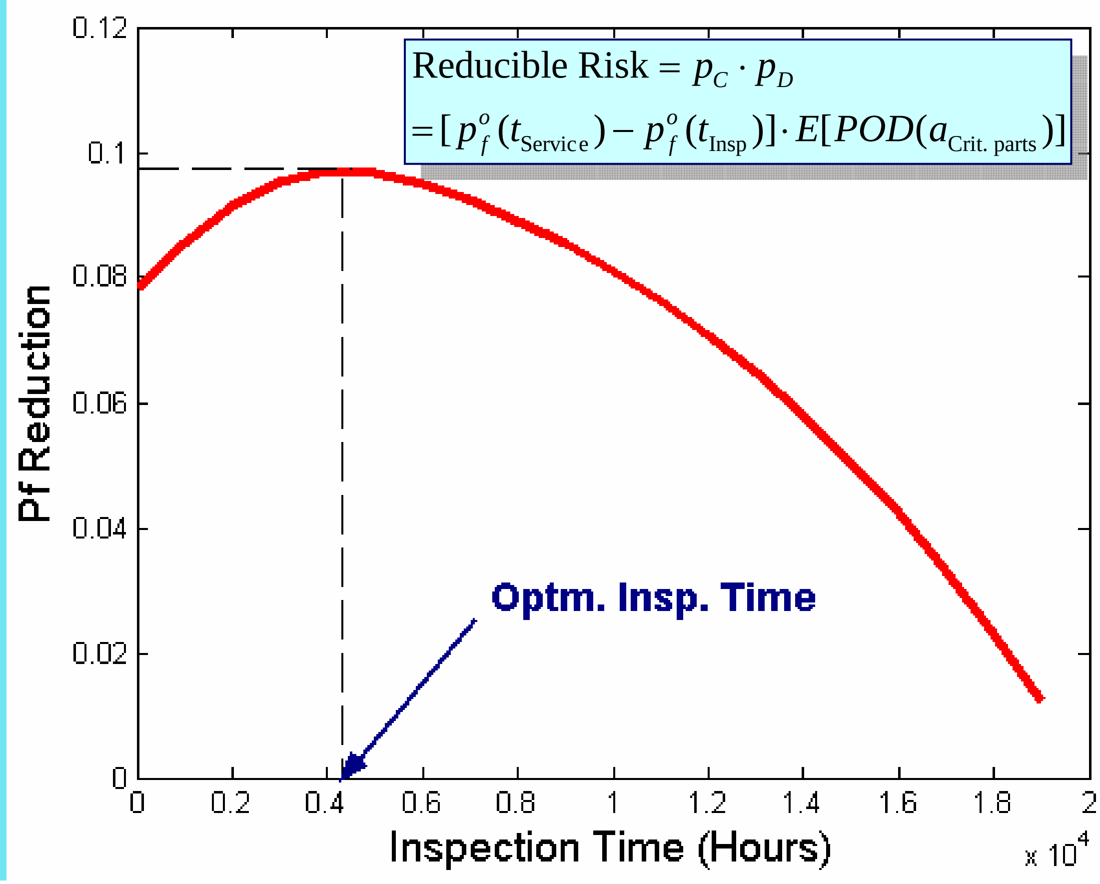
Goal – Optimize inspection schedule to minimize risk

RBDT Yields Optimal Inspection Schedule

Systematic approach for probabilistic fracture mechanics damage tolerance analysis with maintenance planning under various uncertainties

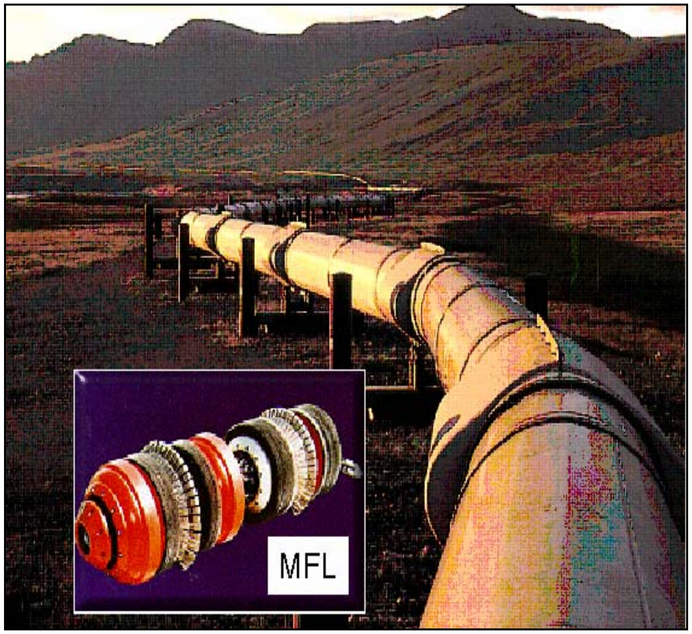
Stage 1: compute risk without inspection

Stage 2: compute risk with inspection by simulating inspection and maintenance effects using the samples generated from the Stage 1 failure domain



Reliability-based Damage Tolerance Application Pipeline Maintenance Optimization

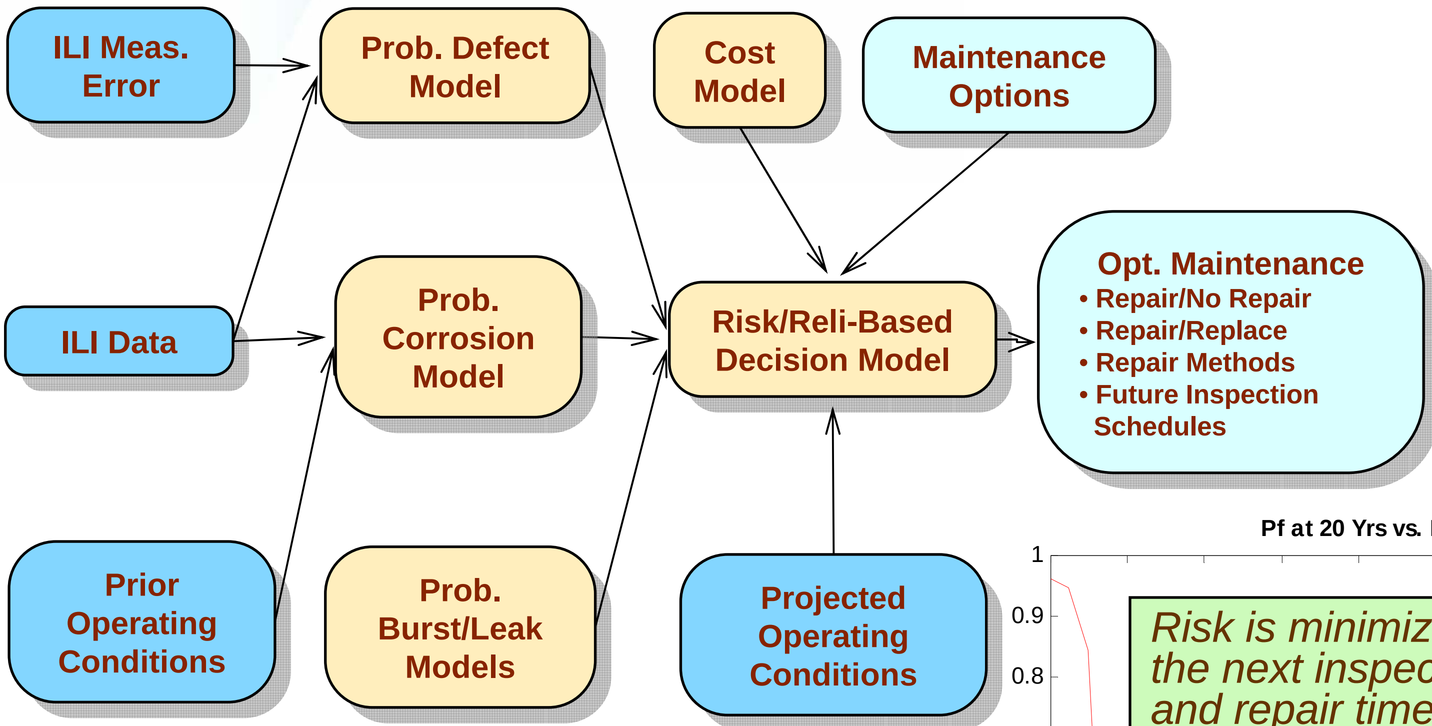
- Corrosive environments cause metal losses
- Two major failure modes with uncertainties
  - Burst can cause a high consequence but is less likely to occur
  - Leak has a low consequence but is more likely to occur
- In-line inspection devices can detect significant defects
- Options to maintain integrity at different risk/cost:
  - Defect monitoring using high resolution ILI devices (cost issue)
  - Repair/replace sections (cost issue)
  - Reduce operating pressure (production loss)
  - Corrosion mitigation (cost issue)
- Objective
  - Develop maintenance optimization software using ILI data and probabilistic failure and cost models



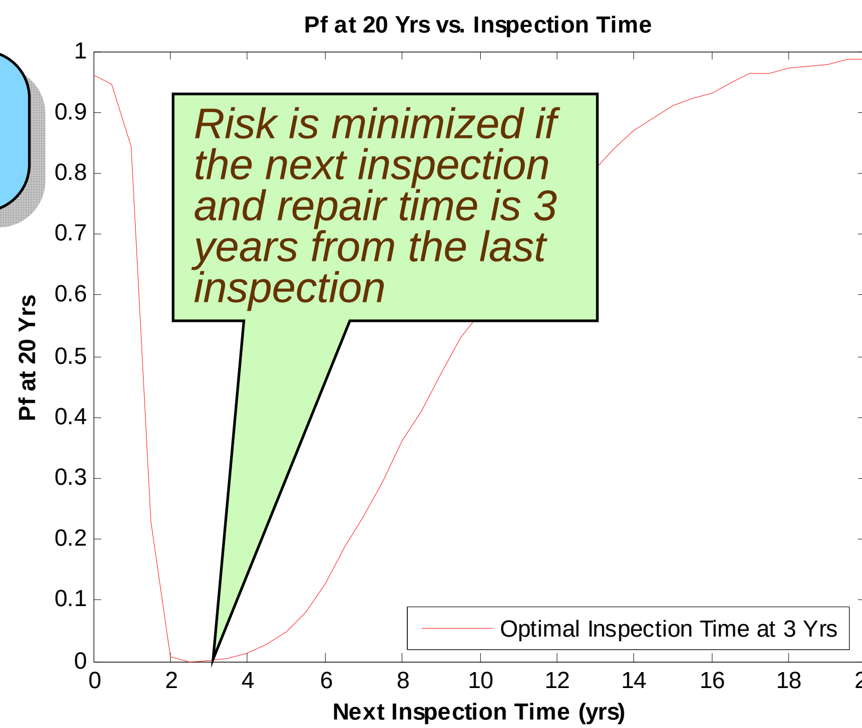
In Line Inspection

Magnetic Flux Leakage and other ILI devices can travel through pipelines to detect metal losses

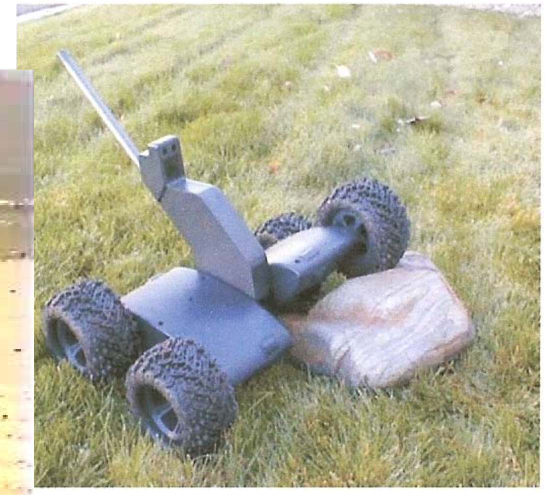
Pipeline Maintenance Example

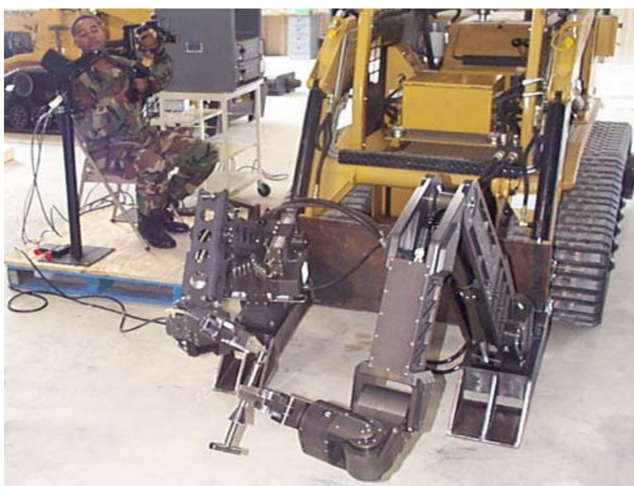


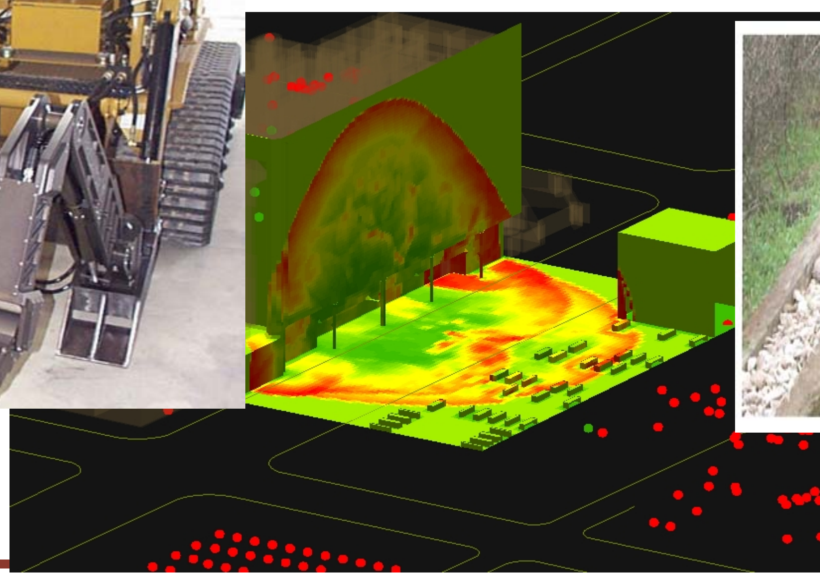
Pipeline Maintenance Optimization Methodology



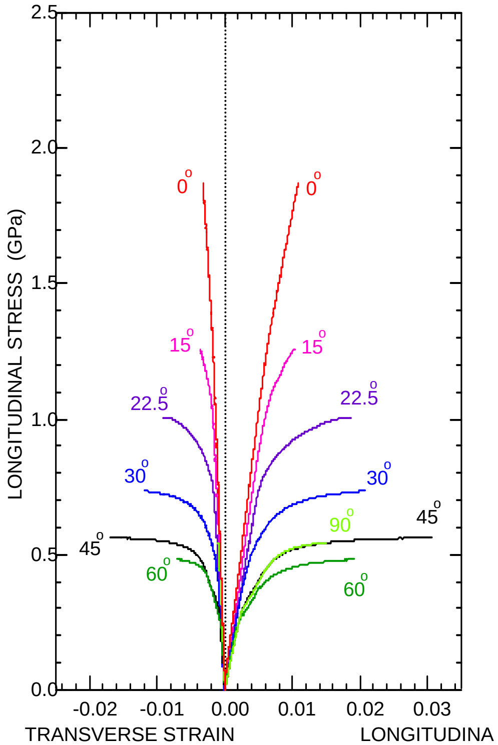
Another Application – Robotic/Unmanned Systems Design







Implications for T&E



Experimental data

Material Testing

Material Constitutive Modeling

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Component Analyses

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Subassembly Analyses

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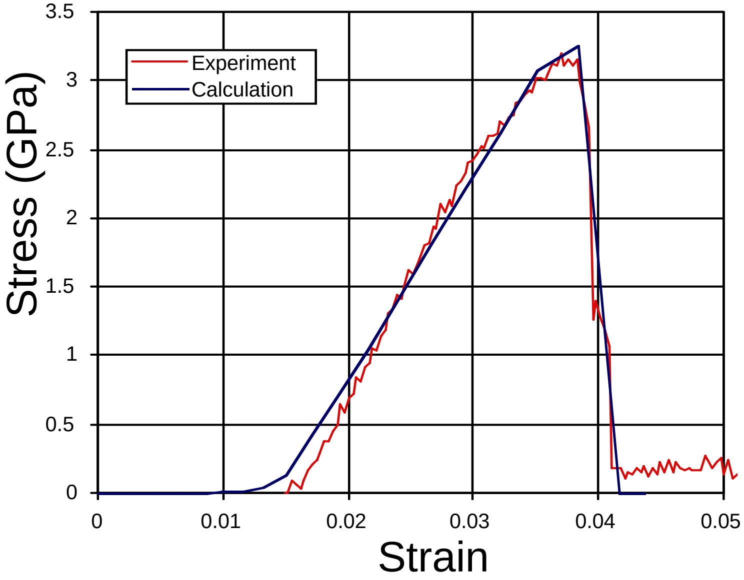
Global Analyses

Observables

Validation Tests



Building block approach requires testing at all levels

Wrap-up

- Accomplishments
  - Tools for taking a reliability-based approach to design and sustainment that can result in cost savings and risk reduction
  - Traceable predictions of reliability and performance changes
  - Computationally fast and efficient methods
- Challenges
  - Scalability of approach
  - Understanding material failure properties
  - Cascade of variable and interrelationships
    - Non-unitized structures
  - “User friendliness”
    - Enable use by decision-makers

Path Ahead

- Mature/prove methods for specifying probability distributions
  - ARA's Klein Associates Division (cognitive scientists)
- Refine the understanding of the impact and interaction of the uncontrollable random variables
- Accelerate collection of data to inform physics-based models
- Continue to evolve cost- and time-effective testing approaches for verifying reliability