Probabilistic Damage Tolerance using the FAA-Sponsored SMART|DT Software

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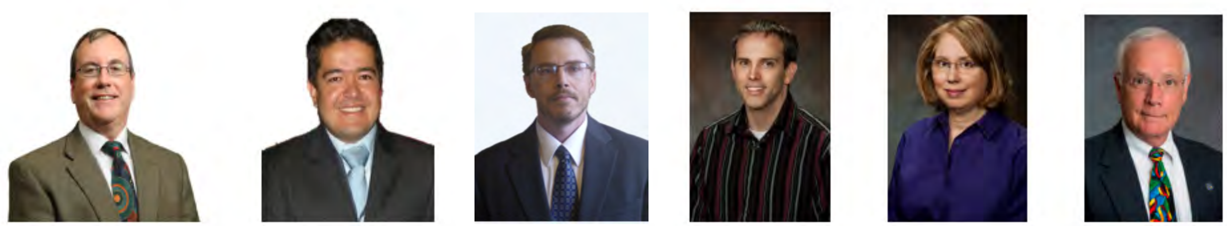
Textron Aviation (Cessna)

Marv Nuss

Nuss Sustainment Solutions



ASIP Conference - San Antonio, TX. December 1-3, 2015

Probabilistic Fatigue Management for General Aviation

- FAA established its "Safety Risk Management Policy" in 1998 (FAA Order 8040.4, revised to 8040.4A in 2012)
- FAA Aviation Safety organization (AVS) followed with its Safety Management System (SMS)
  - FAA Aircraft Certification Service (AIR) SMS includes specific policies regarding risk assessment and management
    - Example: AC 91-82A – introduces probabilistic methods as an option
      - Determine inspection threshold
      - Time in service for a part modification
  - "Monitor Safety/Analyze Data" (MSAD) is FAA Aircraft Certification Service's process to manage risk:
    - "Designed to promote data-driven, risk-based continued operational safety decision making."
    - Requires use of risk assessment and risk management concepts
      - The MSAD process is documented in FAA Order 8110.107A (2012)
    - TARAM (Transport Airplanes – PS-ANM-25-05 – 2011)
    - SARA (Small Airplanes – not yet published)

Adapted from Marv Nuss' "Sustainment and Continued Airworthiness for Aircraft Structures Short Course"

Probabilistic Fatigue Management for General Aviation

- FAA's MSAD standardizes the safety risk associated with any failure
  - Mechanical, electrical, engine and fuel systems, and structure
- Probabilistic methods meet the need for data driven risk assessment and risk management
- FAA ad hoc application successfully solved serious general aviation structural safety concerns
  - Cessna 402 light twin airplane
  - Thrush ag airplane
- FAA management supported research into probabilistic approach to refine assessment methods

Adapted from Marv Nuss' "Sustainment and Continued Airworthiness for Aircraft Structures Short Course"

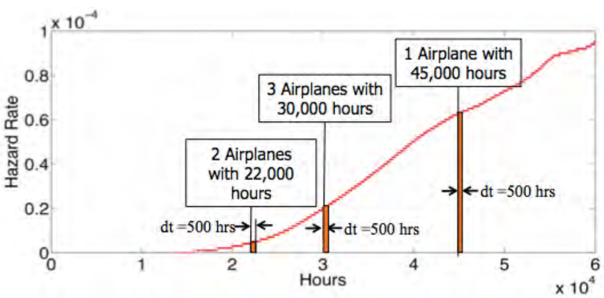
Program Overview

Fatigue

Damage Tolerance

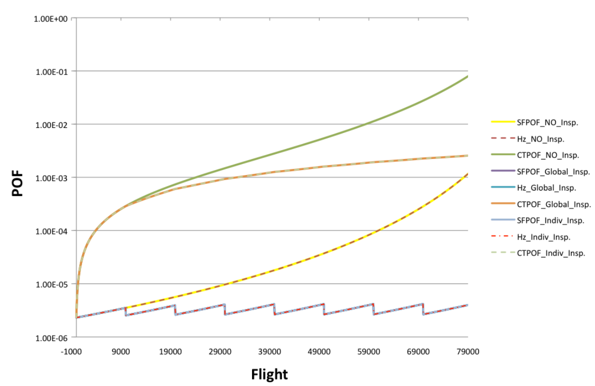
Probabilistic Fatigue Analysis for Small Airplanes ($SMART_{LD}$)

Safe-life Approach



- Prob. Life distribution
- Hazard Rate
- Sensitivity Analysis

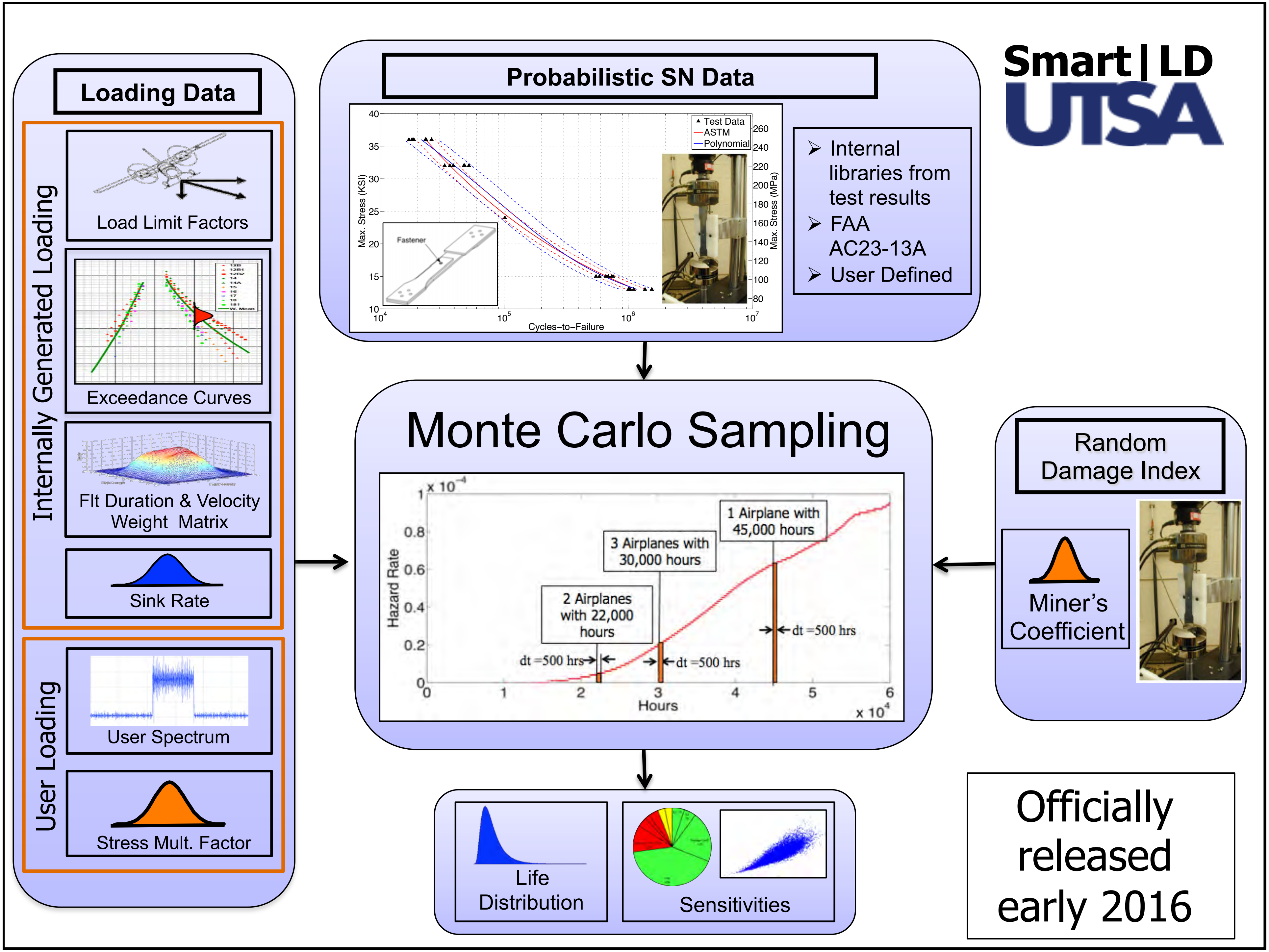
Probabilistic Damage Tolerance Analysis for Small Airplane ($SMART_{DT}$)



- SFPOF, Hz, CTPOF
- Inspection/Repair Effect
- Sensitivity Analysis

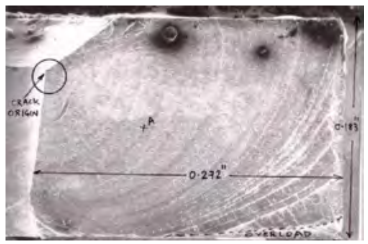
Probabilistic Fatigue Management Program for General Aviation

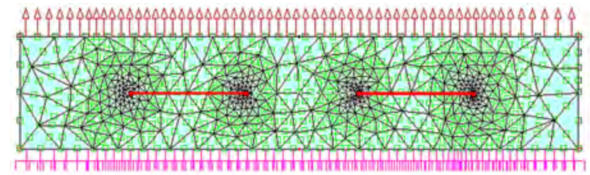
- Develop experience and familiarity with probabilistic approaches within engineering personnel that design, manufacture and maintain general aviation aircraft.
- Verification with in-service findings.
- Develop a Probabilistically-based fatigue management plan (PFMP) for general aviation


Loading Data
Internally Generated Loading
Load Limit Factors
Exceedance Curves
Flt Duration & Velocity Weight Matrix
Sink Rate
User Loading
User Spectrum
Stress Mult. Factor
Probabilistic SN Data
Test Data
ASTM
Polynomial
Fastener
Max. Stress (KSI)
Max. Stress (MPa)
Cycles–to–Failure
Internal libraries from test results
FAA AC23-13A
User Defined
Smart | LD
UTSA
Monte Carlo Sampling
Hazard Rate
Hours
x 10^-4
x 10^4
1 Airplane with 45,000 hours
3 Airplanes with 30,000 hours
2 Airplanes with 22,000 hours
dt =500 hrs
Random Damage Index
Miner's Coefficient
Life Distribution
Sensitivities
Officially released early 2016

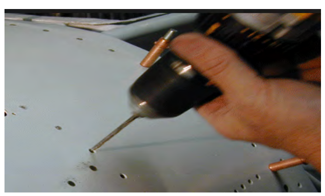
Development Philosophy

- Run any crack growth model



- Consider any repair scenario

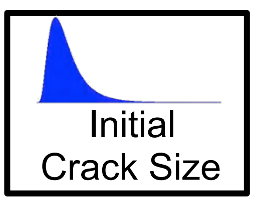


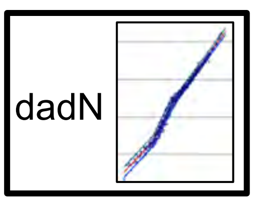
Oversized Hole

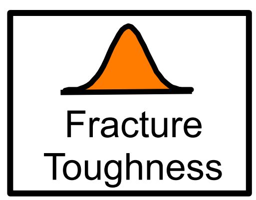
Doubler

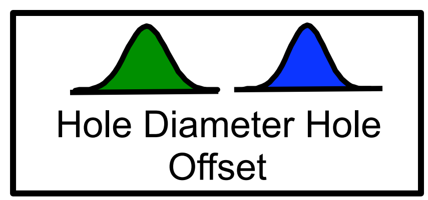
Replacement

- Consider any random variable



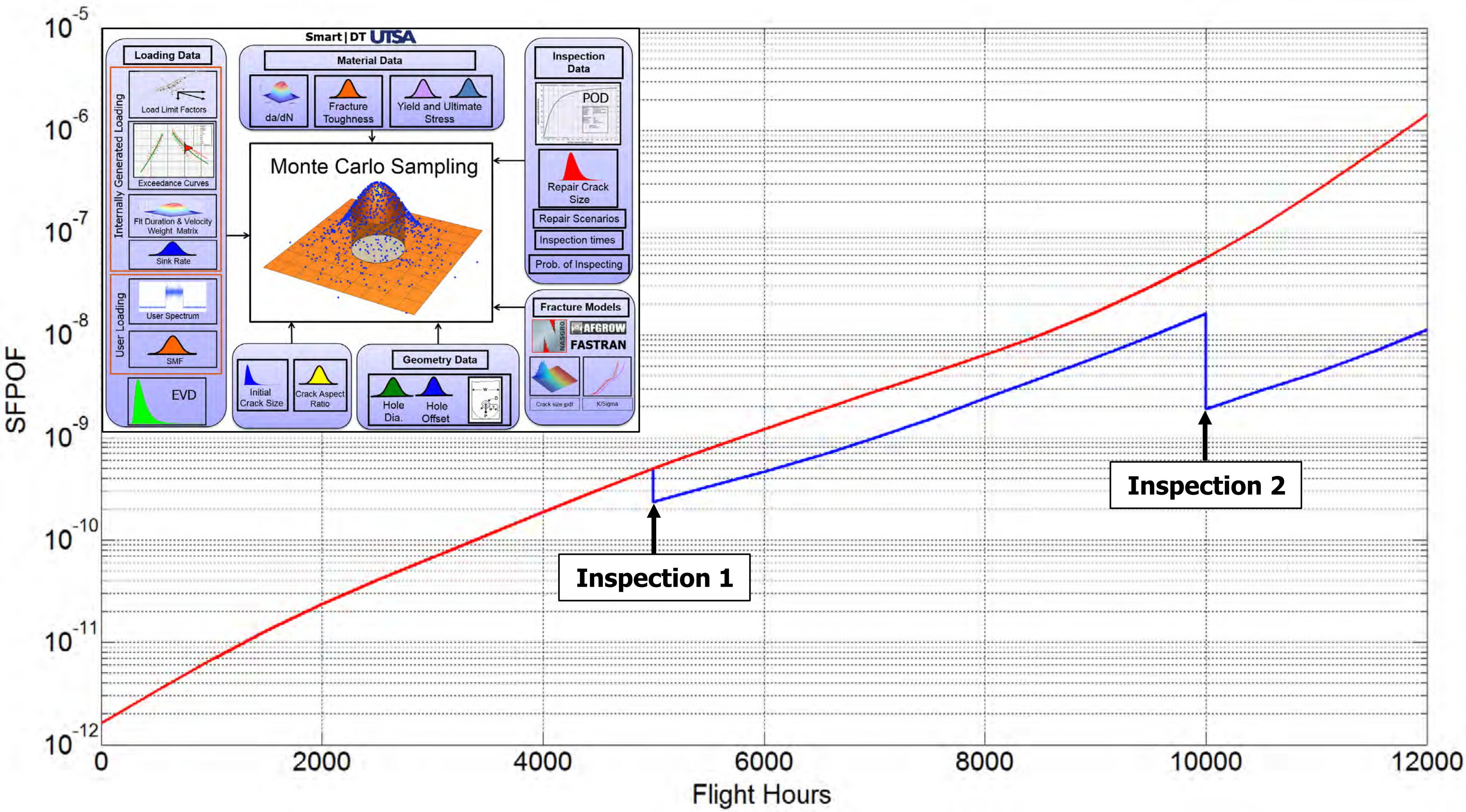






Etc.

Risk Assessment



Probability Equations

The probability-of-failure is the probability that maximum value of the applied stress (during the next flight) will exceed the residual strength σ_{RS} of the aircraft component

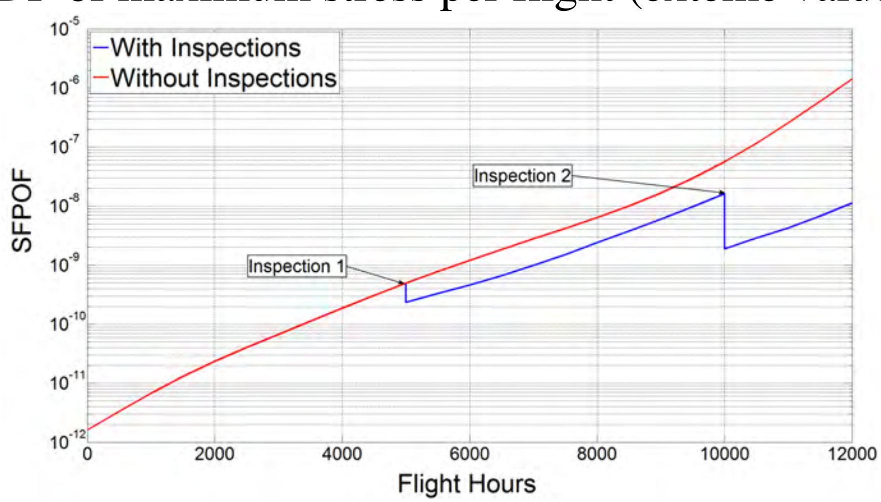
$$POF(t) = P\left[\sigma_{Max} > \sigma_{RS}(t)\right] = \int \left[1 - F_{EVD}\left(\sigma_{RS}(t)\right)\right] f_{\mathbf{x}}(\mathbf{x})\, d\mathbf{x}$$

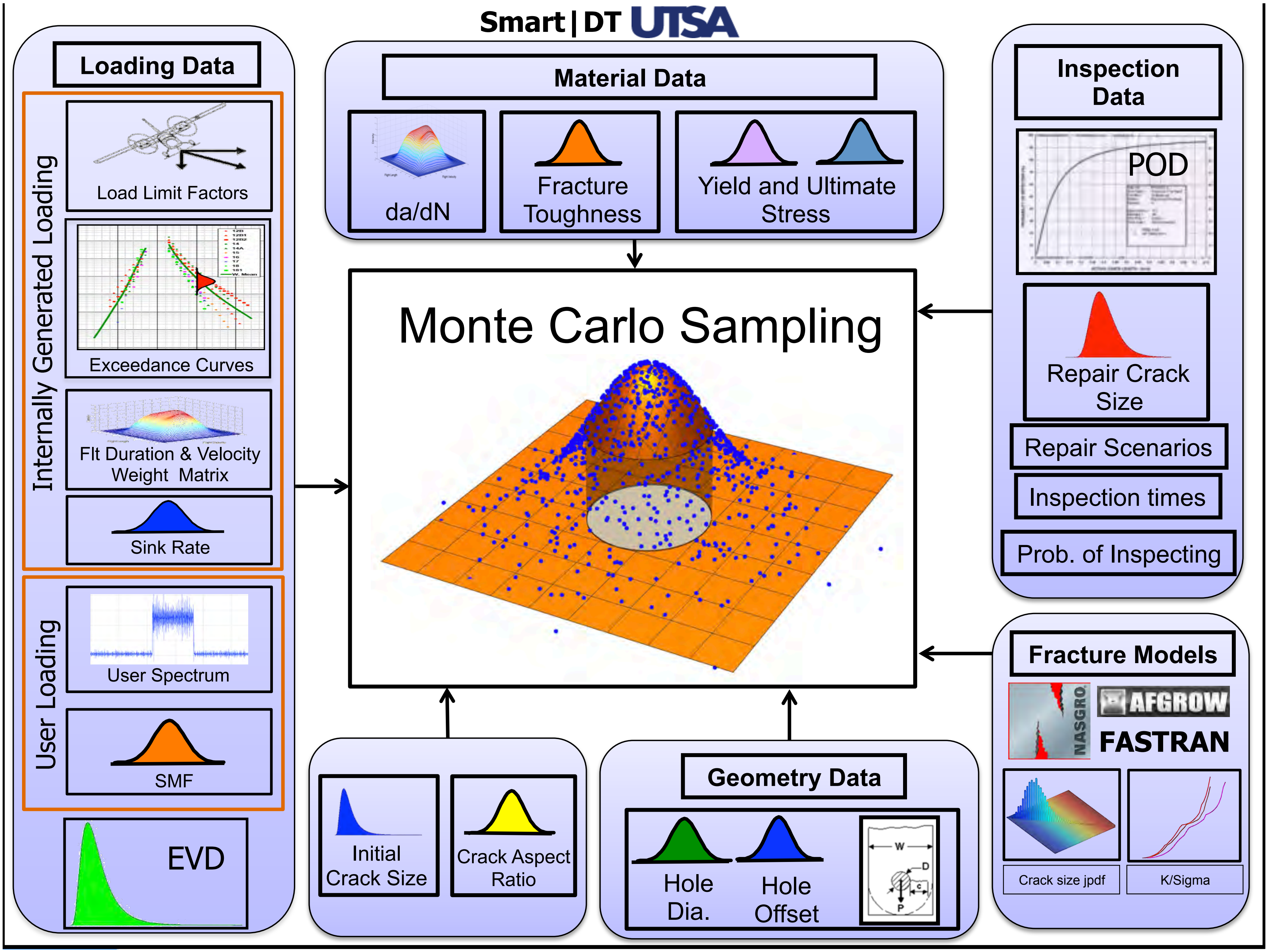
$$CTPOF(t) = \int 1 - \left[\prod_{i=1}^{t} F_{EVD}\left(\sigma_{RS}(t_i)\right)\right] f_{\mathbf{x}}(\mathbf{x}) d\mathbf{x}$$

$$SFPOF(t) = \int \left[\prod_{i=1}^{t-1} F_{EVD}\left(\sigma_{RS}(t_i)\right)\right]\left[1 - F_{EVD}\left(\sigma_{RS}(t)\right)\right] f_{\mathbf{x}}(\mathbf{x}) d\mathbf{x}$$

$$Hz(t) = \int \left[\frac{SFPOF(t)}{1 - CTPOF(t)}\right] f_{\mathbf{x}}(\mathbf{x}) d\mathbf{x}$$

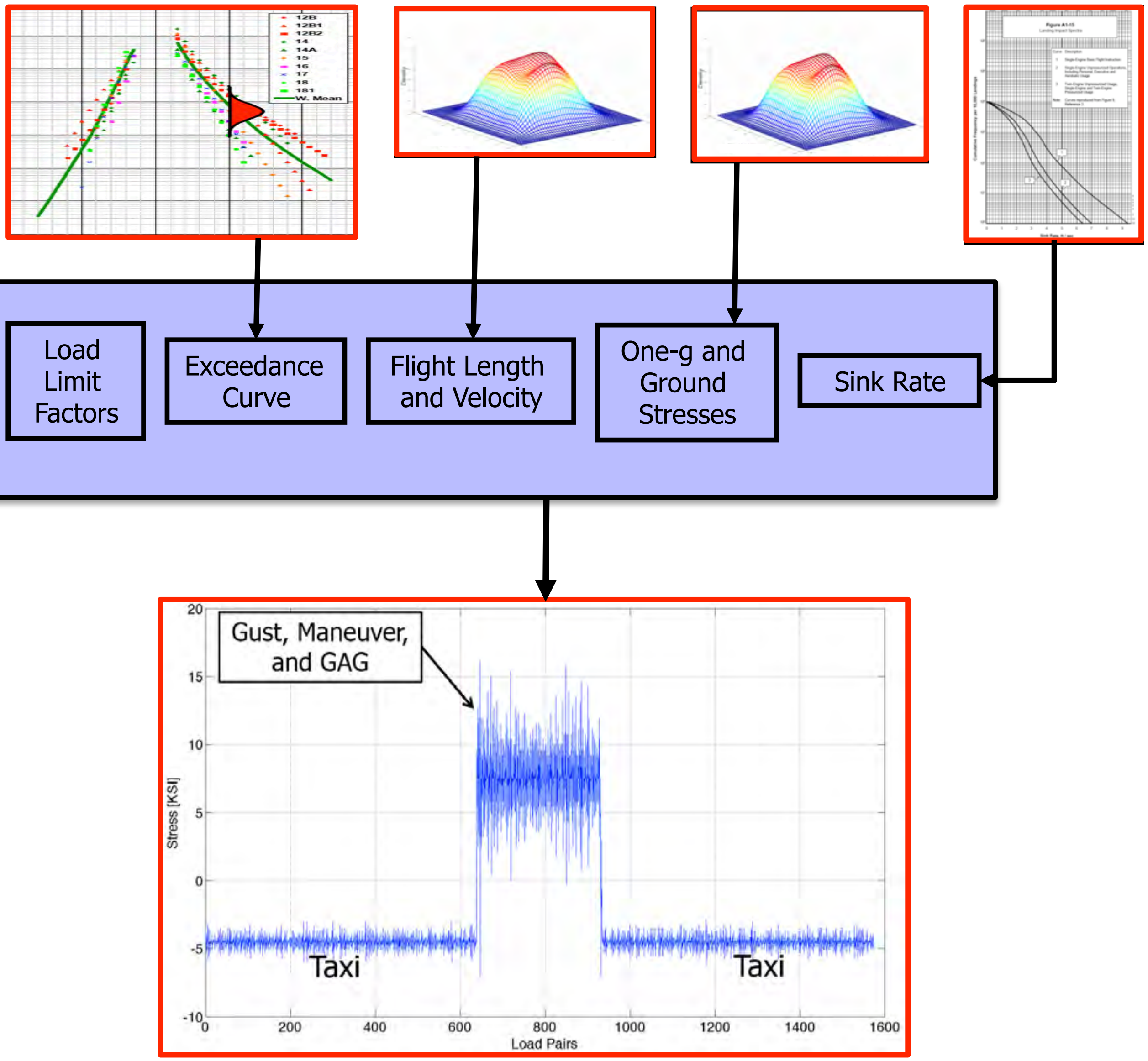
F_{EVD} = CDF of maximum stress per flight (exteme value distribution).





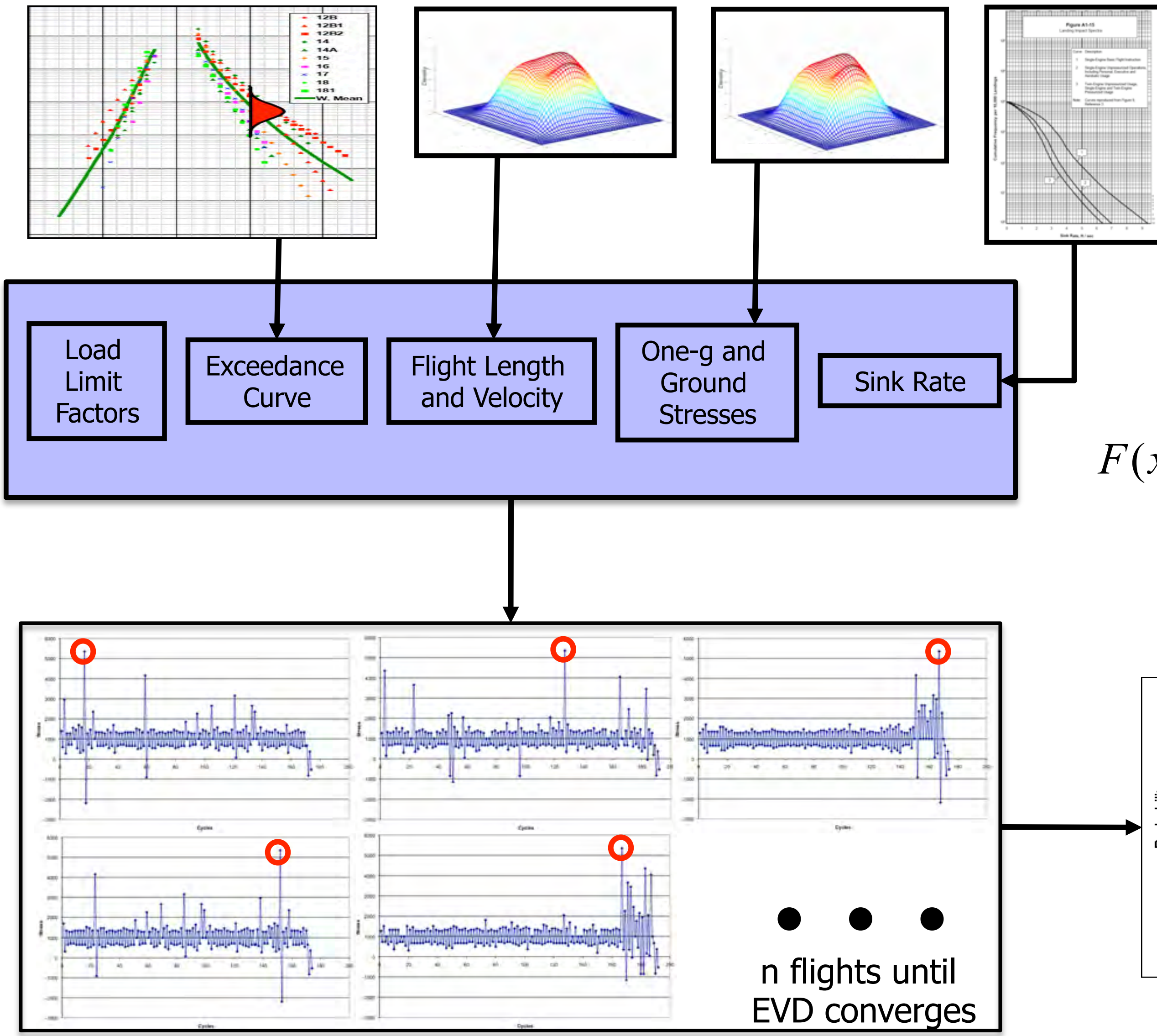
Smart | DT UTSA
Loading Data
Internally Generated Loading
Load Limit Factors
Exceedance Curves
Flt Duration & Velocity Weight Matrix
Sink Rate
User Loading
User Spectrum
SMF
EVD
Material Data
da/dN
Fracture Toughness
Yield and Ultimate Stress
Monte Carlo Sampling
Inspection Data
POD
Repair Crack Size
Repair Scenarios
Inspection times
Prob. of Inspecting
Fracture Models
NASGRO
AFGROW
FASTRAN
Crack size jpdf
K/Sigma
Initial Crack Size
Crack Aspect Ratio
Geometry Data
Hole Dia.
Hole Offset

Spectrum Generation



- ✓ Exceedance curves
  - ✓ internal and user-defined
- ✓ Mixed usages
- ✓ Flight duration and weight matrices random to simulate flight profiles and different operations
- ✓ Randomized flights and stresses
- ✓ Spectrum editing options
- ✓ User-defined spectra
  - ✓ Afgrow format

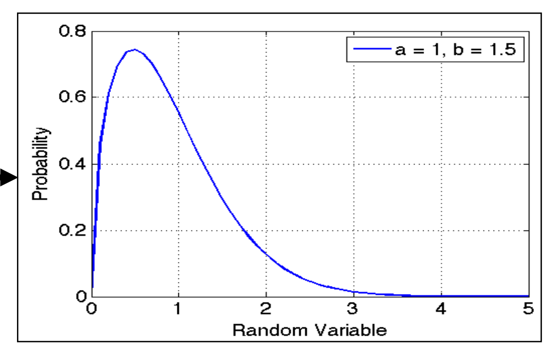
EVD Generation



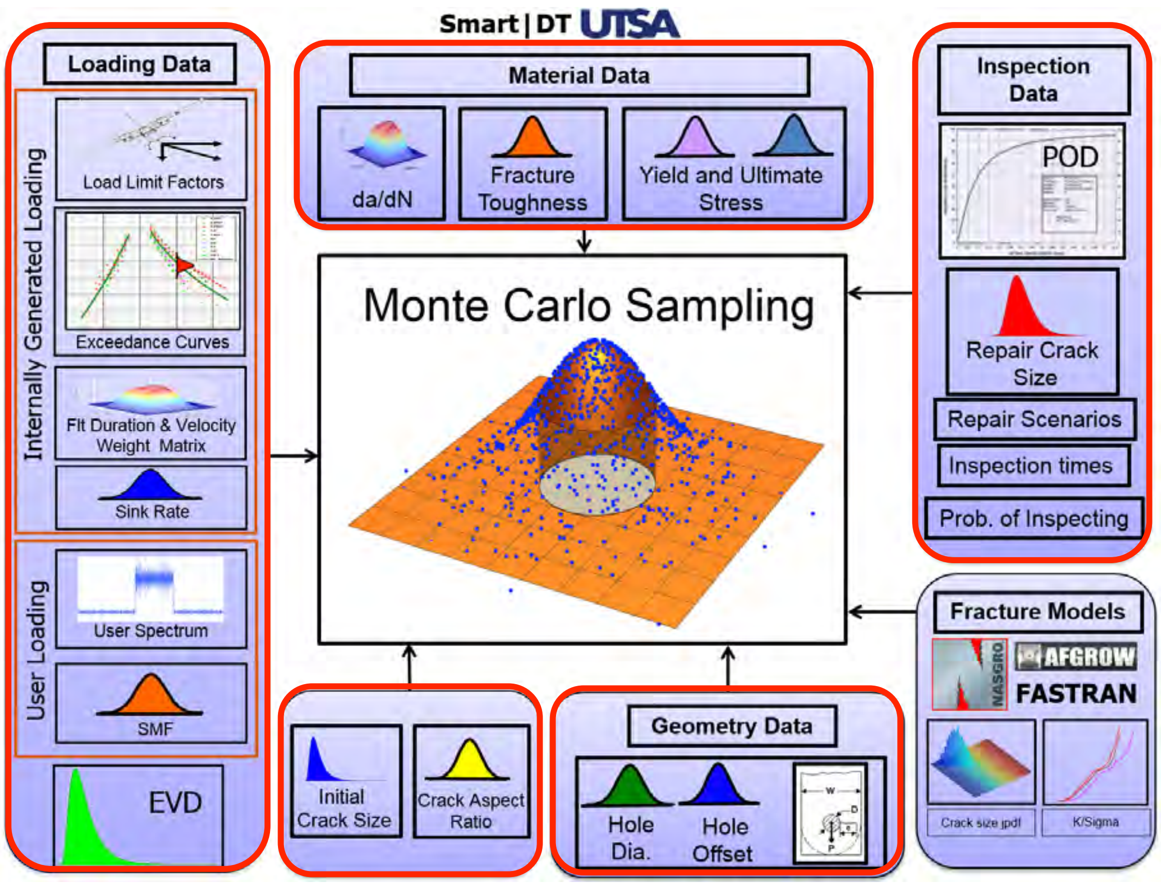
- ✓ EVD computed internally from spectrum

$$F(x) = \exp\left\{ -\left[1 + \xi \left(\frac{x - \mu}{\sigma} \right) \right]^{-1/\xi} \right\}$$

EVD Distribution

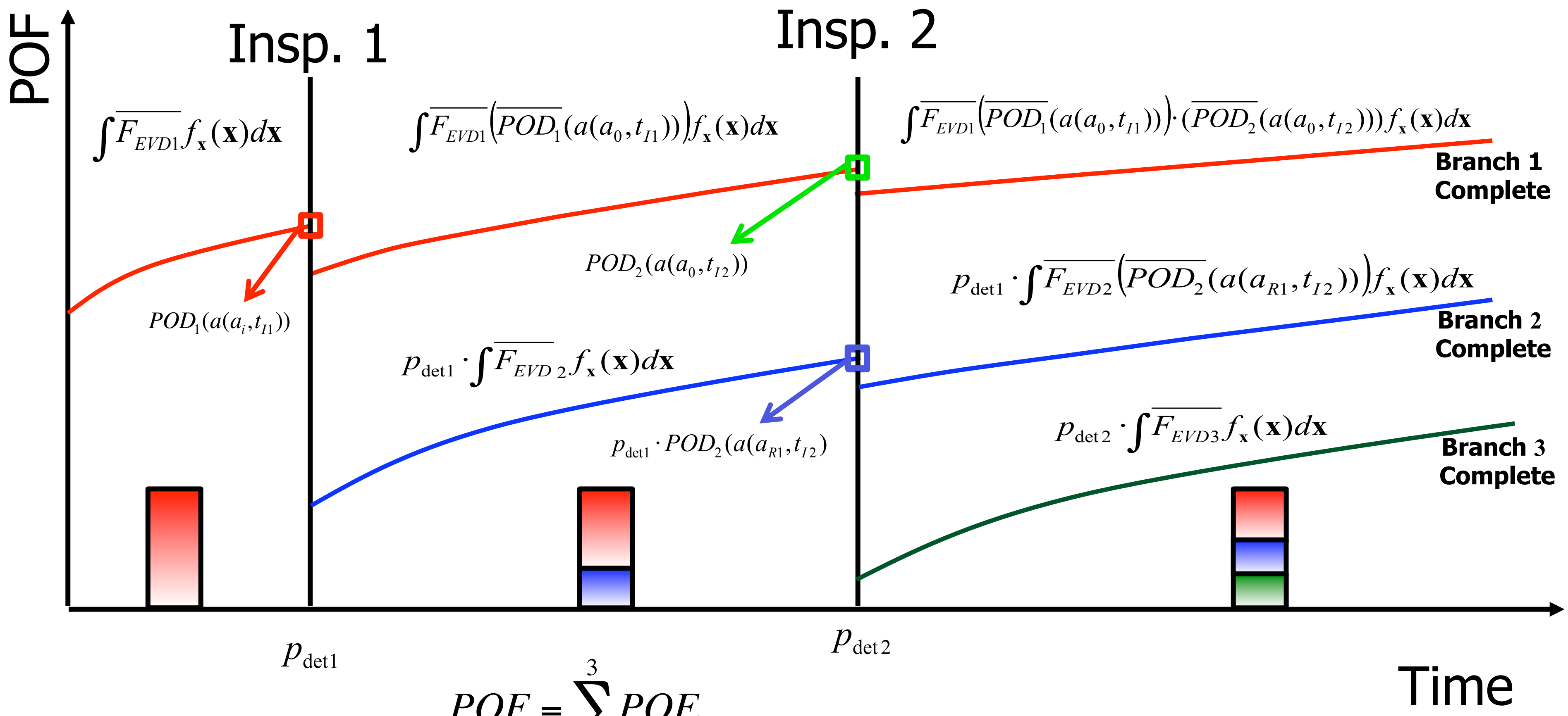


Comprehensive Random Variables



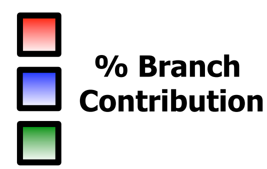
- Loading
- EIFS & aspect ratio
- da/dN
- Fracture toughness
- Yield stress, ultimate stress
- Hole Size & Hole Offset
- POD, POI, Repair Crack Size
- **Expandable**:

Multiple Inspections

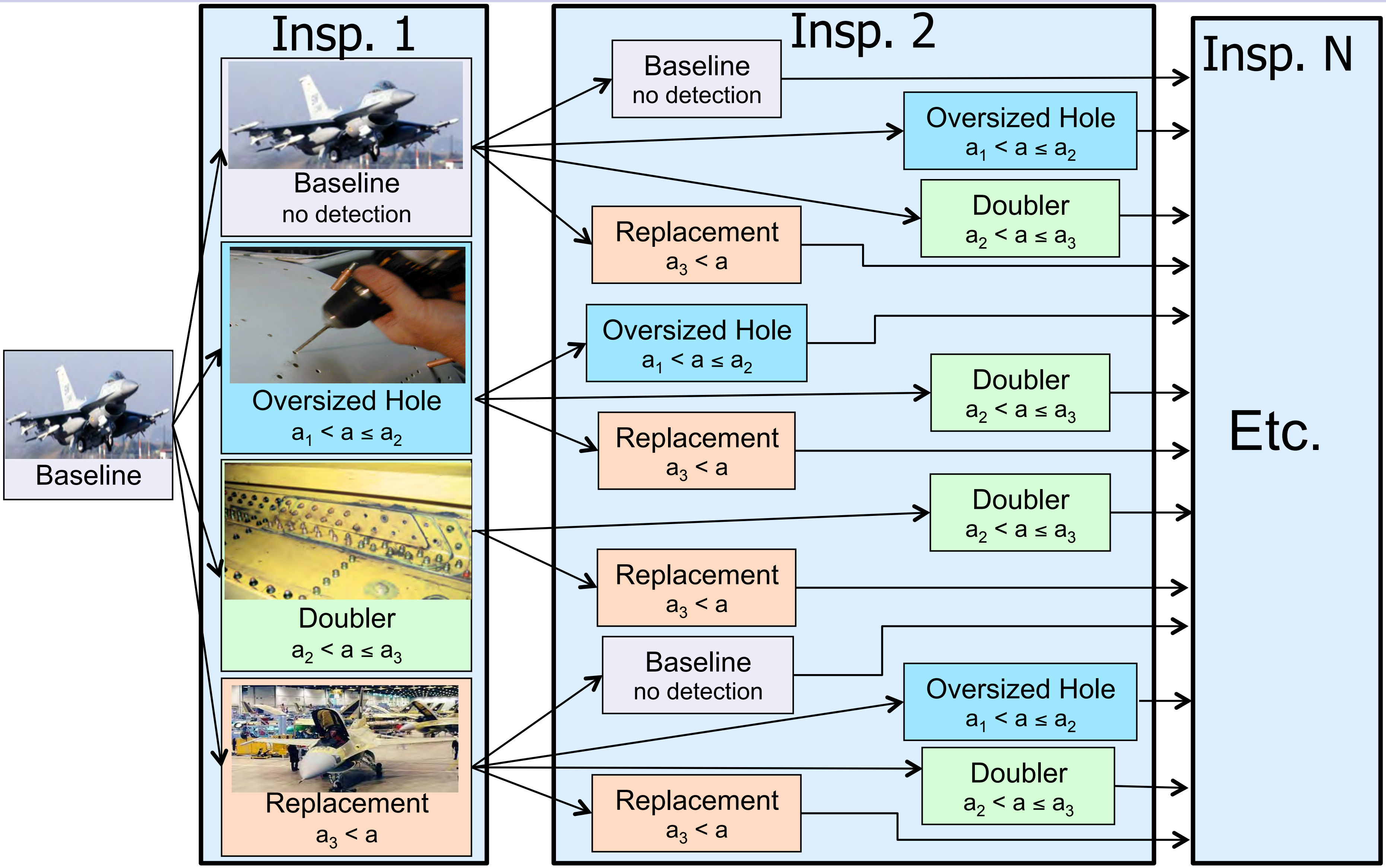


$$POF = \sum_{i=1}^{3} POF_i$$

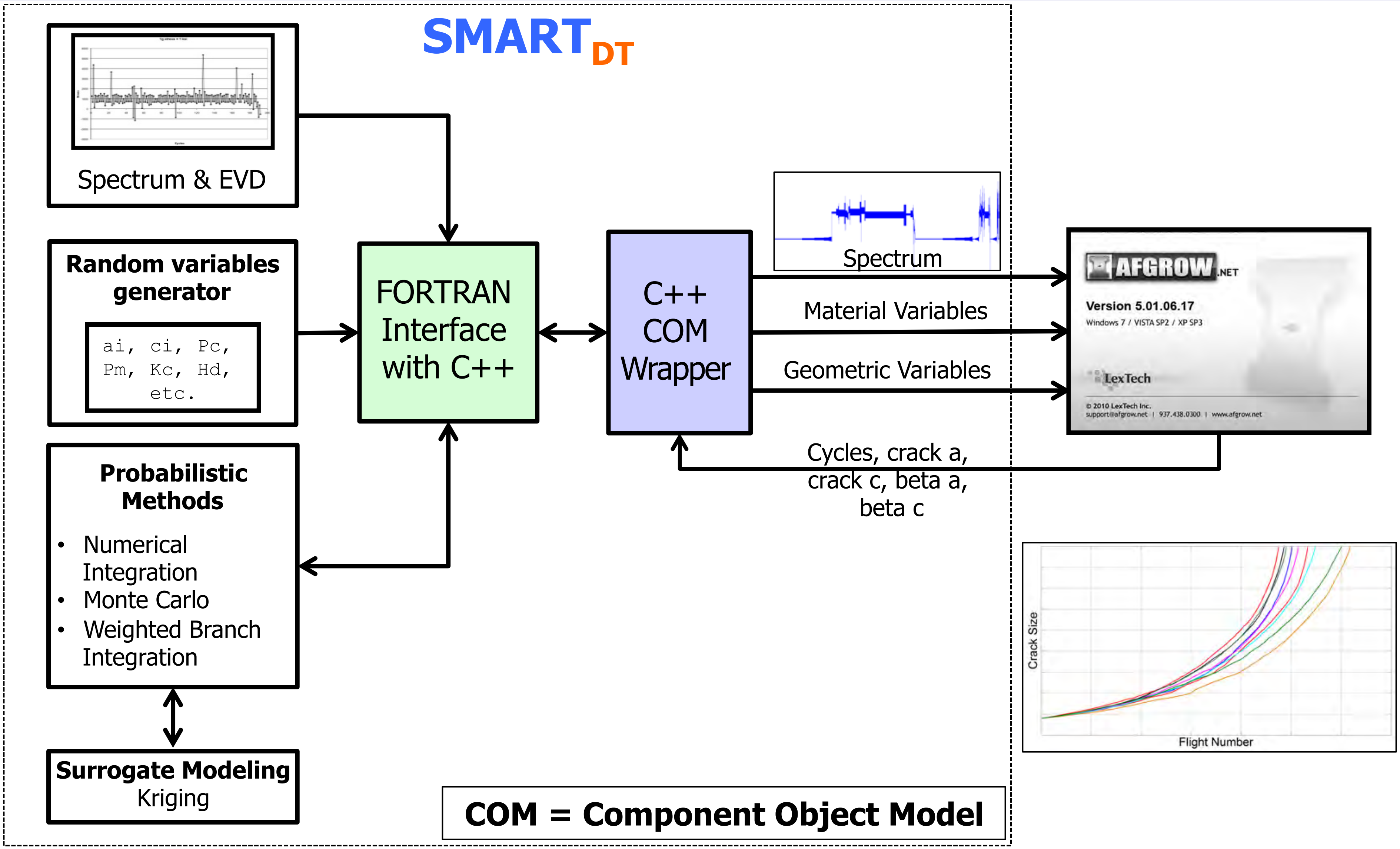
Add the contribution from each branch into the final POF



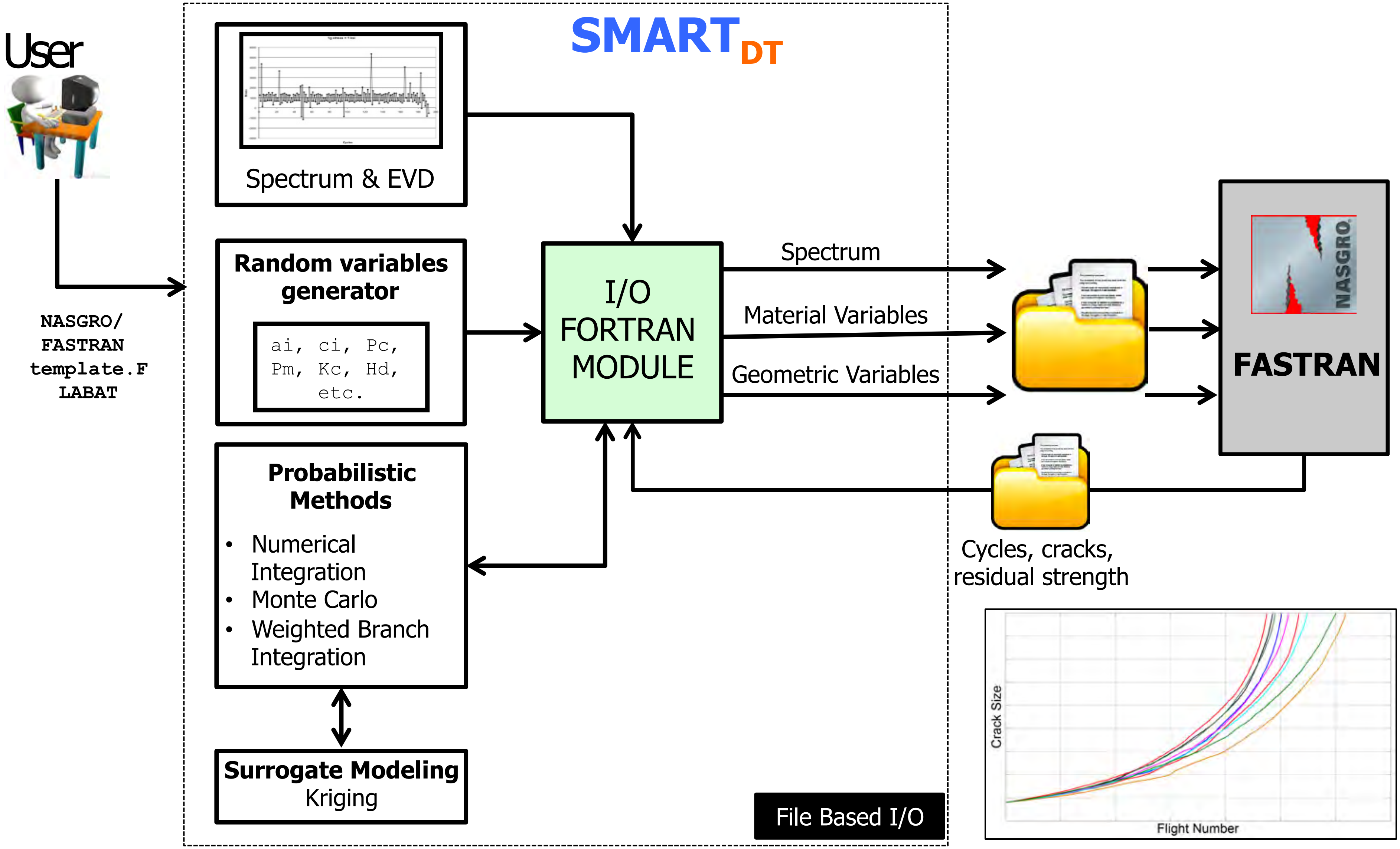
Multiple Repair Example



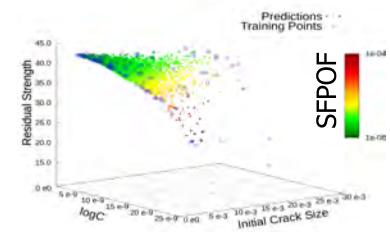
AFGROW Interface: COM driven



FASTRAN/NASGRO Interface Runs in Parallel



Efficient Method



- ✓ Adaptive surrogate model (using Kriging)
- ✓ Multiple random variables
  - ai, Kc, Paris C, crack aspect ratio, hole diameter, hole offset, yield stress
- ✓ User defined error

Analysis Methods

Based on 1B Samples - 1 Core

Master Curve
Monte Carlo

Inputs:
- ✓Only a_i and K_c Random
- ✓Representative Spectrum
- ✓Inspection/Repair

Output: ✓Hz, SFPOF, CTPOF

1X – Computational Cost

Adaptive Kriging
Monte Carlo

Inputs:
- ✓Multiple Rnd variables
- ✓Representative Spectrum
- ✓Inspection/Repair

Output: ✓Hz, SFPOF, CTPOF

~200X - Computational Cost
(With 1,000 Training pts)

4,000x Speedup

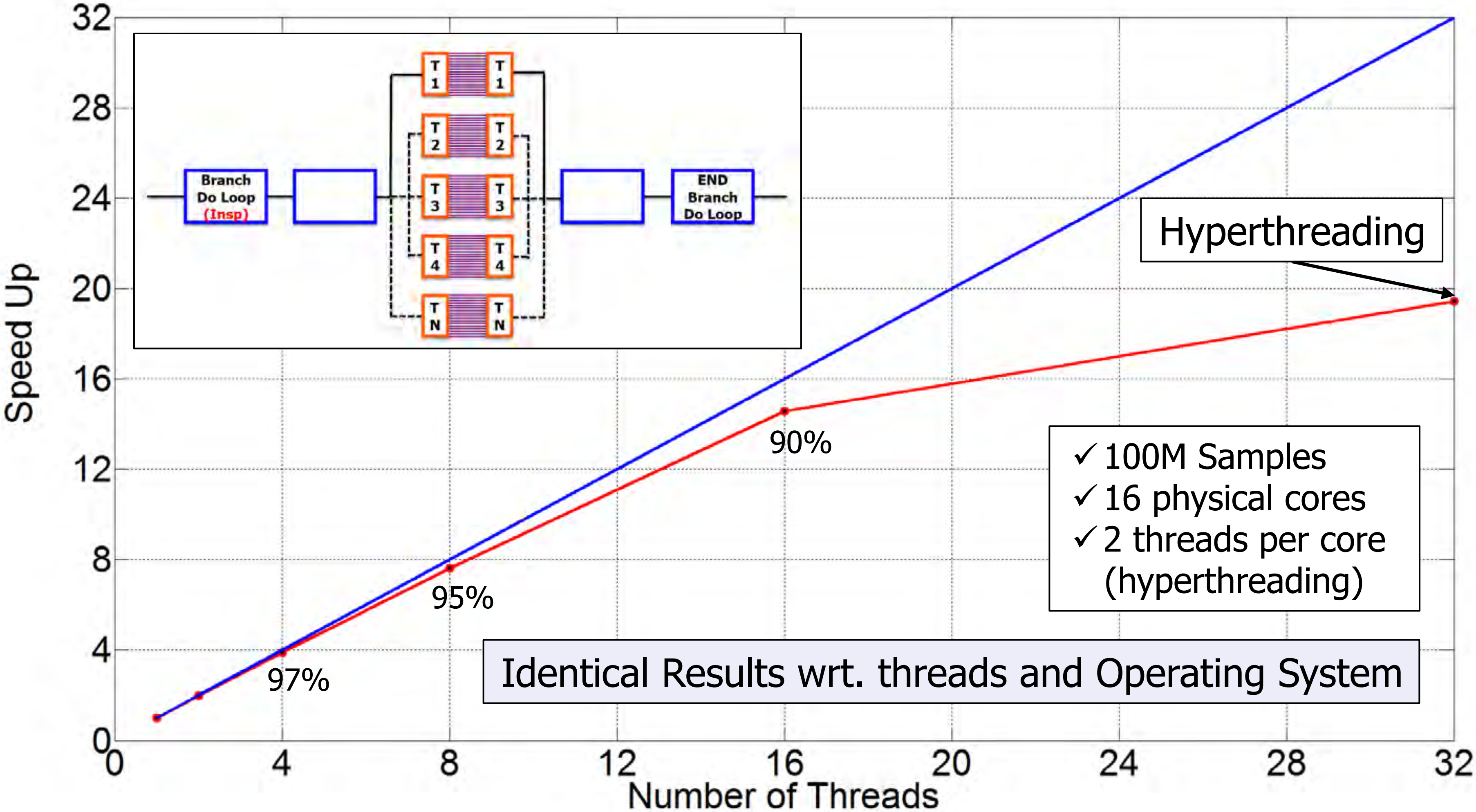
Full Nasgro/Afgrow
Monte Carlo

Inputs:
- ✓Multiple Rnd variables
- ✓Multiple Spectrum
- ✓Inspection/Repair

Output: ✓Hz, SFPOF, CTPOF

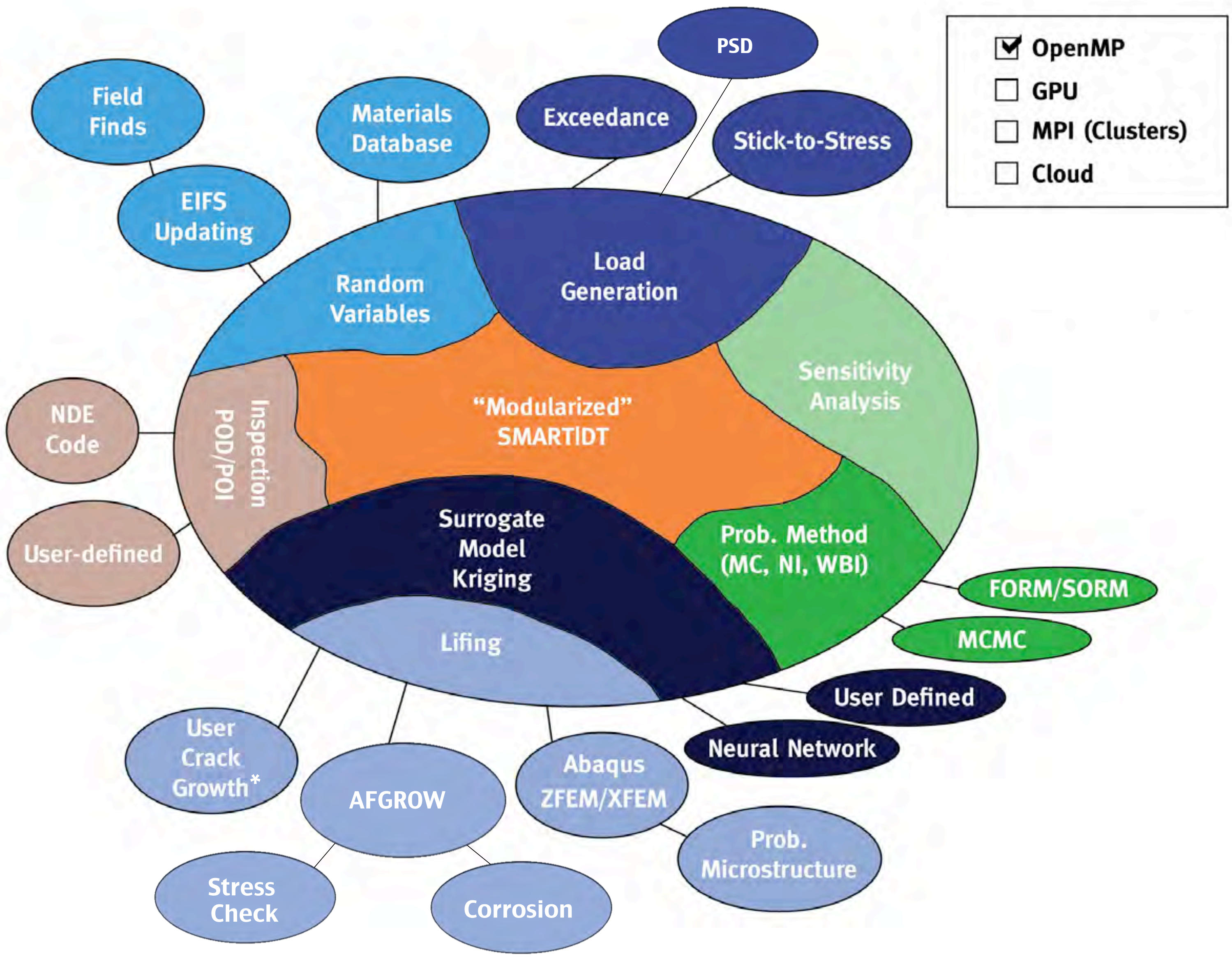
~800,000X - Computational Cost

Parallel & Vectorized



PID	USER	PR	NI	VIRT	RES	SHR	S	%CPU	%MEM	TIME+	COMMAND
23419	pze593	20	0	2698m	128m	2084	S	3199.5	0.0	2:39.23	smartdta.exe

Plays well with Others

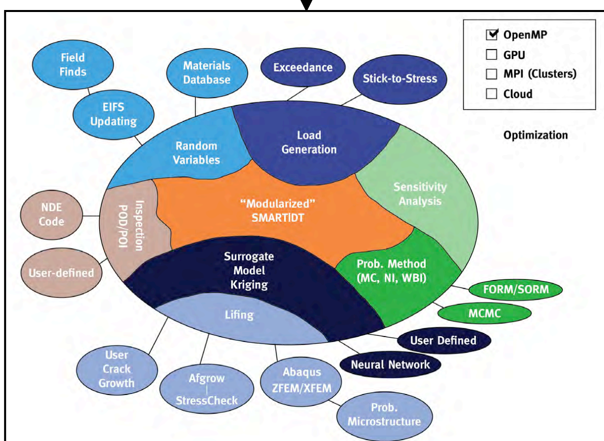


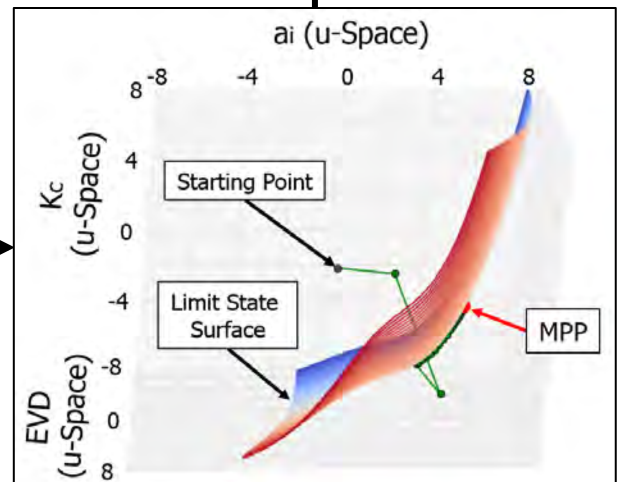
SMART Modularization (FORM Analysis)

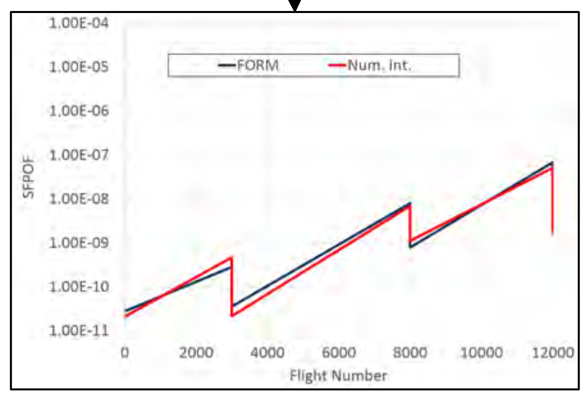
SMART input File

SMART User Samples File

```
Monte Carlo Method = MC
Numb of Insp. =  0
Numb of Samples =         100
ai                  Kc                  Pm                   PC
3.025E-3          34.8E0     2.70000000e+00     -8.10000000e+00
```



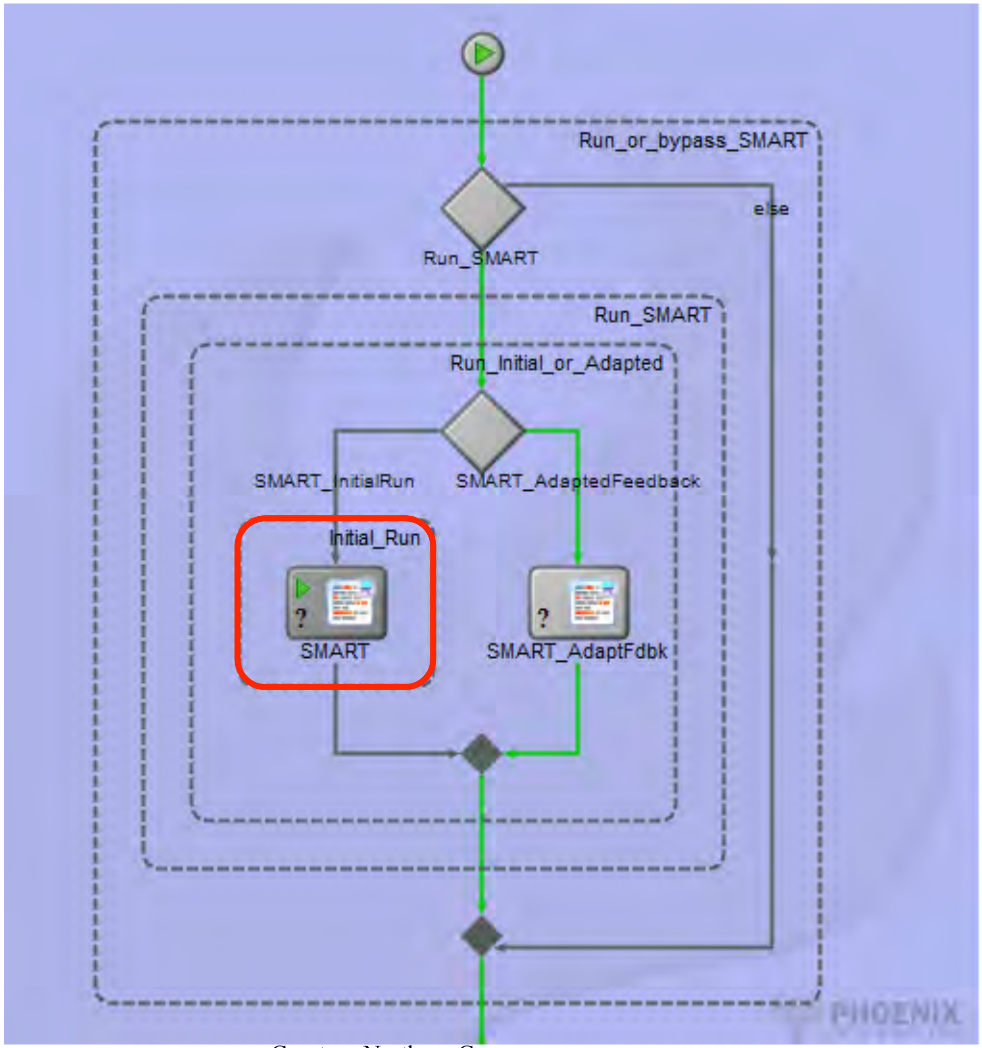




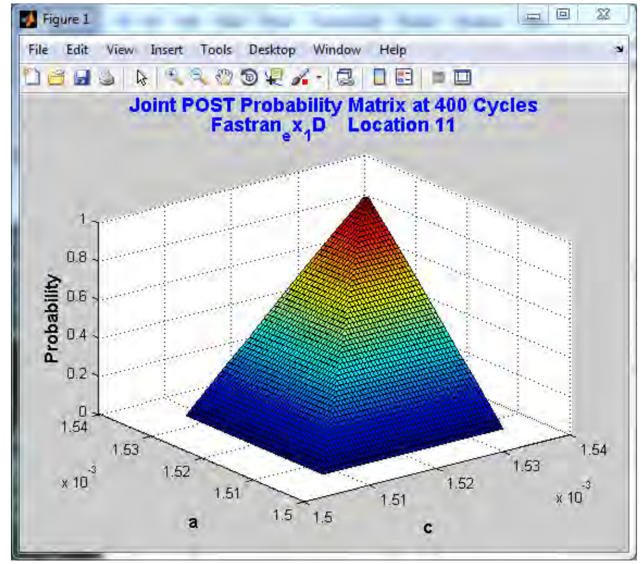
	FORM	Num. Int.	MC Sampling
Fn. Evaluations	~200	~10,000	>100M

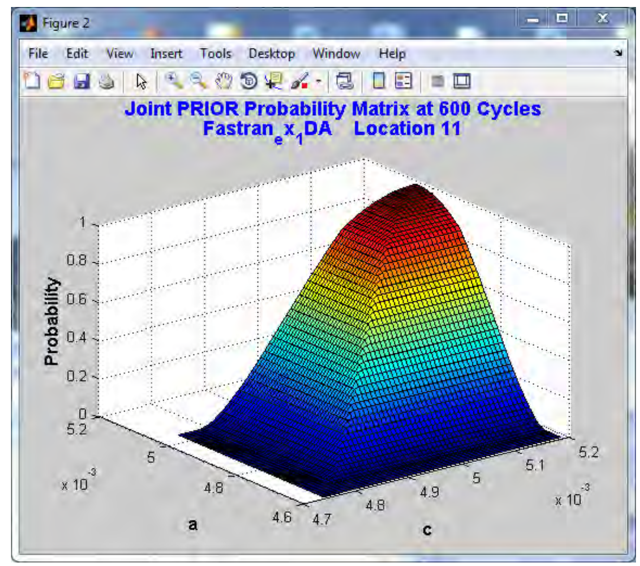
Integration within ModelCenter

Adaptation of crack size

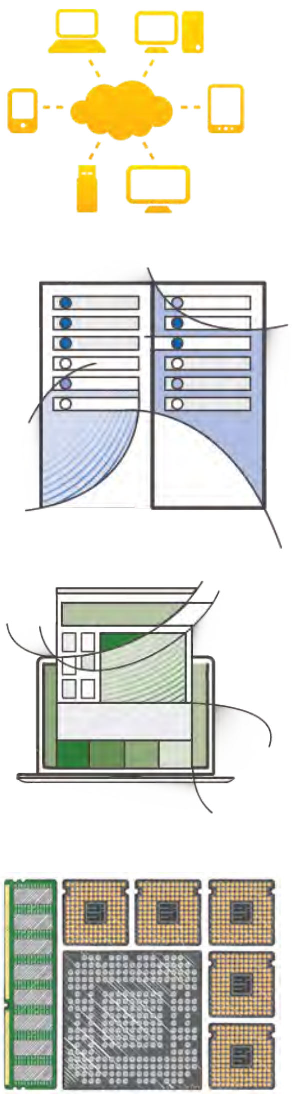


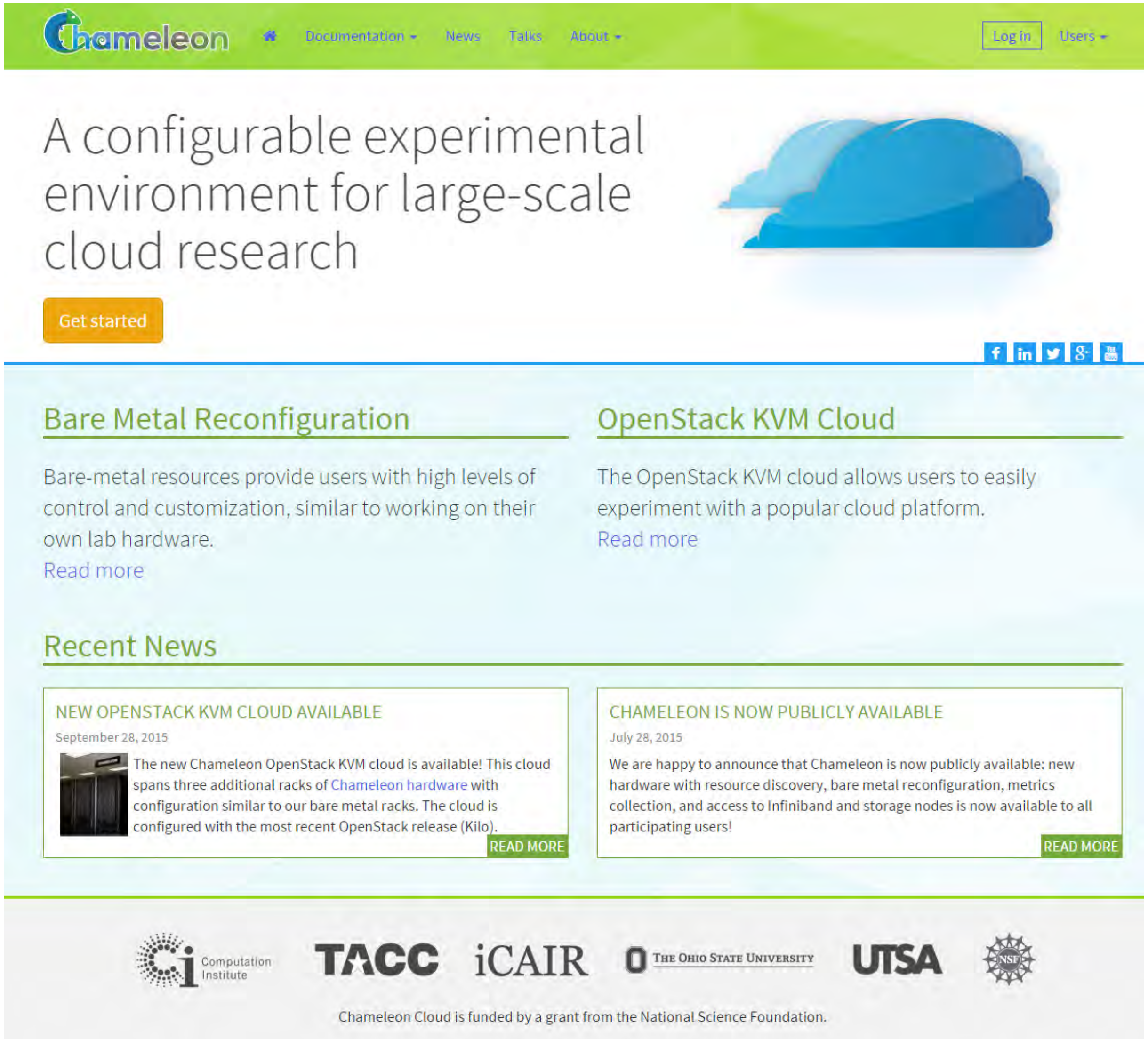
Courtesy Northrop Grumman

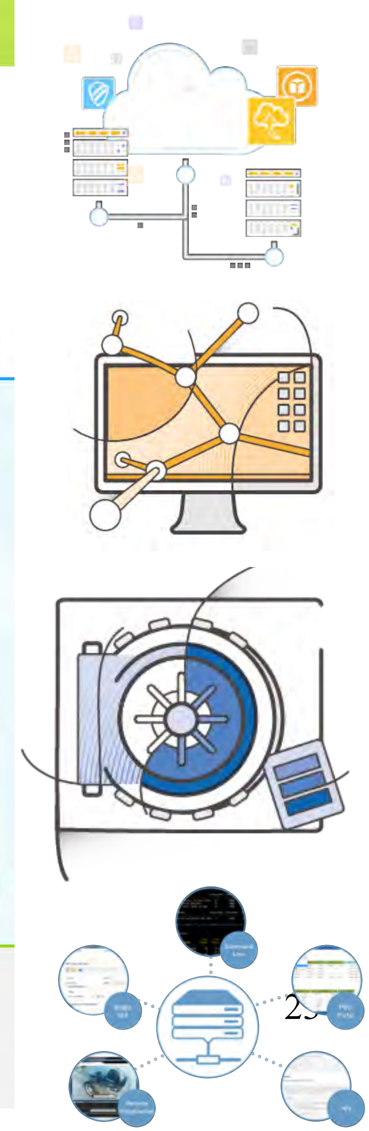




Cloud Computing



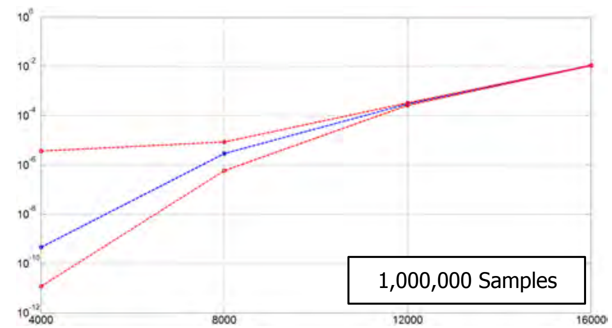




Technology Development Summary

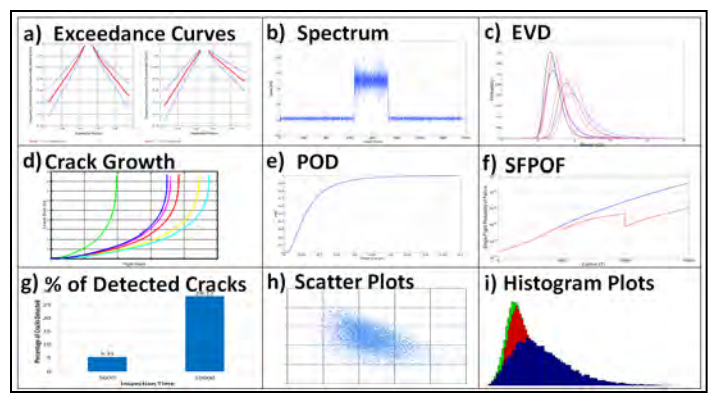
FAA Funding
SBIR Phase I Funding
ADT funding

- ✓ Spectrum loading generation
- ✓ Extreme value distribution
- ✓ Probability calculations
- ✓ Direct NASGRO and AFGROW interfaces
- ✓ Probabilistic methods (WBI, Monte Carlo sampling, numerical integration)
- ✓ Kriging for efficient probabilistic fracture analysis
- ✓ Inspection capabilities (Any number of inspections, Arbitrary repair crack size distribution (lognormal, tabular, Weibull, deterministic), Arbitrary POD (lognormal, tabular), Deterministic POD, User defined probability of inspection
- ✓ Multiple repair scenarios within/between inspections
- ✓ Multiple random variables (ai, Kc, Evd, da/dN, hole diameter, hole offset, crack aspect ratio, yield stress, ultimate stress).
- ✓ HPC implementation (parallel and vectorized)
- ✓ Sensitivity module (under development)
- ✓ Graphical user interface
- ✓ FASTRAN Interface
- ✓ Sensor Interface (crack size distribution write and read at any time of the analysis)
- ✓ Integration with Model Center



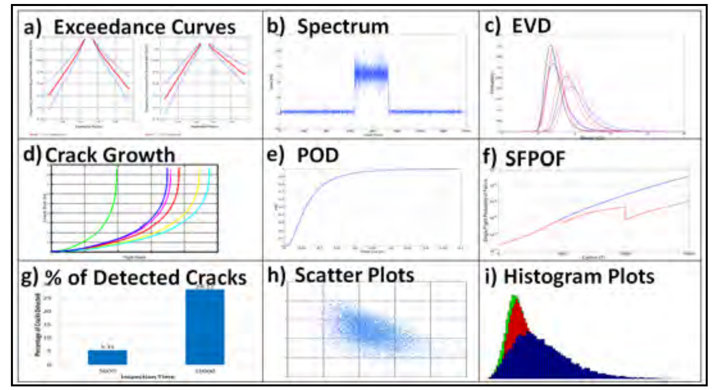
Future Development

- ➢ Importance Sampling
- ➢ Remaining Useful Life
- ➢ Probabilistic Database of Random Variables and Results
- ➢ Cluster/Cloud Computing
- ➢ *Optimized inspections schedules on a risk/cost basis*
- ➢ *Structural health monitoring and prognosis*
- ➢ *First/Second Order Reliability Method (FORM/SORM)*
- ➢ *Multiple control points*
- ➢ *Bayesian updating*
- ➢ *User access to all algorithms (modularization and COM enable software)*



Upcoming plans

- Rollout plan
  - Smart|LD – early 2016 official release
  - Smart|DT – multi-phase rollout
    - Phase I: Spring 2016:
      - Master curve implementation, WBI with multiple repair, multi-threaded, Nasgro/Afgrow/Fastran interfaces.
    - Phase II: Late 2016, Early 2017
      - Multiple random variables (dadN, geometry), numerical integration, Kriging surrogate modeling, sensitivities, importance sampling
    - Phase III: Future plans
      - Cloud capabilities, optimized inspection schedule, probabilistic database, etc.
  - Training
    - AA&S 2016
      - Monday morning: LD
      - Monday afternoon: DT
      - Presentation on Efficient Methods for POF Calculations
- Web site for more information
  - https://smartutsa.wordpress.com
  - harry.millwater@utsa.edu
  - juan.ocampo@utsa.edu

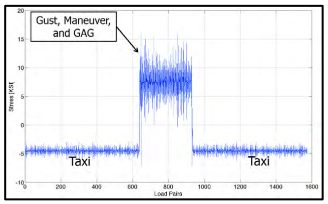


Web site

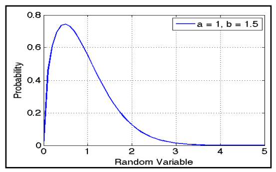
Smart|DT

https://smartutsa.wordpress.com

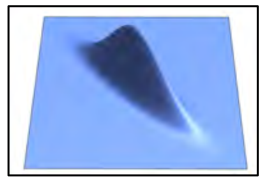
Loading Generation



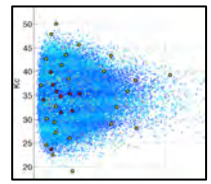
EVD Dist



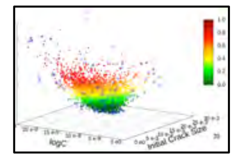
dadN variability



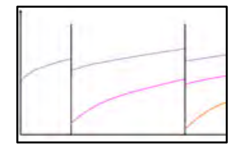
Monte Carlo



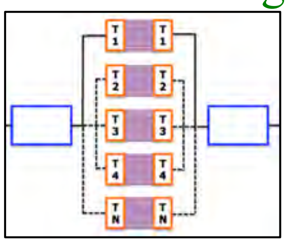
Kriging surrogate



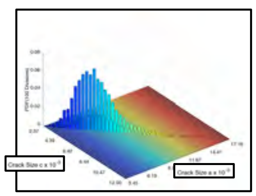
WBI



HPC - multithreading



Joint a & c interpolation

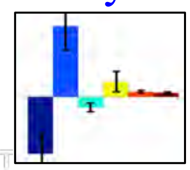


Nasgro & Fastran interface

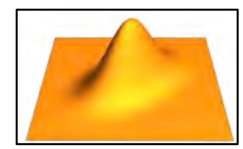
Afgrow interface w COM

AFGROW

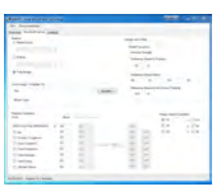
Sensitivity analysis



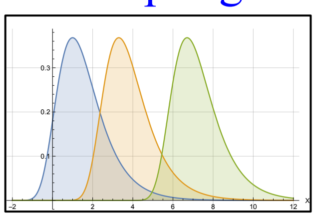
Numerical Integration



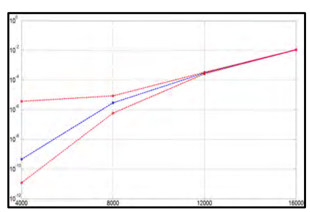
GUI



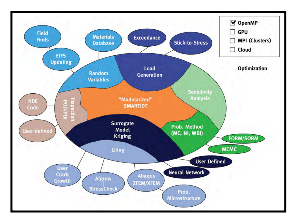
Importance sampling



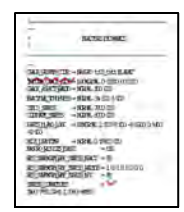
Confidence Bounds



Interoperability



Scriptable



GPU MPI/Cloud

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