Probabilistic Damage Tolerance for Aircraft Fleets Using the FAA-Sponsored SMART|DT Software

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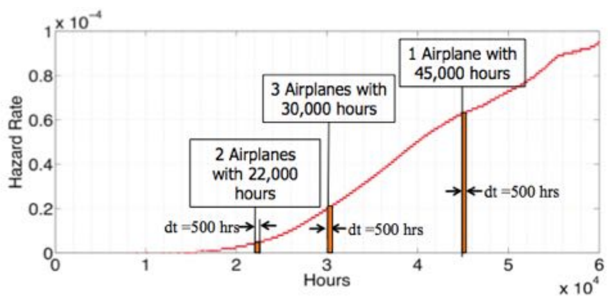
Program Overview

Fatigue

Damage Tolerance

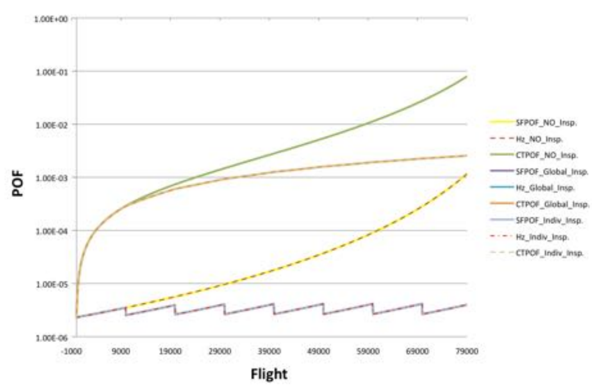
Probabilistic Fatigue Analysis for Small Airplanes ($SMART_{LD}$)

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

FAA Support of Probabilistic Fatigue and Damage Tolerance

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Small Airplane Directorate

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FAA Interest in Probabilistic Fatigue/DT

- **FAA Order 8110.107A Monitor Safety/Analyze Data (MSAD) (10/1/2012)**
  - FAA will use quantitative risk analysis in making continued operational safety decisions. (Airworthiness Directives)
- **Order has effect of requiring probabilistic methods when applicable.**

FAA Interest in Probabilistic Fatigue/DT

- **Even before the Order was published, FAA Small Airplane Directorate (SAD) was adopting probabilistic methods.**

- **Airworthiness Directive for Cessna 402**

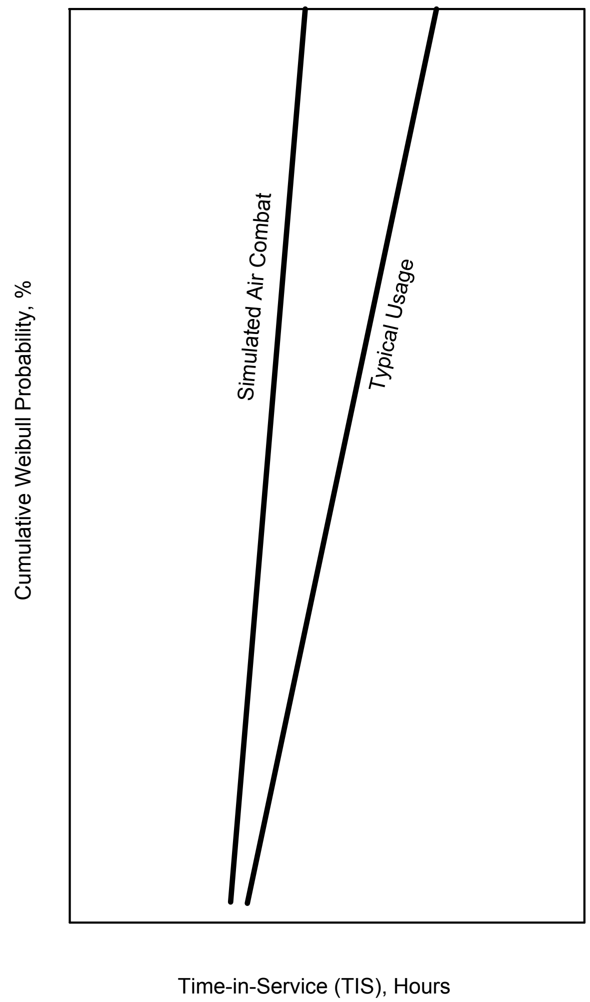
  – Spar cracking with critical crack size less than detectable crack size

  – Large percentage of fleet older than ‘life-limit’ solution, would have caused groundings

  – Used risk management to schedule modifications considering time-in-service and modification resources.

FAA Interest in Probabilistic Fatigue/DT

- **SAD often deals with diverse fleet usage**
  - Minority sub-fleet operated with more severe stress spectrum than remainder of fleet
  - Relative risk between different stress spectra
  - Insight into how to manage risk within constraints of 14 CFR Part 39 Airworthiness Directives



FAA Interest in Probabilistic Fatigue/DT

- **Revision of AC 23-13**

  - Review historical guidance (AFS-120-73-2)
    - Why scatter factor = 4.0?
    - Why gust and maneuver spectra offset by 1.5 standard deviations?
    - 'Deterministic' solution to probabilistic problem

  - Used Monte Carlo simulations to validate
    - 'Probability Basis of Safe-Life Evaluations in Small Airplanes', 9th Joint FAA/DoD/NASA Aging Aircraft Conference

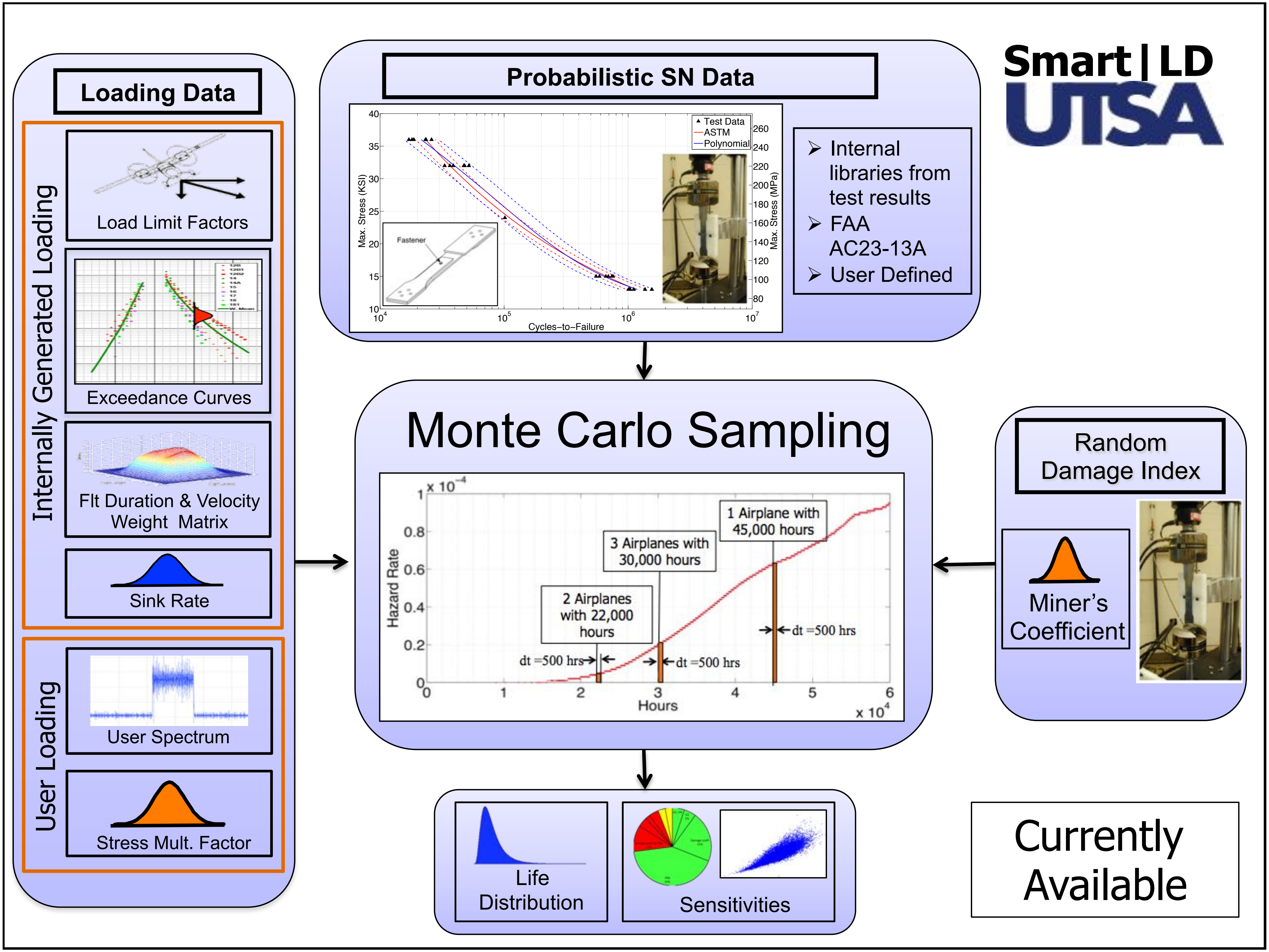
    - $SMART_{LD}$ gives expanded capabilities to in-house FAA Monte Carlo simulations

FAA Interest in Probabilistic Fatigue/DT

- **$SMART_{LD}$ and $SMART_{DT}$ gives the FAA the capability to use probabilistic fatigue/DT to:**
  - Update regulations, policy, and guidance
  - Evaluate unsafe conditions and design corrective actions

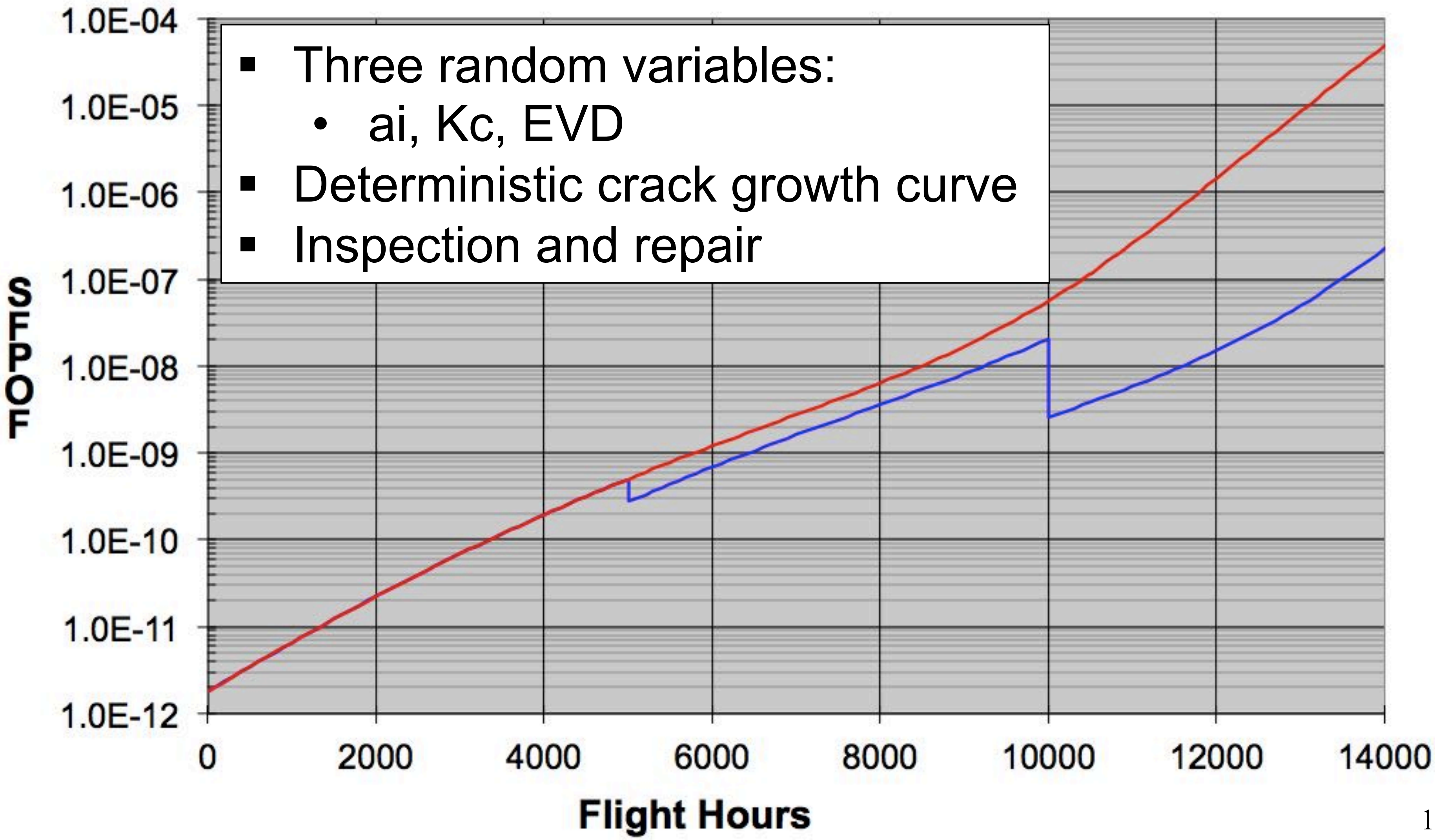
Additional Questions:

- **How can the SMART Technology be used in transport Airplanes?**
- **How to incorporate this technology for early stages of the airplane life (Also for design, not only airworthiness,)**


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
1 Airplane with 45,000 hours
3 Airplanes with 30,000 hours
2 Airplanes with 22,000 hours
dt =500 hrs
dt =500 hrs
dt =500 hrs
Hazard Rate
Hours
x 10^-4
x 10^4
Random Damage Index
Miner's Coefficient
Life Distribution
Sensitivities
Currently Available

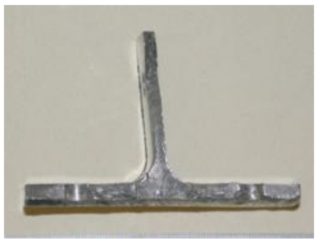
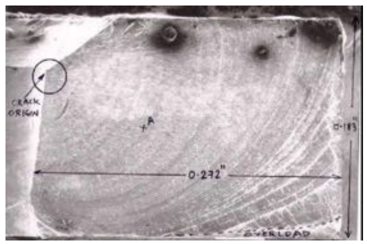
Previous S-O-T-A

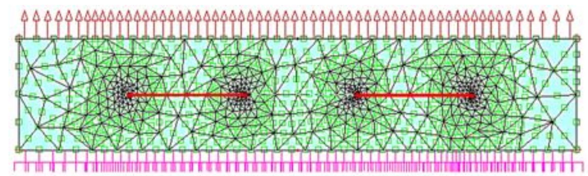
- Three random variables:
  - ai, Kc, EVD
- Deterministic crack growth curve
- Inspection and repair



Development Philosophy

- Run any crack growth model



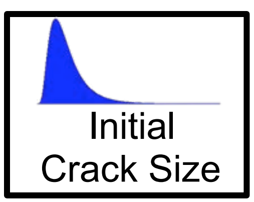
- Consider any repair scenario

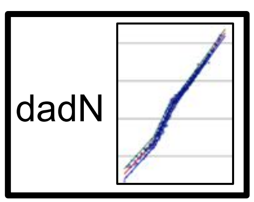

Oversized Hole

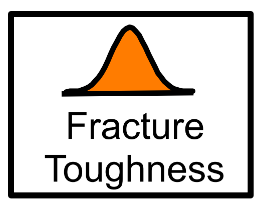

Doubler

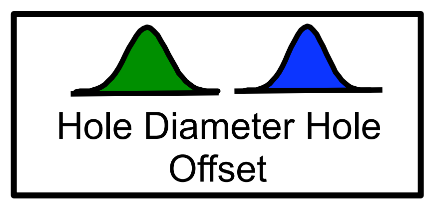

Replacement

- Consider any random variable

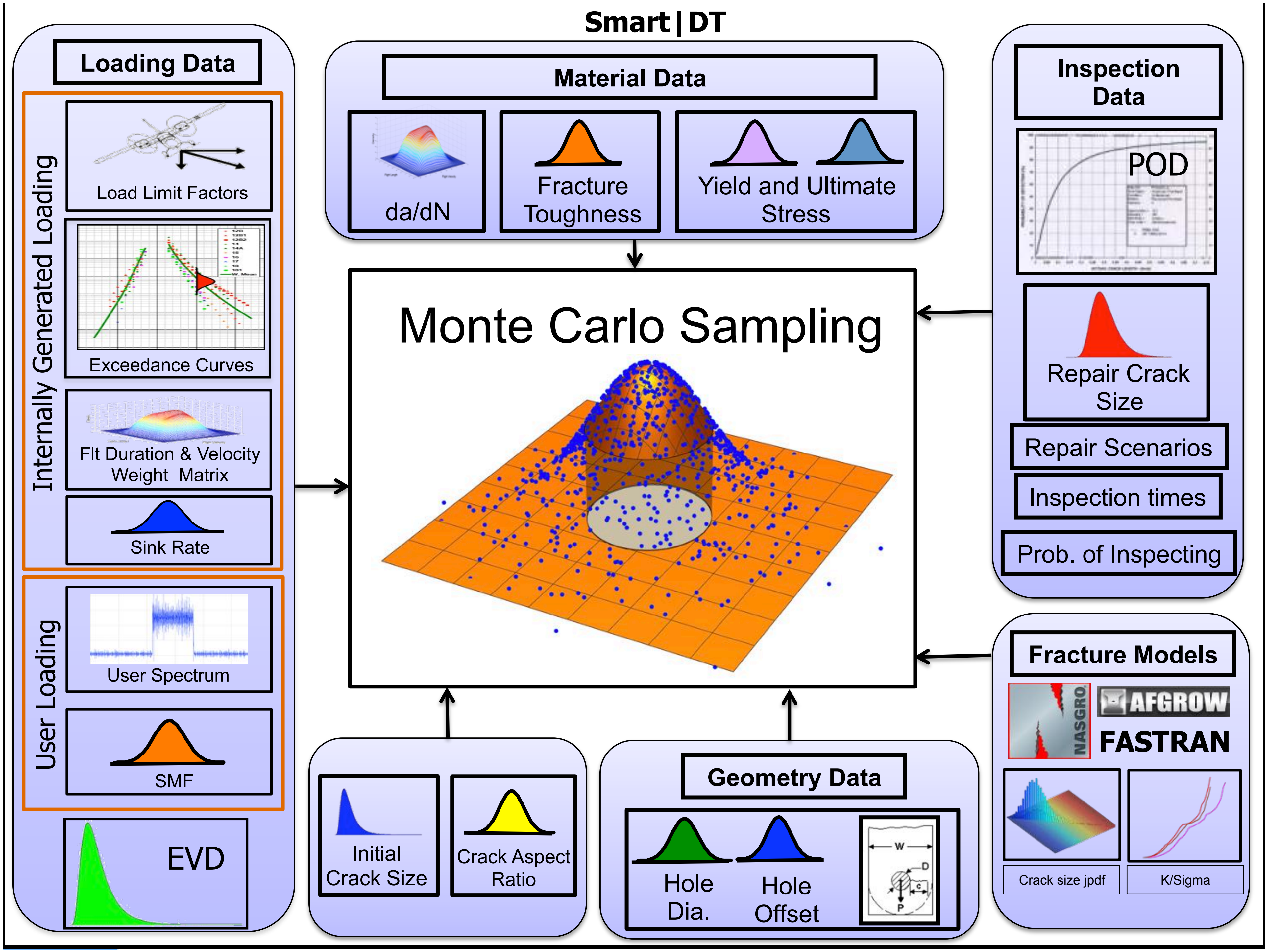








Etc.


Smart | DT
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

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

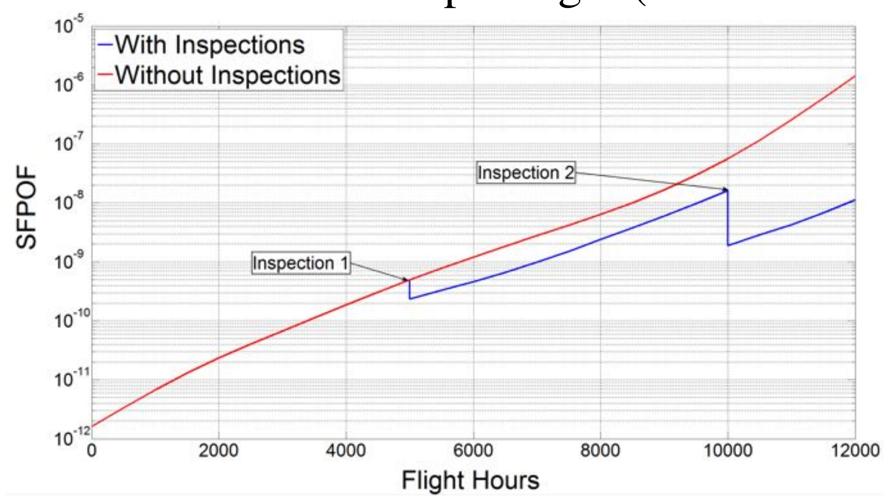
$$POF_{\text{no-surv}}(t) = P\left[\sigma_{Max} > \sigma_{RS}(t)\right] = \int \left[1 - F_{EVD}\left(\sigma_{RS}(t)\right)\right] f_{\mathbf{x}}(\mathbf{x})\, d\mathbf{x}$$

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

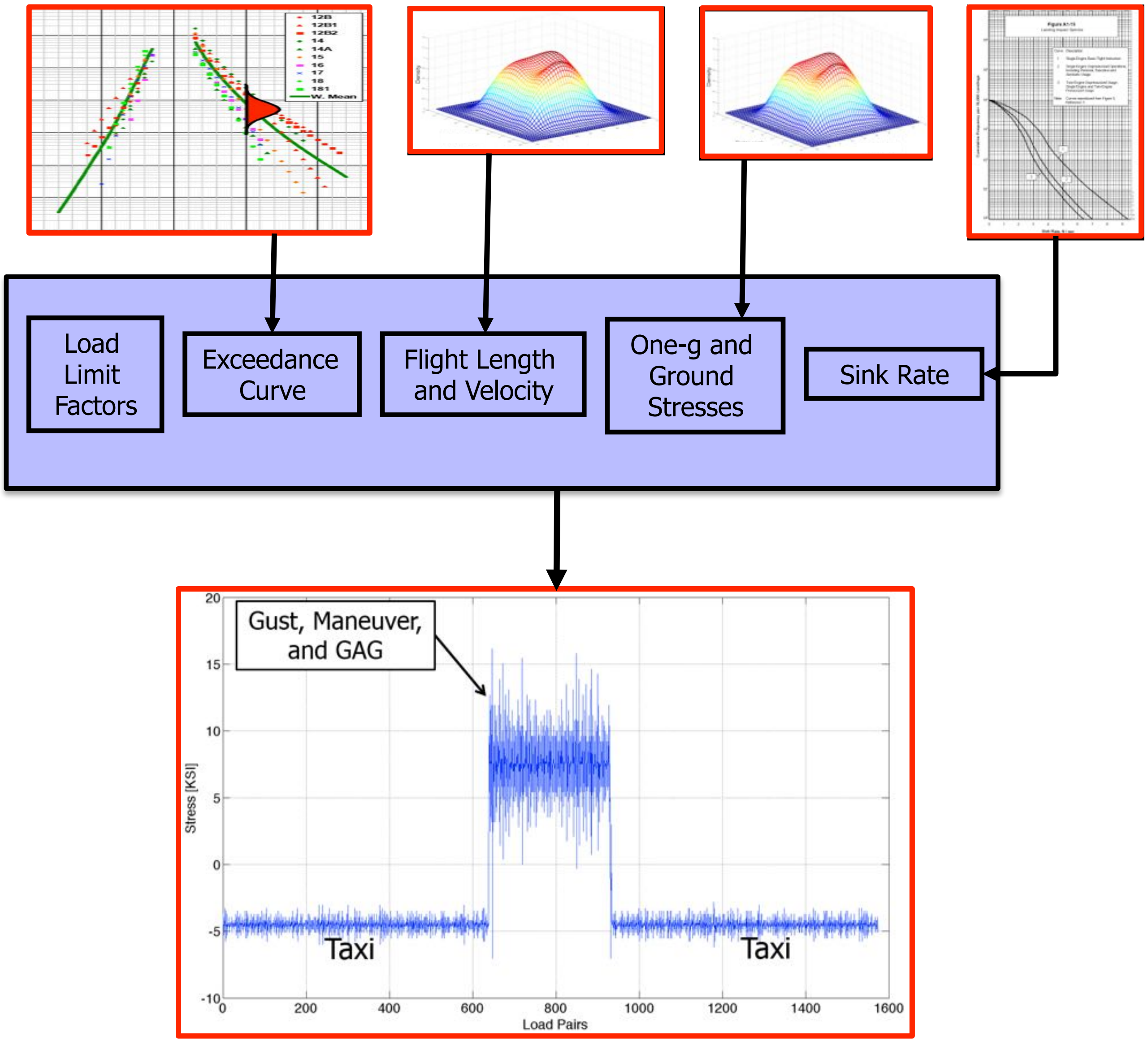
$$POF_{\text{surv}}(t) = \int \left[\prod_{i=1}^{t-1} F_{EVD}\left(\sigma_{RS}(t_i)\right)\right]\left[1 - F_{EVD}\left(\sigma_{RS}(t)\right)\right] f_{\mathbf{x}}(\mathbf{x})\, d\mathbf{x}$$

$$Hz(t) = \frac{POF_{\text{surv}}(t)}{1 - CTPOF(t)}$$

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

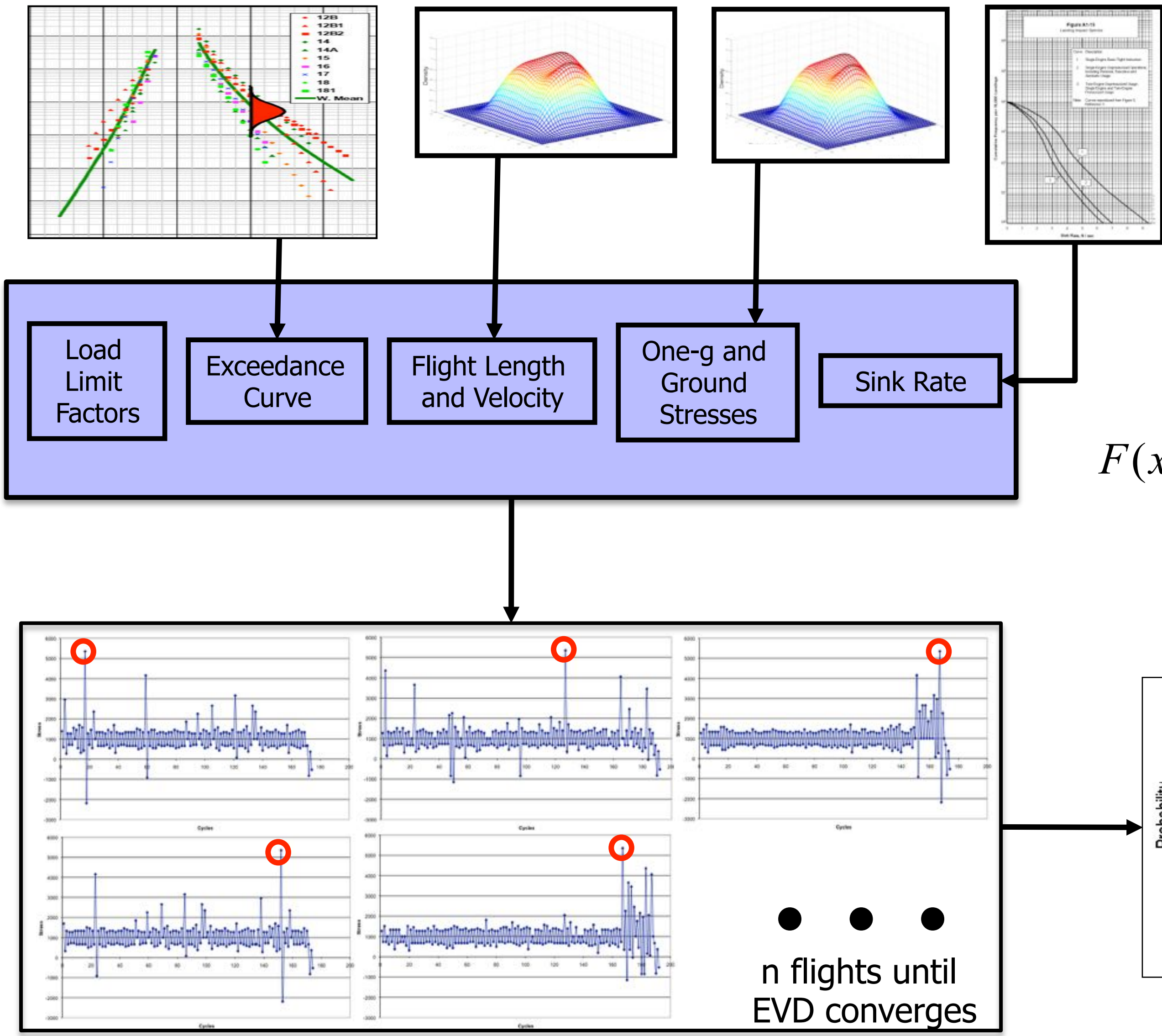


Spectrum Generation



- ✓ 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

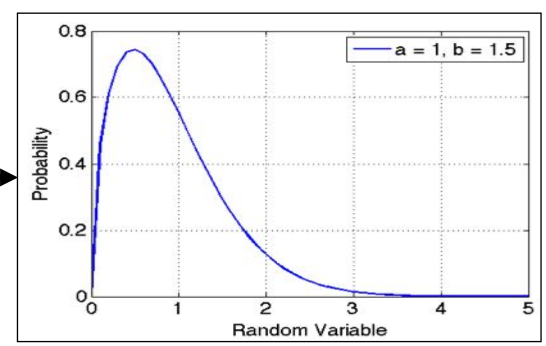
EVD Generation



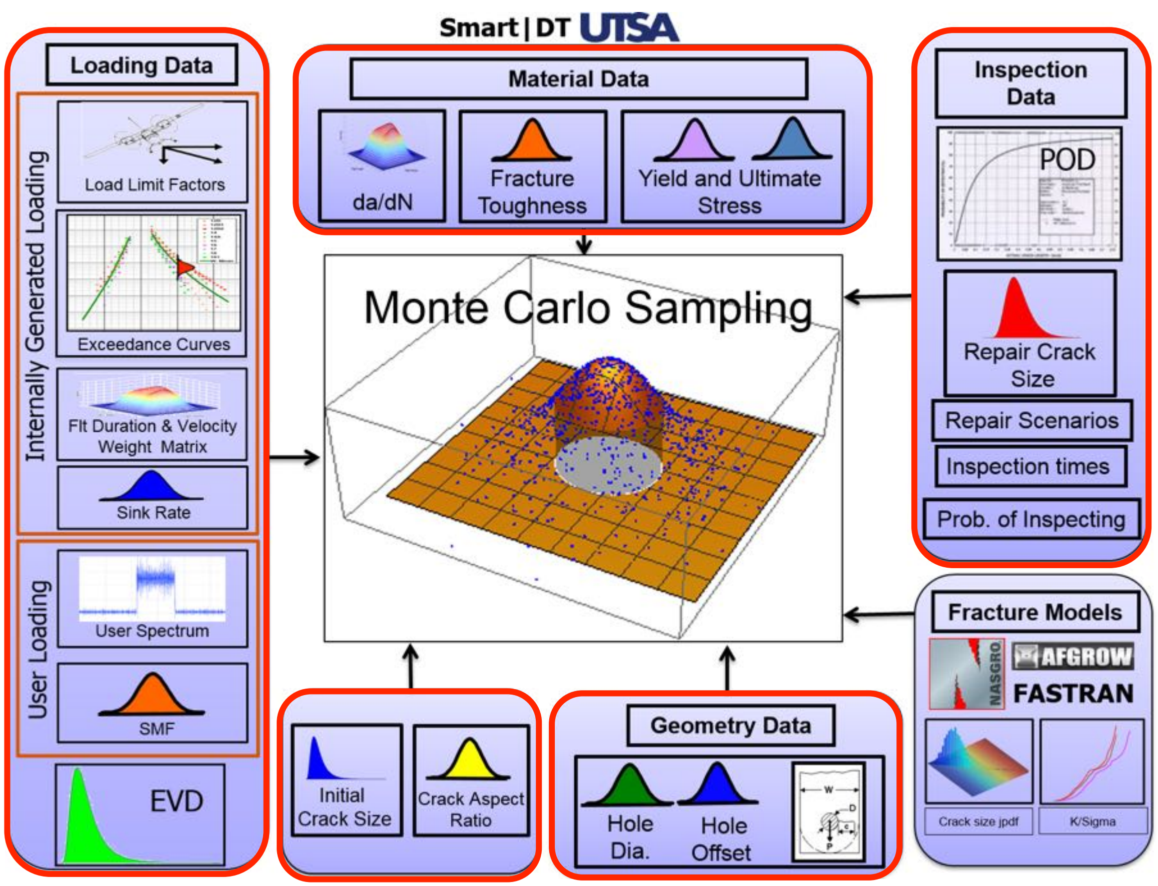
- ✓ EVD computed internally from spectrum

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

EVD Distribution

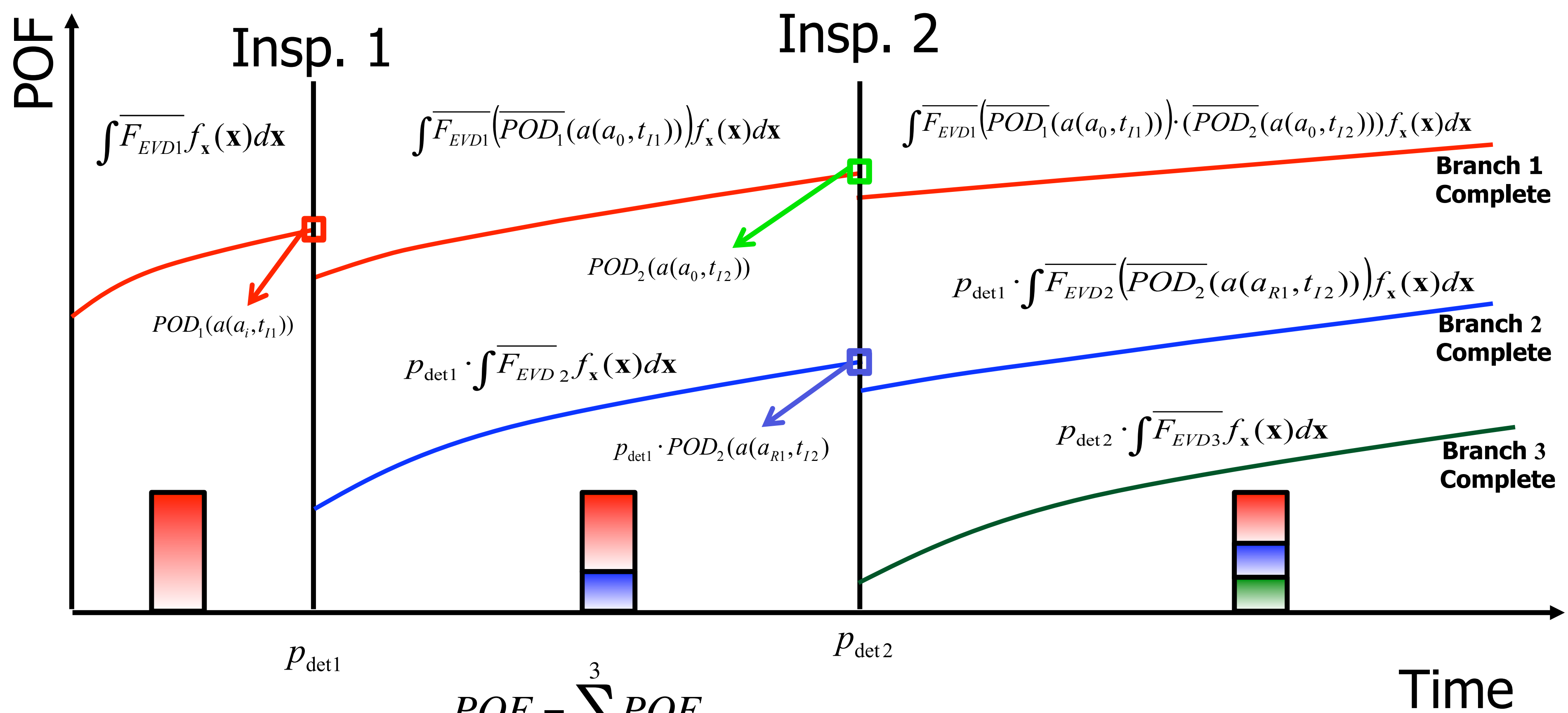


Comprehensive Random Variables



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

Multiple Inspections

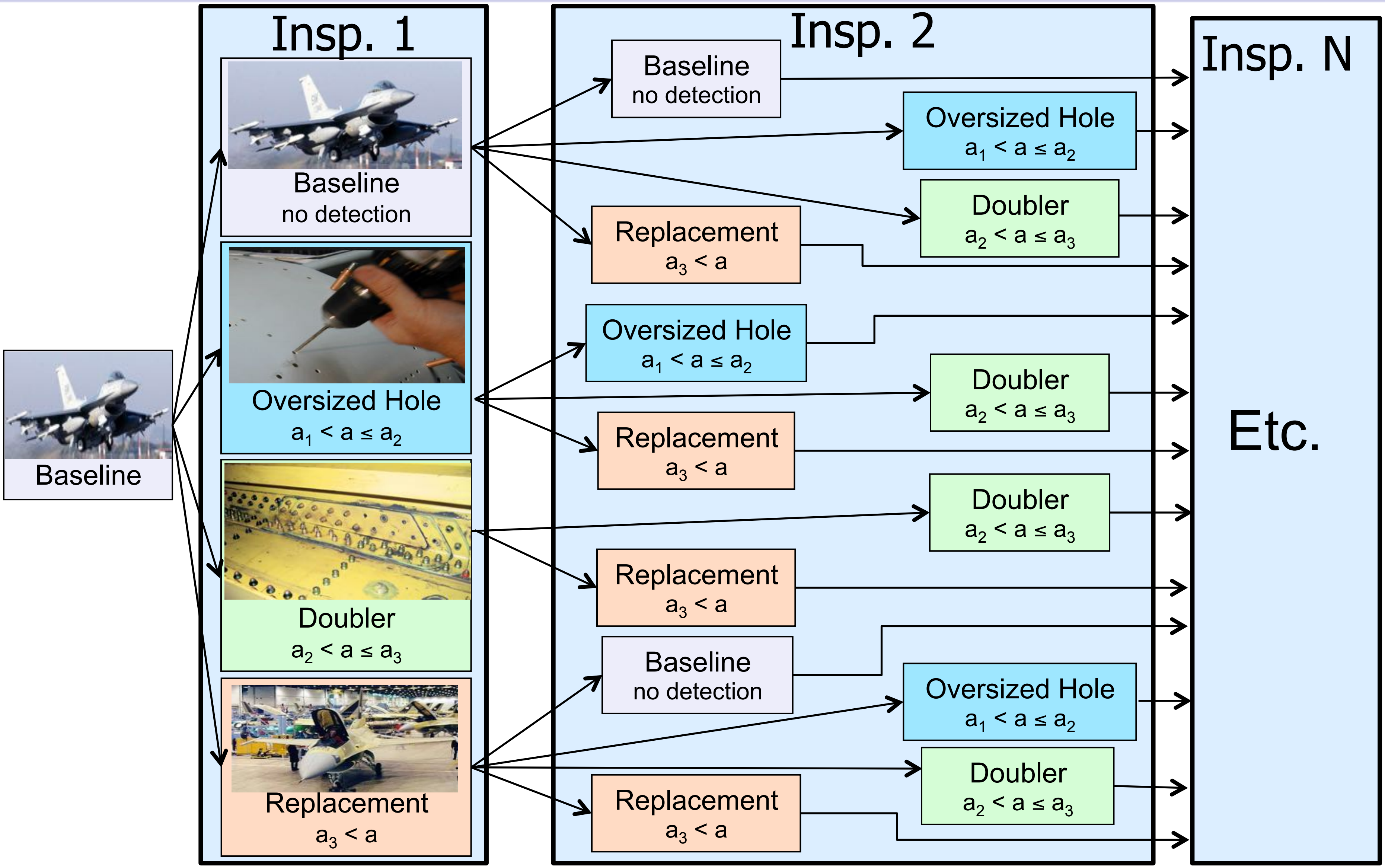


$$POF = \sum_{i=1}^{3} POF_i$$

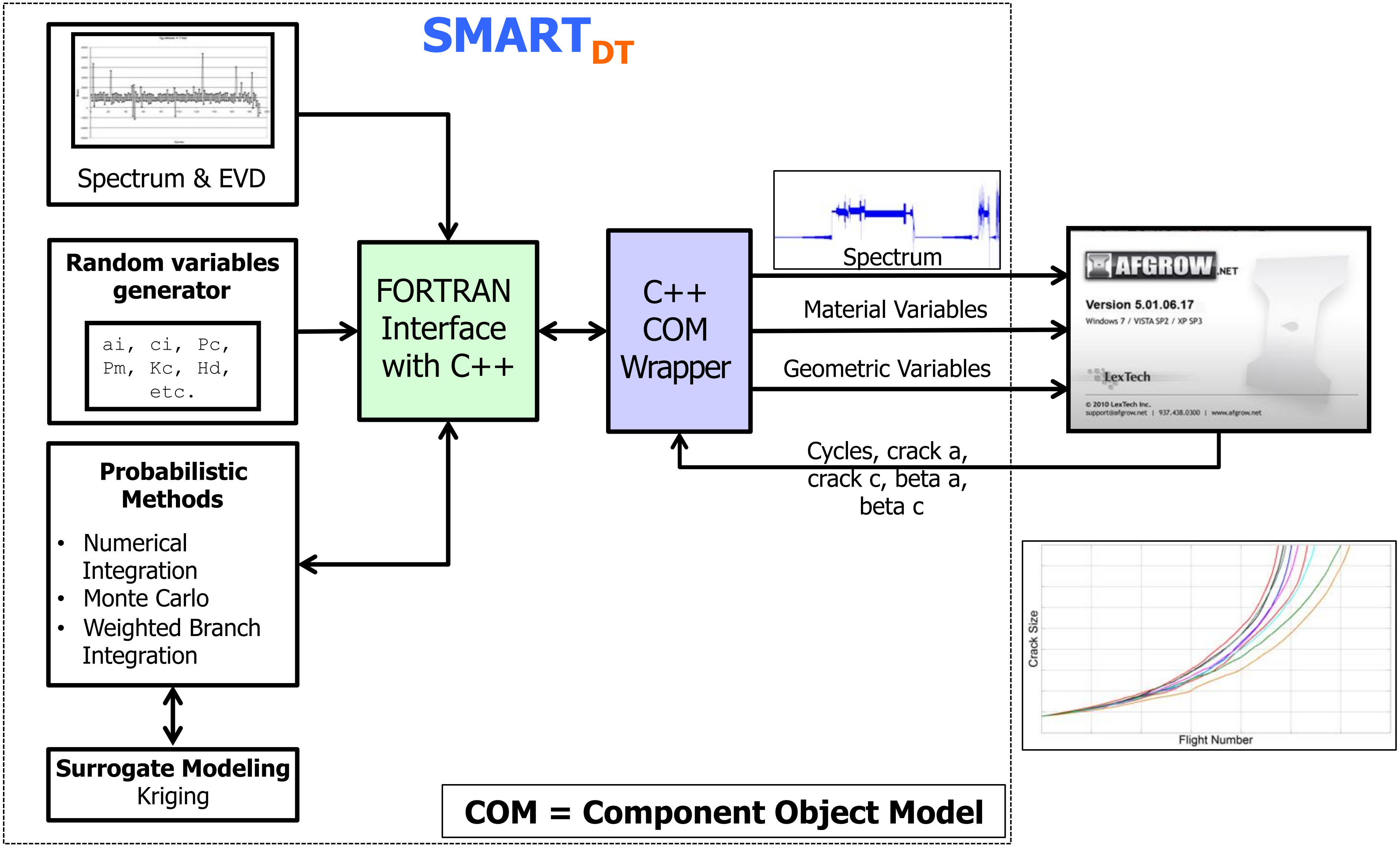
Add the contribution from each branch into the final POF

% Branch Contribution

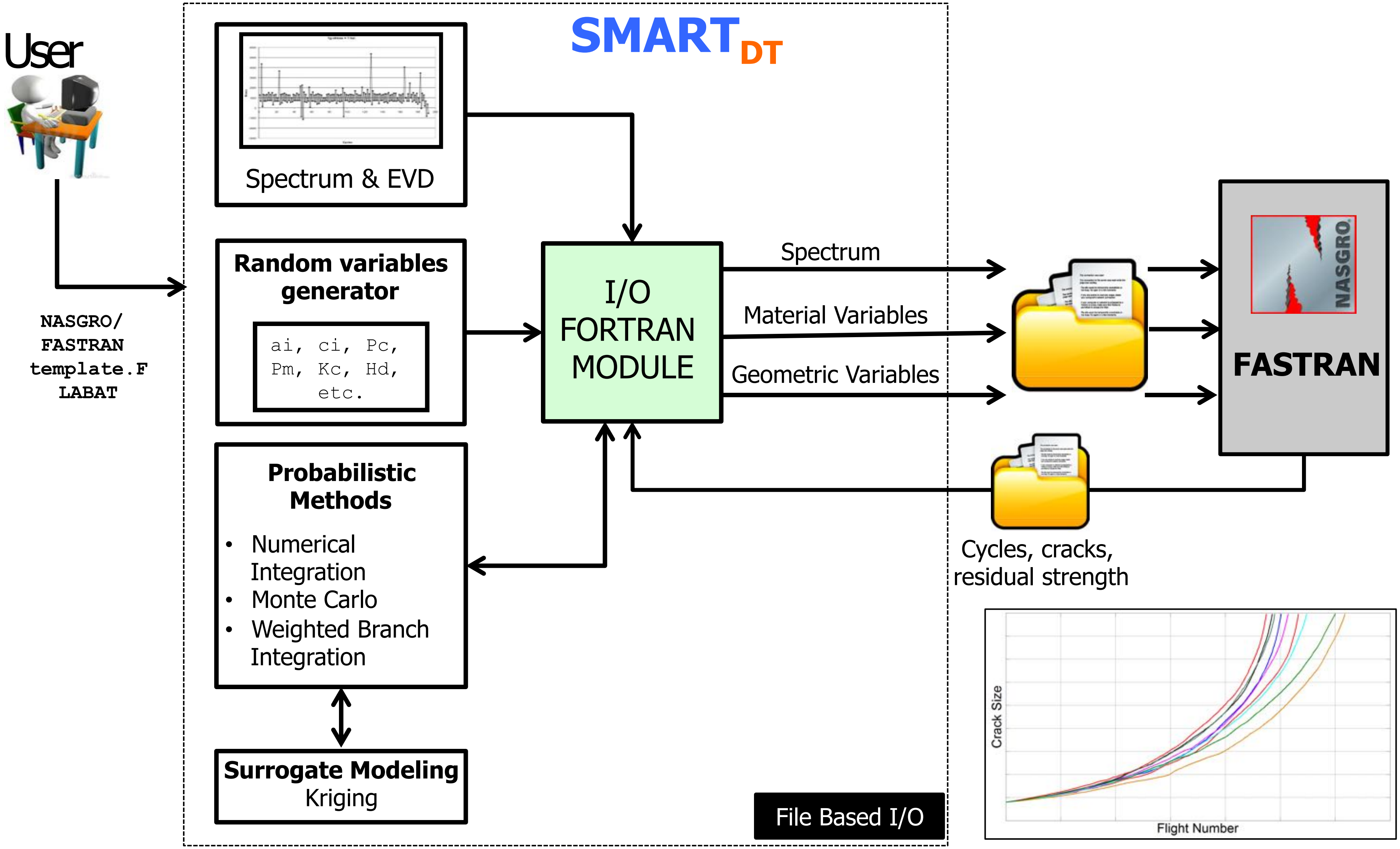
Multiple Repair Example (Future Version)



AFGROW Interface: COM driven



FASTRAN/NASGRO Interface Runs in Parallel

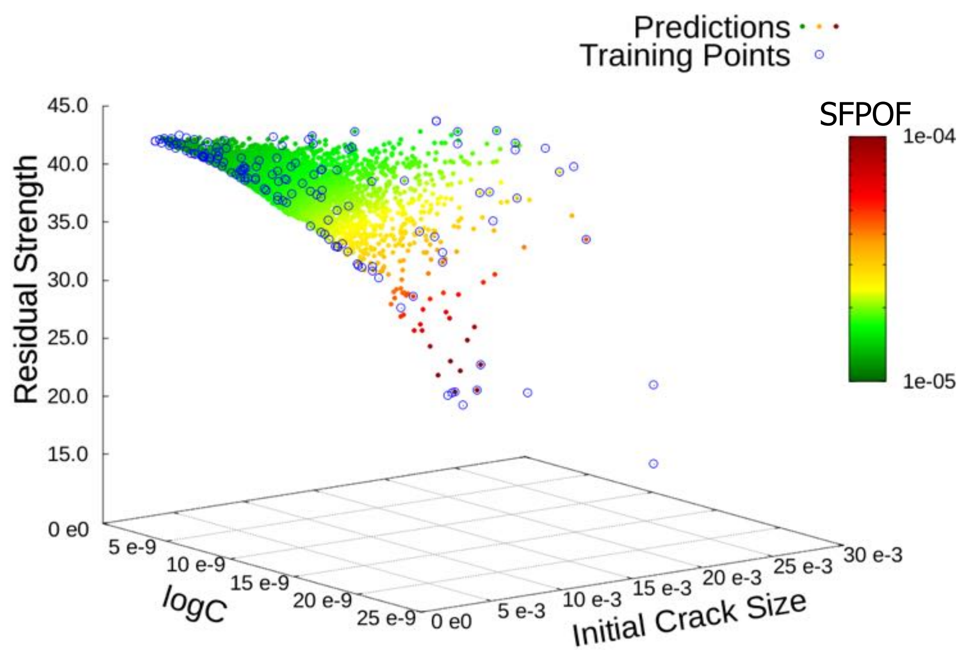


Kriging Surrogate Model

- Efficient Method to compute Crack Size (a) and Residual Strength (RS).
  - Train surface with crack growth analyses.

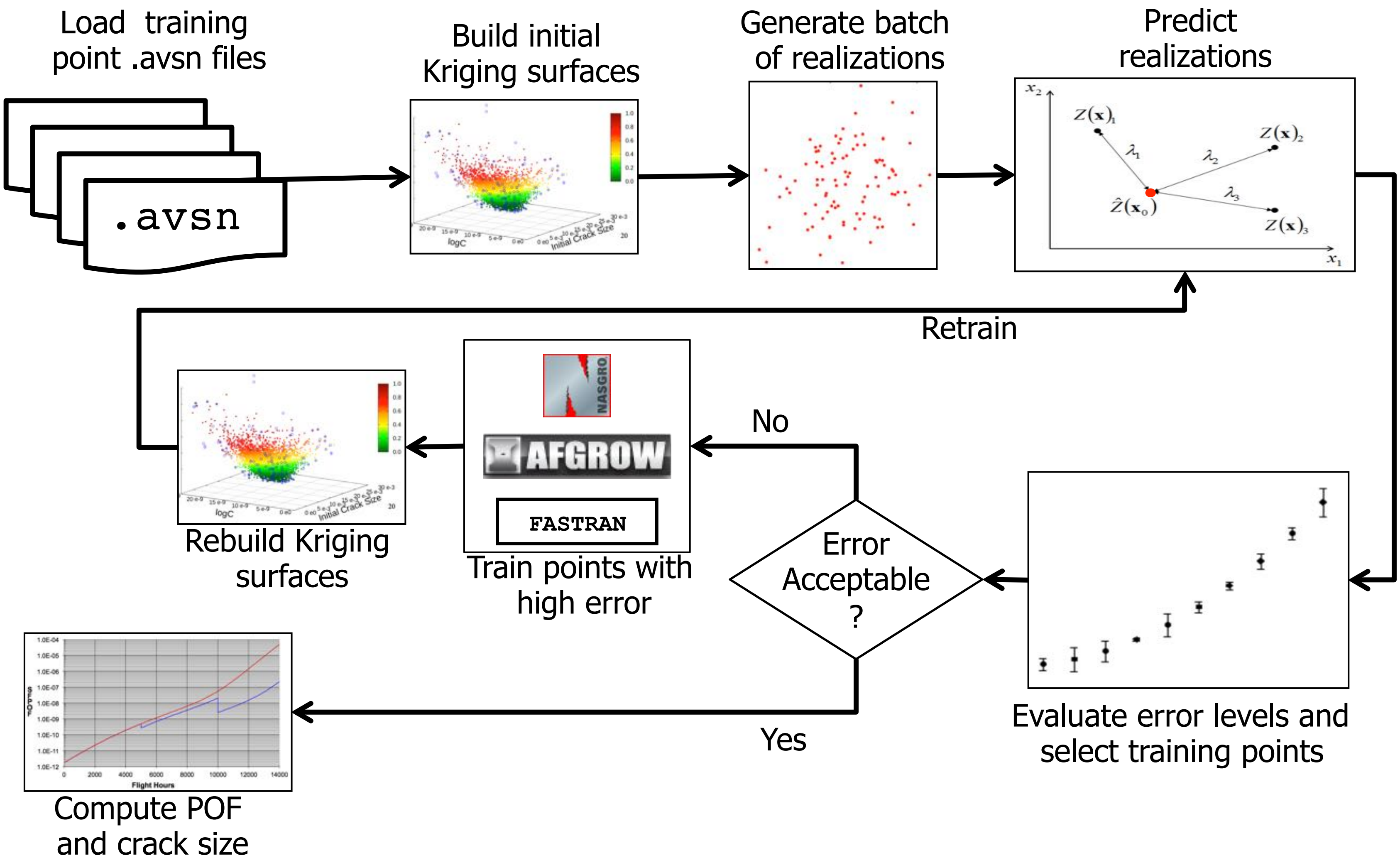
$$\frac{\partial a}{\partial N} = f(\Delta K, a, c)$$
$$\frac{\partial c}{\partial N} = f(\Delta K, a, c)$$

$$f(x) + Z(x)$$

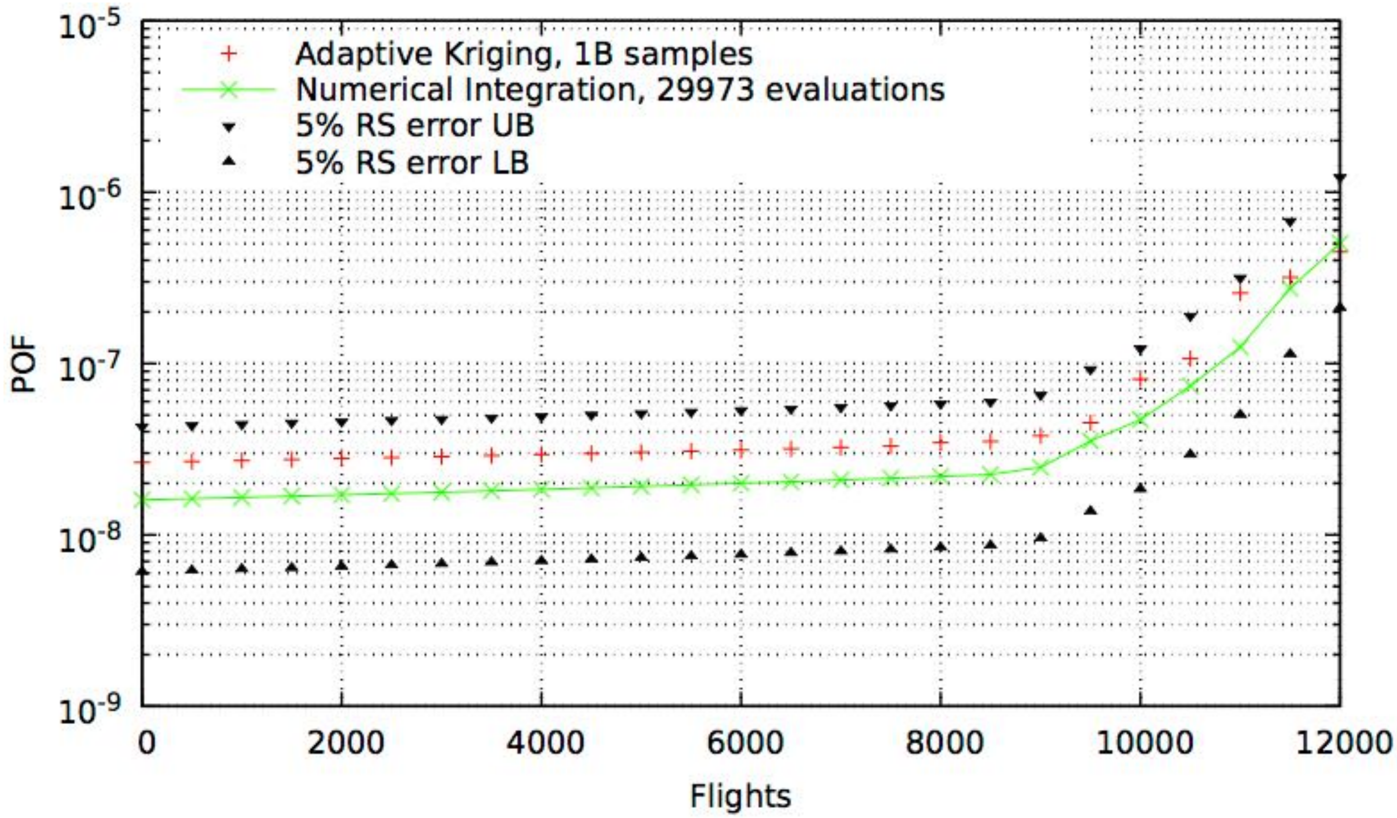


  - After building the Kriging surface predict “a” and “RS”.

Adaptive Surrogate Model Error Reduction



Paper Example Problem

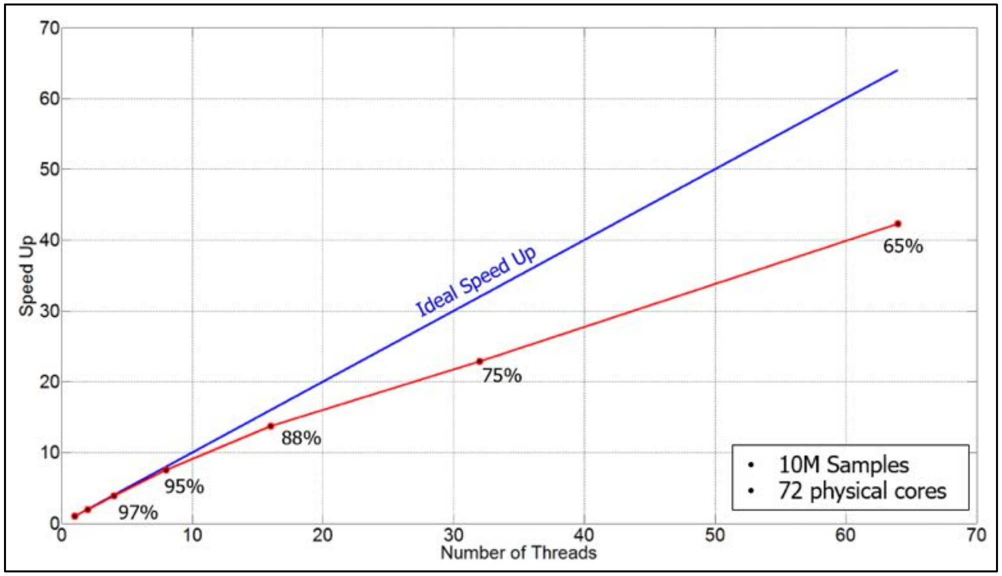


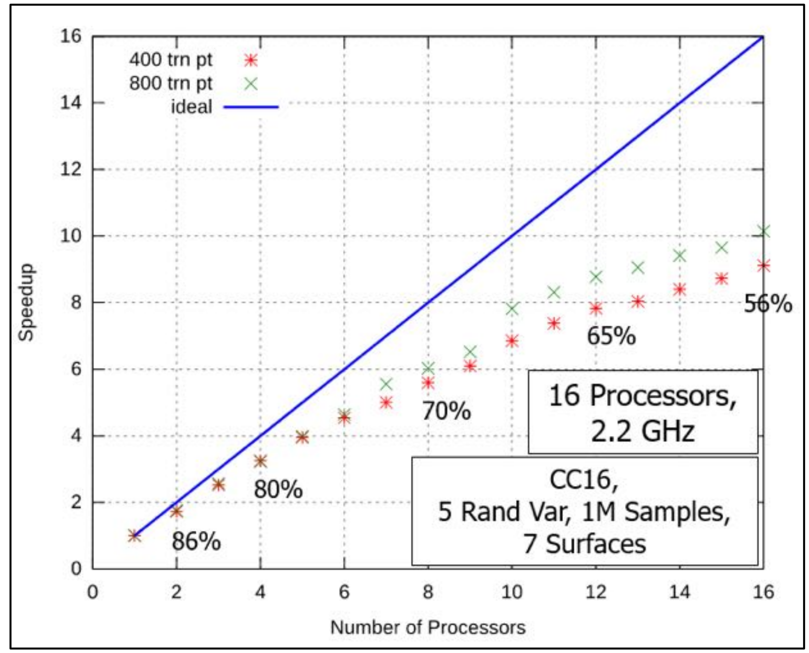
Kriging predictions are within 5% residual strength error bounds indicated

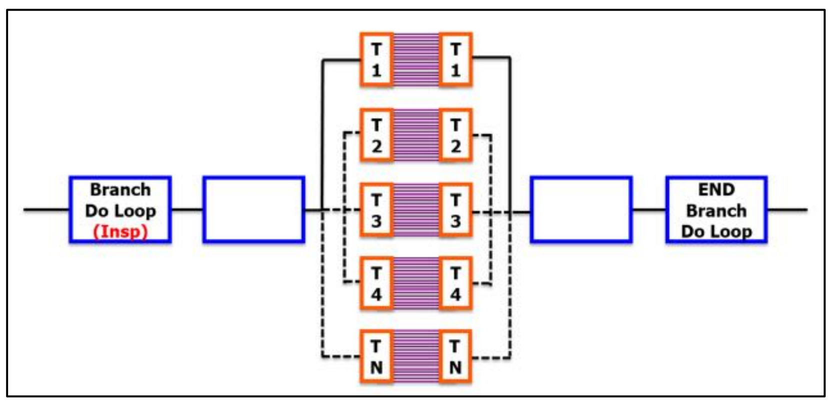
6 RVs: a_i , k_c, paris c, $ø_{hole}$, edge dist, σ_{max}

- 128 initial training points
- 921 additional training points
- Runtime 8.5 hours on 16 processors

Parallel & Vectorized (Master Curve)



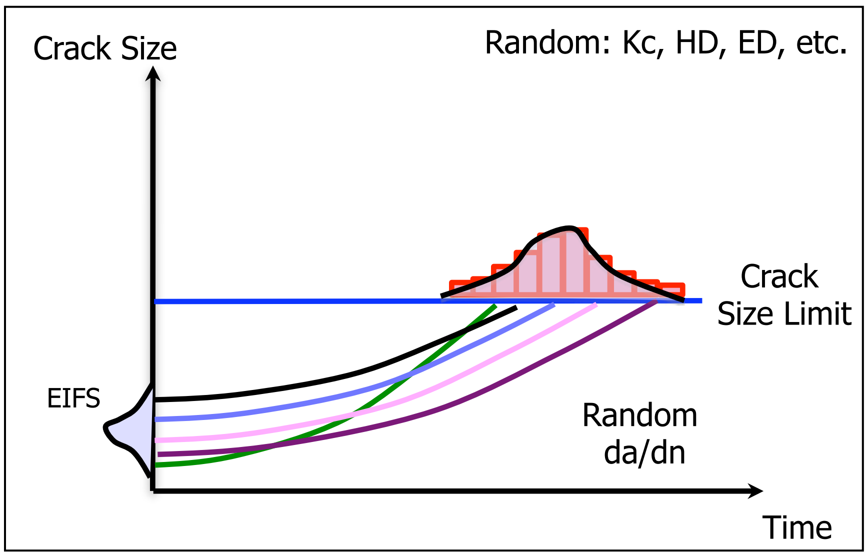


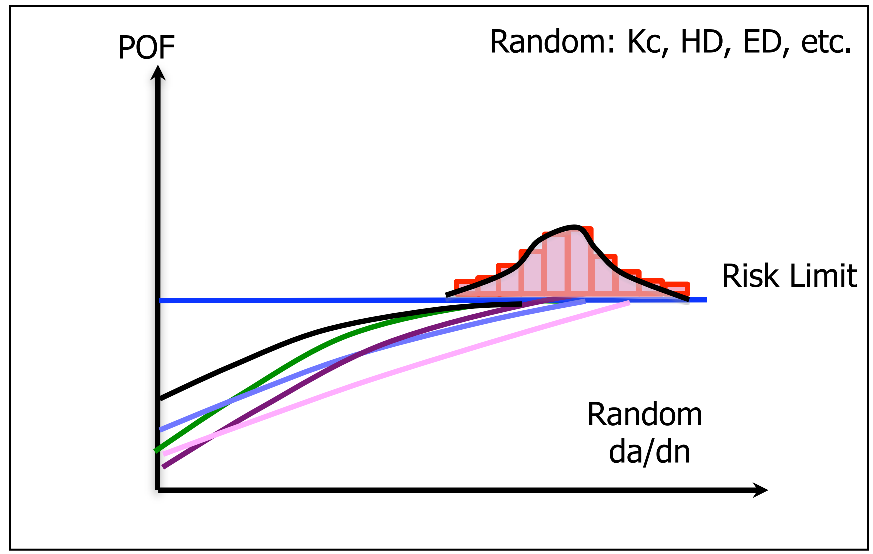


Identical Results wrt threads and operating system

Remaining Useful Life Calculations

SMART drives the fracture mechanics analysis to an user-defined crack length or the probabilistic calculations to an user defined risk level



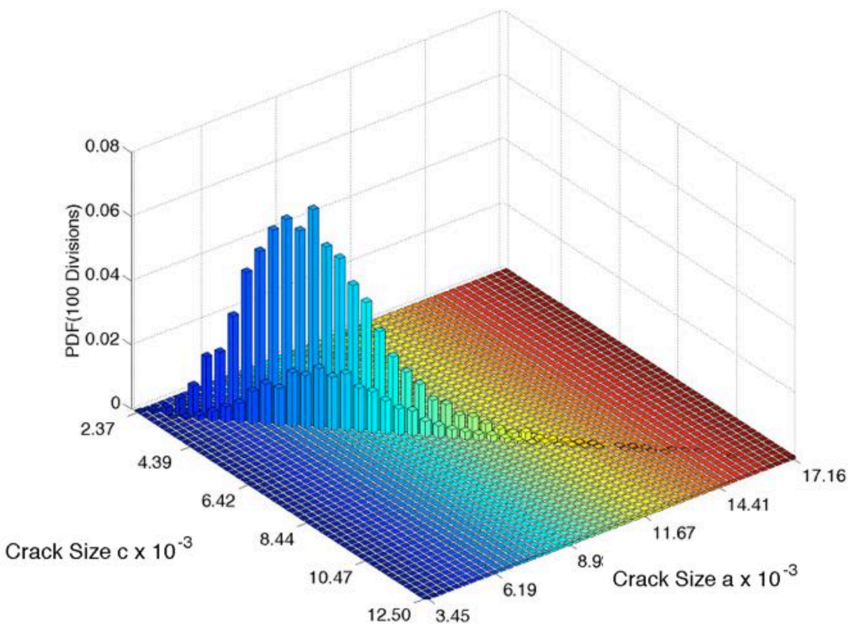


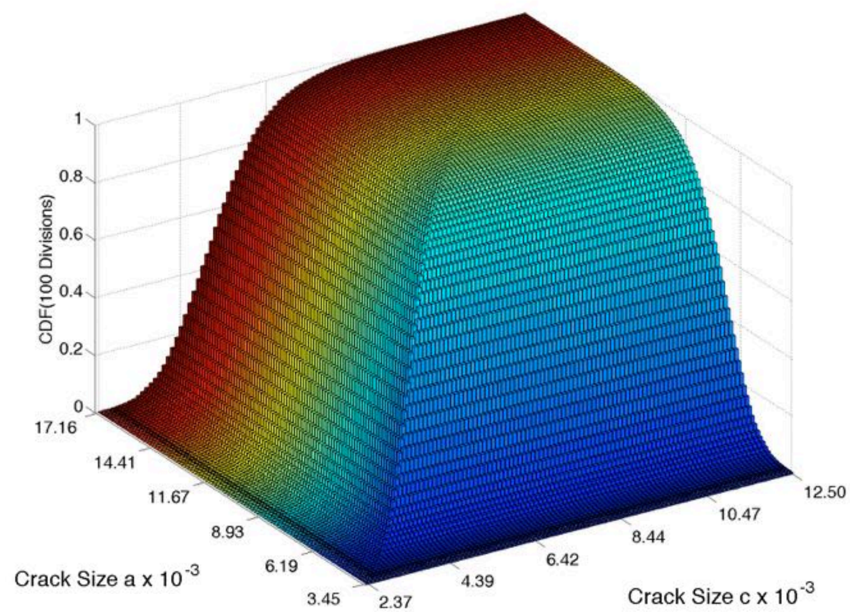
Applications:

- Largest crack size that can be drilled out in a CP location
- Crack size corresponding to a crack that has a 90% chance of being found, with 95% confidence, with NDI

Crack Size Distributions

Both “a” and “c” crack tips tracked through time.
Joint distribution computed.



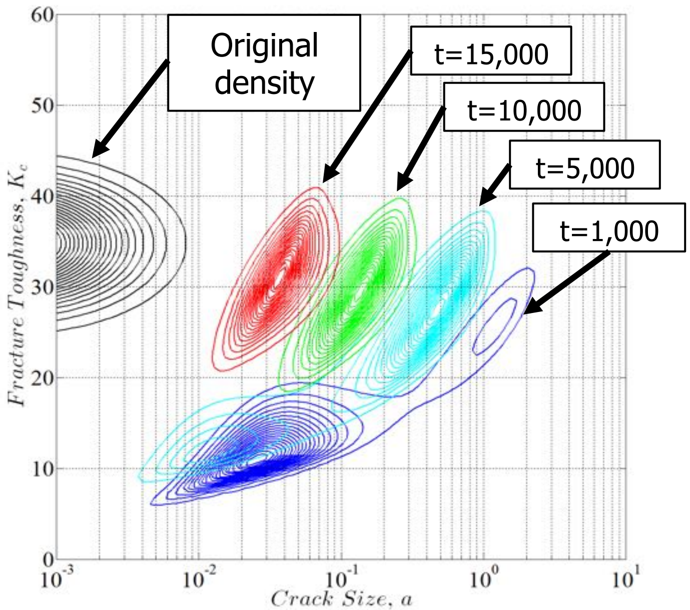


Crack Size at time = 5000

Advance Sampling Methods

Optimal parameters for the random variables to efficiently compute the probability of failure.

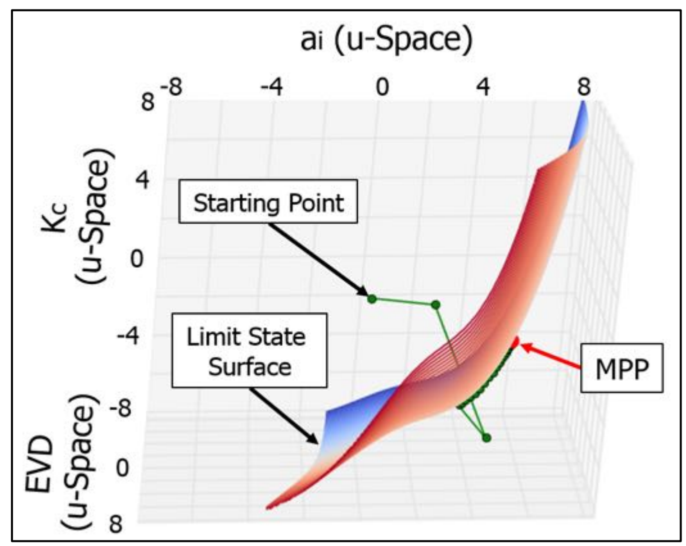
$$POF = \int_{-\infty}^{\infty}\left[1 - F_{max}\left(\sigma_{RS}\right)\right] \frac{f_X(x;u)}{q_X(x;v^*)} q_X(x;v^*)\,dx$$



Imp. Sampling $-a_i$ and K_c

Fast approximate method to compute low POF values

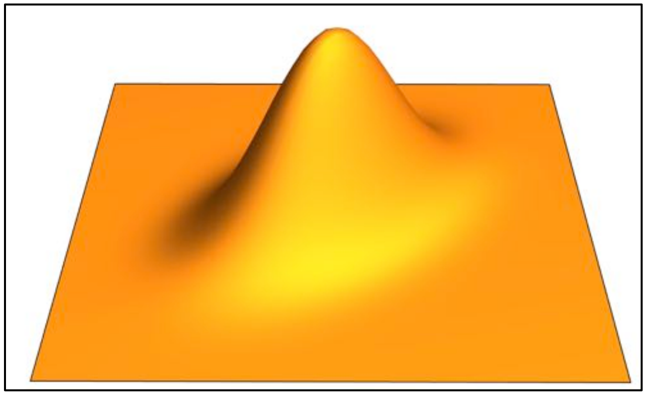
$$POF = \Phi(\beta)$$

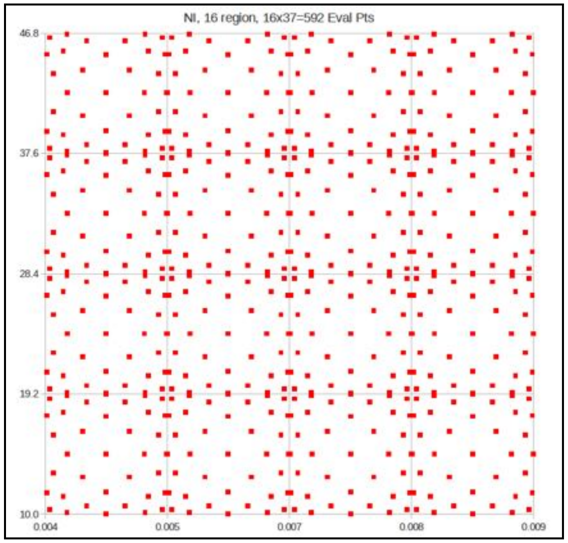


Most Probable Point (MPP)

Numerical Integration

- Adaptive numerical integration.
  - Adaptive strategies
  - Error estimates
  - Specify number of evaluations
  - Specify error
  - High dimensional integrals

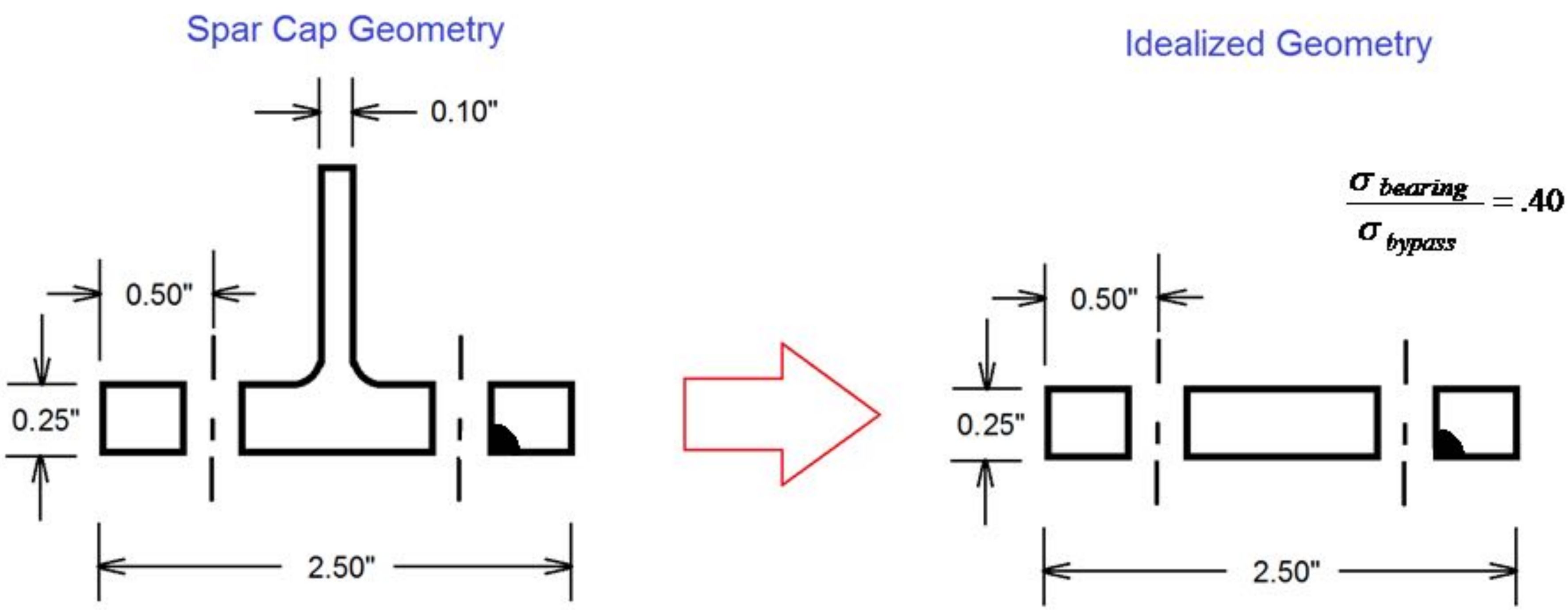




Example Problem Overview

Twin engine unpressurized airplane with a history of fatigue cracks in the wing spar cap

Problem Overview



Deterministic Variables	Value
Hole radius	0.156 in
Cap Thickness	0.250 in
Cap Width	2.50 in

Problem Overview

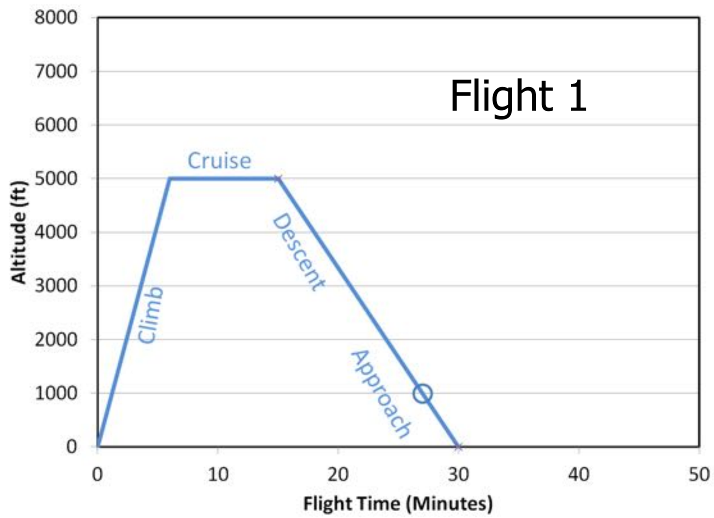
Loading Parameters	Value
Aircraft Usage	Twin Engine Unpressurized General Usage
Design Maneuver Load Factors	3.60 (high) -1.50 (low)
Design Gust Load Factors	4.50 (high) -2.50 (low)
Ground Stress	-50 psi (Flight 1) -70 psi (Flight 2)
One g Stress	9500 psi (Flight 1) 8800 psi (Flight 2)
Average Velocity	200 knots (Flight 1) 200 knots (Flight 2)
Number of Flight Times	1 (Flight 1) 1 (Flight 2)
Number of Velocities	5 (Flight 1) 5 (Flight 2)

Problem Overview

Random Variables	Distribution	Parameters
Initial Crack Size	Lognormal	Mean = 0.005 in Standard deviation = 0.002 in
Fracture Toughness	Normal	Mean = 35.0 ksi√ in Standard deviation = 1.1 ksi√ in
Paris m	Binormal	Mean = 3.80 Standard deviation = 0.04
Paris c (log)	Binormal	Mean = -9.00 Standard deviation = 0.04
Ultimate Stress	Normal	Mean = 80.0 ksi Standard deviation = 3.0 ksi
Yield Stress	Normal	Mean = 65.0 ksi Standard deviation = 2.0 ksi
Hole Offset	Normal	Mean = 0.50 in Standard deviation = .025 in

Other Parameters	Distribution
Crack Growth Program	NASGRO

Define Flight Matrices



Segment	Weight	KEAS	% Duration
CLIMB	6580	140	0.20
CRUISE	6440	160	0.50
DESCENT	6300	180	0.20
APPROACH	6160	120	0.10

V_C = 200 KEAS

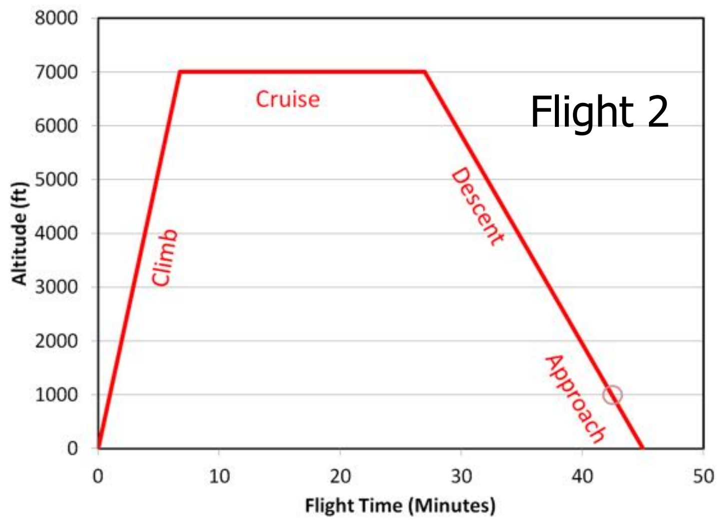
MTOW = 7000 lb

Sort matrix in ascending order for speed & weight

Flight Time (hrs)	% of Flights	Average Speed During Flight, % Max Takeoff Weight				
		0.88	0.90	0.92	0.94	0.96
0.5	1.0	0.10	0.20	0.50	0.20	0.0

Flight Time (hrs)	% of Flights	Average Speed During Flight, % Design Velocity				
		0.60	0.70	0.80	0.90	1.00
0.5	1.0	0.10	0.20	0.50	0.20	0.0

Define Flight Matrices



Segment	Weight	KEAS	% Duration
CLIMB	6720	140	0.15
CRUISE	6580	160	0.60
DESCENT	6440	180	0.15
APPROACH	6300	120	0.10

V_C = 200 KEAS

MTOW = 7000 lb

Sort matrix in ascending order for speed & weight

Flight Time (hrs)	% of Flights	Average Speed During Flight, % Max Takeoff Weight				
		0.80	0.90	0.92	0.94	0.96
0.75	1.0	0.0	0.10	0.15	0.60	0.15

Flight Time (hrs)	% of Flights	Average Speed During Flight, % Design Velocity				
		0.600	0.70	0.80	0.90	1.00
0.75	1.0	0.10	0.15	0.60	0.15	0.00

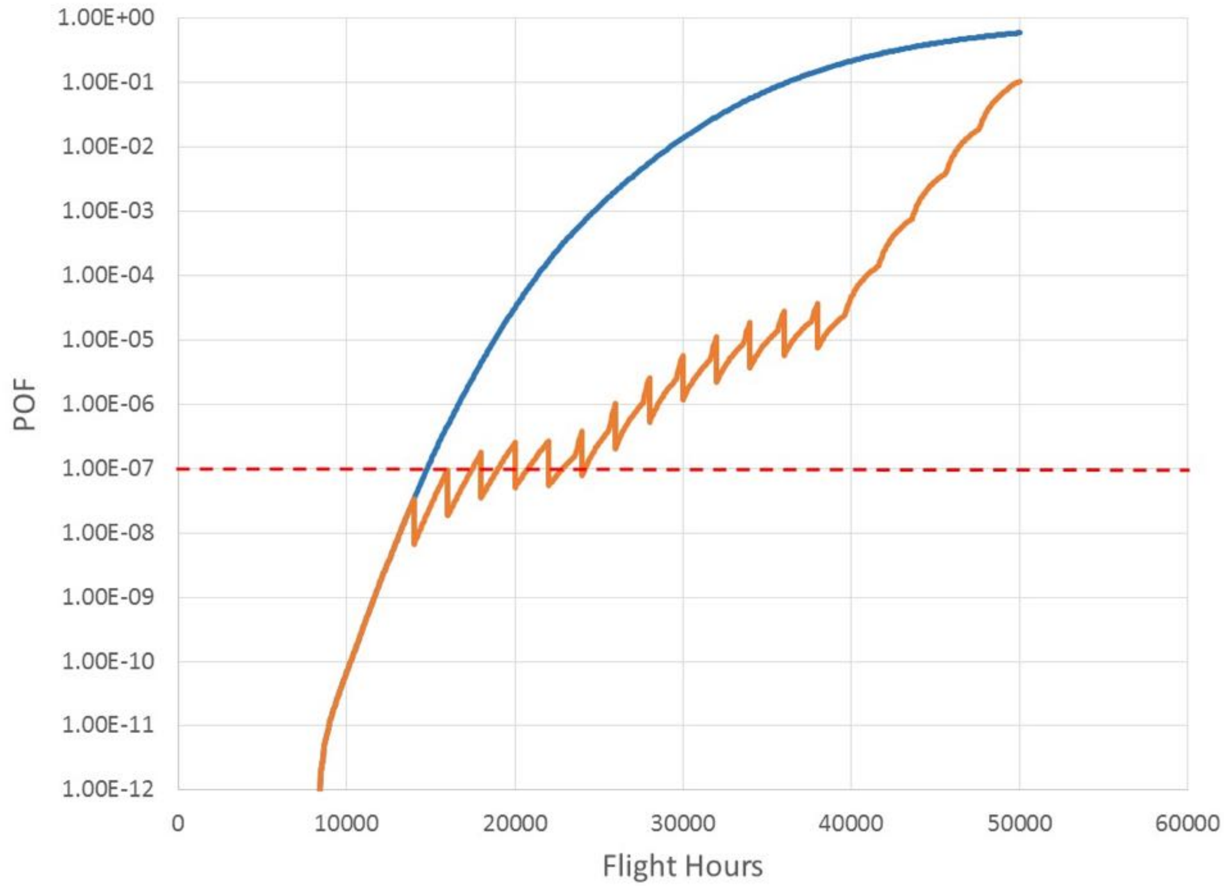
Problem Overview

Inspection Parameters	Value
Number of Inspection Types	One - Single Repair
Inspection Type	Eddy Current
Inspection Schedule	14,000 Hour Initial 2,000 Hour Repetitive
Probability of Inspection	80%
Probability of Detection	Deterministic
Detectable Crack Size	.06 inch
Repair Crack POD	Deterministic
Repair Crack Size	.01 inch

Plot POF

Summary

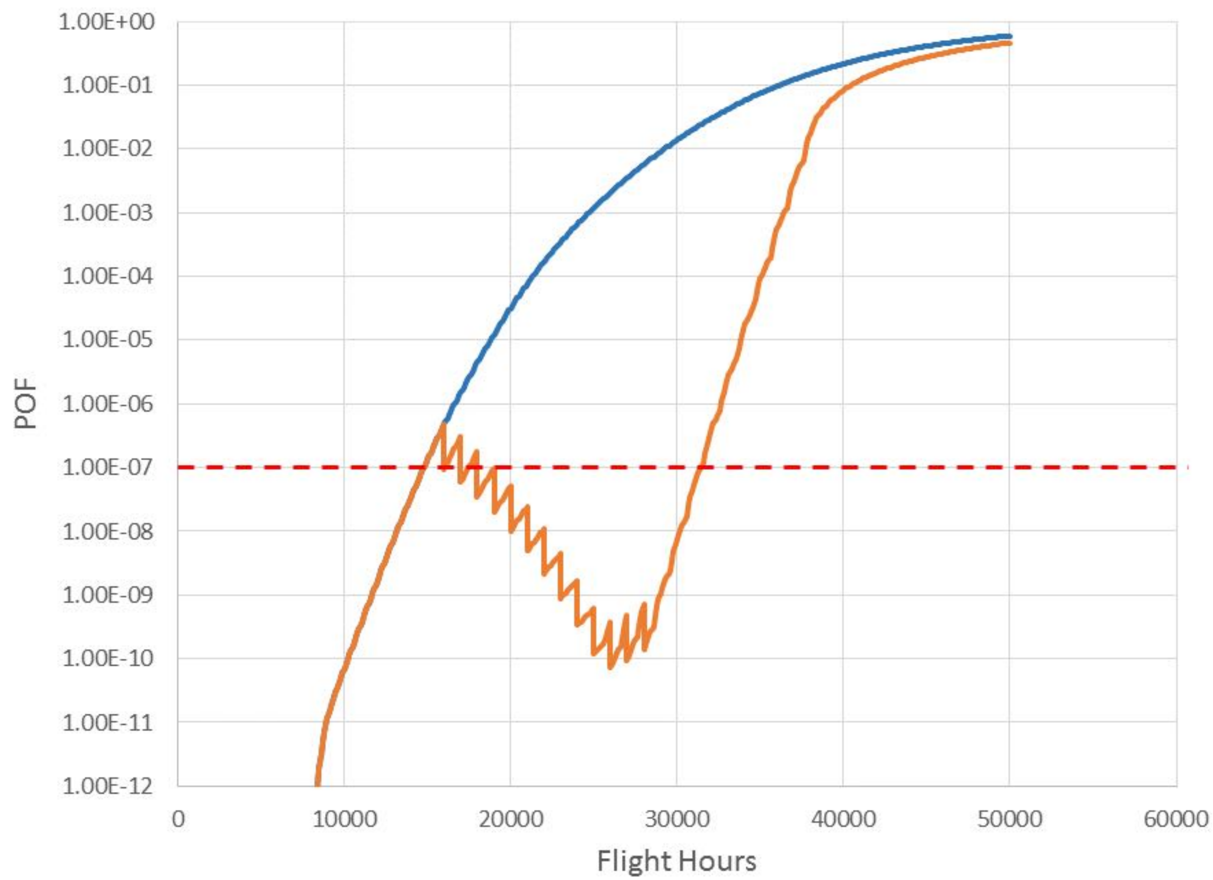
- POF >10^{-7}
- Start inspections 2000 hours later
- Reduce inspection to 1000 hours



Plot POF

Summary

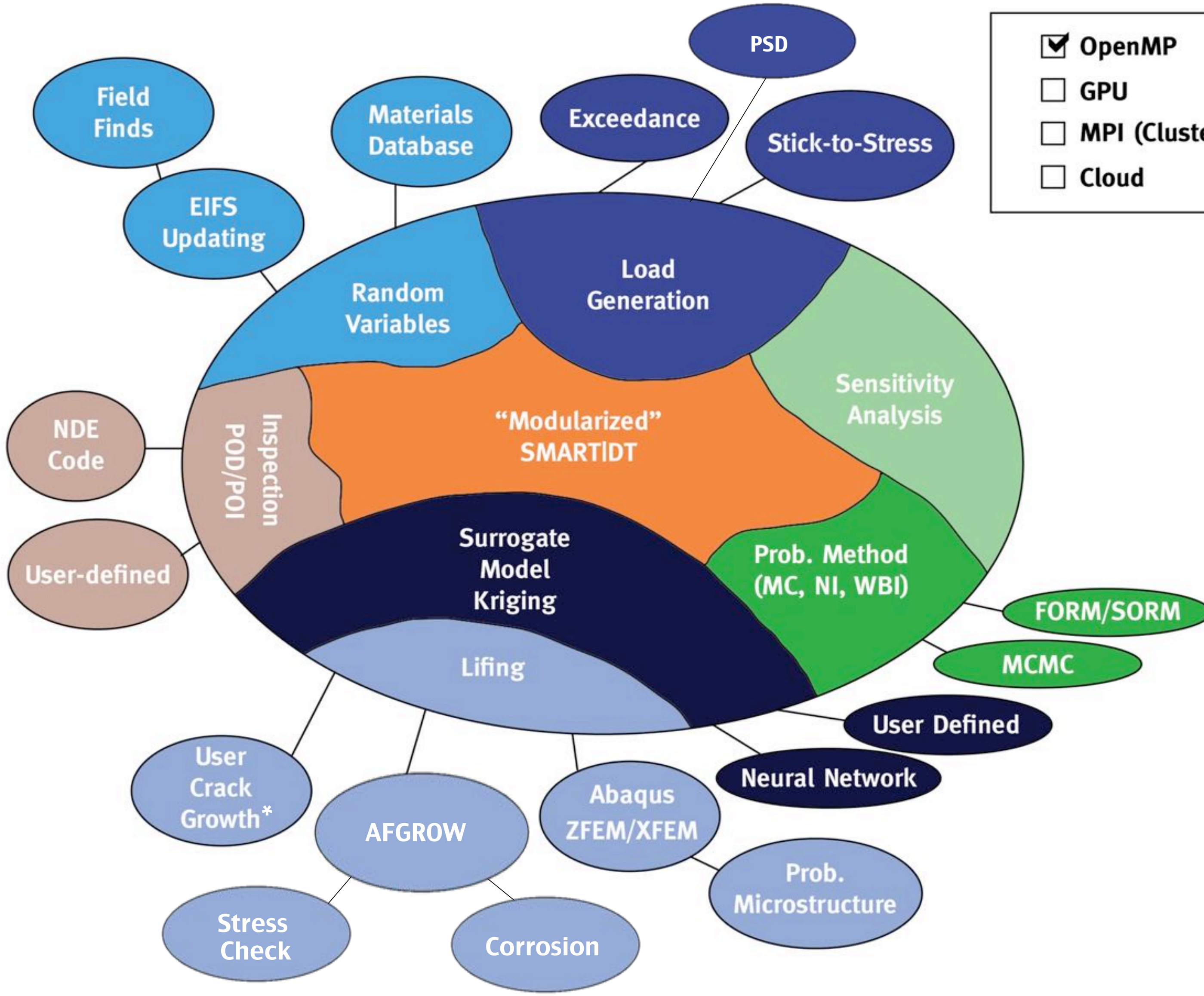
- Corner Crack
- Master Curve
- Nasgro
  - CC16
- Random Variables
  - Initial Crack Size



Future-Current Work

- Development of an internal probabilistic data base
- Development of an internal crack growth
- Advance sampling methods
- Probabilistic Residual Stresses
- PDTA on composites
- Risk based inspections
- Development of training material

Plays well with Others

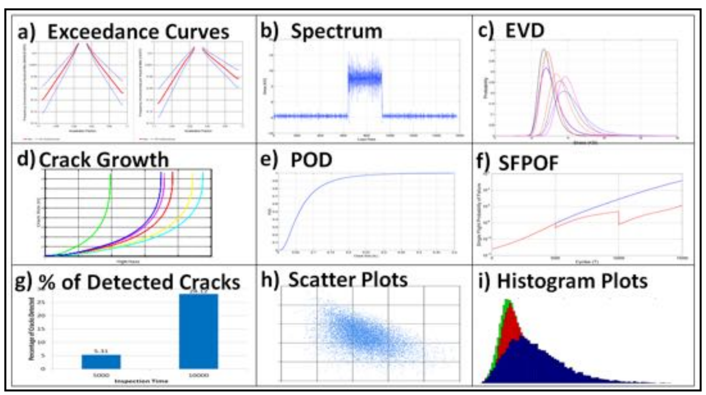


- [x] OpenMP
- [ ] GPU
- [ ] MPI (Clusters)
- [ ] Cloud

Code Availability

- For more information contact:
  - jocampo@stmarytx.edu
  - harry.millwater@utsa.edu

http://smart-software.utsa.edu

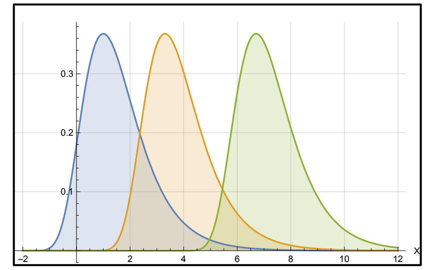


Acknowledgements

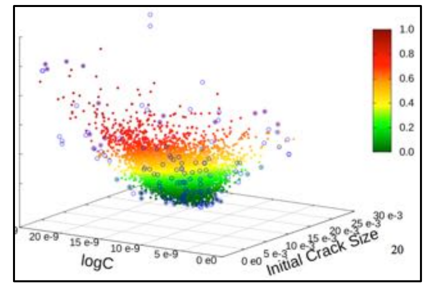
- Probabilistic Damage Tolerance-Based Maintenance Planning for Small Airplanes, Sep. 2009-Aug. 2012, Federal Aviation Administration, Grant 09-G-016
- Probabilistic Fatigue Management Program for General Aviation, Sep. 2012-Aug. 2016, Federal Aviation Administration, Grant 12-G-012
  - Sohrob Mattaghi (FAA Tech Center) – Program Manager
  - Michael Reyer (Kansas City) - Sponsor

Smart|DT Capabilities

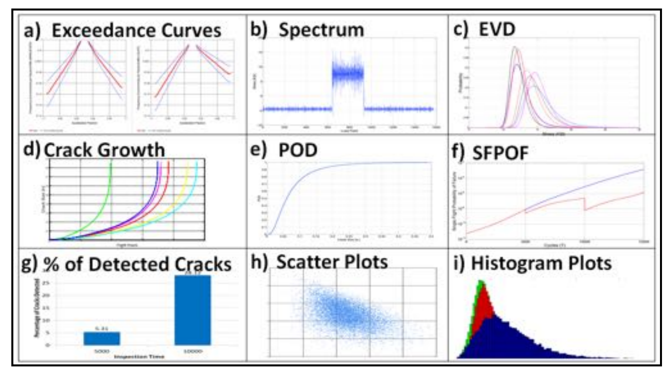
- Loading Generation
  - Computed from exceedance curves (Internal library and user exceedance option) – Weighted usage available.
  - Flight Duration and weight matrices, Design load limit factors, one-g stress, and ground stress as user input.
  - Stresses and/or flights randomizations
  - Spectrum editing option (Rainflow, rise/fall, Dead band)
  - User-defined spectra (Afgrow format)
- Extreme Value Distribution
  - User input, e.g., Gumbel, Frechet , and Weibull.
  - Ultimate/Limit load (deterministic)
  - Computed from exceedance curves, weight matrix, etc. (Gumbel, Frechet , and Weibull)



- Probability calculations
  - POF (survival / no survival term)
  - Hazard fn. (with survival term)
  - Cumulative POF
- Crack growth
  - Direct Afgrow and Nasgro link
  - Through, Corner, Surface crack growth geometry options
  - Master curve for 2D (ai and Kc) interpolation (user input or developed from NASGRO/AFGROW)
  - Kriging for efficient probabilistic fracture analysis



- Probabilistic methods
  - Standard Monte Carlo
  - Numerical integration
  - Weighted Branch Integration Method
  - Remaining Useful Life Calculations
  - Importance Sampling



- Inspection capabilities
  - Any number of inspections (arbitrary limit set to 15)
  - Arbitrary repair crack size distribution (lognormal, tabular, Weibull, deterministic)
  - Arbitrary POD (lognormal, tabular)
  - Deterministic POD
  - User defined probability of inspection
  - Different repair scenarios within/between inspections
- Random variables
  - ai, Kc, Evd, da/dN, hole diameter, hole offset
  - crack aspect ratio, yield stress, ultimate stress, loading
- Computational implementation
  - Standard Fortran 95/03/08, Windows and Unix (Intel ifort compiler)
  - HPC Implementation (parallel and vectorized)