Risk Calculations Using the FAA SMART Probabilistic Damage Tolerance Software and AFGROW

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AFGROW Users Workshop

Layton, UT – September 15-16, 2015

Outline

- ✓ Program Overview
- ✓ SMART|DT Capabilities
- ✓ External Crack Growth Interface
- ✓ Master Curve Approach Using AFGROW
- ✓ Numerical Integration and Sampling Using AFGROW
- ✓ Kriging Surrogate Model Using AFGROW

Program Overview

2007-2011

- ✓ Code Released
  - ✓ Textron
  - ✓ Cirrus Aircraft

- Hazard Rate
- Sensitivity Analysis

2009-2013

2012-2016

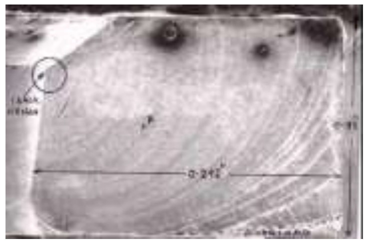
- ✓ Federal Aviation Administration.
  - ✓ Tech Center (Atlantic City). Sohrob Mattagi
  - ✓ Small Airplane Directorate Office (Kansas City). Mike Reyer
  - ✓ Michael Gorelik (Chief Scientific and Technical Advisor F&DT).
- ✓ Textron Aviation.
  - ✓ Cessna (Beth Gamble and Christopher Hurst).
- ✓ Nuss Sustainment Solutions
  - ✓ Marv Nuss.
- ✓ Airframe Digital Twin (NGC)
- ✓ Visiting OEM ASIP engineers to deliver software and do training fall 2015.

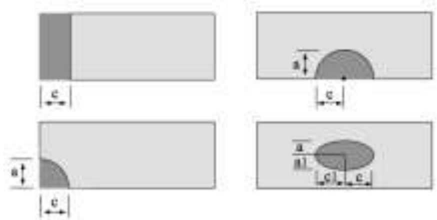
- Inspection/Repair Effect
- Sensitivity Analysis

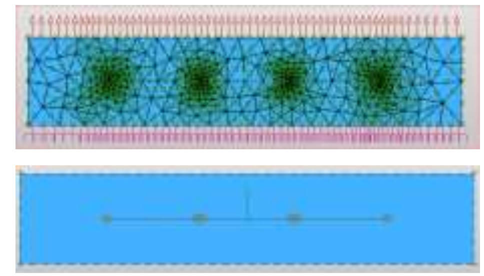
- Develop a Probabilistically-based fatigue management plan (PFMP) for general aviation

Development Philosophy

- Run any crack growth model







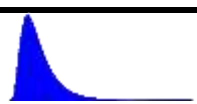
- Consider any repair scenario

Oversized Hole

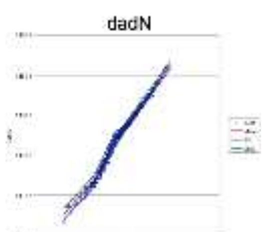
Doubler

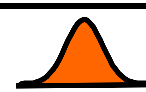
Replacement

- Consider any random variable

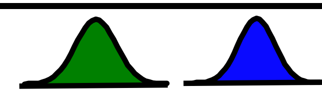


Initial Crack Size





Fracture Toughness



Hole Diameter Hole Offset

Etc.

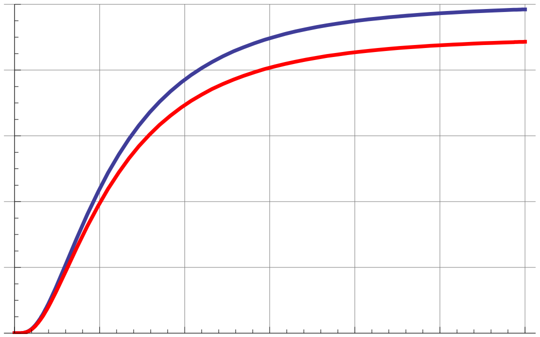
What PDTA Does?

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

$$P_f = P\left[\sigma_{Max} > \left(\frac{K_C}{\beta(a(a_o,t))\sqrt{\pi a(a_o,t)}}\right)\right] = P\left[\sigma_{Max} > \sigma_{RS}\right]$$

$$POF(t) = \int\left[1 - F_{EVD}\left(\frac{K_C}{\beta(a(a_o,t))\sqrt{\pi a(a_o,t)}}\right)\right] f_{\mathbf{x}}(\mathbf{x})\,d\mathbf{x}$$

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



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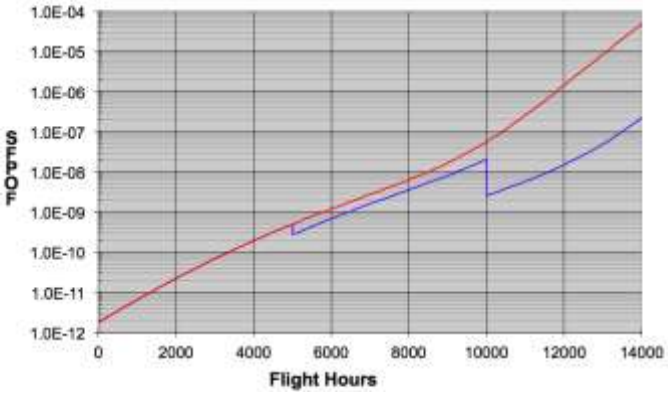


Smart|DT Capabilities

- 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
  - SFPOF (survival / no survival term)
  - Hazard fn. (with survival term)
  - Cumulative (with survival term)
- Crack growth
  - Direct Afgrow, Nasgro, & Fastran 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
  - Weighted Branch Integration Method
  - Standard Monte Carlo
  - Numerical integration for high dimensions
- 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.
- Computational implementation
  - Standard Fortran 95/03, Windows and Unix (Intel ifort compiler)
  - HPC Implementation (parallel and vectorized)

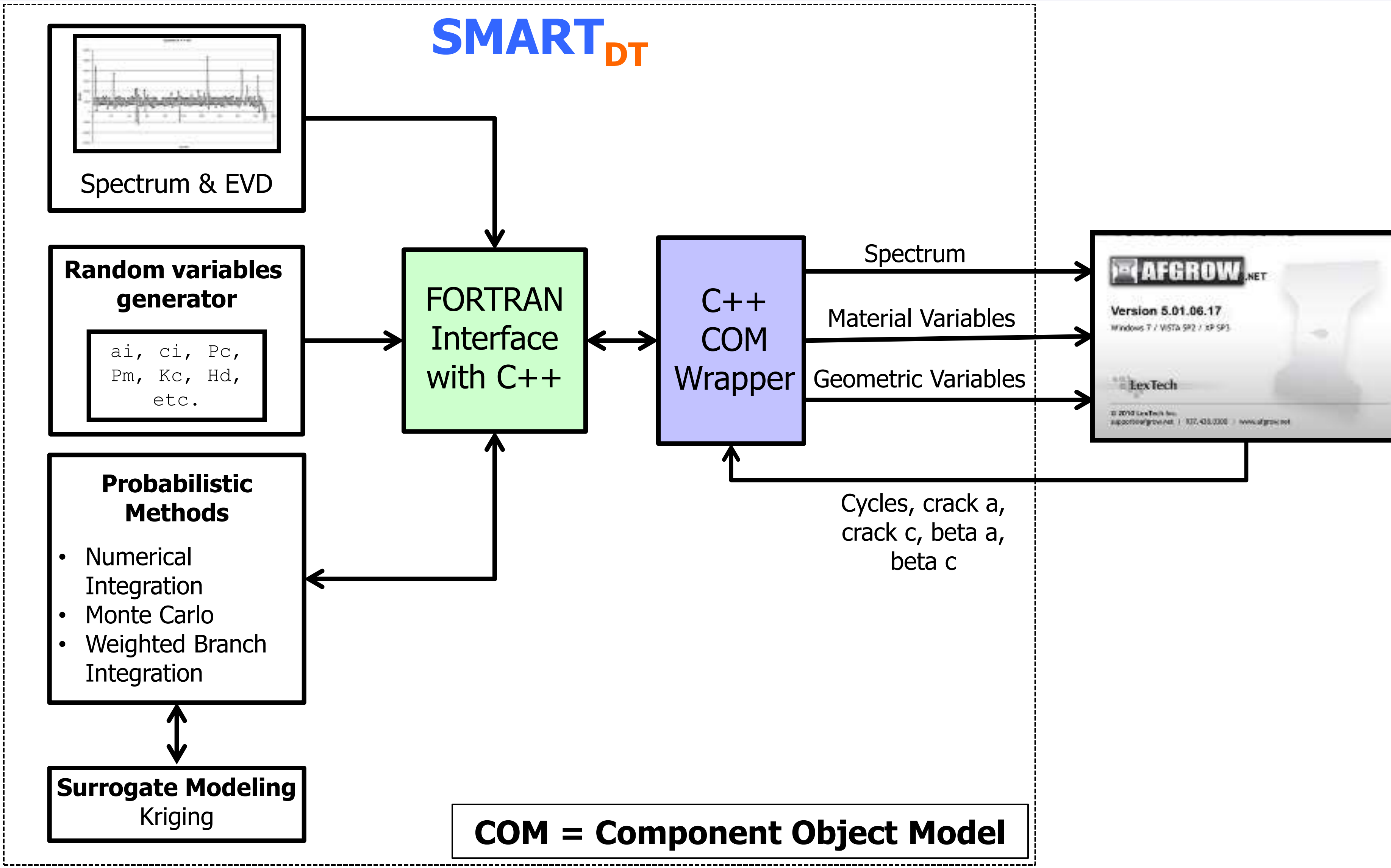
Unique capabilities in blue

External Crack Growth Interface

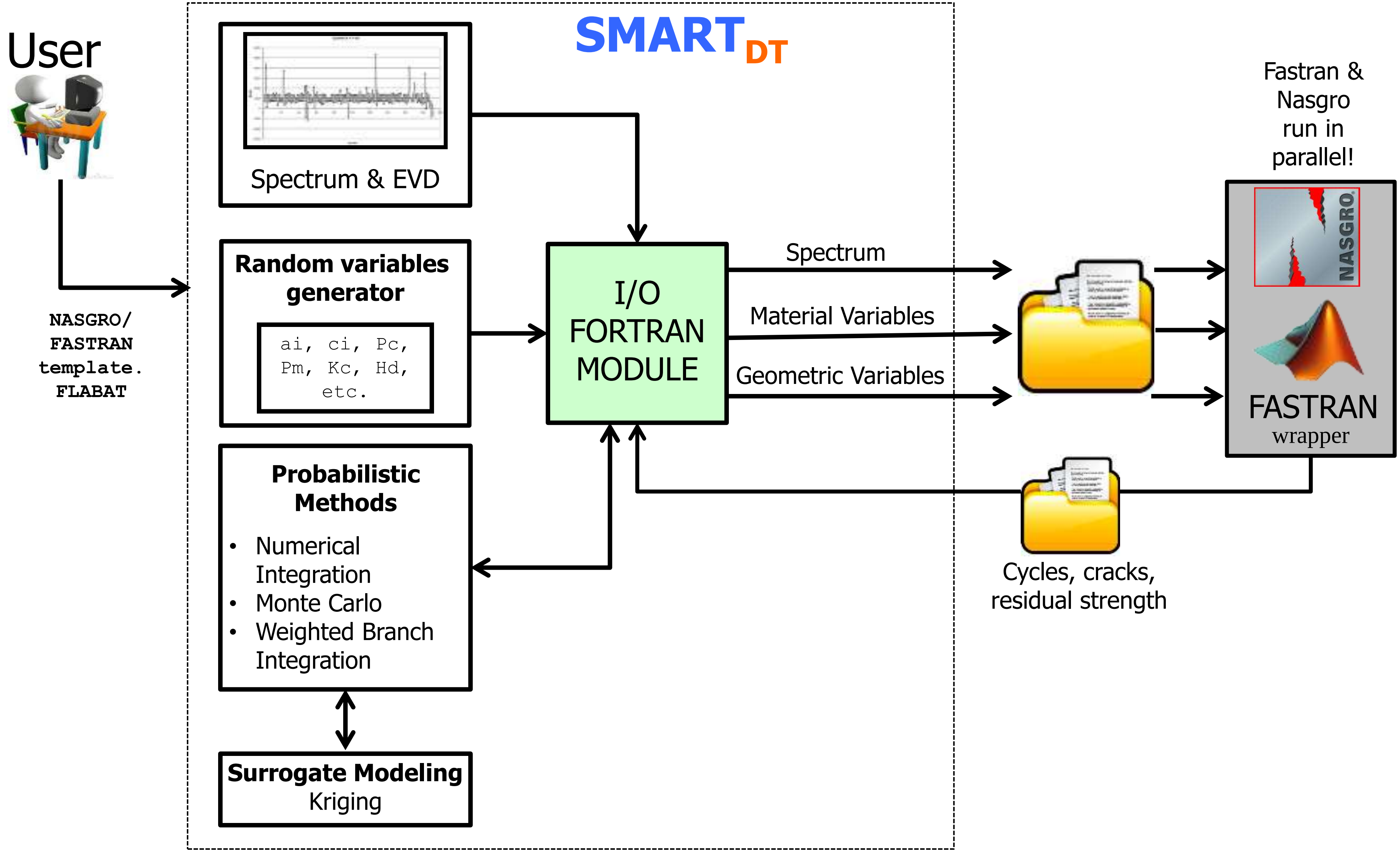
SMART_{DT}

SMall Aircraft Risk Technology - Damage Tolerance Analysis

AFGROW Interface: COM driven



FASTRAN/NASGRO Interface
File based I/O

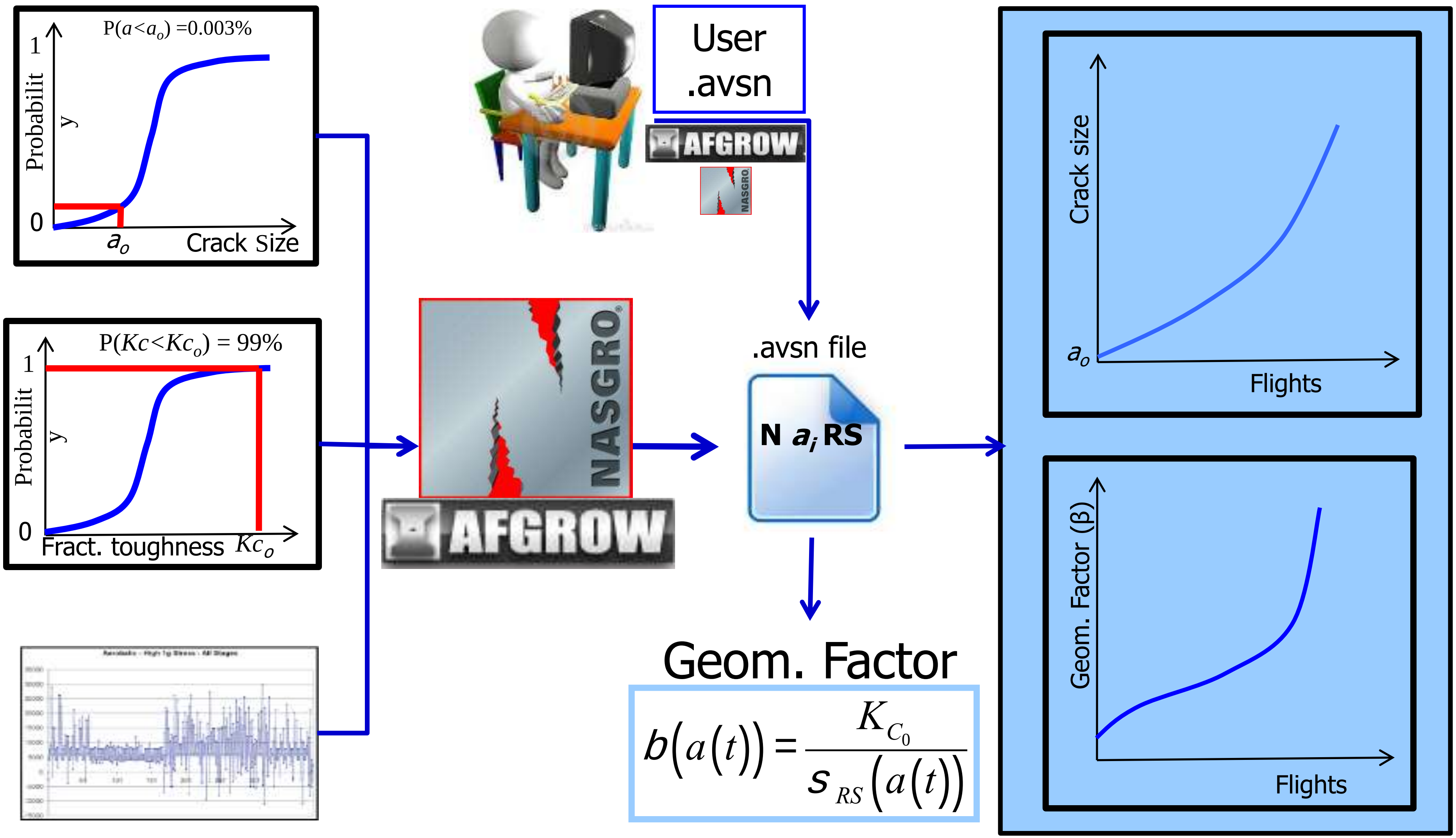


Master Curve Approach

SMART$_{DT}$

SMall Aircraft Risk Technology - Damage Tolerance Analysis

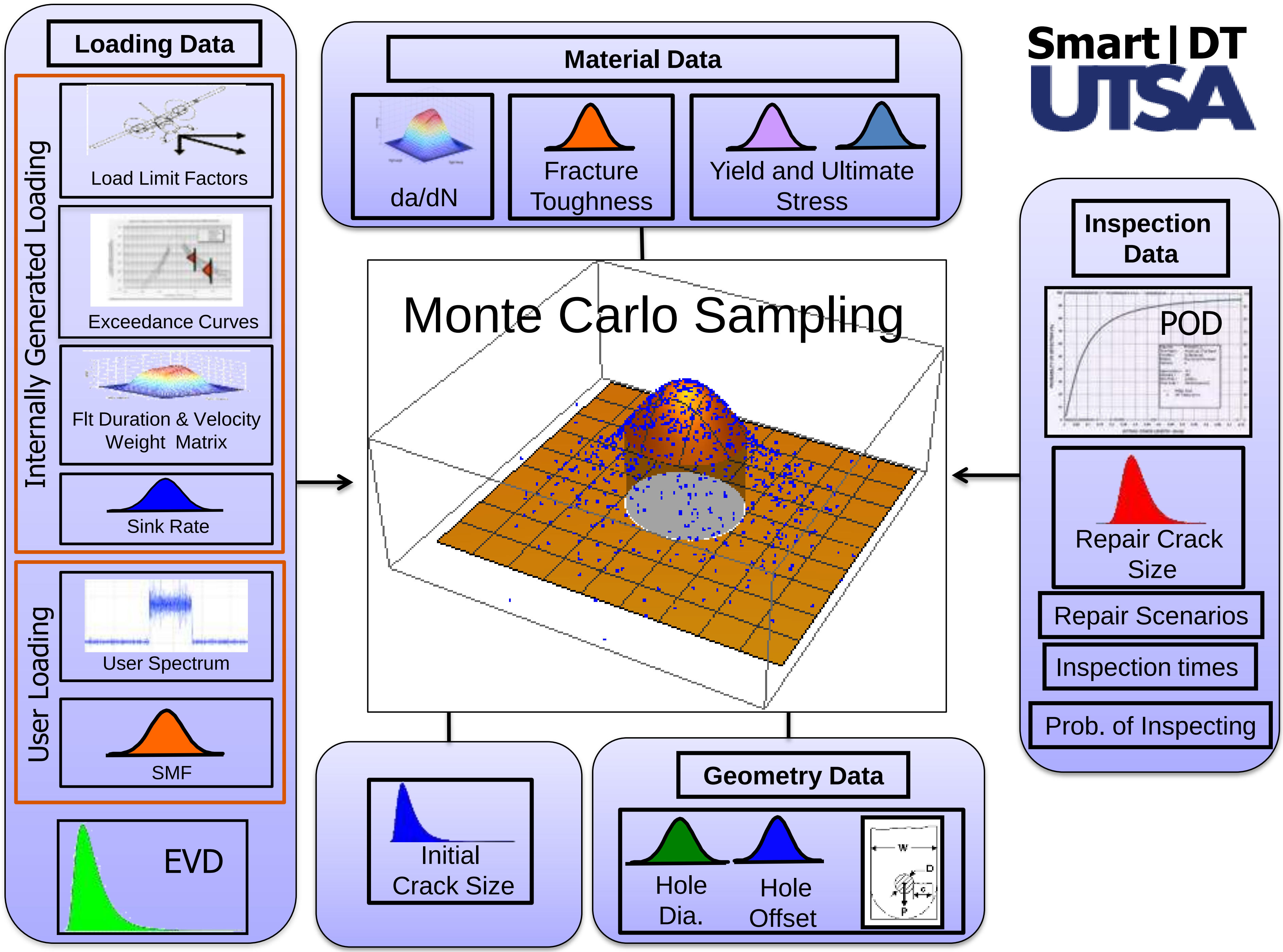
Master Curve Approach



Numerical Integration and Sampling Approach

SMART_{DT}

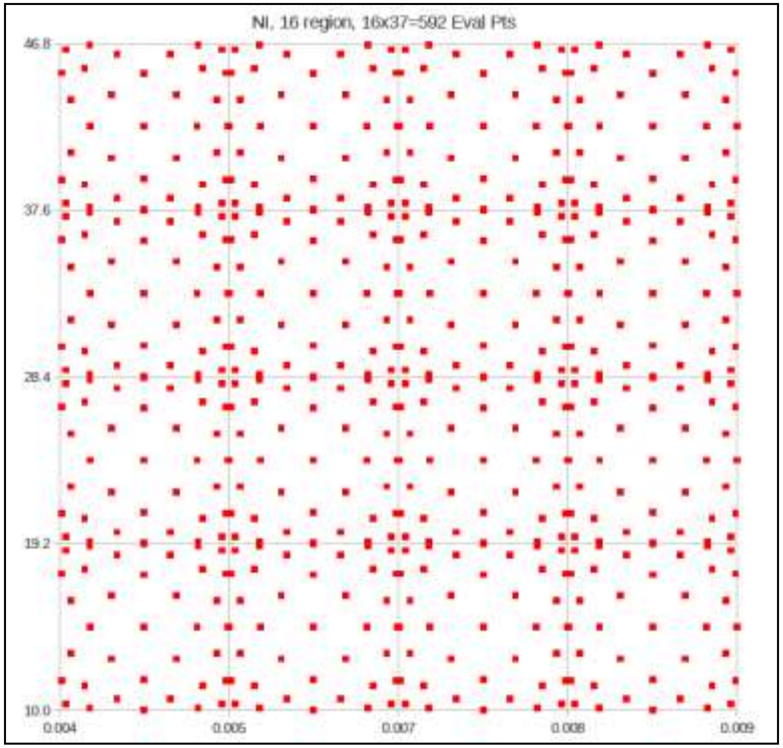
SMall Aircraft Risk Technology - Damage Tolerance Analysis



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
Smart | DT
UTSA
Monte Carlo Sampling
Inspection Data
POD
Repair Crack Size
Repair Scenarios
Inspection times
Prob. of Inspecting
Initial Crack Size
Geometry Data
Hole Dia.
Hole Offset

Numerical Integration

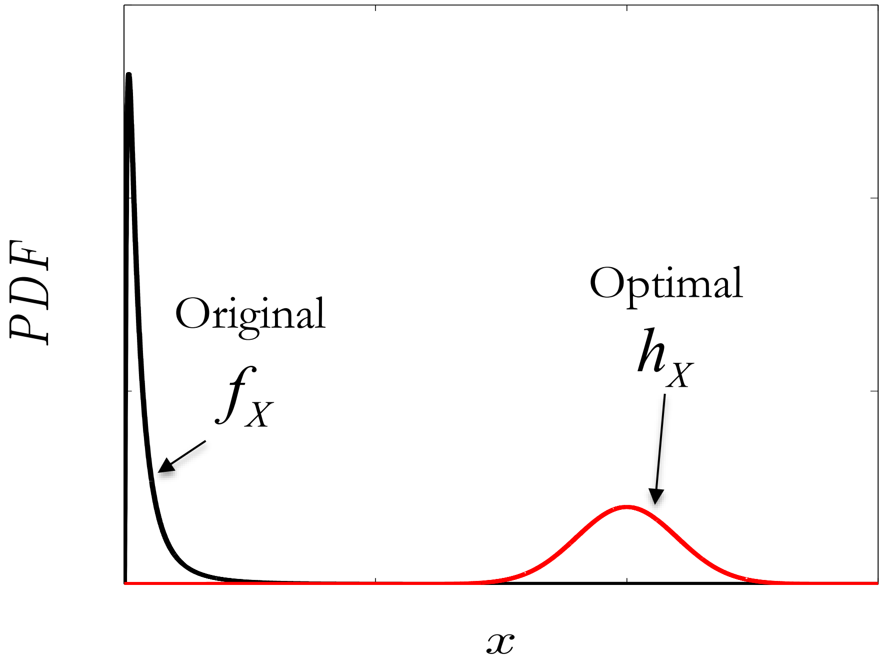
- Adaptive numerical integration.
  - Open source, free, and academically published.
  - Adaptive strategies.
  - Error estimates.
  - Specify number of evaluations.
  - Specify error.
  - High dimensional integrals.
    - Up to 5 dimensions have been tested.



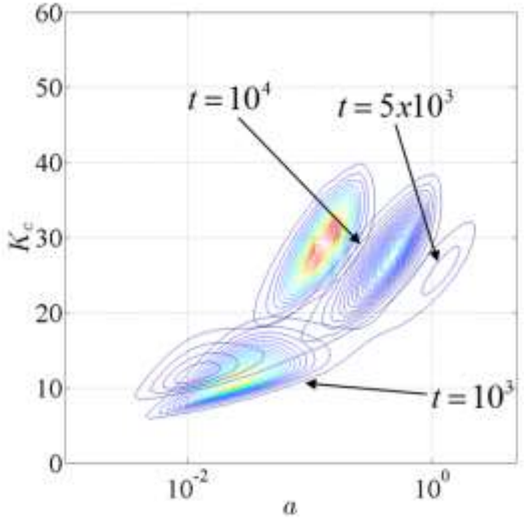
Imp. Sampling

Methods to determine optimal parameters for initial crack size, fracture toughness and other random variables.

$$Pf \approx \frac{1}{N} \sum \left\{ (1 - F_{EVD}) \frac{f_X(x)}{h_X(x)} \right\} h_X(x)$$



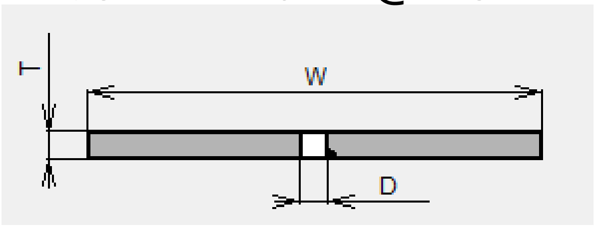
Time Dependent!



Input Parameters

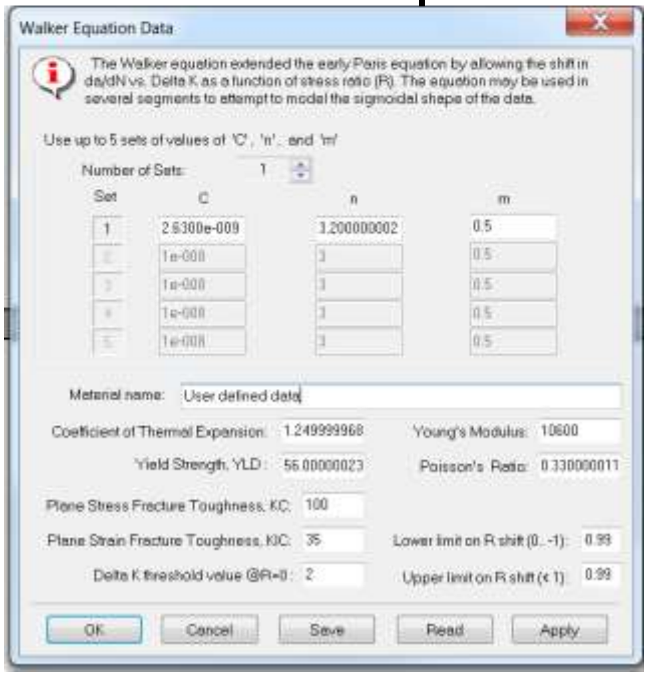
Master Curve Example

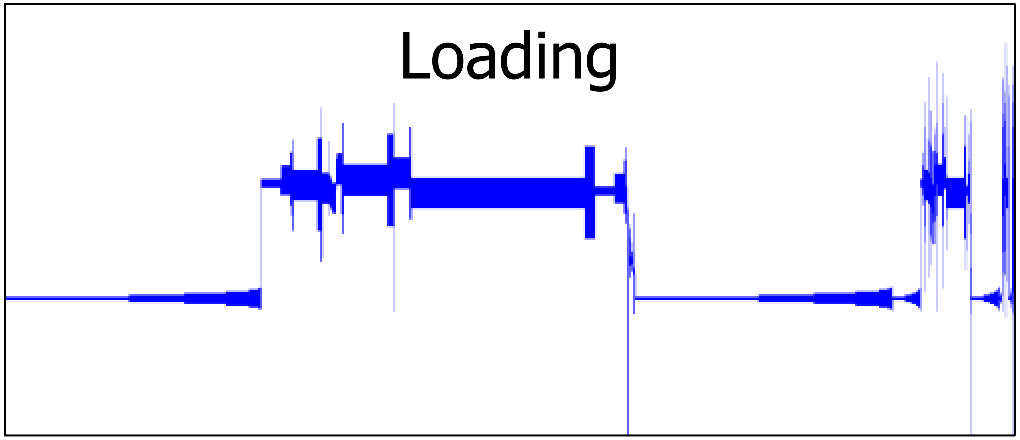
Corner crack @ hole



Parameter	Value
T	0.09 in
W	4.0 in
D	0.25 in

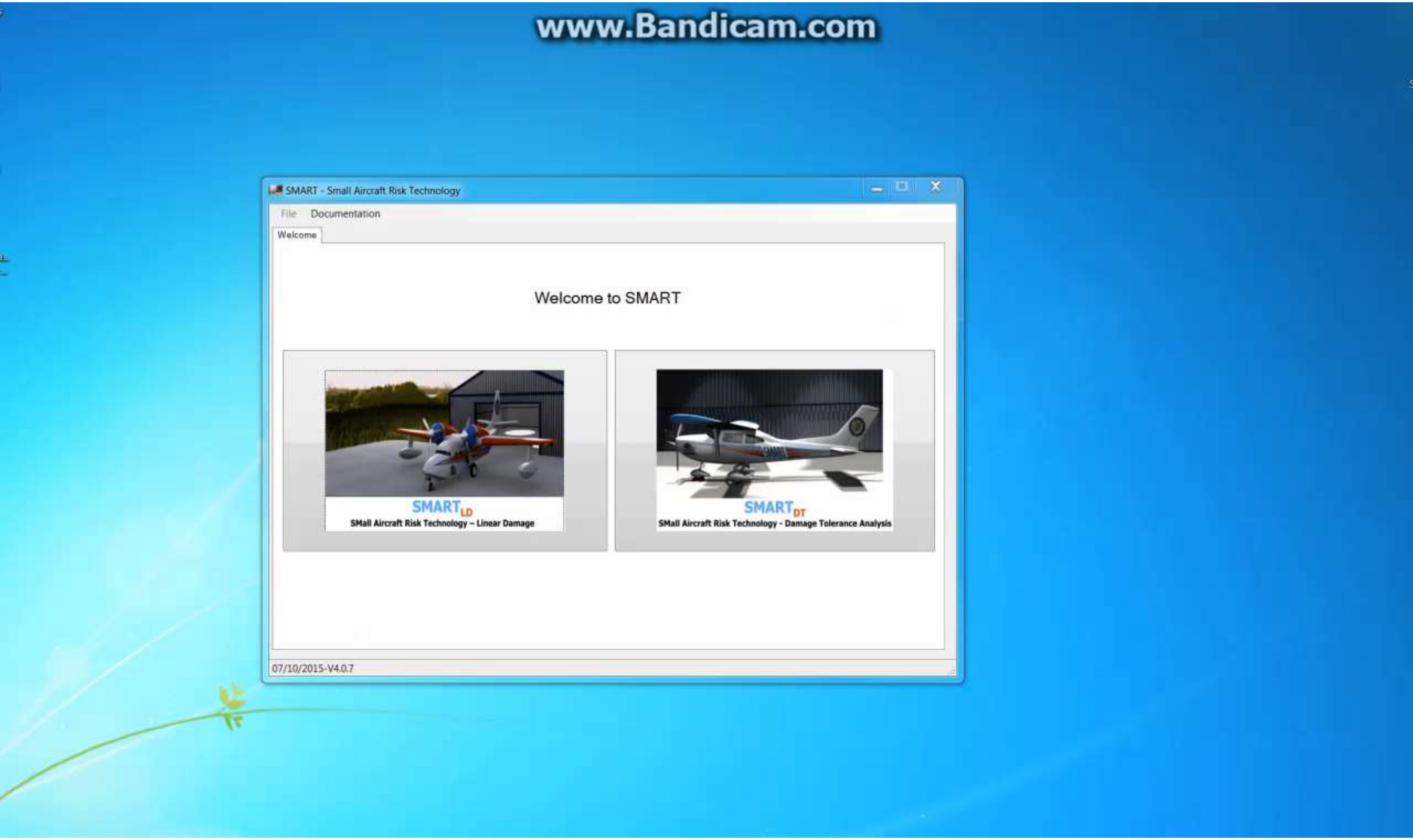
Mat. Prop.



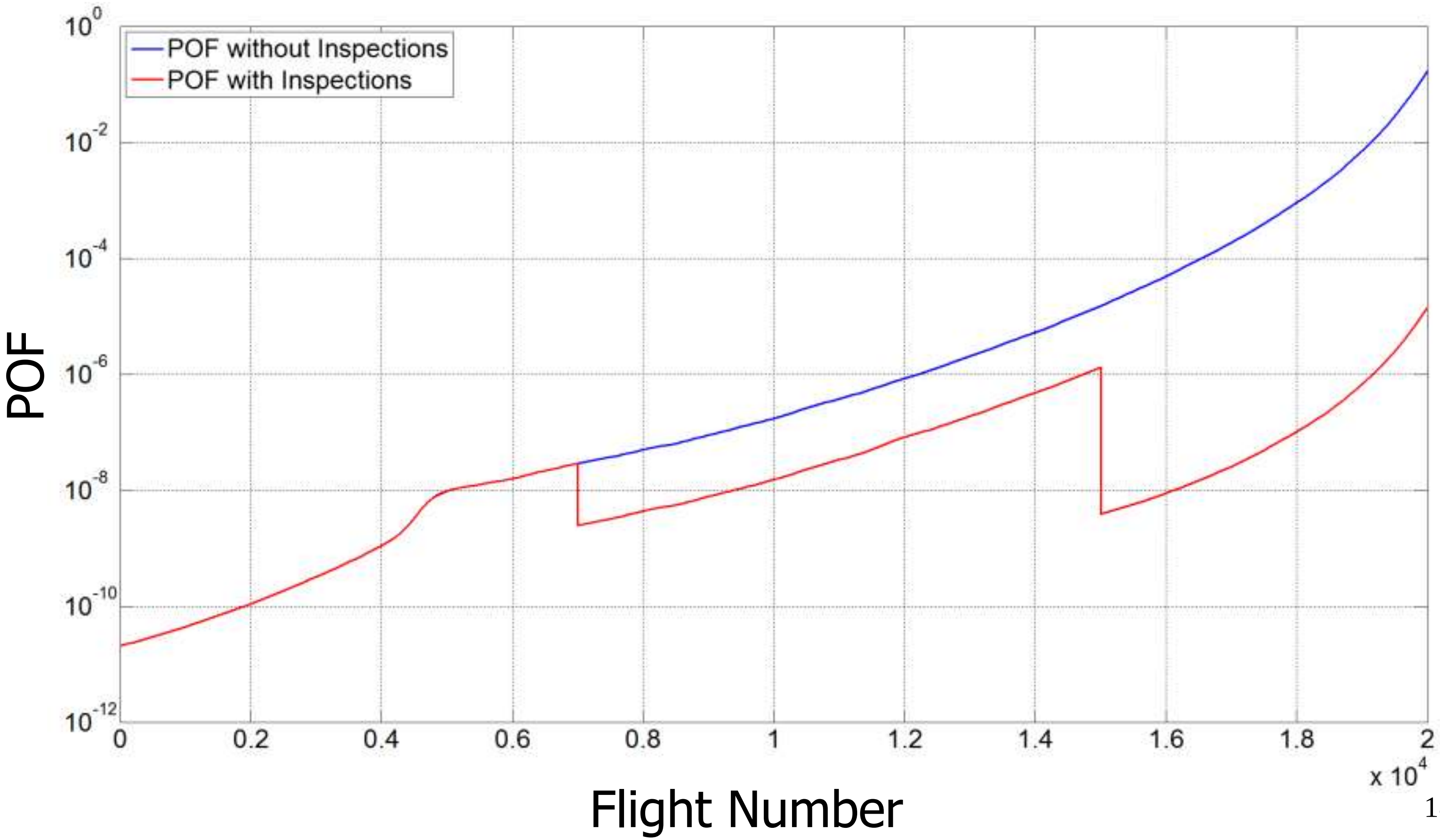


Random Variables	Value
Fracture Toughness Distribution (Normal)	Mean = 34.5ksi√in, Standard Deviation = 3.8 ksi√in.
Initial & Repair Lognormal Size Distribution (a & c) (Lognormal)	Mean = 0.05 in, Standard Deviation = 0.001 in.
Extreme Value Distribution (Gumbel)	Location = 14.5, Scale = 0.8, and Shape = 0.0
Inspections (5,000 & 10,000)	POD Lognormal Mean = 0.07in, Standard Deviation = 0.06

SMART AFGROW

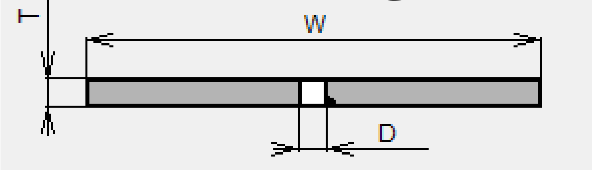


Numerical Integration POF Results



Input Parameters
Multiple Random Variables

Corner crack @ hole



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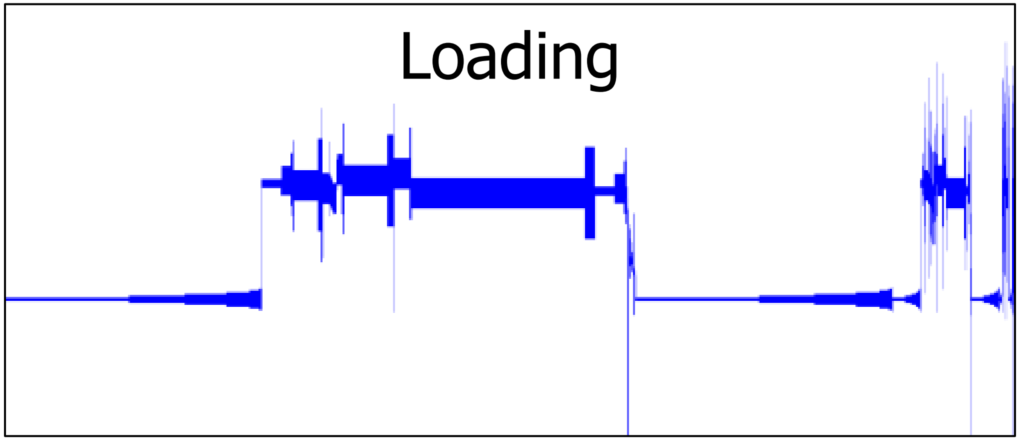
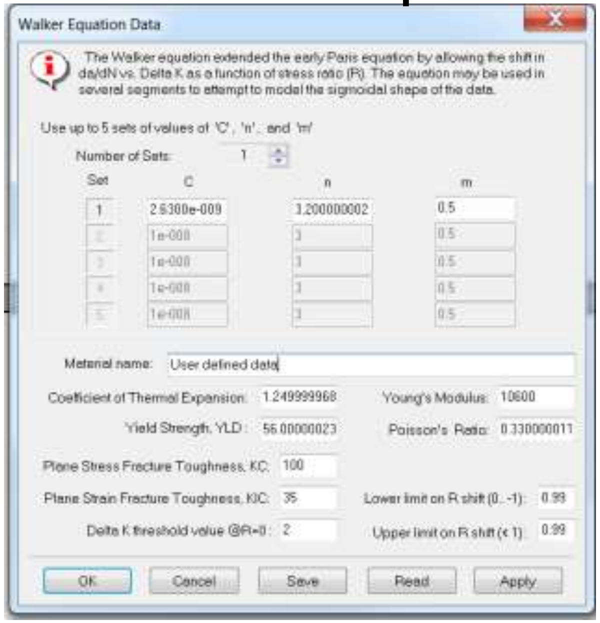
T	0.09 in
W	4.0 in

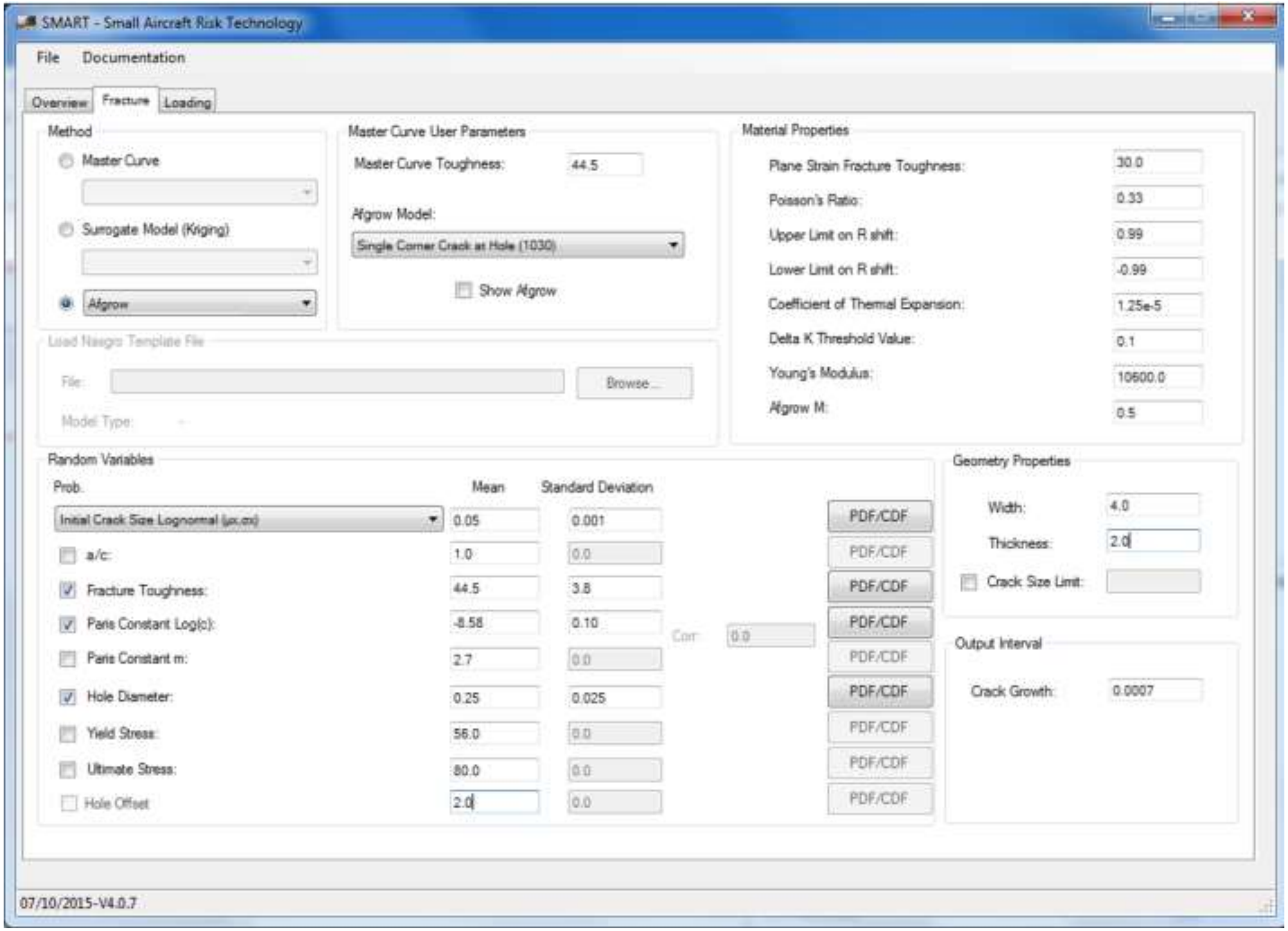


Mat. Prop.



Random Variables	Value
Fracture Toughness Distribution (Normal)	Mean = 44.5ksi√in, Standard Deviation = 3.8 ksi√in.
Crack Growth Parameters (Normal)	Paris Log(C): Mean = -8.58, Standard Deviation = 0.08 Paris m = 2.7
Initial Crack Distribution (Lognormal)	Mean = 0.05 in, Standard Deviation = 0.001 in.
Extreme Value Distribution (Gumbel)	Location = 14.5, Scale = 0.8, and Shape = 0.0
Hole Diameter (Normal)	Mean = 0.25 in, Standard Deviation = 0.025 in

Numerical Integration AFGROW Run



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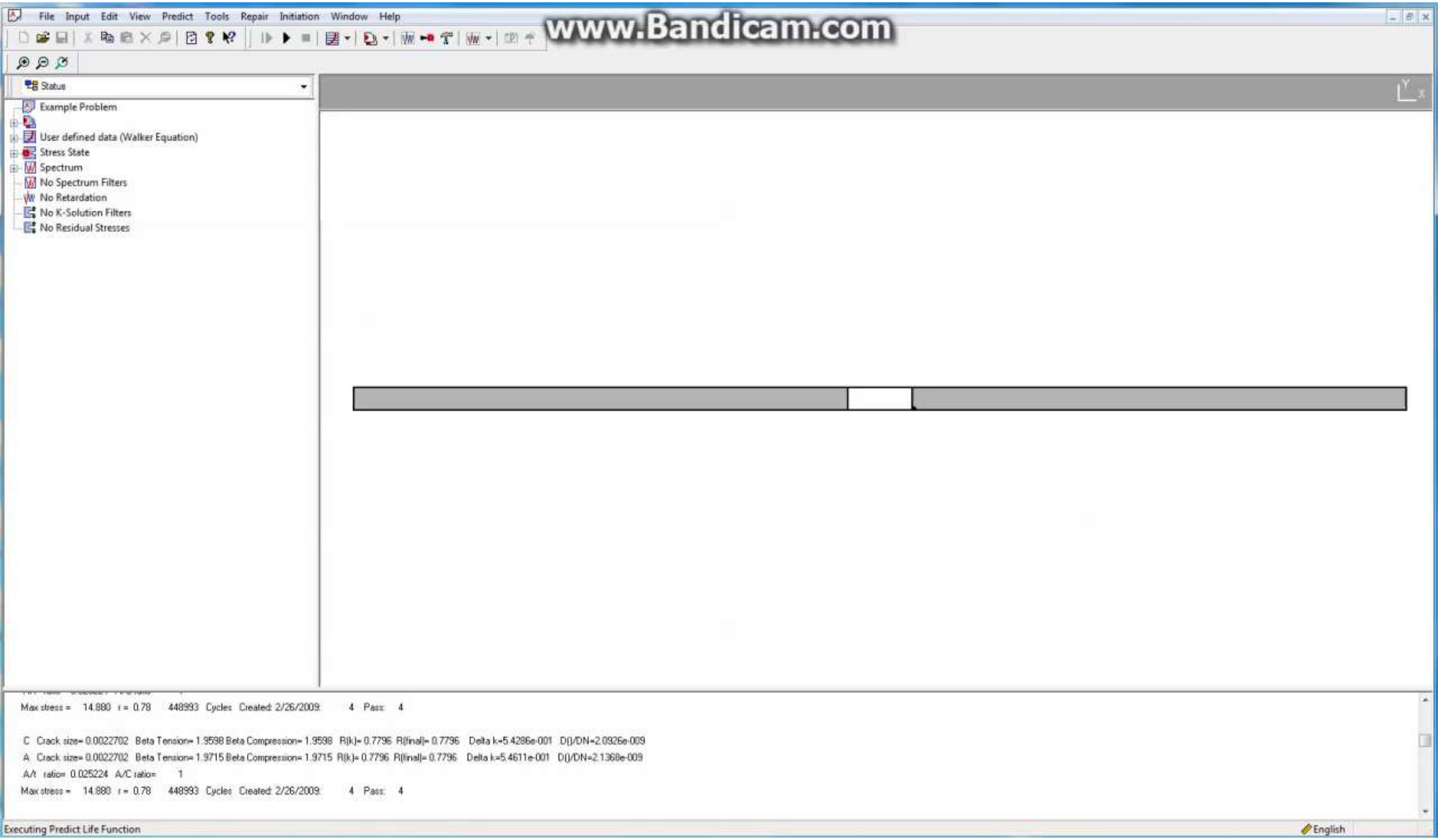
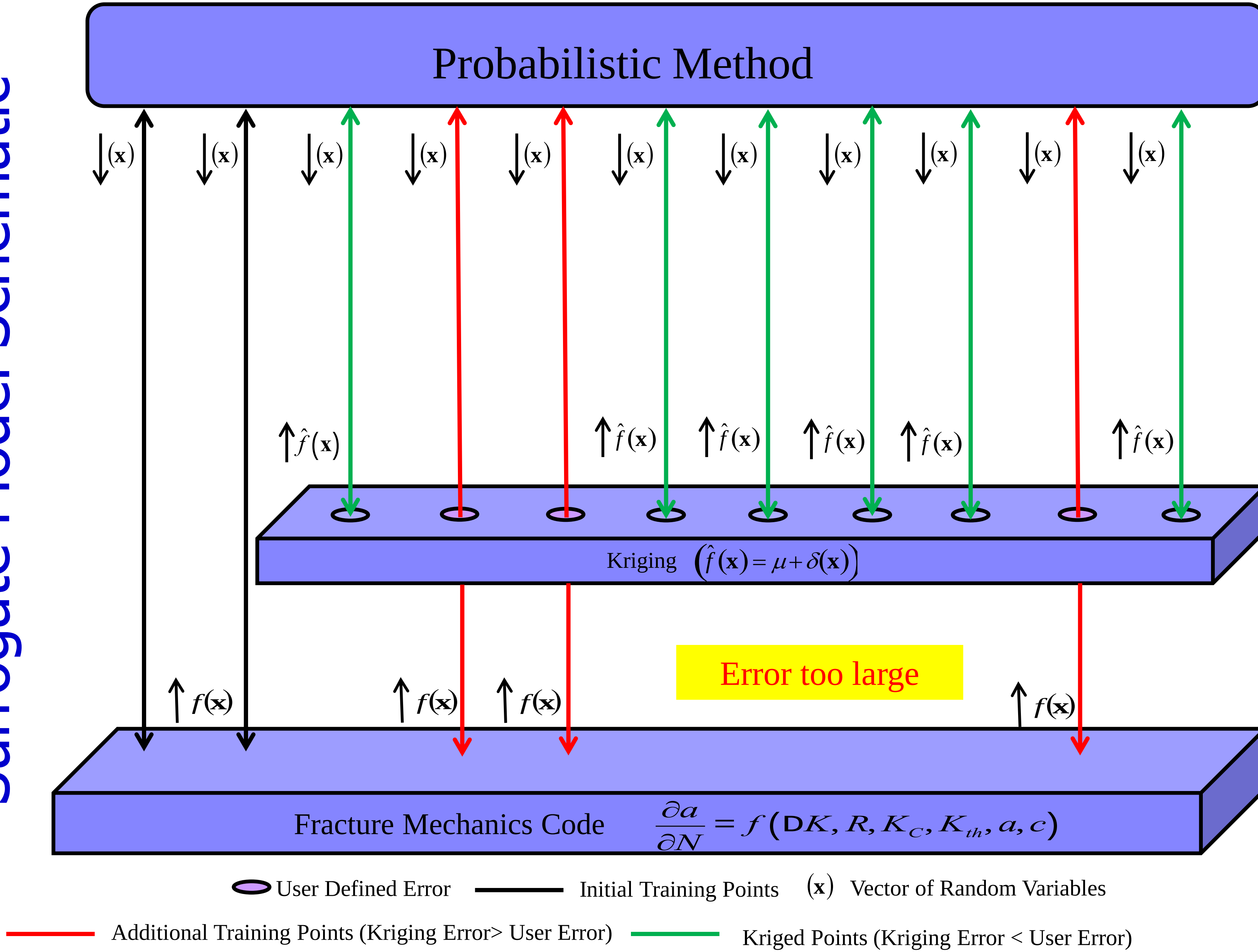


Kriging Approach

SMART$_{DT}$

SMall Aircraft Risk Technology - Damage Tolerance Analysis

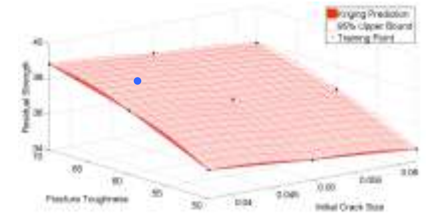
Surrogate Model Schematic

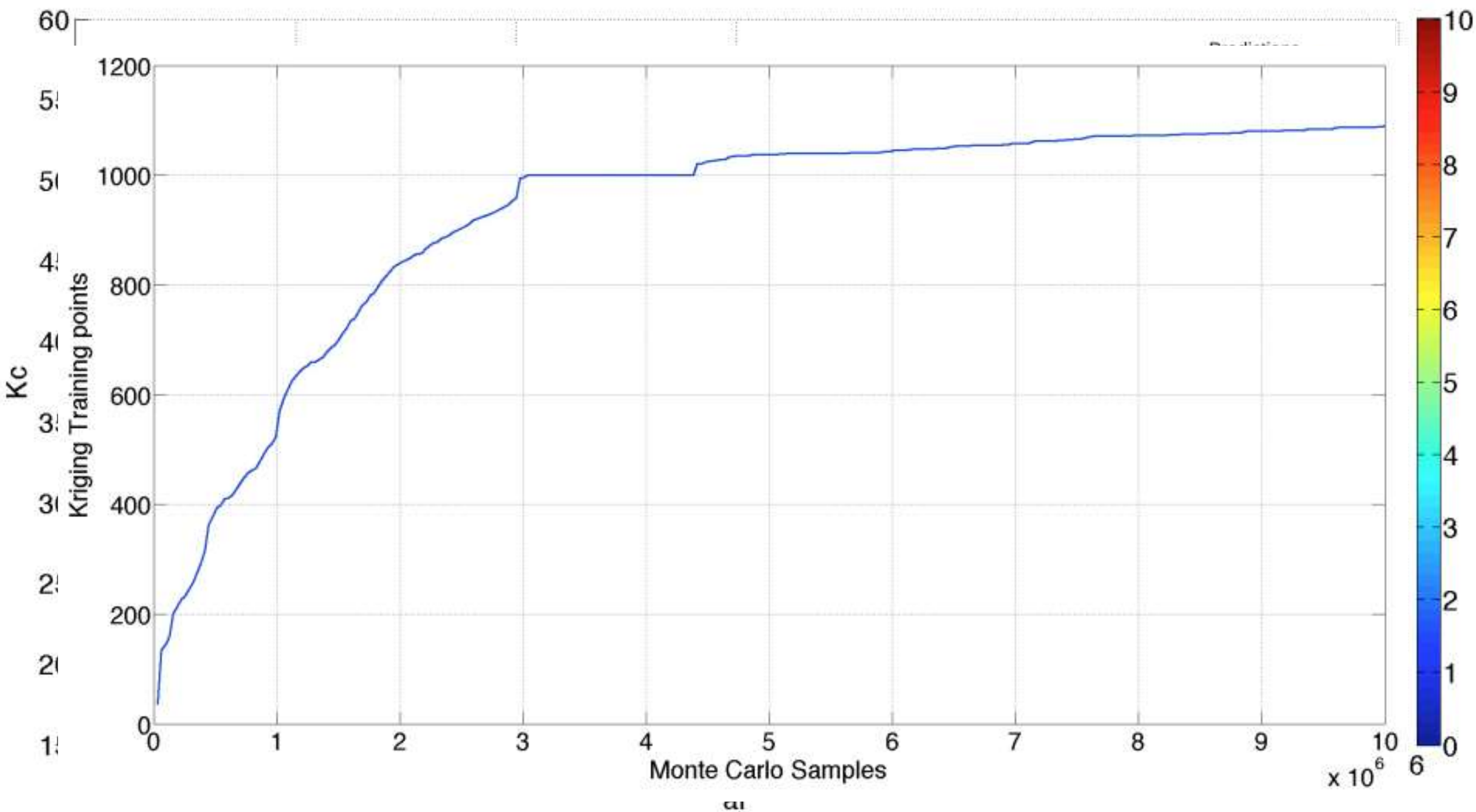


Kriging Summary

- ✓ Multiple random variables
  - ✓ ai, Kc, Paris C, crack aspect ratio, hole diameter, hole offset, yield stress, ultimate stress, peak stress
- ✓ User-defined error for residual strength and crack growth predictions
- ✓ Residual strength predictions
- ✓ Through, corner, and surface crack size predictions
- ✓ HPC implementation (vectorized and parallel)
- ✓ Direct link to external crack growth codes:
  - ✓ NASGRO and FASTRAN in parallel (File based)
  - ✓ AFGROW (COM based)
- ✓ Previous training points can be reused
- ✓ Independent Kriging surfaces thru time

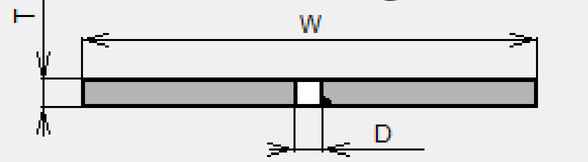
Kriging Schemetic





Input Parameters
Multiple Random Variables

Corner crack @ hole



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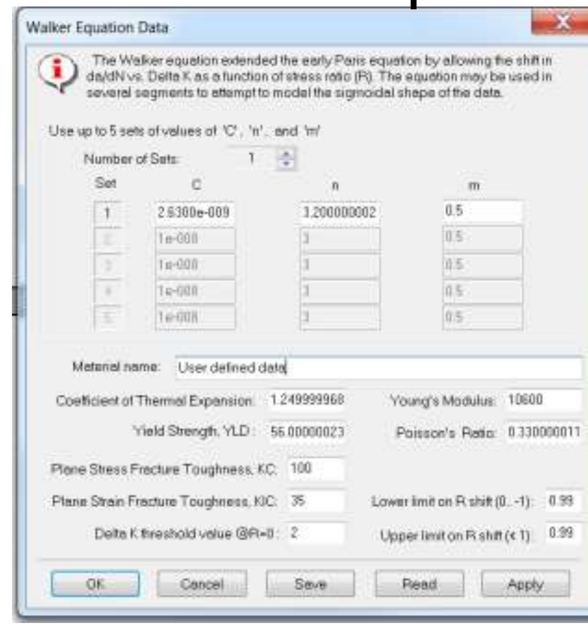

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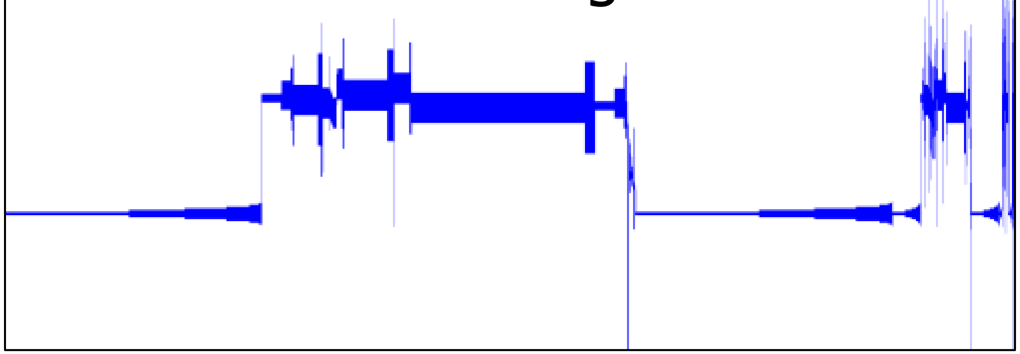

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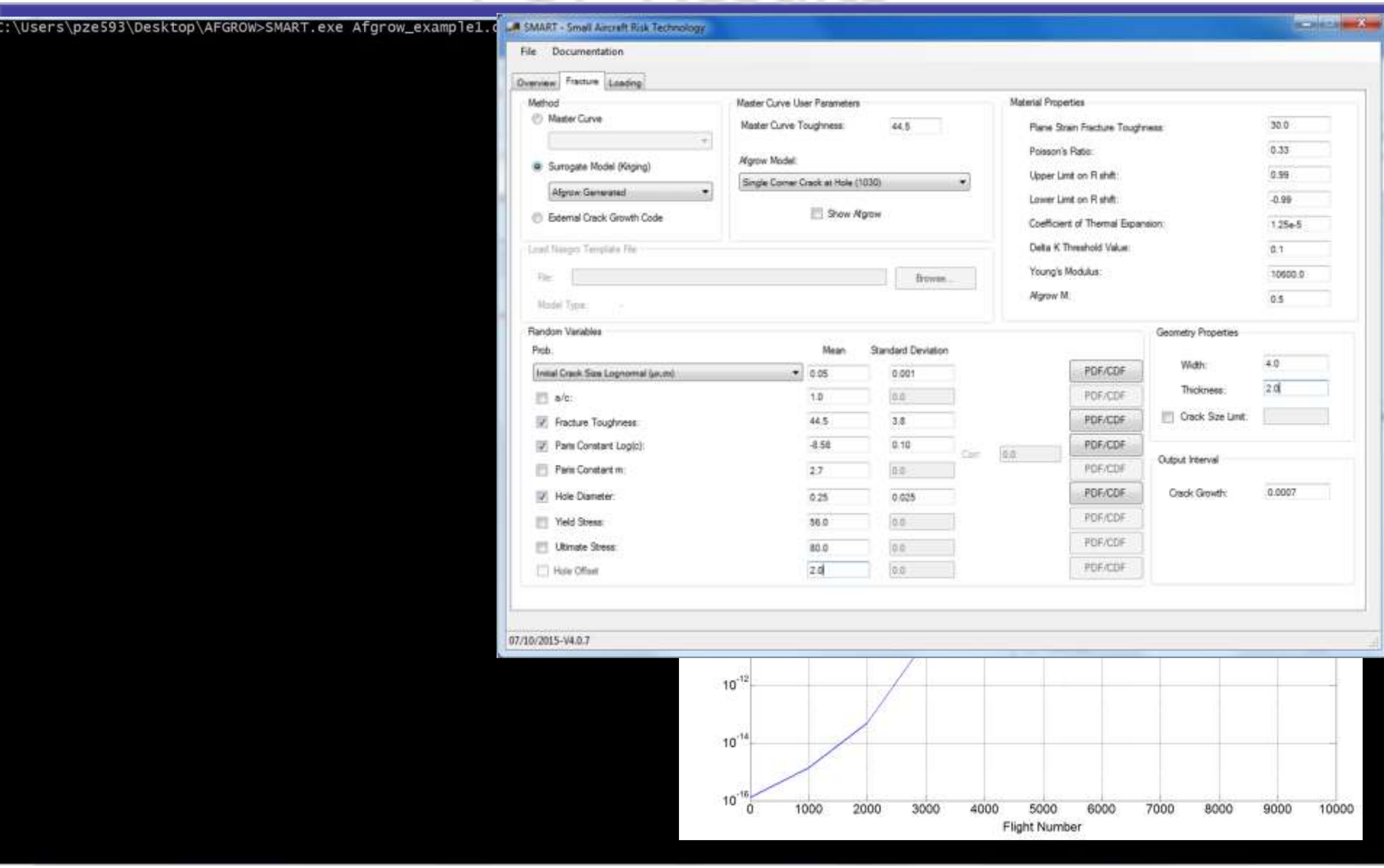
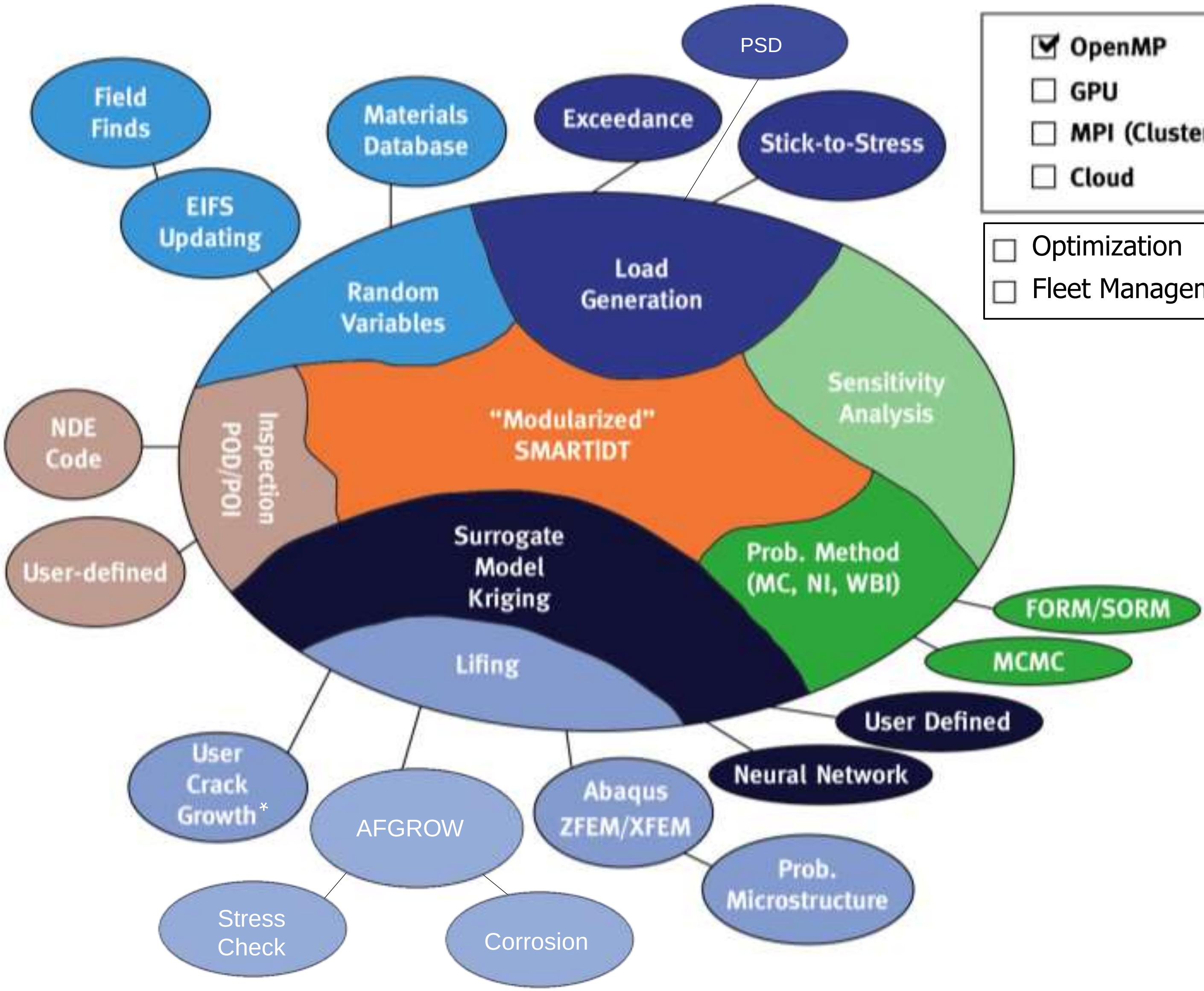


Plays well with Others



- ☑ OpenMP
- ☐ GPU
- ☐ MPI (Clusters)
- ☐ Cloud

- ☐ Optimization
- ☐ Fleet Management

Potential Future Efforts

- MSD
  - Expand to risk assessment method to structures with MSD
- Play well with others
  - Python scripts and/or COM enabled
- Provide flexibility for future enhancements
  - User access to algorithms (modularization and COM-enable software)
- Take advantages of full range of computer capabilities
  - Multithreading, {GPU, MPI, Cloud, Intel Mic}

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 (Ks City) - Sponsor

Thank you!!

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