

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



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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

2009-2013

- ✓ 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.

2012-2016

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

- Hazard Rate
- Sensitivity Analysis

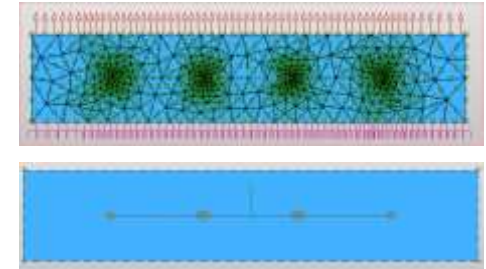
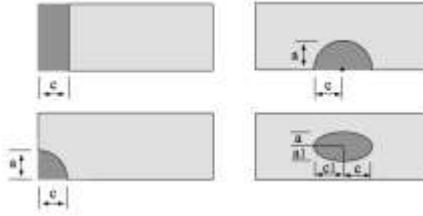
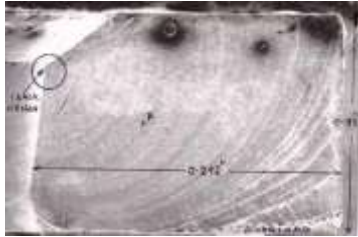
- Inspection/Repair Effect
- Sensitivity Analysis

Hazard Rate

DOE



- Run any crack growth model



- Consider any repair scenario



Oversized Hole

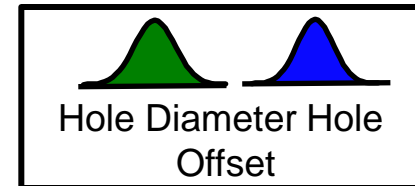
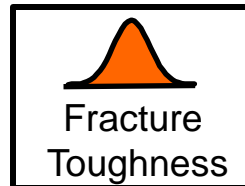
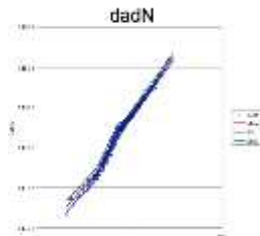
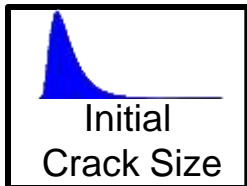


Doubler



Replacement

- Consider any random variable



Etc.



What PDTA Does?

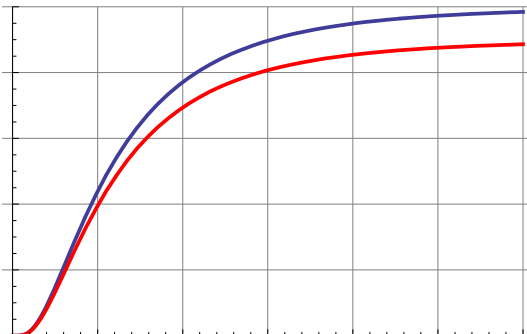


The probability-of-failure is the probability that maximum value of the applied stress (during the next flight) will exceed the residual strength σ_{RS} of the aircraft component

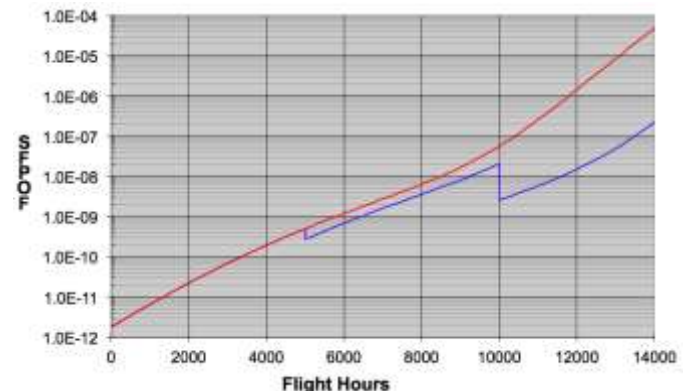
$$P_f = P \left[\sigma_{Max} > \left(\frac{K_C}{\beta(a(a_o, t)) \sqrt{\pi a(a_o, t)}} \right) \right] = P[\sigma_{Max} > \sigma_{RS}]$$

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

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



()



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}

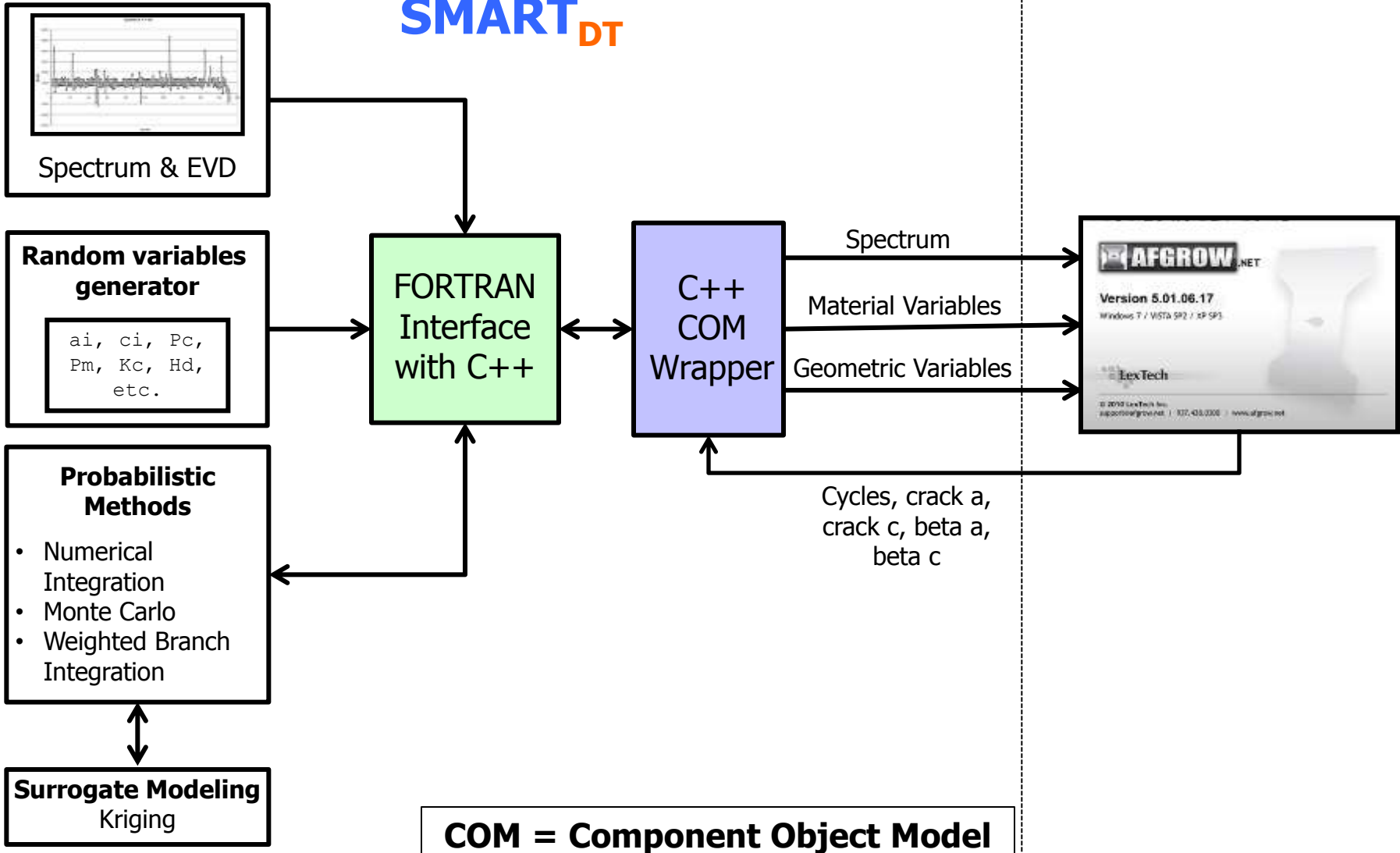
SMall Aircraft Risk Technology - Damage Tolerance Analysis



AFGROW Interface: COM driven



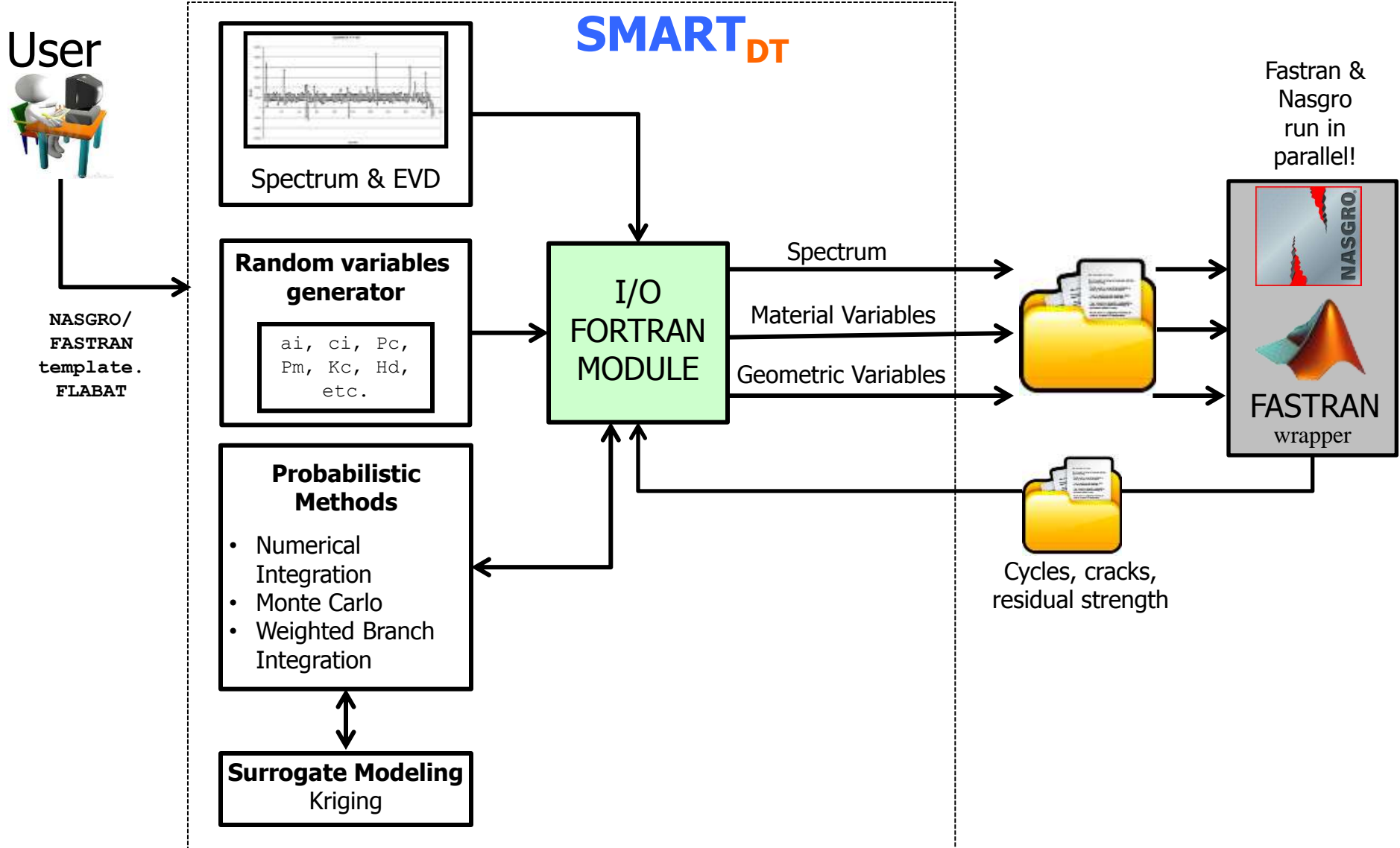
SMART_{DT}





FASTRAN/NASGRO Interface

File based I/O





Master Curve Approach

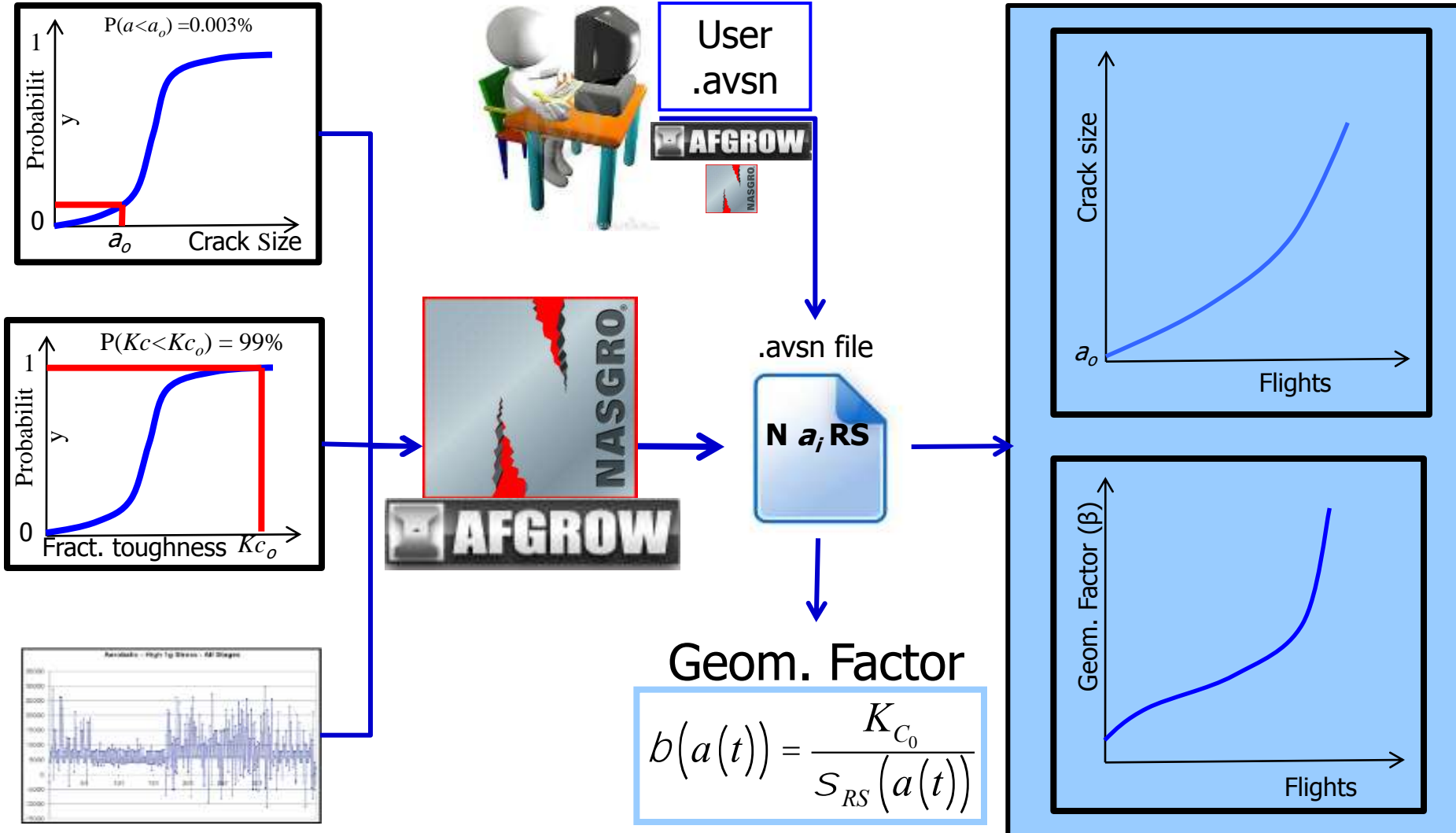


SMART_{DT}

SMall Aircraft Risk Technology - Damage Tolerance Analysis



Master Curve Approach



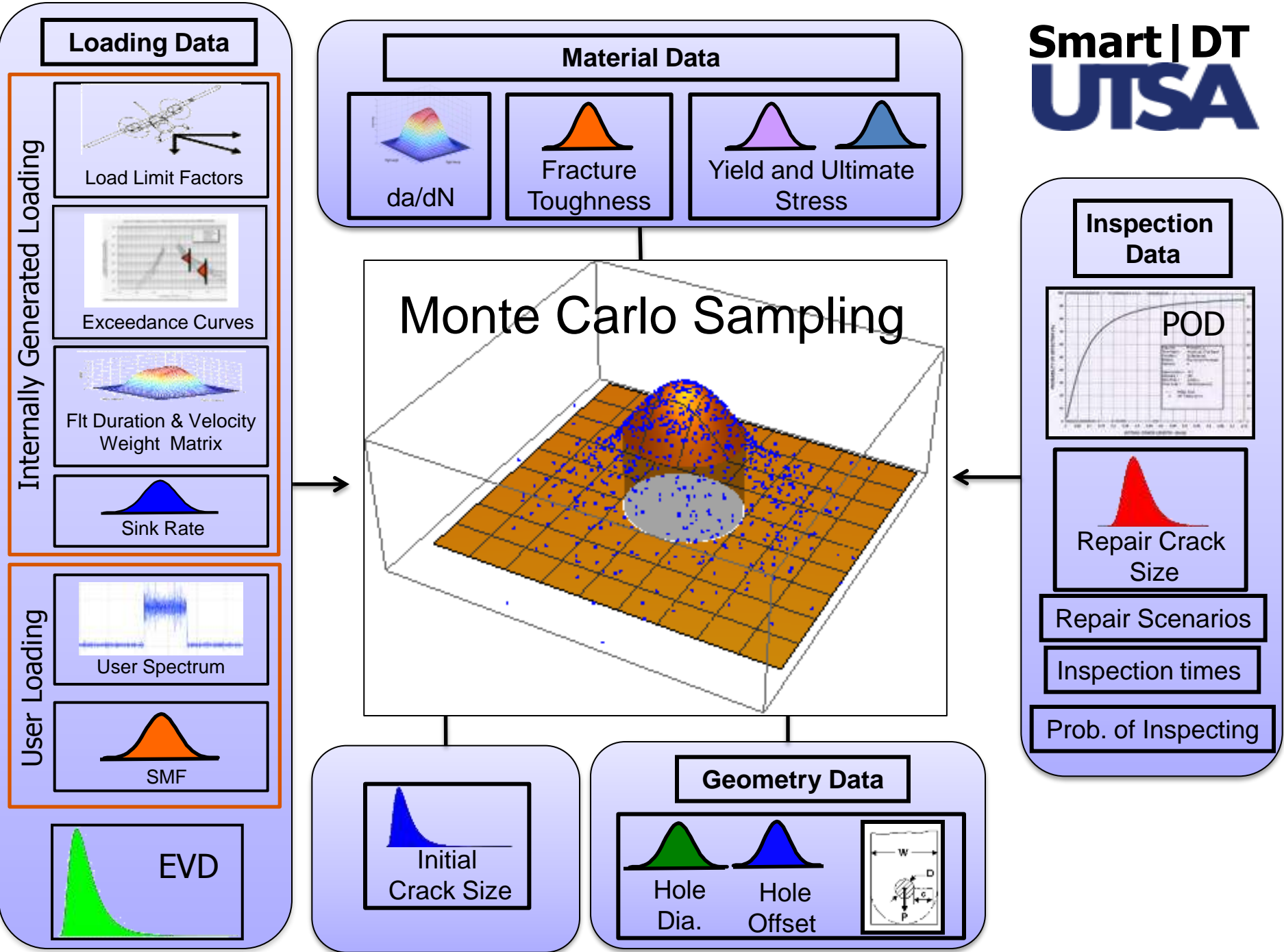


Numerical Integration and Sampling Approach



SMART_{DT}

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Loading Data

Material Data

Inspection Data

Monte Carlo Sampling

Geometry Data

Internally Generated Loading

User Loading

Load Limit Factors

Exceedance Curves

Flt Duration & Velocity Weight Matrix

Sink Rate

User Spectrum

SMF

EVD

da/dN

Fracture Toughness

Yield and Ultimate Stress

POD

Repair Crack Size

Repair Scenarios

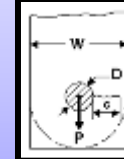
Inspection times

Prob. of Inspecting

Initial Crack Size

Hole Dia.

Hole Offset

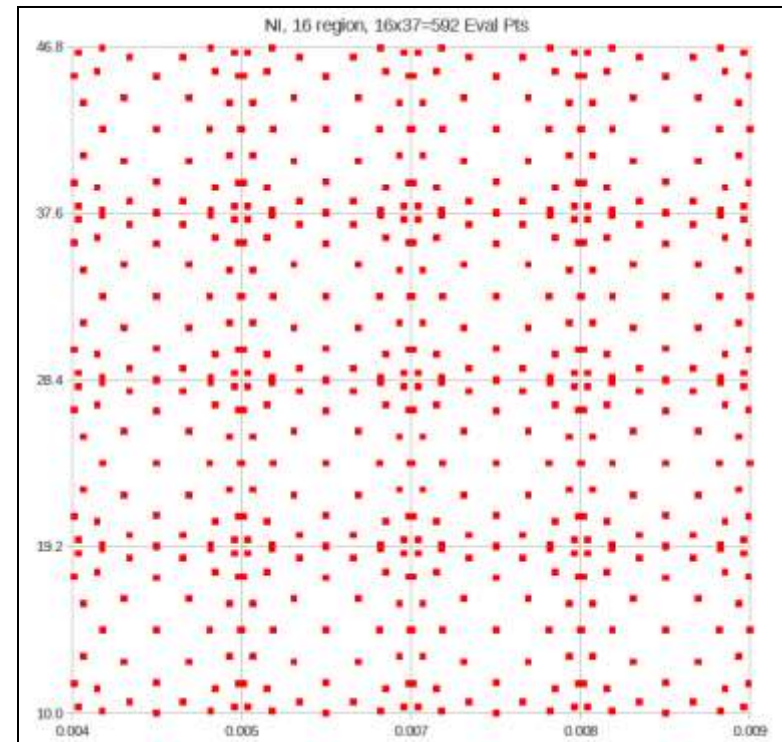




Numerical Integration



- 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.

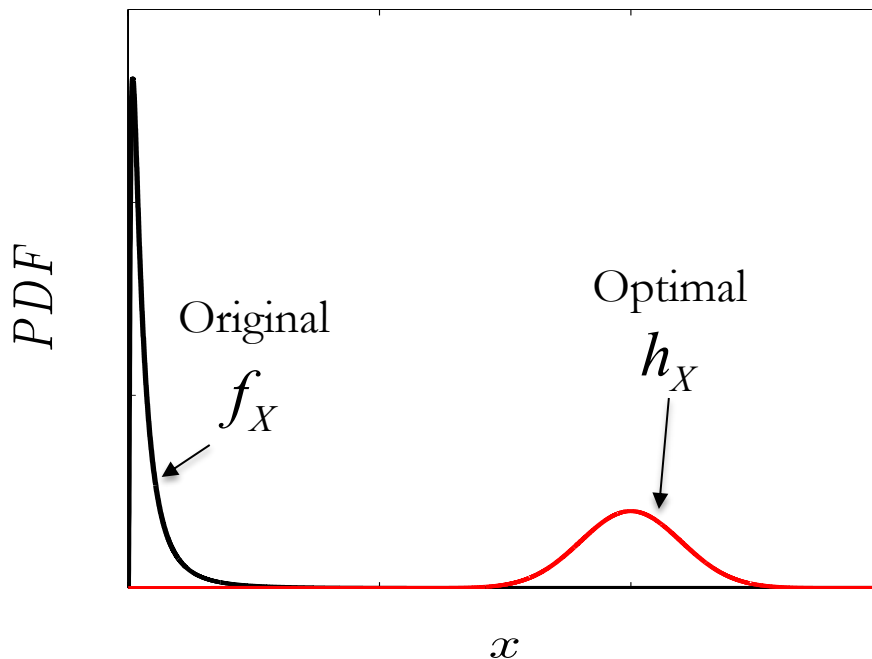


Imp. Sampling

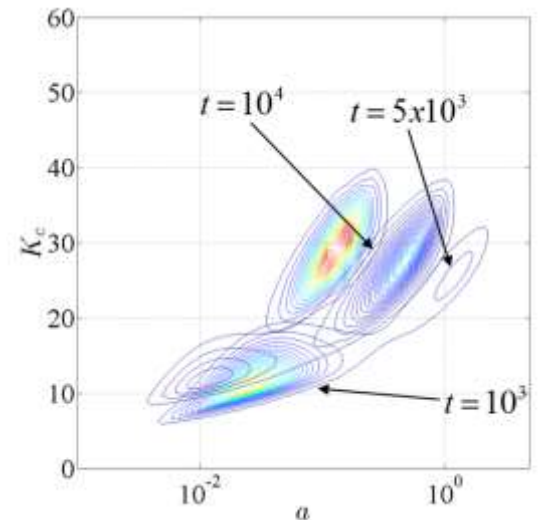


Methods to determine optimal parameters for initial crack size, fracture toughness and other random variables.

$$Pf \gg \frac{1}{N} \int_{\hat{x}}^{\hat{x}} (1 - F_{EVD}) \frac{f_X(x)}{h_X(x)} \dot{y} h_X(x)$$



Time Dependent!



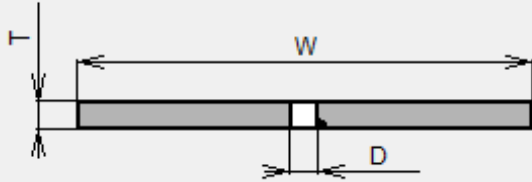


Input Parameters

Master Curve Example



Corner crack @ hole



| Parameter | Value |
|-----------|---------|
| T | 0.09 in |
| W | 4.0 in |
| D | 0.25 in |

Mat. Prop.

Walker Equation Data

The Walker equation extended the early Paris equation by allowing the shift in da/dN vs. Delta K, as a function of stress ratio (R). The equation may be used in several segments to attempt to model the sigmoidal shape of the data.

Use up to 5 sets of values of 'C', 'n', and 'm'

Number of Sets: 1

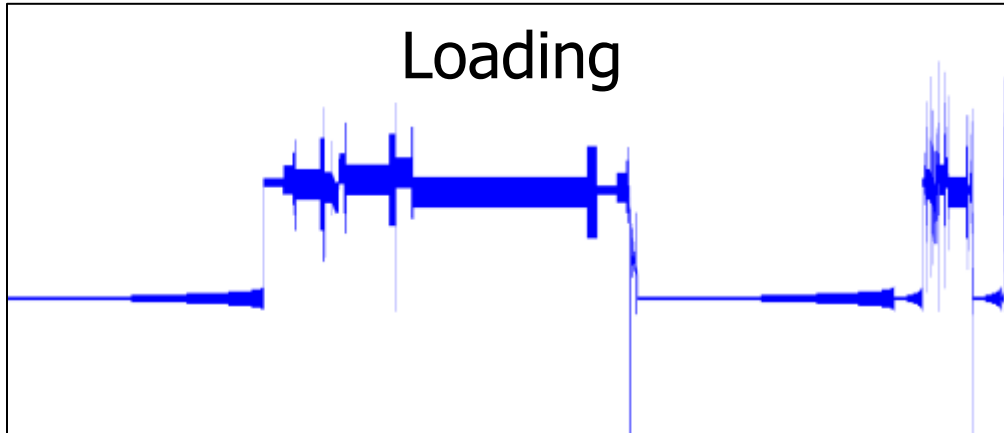
| Set | C | n | m |
|-----|-------------|-------------|-----|
| 1 | 2.6300e-009 | 1.200000002 | 0.5 |
| 2 | 1e-008 | 3 | 0.5 |
| 3 | 1e-008 | 3 | 0.5 |
| 4 | 1e-008 | 3 | 0.5 |
| 5 | 1e-008 | 3 | 0.5 |

Material name: User defined data

Coefficient of Thermal Expansion: 1.249999968 Young's Modulus: 10600
 Yield Strength, YLD: 56.00000023 Poisson's Ratio: 0.330000011

Plane Stress Fracture Toughness, K_{IC}: 100
 Plane Strain Fracture Toughness, K_{IC}: 35 Lower limit on R shift (0. -1): 0.99
 Delta K threshold value @R=0: 2 Upper limit on R shift (+1): 0.99

Buttons: OK, Cancel, Save, Read, Apply



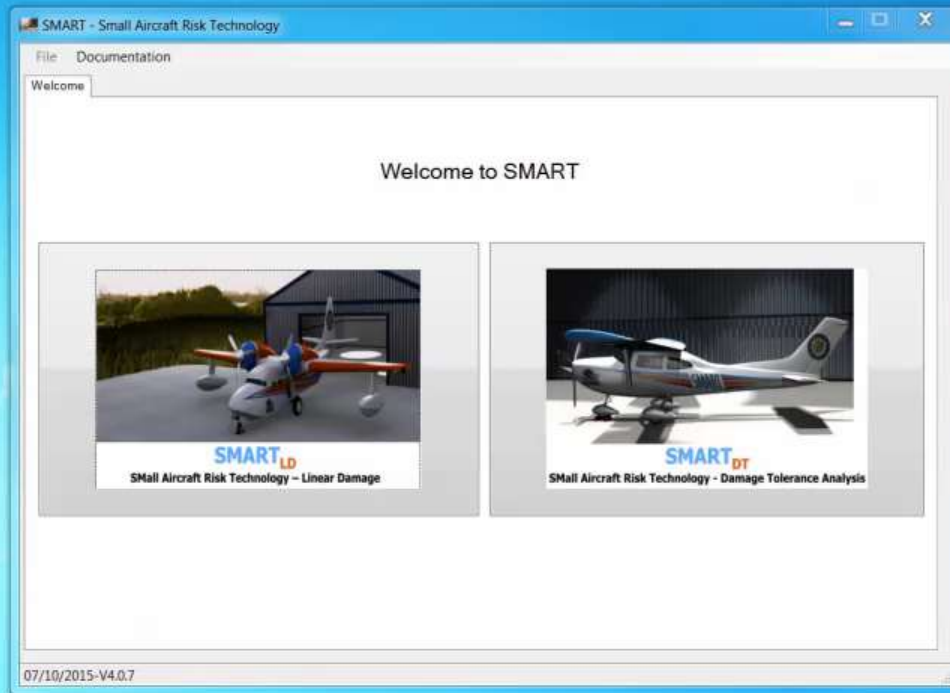
| Random Variables | Value |
|--|---|
| Fracture Toughness Distribution (Normal) | Mean = 34.5ksi√in, Standard Deviation = 3.8 ksi√in. |
| Initial & Repair Lognormal Size Distribution (a & c) (Lognormal) | Mean = 0.05 in, Standard Deviation = 0.001 in. |
| Extreme Value Distribution (Gumbel) | Location = 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

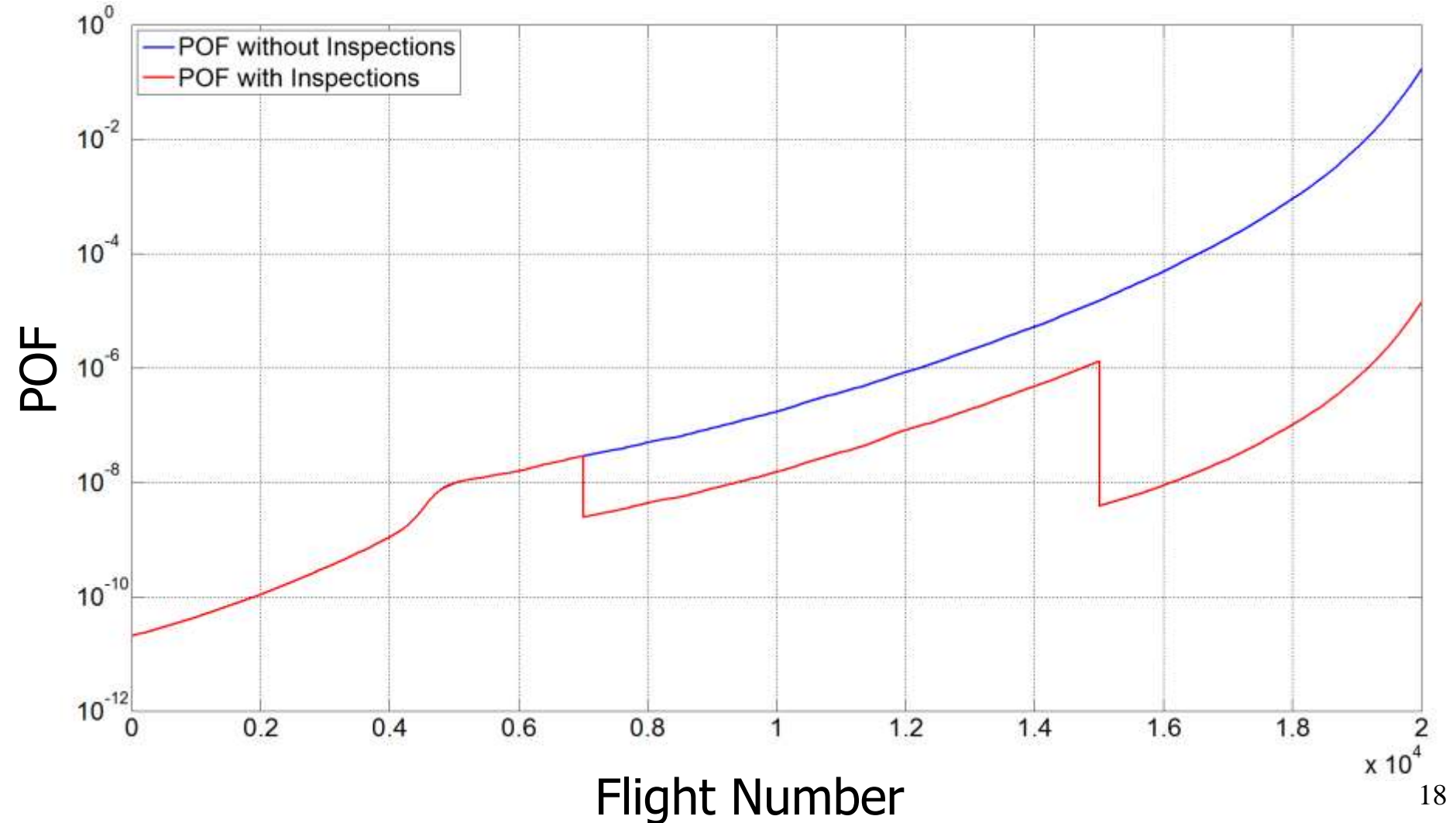


www.Bandicam.com





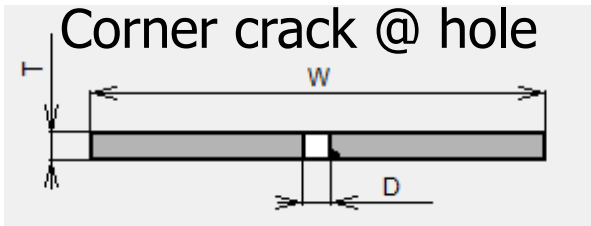
Numerical Integration POF Results



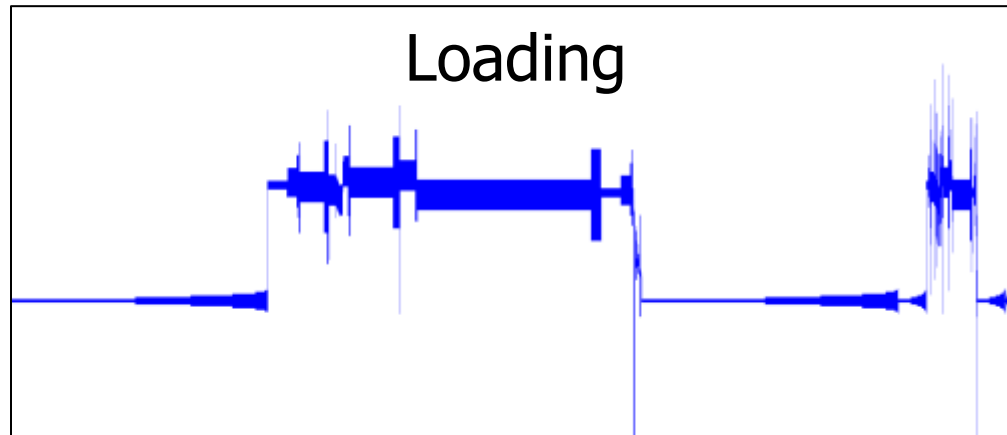


Input Parameters

Multiple Random Variables



| Parameter | Value |
|-----------|---------|
| T | 0.09 in |
| W | 4.0 in |



Mat. Prop.

Walker Equation Data

The Walker equation extended the early Paris equation by allowing the shift in da/dN vs. ΔK as a function of stress ratio (R). The equation may be used in several segments to attempt to model the sigmoidal shape of the data.

Use up to 5 sets of values of 'C', 'n' and 'm'

Number of Sets: 1

| Set | C | n | m |
|-----|-------------|-------------|-----|
| 1 | 2.5300e-009 | 1.200000002 | 0.5 |
| 2 | 1e-000 | 1 | 0.5 |
| 3 | 1e-000 | 1 | 0.5 |
| 4 | 1e-000 | 1 | 0.5 |
| 5 | 1e-000 | 1 | 0.5 |

Material name: User defined data

Coefficient of Thermal Expansion: 1.249999968 Young's Modulus: 10600
 Yield Strength, YLD: 56.00000023 Poisson's Ratio: 0.330000011

Plane Stress Fracture Toughness, KIC: 100
 Plane Strain Fracture Toughness, KIC: 35 Lower limit on R shift (0. -1): 0.99
 Delta K threshold value @R=0: 2 Upper limit on R shift (x 1): 0.99

OK Cancel Save Read Apply

| 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



SMART - Small Aircraft Risk Technology

File Documentation

Overview Fracture Loading

Method

- Master Curve
- Surrogate Model (Kriging)
- Afgrow

Master Curve User Parameters

Master Curve Toughness: 44.5

Afgrow Model: Single Corner Crack at Hole (1030)

Show Afgrow

Material Properties

Plane Strain Fracture Toughness: 30.0

Poisson's Ratio: 0.33

Upper Limit on R shift: 0.99

Lower Limit on R shift: -0.99

Coefficient of Thermal Expansion: 1.25e-5

Delta K Threshold Value: 0.1

Young's Modulus: 10600.0

Afgrow M: 0.5

Used Nasa Template File

File: Browse...

Model Type:

Random Variables

| Prob. | Mean | Standard Deviation |
|--|-------|--------------------|
| Initial Crack Size Lognormal (μ, σ) | 0.05 | 0.001 |
| <input type="checkbox"/> a/c: | 1.0 | 0.0 |
| <input checked="" type="checkbox"/> Fracture Toughness: | 44.5 | 3.8 |
| <input checked="" type="checkbox"/> Paris Constant Log(c): | -8.58 | 0.10 |
| <input type="checkbox"/> Paris Constant m: | 2.7 | 0.0 |
| <input checked="" type="checkbox"/> Hole Diameter: | 0.25 | 0.025 |
| <input type="checkbox"/> Yield Stress: | 56.0 | 0.0 |
| <input type="checkbox"/> Ultimate Stress: | 80.0 | 0.0 |
| <input type="checkbox"/> Hole Offset: | 2.0 | 0.0 |

Corr: 0.0

PDF/CDF

PDF/CDF

PDF/CDF

PDF/CDF

PDF/CDF

PDF/CDF

PDF/CDF

PDF/CDF

PDF/CDF

Geometry Properties

Width: 4.0

Thickness: 2.0

Crack Size Limit:

Output Interval

Crack Growth: 0.0007

07/10/2015-V4.0.7



Numerical Integration AFGROW Run



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File Input Edit View Predict Tools Repair Initiation Window Help

Status

- Example Problem
- User defined data (Walker Equation)
- Stress State
- Spectrum
- No Spectrum Filters
- No Retardation
- No K-Solution Filters
- No Residual Stresses

Max stress = 14.880 $r = 0.78$ 448993 Cycles Created: 2/26/2009 4 Pass: 4

C Crack size= 0.0022702 Beta Tension= 1.9598 Beta Compression= 1.9598 R(k)= 0.7796 R(final)= 0.7796 Delta k=5.4286e-001 D(I)/DN=2.0926e-009
A Crack size= 0.0022702 Beta Tension= 1.9715 Beta Compression= 1.9715 R(k)= 0.7796 R(final)= 0.7796 Delta k=5.4611e-001 D(I)/DN=2.1368e-009
A/A ratio= 0.025224 A/C ratio= 1

Max stress = 14.880 $r = 0.78$ 448993 Cycles Created: 2/26/2009 4 Pass: 4

Executing Predict Life Function English



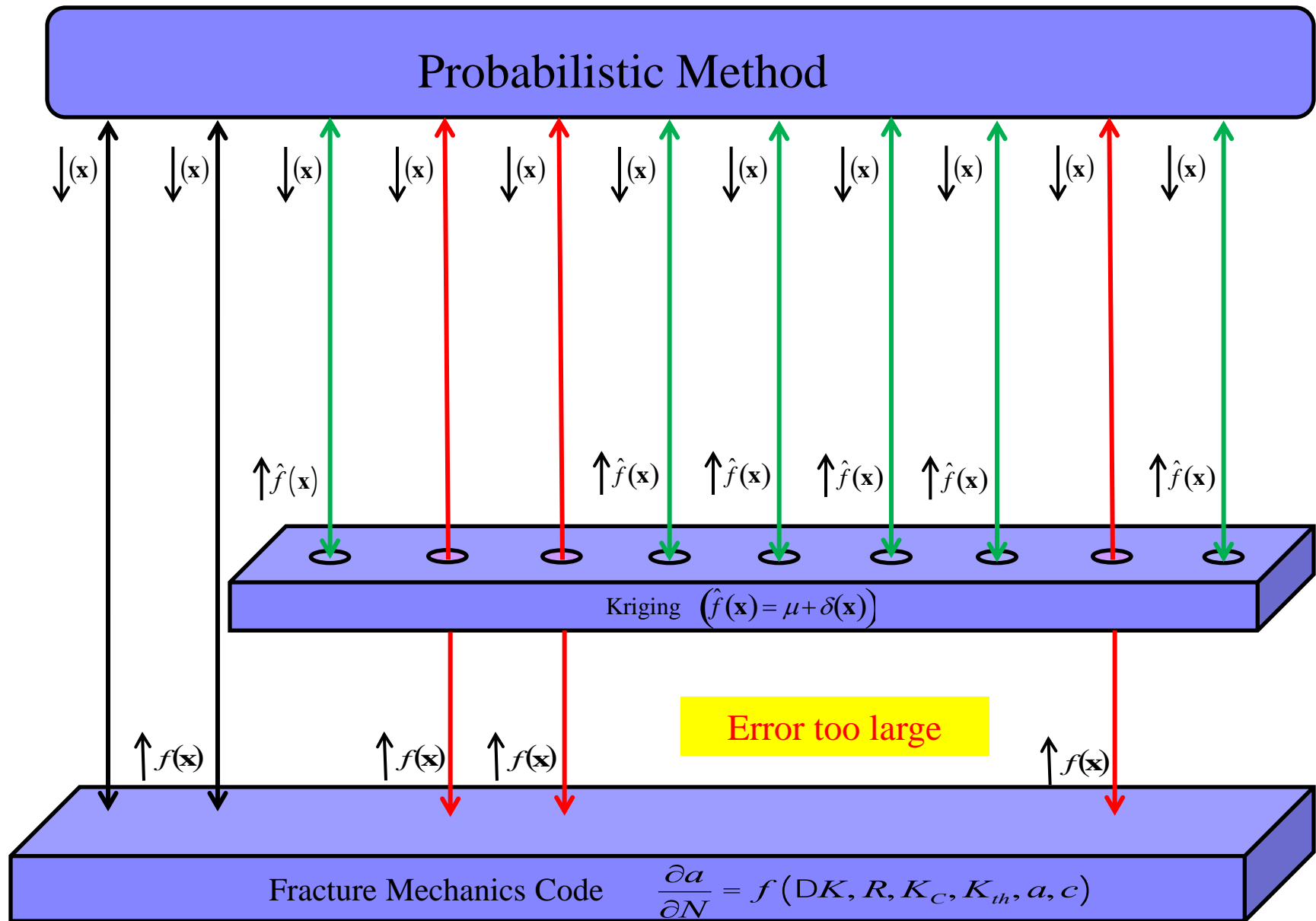
Kriging Approach



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Surrogate Model Schematic



○ User Defined Error
 — Initial Training Points
 (\mathbf{x}) Vector of Random Variables

— Additional Training Points (Kriging Error > User Error)
 — Kriged Points (Kriging Error < User Error)



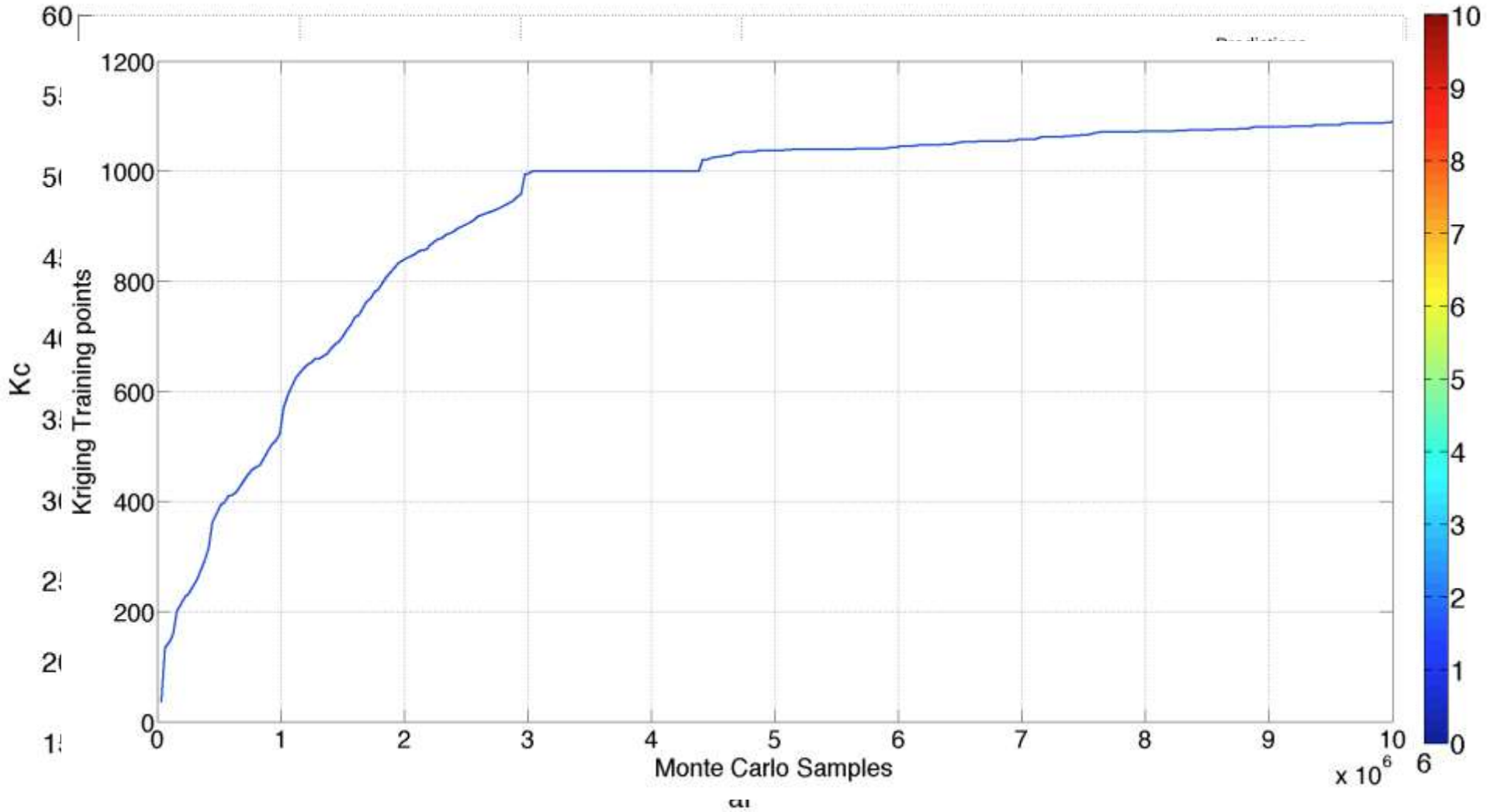
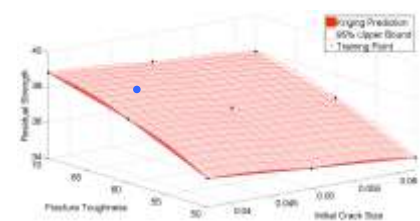
Kriging Summary



- ✓ Multiple random variables
 - ✓ a_i , K_c , 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



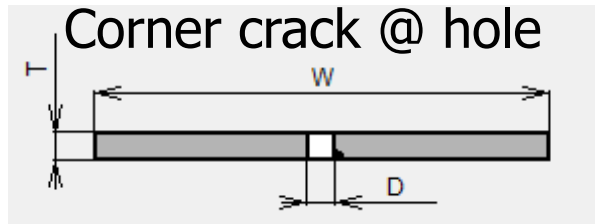
Kriging Schemetic



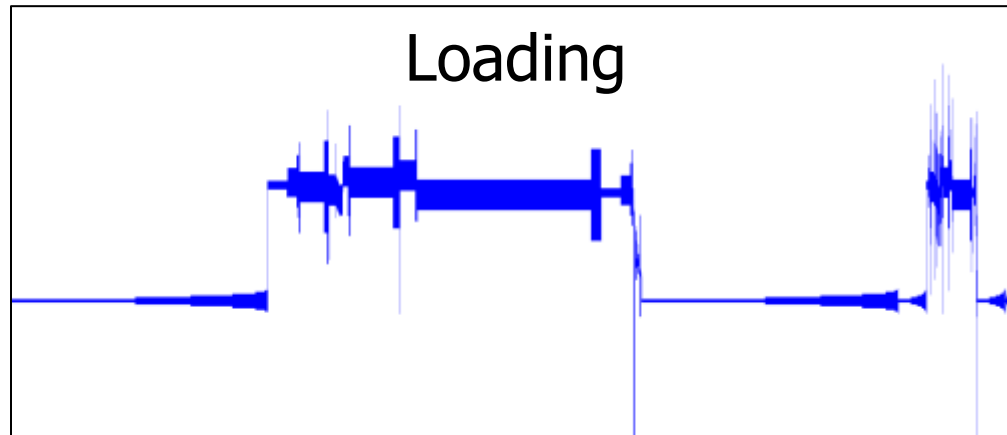


Input Parameters

Multiple Random Variables



| Parameter | Value |
|-----------|---------|
| T | 0.09 in |
| W | 4.0 in |



Mat. Prop.

Walker Equation Data

The Walker equation extended the early Paris equation by allowing the shift in da/dN vs. ΔK as a function of stress ratio (R). The equation may be used in several segments to attempt to model the sigmoidal shape of the data.

Use up to 5 sets of values of 'C', 'n' and 'm'

Number of Sets: 1

| Set | C | n | m |
|-----|-------------|-------------|-----|
| 1 | 2.5300e-009 | 1.200000002 | 0.5 |
| 2 | 1e-000 | 1 | 0.5 |
| 3 | 1e-000 | 1 | 0.5 |
| 4 | 1e-000 | 1 | 0.5 |
| 5 | 1e-000 | 1 | 0.5 |

Material name: User defined data

Coefficient of Thermal Expansion: 1.249999968 Young's Modulus: 10600
 Yield Strength, YLD: 56.00000023 Poisson's Ratio: 0.330000011

Plane Stress Fracture Toughness, KIC: 100
 Plane Strain Fracture Toughness, KIC: 35 Lower limit on R shift (0. -1): 0.99
 Delta K threshold value @R=0: 2 Upper limit on R shift (x 1): 0.99

OK Cancel Save Read Apply

| 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 POF Results



C:\Users\pze593\Desktop\AFGROW>SMART.exe Afgrow_example1.d

SMART - Small Aircraft Risk Technology

File Documentation

Overview Fracture Loading

Method

- Master Curve
- Surrogate Model (Kriging)
 - Afgrow Generated
- External Crack Growth Code

Master Curve User Parameters

Master Curve Toughness: 44.5

Afgrow Model: Single Corner Crack at Hole (1030)

Show Afgrow

Material Properties

Plane Strain Fracture Toughness: 30.0

Poisson's Ratio: 0.33

Upper Limit on R shift: 0.99

Lower Limit on R shift: -0.99

Coefficient of Thermal Expansion: 1.25e-5

Delta K Threshold Value: 0.1

Young's Modulus: 10600.0

Afgrow M: 0.5

Limit Nisego Template File

File: Browse...

Model Type: -

Random Variables

| Prob. | Mean | Standard Deviation |
|--|-------|--------------------|
| Initial Crack Size Lognormal (µm) | 0.05 | 0.001 |
| <input type="checkbox"/> a/c: | 1.0 | 0.0 |
| <input checked="" type="checkbox"/> Fracture Toughness: | 44.5 | 3.8 |
| <input checked="" type="checkbox"/> Paris Constant Log(p): | -8.58 | 0.10 |
| <input type="checkbox"/> Paris Constant m: | 2.7 | 0.0 |
| <input checked="" type="checkbox"/> Hole Diameter: | 0.25 | 0.025 |
| <input type="checkbox"/> Yield Stress: | 36.0 | 0.0 |
| <input type="checkbox"/> Ultimate Stress: | 80.0 | 0.0 |
| <input type="checkbox"/> Hole Offset: | 2.0 | 0.0 |

Corr: 0.0

Geometry Properties

Width: 4.0

Thickness: 2.0

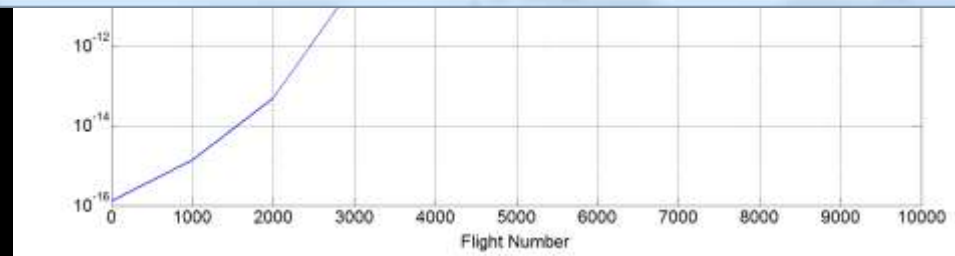
Crack Size Limit:

Output Interval

Crack Growth: 0.0007

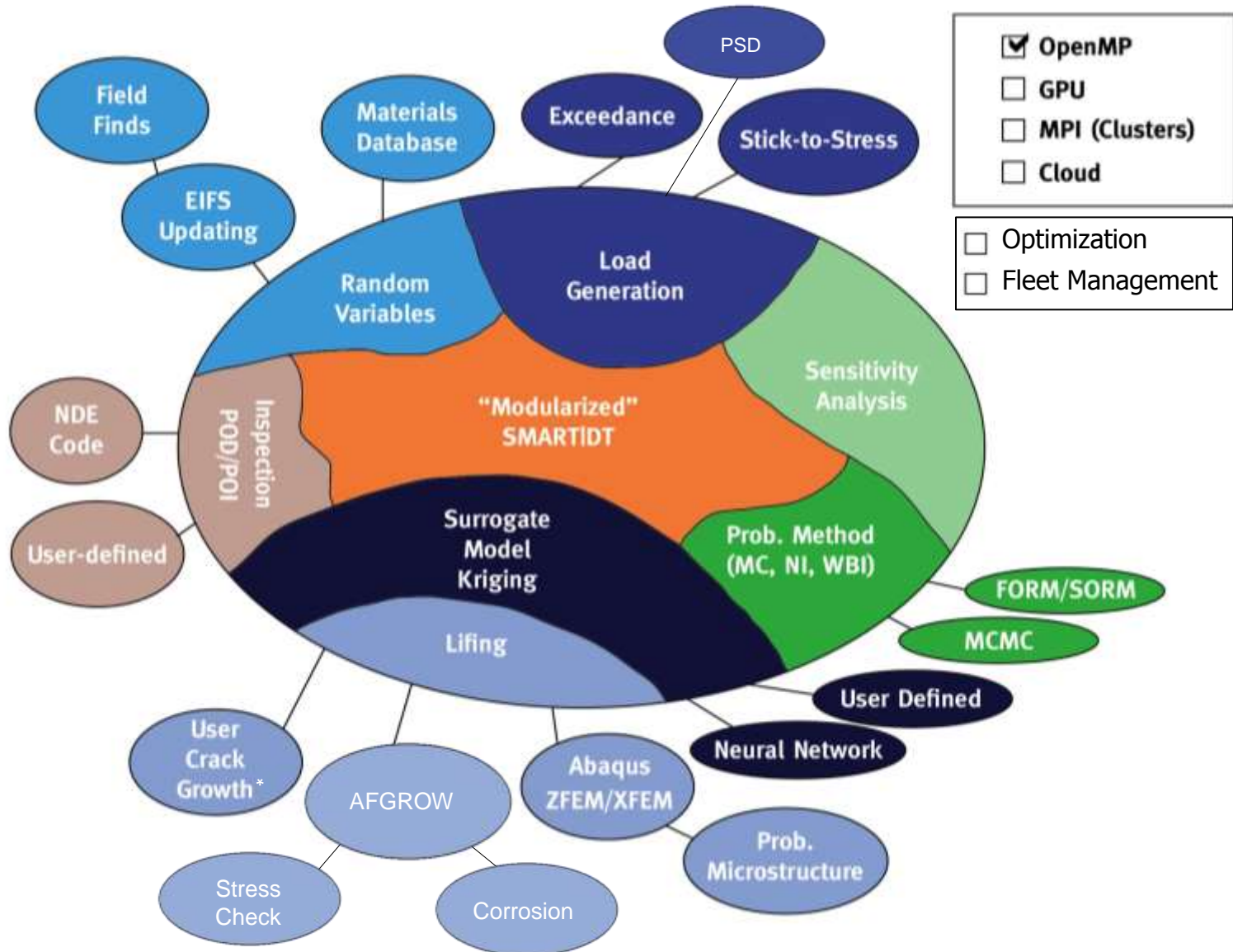
PDF/CDF buttons: PDF/CDF, PDF/CDF, PDF/CDF, PDF/CDF, PDF/CDF, PDF/CDF, PDF/CDF, PDF/CDF

07/10/2015-V4.0.7





Plays well with Others





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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