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Development and Demonstration of Damage Tolerance Airframe Digital Twin Methods and Tools

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ICAF International Committee on Aeronautical Fatigue and Structural Integrity

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CF-188A/B

No. of aircraft: 138

Initial service life: 6,000 h

Safe-life

⬇

Damage tolerance

✚

Risk assessment

F-35A

No. of aircraft: 88

Initial service life: 8,000 h (90% of fleet)

Durability and damage tolerance life requirements (MIL-STD 1530)

Can we do better than current ASIP force management execution methods?

Source: https://www.canada.ca/en/air-force/services/aircraft/cf-188.html

Outline

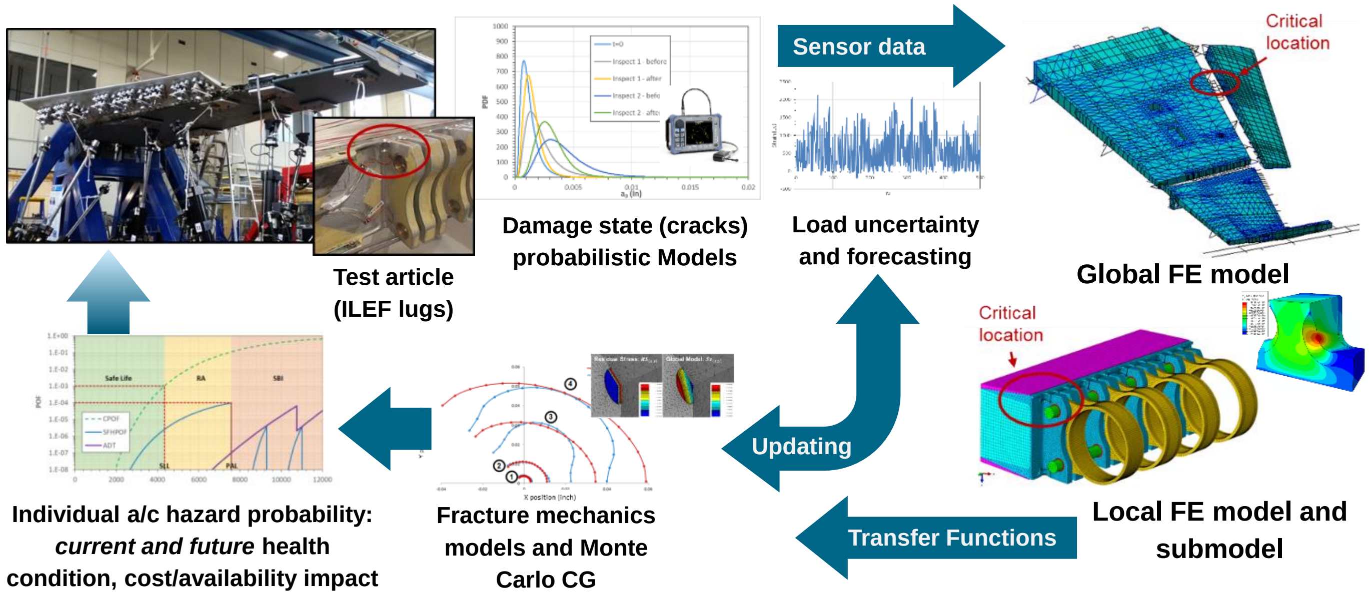
- Definition
- Overview of NRC’s Airframe Digital Twin Framework
- Initial Crack Size Distribution (ICSD)
- Bayesian Inference of Crack Size Distribution (CSD)
- CF-188 Case Study
- Concluding Remarks

Airframe Digital Twin (ADT)

Definition

Digital representation that mirrors and predicts usage and performance over the life of a specific individual airframe.

- Representative of as-built, as-operated, and as-maintained airframe system
- Simulations that use best available models, sensor information, and data
- Multi-physics, multi-scale, probabilistic



More representative digital models

More accurate structural integrity assessments

Better-informed maintenance decisions

Airframe Digital Twin (ADT) Framework

Overview

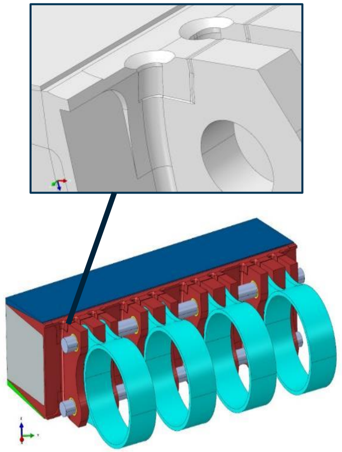
Each fatigue critical area (FCA) of each aircraft is unique:

- **Physical model:**
  - Nominal dimensions and properties
  - Distinct dimensions and properties (as needed)

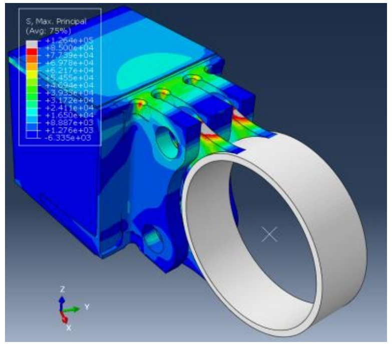
Airframe Digital Twin (ADT) Framework

Overview

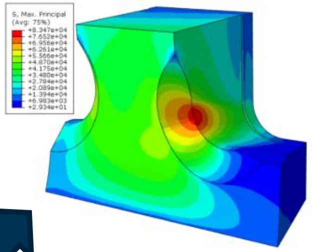
CF-188 inboard leading edge flap lugs with modifications



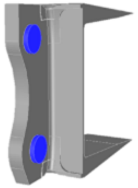
Representative CAD



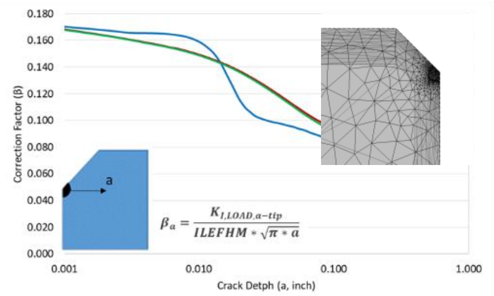
Local Model

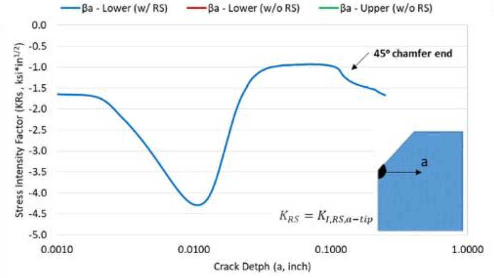


Sub-Modelling



Simplified Local Modelling

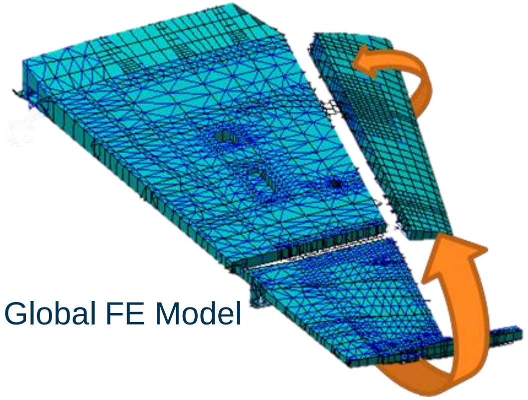




Fracture Mechanics Analyses

AFGROW

NASGRO



Global FE Model

Picture from Korona Lacasse
Source: https://en.wikipedia.org/wiki/McDonnell_Douglas_CF-18_Hornet

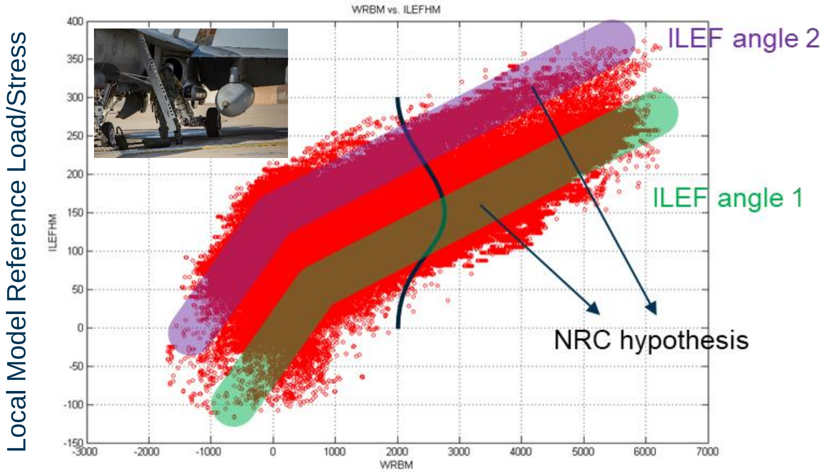
Airframe Digital Twin (ADT) Framework

Overview

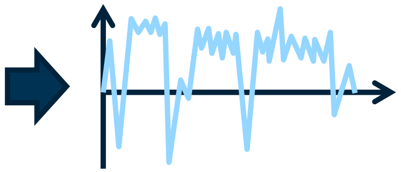
Each fatigue critical area (FCA) of each aircraft is unique:

- **Usage**:
  - Past History: IAT data (strains, accelerations, maneuvers, mission, etc.)
  - Forecast: Random spectra based on expected mission mix

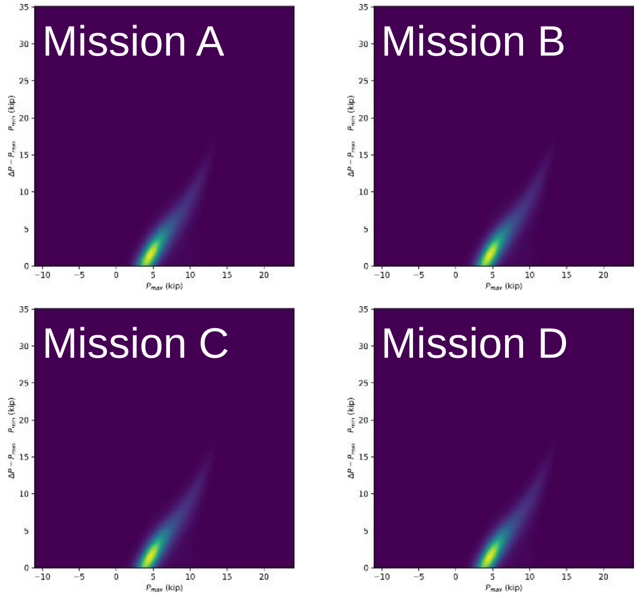
From IAT Data → Loading Spectrum

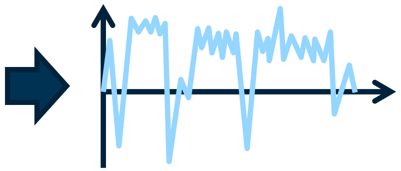


Individual Aircraft Tracking Data



From IAT Historic Data → Loading Spectrum





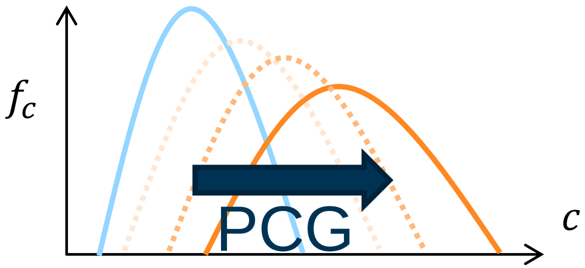
Airframe Digital Twin (ADT) Framework

Overview

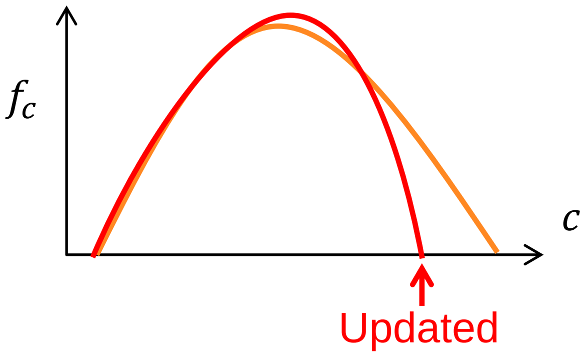
Each fatigue critical area (FCA) of each aircraft is unique:

- **Damage**:
  - Past History: Predicted crack size distribution over time based on known usage
  - Update: Infer crack size distribution from NDI results at inspection
  - Forecast: Forecast crack size distribution from projected usage

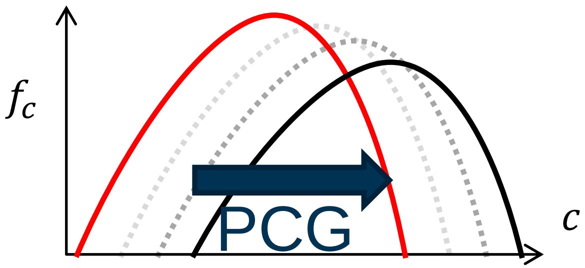
Past → Present
(known usage)



Present → Updated
(Bayesian inference from NDI)



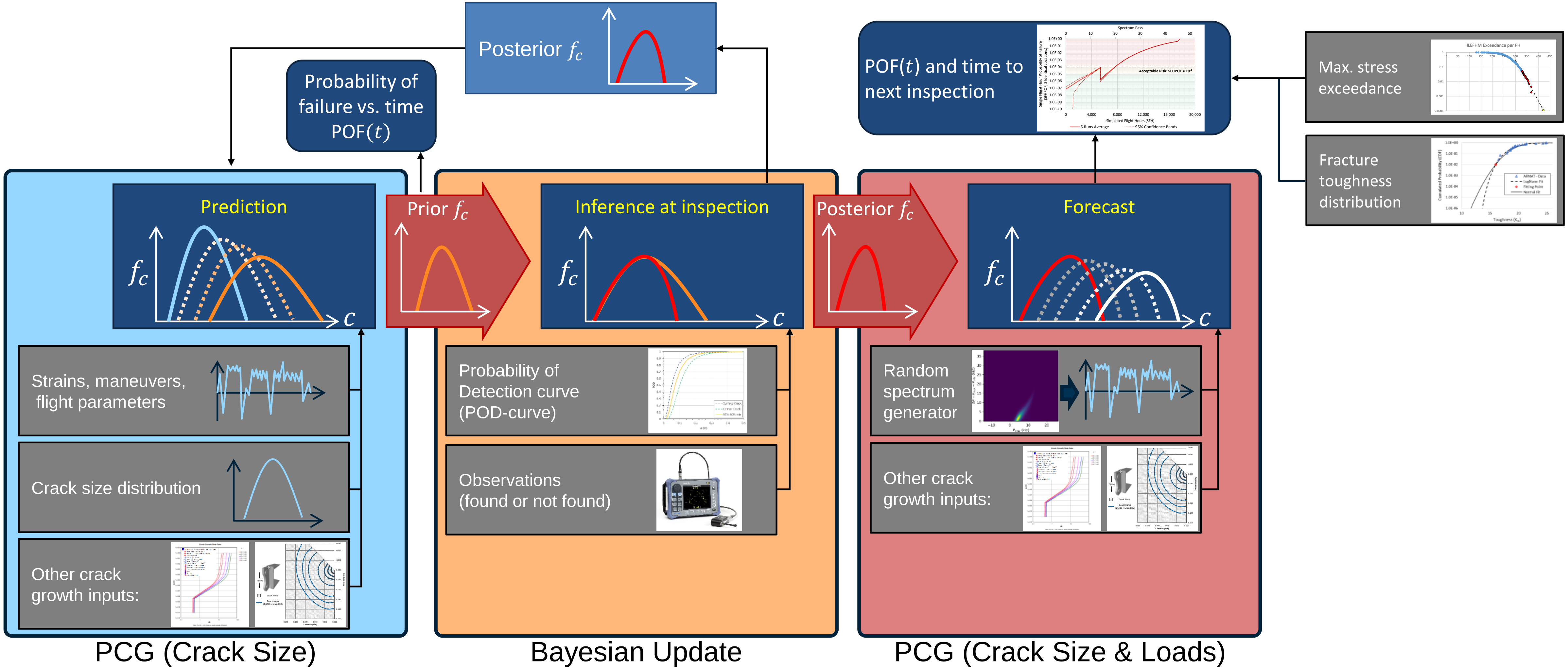
Updated → Future
(unknown usage)



PCG: Probabilistic Crack Growth

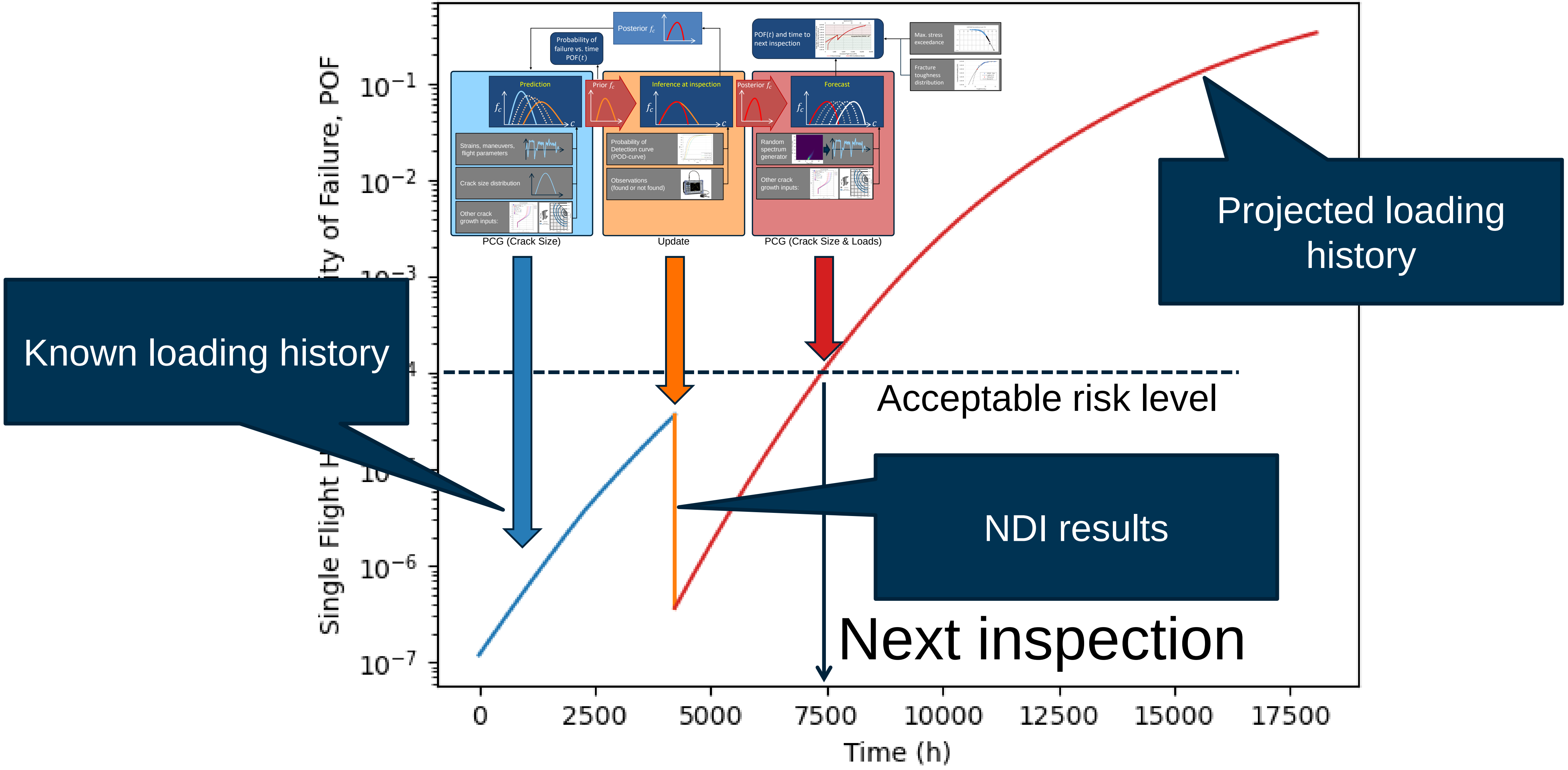
Airframe Digital Twin (ADT) Framework

Concept



Airframe Digital Twin (ADT) Framework

Conceptual Example with a Single Inspection



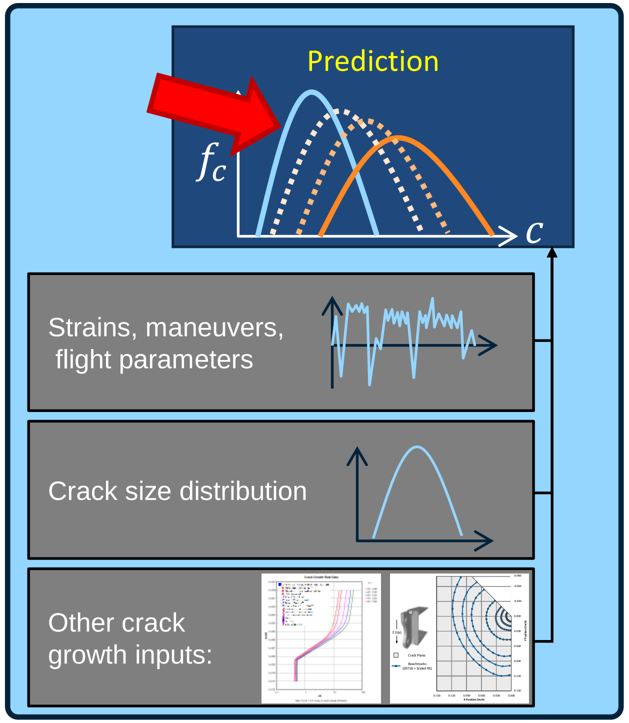
Initial Crack Size Distribution

- **Initial crack size distribution has significant effect on the resulting POF and inspection intervals.**
- **Many approaches:**

Easy to solve using Bayes inference.
Requires POD-curve and prior crack size distribution.

  - Probability of missing a crack after manufacturing:
    - From un-informed prior crack size distribution (i.e. uniform)
    - From known prior crack size distribution
  - Quantitative fractography
  - Mixing different sources of nucleation features:
    - Pores
    - Corrosion pits
    - Scratches
    - …

Focus of today's discussion



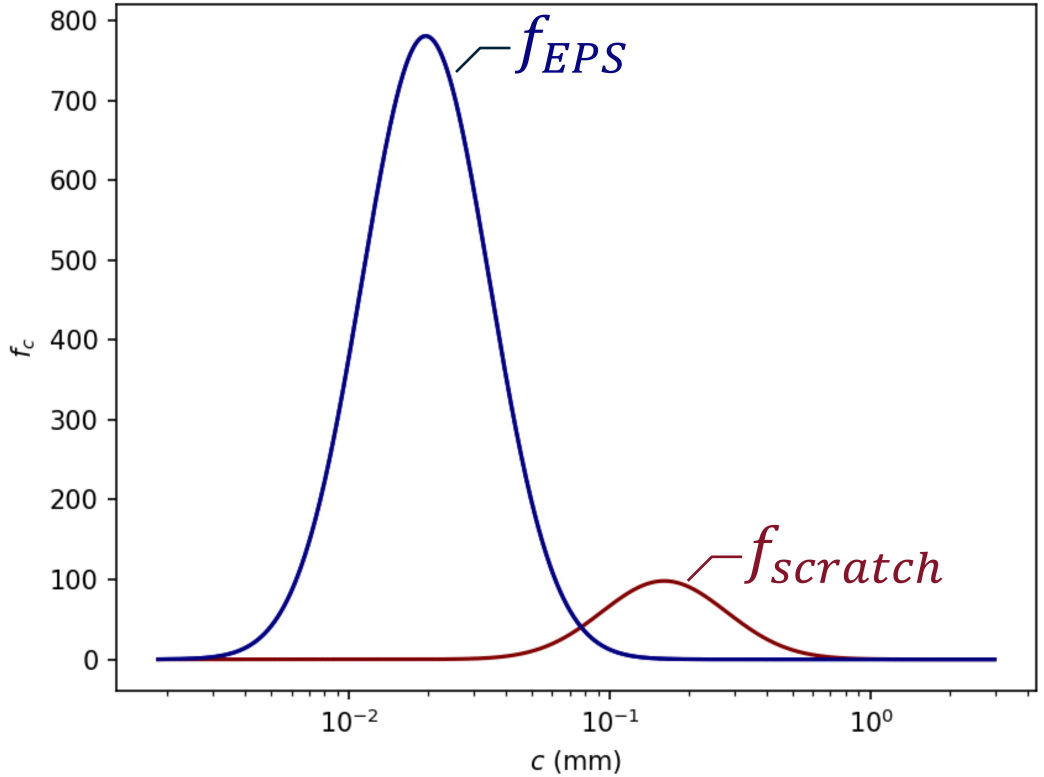
Initial Crack Size Distribution (ICSD)

Mixture Distribution Model

The ICSD was represented using a mixture model:

$$f_c = w f_{scratch} + (1 - w) f_{EPS}$$

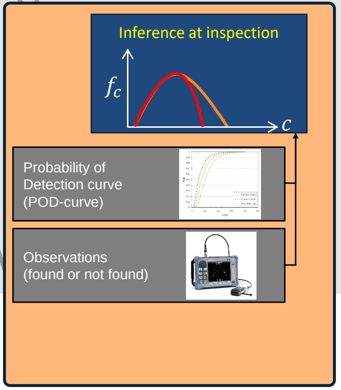
f_{EPS}	Equivalent Precrack Size (EPS) distribution from specimens that were peened. Most cracks nucleated from laps and folds produced by peening[1]
$f_{scratch}$	Scratch size distribution[2]
w	Probability of having a scratch [0,1]
f_c	Crack size distribution (mixture model)
c	Crack size



NOTES:
1: L. Molent, Q. Sun, and A. Green, "Characterisation of equivalent initial flaw sizes in 7050 aluminium alloy," Fatigue & Fracture of Engineering Materials & Structures, vol. 29, no. 11, pp. 916-937, 2006.
2: D. Ball, "Examination of Durability and Damage Tolerance Design Criteria," in USAF Aircraft Structural Integrity Program Conference, San Antonio, Texas, United States of America, 2012.

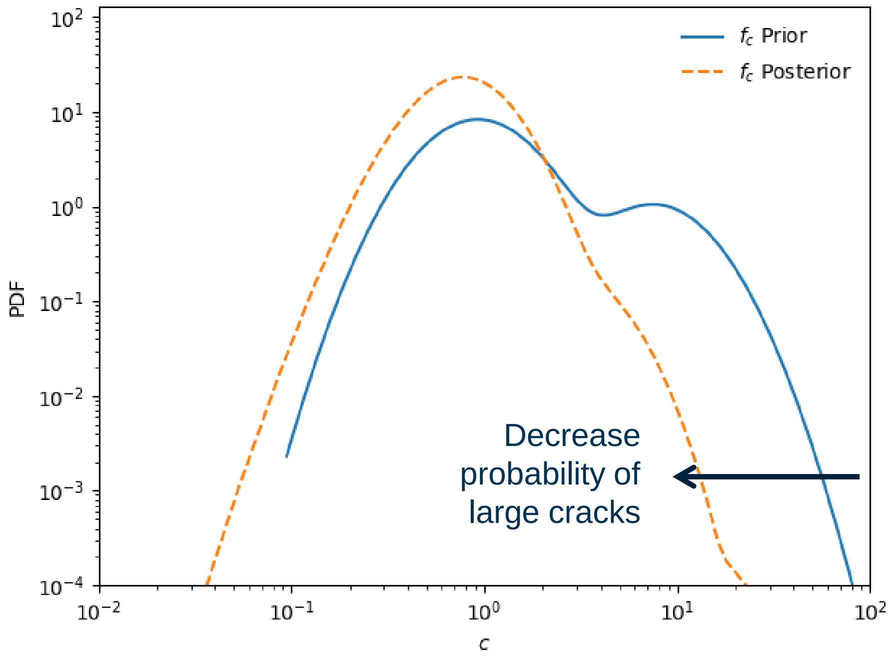
Bayesian Inference of Crack Size Distribution (CSD)

Two Approaches; Two Meanings



Direct CSD inference:

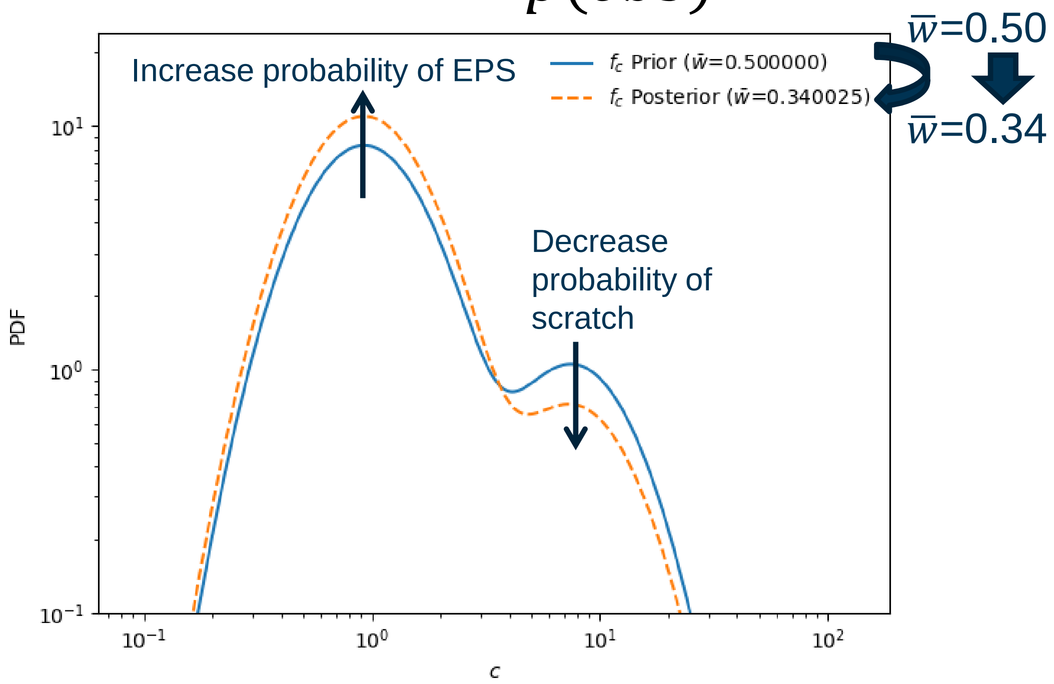
$$p(c|obs) = \frac{p(obs|c)p(c)}{p(obs)}$$



Modifies the constituting mixture distributions

Mixture weight inference:

$$p(w|obs) = \frac{p(obs|w)p(w)}{p(obs)}$$



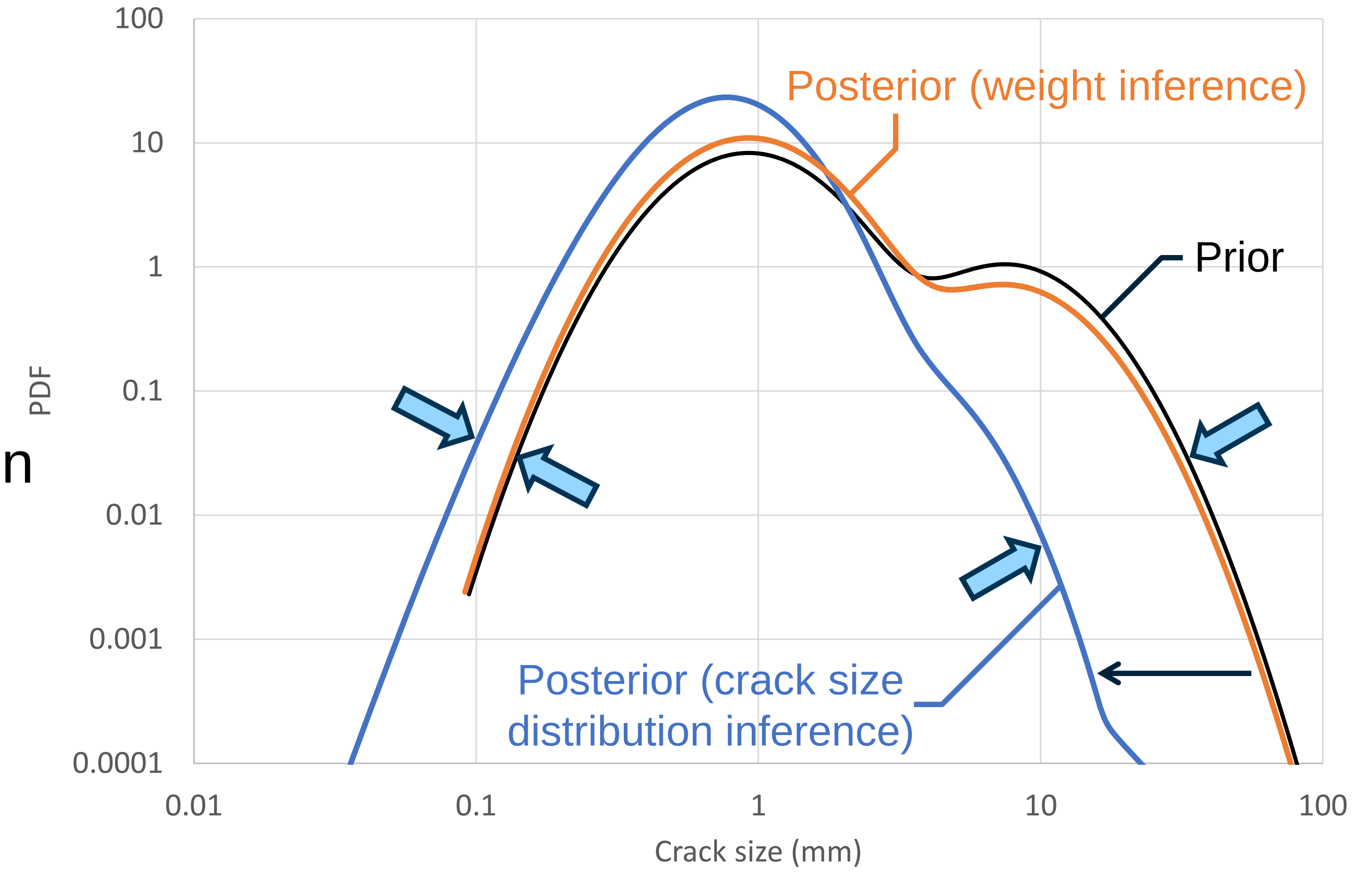
Modifies the weight of the constituting distributions (constituting mixture distributions are intact)

Bayesian Inference of Crack Size Distribution (CSD)

Two Approaches; Two Meanings

Direct CSD inference:

- ⊕ If NOT confident in constituting ICSD
- ⊕ More impact on CSD (and risk)
- ⊖ Mixture cannot be separated after inference
- ⊖ Can growth slower than EPS distribution

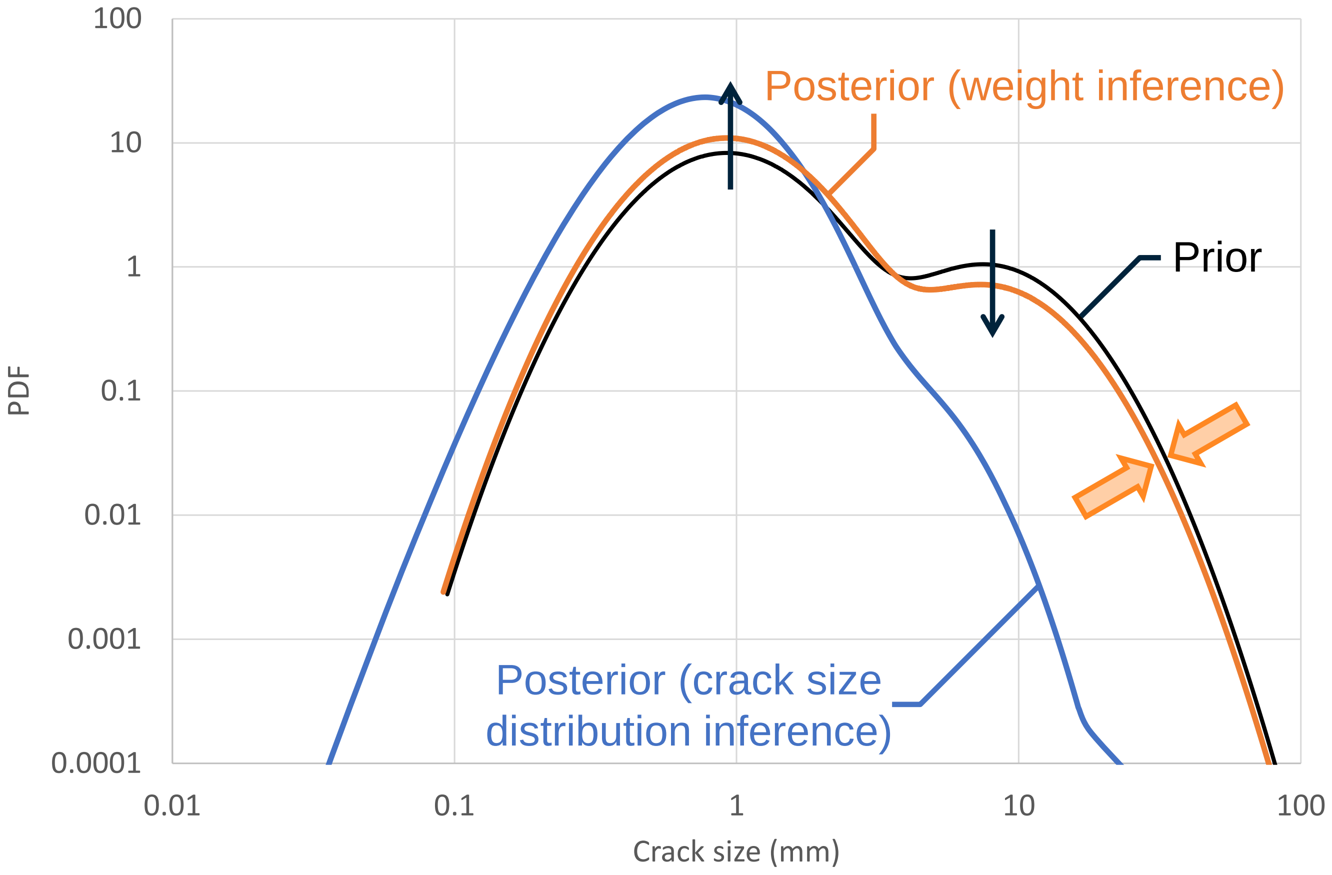


Bayesian Inference of Crack Size Distribution (CSD)

Two Approaches; Two Meanings

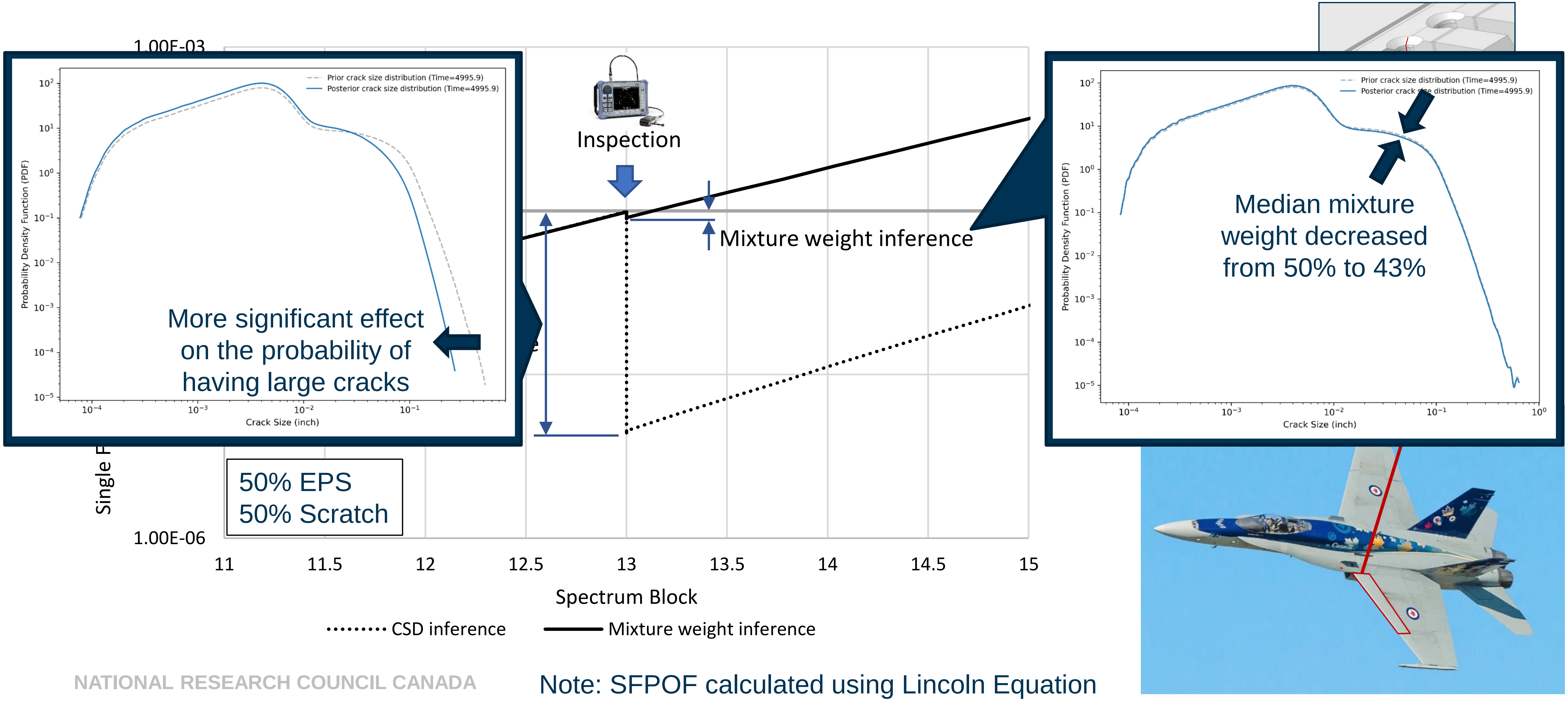
Mixture weight inference:

- (+) If confident in constituting ICSD
- (+) Cannot grow slower than EPS distribution
- (+) Constituting CSD can be used fleet wide; weight adjusted on a tail-basis
- (+) Numerical advantage for sampling
- (−) No significant impact on resulting CSD for tested cases. Further investigation required.



CF-188 Inboard Leading Edge Flap (ILEF) Lugs

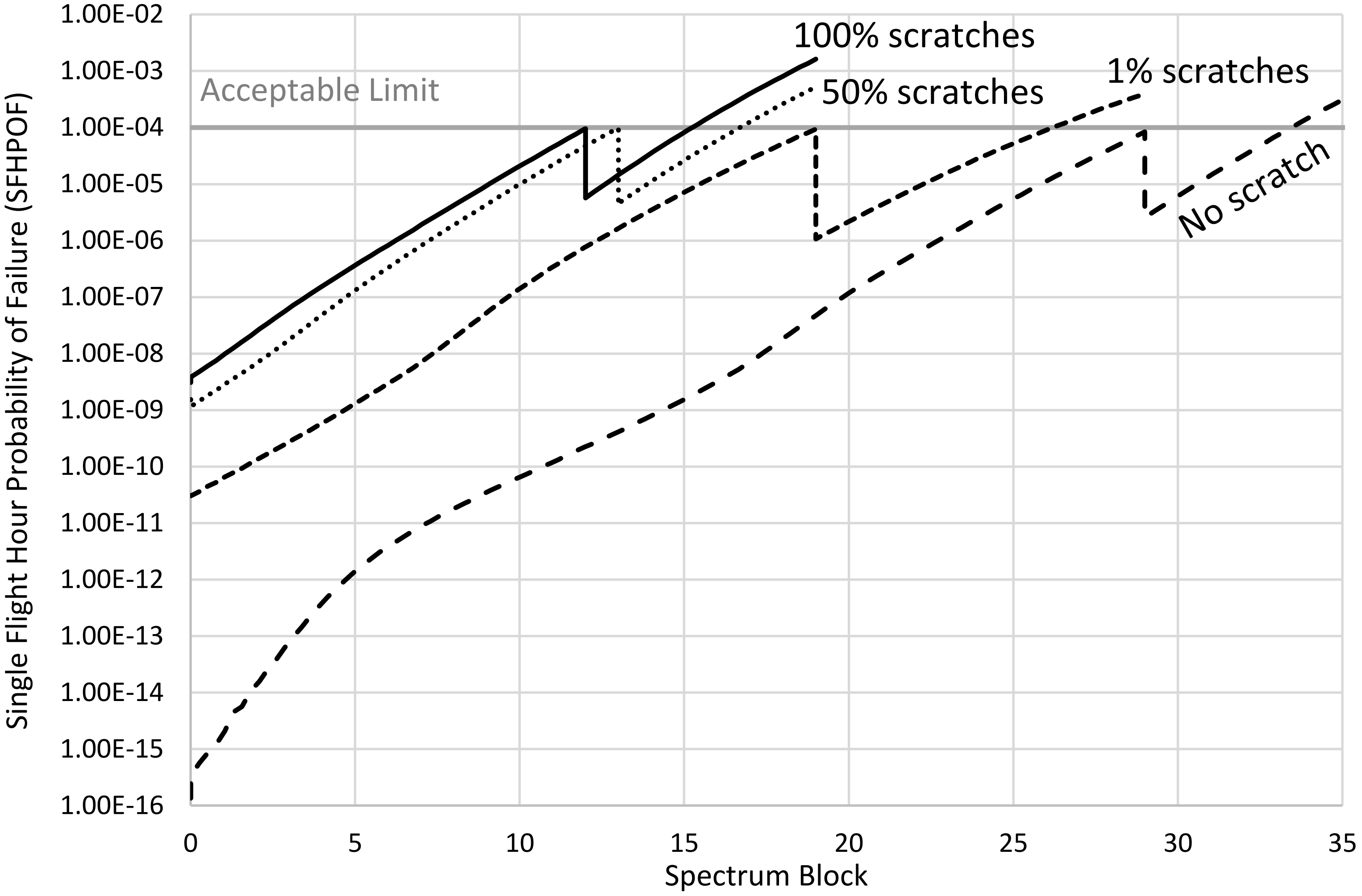
Effect of Inference Methods



Note: SFPOF calculated using Lincoln Equation

CF-188 Inboard Leading Edge Flap Lugs

Effect of Probability of Nucleating from a Scratch



Decreasing the % of cracks nucleating from scratches:

- Decreases risk
- Increases time to acceptable risk limit (10^{-4} SFHPOF)
- Affects inspection interval

Assuming that 100% of cracks are nucleating from scratches is possibly conservative but is it realistic?

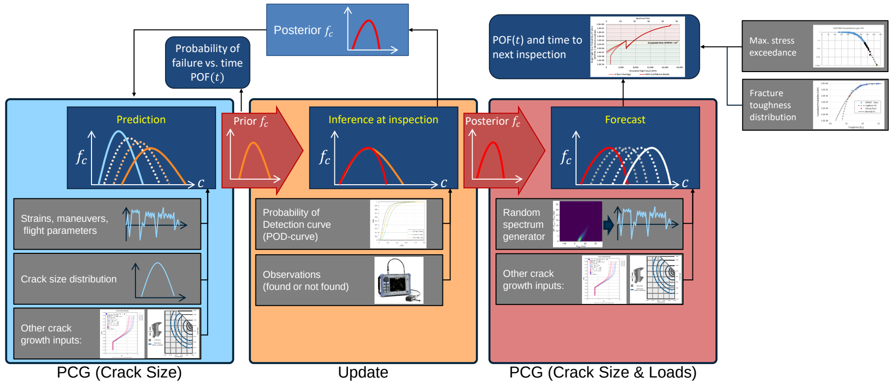
ICSD modelling using mixture model provides the flexibility of adjusting the assumptions based on data and engineering assumptions.

Note: SFPOF calculated using Lincoln Equation

Concluding Remarks

ADT Framework

- **NRC developed an ADT framework and in-house algorithms**
- **Features:**
  - Probabilistic crack growth algorithms
  - Probabilistic load estimations and forecasting
  - High-fidelity finite element models
  - Crack size updating from non-destructive inspection results
  - Advanced risk-based approaches

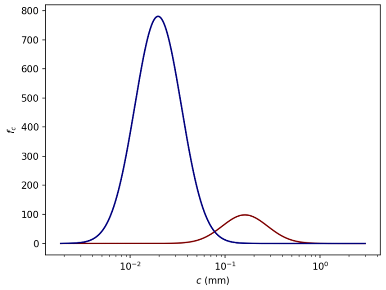


- **ADT Framework successfully tested using CF-188 Inboard Leading Edge Flap (ILEF) component test**
  - Used as a benchmark problem for the development and testing of new features
  - Comparison with CF-188 Lifing Methods
  - Sensitivity analyses

Concluding Remarks

Crack Size Distribution Modelling using Mixture Distributions

- **Used to mix identifiable and quantifiable sources of damage**
  - Specimens: typically only pores or surface features
  - In-service findings: pores, surface features, scratches, corrosion pits,...
  - Probability of having scratches and pits could increase over time…



- **Different initial damage types could have different growth models:**
  - Crack growth models for pores and scratches (function of loading cycles)
  - Corrosion models for pits (function of time and environment)
  - Synergy between the models: pits $\rightarrow$ fatigue cracks

QUESTIONS?

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