NRC·CNRC

Development and Demonstration of a Digital Twin Analysis Framework for Airframe Life Assessment

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Introduction

Background

Current Airframe Life Cycle Management

- Current methods can be overly conservative when accounting for uncertainties and variability in individual aircraft manufacturing, usage, and potential damage.
- This conservatism can lead to prolonged downtime, unnecessary fleet-wide inspections, and increased operating costs.

Background

NRC/RCAF Airframe Digital Twin (ADT) Project

- Objective: Develop and assess the adaptability of the ADT technology to Royal Canadian Air Force (RCAF) fleets.
- Approach: Probabilistic crack growth modelling, probabilistic usage forecasting, Bayesian model updating, high-fidelity structural modelling, quantitative risk assessment of individual aircraft components.
- Desired Outcome: Enhance the accuracy of individual airframe damage state diagnosis and prognosis to better inform maintenance decision making.

Digital Twin

"A virtual replica of a physical entity that is synchronized across time. Digital twins exist to replicate configuration, performance, or history of a system."

Source: MIL-HDBK-539 "DoD Handbook – Digital Engineering and Modelling Practices", Dec. 2022.

"A set of virtual information constructs that mimics the structure, context and behavior of an individual/unique physical asset, or a group of physical assets, is dynamically updated with data from its physical twin throughout its life cycle and informs decisions that realize value."

Source: "Digital Twin: Definition & Value – An AIAA and AIA Position Paper", Dec. 2020.

Airframe Digital Twin

"A digital representation, i.e. an integrated multi-physics, multi-scale, probabilistic simulation of an as-built/as-maintained airframe system that uses the best available models, sensor information and data, to mirror and predict activities/performance over the life of the corresponding individual airframe."

Adapted from Glaessgen, E. H., and Stargel, D. S., "The digital twin paradigm for future NASA and U.S. Air Force vehicles," 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference – Special Session on the Digital Twin, Honolulu, HI, Apr. 2012.

ADT Framework

ADT Framework

Overview

Digital twinning for sustainment based on the AFRL/GE P^2IAT framework[1] and demo

- Aircraft specific:
  - Physical properties (geometry, shot peening, cold work, etc.)
  - Individual aircraft tracking (IAT) and forecasting
- Quantitative risk assessment (QRA):
  - Probability of failure (POF) as a function of time
  - Quantified risk thresholds (hazard rates) linked to consequence of failure

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[1] E. Tuegel, "The Airframe Digital Twin: Some Challenges to Realization," in 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, Hawaii, United States of America, 2012.

ADT Framework

Overview

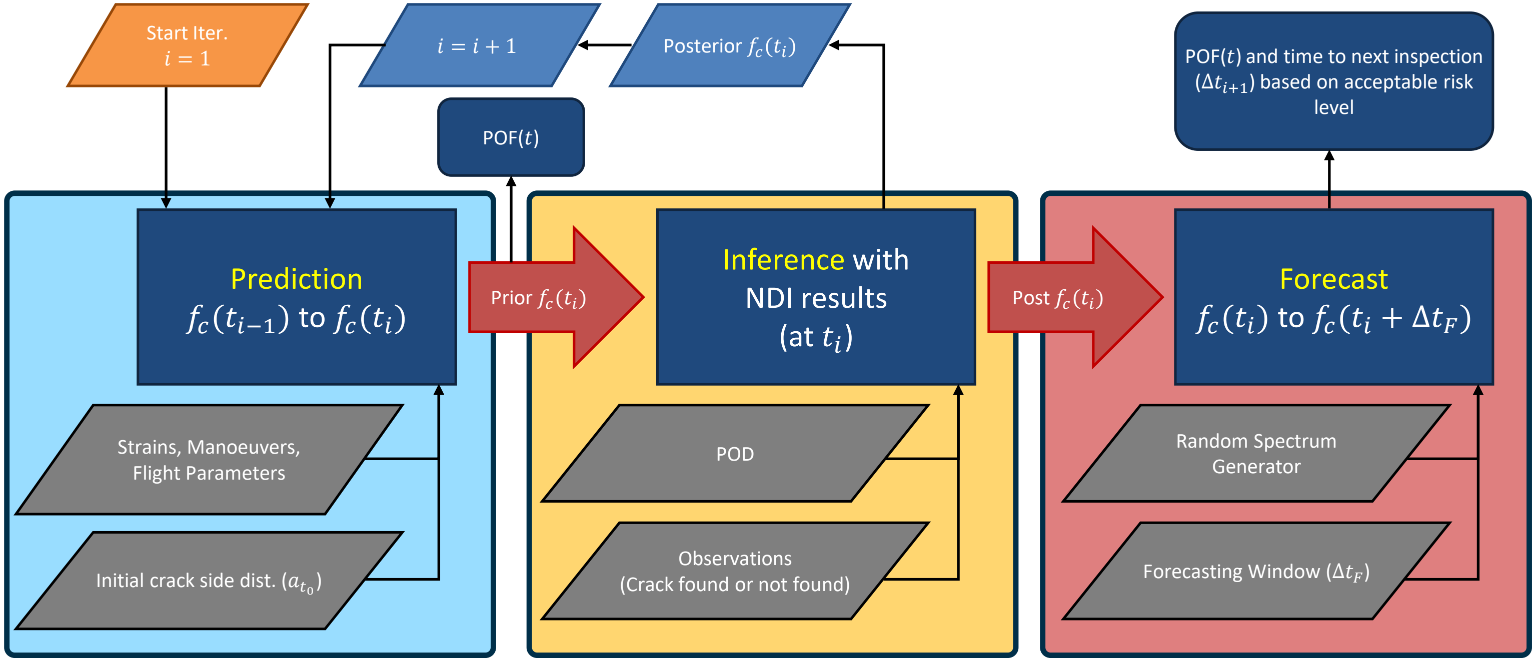
Digital twinning for sustainment based on the AFRL/GE P^{2}IAT framework and demo

- Probabilistic crack growth (fracture mechanics):
  - Uncertain usage, damage, fracture toughness
  - Physics-based, e.g. IDS or EPS approaches instead of EIDS*
  - Parameters uncertainty based on the level of confidence
- Individual model updating:
  - Probabilistic damage state (crack size distribution)
    - Periodic non-destructive inspection (NDI) results
    - Load history
  - Usage characteristics (forecasting)

* IDS: Initial discontinuity state
EPS: Equivalent pre-crack size
EIDS: Equivalent initial damage size

ADT Framework

Three-Phase Process



Start Iter.
$i = 1$

$i = i + 1$

Posterior $f_c(t_i)$

POF(t)

POF(t) and time to next inspection (Δt_{i+1}) based on acceptable risk level

Prediction
$f_c(t_{i-1})$ to $f_c(t_i)$

Strains, Manoeuvers, Flight Parameters

Initial crack side dist. (a_{t_0})

Prior $f_c(t_i)$

Inference with NDI results (at t_i)

POD

Observations
(Crack found or not found)

Post $f_c(t_i)$

Forecast
$f_c(t_i)$ to $f_c(t_i + \Delta t_F)$

Random Spectrum Generator

Forecasting Window (Δt_F)

Probabilistic Crack Growth
(crack size)

Crack Size Inference

Probabilistic Crack Growth
(crack size & loads)

t_i: time at i^{th} inspection

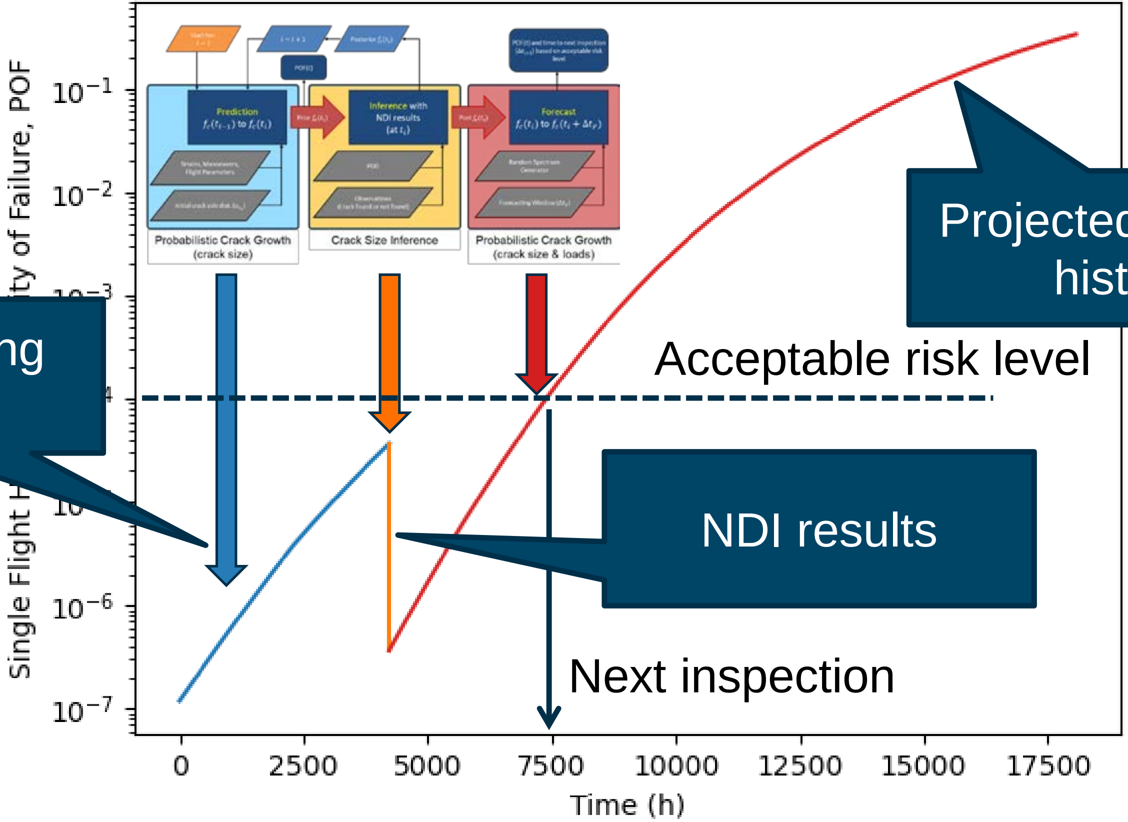
$f_c(t)$: crack size distribution at time t

Δt_F: forecasting period

POF(t): probability of failure at time t

ADT Framework

Three-Phase Process



Projected loading history

Acceptable risk level

Known loading history

NDI results

Next inspection

ADT Framework Demonstration

ADT Tech-Demo on CF-188 Inboard Leading Edge Flap (ILEF)

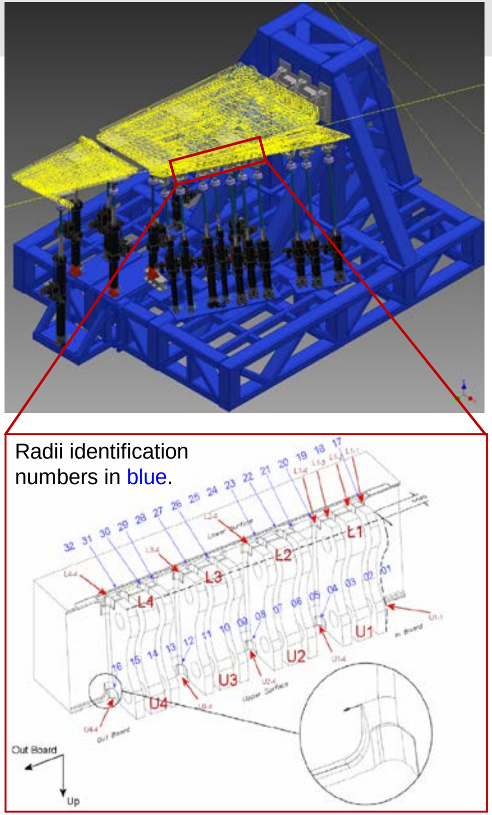
Demonstration Objectives:

- Develop, implement, validate the ADT Framework
  - Focus: practical/efficient implementation, sensitivity study of parameters and assumptions
- Assess feasibility on representative airframe component
  - Focus: gap analysis, adoptability
- Compare ADT with the current CF-188 life management methodology
  - Focus: potential benefits (e.g. more accurate life estimation, improved hazard probability/rate, etc.)

ADT Tech-Demo on RCAF CF-188 Inboard Leading Edge Flap (ILEF)

Physical Twin:

- Full-scale life extension test performed at NRC
- Life-limiting item: ILEF mounting lugs (retired) - same as in fleet (blend + shot-peening mod)
- Spectrum developed from IAT data
- Representative inspection methods
- Wing Root Bending Moment (WRBM) could be determined using the wing root strain measurements (similar to actual IAT)

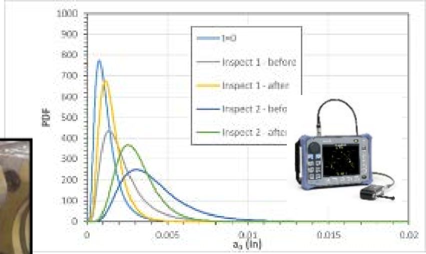

Radii identification numbers in blue.

FT382 and ILEF lug sets

CF-188 ILEF ADT Simulation

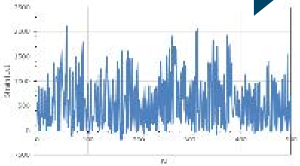
Main Elements

Test article (ILEF lugs)

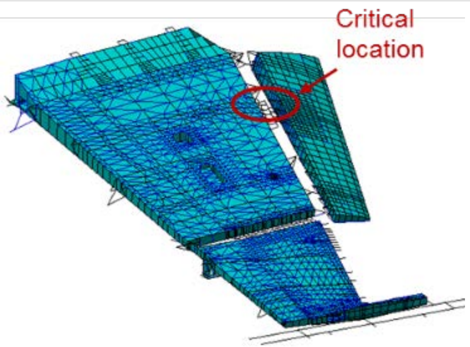


Damage state (cracks) probabilistic models

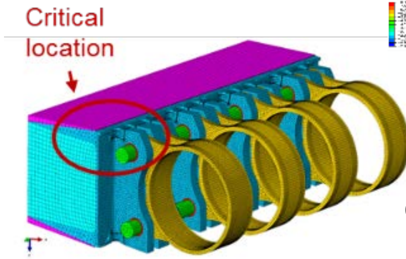
Sensor data

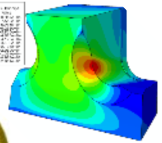


Load uncertainty and forecasting



Global FE model



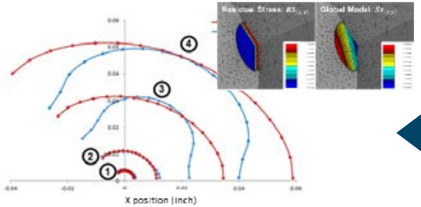


Mod geometry

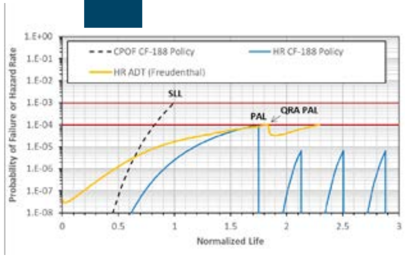
Local FE model and submodel

Transfer Functions

Updating



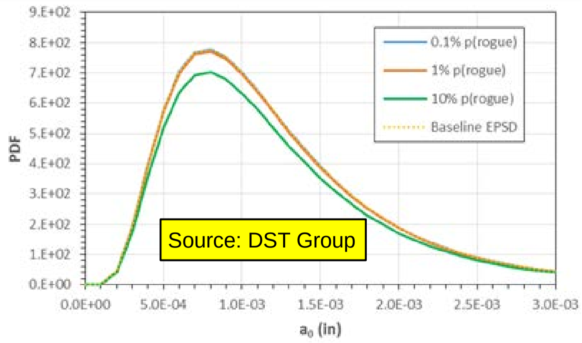
Fracture mechanics models incl. residual stresses / Monte Carlo crack growth



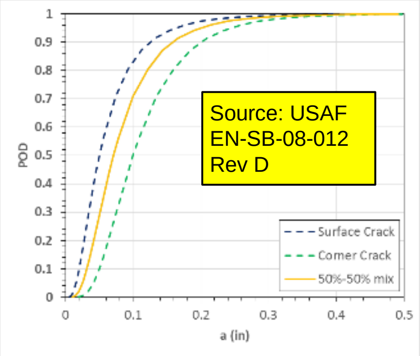
Individual a/c hazard probability: *current and future* health condition, cost/availability impact

CF-188 ILEF ADT Simulation

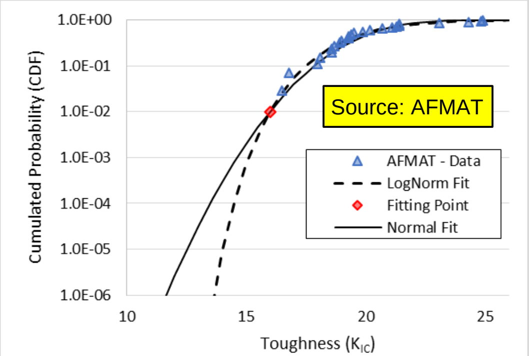
Major Analysis Inputs



Source: DST Group



Source: USAF EN-SB-08-012 Rev D

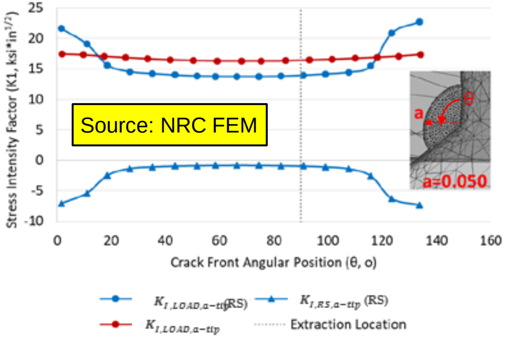


Source: AFMAT

Initial crack size distribution

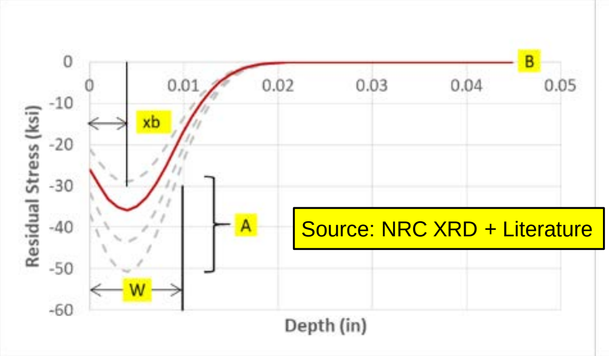
Probability of detection

Fracture toughness distribution



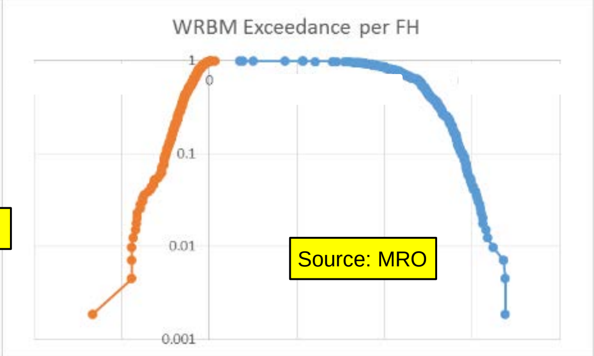
Source: NRC FEM

Stress intensity factor solution



Source: NRC XRD + Literature

Residual stress profile



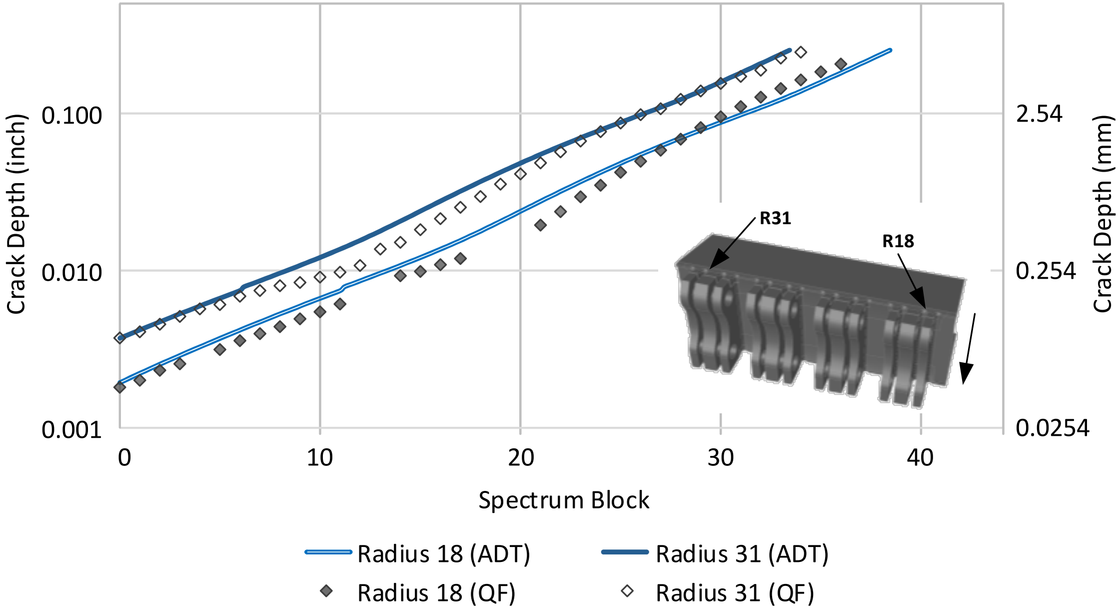
Source: MRO

Stress exceedance

CF-188 ILEF ADT Simulation

Model Validation

Analytical Crack Growth vs. Quantified Fractography (QF):



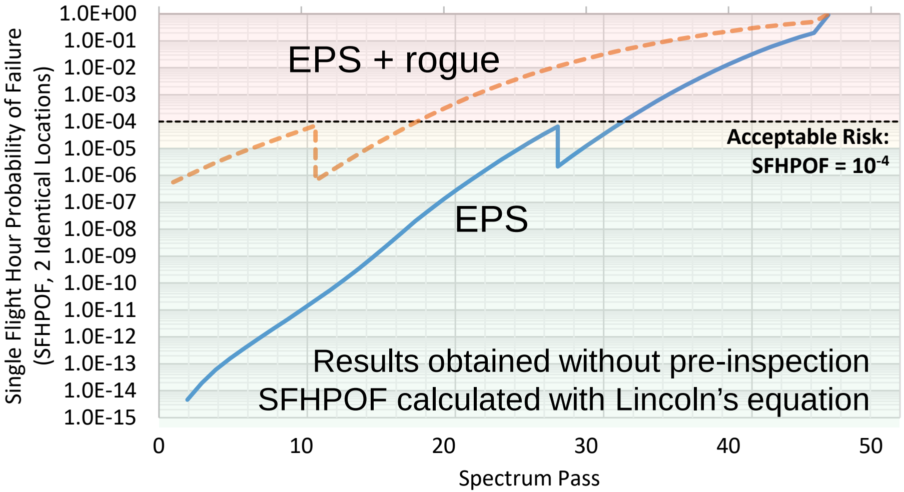
CF-188 ILEF ADT Simulation

Sensitivity Study: Initial Crack Size Distribution (ICSD)

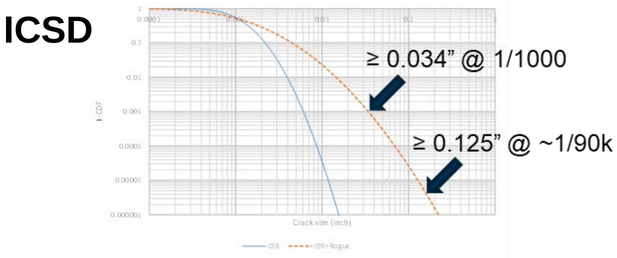
Objectives: Quantify the effects of increasing the probability of large initial cracks (e.g. rogue flaws)

Approach: Increase the standard deviation of the ICSD

Outcome: Significantly reduces the time to the first inspection



Results obtained without pre-inspection
SFHPOF calculated with Lincoln's equation



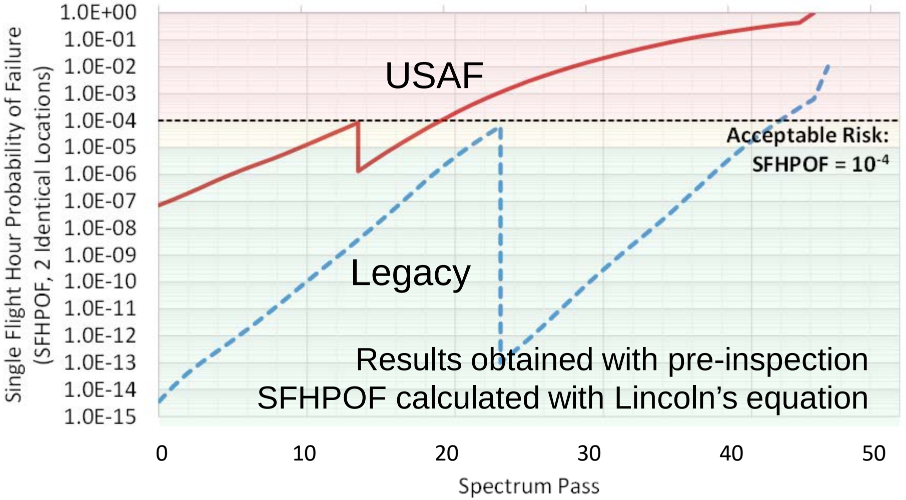
CF-188 ILEF ADT Simulation

Sensitivity Study: Probability of Detection (POD)

Objectives: Compare the effects of using the POD recommended by USAF[1] instead of the legacy CF-188 values

Approach: Estimate POD curves from a_{50} and a_{90} values

Outcome: Significantly reduces the time to the first inspection



Results obtained with pre-inspection SFHPOF calculated with Lincoln's equation

POD	USAF	Legacy[2]
a_{50}	0.050	0.006
a_{90}	0.125	0.015

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[1] Bair, R. *et al.* (2018), "In-Service Inspection Crack Size Assumptions for Metallic Structures", EN-SB-08-012, Revision D, the United States Air Force.

[2] For sensitivity study only - Derived from SES DI 3128 Rev A, "Detectable Crack Sizes for CF-18 Nondestructive Inspection Techniques", Nov. 2008. Not used for the CF188 ILEF.

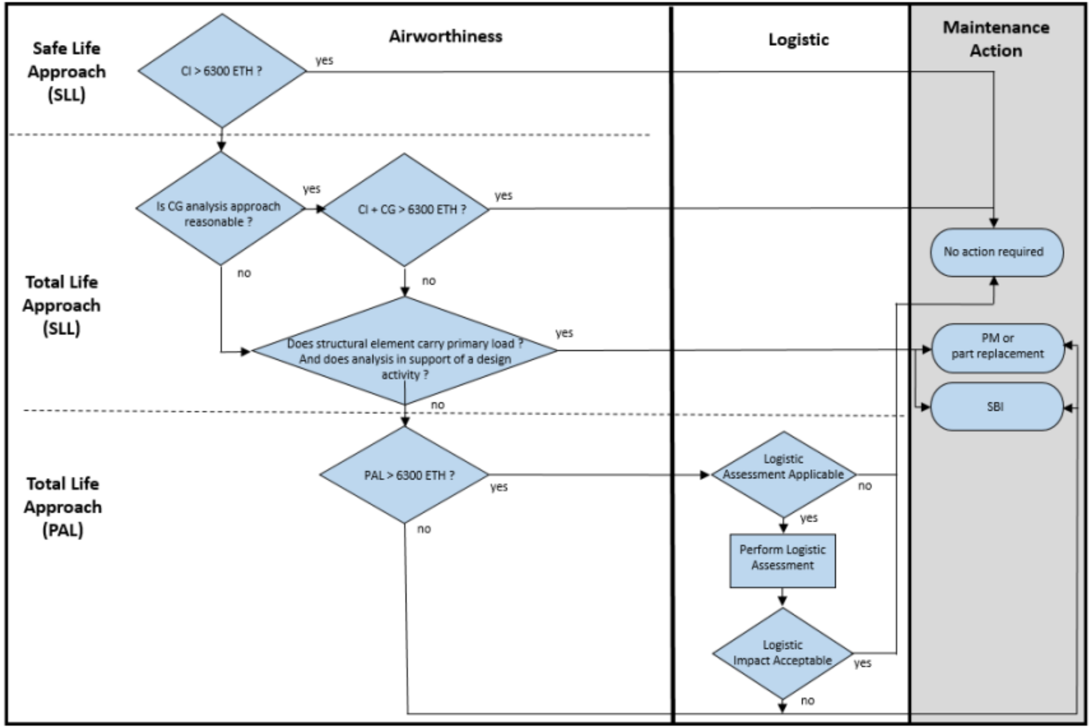
Methods Comparison

CF-188 Life Management Policy

Three phases:

1. Safe Life / Total Life (SLL)
   - Crack initiation (CI) life + crack growth (CG) life
   - Cumulative POF (CPOF) → Safe Life Limit (SLL)
2. Total Life (PAL)
   - Hazard rate → Point of Acceptable Limit (PAL)
3. Safety by Inspection

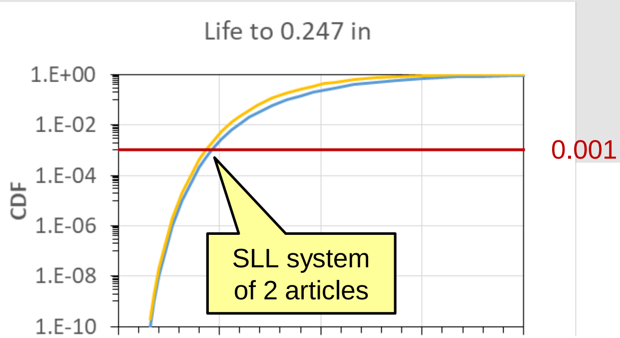
Note: For comparison purpose only. The analytical life of the actual CF-188 ILEF lugs is based on Total Life (CI+CG)



CF-188 Lifing Methodology

Methods Comparison

CF-188 Life Management Policy



ILEF Lugs Safe Life Limit (SLL)

- CPOF = 10^{-3} per A/C (2 articles)

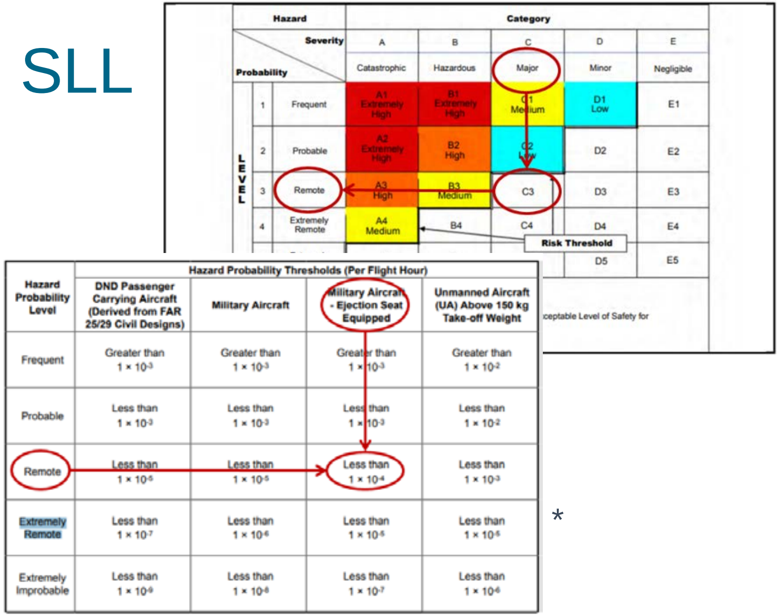
Point of Acceptable Limit (PAL): 1.75 SLL

- Hazard Severity: "Major"
- Hazard Probability Threshold: ≤ 10^{-4} per FH ("Remote")

Inspection Interval: 0.40 SLL

- $(N_{crit} - N_{detect}^{*})$ / Test Factor

Note: For comparison purpose only. The analytical life of the actual CF-188 ILEF lugs is based on Total Life (CI+CG)



Hazard			Category				
		Severity	A	B	C	D	E
Probability			Catastrophic	Hazardous	Major	Minor	Negligible
LEVEL	1	Frequent	A1 Extremely High	B1 Extremely High	C1 Medium	D1 Low	E1
	2	Probable	A2 Extremely High	B2 High	C2 Low	D2	E2
	3	Remote	A3 High	B3 Medium	C3	D3	E3
	4	Extremely Remote	A4 Medium	B4	C4	D4	E4
						D5	E5

Risk Threshold

ceptable Level of Safety for

Hazard Probability Level	Hazard Probability Thresholds (Per Flight Hour)			
	DND Passenger Carrying Aircraft (Derived from FAR 25/29 Civil Designs)	Military Aircraft	Military Aircraft - Ejection Seat Equipped	Unmanned Aircraft (UA) Above 150 kg Take-off Weight
Frequent	Greater than 1×10^{-3}	Greater than 1×10^{-3}	Greater than 1×10^{-3}	Greater than 1×10^{-2}
Probable	Less than 1×10^{-3}	Less than 1×10^{-3}	Less than 1×10^{-3}	Less than 1×10^{-2}
Remote	Less than 1×10^{-5}	Less than 1×10^{-5}	Less than 1×10^{-4}	Less than 1×10^{-3}
Extremely Remote	Less than 1×10^{-7}	Less than 1×10^{-6}	Less than 1×10^{-5}	Less than 1×10^{-5}
Extremely Improbable	Less than 1×10^{-9}	Less than 1×10^{-8}	Less than 1×10^{-7}	Less than 1×10^{-6}

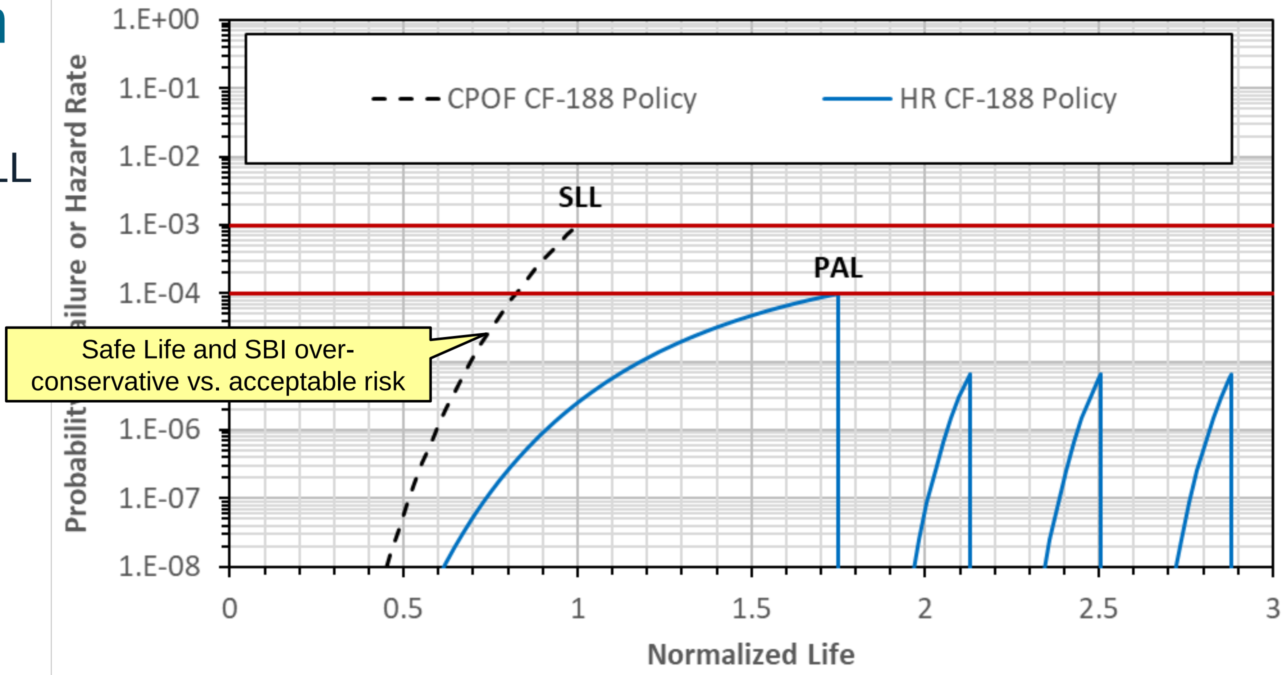
Using legacy CF-188 POD assumptions

Methods Comparison

CF-188 Life Management Policy vs. ADT

Current Approach

- PAL: 1.75 SLL
- 2nd inspection: 2.13 SLL



Safe Life and SBI over-conservative vs. acceptable risk

Methods Comparison

CF-188 Life Management Policy vs. ADT

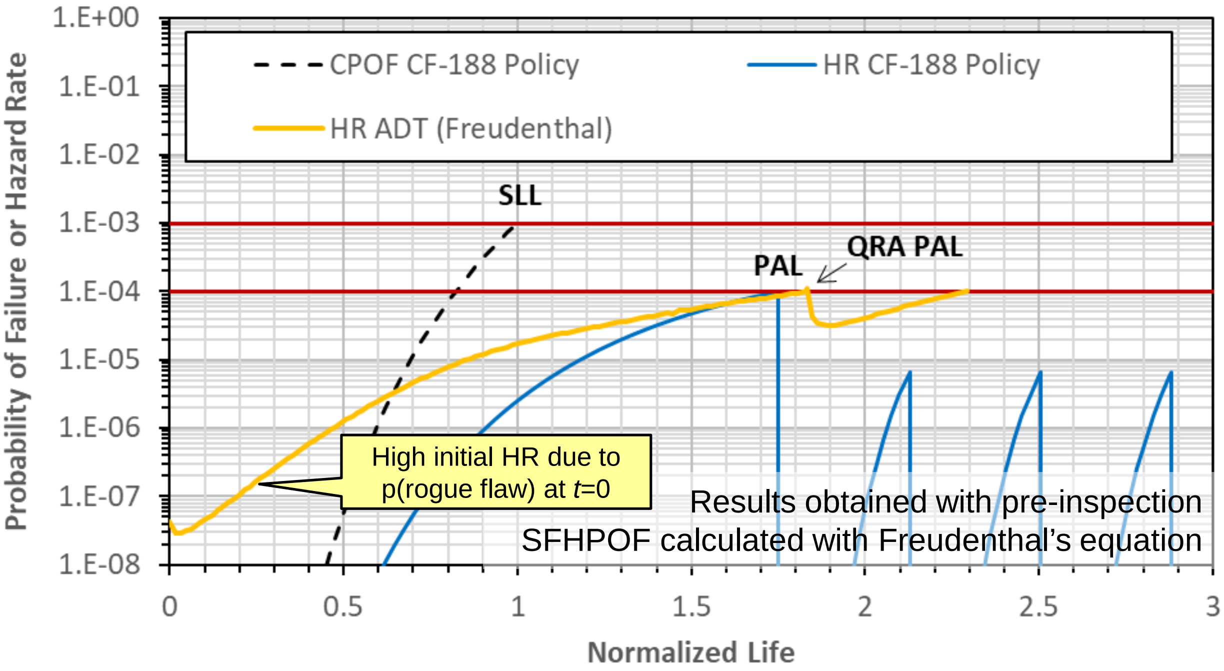
Current Approach

- PAL: 1.75 SLL
- 2nd inspection: 2.13 SLL

ADT (Life/1.5)[1]

Rogue flaw ICSD, NDI at *t* = 0, USAF POD

- PAL: 1.83 SLL
- 2nd inspection: 2.29 SLL



High initial HR due to p(rogue flaw) at *t*=0

Results obtained with pre-inspection SFHPOF calculated with Freudenthal's equation

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[1] Includes a tracking factor (TF) of 1.5 to simulate load uncertainty

Methods Comparison

CF-188 Life Management Policy vs. ADT

Current Approach

- PAL: 1.75 SLL
- 2nd inspection: 2.13 SLL

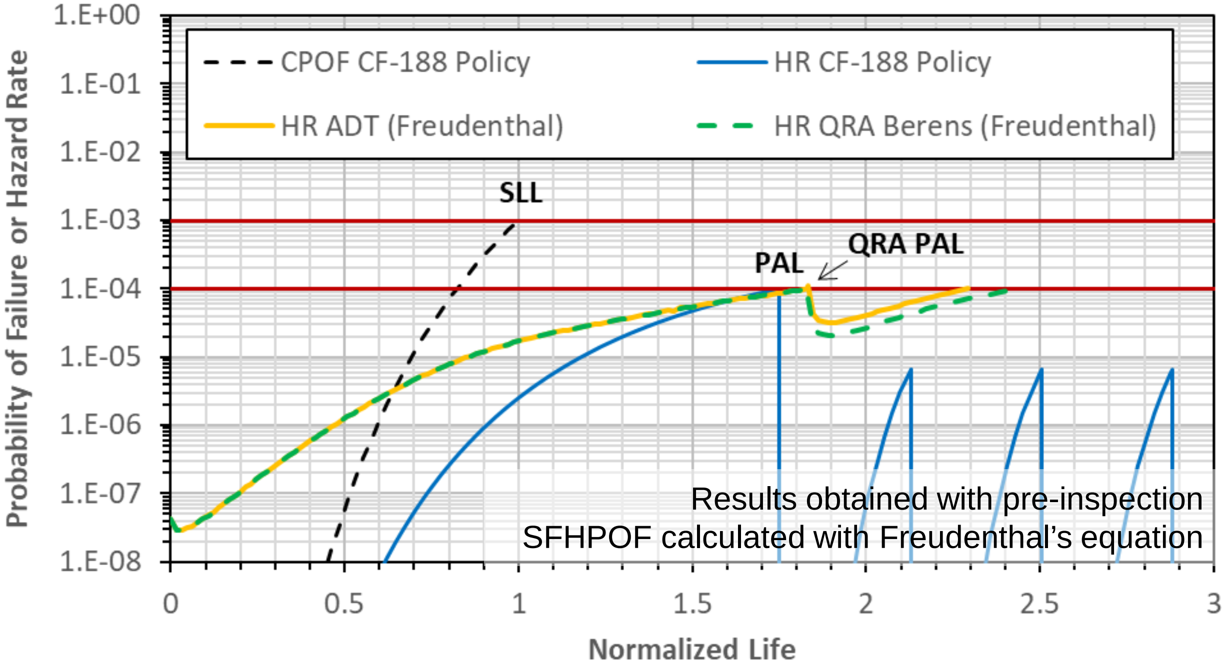
ADT (Life/1.5)[1]

Rogue flaw ICSD, NDI at *t* = 0, USAF POD

- PAL: 1.83 SLL
- 2nd inspection: 2.29 SLL

QRA[2] (Life/1.5)[1]

- 2nd inspection: 2.44 SLL



Results obtained with pre-inspection SFHPOF calculated with Freudenthal's equation

---

[1] Includes a tracking factor (TF) of 1.5 to simulate load uncertainty

[2] Berens updating (e.g. repair simulation in PROF)

Methods Comparison

CF-188 Life Management Policy vs. ADT

Discussion

- For the CF-188 ILEF demo, the ADT approach provided limited benefits
  - The assumed critical crack size was small vs. detection capability (POD) (limited benefits from Bayesian updating)
- However the ADT formulation used “more severe” assumptions
  - Initial state of discontinuities included an increased probability of large defects
  - The probability of crack detection was significantly lower than in the current approach

Conclusion

Conclusion

NRC in-house ADT framework and CF-188 ILEF Demo

- Probabilistic crack growth simulation (Monte Carlo) that includes multiple probabilistic and/or deterministic parameters (ex. ICSD, residual stress, geometry).
- Quantitative risk assessment able to quantify the effects of modelling and analysis assumptions on the calculated probability of failure.
- Probabilistic load modelling including and forecasting load uncertainties more accurately.
- Bayesian inference providing a way to include new NDI information (inspection, found/no-found).

Conclusion

Additional Development and Investigations

- Probability of large or “rogue” flaws / mixture models[1]
- Accurate and efficient hazard rate calculation (Freudenthal)
- Survival analysis (Monte Carlo) including importance sampling
- Load uncertainties
  - Prediction phase: resolution of the IAT system, accuracy of load transfer functions
  - Forecast phase: future usage/missions + randomness inherent to each mission type
- Digital twinning for helicopter applications (probabilistic safe life analysis)

[1] Y. Bombardier, G. Renaud and M. Liao, “Development and Demonstration of Damage Tolerance Airframe Digital Twin Methods and Tools,” in the 38th Conference and 31st Symposium of the International Committee on Aeronautical Fatigue and Structural Integrity (ICAF), Delft, the Netherlands, 2023.

Acknowledgement

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- Airframe Digital Twin (ADT) Technology Adaptability Assessment and Technology Demonstration - Defence Research and Development Canada (DRDC) and National Research Council Canada (NRC)
- Dual-Use Tech-Watch - National Research Council Canada (NRC)

Thank you

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