31st ICAF Symposium – Delft, 26-29 June 2023

DEVELOPMENT AND DEMONSTRATION OF DAMAGE TOLERANCE AIRFRAME DIGITAL TWIN METHODS AND TOOLS

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Abstract: This paper provides an overview of the Airframe Digital Twin (ADT) Framework that is being developed by the National Research Council of Canada (NRC). The NRC ADT Framework was used to simulate the durability and damage tolerance fatigue test of a CF-188 aircraft inboard leading edge flap (ILEF), referred to as FT382. The ADT twinned the critical locations at the ILEF attachment lugs. The lugs were used to develop and demonstrate the ADT Framework, perform sensitivity studies, and assess the potential benefits of using digital twin concepts for lifing and sustainment of airframe structures. In this paper, two specific modelling aspects of the ILEF ADT model are presented: the modelling of initial crack size using mixture distributions and the simulation of non-destructive inspections using two inference methods. The effects of these two modelling aspects are expressed in terms of single flight hour probability of failure (SFHPOF) for the ADT model of the ILEF attachment lugs.

Keywords: Digital twin, quantitative risk assessment, damage tolerance, probabilistic crack growth, bayesian inference

INTRODUCTION

Current airframe life cycle management approaches can be overly conservative when accounting for uncertainties in individual aircraft manufacturing, usage, and unexpected damage. This conservatism can lead to prolonged downtime, unnecessary fleet-wide inspections, and increased operating costs. Based on this premise, the National Research Council of Canada (NRC) has been evaluating various technologies that can optimize maintenance of individual aircraft to decrease overall maintenance and support costs for the Royal Canadian Air Force (RCAF) aircraft fleets. The digital twin technology has been identified as a promising concept that could revolutionize airframe sustainment.

In collaboration with Defence Research and Development Canada (DRDC), NRC has been developing an ADT Framework to support sustainment of RCAF aircraft fleets. This paper presents an overview of the ADT Framework developed by NRC. The application of the ADT Framework is also demonstrated on a real structure by digitally twinning the inboard leading edge flap (ILEF) attachment lugs of a CF-188 wing recently tested at NRC.

AIRFRAME DIGITAL TWIN FRAMEWORK KEY CONCEPTS

The primary objective of the airframe digital twin (ADT) Framework developed by NRC is to enhance the accuracy of structural diagnosis and prognosis to facilitate better maintenance decisions. The NRC ADT Framework integrates cutting-edge structural analysis, probabilistic modelling techniques, including advanced probabilistic crack growth modelling, high-fidelity finite element simulations, and quantitative risk assessment. The framework also provides the capability to periodically update the probabilistic inputs of these models as new data about the airframe becomes available, such as inspection results, usage, and other relevant factors.

As its name implies, the NRC ADT Framework relies on digital representations, or "twins", of the critical locations. Conceptually, each critical location of each aircraft may have its own digital twin. Data from each individual aircraft is then used to update the twins for all critical locations to mimic the actual history (usage, modifications, damage, etc.). Combining life prognostics of each twin results in a better probabilistic representation of the future state of the aircraft and allows to make better maintenance decisions.

Uncertainty quantification

Uncertainty quantification (UQ) is at the core of the NRC ADT Framework. It consists in integrating and propagating uncertainties in airframe life predictions. UQ provides the opportunity to tailor modelling assumptions based on the completeness and level of confidence in the available data. It also allows the integration of information that can be used with an inference process, such as non-destructive inspection results. For example, the probability of missing a large crack during an inspection can intrinsically be included in the ADT Framework, as opposed to relying on the traditional rogue flaw assumption enforced by the damage tolerance approach. For this particular case, the rogue flaw assumption is typically considered conservative, leading to shorter inspection intervals, reduced availability, and higher maintenance costs. Updating the probabilistic distributions of the input parameters, as new information becomes available, has the potential to improve the accuracy of physics-based structural diagnosis and prognosis models. The main uncertainties considered in the NRC ADT Framework are described next.

Damage size. The damage size is defined as the size of the actual physical crack that may be present at a specific location in a structure. Technically, any crack can be measured given the proper tools and techniques. However, doing so is usually impractical. For crack-growth based life calculations, it is always assumed that an initial crack is present at the critical location. The initial crack size is unknown and commonly used non-destructive inspection techniques cannot typically detect cracks after manufacturing.

The damage tolerance approach simplifies this problem by assuming a relatively large crack. Its size is typically determined from the largest crack that can be missed upon inspection, e.g. a radial corner crack of 1.27 mm (0.050 inch) for bolt-hole eddy current (BHEC) inspection [1]. Other approaches are to determine an "initial discontinuity state" (IDS) distribution based on microscopic observations [2] or an "equivalent pre-crack size" (EPS) distribution based on quantitative fractography studies [3]. For example, an average EPS of 0.1 mm (0.0004 inch) is typically assumed for machined 7050 aluminium surfaces. This average value is therefore significantly smaller than that prescribed by the damage tolerance approach, possibly offering opportunities to relax the repeated inspection interval requirement. In order to use this assumption, however, the crack size has to be treated as a distribution instead of a conservative deterministic value. Moreover, the probability of having large cracks needs to be intrinsically included in the crack size distribution. This type of uncertainty is an integral part of the NRC ADT Framework.

Probability of detection. The probability of detection (POD) is defined as the probability of detecting a crack of a given size. The POD is typically determined using a rigorous approach for a given material, inspection technique, structure geometry, and expected crack nucleation site (edge, surface, interface, etc.). Additional variability can also be included, such as the detection capabilities within a group of inspectors and the probability of performing an inspection. The POD is represented as a curve that monotonically increases from 0% to 100% as the crack size increases. It can therefore be represented as a cumulative distribution, e.g. the probability of detecting a crack smaller or equal to a certain size. Using the ADT Framework, inspection results, including null findings, are used to provide feedback to the model. Typically, they are of the “hit/miss” type, indicating, with a certain level of confidence, that a crack has been detected or not. As such, they should not be treated as deterministic inputs, but rather as probabilities that cracks of certain sizes are present in the structure. The NRC ADT Framework has the capability to infer the crack size distribution from the POD and inspection results.

Local loads. Local loads are defined as the loads or stresses that are used for lifing a critical location. Typically, local loads are determined using load transfer functions. These functions can be derived using finite element analyses and/or from strain survey results. The load transfer functions are typically expressed in terms of interface loads, e.g. wing root bending moment (WRBM) for the CF-188 aircraft. The interface loads are themselves expressed in terms of a limited number of flight parameters or strain gauge readings. While this approach can work well for some cases, the level of correlation between the local stresses and the underlying measured values differs for each critical location and its uncertainty is rarely quantified.

An example of this challenging problem is the local stresses at the CF-188 inboard leading edge flap (ILEF) attachment lugs. For this case, the WRBM can be used to estimate the local stresses. However, the local stresses at the ILEF attachment lugs are not strongly correlated with the WRBM without considering additional factors, such as the ILEF deflection angle, aircraft angle of attack, altitude, Mach number, etc. As a consequence, the uncertainties in local stresses obtained from WRBM can be significant. Because of this deficiency, the ILEF loads are currently not tracked by the RCAF. Instead, the RCAF tracks the ILEF component flight hours (CFH), and scales the ILEF lugs certified life by a load tracking factor (TF) of 1.5. According to NRC’s understanding, there is no strong scientific basis for this value. As such, the TF of 1.5 could be conservative or not.

Future loads. Load forecasting is performed by predicting future usage of the aircraft and the resulting loads expected at the critical locations. Realistic load forecasting is essential for generating meaningful structural prognosis. Forecasting aircraft usage in terms of the expected mission mix can be challenging. Forecasting load sequences at a critical location is at least one order of magnitude more complex than calculating local loads from known usage. With historical IAT data, it is possible to develop a statistical model for each type of mission. These models can then be used to quantify the effect of mission load variability on lifing. The NRC ADT Framework can simulate future usage with stochastic load models based on estimated mission mixes that can be either deterministic (e.g. 60% training, 40% others) or probabilistic (e.g. 60% training with a standard deviation of 0.1).

Uncertainty evolution

One important feature of NRC ADT Framework is that it has the ability to quantify the effect of the uncertainties on fatigue and crack growth lives and the resulting probability of structural failure. The Framework also provides a powerful capability to reduce some of this uncertainty as information about the airframe is collected. Two approaches are used to achieve this, depending on the type of uncertainty.

Inference of crack size distribution from non-destructive inspections. The uncertainty related to crack size is typically reduced by using information obtained during the non-destructive inspections. This process is done using Bayesian inference by updating the crack size distribution based on the likelihood of detecting a crack during the inspection. This likelihood is calculated based on the crack size distribution expected from the recorded aircraft usage and the POD related to the selected non-destructive inspection technique (NDT).

Bayesian statistics is particularly well suited for problems where the number of observations, inspection results for this case, are limited. Bayesian statistics fuses engineering knowledge, determined by assumptions and models, with observations. For example, if a model predicts a crack size distribution with a mean crack size of 0.125 inch, then the probability of detecting this relatively large crack would be high, e.g. 99%, based on a representative BHEC POD curve. As such, the likelihood of finding this crack during an inspection would be high. However, if no crack is found upon inspection, it would suggest that the assumptions and/or model used to predict the crack size distribution is not representative. In that case, the assumptions and/or model could be updated using Bayesian statistics by modifying the crack size distribution based on the likelihood of detecting (or not) a crack. This capability is included in the NRC ADT Framework to refine the modelling assumptions as more data are obtained throughout the life of the aircraft.

Frequentist updating of load distribution. Load forecasting uses the traditional frequentist approach to refine the statistical model for each type of mission as more flight data are obtained and processed. Due to the large amount of data collected, the frequentist approach is better suited than the Bayesian approach for refining the load forecasting models.

AIRFRAME DIGITAL TWIN FRAMEWORK IMPLEMENTATION

The workflow of the NRC ADT Framework is composed of the three following phases and illustrated in Figure 1:

- **Prediction:** The objective of the Prediction Phase is to estimate the crack size distribution at the current time, knowing the aircraft loads from the individual aircraft tracking (IAT) system and assuming an initial damage state. The initial damage state is defined by the initial discontinuity state (IDS) distribution, equivalent initial flaw size distribution (EIFSD), or other types of initial crack size distributions. The crack size distribution at the current time is calculated using probabilistic crack growth (PCG) simulation from the crack size distribution at the previous calculation time. Additional uncertainties can be included in the PCG, such as those related to the IAT system or the load transfer function between the IAT data and local reference stress. The term “Prediction” used in this context does not correspond to the calculation of events or results to occur in the future.
- **Inference:** The Inference Phase fuses the inspection results (found/no-found or crack size), the probability of detection (POD), and the crack size distribution at the inspection time, calculated from the Prediction Phase. During this phase, the crack size distribution is adjusted from the likelihood that a crack is detected or not. For example, if the PCG simulations predict high probability of having large cracks at the current time and no crack is found, then the assumed crack size distribution is likely too conservative and the probability of having these large cracks needs to be reduced. This process is based on Bayes’ theorem and the adjusted crack size distribution is used as the prior crack size distribution for the next Prediction Phase.
- **Forecast:** The objective of the Forecast Phase is to calculate the probability of failure (POF) as a function of future time and determine the time at the next inspection based on the acceptable risk level. This is done by conducting PCG from the crack size distribution obtained from the Inference Phase. As opposed to the Prediction Phase, the load history for the Forecast Phase is unknown, but can be estimated based on scenarios: mission profile, pilots, location, etc. The maintenance schedule is then determined based on the acceptable risk level as defined in fleet management documents, such as the Aircraft Structural Integrity Program (ASIP) from the United States Air Force (USAF) [4] and the Record of Airworthiness Risk Management (RARM) from the RCAF [5].

The three phases are executed sequentially, starting from the Prediction Phase. The main input and output parameters for each phase are summarized in Table 1. The crack size distribution is used to transfer information from one phase to the next.

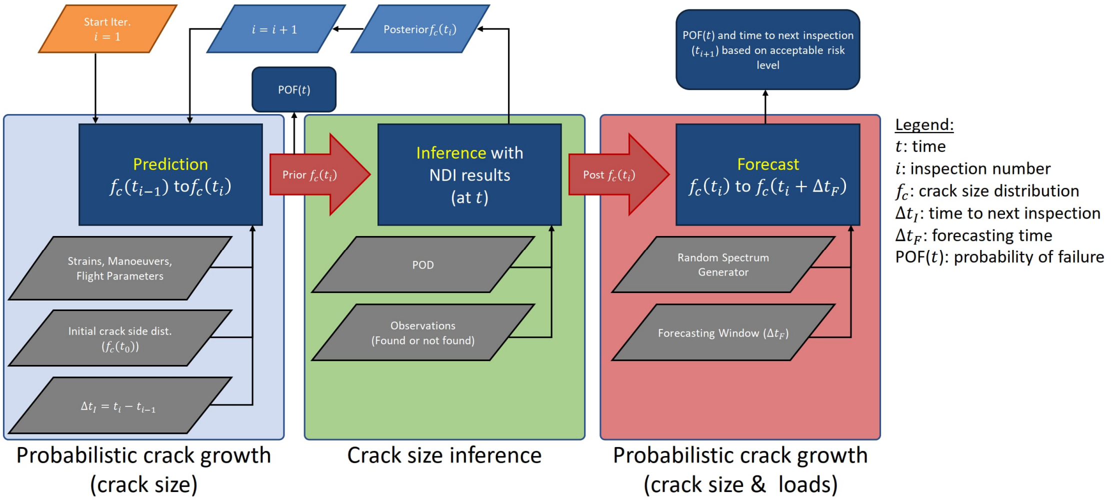

Figure 1: NRC ADT Framework 3-phase methodology

Table 1: Main input and output parameters of the ADT Framework

Phase	Input	Output
Prediction**	– Loading spectrum (known usage) – Posterior crack size distribution from the previous Inference Phase*	– Crack size distribution as a function of time – Probability of failure as a function of time (optional)
Inference	– Probability of detection of NDI technique – NDI results – Prior crack size distribution at inspection time, obtained from the Prediction Phase	– Posterior crack size distribution at inspection time after inference
Forecast**	– Loading spectrum (forecasted usage) – Posterior crack size distribution, from the Inference Phase	– Crack size distribution as a function of time – Probability of failure as a function of time

* For the first analysis, the posterior crack size distribution obtained by inference is not available. Consequently, the initial discontinuity state (IDS) or equivalent initial flaw size (EIFS) distributions can be used as an initial crack size distribution for the Prediction Phase.

** The Prediction and Forecast Phases require additional inputs not listed in this table to perform crack growth simulation, such as material properties, crack growth model, load uncertainty models, geometric correction factor, and residual stress.

As crack size distributions are used to transfer information from one phase to the next, it is very important to use a statistical distribution model that can adequately represent the prevalence of typical crack sizes. It was found, however, that standard parametric distributions, such as the lognormal distribution typically used to model crack sizes, were unable to accurately represent the evolving crack sizes caused by the crack growth and the inference processes. For example, conducting a probabilistic crack growth analysis from a lognormal distribution of the initial discontinuity state (IDS) showed that the smallest cracks may not grow at all, whereas the rest of the cracks do grow. Over time, the resulting crack size distribution is not fitted well anymore by a lognormal distribution or any other parametric distribution. The Inference Phase also modifies the shape of the statistical distribution, making it incompatible with parametric distributions. For this reason, a nonparametric crack size distribution is used in an attempt to improve the correlation between the probabilistic crack growth results and the fitted statistical distribution model [6].

The crack growth analyses conducted as part of the Prediction and Forecasting Phases are done using existing deterministic crack growth algorithms, similar to the crack growth algorithms included in commercial crack growth software such as AFGROW and NASGRO. The particularity the probabilistic crack growth analyses performed within the Prediction and Forecasting Phases are that:

- several (i.e. millions) of deterministic crack growth simulations are carried out, where each crack growth analysis is referred to as a trial;
- a random initial crack size is used for each trial; and
- a random loading spectrum can be used for each trial.

As a consequence, the crack growth algorithm used for the ADT Framework needs to be very efficient in order to complete the PCG simulations within acceptable time. This is achieved using highly optimized algorithm and parallel computation using modern multi-core processors.

The Inference Phase uses Bayes' theorem to infer the crack size distribution, considering the probability of detection (POD) and the non-destructive inspection (NDI) results. The Bayesian models used for inferring the crack size distribution are presented in the following section.

The probability of failure (POF) is the central outcome of the quantitative risk assessment and is calculated as a function of time. This metric allows operators to monitor the risk of structural failure and assess the effects of various risk mitigation approaches, such as the modification of the mission profiles and the modification of the inspection methods and intervals. The probability of failure is currently calculated using the Lincoln equation [7].

The ADT Framework was implemented in an in-house computer program developed by NRC. The program was developed using the Python and C++ with open-source libraries, enabling its use without additional licensing fees and license limitations. The program runs on entry-level desktop computers. However, the run-time is significantly reduced if high-end computers with multi-core processors are used.

INFERENCE OF CRACK SIZE DISTRIBUTION

The selection of the initial crack size distribution (ICSD) has significant impact on the evolution of the POF as a function of time. NRC has assessed various approaches for selecting the ICSD:

- **Equivalent Pre-crack Size (EPS):** The EPS is an approximation of a physical measurement of the initiating flaw or discontinuity [3]. The EPS distribution is calculated by projecting the crack size to time zero from experimental data using an empirical crack growth model. Depending on the source of experimental data, the EPS distribution may or may not include "rogue" flaws that could be induced during manufacturing, assembly, or maintenance. As these "rogue" flaws may drive the POF, the EPS may only provide a lower-bound POF unless the EPS distribution includes the size of these unpredictable and unexpected flaws.
- **EPS with larger standard deviation:** A simple approach for including the probability of having "rogue" flaws is to widen the EPS distribution. This was initially done by increasing the standard deviation of the EPS distribution to target a 1/100000 probability of having a rogue crack larger than 3.18 mm (0.125 inch).
- **Mixture models:** Work presented by Ball [8] highlighted the opportunity to segregate the sources of initial quality defects. Ball presented initial defect size distributions for micro-pores and particles, etch pits, and surface scratches. Based on these findings, the ICSD can be

composed of a combination of different defects based on an initial mixture, e.g. 50% micro-pores and 50% scratches.

Depending on the ICSD type, NRC developed two approaches for inferring the crack size distribution (CSD) from non-destructive inspections. If mixture CSD are used, then it is possible to infer the mixture weight based on NDI result. Otherwise, it is simply possible to infer the CSD from the NDI result. The meaning of these two approaches is quite different and is discussed in the following sections.

Inference of mixture weight

The mixture CSD is defined as follows for a mixture of two distributions:

$$f_c = \overline{w} f_a + (1 - \overline{w}) f_b \tag{1}$$

where $\overline{w}$ is the average weight of the weight distribution f_w, controlling the probability of having a crack size from distribution a. f_a and f_b are the probability density functions of distributions a and b, respectively.

The weight distribution is inferred using the Bayes' theorem as follows:

$$f_{w|obs} = \frac{f_{obs|w}\, f_w}{f_{obs}} \tag{2}$$

where $f_{w|obs}$ is the posterior weight distribution given the observation (obs) from the "hit-miss" non-destructive inspection (NDI) result. $f_{obs|w}$ is the likelihood of observing the NDI result for the given weight distribution. f_w is the prior weight distribution. Finally, f_{obs} is the probability of observing this NDI result, which can also be interpreted as a way to normalize the numerator of the Bayes' theorem equation.

The likelihood is calculated as follows:

$$f_{obs|w} \sim Ber(p = POD(w), k = obs) \tag{3}$$

where $Ber(p = POD(w), k = obs)$ is the probability of observing the NDI result ("hit-miss") given the mixture weight.

Finally, the probability of detecting a crack for the given weight is calculated as follows:

$$POD(w) = \int_0^\infty f_c(c, w) POD(c) dc \tag{4}$$

Once the posterior weight distribution, $f_{w|obs}$, is obtained, the average of the weight distribution, $\overline{w}$, is calculated and used in Equation (1) to update the CSD.

The meaning of inferring the mixture weight is different from inferring the CSD. This approach implies that the distributions composing the mixture model, i.e. f_a and f_b in Equation (1), are representative of the population of cracks that could be found in a fleet of aircraft sharing the same material, manufacturing processes, and geometry. Inferring the mixture weight actually determines which type of defect is more likely probable at the inspected location, rather than its size. For example, inferring the mixture weight of a CSD composed of 50% pore defects and 50% scratch defects will permit to infer the type of defect that is more likely present at the inspected location based on the NDI. Numerical examples for the CF-188 inboard leading edge flap (ILEF) technology demonstrator are provided in the next section.

Inference of the CSD

The CSD, denoted f_c below, can be directly inferred from the NDI results as follows:

$$f_{c|obs} = \frac{f_{obs|c}\, f_c}{f_{obs}} \tag{5}$$

where $f_{c|obs}$ is the posterior CSD given the observation (obs) from the "hit-miss" non-destructive inspection (NDI) result. $f_{obs|c}$ is the likelihood of observing the NDI result for the given CSD.

The likelihood is calculated as follows:

$$f_{obs|c} \sim Ber(p = POD(c), k = obs) \tag{6}$$

where $Ber(p = POD(c), k = obs)$ is the probability of observing the NDI result ("hit-miss") given the current CSD. The equation for the $POD(c)$ is simply the POD curve as typically modelled following the guidelines in MIL-HDBK-1823A [9].

Inferring the CSD implies that the ICSD was not representative based on the NDI results for this particular location. Conceptually, this implies that CSD inference indirectly refines the ICSD at the critical location.

If the ICSD is a mixture model, it is also possible to infer the CSD instead of the mixture weight. This is simply done by merging the CSD composing the mixture model with given mixture weights. This approach, however, prevents segregating the defect types composing the posterior distribution.

Examples of CSD inference is presented for the CF-188 ILEF technology demonstrator in the next section.

CF-188 INBOARD LEADING EDGE FLAP TECHNOLOGY DEMONSTRATOR

FT382 Overview

NRC completed a durability and damage tolerance test of a retired CF-188 inboard leading edge flap (ILEF) [10]. This full-scale fatigue test is referred to as FT382 and is shown in Figure 2. The critical locations are radii at the ILEF attachment lugs illustrated in Figure 2. These lugs had been previously modified by blending and shot peening the radii. This life extension modification was required as these locations were considered critical and life limiting. The fatigue and damage tolerance testing was followed by a residual strength static tests at 120% of the design limit load. This work was carried out for the Department of National Defence (DND) as part of the life extension program of the CF-188 flight control surfaces.

During the FT382 fatigue test, inspections were carried out after each spectrum block. This frequency of inspection was selected to detect potential early cracking within the shot-peened areas of the modified lugs. The lug inspections were carried out using eddy current. The first damage was reported after the completion of Block 38 at Radius 18, identified in Figure 2. At that time, the estimated crack size was 0.030 inch based on the eddy current signal from the calibration block. Liquid penetrant inspection (LPI) and Repliset© were also used to confirm the crack indication. The fatigue test was continued up to Block 46. Inspections were carried out after each spectrum block until the end of the fatigue test. New crack indications were found after Block 39 at Radii 31, 15, and 16. The inspection at Block 39 estimated the crack size to be 0.040 inch for all four radii (15, 16, 18, and 31). Quantitative fractography (QF) was performed after FT382 to measure the crack sizes and calculate the crack growth rates.

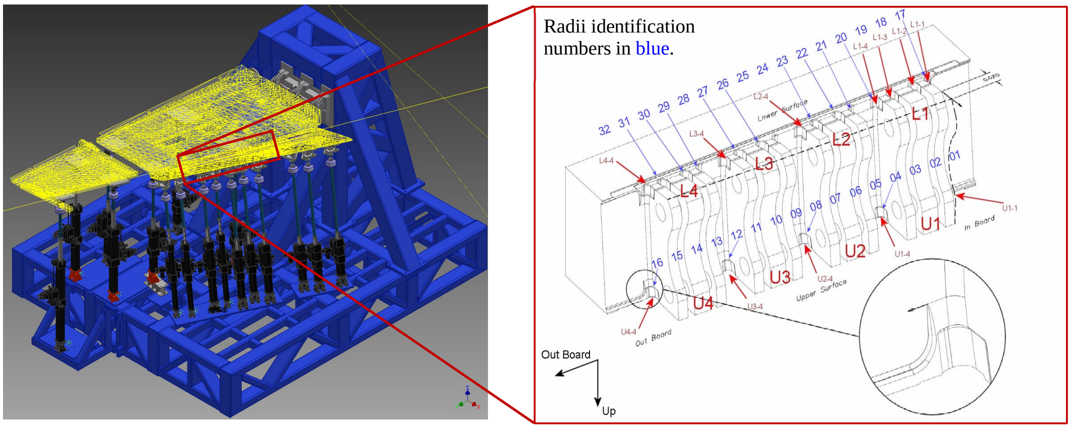

Figure 2: ILEF areas of interest

Digital twin of the CF-188 ILEF attachment lug

The digital twin of the CF-188 ILEF attachment lugs was developed by NRC [6]. This required the development of a three-dimensional geometric model, the measurement of the residual stresses at the lugs using X-ray diffraction, the development of a stress intensity factor solution using StressCheck [11] and BAMF [12], and the development of a load transfer function between the wing root bending moment (WRBM) and the ILEF hinge moment (ILEFHM) at the critical attachment lug. The 7050-T7451 aluminium crack growth rate model developed by Burchill et al. [13] was used. The crack growth results of the ADT Framework of the CF-188 ILEF attachment lug was validated against the FT382 QF results. Comparisons between the QF results and predicted crack growth curves are presented in Figure 3 for Radii 18 and 31. As shown, good agreement was obtained between the measured and predicted crack growth rates. This comparison provides some confidence that the ADT PCG simulation results were representative of the crack growth that can occur at the CF-188 ILEF attachment lugs.

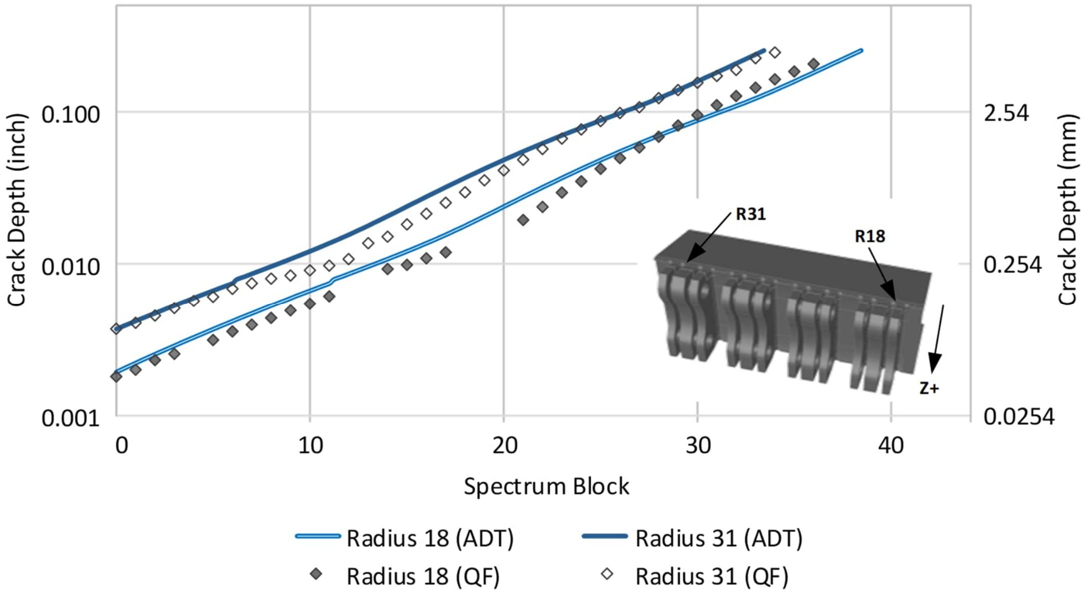

Figure 3: Comparison between the crack growth curves obtained using the crack growth model (lines) and the quantitative fractography results (symbols)

For the ADT simulations presented in this paper, five ICSD scenarios were considered. These scenarios were created by mixing the two ICSD presented in Table 2. The first ICSD, f_a, represents the population of scratches measured at the surface of parts. The results presented by Ball [8] were represented using a lognormal distribution. While the objective is to represent the population of scratch sizes, it is understood that this distribution is likely a function of several parameters not stated by Ball and should not be used without thorough assessment. The second ICSD, f_b, represents the population of EPS. The EPS distribution was developed from peened 7050-T7451 aluminium specimens [3]. According to the investigation performed by Molent et al. [3], all cracks representing the EPS nucleated from laps and folds produced by the peening process.

Table 2: Initial crack size lognormal distribution parameters

Initial crack size distribution	Symbol	Lognormal Parameters (unit: millimetre)		Lognormal Parameters (unit: inch)	
		μ	σ	μ	σ
Scratch sizes	f_a	-1.522051	0.55	-4.756800	0.55
EPS	f_b	-3.611918	0.564133	-6.846668	0.564133

The five ICSD scenarios considered for the CF-188 ILEF ADT demonstrator are presented in Table 3. These scenarios were developed by combining the two ICSD presented in Table 2 as described as follows:

- **Scenario 1:** All cracks nucleated from laps and folds produced by the peening process.
- **Scenario 2:** All cracks nucleated from surface scratches.
- **Scenario 3:** 50% of the cracks nucleated from the EPS (laps and folds produced by peening) and 50% of the cracks nucleated from surface scratches. For this scenario, the inspection was modelled by inferring the CSD from NDI results.
- **Scenario 4:** 99% of the cracks nucleated from the EPS (laps and folds produced by peening) and 1% of the cracks nucleated from surface scratches. For this scenario, the inspection was modelled by inferring the CSD from NDI results.
- **Scenario 5:** 50% of the cracks nucleated from the EPS (laps and folds produced by peening) and 50% of the cracks nucleated from surface scratches. The mixture distribution was kept separated, such that two PCG were performed: one for the EPS ICSD and one for the scratch ICSD. For this scenario, the inspection was modelled by inferring the weight of the mixture model from NDI results. Mixing of the resulting CSD was only required for simulating the inspection and calculating the POF. For this scenario, an uninformed prior weight distribution was assumed and was modelled using a uniform distribution, ranging from 0 to 1.

As identified in Table 3, the inspections were simulated by inferring either the CSD or the mixture weight. To simulate the inspection, a POD curve was developed based on the POD data found in the United State Air Force Service Bulletin EN-SN-08-12 for manual Eddy current surface inspections at the radii [1]. The POD curve was represented by the cumulative distribution function of a lognormal distribution with an a_{50} of 1.27 mm (0.050 inch) and an a_{90} of 3.18 mm (0.125 inch).

The single flight hour POF (SFHPOF) was calculated using Lincoln's formulation [7] as a hazard rate. It is understood that Lincoln's formulation does not provide a true hazard rate. However, it has been traditionally used for risk assessment of aircraft structures and has been found to be conservative compared to more accurate formulations, such as Freudenthal [14] or conditional SFHPOF [15].

Table 3: CF-188 ILEF ADT simulation scenarios

Scenario	ICSD Type	Fraction of EPS Cracks	Inference Method	CSD $f_c = \bar{w} f_a + (1 - \bar{w}) f_b$	Time to Inspect (Block)
1	Lognormal	100%	CSD	$\bar{w} = 0$ (100% probability of starting from an EPS)	29
2	Lognormal	0%	CSD	$\bar{w} = 1$ (100% probability of starting from a scratch)	12
3	Mixture Model	50%	CSD	$f_w \sim Beta(1{,}1);\ \bar{w} = 0.5$ (50% probability of starting from a scratch)	13
4	Mixture Model	99%	CSD	$f_w \sim Beta(1{,}99);\ \bar{w} = 0.01$ (1% probability of starting from a scratch)	19
5	Mixture Model	50%	Weight	$f_w \sim Beta(1{,}1);\ \bar{w} = 0.5$ (50% probability of starting from a scratch)	13

In addition to the CSD as a function of time obtained using Monte Carlo PCG, the following inputs were used to calculate the SFHPOF:

- **ILEF hinge moment (ILEFHM) exceedance:** The FT382 maximum WRBM exceedance curve was used to calculate the ILEFHM at the critical attachment lug using a transfer function. The maximum ILEFHM distribution was modelled using a Gumbel distribution.
- **Fracture mechanics parameters:** The stress intensity factor solution and residual stress intensity factor solution, obtained from finite element analyses, were used to calculate the maximum stress intensity factor at the crack tip for the given ILEFHM.
- **Fracture toughness:** The plain strain fracture toughness data from the AFMAT database [16] was used to develop the plain strain fracture toughness distribution, which was represented using a lognormal distribution. The plain strain to plane stress fracture toughness ratio was also used for calculating the fracture toughness based on the calculated stress state at the crack tip.

Numerical analysis procedure

All ADT simulations presented in this paper were conducted using the following procedure:

- **Prediction Phase:** Perform a Monte Carlo PCG simulation from the ICSD, as defined in Table 3, to a SFHPOF of 10^{-4}.
- **Inspection Phase:** Simulate an inspection at the critical lug radius by inferring the CSD or mixture weight at the inspection time (defined when the SFHPOF reaches 10^{-4}) and assuming that no crack has been detected. Calculate the new inferred CSD to be used for the next Prediction and Forecast Phases.
- **Forecast Phase:** Perform a Monte Carlo PCG from the CSD inferred at the inspection time to a future time until the SFHPOF exceeds 10^{-4}. For this phase, loads are typically unknown. For the scenarios presented in this paper, no load forecasting was done to highlight the effect of the ICSD on the SFHPOF.

All Monte Carlo PCG simulations used five seeds of 1,000,000 samples each, for a total of 5,000,000 samples. The PCG results were stored as a function of time, enabling the extraction of crack sizes for all samples at each predefined time step. For each time step, a CSD was calculated by averaging the results from the five seeds and modelled using a non-parametric distribution with exponential extrapolation. This approach was found to provide a stable CSD.

Effect of the initial crack size distribution on the single flight hour probability of failure

The SFHPOF was calculated for the five scenarios presented in Table 3. First, the effect of the fraction of cracks growing from the EPS ICSD was assessed. For this assessment, the CSD inference method was used, which corresponds to Scenarios 1 to 4. As such, the EPS fraction was increased from 0% (all cracks nucleated from scratches) to 100% (all crack nucleated from the EPS). The SFHPOF results for this assessment is graphically presented in Figure 4, where the SFHPOF increases with time. The inspections for these scenarios are scheduled when the SFHPOF reached 10^{-4}, after which the SFHPOF is reduced as the simulated inspection did not find any crack. After the inspection, the component is returned to service and the SFHPOF is forecasted based on the expected future loads. This allows scheduling of the next inspection, i.e. when the SFHPOF reaches 10^{-4} again.

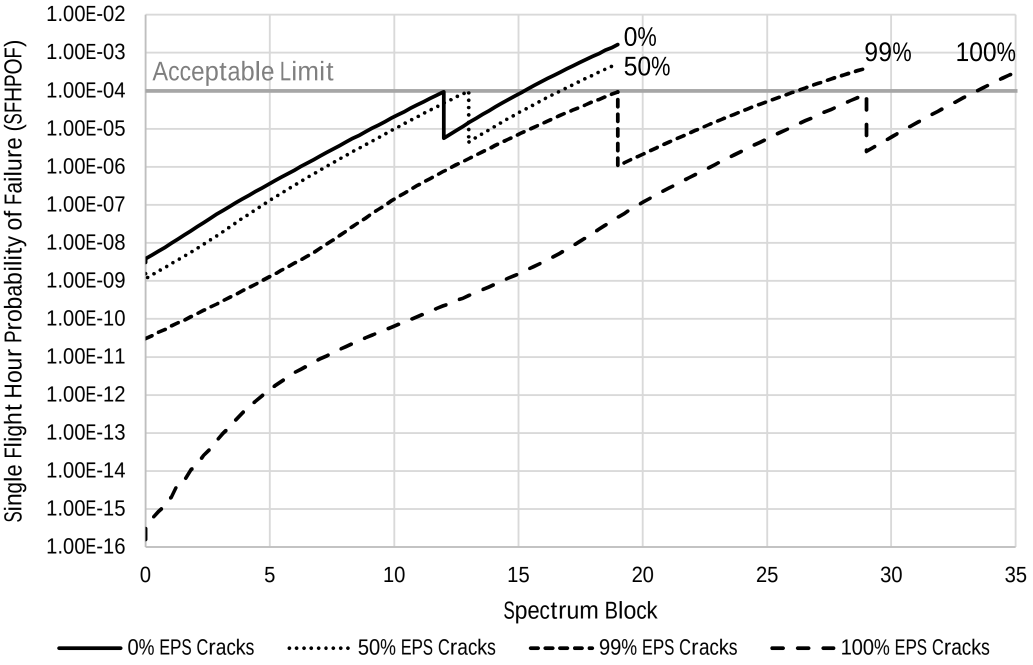

Figure 4: Effect of EPS fraction (%) on SFHPOF results

The time at which the first and second inspections were established is summarized in Table 4. As expected, the inspection interval increases as the fraction of cracks caused by scratches decreases. For the CF-188 ILEF case study, this analysis suggests that the lugs should be inspected at Block 12 if their surfaces are known to be scratched (0% EPS cracks), which is significantly faster than if the surface only had shot peening marks (100% EPS cracks). The reality could be between these two limit cases if these were the only types of damages present at the lugs.

Table 4: Effect of EPS fraction (%) on time to inspection

Fraction of crack originating from EPS	Time at first Inspection (Spectrum Block)	Time at second inspection (Spectrum Block)	Interval between first and second inspections (Spectrum Block)
0%	12.00	15.12	3.12
50%	13.00	16.64	3.64
99%	19.00	26.03	7.03
100%	29.00	33.42	4.42

The calculated inspection interval to the second inspection varied from 3.12 to 7.03 Spectrum Block for the simulation performed using CSD inference. The amount of SFHPOF reduction caused by the inspection is difficult to interpret. However, it is understood the probability of having large cracks is reduced further than the probability of having small cracks if no crack has been found during NDI; affecting the resulting CSD and SFHPOF differently.

The effect of the inference method was also assessed. As presented earlier, the CSD inference method modifies the CSD after the inspection, whereas the mixture weight inference method only modifies the weight of the mixture model. The effect of the inference method on the resulting SFHPOF results are compared in Figure 5 for the CF-188 ILEF case study. This comparison shows that inferring the weight of the mixture distribution did not significantly reduce the SFHPOF. In this case, the average weight was reduced from 50% to 43% of the cracks nucleating from scratches. While this reduction is aligned with the observed NDI results (no crack detected), it is insufficient to decrease the SFHPOF sufficiently to provide a practical inspection interval. From the digital twin perspective, the mixture weight inference could be effective, but further investigation is required to fully comprehend the proper utilization of this method, given that:

- This method assumes that the ICSD composing the mixture model are representative of the current critical location of the fleet. However, the method does not permit to modify the ICSD for the scratches of this specific aircraft if this particular location does not have large scratches, but only the probability of having a scratch that is representative of the scratches found on the fleet.
- The location selected for the demonstration is not well suited for damage tolerance, as the POD for a surface crack at the lug may not be suitable to reliably detect a crack before failure. Evaluating this method using another test case could provide another perspective on the method. This other case study should have a critical crack size substantially larger than its $a_{90/95}$ POD capability.

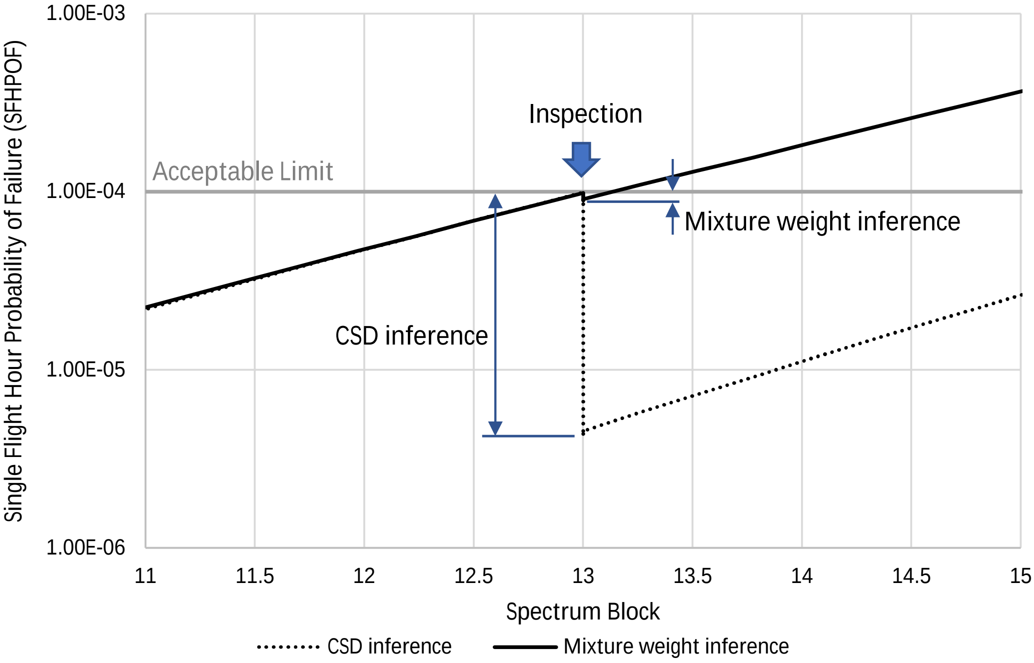

Figure 5: Effect of inspection on SFHPOH using two inference methods: CSD inference and mixture weight inference

CONCLUDING REMARKS AND OUTLOOK

Managing aircraft fleets is very challenging in an era where aging aircraft needs to be retired while the the higher costs of next generation aircraft limit the size of the new fleets. Reducing unanticipated cracking and failures while minimizing the number and frequency of NDI could help reducing the operating costs while meeting the mission requirements [17]. This, however, requires fundamental changes in how airframes are maintained. Currently, the damage tolerant (DT) design philosophy relies on conservative deterministic assumptions to define repeated inspection intervals [18]. These assumptions aim at including the effect of all uncertainties (flaw sizes, loads, etc.). While this approach has been used sucessfully to maintain many civil and military aircraft, the conservatism build into the DT requirements may require extensive (and unecessary) inspections and limit life extension options. The risk approach, used for the ADT Framework presented in this paper, provides the tools and methods to relax some of the DT conservative assumptions. Consequently, the adoption of the ADT Framework proposed in this paper requires a change in how aircraft are currently lifed; moving from conservative deterministic approaches to quantitative risk assessment approaches.

Recent improvements incorporated into the ADT framework expanded its capability to real-world applications, allowing users to:

- Maintain an aircraft using a risk-based approach. Risk can be quantified in terms of single flight-hour probability of failure (SFHPOF) / hazard rate, or cumulative probability of failure.
- Perform tail-specific analyses based on available data, including inspection results and load monitoring.
- Update prior engineering assumptions based on data collected throughout the life of the aircraft. This includes loads and ICSD that have significant effect of the SFHPOF.
- Intrinsically include uncertainty quantification, such that the known unknowns are modelled and affect the calculated life distribution. This approach theoretically replaces legacy engineering approaches that rely on safety factors.
- Adjust the complexity of the analyses based on available information. At a minimum, the initial crack size distribution (ICSD) and the probability of detection (POD) curve should be provided. However, as shown in this paper, the work from other organizations and engineering judgement can be leveraged to estimate these parameters. While more representative values should yield to more reliable results, conservative assumptions can also be used provided that the inference capability of the framework could help to refine these assumptions throughout the life of the aircraft.

The application of the ADT Framework to the CF-188 ILEF attachment lugs provided an excellent opportunity to develop and test the new concepts but it was found that this case study might not be well suited for the DT-based approaches. In this paper, the use of mixture distributions for modelling the ICSD has been investigated. While this modelling method requires additional data in the form of ICSD for various types of defects, it was shown that these data can be obtained from the literature and measurements to develop more physics-based ICSD supported by tests and in-service data.

The NDI simulation methods were also investigated using the CF-188 ILEF case study. This assessment showed that only the CSD inference method could sufficiently decrease the SFHPOF to allow safety by periodic inspections. However, it is recommended to investigate the mixture weight inference method further before drawing strong conclusions on its relevance for lifing and sustainment of airframe structures.

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