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

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ABSTRACT

The National Research Council of Canada (NRC) is currently developing an Airframe Digital Twin (ADT) framework based on quantitative risk assessment and probabilistic crack growth. This paper gives a high-level overview of the current state of the NRC ADT framework, presents a demonstration of its application to a CF-188 (F/A-18) wing component, and shows that the digital twin concept could be used to improve the current CF-188 life management policy. Upon further development and validation, it is believed that the use of digital twin technologies has the potential to enhance the accuracy of individual aircraft diagnosis and prognosis tools to better inform fleet-management decision making.

1.0 INTRODUCTION

Current airframe life cycle management approaches, based on deterministic safe life and damage tolerance principles, 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.

In collaboration with the Canadian Department of National Defence (DND), the National Research Council of Canada (NRC) is currently developing an airframe digital twin (ADT) framework to assess the adaptability of this technology to Royal Canadian Air Force (RCAF) fleets. This framework is based on probabilistic crack growth modelling, probabilistic usage forecasting, Bayesian model updating, high-fidelity structural modelling, and quantitative risk assessment of individual aircraft components.

The ADT framework developed by NRC uses concepts proposed by the United States Air Force Research Laboratory [1], aiming at enhancing the accuracy of the diagnosis and prognosis of individual aircraft to better inform maintenance decision making. The framework provides the capability to periodically update the probabilistic inputs of its constituting models as new data becomes available, such as inspection results and usage obtained from the individual aircraft tracking (IAT) system.

At its current stage of development, the NRC ADT framework focuses on digital representations of individual critical structural locations. Conceptually, all critical locations of an individual airframe can be combined to form the digital twin of that particular airframe. The data collected from each aircraft can then be used to update the models associated with each critical location and mirror its actual state and history (usage, modifications, damage, etc.). Combining the life prognostic from all individual locations results in a better probabilistic representation of the current and future state of that specific aircraft.

This paper provides an overview of the NRC ADT framework, including current development efforts carried out to make it more functional and more efficient. An application of the framework is also presented using a CF-188 (F/A-18) wing component, for which the probability of structural failure resulting from ADT is compared with the one resulting from the current CF-188 life management policy.

2.0 ADT FRAMEWORK

2.1 Quantitative Risk Assessment and Probabilistic Crack Growth

The NRC ADT framework is based on quantitative risk assessment (QRA), where the probability of failure (POF) of a structural component is calculated as a function of time and compared to thresholds related to the potential consequences of failure. In its simplest form, the POF is determined by evaluating the probability that the expected operational loads exceed the residual strength resulting from damage assumed to grow in a structure.

The POF is calculated by the NRC ADT framework from probabilistic crack growth (PCG). Small cracks are assumed to be present at the considered structural location when the aircraft enters service. This damage state is represented by an initial crack size distribution, corresponding to the probability that initial intrinsic discontinuities of various sizes be present in the material. Ideally, this distribution should be developed from measured characteristics of the location's material and manufacturing process. As the aircraft accumulates flight hours, mechanical loads act on the location and the crack size distribution evolves towards larger cracks, resulting in higher POF values.

Typically, the actual state of damage at a structural location is not known until cracks become large enough to be reliability detected by non-destructive inspection (NDI). Therefore, the POF is initially highly dependent on the assumed initial crack size distribution. Each inspection, however, can provide information that can be used to update the distribution of crack sizes predicted at the inspection time, even if no crack is detected. The amount of updating directly depends on the performance of the used NDI technique, measured in terms of probability of detection (POD), and the assumed crack size distribution at the inspection time.

2.2 Three-Phase Analysis Process

The NRC ADT framework consists of three analysis phases, shown in Figure 1 for a periodic inspection scenario. In this figure, t_i is the time at the i^{th} inspection, $f_c(t)$ is the crack size distribution at time t, Δt_F is the forecasting period and POF(t) is the probability of failure at time t. The main input and output parameters to this framework are listed in Table 1.

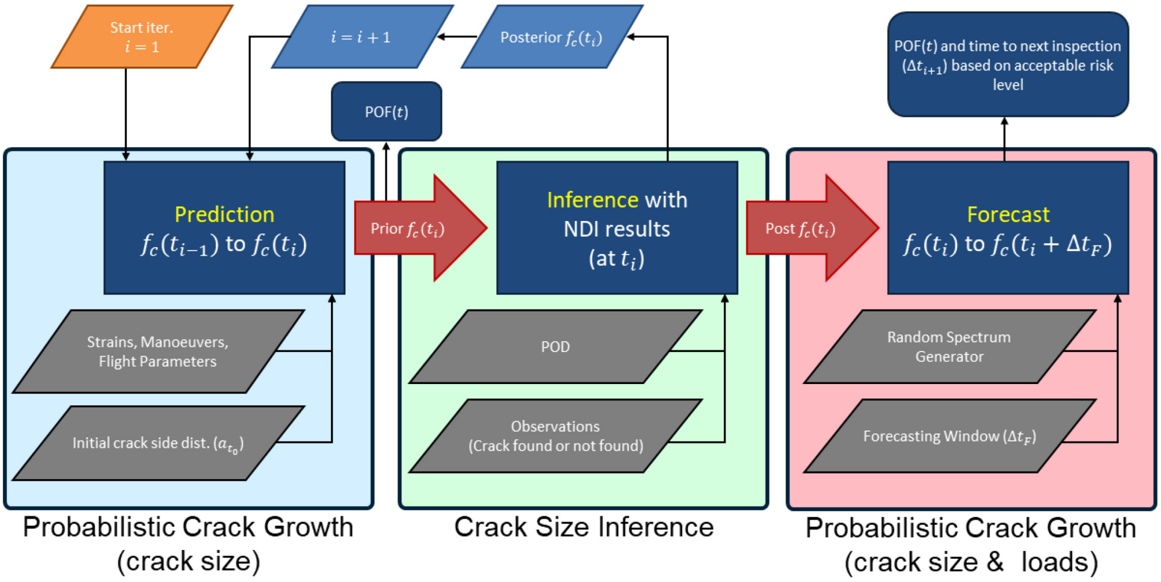

Figure 1: ADT framework methodology.

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[1]	• 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[2]	• 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

[1] For the first prediction, the posterior crack size distribution obtained by inference is not available. The assumed initial crack size distribution is used instead.

[2] The prediction and forecast phases require additional inputs, such as material properties, crack growth rates, load uncertainties, geometric correction factor, and residual stresses.

The first phase, the "Prediction", is performed when new usage data are obtained from the IAT system. It uses the loads recorded by the aircraft to calculate the crack size distribution at the current time from the crack size distribution at the previous time. Additional uncertainties can also be included, such as those related to the IAT system, or the load transfer function between the IAT data and local load or stress.

The second phase, the "Inference", is performed following an NDI. It updates the crack size distribution obtained from the prediction phase with the likelihood of detecting cracks using the selected inspection technique. This process is based on Bayes' theorem. The updated crack size distribution, which is dependent on the POD, is then used as the initial crack size distribution for the next prediction phase.

The third phase, the "Forecast", calculates the future POF using probabilistic crack growth from the updated crack size distribution. The future loading is unknown for this phase but can be estimated from scenarios related to the expected usage (mission profiles, rotations, pilots, location, etc). The future POF can then be used to adjust the maintenance schedule based on the acceptable risk level.

2.3 Framework Implementation

As crack size distributions are used to transfer information from one phase to the next, it is paramount to use statistical distributions that can adequately represent the occurrence of different crack sizes. Standard parametric distributions, such as the lognormal distribution, may be unable to accurately represent the evolution of the crack size distribution from the crack growth and inference processes. For this reason, nonparametric crack size distributions are used to accurately describe the probabilistic crack growth results.

The crack growth analyses conducted as part of the prediction and forecasting phases are performed with a deterministic fatigue crack growth rate model. The PCG analyses involve millions of deterministic crack growth Monte Carlo simulations, each starting from a random initial crack size and, possibly, a random loading spectrum. These random loading spectra can be generated using various methods considering IAT data, model uncertainty, measurement errors, and missing data.

The evolution of the POF as a function of time is the main outcome of the ADT QRA. It allows the operator to monitor the risk and assess different mitigation approaches, including modifications of the aircraft assigned usage, inspection method, or inspection intervals. The probability of failure can be calculated using the Lincoln equation [2] or the Freudenthal equation [3].

NRC implemented the ADT framework as an in-house computer program. This program was developed using the Python and C++ programming languages and leveraged open-source libraries, such that it could be used without licensing fees or limitations. While computationally intensive, the program runs on entry-level desktop computers, but the run-time is significantly reduced if high-end computers with multi-core processors are used.

3.0 ADT FRAMEWORK DEMONSTRATION

3.1 FT382 CF-188 Inboard Leading-Edge Flap Test

The structural full-scale CF-188 life extension test FT382 [4], carried out at NRC, was used as a demonstration platform to develop, implement, and validate the NRC ADT framework. For this test, the transmission lug radii of the wing inboard leading-edge flap (ILEF) were the life-limiting locations. This specific test was selected to assess the adaptability of the ADT methodology by the RCAF because it involved several features representative of a flying CF-188. For instance, the tested component, which was retired from service, included the blend and shot-peening modification currently present the fleet. Furthermore, the applied load spectrum was representative of current and expected future fleet usage, strain gauge data was equivalent to those used in service to calculate loads, and eddy current inspections were performed periodically using the RCAF procedure. The test life-limiting locations are presented in Figure 2.

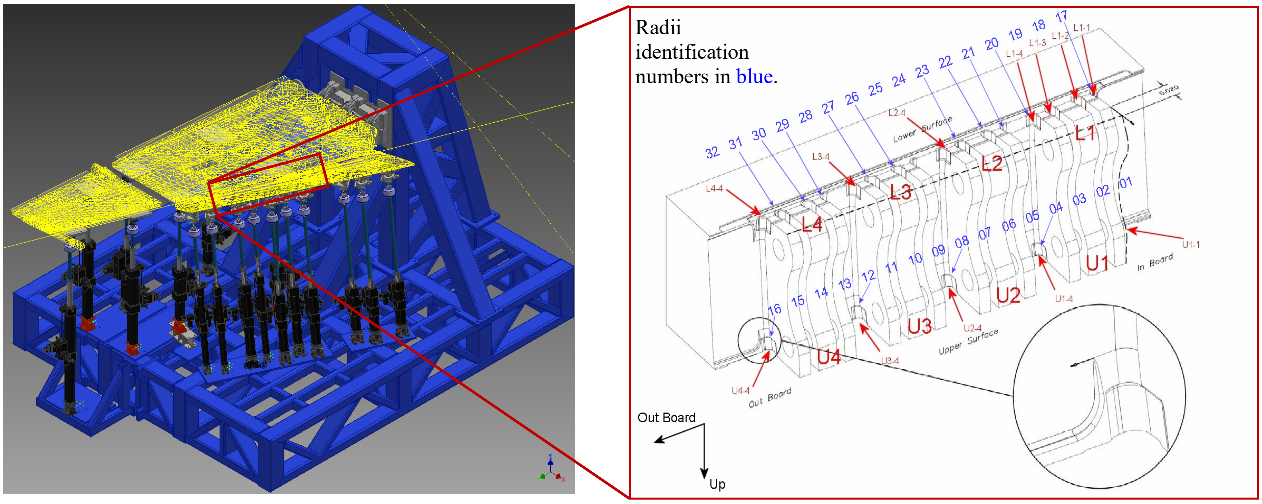

Figure 2: CF-188 inner leading-edge flap test and life-limiting location.

Eddy current inspections were carried out after each spectrum block during the test to detect potential early cracking within the shot-peened areas of the modified lug radii. The first damage was reported after the completion of Block 38 at Radius 18, identified in Figure 2. The fatigue test was continued until the application of Block 46. Quantitative fractography (QF) was performed after the test to measure the crack sizes and calculate the crack growth rates.

3.2 FT382 CF-188 ILEF Digital Twin

The ADT analysis of the ILEF lugs required probabilistic inputs pertaining to the initial crack size distribution, POD, fracture toughness, and stress exceedance. In addition, load transfer functions and stress intensity factor solutions, including the effect of pin loading and residual stresses from shot peening, were developed from finite element models.

Local high-fidelity three-dimensional finite element (FE) models of the blended lugs were developed in Abaqus [5], StressCheck [6], and BAMF [7] to develop the stress intensity factor solutions required to perform crack growth simulation of the modified lug geometry. The surface residual stresses due to shot peening were measured using X-ray diffraction and a stress intensity factor solution was developed to consider their effect on crack growth. A global model of the CF-188 wing was used to develop load transfer functions between the wing root bending moment (WRBM), the ILEF hinge moment (ILEFHM), and the lug pin loads. Illustrations of the various finite element models are presented in Figure 3, within a flow-chart illustrating the FT382 CF-188 ILEF digital twin analysis sequence

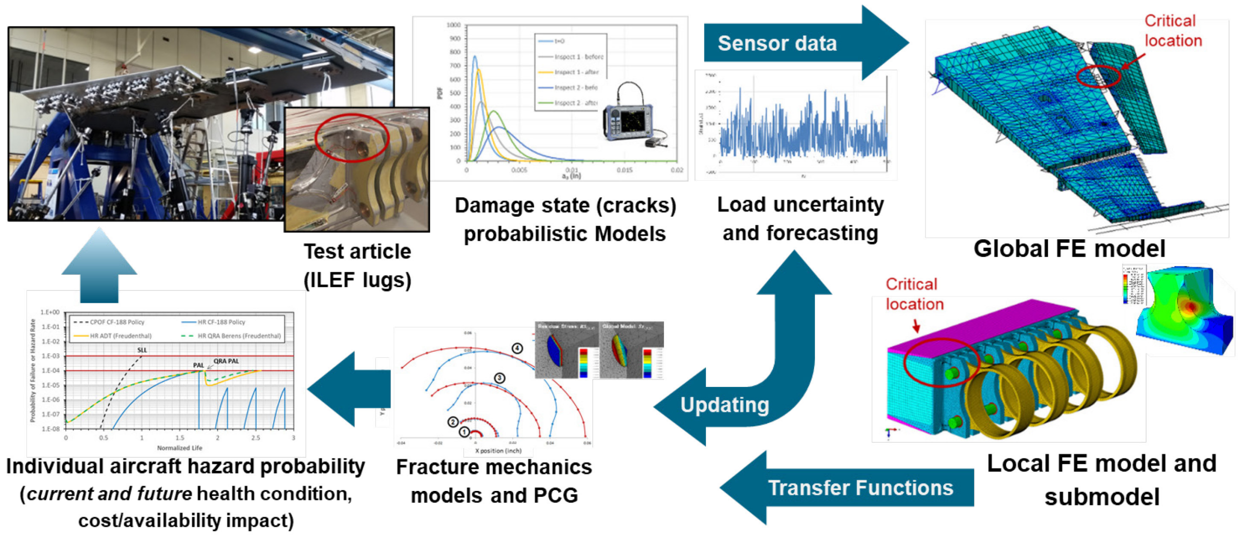

Figure 3: FT382 CF-188 ILEF digital twin analysis sequence.

A model developed by the Defence Science and Technology Group (DST) of Australia was used to characterize the 7050-T7451 aluminium crack growth rate [8]. This model has been shown to provide good predictions for small cracks. Crack growth simulations were validated against the FT382 QF results for Radii 18 and 31. As shown in Figure 4, good agreement was obtained between the measured and predicted crack growth. This comparison provided confidence that the simulation results were representative of the crack growth occurring at the considered attachment lugs radii.

The equivalent pre-crack size (EPS) distribution developed by DST for peened 7050-T7451 aluminium [9] was selected as the initial crack size distribution. Conceptually, the EPS approximates the dimension of crack-nucleating features by projecting QF crack measurements to time zero using an exponential crack growth regression. In this work, the EPS distribution was assumed to be representative of the initial discontinuities present after the modification, without considering larger flaws that could be induced from mishaps during manufacturing, assembly, and maintenance. As such potential flaws may severely affect the POF, the usage of the EPS distribution may only provide a lower-bound estimate of the risk. In this demonstration example, a simple approach was used to add the probability of having larger flaws at time zero. It consisted in increasing the standard deviation of the EPS distribution to make the probability of having a crack larger than 0.86 mm (0.034 inch) equal to 10^{-3}.

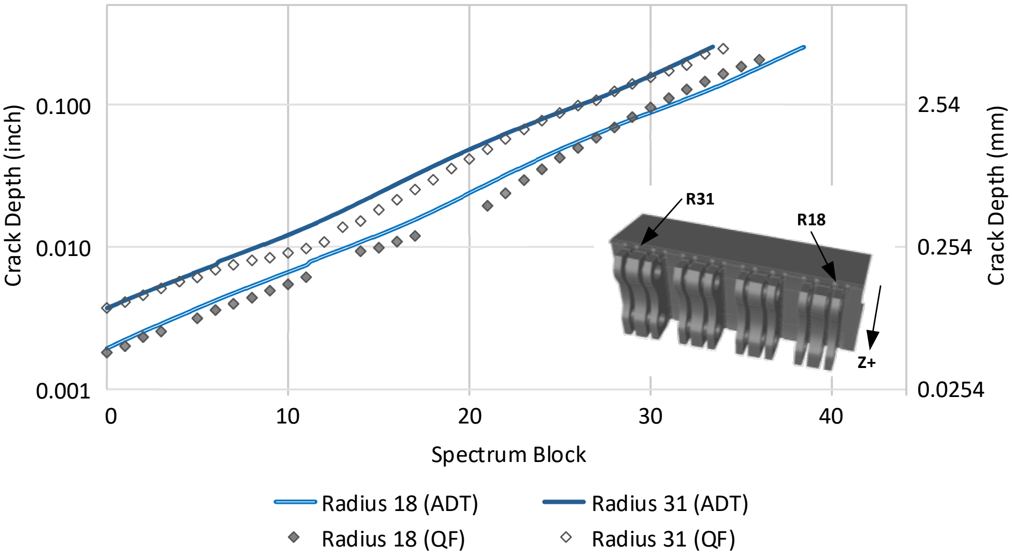

Figure 4: Comparison between the simulated crack growth and QF results.

A representative POD curve for the non-destructive inspection performed in the test was generated from data published by the United State Air Force for manual eddy current surface inspections at a radius [10]. According to these data, there is a 50% probability of detecting a crack equal or longer than 1.27 mm (0.050 in) with this method, and a 90% probability of detecting a crack equal or longer than 3.18 mm (0.125 in).

The hazard rate (HR), expressed in terms of single flight hour (FH) POF (SFHPOF), was calculated using Freudenthal's equation [3]. This formulation has been verified to be preferable over Lincoln's equation for this type of application [3], [11].

3.3 Results and Comparison with Current Approach

A comparison between cumulative probability of failure (CPOF) and HR results obtained from the ADT framework and the current CF-188 life management practices [12] is presented in Figure 5. In this plot, the life is normalized with respect to the safe life limit (SLL), defined as the time when the CPOF, determined from the CF-188 life management policy, reaches 10^{-3}. If this life limit is short of a target life, a risk assessment can be performed based on the point of acceptable limit (PAL), defined as the time when the HR, or SFHPOF in this case, reaches a certain threshold. Based on the hazard severity of the CF-188 ILEF, this threshold was set to be 10^{-4} per FH which results in a normalized life of 1.75. The SLL and PAL life limits obtained from the CF-188 life management policy are based on life distributions determined from the full-scale test results. This approach is different from the current ADT implementation that uses crack size distributions instead of life distributions.

For the example presented in Figure 5, it was assumed that the ILEFHM loading spectrum was known and available as an input to the ADT framework. This assumption simplified the problem by neglecting load uncertainties in the crack growth analysis. However, in order to compare the different analysis approaches, the lives obtained by the ADT calculations were divided by a load tracking factor of 1.5, which is the factor prescribed by the CF-188 life management policy to account for load uncertainties in this component. Using these assumptions, the ADT normalized PAL, determined from QRA calculations, is 1.83.

During the early stage of life, the HR obtained from the ADT approach (orange curve, calculated using ProDTA [3]) is significantly higher than that of the current CF-188 method (blue curve). This is due to the artificially increased probability of a large or "rogue" flaw that was included in the initial crack size distribution. However, as flight hours are expended, the ADT HR increases relatively slowly and reaches the SFHPOF threshold of 10^{-4} per FH slightly later than the CF-188 policy PAL.

In the ADT scenario depicted in Figure 5, it was assumed that an inspection was performed at the ADT PAL, and that no crack was detected. This inspection was simulated using the Bayesian approach and reduced the probability of having large flaws. The post-inspection HR was reduced, and its growth rate remained low, resulting in an inspection interval, before the first and second inspection, approximately 20% longer than that resulting from the current CF-188 method.

For the current CF-188 method, the inspection was simulated by reducing to the crack size to the crack that is detectable 90% of the time with a confidence of 95%. Legacy practices assume this value to be $a_{90/95}$ = 0.508 mm (0.020 in), which is significantly lower than the corresponding value in POD data used for the ADT calculation ($a_{90/95}$ = 6.35 mm or 0.25 in Ref. [10]). This assumption resulted in a significant drop in SFHPOF. Nonetheless, the subsequent inspection intervals are relatively short because they are based on safe life calculations, which use scatter and uncertainty factors, instead of the HR/SFHPOF which in this case only uses the load tracking factor of 1.5.

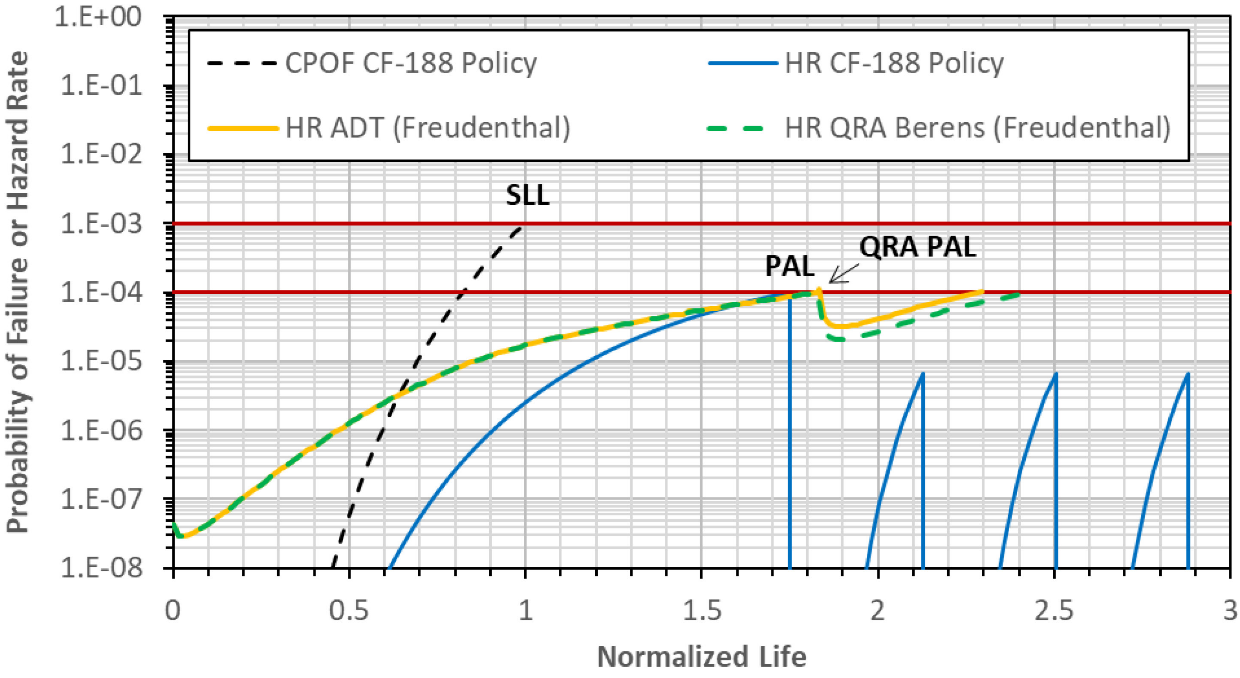

Figure 5: NRC ADT demonstration (CF-188 ILEF transmission lugs).

The ADT approach updates the crack size distribution based on actual airframe crack inspection results. If no crack is detected and the models predict a significant likelihood of crack detection, the probability density of the largest crack sizes in the distribution is reduced. Conversely, if crack detection is unlikely and a crack is detected, the density of large cracks is increased. This updating method is different from the traditional QRA crack size distribution update proposed by Berens [13], for which cracks assumed to be detected are modified or repaired. The updating approach in this case consists of replacing the size of the detected cracks by discontinuity sizes assumed for the repair. The dashed green curve in Figure 5 corresponds to this scenario, calculated using ProDTA [3], where the repair crack size distribution was assumed to be the same as the initial crack size distribution and the pre-repair and post-repair crack growth models were the same. In this case, it was determined that the likelihood of detecting and repairing a crack was 28.8% at the QRA PAL. The HR resulting from the ADT and traditional QRA methods are the same up to the first inspection because they both used the same deterministic loads. However, the different updating approaches resulted in different post-inspection HR values. For this specific case, the traditional QRA approach resulted in a longer inspection interval.

3.4 Discussion, Current and Future Work

For the CF-188 ILEF demonstration case presented in this paper, the ADT approach provided limited improvements over the current CF-188 life management approach. One of the reasons for this outcome is that the critical crack size for this location was assumed to be relatively small (approximately 6.35 mm or 0.25 in). Sensitivity studies showed that the HR could be reduced significantly more after Bayesian updating when the critical crack size is significantly larger than the cracks that can be reliably detected (larger cracks at the time of inspection).

Other sensitivity studies showed that the probability of large or “rogue” flaws being present at time zero has a significant impact on the POF. The results presented herein assumed a simple modification to include such initial damage by modifying the initial crack size distribution. Other options using mixture models are currently under investigation at NRC [14].

The POF calculation method can also lead to significant differences in the predicted risk level. Several studies suggest that the Lincoln equation [2] is conservative but may overly reduce the time to inspection [3], [11]. As such, current efforts are being made to implement an efficient algorithm to calculate the POF based on the Freudenthal equation [3].

It is important to accurately characterise the POD of the NDI method employed at the considered location. If specific POD studies are not available, reliable unbiased data, such as provided by EN-SB-08-012D [10] should be used. It was noticed through parametric studies that typical NDI methods may not result in significant crack size distribution updates if the critical crack size is not significantly larger than the detection capabilities of the selected NDI technique.

Finally, the inclusion of load uncertainties in the analysis, both for the prediction and forecast phases, is currently being addressed. For the prediction phase, these uncertainties can be related to, for example, the resolution of the IAT system or the accuracy of the load transfer functions. For the forecast phase, these uncertainties can be related to future missions, or randomness inherent to mission types, in addition to those present in the prediction phase. For the CF-188 ILEF demonstration case, the inclusion of load uncertainties has a potential to reduce the current load tracking factor of 1.5.

4.0 CONCLUSION

Results such as those presented in Figure 5 suggest that the implemented ADT framework could provide benefits for airframe life assessment and fleet management, even with more severe assumptions regarding the initial state of discontinuities in the structure and probability of crack detection. It can provide a better probabilistic representation of the future state of aircraft fleets and can allow more accurate risk-based decision making for individual aircraft components. However, the calculated risk strongly depends on the probabilistic distributions defining some of the key analysis parameters, such as the initial crack size distribution and the POD.

The ADT framework presented in this paper is based on probabilistic crack growth and should be adaptable to most airframe locations usually analysed using damage tolerances principles. Another digital twin project was recently initiated at NRC to cover locations analysed with safe life methods, which is particularly common for helicopter airframes. It is believed that these two options will offer a foundation able to streamline the progressive adoption of the ADT technology to most of the common life-limiting airframe locations, without disruptive changes.

5.0 ACKNOWLEDGEMENT

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