

Development of Initial Crack Size Distribution for Risk Assessment of Aircraft Structures

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ABSTRACT

This paper presents the methodologies for determining the initial crack size distribution (ICSD) for risk assessment of aircraft structures, as well as their application on several case studies of aircraft structural risk analysis. Three approaches were developed and presented for determining an ICSD using, a) small sample size ($n < 40$) of damage data from in-service, full-scale test, and teardown inspection, b) extremely small sample size ($n < 5$) of in-service/full-scale/teardown data; and c) the material initial discontinuity states (IDS), e.g. particle, pore, and manufacturing induced damages, developed from the Holistic Structural Integrity Process (HOLSIP) framework. Some case studies are presented to show how to use these approaches to develop an ICSD, and its impact on aircraft structural risk analysis. It is expected that the developed methodologies and sensitivity study process could help to carry out a practical risk analysis for generic aircraft structures.

1. INTRODUCTION

A risk based management approach/tool has been adopted by most military air fleets (e.g. US DoD (MIL-STD-820), UK MoD (ADRM)) to assure aircraft safety and maintain airworthiness. In 2005, quantitative risk analysis was formally required in the USAF aircraft structural integrity program (ASIP) (MIL-STD-1530C). In the past few years, the Canadian Forces (CF) also introduced and revised a Record of Airworthiness Risk Management (RARM) process to manage technical and operational airworthiness for all CF aircraft [1][2]. Today, the RARM has become the single most critical decision making tool in the CF air force [3]. In RARM, both *qualitative* (defining hazard probability as ‘frequent’, ‘remote’, ‘extreme improbable’, etc.) and *quantitative* (defining hazard probability as ‘ 10^{-3} ’, ‘ 10^{-5} ’, ‘ 10^{-8} ’, etc.) risks are defined for all CF aircraft platforms including UAV (unmanned air vehicle) and helicopter [2]. When there is sufficient data available, a *quantitative* risk assessment (QRA) can be done to substantiate the assignment of a risk index number. The QRA can provide a better evaluation of the conditions of aging fleets and better support to the decision making process.

For damage tolerant analysis (DTA) based risk assessment, the initial crack size distribution (ICSD) is the input that affects risk analysis results most significantly [4][5]. It is also very costly and difficult to get in-service data for determining an ICSD distribution [6]. As such, the ICSD can be the biggest hurdle for carrying out a quantitative risk assessment. This paper first summarizes an NRC (National Research Council Canada) risk analysis method and tool, and then presents several methodologies developed for determining an ICSD, along with some practical examples on developing and using the ICSD for aircraft structural risk analysis.

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2. RISK ASSESSMENT METHODOLOGY AND TOOL

According to MIL-STD-1530C, risk analysis is an evaluation of a potential hazard severity and probability of occurrence. For aircraft structural applications, the potential hazards include structural failures that can cause injury or death to personnel, damage to or loss of the aircraft, or reduction of mission readiness/availability. The most important task in risk assessment is to calculate the probability of failure (PoF) of aircraft structures. Similar to US DoD (JSSG2006, MIL-STD-1530C), CF uses single *flight hour* PoF (hazard probability per *flight hour*) to measure the risk level of critical locations.

Under DRDC (Defense Research and Development Canada) and NRC collaborative projects, NRC has been carrying out research on structural risk analysis since 1999. In the beginning, NRC evaluated and used the USAF (US Air Forces) tool PROF (Probability of Fracture) for PoF study. Because of the limitations of PROF for some applications, especially related to corrosion risk assessment, NRC developed an in-house tool, ProDTA (Probabilistic Damage Tolerance Analysis), for structural risk analysis by taking into account both conventional fatigue damage and age related environmental damage (i.e. corrosion) [7][8]. Figure 1 presents the major inputs of ProDTA, which are grouped into fatigue and corrosion related inputs.

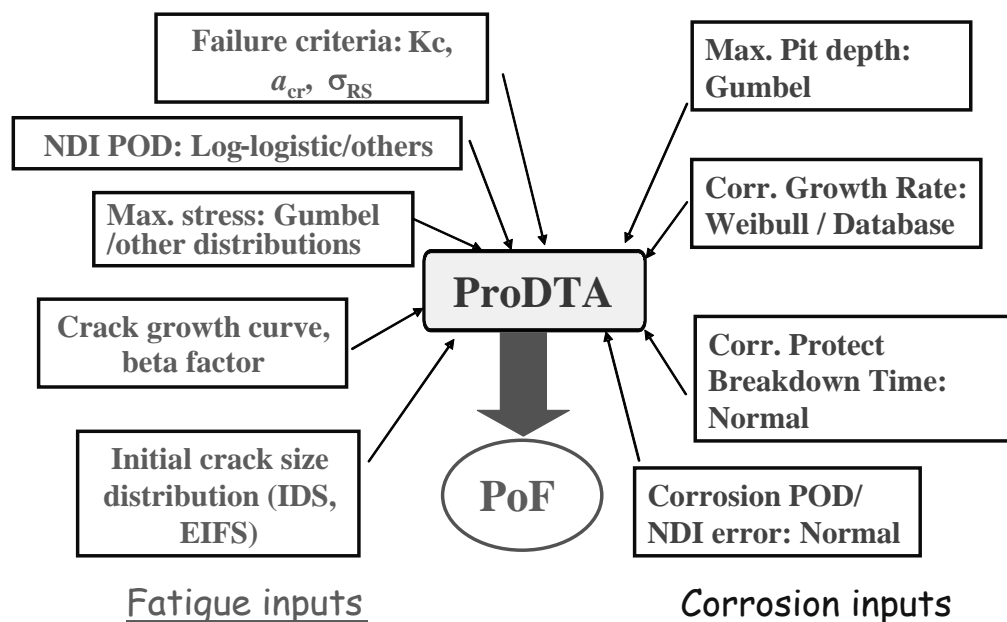


Figure 1: Main inputs for NRC in-house tool ProDTA

Without the corrosion effect, ProDTA uses similar methodologies to those of the USAF PROF [9]. However, ProDTA uses different numerical techniques/algorithms to calculate a PoF. More importantly, ProDTA has flexibility to use various statistical models for different inputs, depending on the actual fleet data that is available. For the corrosion risk assessment, ProDTA uses a Monte Carlo Simulation coupled with numerical integration to calculate the PoF [7][8].

In ProDTA, three types of PoF can be calculated separately or jointly, depending on application, they are,

$$K_C \text{ criterion : } PoF(t) = \int_0^{a_c} f(a) \int_0^{\infty} f_{K_C}(K_C) (1 - H_{\sigma}[\sigma_C(a, K_C)]) dK_C da \quad (1)$$

$$\text{Residual strength criterion : } PoF(t) = \int_0^{a_c} f(a) (1 - H_{\sigma}[\sigma_{RS}(a)]) da \quad (2)$$

$$\text{Critical crack size criterion : } PoF(t) = f(a) / [1 - F(a)], F(a) = 1 - \int_0^{a_c} f(a) da \quad (3)$$

where

$PoF(t)$:	Single flight hour PoF at time t
$f(a)$:	Probabilistic density function (pdf) of crack size a , at time t
$f_{K_C}(K_C)$:	pdf of fracture toughness K_C
$H(\sigma)$:	Distribution of the maximum stress per flight hour
$\sigma_C(a, K_C) = K_C [\beta(a) \sqrt{\pi a}]$:	Critical stress at a given crack size a , stress intensity factor related beta factor $\beta(a)$, and K_C
$\sigma_{RS}(a)$:	Residual strength as a function of crack size a
$F(a)$:	Cumulative distribution function (CDF) of crack size at time t , i.e., the probability that the crack length is smaller than a , at time t

The $PoF(t)$ of eq. (1) accounts for the failure probability that the crack length is smaller than a_c , but the stress level encountered during the single flight hour is greater than $\sigma_C(a, K_C)$, dominated by K_C and a . This probability is the same as a *hazard rate* for a single flight hour.

The $PoF(t)$ of eq. (2) accounts for the failure probability that the crack length is smaller than a_c , but the stress level encountered during the single flight hour is greater than $\sigma_{RS}(a)$ dominated by crack size a . This probability is the same as a hazard rate for a single flight hour.

The $PoF(t)$ of eq. (3) accounts for the failure probability that the crack length is greater than a critical crack length a_c , on condition that there is no failure before time t . It should be noted that, for extreme remote probability ($F(a) < 10^{-7}$), the $PoF(t)$ (*hazard rate*) is almost the same as $f(a)$, since the non-failure condition term, i.e., the denominator term $[1 - F(a)] = [1 - 10^{-7}]$ is approximately 1.0.

3. ICSD METHODOLOGIES AND CASE STUDIES

From Figure 1, it is shown that, without the corrosion effects, the major inputs for a risk analysis are, ICSD, crack growth curve including geometry factor (beta), maximum stress distribution, probability of detection (POD), and residual strength or K_C distribution. From equations (1) to (3), it is shown that a PoF is closely related to the crack size distribution $F(a)$. In a risk analysis, $F(a)$ is grown from an ICSD, based on a master crack growth curve or program. Depending on the crack data available, different methods can be used for determining an ICSD. The methodologies were developed and presented below, along with some case studies.

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3.1 APPROACH 1 – determining an ICSD/EIFSD (Equivalent Initial Flaw Size Distribution) with a small sample size ($n < 40$ ¹) of crack data from different aircraft in service, full scale test, and/or teardown. Small sample size data is common, especially for a small fleet. The detected crack data are assumed to be reliable or confirmed with fractography during teardown. If available, the “no-crack” inspections should be considered, for instance, to have missed the cracks whose sizes are just below the NDI (non-destructive inspection) threshold (conservative assumption). In either way, an ICSD/EIFSD can be determined using the following two methods.

- 1) **TTCS to EIFSD method (TTCS=Time to Crack Size)**: the detected crack data can be first regressed to a common crack size a_{TTCS} to determine a TTCS distribution, then the TTCS distribution can be back calculated/regressed to an EIFSD, using a master crack growth curve or crack growth program. The principle of this method is to use the crack growth curve to translate the percentile of the TTCS distribution to percentiles of the EIFS smaller than a certain crack size (low percentile of TTCS distribution translates to high percentile of the EIFSD, and vice versa). Figure 2 illustrates the concept of this method.

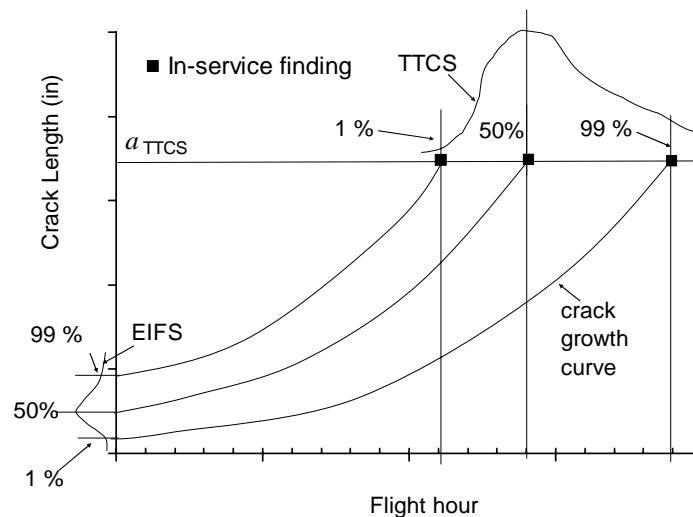


Figure 2: Determining an ICSD/EIFSD from a TTCS distribution

In the case where an exponential function, $a = a_0 \text{Exp}(b \cdot t)$, can be used to describe the crack growth curve, a closed-form EIFSD distribution can be derived from a TTCS distribution [10]. If the TTCS follows a Lognormal distribution, so does the EIFSD; if the TTCS follows a Weibull distribution, the EIFSD follows a compatible Weibull distribution.

- 2) **Direct EIFSD method**: the detected crack data are directly regressed to time zero to determine the EIFS values, based on a master crack growth curve or program. The EIFS values can be fitted with a statistical distribution. Ideally, the loading spectrum of individual aircraft should be used in the regression, but often the spectrum is not available or not covering enough critical locations. Thus a DaDTA (Durability and Damage Tolerant Analysis)/DTA (Damage Tolerant Analysis) design curve and loading spectrum can be

¹ For most statistical hypothesis tests including Anderson-Darling goodness-of-fit test, the least sample size of 40 is needed to differ a Lognormal from a Weibull distribution at a significance level (Probability of Type-I error) of 5%, with a power (1-Probability of Type-II error) of over 50% [11]

used for the regression analysis; this would result in an EIFSD suitable for the whole fleet. Figure 3 illustrates the concept of this method.

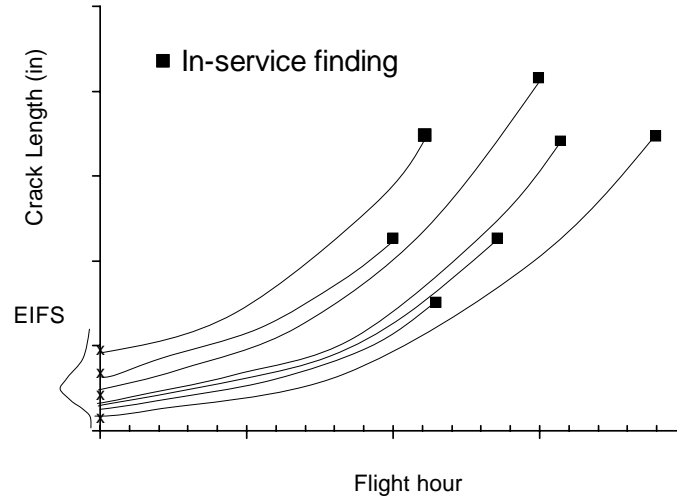


Figure 3: Determining an ICSD/EIFSD from in-service data directly

As mentioned, either a master crack growth curve or program can be used in the regression analysis, more details are described below,

a) Using an existing DaDTA/DTA crack growth curve to regress the EIFS: This DaDTA/DTA curve is usually analyzed using a representative loading spectrum for the aircraft. As a DaDTA curve often starts from an initial crack size of 0.005” or smaller and a DTA curve starts from 0.05”, an exponential function can be used to extrapolate the curve to smaller EIFS values. A DaDTA curve (0.005”) is better than a DTA curve (0.05”) due to less extrapolation to the smaller EIFS.

b) Using a crack growth program to regress the EIFS: When a calibrated crack growth program (calibrated with tests) is available, the program can be used to find an EIFS through an iteration process. Normally a crack growth program does not include short/small crack model ($da/dN-\Delta K$), so the da/dN curve has to be extrapolated to the short crack regions from the long crack da/dN data.

Since both regression methods involve extrapolation to the short/small crack regime, even down to the nucleation region, EIFS can be any numerical value which is not related to a physical cracking feature. The derived EIFSD are *solely* dependent on the master crack growth curve or program used. Therefore, in a risk analysis program, it is very important to use the same crack growth curve or program to grow the ICSD/EIFSD, so the in-service crack size distribution can be reproduced for PoF calculation. Figure 4 shows that the crack size distribution $F(a)$ at time t , grown by NRC ProDTA, matches the in-service findings.

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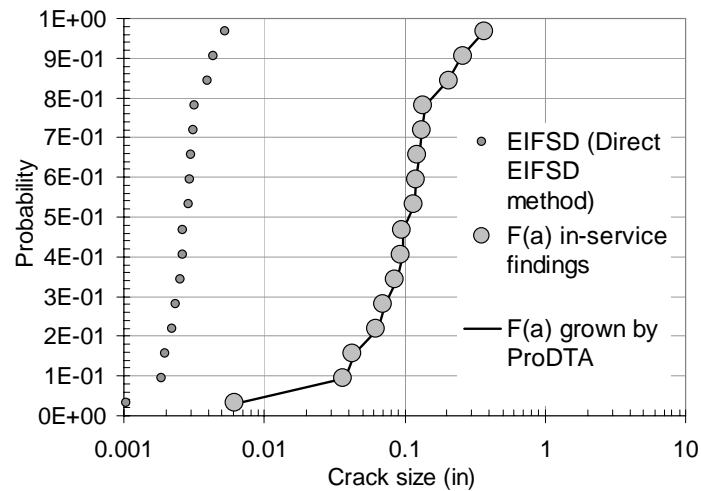


Figure 4: An EIFSD, in-service crack distribution, and grown crack distribution by ProDTA

Due to a finite number of in-service data, the extreme tail ($\leq 10^{-7}$ probability) of the crack size distribution can not practically be verified. Caution is needed to fit a statistical distribution to TTCS and EIFS data. When fitting the TTCS data with a statistical distribution, a good fit to the left tail is critical since it represents the shortest lives which has greatest impact on the PoF results. When fitting an ICSD/EIFSD with a distribution, a good fit to the right tail is critical since it represents the largest initial crack sizes which affects the PoF results most significantly.

In general, for the same data set, a Lognormal distribution will have a longer right tail than that of a Weibull distribution, especially when the probability is larger than $(1-10^{-4})$ [4]. An exponential distribution is usually situated in-between the Lognormal and Weibull distributions. Therefore, if used for an ICSD/EIFSD, a Lognormal distribution would result in higher PoF results. Consequently, for a small data set, sometimes a Lognormal ICSD distribution can result in too conservative PoF results. Engineering judgement is very important for selecting the proper distribution for an ICSD/EIFSD.

Example Case A – In a transport aircraft fleet, 46 inspections were completed for one fatigue critical location in different aircraft, at different flight hours. Among these inspections, 16 cracks were found/confirmed at this location, as shown in Figure 5, while the other 30 inspections resulted in “no-crack”. Statistically, the 30 no-crack findings were treated as censored data [12].

Using a representative DaDTA curve, 16 EIFS values were directly regressed to time zero and plotted in Figure 5. This figure also presents the TTCS values by regressing the 16 cracks to a common crack size of 0.2”. These EIFS and TTCS values were fitted using both Lognormal and Weibull distributions. In the next several paragraphs, a number of ICSD/EIFSD distributions will be presented along with the corresponding risk analysis results. Each paragraph addresses one aspect/factor affecting the ICSD/EIFSD development.

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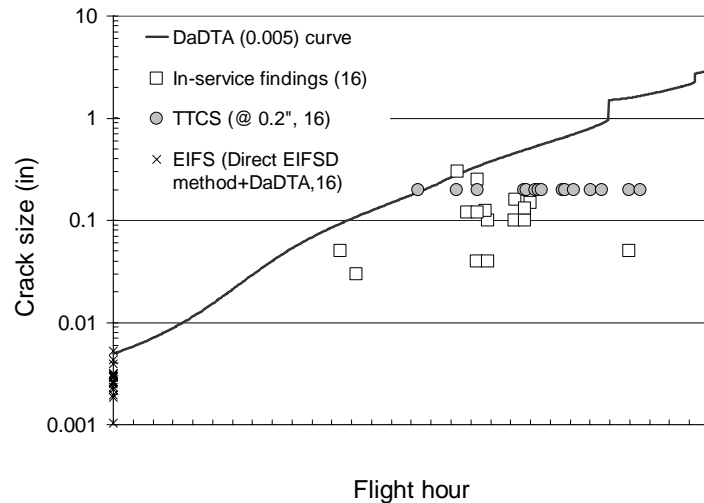


Figure 5: In-service findings and TTCS regressed by a DaDTA curve

DaDTA vs. DTA curve: Figure 6 presents the EIFS regressed by the master DTA (0.05”) and DaDTA (0.005”) curves, and an actual crack growth program including crack growth retardation effect, developed by NRC for this transport aircraft [13]. Note that the EIFS values were ranked and presented in a format of probability of exceedence to better show the tail of the distribution. The symmetrical ranking method ($P_i=(i-0.5)/n$, i.e. Hazen method) was used to determine the plotting positions for some distributions. It is shown that, for this case, the master DaDTA (0.005”) curve gave almost the same EIFS values as the actual crack growth program. Therefore, the DaDTA (0.005”) curve was used in the following EIFSD regression and PoF calculation.

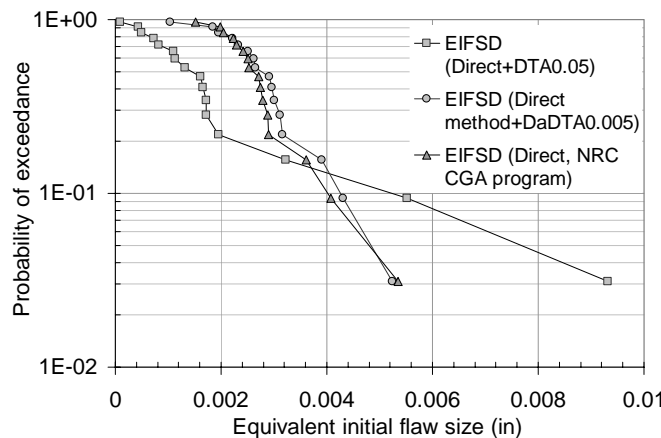


Figure 6 EIFS values regressed using master curves (DaDTA (0.005), DTA (0.050)) and NRC crack growth program

Lognomal vs. Weibull distribution: Figure 7 presents a number of EIFSDs determined by different methods. It is shown that the EIFS (Direct EIFSD+DaDTA) data is not adequate for a risk analysis due to its short tail

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($<10^{-2}$). Thus both the Weibull and Lognormal distributions were used to fit the data for risk analysis. In this figure, '2PWei' means a 2-parameter Weibull distribution, and '2PLN' means a 2-parameter Lognormal distribution. The Anderson-Darling goodness-of-fit tests were carried out and indicated that a 2P Lognormal distribution fitted the EIFSD data better than a 2P Weibull. It should be noted that the EIFSD (2Wei, TTCS to EIFSD) had a very high tail (i.e., the probability of exceeding 0.050" crack is $\sim 10^{-3}$), which was deemed not realistic from an engineering judgment. For all these EIFSDs, risk analyses were carried out using the NRC risk analysis code ProDTA and the PoF results are presented in Figure 8. The influence of an EIFSD on the PoF results can be seen by comparing Figure 7 and Figure 8. This type of sensitivity study would give the structural engineer more confidence to select an ICSD for a risk analysis.

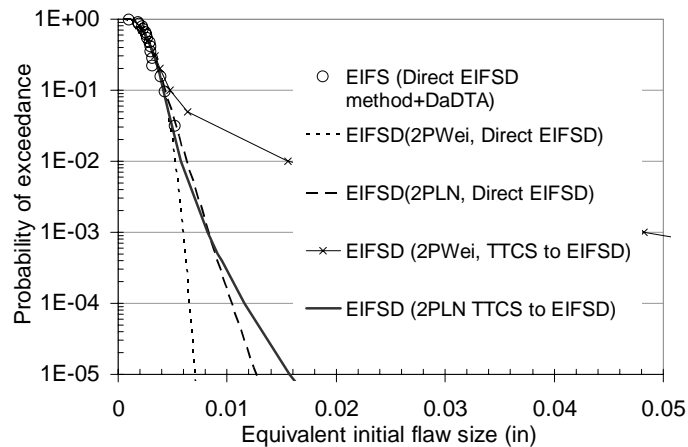


Figure 7: EIFSD determined by different methods (2PWei: 2-parameter Weibull distribution, 2PLN: 2-parameter Lognormal distribution)

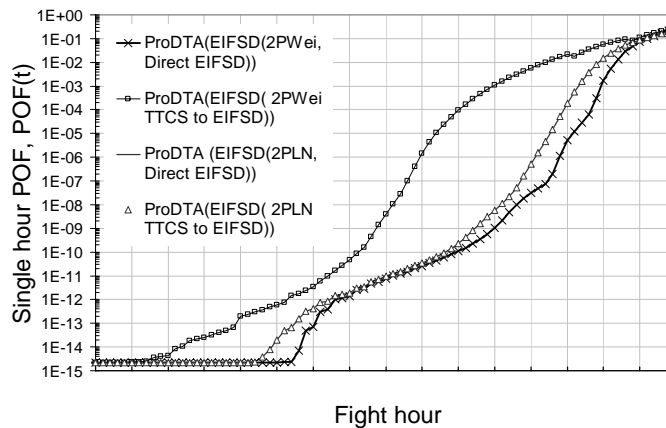


Figure 8: PoF results using different EIFSDs

Censored vs. non-censored data: Assume the other 30 "no-crack" findings had cracks whose sizes are equal to or less than the NDI threshold (0.030"), the censored EIFS data and fitted distribution were determined using the 'Direct EIFSD method', and plotted in Figure 9. The censored data are plotted using the Leonard-Johnson

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revision on Hazen’s ranks [14], and the distribution was determined using the maximum likelihood method. Apparently, the censored EIFSD shows about 10^1 lower probability of exceeding a certain crack size, than the uncensored EIFSD. Thus the censored EIFSD would result in about 10^1 lower PoF results in a risk analysis, as shown in Figure 10.

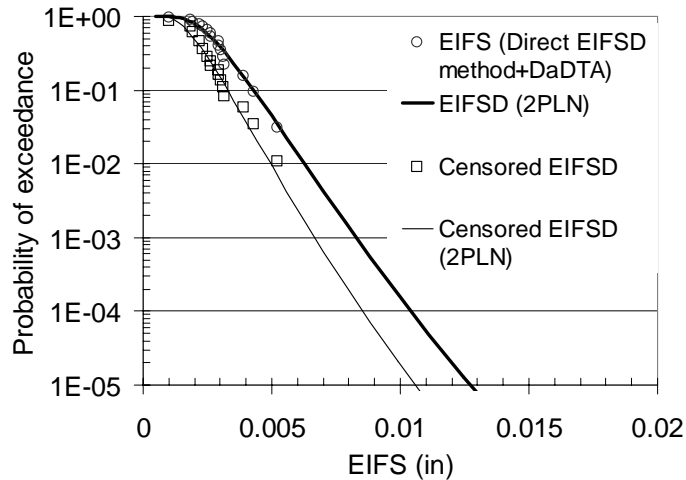


Figure 9: EIFSD vs. censored EIFSD, data and fitted distribution

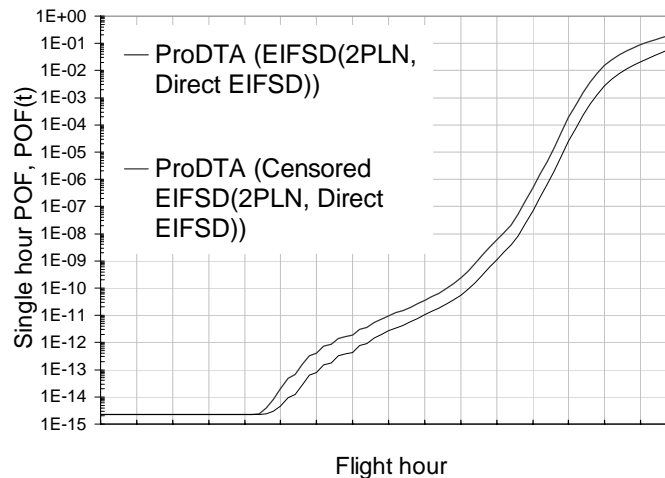


Figure 10: PoF results using the uncensored and censored EIFSDs

Confidence bands of ICSD/EIFSD: Sometimes the confidence bands can be obtained to provide additional confidence on the ICSD/EIFSD distribution. Figure 11 presents the EIFSD fitted by a 2P Lognormal distribution, along with the 95% confidence bands (lower and upper). Using the lower and upper banded EIFSD, two PoF curves were calculated using NRC ProDTA, as shown in Figure 12. The figure shows the range of PoF results which may be used for better decision-making purpose.

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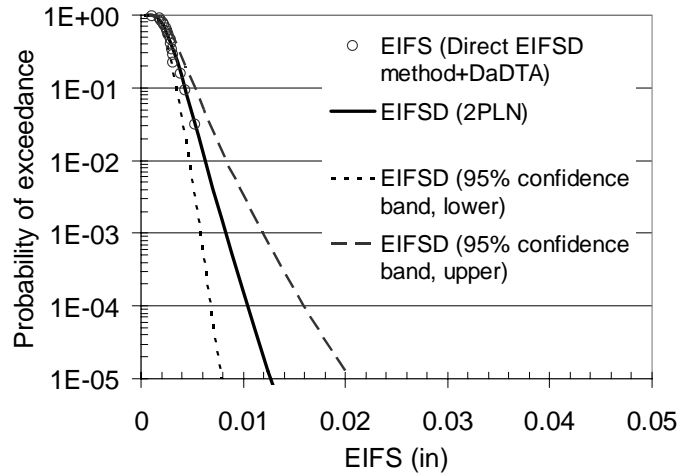


Figure 11 Confidence bands of ICSD/EIFSD

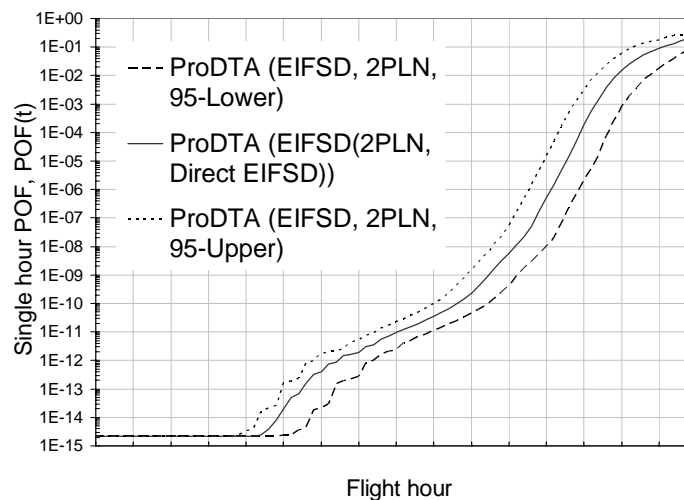


Figure 12 PoF results using the EIFSDs with 95% confidence bands

3.2 APPROACH 2 – with an extremely small sample size ($n < 5$ ²) of crack data from in-service or full scale tests, for instance, only 1 datum from an early in-service finding or 2 data points from full scale tests. In this case, the one or two data points can be regressed to determine an EIFS with certain percentiles, but the scatter of the EIFSD has to be determined from other sources or a TTCS distribution. Some historical data show that a TTCS standard deviation can be relatively consistent for the same or similar structural locations. For example, for aluminium alloys, the standard deviation of a Lognormal life distribution (i.e. TTCL, time to crack initiation) is about 0.12, or the shape factor of a Weibull life distribution is about 4.0 [15]. These values might be used as first approximations to estimate the TTCS distribution for aluminium structures.

² For most statistical hypothesis tests including Anderson-Darling goodness-of-fit test, the power to differ a Lognormal from a Weibull distribution is lower than 10% for a small sample ($n < 5$), at 5% significance level. In other words, a small sample data can be fitted by many distributions [11].

Example Case B – In a small transport fleet, only one crack (0.030”) was found from the inspection of 396 fasteners holes at time T^* , the other 395 holes were assumed to have no cracks or cracks below the NDI threshold. This inspection finding represents $p^*=1/396$ percentile in the TTCS distribution. First, the “TTCS to EIFSD method” was used to determine the EIFSD. Assume the TTCS followed a Lognormal distribution and its standard deviation was determined using the in-service damage data from another fleet (same aircraft), as $\sigma_{\ln TTCS} = 0.13$. The mean ($\mu_{\ln TTCS}$) of the TTCS distribution was then determined, in association with the percentile of the only crack finding,

$$p^* = \Phi \left[\frac{\ln(T^*) - \mu_{TTCS}}{\sigma_{TTCS}} \right] \rightarrow \mu_{TTCS} = \ln(T^*) - \Phi^{-1}[p^*] \cdot \sigma_{TTCS} \quad (4)$$

where $\Phi[\dots]$ is the CDF of a standard Normal distribution. Using a DaDTA curve, the TTCS distribution was regressed to determine an EIFSD, as shown in Figure 13. Second, using the ‘Direct EIFSD’ method, the only detected crack datum was regressed to time zero to get an EIFS*, which represents the $p^*=1/396$ percentile in the EIFSD. The in-service data from another fleet was regressed to determine the same number of EIFS values. Assume the EIFSD is a Lognormal distribution, and its standard deviation can be determined from the EIFSD for another fleet (same aircraft), i.e., $\sigma_{\ln EIFS}=0.64$. The mean ($\mu_{\ln EIFS}$) of the EIFSD can be calculated as,

$$\mu_{\ln EIFS} = \ln(EIFS^*) - \Phi^{-1}[p^*] \cdot \sigma_{\ln EIFS} \quad (5)$$

The second EIFSD was also presented in Figure 13, which is shown to be close to the first EIFSD from the ‘TTCS to EIFSD method’. In this case, the overall EIFS values were very small, which was caused by the crack growth curve used in the regression. Using ProDTA, the single flight hour PoF results were calculated based on these two EIFSDs. As shown in Figure 14, the two EIFSDs also gave very similar PoF results.

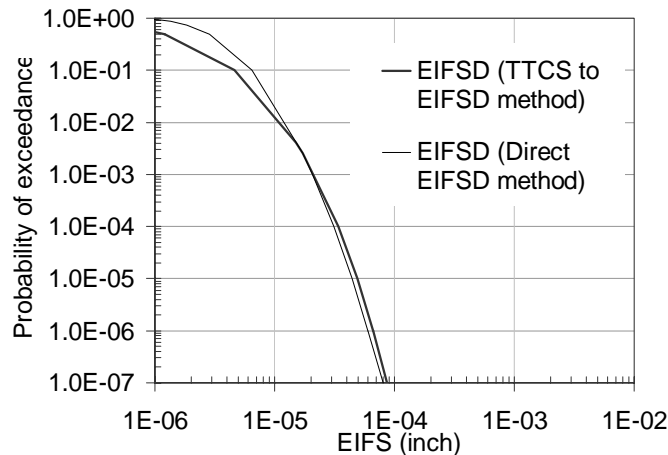


Figure 13: EIFSDs determined using two methods

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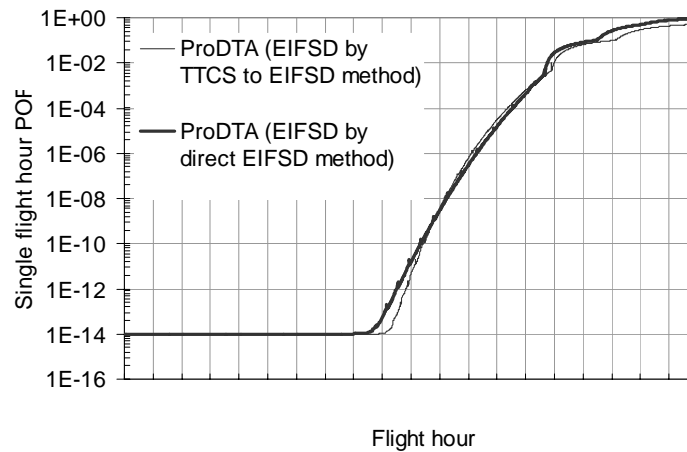


Figure 14: Single flight hour PoF results by using two EIFSDs

The above approaches are normally applicable for aging aircraft, with some in-service data. For a new aircraft, in the early stage of life, in which no in-service or historical data are available, the following approach is proposed to determine an ICSD for risk analysis. This type of risk analysis can help realize proactive maintenance.

3.3 APPROACH 3 – when no crack data are available from service, material and/or coupon test data can be used to determine an ICSD. This case may also occur in the design stage of new aircraft using new material, or in the early service stage of a new aircraft. In this case, the material initial discontinuity states (IDS, e.g. particle, pore, and manufacturing marks, scratches) can be applied to develop an ICSD, along with coupon fatigue test data. The IDS concept was first developed under the HOLSIP (Holistic Structural Integrity Process) framework, which is still under development [3][17]. Different from the EIFS, the IDS are physical features related to crack nucleation, growth, and failure. Physics based models are needed to be developed in association with the IDS distribution in order to predict the modified discontinuity states (MDS) that evolved from the IDS distribution. Since the IDS represents the overall material discontinuity population for potential crack nucleation features, coupon level tests and failure analysis can be used to determine the subset of the IDS distribution that are responsible for different failures. The IDS databases have been developed for several aluminium alloys such as 2024, 7075, and 7050 [18][19][20], and some successes have been made in life estimation based on the HOLSIP/IDS approach, mostly at coupon level [21][22].

Example Case C: Using the data from the example case A and [4], an in-service data based EIFSD was determined, as presented in Figure 15. In addition, this figure presents an IDS distribution determined using NRC coupon test results and MIL-HDBK-5 S-N curves on 2024 and 7075 aluminium alloys, as well as another coupon based IDS distribution from a previous project [16]. It is shown that the coupon test based ICSD/IDS distributions are comparable with the ICSD/EIFSD from the in-service data. As shown in Figure 16, the PoF results using the coupon test based ICSD/IDS distributions gave similar PoF results to that from the in-service data.

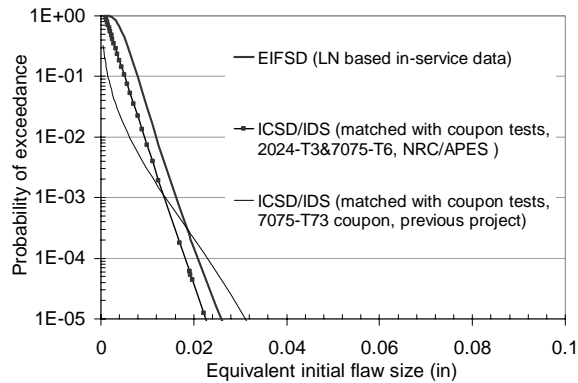


Figure 15: Coupon test based ICSD/IDS distribution

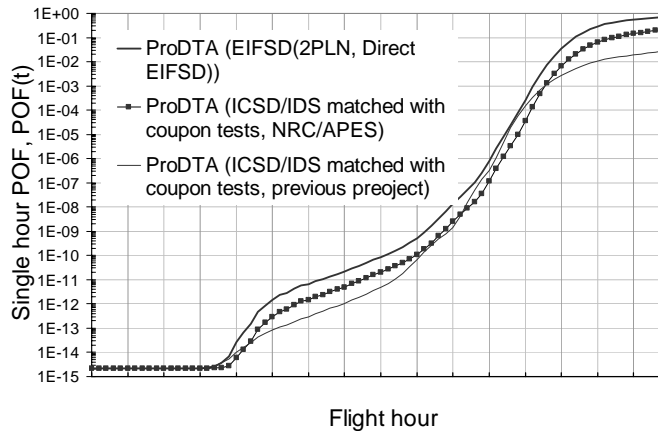


Figure 16: PoF results based on an IDS distribution

The results in these figures are promising, but more research is needed to correlate an IDS distribution with in-service failure, at component/full scale level with environmental effects. The HOLSIP approach is designed to provide accurate life estimation for complex structures under a real environment. It is clearly beneficial to use the HOLSIP/IDS approach to carry out an early stage risk assessment. In addition, the HOLSIP approach can be integrated with a SHM (Structural Health Monitoring) system, by providing a prior crack size distribution, which can be updated based on the sensor and/or NDI results using statistical approaches and data fusion. The updated crack size distribution would result in more accurate PoF results. The HOLSIP based risk assessment, in association with a SHM system, can become a practical approach for future early stage risk assessment of aircraft structures.

4. DISCUSSION

NDI uncertainty – when the NDI uncertainty is taken into account for the detected crack data in service, the detected crack distribution may not be same as the ‘real’ or total crack distribution. Assume an NDI POD is known, the detected crack size distribution can be converted to the ‘real’ crack size distribution before the inspection, using the Berens’ model [23]. Let $f(a)$ represent the probability density function of the total crack distribution before the inspection $F(a)$, $PD(a)$ and $PM(a)$ represent the proportions of cracks ($<a$) detected and

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missed at the inspection, respectively, then,

$$P_D(a) = \int_0^a f(x)POD(x)dx \quad (6)$$

and (7)

$$P_D(a) + P_M(a) = F(a)$$

The CDFs for the detected and missed cracks are given by

$$F_D(a) = P_D(a) / P_D(\infty) \quad (8)$$

$$F_M(a) = P_M(a) / P_M(\infty) \quad (9)$$

With some detected crack data, $P_D(a)$ can be calculated. When the $POD(a)$ function is assumed to be known, the maximum likelihood method can be used to estimate the parameters of a Lognormal or Weibull distribution $F(a)$. This method already provided some reasonable results but are considered to be preliminary [9]. Another engineering approach was also proposed for determining the parameters of $F(a)$, even when the $POD(a)$ is unknown. This approach is based on varying the parameters of the $F(a)$ model (and $POD(a)$ model if unknown) until a visual fit between the observed $F_D(a)$ and the analytical $F_D(a)$ is obtained. The estimated $F(a)$ can then be used to regress to an EIFSD using the methods presented in this paper.

Example Case D: Using the in-service data presented in [4], $F(a)$ (total crack CDF) and $F_D(a)$ (CDF of finds) were estimated using Berens program, as shown in Figure 17 (a). In this paper, Berens' visual fit was refined by the Kolmogorov-Smirnov goodness-of-fit test method. The in-service data were first regressed to the same time (flight hour) to determine the $F_D(a)$. Given the POD function associated with the eddy current inspection, the estimated $F(a)$ was found to be lower than $F_D(a)$, as seen in Figure 17 (b). If the estimated $F(a)$, instead of $F_D(a)$, was used to determine an ICSD/EIFSD, it would result in a lower ICSD/EIFSD, which would give lower PoF results, as discussed before. It should be noted that this trend may be varied with different in-service data and POD curves.

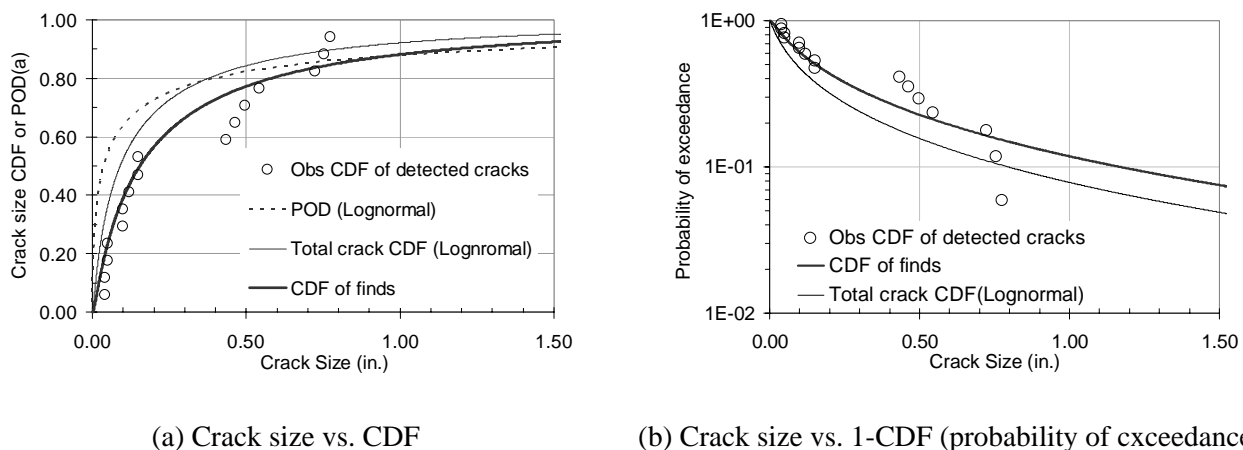


Figure 17: Determining crack size distribution considering a POD, using Berens model [23]

5. CONCLUDING REMARKS

The ICSD is the most important input for a structural risk analysis. In the risk analysis, an important criterion is that the developed ICSD/EIFSD must be grown to match with the crack size distribution found in service, full-scale test, or teardown inspections. This requires that the same crack growth curve and/or program must be used for both risk analysis and ICSD/EIFSD regression. A risk analyst must not only have access to the risk analysis program, but also a clear understating to the crack growth curve/program employed.

In this paper, three approaches were presented to develop an ICSD/EIFSD using small ($n < 40$), extremely small ($n < 5$) sample size of in-service data, and an IDS distribution from the HOLSIP framework. For small sample size of data, 'no-crack' inspections (censored data) can be considered to develop an ICSD/EIFSD, which, in general, could result in lower PoF results. When NDI uncertainty are involved in the in-service data for both detected and 'no-crack' data, advanced statistical methods are needed to determine an ICSD/EIFSD with/without POD. When there is very few in-service data, historical data like, TTCS or TTCI, on the same aircraft and materials may be used as a first trial for developing an ICSD/EIFSD. Engineering judgement is also needed and often critical to select an appropriate ICSD for a risk analysis. The IDS distribution developed in the HOLSIP framework is a physical measurement for ICSD, which can be developed based on cost-effectively coupon tests. In association with physics based modeling and a health monitoring system, the IDS/HOLSIP approach can provide a better capability than the EIFSD approach, to support a proactive risk assessment for aircraft structures in the early stage of service.

Recall the PoF is a combination of ICSD and other parameters (maximum stress distribution, residual strength etc.), thus the specific impacts of ICSD/EIFSD on the PoF results, shown in the case studies of this paper, may not be applicable to other data. However, the process/methodologies presented in this paper should be valid to examine the impact of this key parameter on risk analysis results.

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