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

PROBABILISTIC LIFING OF A SECOND OVERSIZE HOLE MODIFICATION

Guillaume Renaud[1], Éric Dionne[2] and Min Liao[2]

[1] National Research Council Canada, guillaume.renaud@nrc-cnrc.gc.ca
[2] National Research Council Canada

Abstract: Hole oversizing is a common technique used to remove potential or existing cracks in fastener holes. When used as a fleet-wide modification, hole oversizing is often preceded by non-destructive inspection that does not necessarily report damage. Depending on the crack detection capability and the level of oversizing, undetected cracks may not be completely removed by the modification. The approach currently used by the Royal Canadian Air Force for lifing the CF-188 second oversized holes is to assume that an undetected residual crack is always present at the hole after the modification. This approach may be overly conservative, especially in a safe life analysis context. This paper presents a probabilistic methodology that reduces conservatism by estimating the post-modification damage state from the pre-modification crack size distribution, which can be determined from the CF-188 lifing methodology. It is seen through an example that such methodology could be useful for increasing the safe life limit of locations that are short of their target life, especially for ageing fleets.

Keywords: Hole oversizing, structural modification, safe life, probabilistic method

INTRODUCTION

Enlarging a hole to its second oversize is a common airframe maintenance operation. Early in the life of the Royal Canadian Air Force (RCAF) CF-188, this structural modification was seen as a confidence cut, leading to a full life reset of the enlarged hole. However, after some accumulated usage, airframe cracks may become too large to be completely removed by the oversize, yet too small to be reliably detected by typical Non-Destructive Inspection (NDI) methods. As such, guidelines have been established to assume that, after a certain level of expended airframe fatigue life, a residual crack would exist at all holes that underwent a second oversize modification. However, as the CF-188 fleet approaches retirement, it appears that this conservative guideline results in likely unnecessary costly inspections for several Life Limiting Items (LLI).

The National Research Council of Canada (NRC) has been tasked by the RCAF to evaluate and further develop a practical probabilistic analysis methodology [1] proposed by the CF-188 maintenance, repair and overhaul contractor, L3Harris, to better evaluate the risk associated with second oversized holes. This probabilistic method establishes a post-modification safe life limit by combining the probability of cracks exceeding the radial cut size at the modification incorporation time (MIT) with the probability of crack detection of the selected NDI method. This updated safe life limit, corresponding to an acceptable cumulative probability of failure (CPOF), can then be applied fleet wide with additional assumptions.

A particular fleet-wide implementation approach proposed by L3Harris was shown by NRC to be conservative for the analysis of an investigated location, LLI 855.

Enhancements of the proposed method were developed and assessed by NRC. These enhancements include different assumptions related to the probability of detection, the ability to apply the method tail-by-tail, and modifications to make it compatible with the current CF-188 risk assessment methodology. This paper briefly describes the current methodology employed by the RCAF for lifing the second oversized holes, and gives an overview of the probabilistic lifing options assessed by NRC. Comparisons of the different methods are made using LLI 855, a location that underwent a second hole oversize modification in the CF-188 fleet.

STANDARD METHODOLOGY

CF-188 lifing methodology

The CF-188 was designed to United States Navy specifications but its fatigue lifing philosophy was later modified by the RCAF. It follows a safe-life approach, combined with damage tolerance elements when required [2]. The so-called safe life of a LLI is composed of a “crack initiation” (CI) phase, which can be followed by a “crack growth” (CG) phase. In this context, crack initiation corresponds to a fatigue crack growing to a size of 0.254 mm (0.01 in).

Typically, CI and CG life distributions are established from in-service or test data. The CI life corresponds to the life from time zero to a crack size of 0.254 mm (0.01 in), whereas the CG life corresponds to the life from 0.254 mm (0.01 in) to a critical crack size, a_{crit}. In order for the CG life to be valid, residual strength criteria must be met at a_{crit}. Once the two distributions are established, “factored” CI and CG lives are defined as the lives corresponding to a cumulative density of 0.001 for the aircraft, seen as the CPOF. This probability of failure depends on the calculated or assumed life scatter, the number of test points, the number of articles on the aircraft and uncertainty factors related to loads, load tracking and, when applicable, analysis credibility. The sum of the two factored CI and GC lives is the so-called “safe life limit” (SLL). If this safe life is below the LLI target life, an alternative lifing approach, based on the acceptable hazard rate defined in terms of probability of failure per flight hour, can be used. If the life determined from this alternative approach is still too low, a safety-by-inspection approach can be envisaged.

Example: CF-188 LLI 855

As an example, LLI 855 [3] is a location of the CF-188 Y488 bulkhead that underwent a second oversize hole modification. This item includes two articles (left, right), each representing eight holes that can potentially contain a crack. A sketch of this LLI is provided in Figure 1.

The CI life distribution for this LLI was established from the damage growth inferred from NDI results, regressed to a common crack size of 0.254 mm (0.01 in). The CG curve and CG life distribution were established using a combination of full-scale and analytical data, along with uncertainty factors. In this case, a_{crit} was assumed to be 10.44 mm (0.411 in), a crack size that was shown to meet the required residual strength criteria in full-scale testing. Using the CI and CG distributions, the factored CI and CG lives were calculated to be 38.5% and 42.4% of the LLI target life, respectively. The SLL for this location was therefore calculated to be 80.9% of the target life, which justifies the structural modification. The calculated life distributions are presented as cumulative distributions in log-linear scales in Figure 2. Because there are two articles on the airplane for this LLI, and because failure is assumed if any of the two articles fails, the factored lives correspond to a CPOF of 0.005, obtained by simple system reliability calculation.

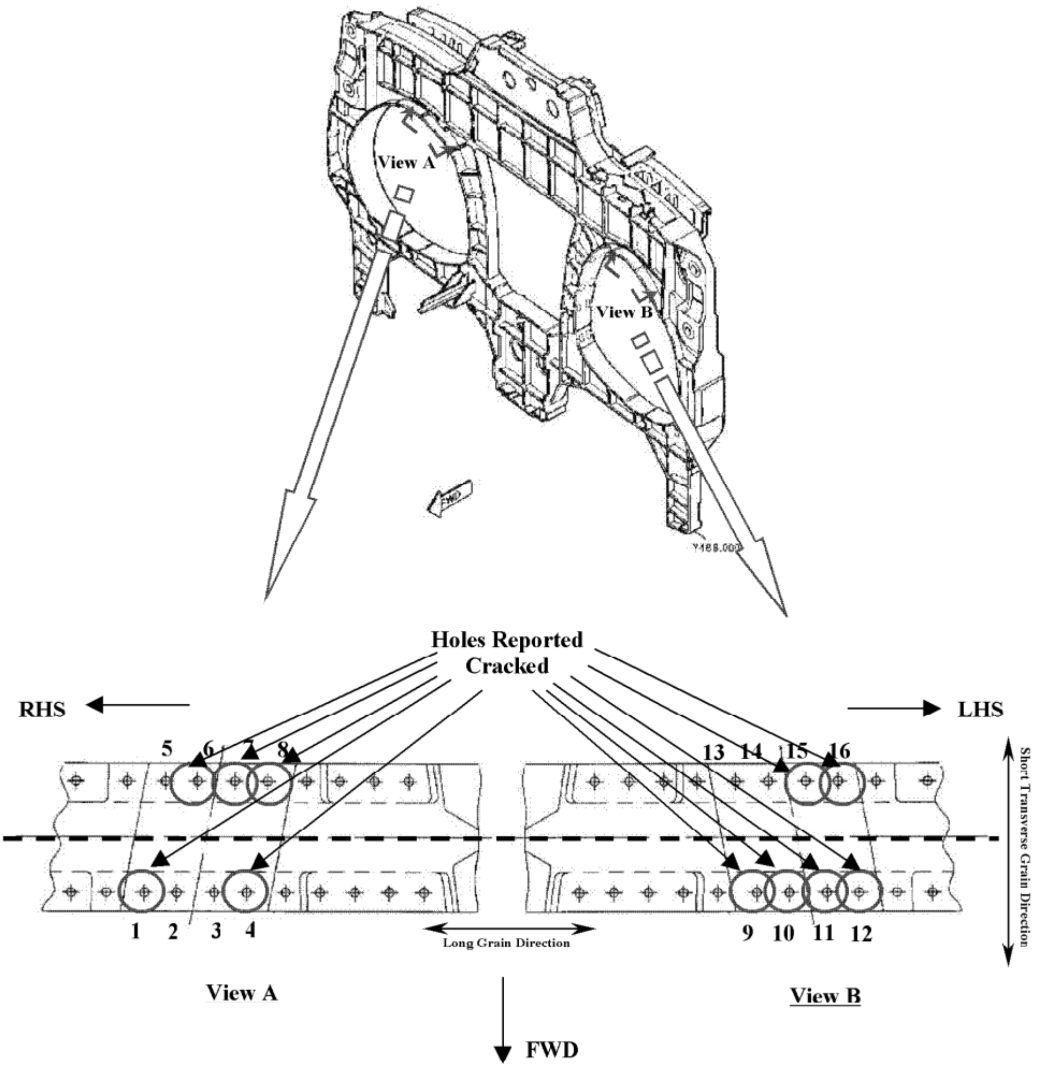

Figure 1: CF-188 LLI 855 - Y488 bulkhead at stringer recess [3].

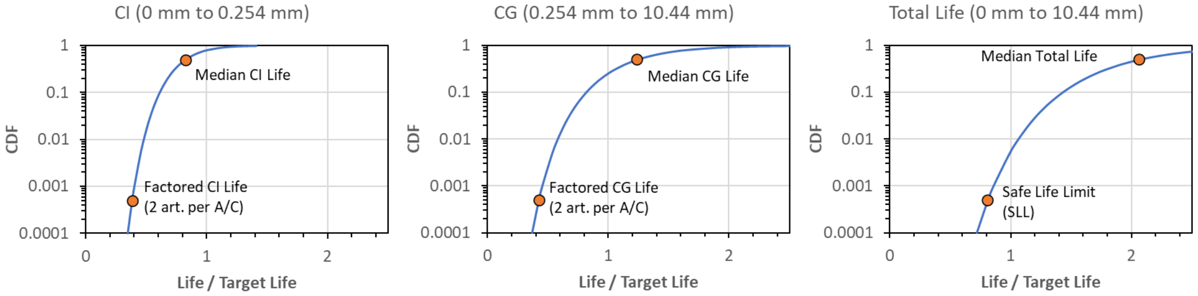

Figure 2: Crack initiation, crack growth and total lives for CF-188 LLI 855.

The crack size distributions for LLI 855 at the factored CI life and at the SLL are presented in Figure 3, along with the crack growth curves that correspond to CPOF values of 0.0005 (safe life) and 0.5 (median life).

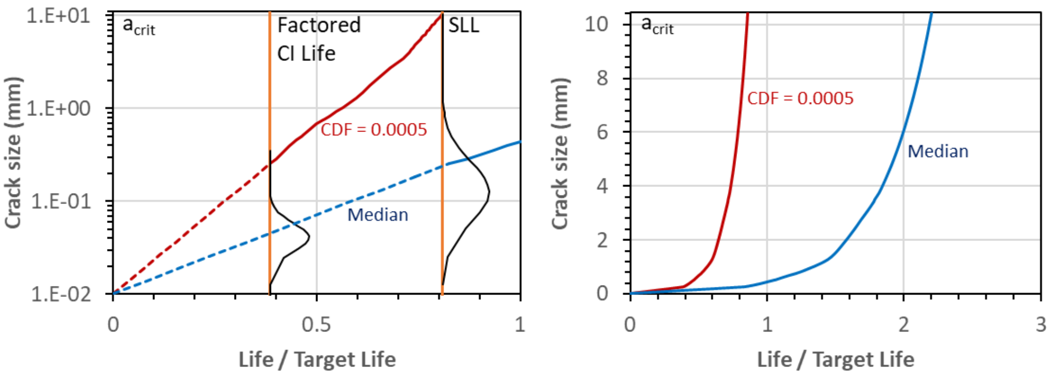

Figure 3: Crack size distributions and crack growth curves for CF-188 LLI 855.

It is seen from Figure 3 that the initial damage condition assumed for CF-188 LLI 855 in this example is equivalent to a crack size of 10 micrometres. This size has been shown to be the typical pit depth resulting from the etching applied to the CF-188 bulkhead material [4]. This assumption is consistent with the CF-188 safe life philosophy, which assumes representative initial damage conditions and applies scatter and uncertainty factors on life. This is different from the damage tolerance philosophy, where the worst-case scenario, corresponding the maximum crack size that can be left undetected at time zero, is assumed. A comparison between the lives obtained with the CF-188 safe life methodology and a damage tolerance analysis (DTA) approach is presented in Figure 4. In this case, the initial crack size for the DTA is 1.27 mm (0.05 in), which corresponds to the $a_{90/95}$ value for bolt hole eddy current NDI [5].

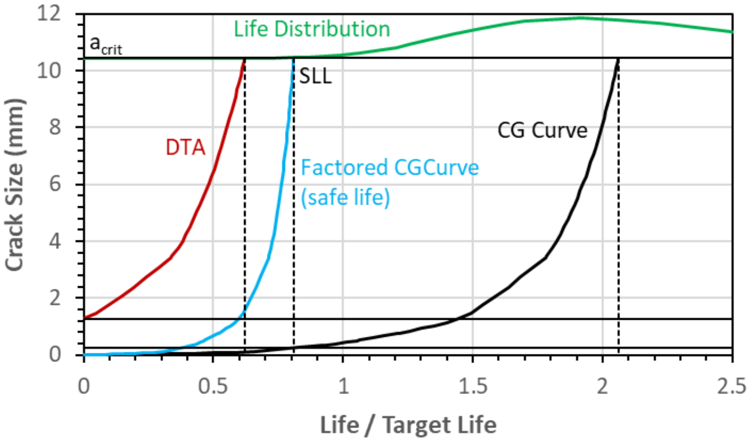

Figure 4: Crack size distributions and crack growth curves for CF-188 LLI 855.

In this figure, uncertainty factors related to loads, load tracking and/or analysis credibility are embedded in the CG curve. The ratio between the safe life, corresponding to a life cumulative density of 0.001 per aircraft, and the median life (CG curve in Figure 4) is the so-called material scatter factor on life. This scatter factor can be seen as a life scaling factor that depends on the standard deviation assumed for the life distribution, the number of test points and number of articles in consideration on the aircraft. The DTA curve in Figure 4 was obtained by a pure shift of the median CG curve to the left to an initial crack size of 1.27 mm (0.05 in), without life scaling. For the DTA approach, inspection intervals would need to be established as a fraction of the DTA life. For the CF-188, this fraction would typically be one third, allowing two inspections before the crack grows to a_{crit}.

Typical hole oversize modification process for the CF-188

A second oversize hole modification typically increases the diameter of the hole by 0.79 mm (1/32 in), resulting in a radial cut that ranges between 0.36 mm and 0.41 mm (0.014 in to 0.016 in), depending on tolerances. Prior to oversizing the hole, it is common to ream it to renew its surface in order to improve the detectability of potential cracks. A non-destructive inspection is usually performed before and after proceeding to the modification.

Assuming that a radial cut depth of a_{cut} results from the hole oversizing, any crack with a depth a higher than a_{cut} at the MIT would not be completely removed by the modification. After oversizing, the residual crack would be $\langle a - a_{cut} \rangle$. During the inspection, the crack depth is $a - a_{ream}$, where a_{ream} is the depth of the radial cut induced by the pre-inspection reaming. Usually, there exists a crack depth, referred to as a_{det}, that is assumed to be 100% detectable by the selected NDI technique. In practice, this value typically corresponds to the crack size with a 90% probability of detection at a confidence level of 95% [6]. The geometric variables involved in the second oversize hole modification are presented in Figure 5.

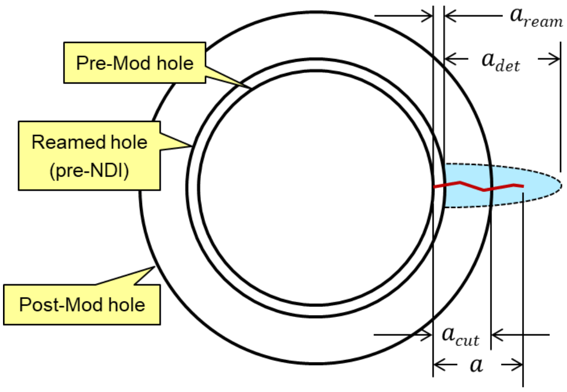

Figure 5: Hole oversize variables.

Analysis guidelines

If the hole oversizing is performed before the factored CI life is reached, it is deemed reasonable to assume that no residual crack would exist at the hole after the modification. Indeed, a radial cut of 0.36 mm to 0.41 mm (0.014 in to 0.016 in) would be applied at a time when the probability that the crack has reached the CI size of 0.254 mm (0.01 in) is less than 0.001. Conservatively, the current CF-188 analysis methodology does not reset the hole life in such case. Its remaining life is assumed equal to the remaining CI life plus the CG life from 0.254 mm (0.01 in) to the critical crack length [7].

If the oversize is performed after the factored CI life, and if a pre-modification inspection revealed no crack, the remaining life is assumed to be the CG life from a residual crack with a depth of $a_{res} = a_{det} + a_{ream} - a_{cut}$, corresponding to the largest crack that could have been missed by the NDI, minus the material cut from the hole. A summary of the analysis guidelines for a second oversize hole modification is presented as a flow-chart in Figure 6.

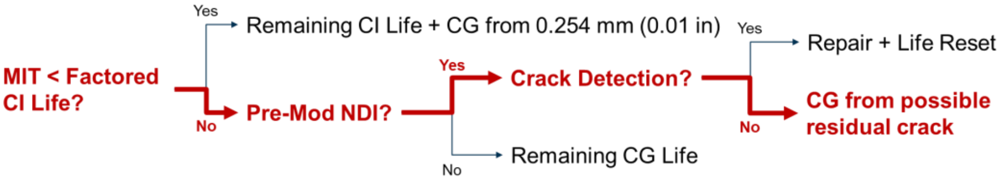

Figure 6: Remaining life flow-chart for second oversize hole modification analysis.

Example: ALEX 6.0

As an example, ALEX 6.0 is a second oversize hole modification [3] that was applied to LLI 855 at an average MIT of 57.3% of the target life. For this modification, a_{cut} and a_{ream} were assumed to be 0.36 mm (0.014 in) and 0.04 mm (0.0015 in), respectively. The post-modification safe life was calculated for different values of a_{det}: 0.51 mm (0.02 in), 0.57 mm (0.0225 in), 0.89 mm (0.035 in) and 1.27 mm (0.05 in). For reference, a_{det} = 0.57 mm (0.0225 in) results in a post-modification crack depth of a_{res} = 0.254

mm (0.01 in), which is the CI length, and an a_{det} = 1.27 mm (0.05 in) corresponds to $a_{90/95}$ for bolt hole eddy current NDI [5].

Assuming a MIT later than the factored CI life and no crack detection prior to the modification, the post-modification life, which is equal to the MIT plus the remaining life, is plotted as a function of the MIT in Figure 7, from which the following observations can be made:

- Post-modification lives are longer for later MIT because the remaining life is constant for a given value of a_{det} (the remaining life is independent of the MIT).
- Poorer crack detectability results in shorter remaining lives.
- The best-case scenario, a full life reset, results in sufficient post-modification life only if the MIT is higher than 20% of the target life.
- The post-modification life at the average MIT (57.3% of the target life) does not reach the target life unless a_{det} is approximately 0.57 mm (0.0225 in) or less.
- The post-modification life does not reach the target life for any of the considered a_{det} values for the earliest modifications (the CF-188 fleet MIT range is shown as the shaded area).

Considering that, by definition, there is only a 0.1% probability that a crack larger than 0.254 mm (0.01 in) is present at the hole at the factored CI life, the last observation may be seen as overly conservative. Indeed, it imposes a 100% probability of having a post-modification residual crack, ranging between 0.19 mm (0.0075 in) and 0.95 mm (0.0375 in) for the considered a_{det} values, even after a 0.36 mm (0.014 in) radial cut.

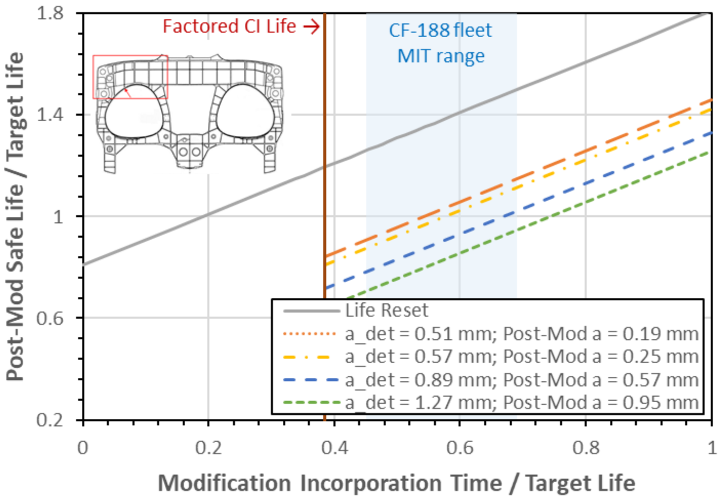

Figure 7: Current method post-modification life vs. MIT for CF-188 ALEX 6.0 (LLI 855).

SIMPLIFIED PROBABILISTIC METHODOLOGY

Simplified probabilistic analysis procedure

Using the CF-188 lifing methodology, it is possible to calculate a crack size distribution at any time, as depicted in Figure 3. The crack size distribution at the MIT can therefore be used to simulate an inspection and estimate the probability of leaving a residual crack after the oversize modification. Using simple assumptions, this probability can be established by separating the pre-modification crack size distribution in three ranges:

For $a < a_{cut}$, the crack can be assumed to be completely removed by the modification. In this case, the life of the hole is reset.

If $a > a_{det} + a_{ream}$, the crack can be assumed to be detected. In this case, the hole is repaired, and its life is reset.

For $a_{cut} < a < a_{det} + a_{ream}$, the crack may be detected or missed by the pre-modification NDI, and it is not completely removed by the oversize. If the crack is detected, the hole is repaired and its life is reset. If the crack is not detected, a residual crack depth of $a_{res} = a_{det} + a_{ream} - a_{cut}$ is assumed after the modification.

Several assumptions are used in this simplified probabilistic approach, as listed next.

- a_{det} is known for the considered LLI and inspection method, and the probability of detection (POD) can be estimated for cracks larger than $a_{cut} - a_{ream}$ but smaller than a_{det}. Conservatively, this POD could be assumed to be zero.
- Oversizing the hole reduces the size of the crack by a_{cut}. There is no probability of adding damage by the inspection or the modification processes.
- The residual cracks are assumed to have a common post-modification crack size a_{res}, that depends on a_{det}. The accumulation of crack "initiation" damage where the oversized hole edge is to be located is not considered.
- Failure occurs at a_{crit}, a crack size that has been shown to be able to sustain the required residual strength loads. The real critical crack size could be significantly larger if a_{crit} is taken from a full-scale fatigue test that was stopped with a non-critical damage size at the considered location.
- Damage evolution complies with the CF-188 lifing policy. The total crack size distribution at a given time results from both the CI and CG life distributions. The SLL is fixed at a CPOF of 0.001 per aircraft, or 0.0005 if two articles are present on the aircraft.
- The CPOF after the modification depends solely on the remining cracks. The ranges of the pre-modification crack size distribution that resulted in life reset do not contribute to the CPOF.

Using these assumptions, the CPOF after the modification can be stated as

$$CPOF(t)_{PM} = P(A)P(B)CPOF(t)_{a_{res}} \tag{1}$$

where $CPOF(t)_{PM}$ is the post-modification CPOF, at time t after the MIT, and $CPOF(t)_{a_{res}}$ is the CPOF at time t resulting from CG starting at $a = a_{res}$. The other terms are defined below.

The post-modification life calculation consists of 5 steps, defined as the following:

Step 1. Determine $P(A) = P(a_{cut} < a < a_{det} + a_{ream})_{MIT}$, which is the probability of having a crack at the MIT that is too large to be completely removed by the oversize but too small to be assumed 100% detectable by the pre-modification NDI.
Step 2. Determine $P(B) = 1 - POD(a_{cut} - a_{ream})$, which is the probability of not detecting the cracks addressed by $P(A)$. Conservatively, it is seen as the probability of missing the smallest possible crack that will not be completely removed by the oversize.
Step 3. Calculate $P(A)P(B)$, which is the probability of having a residual crack after the modification.
Step 4. Determine the remaining life t that results in the acceptable CPOF, i.e. $CPOF(t)_{PM}$ = 0.0005 per article in Eqn. (1) if there are two articles in the LLI.
Step 5. Calculate the post-modification SLL as the MIT + t.

Application of the simplified approach to ALEX 6.0

For the ALEX 6.0 modification of the CF-188 LLI 885, the following parameters were selected: a_{cut} = 0.36 mm (0.014 in), a_{ream} = 0.04 mm (0.0015 in), a_{det} = 0.57 mm (0.0225 in), a_{crit} = 10.44 mm (0.411 in), MIT = 57.3% of the target life (average MIT for the fleet). The common post-modification crack size was assumed to be $a_{res} = a_{det} + a_{ream} - a_{cut}$ = 0.254 mm (0.01 in), which is the largest crack at the MIT that could be left undetected after the pre-NDI reaming, minus the material removed by the hole oversizing.

Step 1: The probability of a crack exceeding a_{cut} at the MIT is 2.16%. This value can be calculated either from the distribution of life to a crack of 0.36 mm (0.014 in), or from the crack size distribution at the MIT, as shown in Figure 8.

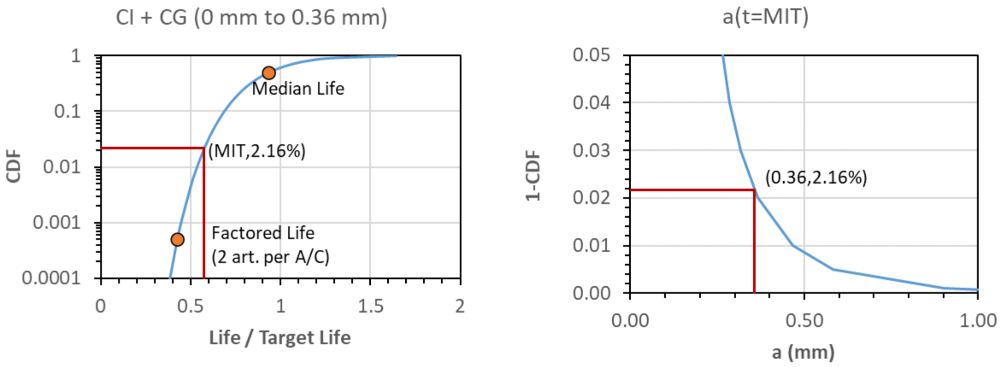

Figure 8: $P(a > a_{cut})$ for CF-188 ALEX 6.0.

Similarly, the probability of a crack exceeding $a_{det} + a_{ream}$ = 0.61 mm (0.024 in) can be calculated to be 0.60%. $P(A)$ can therefore be calculated as 2.16% - 0.60% = 1.56%.

Step 2: Based on previous experience, an average probability of missing a crack between 0.36 mm (0.014 in) and 0.61 mm (0.024 in) by the NDI, $P(B)$, was estimated to be 50%.

Step 3: Combining the above two results, the probability of having a residual crack after the inspection and hole oversizing modification, $P(A)P(B)$, can be estimated to be 0.78%.

Step 4: Having two articles on the aircraft, Eqn. (1) can be rewritten as $CPOF(t)$ = 0.0005/0.78% = 6.39%. Solving for t from the CG life distribution of cracks growing from a_{res} = 0.254 mm (0.01 in) to a_{crit} = 10.44 mm (0.411 in), the remaining life can be calculated to be 75.4% of the target life.

Step 5: Adding the MIT to the calculated remaining life, the post-modification SLL is 132.7% of the target life.

A more conservative assumption can also be made on crack detectability, namely that no crack is detected by NDI. All cracks above a_{cut} at the MIT ($P(A)$ = 2.16%) are retained, and none of them are detected, ($P(B)$ = 100%). In this case, Eqn. 1 can be rewritten as $CPOF(t)$ = 0.0005/2.16% = 2.31% and the post-modification SLL becomes 122% of the target life.

Using this simplified probabilistic methodology, it is seen that the ALEX 6.0 modification reduces the CPOF enough to make the SLL reach the target if it is performed at 57.3% of the target life, even if NDI crack detection below is neglected during NDI (POD=0). However, some assumptions may be non-conservative. First, the post-modification crack size was assumed constant, regardless of the pre-modification crack size distribution, but dependent on an assumed a_{det}. The a_{det} value used in the ALEX 6.0 example, 0.57 mm (0.0225 in), is much lower than the $a_{90/95}$ value of 1.27 mm (0.05 in) used by the United States Air Force (USAF) for bolt hole eddy current [5]. Such crack detection capability would result in larger residual cracks and a lower safe life limit. Another assumption is that the crack sizes that result in a hole repair and life reset, either because they are completely removed by the oversize process or because they are detected during the pre-modification NDI, do not contribute to the post-modification CPOF. Although the contribution of these crack sizes may be negligible for late MIT, because the CPOF would be dominated by a high probability of having residual cracks, they cannot be excluded from the CPOF calculation at lower MIT. In such case, this methodology could result in an infinite post-modification life if $P(A)$ at MIT is negligible. This effect is illustrated in Figure 9 for the ALEX 6.0 example.

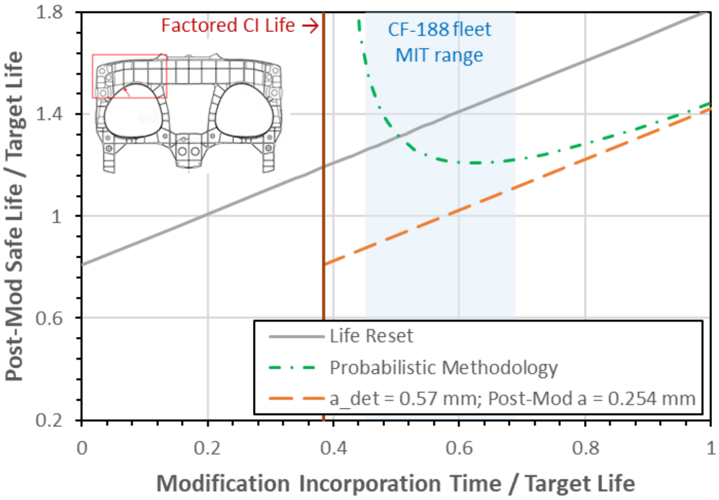

Figure 9: Simplified probabilistic methodology (ALEX 6.0).

ENHANCED PROBABILISTIC METHODOLOGY

Enhancement 1: CPOF contribution from all cracks

In the simplified probabilistic methodology described above, the portions of the crack size distribution at the MIT that resulted in the repair and life reset of the hole were not included in the CPOF calculation. In order to consider the entirety of the crack size distribution, two populations of cracks must be mixed as a weighted sum of two life distributions. The first population corresponds to the life of the cracks not completely removed by the modification. This life distribution is calculated using the aforementioned methodology. The second population corresponds to the life of the repaired holes, assumed to start in the same condition what prevailed at time zero. This life population is calculated from the standard CF-188 lifing methodology, assuming complete life reset at the MIT. The relative weight of the two populations is dictated by the amount of crack found from the pre-modification NDI.

The ALEX 6.0 modification was analysed with this approach, using a_{det} = 0.57 mm (0.0225 in), which results in a_{res} = 0.254 mm (0.01 in) for all cracks that exceeded a_{cut} at MIT. The resulting post-modification life distribution, assuming no detection during NDI (POD=0), is presented in Figure 10. The resulting curve transitions from the complete life reset, at early MIT, to a 100% probability of having remaining cracks, which is the current CF-188 analysis approach. In this example, the post-modification life reaches the target life for the entire range of CF-188 MIT.

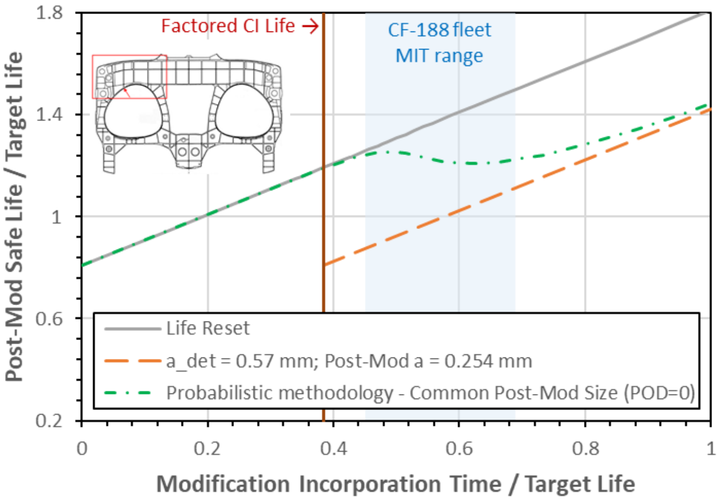

Figure 10: Probabilistic methodology – CPOF contribution from all cracks (ALEX 6.0, POD=0).

Enhancement 2: Actual residual crack sizes

Assuming a common post-modification residual crack size can be conservative for early modifications and non-conservative for late modifications. A better approach is to calculate the residual crack size distribution resulting from the crack size distribution at the MIT, minus the material removed by the hole oversizing. This approach does not require the use of an assumed a_{det} to determine the post-modification crack sizes. The resulting post-modification life for the ALEX 6.0 example, assuming POD=0, is presented in Figure 11. In this case, because large cracks are assumed undetected by NDI and retained in the distribution after the hole oversizing, the post-modification life does not reach the target for most of the CF-188 fleet MIT range. Further, larger and larger cracks are left in the structure for increasing MIT values, until the remaining life is zero. This result explains why the post-modification life in this case is solely the MIT for MIT values larger than 80% of the target life.

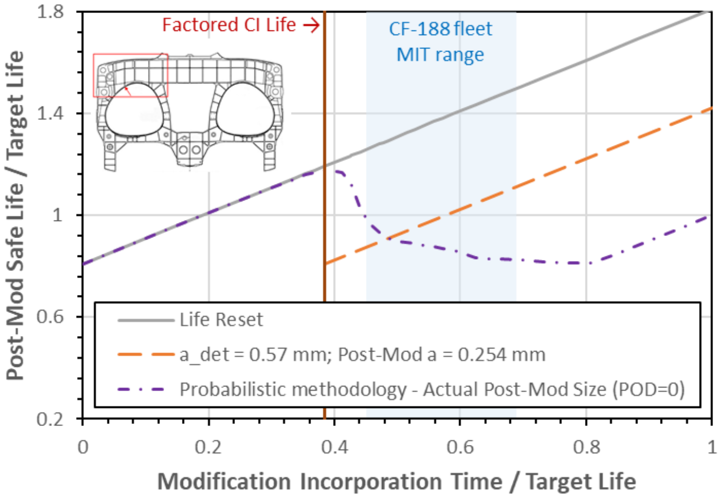

Figure 11: Probabilistic methodology – Actual residual crack sizes (ALEX 6.0, POD=0).

Enhancement 3: Realistic POD

As seen in Figure 11, the assumption that no crack is detected during the pre-modification NDI becomes very severe if the actual residual crack sizes are used in the analysis. Indeed, large cracks are expected to be detectable and should not be present after the modification. This simplifying assumption can however be removed by the use of a complete $POD(a)$ curve. In such case, the NDI is simulated by multiplying the crack size distribution at the MIT by $POD(a)$ in order to determine a crack detection likelihood as function of crack size. The proportion of life reset can then be determined from the likelihood of detecting and repairing cracks for which $a > a_{cut}$ at MIT, added to the proportion of direct life resetting from the oversize ($a < a_{cut}$ at MIT). Using a full $POD(a)$ curve derived from the a_{50} and a_{90} detection capability of bolt hole eddy current in aluminium [5], this strategy was applied to the ALEX 6.0 example, as presented in Figure 12. In this case, the POD curve was represented by the cumulative density function of a lognormal distribution in which a_{50} is 0.51 mm (0.02 in) and a_{90} is 1.02 mm (0.04 in).

In this case, the realistic crack detection capability is able to eliminate enough of the large cracks to make the ALEX 6.0 modification reach the target life for the entire CF-188 fleet MIT range. This version of the probabilistic lifing methodology for a second oversize hole modification is the one that has the most physics basis.

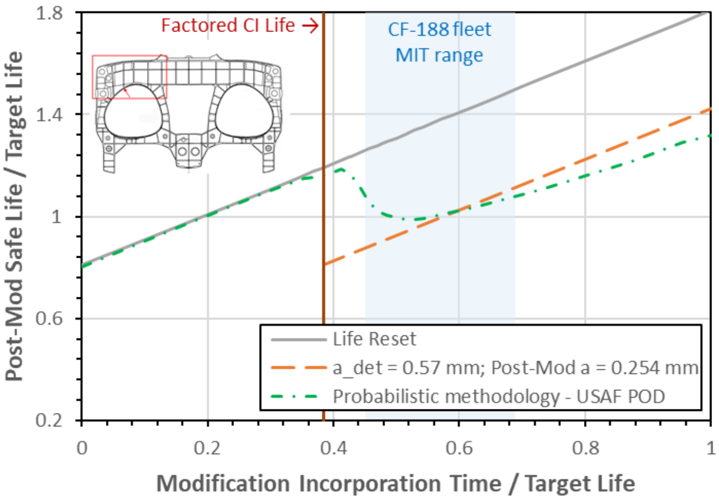

Figure 12: Probabilistic methodology – Realistic POD (ALEX 6.0).

CONCLUSION

The probabilistic methodology proposed by L3Harris [1] has already been shown to be useful when implemented fleet-wide, with additional assumptions, to reduce maintenance costs while maintaining an acceptable probability of failure. NRC assessed this methodology and enhanced it to better characterise the probability of detection and its effect on the residual cracks, and to add the ability to apply the method tail-by-tail. These enhancements were demonstrated on ALEX 6.0, a second oversize hole modification performed on the CF-188 LLI 855.

Further enhancements of the methodology are possible. For instance, the full methodology, including the contribution from all cracks, the actual residual crack sizes, and a realistic POD, was modified to perform typical risk assessment (RA) calculations. The CF-188 lifing policy [2] states that RA can be used when the SLL does not reach the target life. A preliminary investigation of the use of the second oversize hole modification methodology for RA is presented in Figure 13 for the ALEX 6.0 problem. In this case, several hazard rates, expressed as single flight hour probability of failure (SFHPOH) are plotted as functions of the MIT. This information could then be used in a RA approach.

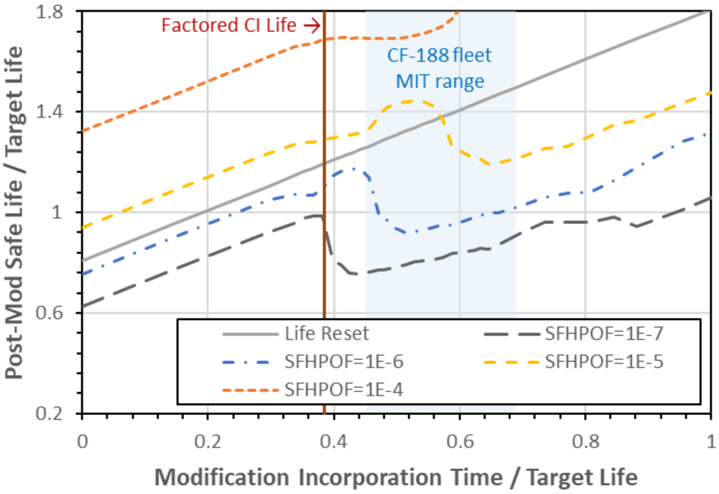

Figure 13: Probabilistic methodology – Hazard rate calculation (ALEX 6.0).

REFERENCES

[1] L3Harris (2021), "Analytical Refinement to Assess Modifications Installing 2nd Oversize with Remaining Cracks", PCM-318-1028 Revision A.

[2] Canadian Forces (2009), "CF188 Structural Integrity Standard for Continued Airworthiness", Appendix 9 to Annex A to CF188 CMATC.

[3] L3-MAS Canada (2005), "Modification Instruction – C-12-188-000/CD-184 (ALEX 6.0) Structural Fatigue Life Improvement of Bulkhead and Stringer at Y488.0 Oversize Holes / Fastener Substitution", SES DI 2877.

[4] Molent, L., Sun, Q., and Green, A. (2006), "Characterisation of equivalent initial flaw sizes in 7050 aluminium alloy", *Fatigue & Fracture of Engineering Materials & Structures*, 29(11): p. 916-937.

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

[6] Department of Defense (2009), "Nondestructive Evaluation System Reliability Assessment", MIL-HDBK-1823A.

[7] L3Harris (2022), "Durability and Damage Tolerance Assessment Plan", SES DI 0180, Revision D.