UTILIZING CONDEMNATIONS, RETIREMENTS AND MODS TO IMPROVE THE STRUCTURAL RISK ANALYSIS OF THE T-38: TURNING TRASH INTO TREASURE

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Abstract: With the T-38 Talon entering its fourth 20-year lifetime, engineering has increasingly relied upon a robust risk analysis to ensure safety of flight. This paper will outline how the T-38 engineering team has implemented a successful risk management plan that utilizes teardown results from fleet condemnations, retirements and major modification programs to achieve structural safety. Along with teardown failure analysis of large cracks from condemnations, T-38 engineering has identified and executed numerous retired wing teardowns to measure and record the smaller crack findings as well. In addition, simple teardown and failure analyses were conducted on structural items removed and replaced during a major modification fuselage program. These efforts were able to capture valuable data on fatigue critical, life limited parts that would have otherwise been discarded. A thorough failure analysis of detected cracks allows an analyst to build a robust Equivalent Initial Flaw Size (EIFS) distribution dataset for probabilistic risk analysis. This marked a move to a more proactive, rather than reactive, risk management plan. Combined with maintenance records, T-38 now has an extensive library of thousands of findings covering several wing and fuselage Fatigue Critical Locations (FCLs). This allows the creation of FCL-specific EIFS distributions rather than a general detail (e.g. fastener hole) or purely material-based distributions.

The risk analysis process, including gathering teardown failure analysis data, building an EIFS distribution, and PROF (Probability of Fracture software) analysis, will be shown in detail for three locations. For the first case study, a set of condemnation data was used to develop an EIFS distribution that resulted in a Uniform distribution versus the typical Weibull distribution. The second case study at a wing FCL had teardown findings contrary to previous damage tolerance assumptions. Incorporating the teardown findings produced a probability of failure much lower than previously calculated. The third case study will show how historical teardown data was used to enhance the risk analysis for a previously unknown fuselage FCL.

Keywords: EIFS, failure investigation, fatigue, risk analysis, teardown

INTRODUCTION

Destructive teardowns are an extremely valuable tool in understanding the structural integrity of aircraft and the full reality of fleet damage. Information gleaned from structural teardown analysis can help inform and guide maintenance and inspection cycles, lifecycle management, and risk analyses. Over the last decade and multiple support contracts, the T-38 engineering team and Southwest Research Institute have built a strong and continued commitment to performing structural teardowns on a wide variety of components. This includes two fuselages, dozens of wings and landing gear sets, and hundreds of individual parts removed during one-time and recurring inspections or modification programs. Structure retired or condemned for high use time or severe in-service damage, and critical components replaced during scheduled maintenance and modification programs are often perfect teardown articles as they present “lead the fleet” and worst-case data points to help guide the future management of the remaining fleet.

Through multiple teardown efforts, a consistent team has streamlined the process of identifying valuable teardown candidates and structural areas, then guiding the extraction, disassembly and preparation of parts to be inspected. The parts undergo various types of non-destructive inspection based on the material, geometry, and the type of damage to be identified. These inspections can include close visual, fluorescent penetrant, magnetic particle, bolt hole eddy current, and eddy current surface scan, among others. This teardown process produces crack, corrosion, and mechanical damage indications identified by type and size of damage, part number, specific hole or surface location, and documented thoroughly with photographs. Importantly, the serial number or tail number of components is also always tracked when available, so any damages can be related to the component’s service history and flight time. Various aspects of structural teardowns can be seen in Figure 1.

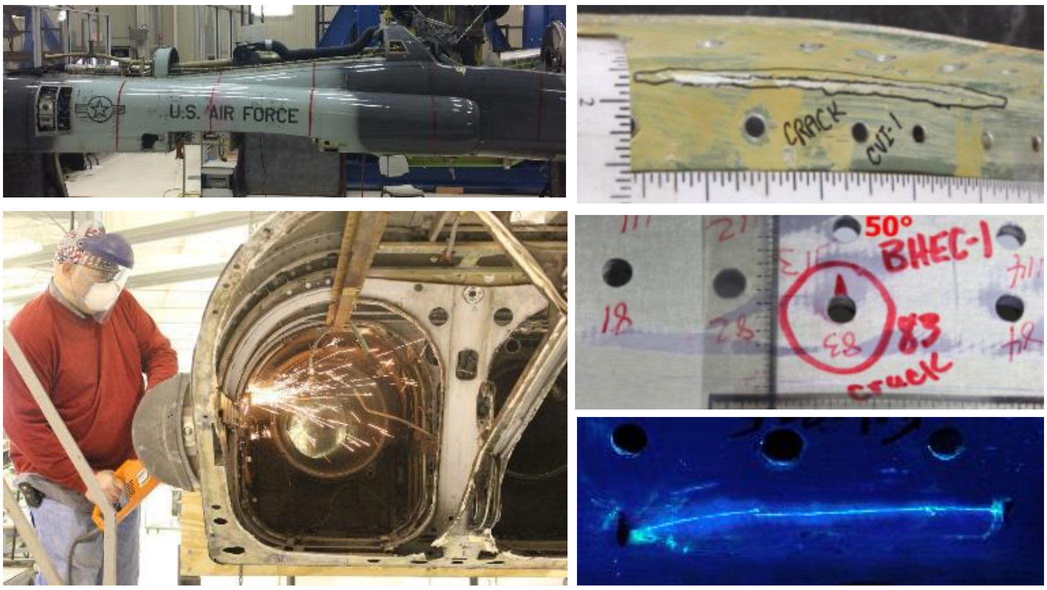

Figure 1: Sectioning, disassembly, and inspections during strctural teardowns.

The results of these teardown inspections are a mountain of data, often thousands of indications of differing severity and on various types of components. These must then be confirmed as a specific failure mode through detailed analysis to identify the specifics of corrosion or fatigue failures such as crack size and nucleation. With limited resources, the indications are prioritized by locations of interest, damage severity, and uniqueness to select which indications will receive analysis. An example of how indications can be plotted on the wing geometry to identify “hot spots” of fatigue damage can be seen in Figure 2.

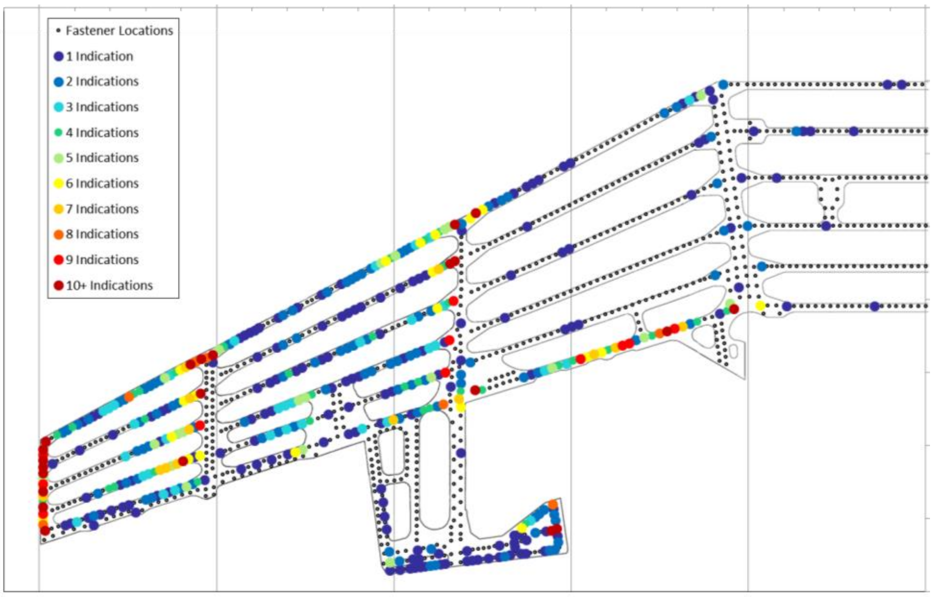

Figure 2: Wing fatigue crack location heat map.

Indications and confirmed fatigue crack data can then be utilized by engineering to inform new inspection areas or procedures, to evaluate the economic life of the structure, to support durability and Damage Tolerance Analysis (DTA) correlations, validate NonDestructive Inspection (NDI) probability of detection capabilities, supply data for risk analyses Equivalent Initial Flaw Size (EIFS) distributions, and other tasks for continued successful management of the weapons system.

In this paper, the background of the Probability of Fracture (PROF) software is detailed with an emphasis on the creation of an EIFS distribution using data obtained from structural teardowns. Three case studies are presented for both wing and fuselage structures. For the first case study, a set of condemnation data was used to develop an EIFS distribution that resulted in a Uniform distribution versus the typical Weibull distribution. The second case study at a wing FCL had wing retirement teardown findings contrary to previous damage tolerance assumptions. Incorporating the teardown findings produced a probability of failure much lower than previously calculated. The third case study will show how historical teardown data from a fuselage modification program was used to enhance the risk analysis for a previously unknown fuselage FCL.

BACKGROUND

The primary objective of a structural risk analysis is the calculation of the Single Flight Probability of Fracture (SFPOF) of a Fatigue Critical Location (FCL). Specifically, this is the probability that the maximum stress encountered in a flight will produce a stress intensity factor that exceeds the fracture toughness of the material. The SFPOF for aircraft structures is calculated using a probabilistic approach to fracture mechanics analyses. Generally, an SFPOF of less than 10^{-7} is considered acceptable, while an SFPOF above 10^{-5} is unacceptable.

T-38 engineering uses the PROF software [1] as the primary tool for quantifying risks associated with inspection, replacement, and retirement decisions for aging aircraft. PROF accounts for a growing population of cracks in aircraft structure while factoring in the variation associated with material properties, usage, inspection, and repair. PROF was designed to specifically handle data that is available as a result of a DTA. Inputs include material and geometry information, aircraft usage, NDI information, and repair capabilities. Items 1, 2, 7, and 8 in Table 1 are deterministic input parameters, while the remaining items are probabilistic or random variables.

Table 1: Input data for PROF risk analysis.

Item	*Description*	*Type*	*Form*	*Source*
1	Normalized Stress Intensity Factor	Deterministic	Tabular	DTA
2	Crack Growth Life Curve	Deterministic	Tabular	DTA
3	Fracture Toughness	Random	Parameters	DTA/Material Data
4	Initial Flaw Size Distribution	Random	Tabular	Teardown/Estimates
5	Repair Flaw Size Distribution	Random	Tabular	Estimates
6	Maximum Stress per Flight	Random	Parameters	DTA/Flight Data
7	Inspection Intervals	Deterministic	Constants	DTA
8	Number of Analysis Locations	Deterministic	Constants	Aircraft Data
9	NDI Probability of Detection	Random	Parameters	NDI Studies

The use of fracture mechanics-based risk analysis requires some representation of an initial flaw size. Naturally, this variable is treated probabilistically due to the variation and overall uncertainty in crack growth and nucleation life. While each analysis is unique, the initial flaw size distribution has been shown to have the most significant effect on the SFPOF calculation for the T-38 [2].

In a laboratory environment, variabilities in the microstructure, controlled corrosion conditions, and surface finish can account for most of the overall variability in an initial flaw size distribution. However, actual aircraft structures encounter machining variabilities, induced damage due to maintenance, and other hard-to-predict occurrences. Therefore, the most common approach for estimating the initial flaw size is the Equivalent Initial Flaw Size (EIFS) method. Using a crack growth curve, an in-service crack finding is back-extrapolated to determine its equivalency to a hypothetical crack that had been present at the time the part was put into service. An EIFS distribution can then be determined from multiple findings. An illustration of the method is shown in Figure 3.

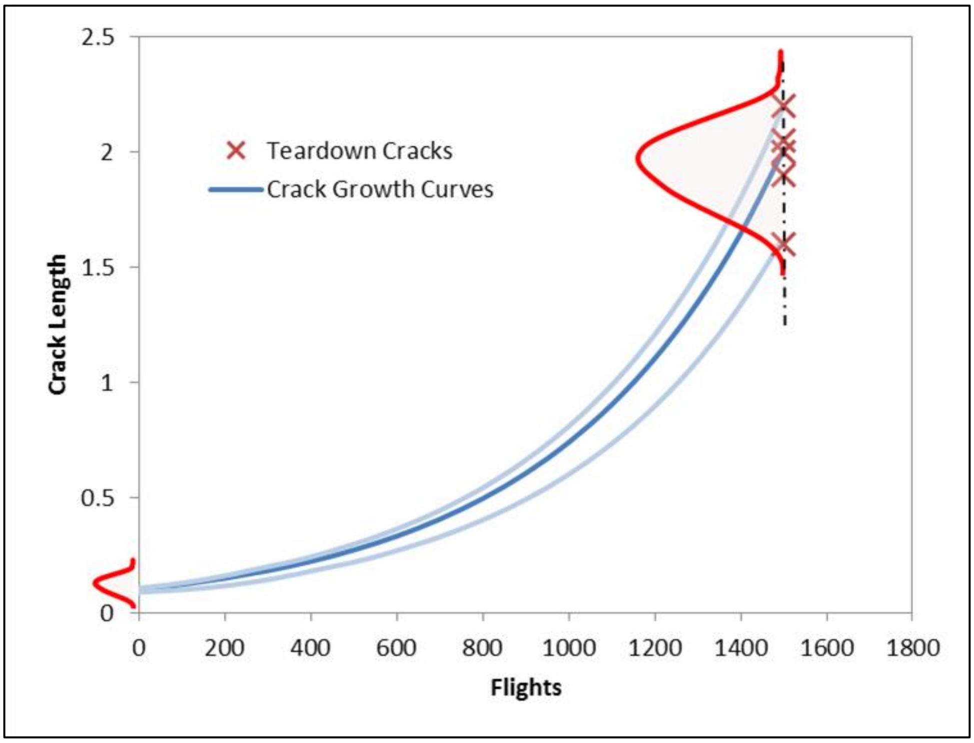

Figure 3: Illustration of the equivalent initial flaw size method.

Note that MIL-STD-1530D uses the term “Equivalent Initial Damage Size” (EIDS) distribution, whereas MIL-STD-1530C used “Equivalent Initial Flaw Size” distribution. However, the definition across versions remains essentially the same:

> *“The equivalent initial damage size distribution is an analytical characterization of the initial quality of the aircraft structure at the time of manufacture, modification, or repair. The EIDS distribution is derived by analytically determining the initial damage size distribution that characterizes the measured damage size distribution observed during test or in service.”* [3]

To compound the difficulty of obtaining an EIFS distribution, actual in-service crack data is difficult to acquire. The ideal data would require metallurgical and fractographic analysis of the cracked structure; however, this cannot be done without destructive examination. In the late 1990s, SwRI developed distributions using the EIFS method for the T-38 wing fastener holes from the full-scale durability test. The crack findings and resulting EIFS data were separated into two groups – coldworked and non-coldworked fastener holes.

In the late 2000s, T-38 engineering wanted to take a risk-based approach to fleet management, which up to this point had been primarily based on deterministic analysis. While having overall advantages in cost and safety, this required more teardowns so that FCL-specific EIFS distributions could be constructed, leading to more precise risk analyses. This was the origin of the T-38’s extensive teardown program. Since the effort began, the T-38 program now has FCL-specific distributions for all of the highest priority wing and fuselage locations, comprising approximately ten unique distributions. The T-38 Program Office is now managing the fleet through risk analysis by adjusting inspection intervals when necessary, setting technically acceptable schedules for one-time inspections, and prioritizing the replacement of the highest-risk parts.

CONDEMNATIONS

The successful full-scale fatigue test of two T-38 wings under different usages, presented at ICAF2017 [4], resulted in a failure at a mechanically milled pocket in the lower wing skin. Multiple cracks nucleated at machine marks left from the milling process. These cracks linked causing multiple ratchet marks on the crack face. An image of the milled pocket crack is shown in Figure 4.

Figure 4: Wing skin milled pocket fatigue failure.

All four locations in the full-scale wing fatigue tests were found to be cracked, left and right side on both wings. These cracks were used to create an initial EIFS Weibull distribution and a risk analysis was performed. From the initial risk analysis, a revisit of the non-destructive inspection method and procedure was warranted. Aircraft wings with a positive indication were condemned and the milled pocket was excised from the wing and sent for failure analysis. Since then, 36 confirmed cracks have undergone a failure analysis and the cracks measured. An EIFS distribution was created that clearly showed a uniform distribution of the data. The uniform distribution arises in manufacturing where a mass-produced part gradually changes dimension through tool wear and increased tool forces between setups [5]. The initial and current EIFS distributions are shown in Figure 5.

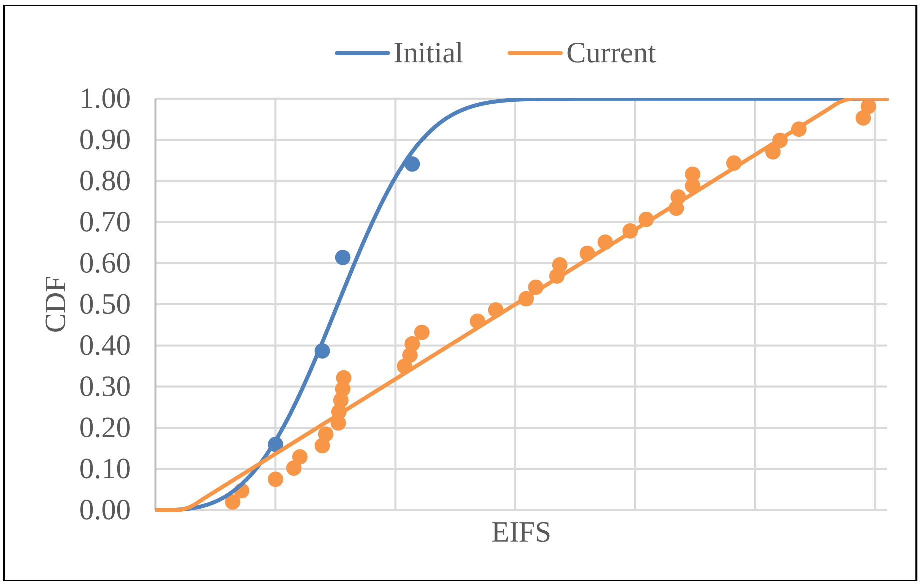

Figure 5: Wing skin milled pocket initial vs current EIFS distributions.

Both EIFS distributions were used in PROF risk analysis keeping all other inputs constant, which is shown in Figure 6. The SFPOF for the current uniform EIFS distribution resulted in six magnitudes greater than the initial Weibull EIFS distribution SFPOF during the early flight hours, resulting in a higher risk earlier in the wing's life. The initial SFPOF accumulates 10 times the risk at its maximum than the current SFPOF. Both EIFS distributions level out to the same risk late in life.

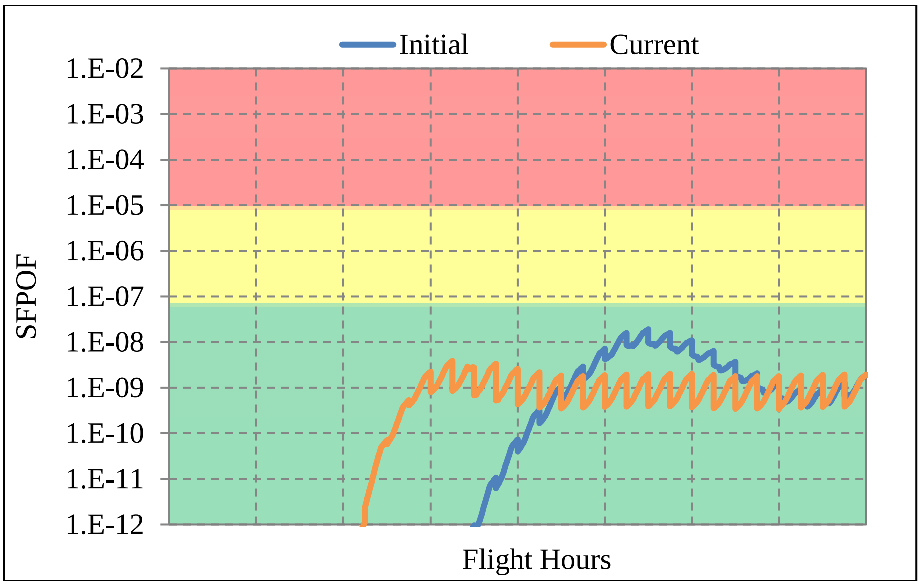

Figure 6: Wing skin milled pocket risk analysis for initial vs current EIFS distributions.

RETIREMENTS

The second case study consists of a coldworked, countersunk hole in the T-38 lower wing skin. A PROF analysis of this location showed that the risk was expected to become unacceptable within the lifetime of the wing and may necessitate more frequent inspections. The analysis used a legacy EIFS distribution from the wing durability test. This distribution was not specific to any one location and instead captured the variability from all cold expanded holes in the lower wing skin. The risk seemed unusually high since no cracks had been found at this location in the field and no wings were condemned due to this location. A review of teardown results from retired wings found over 30 failure analyses with measured cracks at this location. Out of these findings, the largest recorded crack size was 1.8 mm, which is an order of magnitude less than the critical crack size. Also of note was that the failure analyses revealed that all cracks had nucleated from the faying surface of the hole, whereas the DTA assumed that the crack originated at the countersunk knee. An image of a faying surface crack is shown in Figure 7.

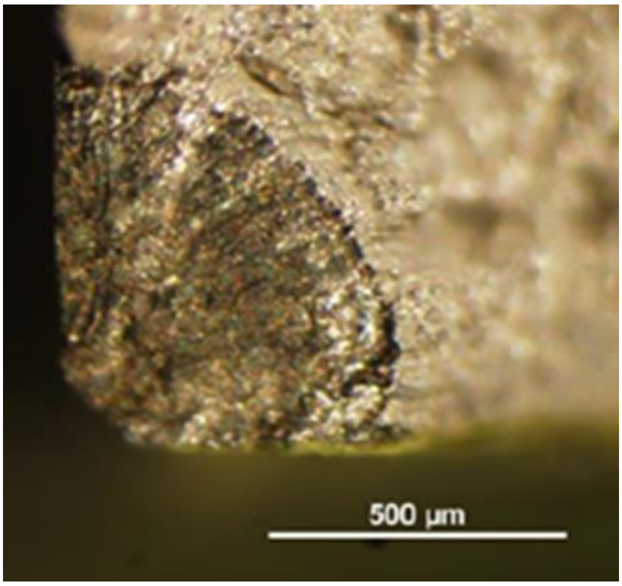

Figure 7: Faying surface corner crack.

The risk analysis was revisited with two major changes: 1) the crack growth was reanalyzed with the crack nucleating from the faying surface of a countersunk hole instead of the knee, and 2) an EIFS distribution was created based on the failure analysis crack findings and new crack growth curve. Figure 8 shows two EIFS distributions and one dataset. The new EIFS distribution using the faying surface model is the solid orange line and the legacy coldworked fastener hole EIFS distribution is the blue line. The reduced dataset used to create the new distribution is plotted as orange circles. Interestingly, the new distribution contains larger cracks than the legacy coldworked fastener hole distribution. However, putting the crack at the faying surface rather than the knee increased the analytical life by a factor of almost four.

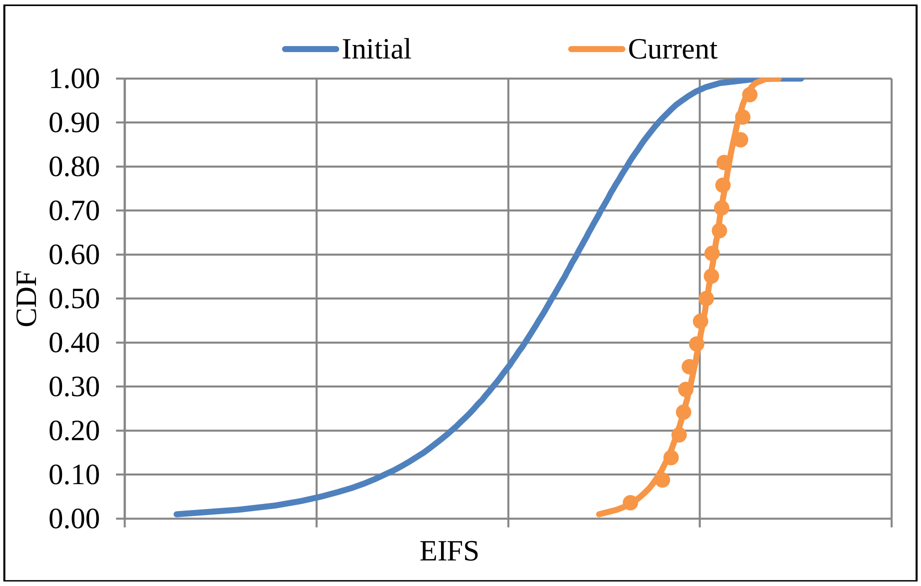

Figure 8: Coldworked hole initial vs. current EIFS distributions.

The faying surface crack growth curve, normalized stress intensity factor, and new EIFS distribution were input into a PROF risk analysis. With all other inputs remaining the same, the new results showed that the SFPOF remained below 10^{-7} for the expected lifetime of the wing. Thus, teardowns from retired and condemned wings identified the true crack location and were essential for lowering the risk and preventing unwarranted extra inspections. The initial and current SFPOF curves are shown in Figure 9.

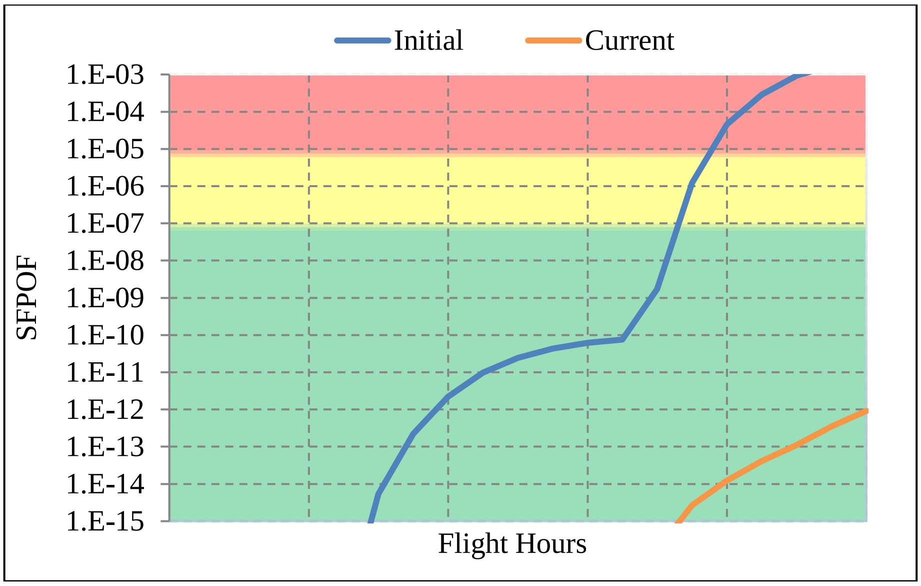

Figure 9: Coldworked countersunk hole risk analysis for initial vs current EIFS distributions.

STRUCTURAL MODIFICATION PROGRAM

In 2017, a crack was found on a fuselage longeron from a routine visual inspection of the area. This was the first confirmed crack at this location on a high time aircraft. The aircraft was located at a maintenance facility where the fuselage modification program was performed. The longeron was removed and replaced and the cracked longeron sent for a failure analysis investigation. The failure analysis determined that the crack was propagated by fatigue and nucleated at a fastener on the faying surface shown in Figure 10. Sites 1 and 2 are the primary cracking locations, where sites 3 and 4 are secondary cracking (i.e. continuing damage).

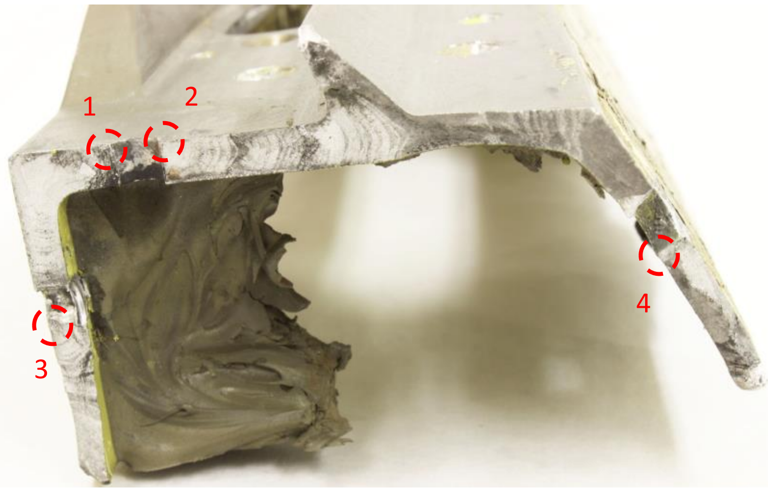

Figure 10: Fuselage longeron fatigue failure.

At that time, select parts were removed from the fuselage modification program aircraft and inspected. Two additional crack indications were broken open to measure crack sizes. Since the initial analysis performed in 2017, there have been 24 confirmed cracks at this location. It was observed that 10 of these cracks were double cracks (i.e. a crack on each side of the fastener) and 14 were single cracks. There was no apparent bias between left and right, or outboard/inboard of the fastener. Two DTA curves were created for both the double crack and single crack scenarios to aid in the determination of the corresponding EIFS of the primary crack. An EIFS of each finding and a Bernard's approximation for Median Ranks (BMR) were calculated and used to create a Weibull EIFS distribution. The initial and current EIFS distributions are shown in Figure 11.

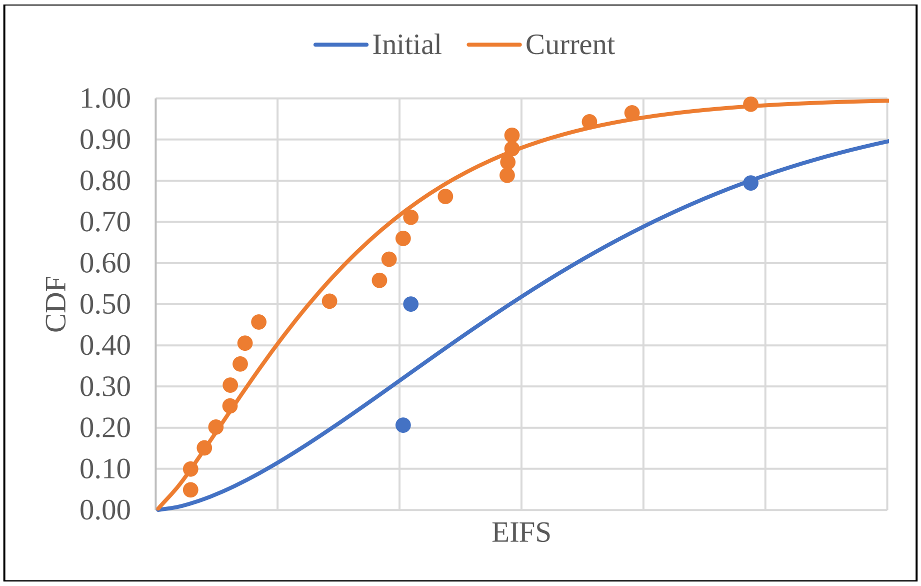

Figure 11: Fuselage longeron initial vs current EIFS distributions.

Both EIFS distributions were used in the PROF risk analysis keeping all other inputs constant, which is shown in Figure 12. The SFPOF was reduced by 1/100th at its greatest point for the current EIFS distribution. The initial EIFS curve returns to the current EIFS curve after several inspections have occurred. The reduction in risk has the potential to extend the inspection interval while maintaining an acceptable amount of risk.

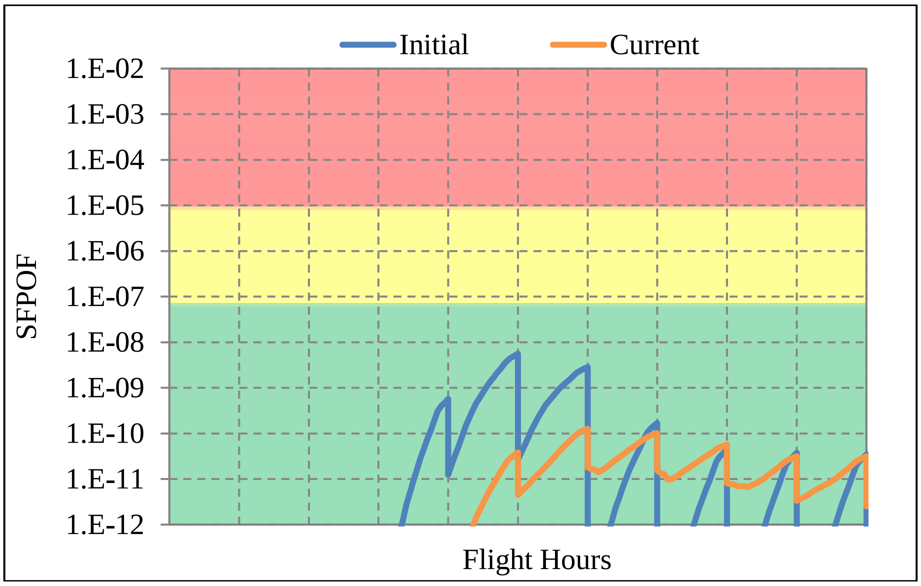

Figure 12: Fuselage longeron risk analysis for initial vs current EIFS distributions.

CONCLUSION

The teardown and inspection of two fuselages, dozens of wings, and hundreds of individual parts has resulted in a robust risk-based approach to fleet management. The failure analyses of condemned wings showed that the EIFS distribution that was based on two wing test articles was unconservative at a milled pocket location in the lower wing skin. A Uniform distribution was observed in the EIFS data from cracks that nucleated at tool marks in a mechanically milled pocket radius. The teardown findings of retired wings resulted in dozens of small cracks at a faying surface of a coldworked countersunk fastener hole. This prompted a change to the DTA nucleation site as well as a new EIFS distribution that had larger cracks than the legacy EIFS distribution. However, due to the change in cracking location, the SFPOF risk was significantly reduced. Finally, the teardown inspection of parts that were removed and replaced in a structural modification program was able to supplement existing damage found at a previously unknown fuselage FCL. This resulted in a lower SFPOF risk by shifting the EIFS distribution to smaller crack sizes. From the teardown effort, The T-38 Program Office is now managing the fleet through risk analysis by adjusting inspection intervals when necessary, setting technically acceptable schedules for one-time inspections, and prioritizing the replacement of the highest-risk parts.

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