

8.2 Sustainment Engineering

A fleet of aircraft is considered to be aging when the FSMP must be modified due to: a) widespread fatigue damage, b) corrosion, c), repairs, or d) use beyond original life goals. Sustainment is the process by which the individual aircraft of an aging fleet are maintained in an airworthy state. Since both the actual maintenance actions and the analyses needed to plan the maintenance actions constitute sustainment, damage tolerance analyses will play a key role in scheduling the structural integrity related maintenance.

Currently, there are three structures related sustainment issues: widespread fatigue damage, corrosion, and repairs. The damage tolerance issues associated with repairs are discussed in Section 9. The following subsections briefly address widespread fatigue damage and corrosion. Research for methods for incorporating WFD and corrosion in the damage tolerance based FSMP is ongoing. Because of its role in assessing widespread fatigue and corrosion damage, a [subsection \(8.2.3\)](#) is also presented on structural risk analysis.

8.2.1 Widespread Fatigue Damage

The Technical Oversight Group for Aging Aircraft (TOGAA) of the Federal Aviation Administration adopted the following definition of widespread fatigue damage (WFD) for aging aircraft [Lincoln, 2000]:

“The simultaneous presence of cracks at multiple structural details characterizes the onset of WFD. These cracks are of sufficient size and density whereby the structure will no longer meet its damage tolerance requirement (e.g. maintaining required residual strength after partial structural failure).

Where damage tolerance is defined as follows:

Damage tolerance is the attribute of a structure that permits it to retain its required residual strength for a period of unrepaired usage. It must be able to do this after it has sustained specified levels of fatigue, corrosion, accidental, or discrete source damage. Examples of such damage are (a) unstable propagation of fatigue cracks, (b) unstable propagation of initial or service induced damage, and /or (c) impact damage from a discrete source.”

Current critical aircraft structures are designed to be damage tolerant. The structure is designed to withstand failures or discrete source damage for a defined period of operation during which the damage will be detected. For fail-safe designed structures, the analyses and tests for demonstrating fail-safety are based on the redundant or crack-stopping component to be essentially undamaged. However, if an aging airframe is experiencing WFD, the remaining structure in the load path may not be capable of stopping the propagation of the damage. Thus, WFD considerations shift the emphasis from the growth of a dominant, monolithic crack to the loss of fail-safety due to many small cracks. This shift in emphasis has major ramifications with respect to the application of the ASIP damage tolerance process.

A damage tolerance criterion for scheduling inspections for WFD would need to be based both on the size of the cracks to be reliably detected and on the number and location of the cracks in the crack-stopping structure. It has been shown that cracks on the order of 0.040 in. in the crack stopper can compromise fail-safety [Swift, 1987, 1992a, 1992b]. At present, the reliable detection of such small cracks, while possible, is cost prohibitive for the many details over the broad

expanse of structure that would need inspection. Further, the damage tolerance analysis process is essentially deterministic. The loss of fail-safety can occur as a result of many combinations of crack sizes and locations in the crack stopper of the propagating damage. The use of conservative, fixed-crack sizes in all of the crack stopper details would permit a deterministic analysis but would lead to unacceptably short inspection intervals. Therefore, maintenance planning for WFD cannot be done with the ASIP damage tolerance process.

Since the aircraft can perform normal flight operations with WFD, its presence can easily be overlooked. The problem for maintenance planning is to predict to onset of WFD so that repair, replacement, or retirement decisions can be made. At present, there is no standard method for predicting the onset of WFD but structural risk analysis has been used in the decision making process. The risk analysis objective is to determine the number of flight hours at which the probability of structural failure given a discrete source damage event exceeds a defined level. For example, in a risk analysis of the C-5A, probability of failure given the discrete source damage greater than 10^{-4} was judged to be an unacceptable level of fail safety [Lincoln, 2000]. Risk analysis is discussed in [Section 8.2.3](#), but it might be noted that predicting the growth of small cracks can play an integral part of risk analyses.

There are two general scenarios for WFD that affect fail-safety. These are referred to as multiple-site damage (MSD) and multiple-element damage (MED). MSD is usually considered to be fatigue cracking in multiple details of the same structural element. A discrete source damage event (i.e. failure of an integral detail of an element) would raise stress levels in the remainder of the structural element. The discrete source damage event could be caused by an external disturbance or by the sudden linking of cracks in the element. An example of MSD leading to the loss of fail safety is provided by the failure in an Aloha Airlines Boeing 737 in April 1988. The failure occurred after the airframe had experienced 89,960 flights. Subsequent analyses have shown that the airframe had lost fail-safety at about 40,000 flights due to MSD (see NTSB [1989] and Lincoln [2000]).

In the MED scenario, fatigue cracking occurs in two or more multiple elements that support the same load path. Failure of selected combinations of the elements may not lead to system failure, but the effects of the failures may well lead to load and geometry effects that do influence the integrity of the remaining structure. An example of MED is provided by the fatigue cracking at WS-405 of the C-141 aircraft [Alford, et al., 1992].

8.2.2 Corrosion

Although corrosion is a major contributor to the costs of structural maintenance of aging aircraft, corrosion has not been a safety issue to date. Accordingly, corrosion has not been emphasized in ASIP. JSSG-2006 recognizes that corrosion can affect operational readiness through enhanced initiation of flaws that degrade damage tolerance, durability and residual strength. Corrosion prevention and control is addressed in Paragraph A.3.11.2 of JSSG-2006, but the emphasis here is on material selection and corrosion prevention systems. The guidance states that corrosion will not occur during the planned service life and usage because the corrosion prevention system will remain effective during the planned service life and usage. Planning for corrosion maintenance is a not formal part of the FSMP of MIL-HDBK-1530. In fact, there is no reference to corrosion in the Force Management Tasks IV and V of MIL-HDBK-1530. In Appendix B, “Additional Guidance for Aging Aircraft”, of MIL-HDBK-1530, corrosion is recognized as an aging aircraft issue. The guidance in Appendix B states that inspections for corrosion in aging aircraft should

be conducted. If corrosion is found, it should be removed. If, on rare occasion, the corrosion cannot be removed, the effect of the corrosion on structural integrity should be determined and the safety inspection schedule should be modified. This approach to maintenance is often referred to as “find it and fix it”.

Corrosion is an economic burden in sustainment. Inspections for hidden corrosion are currently being performed during routine, depot level maintenance cycles. When corrosion is detected, the damage is repaired or the damaged component is replaced. Cost savings could be realized if the timing of corrosion maintenance actions could be optimized. However, at present there are no accepted analytical methods for predicting the initiation and growth of corrosion, so that a severity-of-damage type approach to scheduling inspections is not currently feasible. Such an “anticipate and manage” approach to corrosion maintenance is under development (see, for example, Peeler, et al. [2001], Brooks, et al. [2001], and Lang, et al. [2001]). This approach depends on knowing the condition of the corrosion damage through NDI, understanding the corrosion growth rates as affected by the environment, and predicting the future corrosion condition using models of corrosion growth. The present and predicted future states of the corrosion condition can then be used in structural integrity calculations to determine remaining strength and life. Disposition may now include flying the aircraft with known corrosion present, among other alternatives. Economical disposition can be made while maintaining aircraft safety.

For damage-based inspection scheduling, the capability of NDI systems must be characterized in terms of the damage metric being modeled. Refer to Section 3.1.3 for a discussion of characterizing the corrosion detection capability of NDI systems.

8.2.3 Structural Risk Analysis

The complex combinations of potential cracking within and between structural elements and the unknown state of the fatigue damage in aging aircraft essentially preclude the use of deterministic crack growth calculations for estimating the onset of WFD. Accordingly, structural risk analyses are being used to quantify structural capability. Current practice is to express structural risk in terms of the single-flight probability of failure as a function of experienced flights or flight hours from a reference age. According to Lincoln [2000], in the USAF, the acceptable upper bound on the single-flight failure probability is 10^{-7} . This degree of risk implies that less than one failure would be expected in any given fleet.

When an airframe enters service, estimates-of-failure probability would be based on the growth of monolithic cracks at the most severe, known critical locations and would be extremely small. Such estimates would be made on the basis of a probabilistic characterization of initial quality. Currently, the equivalent initial flaw size distribution is used to model the crack sizes at the critical locations. In the probabilistic approach to maintenance scheduling, inspections would be planned at intervals that keep the failure probabilities of the monolithic structures below 10^{-7} . In the aging aircraft scenarios, crack size distributions are obtained for the critical locations in the complete load path as the basis for the estimates of failure probability. Structural failure probability is then calculated as the conditional probability of inadequate strength given the condition of the elements in the load path. For example, assume there is a 10^{-3} probability of a discrete source damage event, such as a sudden fatigue crack linkup across two bays in a fuselage lap joint. To maintain an overall catastrophic failure probability less than 10^{-7} , the probability of failure in this damaged state must be less than 10^{-4} . In this example, loss of fail safety can be said to occur at the number of flight hours when the WFD reaches the state at which the probability of surviving

the discrete event exceeds 10^{-4} . The number of flight hours to reach such a state of fatigue cracking has been suggested as the definition of the onset of WFD [Lincoln, 1997].

There are several approaches that can be used to calculate single flight failure probability, but the USAF has available a computer program named PROBABILITY OF FRacture (PROF) for risk analysis in aging aircraft. PROF is a computer program that runs in the Windows environment on a personal computer and was specifically written to interface with the data that is available as a result of ASIP. See Berens, et al. [1991] and Hovey, et al. [1998] for complete descriptions of the development of the program and its update to the Windows environment. [Figure 8.2.1](#) is a schematic of the program for calculating probability of failure as a function of flight hours for a monolithic crack. The figure illustrates the types of data required to perform an analysis and the probability of failure (POF) output that is calculated as a function of flight hours. Another calculation module in PROF calculates probability of failure due to a discrete source damage event.

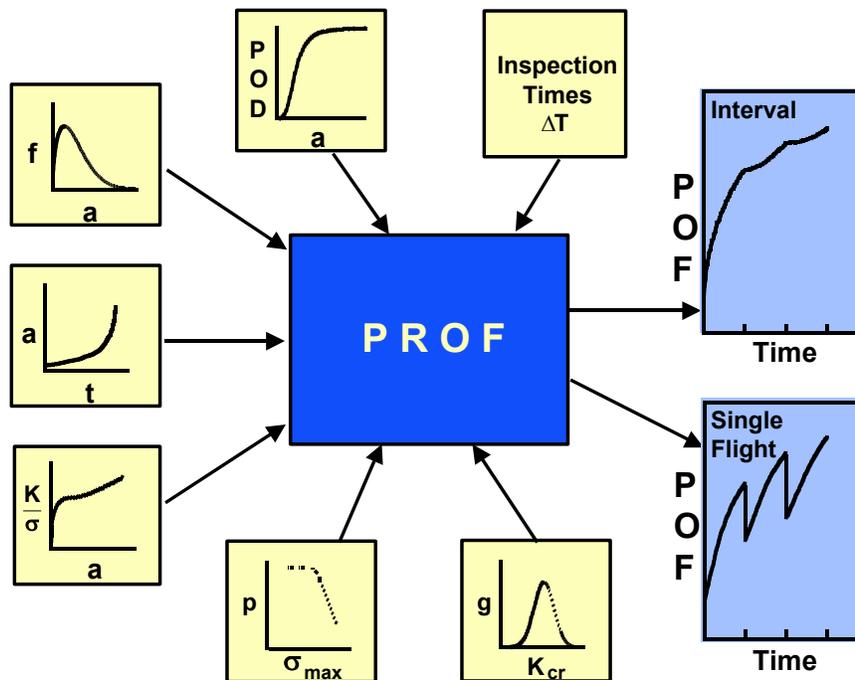


Figure 8.2.1 Schematic of the PROF Computer Program

Under ASIP, crack life predictions (a versus T) are available for every known critical location. This implies the availability of:

- a) the flight by flight stress spectrum, from which the distribution of maximum stress per flight can be obtained;
- b) stress intensity factors as a function of crack size, a versus K/σ ; and,
- c) fracture toughness, K_{cr} , from which a distribution of fracture toughness can be inferred.

The initiating crack size distribution can be obtained from inspection feedback, tear-down inspections, or equivalent initial flaw sizes. Probability of detection as a function of crack size,

POD(a), is from a characterization of the capability of the non-destructive inspection system used during the safety inspections.

The starting point of a PROF analysis can be representative of any arbitrary number of hours in the life of the fleet. PROF uses the deterministic a versus T curve to project the percentiles of the initiating crack size distribution as a function of flight hours. At defined flight hour increments, the single-flight probability of fracture is calculated from the distributions of crack size, maximum stress per flight, and fracture toughness. That is, the single-flight fracture probability is the probability that the maximum stress intensity factor (combination of the distributions of maximum stress per flight and crack sizes) during the flight exceeds the critical stress intensity factor.

At a maintenance cycle, the distribution of crack sizes is changed in accordance with the POD(a) function and the equivalent repair crack size distribution. It is assumed that all detected cracks are repaired and the equivalent repair crack size distribution accounts for the repaired cracks. PROF produces files of both the pre- and post-inspection crack size distributions. The availability of these distributions allows changing the analysis conditions at inspection times set by the analyst.

The a versus T , a versus K/σ , and crack size distributions are input to PROF in tabular form. Fracture toughness is modeled by a normal distribution and requires values for the mean and standard deviation. Maximum stress per flight is modeled by the Gumbel extreme value distribution and the parameters of the distribution can be obtained from a fit of either a flight-by-flight stress spectrum, or an exceedance curve of all of the stresses in the spectrum. The POD(a) function is modeled by a cumulative lognormal distribution with parameters μ and σ . Fifty percent of the cracks of size μ would be detected. The parameter, σ , determines the flatness of the POD(a) function with smaller values implying steeper POD(a) functions.

The module for the calculation of failure probability given discrete source damage also requires an evaluation of the residual strength in the presence of partial structural failure. Procedures for determining residual strength in the presence of discrete source damage for a number of representative aircraft skin structures can be found in Swift [1993].

Sensitivity studies have been performed on the application of PROF in representative problems [Berens, et al., 1991]. These studies have indicated that, although the absolute magnitudes of the fracture probabilities are strongly dependent on the input, relative magnitudes tend to remain consistent when factors are varied one at a time. Because of the indefinite nature of some of the input data, particularly the crack size information, absolute magnitudes of the fracture probabilities are suspect. However, it is believed that relative differences resulting from consistent variations in the better-defined input factors are meaningful.

A single run of PROF analyzes the growth of a crack for a single geometry, including crack type and shape. The analysis would apply to the population of structural details that both have this geometry and are subject to an equivalent stress spectrum. The output includes fracture probabilities for a single structural detail, for a single aircraft when there are multiple equivalent details, and for the entire fleet. The inspection intervals are set by the analyst, including the possibility for an immediate inspection at time zero.

More complex problems can be analyzed by combining the results of multiple runs. First, intermediate output can be used to initiate new runs for changed conditions. Examples of such analyses would include the introduction of corrosive thinning of the material, the effect of over-

sizing holes during repairs, and the effects of changing usage. The results from multiple runs for different details can also be combined to model more complex scenarios. Examples of such scenarios include the analyses of multi-element and multi-site damage.

There are four examples of the application of risk analysis in sustainment scenarios in the Sample Problem Section of the Handbook. The sample problems addressed are:

- a) **Problem No. UDRI-2** – Structural Risk Assessment for a Discrete Source Damage Threat to the Fail Safety Capability of Stringer 7 in a Boeing 707 JSTARS Airframe.
- b) **Problem NO. UDRI-3** – Structural Risk Assessment for the Multiple-Element Damage Scenario at WS 405 of a C-141 Airframe.
- c) **Problem No. UDRI-4** – Comparative Risk Assessment of the Thinning Effect of Corrosion on a Representative Lap Joint.
- d) **Problem No. NRC-3** – Effect of Discontinuity States on the Risk Assessment of Corroded Fuselage Lap Joints.