Damage Tolerant Risk Analysis Techniques for Evaluating the Structural Integrity of Aircraft Structures

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ABSTRACT

Over the last 20 years, the United States Air Force (USAF) has evolved a methodology for using risk assessments to protect the structural integrity of aging aircraft. This methodology has matured over the last several years to the point where the products of risk assessments can now be used to effectively communicate the risk of a potential catastrophic structural failure to USAF leadership in a standard way. Examples of applications where risk assessment methodology have been recently used are presented along with guidelines for assessing the accuracy of the methodology in anticipating structural failures. The methodology has also been shown to be useful in establishing optimum inspection schedules for potentially cracked structures and for developing optimum nondestructive inspection (NDI) techniques for the expected crack population at the location of interest.

1 INTRODUCTION

Airframe structure risk analyses provide quantitative information to evaluate aircraft safety and useful service life as summarized in Babish [1]. The USAF has routinely used airframe structure risk analysis results to balance safety, cost and readiness of numerous weapon systems by answering the following types of questions:

Are aircraft operating at unacceptable risk levels?
How do inspection interval changes impact safety and cost?
What is the cost of inspection and repair versus modification?
When should the weapon system be retired?

The risk analysis method is probabilistic since probability distributions of crack size, maximum stress per flight, fracture toughness and non-destructive inspection technique are required, see [1-6] for details. For airframe structure applications, the risk analysis determines the probability that the maximum stress in a flight will produce a stress intensity factor (for the current crack size) that exceeds the material fracture toughness based on fracture mechanics principles.

The USAF has repeatedly used this type of risk analyses to evaluate airframe structure safety and economic issues such as static strength short-falls, cracking of in-service aircraft, safety and economic impact associated with service life extension, and repair versus modification efforts to protect structural integrity. [1-6] provide examples where and how the airframe structure risk analysis method has been used to quantify safety and those economic factors that affect airframe service life. The USAF is now moving to make quantitative risk assessment/risk management an integral part of its structural integrity program, see Babish, Gallagher [1, 7]

2 BACKGROUND

The United States Air Force (USAF) initiated the Aircraft Structural Integrity Program (ASIP) in November 1958 using a probabilistic approach for establishing the safety of their aircraft. This process was called “safe life” and relied upon the results of a laboratory test of a full-scale airframe. Aircraft failures in service arising from the safe life process demanded a fundamental change be made in the approach to design, qualification, and inspection of aircraft. The damage tolerance approach (Fig. 1, Tiffany [8]) emerged as the candidate chosen for this change and the USAF formally made the damage tolerance approach a part of ASIP with the publication of MIL-STD-1530A, in December 1975. Although USAF regulation and/or guidance that governs ASIP execution has evolved over the years, the fundamental ASIP requirements have remained unchanged.

The ASIP military standard (MIL-STD-1530B, [9]) repeatedly cites the aircraft structures joint service specification guide (JSSG-2006, [10]) for guidance on establishing structural performance and verification requirements for the airframe structure. JSSG-2006 contains the rationale, guidance, lessons-learned and instructions necessary to tailor the requirements for each weapon system and provides guidance on the methods used to verify that the requirements have been met. Within this document, the stated maximum acceptable frequency of a structural failure leading to the loss of the air vehicle is 1 x 10^{-7} occurrences per flight. This requirement has been the benchmark for the USAF airframe structure risk analyses that have been conducted and the methods used to determine the risk level are provided in this paper.

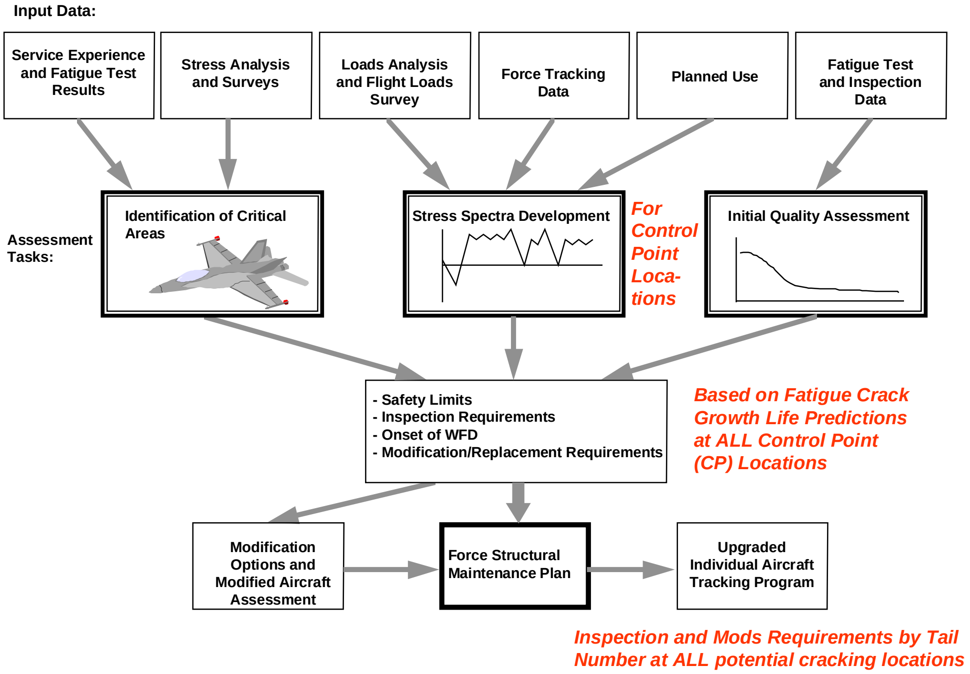

Figure 1. The essence of the damage tolerance design approach applied to protect safety at each fatigue control point, see Tiffany [8]

3 DISCUSSION

3.1 Overview of Risk Analysis Method

Figure 2 summarizes the inputs required to perform an airframe structure risk analysis. These include probabilistic and deterministic data as well as specific aircraft related information. The probabilistic data includes: equivalent flaw size, repair flaw size, fracture toughness, probability of detection, and the maximum stress per flight. The deterministic data required is obtained from the crack growth analyses that are conducted for fatigue critical locations and includes the normalized stress intensity function and the fatigue crack growth curve. The remaining classification of input data is the aircraft related data that includes: number of locations, number of aircraft, hours per flight, and the inspection and repair intervals to be studied.

A computer program, **PR**obability **O**f **F**racture (PROF), was written to facilitate the USAF implementation of airframe structural risk analysis, see Berens [11, 12]. The PROF program can be used to determine the probability of failure due to fatigue cracking, discrete source damage, Widespread Fatigue Damage (WFD) and corrosion thinning in metallic structures. The USAF recently used PROF to support risk assessments on A-10 and T-37 aircraft fleets, see Thomsen, Cardinal [2, 6].

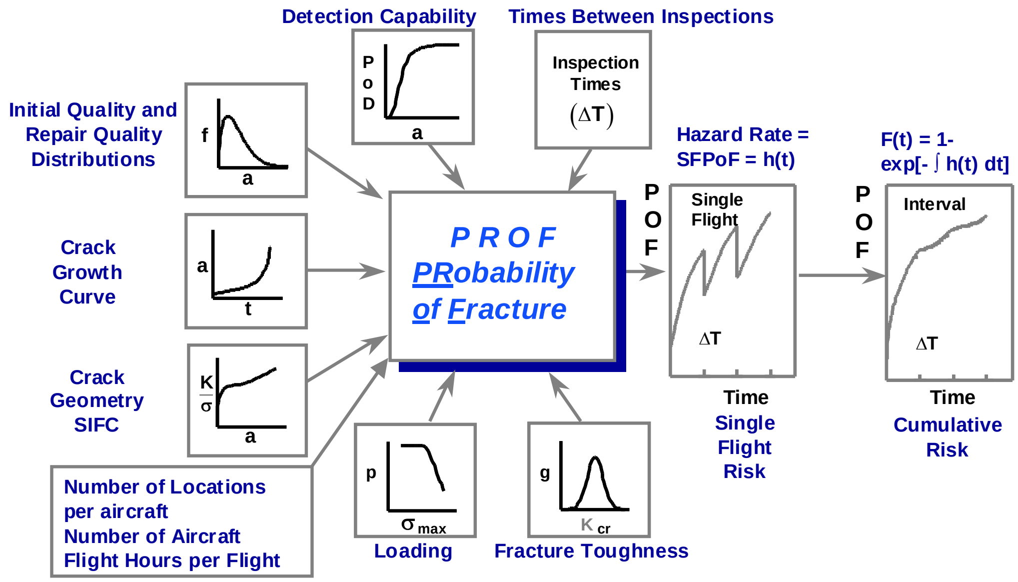

Figure 2. Risk Analysis Input parameters and single flight probability of Failure (SFPoF), see Babish [1]

3.2 Summarizing Risks

To effectively communicate risk analysis results, it is important to ensure that common expressions and definitions are used. The Single Flight Probability of Failure and the Cumulative Distribution Function are expressions that are routinely utilized in the USAF and are hereby defined. The Single Flight Probability of Failure (SFPoF) is the instantaneous risk at some time in the aircraft life and is frequently referred to as the hazard rate. Another way to state this is the probability of failure in the flight given that a failure has not occurred previously. Mathematically the SFPoF is given by the probability density function divided by one minus the cumulative distribution function. The Cumulative Distribution Function (CDF) is the probability of failure in any flight before a given time. This can be used to compute the probability of failure after a given number of flights for a single aircraft or a group of aircraft. It can also be used to estimate the number of expected losses for a group of aircraft.

JSSG-2006 provides guidance on the maximum allowable probability of detrimental deformation and structural failure. For design guidance, this is limited to cases where deterministic values have no precedence or basis. JSSG-2006 states the maximum acceptable frequency of the loss of adequate structural rigidity, or proper structural functioning, or structural failure leading to loss of the air vehicle is 1×10^{-7} occurrences per flight. The USAF practice for risk thresholds has historically been:

(1) A SFPoF $< 10^{-7}$ is adequate for long-term operations.
(2) Limit the exposure when the SFPoF is between 10^{-7} and 10^{-5}.
(3) A SFPoF $> 10^{-5}$ is considered unacceptable.

3.3 Key Input

The Equivalent Flaw Size (EFS) distribution is the description of the population of cracks that are representative of a critical location in the structure at a given time. This data is normally obtained during teardown inspections of either fatigue test articles or in-service aircraft. Fracture mechanics can be used to translate the cracks found to time zero to obtain the Equivalent Initial Flaw Size (EIFS) distribution or to a common fight hour that minimizes translation to obtain the EFS distribution. The EFS distribution is usually the most difficult input data to obtain since it requires a substantial amount of data to be adequately characterized. The EFS distribution has a significant impact on the risk analysis results and every attempt should be made to estimate it accurately. To facilitate this effort, fleet cracking data should be routinely collected to include airframe location, crack size, flight hours, and equivalent flight hours based on actual usage as a minimum to establish and continually refine the EFS distribution. In addition, airframe structural components removed from the aircraft should be thoroughly examined prior to scrapping the parts.

To illustrate the importance of properly characterizing the EFS, Figure 3 provides Equivalent Initial Flaw Size (EIFS) distributions that have been characterized for the materials used in several USAF aircraft. These are described as “initial” distributions since the crack growth curve was used to translate the cracks discovered to time zero. Figure 3 plots the EIFS data as the cumulative distribution function versus crack size in inches. The plotting method was modified to highlight the differences at the “tail” of the distribution. Figure 4 provides this result by plotting the probability of exceeding a given flaw size (one minus the cumulative distribution function) versus crack size in inches. This result illustrates the significant differences in the EFS that have been characterized for several USAF aircraft and the importance of establishing the proper distribution for the aircraft that is analyzed.

The magnitude of the risk for a structural failure in a fleet of aircraft is very heavily influenced by the sizes of the growing crack population at a given location and the capability of the nondestructive inspection (NDI) system used to detect cracks at that location. The probability of detection (POD) curve (shown in Fig.2) characterizes the NDI system capability. A condensation of available reference data for demonstrated NDI performance capabilities in terms of probability of detection (POD) curves is provided in the Nondestructive Evaluation Capabilities Data Book, see Rummel [13]. When the crack sizes exceed the minimum POD threshold, the risk of structural failure starts to grow exponentially, mainly because not all of these cracks will be detected by the NDI system. These missed cracks affect the rate of risk growth, and subsequent inspections must be planned to ensure that these cracks don’t reach critical size, and cause failure. When the crack size population approaches the critical crack size, the NDI system is not likely to protect safety and airframe structure modifications are required at this stage.

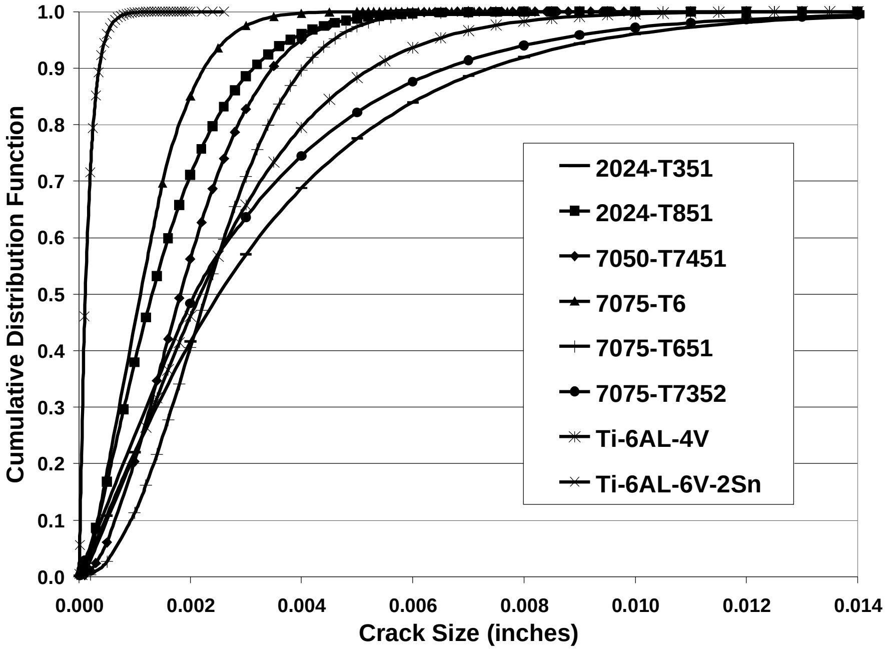

Figure 3. Cumulative Distribution Function (CDF) for several equivalent initial flaw sizes (EIFS) distributions

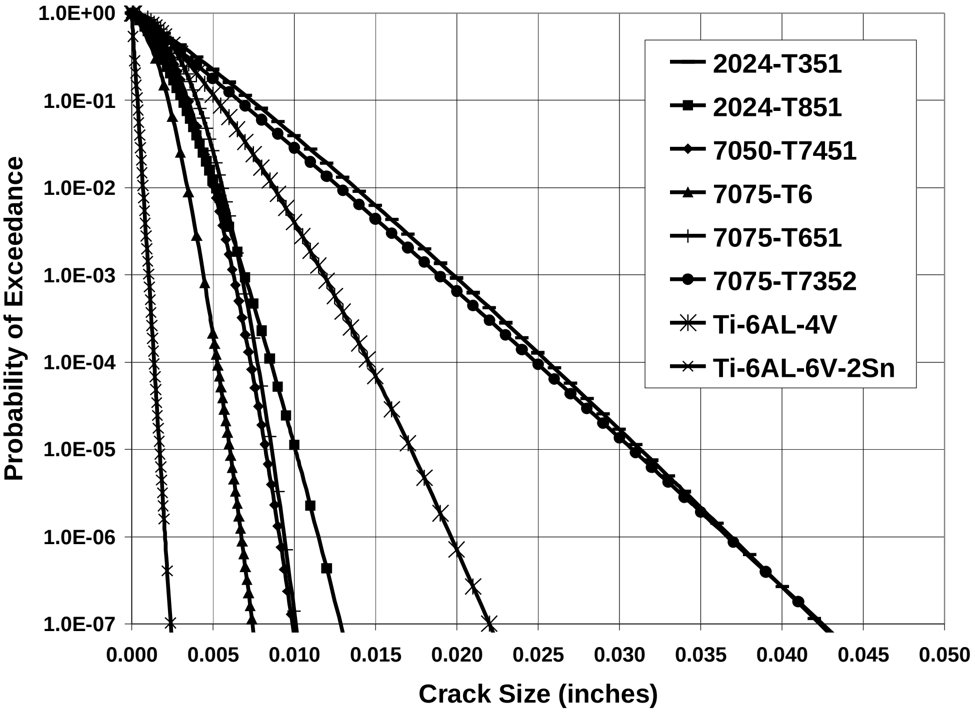

Figure 4. Probability of Exceedances Format (1-CDF) for data shown in Fig. 3

4 SUMMARY

Probabilistic risk analysis methods are well established and have been repeatedly used within the USAF. A majority of the input data is readily available for an aircraft system with good documentation. This includes the crack growth analysis, stress spectra, material properties, etc. The risk analysis approach has been successfully applied to USAF aircraft to establish the maintenance actions required to protect structural integrity and to evaluate alternate maintenance methods and intervals. Highlighted in this paper is the critical relationship between the equivalent flaw size distribution and inspection capability.

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