Risk Assessment of an Aging Military Aircraft

John W. Lincoln*
Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio

The paper examines the adequacy of the U.S. Air Force damage tolerance inspection criterion for protecting the safety of the flight of an aging military trainer aircraft. This is done through a risk assessment based on cracks found in teardown inspections of retired wings. The crack population is combined with stress probabilities representing service experience to determine single flight probability of failure and the single aircraft probability of failure after a given time. These quantities are then used as a basis for judging the required inspection interval. For the case studied, the 0.9 probability of detection inspection criterion in the Air Force damage tolerance requirements may be unconservative.

Introduction

SEVERAL methods have been used by aircraft structural engineers to preclude the catastrophic consequences of fatigue cracking. One method that has been widely used and is still being used in the United States and in Europe is the reliability method. In this method, the structure is tested with simulated operational loads for multiple lifetimes to obtain the desired confidence that the service aircraft would not fail. In the late sixties and early seventies, the mathematical basis for the reliability method was established. Another approach that has been used with considerable success is the damage tolerance method. In this method the analyst assumes that the structure has a remotely occurring (rogue) defect at the time of manufacture and then selects the material and determines the stress to achieve the desired inspection program. In the early seventies the U.S. Air Force (USAF) stopped using the reliability method and elected to use the damage tolerance method. The authors of the USAF damage tolerance requirements chose to make the method deterministic rather than probabilistic. That is, the initial flaw (or crack) is a specific number, and the critical crack length is based on a specific load. Also, the inspection capability is based on one point of the probability of detection function.[1] That is, all cracks longer than the one corresponding to this one point of the probability of detection function are assumed to be found when the aircraft is inspected. Experience with the method through numerous damage tolerance assessments has proven the wisdom of the choice of the deterministic approach. There was, however, a question in the minds of the authors about the portion of the damage tolerance requirements that defined the recurring inspection interval. The point selected from the inspection probability of detection (POD) functions was the point associated with a ninety percent probability of detection. The selection of ninety percent probability of detection as an acceptable reliability for inspections was somewhat arbitrary. Part of the motivation for this selection was that this probability could be relatively easily established through a laboratory program. However the question is: "Is a ninety percent probability of detection adequate to protect safety?" It is the purpose of this paper to examine this question for a particular weapon system. The method used to address this question is yet another method that may be used to protect the safety of aircraft. It is referred to as the risk assessment method. The method is probabilistic in that is uses both the crack size and stress probability distributions and the complete inspection POD function to determine the single flight and the single aircraft probability of failure at a given time. Based on these quantities, one can permit flight based on what is conceived as an acceptable risk.

The opportunity to address this question arose when a service flight loads survey on an Air Force trainer showed that in the late seventies there was a mission change. This change made the load environment considerably more severe than that used in a damage tolerance assessment of this trainer in the mid-seventies time period. The consequences of this increased usage severity was determined by an update of the damage tolerance assessment. This new assessment, which as in the previous assessment used the ninety percent POD for inspections, showed that the inspection frequency should be increased by approximately a factor of three. This would, of course, significantly increase the inspection costs and associated aircraft downtime. To determine if this increased inspection burden was essential to maintain the safety of these aircraft, a risk assessment was performed.

Risk Assessment Methodology

The details of the risk assessment method and a computer program listing are given in Ref. 2. The essential features of the method as applied to the trainer aircraft of interest are described as follows. There are several input data items that are required. One of these is a description of populations of cracks that are representative of the critical locations in the structure. This is usually the most difficult to obtain of all of the input data and, consequently, is the chief inhibitor to more widespread use of risk assessments. Fortuntely, for this trainer, there was a raw data base from which an estimate of the crack population could be made. Over the past several years, destructive teardown inspections have been made on retired trainer wings to provide insight into the possibility of a cracking problem. In all, 19 wings have been torn down and detailed inspections made to quantify the extent of cracking. These examinations revealed that in the critical locations (approximately 100 fastener or drain holes per wing), roughly 25% of the holes had cracks. The upper bound of these cracks was approximately 2.5 mm. The crack findings are detailed in

Presented as Paper 84-0851 at the AIAA/ASME/AHS 24th Structures, Structural Dynamics and Materials Conference, Palm Springs, Calif., May 14-16, 1984; received June 6, 1984; revision received Jan. 15, 1985.

*Technical Expert, Structures Division. Associate Fellow AIAA.

Table 1 Summary of findings from wing teardown inspections

Critical location	No. of wings	Holes per wing	Total holes	Total cracks	Percent cracked
W.S.0.0 fastener	19	49	931	211	22.66
W.S.0.0 drain	19	1	19	4	21.05
W.S.26.6 fastener	19	6	114	57	50.0
W.S.26.6 drain	19	2	38	23	60.53
W.S.40.0 fastener	19	44	836	247	29.65

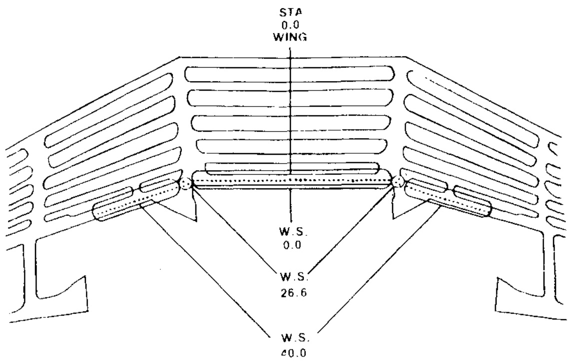

Fig. 1 Critical areas in the wing skin.

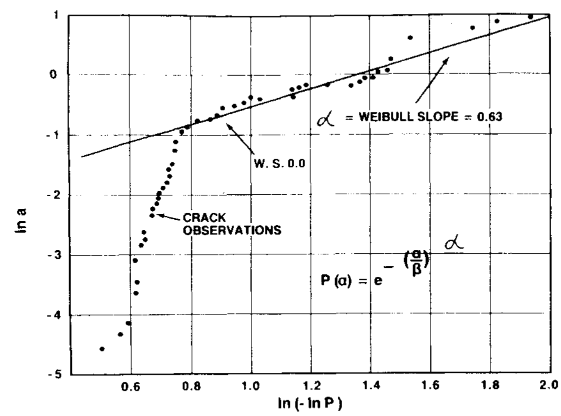

Fig. 2 Weibull fit to observed cracks.

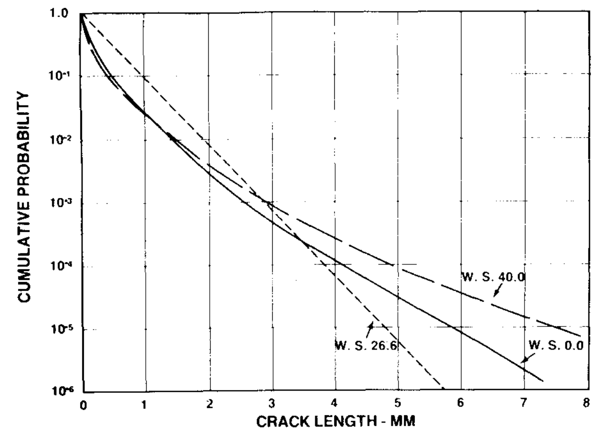

Fig. 3 Derived cumulative probability of exceeding a given crack length.

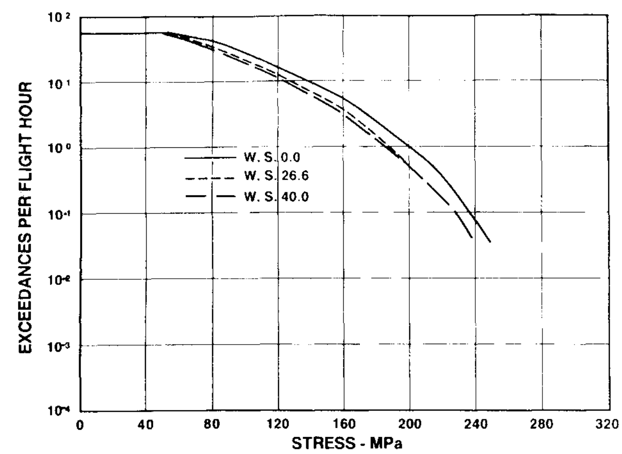

Fig. 4 Wing stress exceedance functions.

Table 1 for the wing layout shown in Fig. 1. These data were judged as an adequate raw data base to define the crack population.

Obviously, not all of the wings were torn down at the same number of equivalent hours of trainer usage. Therefore, the first step in the process was to get the crack lengths referenced to the same number of flight hours. To minimize the changes in the observed individual aircraft crack lengths, the average of the 19 aircraft equivalent number of trainer hours was used. This average was calculated to be 10,200 hours. The crack lengths at 10,200 hours for a given aircraft of the 19 were then derived by a fracture analysis which provided the basis for calculating the length the crack would be or would have been at 10,2000 hours. These calculated crack lengths, a, were then used to generate a sample cumulative probability distribution.[3] The next step in the process was to derive an analytical expression for the cumulative probability P. This is needed to facilitate needed computations and to extrapolate the cumulative probability distribution to approximately 10^{-6}. The log normal and the Weibull probability distributions were used to try to fit the sample cumulative probability. The Weibull distribution proved to be significantly superior to the log normal distribution, but as can be seen from Fig. 2, there is a different Weibull slope (shape parameter) for small cracks than for large cracks. The large cracks are the only ones that significantly contribute to the risk, so consequently the small crack portion may be ignored. This two mode characteristic is not without precedent. Data taken from a teardown inspection of a transport aircraft also displayed this same feature. Figure 3 shows the derived Weibull distributions for the three critical locations on the lower wing skin.

Another data item required for this analysis is the probability of exceeding a given stress at a critical location in a single flight. The data base from which this is derived is the stress exceedance function, which is the number of exceedances of a given stress. The exceedance function is often used as an input for a durability or damage tolerance analysis and therefore is usually available. The cumulative probability for stress is derived from the exceedance function as follows. First, the exceedance function ordinate is transformed to exceedances per flight by multiplying the number of exceedances per hour by the number of hours per flight. Second, the exceedances per flight greater than one are made equal to one. Finally, if it is assumed that there is no more than one counted exceedance

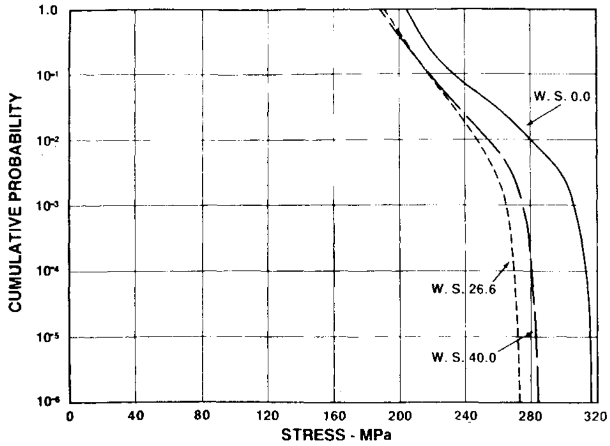

Fig. 5 Wing stress probability functions.

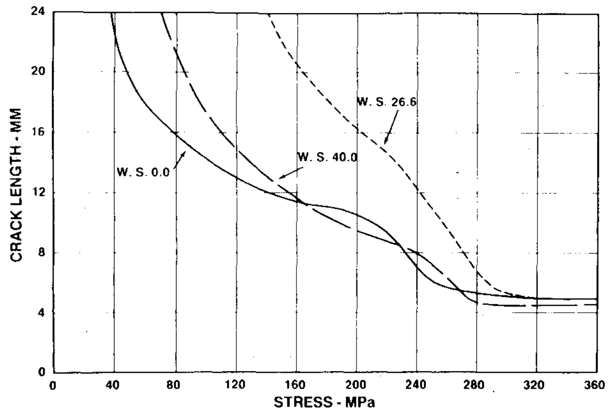

Fig. 6 Critical crack length in wing structure.

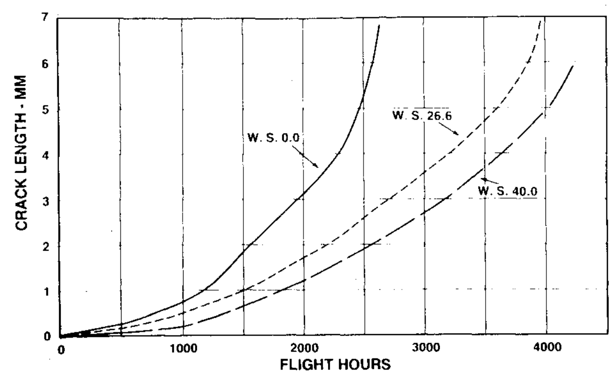

Fig. 7 Crack growth at critical locations.

per flight, then the resulting function defines the fraction of the flights for which a given stress is exceeded. This function is, therefore, the cumulative probability of exceeding a given stress in a single flight. The cumulative probability for stress was numerically extrapolated to approximately 10^{-6}. This extrapolation was based on the shape of the tail of exceedance functions for this type of aircraft. Variations in these extrapolations, that were judged to be reasonable, were studied, and it was determined that the actions derived from this risk assessment would not be significantly changed. However, it must be pointed out that for any given aircraft there could be a "rogue" defect, or it may be subjected to a "rogue" stress that would not be derivable from the probability functions. The risk of these events is not quantifiable, but based on previous service experience, it appears to be small. The exceedance functions are shown in Fig. 4, and the resulting cumulative probabilities for stress are shown in Fig. 5.

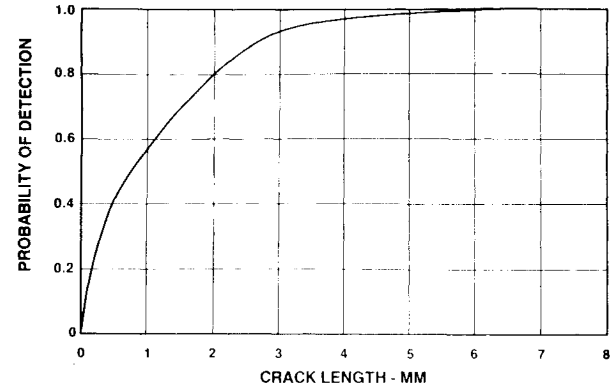

Fig. 8 Wing inspection reliability.

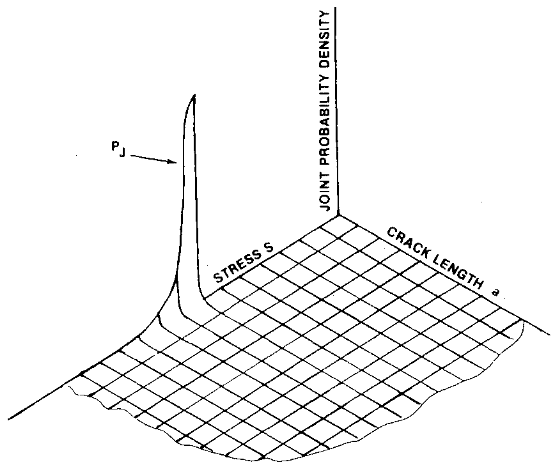

Fig. 9 Joint probability of crack length and stress.

The remaining input data items are the critical crack size vs stress shown in Fig. 6, the crack length vs flight hours as shown in Fig. 7, and the inspection probability of detection function shown in Fig. 8. The shape of the probability of detection function for the ultrasonic inspection of the trainer aircraft was taken from Ref. 1. The probability of detection from Ref. 1 was shifted so that the 0.90 probability of detection flaw size (2.54 mm) used in the trainer damage tolerance analysis was a point of the risk assessment probability of detection function. This provided a consistent basis from which the results of the damage tolerance assessment could be compared with the risk assessment. It is noted that the probability of detection function is used quite differently in the risk assessment than in the damage tolerance assessment. For the risk assessment, the entire function is usually used since the probability of detecting the cracks in the crack length exceedance function is needed. In the damage tolerance assessment, as indicated earlier, only one point of the probability of detection function is used.

Since the crack size at a location in the structure at a given time does not depend on the stress that may occur at this location after this time, the joint probability density function for crack size and stress is the product of the crack length and stress probability density functions. The crack size probability density function is immediately available since the Weibull parameters were derived for the crack length cumulative probability. The stress probability density function is somewhat more difficult to obtain since the cumulative probability for stress was available only in numerical form. A numerical differentiation was, therefore, required to derive the desired result. The joint probability density function (P_J)

for wing station 0.0 for crack length a and stress s is shown in Fig. 9. For stresses less than those encountered once per flight, this function is zero. This is a consequence of the cumulative probability function for stress having zero slope up to the once per flight stress. For stresses that have a greater than once per flight occurrence, the joint probability density function is greater than zero. It should be noted that since the crack length density function decays rapidly toward zero as the crack length increases, the joint density function also decays rapidly in the crack length direction. The joint density function, of course, properly represents the relative importance of the stresses and crack sizes. This joint probability distribution is time dependent since the crack length is time dependent. The surface formed by a vertical projection of the critical crack length vs stress line divides the volume under the joint probability density function into two volumes (see Fig. 10). The volume under the shaded surface is the single flight probability of failure, $p_F{}^2$, calculated from

$$p_F = \iint_R P_J \mathrm{d}A$$

where R is the region "outside" the critical crack size vs stress line in the stress-crack length plane. This is the single flight probability of failure for one point in this location in the structure. At this location there is more than one fastener hole subjected to the same stress field. However, there will be, in general, a different crack size in each of these holes. Therefore, the probability of failure of a given hole does not depend on the probability of failure of another hole at this location. Thus, the single flight probability of failure of all N points (e.g., fastener holes) at this location is one minus the single flight probability of *no* failure for one point to the Nth power. The single flight probability of failure may be easily used to compute the probability of failure after a given number of flights for a single aircraft or a group of aircraft. One may also compute an estimate of the expected number of losses for a group of aircraft.

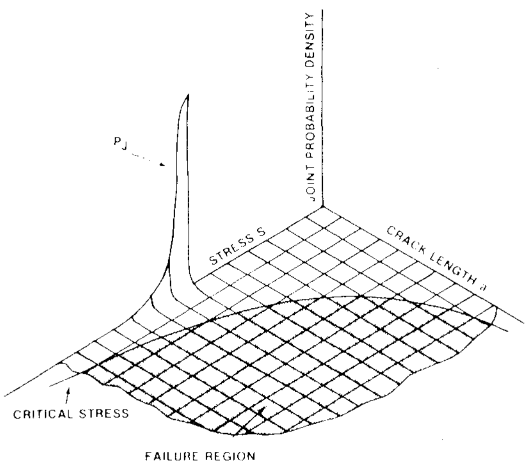

Fig. 10 Basis for computing failure probability.

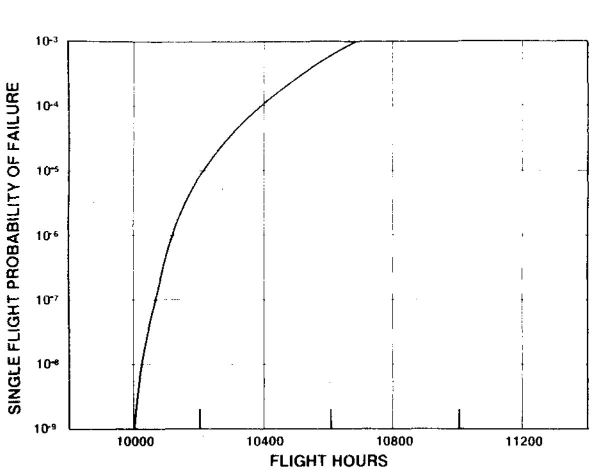

Fig. 11 Single flight probability of failure for original inspection program.

Risk Interpretation

At this time, the USAF is not contemplating incorporating a probability of failure requirement in any structural specification to be used for new designs. The risk assessment methodology, however, can be useful for analyzing aircraft components nearing the end of their useful lives. It provides the manager with decision-making information not available by other means. The single flight probability of failure provides the manager with an instantaneous view of the risk at some point in time of the aircraft's life. This quantity may, however, be difficult to interpret. One basis for interpretation of this quantity is to relate it to the risk we accept in our everyday living. For example, the risk of a major accident that we accept in driving an automobile to work and back home is of the order of 10^{-6}. Another basis that a manager could use for risk interpretation is the precedents that have been set for other aging aircraft. For most military systems, a single flight probability of failure of 10^{-7} or less is considered adequate to ensure safety for long-term operations. For single flight probability of failure greater than 10^{-7}, consideration should be given to limiting the exposure by modification or replacement. If this quantity is 10^{-5} or greater for an extended period of time, the failure rate should be considered unacceptable. The probability of failure after a given number of flight hours or the expected number of aircraft losses are quantities that are generally more meaningful to the decision maker. These quantities are also useful for judging the influence of changes in an inspection program. The nature of the analysis itself relieves the manager from at least part of the interpretation problem. The reason for this lies in the crack growth curve. As the cracks become longer (which increases the risk), the crack growth rate grows larger, accelerating the risk. The consequence of this is that, in the absence of inspections, the single flight probability of failure will change from acceptable to definitely unacceptable in a relatively few flight hours. This feature is depicted in some of the results discussed below.

Discussion of Results

In the mid-seventies, a damage tolerance assessment was performed for the trainer discussed above in Air Training Command usage. This study concluded that the wing center section should be inspected at intervals of 1350 flight hours. This was based on an inspection capability of 2.54 mm (corner crack) and an inspection at one half of the safety limit (the time required to grow a 2.54 mm crack to a 5.5 mm critical size crack). In the late seventies, a usage change took place that made the loading environment more severe. A damage tolerance reassessment was made for this new usage, and it was found that, under the same ground rules, the recurring inspection interval should be changed to 430 hours. It is noted that 430 hours are one half of the calculated 860 hours safety limit. The safety limit is the point in time at which the aircraft would have to be inspected or restricted until the inspection was accomplished.

To provide a preliminary evaluation of the necessity of performing inspections at an increased rate, a risk assessment for new usage but old inspection schedule was performed. The results of this calculation are shown in Fig. 11. It was assumed (arbitrarily) that an inspection had been performed at 9,600 flight hours. The next inspection would have been scheduled for 10,950 hours. It is seen from Fig. 11 that long before the next inspection would be due, the single flight probability of

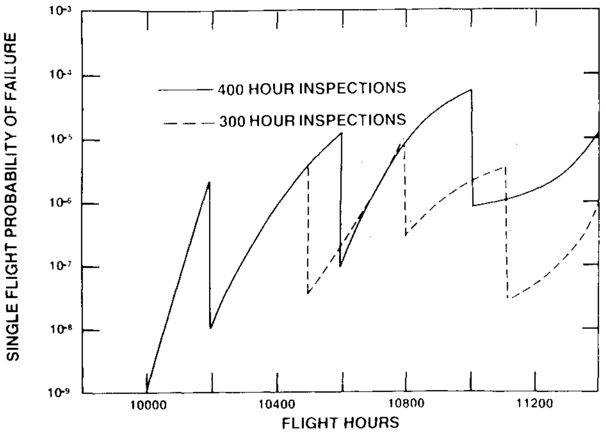

Fig. 12 Impact of inspection on single flight failure probability.

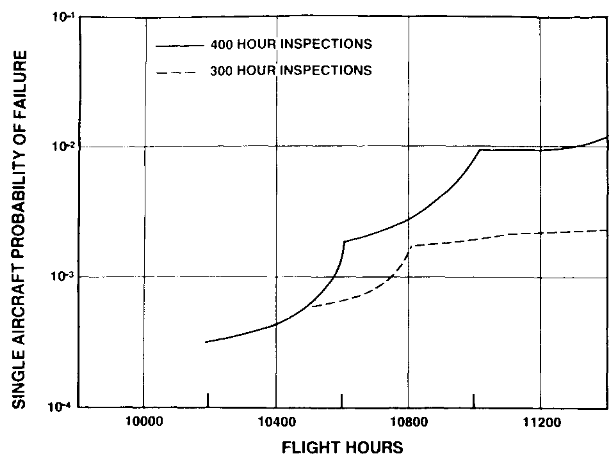

Fig. 13 Impact of inspections on failure probability.

failure has risen significantly. Based on the accumulation of these single flight failure probabilities, the probability of failure for a single aircraft was found to have increased to 0.4 before the next inspection was due. This was obviously too high for safe operations.

Next, the risk was calculated for a recurring inspection interval of 400 hours (slightly less than the damage tolerance assessment derived 430 hours). The associated single flight probability of failure for this case is shown in Fig. 12. The 400 hour interval shows a significant improvement over the 1350 hour interval. The single flight probability of failure may be used to compute the probability of failure of a single aircraft after a given number of flights. This calculation is accomplished by subtracting from one the product of the probability of no failure of the given number of single flights. However, when these single flight probabilities are converted to the probability of failure for a single aircraft (see Fig. 13), it was found that long-term operation would result in a greater than desired chance for loss of an aircraft.

When the inspection interval was reduced to 300 hours from 400 hours, the probability of failure for a single aircraft was reduced by approximately a factor of five. This is shown in Fig. 13. The resultant chance of loss of an aircraft was small enough to be accepted. Further reduction of the inspection interval to 200 hours reduced the single aircraft probability of failure to approximately 5×10^{-4}. This reduced the risk, but the reduction was not judged to be required to protect the safety of these aircraft.

Conclusions

Before a conclusion is made on the adequacy of the inspection criteria used in the damage tolerance assessment of this trainer aircraft, it must be remembered that some of these wings were in the latter stage of their life. They have operated safely for many years with the inspection program derived from the damage tolerance assessment. The risk assessment results show that this successful operational experience should have been expected. The risk assessment also shows that inspections are extremely influential in reducing the probability of failure. This may be seen from a comparison of Figs. 11 and 12. The problem with this trainer is that cracks/defects that are likely to be initially present in the structure have grown and are becoming close to critical length in the high time aircraft. Therefore, the safety of the structure, which earlier relied on small initial defects, now relies on detection of cracks through inspections. It turned out for this trainer that the 0.9 probability of detection, which was used in the damage tolerance assessment for the new usage, provided an inspection interval of 430 hours. This inspection interval if used on high time aircraft may not adequately protect safety. This conclusion is derived from the risk analysis results shown in Fig. 11. For this trainer, if the damage tolerance assessment had used a detectable flaw size corresponding to 0.94 probability of detection, then a safe interval would have been provided. In other words, the probability of detection for the damage tolerance assessment required only a relatively small change. It is not known at this time if the results found in this study can be generalized. Therefore, for aircraft that have cracks derived from fatigue (i.e., aging), the structural engineer should use all methods available to him to define inspections and/or modifications that will ensure that safety of flight is protected. For new aircraft design, the materials and stresses should be selected such that the risk of failure throughout the aircraft's life is low without inspections. This goal is believed to be met through the new version of the U.S. Air Force damage tolerance requirements in MIL-A-87221.

Acknowledgments

The author is indebted to Mr. Clifford Massey from the San Antonio Air Logistics Center (SA-ALC) and his co-workers for their significant contribution to this effort. The author would also like to thank the SA-ALC management for the opportunity to work on this project.

References

[1]Lewis, W. G., Dodd, B. D., Sproat, W. H., and Hamilton, J. M., "Reliability of Nondestructive Inspections—Final Report," SA-ALC/MME 76-6-38-1, Dec. 1978.

[2]Lincoln, J. W., "Method for Computation of Structural Failure Probability for an Aircraft," ASD-TR-80-5035, July 1980.

[3]Gumbel, E. J., "Statistical Theory of Extreme Values and Some Practical Applications," National Bureau of Standards Applied Mathematics Series 33, Feb. 1954.