USING PROBABILISTIC SIMULATIONS IN ORDER TO MINIMIZE FATIGUE FAILURES IN METALLIC STRUCTURES

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ABSTRACT

The advantages of using probabilistic simulations, in order to develop a strategy aimed at minimizing fatigue failures, are demonstrated. The INSIM (INspection SIMulation) computer program has been developed in order to simulate the entire fatigue environment that a structure must withstand. INSIM simulates, in a probabilistic manner, service life variation, service load severity, time to crack-initiation, crack growth history and NDI detection capability. Examples are brought from: single vs. dual load-path structures, determining optimum inspection thresholds, performing trade-offs between stress levels and inspection parameters, evaluating the effects of fleet aging, and determining the relative merits of multiple inspections vs. a terminating action. In each case, the INSIM probabilistic simulations are able to point to optimum solutions, which could not be obtained rationally using conventional fatigue and damage-tolerance methodology.

INTRODUCTION

The fatigue or damage-tolerance analyst needs to develop a strategy in order to minimize the probability of a fatigue failure in service. Among the various options that can be incorporated into this strategy are:

- Designing for a long crack-initiation life
- Designing for a long crack growth life
- Designing for crack detectability
- Adding multiple load-path (fail-safe) features
- Selecting suitable NDI methods and inspection intervals
- Selecting a suitable inspection threshold
- Selecting a reasonable target life

These options can be implemented by selecting suitable alloys, design stress levels, design features, target life and NDI methods; some of which are interrelated. In many cases, a probabilistic analysis, which considers all aspects of the fatigue process, is needed in order to optimize the selection of options.

Previous probabilistic simulations have shown that all aspects of the fatigue process affect the probability of failure [4]. For example, shot-peening a structure will increase its crack-initiation life, but will have only a minor effect on its crack growth life. Nevertheless, shot-peening will effectively reduce the probability of failure [4], and may, therefore, be advantageous. This conclusion would not result from a conventional damage-tolerance analysis, but only from a probabilistic simulation that considered all aspects of the fatigue process.
SIMULATION OF THE FATIGUE PROCESS

The INSIM (INspection SIMulation) computer program, which is described in detail in [1]–[4], has been developed in order to simulate the entire fatigue environment that a structure must withstand. INSIM simulates, in a probabilistic manner, service life variation, service load severity, time to crack-initiation, crack growth history and NDI detection capability.

Cracks initiate at critical locations of aircraft structures. These cracks propagate and, unless detected and repaired, will eventually result in a failure. There are three, mutually exclusive, outcomes of the fatigue process:

(1) The aircraft may reach the end of its operational life and be retired from service. The retired aircraft may or may not have undetected cracks at critical locations.

(2) A crack may be detected during scheduled maintenance operations. The affected part is usually repaired or replaced.

(3) A crack reaches its critical size undetected and the structure fails in service.

Crack initiation, crack growth and crack detection characteristics of a specific structural location are input into INSIM, which performs the simulation of the fatigue process for every aircraft in an large virtual fleet. Cracks initiate at various times and grow at variable rates in each aircraft. Inspections are performed according to a predetermined schedule, using as many as six different NDI methods. Cracks are detected during these inspections according to the statistical expectation of detection. As the simulation proceeds from aircraft to aircraft, cracks are detected, aircraft are retired from service or failures occur. The computer acts as a scorekeeper, amasses the statistics and summarizes the results. In order to provide statistically significant results, a large number of simulations must be performed. In a typical analysis, 3,000,000 inspections are performed for a virtual fleet of 1,000,000 aircraft, taking less than two minutes on a Pentium 4 equipped computer. Based on these simulations, INSIM calculates the probability that failure has occurred.

Figure 1 shows a typical output summary from an INSIM analysis. In this example, a virtual fleet of 1,000,000 aircraft is allowed to operate until retirement, crack detection or failure. The mean life to retirement is planned to be 40,000 flights while the high-time aircraft is expected to reach 60,000 flights. A specific critical location is inspected, using the high-frequency eddy-current method, beginning at 15,000 flights and then at 6000 flight intervals. The selected location has been defined as “problematic” since its mean life to crack-initiation was selected to be only 20,000 flights. As the results shown in Figure 1 indicate, the actual time to crack-initiation ranged from 607 flights to 50,647 flights. The results of the simulation show that about 6.3% will actually retire as planned, 93.6% will have cracks detected in service and 0.03% will actually fail in service.
SINGLE OR MULTIPLE LOAD-PATHS

This is the first of five examples where probabilistic simulations can be used to arrive at a rational strategy for minimizing fatigue failures, and not one based on intuition alone.

Aircraft certified to FAA regulations prior to 1978, had to show *fail-safe capability* by demonstrating the existence of multiple load-paths for all significant structural items. This substantiation methodology is sometimes called “Safety by Design” [6]. Brot [5] dealt with safe-life substantiations for compact structures where the crack-initiation life dominates the total fatigue life. Eastin [6] reviewed the various strategies used to substantiate structures against fatigue damage and concluded that “Fail-Safe” is not an effective method for providing safety. Eastin and Bristow [7] described, in much detail, the 1977 Lusaka B707 accident, which questioned the validity of the fail-safe substantiation approach.

In 1978, the FAA adopted damage-tolerance methodology for Part 25 certifications, which replaced the previous fail-safe philosophy. Although there is no longer any (Part 25) formal requirement to design with multiple load-paths, many aircraft components continue to be designed in this manner.

*INSIM* simulations were used to study the benefits of multiple load-path design, and whether this strategy is advantageous. The aircraft data of the “problematic location” shown in Figure 1 was used as a baseline. The single load-path structure was modeled by the crack growth behavior shown in Figure 2a.
In order to simulate a dual load-path structure, both load-paths are assumed to share the load equally, at the same stress level that was assumed for the single load-path structure. When the first load-path fails, the second load-path carries the entire load. Continuing damage methodology was used to characterize the crack growth, as is shown in Figure 2b. This leads to a very quick failure of the remaining load-path, as is shown in Figure 2b, and as was described in [5], [6] and [7].

The results of **INSIM** simulations are shown in Figure 3, in which the probability of failure is shown as a function of the eddy-current inspection interval. Figure 3 indicates that,
for an inspection interval below 4500 flights, no failures are expected to occur for either configuration. As the inspection interval is increased beyond 4500 flights, the probability of failure, corresponding to the single load-path structure, rises rapidly. The probability of failure, for the dual load-path structure remains much lower, thereby demonstrating the superiority of the dual load-path concept. However, if a specific probability of failure is selected (for example, 0.05%), the benefit of the dual load-path concept can be compensated for by reducing the inspection interval moderately for the single load-path structure (for example, from 6200 flights to 5000 flights). Alternately, by slightly reducing stresses on the single load-path structure, its crack-initiation and crack growth lives will be increased, thereby allowing its inspection interval to be equivalent of that of the dual load-path structure.

The designer must weigh the benefit of a longer inspection interval against the increase in weight, cost and complexity for the dual load-path structure. Probabilistic simulations, such as INSIM can help perform this evaluation in order to arrive at a rational solution.

![Graph showing the comparison of inspection intervals for single and dual load-path structures.]

**Figure 3: Inspection Intervals for Single and Dual Load-Path Structures**

**SELECTING A SUITABLE INSPECTION THRESHOLD**

The pioneers of damage-tolerance philosophy were the USAF, who introduced MIL-A-83444 in 1974. In 1978, the FAA adopted the damage-tolerance philosophy for civil aircraft.

MIL-A-83444 specified that the threshold (initial) inspection should take place at 50% of the time that a 0.05” crack will need to grow to a critical size. On the other hand, FAR 25.571, which defined the damage-tolerance regulations for civil aircraft, did not initially recognize the concept of an inspection threshold. A long inspection threshold obviously appeals to the manufacturer and operator, who can delay maintenance to a later date. It is based on the assumption that there is only a very small probability that cracks will exist early in an aircraft designed to be damage-tolerant. Therefore, the initial inspection can be safely delayed to a later stage of operation.
Various aircraft manufacturers began to use in-house criteria (based on crack-initiation or crack growth characteristics) to specify the inspection threshold. In 1983, Tom Swift of the FAA defined his unofficial guidelines for damage-tolerance methodology [8] which included the adoption of the MIL-A-83444 requirement that the first inspection should take place not later than 50% of the time that a 0.05” crack will need to grow to a critical size. To this criterion, he added an additional criterion that the inspection threshold should not exceed 50% of the aircraft target life. Some, but not all, aircraft manufacturers adopted Swift’s criteria for the inspection threshold. It has been stated [7] that, in some cases, the MIL-A-83444 and Swift criterion may be “inefficient” and overly conservative.

In 1999, another unofficial FAA guideline [9] was published in order to provide criteria for damage-tolerance substantiations. This document included an additional criterion for establishing the inspection threshold: not later than the time it takes for a 0.050” crack to reach a size that will be detected 90% of the time, using the NDI method specified. This criterion is based on the philosophy of starting the inspections at the earliest opportunity that is likely to detect a crack. When the criterion of [9] is used with advanced NDI methods, it can result in a very short inspection threshold.

In 1998, the FAA introduced amendment 96 of the FAR-25 regulations, which dealt with the subject of inspection thresholds for the first time. It differentiated between single and multiple load-path structures. For multiple load-path structures, it allowed the manufacturer to select a suitable inspection threshold using crack-initiation or crack growth criteria. For a single load-path structure, it required the use of a crack growth criterion for defining the inspection threshold.

To summarize, [8] promoted the use of the “50% of crack growth life criterion” for establishing the inspection threshold. It was implied [7] that this criterion might be overly conservative in some cases. The inspection threshold was later specified [9] as the “life to detectable crack criterion” which often results in a very short threshold.

Present damage-tolerance methodology is not suited for selecting an optimum strategy for defining inspection thresholds. A probabilistic analysis is required in order to do so.

Using the data shown in Figures 1 and 2, INSIM simulations were used to study the matter and to evaluate the two proposed methods, [8] and [9], for selecting the inspection threshold. According to the “50% of crack growth life criterion” [8], the inspection threshold should be at about 6000 flights for the single load-path configuration and at about 6500 flights for the dual load-path structure. According to the “life to detectable crack criterion” [9], the inspection should be no later than 4000 flights for either configuration.

A series of INSIM simulations were performed, beginning at a zero inspection threshold and ending at an 18,000 flight threshold. The results, for both configurations, are shown in Figure 4.

Figure 4 shows that, up to a 13,000 flight threshold for the single load-path structure and a 15,000 flight threshold for the dual load-path structure, there is virtually no increase in the probability of failure as the inspection threshold is increased. Only at inspection thresholds beyond these values do the probabilities of failure begin to increase. Figure 4 clearly shows no advantage to begin inspecting at 4000 flights, as defined by the “life to detectable criterion” [9]. Figure 4 also shows that inspecting at 6000 – 6500 flights, per the “50% of...
crack growth life criterion” [8], is overly conservative and may be safely increased, as was suggested in [7]. (It should be noted that INSIM simulations were performed for a wide range of configurations. The results shown in Figure 4 are typical of the results obtained.)

Based on these, and many other results, it is suggested that the inspection threshold (IT) could be defined by the following equation:

\[ IT = FL/4 + CG/2 \]  \hspace{1cm} (1)

where FL is the mean life to crack-initiation and CG is the crack growth life (initial to critical) of the specific detail. Of course, additional “administrative restrictions”, such as not exceeding 60% of the aircraft target life or not exceeding 80% of the crack growth life, could also be imposed. Figure 4 shows the inspection thresholds defined by Equation (1) for both configurations. Clearly, the thresholds defined by this equation are still conservative for this and most other configurations that were evaluated.

Again, it must be emphasized, that without using probabilistic methods, the optimum inspection threshold could not be determined in a rational manner.

**TRADE-OFFS BETWEEN STRESS LEVELS AND INSPECTION PARAMETERS**

One of the important advantages of the damage-tolerance methodology is that it provides a rational manner for determining inspection intervals. The damage-tolerance analysis determines the time that a crack will grow from a detectable size to a critical size. The inspection interval is often selected to be 50% of this time, thereby insuring two opportunities
to detect a crack before failure. This feature of damage-tolerance methodology allows the analyst to trade-off design parameters against inspection parameters, in order to achieve an optimum design from the standpoint of weight and maintenance economy. For example, the fatigue analyst can raise the stress level (and reduce weight) at the cost of more frequent inspections (increased maintenance cost). Likewise, he can reduce the stress level and increase the inspection interval. In every case, the damage-tolerance methodology implies that a constant level of safety will be maintained for each of these trade-offs.

*INSIM* allows us to examine, in a critical manner, these trade-offs and determine if all the solutions offer a constant level of safety. A typical splice joint was selected with the remote stress ranging from 15 ksi to 23 ksi and the bearing stress at the fastener kept at three times the remote stress. This very high level of load-transfer was selected in order to demonstrate a point. At less extreme levels of load-transfer, the variations in results for the trade-off studies would be far smaller.

Figure 5 shows the results of the trade-off study performed by damage-tolerance methodology. The inspection intervals, determined from the damage-tolerance requirements, range from 500 flights to 3700 flights, with the shortest interval associated with the highest stress level. Each of the trade-off study solutions was then examined using the *INSIM* simulation method. In every case, nominal crack-initiation and crack growth lives were calculated using standard methods.

![Graph showing the effect of damage-tolerance trade-offs on the probability of failure.](image)

**Figure 5: Effect of Damage-Tolerance Trade-offs on the Probability of Failure**

Figure 5 shows the results of the simulation with expected probability of failure plotted against remote stress level, for the specific intervals prescribed by the damage-tolerance requirements. If the trade-off study performed by the damage-tolerance methodology were valid, Figure 5 would show a nearly constant value of probability of failure. Instead, the curve begins with a probability of failure of about 0.001% at the lowest stress level; it rises to 0.9% at a stress level of 19 ksi, and again falls to 0.008% at the highest stress level. Clearly, the damage-tolerance methodology overestimates the optimum inspection interval in certain
cases and underestimates the optimum interval in others, as compared to the simulation. Damage-tolerance methodology is aimed to optimize inspections for detectable cracks that grow to critical cracks. Its inspections are not optimized for the usual situation, where cracks initiate and then grow to critical from very small cracks. Thus, the damage-tolerance methodology cannot always be relied upon to yield a constant level of safety when it is used for trade-off studies, and a probabilistic analysis is needed to properly evaluate the trade-offs.

EVALUATING THE EFFECT OF FLEET AGING

A popular notion exists within the fatigue and damage-tolerance community, that aircraft designed to the damage-tolerance regulations are unaffected by increased service life (aging). The basis of this notion is that damage-tolerance designed aircraft can safely operate for at least two inspection intervals between a detectable crack and a critical crack. Therefore, after each inspection, the absence of a detected crack implies that the aircraft can be safely operated until the next inspection with absolute assurance that a fatigue failure will not occur in the interim. As such, the service life can be continuously increased, without modifying inspection methods and intervals.

Due to the statistical nature of the fatigue processes and of crack detection capability, this is not the case. The mechanism of increased probabilities of failure as a result of aging is due to increased rates of crack-initiation, which begin to overwhelm the crack inspection capabilities. This aging mechanism is always at work and it result in an ever increasing probability of failure as the fleet ages. Again, it must be emphasized that present damage-tolerance methodology is not equipped to evaluate the loss of safety as the aircraft ages.

Structural integrity of a fleet of aircraft can be viewed as a constant battle between advancing fatigue and corrosion damage and the activities performed to contain the damage. The situation can be regarded analogous to an actual battle, whose defense plan is described in Figure 6. There are three lines of defense, as is shown in Figure 6. The outer perimeter defense represents crack-initiation control that includes controlling stress levels, load-transfer, design features and surface treatments of critical locations. These measures tend to delay crack-initiation and not to eliminate it. The second line of defense, as is shown in Figure 6, represents crack-growth control. This includes controlling stress levels, material properties and design features in order to reduce the crack-growth rate. The final defense shown in Figure 6 represents crack detection capability. This includes specifying NDI methods and intervals that will detect advancing fatigue damage before structural integrity is compromised.

Figure 6 also indicates that we are assisted by a “secret weapon” in our battle for structural integrity – aircraft retirement. Aircraft are generally retired when they become obsolete or are no longer economically viable. All aircraft retire with fatigue damage at critical locations. Some aircraft retire with cracks that have already initiated but have not yet been detected. As aircraft retire, their fatigue damage retires along with them. This statement is extremely significant because it means that any damage that has been retired can no longer result in fatigue failures.
Figure 6: The Battle for Structural Integrity

Figure 7: Damage-Tolerance Methodology under a Fleet Aging Scenario

Figure 7 shows, in the same analogous manner, how the ability of damage-tolerance methodology will be affected by the aging fleet. Structures designer under the damage-tolerance philosophy often do not emphasize crack-initiation control; therefore the “crack-initiation control gate” is shown to be open in Figure 7. With the virtual absence of aircraft retirement, nearly all the damage detection will have to be performed by the NDI facilities. Since no inspection method is capable of detecting every crack, it is likely that the rate of
failures will increase and fleet structural integrity will be compromised. Clearly, additional defense capability must be provided for those instances where the present damage-tolerance methodology is unable to prevent a breach of all three lines of defense.

In order to study the effect of fleet aging on the probability of failure, INSIM simulations were used. A typical splice configuration was used for this study. A remote stress of 20 ksi was assumed, together with a bearing stress of 40 ksi. The FAR-25 damage-tolerance regulations were used to determine that the structure should be inspected, using a liquid-penetrant method, at 1500 flight intervals. In all cases, it was assumed that the fleet service life to retirement follows a normal distribution with extreme values (±3σ) taken as 150% and 50% of the mean life of the fleet. The nominal crack-initiation life was calculated using a strain-life method.

Figure 8 describes the results of the study and shows the expected probability of failure as a function of the mean fleet life. It clearly demonstrates that, as the fleet ages, the probability of failure increases, even though the inspection interval was selected on the basis of damage-tolerance criteria.

Figure 8 describes how to define an “aging program” to control the rising probability of failure accompanied by fleet aging. By reducing the inspection interval as each aircraft reaches a predetermined life, the increasing probability of failures can be minimized. In the above study, the interval was reduced from 1500 flights to 800 flights as each aircraft reached 20,000 flights. As is shown in Figure 8, this simple modification significantly reduced the probability of failure of the aging fleet.

![Figure 8: Effect of Fleet Aging on the Probability of Failure](image-url)
This study demonstrates one of the limitations of the damage-tolerance regulations. Nowhere in the regulations is there a hint that inspection intervals and methods need be modified as the fleet ages. In fact, the regulations imply the opposite – that no changes are needed. Only a probabilistic analysis, such as that performed by INSIM, will disclose the aging effect, and help define the required “aging program”.

PERIODIC INSPECTIONS OR A TERMINATING ACTION

When an aircraft structure is shown to have an insufficient fatigue life, two approaches can be followed:

1. Frequent periodic inspections, as dictated by the damage-tolerance regulations, can be employed, with the part repaired or replaced only after a crack is detected.

2. A redesigned part, which only requires minimal inspections, can be substituted. This is referred to as a “terminating action”.

Manufacturers and operators often prefer the first approach since the cost of designing, manufacturing and purchasing the improved part is eliminated.

The relative merits of both approaches can be evaluated using INSIM. In this example, a part having a required service life of 15,000 hours was found to have a mean life to crack-initiation of only 6000 hours and a mean crack growth life of 2200 hours. Damage-tolerance considerations dictated a liquid-penetrant inspection every 250 hours, with the part repaired or replaced whenever a crack is detected, as is shown in Table 1.

The alternate approach was to redesign the part, and thereby terminate the need for the frequent inspections. The redesigned part was found to have a mean life to crack-initiation of 30,000 hours and a mean crack growth life of 15,000 hours. A damage-tolerance analysis resulted in a liquid-penetrant inspection interval of 4000 hours, with an inspection threshold at 7500 hours, as is shown in Table 1.

A simple comparison of the results indicates that, with the periodic inspection approach, sixty inspections will be required during the 15,000 hour service life. With the terminating action approach, only two inspections will be needed during the same service life. The question arises whether two inspections for the redesigned part can yield the same level of safety that was required by sixty inspections for the original part.

INSIM simulations were used to evaluate both approaches. The first approach resulted in a mean time to crack detection of about 6500 hours, resulting in the repair or replacement of the part, and a probability of failure of 0.002%, as is shown in Table 1. For the terminating action, virtually all the parts can be expected to survive the 15,000 hour service life and have a probability of failure of essentially zero.

This example illustrates how probabilistic analyses can be used by the manufacturer, operator or certifying authority to evaluate the relative benefits of periodic inspections vs. a terminating action.
Table 1: Periodic Inspections vs. a Terminating Action

<table>
<thead>
<tr>
<th></th>
<th>Periodic Inspections</th>
<th>Terminating Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Repair or replacement when a crack is detected</td>
<td>Redesigned Part</td>
</tr>
<tr>
<td>Required Service Life</td>
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<td>15,000 hours</td>
</tr>
<tr>
<td>Mean Crack Initiation Life</td>
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<td>30,000 hours</td>
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<tr>
<td>Crack Growth Life</td>
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<td>Inspection Interval</td>
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<tr>
<td>Mean Time to Part Repair or Replacement</td>
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<td>None required</td>
</tr>
<tr>
<td>Probability of Failure</td>
<td>0.002%</td>
<td>0%</td>
</tr>
</tbody>
</table>

SUMMARY AND CONCLUSIONS

The advantages of using probabilistic simulations, in order to develop a strategy aimed at minimizing fatigue failures, have been demonstrated. Examples were brought from: single vs. dual load-path structures, determining optimum inspection thresholds, performing trade-offs between stress levels and inspection parameters, evaluating the effects of fleet aging, and determining the relative merits of multiple inspections vs. a terminating action. In each case, the INSIM probabilistic simulations were able to point to optimum solutions, which could not be obtained rationally using conventional fatigue and damage-tolerance methodology.

REFERENCES


