ASSESSING THE RELIABILITY OF FAIL-SAFE STRUCTURES

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Abstract: A computer simulation method is described, that can be used to assess the reliability of a dual-path fail-safe design. The method allows for a rational selection of inspection thresholds and intervals. A parametric study was performed describing the effect of various parameters on the probability of failure. Specific recommendations are given for the design of reliable fail-safe structures.

INTRODUCTION

Fail-safe structures have been used for many years in aviation in order to enhance the reliability of aircraft structures. Even after the introduction of the damage-tolerance regulations in the 70s, which no longer required fail-safe design features, many primary aircraft structures continued to be designed for fail-safety. Recently, there have been proposals made to reinstate fail-safe requirements in the FAR-25 and JAR-25 Regulations.

Fail-safe structural concepts for aircraft appear to be very attractive. Failure of any single member will not result in the total failure of the aircraft. However, upon a closer examination, the weakness of the fail-safe concept emerges. Fail-safety can only be reliable if the operator is aware that a structural member has failed. Under the present state-of-the-art, this is accomplished by performing periodic inspections in order to detect the failure of a structural member. These inspections result in aircraft downtime, which interferes with the smooth operation of the fleet. These structural inspections need to be very frequent, since the remaining members can fail shortly after the failure of the primary member.

At present, there seem to be a lack of rational methods available to assess the reliability of fail-safe designs as a function of the selected inspection interval. Matthews and Neal [1] have addressed the subject, but their work does not consider inspections and it is addressed to a very specific configuration.

SIMULATION OF A FATIGUE FAILURE

A computer simulation program, Fail-Safe, has been developed in order to simulate a dual-path fail-safe design. The members are assumed to be discrete elements (such as lugs, pins or hinges) where the crack growth lives are likely to be short compared to the crack initiation lives. The lives to failure are represented by a two-parameter Weibull distribution while the service life to retirement is represented by a normal distribution.

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It is assumed that each inspection serves to determine only that both load-paths are still intact. It is further assumed that, since the inspections are intended only to disclose the failure of an entire load-path, they are 100% reliable. The Fail-Safe operator selects the values of inspection threshold and interval to be used in the simulation. The computer program performs a large number of simulations and determines for each simulation:

1. Has the aircraft retired from service with both members intact?
2. Has one member failed but the failure was detected prior to total failure?
3. Has a total (catastrophic) failure occurred?

From the statistical results of a large number of simulations, the computer program determines the probability of total failure. The program operator can then modify the inspection threshold and inspection interval until the required reliability is achieved.

As previously stated, the lives to failure are represented by a two-parameter Weibull distribution, which is often used to describe the structural reliability for fatigue failures [2]–[8]. The cumulative probability distribution of fatigue failures is given by:

\[
F(Y/\beta) = 1 - e^{-\left(\frac{Y}{\beta}\right)^\alpha}
\]

Where \( Y \) represents the fatigue life of a specific structure; \( \alpha \) is the Weibull shape (scatter) factor; and \( \beta \) represents the Weibull Characteristic life. (\( \alpha \) and \( \beta \) are the two parameters used in this Weibull distribution.) \( F(Y/\beta) \) represents the probability of failure before reaching the normalized life ratio \( Y/\beta \).

\( \alpha \), which controls the scatter, is usually assumed to be a function of the material from which the structure is manufactured. (Lower values of \( \alpha \) result in increased scatter.) Industry usage specifies that aluminum structures are generally assigned an \( \alpha \) of 4, titanium or moderate-strength steel (UTS < 240 ksi) are taken to have an \( \alpha \) of 3, while high-strength steel (UTS > 240 ksi) is assumed to have an \( \alpha \) of 2.2 [6] and [7].

\( \beta \), which is a measure of the characteristic life of the structure is generally taken to be the average fatigue life, as determined by testing or analysis. (To be precise, if \( Y/\beta = 1 \) is input into Equation (1), the resulting probability of failure will be 63.2%, and not 50%, regardless of the value of \( \alpha \).)

Equation (1) is plotted in Figure 1 for three values of \( \alpha \). For any value of normalized life, \( Y/\beta \), less than 1, lower values of \( \alpha \) correspond to higher probabilities of failure, as would be expected. At \( Y/\beta = 1 \), all the curves converge to the probability of failure of 63.2%.

As was stated previously, the service life to retirement is represented by a normal distribution. This means that the fleet is assigned a mean life to retirement as well as a standard deviation, based on accumulated service data. During the simulation process, each simulation is assigned a retirement life based on the above statistical data. Any structure that reaches retirement before suffering a total failure is assumed not to have failed.
The simulation process proceeds as follows:

- The operator inputs the *design life, mean life to retirement* and *standard deviation of the mean life*.

- The mean fatigue lives of the primary and secondary paths are determined by analysis or testing. They are input as follows:

  \( FL_{11} \): Mean fatigue life of the primary load-path with the entire structure intact  
  \( FL_{12} \): Mean fatigue life of the primary load-path with the secondary path failed  
  \( FL_{21} \): Mean fatigue life of the secondary load-path with the entire structure intact  
  \( FL_{22} \): Mean fatigue life of the secondary load-path with the primary path failed

(The primary load-path is defined as the path having the lower fatigue life. Due to the statistical nature of fatigue failures, it is possible that the secondary path will fail before the primary path. *Fail-Safe* accounts for this possibility.)

- The Weibull shape-factors, \( \alpha_1 \) and \( \alpha_2 \) for the two load-paths are then input. Finally, the *inspection threshold* (initial inspection) and *inspection interval* are input. The number of *simulations to be performed* is then selected.

For each simulation, the program *randomly* calculates the life to retirement, the life to failure of the primary load-path and the life to failure of the secondary load-path. (The program uses Miner’s rule of cumulative damage to calculate the life of the secondary path, which performs partially with the entire structure intact and partially with the primary load-path failed.) *Fail-Safe* then compares the total-failure life with the life to retirement and the inspection schedule. The program determines if a double failure would have occurred before the threshold inspection or between inspections. The program repeats the process according to the number of repetitions that were selected (usually more than 80,000), and displays the failure statistics in real-time.

Figure 2 is a description of a typical output screen of *Fail-Safe*, showing the input values and the statistical results of the simulation.

**PARAMETRIC STUDIES**

A series of parametric studies were performed using *Fail-Safe*, accounting for such variables as: inspection threshold, inspection interval, aircraft aging, the effect of materials used, mean fatigue life and the ratio of secondary to primary load-path fatigue life. Each parametric study resulted in a series of calculations for the probability of total failure.

**Effect of Inspection Threshold and Interval**

A typical aluminum fail-safe structure was simulated, having a design life of 20,000 flights. The primary path was assumed to have a mean fatigue life of 60,000 flights while the secondary path had a mean fatigue life of 120,000 flights. (The corresponding values of mean fatigue life, with the opposite path failed, were taken as 2,600 flights and 4,500 flights for the primary and secondary paths respectively.) A mean life to retirement of
18,000 flights with a standard deviation of 2,000 flights were selected. These parameters were defined as the baseline configuration for the entire parametric study.

Various inspection intervals, with and without an inspection threshold were simulated and the results are shown in Figure 3. The figure indicates that increasing the inspection interval increases the probability of failure. Figure 3 also indicates that an inspection threshold of 8,000 flights (40% of the design life) has only a minor effect on the probability of failure. It should be noted that for these runs, approximately 99% of the simulations result in the structure retiring totally intact. This is consistent with [9] in which it is stated: “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.”

Effect of Aircraft Aging

Aircraft are often used beyond their design goals. In Figure 4, the 18,000 flight mean retirement life used in the baseline example was extended up to 36,000 flights. When the inspection interval was kept at 2,000 flights, the probability of failure increased from 0.031% to 1.03%. Table 1 contains a summary of the aging aircraft simulations. For each of the three aging aircraft simulations that were performed, Table 1 summarizes the probability of retiring with both paths totally intact, the probability of failure of one path and the probability of failure of both paths, which is defined as a total failure.

When the mean retirement life was 18,000 flights, approximately 99% of the fleet reached retirement with both paths intact. This meant that the periodic inspections had only to deal with the 1% of aircraft that suffered a single fatigue failure. The results of Table 1 show that the inspections were able to detect nearly all the single failures in time. When the mean retirement life was extended to 36,000 flights, only about 86% of the fleet retired totally intact, as is shown in Table 1. This means that the inspection program had to deal with nearly 14 times as many single failures as for the first case. The periodic inspections were not able to detect all the single failure in time, resulting in the failure of more than 1% of the fleet. The loss of the aircraft retirement effect is the main reason why the probability of failure increased significantly as the fleet aged. Only by drastically reducing the inspection intervals, the probability of failure could be maintained at a constant value, as is shown in Figure 4. As the mean retirement life was increased from 18,000 flights to 36,000 flights, the inspection interval had to be reduced from 2,000 flights to 150 flights in order to maintain a constant probability of failure.

Effect of Material Selection

It was previously explained that the degree of fatigue life scatter is governed by the shape-factor, $\alpha$, used in the two-parameter Weibull distribution. It is generally accepted that steel and titanium exhibit greater fatigue life scatter than aluminum. This is reflected by the typical value of $\alpha$ that was used for each material. Simulations were performed to test the sensitivity of the selected material on the probability of failure. The simulations were performed for aluminum structures ($\alpha = 4$), moderate-strength steel having an
ultimate tensile strength (UTS) of less than 240 ksi or titanium ($\alpha = 3$), and high-strength steel having an UTS greater than 240 ksi ($\alpha = 2.2$).

The results, which are shown in Figure 5, show that for a constant inspection interval of 2,000 flights, the increased scatter corresponding to the lower values of $\alpha$, results in a much increased probability of failure. The 0.031% probability of failure, for the baseline aluminum structure, increased to 2.29% for the high-strength steel. In order to restore the probability of failure to about 0.03%, the inspection intervals must be reduced significantly, as is shown in Figure 5. For the moderate-strength steel or titanium the interval must be reduced from 2,000 flights to 500 flights while for the high-strength steel, the interval must be reduced to 100 flights. This demonstrates the need for selecting materials having inherently low scatter for a fail-safe design.

**Effect of Material Mix**

Sometimes, a hybrid fail-safe design is used where the two load-paths are manufactured from two different materials. A study was performed having one path manufactured from aluminum while the other path is manufactured from titanium. There remain two possibilities: the primary (shorter life) path can be made from aluminum or from titanium. Both these possibilities were studied and are presented in Figure 6.

The same parameters were used in this study as in the baseline study, except for the shape-factor, $\alpha$. The results shown in Figure 6 indicate that it is better to introduce the titanium in the primary path and aluminum in the secondary path. This is likely to be impracticable, since the titanium path usually will have a longer fatigue life than the aluminum path, thereby becoming the secondary path.

Figure 6 also shows that the hybrid design is inferior to the all-aluminum baseline. (See Figure 5.) For the identical parameters, the all-aluminum design will have a probability of failure of 0.031%, while the aluminum-titanium material mix will result in a probability of failure between 0.12% and 0.17%. In order to reduce the probabilities of failure to values equivalent to the all-aluminum design, the inspection threshold and interval must be significantly reduced, as is shown in Figure 6.

**Effect of Mean Fatigue Life**

One way of reducing the probability of failure is to increase the mean fatigue lives of both of the paths. The ratio of the primary path fatigue life to the design life was varied, and the results are shown in Figure 7. (In all cases, the secondary path was designed to have twice the fatigue life of the primary path.) Figure 7 shows that increasing the ratio between the fatigue life and the design life has a significant effect on the probability of failure. Figure 7 also indicates that the ratio of the primary path fatigue life to the design life should be three (or larger) for a successful fail-safe design.

**Effect of Secondary Path to Primary Path Fatigue Life Ratio**

Fail-safe structures are often designed with two identical load-paths. This can be shown to be ineffective from the standpoint of fail-safety. When the primary path fails, and the entire load is transferred to the secondary path, the fatigue life of the secondary path will be reduced by a factor of 20 – 30, as is dictated by the S-N curve of the material. In order to achieve a reasonable fatigue life after failure of the primary path, the secondary path must be made much stronger than the primary path. As the secondary path is made
stronger, and its mean fatigue life increases, the probability of total failure will decrease. A parametric study was performed to determine the optimum range of the secondary path to primary path fatigue life ratio. The results of this study are shown in Figure 8. Using the baseline inspection threshold and interval, the results shown in Figure 8 clearly show that an increase in this ratio reduces the probability of failure. It also indicates that the ratio of the secondary path to primary path fatigue life should be at least two.

Figure 8 also shows that, by modifying the inspection threshold and interval, the probability of failure can be brought to the baseline value of about 0.03%.

**FAIL-SAFE DESIGN RECOMMENDATIONS**

Based on these studies, recommendations can be given concerning inspection thresholds and intervals, preferred materials and optimized ratios of fatigue lives. These recommendations will allow the design of a dual-path fail-safe system having rationally determined inspection thresholds and intervals. Of course, it is preferable to perform the analysis for the specific parameters using a simulation program. But, in the absence of such a program, the following recommendations should suffice.

Table 2 summarizes the design recommendations arising from the parametric study presented above and from additional studies that were performed using the *fail-safe* program. Table 2 recommends the design values to be used for the mean fatigue lives of the two paths as well as the inspection threshold and intervals to be used to insure a reliable fail-safe design. Table 2 gives recommended values for an aluminum design, for a titanium or moderate-strength steel design and for a hybrid aluminum-titanium design. It should be noted that all the parameters are normalized to the design life, except for the inspection interval whose optimum value was found to be virtually independent of the design life.

The above recommendations are intended for applications where the fleet usage does not exceed the design life. For an aging fleet, the inspection intervals must be further reduced, as was demonstrated in Figure 4.

It should be noted from Table 1 and from Figure 5, that there seems to be little advantage in using titanium or steel that reportedly have higher fatigue life scatter than the aluminum.

**SUMMARY**

The *fail-safe* computer program, used to simulate a dual-path fail-safe design, was described. The method allows for a rational selection of inspection thresholds and intervals for the fail-safe design. A parametric study was performed describing the effect of various parameters on the probability of failure. Specific recommendations were given which can be used to design reliable fail-safe structures.
REFERENCES


Table 1: Results of the Aging Aircraft Simulations

<table>
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<tr>
<th>Mean Retirement Life (Flights)</th>
<th>Probability of Retiring Totally Intact</th>
<th>Probability of a Single Failure *</th>
<th>Probability of a Total Failure</th>
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<tbody>
<tr>
<td>18000</td>
<td>99.0%</td>
<td>0.9%</td>
<td>0.031%</td>
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<tr>
<td>27000</td>
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<td>4.2%</td>
<td>0.27%</td>
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<td>36000</td>
<td>86.5%</td>
<td>12.4%</td>
<td>1.03%</td>
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</tbody>
</table>

* - Discovered by inspection or at aircraft retirement
Table 2: Fail-Safe Design Recommendations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Aluminum</th>
<th>Steel (UTS &lt; 240 ksi) or Titanium</th>
<th>Hybrid Materials (Aluminum-Titanium)</th>
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</thead>
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<td>Mean Fatigue Life of Primary Load Path:</td>
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<td>4 x DL</td>
<td>3 x DL (Aluminum)</td>
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<tr>
<td>Mean Fatigue Life of Secondary Load Path:</td>
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<td>8 x DL</td>
<td>8 x DL (Titanium)</td>
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<td>Inspection Threshold:</td>
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<td>0.20 x DL</td>
<td>0.40 x DL</td>
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<tr>
<td>Inspection Interval:</td>
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<td>1000 Flights</td>
<td>1000 Flights</td>
</tr>
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</table>

DL = Design Life

Figure 1: Cumulative Probability Distribution of Fatigue Failures as Described by the Two-Parameter Weibull Distribution
Figure 2: Description of a Typical Output Screen of Fail-Safe, Showing Input Values and the Statistical Results of the Simulation.

Figure 3: Effect of Inspection Threshold and Intervals on the Probability of Failure
Figure 4: Effect of Aircraft Aging on the Probability of Failure

Figure 5: Effect of Material Selection on the Probability of Failure
Presented at the ICAF 2001 Conference, Toulouse

Figure 6: Effect of Material Mix on the Probability of Failure

Figure 7: Effect of Mean Fatigue Life on the Probability of Failure
Figure 8: Effect of Secondary Path to Primary Path Fatigue Life on the Probability of Failure