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Can pitting corrosion change the location of fatigue failures in aircraft?

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ABSTRACT

In this paper we hypothesize that pitting corrosion can alter the location of fatigue failures in aircraft. This is in addition to the reductions in fatigue life it causes. The investigation began by developing a predictive Monte Carlo model of the fatigue behavior of low-k_t specimens of the aluminum alloy 7010-T7651. The model's fatigue life predictions were an excellent match to experimental fatigue life data from previous DSTO research for the same specimen geometry and material. The model was then used to predict the proportion of failures due to pitting corrosion as a function of the location of the corrosion strike. These predictions were compared to the results of an experimental trial of specimens which had been corroded at the same offset locations. The predicted and experimental proportions of failures were in close agreement. The paper concludes with a discussion of an integrated model of corrosion pit nucleation and growth followed by fatigue crack growth to failure. The purpose of this integrated model is to give the Royal Australian Air Force an end-to-end model to predict the damaging effects of pitting corrosion on aircraft structural integrity.

1. Introduction

The last few decades have seen a steady increase in the average age of aircraft fleets worldwide. This has arisen because of the enormous cost of replacing these fleets. Therefore, rather than being replaced at their originally scheduled retirement date, aircraft are being retained far beyond this date. Examples include the F-111, which was in service with the RAAF from 1973 until 2010 [1], and the B-52, which has been in-service with the USAF since 1955 [2].

Retaining aircraft in this way has not been without consequence. While it has delayed the cost of new acquisitions, the cost of aircraft maintenance increases steadily through life [3]. This is largely due to environmental effects such as corrosion which were not considered or even known of during the design phase.

It should be noted, however, that fatigue damage due to mechanical loading also accumulates during the life of aircraft. In contrast to corrosion, however, several methods of accounting for the effects of fatigue damage have been approved by airworthiness regulators, such as the FAA, and are in common use.

2. Background

A great deal of research has shown that corrosion reduces the fatigue endurance of materials and aircraft [4–20]. However, there is minimal literature on how corrosion affects the location of fatigue failures in aircraft. Barter et al. describe the in-flight failure of the right hand trailing edge flap (TEF) lug of a RAAF F/A-18 [4]. This component had an expected fatigue life exceeding that of the aircraft. Corrosion pits in the lug caused it to fail by fatigue which caused the flap to separate from the aircraft. This severely damaged the aircraft's vertical stabilizers, dorsal deck and left-hand horizontal stabilizer. Further investigation found two other cracked lugs in the RAAF fleet. Similar failures occurred in US Navy and Canadian Forces aircraft. Barter et al. found that the AA7050-T7451 material of the lugs was prone to pitting which the then current non-destructive inspection technique could not detect.

Mills and Honeycutt [21] examined the fatigue failure of a fuselage frame from a C-141. The critical fatigue crack in this fuselage frame initiated from a corrosion pit located in a region of the frame with a supposedly infinite life. The component's unexpected failure was of great concern for the USAF which was faced with the prospect of a fleet-wide replacement program. Durability analysis predicted an infinite life. This was demonstrably untrue given the in-service failures of the components at around 35–43 thousand flying hours. In contrast, a defect tolerant analysis would have led to expensive and unnecessary inspections. However, adding an equivalent crack to represent the pitting damage to the analysis led to fatigue life predictions similar to the observed in-service life of the component. This provided a means of predicting and managing the failure of the fuselage frames without an excessive inspection and maintenance regime.

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Fjeldstad et al. [22] modeled how changes in stress gradient affected the location of fatigue failures in a double-edge notched fatigue specimen of a high strength steel. They used a Monte Carlo model developed by Wormsen et al. [23,24] which can model components of arbitrary shape. It does this by post-processing a finite element (FE) model of the component of interest. The model then adds initiation sites to the model. The size, orientation and location of these sites were modeled using statistical distributions. Each initiation site was treated as an equivalent crack oriented normal to the maximum principal stress at its location. The initiation sites were assumed to not interact. The growth of cracks from these sites was then simulated.

The assumption of independent growth of adjacent defects made here and by others [22,25] is commonly made. Many studies suggest that this is a reasonable assumption as long as the defects are more than a diameter apart (e.g. [26–29]).

The same conclusion has been reached for both voids (i.e. pits and pores) and cracks. Where significant interaction has been reported the defects have been less than a diameter apart (e.g. [30]).

3. Modeling

This section describes the development of the Corrosion Criticality Model (hereafter the 'model'). The model used the Monte Carlo method without variance reduction techniques. These methods were avoided as they require *a priori* assumptions of the model's behavior and results. The model was implemented using the software package Igor Pro (Version 6.2.2.2) [31]. Its inputs are:

1. Specimen geometry,
2. Corrosion strike geometry and corrosion pit location,
3. Equivalent crack geometry,
4. Fatigue crack growth data,
5. Fatigue crack closure,
6. Fatigue life lookup table,
7. Far-field loading conditions, and
8. Inclusion and pit size distributions.

Each of these inputs and the model's algorithm are described in detail below.

3.1. Algorithm

This section describes the model's algorithm and rationale. The model is a weakest link model. Therefore it predicts the life of the model element that fails first. In this context, a model element is a surface inclusion or corrosion pit and its associated fatigue crack. The model also estimates the probability of failure due to a pit at a given position on the specimen. Fig. 1 is a flowchart of the model's algorithm.

3.1.1. Steps 1–5: array and variable initialization

Starting the model invokes two procedures in series. The first updates the pit and inclusion size distributions to ensure that these distributions are current. The second procedure is the model's main loop. The model ends when its main loop (Fig. 1, Steps 6–17) is complete and the results have been output (Step 18).

Steps 2–5 of the algorithm prepare the storage arrays and variables needed by the model. Initially the elements in these arrays are set equal to NaN (Not a Number). They are not given values until the model's main loop where they are used to record the characteristics of the critical defect for each iteration of the model. Next the program determines how many inclusions and pits are to be modeled in each iteration of the model. The use of extreme value statistics means that it is only necessary to model the largest pit or inclusion in a given element. This greatly reduces the computational demands of the model.

3.1.2. Steps 6–18: main loop and model termination

These steps are the model's main loop. Each iteration of this loop simulates a single fatigue test. The loop ends when the number of iterations set by the user is reached. In Step 7 a random set of inclusions are created based on the defect size distributions for each defect type. In Steps 8 and 9 the location of the center of the corrosion strike is determined. If the corrosion strike is randomly located the center of the corrosion strike is calculated for each iteration. Otherwise, the center of the corrosion strike is set to the user selected value. The pits in this corrosion strike are generated in Step 11 assuming that the user has asked for corrosion pits to be modeled (Step 10). Otherwise, no corrosion pits are created. This allowed the model to predict the fatigue behavior of uncorroded specimens.

The pit and inclusion with the shortest fatigue lives for their defect type are identified in Steps 12 and 13 respectively. These fatigue life minima are then compared in Step 14 to determine if the specimen failed due to a pit or an inclusion. If failure was due to an inclusion then the characteristics of the critical inclusion are recorded in the results array in Step 15. Conversely, if failure was due to a corrosion pit then the characteristics of the critical pit are recorded in Step 16.

The last step in the main loop is Step 17. If the set number of iterations has been completed then the main loop terminates and execution moves onto Step 18. Otherwise, the program returns to Step 6 to repeat the program's main loop. In Step 18, the model's final results are calculated and output.

3.2. Specimen geometry

The specimen geometry used in the model (Fig. 2) is the same as that used by Crawford et al. [9,10]. It is a 420 mm long low-k_t fatigue specimen whose rectangular cross section has slightly ($r = 1.5$ mm) rounded corners. This specimen geometry conforms to the dimensional requirements of ASTM 466-07 [32]. The longitudinal axis of the specimen is parallel to the rolling direction of the source material while the corroded surface of the specimen is the material's rolling plane.

Urbani developed a FE model of this specimen [33]. From his model it was found that the normalized direct stress ($\sigma_{norm,i}$) parallel to its longitudinal centerline could be approximated by the following equation:

$$\begin{aligned}\sigma_{norm,i} = {} & 1 + 9.13784 \times 10^{-4}|d_i| - 2.68246 \times 10^{-4}|d_i|^2 \\ & + 2.96371 \times 10^{-6}|d_i|^3 - 9.58524 \times 10^{-9}|d_i|^4 \end{aligned} \tag{1}$$

where $\sigma_{norm,i}$ is the normalized direct stress (σ_i/σ_{max}), σ_i is the direct stress at absolute distance $|d_i|$, σ_{max} is the maximum stress at the thinnest part of the specimen's gauge section ($d_i = 0$), and $|d_i|$ is the absolute distance from the specimen's midpoint (in millimeters) for the i-th iteration of the model. Note that $|d_i|$ must be less than 97 mm.

Eq. (1) is plotted versus $|d_i|$ in Fig. 3. As shown by the inset figure Eq. (1) has a maximum at $|d_i| \approx 1.75$ mm rather than at zero as intended. The error at this point was only 0.079%, which was considered too small to warrant correction. Unfortunately, this error was only discovered at the end of modeling.

3.3. Corrosion strike geometry and corrosion pit locations

Corrosion was assumed to occur at discrete locations, called 'corrosion strikes' rather than generally. This is based on RAAF experience where corrosion on aircraft is associated with localized