# Aircraft Structural Integrity: The Impact of Corrosion

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## ABSTRACT
This paper discusses the development of methods, which will allow aircraft structural integrity to be maintained under conditions where an airframe is deteriorating through corrosion. The program discussed is exploring methods of assessing corrosion damage in terms which are compatible with existing life management approaches. In practical terms this involves relating the corrosion damage to an equivalent cracked condition, to determine the point at which corrosion would reduce the remaining fatigue life of the aircraft to an unacceptable level. While a number of types of corrosion are being examined this paper discusses only pitting and exfoliation corrosion.

## KEYWORDS
Corrosion, structural integrity, aircraft, pitting, exfoliation

## INTRODUCTION
In 1997, DSTO established a research program examining the effects of corrosion on aircraft structural integrity based on RAAF fleet observations detailed in [1] and worldwide research detailed in [2]. This research aims to provide a basis for introducing corrosion into the approaches used to manage aircraft structural integrity in the Australian Defence Force (ADF). This will allow the ADF to minimise both the cost and risk of owning and operating aircraft in which corrosion might become a threat to safety or fleet viability.

## PITTING CORROSION RESEARCH
Both the F/A-18 and F-111 in RAAF service have had problems with pitting in structural components initiating fatigue failure [3,4]. However, in a number of cases pitting has also been observed that has not initiated fatigue cracks. The present airworthiness requirements call for the immediate removal of the pitting corrosion, in some cases tripling maintenance times or requiring component replacement. At the same time research at DSTO has shown that the use of certain corrosion protection compounds (CPC's), can greatly retard pitting corrosion [5].

The significant question in terms of improved fleet management is "can pitting corrosion be treated and left in place to a more suitable maintenance opportunity". To answer this question by equating a pit to a crack whose size gives it the same fatigue life, a number of matters need to be addressed; 1) what are the shape and dimension "metrics" of the corrosion pits, 2) what is the spatial distribution of the pits, 3) which critical pit "metric" can be correlated to fatigue life, and 4) how can this information be used in aircraft lifing models. Questions 1 and 2 can be determined from fractography and measurement of large numbers of pits. Questions 3 and 4 are more difficult. DSTO has adopted [6] an approach identified in early research conducted by the USAF on machining marks and their effect on fatigue initiation, which identified the possible use of an Equivalent Initial Flaw Size (EIFS) parameter. The EIFS approach, described in DSTO as

Equivalent Precrack Size (EPS), relies on identifying the crack size which gives the same fatigue life as the corroded specimen. It is important to note two things; 1) that the fatigue life of the cracked configuration is generally determined using a fatigue life prediction model and 2) that the EPS is not real and may bear no relationship to any physical dimension.

The F/A-18 has a number of structural components manufactured from thick (>100mm) rolled 7050-T7451 plate. This plate has a tendency to form very deep corrosion pits due to its microstructure [7]. To examine what effect this sort of pitting would have on a component's structural integrity an extensive test program was initiated. The specimens were flat dogbones, 30mm wide and 10mm thick with a 6mm-diameter hole in the middle to provide a stress concentration [7]. The specimens were all tested in a chamber to keep relative humidity below 20%. The corroded specimens had been subjected to 3.5%NaCl for 24hours [7]. The fatigue test results are shown in Figure 1.

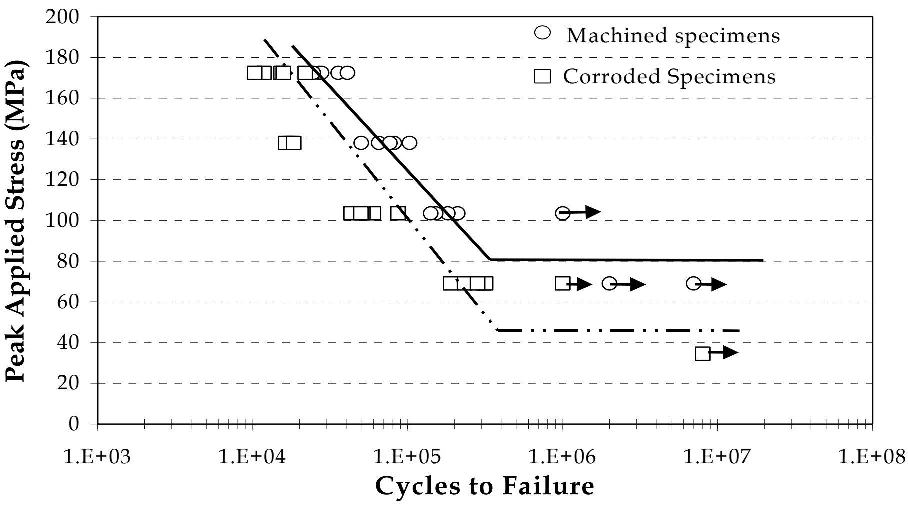


**Figure 1:** Comparison of machined specimen fatigue life with corroded specimen fatigue life.

Figure 1 clearly shows that the corrosion pits have two effects on fatigue: 1) a 50% reduction in the fatigue strength limit and 2) a general reduction in fatigue life which varies with stress. These results are very similar to results obtained by Pao [8] on the same material, but using a different specimen configuration (although with the same $k_t$) and a different corrosion time (>300hrs). Fractographic examination revealed large corrosion pits.

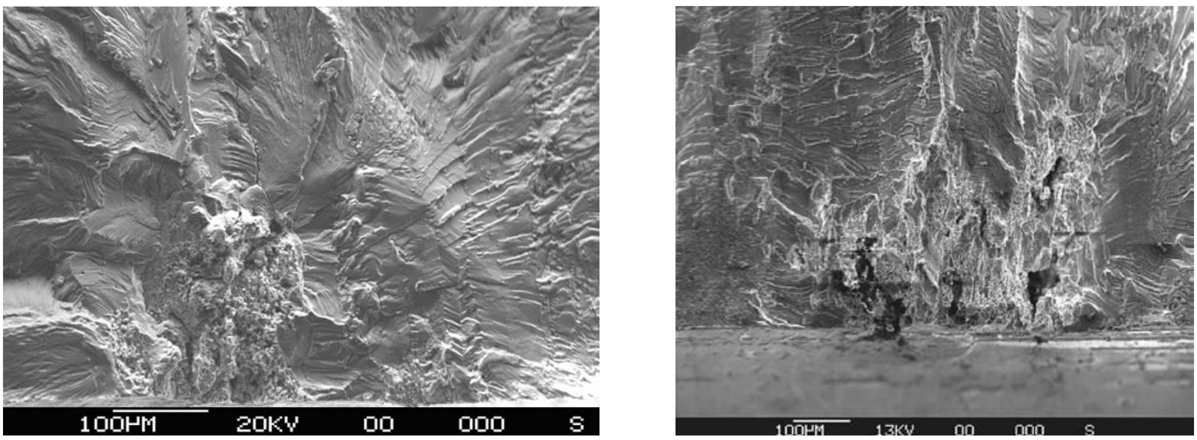


**Figure 2:** Typical 7050-T7451 corrosion pits on a coupon bore surface – 24hrs at 3.5%NaCl. In both cases the corrosion pits initiated a fatigue crack.

The corrosion pits "metrics" were measured from all pits that initiated a fatigue crack on the fracture surface. Also noted were the pit or pits that initiated the major crack. This provided a distribution of pit depths that initiated fatigue cracks, Figure 3. The distinction between pits and inclusions is blurred at depths below 100μm , and sizes below this are in fact usually inclusions and porosity; pit depths above 380μm are generally pit clusters where it is not possible to distinguish individual pits. Pit depth is only one of the "metrics" collected along with pit aspect ratio, pit tip radius, pit area and pit opening width.

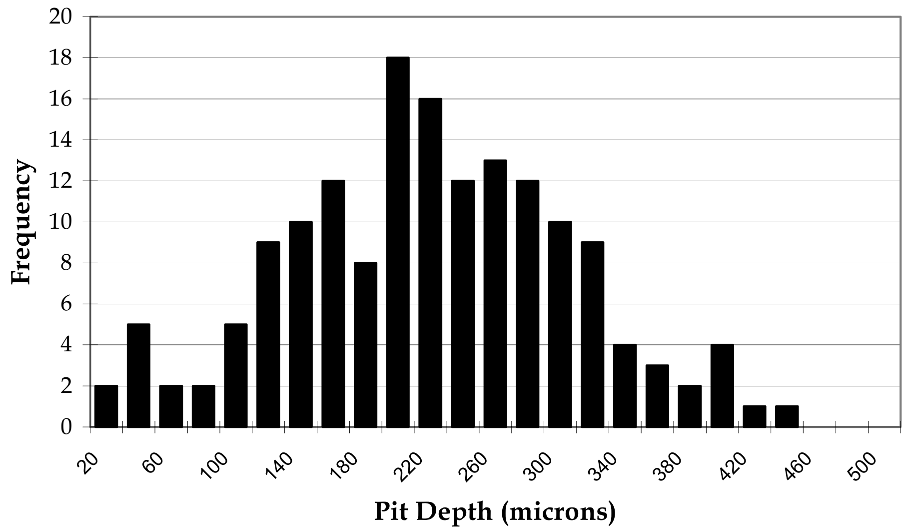


**Figure 3:** Distribution of depths for the flaws that initiated fatigue cracks. Below 100μm, these are generally inclusions and porosity, above 380μm, generally pit clusters.

The EPS modelling used AFGROW, a fatigue crack growth program developed by the USAF [9]. Several specimen geometries were examined; 1) a double corner crack, 2) a double surface crack and 3) a double through crack. A comparison of the pit depth vs EPS depth is shown in Figure 4. The best correlation between pit depth and EPS was with the double corner crack geometry. As can be seen there is a substantial amount of scatter in the relationship between pit depth and EPS, although the scatter is less than with pit width vs EPS and pit area vs EPS.

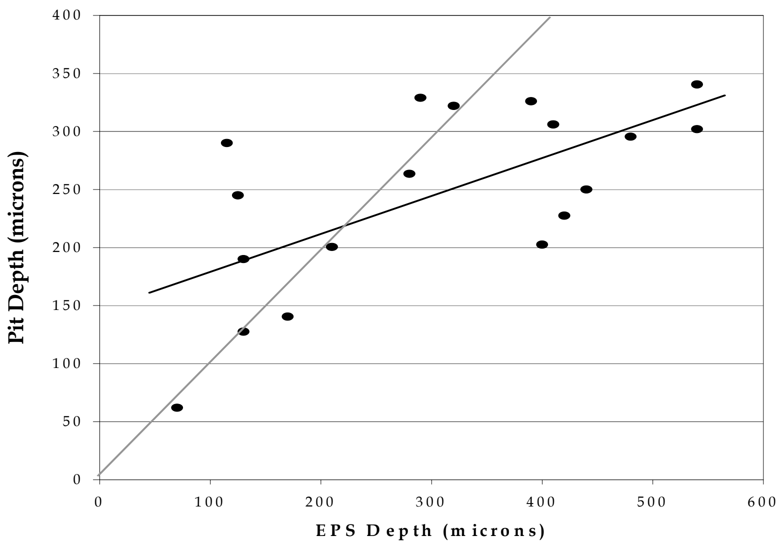


**Figure 4:** A comparison between pit depth and EPS depth. The dark line is the line of best fit and the light grey line is pit depth = EPS depth.

Research into the effect of pitting on structural integrity is also examining high strength steel, D6ac, which is used in the structural components of the F-111. While in its early stages the EPS approach appears to be substantially better, with higher correlations due to the reproducible and uniform nature of pitting in D6ac – all pits are close to hemispherical, Figure 5.

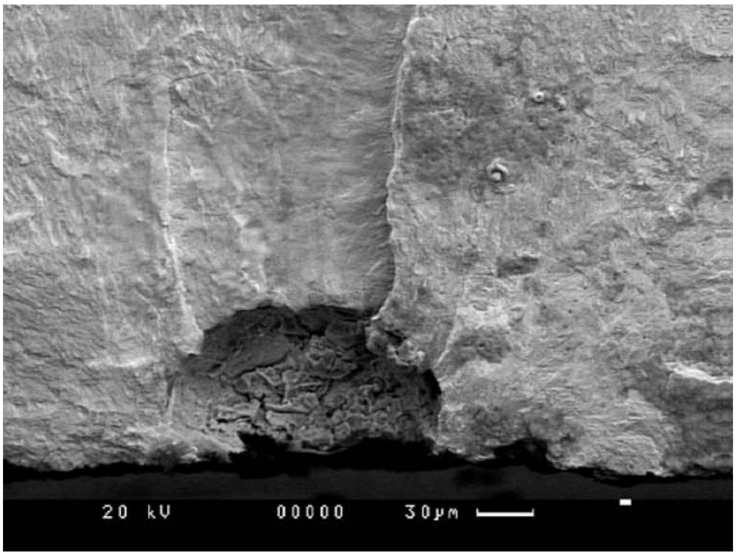


**Figure 5:** Corrosion pit and fatigue fracture generated in high strength steel fatigue specimen.

## EXFOLIATION CORROSION RESEARCH

Flat dogbone test specimens, [10], were machined from 6mm thick 2024-T351 and 7075-T651 plates. In the centre of the 20mm wide gauge section, a circular region was exfoliated with EXCO solution (ASTM Standard G-34). Exposure times in EXCO ranged from 2-300 hours. Damage states ranged from mild pitting at short exposure times to severe flaking up to 400-550 µm deep at times approaching 300 hours. The specimens were fatigue tested at 240 MPa, R=+0.1 until fracture occurred and were tested in air at relative humidities of either <20%RH, $f$ = 10 Hz or >90%RH, $f$ = 2 Hz.

For both materials, there was a very rapid initial decrease in fatigue life with small exposure times (<10 hours) and then the gradual levelling out with longer exfoliation times. The results indicate that the major effect of the exfoliation corrosion on fatigue life is to cause a dramatic reduction in life with small corrosion depths, suggesting that most of the fatigue effect is associated with the introduction of small pits, rather than more general stress concentration associated with the bulk of the exfoliation attack.

Examination of the exfoliated region showed grain lift-off and separation typical of exfoliation. At the short exposure times, multiple distinct pit-like nucleation sites were present, but as the exposure time increased, these sites joined together to become one large exfoliated region. New pit-like discontinuities were visible at the base of the exfoliation. This observation forms the basis of an exfoliation/fatigue model discussed below.

Figure 6 is an example of corrosion damage in 7075-T651 aluminium after 48 hours exposure in EXCO. In most cases with the 7075, the pits that caused fatigue failure were approximately 60-100µm deep. Around the base of these pits, areas of intergranular attack could be seen, but these regions were quite small, 10 to 30µm in depth.

A number of models have been proposed to describe exfoliation corrosion. Russo et al. [10] undertook 2D modelling based on an Equivalent Precrack Size (EPS) approach. The approach was to predict the growth life of a crack-like defect that represented some geometrical feature of the gross or macroscopic exfoliation corrosion.

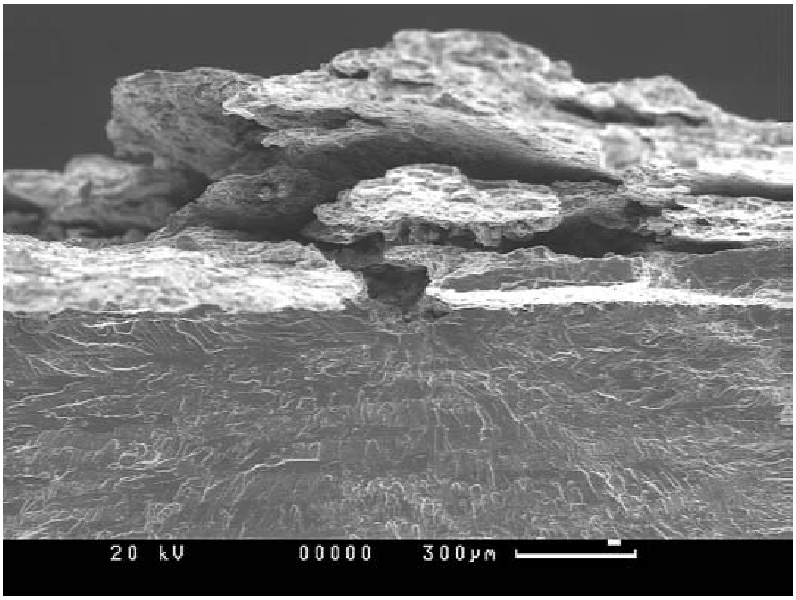


**Figure 6:** Fatigue crack origin under exfoliated grains, 7075-T651.

If this growth life were to be similar to that of the real corroded specimens, then the crack-like defect could be regarded as the EPS and could be substituted for the corrosion in further analyses. Three geometrical representations were considered:

1) a semi-elliptical crack with the same dimensions as a 2D slice through the exfoliation,
2) a semi-circular crack with a depth equal to that of the exfoliation, and
3) a geometric stress concentration, as though the exfoliation was blended out with a typical inclusion-sized starter crack (a=3μm and c=9μm) at the base.

The exfoliation/fatigue model was further refined based on the observation that the deepening exfoliation corrosion geometry has at its base pit-like intrusions from which intergranular cracks grow (model 4). The combination of a pit and crack represents a *process zone* that progresses through the material.

The proposed model is shown in Figure 7, where the process zone forms under environmental influences in the first few hours of exposure to EXCO. The authors postulate that for modelling purposes, the size of the zone stabilises and is followed by formation of the exfoliation stress concentrator.

To model the impact of the process zone on fatigue, notch (pit) and crack (intergranular attack) combinations derived from the experimental observations of different corrosion stages were input to FASTRAN II [11]. Figure 8 shows the three models used for 7075-T651 prediction, a range of initial crack sizes was explored based on experimental observations. In this case, model (4a) varies notch (pit) size with a 10μm crack, model (4b) varies pit size with a 20μm crack, and model (4c) varies pit size with a 30μm crack. All sub-models include the small effect of the overall material removal, which further reduces life for the more extensively corroded cases, and all give slightly unconservative results, close to the experimental data.

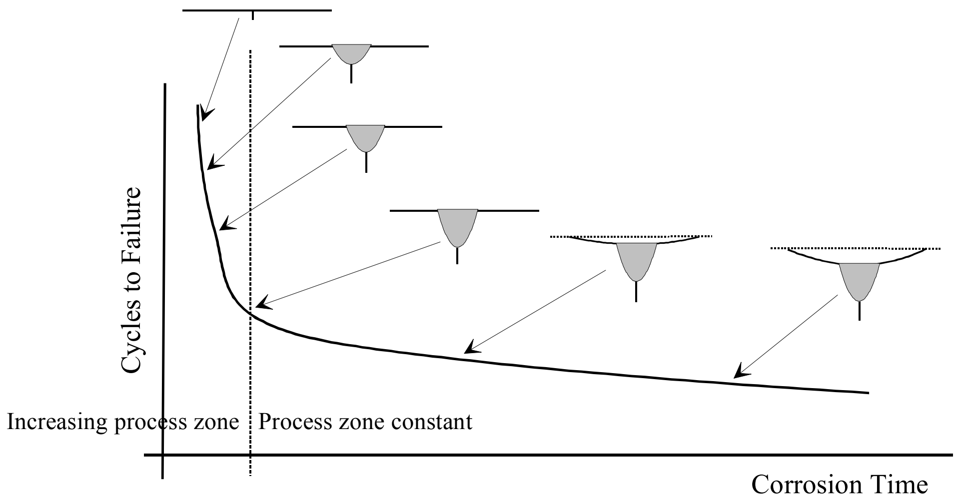


**Figure 7:** Concept of how process zone interacts with exfoliation over increasing corrosion time to affect fatigue life.

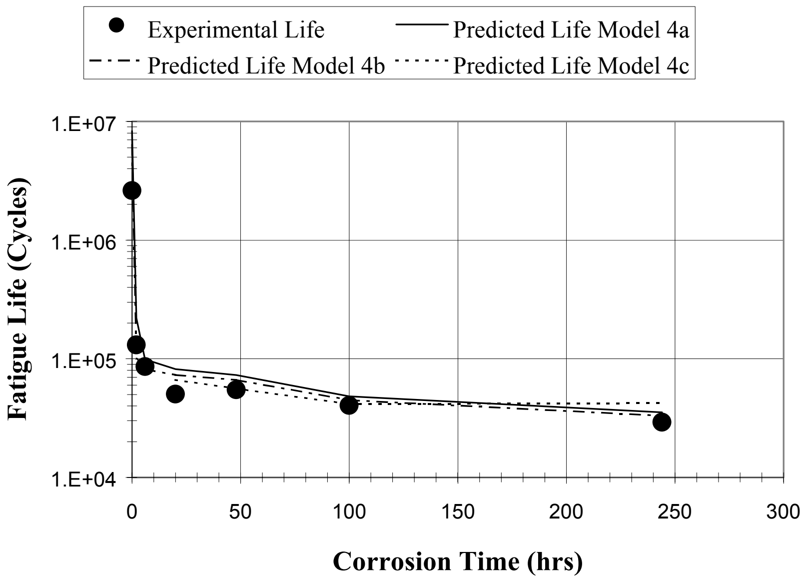


Figure 8: **Remaining Cycles to Failure vs. Corrosion Time for 7075-T651 aluminium along with the three variants in model 4 discussed in the paper.**

## CONCLUSION

DSTO has developed models for the fatigue impact both pitting and exfoliation corrosion. To date the models have been tested with success on constant amplitude fatigue specimens. The next stage is to determine whether the models apply equally well for spectrum loading on laboratory specimens and whether the same approach can be extended to a wider range of materials, or aircraft components. In a number of special cases, real aircraft structure has been or is being tested containing either laboratory produced corrosion or real time environment corrosion.

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