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THE INFLUENCE OF CORROSION ON AIRCRAFT STRUCTURAL INTEGRITY

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Abstract

This paper outlines a research program initiated at AMRL to assess the influence of corrosion on aircraft structural integrity, and some of the early results achieved. The research program objectives are to:

1) Develop analytical techniques for incorporating corrosion damage into structural integrity assessments.
2) Determine the influence of prior corrosion on the structural behaviour of typical military aircraft joints.
3) Determine the influence of remedial corrosion preventive methods on the fatigue performance of typical military aircraft joints.
4) Determine the consequences of the relationship between aircraft operational environment and fatigue loading, in terms of impact on fatigue crack growth.

The research aims to provide a basis for introducing corrosion into the approaches used to manage aircraft structural integrity in the ADF, and hence to minimise both the cost and risk of owning and operating aircraft in which corrosion might become a threat to safety or fleet viability.

Corrosion and Structural Integrity in ADF Aircraft

In recent years corrosion has threatened the structural integrity of several RAAF aircraft types. Two notable examples include corrosion in the tailplane of the Macchi jet trainer and in the F/A-18 trailing edge flap system; the significance of these cases is described in the following sections.

Macchi Jet Trainer

The loss of a Macchi aircraft as a result of fatigue cracking led to an extensive program (the Macchi Recovery Program) in which fleet crack management was reviewed. During a tear-down of a Macchi tailplane(1), large stress corrosion cracks were discovered, emanating from a number of rivet and screw holes. The location of these cracks prevented their detection *in situ* using NDI methods.

The stress corrosion cracking occurred at a number of holes in the spar, with the largest crack being some 40mm wide and 50mm long, Figure 1. The cracking was usually laminar, but in some locations was observed to be growing along a cylindrical surface associated with the morphology of the extruded microstructure.

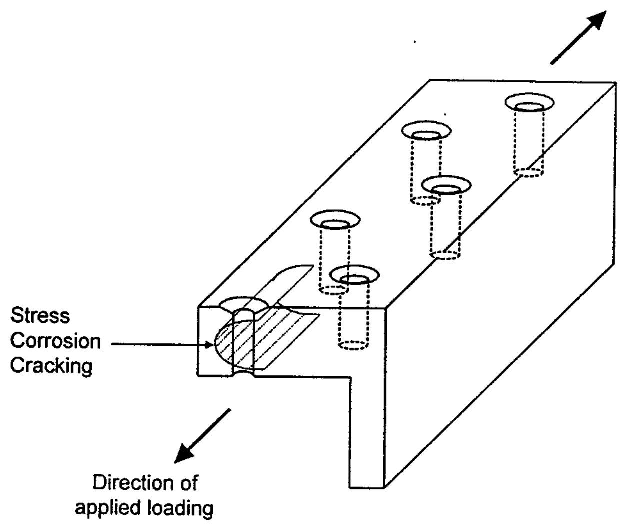


Figure 1: Typical laminar stress corrosion cracking found in a Macchi tailplane spar(1).

The effect of this cracking on structural integrity of the aircraft was particularly difficult to assess, since the cracking is in the same plane as the loading, and conventional methods of assessing fatigue and strength are not applicable. In order to allow continued service, it was necessary to be sure that the fatigue and static strength of the tailplane was not compromised by the presence of the corrosion cracking. The approach adopted included full-scale strength testing, and these tests at AMRL indicated that the SCC had no adverse effect on the strength of the tail plane. The likelihood of the cracking having a longer-term effect on fatigue life, however, could not be assessed, and the spars were replaced over a period of time.

F/A-18 Trailing Edge Flap

During 1996, a Trailing Edge Flap (TEF) separated from an F/A-18 causing extensive post failure damage to the aircraft. The departure was caused by failure of the TEF hinge lug, and on the basis of evidence that cracking had existed in the lug, a detailed fleet-wide examination of the lug was conducted, revealing three more lugs with large cracks over 1.5mm deep. A detailed fractographic analysis[2] of the cracked lugs revealed the presence of extensive pitting and numerous small cracks, Figure 2, and confirmed that the fatigue cracking was being accelerated by the corrosion.

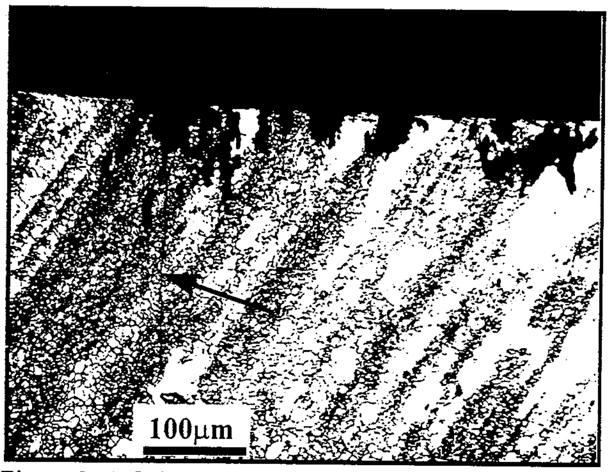


Figure 2: A fatigue crack growing from corrosion pits on the surface of a lug bore[2].

The presence of this corrosion was due to a break down of the corrosion protection scheme. The pits initiated fatigue cracks and allowed the environment to reach the crack tip and accelerate fatigue crack growth.

The significance of this event was that it highlighted the major effect that corrosion can have in reducing the life of a critical part; in this case the fatigue life of the lug was reduced by approximately two orders of magnitude compared to the life predicted by the manufacturer. Corrosion had not been factored into the initial life prediction, and had caused the early development of fatigue cracks and an increased growth rate of the cracks.

AMRL Research Program

A review of materials-related problem areas in Australian aircraft[3] identified the increasing significance of corrosion in ADF aircraft. In view of the ageing of the ADF fleet, and the likely impact of increasing costs for corrosion management, the review identified a need for:

1. Improved corrosion control methods, and
2. Methods of assessing the structural integrity implications of corrosion.

To address the second requirement, an extensive review of the effects of corrosion on structural integrity was conducted at AMRL[4]. This review concluded that no single analytical approach was available to allow engineering assessment of corrosion, and proposed a research program which would identify methods of incorporating corrosion into *existing* structural integrity assessment approaches.

The review[4] identified a number of research avenues which needed to be explored to meet these needs:

1. The possibility of using Equivalent Initial Flaw Size (EIFS) concepts to describe corrosion, in particular exfoliation and pitting, in terms which could be used directly in fatigue life assessments.
2. The effect of laminar defects, such as stress corrosion cracking, on fatigue life.
3. A correlation between environments applied in accelerated laboratory fatigue tests, and real service experience.
4. The effect of corrosion and corrosion preventive compounds (CPC's) on mechanical joints.

An extensive program has been commenced to investigate these topics, with the aim of providing the Australian Defence Force with an improved ability to incorporate corrosion in its structural integrity management programs. The major parts of this AMRL program are summarised in the following sections.

EIFS of Corrosion

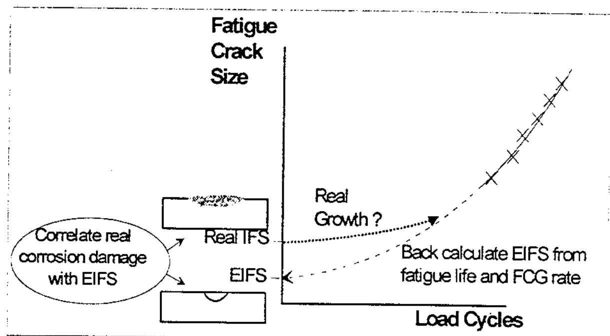
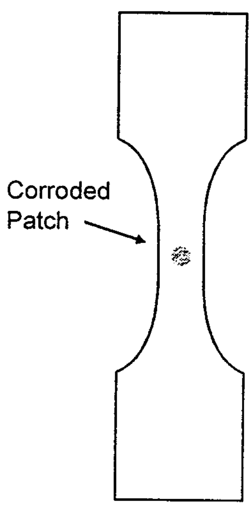


Figure 3: The equivalent initial flaw size(EIFS) concept. Measured crack growth, and crack growth modelling, allow definition of an initial fatigue crack which would give the same fatigue life as the real damage. This equivalent initial flaw may then be used in fatigue life prediction. Research is required to define the EIFS for each real flaw configuration.

The EIFS concept is based on representing a flaw (of any kind) as a fatigue crack of a size which will give the same fatigue life. The size of the notional fatigue crack (the Equivalent Initial Flaw Size) is obtained by observing crack growth from the real defect, and back-extrapolation of this crack growth to zero time ie. to a notional initial crack size. While this "equivalent initial flaw" (EIF) might not correspond directly to, say, the depth of the real initiating defect, some relationship will exist between the EIFS and the real defect. A knowledge of this relationship will then allow real defects to be described in terms of their EIFS for the purpose of calculating crack growth. Figure 3.

The initial AMRL work has focused on defining the EIFS for various corrosion forms; initial work has concentrated on exfoliation corrosion, a common form of corrosion in wrought aluminium alloys, although similar programs are being started on pitting corrosion in both steels and aluminium alloys. Crack growth modelling uses the FASTRAN fatigue crack growth program developed by Newman[5]. FASTRAN is used extensively at AMRL for fatigue life modelling and has been shown to be one of the more promising methods for predicting fatigue lives [6]. The exfoliated specimens were prepared using two common aircraft materials: 2024-T351 and 7075-T651, which were exposed to an EXCO solution (although a number of specimens are also being prepared by natural weathering). After exfoliating the surface over a controlled area, each specimen was dried under vacuum and then stored under vacuum until testing. To ensure that the corrosion does not re-initiate and the crack growth is only from the original corrosion damage the specimens were tested in air with relative humidity less than 10%. The specimens were tested at a frequency of 5Hz.

A variety of tests are applied to samples of the different corrosion cases used, in order to identify characteristics of the corrosion which can be related to the EIFS data.



2024-T351
7075-T651
Aluminium alloys

Figure 4: Specimen geometry used for testing and modelling.

Structural Corrosion Test Program

The significance of laminar defects in terms of their ability to promote failure is poorly understood, and is being addressed through laboratory testing and analysis. Ideally, however, the structural significance of service corrosion needs to be assessed using samples which are realistic in their construction and service history. When the size of the Macchi Jet Trainer fleet was reduced, a number of tailplanes were tested statically as part of the Macchi Recovery Program[1] and provided good strain data. It is proposed to undertake fatigue tests on several tailplanes which exhibit corrosion to establish the possible effect of service-induced corrosion damage on fatigue life.

Following fatigue testing, the tailplanes will be torn down to determine where the dominant fatigue cracks have initiated, and whether any service-induced corrosion was involved. This testing will provide increased confidence about the likelihood of service-induced corrosion affecting fatigue life.

Long Term Corrosion Testing

While the use of accelerated fatigue testing is widely accepted, the usefulness of conducting accelerated fatigue tests in aggressive environments, in an attempt to simulate service-induced corrosion effects, is far from obvious. Intuitively, acceleration of corrosion - related testing would not appear to provide the equivalent of long term corrosion tests. However, it is impractical for tests to be run for 20 years, as the point of testing is to provide information about possible problems before they occur in the fleet, and accelerated testing is still used widely, without a clear understanding of its relevance. AMRL is therefore developing an experimental test program to determine baseline data which can be used to evaluate corrosion tests.

The approach used is to use careful measurement of crack length to determine the growth of cracks under "realistic" service loading and environmental cycling, and to do so over time periods much shorter than would normally be required for cracks to grow to failure in service. This baseline data will then allow comparison with accelerated testing, and will also allow an investigation into the possible decoupling of the load and environmental cycles. The latter is of interest since it is likely that corrosion and fatigue occur during different parts of an aircraft mission, and confirmation that the two can be decoupled will allow a more rational prediction of the effect of corrosion.

One of the significant problems in this type of testing is obtaining a environmental history (temperature, and humidity spectrum) for an aircraft. Measurement of environments in RAAF P-3C aircraft by Maritime Platforms Division will provide detailed environment sequences; a proposed cycle is shown in Figure 5. [7].

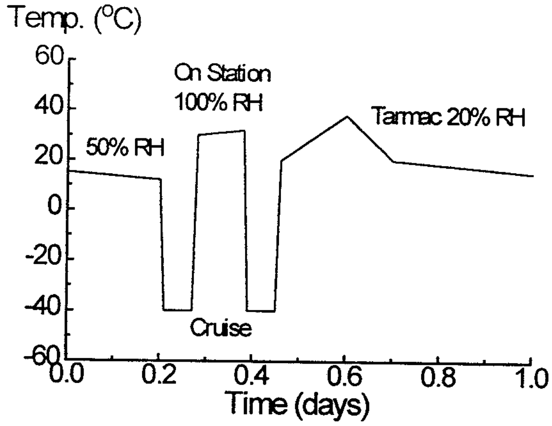


Figure 5: Environment cycle representing P3C Orion mission. RH= relative humidity.

A modified TWIST spectrum has been adopted for the loading spectrum, with the load exceedences adjusted to match the P3C anti submarine role. This spectrum is based on a high-level cruise to the target site and then a low level run over the ocean, followed by a high altitude cruise back to base, and possible exposure to tarmac temperatures. There are sound reasons for choosing this aircraft and mission; the aircraft is typical of many which are classed as ageing, in that corrosion and corrosion/fatigue interactions could be significant in determining the airframe life, and at the same time, the loading and environment cycles are fairly simple and are representative of much of the aircraft's usage.

Each test specimen will do a week's worth of flying, ie. seven daily missions, surrounded by time on the ground (not under shelter), followed by four weeks of non-loading representing hangar maintenance. This will ensure that each specimen has approximately the correct number of loaded flight hours and on-ground hours.

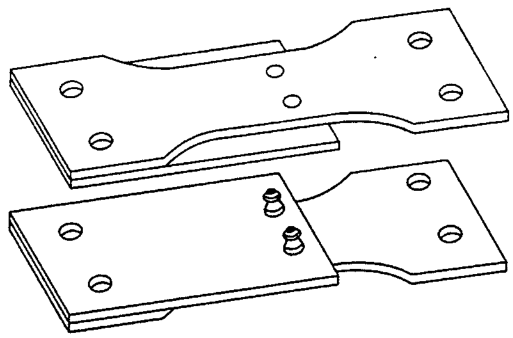
If suitably accurate baseline data can be obtained, by measuring crack growth over a period of few months, with known loading and environment, it will be used to examine the effectiveness of accelerated testing, and the potential value of other simulations, such as decoupled load/environment testing.

Effect of Corrosion and CPC on fatigue of Mechanical Joints

One of the major concerns about corrosion is that it might alter the load transfer in structural joints, and could then change the location and nature of failure. Similarly, the use of oily film CPCs to retard corrosion in aircraft could affect load transfer in any joints in the treated area, with similar results. An AMRL research program contracted to the Australian Defence Force Academy, aims to determine the effect of corrosion, and oily film CPCs, on load transfer and thus fatigue crack development in a joint considered to be representative of many in ADF service. This research is intended to develop knowledge of the overall influence of corrosion on such joints.

A second aim is to determine whether CPCs will stop corrosion from propagating in jointed specimens. A knowledge of the effectiveness of CPC's is essential to support investigation and assessment of corrosion in service aircraft, since crack growth predictions for any corroded area will need to be based on crack growth data for the appropriate environment, active or inert.

The specimen being used is the 1 ½ dogbone specimen used in a very successful AGARD[8] series on corrosion, Figure 6.



Corrosion Fatigue Cooperative Testing Programme (CFCTP) Specimen

Figure 6: The 1 ½ dogbone specimen used for testing and modelling.

The choice of specimen was influenced by the large statistical database generated in the original AGARD[8] program and a substantial amount of analysis using a finite element model by NLR[9].

The specimens were carefully manufactured and assembled according to strict procedures laid down in the AGARD program. The CPC was also added under carefully controlled conditions. A dam was built around each bolt and along the edges and filled with CPC, which was then allowed to wick into the joint for 24hrs before testing.

The testing was completed at 1Hz to encourage corrosion of the specimen and/or corrosion/fatigue interaction.

Initial Research Results

While the research described above is in its early stages, results are becoming available from the programs on the EIFS of exfoliation and the effect of CPCs on fatigue of mechanical joints:

Results (EIFS of Exfoliation Corrosion)

Changes in the depth and width of the exfoliation damage with time of exposure to the corroding environment is shown for both alloys in figures 7 and 8. The exfoliation spreads out (in width) along the grain direction about 100 times faster than it grows in depth with time. In both cases the rate of increase in the extent (width or depth) of exfoliation slows with time.

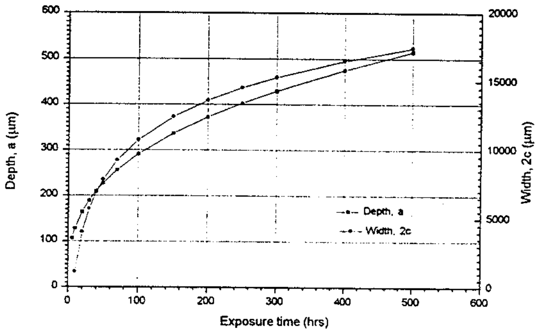


Figure 7: The depth and width of exfoliation damage in 2024-T351 aluminium alloy.

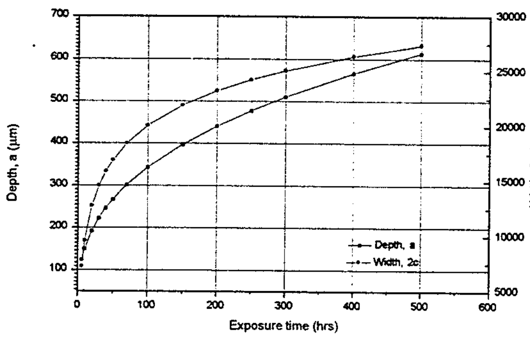


Figure 8: The depth and width of exfoliation damage in 7075-T651 aluminium alloy.

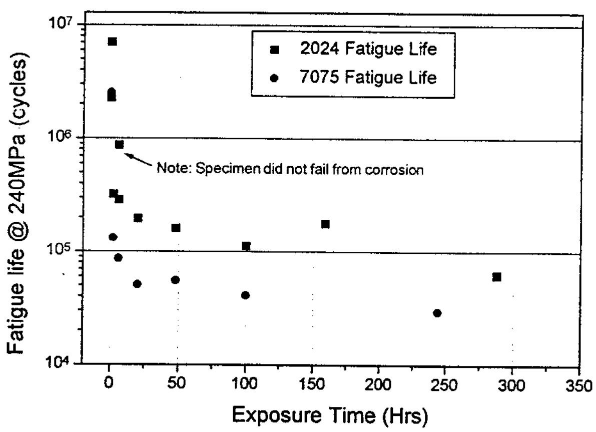


Figure 9: The fatigue life variation in the exfoliated specimens, as a function of exposure time.

The EXCO solution is more aggressive on the 7075 aluminium alloy than the 2024 alloy, leading to significantly deeper corrosion.

The results show a very steep initial fall-off in fatigue life with corrosion exposure time (<10hrs) and then a flattening out as the corrosion time increases (>10 hrs). In one case, despite obvious corrosion pits on the surface, the fatigue crack initiated from another surface flaw.

The results indicate that the major effect of the 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 geometrical stress concentrators.

Measurement of corrosion defects, Figure 10, provides the various size parameters which can be used in a crack growth model like FASTRAN II. For the zero-corrosion case FASTRAN II gave a reasonably good prediction of fatigue life; assuming that the initial flaw was a typical inclusion, with a=3µm and c=9µm[10], the model predicted a fatigue life between the two experimental results.

Figure 10a: Exfoliation in 7075 after 20 hrs immersion (40X) secondary electron image

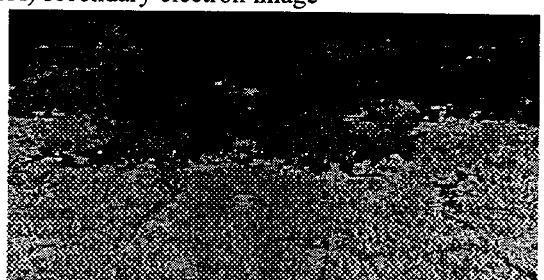


Figure 10b: Exfoliation in 7075 after 20 hrs immersion showing crack initiating from corrosion (33X) back scattered image.

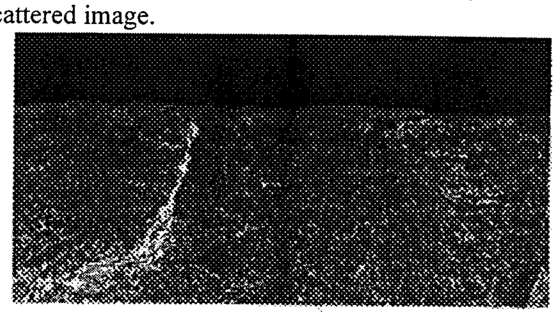


Figure 10c: Exfoliation in 7075 after 6 hrs immersion showing multiple initiation sites (25X) secondary electron image.

If the overall profile (in depth and length) of the corrosion defect is assumed to be a crack, Figure 11, the model predicts a substantially lower fatigue life than found experimentally. This level of conservatism arising from such an assumption is un-surprising.

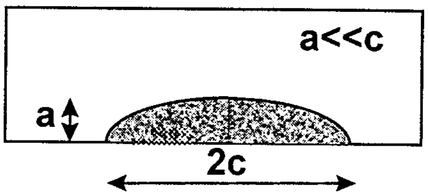


Figure 11:Crack with the same aspect ratio as the exfoliation corrosion.

An alternative approach - assuming the corrosion defect behaves as if it were a crack of equivalent depth but of semi-circular shape - is shown in Figure 12, and under-predicts the fatigue life as shown in Figure 13.

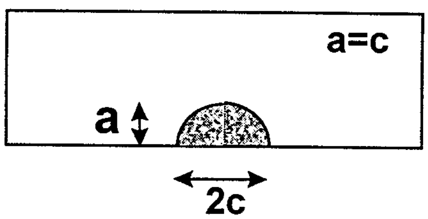


Figure 12: Crack with a semi-circular crack the same depth as the exfoliation corrosion.

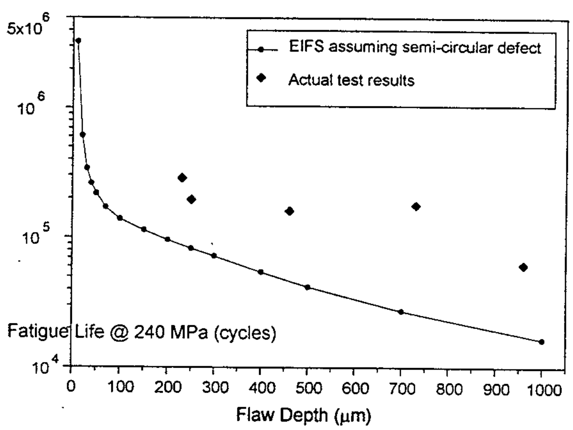


Figure 13:A comparison between experimental fatigue lives and predictions of fatigue life, based on a semi-circular EIF, for different initial crack depths (2024 alloy specimens).

A model which considers the overall corrosion defect as a geometrical stress concentrator which changes shape with time, predicts a gentle decrease in the fatigue life curve similar to that seen for 10+ hours corrosion time, but substantially over-predicts the fatigue life. These approaches (all crack, and all stress concentrator, with a natural initial defect) appear to represent conservative and non-conservative extreme cases, respectively.

A model is being developed which assumes that two fatigue-controlling factors are affecting fatigue life in the exfoliation corroded specimens. It assumes that there is a constant "process zone" of corrosion damage at the base of the overall corroded region representing penetration of the corrosion across the laminar grain structure, while the overall macroscopic region of damage slowly changes with time. Fatigue progression from this process zone is controlled by the overall stress concentration of the corroded geometry, and competition occurs between fatigue crack growth and general deepening of the corroded region. In effect, the exfoliation might be treatable as if it were pits or penetrations at the base of a gradually expanding and deepening stress concentrator, Figure 14. The approach is of interest because it might be a concept applicable to both exfoliation and pitting types of corrosion.

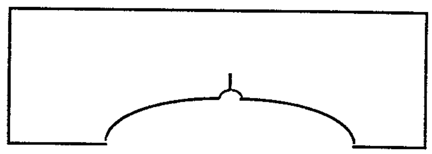


Figure 14: A possible model assumes an overall stress concentrator with the same overall aspect ratio as the exfoliation, and with a pit or process zone of constant size at the base, from which fatigue cracking can develop.

Research is now focussing on determining the shape of the features which lead to fatigue crack development and the possible stress intensity factors for fatigue cracking at these features. Subsequently the stress intensity factor for a crack at a small pit in the corroded region will be inserted in the fatigue life model. Further research will examine the possible application of the same approach to pitting corrosion.

Results - Effect of Corrosion and CPC on Mechanical Joints

The first stage of testing has been completed[11], comparing the effect of oily film CPC's on dry and wet specimens at two test stresses. The results (Figure 15) indicate that there is no significant difference between the three test conditions when tested at 210MPa. At the 144MPa test stress the dry air tests appear to give a longer life than both the wet test and dry + CPC test conditions.

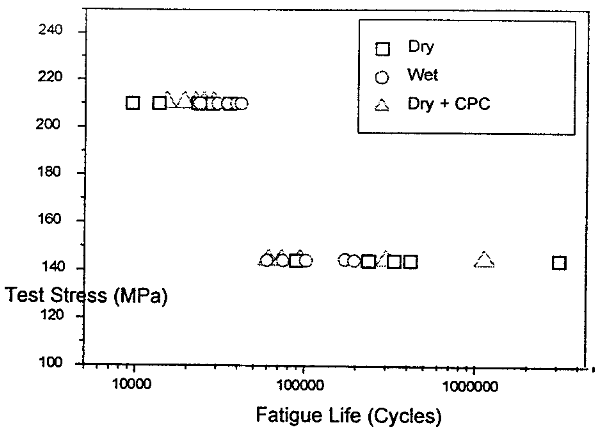


Figure 15: Fatigue life versus stress for a number of test conditions, (a) Dry air, (b) wet and (c) dry + CPC.

Detailed analysis of the fracture surfaces is under way. Initial observations indicate a number of interesting areas.

1) The CPC was present on all fatigue crack faces.
2) Very little CPC could be located down the bore of the fastener holes, although CPC was present between the plates.
3) Cracking in non-CPC specimens initiated from fretting between the faying surfaces.
4) Cracking in CPC specimens initiated from fretting down the bore.
5) The cadmium plated steel Hi-lok fasteners had corroded, but there was no sign of corrosion on the aluminium surfaces.

The next phase of the experimental program will examine the effect of pre-corrosion under these same test conditions

Conclusion

A review[4] by DSTO identified a requirement for research to develop an ability to incorporate corrosion effects in aircraft fatigue life management approaches. Several research programs are now being undertaken to meet this requirement; the topics being addressed focus on developing tools for assessing the types of corrosion found in ADF aircraft, and identifying the levels of risk posed by various types of corrosion defect. Key issues are the evaluation of corrosion metrics, such as the Equivalent Initial Flaw Size, which can be used in current fatigue crack growth prediction models, and the assessment of laminar defects such as stress corrosion cracking. Initial results are providing an insight into potential models for exfoliation corrosion, and the fatigue behaviour of mechanical joints.

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