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The Implications of Corrosion with respect to Aircraft Structural Integrity

G.K. Cole, G. Clark and P.K. Sharp

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Airframes and Engines Division
Aeronautical and Maritime Research Laboratory

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ABSTRACT

This report discusses the influence of corrosion on aircraft structural integrity. Brief introductions to corrosion in aircraft and aircraft structural integrity are provided and the literature concerned with the effect of prior corrosion and corrosive environments on static strength and fatigue performance is reviewed. RAAF and overseas experience with structural integrity issues associated with corrosion in aircraft is described, with emphasis placed on corrosion in airframes and other structural elements. The report discusses the difficulties associated with incorporating the effects of corrosion into conventional life management approaches and the contribution of corrosion control programs to continuing airworthiness. Where possible, current research programs throughout the world are reviewed. Finally, potential areas of research are identified, primarily on the basis of their potential usefulness for the future support of RAAF aircraft, and opportunities for collaborative research.

RELEASE LIMITATION

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The Implications of Corrosion with respect to Aircraft Structural Integrity

Executive Summary (U)

Increasing economic pressure has encouraged extension of the service lives of many civil and military aircraft fleets beyond their original design goals. Consequently, since the incidence of corrosion tends to increase with aircraft age, its importance as a life limiting form of degradation has increased in these fleets. While the proportion of aircraft accidents and incidents attributed directly to the presence of corrosion is relatively small, the potential of corrosion damage and corrosive environments to cause or accelerate structural failure in aircraft will need to be incorporated into RAAF fleet structural integrity management approaches.

In several recent cases the presence of corrosion has raised uncertainties over the continued airworthiness of some RAAF aircraft and, while these cases were resolved, structural integrity concerns associated with the detection of corrosion can lead to reduced aircraft availability and substantial increases in maintenance and support costs. Recent examples of this have included the discovery of stress corrosion cracking in P-3C Orion wing rear spar caps and Macchi MB326H tailplane spar caps. The absence of suitable methods of analysing the effect of this type of corrosion damage on the static strength and fatigue performance of these components made it impossible to guarantee the long-term airworthiness of these aircraft. It was therefore ultimately necessary to replace the components at some considerable cost.

The main aims of this report have been:

- To review the literature concerned with the effects of prior corrosion and corrosive environments on aircraft static strength and fatigue performance.
- To identify and review current research programs in this area.
- To identify potential research areas which could most effectively assist the RAAF in the management of structural integrity issues associated with corrosion in ageing aircraft fleets.

It has been concluded from the review that the engineering assessment of corrosion in aircraft structures is a complex problem and a multidisciplinary approach is required to address critical issues in a number of key areas. These include:

- Incorporating corrosion damage and environmental effects into conventional structural life management approaches.
- Characterising aircraft operating environments.
- Determining realistic upper bounds of corrosion progression.
- Determining the effectiveness of corrosion preventive compounds in retarding the growth of corrosion while at the same time preserving airframe structural performance.

* Modelling the initiation of fatigue cracking from corrosion damage.

Future research aimed at resolving these and other issues will benefit from a range of activities at three different levels:

1. Data surveys, information exchange, and the evaluation of existing corrosion management programs.
2. Applied research, aimed at addressing specific life management issues.
3. Strategic research, aimed at addressing developing capability in key areas.

Potential areas of research are discussed on the basis of their usefulness for the support of RAAF aircraft, the risk associated with obtaining useful outcomes, and the possibility of obtaining benefit from overseas collaboration. A potential research program is presented in the final chapter of the report.

Authors

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Geoff Cole graduated from the University of Western Australia with a Bachelor of Engineering degree in 1987, and from Monash University with a PhD in 1995. Since joining AMRL in 1994 he has contributed to the PC9/A full-scale fatigue test program and research into the effect of corrosion on the fatigue performance of aluminium alloys.

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Graham Clark, Principal Research Scientist. Graduated from University of Cambridge in 1972 in Natural Sciences. After completing research for a PhD on the growth of fatigue cracks at notches, undertook post-doctoral research at Cambridge on the detection and growth of cracks in submarine nuclear pressure vessels. In 1977 he commenced work at DSTO in Maribyrnong, leading research on cracking in thick-walled pressure vessels, which developed a comprehensive fracture control plan for Australian manufactured ordnance and a capability for predicting ordnance fatigue lives. In 1984 he moved to Fishermens Bend, where he established a research program on the damage tolerance of thick carbon-fibre composite materials, involving modelling and experimental investigation of impact damage in aircraft materials. In his present position, he leads tasks which support defect assessment in ADF aircraft, NDI evaluation and fatigue crack growth research. He is also chairperson of the AMRL Accident Investigation Committee.

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Khan Sharp, Professional Officer 2. Graduated from Monash University in 1987 having obtained a Materials Engineering Degree with Honours. In 1990 having completed a Masters of Engineering Science he commenced work in the Fatigue and Fracture Detection and Assessment area. Over the past 6 years he has been involved in the metallurgical investigation of aircraft structures and components, fractographic analysis of fatigue surfaces and research into fatigue crack growth and fracture of aircraft materials. He has completed extensive research into novel methods of retarding crack growth and innovative NDI methods. He is presently involved in research tasks on the structural integrity effects of corrosion and fatigue and fracture.

Contents

List of abbreviations

AGARD	Advisory Group for Aerospace Research and Development
AMRL	Aeronautical and Maritime Research Laboratory
CPC	Corrosion Preventive Compound
CPCP	Corrosion Prevention and Control Program
EIFS	Equivalent Initial Flaw Size
ESDU	Engineering Sciences Data Unit
FAA	Federal Aviation Administration (United States of America)
NASA	National Aeronautics and Space Administration
NDI	Nondestructive Inspection
OEM	Original Equipment Manufacturer
RAAF	Royal Australian Air Force
RAE	Royal Aerospace Establishment (United Kingdom)
RH	Relative Humidity
SCC	Stress Corrosion Cracking
WDCP	Water Displacing Corrosion Preventive

1. Introduction

In recent years, increasing economic pressure has encouraged the planned extension of service lives for many civil and military aircraft fleets. This has been assisted by the view that aircraft structural design is sufficiently well understood to permit such extension to be performed without undue risk. However, the in-flight decompression of an Aloha Airlines 737-200 in 1988, in which eighteen feet of the upper fuselage lobe separated along a lap joint, and several other highly-publicised incidents, have focussed the attention of media, manufacturers, operators and regulators on the continued airworthiness of ageing aircraft and acted as a catalyst for research into the management of multiple-site fatigue damage and corrosion.

Multiple-site fatigue damage (MSD) research has focussed heavily on the problem of multiple hole configurations, particularly in pressure hulls, where the accepted safeguards against catastrophic failure, namely crack-stopping features such as tear straps are rendered ineffective by the presence of small fatigue cracks at many holes in a row; these cracks provide a relatively easy path for the primary crack, which can then propagate over substantial distances instead of being arrested or deflected as it should at the tear strap. Major research efforts have been concentrated on methods for predicting fracture behaviour of MSD, methods of detecting the cracks, and on improved resistance to hole cracking.

To date, the proportion of aircraft accidents or incidents which may be attributed directly to the presence of corrosion in airframe structures is relatively small (Campbell and Lahey (1984), Hoeppner *et al.* (1995)), and until recently relatively little research has been directed toward the implications of corrosion on aircraft structural integrity. Nevertheless, the potential of corrosion damage and corrosive environments to cause or accelerate structural failure in aircraft is well recognised. These concerns have been addressed principally by the gradual introduction of improved corrosion protection schemes, and continued reliance on repairs based on metallic (or more recently, composite) reinforcement.

While ageing aircraft issues have been associated mainly with civil aircraft, military aircraft fleets have been subject to the same economic pressures, and indeed, many life extension procedures, focussing largely on fatigue cracking problems, are now well established for military aircraft. Corrosion in military aircraft has been addressed in a similar manner as civil aircraft, namely, through improved corrosion control measures such as more sensitive detection methods and wider use of preventive treatments.

Recent changes in the Royal Australian Air Force (RAAF) have led to a more structured approach to the management of structural airworthiness matters. These changes, and a growing awareness of ageing aircraft concerns, have highlighted several recent examples where the presence of corrosion has raised uncertainties over the continued airworthiness of some RAAF aircraft.

It is therefore timely to review in detail the implications of corrosion on aircraft structural integrity. This report has several aims. The first of these is to review the literature concerned with the effects of corrosion and environment on static strength and fatigue performance, the essential components of aircraft structural integrity. The second is to identify and review current research programs in this area. The third is to identify areas in which potential future research could most effectively assist RAAF management of the structural integrity issues associated with corrosion in ageing aircraft fleets. Particular emphasis is placed in this report on the effects of prior corrosion and corrosive environments on aircraft structure which is subjected to flight or ground loads, such as fuselage, wing and landing gear systems. While it is recognised that corrosion may affect other aircraft systems (for example, engines, flight control systems, and fuel systems), problems which are specific to these systems are not considered within the scope of this review.

The report is organised in the following manner. Chapters 2 and 3 provide a general background to the subjects of corrosion in aircraft and aircraft structural integrity. Chapters 4 and 5 review the scientific and engineering literature on the effects of corrosion and corrosive environments on static strength and fatigue performance. The discussion in these chapters is general although emphasis is placed on materials and structures which are relevant to aircraft. Chapter 6 discusses the broader implications of corrosion with respect to issues surrounding aircraft structural integrity and identifies areas for future development. Chapter 7 discusses potential areas of research on the basis of their usefulness for the support of RAAF aircraft, the risk associated with obtaining useful outcomes, and the possibility of obtaining benefit from overseas collaboration.

2. Corrosion in aircraft

2.1 Introduction

A detailed discussion of the many forms of corrosive attack which aircraft experience is beyond the scope of this report. RAAF Defence Instruction AAP 7021.014-2 (Chin Quan (1992)) provides details of many different forms of corrosion in a wide range of airframe materials. Some of these forms of corrosion are rare, or confined to uncommon alloy/environment systems, while others are superficial and are often removed for cosmetic reasons only. Only a handful of different types of corrosive attack are both common enough and severe enough to form a consistent threat to aircraft structural integrity (Wallace *et al.* (1985)); these are:

- pitting corrosion,
- intergranular corrosion,
- exfoliation corrosion,
- stress corrosion cracking,
- corrosion fatigue, and
- uniform corrosion.

These forms of corrosion have the capacity to reduce the load carrying capacity of a structure, to provide an initiation point for fatigue cracking, or to increase fatigue crack growth rates.

The purpose of this chapter is to describe briefly each of these six forms of corrosion. As discussed in a later chapter of this report, an understanding of the growth characteristics of defects is fundamental to the maintenance of structural integrity; where corrosion is involved, it may be necessary to identify the different contributions to the overall growth rate associated with:

(a) the growth of the corrosion damage by corrosion processes,
(b) the initiation and growth of fatigue cracking from corrosion damage, and
(c) the process of corrosion fatigue.

Where corrosion itself degrades the residual strength of the structure by, for example, reducing section thickness, the defect growth rate is simply the corrosion initiation and growth rate. Where fatigue cracking initiates from corrosion damage, the defect growth rate may be an extremely complex function of time, environment and load history, in which it may be convenient to regard the corrosion stage as being equivalent to the initiation stage of fatigue. However, in the case of corrosion fatigue, the separation of the processes of corrosion and fatigue is usually not possible.

The growth rate of corrosion can be sufficiently high to be significant in terms of structural integrity, and any relevant attempts to model or describe the development and growth of corrosion are discussed as appropriate.

2.2 Types of corrosion which may affect aircraft structural integrity

2.2.1 Pitting corrosion

Pitting is a form of localised corrosion which occurs on the surface of metals, and takes the form of cavities in an otherwise relatively uncorroded surface. These cavities may vary from deep pits of small diameter to larger, relatively shallow depressions. The initiation of pitting is associated with local breakdown of protective surface films.

Pitting is a severe form of corrosion because it may cause the perforation of thin component sections, as well as creating stress raisers which may induce the onset of stress corrosion cracking or corrosion fatigue. There is strong evidence to suggest that under the action of cyclic loading, there is a synergistic interaction between pitting and the early stages of corrosion fatigue crack growth.

Susceptible materials include aluminium and magnesium alloys, stainless steels, and steels plated or coated with aluminium, cadmium or zinc.

It has been proposed by Kondo (1989) that the growth of corrosion pits may be modelled using the simplifying assumptions that the pit is hemispherical in shape, and grows at a constant volumetric rate. The relationship between the pit depth, r, the bulk dissolution rate, B, and time, t, is then given by

$$(2/3)\pi r^3 = Bt \tag{2.1}$$

In practice, pit shapes are known to display considerable variability, and furthermore, the shape of pitting can change as time progresses, particularly as pits amalgamate (Chen *et al.* (1996)). At one extreme is the example given in Figure 2-1 which shows relatively deep, narrow pits in a 7050 aluminium alloy flap hinge lug from a RAAF F/A-18. In this case, the progression of the corrosion is probably being influenced by the developing fatigue crack at the base of the pit. On the other hand, large, shallow pits may be associated with multiple initiation sites. In view of this variability in pit shape, and the interaction which occurs between pit growth and the early stages of fatigue crack growth, Kondo's model would appear to be simple, but probably unrealistic. It seems reasonable to conclude that more research work is required before pitting corrosion can be modelled with a high level of confidence.

Pitting is normally repaired by either machining out the affected area and blending the machined section to the remaining material, or replacing the component if damage limits have been exceeded.

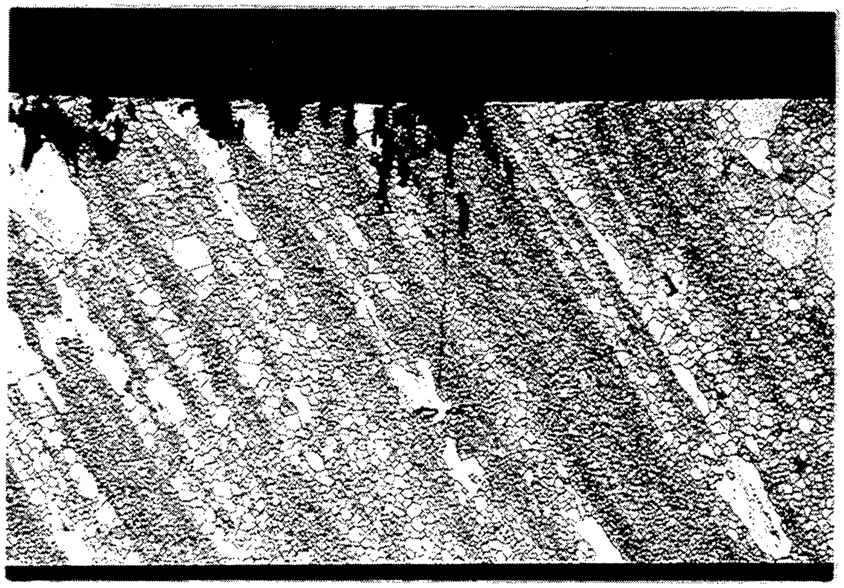


Figure 2-1: Corrosion pitting in a forged 7050 aluminium alloy trailing edge flap hinge lug from a RAAF F/A-18 aircraft. The relatively deep, narrow pits are oriented perpendicular to the applied stress, rather than following the microstructure, indicating that pit growth is probably being affected by the developing fatigue crack. After Sharp et al. (1992).

2.2.2 Intergranular corrosion

Intergranular corrosion occurs in a number of susceptible alloys after they have been subjected to specific heat treatments. Certain alloying elements migrate to grain boundaries during these heat treatments, and form corrosion cells on a microscopic scale.

The grain boundary precipitate and adjacent element-depleted region usually constitute cathodic and anodic areas respectively. In the presence of an electrolyte, rapid corrosion may occur adjacent to the grain boundaries, with relatively little attack within the grains.

Intergranular corrosion can be characterised by a network of corrosion following the grain boundaries in a localised region. An example of intergranular corrosion in 7075-T6 aluminium alloy is shown in Figure 2-2. Deep, crack-like intergranular penetrations may also occur at the exposed end grain of rolled and extruded sections. In these cases the progression of the corrosion is facilitated by the density of grain boundaries provided by a flattened, elongated grain structure which results from the extrusion process. An example of this type of corrosion is shown in Figure 2-3.

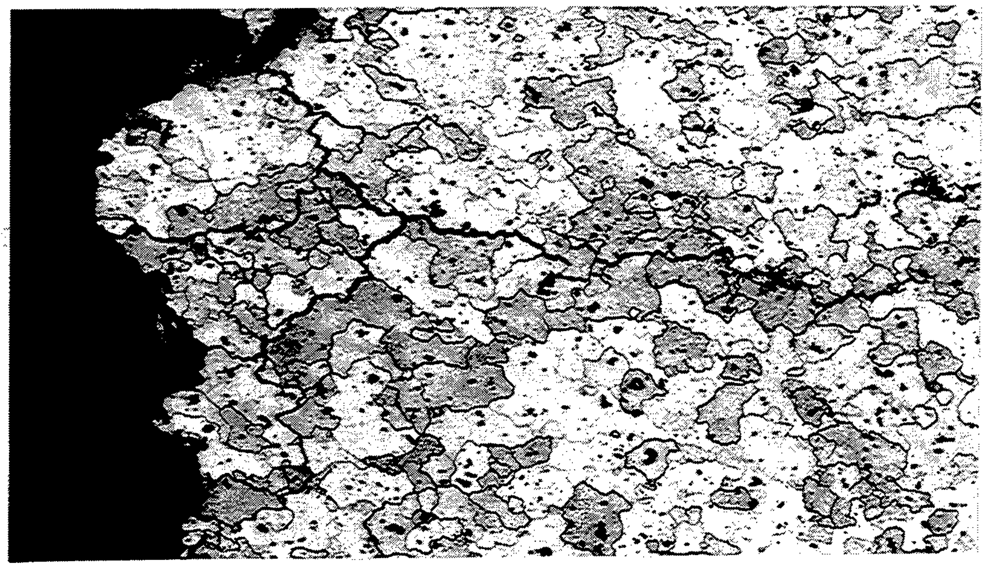


Figure 2-2: Network of intergranular corrosion in a 7075-T6 aluminium alloy main landing gear up sensing rod from a RAAF F-111 aircraft.

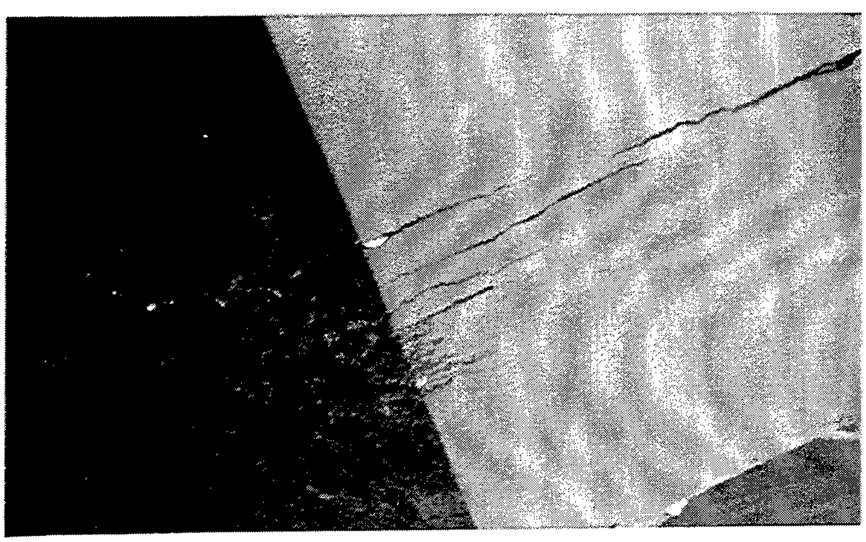


Figure 2-3: Deep, crack-like intergranular penetrations in a 2014 aluminium alloy brake cylinder block.

Intergranular corrosion is a serious form of corrosion which may penetrate deeply into the material while displaying little indication on the surface of the severity of the damage. It is often difficult to remove this damage completely and where a suitable stress exists, stress corrosion cracking may develop. The wedging effect of corrosion product may also provide sufficient stress to drive stress corrosion.

Susceptible materials include 2xxx series aluminium alloys aged at room temperature (T3 temper), 7xxx series aluminium alloys in the peak aged (T6 temper) condition, and austenitic stainless steels.

In practice the growth of intergranular corrosion is highly dependent on chemical and metallurgical conditions and can not be predicted to any useful extent.

While intergranular corrosion may in some instances be repaired by machining out the affected area, it can be difficult to ensure that the affected material has been removed completely. Therefore, intergranular corrosion is often managed by replacing the component.

2.2.3 Exfoliation

Exfoliation corrosion is a term applied to intergranular corrosion in materials which have a directional grain structures (i.e. layers of flattened, elongated grains). Such grain structures, produced during rolling or extruding processes, are typically found in many aluminium alloy aircraft skins, spars and longerons.

This type of corrosion is characterised (and distinguished from intergranular corrosion) by the surface bulging, and eventually flaking, due to the force produced by corrosion products which occupy more volume than the original alloy. It often originates where the end grain of the material is exposed, for example at fastener holes. An example is shown in Figure 2-4.

Exfoliation is a severe form of corrosion because extensive attack and serious structural weakening may occur before much visible corrosion product accumulates at the surface.

Susceptible materials include high strength aluminium alloys in certain tempers. The 2xxx series alloys are susceptible when aged at room temperature (T3 temper), while the 7xxx series alloys are susceptible in the peak aged (T6 temper) condition. Improper heat treatment or heat damage which promotes grain growth also increases susceptibility.

In practice the progression of exfoliation corrosion can not be predicted to any useful extent.

Exfoliation corrosion is normally repaired by machining out the affected area, or replacing the component if damage limits have been exceeded.

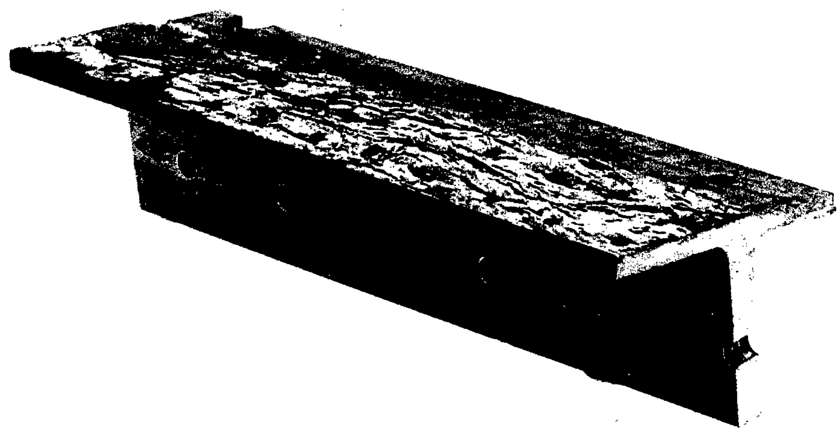


Figure 2-4: Exfoliation corrosion in an extruded 7075-T6 aluminium alloy spar cap from a C-130 aircraft.

2.2.4 Stress corrosion cracking

Stress corrosion cracking occurs under the simultaneous action of corrosion and a sustained tensile stress. The stress may be externally applied, such as a service stress or that which may arise from the fitting of badly mated parts, or internal to the part resulting from cold working or unequal cooling rates during manufacture.

Stress corrosion cracking originates at a surface and is typically characterised by a relatively long initiation period, with protective film breakdown and the formation of a stress concentrating pit, prior to crack growth. Cracking may be intergranular or transgranular with respect to the microstructure. The rate of stress corrosion cracking decreases as the stress is reduced, and there is a minimum stress below which stress corrosion cracking does not occur.

Stress corrosion cracking can be a severe form of deterioration because it may not be readily apparent during the course of visual inspection, and because assembly stresses and internal stresses are seldom detected.

Certain materials and orientations are particularly susceptible to this form of corrosion.

Among aluminium alloys, the plane normal to the short transverse direction is particularly susceptible to stress corrosion cracking and even alloys of low susceptibility may suffer cracking if the design permits excessive residual and assembly stresses in the short transverse direction. In general, while 2xxx series alloys are susceptible to stress corrosion cracking when aged at room temperature (e.g. T3 temper), artificial ageing for a few hours at temperatures between 175 and 190°C can greatly reduce their susceptibility. Compared with naturally aged alloys, artificial ageing leads to increased tensile strength, but reduced ductility and resistance to fatigue. The 7xxx series alloys are very susceptible to stress corrosion cracking in the plane normal to the short transverse direction when they are in the peak aged (T6 temper) condition. Subsequent overageing treatments can lead to progressive improvements in stress corrosion resistance with ageing time (e.g. T76, T736, T73 tempers). There is a progressive reduction in tensile strength on overageing, although toughness is generally improved. Examples of stress corrosion cracking in aluminium components on RAAF aircraft have included Boeing 707 flap track support fittings which were forged from the particularly sensitive 7079-T6 alloy (Athiniotis (1996)), and C-130 bow beam fittings which were manufactured from 7075-T6 (Athiniotis (1995b). The C-130 bow beam fittings provided a particularly interesting example in which a fatigue crack had occurred at a fastener hole and (probably by assisting the ingress of moisture) promoted stress corrosion cracking *perpendicular* to the fatigue crack. The interaction between the fatigue crack and the stress corrosion cracking is shown in Figure 2-5.

Titanium alloys form a stable oxide layer and are corrosion resistant in most environments. As pitting is the normal initiator of stress corrosion cracking, it follows that titanium alloys without crack-like defects are not generally susceptible to stress corrosion cracking. However, certain titanium alloys such as Ti-6Al-4V are susceptible if a crack or defect is present. Additionally, titanium alloys may be embrittled by certain environments which leads to an increased susceptibility to fracture. These include: chlorinated hydrocarbons (e.g. some degreasers and paint strippers), fluorinated sealants, cadmium, silver, methanol, and some hydraulic fluids at high temperatures.

High strength steels may be susceptible to stress corrosion cracking, and stress corrosion should be considered a hazard for steels with an ultimate tensile strength close to or exceeding 1450 MPa. Notably, this includes the steel D6ac, used extensively in the F-111.

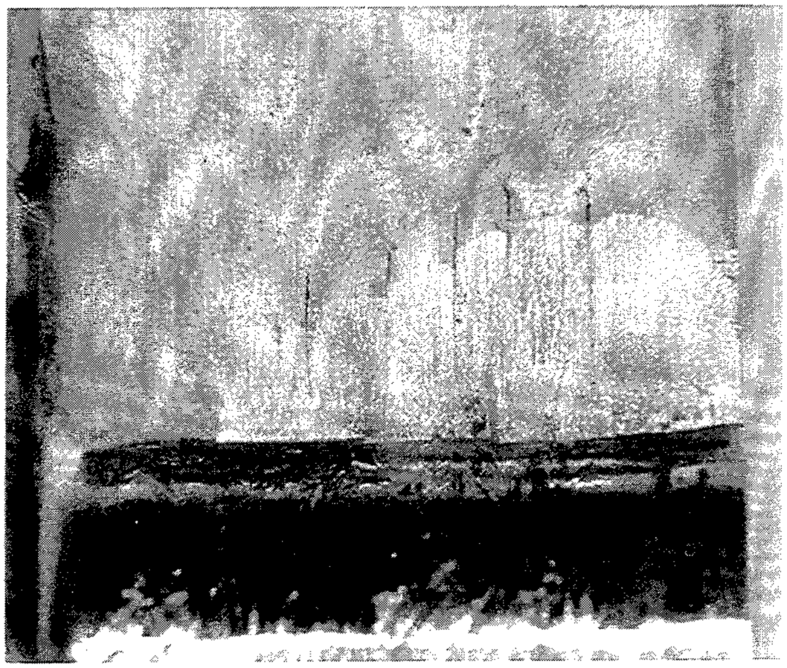
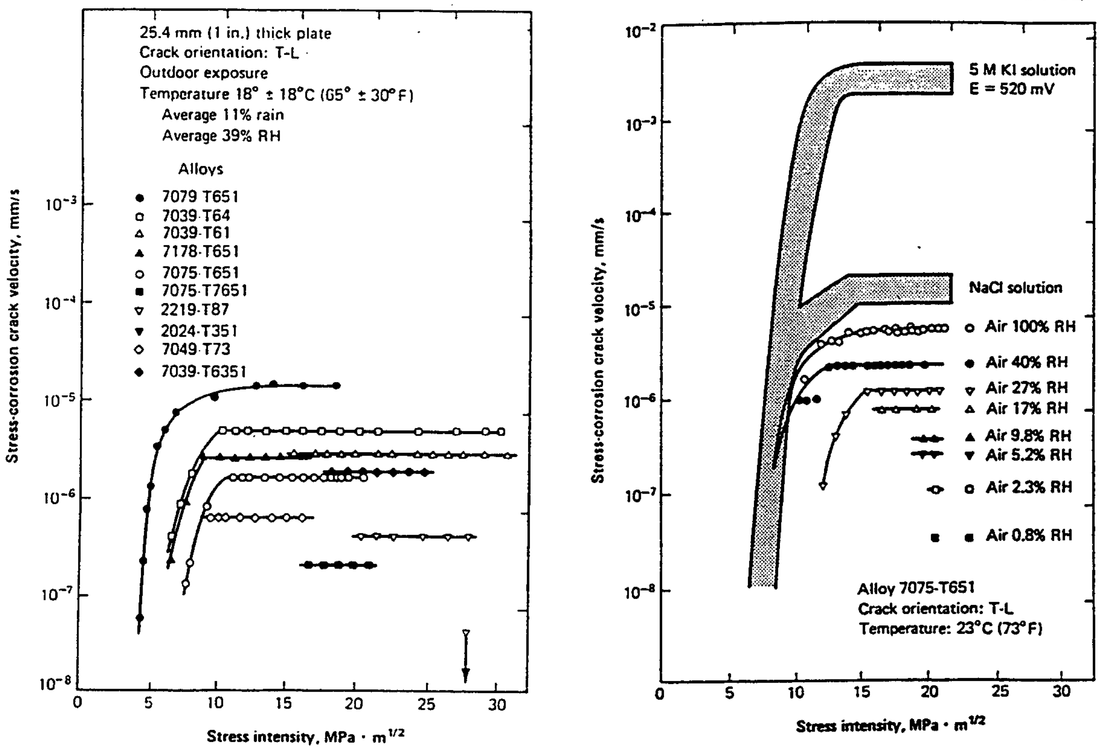


Figure 2-5: Interaction between stress corrosion cracks (growing into the page) and fatigue cracking (in the plane of the page) in a C-130 bow beam fitting. After Athiniotis (1995b).

A more detailed discussion on the susceptibility of aircraft alloys to stress corrosion cracking may be found in the United Kingdom Defence Standard 00-970 (DEF STAN 970), Leaflet 406/1 (1983).

The growth of stress corrosion cracks is dependent on the stress intensity factor at the crack tip (which is a function of the length and geometry of the crack) and the nature of the corrosive environment. A threshold stress intensity factor (conventionally denoted K_{ISCC}) exists, below which stress corrosion cracks do not propagate. The value of K_{ISCC} depends on the combination of material and environment as well as the orientation of the crack with respect to the grain structure in the component.

Stress corrosion crack velocities for several high-strength aluminium alloys in an outdoor environment are shown in Figure 2-6(a). This figure clearly shows the reduction in stress corrosion crack rate which results from overageing 7075 alloy from the peak aged (i.e. maximum strength) T651 temper to the lower strength T7651 temper. Figure 2-6(b) shows the effect of varying environment on the stress corrosion crack growth rate of 7075 alloy in the susceptible T651 temper.



(a) (b)

Figure 2-6: (a) Effect of outdoor exposure and stress intensity factor on stress corrosion crack velocity in several high strength aluminium alloys; and (b) effect of environment on stress corrosion crack velocity in 7075-T651 aluminium alloy. After Gangloff and Kim (1993).

However, it is crucial to recognise that such stress corrosion crack velocities are of limited value if the cracking is driven by assembly or residual stresses whose magnitude is unknown. In practical terms it is usually impossible to draw any conclusions regarding the length of time a stress corrosion crack has been present, and difficult to predict how rapidly it will grow in the future.

In most instances stress corrosion cracking is rectified by replacement of the component.

2.2.5 Corrosion fatigue

Corrosion fatigue refers to the synergistic interaction between a corrosive environment and fatigue crack propagation. The presence of a corrosive environment accelerates fatigue crack growth in most common engineering alloys, and may also reduce the value of the threshold stress intensity factor range, i.e. the condition under which a fatigue crack ceases to propagate.

Corrosion fatigue implies the existence of some stress concentrating feature, often a corrosion pit.

The severity of this form of corrosion depends upon the extent to which the environment modifies fatigue crack growth behaviour, and may be very substantial; under some circumstances crack growth rates may be accelerated by an order of magnitude.

Some materials are particularly susceptible to corrosion fatigue in the environments experienced by operational aircraft. These include stress corrosion sensitive aluminium alloy extrusions and forgings, recently developed aluminium-lithium alloys, some titanium alloys, and some high strength steels.

Considerable research effort (documented later in Chapter 5) has been spent in attempting to describe the mechanisms of corrosion fatigue, and quantify its effects.

Corrosion fatigue is normally repaired in the same manner as fatigue damage, that is, by machining out the affected area, applying a validated repair, or replacing the component. The influence of subsequent corrosion on the repair should be considered.

2.2.6 Uniform corrosion

Uniform surface corrosion, as the name implies, is a form of attack which slowly reduces the cross-section of the metal. It usually occurs as a result of the direct exposure of a metal surface to oxygen or sulphur in the air, or an electrolyte.

Initially, general corrosion produces an etching of the surface which becomes dull, rough, or possibly frosted in appearance.

Uniform corrosion is unusual where some form corrosion protection scheme has been applied, because the corrosion will tend to be localised at areas where the protection scheme has deteriorated, or has been damaged.

Uniform corrosion is generally not a severe form of deterioration provided it is detected and treated at an early stage. However, in extreme cases it may cause appreciable thinning of the metal, or, if it occurs within a joint, the trapped corrosion products may cause bulging or separation of the joint. Furthermore, if left untreated, surface corrosion may initiate more damaging forms of corrosion.

Rates of uniform surface corrosion may be determined empirically from comparatively simple tests. Corrosion rates are often expressed as weight loss per unit time.

Uniform surface corrosion is generally repaired by removing the corrosion products, and lightly abrading the metal to restore its surface finish.

2.3 Methods of preventing corrosion

Sophisticated corrosion protection schemes are used on aircraft structures to prevent corrosive attack. Enhanced protection is sometimes provided in susceptible areas through the use of corrosion inhibitors and corrosion preventive compounds. While a comprehensive discussion of these subjects is beyond the scope of this report, they will be introduced briefly at this point because their role in maintaining airworthiness will be discussed in later chapters.

2.3.1 Protection schemes

High strength aluminium alloys remain the predominant metallic material used in the construction of airframes. Aluminium alloy sheet is often coated during manufacture with a thin layer of pure aluminium (Alclad) which resists corrosive attack. Alternatively, smaller components may be anodized, which increases the thickness of the naturally protective aluminium oxide film. Other aluminium components are usually protected by the application of a chemical conversion coating, sealant, primer and topcoat.

Chemical conversion coatings, also known as chromate conversion coatings, chemical films, or pretreatments are aqueous acid solutions of active inorganic compounds which convert aluminium surfaces to a corrosion resistant film. Properly applied, these films provide corrosion resistance to the metal and improve the adhesion of subsequently applied paints.

Sealants are used around windows, in joints open to the weather, to isolate pressurised areas, in fuel tanks, in firewalls etc. They prevent the intrusion of moisture, salt, dust, and aircraft fluids, which can lead to extensive corrosion. There are numerous proprietary sealants, falling into two main categories. Polysulphide, polythioether, and polyurethane sealants consist of two parts, a base and a curing agent, which form a rubbery solid after mixing. Silicone sealants, on the other hand, cure by reacting with moisture in the air.

The paint system on an aircraft consists of a primer coat and a topcoat. The primer promotes adhesion and contains corrosion inhibitors, while the topcoat provides durability to the paint system, including weather and chemical resistance, along with the colouring necessary for operational requirements.

2.3.2 Corrosion inhibitors and corrosion preventive compounds

Corrosion inhibitors are chemical substances (often chromates, phosphates, nitrites, borates, and amines) which are normally added in small concentrations to other compounds or fluids in order to prevent corrosive attack. They are often incorporated into sealants, primers and paints, as well as fuels, coolants, hydraulic fluids, and other liquids which may come in contact with metallic components. Inhibitors are specific to the alloy to be protected, the compound to which it is added, and the environment in which the component operates. For example, chromates are sometimes used in paints and sealants to prevent corrosion in aluminium structure. The concentration level of the inhibitor is often important in determining its effectiveness.

Corrosion Preventive Compounds (CPCs), also commonly known as Water Displacing Corrosion Preventives (WDCPs) typically contain a film former such as an oil, grease or resin, a volatile, low surface-tension carrier solvent, a non-volatile hydrophobic additive, and various corrosion inhibtors. They act by firstly spreading across surfaces and penetrating into crevices while displacing any water which may be present. Evaporation of the water displacing compound and the carrier solvent leaves a waterproof film containing the hydrophobic additive and the corrosion inhibitor. CPCs are classified according to the type of film deposited on the surface, namely: oily, a soft and waxy film, or hard and resinous.

All CPCs are effective in reducing general corrosion to some degree (Wilson and Devereux (1984), Trathen and Hinton (1994)). Waxy or hard film CPCs are most effective in preventing general corrosion and surface pitting, while oily film CPCs are most able to penetrate crevices and have been shown to significantly reduce the rates of stress corrosion cracking (Trathen and Hinton (1994)), and corrosion fatigue (Agarwala and De Luccia (1980). Figure 2-7 shows the reduction in stress corrosion crack growth rate of 7075-T651 aluminium alloy which occurs after the application of WD-40, a commercial CPC. Figure 2-8 shows the reduction in corrosion fatigue crack growth rate of 4340 high strength steel after the application of oily film CPCs.

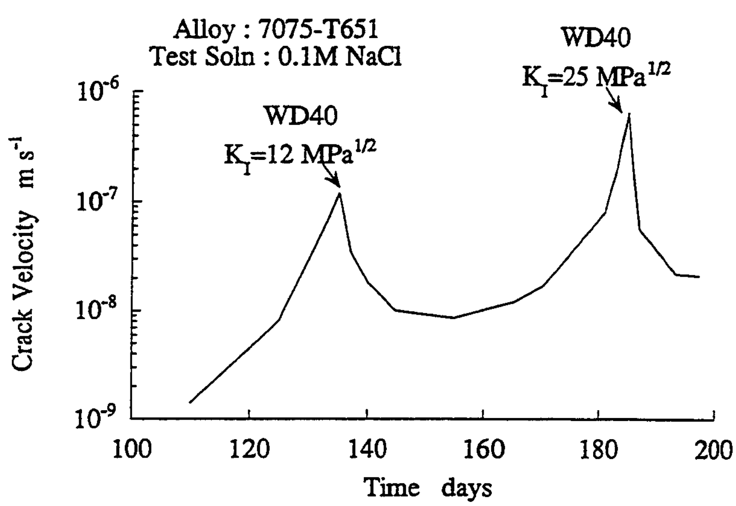


Figure 2-7: Reduction in stress corrosion crack velocity in 7075-T651 aluminium alloy caused by the application of WD-40. After Trathen and Hinton (1994).

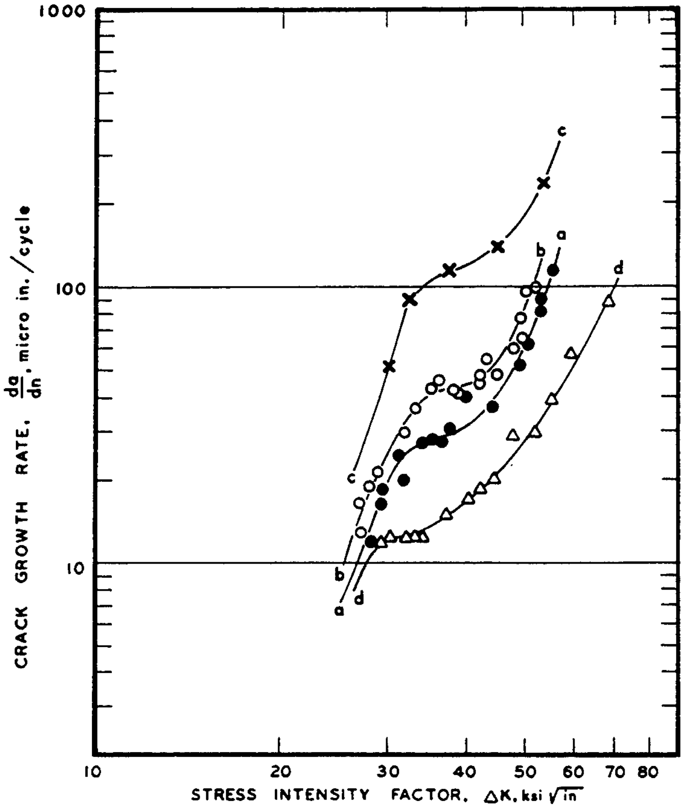


Figure 2-8: Reduction in corrosion fatigue crack growth rate in 4340 steel caused by application of corrosion inhibitors. Curves a-a and b-b represent environments of 90% relative humidity plus inhibitors; curve c-c represents 90% relative humidity only; curve d-d represents dry air (<15% humidity). After Agarwala and De Luccia (1980).

2.4 Corrosion surveys

There are several important corrosion survey programs which are currently being undertaken by the USAF.

As part of a life extension program, the USAF has undertaken a comprehensive teardown inspection of a retired KC-135 aircraft in order to determine the extent and severity of hidden corrosion (Nieser (1995)). An important aspect of this program is the evaluation of nondestructive inspection equipment aimed at detecting and quantifying corrosion damage.

Further, the Wright Laboratories are presently coordinating surveys of C-130, J-Stars (707), and C-5 aircraft for corrosion and widespread fatigue damage. The approach is to gather data from repair orders and teardown inspections where available, and a teardown inspection of a J-Stars (707) aircraft is planned.

3. Aircraft structural integrity

3.1 Introduction

Until recently, the obsolescence of aircraft which are approaching the end of their design life was ensured by the continued advance of aircraft technology. Under these circumstances, fatigue (which is usage rather than time dependent) presented the major risk to aircraft structural integrity, leading to the development of design philosophies which were aimed at minimising the risk of structural failure through fatigue crack growth. These philosophies have evolved to accommodate the deficiencies which became apparent in earlier approaches, and the extension of service lives beyond original design goals. They can now be regarded as structural fatigue management philosophies as well as design approaches, reflecting the need for the continuing management of structural fatigue throughout the service life of the aircraft.

As airframe design has matured, and economic constraints have become more acute, there has been increasing pressure to extend aircraft service lives beyond their original design goals. This pressure, reinforced by several major incidents, has raised concerns regarding the effect of corrosion on aircraft structural integrity, and has focussed attention on the development of structured programs aimed at controlling and preventing corrosion. Significantly, an increasing awareness that the interaction between corrosion and fatigue can create a much more potent threat to structural integrity than either the effects of corrosion or fatigue taken separately, has prompted interest in proposals that the effects of corrosion should be incorporated into aircraft structural integrity design philosophies. There appears to be widespread agreement between designers, operators and regulators that such a development is desirable, and furthermore that an appropriate methodology has not yet been developed to achieve this goal.

A detailed discussion of structural design philosophies which aim to minimise the risk of fatigue failure is beyond the scope of this report. However, a basic understanding of such philosophies is helpful in understanding the implications of corrosion and corrosive environments on aircraft structural integrity. The purpose of this chapter is to introduce these philosophies, as well as to describe in more detail the pre-requisite elements of aircraft structural integrity. The final section of this chapter discusses formal corrosion prevention and control programs.

3.2 Aircraft design philosophies for structural integrity

Aircraft in current military service are designed in accordance with one of three major structural integrity philosophies: the safe-life, fail-safe, or damage tolerant design approaches[1]. While recognising that the assurance of structural integrity *in service* may utilise features of all three philosophies, and indeed, current *design* approaches may have characteristics drawn from earlier philosophies, it is convenient here to describe the major features of each approach separately.

Safe-life design relies on a component, assembly or structure being assigned a "safe" service life based on an acceptable probability of failure under a given loading spectrum. At the end of this service life the component or structure is retired from service. The predicted design life is usually based on small scale specimen testing, and the design is commonly supported by a full-scale fatigue test which should demonstrate a life equivalent to the required service life multiplied by a suitable factor of safety. This factor of safety caters for variability in the fatigue data and errors in the prediction of fatigue performance under complex service environments. Most military fixed-wing aircraft and helicopters currently in service have been designed to safe-life principles, and the philosophy is usually used for components which exhibit no signs of distress before significant loss of function (for example, landing gear). Safe-life design has one major deficiency; service life may be reduced severely by the presence of initial defects, or service-related damage which was not represented in the original small-scale or full-scale tests.

The fail-safe approach is used in most civil transport aircraft, and relies on multiple load path design; the fundamental feature of fail-safety is structural redundancy, that is, the structural unit contains multiple load bearing paths or crack arrest features, so that after the failure of any single path, or the rapid propagation of a crack, the structure remains essentially intact and retains an adequate load-carrying capacity. In its original form, fail-safety had the drawback that once a member failed, load was shed to adjacent members, reducing their fatigue life.

Damage tolerance design assumes the existence of flaws in the structure prior to service usage. These flaws are generally assumed to be a consequence of the methods used during the manufacture of the airframe. The design rests upon estimating the growth of these flaws under the influence of service loading using the principles of fracture mechanics. Knowledge of the growth of such defects, and how the residual strength of the structure may be compromised as cracks develop, forms the basis for setting appropriate inspection intervals. This principle is illustrated in Figure 3-1; here, an initial flaw size consistent with the pre-service nondestructive inspection (NDI) detection limit is assumed to exist at the beginning of the service life. The

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[1] An earlier approach, based on design using static strength only, has not been relied upon for durability since the occurrence of a number of fatigue-related accidents to military aircraft in the late 1940's, and failures of civil passenger aircraft (the Comet) in the 1950s.

growth of this flaw is estimated along with the length that is likely to result in catastrophic failure of the structure. The calculation of a suitable inspection interval is based on crack growth analysis, knowledge of the fatigue and fracture properties of the material, and knowledge of the service loading environment. To reflect uncertainties in this knowledge, and probabilities of detection less than 100%, it is usual to select an inspection interval which allows at least two opportunities to detect the crack prior to it reaching its critical length. At the end of each inspection, if no crack is detected, a flaw is still assumed to exist which is now equivalent to the in-service nondestructive inspection detection limit (normally greater than the pre-service detection limit). The entire approach is supported by a suitable testing program.

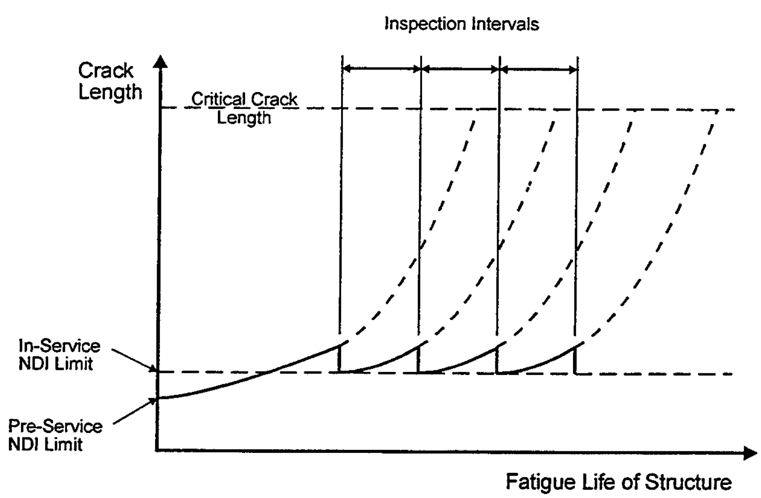

Figure 3-1: Schematic representation of the damage tolerance philosophy. Inspection intervals are set so that an assumed flaw will be detected before it reaches a critical length.

The damage tolerance approach classifies primary structure in the aircraft as either slow crack growth or fail-safe. Slow crack growth structure refers to single load path structure without crack arrest features, for example, landing gear members. If a crack initiates in either slow crack growth or fail-safe structure, adequate load-carrying capacity should be retained until the crack is detected during a future programmed inspection. In the case of fail-safe structure, allowance must be made for the increased likelihood of fatigue cracking along the load paths adjacent to a failed element because of load shedding.

Damage tolerant design is now featured in most modern civil transport aircraft, principally using a fail-safe approach, and in some military aircraft, which rely more heavily upon slow crack growth structure.

In effect, the major difference between safe-life and damage tolerant design is that damage tolerance demonstrates safety in the presence of cracks and may, on occasion, permit continued operation with known cracks after their detection. Furthermore, the damage tolerance philosophy recognises the need to identify component failures and relies on regular in-service inspection procedures to minimise the time a cracked member or failed component remains in service.

There are many instances where aircraft designed on the safe-life principle have developed cracks before their design lifetime has been achieved, or where technical and economic considerations have demanded the extension of their service lives beyond original design goals. In these cases, airworthiness is often assured using a safety-by- inspection approach. Here, a damage tolerance approach may be applied to fatigue critical sections of the structure. This forms the basis for an inspection program aimed at assuring the long term integrity of the aircraft.

The major design philosophies are described in detail in various military standards. Of particular interest are the American Department of Defense MIL-STD-1530A and AFGS-87221A which form the basis of the current United States Air Force design philosophy, and DEF STAN 00-970, Chapter 201 which describes the requirements for the fatigue design of British military aircraft.

AFGS-87221A provides guidance aimed at introducing damage tolerant designs into aircraft structures. Guidance is provided on the appropriate load spectra for various classes of military aircraft, the size of initial flaws which should be assumed, and the methodology for carrying out a durability and damage tolerance analysis (DADTA) which predicts the growth of the flaw under service loading.

DEF STAN 00-970 describes requirements for the design of aircraft structures and systems using both the safe-life and damage-tolerance philosophies. It suggests that the safe-life philosophy must be used where components exhibit no signs of distress before significant loss of function and can be used in all other circumstances except where a component is subject to accidental damage or where the aircraft specification requires fatigue-related inspections to be included in reliability-centred maintenance.

There are some notable aspects of these standards. Firstly, they are not applicable in cases where large numbers of small, virtually undetectable cracks may suddenly link-up to form a single crack of catastrophic proportions (i.e. multi-site damage). Secondly, allowance is made, in general terms, for the influence of environment on fatigue crack growth. For example, Leaflet 201/1 in DEF STAN 00-970 recognises that there is evidence that crack propagation rates can increase in corrosive environments and suggests that environmental effects must therefore be considered. Similarly, MIL-STD-1530A recommends that the durability and damage tolerance procedures shall account for those factors affecting the time for cracks or equivalent damage to reach sizes large enough to cause uneconomical functional problems, repair, modification or replacement. These factors shall include initial quality and initial quality variations, chemical/thermal environment, load sequence and environment interaction effects, material property variations, and analytical uncertainties.

The crucial point, however, is that neither standard provides firm guidance on the manner in which environmental factors are to be taken into consideration. Critical issues include:

1. the appropriate environment applicable during fatigue life analysis and testing,
2. the nature of load sequence and environment interaction effects, and
3. how corrosion-related defects are to be considered in safe-life and damage tolerance analyses.

In general, full-scale tests used to validate airframe design are carried out under laboratory conditions, and guidance is provided on the interpretation of the results from such tests when considering the safe lives of service aircraft. However, the degrading effects of corrosive environments are not considered explicitly. There is also no guidance provided on how variations in fatigue loading and environment may combine to accelerate or retard the propagation of fatigue cracking. Also of major significance is the manner in which corrosion-related defects are to be treated in damage tolerance analyses. This may require some guidance on issues such as the assumptions required for the prediction of the progression of corrosion defects to fatigue cracks, and their subsequent propagation.

3.3 The elements of aircraft structural integrity

Depending on the philosophy adopted during the design and maintenance of a military aircraft, its continued airworthiness relies on several pre-requisites. In the case of aircraft designed in accordance with the safe-life philosophy, a representative full-scale fatigue test is required. In the case of aircraft designed to the damage tolerance philosophy, the airworthiness depends on the reliable inspection of critical sections of the structure, the determination of residual strength if defects are found, and the prediction of defect growth.

3.3.1 Full-scale fatigue testing

The full-scale fatigue test has three primary objectives:

1. to demonstrate compliance with an appropriate specification (for example, DEF STAN 00-970),
2. to identify any features which have insufficient fatigue life, and
3. to demonstrate crack growth characteristics for components which are to be treated on a damage tolerance basis.

In the case of military aircraft, it is common to test safe-life designs to the equivalent of 5 service lifetimes (or $3^1/_3$ times in the case of airframes which are fitted with instruments and monitored). These factors account for the scatter inherent in fatigue testing. For damage tolerant designs, it is common to test the structure to 3 service lifetimes.

On completion of the fatigue test it is desirable to demonstrate that 1.2 times the design limit load can be sustained by the structure. After this final substantiation of the load carrying capacity, a teardown inspection is carried out with the aim of revealing any significant damage which has not been observed during the test.

Full-scale fatigue tests do not generally attempt to account for the influence of corrosive environments, largely because of the extra complexity and cost involved. Many full-scale fatigue tests are carried out in an indoor laboratory where no special control is placed on the temperature or humidity of the air. Exceptions to this have included tests conducted by the RAE during the 1950s and 1960s (Winkworth (1961)), and tests carried out by the Boeing Company on large civil jet transport aircraft (Goranson and Miller (1989), Varanasi and McGuire (1995)). Within the Boeing company it is standard practice to carry out full-scale fatigue tests in an outdoors environment. However, such tests have a typical duration of between 1 and 2 years, and therefore cannot be considered to adequately represent the type of corrosion defects typically found on service aircraft. For this reason, Boeing and other civil jet transport manufacturers have pursued a policy of repurchasing from operators aircraft which are approaching or have exceeded their design life, and conducting further full-scale fatigue testing. While such tests cannot account properly for the full range of deterioration expected in the fleet as a result of aircraft-to-aircraft variability, and variations in environment and maintenance, they nevertheless provide valuable information about the fatigue behaviour of aircraft which contain repairs and service-related defects such as corrosion and accidental damage. Such information greatly increases the confidence in any life extension proposed for these aircraft.

3.3.2 Inspection

During the course of their service lives, aircraft are routinely inspected using a variety of nondestructive inspection methods; such inspections often arise as a solution to in-service problems, but may be part of a regular inspection required as part of the design.

There has been considerable interest in recent times in the inspection of airframes for corrosion. While visual inspection remains the most widely used inspection approach for the majority of aircraft components, other conventional nondestructive inspection techniques have also been applied to the detection of hidden corrosion (i.e. corrosion not detectable by visual means); comprehensive summaries are provided by Beissner and Birring (1988), Ansley *et al.* (1992), Smith and Bruce (1994), Agarwala *et al.* (1995), and Bruce (1992, 1995). The techniques most applicable to RAAF operations have been reviewed by Bishop *et al.* (1993).

Considerable work has been aimed at enhancing these conventional methods of non-destructive inspection for the detection of hidden corrosion. These techniques have included radiography, ultrasonics, eddy current, and thermal imaging (Smith (1992), Winfree and Heyman (1991)), and the relative capabilities of these methods is shown in Table 3-1. The second and third columns in this table refer to the minimum material loss in a single plate which can be detected under ideal laboratory conditions, and the minimum material loss under practical conditions respectively. It is important to observe that most conventional nondestructive inspection equipment is optimised for the detection of crack-like defects. The detection limits given in Table 3-1 refer to enhancements of conventional techniques aimed specifically at detecting corrosion.

Table 3-1: Capabilities of non-destructive inspection methods which have been enhanced for corrosion detection. Detection limits refer to the minimum material loss in a single plate. Note that "in-field" detection limits may be degraded (possibly by orders of magnitude) from the figures presented, as a result of a wide range of factors. After Bruce (1992).

NDI Method	Laboratory detection limit (mm)	Practical detection limit (mm)	Effect of Layers	Effect of Fasteners
X-Radiography	0.08	0.25	No effect (unless products trapped)	No effect
Neutron Radiography	0.08 of corrosion product	0.25 of corrosion product	May be unusable if hydrogen present	No effect unless hydrogen present
Ultrasonic thickness measurement	0.01	0.05	1 or 2	No effect unless under countersink
Ultrasonic amplitude measurement	0.02	0.1	1 or 2	May be affected by surface quality
Eddy Current	(a)	0.1	Usable but difficult to interpret	Unusable close to fasteners
Thermography	3.0, or 50% thickness	(b)	1	Unusable within 20-30 mm

Notes: (a) The sensitivity of eddy current methods varies so greatly depending on probe geometry, frequency, and material thickness that it is impossible to specify a minimum laboratory detectability.
(b) There is insufficient experience in the use of thermography for corrosion detection to assign a realistic practical detection limit.

Alcott (1994) has discussed the use of existing non-destructive inspection techniques to detect hidden corrosion in the fuselage lap joints of KC-135 and E-3 aircraft, and concluded that the reliability of detection is heavily dependent on the skill and knowledge of the operator. For example, one operator using ultrasonic equipment detected 100% of the hidden corrosion with only 15% false calls (i.e. detecting corrosion when, in fact, none was present), while another operator, also using ultrasonic equipment failed to detect any of the hidden corrosion and had a false call rate of 100%! The results of eddy current inspections showed similar variability between individual operators.

There is considerable ongoing research into improving existing methods of non-destructive inspection, and developing new techniques aimed at detecting hidden corrosion. Among the more promising of these are enhanced visual techniques, and advanced X-radiography methods (Beattie *et al.* (1994)).

An example of an enhanced visual technique is the double pass retroreflection, or D-Sight technique (Komorowski *et al.* (1995)). Reflected light at a low angle of incidence is used to enhance out of plane deformations, and is ideally suited to detecting the "pillowing" which is associated with corrosion on the faying surfaces of lap joints between thin sections. The D-Sight technique has the advantage of being able to inspect large areas relatively quickly, however, at low levels of corrosion (2 to 3% of the thickness) surface irregularities produced during manufacture may lead to false calls. In particular, where joints have been reworked with a thick layer of sealant, it may give indications similar to those from a corroded joint.

An advanced radiographic technique which has been described by Bishop *et al.* (1993) is Compton backscattering. This relies on the principle that some materials can produce large amounts of back-scattered X-radiation when irradiated by an X-ray beam. A collimator is used to isolate the radiation from a particular element of material, and by scanning the whole system, the whole component may be examined, building up a three dimensional image, the variations in backscattered intensity providing an indication of variations in material density. Compton scattering has the potential to image hidden corrosion products by virtue of the change in surface morphology, or as a result of the variation in the density between the metal and the corrosion product itself. Recent AMRL experimental work has indicated that there is potential in this method, but the technology needs further development to allow application to a number of problems of interest to the RAAF.

Sensors designed to monitor corrosion activity have also received some attention (Rothwell and Eden (1992), Smart and Weetman (1995)). These are usually based on monitoring the electrochemical signals which are generated spontaneously by changes in the electrochemical conditions at the corroding surface. In theory, this enables the identification of the corrosion processes (such as the degradation of corrosion protection schemes, pitting, stress corrosion cracking etc.) which precede the development of observable damage, although little has been demonstrated beyond the laboratory to date. These sensors further offer the possibility of identifying the most corrosive periods during the operation of an aircraft.

3.3.3 Residual strength

The residual strength of a component or structure may be determined by an appropriate structural analysis, or by a suitable testing program, or both. The analysis or tests must contain a sufficient degree of conservatism to allow for uncertainties in the applied loads and environmental conditions.

A structural analysis to determine the effect of defects or cracks on static strength needs to consider all possible failure modes, such as elastic instability and fracture. Specialised stress analysis techniques such as the finite element method may be used; recent developments in these types of analysis have been described by Harris *et al.* (1995). In general, the usefulness and accuracy of such analyses is limited by the time and expense incurred modelling complex structural configurations, and by the uncertainties in the input loading data.

On the experimental verification of residual strength, DEF STAN 00-970 states that, on the completion of a full-scale fatigue test, it is *desirable* to demonstrate that 1.2 times the design limit load can be sustained in each of the principal fatigue-loading cases.

AFGS-87221A allows the residual strength to be established by the application of a proof load. Perhaps the best example of this is the cold proof loading test applied to the F-111 aircraft (Buntin (1971). This test serves, in part, to verify the residual strength of the ultra high strength steel wing carry-through structure by applying critical design limit loads to the wings. Conservatism is introduced by carrying out the entire proof loading procedure at -40°C, which is below the minimum expected service temperature[2]. The fracture toughness of the steel is lower at this temperature than at normal service temperatures.

Aircraft structural repair manuals usually provide guidance on the negligible damage limits for each major structural item, i.e. the maximum amount of material that may be removed from the item while preserving its design limit load-carrying capacity. The effect on residual strength of types of corrosion, and their repairs, which simply reduce the thickness of components may be accounted for relatively easily by observing the negligible damage limits. However the effect on residual strength of corrosion which does not reduce component thickness, such as intergranular corrosion and stress corrosion cracking, is not so easily predicted. It is, however, clearly of interest in the determination of aircraft structural integrity and this topic is discussed more fully in Chapter 4.

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[2] This level of conservatism also serves to provide an assurance of fracture safety for a future service period; in this respect the test is in part an application of a safety-by-inspection approach.

3.3.4 Defect growth

It can be seen from Figure 3-1 that the prediction of defect growth is an important factor in setting appropriate inspection intervals. This is usually accomplished by analysis using the principles of linear elastic fracture mechanics. The pre-requisites for such an analysis include a knowledge of the service loading spectrum applied to the component or structure, a stress analysis which is sufficiently detailed to provide stress intensity factors at potential defects, experimental data describing fatigue crack propagation in the material concerned, and a fatigue crack growth model which has been suitably validated against experimental crack growth data.

Experimental fatigue crack propagation data is usually derived under constant amplitude loading conditions and is presented in the form of curves describing the relationship between the crack growth increment per fatigue cycle, da/dN, and the stress intensity factor range at the tip of the crack, ΔK, which is a function of the length and geometry of the crack. The operation of aircraft in corrosive environments is often accounted for by using experimental fatigue crack propagation data which has been derived in an appropriate environment, for example, humid air, and the choice of a particularly severe environment may introduce some conservatism to the prediction.

Fatigue crack growth models vary in complexity and capability. A good model will be able to account for load sequence effects. At present, fatigue crack growth models remain a topic of keen research interest (Lazzeri *et al.* (1995)); they tend to be used primarily in situations where small-scale tests already reproduce many of the service conditions expected, and in which, therefore, the model is required to deal only with relatively minor variations in service conditions.

The effects of corrosion and the presence of corrosive environments has a significant influence on the initiation and propagation of fatigue cracks. This clearly has major implications for the setting of appropriate inspection intervals and is discussed in detail in Chapter 5.

3.4 Corrosion Prevention and Control Programs

3.4.1 Civil experience

The potential for corrosion to interfere with the operation of aircraft systems and structures and therefore jeopardize airworthiness has been recognised by aircraft operators, manufacturers and airworthiness authorities for some time. Increasing concern over the airworthiness of the ageing jet transport fleet—highlighted by the Aloha Airlines 737 incident—has led to the development and increasing acceptance of formal aircraft corrosion prevention and control programs (CPCPs).

The United States Federal Aviation Administration (FAA) Advisory Circular AC 43-4A describes the basic philosophy of a corrosion prevention and control program, which should consist of the following:

1. adequately trained personnel in the recognition of corrosion including conditions, detection and identification, cleaning, treating, and preservation;
2. thorough knowledge of corrosion identification techniques;
3. proper emphasis on the concept of all hands responsibility for corrosion control;
4. inspection for corrosion on a scheduled basis;
5. aircraft washing at regularly scheduled intervals;
6. routine cleaning or wipe down of all exposed unpainted surfaces;
7. keeping drain holes and passages open and functional;
8. inspection, removal, and reapplication of preservation compounds on a scheduled basis;
9. early detection and repair of damaged protective coatings;
10. thorough cleaning, lubrication, and preservation at prescribed intervals;
11. prompt corrosion treatment after detection;
12. accurate record keeping and reporting of material or design deficiencies; and
13. use of appropriate materials, equipment, and technical publications.

This circular also describes in general terms corrosion protection schemes, the identification and classification of various forms of corrosion, procedures for removing corrosion when it occurs, and subsequently treating the affected area in order to prevent further attack. Corrosion inspection intervals for general structure are suggested on the basis of the environment in which the aircraft operates. The suggested intervals are 90 days for mild environments, 45 days for moderate environments, and 15 days for severe environments.

Corrosion prevention and control programs may also be supported by aircraft manufacturers. For example, programs have been developed by the Boeing company, in conjunction with operators and the FAA, to establish mandatory corrosion inspection and maintenance procedures for most of the Boeing range of civil jet transport aircraft (Goranson and Miller (1989), Goranson (1991)). The results of teardown inspections of ageing aircraft have been combined with representative worldwide fleet surveys to develop baseline programs which represent the minimum requirements for typical operators. Individual operators who experience significant corrosion after applying the baseline program must then modify or improve their particular program until corrosion is controlled within acceptable severity limits. The CPCPs establish the corrosion inspection thresholds and repeat inspection intervals for specific locations in the structure of each aircraft model. Furthermore, they describe procedures for inspection, classification of corrosion damage, and its subsequent repair. Corrosion is classified according to its severity, which reflects the increased risk of structural failure and the likely rate of recurrence. For example:

(a) Level 1 corrosion refers to corrosion that may be blended out within the allowable limits specified in the aircraft structural repair manual, or which exceeds these limits only after multiple inspections or as a result of a unique event.
(b) Level 2 refers to corrosion which has progressed beyond allowable limits within a single inspection period.
(c) Level 3 refers to corrosion which represents a potential urgent airworthiness concern.

The general approach taken is to attempt to reduce the incidence of Levels 2 and 3 corrosion by improved treatment and increased inspection frequency.

An important feature of the program is the necessity to report the incidence of Level 2 and 3 corrosion to the manufacturer. This information enables the continuing development of the CPCP.

There have been some noteworthy outcomes from the Boeing experience in developing corrosion prevention and control programs:

1. Surveys have indicated that the aircraft which were in the best condition were those where the operators had initiated corrosion prevention and control procedures early in the life of the aircraft. This finding provided a strong indication that good maintenance practices far outweigh aircraft age as a factor influencing corrosion. The application of effective preventive measures after corrosion has been repaired is also important. Indeed, Boeing have cautioned that corrosion prevention and control measures must be aggressively pursued both to reduce the need for extensive repair and to promote continued airworthiness.

2. Boeing consider that corrosion damage may or may not be time or usage dependent. For example, deterioration resulting from a breakdown in a surface protection system is more probable as calendar age increases; conversely corrosion due to spillage or a leaking seal is treated as a random discrete event.

Figure 3-2 illustrates the concept of damage due to corrosion being established at a constant rate relatively early in the life of an aircraft, and then possibly increasing as the aircraft approaches its design life. The rate of corrosion damage may be kept fairly constant throughout the life of the aircraft through the careful observation of an appropriate corrosion control plan, however, it is increasingly likely that corrosion will be associated with other forms of damage such as fatigue cracking. These observations have an important consequence for the setting of inspection thresholds. For example, if the occurrence of corrosion is assumed to be random, the threshold inspection interval for corrosion damage should be the same as the repeat inspection interval.

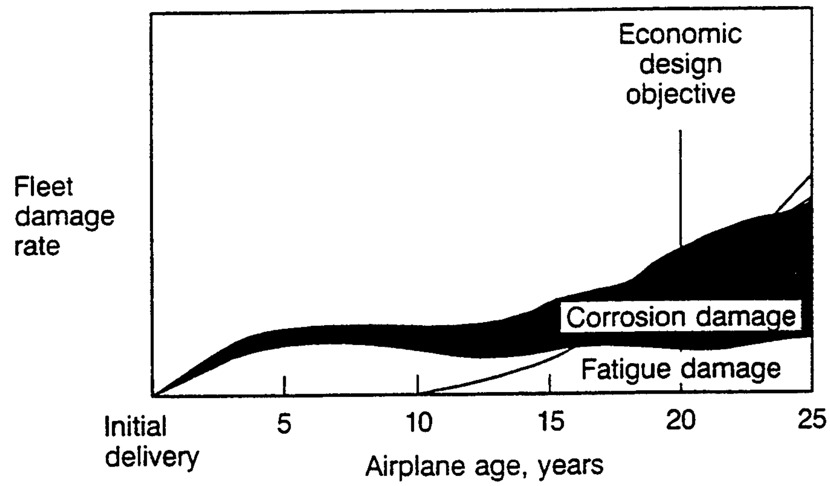


Figure 3-2: Expected corrosion and fatigue damage rates through the life of a civil jet transport aircraft.

3.4.2 RAAF applications

At present, the Boeing Corrosion Prevention and Control Program is applicable to only the B707 aircraft in the RAAF fleet. It represents a structured, inspection-based approach to the management of corrosion, and as such, offers significant benefits over the *ad hoc* approach adopted by some other manufacturers. Clearly, while it would be desirable for RAAF to have access to similar plans for other aircraft types, it would be difficult for RAAF to generate such programs without active involvement of the OEM (and in particular, without access to the worldwide fleet database and corrosion reporting systems which only the OEM can manage). Nevertheless, it is likely that there would be some benefit to RAAF in examining the Boeing approach (and others) to determine whether or not some aspects could be applied more widely. Possible examples include the classification system for corrosion, and the use of inspection intervals for corrosion which are responsive to the corrosion severity.

4. The influence of prior corrosion and corrosive environments on residual strength

4.1 Introduction

The previous chapter on aircraft structural integrity indicated the well-defined techniques which exist for the calculation of residual strength in the presence of fatigue damage. However, methods for calculating residual strength when corrosion is present are less well defined.

It is therefore relevant to review the literature concerned with environmental effects on residual strength. By way of introduction this chapter describes some recent examples where the presence of corrosion has raised concerns regarding the static structural strength of RAAF aircraft. The literature describing the effects of prior corrosion and corrosive environments on static strength is then reviewed. The effects of corrosion repair and control on static strength are then discussed before the major points and conclusions of the chapter are summarised.

4.2 Examples and experience

All RAAF aircraft types are subject to corrosion strikes, and it would not be productive to list all cases. Many of these strikes, if left untreated, would pose a threat to structural strength, but in most cases, relatively basic corrosion management procedures prevent any concerns from arising. Several cases, however, have highlighted concerns about corrosion affecting the structural strength of RAAF aircraft; these include the tailplane spar caps of the Macchi MB326H, the wing rear spar caps on the P3-C, and the Butt Line 20 longerons in the C-130. These examples are discussed briefly below.

4.2.1 RAAF - Macchi tailplane spar caps

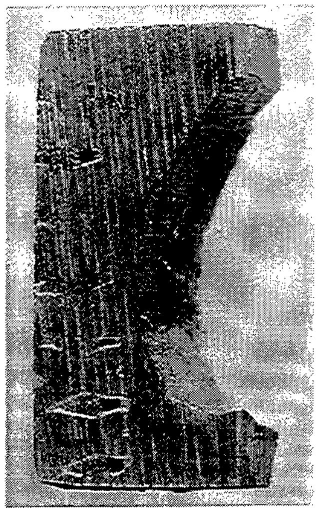
In the case of the MB326H, teardown inspections carried out during the Macchi Recovery Program revealed stress corrosion cracking in the upper and lower spar caps of the horizontal tailplane. The cracking had propagated in the lengthwise direction of the spar caps, which were manufactured from a 7075-T6 aluminium alloy extrusion. The initial response to the detection of the stress corrosion cracks was to develop an inspection procedure to enable the Macchi fleet to continue operation through to its planned withdrawal date. However, limitations with the available inspection techniques, accessibility, and corrosion inhibiting methods, and lack of a suitably accurate prediction capability for the growth of SCC made it impossible to guarantee the long term airworthiness of the horizontal tailplane. In the long term it was therefore necessary to replace the spar caps.

However, it was necessary to assess the structural integrity of the spar caps for short-term use until they could be replaced. As part of this program, static testing of two horizontal tailplanes retired after approximately 20 years service was carried out by AMRL (Luke *et al.* (1995)). The purpose of these tests was to demonstrate the load-carrying capacity of tailplanes containing stress corrosion cracking typical of the fleet.

Both tailplanes sustained the Design Limit Load (DLL) and were further tested to failure. Final failure occurred at 2.5 times the DLL in a region of the spar remote from any stress corrosion cracking. This final failure load was consistent with tests conducted by the original manufacturer. Subsequent teardown inspection revealed that stress corrosion cracks up to 30 mm in length existed in the spar caps (Athiniotis (1995a)). The cracking had propagated in the lengthwise direction of the spar caps, Figure 4-1. This orientation is typical of stress corrosion cracking in extruded sections where the elongated grain structure increases the susceptibility in the longitudinal direction. Since there was no evidence that static testing had caused the cracks to tear or propagate in any other way, it was concluded that the presence of stress corrosion cracks of this orientation and length had little effect on the static strength of the tailplane. However, the sparse distribution of the stress corrosion cracking prevented any additional conclusions being drawn about the effect of multiple damage sites, including their ability to join up and compromise residual strength. Together with a number of other considerations, the high level of residual strength demonstrated in the test allowed the continued operation of the fleet until tailplane spars could be replaced.

4.2.2 RAAF - P-3C wing rear spar caps

RAAF P-3C aircraft spend a significant portion of their operating time flying at low level over a marine environment. A RAAF survey of three P-3C aircraft revealed a variety of corrosion problems in the upper and lower wing rear spar caps, including exfoliation and stress corrosion cracking (Remacha (1993)). On one aircraft the corrosion damage was such that the manufacturer was unwilling to permit normal aircraft operations without appropriate repair actions (Dale (1993)). Uncertainties regarding the residual strength of the structure, particularly the behaviour of stress corrosion cracks (which had propagated in the lengthwise direction of the spar caps) under the action of compressive loads, led to the decision to refurbish the wings in selected P-3C aircraft by replacing the spar caps.



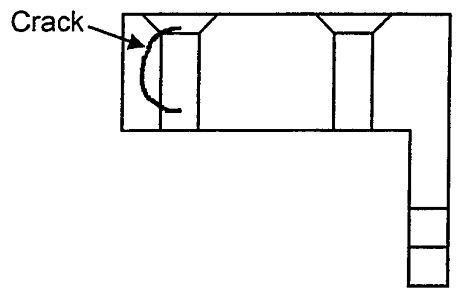


Figure 4-1: Stress corrosion cracking in a 7075-T6 aluminium alloy tailplane spar cap from a Macchi MB326H. The crack propagated along the lengthwise direction of the spar cap. After Athiniotis (1995a).

4.2.3 RAAF - C-130 Butt Line 20 longerons

Intergranular corrosion was detected in the Butt Line 20 longerons of a RAAF C-130 aircraft during routine inspection. The corrosion originated at the bores of fastener holes in the flanges and had formed laminar defects parallel to the flange surface. Further inspections determined that most aircraft in the fleet suffered similar corrosion. While the intergranular corrosion itself removes a minimal amount of material from the longeron, the repair of this corrosion by grindout would have necessitated the grinding out of considerable areas of sound material in order to access the intergranular corrosion (Van Dijk (1992)). Such grindout repairs would have necessitated substantial reinforcement of the repaired region in order to restore the residual strength of the structure, while replacement of the longerons would have been difficult and expensive. In some aircraft the problem was managed by treating the corrosion with a corrosion preventive compound to control its progress while continuing a regular monitoring program. The problem is significant in that the stressing is fairly complex at that location, and the corrosion was oriented in a direction which was close to parallel to the major stressing direction; as a result, no analysis approach was apparent. One proposed residual strength analysis adopted a very conservative approach, assuming that the corrosion was equivalent to a deep crack-like defect oriented normal to the major stress direction.

4.3 The effect of prior corrosion on static strength

Upon detection of corrosion in an airframe, it is usually removed in accordance with the aircraft structural repair manual. It is common for the manual to provide "negligible damage limits" which represent the maximum depth of corrosion which may be removed without compromising the ability of the structure to sustain its design loads. When the depth of corrosion has progressed beyond these limits the part is either replaced, or repaired using a metallic or composite patch to assure its residual strength.

There are instances, however, when this approach may not reflect the likely effect of corrosion on residual strength. For example, stress corrosion cracking and intergranular corrosion remove a negligible amount of load-bearing material, and the orientation of these types of defects is commonly parallel to the applied service stresses. It is therefore difficult to relate the length of stress corrosion cracking, or its depthwise location in the component, to the negligible damage limits for grindout type repairs.

Clearly, corrosion which removes negligible load bearing material and is oriented along a spar is only likely to cause failure by either:

1. buckling under compression loading, or
2. promotion of fastener failure.

Shaw (1994b) has described a procedure for calculating the critical length of stress corrosion cracks in P-3C wing rear spar caps by equating the buckling strength of the leg of the spar cap which becomes unsupported as a result of stress corrosion cracking, to the crippling strength of an intact spar cap. This approach illustrates one method of accounting for the effects of corrosion in the determination of residual strength, namely, making a suitably conservative assumption about the structural behaviour of in the presence of corrosion, and carrying out a conventional engineering analysis.

While the incorporation of the geometric effects of corrosion into conventional engineering analyses appears a reasonable approach to determining the effects of corrosion on residual strength, there appears to have been surprisingly little research aimed at validating such procedures.

Despite the scarcity of research dealing with the influence of prior corrosion on the static strength of aircraft structures there are several recent research programs which are worth discussing.

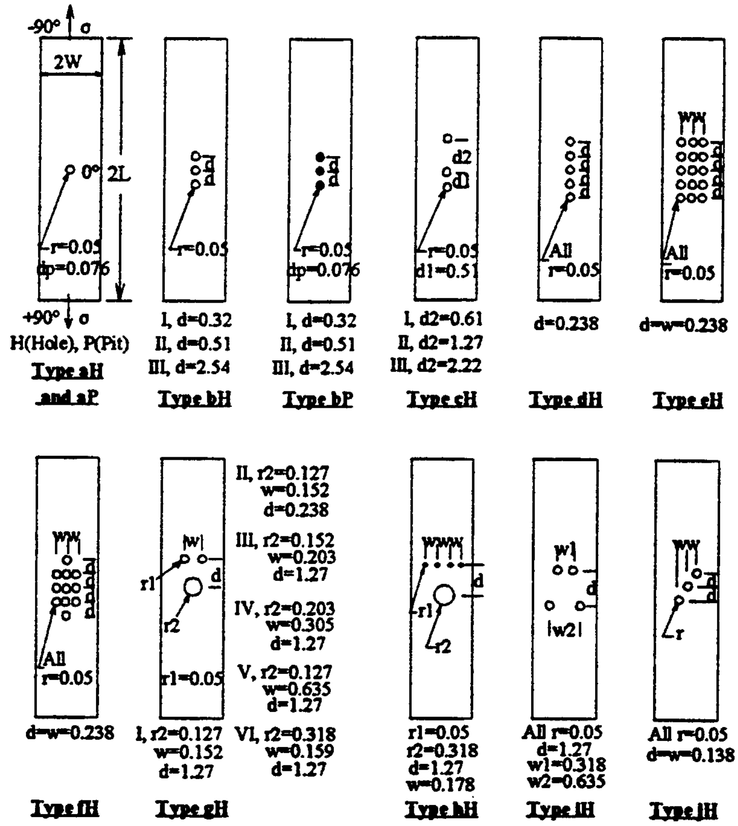
The effect of prior corrosion and natural "weathering" on the mechanical properties of aircraft materials has been investigated by Grandt (1995) as part of the USAF KC-135 life extension program. Samples of aluminium alloy sheet material of grades 2024-T3, 7075-T6 and 7178-T6 were taken from three aircraft which had experienced in excess of

20 years service. The corrosion was characterised (unfortunately, only subjectively) as "light" in the 7075-T6, "moderate" in the 2024-T3, and "none" in the 7178-T6. Static tensile tests were carried out on all three materials and the tensile stress-strain properties were found to be unchanged with respect to handbook data for virgin material. These results agree with independent work reported by Smith *et al.* (1995) which showed that two years outdoor exposure in a coastal environment caused little degradation in the ultimate tensile strength of 2024-T3 sheet. However, similar exposure led to a 20% reduction in the apparent ultimate tensile strength of 2014-T6 sheet. The most likely reason for this was that the reduction in area caused by the high weight loss and severe pitting of this alloy was not accounted for when calculating the tensile strength.

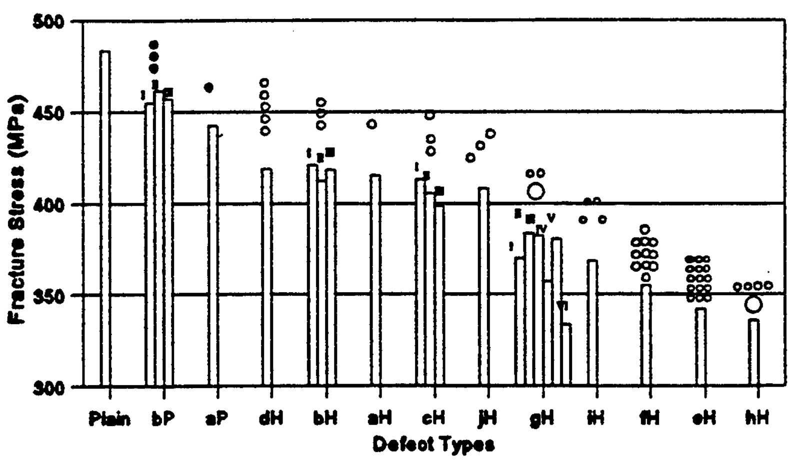
Exploratory work on the effect of corrosion pitting on the fracture strength of 2024-T3 aluminium alloy sheet has been carried out by Mal and Lee (1995). Different sizes of holes in varying arrangements were drilled in tensile specimens to simulate different pit topology in corroded sheets. In some cases the drilled holes perforated the specimens while in others the holes were drilled through only part of the thickness of the sheet. Typical patterns of holes are shown in Figure 4-2(a). The specimens were loaded statically in tension until failure and the fracture stress recorded. The results are shown in Figure 4-2(b). Generally speaking, arrays of small, closely spaced holes appear more deleterious than larger, more widely distributed holes. A finite element analysis of several specimens was conducted in support of the experimental work and some agreement was obtained. Considerably more work would be required to develop the conclusions of this study to predict the static strength of aircraft components subject to pitting corrosion.

Chubb *et al.* (1995) have investigated the effect of exfoliation corrosion on the fracture strength of 7178-T6 aluminium alloy specimens. Figure 4-3 illustrates how patches of exfoliation corrosion were produced on one side of the fracture specimens by exposing this area to EXCO, an aggressive chemical solution, which generated exfoliation corrosion to a depth of 0.6 mm (approximately 12% of the material thickness) in just four days. A fatigue crack was propagated from a starter notch at the edge of each specimen into the corroded patch. The fracture toughness of these specimens was compared to the as-received sheet as well as specimens which had been mechanically thinned in the patch region by machining. The reduction in fracture toughness caused by the corrosion was less than 10%, and was consistent with the thinning of the plate. It can therefore be concluded that under these conditions there was no significant reduction in the toughness of the bulk material, and that the influence of corrosion can be satisfactorily accounted for by the reduction in material thickness.

The effects of corrosion altering the geometry of fuselage lap joints have been investigated by Bellinger *et al.* (1994, 1995). Figure 4-4 shows the joint examined. A model was developed which predicted the out of plane displacements, or "pillowing" which is caused by corrosion of the faying surfaces in the joint. This pillowing is caused by the considerable increase in volume which takes place as aluminium on the faying surface is converted to corrosion product. The most important effect of this



(a)



(b)

Figure 4-2: Experimental investigation of the effect of corrosion pitting on static strength. (a) Configuration of drilled holes used to simulate varying corrosion pit topology; (b) Fracture strength of specimens. After Mal and Lee (1995).

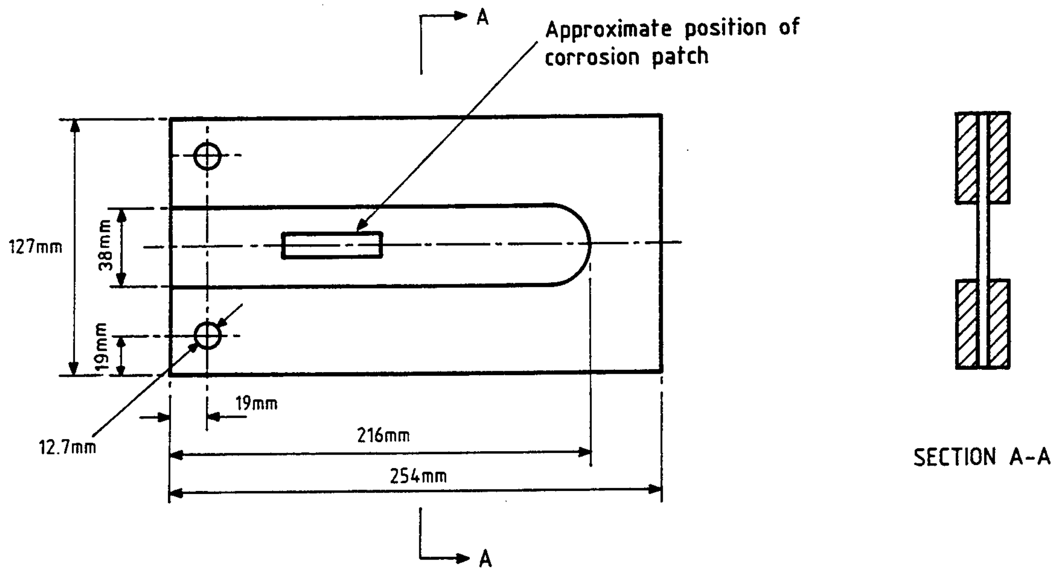


Figure 4-3: Test specimen used to investigate the effect of exfoliation corrosion on the fracture strength of 7178-T6 aluminium alloy. After Chubb et al. (1995).

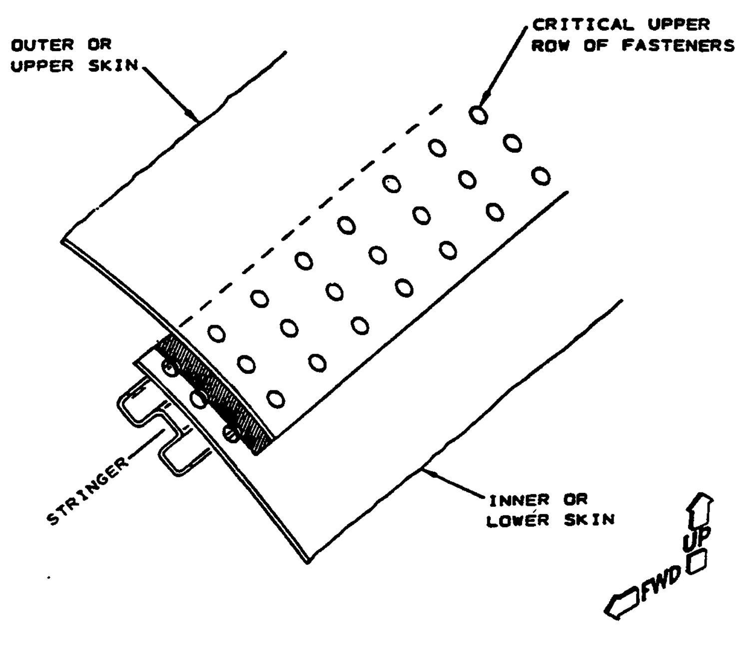


Figure 4-4: Configuration of the fuselage lap joint studied by Bellinger et al. (1994).

pillowing from the viewpoint of structural integrity is that relatively high levels of secondary bending stress may be induced under service loading. Bellinger *et al.* have reported that, under service loading, the stress at the critical row of rivets on the outer skin of a typical 2024-T3 lap joint may reach the material yield strength with only a 6% loss in thickness due to corrosion. Therefore the effect of corrosion in this case is to increase the stresses to a significantly greater level than can be accounted for by material thinning. While this investigation was directed at fuselage lap joints, similar behaviour may also be expected in any load-carrying joints made from aluminium alloy where corrosion can occur on the faying surfaces.

In general, the load transfer capability of the joint will be altered by the poor faying surface contact, the faying surface corrosion causing increased fastener load transfer.

4.4 The effect of corrosive environments on static strength

There has been little work aimed at establishing the influence of corrosive environments on the static strength of aircraft materials or structures. This is perhaps not surprising in view of the vastly different rates by which corrosion and the mechanisms controlling static failure occur. It therefore seems reasonable to assume that the corrosion mechanisms prevalent on aircraft structures have no direct influence on static strength.

However, it is well known that the resistance of some materials to rapid fracture is substantially lowered by the presence of certain environments (Lynch (1988)). This is particularly the case for some alloys in liquid metal environments. An example is 7075 aluminium alloy exposed to mercury.

The fracture resistance of some alloys may be reduced when exposed to environments which can introduce hydrogen into the material. This is known as hydrogen-assisted cracking (sometimes known as hydrogen embrittlement). The precise mechanism of hydrogen assisted cracking remains the subject of debate. However, the most likely process appears to be that hydrogen is adsorbed on the surface of a solid metal by the processes of gas dissociation or proton reduction. The atomic hydrogen diffuses into the metal, where it exists interstitially. At interior cavities, such as the interfaces produced when inclusions contract on cooling from the melt or decohere during rolling, or at regions of high triaxial stress, the hydrogen atoms are free to recombine to form gas. The significant features are, firstly, that hydrogen gas at the interior cavities is at high pressure and so exerts a force tending to separate the metal atoms, and secondly, that hydrogen atoms at the grain boundaries lower the cohesive force between the grains.

The ability of hydrogen to reduce fracture toughness is implicated in a range of corrosion processes; the moisture in the environment (atmospheric water vapour, liquid water, or the hydrogen in hydroxides in corrosion product) can be the source of the hydrogen, and the time-dependence of the corrosion process may well be related to the time-dependence of the hydrogen adsorption, dissociation and diffusion processes.

High strength steels tend to be susceptible to hydrogen assisted cracking in certain environments, and a major concern is therefore the possible embrittlement of high strength steel parts such as landing gear components as a result of corrosion or inadequate plating processes. Overall, however, there is little evidence to suggest that the material/environment systems commonly encountered in airframes exhibit hydrogen assisted cracking.

4.5 The effect of corrosion repair and control on static strength

Provided that corrosion damage is localised and within negligible damage limits it is usually repaired by machining out the affected area. Grinding is the most common method for this with the damaged areas blended to the existing surfaces in order to minimise any stress concentration effect. It is generally assumed that the grinding removes all corrosion damage and, provided negligible damage limits are observed, there is no loss of ultimate load carrying capacity. If corrosion damage exceeds negligible damage limits, components are usually replaced, although a thoroughly validated repair may also be acceptable on occasions. Such repairs are usually in the form of a metallic or bonded composite patch which restores the strength of the structure to its original level. In some cases repairs may be validated by an appropriate testing program in conjunction with advanced structural analysis techniques such as the finite element method.

Corrosion preventive compounds are being used increasingly as methods of controlling the progress of corrosion. These compounds are usually designed to penetrate joints, displace any moisture present, and leave an oily or waxy film which provides a physical barrier to further corrosive attack. However, these films have lubricating qualities which may alter the load path through joints which rely on friction between the faying surfaces for load transfer. The effects of CPCs on the static strength of joints in aircraft structures does not appear to have been investigated thoroughly.

4.6 Summary

- The RAAF have experienced cases where the presence of corrosion has raised concerns over the ability of airframes to safely sustain design loads. Corrosion causing particular concern is laminar corrosion such as stress corrosion cracking or intergranular penetrations, which are not readily amenable to stress analysis.

- There have been notable attempts to model the effects of corrosion on residual strength by incorporating conservative assumptions into conventional engineering stress analyses. There appears to have been little experimental validation of the approaches used.

- Research indicates that corrosion has little effect on the mechanical properties of materials. Its main effect from the viewpoint of static strength is in removing load bearing material and introducing stress concentrations or discontinuities into the structure. For example, pitting appears to have little effect on static strength provided that the load bearing area is not significantly reduced and the stress concentration caused by the pit does not initiate fracture.

- When exfoliation occurs on a free surface it does not appear to cause any immediate reduction in the fracture toughness of susceptible aluminium alloys above what would be expected by the material thinning caused by the corrosion. Therefore, in the presence of an existing crack, it seems reasonable to model the effect of exfoliation by simply ignoring the corroded material. However, this approach would need to be reassessed if the exfoliation occurred at the faying surface of a joint where the bulging caused by the corrosion alters the load path through the joint and causes undesirable stress concentration.

- Most instances of stress corrosion cracking occur in extruded sections where either residual stresses or assembly stresses have caused the stress corrosion cracks to propagate *parallel* to the direction of applied service loading. The effect of such defects on residual strength remains largely untested.

- While high-strength steels and high-strength aluminium alloys are known to be susceptible to hydrogen-assisted cracking, there is no evidence to suggest that the material/environment systems commonly encountered in airframes are susceptible to hydrogen assisted fracture.

5. The influence of prior corrosion and corrosive environments on fatigue behaviour

5.1 Introduction

Well established techniques exist for validating the fatigue design of aircraft in benign environments. These include conducting full-scale fatigue tests to determine the safe-life of a structure, or small-scale or assembly testing used for establishing fatigue crack growth properties as a basis for damage tolerance assessment. The crucial point is, however, that the design approaches are validated customarily using benign environments. The effects of either

(a) corrosion as an initiator of fatigue cracking, or
(b) corrosive environments accelerating fatigue crack growth,

are not sufficiently understood to permit them to be incorporated with confidence into structural integrity assessments on a routine basis. This review therefore examined the literature concerned with the effects of prior corrosion and corrosive environments on fatigue performance.

Firstly, this chapter briefly reviews several cases where the presence of corrosion or corrosive environments have raised concern over the fatigue performance of RAAF aircraft. Secondly, research into the effects of prior corrosion and corrosive environments on fatigue crack initiation and growth is discussed. Considerable effort has been spent researching this topic and the literature is extensive. The discussion is therefore centred on materials which are relevant to aircraft structures. Separate sections deal with the role of prior corrosion in initiating fatigue cracking, the propagation of fatigue cracks through corroded regions of structure, and the complex issue of corrosion fatigue crack growth. Thirdly, the effects of corrosion repair and control on fatigue performance are reviewed, and finally, methods used in other industries to predict corrosion fatigue crack growth are briefly reviewed before the important points of the chapter are summarised.

The terms "fatigue crack initiation" and "fatigue crack growth" are used separately in this chapter. The use of the term fatigue crack initiation is perhaps out of step with recent thinking on fatigue, and fractographic evidence, which suggests that fatigue originates from virtually the first loading cycle at defects which may be of a size less than the microstructure (Miller (1993)). This implies that the fatigue life of an engineering structure may be described entirely by fatigue crack growth, and indeed much contemporary study is directed at quantifying the growth of very small fatigue cracks.

Despite the evidence suggesting that the concept of fatigue crack initiation does not faithfully describe the mechanism of fatigue, it may be argued that the concept retains some merit in an engineering sense. This is because critical sections in engineering structures such as aircraft are customarily inspected using methods which have a finite sensitivity, and in some structural integrity philosophies if no cracks are found the structure is assumed to be undamaged from the viewpoint of fatigue.

It is not the purpose of this report to enter the debate regarding the relative merits of the concept of fatigue crack initiation. However, there is considerable evidence that localised corrosion damage, such as pits, can provide nucleation sites for fatigue failure, and this report will discuss the influence of environment on the development of dominant, detectable cracks as well as its influence on fatigue crack growth.

5.2 Examples and experience

Examples of where the effects of prior corrosion or the presence of a corrosive environment have apparently influenced the initiation or propagation of fatigue cracks in RAAF aircraft have included the F/A-18 trailing edge flap hinge lug, the Macchi MB326H centre section spar booms, and the C-130 bow beam end fittings. There have been numerous other similar examples cited in the literature.

5.2.1 RAAF - F/A-18 trailing edge flap hinge lug

The trailing edge flap (TEF) outer hinge lug of a RAAF F/A-18 failed during flight and resulted in the loss of the flap. This incident prompted a fleetwide inspection which revealed two other cracked lugs. Investigation of these cracked lugs by Sharp *et al.* (1995) revealed that fatigue cracking originated at corrosion pits which were strongly oriented in the direction of the fatigue cracking rather than the material grain flow (see Figure 2-1). This suggested an interaction between corrosion pitting and fatigue crack growth. Extensive corrosion product was found on the fatigue fracture surfaces and their appearance was consistent with corrosion fatigue. Most importantly, the fatigue crack growth rates appeared to be significantly greater than those predicted by the manufacturer. In predicting fatigue crack growth rates, the manufacturer used a model which does not account for the influence of environment on fatigue crack growth. This result cast some doubt over the inspection interval recommended by the manufacturer, and a revised interval was recommended by AMRL.

5.2.2 RAAF - Macchi centre-section spar booms

The steel centre-section spar booms in Macchi MB326H aircraft were managed for many years on a safety-by-inspection basis where cracks in bolt holes were maintained in service. A prime requirement of such an approach, however, is that the next most critical region must be known. Early fatigue tests conducted by the OEM indicated that this region was the centre-section screw holes. Inspection of screw holes in RAAF aircraft during teardown, however, revealed that some screw holes had been inadequately protected against corrosion and were displaying substantial pitting corrosion. This of course then raised the possibility that the corroded screw holes could become critical. Two approaches were used to deal with the problem:

(a) The holes were opened up and cleaned out chemically prior to reprotecting against corrosion.
(b) Fatigue tests on service booms (Athiniotis *et al.* (1996)) demonstrated that the critical regions were firstly the bolt holes, and secondly, a specific location where a bolt hole and screw hole nearly intersected.

5.2.3 RAAF - C-130 bow beam end fittings

The port and starboard bow beam end fittings of a RAAF C-130 were found to be cracked during routine maintenance. Inspection of the cracked fittings revealed that fatigue cracks had initiated at several fastener holes, and in some cases stress corrosion cracks had propagated perpendicular to the fatigue cracks. The interaction between the fatigue and stress corrosion cracks is shown in Figure 2-4. The stress corrosion cracking was only found to occur at holes where a fatigue crack was present, indicating that the fatigue crack assisted the ingress of moisture and therefore promoted stress corrosion cracking. In turn, the presence of the stress corrosion cracks visibly altered the constraint along the growing front of the fatigue crack. While of interest, this type of complex interaction between fatigue and stress corrosion cracking is rare.

5.2.4 Other examples

In addition to the above examples there have been numerous cases reported in the literature where corrosive environments have been present during the growth of fatigue cracks in aircraft structures (Wallace *et al.* (1985), Peel and Jones (1982), Jansen and Wanhill (1994)). Some of these have been investigated in detail to establish what influence, if any, environment had on fatigue crack growth. Jansen and Wanhill (1994) investigated the contribution of environment to the fatigue cracking of 2024-T3 lap joints from F28 Mk 4000 civil transport aircraft and found no evidence that corrosion initiated this cracking. Furthermore, despite the fracture surfaces being slightly corroded, there were no indications that the crack growth rates were especially high because of the presence of a corrosive environment.

Overall, there appears to be no general consensus regarding the quantitative influence of corrosion on the propagation of fatigue crack growth in aircraft structures. This is undoubtedly due to the wide range of materials used in such structures, all of which have varying sensitivity to corrosive environments, and the wide variation in the loading and chemical environments experienced by aircraft.

5.3 The effect of prior corrosion and corrosive environments on fatigue crack initiation

Instances where the presence of corrosion damage has been associated with the rapid initiation of fatigue cracking have been described, and it is therefore relevant to review the literature concerned with the effects of prior corrosion and corrosive environments on fatigue crack initiation. Factors influencing fatigue crack initiation are discussed before methods of predicting crack initiation are reviewed.

5.3.1 Factors influencing fatigue crack initiation in corrosive environments

The effect of a corrosive environment on the total fatigue life and fatigue strength of simple laboratory specimens is shown qualitatively in Figure 5-1. This diagram illustrates several important points.

- Firstly, at high stress levels and relatively short fatigue lives prior corrosion is more detrimental than the presence of a corrosive environment.
- Secondly, at lower stress levels and longer lives the concurrent action of corrosion and fatigue is far more detrimental than the separate effects of prior corrosion and fatigue.
- Thirdly, whether or not there is a fatigue limit in benign environments, the presence of a corrosive environment tends to eliminate the fatigue limit.

The last two of these points are associated with the effect of corrosive environments on fatigue crack growth which is discussed in a later section of this report.

The first point, however, is explained by the observation that in simple specimens fatigue almost always initiates at any preexisting localised corrosion damage. This may be intergranular corrosion in susceptible materials, or corrosion pitting (Wanhill (1977), Forsyth (1980), Ma and Hoeppner (1994), Schutz (1995), Schmidt *et al.* (1995)). The fatigue performance of such specimens has been linked to the size and shape of corrosion damage caused by prior exposure to a corrosive environment. For example, Figure 5-2 shows the effect of mean pit depth on the total fatigue life of 2024-T3

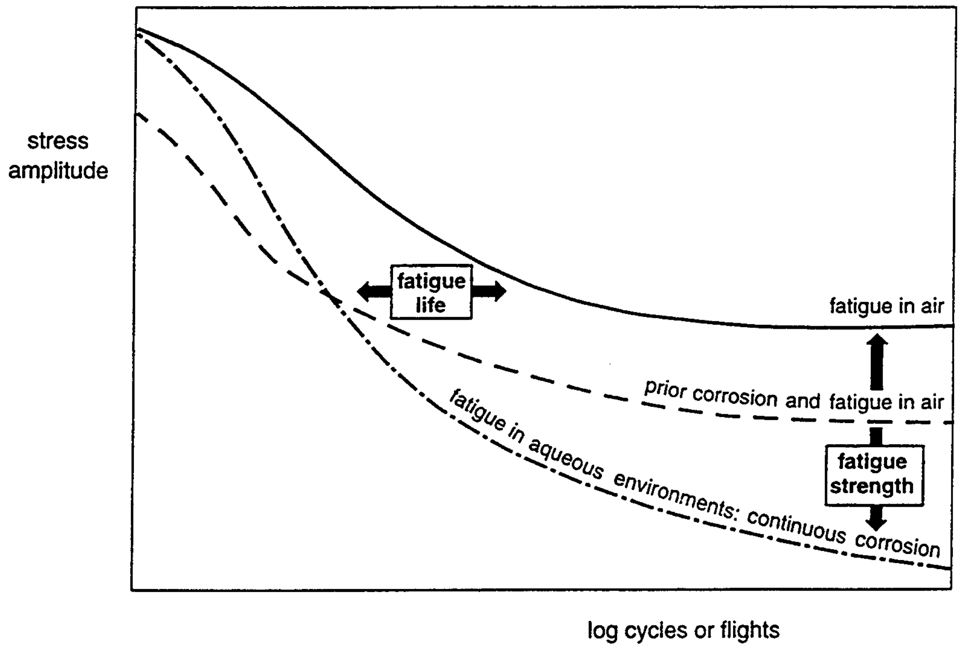


Figure 5-1: Schematic diagram illustrating the effects of corrosion on the fatigue life and fatigue strength of simple laboratory specimens tested under constant amplitude loading. After Wanhill (1994).

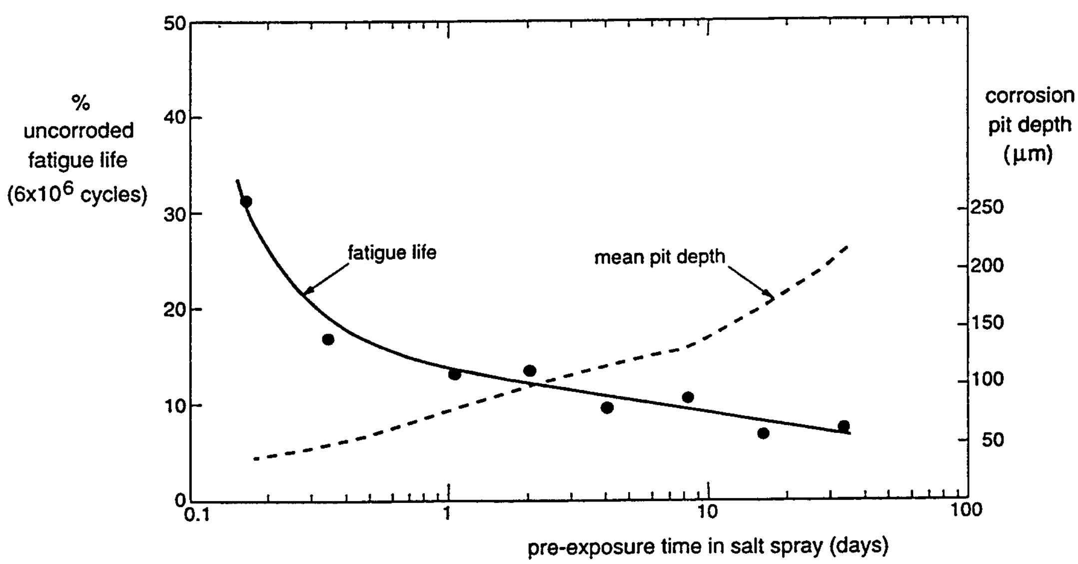


Figure 5-2: Relationship between depth of corrosion pitting and reduction in fatigue life of 2024-T4 aluminium alloy specimens. Fatigue tests carried out in laboratory air, R = -1. After Wanhill (1977).

specimens, while Figure 5-3 shows the degradation of fatigue behaviour of 7075-T73 sheet resulting from pitting induced by prior exposure to a salt water fog.

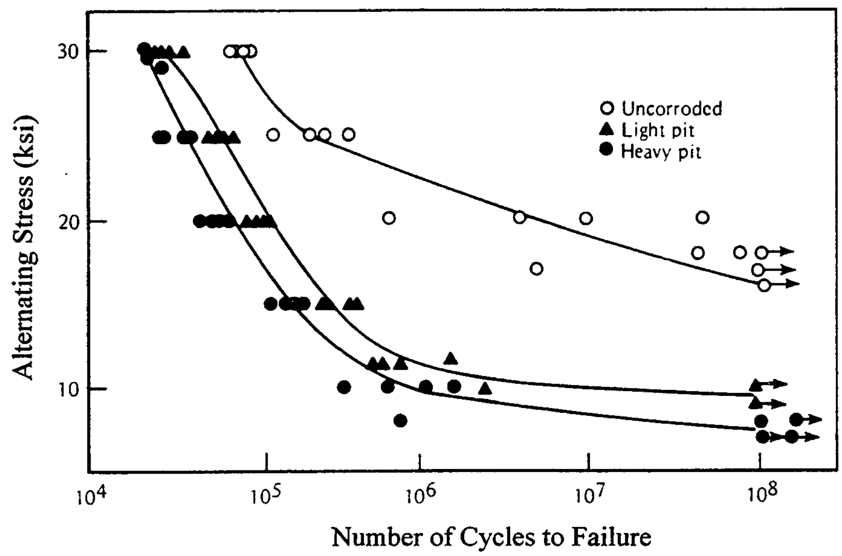


Figure 5-3: Effect of corrosion pitting on the constant amplitude fatigue behaviour of 7075-T73 aluminium alloy sheet specimens. Fatigue tests carried out in laboratory air, R = -1. After Jaske et al. (1981).

An investigation of the fatigue performance of 7050-T7451 material, similar to that used in the bulkheads of the F/A-18, carried out by AMRL has indicated that intergranular corrosion with a depth between 30 and 100 μm is more detrimental to fatigue life than other initiators of fatigue cracking such as inclusions and porosity (Sharp and Barter (1992)). This was attributed to the crack-like shape of the intergranular corrosion.

Figure 5-4 shows the results of spectrum fatigue tests on a number of high strength aluminium alloys which had been exposed to a corrosive environment for different periods of time prior to fatigue testing. There are two points to note from these results. Firstly, the overall fatigue lives are dominated by the initiation of a 0.4 mm long crack. Secondly, despite overageing the 2024 and 7075 alloys to T851 and T73 tempers respectively (which improves their resistance to exfoliation and stress corrosion cracking) their fatigue performance after exposure to salt water solution was inferior to the same alloys in the peak aged condition.

Grandt (1995) has examined the effect of environmental degradation on the fatigue behaviour of materials taken from a retired USAF KC-135 aircraft. This study is of particular interest because it includes materials containing varying degrees of environmental damage accumulated during service (rather than accelerated damage produced in the laboratory). The aluminium alloys considered in the experimental program included 2024-T3 from access panels, fuselage panels, and doubler structure, 7075-T6 from fuselage lap joints, and 7178-T6 from the upper wing skin. Unfortunately the nature of the corrosion damage was not reported in detail, however, "moderate" corrosion on 2024-T3 specimens led to a constant amplitude fatigue life of approximately one quarter of the original specification, while "light" corrosion resulted in a similar reduction in fatigue life in the 7075-T6 specimens. No fractographic analysis of the specimens was reported to confirm the fatigue initiation sites.

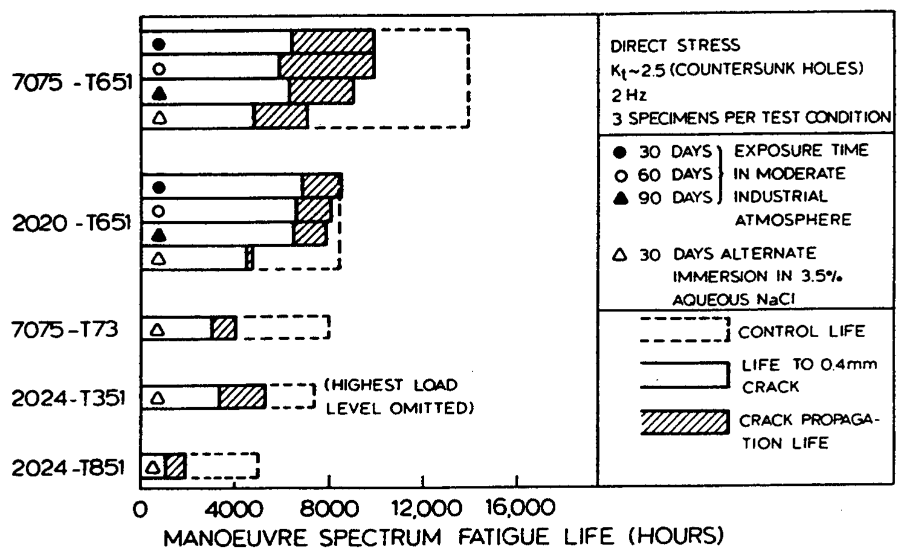


Figure 5-4: Effect of prior exposure on the spectrum fatigue life of high strength aluminium alloy specimens. After Wanhill (1977).

Fretting[3] at structural joints is another mechanism which accelerates fatigue crack initiation (Hoeppner *et al.* (1994)). While an oxidizing environment is not necessary for fretting wear to occur, fretting is exacerbated by the presence of a corrosive environment.

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[3] The term "fretting" is often used to describe the deterioration at the interface between contacting surfaces undergoing low amplitude oscillatory motion, such as that which can occur between faying surfaces, and between holes and fasteners. A comprehensive discussion of this phenomenon may be found in Waterhouse and Lindley (1994).

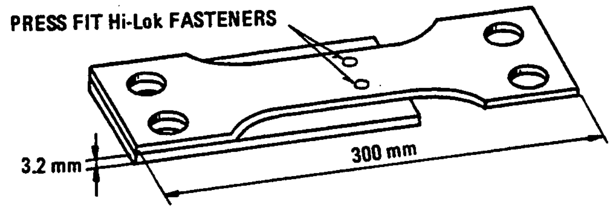
While the crack initiation lives of simple laboratory specimens are reduced by exposure to corrosive environments, some caution must be exercised in extending this result to joints in aircraft structures. Prior exposure appears to have a much less significant effect on the fatigue performance of practical joints when a sound corrosion protection system is in place and fasteners remain tight (Wanhill (1977), Schutz (1995)). An example of this is described in the AGARD Fatigue in Aircraft Corrosion Testing Programme (Wanhill *et al.* (1989)) where 1½ dogbone specimens, which were designed to be representative of fatigue critical joints in military aircraft, were exposed to a 5% salt water solution for 72 hours, and then fatigue tested under spectrum loading. Prior exposure had relatively little effect on overall fatigue life when an appropriate corrosion protection scheme was employed (Figure 5-5). In this case the corrosion protection scheme consisted of anodizing, applying a chromate containing primer, and finally applying a polyurethane topcoat after all fasteners had been installed. The specimens were prestressed at approximately -60°C in order to crack the paint and primer layers around the fasteners, and thereby simulate service conditions. Unfortunately, no details were provided of the nature of the corrosion induced in the specimens after the 72 hour exposure, and whether this simulated the corrosion observed in service aircraft.

The replication of service corrosion in laboratory specimens is not straightforward. The major reason for this is that aggressive solutions are required in short term tests to accelerate paint damage and cause corrosion (Shaw 1994a). These solutions may bear little similarity to naturally occurring environments and the corrosion produced can be significantly different from that which occurs during natural weathering. It is important to emphasise that for replication of service corrosion to be truly successful, the entire test program must simulate the failures experienced by actual aircraft structures.

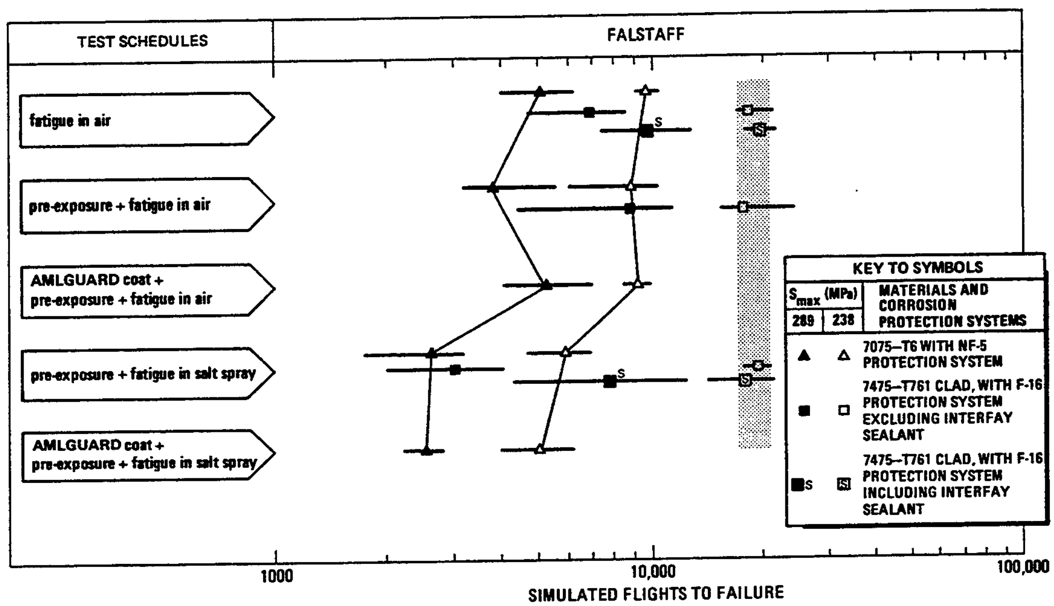
In more realistic specimens the presence of a corrosive environment can alter the site of fatigue crack initiation. This was evident in the Fatigue in Aircraft Corrosion Testing Programme where the introduction of a corrosive environment during fatigue testing tended to shift the origin of fatigue failure from the faying surfaces to the corners of the bores of fastener holes. This tendency of corrosive environments to shift the origin of fatigue failure in joints has potentially important implications for aircraft lifing and warrants further investigation.

The effect of surface treatment, and surface protection schemes on corrosion is clearly of crucial importance, and several systems have featured in published corrosion fatigue studies.

The influence of anodizing on corrosion fatigue performance does not appear to have been investigated systematically. However, several authors have cautioned that anodizing, if not carried out correctly, may cause surface pitting which can act as a fatigue crack initiator (Forsyth (1980), Wanhill (1994b)). Figure 5-6 illustrates the effect of chromic acid anodizing on the fatigue behaviour of notched 7075-T73 and 7050-T736 specimens taken from a forging. In particular the fatigue behaviour of 7050-T73 alloy



(a)



(b)

Figure 5-5: AGARD Fatigue in Aircraft Corrosion Testing Programme; (a) 1½ dogbone test specimen; (b) effect of varying test conditions and corrosion protection schemes on specimen fatigue life under fighter spectrum loading. After Wanhill et al. (1989).

is sensitive to anodizing, mainly because its high copper content promotes intergranular attack during the process. ESDU Data Item 87026 provides further data on the effects of anodizing on the fatigue performance of aluminium alloy specimens and joints when tested in air. The fatigue life of simple notched specimens made from 2024-T3 and 7475-T761 aluminium alloy, tested under gust spectrum loading, may be reduced by as much as 40% by anodizing. However, under nominally the same conditions, the fatigue performance of lap joints may be either degraded or improved by anodizing.

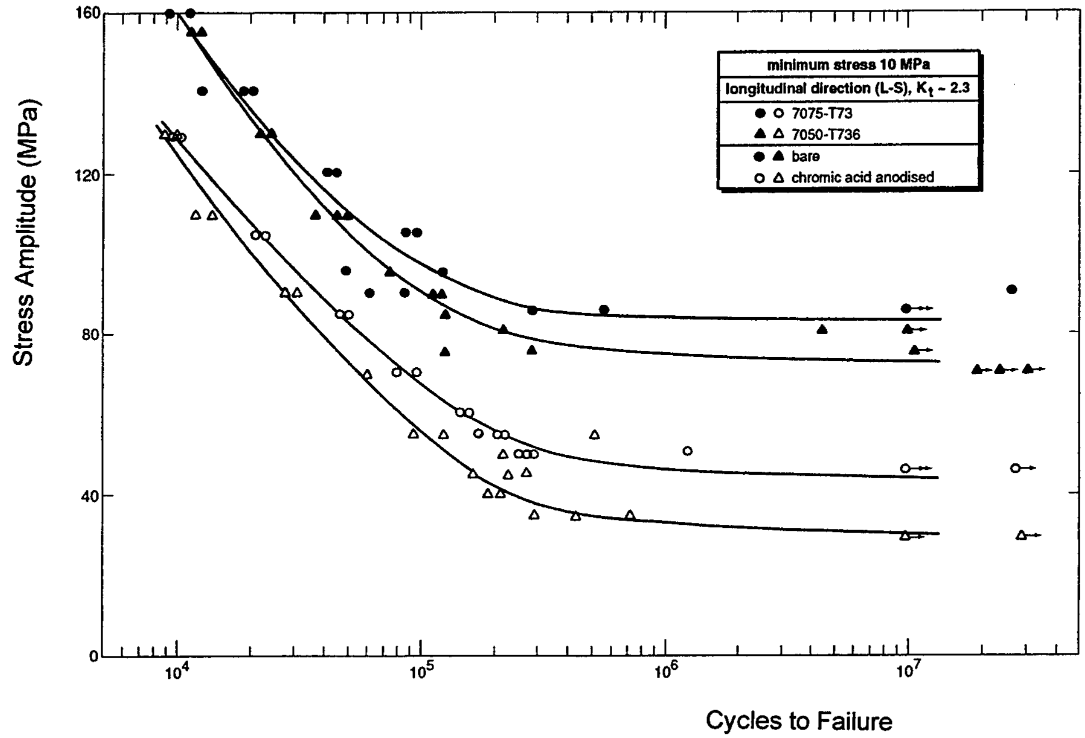


Figure 5-6: Effect of chromic acid anodizing on the fatigue behaviour of notched 7075 and 7050 aluminium alloy specimens. After Wanhill (1994b).

Peening, which introduces compressive residual stresses in the surface layer of the material, generally improves the corrosion fatigue behaviour of unnotched specimens. The beneficial effects of peening undoubtedly arise from the reduced cyclic stress intensity for a defect growing in a peened surface, relative to the same effect in an unpeened material. Shot peening only modifies the residual stress in a thin surface layer (usually less than 1mm thick) and Speidel (1981) has cautioned that unless an appropriate corrosion protection scheme is employed, localised corrosion resulting from long term exposure can penetrate the surface layer and overcome the benefits of peening. Hoeppner *et al.* (1994) have also reported that peening is one of the few reliable methods of improving fretting fatigue performance. Indeed, Wanhill (1990) has recommended that peening be incorporated into repair procedures which involve the machining out of corrosion damage. This is shown diagramatically in Figure 5-7.

Many different coatings have been tested in an attempt to improve fretting fatigue behaviour (Hoeppner *et al.* (1994)), including Corrosion Preventive Compounds (CPCs). There appears to be no general consensus regarding the effect of CPCs on the fatigue behaviour of aircraft joints. This seems to result from the CPC reducing friction and thereby altering the load transfer through the joint. This may be either beneficial or detrimental to the fatigue performance of the joint depending on its design.

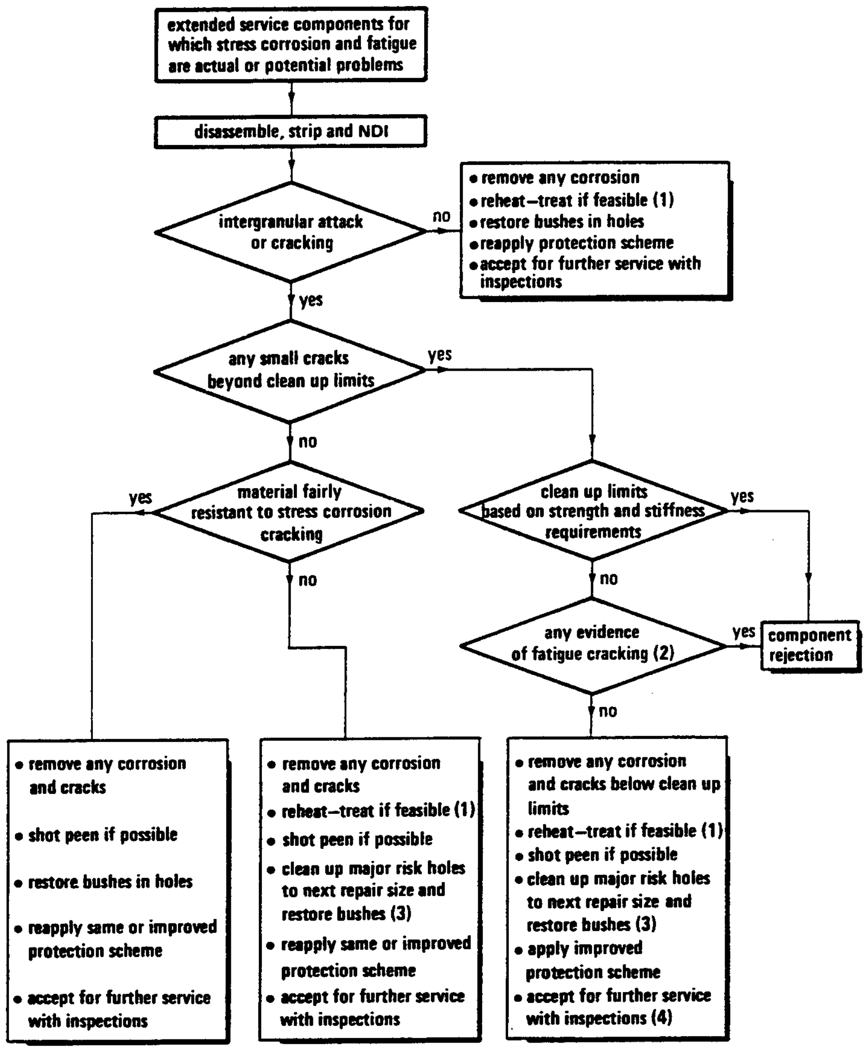


Figure 5-7: Suggested procedure for continued service of high strength aluminium alloy components for which stress corrosion cracking and fatigue are actual or potential problems. Notes: (1) depends whether stress corrosion cracking resistance can be significantly improved without unacceptable loss in strength; (2) destructive failure analysis of a cracked component will probably be required to determine this; (3) with current NDI capabilities clean-up should be 0.25-0.5 mm beyond the point at which NDI ceases to indicate cracks; (4) requires demonstration that any further crack growth is detectable by in-service NDI or is non-critical. After Wanhill (1990).

It appears that other variables such as frequency, mean stress, alloy, heat treatment, and environmental composition only seem to influence fatigue crack initiation in so far as they influence the susceptibility to localised corrosion. For example, Schutz (1995) has made the observation that the effect of frequency on corrosion fatigue behaviour appears to be relatively small when the complete life to failure of a component consists of a long crack initiation and a short propagation phase. Another good example is titanium alloys where prior environmental exposure, or the presence of an environment during fatigue loading, has little effect on fatigue life (Wanhill (1977)). This is because the stable, strong oxide layer which forms on titanium alloys prevents localised corrosion.

In summary, the most important factor influencing fatigue crack initiation in a corrosive environment is the degree of localised corrosion caused by prior exposure, which in practice relies on the presence or integrity of a suitable corrosion protection scheme.

5.3.2 Predicting fatigue crack initiation in corrosive environments

The prediction of fatigue crack initiation in a corrosive environment may be carried out either empirically or analytically.

Empirical Prediction of Fatigue Crack Initiation

The period required to initiate a fatigue crack in the presence of a corrosive environment may be predicted empirically, that is, by conducting an experimental program which simulates as many of the conditions experienced during service as possible. However, such programs usually involve subjecting unnotched or simple laboratory specimens to aggressive environments for a relatively short period in order to simulate long term service corrosion, and, as indicated earlier, extreme caution must be exercised in extrapolating the results of such tests to complex aircraft structures.

An example of such a program is described by Fadragas *et al.* (1994) who conducted fatigue tests on 2024-T3 Alclad sheet specimens containing a chamfered rivet hole. One batch of specimens was tested in the uncorroded condition while another batch was tested after 2 weeks exposure to a 5% salt water spray. Subsequent constant amplitude fatigue testing was carried out with a maximum fatigue stress of 100 MPa, a stress ratio R=0.1, and a frequency of 5 Hz. The number of cycles required to initiate a propagating 0.5 mm long fatigue crack was recorded. The results were presented in the form of a Weibull distribution which predicts the probability of forming a 0.5 mm long fatigue crack after a given number of fatigue cycles. Prior exposure to salt spray increased the probability of early formation of such a fatigue crack. Although no explanation was offered by the authors for this behaviour it seems reasonable to assume that early fatigue cracking was initiated by localised corrosion.

Analytical Prediction of Fatigue Crack Initiation

Several investigators have attempted to predict the time required to initiate corrosion fatigue cracks analytically by making the assumption that fatigue cracks initiate from localised corrosion pits (Hoeppner (1979), Kondo (1989), Harlow and Wei (1994), Nakajima and Tokaji (1995)).

A major ongoing research program which has particular relevance to aircraft structures is being carried out at Lehigh University. A probability approach has been proposed by Wei and others (Harlow and Wei (1994), Wei (1994)) to predict fatigue life in a corrosive environment based on the initiation of a single dominant fatigue crack from a corrosion pit. The processes of corrosion and fatigue damage used in this model are shown schematically in Figures 5-8 and 5-9. Essentially the model involves predicting the time required to initiate a fatigue crack from a growing corrosion pit, and thereafter predicting the corrosion fatigue crack growth rate using a Paris-Erdogan crack growth law, calibrated to allow for the effects of environment. Pit growth has been found to be Faradaic, that is, the volume of the pit increases linearly with time. The model has been developed on the basis of a hemi-spherically shaped pit. Wei argues that competition may occur between pit growth and crack growth in the early stages of fatigue damage; this view is supported by the finding that pit-to-crack transition size appears to depend on frequency, being larger at lower frequencies. For a fatigue crack to "escape" from a corrosion pit the stress intensity factor must be greater than the threshold value and the fatigue crack growth rate must be greater than the pit growth rate (over time). That is

$$\Delta K > \Delta K_{th}, \qquad (da/dt)_{crack} > (da/dt)_{pit}$$

To the authors' knowledge this theory has yet to be applied to predict the formation of fatigue cracking in an actual aircraft. While it certainly offers the possibility of providing useful information for the setting of inspection intervals, several points should be considered.

1. A considerable volume of relevant experimental data is required for the application of probability-based approaches to fatigue or to corrosion.

2. Observations made during the investigation of RAAF F/A-18 trailing edge flap hinge lugs (see Section 5-2) agree with the concept of competition between corrosion pit growth and fatigue crack growth. However, the corrosion pits on the F/A-18 trailing edge flap lugs were deep and crack-like, rather than hemi-spherical as proposed in this model; such variability in geometry would be expected to lead to large changes in overall transition behaviour, and it is difficult to see how to accommodate this variability without resorting to extensive data-gathering on different alloys and environments.

3. It has been observed experimentally that cracks may initiate from corrosion pits as small as 35 μm in depth (Wei (1994)). It is generally accepted that short cracks (less

than 500 μm (0.5 mm) in depth) display fatigue crack growth rates significantly greater than the principles of linear elastic fracture mechanics would suggest. In addition to this, in some instances, evidence has been found of *chemically* short crack behaviour (Piascik and Willard (1994)). This refers to anomalous fatigue crack growth behaviour considerably beyond 500 μm crack length which is usually associated with environment transport mechanisms to the crack tip. These observations considerably complicate the prediction of corrosion fatigue crack growth and (as with the growth of short fatigue cracks in benign environments) considerably more work is required in the area of short corrosion fatigue crack growth if this method is to provide reasonable predictions.

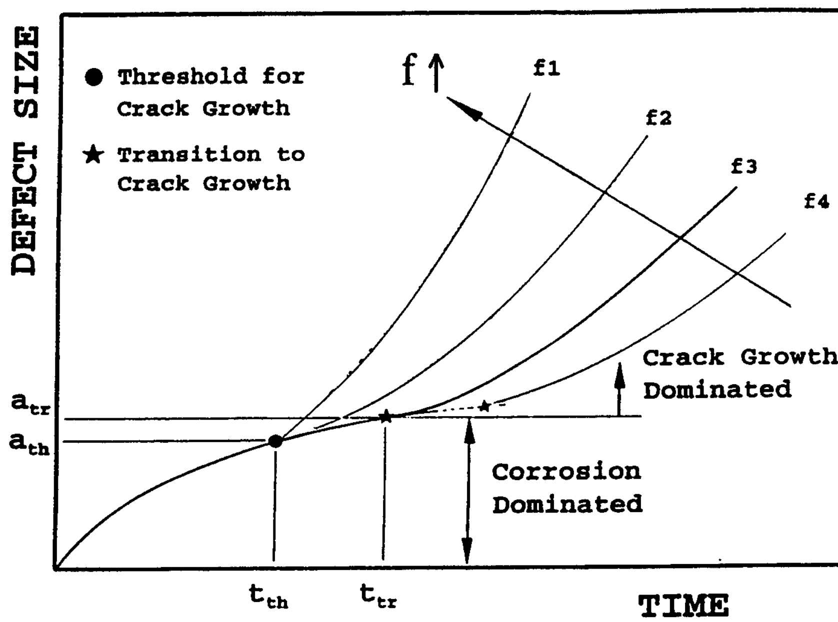


Figure 5-8: Schematic representing the competition between corrosion pitting and corrosion fatigue crack growth from the base of the pit. f refers to frequency with $f_1>f_2>f_3>f_4$. After Wei (1994).

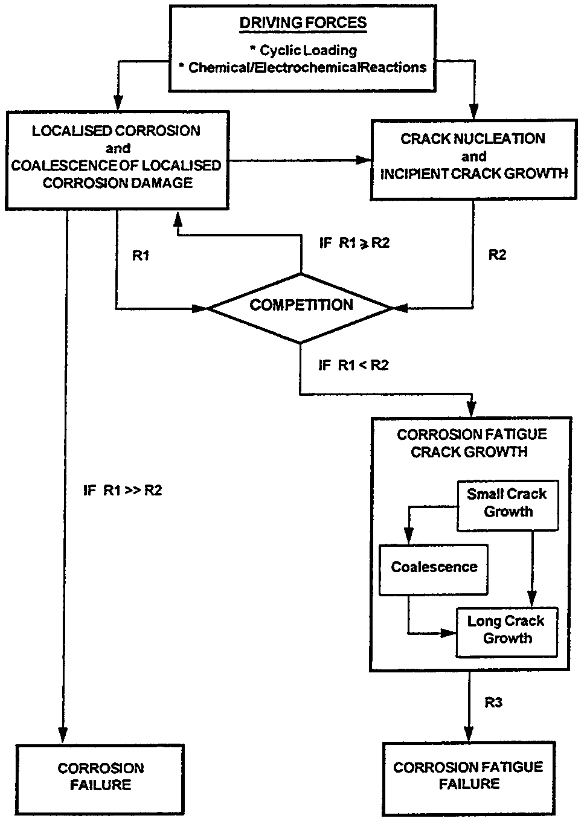


Figure 5-9: Flow diagram representing the corrosion and corrosion fatigue damage model proposed by Wei. R_1, R_2 and R_3 represent the corrosion pit growth rate, the short fatigue crack growth rate, and the corrosion fatigue crack growth rate respectively. After Wei (1994).

4. The development of pitting is critically dependent on the breakdown of corrosion protection schemes. The value of predictions of pitting behaviour are therefore limited by knowledge of the longevity of the protection schemes. This, in turn, depends on whether the scheme deteriorates with time, service usage, accidental damage, or a combination of all three. A predictive corrosion model for the USAF C-5 aircraft which includes an algorithm for predicting the time to initial paint breakdown has been proposed by Miller and Meyer (1987). This algorithm is shown schematically in Figure 5-10. The three factors which contribute most to paint breakdown are ultraviolet radiation, ozone, and sulphur dioxide. Environmental data from USAF bases has been compiled by Fink and Summitt (1980), and these form the basis for predicting the time required for the initial breakdown of the exterior paint scheme, and the onset of corrosion damage. This algorithm does not appear to have been validated against service experience.

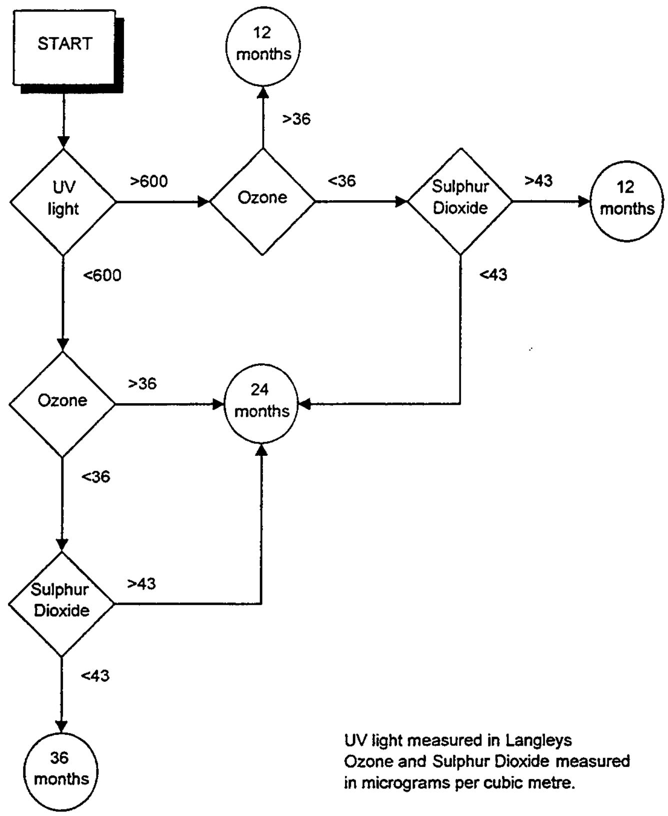


Figure 5-10: Proposed paint breakdown algorithm. The time to breakdown of the protective coating is dependent on exposure to ultraviolet radiation, ozone, and sulphur dioxide. After Miller and Meyer (1987).

It is important to discuss two current research programs at this point. Both Paul (Paul and Groner (1996)) at the USAF Wright Laboratories, and Bucci (Bucci *et al.* (1995)) at ALCOA are researching the characterisation of corrosion damage using an Equivalent Initial Flaw Size (EIFS) approach. This involves firstly fatigue testing simple specimens containing typical corrosion damage, and deriving S-N data. If the assumption is made that the life of the specimen is taken up entirely with fatigue crack growth, then the principles of fracture mechanics can be used to back-calculate the equivalent initial flaw which must have been present to give the observed fatigue life. The advantage of characterising corrosion in this manner is that the EIFS approach is a well established technique for predicting the fatigue performance of damage tolerant structures. Therefore, determining appropriate EIFS values for corrosion offers the possibility of using existing structural integrity philosophies to manage the fatigue implications of corrosion damage.

However, it should be noted that the approach used by Paul and Bucci is based on the assumption that the failure will occur in a discrete sequence comprising:

1. the initiation of a dominant fatigue crack from localised corrosion damage,
2. the growth of the fatigue crack, and
3. the final failure of the component by unstable crack growth.

At the present time this approach does not take into account other failure modes, or any interaction which may take place between corrosion and fatigue processes.

5.4 The effect of prior corrosion on fatigue crack growth

Recently published aircraft structural integrity analyses investigating the effects of corrosion have made the assumption that prior corrosion may be accounted for simply by material thinning, which leads to increased stresses and hence increased crack propagation rates (Berens and Burns (1995), Cazes and Goerung (1995)). This assumption has been investigated by two studies.

Chubb *et al.* (1991) produced patches of localised exfoliation corrosion on one side of 7178-T6, and 2024-T351 aluminium alloy fatigue specimens similar to those shown in Figure 4-3. Subsequent constant amplitude fatigue testing propagated a fatigue crack through regions of sound and corroded material. Changes in fatigue crack growth rate in the 2024-T351 alloy were found to be consistent with the material thinning effects of the exfoliation. However, in the case of 7178-T6 alloy, crack acceleration beyond the effects of material thinning was observed. The reason suggested for this behaviour was that moisture and corrodents may be trapped in the exfoliation and this leads to increased fatigue crack growth as it passes through the corroded region.

Koch *et al.* (1993) conducted similar experiments on 2024-T3 specimens. In this case patches of localised pitting and exfoliation were produced on one side of the specimens. Fatigue crack growth was found to be unaffected by shallow pitting attack. However, fatigue crack growth became irregular when propagating through a region of exfoliation. The explanation offered was that diffusible species, such as hydrogen generated at the corrosion sites, may have changed the physical properties of the aluminium alloy away from the corroded area. However, this fails to explain why the fatigue crack growth was unchanged by pitting corrosion, which would presumably also generate diffusible species. The material thinning effects of exfoliation on fatigue crack growth were not explored in this study.

Further research into the effect of prior corrosion on fatigue crack growth rates is presently being carried out by the USAF at the Wright Laboratories (Paul and Groner (1996)). The material under investigation is aluminium alloy 7075-T651, and the approach is similar to the investigations described above.

5.5 The effect of corrosive environments on fatigue crack growth

An essential component in the determination of the structural integrity of aircraft designed in accordance with damage tolerance principles is understanding the growth of fatigue cracks under the action of service loading spectra. Substantial research effort has been aimed at determining the influence of corrosive environments on the propagation of fatigue cracks, and the literature is extensive. This section is therefore divided into three parts:

1. The nature of fatigue crack growth in the presence of a corrosive environment.
2. The important factors which influence corrosion fatigue crack growth.
3. A review of methods which have been proposed to predict crack propagation in corrosive environments.

5.5.1 The nature of fatigue crack growth in corrosive environments

The influence of corrosive environments on fatigue crack propagation is varied. However, an important conclusion is that in almost all instances it has been found to accelerate the crack growth rate.

Corrosion fatigue (or perhaps more correctly environmentally enhanced fatigue) crack growth behaviour has been characterised into three general patterns (Wei (1979)). These are shown in Figure 5-11 in the form of relationships between cyclic crack growth rate, da/dN, and stress intensity factor range, ΔK. In each case the corrosion fatigue crack growth curve is compared with the crack growth in an inert environment. Each of the three types of behaviour are discussed below.

Type A Behaviour

Type A behaviour is typical of low to moderate strength alloys which are relatively immune to stress corrosion cracking. Its features are:

- The presence of a corrosive environment often reduces the threshold stress intensity factor (which represents the minimum cyclic load range required to propagate an existing fatigue crack).
- The environment also increases the fatigue crack growth rate over most of the stress intensity factor range.
- As the stress intensity factor range approaches the material fracture toughness, crack progression occurs by microvoid nucleation and coalescence ahead of the crack tip, and is therefore unaffected by environment.
- This type of behaviour has also been described as "true" corrosion fatigue (Speidel (1979)) and tends to be cycle dependent rather than time (or frequency) dependent i.e. cyclic frequency has only a minor influence on fatigue crack growth rates.

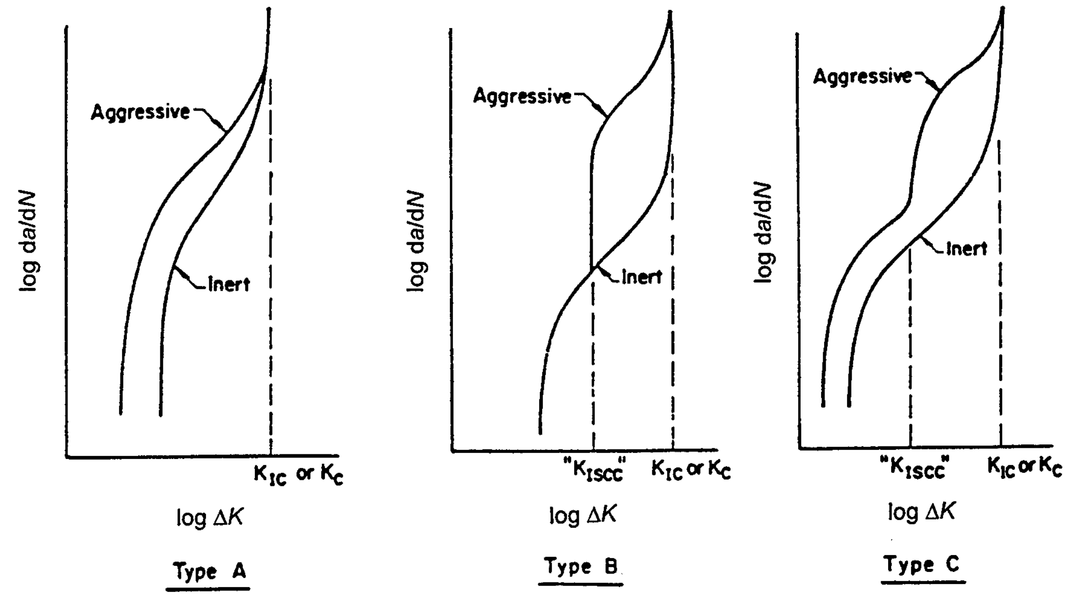


Figure 5-11: Schematic representations of different types of corrosion fatigue crack growth behaviour expressed as plots of crack growth per cycle (da/dN) vs. cyclic stress intensity factor range (ΔK). After Wei (1979).

The exact mechanism responsible for the acceleration of the fatigue crack growth rate in the presence of a corrosive environment has been the subject of intense debate (see for example Vogelesang & Schijve (1980); Lynch (1988); Ford (1989); Chen and Duquette (1990); Stanzl, Mayer & Tschegg (1991)). The two most commonly proposed mechanisms are hydrogen environment embrittlement, and film rupture and anodic dissolution.

Hydrogen embrittlement refers to the situation where hydrogen is adsorbed at the crack surfaces and then dissolved and transported as atomic hydrogen either through the matrix, along grain boundaries, or with dislocation movement. The presence of atomic hydrogen lowers the cohesive force of the metal atoms against separation. This has long been proposed as the most likely cause of monotonic stress corrosion cracking in a variety of alloy/environment systems (Parkins (1992)), and it is therefore not surprising that it has also been used to describe the corrosion fatigue behaviour of many systems, notably aluminium alloys in water vapour, titanium alloys in aqueous chloride, and alloy steels in various electrolytes (Gangloff and Kim (1993)).

Film rupture and anodic dissolution (or slip-dissolution) refers to the situation where a stable oxide film at the crack tip is ruptured, leading to an electrochemical reaction which advances the crack. It has been used to describe the corrosion fatigue behaviour of carbon and stainless steels exposed to high temperature water environments (Ford (1989).

Type B Behaviour

Type B behaviour is typical of alloy/environment systems which are susceptible to stress corrosion cracking, and where substantial stress corrosion cracking occurs during fatigue. In these cases:

- The environment has little effect when the applied stress intensity factor is below the threshold stress intensity factor for stress corrosion cracking, K_{ISCC}.
- When the maximum stress intensity factor exceeds K_{ISCC}, stress corrosion cracking occurs in conjunction with fatigue cracking and the overall environmentally assisted fatigue crack growth rate considerably exceeds the rate for the same alloy in an inert environment.
- Because stress corrosion cracking (which is a time dependent process) makes a considerable contribution to crack growth, the fatigue behaviour in this region is therefore highly dependent on loading frequency. An example of this type of behaviour is shown in Figure 5-12 for a high strength steel in distilled water.

Type C Behaviour

Realistically, many alloy/environment systems exhibit fatigue crack growth behaviour which falls between the two extremes of Types A and B. This is represented by Type C behaviour in Figure 5-11. In these instances:

- The threshold stress intensity factor may be reduced at low stress intensity factor ranges, and cycle dependent behaviour may be exhibited.
- Both cycle and time dependent behaviour is exhibited at medium stress intensity factor ranges.
- Time dependent behaviour is exhibited at stress intensity factor ranges above K_{ISCC}.

5.5.2 Factors influencing fatigue crack growth in corrosive environments

There are many factors which influence fatigue crack growth in corrosive environments. These are summarised in Table 5-1.

From the viewpoint of aircraft structural integrity, the most important variables can be separated into three broad groups:

- Mechanical loading parameters, which includes frequency, mean stress, waveform, and load sequence effects.
- Material properties such as alloy composition, heat treatment, yield strength, and microstructure.

- Environmental parameters, which includes the type of environment (gaseous or aqueous), environment composition, temperature, pressure, and importantly, the presence of coatings and inhibitors.

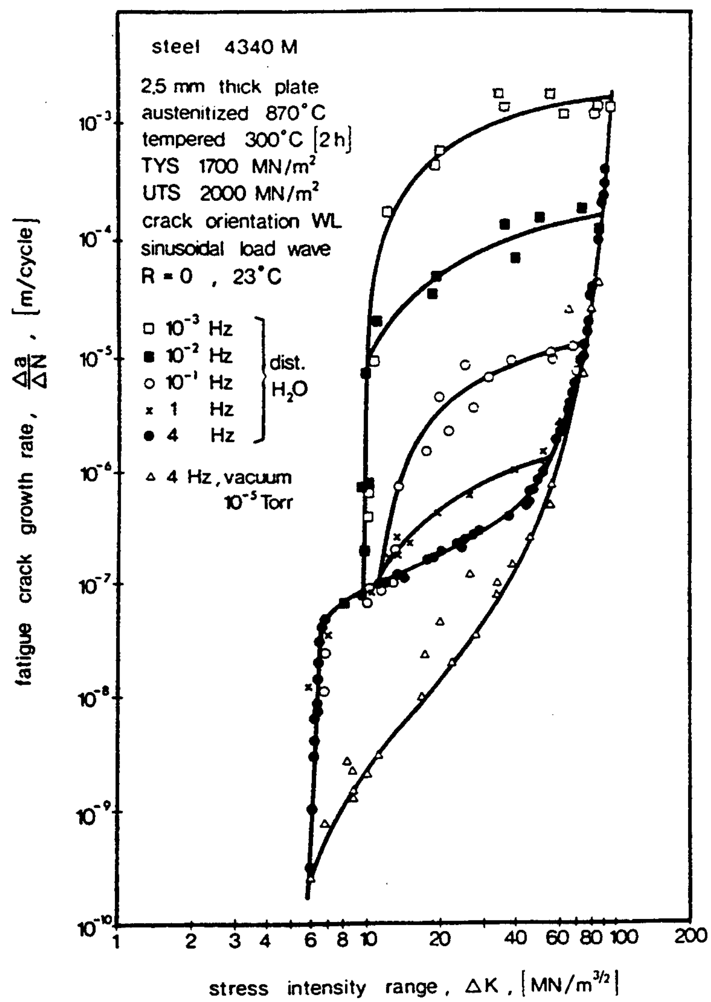


Figure 5-12: Environmentally enhanced fatigue crack growth behaviour of 4340 steel exposed to distilled water. After Gangloff and Kim (1993).

Table 5-1: Summary of factors which may influence corrosion fatigue crack growth.

Mechanical Variables
- Cyclic load frequency,
- Cyclic stress or stress-intensity factor range, $\Delta\sigma$ or ΔK,
- Mean stress,
- Maximum stress or stress-intensity factor, σ_{max} or K_{max},
- Cyclic load waveform (for constant amplitude loading),
- Load sequence during variable amplitude loading,
- Crack closure, and
- Residual stress

Material Variables
- Alloy composition,
- Microstructure,
- Heat-treatment,
- Mechanical working,
- Preferred orientation of grains and grain boundaries, and
- Mechanical properties (strength, fracture toughness *etc.*).

Environmental Variables
- Temperature,
- Pressure,
- Types of environments (gaseous, aqueous *etc.*),
- Concentration of damaging species in aqueous environments,
- pH, and
- Presence of coatings, inhibitors *etc.*

Mechanical Loading Parameters

Frequency

It is fortuitous that, in inert or benign environments, frequency has negligible effect on the fatigue behaviour of most alloys used in aircraft construction. This has enabled accelerated fatigue testing to be used to predict successfully the fatigue performance of components and structures. However, in the presence of corrosive environments, frequency may have a profound effect on fatigue crack growth in many alloys. Indeed, Gangloff (1989) has argued that the time dependence of corrosion fatigue is perhaps the most important aspect of this fracture mode.

The exact relationship between fatigue crack growth rate and frequency is dependent on the alloy/environment system. However, it was noted in the previous section that many alloy/environment systems exhibit Type C fatigue crack growth behaviour (see Figure 5-11). In understanding the effect of frequency, it is helpful to separate fatigue behaviour into different regimes based on the magnitude of the applied stress intensity factor. Three ΔK regimes may be identified, and the frequency dependence may be different in each.

- If K_{max} is above K_{ISCC}, corrosion fatigue tends to be strongly time dependent i.e. da/dN increases with decreasing frequency.
- At moderate ΔK levels below K_{ISCC}, corrosion fatigue crack growth rates generally increase with decreasing frequency, although in some cases the opposite trend may occur.
- At near threshold ΔK levels, corrosion fatigue crack growth rates may be independent of frequency, or may increase with increasing frequency.

For aluminium alloys in the presence of water vapour, fatigue crack growth rates typically vary by a factor of less than 4 at frequencies less than about 10 Hz in normal air (i.e. greater than 5% relative humidity) (Wanhill (1977), Squibb and Bryanton (1993), Squibb (1994)). However, there appears to have been little work carried out to determine the effects of frequency in the important near-threshold regime of the aluminium alloy/water vapour system.

Most tests investigating the effects of aqueous environments on the fatigue crack growth rate of aluminium alloys have used salt water. In this environment frequency effects are usually small if the alloy is immune to stress corrosion cracking (Wanhill (1977), Aliaga and Budillon (1981), Jaske *et al.* (1981), Wanhill *et al.* (1989)). However, alloys which are susceptible to stress corrosion cracking can be extremely sensitive to frequency, particularly at low frequencies, and when the crack is propagating in the ST or SL orientations, i.e. in the rolling plane, normal to the short transverse direction. Figure 5-13 compares the frequency dependence of two aluminium alloys, the SCC susceptible 7079-T651 and the relatively immune 2219-T87.

Much less data exists for titanium alloys. In normal air there appears to be no strong influence of frequency on fatigue crack growth (Wanhill (1977), Gangloff and Kim (1993)). However, there can be significant frequency effects in aqueous solutions, particularly when the maximum stress intensity factor exceeds K_{ISCC}. An example is shown in Figure 5-14.

For carbon and low alloy steels, dry air is generally considered to be a benign environment, and frequency has little effect on the fatigue crack growth rate (Gangloff and Kim (1993), Horstman, Gregory and Schwalbe (1995)). In aqueous solutions, however, there is considerable evidence that the fatigue crack growth rate of steels is usually frequency dependent. For example, there is no discernible effect of frequency on the fatigue crack growth rate of D6ac steel when tested in dry air at frequencies between 0.1 and 3 Hz. However, in distilled water the fatigue crack growth rate may be doubled by decreasing cyclic frequency from 1 Hz to 0.1 Hz (Gallagher (1983)). This is consistent with the susceptibility of this steel to stress corrosion cracking (Gunderson (1970)).

One further general point regarding the influence of frequency on corrosion fatigue should be noted. For alloy/environment systems where fatigue crack growth is frequency dependent, it has generally been observed that increasing the loading frequency decreases the impact of environment on fatigue crack growth rate. Similarly, decreasing loading frequency increases the effect of environment up to some saturation level. This clearly has significant implications for experimental programs.

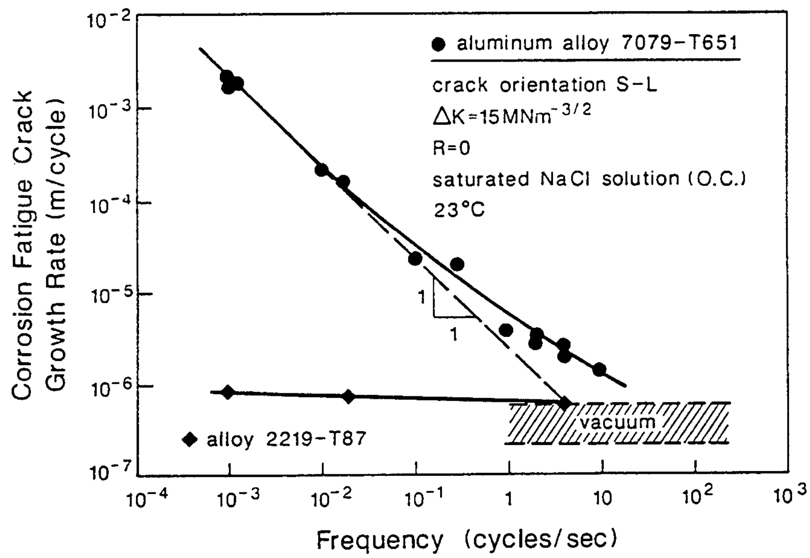


Figure 5-13: Effect of frequency on the corrosion fatigue crack growth rate of two aluminium alloys (the SCC susceptible 7079-T651, and the SCC immune 2219-T87) in salt water solution. After Gangloff (1989).

Mean Stress

For fatigue in benign environments, increasing the mean stress while maintaining the stress range generally increases the fatigue crack growth rate and decreases the threshold stress intensity factor. This behaviour is usually attributed to a reduction in crack closure.

In the presence of a corrosive environment, increasing mean stress also increases the fatigue crack growth rate (Wanhill (1977), Shih and Wei (1983)). In cases where the maximum stress intensity factor exceeds K_{ISCC} this increase can be dramatic (Gangloff and Kim (1993)), and has been explained by the greater opportunity for stress corrosion cracking to occur during the fatigue cycle.

Another phenomenon which has been observed is that repeated breaking and compacting of the oxide layer on the crack faces during fatigue can result in an increased volume of corrosion product which promotes crack closure. Few fatigue studies separate the effect of environment on crack closure from other mean stress (or *R* ratio) effects. The result of this is that in many cases it is difficult to generalise on the effect of mean stress on corrosion fatigue crack growth. The effect of environment on crack closure is discussed in a later section of this report.

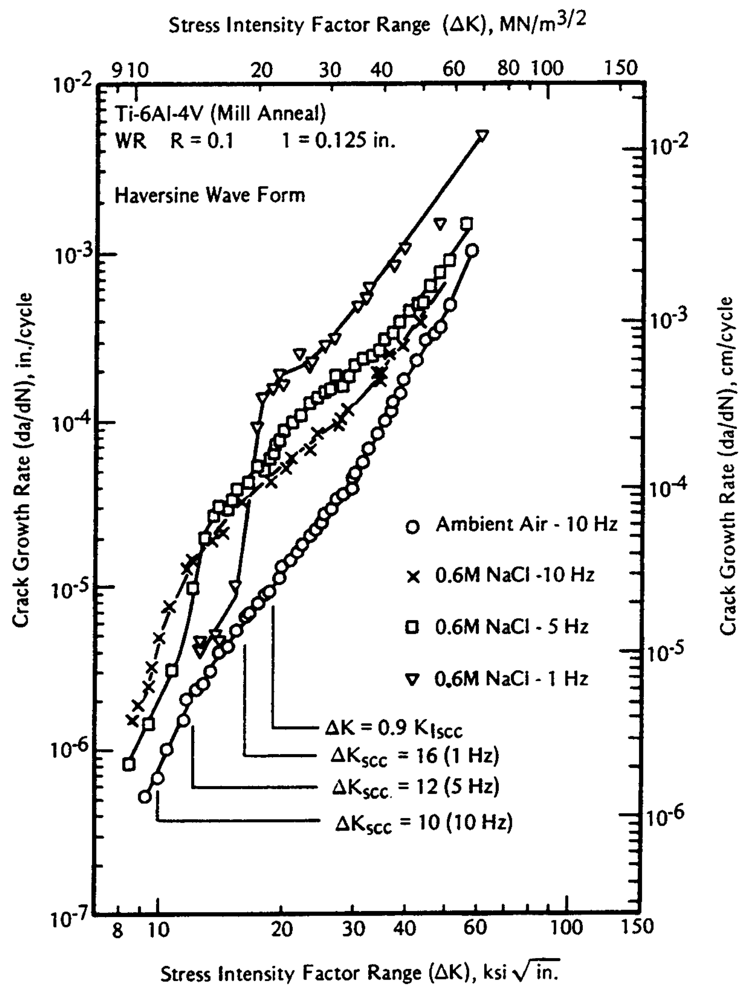


Figure 5-14: Effect of frequency on the corrosion fatigue crack growth rate of Ti-6Al-4V titanium alloy in salt water solution. After Jaske et al. (1981).

Waveform

Gangloff (1989) and Gangloff and Kim (1993) report that waveforms with slow rise times generally tend to increase fatigue crack growth rate in aqueous environments. It has been suggested that such waveforms provide increased time for chemical interactions. For example, Vogelesang (1981) found that at a constant frequency of 0.5 Hz, increasing the rise time from 0.03 seconds to 1.96 seconds increased the fatigue crack growth rate of 7075-T6 aluminium alloy in salt water solution by 50%.

However, the effect of rise time appears to be related to the alloy/environment system. For some systems there appears to be no effect at all.

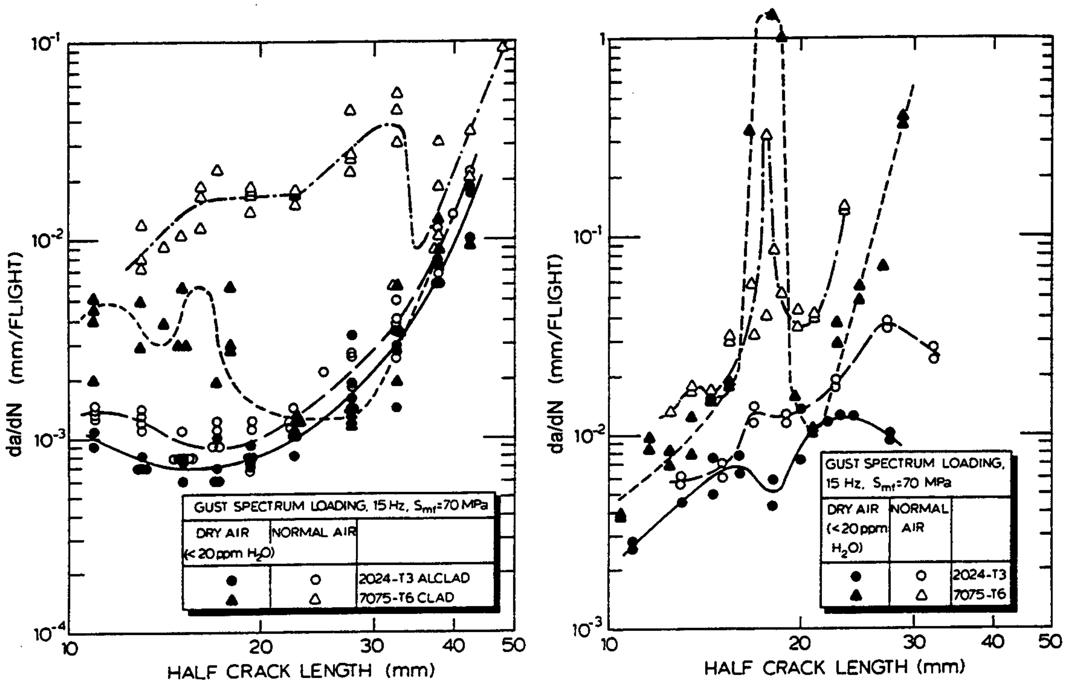
Sequence Effects

It has long been recognised that, even in benign environments, the sequence in which loads are applied during spectrum loading can have a profound effect on fatigue crack growth rate. This is usually associated with fatigue crack growth retardation caused by tensile overloads. There have been remarkably few investigations reporting the effect of corrosive environments on fatigue crack growth rate under spectrum loading for aircraft applications.

Wanhill (1977) has reported the results of tests on 2024-T3 and 7075-T6 aluminium alloy specimens in dry air, normal air, and salt water under gust spectrum loading. Figure 5-15(a) shows the effect of a corrosive environment on fatigue crack growth per flight in 2 mm thick sheet. The results are not unexpected; fatigue crack growth rates were greater in the presence of a corrosive environment, and the largest acceleration in rate occurred in the 7075-T6 alloy. However, the results are neither consistent nor easily explained for the case of 10mm thick sheet. Figure 5-15(b) indicates considerable variability in the fatigue crack growth rate, although it should be pointed out that Wanhill (1977) has reported a thickness effect under constant amplitude and benign environments whereby the fatigue crack growth rate increases with increasing specimen thickness. Also of interest in this case are the very large "peaks" in fatigue crack growth rate which were associated with large tensile loads.

The effect of salt spray on the spectrum fatigue crack growth rate of 7010 aluminium alloy was investigated as part of the RAE contribution to the AGARD Fatigue in Aircraft Corrosion Testing Programme (Wanhill *et al.* (1989)). Constant amplitude fatigue tests indicated that the presence of a salt spray increased the fatigue crack growth rate of the 7010-T7451 alloy by a factor of 3. However, Figure 5-16 shows that, under fighter spectrum loading at a frequency of 10 Hz, the presence of the salt spray had little effect on fatigue crack growth.

The effect of a salt water environment on fatigue crack growth under simplified jet transport spectrum loading has been investigated by Schmidt and Brandecker (1996). Two spectra representing pressurised fuselage loading were applied to 2024-T3 and 6013-T6 aluminium alloy specimens at a frequency of 0.025Hz in both laboratory air and 3.5% salt water solution. The presence of the salt water environment had no effect on fatigue crack growth in the 2024-T3 alloy, and only increased the fatigue crack growth rate in the 6013-T6 alloy at stress intensity factor ranges greater than 17 MPa√m. At these higher stress intensity factor ranges the fatigue crack growth rate was doubled.



(a) (b)

Figure 5-15: Effect of normal air humidity on fatigue crack growth under gust spectrum loading of (a) 2 mm thick, and (b) 10 mm thick 2024-T3 and 7075-T6 aluminium alloy sheet. After Wanhill (1977).

A fundamental consideration is the influence of overloads and underloads on fatigue crack growth in corrosive environments. Goswami and Hoeppner (1995) investigated the influence of tensile overloads on fatigue crack growth in 2024-T851 aluminium alloy, and Ti-6Al-6V-2Sn and Ti-6Al-4V titanium alloy specimens immersed in salt water. Tensile overloads produced fatigue crack growth retardation in 2024-T851 and Ti-6Al-6V-2Sn alloys, much as they would in benign environments. However, similar tensile overloads produced crack extension consistent with stress corrosion cracking in Ti-6Al-4V. This latter type of behaviour has important implications for the modelling of corrosion fatigue crack growth.

Variable amplitude fatigue studies are of considerable importance in the determination of aircraft structural integrity. The inconsistencies in the literature suggest that a considerable amount of work remains to be done in this area, and reflects the relative complexity of environmental fatigue compared to fatigue in benign environments.

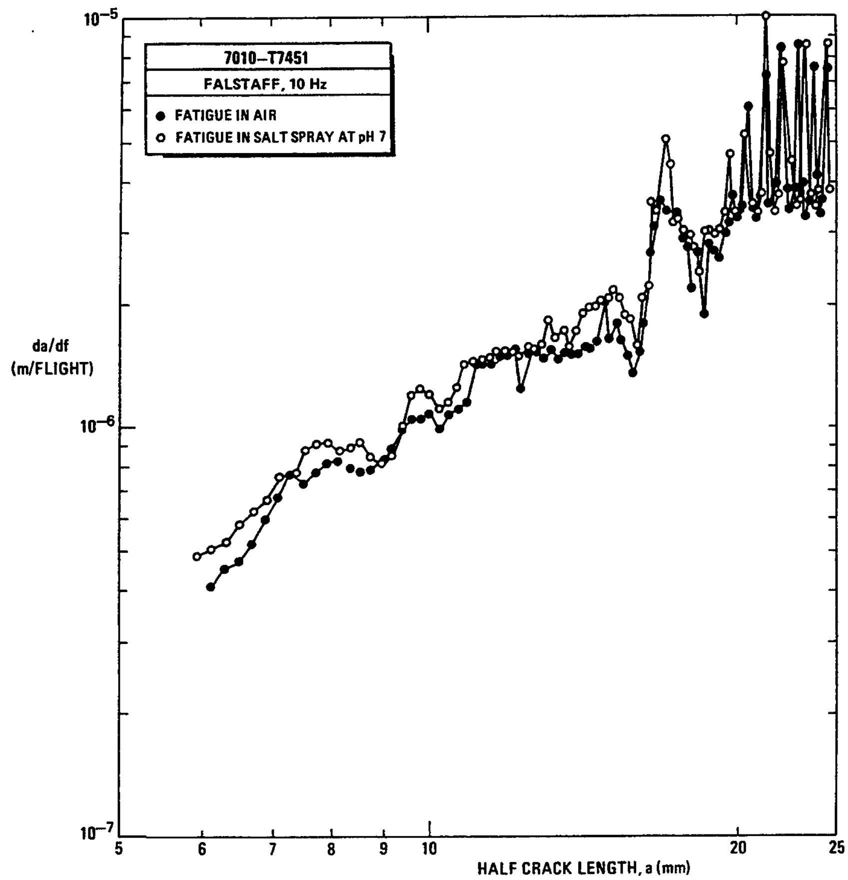


Figure 5-16: Effect of salt spray on fatigue crack growth in 7010-T7451 aluminium alloy under fighter spectrum loading. After Wanhill et al. (1989).

Crack Closure

The mechanical loading parameters previously discussed in this section are extrinsic influences on fatigue crack growth in a corrosive environment, that is, they are a consequence of external loading. An intrinsic parameter which has been found to have a significant influence on fatigue crack growth is crack closure. The concept of crack closure stems from the observation that the crack faces near the tip of a growing fatigue crack close before the tensile load is fully released. This has been used to explain mean stress and retardation effects in basic studies of fatigue crack growth (Schijve (1979)), and it is therefore worthwhile considering the influence of environment on crack closure as a possible research avenue.

Several workers (Suresh *et al.* (1981), Wanhill and Schra, (1990) and Pyun *et al.* (1995)) have observed that the presence of a corrosive environment promotes crack closure at near threshold stress intensity factor levels. This behaviour has been explained by the formation of enhanced corrosion debris within the crack by repeated breaking and compacting of the oxide on the crack faces. This results in an oxide thickness which may be significantly greater than the oxide layer found on an undisturbed surface exposed to the same environment for the same time. This thickened layer of compacted oxide effectively "shields" the crack tip from some portion of the fatigue loading cycle. Wanhill and Schra (1990) have discussed that by exposing 2024-T3 and 7475-T761 aluminium alloys to tank sump water and salt water, the threshold stress intensity factor can be increased and under some circumstances crack arrest may occur.

Similarly, Clark (1986) noted that in near-threshold tests on a maraging steel, an increase in test frequency resulted in a reduction in growth rate per cycle and an increase in the fretting oxide on the fracture surface, both consistent with an increase in crack closure. It was noted that increasing da/dN corresponds to decreasing dN/da i.e. a reduction in the number of cycles over which oxide crushing can occur as the crack advances. In this case, a higher growth rate was associated with the low frequency, low closure condition.

However, it should be emphasised that crack arrest only occurs at very low stress intensity factor ranges. As the stress intensity factor range increases, the presence of a corrosive environment accelerates fatigue crack growth.

Kemp *et al.* (1991) have investigated the effect of salt water on the crack closure of 2024-T351, 7010-T7651 and 8090-T8771 aluminium alloys subjected to moderate stress intensity factor ranges. Both the crack closure and the fatigue crack growth rate of 2024-T351 were virtually unaffected by the presence of salt water. The crack closure of 7010-T7651 was also unaffected by salt water, however the fatigue crack growth rate was increased and this was attributed to a corrosion fatigue mechanism. The presence of salt water considerably reduced the crack closure of 8090-T8771, an Al-Li alloy, while the fatigue crack growth rate was significantly increased. These changes were accompanied by a change in fracture mode; the tortuous fatigue crack path normally associated with Al-Li alloys tested in air (which contributes to crack closure and low fatigue crack growth rates) was replaced by a smoother fracture surface. These results are in agreement with the observations of Chun and Pyun (1995), who also studied the effect of Na_2SO_4 solutions on the crack closure of an Al-Li alloy.

Material Properties

Alloy Composition

Composition has a significant influence on the corrosion fatigue behaviour of aluminium alloys. Wanhill (1977) has discussed how 7xxx series alloys usually demonstrate higher corrosion fatigue crack growth rates in air than 2xxx series alloys, and greater sensitivity to humidity. 7xxx series alloys also show greater sensitivity to the change from air to aqueous environments. Figure 5-17 indicates that increasing the copper content appears to improve the corrosion fatigue behaviour of susceptible 7xxx series alloys.

Remarkably, there does not appear to have been a systematic study of the influence of composition on the corrosion fatigue behaviour of titanium or low alloy steels.

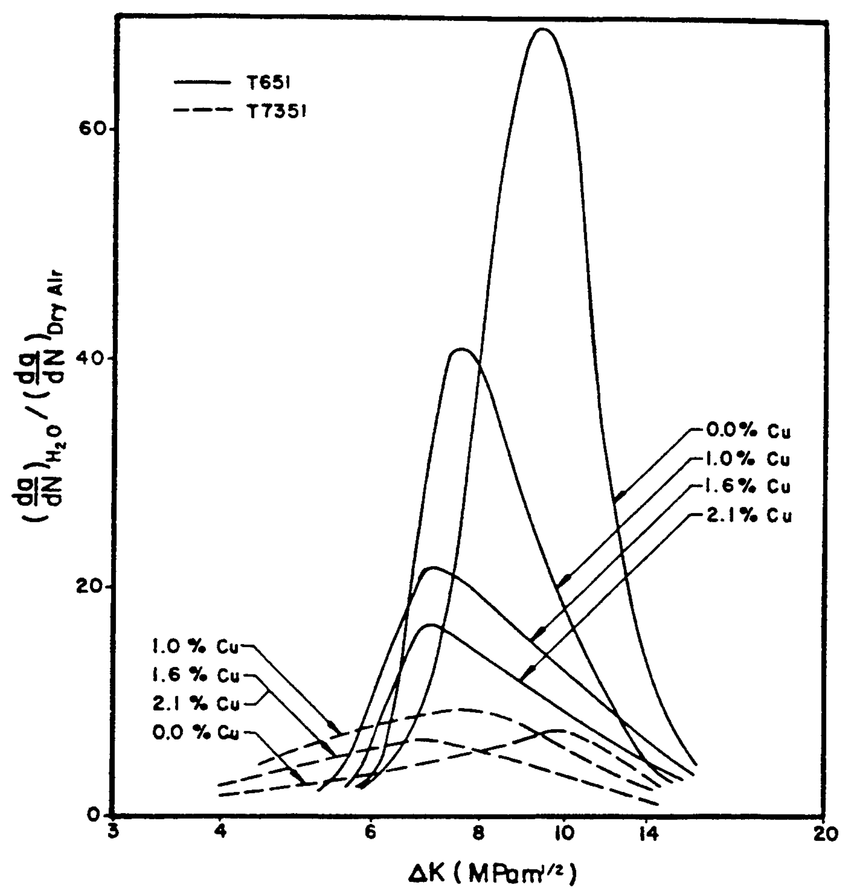


Figure 5-17: Effect of copper content on corrosion fatigue crack growth of a 7xxx series aluminium alloy (Al-6Zn-2Mg). Vertical axis gives the ratio of crack growth per cycle in distilled water to crack growth in dry air. After Gangloff and Kim (1993).

Heat Treatment, Microstructure and Yield Stress

The inter-relationships between heat treatment, microstructure, and yield stress are complex for most engineering alloys, and there does not appear to have been a systematic study of the effects of these variables on corrosion fatigue crack behaviour.

In aqueous environments, overageing usually improves the corrosion fatigue crack growth resistance of 7xxx series aluminium alloys (Wanhill (1977)). However, 2xxx series alloys seem to display greatest resistance to corrosion fatigue crack growth in the naturally aged conditions (e.g. T3 or T4) compared with the artificially aged conditions.

There is relatively little information available in the literature on the effect of microstructure on corrosion fatigue crack behaviour. Certain orientations in some wrought aluminium alloys are susceptible to stress corrosion cracking. For example, the plane normal to the short transverse direction in some alloys such as 7075-T6 is sensitive because the flat, elongated grain structure which is produced during manufacture provides an easily accessible path for the progression of the cracking (cracks growing on other planes are required to deviate substantially out of plane to follow grain boundaries, thus providing effective crack growth retardation). The complex interaction between texture and fatigue crack growth rates in titanium alloys has been discussed by Wanhill (1977). Jaske *et al.* (1981) have suggested that the grain size has little influence on corrosion fatigue crack growth rates of carbon steels. More work is required in this area before results can be generalised.

There is also little information on the effect of yield stress on corrosion fatigue crack growth. Gangloff (1989) has described how yield stress does not appear to influence strongly the corrosion fatigue crack growth rate of ferritic steels in aqueous chloride solutions, where crack propagation is both cycle and time dependent.

Environmental Parameters

The exact nature of the environment to which service aircraft are exposed is perhaps one of the least known aspects influencing their long term durability. This is not surprising given the wide variety of climatic conditions under which aircraft operate. Additionally, fluid leakage and entrapment may expose isolated sections of the airframe to specialised environments, which may also become concentrated in crevices. Relationships would also be expected to exist between the environment and the fatigue loading of the airframe, since, for example, considerable fatigue loading may occur at altitudes where the temperature is low enough to preclude corrosion.

There appears to have been surprisingly little research carried out to determine the exact nature of the environments present in airframes, and their influence on fatigue behaviour. Therefore, little evidence exists upon which to base reasonable arguments about these issues. However, the effect on constant amplitude fatigue crack growth of the environmental variables which may be expected to apply to aircraft are discussed in this section.

Temperature

There has been limited work on the effect of temperature on corrosion fatigue crack growth. Wanhill (1994a) has reported that increasing temperature tends to increase fatigue crack growth rates in aqueous environments, however, no information is apparent on the effect of decreasing temperature below ambient.

The influence of temperature may prove significant in aircraft structures (or at least parts of them) which may be subjected to temperatures ranging from -40 to +50°C. There has been some research in recent times directed at monitoring corrosion activity during flight using electrochemical sensors (Smart and Weetman (1995), Hack (1995)). This has confirmed that corrosion activity increases markedly with increasing temperature. Furthermore, variations in temperature may also be associated with other factors, such as the operation of localised systems such as de-icing heaters.

Further work is clearly required to quantify the effect of temperature on corrosion fatigue crack growth.

Pressure

The influence of pressure on corrosion fatigue crack propagation does not appear to have been studied systematically. However, the effect of reducing pressure to vacuum conditions has been reported by Wanhill (1977). The fatigue crack growth rate of 2024-T3 and 7075-T6 aluminium alloys in vacuum is approximately one quarter of the rate in normal laboratory air. The pressure experienced by service aircraft, however, varies from 1 atmosphere to about 0.2 atmosphere, and within this range it is reasonable to expect little variation in fatigue crack growth rate, particularly as chemical processes such as the formation of oxides in aluminium alloys are known to be halted only by high vacuum conditions.

Environment Composition

Notwithstanding the uncertainties surrounding the exact nature of the environment to which aircraft are exposed, the effect of various commonly encountered environments on constant amplitude fatigue behaviour are discussed below.

Perhaps the most widely encountered environment for many parts of an aircraft structure is normal air, which varies in humidity from about 5% RH to 100% RH.

In the case of aluminium alloys Gangloff and Kim (1993) have described how the fatigue crack growth rate depends on the interrelationship between frequency and humidity. This behaviour is consistent with environmental exposure, that is, fatigue crack growth rates increase as the product of load cycle period and water vapour pressure increases. More accessible examples of the effects of varying humidity on the fatigue crack growth of aluminium alloys are given by Wanhill (1977). Figures 5-18(a) and 5-18(b) show the effects of varying humidity and frequency on the fatigue crack growth of 2024-T3 and 7075-T6 Alclad sheet. It is noteworthy that in some instances the effect of humidity can be significant. Increasing humidity can increase fatigue crack growth rates in some aluminium alloys as much as tenfold.

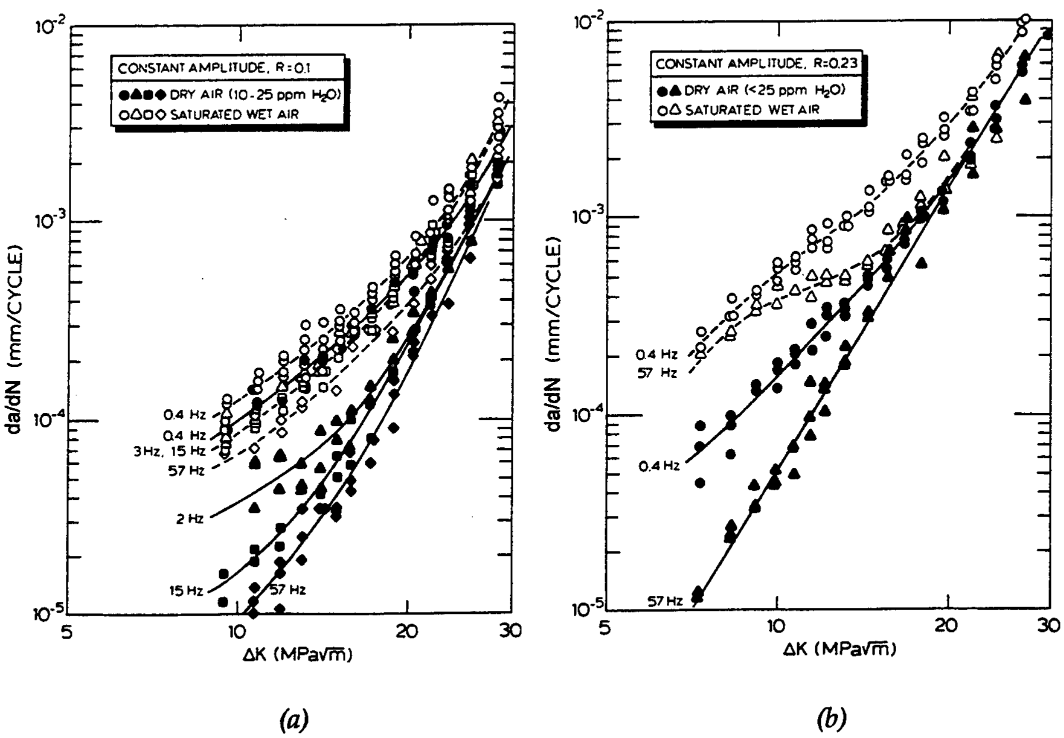


Figure 5-18: Effect of cyclic frequency and humidity on corrosion fatigue crack growth in 1 mm thick clad aluminium alloy sheet; (a) 2024-T3, and (b) 7075-T6. After Wanhill (1977).

It appears that the fatigue crack growth rate of titanium alloys may be increased by increasing humidity, however, this effect seems to be interrelated with other factors such as heat treatment (Wanhill (1977)). A literature search did not reveal any systematic studies of the effects of humidity on the fatigue crack growth of titanium alloys.

The fatigue crack growth rate of high strength steels is sensitive to humidity. For example, Fletcher and Neu (1971) have found that increasing humidity from 10% RH to 80% RH increased the fatigue crack growth rates of an 18% Ni maraging steel, AISI 4340, and D6ac steel by factors between 1.5 and 2 at a test frequency of 15 Hz. However, Argawala and De Luccia (1980) have reported that increasing humidity from less than 15% to 90% RH increases the fatigue crack growth rate of 4340 steel by up to an order of magnitude at a lower test frequency of 0.17 Hz.

Various aqueous solutions and fluids have been used in corrosion fatigue studies on aluminium alloys. These include distilled water, sump tank water, jet fuel and cleaning solvents (Gallagher (1983), ESDU Data Item 88007 (1988)). However, by far the most commonly used is NaCl salt water solution (see for example Wanhill (1977), Jaske *et al.* (1981), Aliaga and Budillon (1981), Schutz (1995)). The strength of salt water solutions are usually about 3.5%, which roughly approximates the salinity of sea water, and have been applied as both solutions and sprays (or fog). Swartz *et al.* (1995) took samples from the bilge area of civil aircraft in an attempt to characterise the environment in this area. Their results are open to question because of the need to rehydrate dried samples (the rehydration ratio has a significant effect on the concentration of species in the solution). Figure 5-19 compares the effect of the bilge solution on fatigue crack growth rates in 7075-T651 aluminium alloy with crack growth rates in dry air and 3.5% NaCl solution.

Generally speaking, 3.5% NaCl solution and sump tank water have the greatest effect on fatigue crack growth rates followed by bilge solution, and other solutions.

Changing from an inert environment to 3.5% NaCl solution results in an increase in the constant amplitude fatigue crack growth rates of damage tolerant aluminium alloys of typically 2 to 4 times (Wanhill (1977)). This generalisation applies to sheet and plate materials which are not susceptible to stress corrosion cracking.

A literature search did not reveal any systematic investigation of the effect of aqueous environments on the fatigue crack growth behaviour of titanium alloys. A further complication is that the effect of aqueous environments is strongly frequency dependent in these alloys, and Figure 5-14 shows that the presence of a salt water solution can significantly increase fatigue crack growth rates at stress intensity factors above K_{ISCC}. However, below K_{ISCC} a more modest increase is observed.

Most corrosion fatigue crack growth data for carbon and low alloy steels has been performed in 3.5% NaCl solution or artificial sea water. Under these conditions fatigue crack growth rates are typically 2 to 3 times the in-air values provided that the alloy is not prone to stress corrosion cracking. Representative results are shown in Figure 5-20. If the alloy is prone to SCC, the corrosion fatigue crack growth rates can be significantly greater. Distilled water increases the fatigue crack growth rate of high strength D6ac steel by a factor of 3 at a frequency of 0.1 Hz, but has little effect at frequencies greater than 3 Hz (Gallagher (1983)).

Also worthwhile discussing at this point is current work by Trathen and Hinton (1996) aimed at characterising the corrosivity of the environment in RAAF P-3C aircraft using electrochemical sensors. The sensors will indicate the time of wetness due to condensation and levels of contaminants in corrosion prone areas of the airframe.

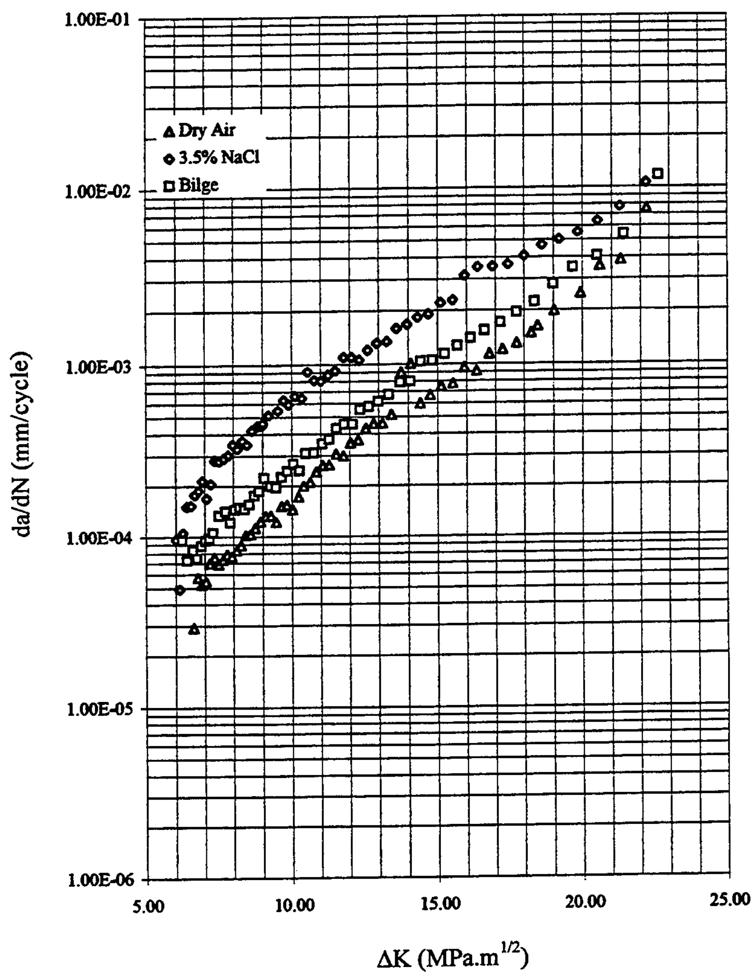


Figure 5-19: Corrosion fatigue crack growth of 13 mm thick 7075-T651 aluminium alloy plate in three different environments: dry air, 3.5% NaCl salt solution, and reconstituted bilge fluid. Test frequency = 1 Hz. After Swartz et al. (1995).

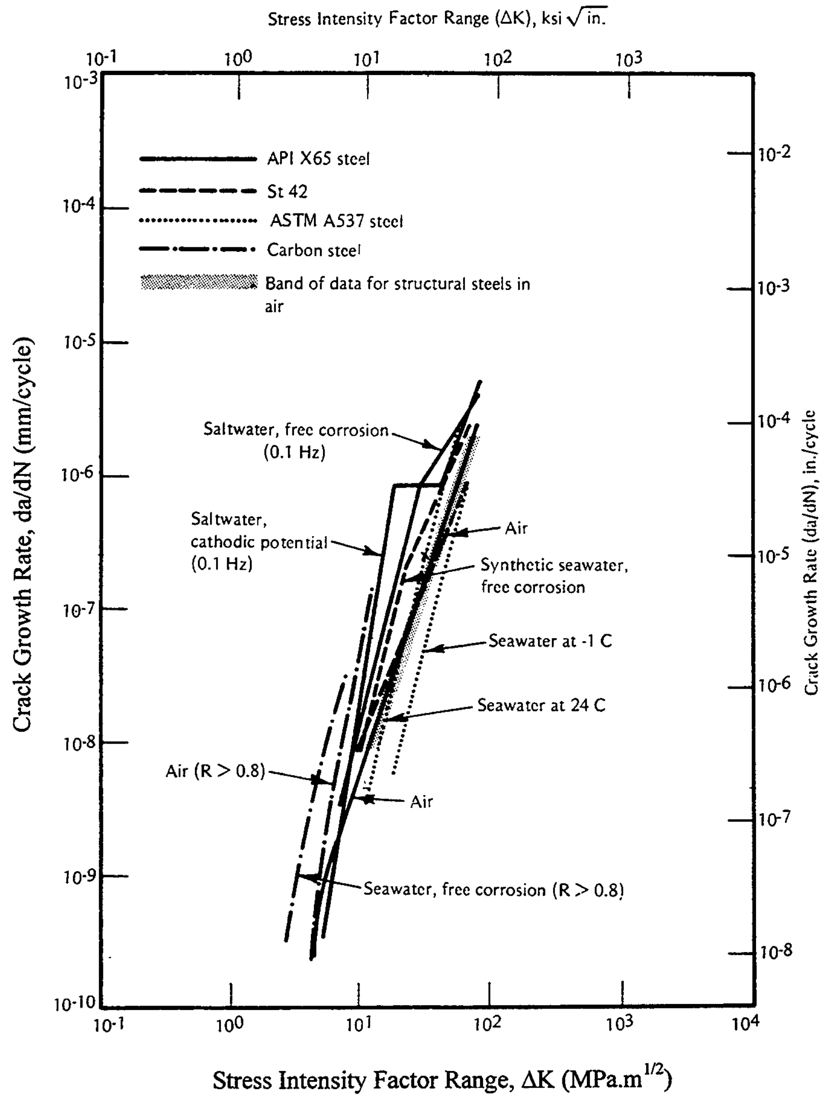


Figure 5-20: Corrosion fatigue crack growth rate of low and medium strength structural steels in air and salt water. After Jaske et al. (1981).

Corrosion Inhibitors

The effect of inhibitors on corrosion fatigue crack growth has been investigated by Khobaib *et al.* (1981), and Squibb and Bryanton (1993). Khobaib tested the effect of a sodium nitrate, and a borax-nitrite based inhibitor on the corrosion fatigue crack growth rate of 2024-T3, 7075-T6, and 7075-T73 aluminium alloys in a salt water solution. Typical results are shown in Figure 5-21; the inhibitor reduced the crack growth rate substantially. Squibb found that the addition of $Na_2Cr_2O_72H_2O$ and Na_2CrO_4 inhibitors to 3.5% NaCl solution resulted in only a marginal improvement in the fatigue crack growth rate of 6013-T6 aluminium alloy. Squibb (1994) also tested 8090-T81 alloy in distilled water and found that adding the same inhibitors could, under some circumstances, reduce the fatigue crack growth rate by a factor of 2.

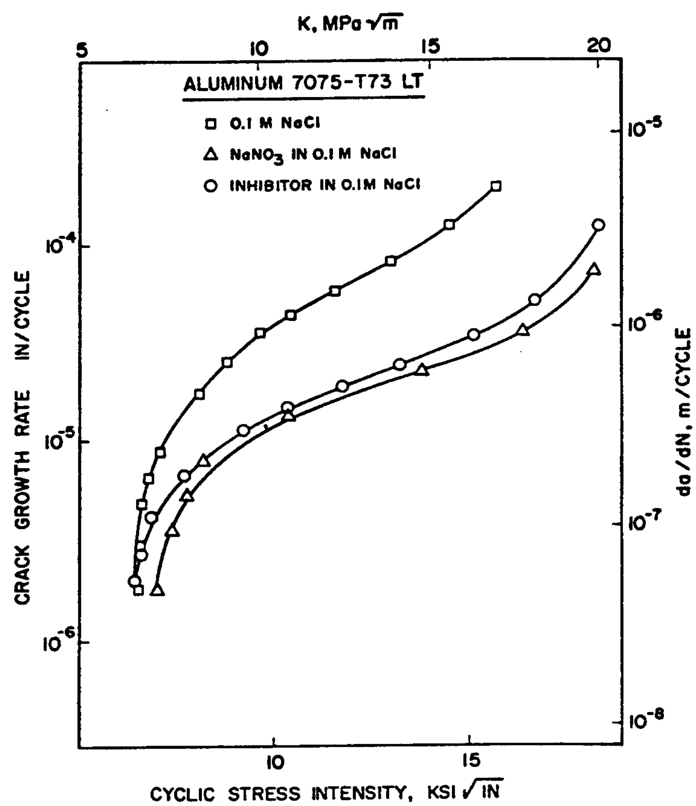


Figure 5-21: Corrosion fatigue crack growth in 7075-T73 aluminium alloy exposed to salt water solution; the addition of sodium nitrate and borax-nitrite based inhibitors reduce the fatigue crack growth rate. Test frequency = 0.1 Hz. After Khobaib et al. (1981).

The effect of introducing corrosion inhibiting compounds into cracks in 4340, a high strength steel, has been investigated by Agarwala and De Luccia (1980). As discussed in the previous section, the fatigue crack growth rate of this steel is sensitive to humidity. A compound consisting of dichromate, borate and nitrite dissolved in xylene was found to reduce the fatigue crack growth rate in humid air considerably. This compound was specifically designed to reduce crack propagation in steels. Similar tests indicated that "Amlguard", a commercial corrosion preventive compound, was ineffective in reducing corrosion fatigue crack growth because it forms a hard film which does not seep to the crack tip.

The use of corrosion preventive or water displacing compounds to reduce corrosion fatigue crack growth rates in aluminium alloys in humid environments does not appear to have been investigated thoroughly.

5.5.3 Prediction of fatigue crack growth in corrosive environments

Gangloff and Kim (1993) have reviewed in detail quantitative crack growth rate models. Two broad groups are apparent: empirical models, and mechanism based models.

Empirical Models

Empirical curve fitting models rely on a systematic regression analysis of relatively extensive experimental fatigue crack propagation data in order to determine the relationship between the fatigue crack growth per cycle, da/dN, and the stress intensity factor range, ΔK. These relationships are applicable to a single combination of material and environment and must also reflect the influence of other important variables such as frequency and mean stress. They are therefore appropriate for applications in which environmental conditions are tightly controlled. A notable example of this approach is the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section XI, Rules for Inservice Inspection of Nuclear Power Plants, which provides a bilinear estimate of da/dN vs. ΔK data for a class of pressure vessel steels in a reactor water environment. This example is discussed more thoroughly in a later section of this chapter.

Gangloff and Kim have discussed how this approach has provided a reasonably good prediction of the fatigue lives of large scale welded tubular components, using a linear summation of crack growth for each fatigue cycle.

The main drawback of empirical curve fitting is the necessity to compile data which reflects the variables encountered in service. This would be a significant problem in the prediction of the fatigue crack growth in most aircraft components and structures because they experience a wide variety of environmental conditions and contain a wide variety of materials.

Mechanism Based Models

Mechanism based models attempt to describe the physical phenomenon of environmentally enhanced fatigue crack growth. Perhaps the simplest of these models makes the assumption that the overall crack growth per cycle in a corrosive environment is simply an addition of the crack growth per cycle in a benign reference environment and the sustained load crack extension caused by stress corrosion cracking during the time for a single fatigue loading cycle. Acceptance of this additive behaviour (i.e. the principle of linear superposition) may be expressed mathematically as

$$(\mathrm{da/dN})_{\mathrm{T}} = (\mathrm{da/dN})_{\mathrm{fat}} + \int (\mathrm{da/dt}) \cdot \mathrm{K(t)dt} \tag{5.1}$$

Where $(\mathrm{d}a/\mathrm{d}N)_{\mathrm{T}}$ is the total fatigue crack growth per cycle, $(\mathrm{d}a/\mathrm{d}N)_{\mathrm{fat}}$ is the crack growth per cycle in a benign environment, and the integral of $(\mathrm{d}a/\mathrm{d}t)K(t)\mathrm{d}t$ is the crack extension caused by stress corrosion cracking during the fatigue cycle. Figure 5-22 further illustrates this concept.

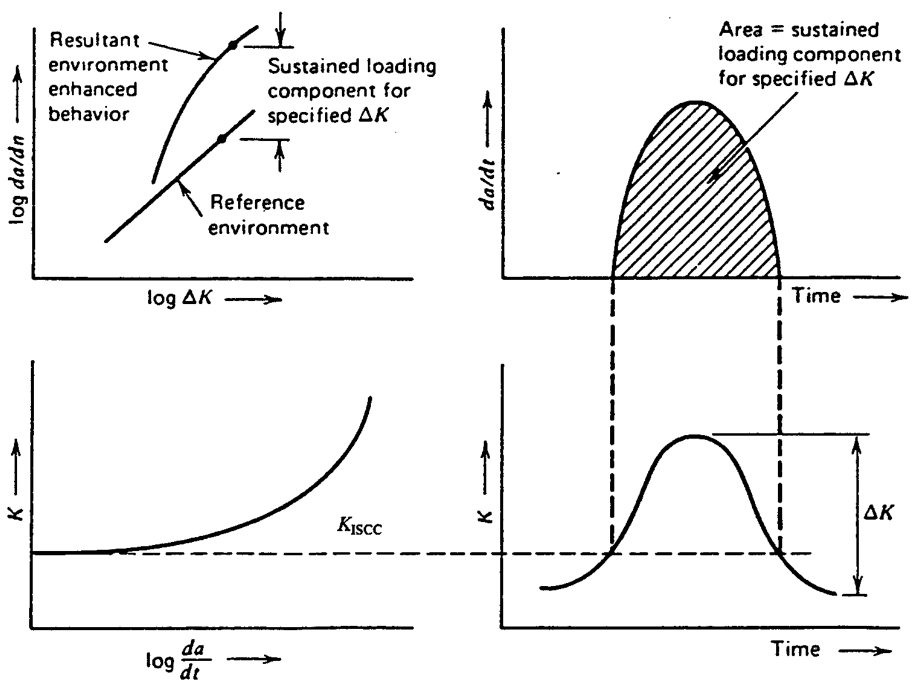


Figure 5-22: Schematic representation of linear superposition. Total crack growth comprises two components: that due to fatigue crack growth in a benign reference environment, and that due to stress corrosion cracking when the stress intensity factor exceeds K_{ISCC}. After Gangloff and Kim (1993).

Linear superposition may be used to predict corrosion fatigue crack growth rates as a function of ΔK, frequency, stress ratio and waveform provided that two conditions are met:

1. the maximum stress intensity during the fatigue cycle must be above K_{ISCC}, and;
2. the increment of crack growth due to stress corrosion cracking must be substantial compared to that due to mechanical fatigue.

This is equivalent to the Type B fatigue behaviour shown in Figure 5-11.

Additionally, the rate of stress corrosion crack growth, $\mathrm{d}a/\mathrm{d}t$, must be known as a function of applied stress intensity factor. As Gangloff and Kim point out, for many materials such data is neither commonly available nor easily determined.

Speidel (1979) has used linear superposition to predict successfully the constant amplitude fatigue crack growth rate of 7079-T651 aluminium alloy in the SCC susceptible short-longitudinal orientation, immersed in saturated saltwater for frequencies between 0.1 Hz and 0.001 Hz, Figure 5-23. However, at a frequency of 1 Hz, the fracture mode changed from intergranular to a mixture of transgranular and intergranular and the superposition model then failed to accurately predict fatigue crack growth.

Mason and Gangloff (1994) attempted to predict the fatigue crack growth of 7075-T651 aluminium alloy in the SCC susceptible short-longitudinal orientation, immersed in saltwater using linear superposition. Superposition underpredicted fatigue crack growth rates for frequencies greater than 0.001 Hz. Figure 5-24 shows typical results.

It is therefore possible to conclude that linear superposition will be successful in predicting corrosion fatigue crack growth only for the weakest orientations in the most SCC susceptible alloys. This result is important, in that generally, while these alloys are found in some locations in older aircraft in the RAAF fleet, the use of such alloys is now avoided. Most materials currently used in aircraft construction have a high K_{ISCC} value relative to typical flawed component stress intensity factor levels, and corrosion fatigue crack growth is substantial below K_{ISCC} (i.e. Type C behaviour in Figure 5-11). In these cases time dependent behaviour may be displayed above K_{ISCC} and cycle dependent behaviour below K_{ISCC}. Wei and Simmons (1981) have argued that the simple linear superposition model may be generalised to describe this behaviour by including an extra term,

$$(\mathrm{d}a/\mathrm{d}N)_T = (\mathrm{d}a/\mathrm{d}N)_{fat} + (\mathrm{d}a/\mathrm{d}N)_{cf} + \int (\mathrm{d}a/\mathrm{d}t) \cdot K(t)\mathrm{d}t \qquad (5.2)$$

where $(\mathrm{d}a/\mathrm{d}N)_{cf}$ represents the contribution to total fatigue crack growth which is attributed to the damage which is driven by the interaction between the environment induced chemical processes and the mechanical processes occurring at the crack tip (i.e. "true" corrosion fatigue). These processes may be caused by different mechanisms which may be time or cycle dependent, and may act together or in competition.

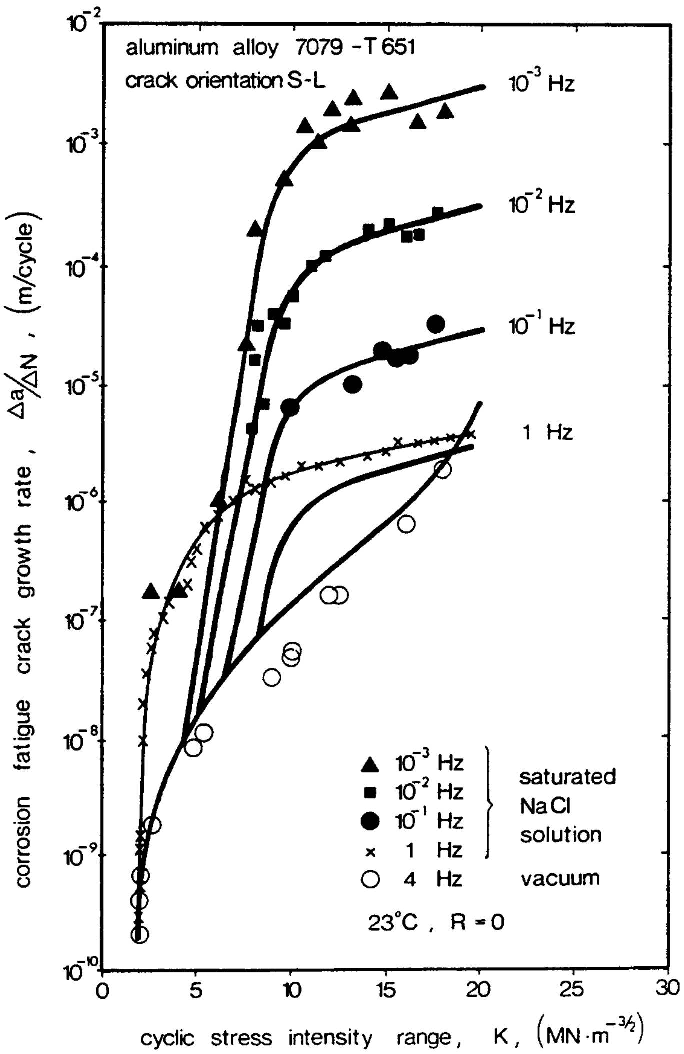


Figure 5-23: Theoretical prediction of corrosion fatigue crack growth rate using the principle of linear superposition (dark lines), and experimental data (individual points). Aluminium alloy 7079-T651 in saturated NaCl solution. After Speidel (1979).

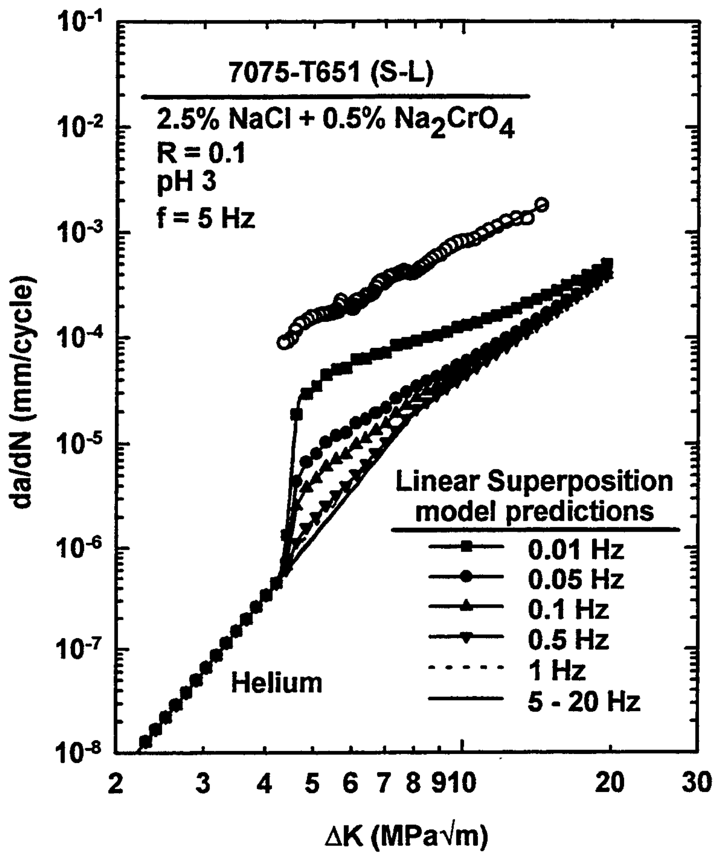


Figure 5-24: Theoretical prediction of corrosion fatigue crack growth rate using the principle of linear superposition, and experimental data at 5 Hz (open circles). Aluminium alloy 7075-T651 in 2.5% NaCl solution + 0.5% Na_2CrO_4. After Mason and Gangloff (1994).

There have been many attempts to describe $(\mathrm{d}a/\mathrm{d}N)_{\mathrm{cf}}$ using models based on the assumed chemical and mechanical processes. A comprehensive discussion of these models is beyond the scope of this report, however, interested readers are referred to Gangloff and Kim (1993). It is sufficient to report that they remain the subject of considerable debate and it is the present authors' belief that considerably more work is essential before such models are useful in an engineering context.

Harlow and Wei (1993) have proposed a probabilistic approach to corrosion fatigue crack growth using the model

$$\left(\mathrm{d}a/\mathrm{d}N\right)_{\mathrm{T}} = \left(\mathrm{d}a/\mathrm{d}N\right)_{\mathrm{fat}} + \left(\mathrm{d}a/\mathrm{d}N\right)_{\mathrm{cf}} \tag{5.3}$$

where $(da/dN)_{fat}$ and $(da/dN)_{cf}$, the fatigue crack growth rates in benign and corrosive environments respectively, are each described by a different Paris-Erdogan law. Several parameters associated with corrosion fatigue, including the initial flaw size, and the Paris-Erdogan constants, are assumed to be random variables. The results of carefully constructed experiments are used to characterise these random variables as Weibull distributions suitable for probability analysis. Harlow and Wei claim this approach enables tight statistical life estimates to be made. However, while the theory of this approach has been investigated, it seems that it is yet to be used in the life prediction of a real structure. This is undoubtedly due in part to the fact that considerable experimental data is required to develop the Weibull distributions in probability based analyses.

Other important technical issues which are likely to influence the successful prediction of corrosion fatigue crack growth in aircraft, and have yet to receive widespread research attention are load sequence effects (i.e. the effect of overloads and underloads), and short crack effects.

It is worthwhile highlighting at this point recent developments in NASGRO, the fatigue crack growth prediction computer program used by NASA. It is planned to release a version of NASGRO in 1997 which will account for environmental effects using the linear superposition model and empirical curve fitting models. However, it is not clear at this stage which alloy/environment combinations will be included in the program.

5.6 The effect of corrosion repair and control on fatigue behaviour

For corrosion damage which is within negligible damage limits, grinding is the most common method of corrosion repair. Care is taken to blend the repaired areas to the remaining material in order to reduce stress concentration effects and therefore minimise the impact of the repair on subsequent fatigue performance. Particular care must be taken when the corrosion repair coincides with some other form of stress concentration such as a fastener hole.

If the grindout repair exceeds the negligible damage limits, a validated metallic or composite patch repair may, on occasion, be used to restore the static strength and fatigue peformance of the structure. If the corrosion is not an isolated case, the possibility of a fatigue or static strength interaction between multiple repairs requires consideration.

The increasing use of corrosion preventive compounds (CPCs) to control corrosion raises concern regarding their effect on the fatigue performance of joints. The reason for this is the belief that the oily film which penetrates into the faying surfaces may alter the load path through the joint and cause premature fatigue failure by relocating the failure region in the structural members, or into the fasteners.

Machin and Mann (1982) examined the effects of CPCs on the fatigue behaviour of specimens representing both high and low load transfer bolted joints. A number of variables were explored using different groups of specimens, including the clamping force provided by the bolts, and the effects of block programmed (spectrum) loading. It was concluded that, for joints with fully tightened bolts under constant amplitude loading, the presence of corrosion preventive compounds reduced the mean fatigue life at high loads, and increased the mean fatigue life at low loads. This result was explained by presuming that the CPC substantially alters the load transfer in the joint at high loads and has a detrimental effect, while at low loads the CPC actually reduces fretting, which was the common initiator of fatigue cracking at this stress level. The results of tests carried out under spectrum loading were less clear. Under "severe" spectrum loading, the use of CPCs actually improved the mean fatigue lives of both high and low load transfer joints. However, under "moderate" spectrum loading the mean lives were either reduced or unchanged depending on whether the joint was either high or low load transfer.

Hoeppner *et al.* (1994) have reviewed the effect of corrosion preventive compounds on the fatigue performance of aircraft joints and also concluded that they can have either a beneficial or detrimental effect on fatigue life, although in most instances they reduce fatigue performance.

The specific effects of CPCs on the fatigue life of joints therefore appears to depend on the design and construction of the joint as well as the nature of the applied loading spectrum. Further research is required before the effects of introducing CPCs can be predicted reliably.

5.7 Methods used by other industries to predict corrosion fatigue behaviour

Predicting the fatigue behaviour of structures is critical in several industries other than aerospace, notably the nuclear and offshore industries. These industries have the advantage that the critical structures are subjected to relatively constant environments. It is perhaps worthwhile briefly reviewing the methods used by these industries to incorporate the effects of corrosive environments into the prediction of fatigue behaviour.

5.7.1 Nuclear Industry

The method of predicting the growth of a pre-existing flaw in nuclear pressure vessels and piping is outlined in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section XI, Rules for Inservice Inspection of Nuclear Power Plants. The method has been discussed by Rahka *et al.* (1984) and involves the following four steps:

1. The stress intensity factor associated with a given loading cycle is calculated taking into account all stresses (membrane, bending, thermal and residual).
2. The incremental crack growth corresponding to the fluctuation in the stress intensity factor is determined by either experimentally derived data, or use of the curves recommended in the ASME code.
3. The flaw size is updated assuming geometric similarity.
4. The process is repeated for the next load cycle.

The relationship between da/dN and ΔK suggested in the ASME code is shown in Figure 5-25. These curves describe the upper bound of fatigue crack growth rates of SA-533 and SA-508 steels, which are typically used in nuclear pressure vessels. These curves have been derived from experimental data for fatigue in air and reactor water environments (Bamford (1979)).

There are two notable features of these curves. Firstly, a linear curve describes the fatigue crack growth rate in air, while bilinear curves describe the fatigue crack growth rate in a reactor water environment. While these curves are empirical, they also reflect to some degree the corrosion fatigue mechanism for this alloy/environment system (which is described by Type C behaviour in Figure 5-11). Secondly, the effect of mean stress during corrosion fatigue is accounted for by providing different curves for different R ratios.

5.7.2 Offshore Industry

Compared with the nuclear industry the offshore industry is less strictly governed by codes of practice in incorporating the effects of corrosion into the determination of structural integrity. However, a relevant document is the British Standards Institute's PD 6493: 1991 which provides guidance on methods for assessing the acceptability of flaws in fusion welded structures. A section of this document is devoted to the prediction of fatigue crack growth using a linear elastic fracture mechanics approach. It is suggested that when obtaining data for these predictions, careful consideration should be given to the effects of testing frequency and waveform on the rate of growth of cracks in aggressive environments. A suggested source of such data is "Corrosion Fatigue of Metals in Marine Environments" by Jaske *et al.* (1981). However, in the absence of specific data, PD 6493 suggests that, for ferritic structural steels the Paris-Erdogan fatigue crack growth law,

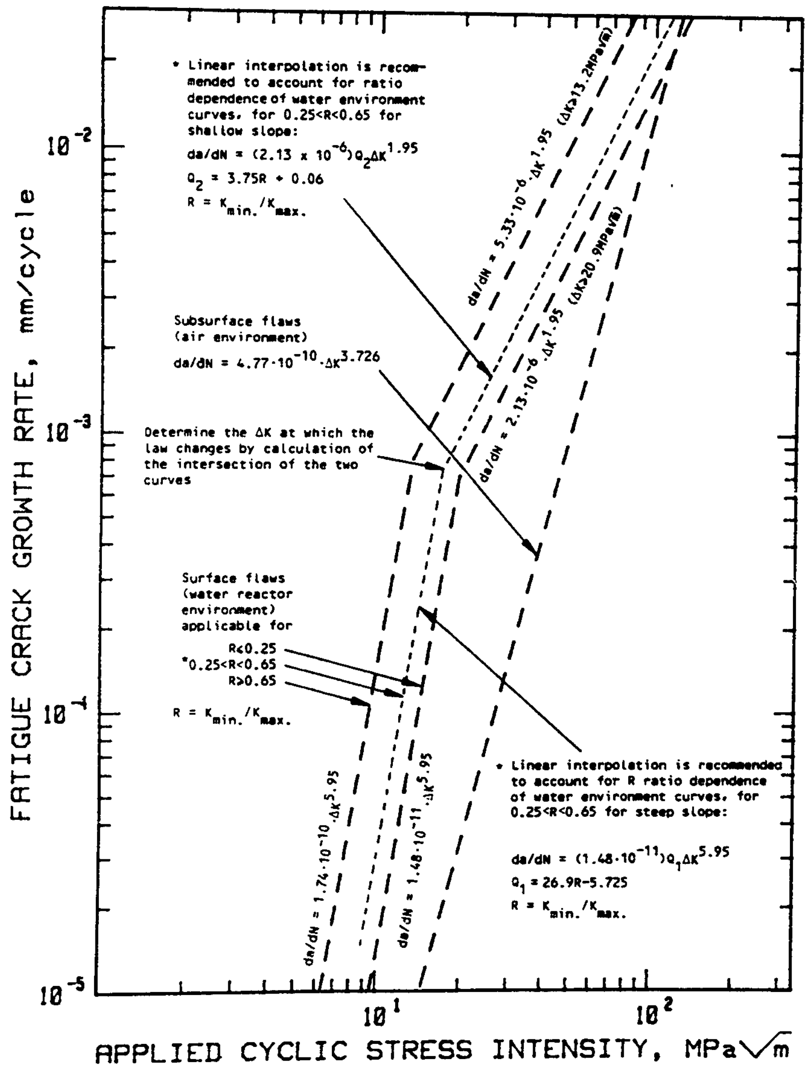


Figure 5-25: Reference fatigue crack growth rate curves for nuclear pressure vessel steels in air and water reactor environments from ASME XI, Appendix A1.

$$da/dN = C(\Delta K)^m \tag{5.4}$$

should be used with the constants $C=3\times10^{-13}$ and $m=3$ in an air environment, and $C=2.3\times10^{-12}$ and $m=3$ in a sea water environment.

In the fatigue strength analysis of mobile offshore units, Det Norske Veritas recommends the use of either S-N curves or a linear elastic fracture mechanics based approach (DNV Classification Note 30.2 (1984)). Various S-N curves are provided which describe the fatigue behaviour of different welded joint details in air. It is recommended that for unprotected joints exposed to sea water the fatigue life is reduced by a factor of 2, consistent with the findings of Tomkins (1984). In the fracture mechanics based analysis, the Paris-Erdogan fatigue crack growth law is used to determine the fatigue life of welded joints. In the absence of relevant fatigue crack growth rate data the following constants are recommended: $C=1.1\times10^{-13}$ and $m=3.1$ in an air environment, and $C=3.4\times10^{-14}$ and $m=3.5$ in a sea water environment.

Grondin and Kulak (1994) have discussed the American Petroleum Institute's Recommended Practice for Drillstem Design and Operating Limits (1989). Here the recommended operating limits for a drillstem are governed by two S-N curves, one which applies to a drillstem operating in an air environment, and another more conservative curve which applies to drillstems operating in corrosive environments. In the presence of such environments, it is recommended that operating stresses be reduced by typically 30-50%. However, the corrosive environment curve retains an endurance limit, and Grondin and Kulak have argued that this is unconservative because laboratory studies have indicated that the endurance limit observed in air is virtually eliminated by the presence of a corrosive environment.

5.8 Summary

- The RAAF has experienced cases where corrosion has initiated fatigue cracking, or where its presence has raised concerns over long term airworthiness. Furthermore, uncertainties concerning the long term effects of corrosive environments on fatigue behaviour have led to the reappraisal of inspection schedules. These experiences are similar to those reported in the wider literature.

- Although it may appear obvious, laboratory studies indicate that corrosive environments have little effect on fatigue behaviour if protection schemes are sound and fasteners remain tight.

- Shot peening may be useful in improving fatigue performance in the short term, however, in the longer term localised corrosion can penetrate the peened layer and initiate fatigue damage.

- Where corrosion has occurred, it may have a profound effect on fatigue life, largely because of the initiation of fatigue cracking from corrosion damage. Prior localised corrosion, such as pitting, may halve fatigue life. The effect of pitting on fatigue performance is strongly associated with its depth.

- Structural integrity analyses have been carried out which model the effect of uniform corrosion simply as a thinning of structural components. Laboratory studies generally support this assumption, although it is necessary to account also for any effects of environment on fatigue crack growth.

- Fatigue crack propagation can be accelerated by the presence of corrosive environments. The relationship between environment and fatigue crack growth is extremely complex and depends on both electrochemical and fatigue mechanisms. However, it is possible to make several observations regarding the effect of corrosive environments on fatigue crack growth. These may be summarised as "rules of thumb":

    1. "True" corrosion fatigue is relatively independent of cyclic frequency.
    2. Stress corrosion cracking under cyclic loading is highly dependent on loading frequency.
    3. 3.5% salt water solution, which is commonly used in laboratory corrosion fatigue tests, appears to be as severe as most environments likely to be encountered by aircraft structures.
    4. For most damage tolerant aluminium alloy sheet and plate, changing the environment from dry air to 3.5% salt water solution increases constant amplitude fatigue crack growth rates by a factor of between 2 and 4, provided the alloy or orientation is not susceptible to stress corrosion cracking.
    5. For aluminium alloys which are susceptible to stress corrosion cracking, changing the environment from dry air to 3.5% salt water solution may increase fatigue crack growth rates by up to an order of magnitude, particularly at low frequencies.
    6. The fatigue crack growth rates of 7xxx series aluminium alloys show greater sensitivity to corrosive environments than the growth rates of 2xxx series alloys.
    7. The presence of corrosive environments does not generally accelerate the initiation of fatigue cracking in titanium alloys, however, it may accelerate fatigue crack growth.
    8. The presence of aqueous environments may increase the fatigue crack growth rate of D6ac steel by a factor of 3 at low frequencies.
    9. Mechanism based models hold the greatest promise for the prediction of corrosion fatigue crack propagation, however, they are immature at the present time.

- The environmental fatigue management of nuclear pressure vessels is achieved using empirical curve fitting models to predict corrosion fatigue crack propagation. However, the environments encountered by these structures are considerably less variable than those experienced by aircraft components.

6. Structural integrity implications of corrosion: areas for development

6.1 Introduction

The preceding chapters of this report have discussed the effects of prior corrosion and the presence of corrosive environments on structural strength and fatigue behaviour. It is the purpose of this chapter to discuss, in specific terms, the implications of corrosion on aircraft structural integrity. Separate sections deal with:

- the experience of aircraft operators and OEMs,
- the effect of corrosion on issues associated with aircraft life management,
- the impact of corrosion protection and control programs on structural integrity management,
- research support requirements:
  - the options available for handling corrosion in fleet aircraft,
  - the prospects of analytical or predictive solutions,
  - options for incorporating corrosion into existing structural integrity management approaches,
  - the effect of corrosion and corrosion treatments on joint integrity, and
  - the effect of corrosion repair on structural integrity.

The major conclusions are emphasised in italics throughout the chapter as well as being collected as a summary at the end.

6.2 Corrosion/structural integrity - operator experience

As an operator of relatively small aircraft fleets, the RAAF has had limited opportunity to acquire experience in dealing with corrosion as a structural integrity issue. However, examples given in the previous chapters have highlighted the potential of environmental factors to cause disruption to orderly fleet management. Penalties may be incurred through increased inspection requirements, costly maintenance actions, and even a need for reassessment of the fleet planned withdrawal dates. Worldwide experience indicates that these problems are more likely to arise as aircraft fleets are kept in service beyond their original design goals.

This review has highlighted the fact that the large aircraft fleets of some overseas operators and OEMs provide a much larger database on corrosion and also provide a better opportunity for observation of any influence of corrosion on structural integrity. The USAF fleet of tanker aircraft, for example, is over 600 in number, and has become a source of major concern in view of its long future service life. Indeed, this concern has generated sizeable research programs aimed at quantifying the effects of corrosion on fleet life (Nieser (1995)). In addition, some civil OEMs have introduced substantial CPCPs to ensure increased fleet life.

Access to information on corrosion strike rate, location and disposition in overseas aircraft which are also in the RAAF inventory would provide early indication of future problems, and allow the RAAF to anticipate changes in maintenance requirements. Similarly, access to information on structural integrity problems with such overseas aircraft would be beneficial in terms of anticipation of problems, and as an indicator of potential management approaches.

Examples of corrosion seriously compromising the structural integrity of airframe structures in rotary-wing aircraft appear scarce in the literature. However, given the similarities in the construction of rotary-wing and fixed-wing airframes, it seems reasonable to assume that that the observations of this report are equally valid for both types of aircraft.

★ *In view of overseas operators and OEMs' access to large aircraft fleets displaying corrosion and the structural integrity related consequences, it is clearly essential that any research avenues pursued as a result of this review make maximum use of information exchange and collaborative programs with those overseas agencies.*

6.3 Implications of corrosion on life management

6.3.1 Analytical life management in the presence of corrosion

The life management philosophies currently used to assure continued airworthiness of military aircraft have been described briefly in Chapter 3. The more advanced of these philosophies (such as damage tolerance and safety-by-inspection) use fracture mechanics as a basis for the rational fatigue management of aircraft fleets, that is, minimising the likelihood of an aircraft structural failure by fatigue or fracture. In these cases, fracture mechanics provides the underlying scientific framework which enables the analytical prediction of fatigue crack growth.

The research reviewed in the course of preparing this report has indicated that, despite extensive experimental and theoretical research, no analogous analytical framework exists for the management of corrosion defects from the viewpoint of aircraft structural integrity.

Obstacles to the development of such an analytical framework include:

(a) the dependence of the corrosion *mechanism* upon many factors including the material, environment, and loading,
(b) the dependence of the *rate* of corrosion upon many factors, and
(c) the environment an aircraft experiences, which can vary significantly over time, depending on climatic factors and its operational role.

★ *No global analytical framework presently exists for the management of corrosion defects from the viewpoint of aircraft structural integrity.*

6.3.2 Experimental modelling and the problem of accelerated testing

It is fortuitous that fatigue is relatively insensitive to frequency effects in benign environments. Therefore accelerated testing of small scale specimens can be used to provide experimental fatigue data for analyses based on fracture mechanics, while testing of large scale specimens is often used to validate analytical predictions of fatigue performance. Spectrum loading, representative of service usage is usually used in such tests.

As well as being subjected to constantly varying fatigue loading, however, military aircraft also experience constantly varying service environments. Therefore, much as there is a fatigue loading spectrum, there is also an associated environmental spectrum. Unlike fatigue, which is cycle dependent, corrosion is time dependent and unlike loading in a fatigue test, the effects of an environmental spectrum cannot be readily accelerated. The effects of various specific environments on constant amplitude fatigue crack growth are reasonably well documented, and there is some limited data on the effect of specific environments on fatigue crack growth under spectrum loading. However, the interaction between fatigue under spectrum loading and varying environmental conditions is not well understood. This means that while military guidelines such as DEF STAN 00-970 and AFGS-87221A stipulate that environmental effects must be accounted for in damage tolerance analyses, there does not exist a firm precedent on how this is to be done.

Empirical models incorporating environmental effects appear to be used in other industries with suitable factors of safety to ensure the continued serviceability of critical plant such as nuclear pressure vessels. However, in these instances the environment does not fluctuate greatly over time, and therefore the interaction between environment and fatigue loading is less likely to cause inaccuracy. To the authors' knowledge environmental effects are customarily accounted for in aircraft durability and damage tolerance assessments by using crack growth data which have been derived in a single relevant corrosive environment, for example humid air. The purpose of this is usually to provide a worst-case scenario. The extent to which this assumption is excessively conservative remains untested.

★ *The possible time based nature of corrosion fatigue must be taken into account in small scale testing along with any effects which may occur as a result of interactions between fatigue loading and a variable environment.*

6.3.3 Full-scale fatigue testing

The review of the literature raises several concerns in relation to incorporating the effects of environment in full-scale fatigue tests. The difficulties of adequately representing service loading as well as airframe build quality in a single full-scale fatigue test are well known; differences in aircraft-to-aircraft loading are accounted for by appropriate small-scale testing and analysis. Two problems arise:

1. The usefulness of the full-scale test as a demonstrator is dependent on its initial condition being as representative of service aircraft as possible. Unfortunately, it is difficult to simulate the form and location of corrosion damage accumulated over years of aircraft service in accelerated laboratory-based tests. It is therefore difficult to simulate the initiation of fatigue from typical corrosion defects in full-scale tests without assuming corrosion which is so severe that the purpose of the test is defeated. An exception occurs in the use of full-scale testing (as in civil aviation) for life extension purposes; in such cases, the fleet condition could be represented by selecting an airframe containing substantial corrosion in all areas of concern.

2. The issue of how the influence of a corrosive environment might be accounted for *during* a full-scale fatigue test has not been resolved. Some development of "environmental" spectra has certainly occurred; a standardized environmental fatigue spectrum, ENSTAFF, has been developed for the full-scale fatigue testing of composite aircraft structures (Gerharz (1987)). It is based on a standard fatigue loading spectrum, FALSTAFF, and aims to represent the mechanical loading and temperature conditions expected for the wing root area of a military fighter aircraft. This spectrum has been developed primarily to deal with concerns that increased temperature degrades the mechanical performance of composite structures. While the idea of developing similar spectra representing mechanical loading and environmental conditions for a metallic structure are appealing, the time based nature of corrosion fatigue is a critical factor, and until realistic environmental effects can be successfully reproduced in small scale accelerated fatigue tests, there is no prospect of using such an approach on a full-scale test article. Furthermore, the interpretation of such tests in the context of fleet management would be much more complex than the interpretation of conventional fatigue tests.

★ *It appears extremely difficult to account for the effects of prior corrosion or environmentally enhanced fatigue in full-scale tests.*

6.4 CPCPs and their contribution to structural integrity management.

6.4.1 Proactive corrosion control programs

The value of well-researched Corrosion Prevention and Control Programs (CPCPs) has been demonstrated by the civil jet transport fleet. In the United States, these have been developed by major manufacturers in conjunction with operators and the United States Federal Aviation Administration to establish mandatory inspection and maintenance procedures for various aircraft. Baseline programs have been developed which represent the minimum requirements for typical operators. The CPCPs establish the corrosion inspection thresholds and repeat inspection intervals. Individual operators that experience significant corrosion after applying the baseline program must then modify or improve their program. The programs are therefore designed to evolve in order to meet the particular needs of the operator and the characteristics of the aircraft.

Some of the experiences of the Boeing company in implementing CPCPs are worth considering, in part because of the extent of the Boeing activity in this area. Firstly, Boeing has conducted representative worldwide fleet surveys in conjunction with major operators to determine the status of fleets with regard to corrosion, fatigue and accidental damage. Structural corrosion has been identified as the largest single maintenance problem for ageing aircraft. Surveys indicated that the aircraft which were in the best condition were those where the operators had initiated corrosion prevention and control procedures early in the life of the aircraft. This finding provides a strong indication that good maintenance practices far outweigh aircraft age as a factor influencing corrosion. Boeing have also concluded from numerous surveys that the application of preventive measures after corrosion has been repaired is important. Indeed, they have cautioned that corrosion prevention and control measures must be aggressively pursued both to reduce the need for extensive repair, and to promote continued airworthiness.

The development and implementation of effective CPCPs requires considerable effort. Firstly, well designed representative fleet surveys are required as the basis of the inspection program. Secondly, operators of relatively small aircraft fleets, such as the RAAF, may face some difficulties in establishing effective CPCPs, and will need to utilise support from the original aircraft manufacturer. In particular, the results of overseas corrosion surveys on aircraft similar to those in the RAAF fleet could prove vital in developing appropriate inspection and treatment programs. Furthermore, the philosophies of CPCPs which have been developed with a strong involvement by both operators and manufacturers could usefully be implemented on other aircraft for which corrosion protection and control activities are not as well supported by the original manufacturer.

★ *Well researched Corrosion Protection and Control Programs are currently used to control corrosion in the ageing civil jet transport fleet. So far, they appear to have been reasonably successful in preventing major incidents in these fleets.*

★ *The wider implementation of Corrosion Protection and Control Programs in RAAF aircraft would benefit from access to data from overseas operators or OEMs. The methodology underlying an effective CPCP in one RAAF aircraft type could be considered for application to other aircraft types.*

6.4.2 NDI developments

Nondestructive inspection plays a major role in CPCPs, and there has been considerable recent research focussed on improving existing nondestructive inspection techniques for corrosion detection, as well as developing new methods. The most promising methods appear to be enhanced visual techniques, which have relatively high scanning rates, radiography, which has the potential to detect corrosion which is embedded under several layers of structure, and advanced versions of eddy current methods.

Older aircraft are more likely to contain hidden corrosion, i.e. corrosion not yet detected. The risks associated with the growth of such corrosion — the growth of corrosion prior to detection to a size threatening structural integrity — can only be addressed fully using programmed inspections. While preventive measures are likely to assist in minimising risk by avoiding or retarding corrosion, further risk reduction will demand the development of improved NDI methods in order to allow earlier detection.

6.4.3 Use of improved materials and protective schemes

An important issue is the contribution of materials selection and corrosion protection schemes in maintaining aircraft structural integrity. It seems obvious to state that corrosion does not present a threat to aircraft structural integrity provided that corrosion protection systems remain intact, fasteners remain tight, and certain particularly susceptible materials are avoided. In this regard, it is significant that newer aircraft designs no longer use the corrosion-prone aluminium alloys employed in some older aircraft, and the early and widespread appearance of corrosion is unlikely in modern aircraft whose designers paid appropriate attention to corrosion protection. The crucial point is that a significant advantage can be gained through the specification of corrosion-resistant materials and corrosion protection systems.

The impact of continuing improvements in design, materials selection, and corrosion protection technology is illustrated in Figure 6-1. Here the corrosion and fatigue related maintenance for Boeing civil jet transport aircraft is plotted against the production line position for two aircraft, the 747 which entered service in 1970, and the

767 which entered service in 1983. This clearly illustrates the point that the influence of corrosion on structural integrity is best addressed at the design and production stages of the life of an aircraft.

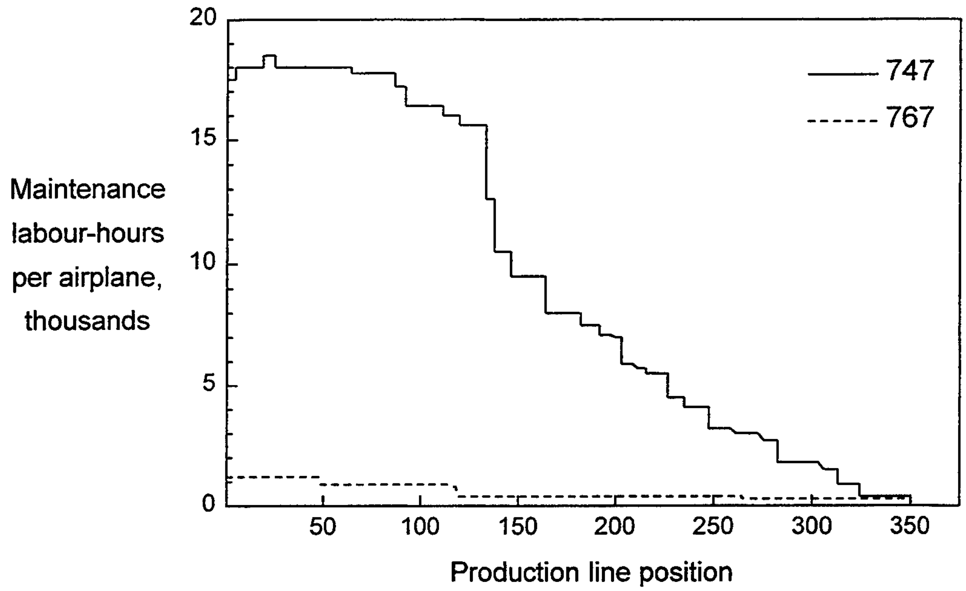


Figure 6-1: The impact of continued improvements in design, materials selection, and corrosion protection technology on corrosion and fatigue related maintenance for Boeing 747 and 767 aircraft after 10 years of service. After Varanasi and McGuire (1995).

The judicious use of teardown of ex-service aircraft (e.g. Macchi MB326H) can provide valuable indications of corrosion strikes, and hence point to possible corrosion-related structural integrity problems, as well as the incidence of fatigue cracking, and should be pursued on an opportunity basis. The acquisition of used aircraft parts specifically for teardown is also possible, noting, however, that such a teardown article would not be representative of the RAAF fleet.

★ *Careful consideration should be given to corrosion protection during the evaluation of new aircraft acquisitions.*

★ *The teardown of ex-service aircraft to identify corrosion and any related structural integrity problems can provide major benefits, and should be considered on an opportunity basis.*

6.5 Research support for improved structural integrity management of corrosion

6.5.1 Hypothetical example of corrosion defect management.

The review indicates clearly that the development of a global analytical framework to deal with corrosion from the viewpoint of aircraft structural integrity would be exceedingly difficult, if not impossible. An alternative, more promising approach to address some aspects of the problem may be to identify and investigate assumptions and approximations regarding corrosion for possible incorporation into existing frameworks of structural integrity management.

★ *A non-global approach offering benefits is to identify and investigate relevant assumptions regarding corrosion effects for possible incorporation into existing frameworks of structural integrity management.*

It is apparent from the preceding discussion that the rational assessment of the implications of corrosion on structural integrity is hampered by a lack of knowledge in some areas. There is therefore a need for research support in these areas to assist with RAAF decision making when corrosion is detected.

In order to highlight areas where such research is required, it is perhaps instructive to consider a hypothetical decision tree which may be applicable when corrosion is detected in an airframe.

Figure 6-2 illustrates the current approach to managing corrosion defects. If the corrosion can be ground out within negligible damage limits, it is usually removed and a corrosion protection scheme is reapplied to the machined region. However, if removal of the corrosion damage exceeds the negligible damage limits, the component is either replaced or repaired by applying a metallic or composite patch.

Figure 6-2 also shows a further option which may be to continue to fly the aircraft in the presence of significant corrosion damage (i.e. corrosion damage close to or exceeding negligible damage limits). This option would almost certainly involve treating the corrosion damage with a CPC to retard its growth. This review has indicated that, to permit this option, greater knowledge about corrosion development and progression, and the effects of corrosion on residual strength and fatigue life is essential. While not necessarily leading to a full model of fatigue life, knowledge of these factors would assist with practical decision making concerning the continued operation of aircraft and the setting of appropriate inspection intervals. One benefit of the use of CPCs to treat corrosion is that the effect of environment is likely to be minimised, thus simplifying decision-making concerning future fatigue life.

These areas requiring further research are discussed in the following sections.

★ *Research which supports the life assessment of treated corrosion damage could provide major benefits by allowing the possibility of continued operation of aircraft with identified corrosion defects.*

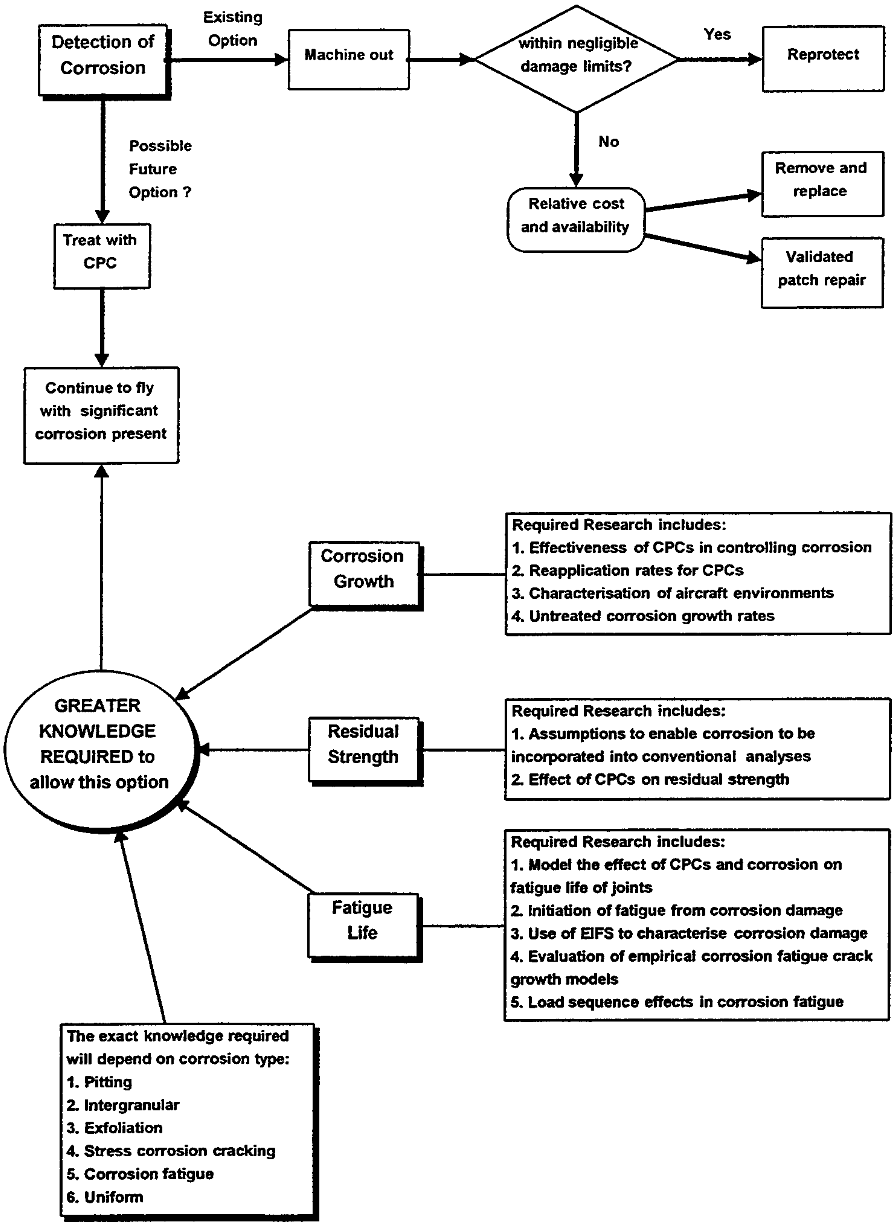


Figure 6-2: Simplified hypothetical decision tree representing options which could be considered for the management of corrosion detected in airframes.

6.5.2 The onset and progression of corrosion

Predictive capability

This review of the literature indicated that there is no reliable method of predicting the onset or progression of corrosion damage. Continued research is required into the development and growth of corrosion in aircraft structures under typical service conditions; any improvement in knowledge in this area would assist in providing a rational basis for the scheduling of corrosion related maintenance. Given the wide array of variables which contribute to the progression of corrosion in airframes, and the sensitivity of some forms of corrosion to changes in these variables, it is unlikely that a global model suitable for the prediction of corrosion growth in airframes will be developed in the foreseeable future. However, with suitable research, and by limiting the range of materials and conditions to those relevant to RAAF fleet aircraft, it should be possible to develop typical (mean) and conservative estimates of the progression rates of various types of corrosion in selected alloys in current and future RAAF service. Some data may be drawn from both the literature and service experience, however, these may require augmentation with suitable laboratory controlled tests.

★ *Continued research into the development of corrosion in airframes offers the potential benefit of assisting with the scheduling of corrosion-related maintenance.*

This problem is compounded by a lack of knowledge regarding the precise nature of the corrosivity of the environments in which aircraft operate, and suitable methods of describing this in terms of corrosion growth. There are three aspects of particular importance:

1. corrosion conditions in aircraft structural configurations,
2. corrosion conditions associated with mission type and mix, and
3. corrosion conditions at specific air bases and storage locations.

The time based nature of corrosion processes adds to the difficulty of collecting data on these subjects. Ongoing work by AMRL aimed at characterising the corrosivity of Australian military air bases (Hinton (1996)), and monitoring corrosion activity during flight is likely to prove useful in this regard. It is envisaged that the development and use of electrochemical corrosion monitoring systems - an area of significant worldwide research - will provide valuable information.

One crucial factor arising from Figure 6-2 is the observation that it is likely that corrosion, once discovered, would be treated with a CPC. Importantly, however, the effectiveness of the various CPC treatments available and their longevity is not yet fully understood. It is therefore essential that research should focus clearly on the assessment of corrosion in the treated state, and be aware of developments in CPC technology; this implies that research into structural integrity matters should be coordinated as much as possible with research into corrosion and corrosion control.

★ *Research into the structural integrity implications of treated corrosion will need to be cognizant of developments in CPC technology.*

Corrosion control using CPCs

Corrosion preventive compounds are used increasingly to control the onset and progression of corrosion in military aircraft, and it is likely that this trend will continue. Research under way into CPC technology needs to be continued to determine appropriate reapplication intervals for achievement of effective corrosion control; the results could have substantial maintenance implications, in that they could lead to the need to introduce an element of time-based maintenance into the current usage-based scheduling of inspection and treatment of fleet aircraft. Consideration of such an option would also be worthwhile if fleet usage varies significantly by aircraft.

★ *The time based nature of corrosion and corrosion control measures suggests that consideration be given to scheduling some maintenance on a time basis as well as a usage basis.*

6.5.3 The effect of corrosion damage on residual strength

Introduction: need for structural analysis methods

One of the justifications used for the considerable effort and cost spent replacing corroded components or repairing corroded structures is the belief that the corrosion might compromise the static strength of the component or structure. However, a review of the literature reveals that this premise remains largely untested. It appears that corrosion has little effect on the bulk mechanical properties of materials. Its main effect from the viewpoint of static strength is in removing load-bearing material and introducing stress concentrations and discontinuities into the structure. Some discontinuities can lead to considerable uncertainty about the determination of static strength; an example is the case of stress corrosion cracking. This form of corrosion causes a negligible loss in cross-sectional area and commonly progresses along the length of extruded sections, which is most often parallel to the direction of applied stress. While it seems reasonable to assume that such cracking will have no influence on the strength of the component when it is loaded in tension, it is conceivable that there may be a loss of compressive load carrying capacity because of the onset of localised buckling, or crippling. The important point is that, with the exception of relatively few investigations (including those carried out by AMRL on retired Macchi tailplanes which indicated that typical stress corrosion cracking of this sort has negligible effect on static strength), the effects of corrosion defects on residual strength remain largely untested.

★ *It seems reasonable to propose that the influence of corrosion on residual strength could be accounted for satisfactorily by incorporating the dimensional changes that it causes into conventional strength analyses.*

Residual strength estimations could require a range of analytical approaches, depending on the failure mode anticipated, the complexity of the system and the stressing information available; the important requirement is for the system engineer to have available approaches which will allow speedy and reliable residual strength estimation for most common configurations. In this regard, there is a requirement for research to establish simple approximate representations of corrosion defects which could be used in more conventional strength analyses (ranging from simple analytical representations to detailed finite element analyses) appropriate for the failure modes being considered (tensile failure, fracture, buckling, loss of stiffness). This would be of benefit by making such analyses more readily useable for the type of decision making depicted in Figure 6-2.

The research work needed to underpin the development of approximate representations would need to be supported by suitable experimental programs which would test the effectiveness of the results. Research should be focussed on situations that have been established by experience to present the most challenging structural integrity concerns, and for which conventional analysis capability is limited by the need to make very conservative assumptions. In practice, this suggests focussing research on laminar defects representing intergranular and exfoliation corrosion at fastener holes, and stress corrosion cracking in spars.

There is a requirement for research to establish simple approximate representations of corrosion defects which could be used in more conventional strength analyses.

Bucci *et al.* (1995) have proposed evaluating fatigue cracks growing from initial corrosion defects using residual strength testing, rather than continued fatigue testing to failure. This approach offers the prospect of gaining an improved understanding of the *rate* at which residual strength is being degraded throughout fatigue life, and since the degradation of residual strength is a primary factor in structural integrity decision-making, this approach would appear to have some advantages.

6.5.4 The effect of corrosion on fatigue

There are several different aspects to the issue of the effects of corrosion and corrosive environments on fatigue life. These may be separated into the initiation of fatigue from existing corrosion, and corrosion fatigue crack growth.

The influence of corrosion on fatigue crack initiation

The initiation of fatigue cracking from certain types of corrosion has been well documented. Further knowledge about the conditions required for corrosion to make the transition to fatigue cracking is required so that the fatigue performance of structures containing corrosion can be predicted.

Considerable research has been aimed at determining the nature of fatigue crack initiation from corrosion pitting. This has revealed the interaction between competing corrosion and fatigue processes which can occur as the defect grows. The models, however, while promising, contain unrealistic assumptions, and require further development. Further research is required to determine the conditions under which other forms of corrosion, such as the laminar corrosion defects in exfoliation, intergranular, and stress corrosion cracking are likely to initiate fatigue cracking. The aim should be to provide a rational basis for the incorporation of such corrosion damage into existing life management philosophies, and to provide and understanding which will support (or give additional confidence to) practical decision making concerning corrosion-related crack development.

★ *Research is required to determine the conditions under which different forms of corrosion, particularly the laminar corrosion defects in exfoliation, intergranular, and stress corrosion cracking, are likely to initiate fatigue cracking*

Since the pitting models have been developed to their present state overseas, they represent an area where clear benefit would be gained by collaborative research in which Australian efforts address the other, largely unexplored areas of initiation from exfoliation and other laminar corrosion defects.

While it is apparent that fatigue cracking may initiate readily from corrosion damage, there remains some uncertainty surrounding the conditions under which corrosion damage makes the transition to fatigue cracking. There is a strong link between the depth of localised corrosion and the reduction in fatigue performance. There has been considerable work aimed at quantifying this, and significant progress has been made. A good example is given by Chubb *et al.* (1996) who has investigated the effect of pitting on the fatigue performance of aluminium alloy specimens containing holes. It was concluded that pitting significantly influenced fatigue performance only when it reached a depth of 0.13 mm (0.005"). Chubb has therefore suggested that an assumed initial flaw of 0.13 mm (0.005") accounts for the influence of corrosion pits up to this size.

The notion of an equivalent initial flaw size corresponding to corrosion damage is potentially powerful and should be explored for other forms of corrosion damage. It also offers the possibility of incorporating corrosion defects into crack growth-based fatigue life approaches, by comparison of the EIFS for the corrosion with the assumed 1.25 mm (0.05") initial flaw used for fatigue life analysis. Further work is also required to adequately resolve the interaction between the growth of corrosion defects by a corrosion mechanism, their transition to fatigue cracks under the action of fluctuating loads, and their subsequent growth by the mechanism of fatigue.

The concept of describing corrosion damage using an EIFS approach is being considered by several researchers, for example (Bucci *et al.* (1995), Paul and Groner (1996)).

A further consideration which will require research before an EIFS concept can be used to assist with identifying future behaviour of corrosion-related defects is that an EIFS is sensitive to the influence of environment on fatigue crack growth rate. Note, however, that the use of CPCs would be expected to reduce or remove this sensitivity, providing improved confidence in any life prediction.

★ *Describing corrosion damage using an Equivalent Initial Flaw Size (EIFS) offers the possibility of incorporating corrosion into conventional life management philosophies based on fatigue crack growth.*

Corrosion fatigue crack growth

It is clear that the presence of corrosive environments causes accelerated fatigue crack propagation in many alloys typically used in aircraft construction. The degree of acceleration is usually determined by a complex interaction between a variety of mechanical and environmental variables and is difficult to predict without some valid experimental data. However, the results of this review indicate that establishing the nature of the environmental fatigue cracking, that is, whether the fatigue behaviour is best described as either stress corrosion cracking under cyclic loading, true corrosion fatigue, or some combination of these two will give some indication of the degree of acceleration which may be expected, and may also determine other characteristics such as the sensitivity to changes in frequency. For example, fatigue crack growth in damage tolerant aluminium alloy sheets and plates exposed to humid air and salt water environments is most often best described as true corrosion fatigue, and crack growth rates may increase by a factor of between 2 and 4 compared with dry air. However, if the alloy is susceptible to stress corrosion cracking and is in the form of a forging or extrusion, the fatigue crack growth is usually best described as a combination of stress corrosion cracking under cyclic loading and corrosion fatigue, and crack growth rates may increase by an order of magnitude in corrosive environments.

Previous attempts to model corrosion fatigue crack growth mechanistically have provided valuable insight into the factors governing the process of corrosion fatigue, however, the prediction of fatigue crack growth remains unreliable in the context of aircraft structural integrity calculations. A substantial research program would need to be mounted to redress this situation. Issues such as the effect of overloads or underloads on fatigue crack growth under environmental conditions, and the effect of altering environment during fatigue crack growth would require further investigation, involving many variables, and with little prospect of developing a more broadly-applicable methodology. However, while research into this area may not lead rapidly to a capability for analytical predictions, there are some potential benefits in conducting some aspects of this program; ultimately, research in this area may provide some insight into the shortcomings of existing fatigue crack growth models when applied under corrosion fatigue conditions, and the knowledge gained could provide benefits in terms of improved confidence levels about handling environmental effects in structural integrity decision making.

A more promising approach would be to evaluate modifications to fatigue crack growth models which allow them to incorporate environmental effects empirically. An example is the NASA fatigue crack propagation software, NASGRO, which is planned to incorporate environmental effects in a version to be released during 1997.

Further long term research would be useful to determine how the interrelationship between aircraft flight environments and fatigue loading influence fatigue crack growth. For example, in some transport aircraft a considerable portion of the total fatigue loading may occur at altitudes where the temperature is low enough to effectively preclude corrosion processes. Under these circumstances environment may play little part in accelerating fatigue crack growth.

★ *Mechanism based models of corrosion fatigue crack growth are immature at the present time. Several basic issues remain unresolved. In the short to medium term the most promising method of modelling corrosion fatigue crack growth appears to be using corrosion fatigue crack growth data in conventional models.*

6.5.5 The effect of corrosion on joint performance

Joints in aircraft structures are vulnerable to both corrosion and fatigue damage. There are two aspects highlighted by this review which merit further discussion. These are the role of corrosion in shifting fatigue crack initiation sites, and the effect of CPCs on fatigue performance.

It has been found in several studies that corrosion in joints can shift fatigue crack initiation sites and therefore the mode of fatigue failure. This can occur through fatigue initiating from localised corrosion rather than from other stress concentrations such as fastener holes, through the corrosion product causing dimensional changes, such as "pillowing" of lap joints when corrosion occurs on the faying surfaces, or through the possibility of the corrosion product changing the load transfer through the joint.

In view of the likelihood of increased use of CPCs for corrosion control, it is important to understand more fully the degradation in joint fatigue performance which occurs as a result of CPC usage. CPCs might be expected to influence joint performance in two ways: firstly by affecting joint load transfer, and secondly by influencing fatigue crack initiation and growth.

The above factors, and the fact that structural joints tend to be prime sites for corrosive attack, are likely to make joints, which are already susceptible to structural degradation by fatigue, particularly sensitive to environmental influences. A detailed understanding of the influence of these factors on fatigue life is currently lacking and is essential if environmental influences on airframes are to be fully addressed. Any research tackling these problems will require, as a priority, the development of an appropriate joint analysis capability.

★ *The development of an analysis capability which is able to address corroded structural joints or those which have been treated with CPCs is recommended.*

6.5.6 The effect of corrosion repair on aircraft structural integrity

The most common response to the detection of corrosion in primary aircraft structure is to repair it at the earliest opportunity. If the corrosion is such that it can be ground out within negligible damage limits, it is usually removed and a corrosion protection scheme is reapplied to the machined region. However, if removal of the corrosion damage would exceed negligible damage limits a decision is made, usually on an economic basis, as to whether the component is replaced, or repaired by machining away the corroded section and applying a metallic or composite patch.

Structural corrosion repairs need to be validated by an appropriate engineering analysis, which must verify that the repair has restored the static strength of the structure as well as its fatigue performance. This last point is particularly relevant to instances where multiple repairs may accumulate in close proximity over several maintenance cycles; a prime requirement is an analytical approach, or experimental data on representative repairs, which will provide guidance about the potential interaction between repairs. This is a major requirement which, since it does not involve environmental factors directly, will not be addressed further in this report.

The potential benefits of peening regions of grindout repair prior to the reapplication of a corrosion protection scheme deserves further investigation; it is not clear, for example, whether the peening improves fatigue life simply through the well-understood residual stress mechanism, or whether there is an additional influence of peening on corrosion resistance.

★ *Research is needed to develop an approach which will define the allowable proximity of multiple repairs for corrosion.*

★ *Research is required to establish the mechanism for (and potential extent of) any life extension obtainable after corrosion repair through the use of peening.*

6.6 Summary

The major conclusions from this chapter are summarised below:

1. In view of overseas operators and OEMs' access to large aircraft fleets displaying corrosion and the structural integrity related consequences, it is clearly essential that any research avenues pursued as a result of this review make maximum use of information exchange and collaborative programs with those overseas agencies.
2. No global analytical framework presently exists for the management of corrosion defects from the viewpoint of aircraft structural integrity.
3. The possible time based nature of corrosion fatigue must be taken into account in small scale testing along with any effects which may occur as a result of interactions between fatigue loading and a variable environment.
4. It appears extremely difficult to account for the effects of prior corrosion or environmentally enhanced fatigue in full-scale tests.
5. Well researched Corrosion Protection and Control Programs are currently used to control corrosion in the ageing civil jet transport fleet. So far, they appear to have been reasonably successful in preventing major incidents in these fleets.
6. The wider implementation of Corrosion Protection and Control Programs in RAAF aircraft would benefit from access to data from overseas operators or OEMs. The methodology underlying an effective CPCP in one RAAF aircraft type could be considered for application to other aircraft types.
7. Careful consideration should be given to corrosion protection during the evaluation of new aircraft acquisitions.
8. The teardown of ex-service aircraft to identify corrosion and any related structural integrity problems can provide major benefits, and should be considered on an opportunity basis.
9. A non-global approach offering benefits is to identify and investigate relevant assumptions regarding corrosion effects for possible incorporation into existing frameworks of structural integrity management.
10. Research which supports the life assessment of treated corrosion damage could provide major benefits by allowing the possibility of continued operation of aircraft with identified corrosion defects.
11. Continued research into the development of corrosion in airframes offers the potential benefit of assisting with the scheduling of corrosion-related maintenance.
12. Research into the structural integrity implications of treated corrosion will need to be cognizant of developments in CPC technology.
13. The time based nature of corrosion and corrosion control measures suggests that consideration be given to scheduling some maintenance on a time basis as well as a usage basis.
14. It seems reasonable to propose that the influence of corrosion on residual strength could be accounted for satisfactorily by incorporating the dimensional changes that it causes into conventional strength analyses.

15. There is a requirement for research to establish simple approximate representations of corrosion defects which could be used in conventional strength analyses.
16. Research is required to determine the conditions under which different forms of corrosion, particularly the laminar corrosion defects in exfoliation, intergranular, and stress corrosion cracking, are likely to initiate fatigue cracking.
17. Describing corrosion damage using an Equivalent Initial Flaw Size (EIFS) offers the possibility of incorporating corrosion into conventional life management philosophies based on fatigue crack growth.
18. Mechanism based models of corrosion fatigue crack growth are immature at the present time. Several basic issues remain unresolved. In the short to medium term the most promising method of modelling corrosion fatigue crack growth appears to be using corrosion fatigue crack growth data in conventional models.
19. The development of an analysis capability which is able to address corroded structural joints or those which have been treated with CPCs is recommended.
20. Research is needed to develop an approach which will define the allowable proximity of multiple repairs for corrosion.
21. Research is required to establish the mechanism for (and potential extent of) any life extension obtainable after corrosion repair through the use of peening.

7. Potential research program

7.1 Introduction

The previous chapters of this report have reviewed in detail the literature regarding the effects of corrosion on static strength and fatigue life, and have discussed the wider implications of corrosion on aircraft structural integrity. Areas requiring further development in order to improve the determination of aircraft structural integrity have been described.

It is the purpose of this chapter to identify those areas of research which would provide maximum benefit as part of a research program.

7.2 Identification of potential research areas

Chapter 6 used the information acquired in the review to identify a range of areas where research could benefit the management of structural integrity, and a number of conclusions were reached.

A potential research program to address these areas is summarised in Table 7-1. This program is categorised into broad areas of research (listed in the left-hand column), as well as different levels of research activity. Any future program will benefit from a range of activities at three different levels:

1. Data surveys, information exchange, and the evaluation of existing corrosion management programs. These types of programs benefit strongly from collaboration with overseas agencies and as a result take some time to set up. They should be viewed as a long-term activity.
2. Applied research, aimed at addressing specific life management issues. In general, these programs would be expected to extend over several years.
3. Strategic research, aimed at developing capability in a number of key areas. The majority of these programs would be expected to require a longer time frame for completion, partly because the inputs are often defined by preceding applied research.

Table 7-1: Potential research program.

	Data Exchange and Fleet Survey	Applied Research	Strategic Research and Capability Development
Incorporation of corrosion into existing methods of structural integrity analysis		Equivalent Initial Flaw (EIF) model of corrosion (exfoliation & pitting) *+ WL(MoU), AL*	1. Incorporation of EIFS into DADTA *+ WL(MoU), AL* 2. Analytical model of passivated exfoliation
Corrosion as a fatigue initiator		Fatigue from laminar corrosion defects: (testing and assessment)	Model of fatigue from laminar corrosion defects.
Corrosion fatigue crack growth		Evaluate existing environmental fatigue crack growth software (e.g. NASGRO)	1. Model refinement 2. Interrelationship of environment and fatigue sequences
Corrosion in joints		Effect of corrosion on representative (AGARD) joint: 1. failure mode 2. load transfer 3. fatigue life *+ SSMD **	Model corrosion as faying surface change *+ SSMD **
Corrosion prevention and fleet management	Wider use of established CPCP approaches	Effect of CPCs on representative (AGARD) joint: 1. load transfer 2. failure mode 3. fatigue life *+ SSMD **	Model CPC effect on interface, refine model *+ SSMD **
Corrosion rates		Characterisation of aircraft environments *SSMD **	Determination of limiting corrosion rates *SSMD **
Fleet survey and incident tracking	1. Teardown (opportunity based) 2. Fleet corrosion and structural integrity survey and reporting program *+ WL(MoU)*		
Inspection	Evaluate viability of time-based inspections	Evaluation of methods for 2nd and 3rd layer corrosion *AED *, SSMD **	

Key to Table 7-1:

......*	Current research activity within AMRL.
+......	Potential for collaboration with overseas agency.
WL(MoU)	Wright Laboratories under Memorandum of Understanding.
AL	ALCOA, USA.
AED	Airframes and Engines Division, AMRL.
SSMD	Ship Structures and Materials Division, AMRL.

The research program described in Table 7-1 reflects the judgement of the authors, based on the findings of this report and a number of other criteria for research. These included:

- the provision of practical benefit to the RAAF,
- the development of background knowledge leading to longer-term benefits,
- the possibility of useful collaborative work with overseas agencies,
- the possibility of contract research within Australia, and
- the availability of suitable test articles and material.

Current research activities within AMRL are noted in the table, along with activities where potential exists for useful collaboration with overseas agencies.

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9. References

AFGS-87221A (1990) Air Force Guide Specification. Aircraft Structures, General Specification for. Department of Defence: USA.

Agarwala V.S. and De Luccia J.J. (1980) New inhibitors for crack arrestment in corrosion fatigue of high strength steels. *Corrosion*. **36**, 208-212.

Agarwala V.S., Bhagat P.K. and Hardy G.L. (1995) Corrosion detection and monitoring of aircraft structures: an overview. *Corrosion Detection and Management of Advanced Airframe Materials, AGARD Conference Proceedings No. 565*. Advisory Group for Aerospace Research and Development, NATO.

Alcott J. (1994) An investigation of nondestructive inspection equipment: detecting hidden corrosion on USAF aircraft. *Materials Evaluation*. **52**, 64-73.

Aliaga D. and Budillon E. (1981) Corrosion fatigue behaviour of some aluminium alloys. *Corrosion Fatigue, AGARD Conference Proceedings No. 316*. Advisory Group for Aerospace Research and Development, NATO.

Ansley G., Bakanas S., Castronuovo M., Grant T. and Vichi F. (1992) Current nondestructive inspection methods for aging aircraft. *DOT/FAA/CT-91/5*. United States Federal Aviation Administration: Atlantic City.

Athiniotis N. (1995a) Macchi tailplane load case 'D' - teardown examination results. *Defect Assessment and Failure Analysis Investigation No. M3/95*. Defence Science and Technology Organisation: Australia.

Athiniotis N. (1995b) Examination of cracked bow beam fitting FS 497 from C130 Hercules A97-004. *Defect Assessment and Failure Analysis Investigation No. M37/95*. Defence Science and Technology Organisation: Australia.

Athiniotis N. (1996) RAAF B707 flap track support fitting cracking. *Fatigue and Fracture Detection and Assessment Investigation Report DSTO-DDP-0172*. Defence Science and Technology Organisation: Australia.

Athiniotis N., Barter S., Van Blaricum T., Clark G. and Sammut L. (1996) RAAF Macchi MB326H centre section lower boom fatigue testing. *DSTO-TR-0328*. Defence Science and Technology Organisation: Australia.

Bamford W.H. (1979) Application of corrosion fatigue crack growth rate data to integrity analyses of nuclear reactor vessels. *Transactions of the ASME - Journal of Engineering Materials and Technology*. **101**, 182-190.

Beattie A., Dahlke L., Gieske J., Hansche B., Phipps G., Roach D., Shagam R. and Thompson K. (1994) Emerging nondestructive inspection methods for aging aircraft. *Sandia Report SAND92-2732*. Sandia National Laboratories: Albuquerque, USA.

Beissner R.E. and Birring A.S. (1988) Nondestructive evaluation methods for characterisation of corrosion. *NTIAC-88-1*. Nondestructive Testing Information Analysis Centre: Austin, Texas.

Bellinger N.C., Krishnakumar S. and Komorowski J.P. (1994) Modelling of pillowing due to corrosion in fuselage lap joints. *Canadian Aeronautics and Space Journal*. **40**, 125-130.

Bellinger N.C. and Komorowski J.P. (1995) The effect of corrosion on the structural integrity of fuselage lap joints. Presentation to the *1995 USAF Structural Integrity Program Conference*. San Antonio, Texas.

Berens A.P. and Burns J.G. (1995) Risk analysis in the presence of corrosion damage. *Widespread Fatigue Damage in Military Aircraft, AGARD CP-568*. Advisory Group for Aerospace Research and Development, NATO.

Bishop B.C., Burke S.K., Clark G. and Scala C.M. (1993) Review of non-destructive inspection methods for potential application to corrosion in P3-C aircraft. *Technical Report ARL-TR-60*. Defence Science and Technology Organisation: Australia.

British Standards Institute PD 6493: 1991. Guidance on methods for assessing the acceptability of flaws in fusion welded structures.

Bruce D.A. (1992) NDT for corrosion in aerospace structures: a review of NDT techniques. *NDT for Corrosion in Aerospace Structures*. Royal Aeronautical Society: London, UK.

Bruce D.A. (1995) Non-destructive detection of corrosion for life management. *Corrosion Detection and Management of Advanced Airframe Materials, AGARD Conference Proceedings No. 565*. Advisory Group for Aerospace Research and Development, NATO.

Bucci R.J., Konish H.J. and Shaw B.J. (1995) A technical plan to address aircraft structural problems arising from corrosion/corrosion fatigue. *USAF Corrosion/Fatigue Planning Meeting*, Wright Laboratories, WPAFB, OH. February 8, 1995.

Buntin W.D. (1971) Concept and coduct of proof test of F-111 production aircraft. Paper presented to the *Royal Aeronautical Society*, 27 October 1971.

Campbell G.S. and Lahey R. (1984) A survey of serious aircraft accidents involving fatigue fracture. *International Journal of Fatigue*. **6**, 25-30.

Cazes R.J. and Goerung F. (1995) Damage tolerance to WFD on combat aircraft - an application to a metallic wing lower panel. *Widespread Fatigue Damage in Military Aircraft, AGARD CP-568*. Advisory Group for Aerospace Research and Development, NATO.

Chen G.S. and Duquette D.J. (1990) The corrosion fatigue behaviour of an aluminium-lithium alloy. *Environment Assisted Fatigue, EGF7* (Ed. P. Scott). Mechanical Engineering Publications: London, UK, 285-308.

Chen G.S., Gao M. and Wei R.P. (1996) Microconstituent induced pitting corrosion in a 2024-T3 aluminium alloy. *Corrosion*. **52**, 8-15.

Chin Quan H.R. (1991) Aircraft Materials and Corrosion Protection Handbook. *Defence Instruction (Air Force) AAP 7021.014-2*. Royal Australian Air Force.

Chubb J.P., Morad T.A., Hockenhull B.S. and Bristow J.W. (1991) The effect of exfoliation corrosion on the fatigue behaviour of structural aluminium alloys. *Structural Integrity of Aging Airplanes* (Eds. S.N. Atluri, S.G. Sampath and P.Tong). Springer-Verlag: Berlin, 87-97.

Chubb J.P., Morad T.A., Hockenhull B.S. and Bristow J.W. (1995) The effect of exfoliation corrosion on the fracture and fatigue behaviour of 7178-T6 aluminium. *International Journal of Fatigue*. **17**, 49-54.

Chubb J.P., Robinson M.J., Worsfold M and Hubble M.J. (1996) Corrosion, fatigue and the effectiveness of temporary preventives in ageing aircraft. *Proceedings of the Fourth International Aerospace Corrosion Control Symposium*: Jakarta, Indonesia.

Chun Y-G. and Pyun S-I. (1995) Ageing effects on fatigue crack closure of an Al-Li-Zr alloy in Na_2SO_4 solution. *Fatigue and Fracture of Engineering Materials and Structures*. **18**, 353-362.

Clark G. (1986) Fatigue at low growth rates in a maraging steel. *Fatigue and Fracture of Engineering Materials and Structures*. **9**, 131-142.

Dale A.A. (1993) The effect of current corrosion trends on RAAF P3C Orion structural life-of-type. *MPLM/2501/700/8/3 Tech Pt3 (44)*. Royal Australian Air Force.

DEF STAN (Defence Standard) 00-970 (1983) Design and airworthiness requirements for service aircraft. Ministry of Defence: UK.

DNV Classification Note 30.2 (1984) Fatigue strength analysis for mobile offshore units. Det Norske Veritas: Hovik, Norway.

ESDU Data Item 87026 (1987) Fatigue strength of anodized aluminium alloy. Engineering Sciences Data Unit: London, UK.

ESDU Data Item 88007 (1988) Effect of environment on fatigue crack propagation in aluminium alloy sheet and plate. Engineering Sciences Data Unit: London, UK.

FAA Advisory Circular AC 43-4A (1991) Corrosion control for aircraft. United States Federal Aviation Administration: Atlantic City.

Fadragas M.I., Fine M.E. and Moran B. (1994) Statistical investigation of fatigue crack initiation and growth around chamfered rivet holes in Alclad 2024-T3 as affected by corrosion. *FAA/NASA International Symposium on Advanced Structural Integrity Methods for Airframe Durability and Damage Tolerance, NASA Conference Publication 3274* (Ed. C.E. Harris), 259-275.

Fink F.T. and Summitt R. (1980) An environmental corrosion severity index and the USAF atmospheric exposure testing program (PACER LIME). *Corrosion 80*, Proceedings of the International Corrosion Forum: Chicago, Illinois.

Fletcher A.R. and Neu C.E. (1971) Fatigue crack growth behaviour of four high strength steels in two humid environments. *NADC-MA-7060*. Naval Air Development Center: Warminster, Pennsylvania.

Ford F.P. (1989) 3 mechanisms of environmentally assisted cracking. *International Journal of Pressure Vessels and Piping*. **40**, 343-362.

Forsyth P.J.E. (1980) The fatigue performance of service aircraft and the relevance of laboratory data. *Journal of the Society of Environmental Engineers.* **19**, 3-10.

Gallagher J. (1983) Damage tolerant design handbook. *MCIC-HB-01R,* Metals Ceramics Information Centre, Batelle Columbus Laboratories: Columbus, Ohio.

Gangloff R.P. (1989) Corrosion fatigue crack propagation in metals. *Environment-Induced Cracking of Metals,* Proceedings, 55-109.

Gangloff R.P. and Kim S-S. (1993) Environment enhanced fatigue crack propagation in metals: inputs to fracture mechanics life prediction models. *NASA Contractor Report 191538.* National Aeronautics and Space Administration: Hampton, Virginia.

Gerharz J.J. (1987) Standardized environmental fatigue sequence for the evaluation of composite components in combat aircraft. *NLR Technical Report TR 87053 U.* National Aerospace Laboratory: The Netherlands.

Goranson U.G. (1991) The aging fleet challenge. *The International Aerospace Congress.* Melbourne, Australia.

Goranson U.G. and Miller M. (1989) Aging jet transport structural evaluation programs. *15th Symposium of the International Commitee on Aeronatical Fatigue,* Jerusalem.

Goswami T. and Hoeppner D.W. (1995) Corrosion fatigue crack growth behaviour of aircraft structural materials. *18th Symposium of the International Commitee on Aeronautical Fatigue.* Melbourne, Australia.

Grandt A.F. (1995) Materials degradation and fatigue in aerospace structures, Second annual report for Air Force Office of Scientific Research grant number F49620-93-1-0377. School of Aeronautics and Astronautics, Purdue University: West Lafayette, Indiana.

Grondin G.Y. and Kulak G.L. (1994) Corrosion fatigue study of drillpipe. *Thirteenth International Conference on Offshore Mechanics and Arctic Engineering.* American Society of Mechanical Engineers.

Gunderson A.W. (1970) Preliminary mechanical property evaluation of D6ac steel in support of the F-111 aircraft recovery program. *Technical Memorandum MAA 70-6.* Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base: Ohio.

Hack T. (1995) Personal Communication.

Harlow D.G. and Wei R.P. (1993) A mechanistically based approach to probability modeling for corrosion fatigue crack growth. *Engineering Fracture Mechanics.* **45**, 79-88.

Harlow D.G. and Wei R.P. (1994) Probability approach for prediction of corrosion and corrosion fatigue life. *AIAA Journal.* 32, 2073-2079.

Harris C.E., Starnes J.H. and Newman J.C. (1995) Development of advanced structural analysis methodologies for predicting widespread fatigue damage in aircraft structures. *Proceedings of the FAA-NASA Sixth International Conference on the Continued Airworthiness of Aircraft Structures,* 139-164.

Hinton B.R.W. (1996) CH-47D Chinook corrosion control plan. *Corrosion Control Letter Report No. 8/96*. Defence Science and Technology Organisation: Australia.

Hoeppner D.W. (1979) Model for prediction of fatigue lives based upon a pitting corrosion fatigue process. *Fatigue Mechanisms, ASTM STP 675*. American Society for Testing and Materials, 841-870.

Hoeppner D.W., Adibnazari S. and Moesser M.W. (1994) Literature review and preliminary studies of fretting and fretting fatigue including special applications to aircraft joints. *DOT/FAA/CT-93/2*. United States Federal Aviation Administration: Atlantic City.

Hoeppner D.W., Grimes L., Hoeppner A., Ledesma J., Mills T. and Shah A. (1995) Corrosion and fretting as critical aviation safety issues: case studies, facts and figures from US aircraft accidents and incidents. *18th Symposium of the International Commitee on Aeronatical Fatigue*. Melbourne, Australia.

Horstmann M., Gregory J.K. and Schwalbe K-H. (1995) Geometry effects on corrosion-fatigue in offshore structural steels. *International Journal of Fatigue*. **17**, 293-299.

Jansen E.F.M. and Wanhill R.J.H. (1994) The role of corrosion in MSD - a case study. *NLR Report CR 94335 C*. National Aerospace Laboratory: The Netherlands.

Jaske C.E., Payer J.H. and Balint V.S. (1981) Corrosion fatigue of metals in marine environments. *MCIC Report 81-42*. Metals and Ceramics Information Centre, Batelle Columbus Laboratories: Columbus, Ohio.

Kemp R.M.J., Wilson R.N. and Gregson P.J. (1991) The role of crack closure in corrosion fatigue of aluminium alloy plate for aerospace structures. *DRA Technical Memorandum Mat/Str 1185*. Defence Research Agency: Farnborough.

Khobaib M., Lynch C.T. and Vahldiek F.W. (1981) Inhibition of corrosion fatigue in high strength aluminium alloys. *Corrosion-NACE*. **36**, 285-292.

Koch G.H., Bieri T.H. and Burns J.G. (1993) Effect of corrosion on fatigue crack propagation in aluminium alloy 2024-T3. *1993 USAF ASIP Conference,* San Antonio: Texas.

Komorowski J.P., Krishnakumar S., Gould R.W., Bellinger N.C., Karpala F. and Hageniers O.L. (1995) Double pass retroflection for corrosion detection in aircraft structures. *Corrosion Detection and Management of Advanced Airframe Materials, AGARD Conference Proceedings No. 565*. Advisory Group for Aerospace Research and Development, NATO.

Kondo Y. (1989) Prediction of fatigue crack initiation life based on pit growth. *Corrosion*. **45**, 7-11.

Lazzeri L., Pieracci A. and Salvetti A. (1995) An evaluation of fatigue crack growth prediction methods used in aircraft design. *18th Symposium of the International Commitee on Aeronautical Fatigue*, Melbourne, Australia.

Luke G.R., Athiniotis N., van Blaricum T. and Barter S. (1995) Static and ultimate load testing of Macchi MB326H tailplanes. *Fatigue and Fracture Detection and Assessment Investigation No. M183/95*. Defence Science and Technology Organisation: Australia.

Lynch S.P. (1988) Environmentally assisted cracking: overview of evidence for an adsorption-induced localised-slip process. *Acta Metallurgica.* **36**, 2639-2661.

Ma L. and Hoeppner D.W. (1994) The effects of pitting on fatigue crack nucleation in 7075-T6 aluminium alloy. *FAA/NASA International Symposium on Advanced Structural Integrity Methods for Airframe Durability and Damage Tolerance, NASA Conference Publication 3274* (Ed. C.E. Harris), 425-440.

Mal A.K. and Lee J. (1995) Crack initiation in aluminium plates with multiple defects. *Structural Integrity in Aging Aircraft* (Eds. C.I. Chang and C.T. Sun). ASME AD-Vol. 47, 111-117.

Machin A.S. and Mann J.Y. (1982) The influence of water-displacing organic corrosion inhibitors on the fatigue behaviour of 2024-T3 alclad aluminium alloy bolted joints. *ARL Structures Report 390.* Defence Science and Technology Organisation: Australia.

Mason M.E. and Gangloff R.P. (1994) Modeling time-dependent corrosion fatigue crack propagation in 7000 series aluminium alloys. *FAA/NASA International Symposium on Advanced Structural Integrity Methods for Airframe Durability and Damage Tolerance, NASA Conference Publication 3274* (Ed. C.E. Harris), 441-462.

Miller K.J. (1993) Materials science perspective of metal fatigue resistance. *Materials Science and Technology.* **9**, 453-461.

Miller R.N. and Meyer F.H. (1987) Preventing aircraft corrosion by predictive corrosion modelling. *Proceedings of the Tri-Service Conference on Corrosion,* Colorado, USA, 359-385.

MIL-STD-1530A (1975) Military Standard. Aircraft Structural Integrity Program, Airplane Requirements. Department of Defense: USA.

Nakajima M. and Tokaji K. (1995) Fatigue life distribution and growth of corrosion pits in a medium carbon steel in 3% NaCl solution. *Fatigue and Fracture of Engineering Materials and Structures.* **18**, 345-351.

Nieser D.E. (1995) Oklahoma City Air Logistics Center (USAF) aging aircraft corrosion program. *Corrosion Detection and Management of Advanced Airframe Materials, AGARD Conference Proceedings No. 565.* Advisory Group for Aerospace Research and Development, NATO.

Paul C. and Groner D. (1996) Corrosion/Fatigue. *United States Air Force Fourth Aging Aircraft Conference,* July 1996.

Parkins R.N. (1992) Current understanding of stress-corrosion cracking. *JOM.* **44**, 12-19.

Peel C.J. and Jones A. (1990) Analysis of failures in aircraft structures. *Metals and Materials.* **6**, 496-502.

Piascik R.S. and Willard S.A. (1994) The growth of small corrosion fatigue cracks in alloy 2024. *Fatigue and Fracture of Engineering Materials and Structures.* **17**, 1247-1259.

Pyun S-I., Orr S-J., Chun Y-G. and Nam S-W. (1995) Environmental effects on crack closure during fatigue in an Al-Zn-Mg-Mn alloy. *British Corrosion Journal.* **30**, 199-202.

Rahka K., Torronen K. and Silen L. (1984) Assessment of fatigue crack growth in a nuclear pressure vessel. *Subcritical Crack Growth Due to Fatigue, Stress Corrosion and Creep* (Ed. J.H. Larsson). Elsevier: London, UK, 365-378.

Remacha J.J. (1993) Fatigue implications pertinent to the RAAF P-3 Orion corrosion recovery programme. *REG4/4080/40/A9-3/1*. Royal Australian Air Force.

Rothwell A.N. and Eden D.A. (1992) Electrochemical noise techniques for determining corrosion rates and mechanisms. *Corrosion 92*, The NACE Annual Conference and Corrosion Show.

Schijve J. (1979) Four lectures on fatigue crack growth. *Engineering Fracture Mechanics*. **11**, 167-221.

Schmidt C.G., Kanzawa C.H., Shockey D.A. and Flournoy T.H. (1995) Corrosion-fatigue crack nucleation in the alclad layer of 2024-T3 commercial aircraft skin. *ASME Winter Annual Symposium - Structural Integrity in Aging Aircraft*. San Francisco, USA.

Schmidt H.J. and Brandecker B. (1996) The effect of environmental conditions and load frequency on the crack initiation life and crack growth in aluminium structure. *FAA/NASA Symposium on Continued Airworthiness of Aircraft Structures*. Atlanta, USA.

Schutz W. (1995) Corrosion fatigue - the forgotten factor in assessing durability. *15th Plantema Memorial Lecture, 18th Symposium of the International Commitee on Aeronatical Fatigue*. Melbourne, Australia.

Sharp P.K. and Barter S.A. (1992) Comparison of fatigue cracking in large and small 7050 aluminium alloy coupons - USN spectrum. *Defect Assessment and Failure Analysis Report No. M43/92*. Defence Science and Technology Organisation: Australia.

Sharp P.K., Barter S.A., Athiniotis N., Bishop B.C. and Clark G. (1995) Investigation of F/A-18 trailing edge flap hinge-lug incident. *DSTO-TR-0124*, Defence Science and Technology Organisation: Australia.

Shaw B.J. (1994a) An artificial corrosion protocol for lap-splices in aircraft skin. *FAA/NASA International Symposium on Advanced Structural Integrity Methods for Airframe Durability and Damage Tolerance, NASA Conference Publication 3274* (Ed. C.E. Harris), 725-739.

Shaw M.J. (1994b) Analysis of stress corrosion cracks in P-3C spar caps. *Report No. DHR-ER-017*. Hawker De Havilland Victoria Limited, Richmond facility: Australia.

Shih T-H. and Wei R.P. (1983) The effects of load ratio on environmentally assisted fatigue crack growth. *Engineering Fracture Mechanics*. **18**, 827-837.

Smart J.D. and Weetman D.C. (1995) Health and usage monitoring systems - corrosion surveillance. *Corrosion Detection and Management of Advanced Airframe Materials, AGARD Conference Proceedings No. 565*. Advisory Group for Aerospace Research and Development, NATO.

Smith C.J.E., Bartlett D.L. and Gray J.A. (1995) The corrosion and protection of advanced aluminium-lithium airframe alloys. *Corrosion Detection and Management of Advanced Airframe*

Materials, AGARD Conference Proceedings No. 565. Advisory Group for Aerospace Research and Development, NATO.

Smith R.A. (1992) Enhancement of conventional NDT methods for corrosion detection in layered skins. *NDT for Corrosion in Aerospace Structures.* Royal Aeronautical Society: London, UK.

Smith R. and Bruce D. (1994) The benefits of nondestructive testing in the corrosion control process and the human factor. *Aerospace Corrosion Control 1994,* Symposium Proceedings. Amsterdam: The Netherlands.

Speidel M.O. (1979) Stress corrosion and corrosion fatigue crack growth in aluminium alloys. *Stress Corrosion Research* (Eds. H. Arup and R.N. Parkins) Sijthoff & Noordhoff: The Netherlands, 117-176.

Speidel M.O. (1981) Effect of shot peening on stress corrosion cracking and corrosion fatigue. *Proceedings of the First International Conference on Shot Peening* (Ed. A. Niku-Lari). Pergamon Press: Oxford, UK, 625-635.

Squibb M.W. (1994) The effect of environment and frequency on the fatigue crack growth properties of aluminium alloys 8090-T81 and 2014-T4. *DRA Technical Report DRA/AS/MS/WP94042/1* Defence Research Agency: Farnborough, UK.

Squibb M.W. and Bryanton M.K. (1993) The effect of environment and specimen size on the fatigue crack growth rate properties of 6013-T6 aluminium alloy. *DRA Technical Report DRA/MS/TR94012/1* Defence Research Agency: Farnborough, UK.

Stanzl S.E., Mayer H.R. and Tschegg E.K. (1991) The influence of air humidity on near-threshold fatigue crack growth of 2024-T3 aluminium alloy. *Materials Science and Engineering, A.* **147**, 45-54.

Suresh S., Zamiski G.F. and Ritchie R.O. (1981) Oxide-induced crack closure: an explanation for near-threshold corrosion fatigue crack growth behaviour. *Metallurgical Transactions A.* **12A**, 1435-1443.

Swartz D.D., Miller M. and Hoeppner D.W. (1995) Chemical environments in commercial transport aircraft and their effect on corrosion fatigue crack propagation. *18th Symposium of the International Commitee on Aeronautical Fatigue*. Melbourne, Australia.

Tomkins B. (1984) Corrosion fatigue: applications in offshore structures. *Subcritical Crack Growth Due to Fatigue, Stress Corrosion and Creep* (Ed. J.H. Larsson). Elsevier: London, UK, 379-402.

Trathen P. and Hinton B. (1994) The control of corrosion and stress corrosion cracking in Macchi tailplane structure. *Corrosion Control Letter Report No. 20/93*. Defence Science and Technology Organisation: Australia.

Trathen P. and Hinton B. (1996) Personal Communication.

Van Dijk P. (1992) C130 BL20 longeron corrosion summary. *Minute Paper LLM/4080/A97/1104-R2*, Royal Australian Air Force.

Varanasi S.R. and McGuire J.F. (1995) Boeing structural design technology improvements. *Proceedings of the FAA-NASA Sixth International conference on continued Airworthiness of Aircraft Structures*, 75-81.

Vogelesang L.B. (1981) Fatigue crack growth in aluminium alloys. *Technical Report LR-324*, Department of Aerospace Engineering, Delft University of Technology: The Netherlands.

Vogelesang L.B. and Schijve J. (1980) Environmental effects on fatigue fracture mode transitions observed in aluminium alloys. *Fatigue of Engineering Materials and Structures*. 3, 85-98.

Wallace W., Hoeppner D.W. and Kandachar P.V. (1985) AGARD Corrosion Handbook, Volume 1 - Aircraft corrosion: causes and case histories. *AGARDograph No. 278*. Advisory Group for Aerospace Research and Development, NATO.

Wanhill R.J.H. (1977) Environmental effects on fatigue of aluminium and titanium alloys. *Corrosion Fatigue of Aircraft Materials, AGARD Report No. 659*. Advisory Group for Aerospace Research and Development, NATO.

Wanhill R.J.H. (1990) Environment-assisted aerospace fatigue problems in the Netherlands. *Environment Assisted Fatigue, EGF7* (Ed. P. Scott). Mechanical Engineering Publications: London, UK, 257-271.

Wanhill R.J.H. (1994a) Aircraft corrosion and fatigue damage assessment. *NLR Technical Publication TP 94401 L*. National Aerospace Laboratory: The Netherlands.

Wanhill R.J.H. (1994b) Damage tolerance engineering property evaluations of aerospace aluminium alloys with emphasis on fatigue crack growth. *NLR TP 94177 U*. National Aerospace Laboratory: The Netherlands.

Wanhill R.J.H., De Luccia J.J. and Russo M.T. (1989) The fatigue in aircraft corrosion testing (FACT) programme. *AGARD Report No. 713*. Advisory Group for Aerospace Research and Development, NATO.

Wanhill R.J.H. and Schra L. (1990) Corrosion fatigue crack arrest in aluminium alloys. *Quantitative Methods in Fractography, ASTM STP 1085*. American Society for Testing and Materials, 144-165.

Waterhouse R.B. and Lindley T.C. (1994) *Fretting Fatigue, ESIS 18*. Mechanical Engineering Publications: London, UK.

Wei R.P. (1979) On understanding environment-enhanced fatigue crack growth - a fundamental approach. In *Fatigue Mechanisms, ASTM STP 675*. American Society for Testing and Materials, 816-840.

Wei R.P. (1994) Corrosion and corrosion fatigue of airframe materials, FAA Grant No. 92-G-0006, semi-annual progress report for period 15 June to 14 December 1994. Department of Mechanical Engineering and Mechanics, Lehigh University: Bethlehem, Pennsylvania.

Wei R.P. and Simmons G.W. (1981) Recent progress in understanding environment assisted fatigue crack growth. *International Journal of Fracture*. 17, 235-247.

Wilson L. and Devereux R.S.G. (1984) The effect of some water-displacing corrosion preventives on corrosion of aluminium alloys 7075-T651 and 2024-T6. *Metals Forum*. 7, 50-54.

Winfree W.P. and Heyman J.S. (1991) Large area QNDE inspection for airframe integrity. *Fatigue Management: 72nd Meeting of the AGARD Structures and Materials Panel*. Bath, UK.

Winkworth W.J. (1961) The fatigue testing of aircraft structures. *Full-Scale Fatigue Testing of Aircraft Structures* (Eds. F.J. Plantema and J. Schijve). Pergamon press: Oxford, UK, 210-232.

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19. ABSTRACT
This report discusses the influence of corrosion on aircraft structural integrity. Brief introductions to corrosion in aircraft and aircraft structural integrity are provided and the literature concerned with the effect of prior corrosion and corrosive environments on static strength and fatigue performance is reviewed. RAAF and overseas experience with structural integrity issues associated with corrosion in aircraft is described, with emphasis placed on corrosion in airframes and other structural elements. The report discusses the difficulties associated with incorporating the effects of corrosion into conventional life management approaches and the contribution of corrosion control programs to continuing airworthiness. Where possible, current research programs throughout the world are reviewed. Finally, potential areas of research are identified, primarily on the basis of their potential usefulness for the future support of RAAF aircraft, and opportunities for collaborative research.

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