

Military Aircraft Structures Airworthiness Advisory Group

Paper 118

The Interaction of Corrosion and Fatigue in Aircraft Structures

Dr K Brown

QinetiQ

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Task Sponsor

Dr Steve Reed, Dstl

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Authorship Panel

Dr D L Bartlett, QinetiQ

Dr E A Birt, QinetiQ

Dr A Kaddour, QinetiQ

Dr R S Oakley, QinetiQ

Paper Closure Statement

A draft version of MASAAG Paper 118 was circulated to all MASAAG Members for comment on 11 September 2012. The MASAAG agreed that the paper provided a valuable summary on the interaction effects of corrosion and fatigue in aircraft structures. However, it was agreed at the 74th MASAAG that appropriate measures were in place to assure structural integrity under such threats and that no further action was considered necessary by the MASAAG at this time. This closure statement was endorsed by the 75th MASAAG on 10 September 2013.

EXECUTIVE SUMMARY

Corrosion and fatigue present risks to aircraft structural integrity and can lead to increased aircraft life cycle costs and reduced aircraft availability. The two processes can interact in a variety of ways, such as the nucleation and growth of fatigue cracks from corrosion damage. These interactions can accelerate markedly the development of damage in the aircraft structure. However, corrosion, fatigue and their interactions can be very sensitive to a wide range of factors, such as material type, structural configuration, load spectra and environment, so that prediction of the damage growth can be difficult.

The traditional UK Ministry of Defence (MoD) approach to the management of structural integrity corrosion risks in service has been a 'find-and-fix' approach. This assumes that corrosion is detected by inspections and removed from the structure or system, with an assessment of the integrity and life of the structure or component being made based upon the remaining material. However, there is evidence from Ageing Aircraft Audits (AAA) that corrosion is not always removed from the aircraft and it is also reasonable to assume that there are a significant number of unknown corrosion locations on aircraft across the fleets. There is at present insufficient relevant information available to MoD Duty Holders and the Military Airworthiness Authority (MAA) as to the likely implications of continued operations with such corrosion present. An extensive literature review has therefore been undertaken to identify the current understanding internationally of corrosion-fatigue interactions in aircraft structure. The findings from the review are presented in this paper.

A generalised corrosion-fatigue process may be broken down into a number of stages. This can aid in developing prediction methods and in assessing the suitability of different approaches to the individual stages. The methods to be used for each stage will depend upon the physical situation and the available approaches. Established approaches and available software should be used as far as possible for the prediction of corrosion-fatigue interactions, as this will minimise time and effort and should increase confidence in the outputs.

An initial assessment has been made of available software for corrosion and fatigue prediction to assess their use in the prediction of potential corrosion-fatigue interactions such as the growth of fatigue cracks from corrosion damage. The corrosion prediction software can address galvanic and pitting corrosion, but further assessment is required of its potential to predict the evolution of those parameters (e.g. pit dimensions) which could influence the development of fatigue cracks from the corrosion. Existing fatigue and fracture software has been used to model the growth of a fatigue crack from an initial flaw related to the corrosion damage. It may be necessary to combine a finite element package for calculation of the stresses in a structural

feature, a corrosion prediction model to assess the growth of corrosion pits, and a fatigue and fracture code to predict the fatigue crack growth from the corrosion pits through to final fracture.

There are a number of structurally significant corrosion types but the most important are probably general attack, pitting corrosion and exfoliation corrosion. The effects of other corrosion types such as crevice corrosion upon fatigue behaviour may be modelled by similar approaches to these three types. Corrosion features which will influence fatigue behaviour include thickness loss (increased stress levels and/or reduced stiffness), corrosion pits (stress concentrations) and corrosion products (changed materials properties and/or stress state).

Fatigue crack growth prediction is in general more advanced than corrosion prediction. The most immediate benefits from the prediction of corrosion-fatigue interactions may thus be realised by improving the accuracy of prediction of fatigue crack growth from corrosion damage and of corrosion fatigue. Such improvements might also allow accurate back-calculation from the required fatigue lives to determine acceptable levels of corrosion in the structure (e.g. corrosion pit dimensions). The effects of corrosion upon fatigue behaviour under aircraft spectrum loading may be different to those for the constant amplitude loading used in much previous work. It may be possible to adapt existing fatigue and fracture software to allow for the effects of corrosion by using suitably modified static material properties and fatigue behaviour. However, consideration needs to be given to the applicability of material data obtained in the laboratory to actual service conditions.

NDE methods can provide detailed measurements of corrosion damage, such as the dimensions of corrosion pits, which can provide inputs to fatigue crack growth software. However, the time and effort required for NDE inspection and fatigue analysis may mean that the use of such detailed data is only practicable for relatively small areas of structure which are of particular concern. Data fusion is the combination of a number of NDE techniques which should potentially allow more rapid scanning to determine the corrosion state of a structure and so could be a practical means of providing suitable inputs to fatigue models.

Data from the maintenance effort required to repair corrosion damage (examples of which are given in an appendix) may be used for the prediction of corrosion in an aircraft structure. This approach has the advantage that the data are obtained for real structures and actual service environments. However, the processes for the recording and analysis of the data must be carefully designed to accurately provide the relevant quantitative information without excessive additional effort on the part of the maintenance organisation. It is recommended that the feasibility of such an approach should be investigated.

AUTHORSHIP

Principal Author:

Dr K Brown, QinetiQ

Authorship Panel:

Dr D L Bartlett, QinetiQ

Dr E A Birt, QinetiQ

Dr A Kaddour, QinetiQ

Dr R S Oakley, QinetiQ

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ABBREVIATIONS

AAA	Ageing Aircraft Audit
CFRP	Carbon Fibre Reinforced Plastic
EAC	Environmentally-Assisted Cracking
ISTAR	Intelligence, Surveillance, Targeting And Reconnaissance
MAA	Military Airworthiness Authority (United Kingdom)
MoD	Ministry of Defence (United Kingdom)
NDE	Non-Destructive Evaluation
RA	(MAA) Regulatory Article
RAAF	Royal Australian Air Force
RAF	Royal Air Force (United Kingdom)
SCC	Stress Corrosion Cracking
S-N	Stress-life (fatigue data)
USAF	United States Air Force
WLIM	White-Light Interference Microscopy

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1 INTRODUCTION

Corrosion and fatigue present risks to aircraft structural integrity and can lead to increased aircraft life cycle costs and reduced aircraft availability (e.g. Hertzberg 2009). An analysis of aircraft structural failures (Findlay and Harrison 2002) found that 55% were due to fatigue, 16% to corrosion and 7% to environmentally-assisted cracking (EAC). Although these data indicate that fatigue represents a greater threat to structural integrity than corrosion, corrosion results in greater life cycle costs than fatigue (*ibid*). As an indication of magnitude, the cost of corrosion to the United States Air Force (USAF) was over \$1 billion in 2001 (Benavides 2009). Some examples of corrosion costs for individual aircraft types are included in Appendix A. As the corrosion costs are primarily due to inspection and maintenance (e.g. Kinzie 2005), corrosion is also likely to give a greater reduction in aircraft availability than fatigue.

Whilst Harrison and Findlay (2002) identified the truly synergistic EAC processes as one group, corrosion and fatigue can also interact in other ways, e.g. it was stated that some of the fatigue failures in the survey may have initiated at stress concentrations produced by corrosion. Fatigue cracking had developed from corrosion pits in the F/A-18 trailing edge flap hinge lug (Clark 2010) and from stress corrosion cracking (SCC) in the C-5A aft crown (Ball et al 2010). A civil Taylorcraft BF12 floatplane was lost in 2007 as a result of the fracture of a wing bracing strut due to extensive corrosion followed by fatigue cracking (NTSB 2008). In December 2008 the Russian MiG-29 fleet was grounded following the loss of two aircraft to corrosion-induced fatigue failure of the vertical tail surfaces (Jane's 2011). Mig-29 vertical tail surfaces have carbon fibre reinforced plastic (CFRP) skins (Dragan et al 2005), showing that corrosion-fatigue interactions are not restricted to all-metal structures.

The interaction of corrosion and fatigue can accelerate markedly the development of damage in the aircraft structure, e.g. full-scale CF-18 fuselage fatigue tests showed a reduction in the fatigue life of an upper outboard longeron by a factor of four when corrosion was present (Bellinger and Liao 2009). However, corrosion, fatigue and their interactions can be very sensitive to a wide range of factors, such as material type, structural configuration, load spectra and environment, so that prediction of the damage growth can be difficult.

The UK Ministry of Defence (MoD) policy and regulation for the management of structural integrity corrosion risks in service has relied upon a 'find-and-fix' approach. This assumes that corrosion is detected by inspections and removed from the structure or system. An assessment of the integrity and life of the structure or component is then made based upon the material remaining. However, evidence from Ageing Aircraft Audits (AAA) suggests that there are an increasing number of incidents across the MoD fleets where corrosion is not being removed

from aircraft. It is also reasonable to assume that there are a significant number of unknown corrosion locations on aircraft across the fleets. It is essential that best advice can be provided to MoD Duty Holders and the Military Airworthiness Authority (MAA) as to the likely implications of continued operations with such corrosion present, e.g. the possible nucleation and growth of fatigue cracks from the corrosion damage. Such advice would be applicable to, for example, Structural Examination Programmes (MAA RA 5720, Paragraph 60), Ageing Aircraft Audits (MAA RA 5723, Paragraph 9a) and Life Extension Programmes (MAA RA 5724, Paragraph 21). It is not currently possible to provide this advice as there is insufficient relevant information available on the potential interactions of corrosion and fatigue in aircraft structures in the service environment.

An extensive literature review has therefore been undertaken to identify the current understanding internationally of corrosion-fatigue interactions in aircraft structure. This has included current approaches to, and understanding of, corrosion prediction, the effects of corrosion on crack nucleation and the growth of fatigue cracks under realistic loading spectra and environmental conditions. An initial assessment has also been made of available software packages for corrosion and fatigue prediction.

The results of the literature review are presented in this report. Section 2 provides a general overview of corrosion-fatigue interactions. Section 3 considers the development and prediction of corrosion and the potential initiation of fatigue cracks from the corrosion damage. Section 4 discusses the prediction of fatigue crack growth in the presence of corrosion and under realistic loading spectra. Conclusions are presented in Section 5 and recommendations in Section 6. Some corrosion costs for USAF and RAF aircraft types are provided and discussed in Appendix A.

2 CORROSION-FATIGUE INTERACTIONS

2.1 THE INTERACTION OF CORROSION AND FATIGUE

Some of the interactions of corrosion and fatigue have already been mentioned in Section 1. Figure 1 shows a schematic representation of the possible stages in a generalised corrosion-fatigue interaction process, although not all of the stages may occur in a given situation. The vertical axis is a representation of the extent of the damage, such as damage depth. The horizontal axis is labelled as time, but it should be noted that in general the corrosion damage is a function of the calendar age of the aircraft or structure and the fatigue crack growth will depend upon the applied load spectrum.

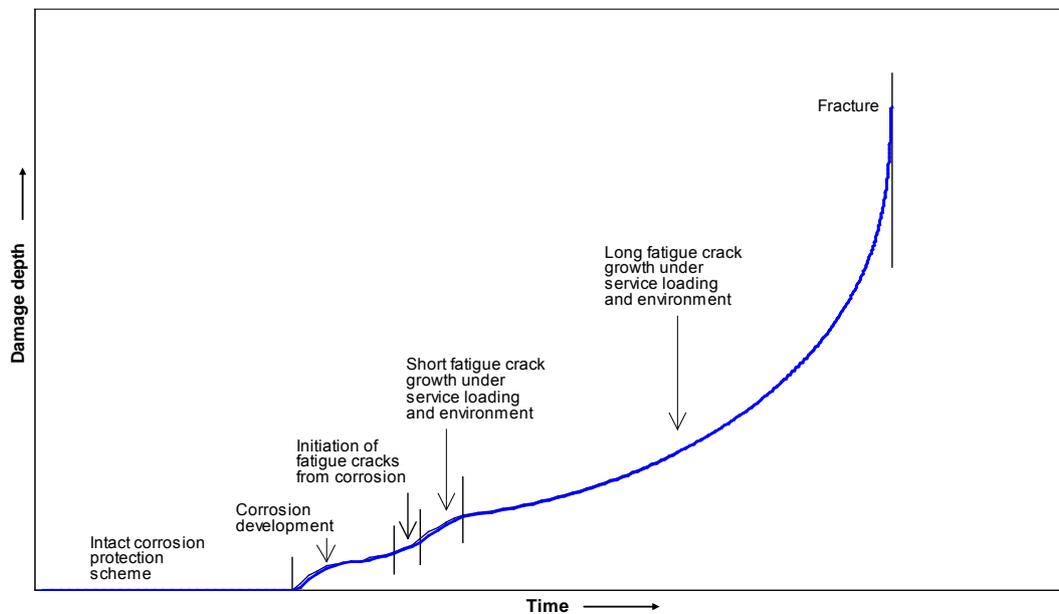


Figure 1 – Schematic representation of possible stages of corrosion-fatigue interaction

Corrosion of the structural materials should not begin until the corrosion protection is damaged (e.g. scratched) or otherwise no longer effective. Corrosion may then begin as one or more of the types described in Section 2.2.3. The corrosion behaviour might be affected by the stress state of the material (see 2.2.5). Fatigue cracks may then initiate from damage such as

corrosion pits, as considered in Section 3.3. These fatigue cracks – or others which nucleated at stress concentration features such as fastener holes – may then develop through short and long fatigue crack growth stages to final fracture. This fatigue crack growth may be subjected to a corrosive environment in addition to spectrum fatigue loading and this may modify the fatigue and fracture behaviour, e.g. by the introduction of EAC mechanisms.

2.2 FACTORS AFFECTING CORROSION AND FATIGUE

The interaction of corrosion and fatigue is influenced by a variety of factors and some of these are considered below. Some further discussion of factors affecting corrosion is also included as part of Appendix A.

2.2.1 AIRCRAFT AGE AND ENVIRONMENT/FATIGUE HISTORY

As shown schematically in Figure 1, corrosion/fatigue damage will develop with time and the number of fatigue cycles. The precise combination of the applied environment and fatigue loading must however be considered when determining the potential for corrosion-fatigue interactions. As an example, an aircraft might be subjected to alternate periods of high temperatures (over 50°C) and high humidity on the ground in a tropical environment, tending to promote corrosion, and fatigue loading at low temperatures in flight at altitude, tending to cause fatigue cracking. The potential corrosion-fatigue interactions might then depend principally upon factors such as the time spent on the ground and the fatigue spectrum in flight.

2.2.2 STRUCTURAL MATERIAL TYPE

The type of material in the aircraft structure can have a major effect on the extent and type of corrosion, fatigue and their interactions. Investigations of corrosion-fatigue interactions for aircraft structural applications have included aluminium alloys such as 2024-T3 (e.g. van der Walde and Hilberry 2008) and 7075-T6 (e.g. Smith et al 2001, Harlow & Wei 2009, Burns et al 2011), and steels such as D6AC (Mills et al 2002) and AF1410 (Rusk et al 2009). There has also been much work on corrosion fatigue of steels for marine and offshore applications (e.g. Coudert and Renaudin 1998) and some of the approaches developed could be potentially relevant to aircraft structures.

2.2.3 CORROSION TYPE

Corrosion types which could potentially be involved in corrosion-fatigue interactions in aircraft structures are described in more detail in Section 3.2. General attack, pitting corrosion and

exfoliation corrosion are probably the most structurally significant forms of corrosion attack (Mills et al 2009). These forms may occur together in an aircraft structure, such as general attack and pitting corrosion. Other types of corrosion may arise from different mechanisms (e.g. galvanic or crevice corrosion), but the resultant damage morphology is generally typical of general attack, pitting corrosion and/or exfoliation corrosion (*ibid*). This suggests that these other types of corrosion may be able to be treated similarly to the three most significant types in terms of, for example, the growth of cracks from corrosion pits. The different corrosion mechanisms would however need to be allowed for in assessing when the corrosion would be sufficiently advanced to lead to the nucleation of fatigue cracks.

2.2.4 OPERATING ENVIRONMENT

Corrosion can vary widely depending upon the applied environment, e.g. it is generally more prevalent in a maritime than a terrestrial environment. As an example, Sun et al (2009) reported marked differences between coastal, urban and industrial environments for the corrosion of 2024 and 7075 aluminium alloys exposed to the atmosphere for twenty years. The geographical locations in which an aircraft operates can thus have significant influences on the development of corrosion and on potential corrosion-fatigue interactions. The recording of the geographical bases and deployment of aircraft is therefore used by aircraft operators such as the USAF (Young and Blair 2011) and Royal Australian Air Force (RAAF) (Trathen 2012) to aid in the prediction of corrosion development in their aircraft.

2.2.5 STRUCTURAL DESIGN

The aircraft structural design can influence the corrosion and fatigue behaviour, e.g. fatigue cracking and corrosive behaviour at a fastener hole can depend on the materials and geometry of the joint (Gaydos 2011). A fuselage lap joint may develop multiple fatigue cracks at the fastener holes as the aircraft approaches or exceeds the design life (Eastaugh et al 1999), whilst crevice corrosion might occur in the lap joint and be accelerated because of the occluded environment (Mills et al 2009). The stress distribution in the structural configuration – possibly including residual stresses, such as at a cold-expanded fastener hole – may also influence the nature of the corrosion-fatigue interactions, e.g. stress corrosion cracking requires a tensile stress in the material (Mills et al 2009). Whether a crack initiates at a corrosion pit or a structural feature such as a fastener hole will in general depend upon the relative stress levels at the two locations. Joining processes such as welding may introduce changes in material properties and residual stresses in the structure, although Ghidini et al (2005) reported that corrosion prior to fatigue gave similar reductions in stress-life (S-N) fatigue behaviour in friction-stir welded 2024-T3 aluminium alloy and the parent material when the weld residual stresses were low.

2.2.6 FATIGUE LOADING SPECTRA

Aircraft loading spectra may be dominated by, for example, manoeuvre loads (combat aircraft wings), gust loads (transport aircraft wings), fuselage pressurisation (transport aircraft) or structural vibration (helicopters). The nature of the applied loading influences fatigue crack initiation and growth but it might also influence the potential corrosion-fatigue interactions, for example if overloads in the spectrum change the fatigue crack opening. The effect of realistic spectrum loading on potential corrosion-fatigue interactions should therefore be addressed.

The effect of the loading frequency on the potential corrosion-fatigue interactions should also be considered. As an example, the moisture ingress into a fatigue crack which is open in each load cycle, and hence the potential for corrosion, may be greater, per cycle, at a lower frequency (as in service) than at a higher frequency (as in laboratory tests).

2.2.7 CORROSION PROTECTION SCHEMES

For many aerospace materials such as high-strength aluminium alloys, the time for corrosion to develop to the critical pit size for fatigue cracking is relatively short and the rate determining step is the time for the corrosion protection scheme – e.g. anodising, paint and/or corrosion protection compounds – to fail at imperfections or damage sites. Failure models for the corrosion protection systems are therefore included in software for corrosion prediction (see Section 3.2).

The effect of corrosion protection schemes applied to the structure may need to be considered for prediction of the fatigue behaviour of the structure. Jaya et al (2010), for example, reported that the presence of corrosion inhibiting compounds had a significant influence on the fatigue life of riveted 2024-T3 aluminium alloy joints, and also on the failure mode of the joints. Anodising might also contribute to a reduction in fatigue performance by promoting earlier crack initiation as a result of the presence of the oxide layer.

2.2.8 MAINTENANCE AND REPAIR

The effects of maintenance and repair should be considered when assessing potential corrosion-fatigue interactions. Maintenance, repair and refurbishment activities which, for example, remove corrosion and fatigue damage or restore corrosion protection schemes should accordingly reduce the potential for corrosion-fatigue interactions (see Appendix A). Repairs might, however, modify behaviour such as moisture ingress to a structure or could introduce new stress concentrations (e.g. at fasteners) and this will also need to be considered.

2.3 MODELLING APPROACHES

The breaking down of the corrosion-fatigue interaction process into a number of stages, as illustrated in Figure 1, is generally used in the development of models for prediction of the process. The number of stages for the corrosion-fatigue process varies between different authors. For example, six are shown in Figure 1, whilst Shi and Mahadevan (2001) have seven for fatigue crack growth from pitting corrosion (compared to Figure 1, they omit the effects of the corrosion protection scheme, divide the corrosion development stage in Figure 1 into pit nucleation and pit growth, and add a separate stage for the transition from short fatigue crack growth to long fatigue crack growth). The number of stages is likely to depend upon both the specific corrosion-fatigue interaction process and the modelling approach to be used. For example, if the crack growth behaviour can be treated as a single process including short crack growth, the transition to long crack behaviour, long fatigue crack growth and fracture, this could all be considered in a single stage of the modelling process. It may be appropriate to consider whether a relatively large number of stages, perhaps with detailed modelling of the physical processes involved, is suitable for practical application, or whether the potential variability in the processes may favour fewer stages, e.g. an initial corrosion-dominated stage leading to fatigue crack initiation, followed by a second stage with fatigue crack growth and fracture, possibly in a corrosive environment.

The division of the potential corrosion-fatigue interaction process into a series of stages as described above should allow the determination of suitable approaches for the assessment and management of the potential corrosion-fatigue interactions for a particular structural application. The suitability of the available models for each stage could then be assessed to determine, for instance, the most appropriate method or whether that stage can be modelled with sufficient levels of confidence. Different approaches might be used for the different stages of the corrosion-fatigue interaction process, e.g. a probabilistic approach for corrosion prediction might be combined with a deterministic approach for fatigue crack growth. It may be that some stages, particularly those for the development of corrosion, cannot be modelled with the required accuracy, so that other approaches may be required, e.g. a measured structural corrosion state might be used to assess the likelihood of fatigue crack development from the corrosion damage or to provide the inputs to fatigue prediction models.

The complexity and variability of the corrosion and fatigue processes and their interactions means that ultimately a probabilistic approach may be the most suitable for the prediction of corrosion-fatigue interactions. Probabilistic methods have been used for corrosion and fatigue individually, including the growth of corrosion pits in aluminium alloys (Rajasankar and Iyer 2006) and the prediction of fatigue crack growth in 2024-T3 aluminium alloy under variable amplitude loading (Jaszal and Kocanda 2012). Shi and Mahadevan (2001) used a probabilistic

approach for the growth of fatigue cracks from corrosion pits, developed by using the different stages described earlier. Probabilistic methods for risk assessments for ageing aircraft lap joints with corrosion-fatigue interactions have been studied by Liao and Komorowski (2004), whilst Harlow and Wei (2009) found generally good agreement between the results from probabilistic modelling of fatigue crack growth from pitting corrosion in 7075-T6 alloy and tear-down inspection data from aircraft lower wing skins, even though simplifying assumptions were made in the modelling.

However, factors such as the variability in the micro-structural properties of the material and the need for well-developed physically and mechanistically based models for many of the complex processes make the use of probabilistic approaches challenging (Harlow and Wei 2009). The modification of existing modelling approaches and software for corrosion and/or fatigue prediction to include the effects of corrosion-fatigue interactions may be more beneficial in the shorter term. Fatigue modelling is in general more advanced than corrosion modelling, and so it is likely that the earliest benefits will be obtained by the modification of fatigue software. Software using such approaches is already available (see Section 2.4) and it may be possible to adapt other existing fatigue crack growth software by, for example, representing corrosion pits as suitable initial flaws or allowing for environmental effects upon the fatigue and fracture properties of the material (see Section 4). Such an evolutionary development of existing software could bring advantages such as reduced development time and effort, being readily tailored to the specific needs of the user and greater confidence in the outputs of the analysis.

2.4 PRELIMINARY SOFTWARE ASSESSMENT

A preliminary assessment of available software packages potentially relevant to the prediction of corrosion-fatigue interactions in aircraft structures has been made by review of the available websites and literature and, where appropriate, experience of the software. The assessment has included software for stress analysis and for the prediction of corrosion life or fatigue and fracture behaviour. Table 1 lists the software which was identified and which was included in the assessment. There are obviously very many Finite Element stress analysis packages available, many of which claim to have fatigue capabilities, but this assessment has been restricted to two of the most commonly used.

Software	Brief Description	Website, Link or Reference
cWorks	Corrosion prediction (Boeing)	Gaydos 2011
EDM ³	Environmental Degradation Measurement, Monitoring and Management model (BAE Systems)	Wagstaff et al 2011
BEASY	Corrosion prediction. Fatigue crack growth and fracture.	www.beasy.com
Eclipse	Fatigue crack growth from corroded topography (Analytical Process/Engineered Solutions [APES] Inc.)	ftp://ftp.rta.nato.int/PubFullText/RTO/AG/.../AG-AVT-140-17.pdf
AFGROW	Fatigue crack growth and fracture (USAF)	www.afgrow.net
NASGRO	Fatigue crack growth and fracture (US National Aeronautics and Space Administration)	www.nasgro.com
N-Code	Fatigue crack growth and fracture	www.ncode.com
FASTRAN	Fatigue crack growth prediction	www.openchannelfoundation.org/projects/FASTRAN_II/
Darwin	Finite element analysis	www.darwin.swri.org
ABAQUS	Finite element analysis	www.appliedgroup.com/abaqus-fea/

Table 1 – Software packages for corrosion and fatigue

2.4.1 CORROSION PREDICTION SOFTWARE

The corrosion prediction software assessed was cWorks, EDM³ and BEASY ‘Corrosion Manager’.

Boeing’s cWorks software calculates the relative susceptibility to corrosion of the different parts of an aircraft structure (Gaydos 2011). The corrosion susceptibility calculations include factors such as material corrosion resistance, protective coatings, environment, moisture and galvanic

interactions (e.g. from the presence of fasteners). The results are then used to determine corrosion-based inspection intervals for existing aircraft or to mitigate the corrosion risk for future designs.

EDM³ is an approach being developed by BAE Systems to manage corrosion on land, sea and air platforms (Wagstaff et al 2011). It allows the user to determine when there is a requirement to repaint the platform to minimise corrosion damage. The approach includes the use of data on coating degradation and metal loss obtained from sensors on the platform as inputs to environmental degradation models to estimate future damage in the present or future environments. The sensors are able to monitor pitting corrosion and can detect pits with diameters of less than 50 microns, which compares with 100-200 microns by visual inspection.

BEASY 'Corrosion Manager' software is designed for the assessment of the risk to components and structures of galvanic corrosion and the effectiveness of surface protection systems (BEASY 2012a). It will predict the location of corrosion in a structure and the corrosion rate. This software has been used, for example, to predict the corrosion between steel bolts and aluminium structure.

The corrosion prediction software is, in general, designed to aid in the selection of materials and protection schemes, to identify areas of the structure which are susceptible to corrosion, calculate corrosion rates and to assess, for example, when re-painting or other maintenance will be required. Galvanic corrosion (cWorks, BEASY) and pitting corrosion (EDM³) are addressed. The prediction of fatigue crack nucleation at corrosion pits is likely to require prediction of the evolution of pit parameters such as width or depth (see Section 3.3). Programmes such as EDM³ may be able to provide some of this data but further assessment of the capabilities of the software is required. Further discussion of corrosion prediction is given in Section 3.2.

2.4.2 FATIGUE AND FRACTURE SOFTWARE

There are a large number of codes for the prediction of fatigue and fracture behaviour under constant amplitude and spectrum loading. Examples in Table 1 include AFGROW, NASGRO, FASTRAN, BEASY and N-Code, whilst in-house codes are also used by many organisations. The software may be used to predict fatigue crack growth from corrosion damage by, for example, using suitable flaws to represent the corrosion damage morphology. This approach is used in the ECLIPSE software (Table 1) and measured corrosion morphology data has been used as an input to BEASY software in an investigation of the nucleation and growth of fatigue cracks from multiple corrosion pits (BEASY 2012b). Material property changes as a result of corrosion may also be included in the analysis. Corrosion fatigue, i.e. fatigue crack growth in a corrosive environment, may be modelled by using suitable fatigue crack growth data or S-N

data, as appropriate, in the models. The modelling of fatigue crack growth from corrosion damage and of corrosion fatigue is discussed further in Section 4.

2.4.3 PREDICTION OF CORROSION AND FATIGUE

The software packages found were primarily for the prediction of either corrosion (Section 2.4.1) or fatigue (Section 2.4.2). The prediction of a complete corrosion-fatigue interaction process is therefore likely to require the combination of a number of codes. The software used would probably depend upon the precise situation being modelled, the available codes and their compatibility. It may be necessary for instance to combine a finite element code for stress analysis of the structure (e.g. ABAQUS or Darwin in Table 1) with a corrosion prediction code (e.g. EDM³) and a fatigue and fracture code (e.g. AFGROW) to model the complete corrosion and fatigue process. The corrosion prediction packages would have to provide suitable inputs to the fatigue software, which might include parameters for material thinning (increased stress and/or reduced stiffness), the development of corrosion pits (stress concentrations) or the development of corrosion products (changed material properties and/or or stress state) as discussed further in Section 4.

2.4.4 PROBABILISTIC APPROACHES

It was suggested in Section 2.3 that probabilistic approaches may ultimately be used for the prediction of corrosion-fatigue interactions. There are a number of methods which could take into consideration the uncertainty in the physical, mechanical, chemical, geometrical and loading variables. These include interval analysis, fuzzy variables, first and second order reliability methods and Monte Carlo simulations. The precise method to be adopted would depend upon factors such as the degree of complexity, accuracy and cost effectiveness. The finite element packages included in Table 1, i.e. ABAQUS and Darwin, have probabilistic capabilities which are potentially applicable to corrosion-fatigue interactions but are largely untested for this application.

3 CORROSION AND FATIGUE CRACK INITIATION

3.1 STRUCTURALLY SIGNIFICANT CORROSION TYPES

Some discussion of corrosion types in aircraft structures has been given in Section 2.2.3. The structurally significant types of corrosion include general attack, pitting corrosion, intergranular corrosion, exfoliation corrosion, crevice corrosion, galvanic corrosion, corrosion fatigue, stress corrosion cracking, hydrogen embrittlement and fretting fatigue (Mills et al 2009). These are briefly described below, along with their potential effects on fatigue crack initiation and growth.

3.1.1 GENERAL ATTACK

General attack is widespread corrosion, with similar damage throughout the corroded region. It may also involve hydrogen embrittlement or secondary bending and local stress raisers from surface roughness (Mills et al 2009). Material thickness loss can result from the corrosion or from the blending-out of the corrosion damage, and this net-section loss can increase general stress levels, with detrimental effects upon the fatigue behaviour. The local stress raisers may also promote the nucleation of fatigue cracks.

3.1.2 PITTING CORROSION

Pitting corrosion results from the attack of surface impurities and weak spots by the corrosive environment (Mills et al 2009). Alloys susceptible to this type of corrosion include 2024-T3 aluminium alloys and steels such as those mentioned in Section 2.2.2. The corrosion produces isolated pits in the surface of the structure, which provide local stress concentrations from which fatigue cracks can grow (e.g. Mills et al 2002). The nucleation and growth of fatigue cracks from corrosion pits has been widely studied, often with modelling of fatigue crack growth from surface flaws whose dimensions are dependent upon those of the corrosion pits (see Section 3.3).

3.1.3 INTERGRANULAR AND EXFOLIATION CORROSION

Intergranular corrosion is the preferential corrosion of material at grain boundaries (Mills et al 2009). High-strength 7000-series aluminium alloys, for instance, can be susceptible because of the accumulation of alloying elements such as copper and zinc at the grain boundaries.

Exfoliation corrosion is a particular form of intergranular corrosion. The corrosion proceeds from the initiation sites along planes parallel to the surface – generally at grain boundaries – and

forms corrosion products that force metal away from the body of the material. This gives a layered appearance in the corroded material. Exfoliation corrosion can influence fatigue cracking by similar mechanisms to pitting corrosion (Mills et al 2009). Modelling has been carried out using similar methods to those for pitting corrosion, e.g. Liao et al (2007) modelled fatigue crack growth from exfoliation damage by representing the exfoliation damage by a surface crack.

The effects of the exfoliation corrosion products may need to be considered in assessing potential corrosion-fatigue interactions. The products will most probably have different material properties to the parent material. The stress state in a corroded structure may also be modified by the restraint of the corroded material – including the corrosion products – by the surrounding structure. An example is that the clamping forces exerted by fasteners – and the fatigue performance of a structural joint – may be increased if corrosion products result in tightening of the joint, or decreased if the joint is loosened by material loss, such as may occur in a corrosive environment (Terada 2001).

3.1.4 GALVANIC AND CREVICE CORROSION

As discussed in Section 2.2.3, corrosion types such as galvanic or crevice corrosion are produced by different mechanisms but have similar effects on the structure to general attack, pitting or intergranular corrosion.

Galvanic corrosion can cause greatly increased corrosion rates in the susceptible material when dissimilar materials are in contact (Mills et al 2009). This type of corrosion might occur, for example, between titanium or steel fasteners and an aluminium alloy aircraft structure. Galvanic corrosion has occurred in the F-22 as the result of the interaction of gap filler materials and paint with aluminum panels, skins, and substructure (Young and Blair 2011).

In crevice corrosion, the occluded environment in the crevice configuration can accelerate corrosion rates (Mills et al 2009). The growth of fatigue cracks from pits produced by crevice corrosion in 2024-T3 aluminium alloy has been studied by Birt et al (2007).

3.1.5 ENVIRONMENTALLY-ASSISTED CRACKING AND FRETTING FATIGUE

Truly synergistic corrosion-fatigue interactions include environmentally-assisted cracking (EAC) and fretting fatigue (Mills et al 2009). EAC processes include corrosion fatigue, stress corrosion cracking (SCC) and hydrogen embrittlement.

Corrosion fatigue is simultaneous corrosion and fatigue, when the fatigue crack growth rates can be very sensitive to the environment. As an example, an aggressive aqueous environment can accelerate fatigue crack growth rates by an order of magnitude in high-strength 7150-T651 aluminium alloy (Gingell and King 1997).

SCC will only take place when three conditions are satisfied, with (1) a susceptible material subjected to (2) a sustained tensile stress in (3) a corrosive environment (Mills et al 2009). Fatigue cracking may then develop from the SCC (e.g. Ball et al 2010).

Hydrogen embrittlement is the result of hydrogen produced by the corrosion process becoming trapped in the material and thereby altering the material properties (Mills et al 2009). This can result in, for example, degradation of the fracture behaviour of high-strength steels used in landing gear (Eliaz et al 2002) or a dramatic tensile ductility loss in 2024-T3 aluminium alloy (Kermanidis et al 2006). Enhanced fatigue crack growth can occur in aluminium alloys, steels and titanium alloys exposed to different environments as a result of hydrogen embrittlement (Hénaff et al 2007).

Fretting fatigue is the result of combined corrosion and wear, when oscillatory small-amplitude relative displacements of mating surfaces take place in the presence of contact forces (Mills et al 2009). The contact forces can lead to stress gradients similar to those at a notch and the oxide debris can produce surface damage such as pitting. Either of these could contribute to the accelerated formation of fatigue cracks.

3.2 CORROSION PREDICTION

The large number of variables affecting corrosion (see Section 2.2) means that corrosion prediction methods should be relevant to the particular situation being considered e.g. it should consider the specific materials and corrosion types in the structure. Corrosion prediction modelling for USAF KC-135 lap joints was, for example, limited to crevice corrosion even though other corrosion types were present (Robertson 1999).

An initial assessment of available software for corrosion prediction was made in Section 2.4.1. The existing corrosion prediction software is in general designed for the prediction of corrosion-related maintenance activities and the susceptibility of a structure to corrosion, rather than predicting the development of features such as corrosion pits which can determine whether fatigue cracks will initiate (see Section 3.3). However, software of this type should be able to identify areas of the structure that are most prone to the development of corrosion. They may also allow estimates to be made of general material thinning which could be required for stress analysis of the structure e.g. the BEASY software will provide estimates of corrosion rates.

However, software such as EDM³, which can provide information on corrosion pit development, may be important for the assessment of whether fatigue cracks will initiate from corrosion damage (see Section 3.3). The predictions may need to include the shape of the pits (e.g. the ratio of width to depth) – e.g. this generally differs between 2024 and 7075 aluminium alloys – as this can alter the stress concentration factor of the pit and hence the fatigue crack development. Possible approaches to the prediction of corrosion pit growth range from the use of simple relationships between pit dimensions and time such as Faraday's Law – i.e. the increase in the pit width and depth are proportional to the cube root of the exposure time in the corrosive environment (Birt et al 2007) – to probabilistic approaches such as that of Rajasankar and Iyer (2006). An example of a corrosion prediction methodology for the onset and growth of corrosion pitting in aircraft structure is given by Dixon et al (2003).

The complexity of the physical processes underlying corrosion mechanisms, together with the variability associated with, for example, environmental or metallurgical factors, may mean that it is not possible to accurately predict the corrosion development by analytical methods and it may be necessary to resort to empirical approaches (Nesic et al 2001). The data for the development of such approaches might be obtained from NDE measurements of corrosion damage parameters (see Section 3.4) or from maintenance data for aircraft structures (Section 3.5). Various methods may be used for the treatment of the data, e.g. Nesic et al (2001) used neural networks for the analysis of corrosion data.

3.3 INITIATION OF FATIGUE CRACKS FROM CORROSION

The initiation of fatigue cracks from corrosion damage has been studied for a range of structural materials, including aluminium alloys (e.g. Burns et al 2011) and steels (e.g. Ebara 2010). These studies have in general addressed the initiation of fatigue cracks from corrosion pits, since the stress concentrations at the pits make them the most likely corrosion damage features at which fatigue cracks will initiate. The size and morphology of the corrosion pits can have significant effects upon the fatigue crack nucleation (e.g. van der Walde and Hilberry 2008) and some investigations have carried out detailed investigation of the effects of pit topography and material microstructure upon fatigue crack initiation (e.g. Burns et al 2011). BEASY (2012c) describes a study of the effect of corrosion pit shape upon the stress concentration factor, whilst Rusk et al (2009) have developed an equivalent stress-raiser model for the nucleation of fatigue cracks at corrosion pits in high-strength steel. The utility of corrosion prediction software such as that assessed in Section 2.4.1 in predicting the nucleation of fatigue cracks from corrosion damage is therefore likely to depend upon their ability to predict the evolution of those pit characteristics that will have an influence upon the crack nucleation. It is therefore recommended that further assessment of software for corrosion prediction (see Section 2.4.1)

should be made to establish its suitability for the prediction of fatigue crack nucleation from corrosion damage.

Whilst the nucleation of fatigue cracks from corrosion damage may be able in some cases (e.g. from a single dominant corrosion pit) to be predicted by detailed modelling of the corrosion surface including the pit morphology, it may not always be possible to use this approach and approximate or empirical methods may be required instead. As an example, Rusk et al (2009) have developed approximate methods to identify localized high stress regions in corroded steel surfaces because the finite element mesh that would be required to accurately reflect the fine details distributed over the entire corrosion patch makes computation unrealistic. Empirical relationships between corrosion pit parameters and fatigue behaviour have also been developed and these are discussed further in Section 3.4.

3.4 NDE CORROSION PARAMETERS

A review of the important corrosion metrics that need to be measured so that remaining life can be predicted from fatigue crack growth models was reported by Birt et al (2006). The type of corrosion taking place was identified as an initial metric for life prediction and the remaining fatigue life was found to be strongly correlated with the presence of corrosion pits, with pit depth, pit area and surface roughness all reported as important metrics. DuQuesnay et al (2003) reported that the corrosion pit depth appeared to be the dominant factor affecting the fatigue life of 7075-T6511 aluminium alloy, whilst Rokhlin et al (1999) have determined an empirical relation between the depth of a single, simulated corrosion pit and the fatigue life of 2024-T3 aluminium alloy. If there is a dominant corrosion pit, measurement of the appropriate pit dimensions may therefore allow their use as inputs to fatigue life prediction models as discussed in Section 4.1.

Birt et al (2007) found good correlations of the fatigue lives of 2024-T3 aluminium alloy specimens containing pitting and crevice corrosion with ultrasonic and eddy-current NDE parameters such as the mean and standard deviation of 50 MHz ultrasonic back-wall amplitude C-scans. Shell et al (2005) have also found correlations between corrosion metrics, obtained by ultrasonic inspection, white-light interference microscopy (WLIM) and radiography, with the fatigue lives of 2024-T3 specimens containing a mix of pitting, intergranular and general corrosion.

Shell et al (2005) reported that using the combined metrics of WLIM roughness and maximum loss in back-wall ultrasonic amplitude gave a significant improvement in the correlation of the NDE parameters with fatigue life. An earlier paper by Forsyth and Komorowski (2000) had also evaluated combining NDE data for fatigue-life prediction. This combining of data is often

referred to as data fusion, which is simply defined as combining multiple inputs into one output. The inputs can be from different NDE techniques (e.g. Forsyth and Komorowski 2000) or different parameters from the same NDE technique (e.g. roughness and thickness loss using an ultrasonic method, as Smith 2004). Data fusion for a lap joint, where both eddy-current and enhanced visual NDE techniques were required to fully characterise the corrosion damage, was described by Forsyth and Komorowski (2000) and Liu and Forsyth (2004).

It is recommended that the use of NDE data fusion techniques for the prediction of corrosion-fatigue interactions should be investigated further. The data fusion techniques might potentially give improved accuracy of predictions compared to a single technique (e.g. Shell et al 2005). However, this investigation should consider in particular whether more rapid inspection of a structure to obtain suitable inputs to predictive models might be possible with a combination of techniques (e.g. general thickness loss and surface roughness) than by detailed corrosion pit measurements using a single technique, which might be prohibitively lengthy and so only suitable for areas of the structure which are of particular concern.

3.5 MAINTENANCE AND OTHER DATA

The use of in-service data from maintenance and other records to build up a model of corrosion in a particular aircraft type is being developed, for example in the United States (Benavides 2009), because of the difficulty of predicting corrosion from mechanistic models. Appendix A gives examples of how corrosion costs for different aircraft types may give indications of the development of corrosion in the aircraft. The data in the appendix is limited to total annual cost per aircraft and so give only very general indications. However, data recorded in sufficient detail and with sufficient accuracy from in-service corrosion data from inspections, maintenance and teardown may be used in the more detailed prediction of corrosion development within the aircraft fleet. Figure 2 shows a Russian example of curves for the prediction of corrosion development in an aircraft fuselage derived using statistical analysis of in-service corrosion data (Nesterenko and Nesterenko 2009).

The maintenance or other in-service data have the advantage that they are obtained from real structure in the service environment and so have the potential to give accurate predictions of corrosion development. However, the data are required to be detailed and quantitative, but without data recording placing an excessive additional burden upon maintenance personnel. Details could include structural location, corrosion protection scheme, material type and corrosion type, as well as quantitative measurements such as the extent or depth of corrosion. The data should be consistently recorded as a function of time and flight hours so that all relevant data are readily available for assessments of the development of corrosion and its

interaction with fatigue. Fatigue data, e.g. the presence or length of fatigue cracks or loads data, might also be required for the assessment of potential corrosion-fatigue interactions. United States Navy maintenance data processes had to be developed to allow recording of inspection and repair corrosion data (Savell et al 2011) and it may be that UK maintenance databases would also need to be modified to allow the recording of suitable data.

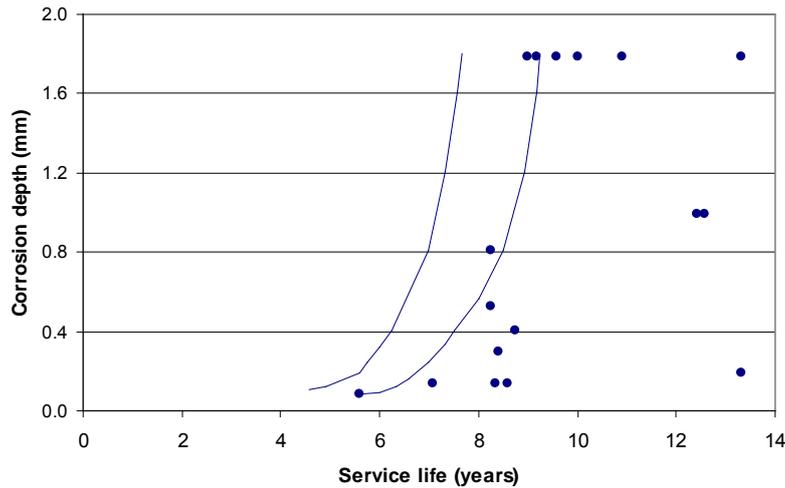


Figure 2 – In-service corrosion data and examples of derived curves for the prediction of corrosion damage development in a Russian aircraft fuselage of D16ATV aluminium alloy (Nesterenko and Nesterenko 2009)

It is therefore recommended that the potential use of maintenance data for the prediction of corrosion and its possible combination with fatigue data for assessment of potential corrosion-fatigue interactions should be investigated. This assessment should include, for example, the type of data available and whether it would be suitable for corrosion prediction, either qualitatively (e.g. identifying the materials or structural elements most susceptible to corrosion) or quantitatively; the methods of recording and storing the data and whether these would need to be modified; combination of the data with any records from corrosion sensors or aircraft geographical history to allow for effects of environment (see Section 2.2.4) and possible analysis methods for the data.

4 FATIGUE CRACK GROWTH

4.1 FATIGUE CRACK GROWTH FROM CORROSION

The general interaction of fatigue and corrosion was illustrated schematically in Figure 1. The later stages are often predicted using available fatigue and fracture software such as that discussed in Section 2.4. The fatigue prediction may be based upon the growth of an initial flaw with parameters which are related to the dimensions of a corrosion pit, such as a semi- or quarter-elliptical flaw of equivalent area to the observed corrosion pit (Gruenberg et al 2004, Van der Walde and Hilberry 2008). As previously noted, factors such as material thinning (higher stresses) and the formation of corrosion products (different material properties, e.g. Bellinger and Liao 2009) may need to be included in the fatigue analysis. The possibility of the interaction of multiple fatigue cracks from corrosion pits may also need to be considered, e.g. van der Walde et al (2005).

The initiation of the fatigue crack at the corrosion damage can depend upon the morphology of the corrosion pit and the resultant stress concentration, as discussed in Section 3.3. A conservative approach sometimes used is to assume immediate initiation of the crack from the corrosion pit, e.g. Burns and Gangloff (2011) for 7000-series aluminium alloys.

As a fatigue crack may grow from a small (of the order of tens of microns) corrosion pit, short crack fatigue behaviour may need to be included in the model to give accurate fatigue predictions. Birt et al (2007) found that the assumed short crack behaviour significantly altered the predicted life of corroded 2024-T3 specimens.

The fatigue crack growth may be influenced by a corrosive environment, e.g. the crack growth rate may be altered by anodic dissolution or hydrogen embrittlement of the material (e.g. Hénaff et al 2007). Corrosion fatigue data may be required to model the crack growth, but should be appropriate to the environmental conditions present in service, e.g. the fatigue of 2024 aluminium alloy differs in air, distilled water and 3.5% NaCl solution (Menan and Hénaff 2010), the last being the approximate composition of seawater. The effect of the loading frequency and sequencing may also need to be considered (see Section 2.2.6).

Environmental exposure may result in changes in the static properties of the structural material, e.g. Kermanidis et al (2006) and Kamoutsi et al (2006) for 2024-T3 aluminium alloy. Such changed material properties might need to be used in, for example, calculation of the effects of overloads in spectrum loading upon the plastic zone at the fatigue crack tip, or in determination of the fracture behaviour of the material. Billy et al (2012) reported that fatigue tests of 2024-

T3511 panels removed from an Airbus A320 wing after service showed no significant differences from virgin material, thereby supporting the use of pristine material fatigue data in prediction.

In addition to life prediction, fatigue calculations might also be used to back-calculate from the required fatigue life to determine allowable damage, such as pit dimensions, for the structure. This might then set the allowable limits for NDE inspections using techniques such as those discussed in Section 3.4, provided that a satisfactory correspondence can be established between the calculated corrosion parameters and the actual corrosion morphology

4.2 SPECTRUM LOADING AND ENVIRONMENT

Most research on corrosion-fatigue interactions has been for constant amplitude loading, e.g. fatigue crack growth from pre-corroded specimens in laboratory air (Birt et al 2007) or corrosion fatigue in environments such as 3.5% NaCl solution (Menan and Hénaff 2010). There is less work for corrosion-fatigue interactions under spectrum loading, which can also result in severe reductions in fatigue lives, e.g. for crack growth from corrosion pits in 7075-T76511 aluminium alloy under a Canadian C-130 transport wing spectrum (DuQuesnay et al 2003). Figure 3 shows the results of modelling to predict the effects upon fatigue life of a 50-micron corrosion pit and different material thickness losses in an aircraft lower wing under a C-130 spectrum (Mills et al 2009).

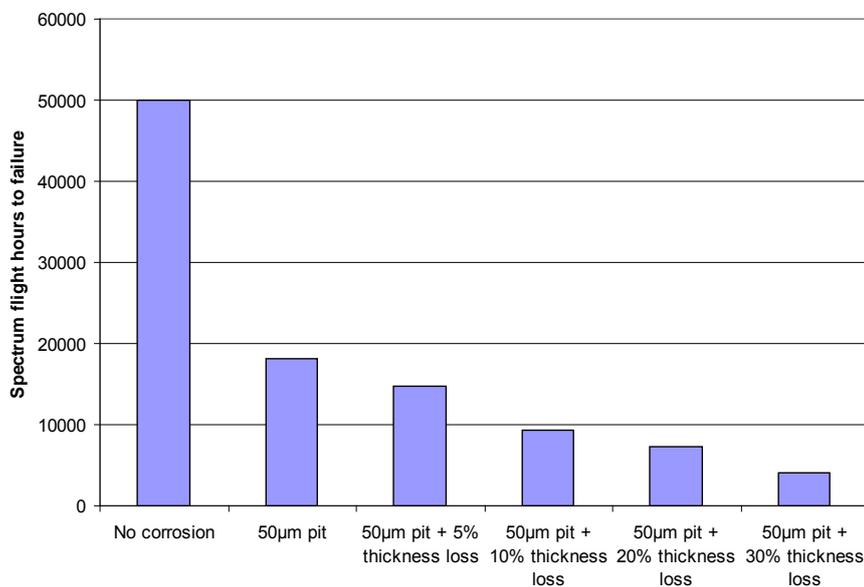


Figure 3 – Example of modelling results for fatigue crack growth from corrosion damage under C-130 lower wing spectrum loading (Mills et al 2009)

The corrosion-fatigue interaction effects may be different for spectrum loading and constant-amplitude loading, e.g. the presence of a salt spray increased fatigue crack growth rates by a factor of three in 7010-T7451 aluminium alloy under constant amplitude loading, but the salt spray had no significant effect upon the crack growth rate for the same alloy under spectrum loading (Cole et al 1997). It is possible, for example, that mechanisms such as changes in crack closure as a result of overloads in the spectrum alter moisture ingress into a crack and so give different corrosion-fatigue interactions to those under constant amplitude loading.

It is therefore recommended that corrosion-fatigue interactions under spectrum loading should be investigated further. This should include fatigue crack growth nucleation and growth from corrosion pits under spectrum loading, and fatigue in a corrosive environment under spectrum loading. The appropriate modifications required to existing fatigue software required for improved predictions could then be determined. Such modifications might include, for example, the use of modified materials properties in the models to allow for the effects of corrosion (see section 4.3).

Corrosion-fatigue interactions under spectrum loading are dependent upon the material type as well as the loading spectrum. Spectrum loading of clad aluminium alloys, for example, gave similar crack propagation rates in indoor and outdoor environments for 2024-T3, but in 7075-T6 the outdoor crack growth rates were a factor of about 1.5 to 2.0 greater than the indoor rates (Schijve and De Rijk 1965). In specimens immersed in salt water, tensile overloads in the loading spectrum produced fatigue crack growth retardation in 2024-T851 and Ti-6Al-6V-2Sn alloys immersed in salt water, much as they would in benign environments, but similar overloads produced crack extension, consistent with SCC, in Ti-6Al-4V (Cole et al 1997). The type of material, corrosion, environment and loading spectrum should thus be considered carefully for any future investigations of corrosion-fatigue interactions under spectrum loading.

5 CONCLUSIONS

Corrosion and fatigue in an aircraft structure may interact in a number of ways. This can include the more rapid initiation of fatigue cracks as a result of corrosion damage or changes in fatigue crack growth rates due to the presence of a corrosive environment. These interactions can lead to increased risks to aircraft structural integrity, increased maintenance costs and reduced aircraft availability.

Corrosion and fatigue, and their interactions, are dependent upon many factors. These include, for example, material type, corrosion type, structural configuration, environment and applied load spectrum. The variability associated with these factors and the dependence of many of them on micro-structural details make prediction of corrosion-fatigue interaction processes (e.g. the initiation of fatigue cracks from corrosion damage) difficult. This potential variability also means that predictions of corrosion-fatigue interactions should specifically address the factors relevant to a given situation (e.g. operating environment).

A generalised corrosion-fatigue process may be broken down into a number of stages. This can aid in developing prediction methods and in assessing the suitability of different approaches to the individual stages. The methods to be used for each stage will depend upon the physical situation and the available approaches. Established approaches and available software should be used as far as possible for the prediction of corrosion-fatigue interactions, as this will minimise time and effort and should increase confidence in the outputs. Advances such as the availability of new software, new approaches such as the use of probabilistic techniques or new methods for corrosion prediction could then be incorporated in the appropriate stages as they become available.

A variety of software is available for the prediction of corrosion or fatigue. The corrosion prediction software can address galvanic and pitting corrosion, corrosion rates and the effects of protective coatings and may calculate, for example, the relative susceptibility of different parts of the aircraft structure to corrosion. The fatigue prediction software may calculate, for example, fatigue crack growth from a corrosion pit under applied spectrum loading. It may be necessary to combine a number of these packages to assess a particular corrosion-fatigue interaction. This might involve a finite element package for calculation of the stresses in a structural feature, a corrosion prediction model to assess the growth of corrosion pits, and a fatigue and fracture code to predict the fatigue crack growth from the corrosion pits through to the final fracture.

There are a number of structurally significant corrosion types but the most important are probably general attack, pitting corrosion and exfoliation corrosion. The effects of other corrosion types such as crevice corrosion upon fatigue behaviour may be modelled by similar

approaches to these three types. Corrosion features which will influence fatigue behaviour include thickness loss (increased stress levels and/or reduced stiffness), corrosion pits (stress concentrations) and corrosion products (changed materials properties and/or stress state).

Fatigue crack growth prediction is in general more advanced than corrosion prediction. The most immediate benefits from the prediction of corrosion-fatigue interactions may thus be realised by improving the accuracy of prediction of fatigue crack growth from corrosion damage and of corrosion fatigue. Such improvements might also allow accurate back-calculation from the required fatigue lives to determine acceptable levels of corrosion in the structure (e.g. corrosion pit dimensions). The effects of corrosion upon fatigue behaviour under aircraft spectrum loading may be different to those for the constant amplitude loading used in much previous work. It may be possible to adapt existing fatigue and fracture software to allow for the effects of corrosion by using suitably modified static material properties and fatigue behaviour. However, consideration needs to be given to the applicability of material data obtained in the laboratory to actual service conditions.

The initiation of fatigue cracks from corrosion damage is mostly from corrosion pits and is therefore highly dependent upon the pit geometry. The prediction of fatigue crack nucleation and growth from corrosion damage may therefore require the ability to predict the evolution of the geometrical factors in the corrosion pits that influence crack nucleation in addition to, for example, the general level of corrosion.

NDE methods can provide detailed measurements of corrosion damage, such as the dimensions of corrosion pits, which can provide inputs to fatigue crack growth software. However, the time and effort required for NDE scanning and fatigue analysis may mean that the use of such detailed data is only practicable for relatively small areas of structure which are of particular concern. Data fusion is the combination of a number of NDE techniques which should potentially allow more rapid scanning to determine the corrosion state of a structure and so could be a practical means of providing suitable inputs to fatigue models. An example of data fusion might be the combination of NDE techniques to measure material thickness loss and surface roughness.

Data from the maintenance effort required to repair corrosion damage may be used for the prediction of corrosion in an aircraft structure. This approach has the advantage that the data are obtained for real structures and actual service environments. However, the processes for the recording and analysis of the data must be carefully designed to accurately provide the relevant quantitative information without excessive additional effort on the part of the maintenance organisation.

6 RECOMMENDATIONS

6.1 GENERAL CONSIDERATIONS

Established approaches and available software should be used as far as possible for the prediction of corrosion-fatigue interactions (Section 2.3).

Each potential corrosion-fatigue interaction process should be broken down into a series of stages to determine the optimum approach and software to be used in each stage (Sections 2.1 and 2.3).

Assessments of potential corrosion-fatigue interactions should allow for factors such as the specific material or corrosion type because of the variability due to these factors (Sections 2.2 and 4.2).

6.2 PREDICTION OF CORROSION-FATIGUE INTERACTIONS

The use of existing fatigue and fracture software for the prediction of fatigue crack growth from corrosion damage should be investigated for aircraft structural features subjected to spectrum loading in realistic service environments (Section 4.2).

Corrosion prediction methods should be assessed for their ability to predict the evolution of the geometrical parameters of corrosion pits which will influence the nucleation of fatigue cracks at the pits (Sections 3.2 and 3.3).

The use of NDE data fusion methods for obtaining corrosion damage input parameters to fatigue software should be investigated (Section 3.4).

A review should be made of the available data for corrosion and fatigue development obtained during maintenance and other activities to assess the potential of the data for use in the prediction of corrosion-fatigue interactions (Section 3.5).

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Appendix A: Corrosion costs for USAF and RAF aircraft types

The cost of corrosion in aircraft structures was touched upon in Section 1. The actual costs of aircraft corrosion may be difficult to quantify and require considerable effort to gather (Pye 1981). Some cost data for USAF and RAF aircraft types are presented in this Appendix. The absolute (USAF) or relative (RAF) costs are of importance for budgetary purposes, but trends in the corrosion costs can also provide indications of the development of corrosion in aircraft structures.

The corrosion cost data given here are manpower and materials costs for maintenance activities related to corrosion. They include aircraft washing and cleaning; the application, inspection and repair of paint schemes and protective coatings; the inspection for and rectification of corrosion damage; and supporting activities such as gaining access to and closure from parts requiring these activities. The relative costs therefore give indications of relative corrosion maintenance effort and so potentially of relative susceptibility to corrosion and corrosion-fatigue interactions. As discussed in Section 3.5, more detailed corrosion maintenance data may be able to be used in corrosion prediction.

Figures A-1 and A-2 show the annual cost of corrosion per aircraft for different USAF aircraft types (Kinzie 2005) plotted against time. The costs are all adjusted to 2004 dollars. Figure A-1 gives the data for the generally larger aircraft types, including bombers (shown in blue), transports/tankers (red) and Intelligence, Surveillance and Targeting (ISTAR) aircraft (green). Figure A-2 includes fighter/attack aircraft (in blue), training aircraft (red) and helicopters (green). The individual helicopter types are not given, but at these dates the USAF operated MH-53, HH-60 and UH-1 helicopters. For each category, the aircraft types are arranged in the key by approximate date of service entry, with the oldest at the top. The approximate empty weight (in tonnes) of each aircraft type is shown against the corresponding cost data in the figure. The data for the aircraft (other than cost) were taken from a variety of sources (principally Jane's publications).

Table A-1 gives relative corrosion maintenance costs (Pye 1981) for RAF aircraft. Data other than costs were taken from a range of sources, including Jane's publications and Thetford (1988). Aircraft characterised as "old" in the table had been introduced into RAF service 20 or more years before the date of the review.

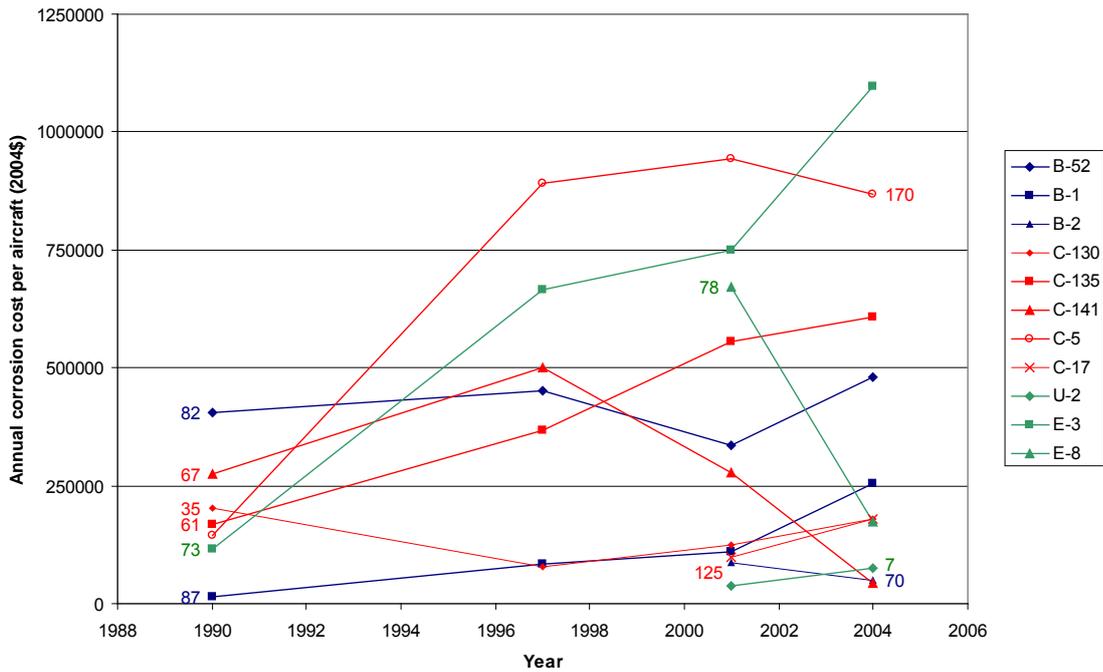


Figure A-1 – Cost of corrosion (Kinzie 2005) for USAF bomber, transport/tanker and ISTAR aircraft (approximate empty weight in tonnes is indicated for each aircraft type)

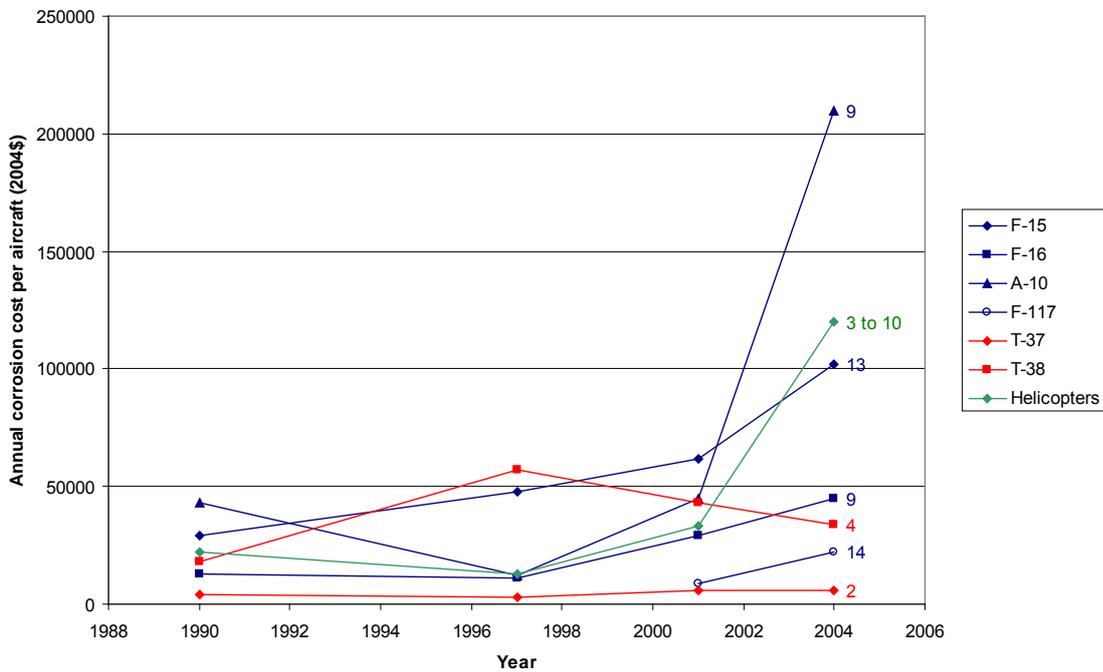


Figure A-2 – Cost of corrosion (Kinzie 2005) for USAF fighter/attack aircraft, training aircraft and helicopters (approximate empty weight in tonnes is indicated for each aircraft type)

Aircraft Category	Example(s)	Empty weight (tonnes)	Cost factor
Small training aircraft	Jet Provost	2	1
Smaller combat aircraft	Jaguar	7	
	Lightning	13	5
Modern land-based helicopter	Puma	3	
Larger combat aircraft	Phantom	14	15
Modern marine environment helicopter	Sea King	6	
Medium-sized transport aircraft	Hercules	35	25
Old marine environment helicopter	Wessex	4	
Old bomber aircraft	Vulcan	37	35
Large transport aircraft	VC10	66	85
Maritime patrol aircraft	Nimrod	39	

Table A-1 – Relative corrosion maintenance cost factors (Pye 1981) for RAF aircraft types

The corrosion cost data in Figures A-1 and A-2 and Table A-1 include a wide range of aircraft types, subjected to different operating environments and mission types. There is considerable variation in the corrosion costs – and hence in the extent of corrosion – between different aircraft types and (from Figures A-1 and A-2) for a given aircraft type with time. This variation is because of the range of factors that can influence the corrosion (see Section 2.2). There will be further significant variations between different aircraft of the same type because of their different service histories. The influence of some factors upon the corrosion in the different aircraft types are discussed below.

A.1 Aircraft weight

Figures A-1 and A-2 and Table A-1 include the aircraft empty weight as indicators of aircraft structure weight. Generally there is an increase in corrosion cost with aircraft empty weight, although factors such as the aircraft age are also very significant. Falugi et al (2000) show a corresponding increase in corrosion cost with the take-off gross weight (up to three times the empty weight) of various USAF aircraft types. Greater weights will in general lead to a greater amount of material potentially susceptible to corrosion and to a greater surface area potentially exposed to a corrosive environment, leading to increased inspection and maintenance costs.

A feature of Table A-1 is that the corrosion costs for helicopters are similar to those for fixed-wing aircraft with weights which are two or more times greater than those of the helicopters. This could reflect differences in structural design and/or operating environment.

A.1 Aircraft age

A general increase of corrosion cost with aircraft age is not unexpected and is shown by the trends for aircraft types such as the E-3 (Sentry) in Figure A-1 and the A-10 in Figure A-2. In Table A-1, the corrosion costs for old marine environment helicopters are higher than for modern marine environment helicopters of greater empty weight. The increasing cost with time can reflect the deterioration of corrosion protection schemes and structural materials.

Figures A-1 and A-2 however also show examples of aircraft types where the corrosion costs have decreased with time. As an example, there is a marked decrease in costs for the C-141 after 1997 in Figure A-1. These cases show the beneficial effects of measures such as the introduction of new variants of the aircraft type and the retirement of older aircraft, which reduce the average age of the aircraft fleet, or of refurbishment programmes which, for example, might replace corroded structure with new components, replace structural materials with types which are less susceptible to corrosion and fatigue or apply improved corrosion protection schemes. Extensive refurbishment could potentially restore an aircraft to its initial uncorroded state, so that the extent and nature of refurbishment has important implications for the conversion of older aircraft to new variants and roles, e.g. the conversion of KC-135 airframes to Airseeker.

A.3 Structural materials

The materials used can be an important factor in the development of corrosion in an aircraft structure. The aircraft types in these data sets predominantly use metallic structural materials, but some also employ composite materials, e.g. the relatively low corrosion costs of the B-2 in Figure A-1 for an aircraft of its weight may result from the use of composite materials in addition to the type's relative newness. Environmental degradation of composite structures will in

general proceed by other mechanisms, such as moisture absorption or exposure to ultra-violet radiation, but metallic elements within the structure may still be susceptible to potential corrosion-fatigue interactions if the corrosive environment has access to them.

A.4 Environment

The service environment is an important factor in the development of corrosion and potential corrosion-fatigue interactions. Table A-1 illustrates that exposure to a maritime environment can lead to increased corrosion compared to land-based operation, e.g. the corrosion costs per unit aircraft weight are greater for a modern marine environment helicopter than for a modern land-based helicopter. Environmental influences on corrosion in current land-based helicopter fleets (e.g. Figure 2.1 in Hertzberg 2009) include temperature, humidity and sand erosion of paints and coatings in desert conditions.

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