Predicting Fatigue Crack Initiation due to the Presence of Intergranular Corrosion in Extruded 7075-T651 Aluminium Alloy

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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September 2014
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B Eng. (Aerospace Engineering)

A thesis submitted to the School of Aerospace, Mechanical and Manufacturing Engineering Collage of Science, Engineering and Health, Royal Melbourne Institute of Technology

As partial fulfilment for the degree of Doctorate of Philosophy

September 2014
This PhD Thesis is dedicated to my father, Warren Harrison, who lost his battle with brain cancer on December 25th, 2012. He taught me how to question and the importance of fully understanding something, not merely accepting it as fact. He introduced me to the world of Science and supported my growth and development in the world of Engineering. Without his strength and his memory, I wouldn’t have been able to complete this work.
DECLARATION

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

Signed: ______________________

Name: Timothy J Harrison

Date: 26/09/2014
ACKNOWLEDGEMENTS

I would like to thank and acknowledge the support and guidance given to me by numerous people including those at RMIT University and especially at the Defence Science and Technology Organisation in Melbourne. Without their support, this PhD candidature would have been much tougher.

I must begin by thanking my PhD supervisors for their guidance and technical support during my candidature. To Dr. Bruce Crawford, whose knowledge of fatigue and the effect corrosion has on it is second to none. To Professor Graham Clark, who first approached me to do this project and continued to support me during his serious illness. And to Professor Milan Brandt, who stepped up when Professor Clark retired and took on my project, which was outside his area of expertise, to provide scientific and academic support. Thanks must also go to RMIT administration staff, particularly Lina Bubic.

Thanks must also go to Chris Loader of DSTO for his support and technical insight in the later stages of my candidature, and for being able to bounce ideas off him when he was involved in the DSTO P-3 Corrosion project. Maria Salagaras and Dr. Stephen Knight must also be thanked for their guidance during the Corrosion Protocol development stage – we finally got there in the end!

Thanks must go to a number of DSTO staff members for their technical insights and training on various pieces of laboratory equipment. The Fatigue and Fracture laboratory staff, particularly David Taylor, Bruce Crosbie and David Parslow. The Forensics group in Steve Toman, Rohan Byrnes, Cathy Smith, Charlie Brady and Bruce Grigson. The Corrosion Control group in Alison Wythe, Grant McAdam, Andrew Butler and Peter Trathen. The DSTO P-3 Intergranular Corrosion program in Andrew Walliker, David Goudie and James Duthie. And finally to the Metallic Airframes group, who took me in as one of their own, in Alex Shehkter, Khan Sharp, Richard Djugum, Pud Baburamani and Qianchu Liu.
Thanks must also go to the Directorate General of Technical Airworthiness, part of the RAAF, who funded this work as well as providing technical insight and helped to organise site visits to P-3 maintenance facilities. Particular thanks must go to Dr. Madabhushi Janardhana who ultimately authorised the funding for this project and to SQNLDR Adam Bowler who, at the time, was head of P-3 structural integrity at DGTA and still offered support after his move to MPSPO.

Thanks must go to important friends that provided personal support, laughter and fun during my candidature. Nick Orchowski at RMIT, and James Niclis and Dave Russell at DSTO for their support while on-site at DSTO. To the Sneaky Butcher crew for endless laughs (but what does that mean?) and to my Triathlon family who helped me discover just how far I really can push myself.

To my brother, Chris, who pushed me along as I went – I couldn’t let him be the only one in the family to get a PhD!

And finally to my mum, Sharon, who showed me strength beyond what I thought was possible and who was always a shining light when things were at their darkest.
ABSTRACT

The management of various forms of corrosion that are present in both civilian and military aircraft is an increasing burden as they age. One particularly insidious form of corrosion is laminar Intergranular Corrosion (IGC) due to the small surface corrosion present, even though the long, sharp fissures can grow parallel to the surface up to and over 5 mm in highly extruded materials. This thesis investigates the fatigue effects of this peculiar form of IGC, particularly focussing on fatigue crack initiation. Its aim is to determine the mechanism behind the early fatigue failure due to IGC and to develop a model that can predict the knock-down factor for the number of cycles to a 1 mm fatigue crack, which is termed “crack initiation”.

This thesis uses the example of IGC on the AP-3C Orion maritime surveillance aircraft, which is currently an issue for fleet operators world-wide as the unknown fatigue effects results in any IGC found being completely removed, leading to significant delays during maintenance. A secondary aim of this thesis is to use these results to develop a tool that can be used by fleet operators to assist in lifeing the AP-3C Orion in the presence of IGC.

A series of constant-amplitude fatigue tests on specimens with a high stress concentration (of 3.0 for a plate-with-hole) showed that IGC reduced the number of cycles to crack initiation and that this reduction was proportional to the depth at which the fatigue crack initiated. Fractography showed two types of initiating features on the corroded specimens. Fatigue cracks initiated at either a corrosion pit at the bore of the hole, or at corroded inclusions situated along the path of the IGC fissure. In contrast, fatigue cracks in the un-corroded specimens initiated at the hole corners.

A Monte Carlo model, combined with finite element analysis, was used to simulate the fatigue specimens. The Monte-Carlo model created representative IGC paths within simulated fatigue
specimens. It then added simulated pits and corroded inclusions at locations along the surfaces of the predicted IGC paths. As a final step it created script files that were submitted to ABAQUS to complete the analysis. This Finite Element analysis showed that IGC only slightly changed the stress concentration at the specimen’s hole. In contrast, pits and corroded inclusions significantly increased the stress concentration. This change explains the two different fatigue initiation locations observed in the fatigue tests. These are:

- When a pit is present at the bore of the hole, it will always have a higher $K_t$ than the hole on its own, and thus fatigue will initiate there.

- If a corroded inclusion is also present the process of crack initiation is a competition between the inclusion and any corrosion pits present. A key factor in this is the distance of the inclusions from the hole bore. Beyond a certain distance (related to the size of the pit) the $K_t$ of the inclusion will be less than that of the pit. This is because the inclusion’s $K_t$ decreases in an exponential fashion as its distance from the hole increases.

The results of the FE analysis and the fatigue tests were combined to produce a model to predict the knock-down factor of the number of cycles to a 1 mm fatigue crack of a population of likely pit sizes and corroded inclusion locations. This model can then be used by fleet operators world-wide to assist in lifeing the AP-3C Orion to attempt to reduce the maintenance load currently experienced during deeper maintenance.
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<th>Full Form</th>
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<tbody>
<tr>
<td>AFGROW</td>
<td>Air Force Grow (software package)</td>
</tr>
<tr>
<td>AFHRS</td>
<td>Airframe Flight Hours</td>
</tr>
<tr>
<td>AFRL</td>
<td>Air Force Research Laboratory (United States Air Force)</td>
</tr>
<tr>
<td>ALC</td>
<td>Adaptive Load Control</td>
</tr>
<tr>
<td>ASIMP</td>
<td>Aircraft Structural Integrity Management Plan</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for the Testing and Materials</td>
</tr>
<tr>
<td>BHEC</td>
<td>Bolt Hole Eddy Current</td>
</tr>
<tr>
<td>CIC</td>
<td>Corrosion Inhibiting Compound</td>
</tr>
<tr>
<td>DCPD</td>
<td>Direct Current Potential Drop</td>
</tr>
<tr>
<td>DNH</td>
<td>Dome Nut Hole</td>
</tr>
<tr>
<td>DOF</td>
<td>Degree of Freedom</td>
</tr>
<tr>
<td>DSTO</td>
<td>Defence Science and Technology Organisation</td>
</tr>
<tr>
<td>ECS</td>
<td>Equivalent Crack Size</td>
</tr>
<tr>
<td>EDM</td>
<td>Electrical Discharge Machining</td>
</tr>
<tr>
<td>EDX</td>
<td>Energy Dispersive X-ray spectroscopy</td>
</tr>
<tr>
<td>EIFS</td>
<td>Equivalent Initial Flaw Size</td>
</tr>
<tr>
<td>EXCO</td>
<td>Exfoliation Corrosion test</td>
</tr>
<tr>
<td>FAMS</td>
<td>Fatigue Analysis of Metallic Structures</td>
</tr>
<tr>
<td>FE</td>
<td>Finite Element</td>
</tr>
<tr>
<td>FFL</td>
<td>Fatigue and Fracture Laboratory (at DSTO)</td>
</tr>
<tr>
<td>ICAPES</td>
<td>Inductively Coupled Plasma Atomic Emission Spectroscopy</td>
</tr>
<tr>
<td>IGC</td>
<td>Intergranular Corrosion</td>
</tr>
<tr>
<td>ITAR</td>
<td>International Traffic in Arms Regulations</td>
</tr>
<tr>
<td>MPT</td>
<td>Multi-Purpose Testware (software package)</td>
</tr>
<tr>
<td>NATA</td>
<td>National Association of Testing Authorities (Australia)</td>
</tr>
<tr>
<td>PFZ</td>
<td>Precipitate Free Zone</td>
</tr>
<tr>
<td>RAAF</td>
<td>Royal Australian Air Force</td>
</tr>
<tr>
<td>RNZAF</td>
<td>Royal New Zealand Air Force</td>
</tr>
<tr>
<td>RST</td>
<td>Residual Strength Testing</td>
</tr>
<tr>
<td>SBI</td>
<td>Safety By Inspection</td>
</tr>
<tr>
<td>SCC</td>
<td>Stress Corrosion Cracking</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>SICAS</td>
<td>Structural Integrity</td>
</tr>
<tr>
<td>SLAP</td>
<td>Service Life Assessment Program</td>
</tr>
<tr>
<td>SMP</td>
<td>Structural Management Plan</td>
</tr>
<tr>
<td>TEF</td>
<td>Trailing Edge Flap</td>
</tr>
<tr>
<td>UN</td>
<td>United Nations</td>
</tr>
<tr>
<td>USAF</td>
<td>United States Air Force</td>
</tr>
<tr>
<td>USN</td>
<td>United States Navy</td>
</tr>
<tr>
<td>XFEM</td>
<td>eXtended Finite Element Method</td>
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### NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_g$</td>
<td>Global IGC path angle</td>
</tr>
<tr>
<td>$A_l$</td>
<td>Local IGC path angle</td>
</tr>
<tr>
<td>$C_{LC}$</td>
<td>Corrosion length FOR loop counter</td>
</tr>
<tr>
<td>$D_{crit}$</td>
<td>Critical depth, depth of initiation</td>
</tr>
<tr>
<td>$D_I$</td>
<td>Initiation depth</td>
</tr>
<tr>
<td>$D_i$</td>
<td>Inclusion depth</td>
</tr>
<tr>
<td>$D_p$</td>
<td>Pit depth</td>
</tr>
<tr>
<td>$G_I$</td>
<td>Individual grain length (LT) based on grain size distribution</td>
</tr>
<tr>
<td>$G_w$</td>
<td>Individual grain width (ST) based on grain size distribution</td>
</tr>
<tr>
<td>$K_{FC}$</td>
<td>Knock-down factor for first visible crack</td>
</tr>
<tr>
<td>$K_{FL}$</td>
<td>Knock-down factor for first ligament</td>
</tr>
<tr>
<td>$K_{OL}$</td>
<td>Knock-down factor for overall fatigue life</td>
</tr>
<tr>
<td>$L_C$</td>
<td>Local angle coefficient</td>
</tr>
<tr>
<td>$L_{CORR}$</td>
<td>Corrosion length</td>
</tr>
<tr>
<td>$L_M$</td>
<td>Grain length mean (LT)</td>
</tr>
<tr>
<td>$L_{SD}$</td>
<td>Grain length standard deviation (LT)</td>
</tr>
<tr>
<td>$LT_{pos}$</td>
<td>Position in LT direction</td>
</tr>
<tr>
<td>$LT_{posMD}$</td>
<td>Position in LT direction with respect to main hole with thickness</td>
</tr>
<tr>
<td>$LT_{posMDO}$</td>
<td>Original position in LT direction with respect to main hole</td>
</tr>
<tr>
<td>$N_I$</td>
<td>Number of paths analysed in one run</td>
</tr>
<tr>
<td>$P_{LEFT}$</td>
<td>Probability of corrosion turning left vs right at a junction</td>
</tr>
<tr>
<td>$P_{TURN}$</td>
<td>Probability of corrosion turning at a junction</td>
</tr>
<tr>
<td>$S_i$</td>
<td>Inclusion size (diameter)</td>
</tr>
<tr>
<td>$ST_{pos}$</td>
<td>Position in ST direction</td>
</tr>
<tr>
<td>$ST_{posMD}$</td>
<td>Position in ST direction with respect to main hole with thickness</td>
</tr>
<tr>
<td>$ST_{posMDO}$</td>
<td>Original position in ST direction with respect to main hole</td>
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<tr>
<td>$W_M$</td>
<td>Grain width mean (ST)</td>
</tr>
<tr>
<td>$W_{SD}$</td>
<td>Grain width standard deviation (ST)</td>
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PUBLICATIONS

Peer-reviewed Journal Papers


Timothy J Harrison, Bruce R Crawford, Graham Clark, Milan Brandt. The development of a predictive model for in-service analysis of intergranular corrosion in the AP-3C Orion. In preparation for submission to Engineering Fracture Mechanics, 2014


**Conference Papers**


CHAPTER 1: INTRODUCTION

Corrosion is an ongoing problem for aging aircraft as it can affect safety of flight. This effect can be effectively managed by a rigorous scheme of inspection for corrosion and maintenance. However, this leads to a large maintenance burden which grows as an aircraft ages. Certain types of corrosion are known to cause early failures in components which would normally be expected to have a service life greater than that of the aircraft. An example is the failure of the Trailing Edge Flap (TEF) lugs in F/A-18 aircraft in Royal Australian Air Force (RAAF), Canadian Forces and United States Navy (USN) service [1]. These failures occurred due to a fatigue crack growing from pitting corrosion in the lug, which typically caused the loss of the TEF and significant damage or loss of the aircraft involved. Barter et al. [1] documented a case where such a failure occurred on a RAAF aircraft. In that case the aircraft was seriously damaged but the pilot, who was unharmed, was able to land it successfully after which it was repaired.

Aircraft structures are typically made of high-strength aluminium alloys. Commonly used alloys include 2024-T3 and 7075-T6 for their good material properties, such as high strength and toughness [2]. These alloys are prone to localised corrosion in the form of pitting, exfoliation, intergranular corrosion (IGC), and stress corrosion cracking (SCC). The impact of corrosion on aircraft structural integrity has been subject of increasing interest in recent years. Work conducted at the Defence Science and Technology Organisation (DSTO) [3-8] and elsewhere [9-13] has been shown that pitting and exfoliation corrosion can both initiate fatigue cracks which reduce the fatigue endurance of the component containing them. Further work has led to the development of models that can quantify these effects with a useful degree of accuracy, such as the Equivalent Crack Size model which can predict fatigue lives of specimens containing pitting corrosion with good accuracy [3, 4].

Laminar IGC is a particularly insidious form of corrosion. As the name suggests, IGC is a form of corrosion that occurs at the grain boundaries of a metal [5]. It is often found in the peak-aged aluminium alloys used in older aircraft. Particularly susceptible are the aluminium
alloys 2024-T3 and 7075-T6 [14, 15]. IGC is insidious as it is difficult to detect with a small initiation visible on the surface and its extent within a material is difficult to quantify. It generally takes two forms, either a network of IGC similar to exfoliation or, in highly extruded materials, a laminar fissure of IGC [15]. It is this laminar form of IGC that is worthy of particular investigation in this work due to its orientation with respect to the loading direction, as discussed in Section 1.2.2, which is not normally associated with fatigue crack initiation. However its exact impact on fatigue is unknown as it has not been previously studied. Reasons for this include difficulty obtaining in-service parts containing IGC and a previous inability to grow laminar IGC fissures to sufficient depths.

Laminar IGC is currently an issue in the wing skins of the AP-3C Orion maritime patrol aircraft, particularly around the Dome Nut Hole (DNH) fasteners. As such, it is used in this Thesis as a real-life example of the problems caused by IGC in highly extruded aluminium alloys.

### 1.1: Intergranular Corrosion on the AP-3C Orion

The RAAF AP-3C Orion, shown in Figure 1, is a versatile aircraft capable of a number of marine roles. These roles include maritime surveillance, anti-submarine and anti-ship warfare, naval fleet support, search and rescue, and survivor supply (air drop) missions [16]. For the purpose of maritime surveillance, the AP-3C is equipped with a number of directional frequency and ranging sonobuoys and a magnetic anomaly boom in the tail [17]. It is capable of carrying a number of weapons, including Mk 46 torpedoes, Maverick and Harpoon air-to-surface missiles in its internal bomb bay (capable of carrying 9,100 kg of ordinances) or on eight underwing pylons [17].
The P-3C Orion (the original aircraft the AP-3C was based on) was introduced in 1962 and was operated under the safe-life airworthiness philosophy until the late nineties [18]. During the thirty-year safe-life period, numerous improvements to safe-life tracking were made; including enhanced analytical methods, updated fleet usage assumptions and refinements to the aircraft operational loads.

In the late nineties there was a need to extend the fleet’s planned withdrawal date to at least 2015 [19]. This required life extension lead to the Service Life Assessment Program (SLAP). This was a joint program between Lockheed Martin\(^1\), the US Navy (USN), the RAAF, the Canadian Forces and the Royal Netherlands Navy [19] with the objective of substantiating the 15,000 hour design life of the AP-3C airframe with an appropriate usage [18], with a second goal to support the transition from safe-life to a safety-by-inspection (SBI) management practice. The Program was conducted between 2000 and 2004 [19]. The RAAF was involved on behalf of the USN, as such the US military specifications were used for the testing conducted by the RAAF. Following this program, a Test Interpretation was undertaken to apply these US-based results to RAAF usage.

The program included finite element (FE) modelling, flight tests to validate spectrum loads; flight and landing usage surveys; the development of a full-scale fatigue test spectrum and specimen tests to validate the crack initiation and growth models [18]. Fleet usage data were collected over a six-year period from 1991-1997 and environmental criteria were determined

---

\(^1\) Lockheed Martin are the Original Equipment Manufacturers for the P-3 Orion
from appropriate United States military specifications [18]. These usage data were collated into a number of test spectra, with a severe one chosen for the full-scale fatigue test to keep with the USN philosophy of applying a severe spectrum [18].

1.2: Maintaining the AP-3C Orion

The fatigue analysis of the AP-3C Orion primary structure is conducted in two stages, separating the fatigue life into initiation and crack growth phases. Crack initiation is predicted using a strain-based approach called Fatigue Analysis of Metallic Structures (FAMS), whereas the crack growth phase is analysed using the program FASTRAN [20], which is based on plasticity-induced crack closure [21] and linear elastic fracture mechanics.

FAMS is a crack initiation model that is based on a local strain approach [18]. It considers plastic deformation that occurs in localised regions where fatigue cracks begin, based on the stresses and strains in these localised regions in addition to material property data. Using the maximum spectrum stresses and a user-specified \( K_n \) value, FAMS outputs the number of times the spectrum needs to be repeated before the cumulative damage matrix (calculated using the Miner-Palmgren\(^2\) method [22]) exceeds a value of one [19], representing the crack length exceeding 0.05 inches. The number of times the spectrum is repeated is easily converted into flight hours.

FASTRAN was used to model the crack growth section of the AP-3C fatigue life from a 1.27 mm (0.05 inch) fatigue crack to failure. FASTRAN is based on a plasticity-induced crack closure model [21]. It was used to calculate the stress level at which the crack tip becomes fully open during cyclic loading. This was then converted, using the K-solution for this particular fastener hole, to determine the crack growth increment for each load cycle. More information regarding FASTRAN and its uses is found in Section 2.3.3.2: .

\(^2\) The Miner-Palmgren method is a linear summation that calculates the fraction of fatigue life taken each time the spectrum is applied and sums each fraction together. When the summation equals one, the fatigue life has been reached.
1.2.1: Limitations of the Current AP-3C Lifeing Methodology

The RAAF’s AP-3C Aircraft Structural Integrity Management Plan (ASIMP) details the specific fatigue management techniques necessary to ensure the continued structural airworthiness of the RAAF AP-3C aircraft [23]. It covers the P-3C Structural Management Plan (SMP) as well as detailing the SBI program. This includes the locations of critical fastener groups and the prescribed action to be conducted by the threshold of 13,500 Airframe Flight Hours (AFHRS) or once fatigue and/or corrosion are found.

These critical areas include the lower wing nacelle attachment points which are made up of rows of DNHs. DNHs are a particular type of fastener that involves a nut permanently riveted to the inside of the wing skin where a bolt threads into from the outside. It is these bolts that hold the engine nacelle on. A schematic is shown in Figure 2. Upper wing attachment points are less important as they see more compressive loads than the lower wing attachment points and do not currently have an inspection/modification requirement for the Life Of Type (LOT) of the aircraft [23]. The fatigue critical section for these fasteners is the actual wing skin, highlighted in grey in Figure 2. Should a fatigue crack grow here, the primary structure of the wing would be affected.

![Figure 2: Schematic of the AP-3C Dome Nut with the wing skin highlighted in grey [24]](image)

The ASIMP states that modifications should be made at these locations by 13,500 AFHRS. The modifications generally involve the installation of ForceTec fasteners following Bolt
Hole Eddy Current (BHEC) inspection. Installing the ForceTec fasteners involves reaming and cold expanding the main hole to limit fatigue crack growth due to the compressive zone imparted to the hole by cold expanding [23].

Certain conditions must be met prior to modifications of the DNHs [23]. These conditions include having round holes, significant edge margin to carry out the cold expansion and reaming, and that no intergranular corrosion is present within the bolt holes (determined by ultrasound techniques). If ultrasound inspection shows intergranular corrosion around the bolt holes, the fastener modification is not carried out. Currently, no fatigue life assessment model exists for when IGC is present in the DNHs, and, as such, any IGC found is completely removed by grinding out the holes and attaching large doublers.

1.2.2: The Form of IGC in the AP-3C Orion

The wing skin on the AP-3C Orion is made from the extruded aluminium alloy 7075-T651. The wing skins are actually a combined stringer-skin machined down from a thicker extrusion. Due to ITAR\(^3\) controls, it is not possible to discuss or illustrate the complete geometry of these wing skins; however the section containing DNHs ranges between 1.5 and 3 mm thick. This material, while being quite strong, is also highly susceptible to corrosion. Corrosion in the AP-3C wing skin usually initiates through moisture and salt ingress following paint coating failure.

In these thin extruded components, IGC fissures grow parallel to the extrusion (L) direction, which is typically parallel to the principal load axis [5, 24]. This form of IGC is typically semi-circular, as found in [24], with longer dimensions in the L direction rather than the T direction. Figure 3 shows the typical orientation of an IGC fissure near a hole and compares it with the usual orientation of a fatigue crack initiated from such a hole. This IGC orientation is not usually associated with the initiation and growth of fatigue cracks since components are not usually designed to carry large through-thickness (S-direction) loads. As such

---

\(^3\) International Traffic in Arms Regulations is a set of regulations that controls the import and export of Defence articles and services, which specifics of the geometry of the wing skins of the AP-3C Orion fall under. As such their disclosure is limited and cannot be discussed here.
conventional linear elastic fracture mechanics analyses give a Mode I crack driving force ($\Delta K$) of zero. However, there have been examples where IGC has progressed along a transverse grain boundary, then continued along another longitudinal grain boundary [24-26]. These small deflections in the IGC fissure may act as stress raisers that might lead to early fatigue initiation in the through-thickness direction, under the dominant longitudinal loads in the component. This potential for stress raisers along the IGC fissure means that representing IGC as a simple longitudinal crack could be unsafe and not representative of real life.

![Figure 3: Schematic illustration of the typical orientations of cracks due to fatigue and intergranular corrosion in the vicinity of a through-thickness hole in a plate. The loading axis of the plate is also shown. Note: Not drawn to scale.](image)

The intergranular corrosion formed from the bore of the main hole is long, sharp fissures up to and over 5 mm in depth. A typical example of this is shown in Figure 4, where two IGC fissures can be seen emanating from the bore of the hole. This type of corrosion normally
forms over the course of 20-30 years [24]. No IGC is present in the satellite holes due to the interference fit of the rivet not allowing any moisture in.

![Image of intergranular corrosion](image)

**Figure 4**: Typical example of intergranular corrosion taken from a serial sectioning of a DNH in the AP-3C Orion [25]

### 1.3: Objectives

There are four objectives for the work presented here. The first is to develop an accelerated method of producing intergranular corrosion that is representative of that found in the AP-3C Orion. IGC on the AP-3C takes many years to form, as discussed in Chapter 4, which is of no use to a PhD project. As such, a new method needs to be developed to produce IGC in a matter of weeks or months, rather than the years it takes to form naturally. This method needs to reproduce the shape of the IGC found on the Orion, including the way it deviates around apparently random grains.

The second outcome is to investigate the cause of early fatigue crack initiation through physical fatigue tests and computational modelling. This outcome will be to determine what feature of IGC around the DNHs is causing early fatigue crack initiation, whether it is the IGC fissure itself or another associated feature that is present.
The third outcome is to develop a relationship between the change in fatigue crack initiation time and some form of metric, where this metric is measurable using post-failure fractography.

The final outcome is to develop a tool that can be used by the world-wide fleet operators to predict the change in fatigue crack initiation time based on a field-measurable metric, with the aim that this metric will be the IGC depth (depth into the material from the bore of the hole, or length of the fissure) found using the ultrasound NDI technique. This tool will allow the fleet operators the ability to assess the IGC damage found and make a decision on whether it actually has to be removed or not, potentially saving maintenance time.

1.4: Outline

This thesis comprises of eight chapters that separate the work into three distinct steps to achieve the objectives discussed in Section 1.3:. Along with the three work chapters (detailed below), this thesis includes an Introduction and Literature Review at the beginning followed by a chapter on the Experimental Material and finishes with Conclusions and Recommendations. 

Chapter Three introduces the material used in this work; AP-3C wing skin material as well as newly purchased 2.023 mm thick 7075-T6 sheet and 6.35 mm thick 7075-T651 extruded bar.

Chapter Four details the steps taken to develop a protocol to produce IGC representative of that found on the AP-3C Orion. This formed the most time-consuming section as each corrosion test took upwards of two months. This work resulted in two protocols being developed, each that can produce IGC. One protocol was more reliable than the other at producing IGC and thus was used for the completion of the work.
Chapter Five details the fatigue test program that investigated the effect IGC has on fatigue initiation in the AP-3C wing skin material. This program uses specimens corroded with the more reliable protocol developed in Chapter Four.

Chapter Six details the development of a model that can predict the fatigue initiation effects of IGC. This chapter details the three distinct steps of creating the model. The first step is the development of a model to predict the path IGC takes through the AP-3C wing skin material. This model uses a Brick Wall style approach and incorporates the grain size distribution of the material as well as the IGC behaviour specific to the protocol described in Chapter Four.

The next step involves the creation of an automated program script that takes the IGC path predicted by the model and analyses it in the FE software package ABAQUS v6.10 [27]. This step showed that IGC by itself has little effect on the stress field around the bore of the hole, and thus should have little effect on crack initiation.

IGC rarely grows on its own – it is often accompanied by pits down the bore of the hole and corroded inclusions along the length of the IGC path. The third step is a modification to the script from the last step to incorporate a surface pit as the initiation of the IGC fissure and corroded inclusions, and the results of the FE analysis of these features. This step found that in most cases the surface pit will be the most important feature for crack initiation unless a corroded inclusion is located close enough to the bore of the hole. This distance, the Critical Inclusion Distance (CID), depends on the size of the surface pit.

Chapter Seven brings the results of the predictive model and the experimental fatigue test program together to produce a model that can predict a knock-down factor for a population of IGC paths, pits and corroded inclusions (with these populations based on experimental results). This knock-down factor can be applied to the time taken for crack initiation of an uncorroded DNH to determine the new time for a corroded DNH.
CHAPTER 2: LITERATURE REVIEW

Presented here is a review of the current literature available regarding the fatigue effects of intergranular corrosion. This review is separated into four main sections covering corrosion and fatigue (separately as this work treats the corrosion and fatigue stages as separate events, not as corrosion fatigue) of aluminium alloys, modelling of fatigue and currently-available models for predicting the fatigue effects of other types of localised corrosion. A summary at the end of the review will highlight the various gaps in the literature and discuss where this work will fit.

2.1: Corrosion of Aluminium Alloys

Corrosion in aluminium alloys is the result of a galvanic reaction between two surfaces that have different corrosion potentials [14, 28-30]. These two areas can be as simple as two completely different materials (for example, a steel rivet in aluminium aircraft wing skin) [2] or as complex (from a corrosion prevention point of view) as differing local microstructures in adjoining areas of the one material [29]. While differing materials can be insulated from each other by using various coatings [31], it is impossible to insulate two adjoining areas within a material, and so the resulting corrosion from these areas is more significant as it is harder to protect against.

This section of the Literature Review will cover aspects of corrosion in aluminium alloys, from causes and various forms to methods of corrosion prevention and reproducing different forms in a laboratory environment.

2.1.1: Overview of the Corrosion of Aluminium Alloys

There are several different forms of corrosion in aluminium alloys. These include general corrosion (typically seen on steels), crevice corrosion and localised forms of corrosion such as
pitting, exfoliation, stress corrosion cracking (SCC) and intergranular corrosion (IGC) [2]. General and crevice corrosion will not be discussed in detail here as they are not applicable to the issue studied in this work. Pitting, exfoliation, SCC and IGC will be discussed separately in more detail; however they all occur due to a similar mechanism of localised galvanic corrosion within the material.

2.1.1.1: Intergranular Corrosion

Intergranular Corrosion is a localised form of corrosion that occurs at or within the grain boundaries of a metal. It can involve a network of corrosion following the grain boundaries in a localised region or can develop into deep cracks in highly extruded or rolled sections [5], such as the wing skin of the AP-3C Orion.

It was generally accepted that the mechanism for intergranular corrosion is a three-phase system [29], comprising of a precipitate free zone (PFZ) along the grain boundaries (Phase 1) acting as the anode and the grain bodies (Phase 2) and precipitates (Phase 3) in the grain boundaries acting as cathodes. This results in a very small anode in contact with a large cathode. During heat treatment the alloying elements, Zn, Mg and Cu, precipitate at the grain boundaries, leaving a PFZ adjacent to the grain boundary. The corrosion potential of these grain boundary precipitates is negative with respect to that of the alloy; when immersed in 3.5% NaCl, the precipitates therefore act as an anodic zone and will be preferentially attacked [14]. According to the literature reviewed, it is believed that there is an order where the PFZs corrode preferentially, followed by the grain boundary precipitates [31, 34-35].

An example of IGC in the 7075-T651 extruded aluminium alloy of the AP-3C wing skin is shown below in Figure 5. This specimen was corroded using the protocol discussed in Section 4.5.1: with corrosion growing left-to-right from the bore of the hole.
2.1.1.2: Pitting Corrosion

Pitting is a form of corrosion involving localised dissolution of grains [11, 28], often caused by the breakdown of a passivating oxide layer that protects the metal surface [28]. Oxide layer breakdown is often caused by the presence of chloride ions [32] or, less frequently, by applied stresses or rapid temperature changes that cause microcracks to form [28].

Pitting is an electrochemical process that occurs preferentially at grain boundaries, precipitates and discontinuities [11, 33, 34] in the presence of an aggressive anion, normally chloride ions [28]. Many possible mechanisms for pitting have been investigated, including localised galvanic corrosion surrounding exposed constituent particles [33], precipitate-free zones (PFZs) [28, 35] and various effects of constituent [33] and intermetallic [28] particles. However these mechanisms all appear to relate to a galvanic reaction between the grain bodies and another section of the microstructure (be that constituent or intermetallic particles, or PFZs).

Pits in aluminium alloys tends to be complex in shape in comparison to the hemispherical-shaped pits of some steels [36]. An example of a complex pit in 7010-T7651 aluminium alloy is shown in Figure 6.

Figure 5: Example of IGC in 7075-T651 extruded aluminium alloy on the AP-3C Orion
Exfoliation corrosion has similarities to intergranular corrosion, however exfoliation results in grain lift-off, causing a loss in load-bearing cross section and an increase in stress [38]. Grain lift-off is due to the corrosion product (typically hydrated aluminium oxide [38]) having a greater specific volume (i.e. a lower density) than the surrounding matrix, causing a significant wedging stress between the grains [5-7, 38, 39].

The literature indicates that exfoliation occurs in materials with a highly directional microstructure [12, 13, 38, 39], and is often the result of extrusion or rolling. This microstructure facilitates a directional attack along the elongated grain boundaries (observed as propagation parallel to the surface [40, 41]). The microstructure promotes the trapping of the corrosion product in the grain boundary regions and, due to the higher specific volume of the corrosion product, results in the grain lift-off shown in Figure 7.

Figure 6: Cross section of pit in 7010-T7451 aluminium alloy [37]

2.1.1.3: Exfoliation Corrosion
2.1.1.4: Stress Corrosion Cracking

Stress corrosion cracking (SCC) is the growth of a crack under the combined influence of a static tensile stress and a reactive environment within a susceptible material [42]. SCC can occur in most metallic structures, however it mainly occurs in thick sections with highly directional grain structures such as extruded or rolled components subjected to short-transverse (ST) stresses [43]. The prevalence of SCC under these conditions is due to the combination of an available crack path and a high probability of residual ST stresses due to forging and fitting. This point is confirmed in Pow et al. [44], Shastry et al. [45] and Braun [46].

Sieradzki [42] believes the mechanism of SCC is a combination of anodic dissolution (similar to intergranular corrosion) and hydrogen embrittlement. It has been discussed by Pow [44], Shastry [45] and Braun [46] that the corrosive medium required for SCC often contains NaCl. Marita et al., [47] Braun [46] and Little et al. [35] believe that, similar to intergranular and exfoliation corrosion, SCC grows by preferentially attacking the grain boundaries. Grain
boundary precipitate size affects both preferential attack of the grain boundaries and hydrogen embrittlement.

Hydrogen embrittlement is referenced many times as a cause of SCC [29, 42, 43, 48, 49], and its effect can be influenced by grain boundary precipitate size. In hydrogen embrittlement, hydrogen ions in solution can do two things; firstly, they can prevent the material’s cathodic protection against the anodic dissolution part of the SCC mechanism [43]. Secondly, hydrogen in solution decreases the cohesive strength of the alloy, which promotes crack growth. Larger grain boundary precipitates contain a larger number of irreversible trapping sites; smaller precipitates contain a greater distribution of reversible trapping sites [48]. Irreversible sites trap hydrogen, reducing the amount of hydrogen in solution nearby these sites whereas reversible sites can release of their hydrogen back into solution. When a crack reaches a trapping site it will ‘see’ hydrogen in solution if it is a reversible site, resulting in a reduced cohesive strength. When a crack tip reaches an irreversible trapping site, there is no hydrogen in solution so cohesive strength is not reduced in that area, inhibiting crack growth [48].

2.1.2: Corrosion Prevention Methods

Heat treating 7075 aluminium alloy to the T6 temper results in a very high yield and tensile strength (T6 is the peak-strength temper for artificially-aged aluminium alloys, including 7075) [2]. The downside to using the T6 temper is its susceptibility to various forms of corrosion due to the continuous distribution of precipitates near the grain boundaries [14, 32, 50]. It is this continuous distribution of grain boundary precipitates that results in a lower resistance to IGC and other forms of corrosion [14]. The T6 temper also produces a high volume of fine precipitates within the grain, consistent with its high strength [14].

Due to this susceptibility to corrosion when peak aged, a number of methods have been investigated that can increase the corrosion resistance of 7075 aluminium alloys. These methods include physical barriers such as paint coatings [31], Corrosion Inhibiting Compounds (CICs) [51] and material temper modification.
Paint coatings are one of the most widespread approaches to corrosion prevention. They typically consist of a number of layers applied to the surface of the component, as shown in Figure 8, to make a very effective corrosion preventative measure [31]. These layers start with a surface chromate that is 0.1-0.2 μm thick adjacent to the metal surface that provides passivation of the metal surface, inhibits corrosion and provides an ideal surface for primer adhesion. The next layer is the approximately 25 μm thick epoxy primer that provides a surface for the topcoat layer to adhere to as well as containing corrosion inhibitors. The approximately 20 μm thick polyurethane topcoat provides the final appearance, protection against environmental and mechanical erosion and retards moisture ingress [31]. Paint coatings provide good protection against corrosion, however they do wear away over time and eventually corrosion will occur.

![Diagram of paint scheme from a typical aircraft coating, showing the various layers present [31]](image)

Corrosion inhibiting compounds (CICs) have been used quite successfully in the past to treat and manage corrosion [52]. Since 1993, there have been several cases in RAAF aircraft where CICs have slowed corrosion growth through either once-off or repeated applications [52]; examples of this include the Macchi MB326H fleet and intergranular corrosion in the C-130 Butt Line 20 longerons [52]. In another case, the main landing gear vertical beams of the C-130, the application and inspection of CICs resulted in no additional SCC growth in the component for six years after their initial application. [52].
Most CICs work on the principle of water displacement resulting in reduced corrosion development and propagation [51]. CICs are proprietary chemicals which may contain a film former, such as oil, grease or resin, a volatile, low surface-tension carrier solvent, a non-volatile hydrophobic additive or various corrosion inhibitors, e.g. sulphonates [51].

Material temper plays an important role in corrosion resistance. One method to increase the general corrosion resistance of an aircraft structure is to choose a material temper that results in the highest corrosion resistance. T73 [32], Retrogression and Re-Aging (RRA), T6I6 and High Temperature Pre-Precipitation (HTPP) [14] heat treatments result in discontinuous grain boundary precipitates compared with the continuous distribution of grain boundary precipitates in the T6 temper, resulting in a lower susceptibility to intergranular corrosion [14]. The T73 temper is the more widely used treatment as T6I6 and HTPP are relatively new material tempers [14] and RRA, which was developed in the 1970s [53], is in the process of being introduced as a pre-treatment for replacement parts on some aircraft [54]. Both RRA and T6I6 have shown good potential as they do not exhibit the large loss of ultimate and yield strength that T73 does (compared to T6) [14]. RRA has shown promise to prevent corrosion forming, but for the AP-3C it cannot be easily applied as it requires the removal of full wing planks.

2.1.3: Fatigue Crack Initiation from Corrosion

Fatigue cracks can initiate from pitting [11] and exfoliation [12, 13, 38] corrosion due to the stress concentrations they cause. Exfoliation can also cause a loss of load carrying area due to grain lift-off [38] reducing the cross-sectional area of a component.

Just as most discontinuities (such as constituent particles) can cause fatigue crack initiation through stress concentrations, pits can also be the origin for fatigue cracks depending on their location [11] due to a competition between these features, based on the stress concentration of each. Jones et al. [11] found that constituent particles within 7075-T6 compete with corrosion pits as crack nucleation sites. Any constituent particle of suitable size and shape and in the
correct location is capable of creating a stress concentrator and nucleating a fatigue crack. Jones et al. [10] also found that a number of cracks originated from pits deeper than originally measured, attributing this to sub-surface growth or ‘tunnelling’ (where a pit grows laterally under the surface) [10].

The investigation of exfoliation corrosion conducted by Sharp et al. [7] indicated that intergranular cracking formed at the base of a pit-like depression within the corroded section. This, combined with the local stress increase caused by the loss of material [38] is likely to be the cause of crack initiation from exfoliation corrosion. Modelling of potential failure from such a configuration could cause a fatigue crack to initiate at the top of an intergranular penetration.

2.1.4: Laboratory-based Reproduction of Intergranular Corrosion

Extensive work has been conducted to attempt to reproduce IGC in a lab-based environment [29, 30, 40, 48, 55, 56]. IGC takes many years to initiate and grow to a significant size [24] on the AP-3C. In the case of most specimen-test programs, the luxury of that much time is not available – the ability to produce representative corrosion within a matter of weeks is important.

Pitting and exfoliation corrosion can be produced in a laboratory within a matter of days or weeks, as discussed in a number of reports [3, 9, 11, 28, 30, 40]. These methods produce representative pit and exfoliation damage distributions as well as being simple, repeatable methods, meaning the amount of corrosion produced is relatively easy to control.

Intergranular corrosion does not share the same ease of reproduction as pitting and exfoliation. The typical reaction of most aluminium alloys in the presence of chloride ions is pitting corrosion, due to a low concentration of oxygen within the pit that forces a galvanic cell between the grain boundary and grain body [29] or a “permanent immersion” type situation where the solution is too aggressive to form sharp IGC [46], meaning producing long, sharp fissures of IGC could be difficult.
Studies in the past have produced IGC using two different methods – either chemical methods involving immersion in a solution, or electrochemical methods involving both immersion in a solution and applying a voltage to the specimen.

Knight et al. [55] were able to use chemical methods to induce up to 500 µm of IGC into the end grains of stubs of 2024-T3 and 7075-T6 aluminium alloys. The method involved placing a small (20 µL) droplet of 3.5% NaCl onto the end-grain and leaving it in a high humidity (97%) atmosphere for up to 7 days [55]. Braun [46] found that using a mixture of nitrates, sulphates and other anions causes a re-passivation of the material to prevent corrosion “blunting”, resulting in long, sharp IGC. Again, however, Braun was unable to produce IGC longer than 500 µm [46].

Marita et al [15] used a potentiodynamic scan to investigate the breakdown potentials of the T6 and other tempers of 7075 aluminium alloy. The breakdown potential indicates when corrosion is likely to occur and is discussed further in Section 4.3.3: Marita at al. found two distinct breakdown potentials in the T6 temper (compared to just one in the W, water quenched, temper), resulting from two distinct phases of corrosion growth. They were able to control the form of corrosion produced by holding the potential between the two breakdowns, producing only intergranular corrosion, whereas above the higher potential pitting corrosion occurred [15].

Previous methods of corrosion initiation were investigated [30, 40, 55-57], such as electrochemical pre-treatment followed by high-humidity storage. However the resulting depths were either not enough, as in the case of [30] where 100-400 µm deep corrosion was grown in 500 hours, or not quick enough, as in the case of [56] where over 500 µm of corrosion was grown in five months. Other methods include the droplet method employed by [55], which grew 700 µm in 168 hours, and the constant immersion methods used by various ASTM Standards [40, 57]. These methods are not sufficient as, at the time of developing a corrosion protocol, it was not known whether the IGC fissure length was of any importance.
As such, any IGC protocol developed should produce IGC up to lengths found in the AP-3C Orion.

2.2: Fatigue of Aluminium Alloys

This section will introduce the fatigue of aluminium alloys and various fatigue testing methods, particularly covering crack growth monitoring during fatigue testing. Fatigue modelling methods will also be discussed as well as their application to fatigue in the presence of corrosion.

2.2.1: Fatigue Testing Methods

Most structural damage occurs due to cyclic loads below yield. Material fatigue testing is one of the main methods for determining the safe-life of a component. It uses similar equipment to tensile strength testing, however instead of a sustained, constant strain rate, a repeated number of load cycles are applied to the specimen. The most basic form of load cycle is constant amplitude loading, as shown in Figure 9. As the name suggests, this loading type uses a series of constant amplitude load cycles that oscillate between a maximum ($\sigma_{\text{max}}$) and minimum ($\sigma_{\text{min}}$) stress.
Figure 9: Constant amplitude loading showing maximum stress ($\sigma_{\text{max}}$), minimum stress ($\sigma_{\text{min}}$), stress amplitude ($\sigma_A$), total stress range ($\Delta \sigma$) and mean stress ($\sigma_{\text{mean}}$) [2]

Constant amplitude loading can provide useful information on trends but it is difficult to apply those results to actual aircraft structures as they rarely undergo constant amplitude loading (the exception being the pressurised fuselage forward of the wing (as aerodynamic loads affect the fuselage between the wing and tailplane)).

The other form of loading is known as variable amplitude or spectrum loading. As the name suggests, it involves a load cycle with variable maximum and minimum stresses about an average (or mean stress), as shown in Figure 10. This loading is more complex than constant amplitude loading; however it can be more representative of the actual loads experienced by structural components. Spectrums are often developed from aircraft loads analysis [19, 20].
Figure 10: Variable amplitude or Spectrum loading showing maximum stress ($\sigma_{\text{max}}$), minimum stress ($\sigma_{\text{min}}$) and mean stress ($\sigma_{\text{mean}}$) [2]

2.2.2: Crack Growth Measurement

2.2.2.1: Marker Bands

As can be seen in Figure 10, there are a number of local peaks (i.e. maxima) in the spectrum – these peaks can create marks on the crack surface that can be correlated to the specific load cycles that occurred [58]. These marks are called a number of names, including beach marks (occasional marks due to occasional marks in the spectrum), striations (typically the result of constant amplitude marker bands), clamshell marks, tide marks or growth rings. An example of these marks on a fracture surface is shown in Figure 11 – a number of marks can be seen as rings emanating from the centre of the specimen.
Figure 11: Fatigue crack propagation marks on a fracture surface of a RAAF Macchi trainer aircraft wing spar [59]

It is possible to use beach marks to monitor crack growth from fatigue testing by purposefully altering the load spectrum to create visible repeated beach marks, in this case known as marker bands [60]. This allows the crack growth to be measured post-failure using optical microscopy; the marker bands can be related to their corresponding change in the load spectrum to determine the crack propagation at that point. For example, Figure 12 is an example of an aircraft spectrum load incorporating both flight and ground loads. Included in this spectrum is a 51 cycle marker block that will give a distinct set of beach marks on the crack surface that can be correlated to a particular point in the spectrum. Marker band analysis, a subset of quantitative fractography, is often used to monitor crack growth.
Once the test specimen has failed, it is examined using an SEM or an optical microscope to look for the various beach marks and marker bands, as shown in Figure 13. These surface marks can be related back to the number of cycles and then flight/spectrum hours. Using this, crack growth rates can be determined.

The conventional method for introducing marker bands into the spectrum is to use a number of cycles near the maximum stress, similar to the marker block from Figure 12. Another
option is to overload the spectrum for a short number of cycles, however this can retard crack growth for a crack length that is roughly proportional to the square of the overload [61]. A newer method for introducing marker bands is to alter the R ratio of blocks of constant amplitude cycles [62] which does not have as significant an effect on local crack growth rate as other methods can. Marker bands can be simple repeated changes in R ratio or can have set patterns, such as the NASA 4-6-10 bands [63] or the bar-coded marker bands proposed by McDonald [62].

2.2.2.2: Direct Current Potential Drop

The direct current potential drop (DCPD) method is often used to measure changes in crack length during fatigue testing [64]. It involves a known electrical current being passed through the specimen by two probes, one above and one below the plane of the crack. Another two probes, attached closer to the crack than the current injecting probes (again with one above and one below the plane of the crack), are used to measure the resulting voltage drop over the crack [64]. The potential drop method is nowadays one of the simplest crack growth measuring methods, as the specialist equipment required to carry out an inspection is available off-the-shelf [65].

The potential drop obtained during testing is not steady due to the constantly changing resistance as the crack propagates; the further the crack propagates, the less material there is for the current to pass through, increasing the resistance [66]. The change in resistance can be correlated to the crack length and time, leading to the crack growth rate. However, DCPD requires an identical reference specimen (as the potential drops across both specimens are compared to each other). Due to the random nature of this form of IGC, DCPD does not give as good a correlation in corroded specimens as it does uncorroded as the baseline area may be different between two corroded specimens [67].
2.3: Fatigue Life Modelling

A number of fatigue crack growth models exist that allow the fatigue life of a specimen or whole aircraft to be predicted. These begin with the “damage accumulation” approaches of the 1950s and 60s through to the complex computational modelling of today.

2.3.1: Damage Accumulation Approach

Early methods for analysing fatigue crack growth attempted to describe damage due to fatigue especially for random loading, as an accumulation of individual “damages” from each cycle. The Miner-Palmgren rule \[22, 68\] is one such approach. It utilises the following equation to determine when failure is likely to occur. The rule states that when there are \(k\) different stress levels in a spectrum, with each containing \(n_i\) cycles, and if \(N_i\) is the number of cycles to failure at said stress level, failure will occur when [69]:

\[
\sum_{i=1}^{k} \frac{n_i}{N_i} = 1
\]

Damage accumulation is also used in strain-based life ing, where the local strain near the crack tip is determined and fed into an equation, such as the Coffin-Manson equation [70]. Strain life ing is often used for crack initiation (crack initiation is often the number of cycles to a crack of a nominal size, such as 0.05” as used in the AP-3C [19] and 0.01” used for the PC-9 [71] life ing). This equation relates the cyclic strain range with the number of cycles to crack initiation. The equation takes the following form:

\[
\varepsilon_a = \frac{\sigma_f^t}{\varepsilon_f} (2N_f)^b + \varepsilon'_f (2N_f)^c
\]

Where \(\varepsilon_a\) is the strain amplitude, and \(\sigma_f, \varepsilon_f, b\) and \(c\) are experimentally-determined material constants and \(N_i\) is cycles to initiation. Even though it was developed in 1954, it is still in use today for life ing aircraft [72-74], including the RAAF P/C-9A trainer aircraft [71].
2.3.2: Predictive Approaches

The follow on from damage accumulation approaches was to attempt to predict the growth of a crack for a certain number load cycles. One such early model was the Paris Law [75], developed in 1961 in an attempt to describe the growth of an initial “crack like“ defect to failure as a single rational theory. Still in use in various forms today [76-78], the Paris Law continues to use the same basic equation that includes the notion of a “stress intensity factor”, $K$.

\[
\frac{da}{dN} = C(\Delta K)^m
\]  

(3)

Where $da/dN$ is the crack growth increment per cycle, $\Delta K$ is the stress intensity factor and $C$ and $m$ are material constants. The stress intensity factor is used to predict the stress state near the crack tip caused by the applied loading; as the crack tip radius is effectively zero, the stresses at the crack tip would be infinite. Stress intensity factors are often determined using difficult mathematics and a number of solutions are available for more common situations [79-83] as well as uncommon ones [84-86]. These solutions are generally only available for standard specimens with no local defects, such as corrosion. Work has been completed in the past to develop K-solutions for corrosion [87], however the computational power required for this is very large and can still take hours to compute even using powerful desktop computers.

2.3.3: Computational Modelling

Computational models are extensions of the numerical approaches discussed previously that require computing power to solve as they often contain complex geometries where accurate formulations of stress intensity factors are near-impossible to solve.
A large number of crack growth analyses use either FASTRAN [6, 7, 18] or AFGROW [9, 12, 13], both of which are commercially available and often used at DSTO. Also, a number of Original Equipment Manufacturers (OEMs) produce their own in-house software packages during the design stage of their aircraft. An example is CI89, developed by McDonnell Douglas for the F/A-18 [88]. A number of other fatigue crack growth models are available, such as METLIFE and ADAMSys, however they will not be discussed in this section. Hu et al. gives a detailed discussion on various fatigue crack growth models utilised by DSTO [88].

Each fatigue crack growth model usually utilises a different fracture mechanics approach to determine crack growth. For example, FASTRAN uses a plasticity-induced crack closure model and AFGROW also uses linear elastic fracture mechanics, whereas METLIFE uses a variation of the Paris Law [88].

AFGROW and FASTRAN do have some similarities. They both use an iterative growth approach where the crack growth increment is calculated for each small change in time (loading cycles). Also, they both calculate ΔK_{eff} from their respective crack-closure methods; using this ΔK_{eff} value and crack growth material data, the crack growth increment is calculated [89].

### 2.3.3.1: AFGROW

Air Force GROW (AFGROW) is crack growth modelling software originally developed by the United States Air Force (USAF) Air Force Research Laboratory (AFRL) [90]. As a crack growth model it does not directly model fatigue life caused by corrosion defects; typically, AFGROW is combined with another model such as the Equivalent Initial Flaw Size (EIFS) model. The EIFS value is input into AFGROW and other parameters, such as loading conditions and specimen metrics (thickness, material properties etc.), as well as corrosion metrics, sometimes referred to as pit metrics, are adjusted until the model fatigue life correlates well with test specimens. By selecting these specimen metrics carefully, the model should be transferable to other specimens, providing the metrics are easy to measure (such as
pit depth, however as this is difficult to measure in aluminium alloys it can be problematic to transfer the model between specimens).

AFGROW uses stress intensity factor solutions derived from linear elastic fracture mechanics [91]. The stress intensity factors are calculated from particular crack geometry, dimensions and stress condition of the specimen. For a given stress cycle, the crack growth rate defines the increment in crack growth; this rate is calculated from crack growth rate (da/dN) versus cyclic stress intensity factor range (ΔK) data for the particular material. The increment in crack growth value is added to the crack size until the crack reaches a critical size. This critical crack size can be user-defined, but is typically when the stress intensity factor equals the fracture toughness of the material.

2.3.3.2: FASTRAN

FASTRAN is a crack growth model created by James C Newman Jr [21] and is based on the plasticity induced crack closure concept and the Dugdale strip yield model [21]. This form of crack closure is due to a zone of residual tensile deformation in the wake of a moving crack tip, causing a compressive stress to be present at the crack tip at zero load [92]. This effectively decreases the amount of crack opening that occurs at maximum loading. During unloading, the crack will close before the load reaches zero. As a crack cannot propagate while it is closed [92], knowledge of the crack opening load (where the applied stress is greater than the residual compressive stress) is required for an accurate prediction of crack growth. The plastic zone caused by the moving crack tip decreases the crack growth rate [92].

FASTRAN is used in the AP-3C lifeing methodology as the crack growth modelling tool. It was used to predict the fatigue life of the component once a crack had reached 0.05 inch, where the crack growth phase begins [18].
2.3.3.3: Finite Element Crack Growth

Some finite element codes include the ability to determine crack growth through analysing the K-solution. These codes utilise a p-type element, rather than the traditional h-type element [93] that allows for higher-order elements to be analysed. The two main codes for this are ABAQUS, through the eXtended Finite Element Method (XFEM), and StressCheck, which uses similar FE elements as ABAQUS. XFEM has been used more for composite structure analysis [94, 95], however it can still be used for aluminium fatigue [96, 97]. StressCheck has been used to good effect in determining K-solutions for particular problems [93], which in turn allows for the determination of beta (geometry) factors. The general equation for relating K-solution to the beta factor is shown below.

\[ K = \beta \sigma \sqrt{\pi a} \]  

(4)

These beta factors can then be put into AFGROW or FASTRAN as those codes handle crack growth better. As with all FE analyses, both these methods have their inaccuracies. As Wright discussed [93], it is often better to obtain beta factors from FE analyses (as complex geometries can be analysed) that are then fed into dedicated crack growth codes.

2.4: Modelling the Effects of Corrosion

This section reviews models for the impact of corrosion on structural life, and covers analysis of the effect of a specific type of corrosion either initially (in the crack initiation phase) or for the whole life of the component (crack initiation and crack growth phases).

Fatigue cracking, in a damage tolerance approach, is usually modelled as growth under cyclic loading from a sharp crack [98]. The difficulty with having corrosion as an initiator is that corrosion damage is not easily represented as a sharp crack-like defect, and these models have value as tools that can describe the early stages of fatigue crack growth from initial their damage. Later, the crack grows to a point that is quite well understood in terms of fracture
and fatigue mechanics [99] and conventional fatigue programs (such as FASTRAN or AFGROW) can be used. Often by the time the crack reaches the stable growth phase, the effect of corrosion is significantly reduced meaning it behaves much more like a ‘normal’ fatigue crack.

Three models are reviewed here, separated into two sections. The Equivalent Crack Size (ECS) model is a numerical model, where the effects of pitting corrosion are determined using a number of fatigue tests. The Process Zone and Soft Inclusion model use finite element analysis programs combined with fatigue analysis programs, where the geometry of exfoliation corrosion is placed in a model and analysed.

2.4.1: Numerical Methods

The US Air Force Research Laboratory (AFRL) developed the Equivalent Initial Flaw Size (EIFS) model as a durability analysis tool for metallic aircraft structures [100]. The EIFS is the initial size of a hypothetical crack which would have the same fatigue life in a pristine specimens/structure as the real life specimen or structure [64]; it accounts for the initial fatigue quality variations (due to manufacturing defects etc.) so that the extent of damage to a component can be quantitatively estimated at any time in its life under service conditions [100].

The EIFS is determined by fatigue testing specimens until failure, then using back-extrapolation of the fractographic results (using beach marks on the fracture surface) to determine the crack length as a function of the number of load cycles applied (from which crack length as a function of time can be found); by extrapolating back to time = 0, the EIFS can be found [100]. It should be noted that the EIFS is not a physical quantity – it is a value extrapolated from experimental data (as shown in Figure 14) so that only long crack growth modelling is used, avoiding short crack growth modelling [99].
The EIFS model was used as a fatigue life prediction model of components containing pitting corrosion. This approach was developed in 2000 to 2005 at DSTO in Australia as part of the Structural Integrity assessment of Corrosion in Aircraft Structures (SICAS) research program [4]. As this research program was investigating the sharp crack equivalent to the pitting damage, this model was called as the Equivalent Crack Size (ECS) model. It uses the underlying assumption is that damage (in this case, a pit of a certain size) will act like a sharp crack of a different (but related) size assuming the same applied loading conditions.

This model involves the adjustment of the defect size in the input stage of AFGROW until an acceptable result in terms of “life to critical” has been achieved, or the growth converges on a common crack size and service life. This is usually an iterative process (as shown in Figure 15) that involves running the simulation a number of times and comparing the predicted results with the tests results to determine, and then minimise, any error [4].

![Figure 14: EIFS methodology [90]](image.png)
At the completion of one set of results, the defect size is related back to a series of “pit metrics”, such as those in Figure 16, which can be measured in the field. The aim is to allow the fatigue life of a component to be calculated based on these pit metrics [4].

*Figure 15: Diagram of the ECS iteration process [4]*
It was found that the ECS model could predict a fatigue life similar to the actual life of the component, however better relationships were found with smooth pits, such as those found in D6AC steel compared with pits found in aluminium. The principal barrier to widespread application is that structurally significant pits are small in relation to the limits of practical NDI methods, however it was stated that there are a number of technologies being developed, such as X-Ray tomography that could lead to further development of the ECS model [4].

**2.4.2: Finite Element Methods**

**2.4.2.1: Process Zone Model**

The Process Zone model is a tool for modelling exfoliation that was developed by DSTO in Australia. It is based on the ECS modelling approach that creates an equivalent crack size that has the same fatigue life as the corroded specimen [7].
Based on the observation that the base of exfoliation corrosion has ‘pit-like intrusions from which intergranular cracks grow’ [6, 7] as in the exfoliation damage was represented as the combination of a pit plus a crack, called the process zone that progresses through the material. This is illustrated in Figure 17.

Figure 17: Geometrical representation Version 4 [7]

Figure 18 shows the progression of the process zone with respect to the number of hours the specimen is exposed for. It shows that initially, the process zone grows in size from just a crack to a pit plus crack. Once the corrosion reaches a certain size, the material surrounding it begins to corrode through exfoliation (as shown by the “material loss by exfoliation” section in Figure 17).
Figure 18: Change in process zone with respect to corrosion time. The solid line represents the data found during testing. [7]

The length of the crack was adjusted from 10 μm to 30 μm (based on physical observation) to determine the ideal crack size for the model. It was found that the results were insensitive to the three different crack sizes, giving an indication that IGC length may not have a large effect on fatigue. A reasonable correlation between the Process Zone model and experimental testing was found [7].

Liao further investigated the process zone in a study of 4 mm thick dog-bone specimens of 7075-T6511 [13]. Three cracking mechanisms were found following a fully reversed, constant amplitude fatigue test of the specimens. Cracks were found from pits on the bottom of the exfoliated surface, from the top of intergranular corrosion and from particles or grains denuded by intergranular corrosion/exfoliation. Instead of using FASTRAN as Sharp et al. did [7], AFGROW was used with a semi-elliptical crack of 120 μm depth to represent the process zone instead of a 100 μm starter notch with a 20 μm crack. The AFGROW model produced good life estimations for the artificially induced pits used in [7]. When using the Process Zone model for naturally-produced exfoliation, the results were not as good. This was because a conservative crack of 100 μm was used, even though the fatigue initiation depth was between 25 and 100 μm in depth, leading to a conservative life prediction [13].
2.4.2.2: Soft Inclusion Model

The soft inclusion model was first proposed in 2003 by Liao et al. [12] during an investigation into the effects of exfoliation corrosion on a wing stringer/skin combination. The idea behind this model is that the exfoliated volume still has some load carrying capability after corrosion has taken place. This is modelled as elements with an adjustable elastic model within the element to replicate for the reduced stiffness in the corroded volume. The model makes three main assumptions [12]:

1. The exfoliated area still had some load carrying capability,
2. The soft inclusion is an isotropic material of uniform depth and
3. There is a “perfect fit” for fasteners; that is no interference or loose fit was modelled.

The entire specimen was modelled but certain elements were selected for the “soft inclusion” that matched the shape of the corroded volume of the specimen, as shown in Figure 19.

![Figure 19: Example of soft inclusion used in [12] showing an example of an exfoliated component (top left) that is modelled using a finite element program (right), with the “soft inclusion” of elements with reduced stiffness highlighted. The model, bottom left, is then analysed using the FE program.](image)
This model showed good potential in determining where cracking was likely to occur. Shown in Figure 20 is a three-part figure showing one corroded specimen. The first image shows the actual failed specimen with arrows indicating the points of crack nucleation. This matched the points of maximum stress in the FE model, shown in the second and third images.

![Image of cracked specimen and FE analysis](image)

*Figure 20: Crack nucleation sites and FE analysis of tension-loaded test specimen [12]*

The soft inclusion model can either be ‘free’ like above, where any element in the FE mesh can be chosen as ‘corroded’, or the model can be slightly constrained, like the model presented by Uebersax *et al.* [15]. Uebersax *et al.* used the Soft Inclusion model investigated by Liao *et al.* [12] in 2009 for their analysis of a 7075-T651 upper wing skin from a retired F-5E [9]. The soft inclusion was modelled using an “off-centre, rotated and truncated ellipsoid” enclosing the fastener hole, as shown in Figure 21. The ellipsoid was split up into eight quadrants to enable non-uniform corrosion damage, as shown in Figure 22. Model testing showed that a reduction of 70% of the corroded material’s elastic modulus showed good correlation between the predicted fatigue lives and the experimental lives.
Figure 21: Soft inclusion ellipsoid around fastener hole [9]

Figure 22: Eight-quadrant version of the Soft Inclusion model [9] showing two examples of corroded fastener holes with their respective “soft inclusion” models, with the area of reduced stiffness shown in darker grey.
The soft inclusion model used the new stress field to create a new set of normalized stress values for AFGROW, from which a conventional fatigue analysis was conducted. The results showed that this model provides a good estimate of the fatigue life reduction due to exfoliation and grind-out. The life estimates for the grind-out model (where all quadrants were given an elastic modulus of zero), stress concentration and analytical crack growth life correlated well with the maximum thickness loss of the grind-out. Analytical lives were within 30% either side of tested lives [9].

2.5: Summary

This literature review has shown a clear gap in the knowledge base regarding the mechanical effects of intergranular corrosion. A number of areas have been covered previously, such as heat treatment effects, grain boundary and chloride influences and other microstructural effects that influence intergranular corrosion susceptibility.

Other forms of localised corrosion have been covered in great detail. The characteristics of exfoliation, SCC and pitting are well known and crack initiation and growth from these forms of corrosion has been studied. Models have been developed that can allow prediction of the fatigue life of components that contain pitting and exfoliation corrosion (Soft Inclusion, Process Zone and ECS models) that show some potential for being used as a possible IGC model. A model has also been developed that can predict the IGC path through a material, but this model has not yet been taken to the next step of a fatigue-based prediction [brick wall model].

One gap was identified when reviewing the current lifeing procedures for the AP-3C Orion. The ASIMP was developed, and that specified the procedures for replacing the dome nuts on the lower wing skins at the nacelle attachment points due to fatigue cracking. However this repair can only take place under certain conditions. One of those conditions is that no
intergranular corrosion is present within the DNH. The ASIMP also says that no intergranular corrosion is to be present within the under-wing DNHs following deeper maintenance.

In the course of reviewing the literature, no fatigue prediction model for intergranular corrosion exists that could fill the gap identified in the lifeing methodology and there is little understanding of crack initiation or growth from it, meaning the fatigue life of a component containing intergranular corrosion cannot be easily determined (as discussed in [5] and [8]). This gap leads to the focus of this project; the aim of this project is to investigate the effect of intergranular corrosion on fatigue crack initiation in aircraft structures and the literature review has described the capability gap that this research intends to fill by specifically focussing on the issue of intergranular corrosion on the AP-3C Orion.

It is expected that this work and model could lead to the possibility of some IGC being left in place in the wing of the AP-3C Orion. It is hypothesised that the IGC fissure itself does result in any change to the fatigue behaviour of the wing skin, it is more a result of the IGC-related features present alongside it that cause a change in fatigue. If this hypothesis holds true, only those IGC-related features (such as pits) need to be removed (rather than the whole IGC fissure), significantly saving maintenance time and cost.
CHAPTER 3: EXPERIMENTAL MATERIAL

Three different variations of peak-aged 7075 aluminium alloy were used in this study; actual AP-3C Orion wing skin material as well as 7075-T6 sheet and 7075-T651 extruded bar that were specifically purchased for this project. Ideally, as this work is investigating the effect of IGC on the AP-3C, the actual material used in the wing skins would be used during testing. However, there was only a limited supply of AP-3C wing that could be machined into test specimens.

Because of this, other options were investigated to replicate the corrosion and fatigue behaviour of the AP-3C wing skin material. These options were 7075-T6 sheet material in the same thickness as the wing skin material (2.032 mm/0.080 inch), and the thinnest 7075-T651 extruded bar that could be found (12.7 mm/0.50 inch).

Prior to any fatigue testing or corrosion protocol development, the composition of each material was determined using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICPAES) at Spectrometer Services Australia, with confirmation using Energy Dispersive X-ray (EDX) composition analysis on a JEOL JSM-6490LA scanning electron microscope (SEM).

The microstructure of each material was also analysed prior to testing to determine its grain and inclusion size distributions. This analysis was performed by cold mounting specimens in clear resin followed by grinding and polishing to a sub-micron mirror finish using standard metallographic procedures [101]. Cold mounting was chosen instead of hot mounting as the latter involves heating the specimen up to 180°C which could have affected the resulting measurements by changing the temper of the material and possibly causing recrystallisation of the grains.

Following polishing, the specimens were imaged using a Leica VMM200 optical microscope. Micrographs of the polished surface (such as Figure 23) were studied for inclusion size and
shape. As the inclusions appeared very dark in contrast to the polished surface, it was possible to use Image J’s Threshold Measure function to isolate the inclusions from the bulk material via contrast control (shown in Figure 24) and automatically measure the bounding rectangle of each inclusion. The results of Image J’s automatic measuring of inclusions were put together into L, LT and ST lengths for over 20,000 inclusions per material.

Figure 23: Micrograph of polished surface showing difference in contrast between inclusions and bulk material
Following inclusion size measurement, the specimens were etched by immersion in Keller’s Reagent to reveal the grain structure. Mounted specimens were immersed in the reagent for 20-30 seconds, depending on the material. Each specimen was initially immersed for 20 seconds, with some requiring extra etching time following optical inspection.

The etched specimens were re-imaged and their grain sizes measuring using the Linear Intercept method [102] with over 100 measurements taken per specimen at approximately half thickness over multiple images (approximately ten measurements per image). As each
measurement covered at least ten grains each (in some cases up to thirty), at least 1,000 grains were measured per material.

**3.1: AP-3C Wing Skin Material**

The main material used in this study was taken directly from an ex-service Royal New Zealand Air Force (RNZAF) AP-3C wing. The material was extruded into approximately 12.5 mm (½ inches) thick stringer-skin shape then machined down from both sides to the final size, which would be roughly located at the T/2 plane. The thickness of the skin section varied from approximately 3 mm near the wing root to approximately 1.5 mm near the wing tip. As the whole wing plank is machined down from the same extrusion, there is no change to the grain structure from wing root to tip. Due to ITAR restrictions, the full geometry of the AP-3C wing skin cannot be described or shown here.

**3.1.1: AP-3C Wing Skin Composition**

The composition of the AP-3C wing skin material, determined through ICPAES and verified with EDX, is given below in Table 1. As can be seen, the material conforms to the nominal composition given in Metallic Materials Properties Development and Standardization [103] except for the amount of zinc present, which may have an effect on the corrosion produced.

<table>
<thead>
<tr>
<th>Material</th>
<th>Si (wt%)</th>
<th>Fe (wt%)</th>
<th>Cu (wt%)</th>
<th>Mn (wt%)</th>
<th>Mg (wt%)</th>
<th>Cr (wt%)</th>
<th>Zn (wt%)</th>
<th>Ti (wt%)</th>
<th>Others (wt%)</th>
<th>Al (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.17</td>
<td>0.41</td>
<td>1.94</td>
<td>0.09</td>
<td>2.57</td>
<td>0.25</td>
<td>6.41</td>
<td>0.04</td>
<td>0.13</td>
<td>Bal.</td>
</tr>
<tr>
<td>Nominal</td>
<td>&lt;0.4</td>
<td>&lt;0.5</td>
<td>1.2-2.0</td>
<td>&lt;0.3</td>
<td>2.1-2.9</td>
<td>0.18-0.28</td>
<td>5.1-6.1</td>
<td>&lt;0.2</td>
<td>&lt;0.15</td>
<td></td>
</tr>
</tbody>
</table>

**3.1.2: AP-3C Wing Skin Microstructure**
A three-face image of the grain structure of the AP-3C wing skin material is given below in Figure 25. Table 2 shows the average and standard deviation of the grain sizes in each direction.

![Three-face image of grain structure of AP-3C wing skin material](image)

**Figure 25: Three-face image of grain structure of AP-3C wing skin material**

**Table 2: Grain sizes of AP-3C wing skin material**

<table>
<thead>
<tr>
<th>Direction</th>
<th>Average (μm)</th>
<th>Standard Deviation (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td>104</td>
<td>36</td>
</tr>
<tr>
<td>Long-Transverse</td>
<td>76</td>
<td>25</td>
</tr>
<tr>
<td>Short-Transverse</td>
<td>8</td>
<td>1</td>
</tr>
</tbody>
</table>

An example of the inclusions present on the polished surface of the AP-3C wing skin material is shown below in Figure 26. The inclusions were measured and their sizes in each direction are given in Table 3 with cumulative distributions of these measurements shown in Figure 27.
Figure 26: Example of inclusions present on polished surface of AP-3C wing skin material

Table 3: Inclusion sizes for AP-3C wing skin material

<table>
<thead>
<tr>
<th>Direction</th>
<th>Average (μm)</th>
<th>Standard Deviation (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td>4.67</td>
<td>7.18</td>
</tr>
<tr>
<td>Long-Transverse</td>
<td>4.91</td>
<td>8.82</td>
</tr>
<tr>
<td>Short-Transverse</td>
<td>4.26</td>
<td>6.25</td>
</tr>
</tbody>
</table>
Due to the limited availability of AP-3C wing skin material, other material options were investigated. The first of these was newly purchased 7075-T6 rolled sheet in the same thickness as the skin section of 2.032mm (0.08 inches). This material was purchased from Airport Metals in Tullamarine, Victoria in 3.66 m (12 ft) by 1.22 m (4 ft) sheets. Prior to purchase, it was known that the fatigue behaviour of the 7075-T6 and the AP-3C wing material were similar enough for their results to be used interchangeably at DSTO [104, 105]

### 3.2.1: 7075-T6 Rolled Sheet Composition

The composition of the 7075-T6 rolled sheet material, determined through ICPAES and verified with EDX, is given below in Table 4. As can be seen, the material conforms to the nominal composition given in Military Handbook 5J [103] except for the Magnesium content which is very slightly under spec.
Table 4: Composition of 7075-T6 rolled sheet material

<table>
<thead>
<tr>
<th>Material</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Zn</th>
<th>Ti</th>
<th>Others</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.16</td>
<td>0.48</td>
<td>1.58</td>
<td>0.12</td>
<td>2.09</td>
<td>0.27</td>
<td>5.21</td>
<td>0.19</td>
<td>0.09</td>
<td>Bal.</td>
</tr>
<tr>
<td>Nominal</td>
<td>&lt;0.4</td>
<td>&lt;0.5</td>
<td>1.2-2.0</td>
<td>&lt;0.3</td>
<td>2.1-2.9</td>
<td>0.18-0.28</td>
<td>5.1-6.1</td>
<td>&lt;0.2</td>
<td>&lt;0.15</td>
<td></td>
</tr>
</tbody>
</table>

3.2.2: 7075-T6 Rolled Sheet Microstructure

A three-face image of the grain structure of the 7075-T6 rolled sheet material is given below in Figure 28. Table 5 shows the average and standard deviation of the grain sizes in each direction.

Figure 28: Three-face image of grain structure of 7075-T6 rolled sheet material
An example of the inclusions present on the polished surface of the 7075-T6 rolled sheet material is shown in Figure 29. The inclusions were measured and their sizes in each direction are given in Table 6 with cumulative distributions of these measurements shown in Figure 30.

Table 5:  Grain sizes of 7075-T6 rolled sheet material

<table>
<thead>
<tr>
<th>Direction</th>
<th>Average (μm)</th>
<th>Standard Deviation (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td>116</td>
<td>29</td>
</tr>
<tr>
<td>Long-Transverse</td>
<td>103</td>
<td>23</td>
</tr>
<tr>
<td>Short-Transverse</td>
<td>38</td>
<td>13</td>
</tr>
</tbody>
</table>

Figure 29: Example of inclusions present on polished surface of 7075-T6 rolled sheet material
Table 6: Inclusion sizes for 7075-T6 rolled sheet material

<table>
<thead>
<tr>
<th>Direction</th>
<th>Average (μm)</th>
<th>Standard Deviation (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td>6.09</td>
<td>7.94</td>
</tr>
<tr>
<td>Long-Transverse</td>
<td>6.12</td>
<td>8.57</td>
</tr>
<tr>
<td>Short-Transverse</td>
<td>4.41</td>
<td>6.28</td>
</tr>
</tbody>
</table>

Figure 30: Inclusion size distribution for 7075-T6 rolled sheet material

3.3: 7075-T651 Extruded Bar

Due to not knowing whether the 7075-T6 sheet material would corrode in a representative manner (similarly to how the AP-3C wing skin material would corrode), 7075-T651 extruded bar was purchased from the USA via ThyssenKrupp Aerospace Australia Pty Ltd. This extruded bar was 1.61 m (64 inches) long and 0.101 m (4 inches) wide. The bar was 12.7 mm (1/2 inch) thick.)
3.3.1: 7075-T651 Extruded Bar Composition

The composition of the 7075-T651 extruded bar material, determined through ICPAES and verified with EDX, is given in Table 7. As can be seen, the material conforms to the nominal composition given in Military Handbook 5J [103] except for the Zinc content which is slightly over spec.

Table 7: Composition of 7075-T651 extruded bar material

<table>
<thead>
<tr>
<th>Material</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Zn</th>
<th>Ti</th>
<th>Others</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>0.22</td>
<td>0.16</td>
<td>1.52</td>
<td>0.21</td>
<td>2.59</td>
<td>0.23</td>
<td>6.17</td>
<td>0.06</td>
<td>0.11</td>
<td>Bal.</td>
</tr>
<tr>
<td>Nominal</td>
<td>&lt;0.4</td>
<td>&lt;0.5</td>
<td>1.2-2.0</td>
<td>&lt;0.3</td>
<td>2.1-2.9</td>
<td>0.18-0.28</td>
<td>5.1-6.1</td>
<td>&lt;0.2</td>
<td>&lt;0.15</td>
<td></td>
</tr>
</tbody>
</table>

3.3.2: 7075-T651 Extruded Bar Microstructure

A three-face image of the grain structure of the 7075-T651 extruded bar material is given below in Figure 31. Table 8 shows the average and standard deviation of the grain sizes in each direction.
Figure 31: Three-face image of grain structure of 7075-T651 extruded bar material

Table 8: Grain sizes of 7075-T651 extruded bar material

<table>
<thead>
<tr>
<th>Direction</th>
<th>Average (μm)</th>
<th>Standard Deviation (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td>296</td>
<td>58</td>
</tr>
<tr>
<td>Long-Transverse</td>
<td>169</td>
<td>42</td>
</tr>
<tr>
<td>Short-Transverse</td>
<td>47</td>
<td>11</td>
</tr>
</tbody>
</table>

An interesting feature of the extruded bar is the change in microstructure through its thickness. The change is not extensive, however it is present. Figure 32 shows a graph of the grain thickness through the extrusion thickness.
Figure 32: Graph of grain sizes in the ST direction (thickness) versus position through extrusion thickness

An example of the inclusions present on the polished surface of the 7075-T651 extruded bar material is shown in Figure 33. The inclusions were measured and their sizes in each direction are given in Table 9 with cumulative distributions of these measurements shown in Figure 34.
Figure 33: Example of inclusions present on polished surface of 7075-T651 extruded bar material

Table 9: Inclusion sizes for 7075-T651 extruded bar material

<table>
<thead>
<tr>
<th>Direction</th>
<th>Average (μm)</th>
<th>Standard Deviation (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td>4.62</td>
<td>6.33</td>
</tr>
<tr>
<td>Long-Transverse</td>
<td>4.01</td>
<td>4.79</td>
</tr>
<tr>
<td>Short-Transverse</td>
<td>3.83</td>
<td>4.13</td>
</tr>
</tbody>
</table>
3.4: Discussion on the Material Differences

The comparison between 7075-T6 sheet and AP-3C wing skin reported here found a significant difference in the grain structures of each. It was found that, while both the sheet and wing skin had pancake-shaped grains (i.e. grains that are much thinner than their length and width), the AP-3C wing skin material appeared to have grains that had non-recrystallised during the extrusion process, whereas the sheet material had larger, recrystallised grains. The non-recrystallised nature of the wing skin material gives it an appearance of long, straight grain boundaries, as shown in Figure 35. This is compared to the more rounded appearance of the LT-ST grain structure of the sheet material shown in Figure 28. This also results in an appearance of inclusions being more clustered or more in line with each other, however it is believed this is just an artefact of highly directional grain structure.

Figure 34: Inclusion size distribution for 7075-T651 extruded bar material
This difference between the wing skin material and the extruded bar is similar, with the extruded bar containing rounder grains than the wing skin, comparing Figure 35 to Figure 31. These differences indicate that there may be a potential difference in the corrosion behaviour of these three materials. It is possible that the appearance of long, straight grain boundaries are contributing to the form of IGC found in the AP-3C, as discussed in Section 1.2.2: . This is in contrast to the rounder grain structure of both the sheet and extruded bar material, which may promote a more “networked” form of IGC. The increased amount of Zn present in the wing skin material may also effect the corrosion produced, and may result in IGC being easier to form in that material than the others.
3.5: Significance of the Differences in Materials Used

The potential differences between the three materials chosen means that further testing is required to determine the physical differences between how each material behaves. If it is found that one of the purchased materials corrodes and fatigues in the same manner as the AP-3C wing skin material, it will be used for testing to save both time and money (in waiting for material to become available then machining down the complex stringer/skin shape). But if the different materials do not exhibit the same corrosion behaviour, only AP-3C wing skin material can be used.
CHAPTER 4: DEVELOPMENT OF A PROTOCOL FOR REPLICATING REAL-LIFE IGC IN THE LABORATORY

4.1: Introduction

It is difficult, if not impossible to obtain real-life corroded RAAF AP-3C Orion parts that can be used as specimens for fatigue testing due to the fact that it is an operational aircraft. The RAAF’s most important requirement is the operational availability of every aircraft. As such, any IGC found is removed upon detection in accordance with the ASIMP [23], which involves oversizing the holes. To obtain corroded DNHs for testing, entire wing planks need to be removed and replaced, which is a significant effort.

Therefore, to do any physical testing, it was necessary to recreate the corrosion found on the aircraft in a laboratory environment. There were three requirements for this:

- The protocol needs to reproduce the IGC found in the AP-3C and limit the amount of other corrosion produced. It needs to replicate the depths found and the way it turns around some grains and not others.

- The process of inducing corrosion needs to be repeatable in that anyone can use the process to produce the same corrosion each time it is used (within the bounds of reality due to the random nature of corrosion formation)

- The process needs to be fast. Real-life IGC generally takes years to form [24], whereas this process needs to produce the same results (as in type of corrosion and extent) in a matter of weeks or months.

This chapter will detail the steps taken to develop two protocols for inducing IGC around representative DNHs, one based on the use of Hydrogen Peroxide and the other using a
mixture of Nitrates and Sulphates. Prior to detailing the steps, the unusual form of IGC found in the AP-3C Orion is discussed followed by an introduction to a number of standard methods used for inducing and examining the corrosion produced.

4.1.1: Form of IGC in the AP-3C Orion

The IGC found in the AP-3C Orion DNHs forms long, straight fissures parallel to the surface of the material, as shown in Figure 5, and is similar in appearance to stress corrosion cracking. However, it is unlikely to be SCC as this form of IGC can be replicated without the application of external stresses; as this is the wing skin, there is little application of a through-thickness load which is required for SCC to form (as discussed in Section 2.1.1.4: ). While the stress intensity for through-thickness loading was not analysed, it was not required as this form of corrosion was able to be reproduced without an externally applied load.

This form of IGC is unique to the highly-extruded wing skin material of the AP-3C; most other examples of IGC form a network of fissures, as examined in [30, 55, 106-108]. It grows due to the formation of a corrosion pit down the bore of the hole following moisture ingress. The local environment causes an IGC fissure to form at the end of this pit, which then grows parallel to the surface [24]. This process of IGC forming was found in the DSTO AP-3C Orion DNH Teardown Report [24]. The work presented here found that in some instances, the IGC path will grow and meet an inclusion along a grain boundary. Due to the local electrochemistry, this inclusion is preferentially corroded (compared with the grain boundary) before the IGC fissure continues to grow, leaving a void in the material.

Any corrosion protocol developed must reproduce this form of IGC within a number of weeks, following the same process (pit development followed by IGC fissure forming).

4.2: Standard Methods Used in this Section
This section will detail some of the methods in this chapter that are used for multiple different corrosion tests. This includes the technique to expose the bore of the hole to the corrosive solution, the inspection technique of serial sectioning mounted specimens and correcting the depth found in serial sectioning to the perpendicular depth at locations around the hole.

4.2.1: Constant Immersion Technique for Fastener Holes

To complete a constant immersion test within a fastener hole, a reservoir is created using the hole that the solution is tipped into. One side of the hole is sealed using a non-reactive sealant by filling the hole with Blue-Tac (to keep the silicone out of the hole) and covering the back face with silicone (for this work, Permasil 626 was used). Once the silicone is dry (after 24 hours), the Blue-Tac is removed and the hole is cleaned with ethanol and cotton swab and dried using a hair dryer. This leaves just the sealant on the back face of the specimen with a reservoir.

This method requires approximately 0.1 mL of solution to fill the 6.35 mm hole enough so a concave meniscus forms at the top of the specimen. A concave meniscus helps prevent the solution wicking out of the hole, causing surface corrosion on the specimen. Once filled, the specimens are placed in a desiccator with a container of a saturated Potassium Sulphate (K₂SO₄) solution to maintain the relative humidity at 97% [109], which stops the solution from evaporating too quickly.

4.2.2: Serial Sectioning Inspection Method

Following exposure, all specimens were examined for their resulting corrosion depths using a serial sectioning method to view a number of “slices” through the specimen. This process began by cutting the specimen down in size to leave approximately 4 mm of material around the hole (as most of the corrosion specimens are 30 mm x 30 mm).

---

Selley’s Permasil 626 is a neutral, non-acid metal sealant used extensively by the DSTO Corrosion Control group.
These cut-down specimens were mounted in resin using cold mounting techniques. Once mounted, the specimens were ground and polished using the Streuers Autopolisher in the DSTO Metallographic laboratory to a sub-micron finish. The autopolisher has the following steps for a “standard” (according to the DSTO Metallographic laboratory procedures) grind and polish:

- 220 grit silicon carbide paper as a bulk grinding stage for one minute
- 9 µm polishing stage, the longest stage at six minutes
- 3 µm polishing stage for three minutes
- Finally an OP-S sub-micron polishing stage for one minute to give the specimen a mirror finish

The polished specimens were then visually inspected and imaged using a Leica VMM200 optical microscope. The resulting images were then measured for IGC length (if any is found on that slice) as well as pit depths and width.

Once the specimen was inspected and any corrosion found was imaged and measured, it was re-ground and polished by the Streuers Autopolisher. This could be set so that a specific amount of material was removed with each stage by specifying a change in specimen height rather than being time-based. In this case, 300 µm was taken off in the first grinding stage, followed by 100 µm and 50 µm respectively for the 9 µm and 3 µm polishing stages. Combined with the time-based OP-S polish stage, the total thickness removed was approximately 500 µm. For the 6.35 mm hole, this resulted in 25-30 slices.

4.2.3: Correcting Visual Depth for Location around the Hole

During inspection, the IGC depth was measured directly from the image surface. However, this measurement is along the ground plane, which is the same at any point around the hole, not perpendicular to the bore of the hole which will give the exact corrosion length. This is shown below in Figure 36, where the measured IGC length, shown by distance \( e \), is shown at a specific slice. However, the true length of IGC is actually distance \( d \), where both of these are
measured from the centreline of the hole (from the exact centre for distance \( d \)). To convert these values to just the IGC length, the radius of the hole is subtracted.

\[
2d^2 + 2c^2 - c^2 = \sqrt{b^2 + c^2}^2 - b^2
\]

\((5)\)

Figure 36: Correcting measured IGC distance to distance perpendicular to the bore of the hole showing the variables used in the correction equation.

A correction factor was made based on the opening distance of the hole on the ground plane, which gives the position of this plane with respect to the centre of the hole. The correction factor uses Pythagoras Theorem to determine the distance to the centre of the hole (distance \( a \)) which can then be used to determine the corrected corrosion length.

The equation below is the correction factor to determine the corrected corrosion length from the measured value and was applied to all IGC found.

\[
d = \sqrt{e^2 + c^2 - b^2}
\]
4.2.4: Etching to Reveal Grain Boundaries

The polished specimens were etched using Keller’s Reagent to reveal the grain boundaries to determine if the corrosion was progressing along the grain boundaries as desired or through the grain bodies. Keller’s Reagent is a mixture of 95 mL of distilled water, 2.5 mL of HNO₃, 1.5 mL of HCl and 1.0 mL of HF.

The Immersion method was used (as opposed to the Swab method), which involves immersing specimens in the reagent for 30 seconds. Following immersion, the specimens were washed with distilled water then rinsed with ethanol and dried. Following each etch, the specimens were inspected under an optical microscope to ensure the required level of etching was achieved. If not, the specimens were re-etched for a further ten seconds until the etching level was satisfactory. If the specimen became over-etched, it was re-ground and polished to remove the etched surface (normally less than 50 µm in thickness).

4.3: Initial Testing of IGC Inducing Methods

This section discusses three methods initially chosen to investigate their potential effectiveness. These three methods are constant immersion in a sodium chloride solution, the droplet method and the potentiostatic electrochemical method.

4.3.1: Constant Immersion in Sodium Chloride Solution

This particular method was an early attempt by the DSTO Corrosion Group in to replicate the IGC found on the AP-3C Orion. It involved filling the fastener hole with a 3.5% NaCl solution for four weeks. The specimens were examined every two to three days to ensure the solution was not drying out. Even though the specimens were stored in high humidity (97%
using Potassium Sulfate ($\text{K}_2\text{SO}_4$) [109]), the solution was still drying out enough that 30-50 
µL of solution top-up was required at each check.

This method resulted in a large amount of pitting corrosion around the bore of the hole, but no 
IGC was found in any specimen. Examples of some of the pits found are shown below in 
Figure 37.

![Figure 37: Examples of pits found using the initial constant immersion method](image)

A total of 234 corrosion pits were found and measured, shown in Figure 38.
Some specimens were etched to reveal the grain structure, an example of which is shown below in Figure 39. This showed that although it was pitting corrosion that formed, the corrosion did progress along or near grain boundaries, meaning this method may be able to be adapted to produce sharper fissures rather than pits.
4.3.2: Droplet Method using Sodium Chloride Solution

The droplet method using sodium chloride solution has been used in the past to induce minor IGC [55]. As such, it was one of the initial methods chosen to investigate. This method involved placing a droplet of 3.5% NaCl solution on the bore of the hole (by placing the specimen on its side), either parallel to the rolling direction or perpendicular to it. The specimen was then left for either one or two weeks in high humidity to ensure the droplet stayed as wetted as possible.

Unfortunately this method did not produce any visible corrosion after two weeks of exposure, and so was abandoned as a possible method in favour of other, more promising, methods.
4.3.3: Electrochemical Methods

A paper by Marita and English found that an applied potential at a certain voltage was able to drive the formation of only sharp intergranular corrosion with very little surface pitting. The theory behind this relates to “breakdown potentials” of the different phases within the aluminium. In simple terms, the breakdown potential is the potential at which that particular phase is most sensitive to corrosion, resulting in a significant increase in corrosion rate [15].

Marita and English [15] found that 7075-T6 aluminium contained two breakdown potentials – one for the grain boundaries and a more negative one for the grains. If the potential was held between the two breakdown potentials (so slightly above the first one), only intergranular corrosion was found. Above the second potential, pitting also occurred on the material’s surface.

The first step in the electrochemical testing presented here was to replicate the breakdown potentials found by Marita and English [15]. A specimen of AP-3C wing skin material was mounted in resin, shown in Figure 40, so the ST face was exposed. An insulated wire was also attached to the back side of the specimen. Scans on two separate specimens resulted in a close match to the Marita and English results, as shown in Figure 41.
Figure 40: Potentiodynamic scan specimen of the AP-3C wing skin material mounted in resin

Figure 41: Polarisation curve for two specimens of AP-3C wing skin material on ST face only
The next step was to attempt a potentiodynamic scan on a specimen with a hole in it. Only the bore of the hole was to be exposed, so silicone was used to mask off the whole back face and all but the hole of the front face. This was done by applying silicone to one side of a blank, un-drilled specimen. A 6.32mm hole was then drilled through the specimen from the silicone side. The back side was sealed using the same method as before by using Blu-Tack in the hole. A ready-to-test specimen is shown in Figure 42.

![Figure 42: Ready-to-test potentiodynamic specimen with hole](image)

Unfortunately, testing inside the hole did not produce the same polarisation curve. A number of specimens were tested however the result was still the same – each polarisation curve for the hole specimens was similar to the red line shown in Figure 43. Along with the different polarisation curve, each specimen had an unknown black substance form on the surface of the hole. This substance was scraped off using a clean scalpel blade and placed onto carbon tape. This was then placed in a JOEL Scanning Electron Microscope (SEM) and an analysis was conducted using Energy Dispersive X-Ray Spectroscopy (EDX).
Figure 43: Polarisation curve of ST faces and an example of an in-hole specimen

Shown in Figure 44 is the result of EDX on the black substance, showing aluminium, oxygen, chlorine and silicone. It was initially thought the substance was due to silicone particles on the exposed surface. The bore of the hole on an un-tested specimen was ground using 1200 grit SiC paper, followed by rinsing with distilled water and ethanol, to remove any potential silicone inside the hole. The ground specimen was tested with the same result as the un-ground specimen.
The EDX of the hole did not yield usable results, with a high count of oxygen and aluminium not indicating what the substance may have been. Due to this and the promising results of the constant immersion work, using potentiostatic methods was discontinued as a method for producing IGC in AP-3C wing skin material.

4.3.4: Summary of Initial Testing Methods

The constant immersion testing was the most promising method with pitting corrosion found in the bore of the hole that follows the grain boundaries. Due to this, the constant immersion method was investigated further to attempt to create fissures rather than pits. The electrochemical method did not produce any noticeable corrosion in the bore of a hole even though the potentiodynamic scan of a flat specimen showed similar results to Marita and English. The reasons for this were unclear. The droplet method did not produce any corrosion in the bore of the hole and so was abandoned.
4.4: ASTM Standard G-110

The results of the initial constant immersion method showed it produced corrosion that progressed along or near the grain boundaries, even though the general form of corrosion was pitting. It was believed that the corrosive medium (3.5% NaCl) was too aggressive to sustain a sharp IGC fissure – it was corroding into the grain bodies at the same time it was corroding the grain boundary. The author believed that this was due to the lack of oxygen able to reach the end of the pit, resulting in pitting rather than allowing IGC to form, as discussed in [29]. A number of different methods were trialled in an attempt to increase the oxygen content in the pit.

One of the early tests to attempt to increase oxygen content involved a two-step process of exposing the bore of the hole to 3.5% NaCl for two weeks, followed by rinsing the hole and leaving it in the high humidity environment for a further four weeks. The resulting corrosion had the form shown in Figure 45, which was the first indication that increasing the oxygen available at the end of the pit can result in IGC forming instead of pits.

Figure 45: Example of the corrosion found using the no-refill dual-step method
By increasing the available oxygen at the tip of the pit, corrosion progressed from that pit along the grain boundary without corroding the grain body. One particular method attempted here was ASTM Standard G-110 [57]. The inclusion of hydrogen peroxide significantly increased the oxygen content in the solution and may have the possibility of inducing more IGC than the previous dual step method, which was limited to approximately 250 µm.

### 4.4.1: Standard Test Methodology

The standard test methodology for ASTM G-110 involves a six hour immersion of specimens in a solution of 5.7% (1 M) NaCl and 0.3% H$_2$O$_2$ to produce IGC [57]. This methodology used flat specimens fully immersed in the solution, however for this test the solution was placed in a silicone-sealed hole. The standard also states that specimens should be etched prior to exposure using a mixture of nitric and hydrofluoric acid, however due to the nature of the hole and associated risks of hydrofluoric acid, this step was not conducted.

The standard test methodology did not result in any visible corrosion around the hole, so two modifications were made. Firstly, the exposure time was increased to allow more opportunity for IGC to form and secondly the concentration of hydrogen peroxide was increased to further increase the oxygen content of the solution. Both these modifications were made concurrently.

It was also found that after the required exposure time the level of fluid had increased significantly, resulting in some of it overflowing the hole. This was due to the saturation concentration of NaCl at 97% RH, which is approximately 0.6M. The solution drew more water from the high humidity to reach this concentration (by increasing the volume of water, the solution is diluted), thus increasing the level of fluid. For this reason, the rest of the tests were conducted using a 3.5% NaCl solution (pre-made in the laboratory) as this was closer to the 0.6M saturation concentration, limiting the chance of overflow (which can cause surface corrosion to form).
4.4.2: Modification of the Standard Test Methodology

The exposure time was increased from six hours to 18 at the same time the concentration of hydrogen peroxide in the solution was increased from 0.3% to 1.2%. Both these changes led to IGC being present around the bore of the hole in small amounts. Following on from this initial modification, the exposure time was increased again. The exposure times increased from 18 hours to up to four weeks. Due to the degradation of hydrogen peroxide in this solution, for exposure times greater than 18 hours, the solution needed to be refreshed every two to three days. It was found that only refreshing the hydrogen peroxide (assuming it has been completely spent at each refresh, so adding 8 µL) rather than topping up the entire solution produced finer IGC and a smaller pit opening thickness, as refreshing the whole solution slowly increased the NaCl concentration.

4.4.3: Masking of Holes during Exposure

Another modification was to mask the holes; the corrosion found in some of the specimens tended to be throughout the whole thickness of the material. By masking the holes, the area that can be corroded is limited to a narrow band near the thickness mid-plane. The specimens were marked with Vishay Barrier J II, a lacquer that is painted onto the specimen and left overnight to cure. A scalpel was then used to make a scrape into the surface (inside the bore of the hole) leaving a very narrow band for the corrosion (only as wide as the thickness of the blade). While just one IGC fissure is not completely typical of the corrosion in the AP-3C, one single strike allows for a better understanding of the effect of IGC without the complication of multiple strikes.

The results from masking the holes showed a dramatic improvement on the type and size of corrosion found. All corrosion fissures were long, thin and sharp following the grain boundaries.

The most significant result came from one particular masked specimen, shown below in Figure 46, with a H$_2$O$_2$ concentration of 1.2% and the hydrogen peroxide was topped up daily for 4 weeks. The resulting corrosion was only one fissure, initiating from the scrape. This
fissure was 1.8mm long (the longest corrosion by far) and had a very sharp, fine tip.

Figure 46: IGC fissure from a masked specimen of AP-3C material exposed to 1.2% H₂O₂ for four weeks

4.4.4: Final Test Protocol using Hydrogen Peroxide

As shown in Figure 46 above, the most significant IGC was caused by the conditions listed below. As such, these are the final test protocol specifications for inducing IGC into AP-3C Orion wing skin material using hydrogen peroxide.

- 3.5% NaCl
- 1.2% H₂O₂
  - Topped up every 3 days
- 4 week exposure
- Hole masked with Vishay’s Barrier J II
  - Scalpel used to scrape a small band of the masking agent away to limit corrosion to that area
- Specimen corroded in controlled environment at
  - 97% RH
  - 15°C Temperature

4.5: Nitrate and Sulphate Method
Originally suggested by Braun [46] and used by Salagaras et al. [25], this method uses a mixture of nitrates and sulphates that act as corrosion inhibitors. The theory is these inhibitors are used up and break down as they do their job of inhibiting. Initially, while the inhibitors are in their highest concentration, all corrosion is inhibited. As they break down over time, they become less effective at inhibiting particular types of corrosion, particularly intergranular corrosion. As more of the nitrates and sulphates are used up, they become less effective at inhibiting the remaining types of corrosion, particularly pitting.

By controlling the refresh rate of the solution (by cleaning the specimen and re-filling with fresh nitrates and sulphates), it is possible to only get IGC with very little corrosion. The exact solution used in this method, and in [25], is:

- 0.6 M NaCl,
- 0.1M sodium bicarbonate,
- 0.03M sodium nitrate
- 0.03M sodium sulphate

The specimens were exposed to this solution for four weeks in a controlled environment of 15°C and 96% RH. The original protocol in Salagaras et al. [25] involved cleaning the specimens and refreshing the solution once a week. This produced long, sharp corrosion fissures up to 2mm long but did not always produce visible IGC, especially in the transverse direction.

4.5.1: Modification to the Salagaras Method

Some testing was completed to determine if using a faster refresh rate (twice or three times a week) would produce more IGC and less pitting. Three times a week proved to be too quick and the inhibiting solution was not used up enough, so little corrosion was found. Twice a week was found to be the best refresh rate as it gives more corrosion than only once a week, up to 3mm. It also had a greater success rate, with all holes examined having at least 1.5mm of IGC. This protocol did not produce the multi-layered IGC as found in Figure 4, however this was acceptable due to the time constraints present in this work. Examples of the corrosion
produced are found in Figure 47.

![Image of IGC found using the modified Nitrate and Sulphate method](image)

*Figure 47: Examples of IGC found using the modified Nitrate and Sulphate method*

**4.6: Application of IGC Protocols to Rolled Sheet Material**

As the P-3 wing plank material was not infinite and at a premium (as it is also being used by the DSTO AP-3C project [104]), other materials were investigated. It was important, however, that the new material behaves the same as the material it is simulating. For instance, one possible material is 7075-T6 sheet material, discussed in Section 3.2: both this and the wing skin have been used in the AP-C3 Fastener Upgrade program as the crack growth properties were the same [104]. For it to be an effective replacement (as it is significantly cheaper and more readily available), it needed to behave the same as the wing skin in all aspects, especially corrosion behaviour.

An investigation into the microstructural differences between the purchased sheet material...
and the P-3 wing skin material was published previously [110]. This showed that there is a difference between the two materials, meaning there was a possibility of the corrosion behaviour being different. The final two protocols were tested to determine if the sheet material could be a viable substitute. Table 10 shows a breakdown of these methods and the differences between the sheet material results and the AP-3C wing skin material.

**Table 10: Summary of corrosion initiation methods used for sheet material**

<table>
<thead>
<tr>
<th>Test Details</th>
<th>Differences in corrosion found (compared to AP-3C wing skin material)</th>
</tr>
</thead>
</table>
| Modified ASTM G-110 with masked hole, 1.2% for 4 weeks | • Similar depths, up to 1.4 mm in one case  
• Higher widths and the tip of the IGC did not taper off like it did in the extrusion |
| Modified Nitrate and Sulphate method | • Significantly shorter depths than in AP-3C wing skin material (nothing found over 700 μm)  
• Less likely to form IGC from the base of pits  
• IGC that did form jumped around a lot, rather than forming long, straight fissures |

**4.7: Application of IGC Protocols to Extruded Bar Material**

Due to the IGC protocols not being as effective at corroding rolled sheet material, another representative material was purchased that may have had closer corrosion behaviour to the AP-3C wing skin material. This material was 7075-T651 extruded bar as described in Section 3.3: . As can be seen from the grain size distributions, this extruded bar is closer in grain sizes to the AP-3C wing skin material, however there is still a difference. This indicates, as it did with the rolled sheet material, that there could have been a difference in the resulting corrosion formed.

There is also a difference in the microstructure through the thickness of the extrusion, as shown in Figure 32. To test the most effective location for inducing IGC, a test section was
removed from the bar (approximately 30 mm x 30 mm) which had four 6.35 mm holes drilled in it (to simulate the DNHs). After the holes were drilled, the test section was cut into 2 mm thick specimens to replicate the thickness of the fatigue specimens.

The representative fastener holes were then corroded using the standard test methods used in the Sheet material testing. The results of these tests are shown below in

**Table 11: Results of testing corrosion protocols on extruded bar material**

<table>
<thead>
<tr>
<th>Test Details</th>
<th>Differences in corrosion found (compared to AP-3C wing skin material)</th>
</tr>
</thead>
</table>
| Modified ASTM G-110 with masked hole, 1.2% for 4 weeks | • Significantly less depth, less than 1 mm  
• More pitting present that AP-3C wing skin material                                                                 |
| Modified Nitrate and Sulphate method              | • Less depth, less than 500 µm  
• More instances of no IGC found  
• IGC jumped around more as with sheet material rather than long, straight fissures |

**4.8: Conclusion**

This chapter detailed the development of two protocols to induce IGC in the AP-3C Orion wing skin material. These protocols were developed from a simple constant immersion method within a hole using a 3.5% NaCl solution and through a series of tests and adaptations finished with two protocols that can produce IGC similar in form to that found on the AP-3C Orion.

The first protocol involved exposing the bore of the hole to a solution of 3.5% NaCl and 1.2% H₂O₂ for four weeks. The inclusion of hydrogen peroxide caused an increase in the available oxygen within the solution, allowing corrosion to continue at the tip of the pit/fissure, rather than corroding into the grain body. Prior to exposure, the bore of the hole was coated in a non-
permeable lacquer (with a ring scraped off with a scalpel in the mid-plane of the thickness) to limit the possible area of corrosion. This protocol was able to produce IGC up to 1.8 mm, with an average corrosion length of 0.9 mm.

The second protocol involved exposing the bore of the hole to a solution of sodium chloride, bicarbonate, nitrate and sulphate for four weeks. The nitrates and sulphates in this solution act as a corrosion inhibitor at particular concentrations. As the concentration changed (as the nitrates and sulphates are used up as they inhibit), different forms of corrosion were allowed to form but not others. As the concentration required to allow IGC to form on its own was higher than the concentration that allowed any form of corrosion to form (particularly pitting corrosion), by refreshing the solution at particular intervals, the form of IGC found on the AP-3C can be replicated. It was found that refreshing the solution twice a week was ideal. Unlike the previous protocol, no masking was required. This protocol was able to produce IGC up to a length of 3.7 mm, with an average of 2.5 mm.

Due to the possibility of a limited supply of AP-3C wing skin material, these protocols were applied to other materials that are easier to obtain. These materials were aluminium alloy 7075-T6 rolled sheet and 7075-T651 extruded bar. However, this did not result in the same form of corrosion being formed in either case. Due to this, the material cannot be substituted for the corroded specimen testing. As the fatigue crack growth behaviour was similar for both the AP-3C wing skin material and newly purchased 7075-T6 rolled sheet, the uncorroded, baseline tests can be conducted on the rolled sheet, allowing more material for the corroded tests.
CHAPTER 5: THE PHYSICAL EFFECT OF INITIATION DEPTH ON FATIGUE LIFE

5.1: Introduction

Before the underlying mechanics of early fatigue initiation due to IGC can be further studied, it is important to determine the physical effect that IGC has on fatigue. Firstly, it needs to be determined if there is actually an effect on fatigue initiation and, if there is, to how strong that effect is. Can the effect be related to a measurable quantity within the material? For example, it has been shown that there is a correlation between pit size and fatigue life \[4, 111\]. Is there a similar relationship for IGC? This question was answered through an experimental test program that compared un-corroded and corroded specimens. This chapter details this experimental program and its results.

5.2: Background

5.2.1: Fatigue Specimen Design

These fatigue specimens were designed to replicate the DNHs found on the AP-3C wings near the engine nacelles. The specimens were originally designed for a DSTO project \[104\] in support of the life extension works currently underway on the AP-3C. Given these specimens already existed, their design was used in the work described here to allow for the possible transfer of results as well as saving the time required to design new specimens. Figure 48 is a diagram of the specimen geometry.
Figure 48: AP-3C DNH specimen geometry. Specimens are between 1.5 mm and 1.7 mm thick. All dimensions are in mm.

5.2.2: Phases of Fatigue Crack Growth in DNH Specimens

Fatigue cracks in the DNH specimens must grow across four separate ligaments, as shown below in Figure 49. Each of these ligaments is associated with edges where fatigue cracks will initiate from during crack growth.

Figure 49: Ligaments in DNH specimens. Figure is not to scale.

There are a number of combinations of how a crack could grow through the fatigue specimen, however according to the work discussed here, in approximately 65% of specimens tested, cracks will grow completely through the first ligament before growing through the second,
then outside of both satellite holes. The other combinations include a crack initiating at Edge 1, then initiating from Edge 2 before growing through Ligament 1. The final combination found has a crack initiating and growing through Ligament 1, then into Ligament 3 prior to initiating at Edge 2. Edge 1 is simply the edge where a fatigue crack initiates first. All things being equal, there is a 50% chance of either edges being nominated as Edge 1.

5.3: Methodology

This section details the steps taken to complete the fatigue testing of the un-corroded and corroded fatigue specimens. It will cover specimen manufacture, corrosion protocol used, crack growth and environmental monitoring, and the loading used. The results of these tests will follow the Methodology section.

5.3.1: Specimen Manufacture

The specimens were manufactured by the QinetiQ Aerospace workshop at the DSTO Melbourne site in conjunction with other specimens being manufactured for the DSTO AP-3C project. These specimens were fly-cut in stages from both sides from an ex-service Royal New Zealand Air Force (RNZAF) wing. As such, the thickness of the material varied from 2.2 mm to 1.5 mm due to the taper of the wing planks.

The specimens were guillotine cut from the bulk material then machined down to the required length and width. The thickness was fly-cut to be the maximum possible while still being machined flat; a variation in the thickness is present due to the changing thickness of the wing plank itself. The main hole in the centre of the specimen was drilled then reamed while the two satellite holes were straight drilled. Figure 50 shows a fully manufactured DNH specimen, showing the layout of the three holes and highlighting the fly-cut surface finish present on each specimen. The slight non-collinearity of the holes are an artefact of how the specimen was oriented during photographing.
5.3.2: Corrosion Protocol

Following machining, the specimens were corroded using the modified nitrate and sulphate corrosion protocol specified in Chapter Four. The rear side of the main hole was covered with silicone to form a reservoir, which the corrosive medium was then poured into. On early specimens, it was found that the corrosive medium could leak out under the silicone along the valleys of the fly-cut surface, resulting in surface corrosion. To fix this, prior to the application of the silicone, the back surface of the specimen was polished using 800 then 1200 grit wet-and-dry silicon carbide paper to produce a flatter surface for the silicone to adhere to. This resulted in little or no leaking of the corrosive medium and significantly less surface corrosion.

All specimens were corroded for the full eight weeks at 96% RH and 15°C. Following corroding, the specimens were washed with distilled water and a clean toothbrush, rinsed with
ethanol then dried with a hairdryer. Storage of the specimens prior to testing was in a freezer at -2°C.

Some surface corrosion was present on the front side of the specimen due to the solution wicking over the edge of the hole, as shown in Figure 51 (a). This minor surface corrosion was removed prior to testing using a dry belt liner and an 800 grit belt, ensuring the specimen did not heat above approximately 50°C (so the whole specimen was still cool enough to touch). Hardness testing was conducted and found no hardening of the surface due to this finishing. Some surface corrosion still remained following this (as removing too much material could cause a significant reduction in load carrying area), however this was mostly away from the expected fatigue crack initiation area, as shown in Figure 51 (b).

![Figure 51: Surface corrosion (a) straight after the eight week exposure, and (b) the worst case following belt finishing in the direction shown with the arrow](image)

**5.3.3: Fatigue Test Set-up**

Fatigue specimens were tested to failure using a 100 kN Instron 1343 load frame in the National Association of Testing Authorities-certified Fatigue and Fracture Laboratory (FFL) at DSTO Fishermans Bend. The load frame was controlled using Instron’s in-house software, MTS 793 Multi-Purpose Testware (MPT), running on a Windows 7 computer.
5.3.3.1: Measuring of Fatigue Crack Size

The size of the fatigue crack was monitored to determine the approximate number of cycles to the first visible crack and to failure of the first and second ligaments in the fatigue specimens. This monitoring was conducted using two methods – marker bands placed within the fatigue spectrum and visually using two crack cameras.

As discussed in Section 2.2.2.1, marker bands use alterations in the loading to produce visible marks on the fatigue surface at the location of the fatigue crack front at the time. In this case, the marker bands were based on the NASA 4-6-10 bands [63] with the 10 band removed. This type of marker band uses a series of 4 and 6 underloads to produce three specific and easily-identifiable bands, as shown in Figure 52 where examples of the 4 and 6 bands are shown. In this work, alternating 4 and 6 bands were placed at the end of 2,000 cycles of constant amplitude loading.
At the start and end of each marker band segment, two uEye crack cameras take images of the central area of the fatigue specimen on the front and back faces. These cameras use a 0.67X magnifier in conjunction with a Navitar lens and are controlled by the commercial software package Ultravision v 2.1.0.2. The field of view is shown below in Figure 53, where a fatigue specimen contains a 2.5 mm crack from the main hole towards the left satellite hole. Crack lengths were measured by comparing the on-screen crack length to the diameter of the main hole.

Figure 52: Optical image of NASA 4 and 6 band series (beginning top right with a 4 band) found on in AP-3C wing skin material fatigue specimens
5.3.3.2: Fatigue Loading Spectrum

Due to the large number of load levels in the marker bands, one block that incorporates a constant amplitude section, a four-band marker, a second constant amplitude section followed by a six-band marker, as well as camera triggers would involve over fifty separate procedure items. These were all incorporated into a single fatigue spectrum file made up of normalized load levels displayed as spectrum turning points. The computer controller then took these load levels and multiplied them by the required peak load. The normalised load levels of this spectrum are shown in Figure 54.
Figure 54: Load levels of the fatigue spectrum used with crack camera trigger locations shown with arrows

During most of the spectrum, the specimen is cycling at 10 Hz, meaning one full cycle (from peak to peak) is completed every 0.2 seconds.

The automatic crack camera trigger involves ramping the load slowly to the peak load, then holding it while the camera triggers. The spectrum then continues from the peak load. This process is shown in Figure 55. The camera is triggered at maximum load to ensure the crack is at its most open, and thus most visible. The load ramping takes place at 0.1 Hz which results in the ramp-and-hold taking place over 10 seconds.
Active load compensation (ALC) was used to ensure the input loads were actually met. ALC monitors the load cell outputs and alters the input through the load frame to ensure the required loads are met. This resulted in an average error in loads reached during testing of less than 3%.

5.3.3.3: Combating Humidity Effects on Fatigue Life

Varying levels of humidity can have an effect on the fatigue crack growth rate of aluminium alloys [112]. To combat this, a humidity chamber was designed and manufactured by the RMIT Student Workshop that attached to standard anti-buckling guides for the AP-3C DNH specimens. Anti-buckling guides were needed to prevent buckling during compressive loads found in the spectrum testing. Even though no compressive loads were present in this work, the anti-buckling guides proved to be a simple and easy to modify carrier for the Perspex
chambers. The humidity chambers were made from clear Perspex with clear photographic ultraviolet filters on the front and back face to ensure as little distortion of the crack camera images as possible. Images of various angles of the humidity chambers are shown below in Figure 56 with its measurements given in Figure 57.

Figure 56: Constructed humidity chamber attached to standard AP-3C DNH specimen anti-buckling guides
Figure 57: Measurements of (a) the humidity chamber and (b) the anti-buckling guide it attaches to (all dimensions in mm)

Originally, the Perspex chambers were sealed using a bead of dried silicone between the anti-buckling guides and the back edge of the chamber. Testing this set-up underwater showed two leaks in this system – one from this bead of silicone and another between the UV filter and the metal ring it attaches to (shown in Figure 58).
To fix the leak between the chamber and buckling guide, the bead was replaced by a strip of Teflon tape on the chamber. The leak between the UV filter and ring was fixed by applying a bead of silicone to the front and back of the filter around the edge where it meets the metal ring.

The humidity chambers had a reservoir built into the base of each chamber to allow a salt solution to be placed to control humidity. Two options are available to control humidity – either the humidity is controlled low, under the transition humidity (of approximately 40%), or above transition. The initial test humidity was going to be in the lower, 10-30% range to keep it in-line with the AP-3C fastener project [105] modelling. A few methods are available for controlling the humidity to this level, one of which is simple silica gel (used as a desiccant). However, upon testing one of the desiccators at DSTO, it was found that the equilibrium humidity of silica gel was approximately 40%. This would place the humidity in the transition range for fatigue crack growth (between low and high humidities) [112].
ASTM Standard E104-85 [109] states that Lithium Chloride will control the relative humidity in the 10-15% RH area. This chemical was not used due to its hazardous nature and the OHS controls that would have been required to use it.

Taking into account the solutions described in [109] and the OHS controls required for each solution, it was decided to use NaCl as the salt solution to control humidity to 75%. ASTM E-104-85 suggests using a just-saturated solution to minimise the possibility of spillage. To achieve this, the salt crystals were placed in the reservoir and de-ionised water was added until the first instance of free water appeared on the surface of the salt crystals.

5.3.3.4: Monitoring Environmental Conditions during Testing

To monitor the environmental conditions during fatigue testing, two Vaisala HMP110 humidity and temperature probes were connected to a DataTaker DT85. The HMP110 probes output an analogue voltage for both the temperature and humidity channels and provide a power in voltage range of 5 to 24V. A probe was inserted into a hole in the side of the humidity chamber and clamped using the supplied mount, as shown below in Figure 59.
The DataTaker DT85 has a large number of analogue channels available. Each analogue channel has an active wire, ground and two channels; with the general set-up being the voltage is read across channel 1 or 2, and ground.

A 12V output channel was found on the DT85 which could be used to power the HMP110 probe. However this only worked when its ground channel (separate from the individual analogue channel’s ground) was attached. As each individual channel needs to have its ground attached, an extra wire was run, in series, from the 12V ground to the analogue channel ground, as shown below in Figure 60.
Once the probes were attached to the DT85 and reading the voltage correctly (with the voltage going up when the humidity or temperature was increased), they were placed in a programmable environmental chamber with a calibrated probe. A number of temperature and humidity levels were set and the voltage was read at each step. This was then input into Microsoft Excel, where two calibration curves were developed.

The DT85 can transpose the input voltage through a simple multiplier or through an actual equation. Once the calibration curves (and thus equations) were developed, they were placed back into the DT85 to show °C and %RH instead of mV for the temperature and humidity. Four more levels were chosen as intermediate tests (so in between the calibration levels) to determine if the calibration was completed correctly. These are shown in Figure 61 where all of the points line up.
Figure 61: Graph of calibration of humidity probe showing the original test/set points and the calibrated points.

The calibration curve equations are:

\[ T = 0.0475(mV) - 40 \]  

\[ RH = 0.0407(mV) \]

Following calibration of the probes, a number of tests were run to determine the time taken to reach the equilibrium humidity of 75% in the laboratory environment (between 20 and 25°C). Figure 62 shows these tests, all of which had different starting points (some at room humidity, others at elevated humidities to simulate changing over the specimen quickly). This graph indicates that equilibrium humidity is reached prior to seven minutes for all tests (with the longest equilibrium taking 7 minutes from 25.3%).
5.3.3.5: Overall Test Set-Up

For testing, the specimen was placed between the anti-buckling guides that already have the filled humidity chambers attached. To make this process easier, a rig was made from standard 70 mm x 19 mm timber to hold the guides at the correct height for the specimen to be placed in. By resting the bottom edge of the specimen on a table that the rig is set on, it was approximately at the correct height with the guides (holes in line with the filters). From here, minor positioning adjustments could be made easily without having to support the whole chamber/guide set-up (and risk spilling the salt solution). This rig is shown in Figure 63.

Figure 62: Graph of humidity versus time for four different starting humidities
The specimen was left in this rig for ten minutes to allow the humidity to equalise before testing. Ten minutes was chosen as it will allowed equalisation to occur from any humidity normally seen in the test laboratory (based on Figure 62). The humidity probe was also inserted into the chamber after the specimen to allow the humidity to rise quicker (as there was no escape for the humidity with the probe inserted). The probe was not permanently
mounted in the chamber as it became difficult to handle the whole set-up due to the probe wire, particularly placing it in the load frame; generally the humidity probe was taken out each time the chamber was moved.

The specimen (with guide and chamber unit) was placed in the load frame with a 6 mm gap between the machine grips and specimen guides. This gap was achieved using a 6mm hex key as it provided a constant 6mm gap from one edge to the other, ensuring alignment in the test frame. The lower grip was then tightened to 1,000 PSI before the crosshead was brought down until the same gap was present at the top grips. The same grip pressure was used in the upper grip.

### 5.3.4: Testing Matrix

Three stress levels were chosen due to the limited number of fatigue specimens available and the variety of possible corrosion amounts; there needs to be a balance between having enough specimens to have some of them contain significant amounts of IGC while ensuring a sufficiently wide range of stresses is tested to investigate any possible stress-related effects. Due to the limited number of fatigue specimens available, only one load ratio, $R = 0.1$, was chosen for testing. While spectrum loading testing may result in a more accurate knock-down factor, due to the time constraint with this project the faster constant amplitude testing was conducted.

Initially, stress levels of 100, 110 and 125 MPa were chosen based on the results of the life scoping tests displayed in Figure 64. It was thought that these stress levels would give a good spread of cycles to failure of approximately 120,000, 70,000 and 35,000 respectively.
However, during baseline testing of the two higher stresses, the test matrix was changed to avoid the possibility of run-outs due to the higher-than-expected fatigue lives of those specimens. Therefore the test matrix was changed to cover 110, 125 and 150 MPa load levels. The number of specimens at each load level is given in Table 12.

<table>
<thead>
<tr>
<th>Peak Stress</th>
<th>Number of Baseline</th>
<th>Number of Corroded</th>
</tr>
</thead>
<tbody>
<tr>
<td>110 MPa</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>125 MPa</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>150 MPa</td>
<td>4</td>
<td>9</td>
</tr>
</tbody>
</table>

**5.4: Overall Fatigue Testing Results**

Presented here are the overall results from fatigue testing in the form of Table A 1.1 and Figure 65, where the uncorroded and corroded specimens are shown with their respective test stress levels and resulting fatigue lives. Failure was defined as the complete separation of the top and bottom halves of the specimen. These results show that IGC does have an effect on
fatigue life; the next few sections will investigate with more detail what this effect is caused by.

Figure 65: Graph of fatigue test results showing number of cycles to failure vs. peak stress

5.5: Fatigue Initiation in Uncorroded Specimens

Fatigue cracks in all baseline tests occurred from an inclusion near the corner of the main hole of the specimen, which is consistent with the K solution available for this DNH configuration [94]. A number of examples of the semi-circular shaped initiation sites, imaged using an SEM, are shown in Figure 66.
Figure 66: Examples of fatigue crack initiation sites in uncorroded, baseline tests taken with an SEM. Initiation sites are outlined in red.

These SEM images were used to determine the diameter of each initiating feature. These results are given in Table A 1.1, where feature size is used to describe the diameter of inclusions.

5.6: Fatigue Initiation in Corroded Specimens

With the introduction of corrosion, the crack initiation mode changes from a corner crack to crack initiation around the corrosion. This crack initiation mode can be broken down further into four specific locations, all relating to surface pits that form down the bore of the hole. Fatigue can initiate from the corner, edge or tip of a pit, or ahead of the pit, as shown in Figure 67. The first three locations can occur when there is just a corrosion pit present; however fatigue initiation ahead of the pit is specific to specimens containing intergranular corrosion.
Figure 67: Specific locations of fatigue crack initiation in the presence of IGC. The origin of the depth measurement is the left edge of this image, at the bore of the hole.

Corroded specimen fatigue fracture surfaces often contained more than one initiation site—most fatigue fracture surfaces contained at least two initiation sites and some had up to five. As with the baseline results, SEM images of the fatigue fracture surfaces were analysed to determine initiating feature size, which, in this case, refers to initiation depth. These results are presented in Table A 1.1 where the deepest initiation found was determined to be the most critical.

The following sections provide details of the specific initiation types, how each is categorised and close up SEM images of each.

5.6.1: Corner of Pit

An initiation at the corner of a pit has been defined here as initiation within 50 μm of the bore of the hole, on the edge of a corrosion pit. 50 μm was chosen as an arbitrary number – it was
not expected that the sub-group of pit-based initiations would have any effect on the type of fatigue initiation encountered (i.e., there is little difference between a corner and edge of pit initiation). Examples of this type of initiation are shown in Figure 68.

Figure 68: Examples of corner of pit initiations
5.6.2: *Edge of Pit*

Initiation at the edge of a corrosion pit is defined here as initiation between the corner of pit initiation limit (50 µm) and a “tip of pit” initiation. Again this 50 µm limit was an arbitrarily set value and has no bearing on the actual fatigue behaviour, it just provided a method of separating the pit-based initiation into smaller groups. Examples of edge of pit initiation are shown in Figure 69.
Figure 69: Examples of edge of pit initiations

5.6.3: Tip of Pit

Initiation at the tip of a corrosion pit is defined here as initiation within 50 μm of the end of a pit. Examples of this type of fatigue initiation are shown in Figure 70.
5.6.4: Ahead of Pit

Initiation ahead of the pit is defined as any initiation deeper into the material than the tip of the corrosion pit. Close examination of these initiation sites lead to the finding that these initiations are a feature of IGC, and not the pitting that accompanies it. As the IGC fissure
grows, it may reach inclusions or larger precipitates along the grain boundaries. Due to the local corrosion potentials of each part (grain body, inclusion/precipitate, PFZ etc.), these inclusions and larger precipitates are likely to be preferentially corroded before the IGC fissure continues along the grain boundary, such as the corrosion order discussed in [29]. As a result of this, a void is left on the path of the IGC fissure the size and shape of the particle that was there. Shown below in Figure 71 are a number of corroded inclusions found both on the fatigue surface and on the IGC surface.
Figure 71: Examples of corroded inclusions

Figure 72 shows an example of fatigue cracks initiating ahead of a corrosion pit.
Figure 72: Examples of ahead of pit initiations. The boundary of the IGC is the edge that appears at the top of (a) and the bottom of (b), with the out-of-focus section just behind it.
5.7: Summary of Fatigue Test Results

As stated, there is a reduction in fatigue life due with the presence of IGC. This reduction could be due to a number of reasons, however given the close relationship between initiation location and surface corrosion pits down the bore of the hole, there is a strong case that this reduction can be related to surface pitting. In all cases, except those where initiation was ahead of the pit, fatigue initiated at the edge of a pit (whether that edge was near the bore of the hole or at the end of the pit). There were no cases of fatigue initiating at the corner of the specimen, as the baseline specimens did.

5.8: Effect of Initiation Depth on Fatigue Life

This relationship between fatigue initiation and corrosion pits lead to an analysis of the effect of initiation depth on fatigue life, presented here. A series of approximations for a knock-down factor due to IGC were made that can be applied to aircraft lifeing. By applying a knock-down factor to the uncorroded test results, an approximation of fatigue life for the corroded specimens can be made.

While not the only geometric parameter which controls fatigue initiation, initiation depth was chosen as a factor to examine further due to its effect on fatigue life for each stress level. Shown below in Figure 73 is a graph of the fatigue life results compared with the maximum initiation depth found for each specimen, separated by stress level. As the initiation depth increases, the relative fatigue life decreases in all three cases. This shows the potential for a good correlation between initiation depth and fatigue knock-down factor.
As a first order approximation, the average fatigue life of the uncorroded specimens were compared with the average of the corroded specimens for each stress level, shown in Table 13. This gave a baseline knock-down factor before the initiation depth was included. Although not very accurate, this did allow for the reasonable step of removing stress as a variable as there was little change in knock-down factor between the stress levels.

**Table 13: First order knock-down factor based on average fatigue lives**

<table>
<thead>
<tr>
<th>Stress Level</th>
<th>Average Uncorroded Fatigue Life</th>
<th>Average Corroded Fatigue Life</th>
<th>Knock-down Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>108,104</td>
<td>59,019</td>
<td>1.93</td>
</tr>
<tr>
<td>125</td>
<td>70,072</td>
<td>37,231</td>
<td>1.88</td>
</tr>
<tr>
<td>150</td>
<td>36,290</td>
<td>19,336</td>
<td>1.87</td>
</tr>
</tbody>
</table>

The knock-down factors based on the average fatigue lives do not account for the wide spread in corroded fatigue lives. At all three stress levels, the highest fatigue life was nearly double the lowest resulting in the large standard deviations given below in Table 14. Further refinement of the knock-down factor is required.
Table 14: Standard deviation of corroded and uncorroded fatigue life results

<table>
<thead>
<tr>
<th>Stress Level (MPa)</th>
<th>Uncorroded Fatigue Life</th>
<th>Uncorroded Std. Dev.</th>
<th>Corroded Fatigue Life</th>
<th>Corroded Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>108,104</td>
<td>14,465</td>
<td>59,019</td>
<td>15,065</td>
</tr>
<tr>
<td>125</td>
<td>70,072</td>
<td>9,381</td>
<td>37,231</td>
<td>10,100</td>
</tr>
<tr>
<td>150</td>
<td>36,290</td>
<td>4,742</td>
<td>19,336</td>
<td>4,072</td>
</tr>
</tbody>
</table>

Table 14 shows that although the average fatigue lives are different between corroded and uncorroded, the standard deviation of each are similar, meaning the change in fatigue life is most likely due to a change in crack initiation and should not result in a change in crack growth rate (which would change the standard deviation).

5.8.2: Second Order Approximation of Knock-down Factor using Initiation Depth

The relationship between initiation depth and knock-down factor from the average uncorroded fatigue life data was investigated as a second order approximation. In this case, instead of comparing the average of the corroded specimen test results to the average of the uncorroded tests, each individual corroded test is compared with the average of the uncorroded tests at its respective stress level. This is shown below in Table A 1.2.

Figure 74 shows a graph of the above results with a linear regression fitted using the least squares method. The coefficient of determination, $R^2$, value for this linear regression is 0.114, meaning there may be a relationship between initiation depth and knock-down factor, however more work can be done to develop a stronger relationship. The equation used for this regression is shown below. The constant value used is 1 as it is assumed that a specimen with an initiation depth of zero will not have a corrosion pit present, and thus will initiate a fatigue crack at the same location as the un-corroded specimens.

$$K_{OL} = 0.0039 \cdot D_I + 1 \quad (8)$$
Figure 74: Graph of knock-down factor vs. initiation depth, where knock-down factor was calculated from each individual corroded test result. Linear regression ($R^2=0.114$) also shown.

In each case, a number of regression types were investigated: linear, polynomial (2\textsuperscript{nd} and 4\textsuperscript{th} order), exponential and logarithmic. Linear regressions achieved the best correlation in all cases.

5.8.3: Third Order Approximation of Knock-down Factor using Cycles to Initiation

Based on the partial success of introducing the initiation depth into the knock-down factor determination process, the other side of the relationship between knock-down factor and initiation depth was investigated to determine if there was a more accurate prediction method than simply comparing overall fatigue lives. The low correlation found in Figure 74 is partly due to the variation in initiation times for each phase of crack growth in these specimens. Even though one or possibly two edges on the fatigue specimen are corroded, and thus initiate cracks more quickly, there are still two or three edges without corrosion, Figure 75. These uncorroded edges (the satellite holes and possibly one side of the main hole) have a wide variety of fatigue crack initiation times due to the wide variety of initiator size.
Figure 75: Corroded and uncorroded edges of DNH fatigue specimens. Fatigue initiates from Edge 1 first due to the presence of corrosion. Edge 2 may or may not be corroded and Edges 3 and 4 are never corroded.

To attempt to remove this variation in initiation time, a knock-down factor was determined for number of cycles to failure of the first ligament, or between the main hole and either satellite hole, Figure 76. This reduces the number of fatigue initiation phases from four to one and should reduce scatter in results.

Figure 76: Failure of the first ligament in DNH specimens

The crack camera images were examined for all fatigue specimens (including baseline) to determine the cycles to failure of the first ligament, which is given below in Table A 1.2. An average was determined for the uncorroded specimens (at each stress level, giving one average fatigue life for each of the three stress levels) and all of the results were then
compared to it to determine a knock-down factor for both corroded and uncorroded specimens.

Plotting the knock-down factors from Table A 1.2 against their respective initiation depths gave a better relationship than using the fatigue life-based knock-down factor. This relationship is shown below in Figure 77 as well as a linear regression that gave an $R^2$ of 0.789. The equation for this relationship is:

$$K_{FL} = 0.07D_I + 1$$  \hspace{1cm} (9)

\[\text{Figure 77: Knock-down factor based on failure of the first ligament versus initiation depth with a linear regression shown (} R^2 = 0.789\)\]

As discussed previously, a fatigue crack will most likely grow through one ligament in the specimen at a time. However, there were some cases where a crack only grew part way through one ligament (from the main hole to one satellite hole) before a crack began growing on the other side of the main hole, as shown in Figure 78. This could result in a change in
crack growth rate due to two cracks growing at once. To reduce this possibility, a shorter time frame was investigated that would insure only one crack is measured at a time.

![Image of two cracks growing simultaneously](image)

*Figure 78: Crack growing through two ligaments simultaneously prior to one reaching its respective satellite hole with arrows indicating the end of each crack*

The crack camera images were re-examined and the number of cycles to the first visible crack was recorded. Due to the resolution of the crack camera, the minimum visible crack size is approximately 1 mm. Figure 79 is a sequence of camera images showing the first visible fatigue crack in specimen BAFT1-02.

Marker bands could have been used to measure the crack length, however it was believed it would be more beneficial to base the analysis and modelling work off surface crack length as this is what is measured in service. However, the surface crack lengths did match up with the marker band position.
Figure 79: Sequence of crack camera images from BAFT1-02 showing an example, highlighted in blue, of the “first visible crack” at 57,729 cycles.

A similar process was used to determine the knock-down factor of the number of cycles to initiation. The average number of cycles at each stress level to the first visible crack for the uncorroded specimens was compared to each individual result (both corroded and uncorroded) to determine their knock-down factor. Table A 1.2 shows the number of cycles to the first visible crack along with their respective knock-down factors.
Figure 80 plots these knock-down factors against initiation depth, with the linear regression shown giving an $R^2$ of 0.914. This is a further improvement on knock-down factor from simply comparing the average fatigue lives. Figure 80 is also broken down into initiation types, from Corner of hole initiations in the baseline specimens, to the various initiation locations around pits and finally to corroded inclusions (“Ahead of Pit” initiations). It should be noted that the corner of the hole initiations do have a knock-down factor less than one in some cases due to the knock-down factor being determined from the average cycles to first visible crack, meaning some results have to be less than the average for the uncorroded specimens (where the average would produce a knock-down factor of 1). The linear regression of this knock-down factor is shown below.

$$K_{FC} = 0.075D_I + 1 \quad (10)$$

Validation of this linear regression was made through a non-parametric correlation using Spearman’s Rho method [113]. Spearman’s Rho is a rank-order correlation coefficient which
measures association at the ordinal level. This is a nonparametric version of the Pearson correlation based on the ranks of the data rather than the actual values. The absolute value of the correlation coefficient indicates the strength, with larger absolute values indicating stronger relationships. The values of the correlation coefficient range from -1 to 1. And since 0.968 is relatively close to 1, this indicates that Initiation Depth and Knock-down Factor are positively correlated.

The significance of each correlation coefficient is also displayed in the correlation table. The significance level (or p-value) is the probability of obtaining results as extreme as the one observed, in this case the P-value is $1 \times 10^{-6}$ (1 in 1 million). According to [113], if the significance level is very small (less than 0.05) then the correlation is significant and the two variables are linearly related. The correlation table is shown below in Table 15.

Table 15: Non-parametric correlation table between initiation depth and knock-down factor based on cycles to first visible crack

<table>
<thead>
<tr>
<th></th>
<th>Initiation Depth</th>
<th>Knock-down Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spearman's rho</td>
<td>Correlation</td>
<td>1.000</td>
</tr>
<tr>
<td></td>
<td>Coefficient</td>
<td></td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td>.</td>
<td>1x10^{-6}</td>
</tr>
<tr>
<td>N</td>
<td>39</td>
<td>39</td>
</tr>
<tr>
<td>Knock-down Factor</td>
<td>Correlation</td>
<td>.968(**)</td>
</tr>
<tr>
<td></td>
<td>Coefficient</td>
<td></td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td>$1 \times 10^{-6}$</td>
<td>.</td>
</tr>
<tr>
<td>N</td>
<td>39</td>
<td>39</td>
</tr>
</tbody>
</table>
5.9: Discussion

As can be seen by the results presented here, there is a clear knock-down of fatigue life due to IGC. An examination of the resulting fracture surfaces showed this is due to microstructural features associated with IGC, rather than the IGC by itself. As stated in both Sections 1.2.2: and 4.1.1: , IGC often grows from the tip of corrosion pits down the bore of the hole. As 17 out of the 27 corroded specimens had fatigue initiate from a pit, it is an important feature of IGC in terms of fatigue crack initiation.

Another significant characteristic of IGC is its ability to corrode inclusions as it grows along grain boundaries. As shown in Figure 71, this produces voids in the material that fatigue cracks can initiate from, as Figure 72 shows. This made up the remaining ten fatigue initiation sites. However, fatigue initiation from corroded inclusions appears to be limited to a maximum depth of 500 μm. Reasons for the limited depth are unclear from fatigue testing alone and are therefore investigated in a later chapter.

No fatigue cracks initiated on corroded specimens from the corner of the specimen, unlike the uncorroded tests. This shows that, with the presence of IGC and its related features, fatigue crack initiation moves from the corner to either a corrosion pit on the bore of the hole, or a corroded inclusion deeper into the material.

5.9.1: Causes of inaccuracy for knock-down factor of cycles to first visible crack

The main inaccuracy of the final knock-down factor (based on cycles to crack initiation) was the resolution of the crack camera, both in terms of physical resolution and the number of images per specimen. At the time of testing, the final characteristic to base the knock-down factor on was unknown, so a balance needed to be struck between detecting a small crack and being able to see both satellite holes. Due to the physical resolution of the camera and lens combination, the smallest detectable crack size was 890 μm. This means a crack must be bigger than this for it to be detectable using the crack camera.
In the initial stages of testing, it was decided to use 2,000 cycles of constant amplitude between each marker band to give a useable number of camera images and bands for post-failure fractography without affecting crack growth significantly by introducing a large number of marker bands. Unfortunately, at the completion of testing it was discovered that this did not give enough camera images during the crack growth phase, meaning there may have been a large gap between a non-visible crack and one that is detected; for example, if a crack is imaged at 870 μm (not visible), it has a large portion of the 2,000 cycles of constant amplitude loading to grow well beyond the visible limit. This resulted in the largest “first visible crack” of 1.21 mm.

One method to increase the accuracy of the number of cycles to crack initiation is to adjust the actual number of cycles to a set number (e.g. exactly 1 mm or 1.27 mm as used in the AP-3C lifeing) based on the crack growth curves (as demonstrated by Yang et al [114]). However, due to the small number of images during the crack growth phase, accurate crack growth curves cannot be made. It is also believed that the increase in accuracy may be limited due to the inherent error in measuring when a crack is first visible only using a computer monitor.

5.10: Conclusion

Fatigue testing of both corroded and uncorroded DNH fatigue specimens found that there is a fatigue life reduction caused by the presence of IGC. A good linear correlation was found between the knock-down factor for the number of cycles to the first visible crack of each specimen and their respective deepest initiating defect found. Further investigation is required, however, to attempt to develop a model that can predict fatigue initiation depths, which can then have the appropriate knock-down factor applied to aid in lifeing the DNH on the AP-3C Orion. Also in need of investigation are the reasons why fatigue initiates at these locations and not at the corner of the main hole in the specimen as with the baseline tests. Finally further investigation is required as to why there is a limiting depth of fatigue initiation from corroded inclusions; is this absolute, or is it possible to have fatigue cracks initiating
from deeper in the material? If it is possible, according to the fatigue test results presented here, very large knock-down factors could be achieved.
CHAPTER 6: DEVELOPMENT OF A MODEL FOR IGC TO UNDERSTAND EARLY CRACK INITIATION

6.1: Introduction

Results of fatigue testing show that the presence of IGC seemingly causes a decrease in fatigue life that could be relatable to the deepest initiation depth measured, but did not give an indication as to what is actually causing it? Why do some specimens fail from pits whereas others fail from ahead of the pit? An FE model was developed to investigate these phenomena. This chapter describes this model and how its predictions can explain the observed fatigue behaviour of the IGC specimens.

6.1.1: Importance of Developing an IGC Model

A computer-based model presents the most efficient method of determining the cause of the fatigue life reduction, rather than exhaustive metallography of the numerous fatigue specimens it would take to determine this cause. Not only is the number of specimens an issue, so too is the time required, with corrosion of the specimens taking four to eight weeks and testing a further four. It is possible to achieve the same number of representative corrosion specimens analysed with just one run of an appropriate model.

One other concern is the amount of material it takes to achieve an accurate result. Due to the presence of surface corrosion, each hole requires approximately 20 mm by 20 mm of material to ensure this surface corrosion does not overlap to keep the local corrosion condition in each hole completely separate. To get a meaningful result, a significant number of specimens are needed, meaning a large quantity of material is required. As discussed in Chapter 4, new material cannot be substituted for the legacy-era material being studied. This means using up valuable material that is hard to come by.
6.1.2: Requirements for an IGC Model

Any model that is developed needs to accurately represent the structural integrity effects of IGC, both in terms of fatigue initiation and crack growth. As discussed in the Introduction, there are many unknowns with respect to the interaction of fatigue cracks and IGC fissures, from whether they will result in any change in crack growth rates to whether the crack initiation mode will change. Any model produced must account for these changes and be supported by experimental results.

6.1.3: Investigation of Possible IGC Models

The initial stage of the modelling work involved investigating several candidate models and deciding on a particular model to work with. Five different, currently available, models were investigated for their positives and negatives and how well they might be able to model the structural integrity effects of IGC. The models examined were:

1. Alteration of the current beta solution
2. Soft inclusion model
3. Equivalent crack size model
4. Brick wall model
5. Mode II failure model

6.1.3.1: Alteration of the Current Beta Solution

As discussed in the Introduction to this chapter, the current lifeing methodology of the RAAF AP-3C Orion uses a mixture of FAMS strain lifeing for the crack initiation phase and FASTRAN for the crack growth phase [18]. Due to the non-standard geometry of the DNH, a custom beta solution is used in FASTRAN that relates the far-field stress to the local stress intensity factor. This beta solution was developed [105] through a number of fatigue tests with crack growth measurements to determine crack growth rates at various crack length intervals.
It can also be developed through finite element methods; however experimental validation still needs to take place.

The AP-3C beta solution was determined [105] using un-corroded specimens; by completing the same methodology on corroded specimens, a relationship can be found to relate far field stress to a stress intensity factor for the corroded section near the hole. Being able to have that relationship for just the corroded section means this model could be incorporated into the current inspection method as IGC depth is measured using ultrasound during deeper maintenance.

Developing this model would require a large number of corroded specimens to be tested to develop crack growth rates for the corroded regions in each test. This would not only involve a large amount of material being used, it also involves a large amount of post-test analysis to measure crack camera results or marker bands.

6.1.3.2: Soft Inclusion Model

The soft inclusion model, as discussed in Section 2.4.2.2, was developed by the National Research Council in Canada for modelling exfoliation corrosion around countersunk holes [12]. The model involves representing the corroded area in MSC/MARC as an area of reduced stiffness, to represent the reduction in load carrying ability of the material. This stiffness reduction was used to develop a new beta solution for crack growth modelling in AFGROW.

This work involved a combination of FE modelling and experimental validation to determine an appropriate value for the stiffness reduction [12]. An initial starter value was chosen and a fatigue life determined (from the new beta solution). The stiffness value was then altered and a new fatigue life determined. This continues until the stiffness value gives an appropriately accurate fatigue life.

This model worked well for exfoliation due to the large corroded area typically present with this form of corrosion. To transfer this to IGC might be less accurate due to the small corroded
area associated with IGC (as corrosion strikes are generally less than 10 µm thick). As found using the Brick Wall model, the change in stress field associated with just an IGC fissure compared with an un-corroded DNH is very small, meaning using this form of model may not produce the accurate results found when modelling exfoliation.

6.1.3.3: Equivalent Crack Size Model

The equivalent crack size model has been used by DSTO to good effect for pitting in both aluminium and steel. As discussed in Section 2.4.1, this involves modelling the pit as an equivalent fatigue crack that gives the same fatigue life [4]. The ECS is determined by calculating the fatigue life of the specimen with a first approximate guess at the ECS. The value for ECS is then altered with each successive analysis until the predicted fatigue life matches the actual fatigue life of the corroded specimen. An ECS value can also be calculated from crack growth curves by back-calculating crack growth to the initiating size.

As the equivalent crack size requires a number of fatigue tests to determine a significantly accurate, this method would require a large amount of material. This method also does not take into account any possible changes in crack growth rate due to the presence of IGC.

6.1.3.4: Brick Wall Model

The brick wall model has been used to predict the path of IGC through aluminium alloy 2024-T3 by representing the material as a “field of grains” where the IGC path grows through. It was first proposed by Zhang et al. [108] and Ruan et al. [106, 107], who used it to predict the shortest path possible for IGC growth in this material. This purely mathematical model uses the grain size distribution and probability that the corrosion path will turn or continue straight at a grain boundary junction. Validation for the Ruan et al. [106] model was completed using foil penetration tests [107].
This type of model can be used to create a corrosion path which can be imported into a finite element program for stress analysis. The benefits of this model are that it is purely mathematical, meaning minimal material needs to be used for validation (only foil penetration type tests would be required, rather than the extremely large amount of material required for a full experimental test program as discussed in Section 6.1.1). Basing a model on that done previously from Zhang et al. [108] and Ruan et al. [106, 107] means validation can be based on their work as well as other methods.

**6.1.3.5: Mode II Failure**

Mode II failure refers to failure due to out-of-plane bending, often seen in carbon fibre due to delamination. This failure mode was discussed in a meeting with RMIT Professor Dr Chun Wang [115], an expert in fracture mechanics and the failure of composite materials. This mode was brought up due the possible out-of-plane loading due to the fastener and how that may cause the IGC to turn into a fatigue crack and turn towards the surface, something Professor Wang had seen similar results in composite materials.

**6.1.4: Selection of Suitable Model**

Comparison of these five models found one stand-out model that showed promise of being able to create a model to describe the structural integrity effects of IGC. The first three models, the Beta solution alteration, the Soft Inclusion and the ECS models, all require a large number of experimental replicates to determine the various factors required. They also have not been applied to IGC; while pitting and exfoliation grow under similar corrosion conditions [5], their final forms are quite different from IGC. Also while the Beta solution and Soft Inclusion models can account for changes in crack growth rate, the ECS model cannot.

The Mode II model, while appropriate elsewhere, is not applicable to the AP-3C. The fastener within the DNH is not an interference fit and does not carry a large out-of-plane load; the only load is from the aerodynamic and weight loading of the engine nacelle, which may produce some secondary bending and promote Mode II cracking, however it is believed this is a small effect.
Therefore the stand-out model is the Brick Wall model. Not only has it been specifically developed for IGC, it can also be made using a mathematical program that can write to a Python script, which can be directly input into ABAQUS for stress analysis.

6.2: Background of Selected Model

6.2.1: Brick Wall Model for Describing IGC Paths

Zhang et al. [108] and Ruan et al. [106, 107] developed a statistical model to describe the relationship between the microstructure of 2024-T3 and the IGC growth rate of the material based on data from foil penetration tests [117, 118] and microstructural measurements. The statistical model treats the grain structure as a brick wall with the minimum path length calculated from the number of grain junctions met through this brick wall. The results of this model can predict the ratio of shortest IGC path length for various orientations of corrosion growth [106].

A different approach was taken in the current work to develop this path prediction model; a Monte-Carlo Markov Chain simulation was used to create a step-by-step progression for the IGC path that allows for determination of position coordinates at any point along the path.

6.2.1.1: Monte-Carlo Markov Chain Simulations

As a Monte-Carlo Markov Chain contains a number of steps, where each step is only influenced by the preceding step, it is ideal for a Brick Wall model. As discussed in Sections 1.2.1: and 2.1.1.1: , IGC forms by corroding along grain boundaries. Looking at a simplified 2-Dimensional case, in this extruded material, IGC first forms in the LT direction along the length of grains. It continues in this direction until it reaches a grain boundary junction, where it either turns up or down and head in the ST direction, along the width of a single grain before continuing along the length of the next grain, as illustrated in Figure 81. This will continue until the corrosion reaches its end point, which is defined by the corrosion length
required by the user. In reality, IGC can progress in the L direction, however as the critical case is nearest the typical fatigue crack path, the LT direction is analysed in more detail.

![Diagram of IGC path](image)

**Figure 81: Two steps of the brick wall model including the decision step**

For the model to accurately describe an IGC path, it has to follow this process by stepping the path individually along the length of grains until a random junction, where it will turn to the grain width direction for one grain before continuing in the length direction. A Monte-Carlo Markov Chain can be set up for this to occur by having two steps; one to describe travel in the LT direction and one in the ST direction. Both steps describe travel along one grain at a time only.

It is assumed that the first step will always occur, as IGC always grows in the LT direction after a step in the ST direction. As growth in the ST direction does not always occur at every grain boundary junction, Step 2 does not always occur.

### 6.2.2: Introduction to Finite Element Analysis and ABAQUS

ABAQUS CAE is a commercially available finite element pre- and post- processor developed by Dassault Systems [27]. The user interface is based on Dassault System’s popular computer aided design program CATIA [119]; as such, building and analysing a simply model is quick and user-friendly. ABAQUS can be used to run a number of different analysis types, from
basic stress analyses through to vibration and buckling analysis [27]. It can also be used for crack growth analysis [96].

As ABAQUS CAE is based on CATIA, construction of a model is graphics-based, with the geometry input using a “draw” function. Other inputs, such as meshing, boundary conditions, loading and material data are all input using a graphical menu bar.

6.2.3: Python Scripting within ABAQUS CAE

Creating complex models with smaller, intricate sections is harder than a basic model (for example, a specimen with IGC is more complex than an un-corroded one), and making numerous, small alterations to a model can become fastidious, with nodal movements tricky. This becomes an issue for a Monte Carlo FE simulation, where one particular feature is changed a number of times; for example an IGC path through the material. If it were to be done by hand, the whole path would need to be re-drawn each time. Using a script, this re-draw process can be automated for each iteration of the model.

A Python script is a file in a particular programming language that ABAQUS reads to create an input file. It contains all the necessary information to build and mesh a model; overall geometry, mesh size requirements, material and property data and loads and boundary conditions. For complete automation it can even have job information and the run command to begin analysis.
6.3: Methodology

6.3.1: Methodology for Describing IGC Paths using Igor Pro

Igor Pro is mathematics and graphics software that allows for coding, known within Igor as Procedures. This section details how the brick wall model is made and applied within Igor Pro, covering the inputs and equations needed as well as the possible analysis outcomes from the model.

6.3.1.1: Basic Model Input Variables

This model, as with the previous Brick Wall Model, requires at least two inputs; the grain size distributions and the probability of the corrosion path turning. This model also incorporates the ability to change the overall length of corrosion. These inputs are detailed below.

6.3.1.2: Grain Size Distributions

In this model, the grain size distributions are input as grain length and width mean and standard deviations, giving four values for this set of inputs. These values were measured using the Linear Line of Best Fit method from optical analysis of wing skin material in Section 3.1: , which were polished and etched using Keller’s Reagent as described in Section 4.2.4: . It is assumed that the material analysed in Section 3.1 is representative of all AP-3C wing skin material as a number of samples were analysed from different locations in the wing skin panel.

6.3.1.3: Probability of Corrosion Path Turning

The probability of the corrosion path ($P_{\text{TURN}}$) turning is based on the corrosion tests from Section 4.5.1: . These specimens were cut into four equal quarters around the hole, polished and etched to reveal the corrosion path and the grain boundaries. Then $P_{\text{TURN}}$ the probability
was determined by simply counting the number of grain triple junctions the corrosion path met, and the number it turned at. The probability was calculated by dividing the number of turns by the number of grain triple junctions. This process was repeated for 47 specimens in total with corrosion lengths from 500 to 3,500 µm.

In addition to the turn probability, another variable was added that specifies the probability that if the corrosion path turns, it will turn left rather than right. This allows a bias to be applied to the corrosion path to analyse extreme cases where the corrosion keeps turning in one direction. It is a user-definable variable. However, it is set to 0.5 by default to produce unbiased growth. Should the user wish to investigate biased growth (if there is a bias in another material towards turning in one direction only), this can be set to a higher probability.

Figure 82 illustrates the fissure propagation actions allowed by the model and shows the probability of each occurring.

\[
\text{Left turn: } P_2 = P_{\text{turn}} \times P_{\text{left}} \\
\text{No turn: } P_1 = (1 - P_{\text{turn}}) \\
\text{Right turn: } P_3 = P_{\text{turn}} \times (1 - P_{\text{left}})
\]

*Figure 82: Illustration of an IGC path turning left or right compared with path continuing straight. The probabilities of each option (P\textsubscript{1} to P\textsubscript{3}) are shown.*

As these are the only three options available in the model then their probabilities must sum to unity:

\[
P_1 + P_2 + P_3 = 1 \tag{11}
\]

Note that the probability of the crack halting at a junction was not considered in the model. This was considered acceptable as the corrosion process was not modelled directly; rather it is the shape of the corrosion path that was modelled. As a result, the electrochemistry and kinetics of the corrosion process were deliberately ignored.
6.3.1.4: Overall Corrosion Length

The overall corrosion length is one of the user-definable input variables – whereas the grain size distribution and turning probability were experimentally determined, the corrosion length varied from 500 to 3,500 µm. Therefore the overall corrosion length was one of the input variables that can be defined by the user. Its default setting was 2,000 µm as this is a rounded number above the crack size limit that needs to be able to be picked up (1.27 mm).

6.3.1.5: Summary of Input Variables

Table 16 is the summary of the required input variables for this Monte-Carlo Markov Chain model to predict the path of IGC through AP-3C wing skin material. $P_{LEFT}$ was assumed to be 0.5 to allow corrosion to turn equally in both directions, rather than bias towards one direction.

Table 16: Summary of Brick Wall Model input variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain Length Mean</td>
<td>$L_M$</td>
<td>76</td>
</tr>
<tr>
<td>Grain Length Standard Deviation</td>
<td>$L_{SD}$</td>
<td>25</td>
</tr>
<tr>
<td>Grain Width Mean</td>
<td>$W_M$</td>
<td>8</td>
</tr>
<tr>
<td>Grain Width Standard Deviation</td>
<td>$W_{SD}$</td>
<td>1</td>
</tr>
<tr>
<td>Probability of Turning</td>
<td>$P_{TURN}$</td>
<td>0.25</td>
</tr>
<tr>
<td>Probability of Turning Left</td>
<td>$P_{LEFT}$</td>
<td>0.5</td>
</tr>
<tr>
<td>Overall Corrosion Length</td>
<td>$L_{CORR}$</td>
<td>User Defined</td>
</tr>
</tbody>
</table>
6.3.2: Application of Input Variables to Brick Wall Simulation

The input variables discussed in Table 16 are taken into Igor and run through a series of equations to determine a corrosion path of an IGC fissure growing from left to right. This section details these equations following a brief introduction to the various terminologies and coding required to analyse those equations.

6.3.2.1: Coding and Terminology in Igor

Igor has a number of commands and functions in its scripting language that do specific operations. The terms used in the Brick Wall model are given below in Table 17.

<table>
<thead>
<tr>
<th>Terminology</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function</td>
<td>String of commands that occur one after another in series</td>
</tr>
<tr>
<td>FOR</td>
<td>Loop command that will continue until a specific condition is met, often a counter reaches a particular number</td>
</tr>
<tr>
<td>IF</td>
<td>Command that will produce one result if a user-defined statement is true.</td>
</tr>
<tr>
<td>Procedure</td>
<td>A number of Functions put together that can operate with other Functions, or independently of them.</td>
</tr>
<tr>
<td>ELSE</td>
<td>Contained within an IF statement that returns a result if the IF statement is false.</td>
</tr>
<tr>
<td>END (IF/FOR/Function)</td>
<td>End of an IF or FOR statement or a function block</td>
</tr>
<tr>
<td>Concatenate</td>
<td>Used to combine data together. In this case, a column of data from within a FOR statement into a 2-Dimesional matrix with the column from each individual FOR loop becoming a specific noise (num)</td>
</tr>
<tr>
<td>enoise (num)</td>
<td>Function that returns a random value drawn from a uniform distribution having a range of [-num, num) [Igor help]</td>
</tr>
</tbody>
</table>

6.3.2.2: Equations Specific to Brick Wall Model

There are four main equations used to create an IGC using the Monte-Carlo Markov Chain that take the input variables given in Table 16 and outputs a single IGC path. The equations
are computed in two stages to allow for separate stepping in the grain length and width direction. These two sets of equations are given below with an explanation of the mathematical steps. In all cases, the new step (“i” position) is based on the previous position, determined by the previous equation (“i - 1”).

At the beginning of the analysis, the LT position \( LT_{pos}(i) \) and the ST position \( ST_{pos}(i) \) are both zero, meaning \( LT_{pos}(1) \) and \( ST_{pos}(1) \) both equal zero.

### 6.3.2.3: Stepping in the length (LT) direction:

\[
LT_{pos}(i) = LT_{pos}(i-1) + \left[ L_M + gnoise(L_{SD}) \right] \\
\]

\[
ST_{pos}(i) = ST_{pos}(i-1) \\
\]

In the first step, there is only movement in the LT direction. As such, the ST position does not change (as given by Equation \( LT_{pos}(i) = LT_{pos}(i-1) + \left[ L_M + gnoise(L_{SD}) \right] \) (12)). In Equation \( ST_{pos}(i) = ST_{pos}(i-1) \) (13), the new position is determined by adding one “grain length” to the previous position in the LT direction \( (LT_{pos}) \). This grain length is determined by taking a random value from the Gaussian distribution (which has a mean of zero) with a standard deviation equal to that of the grain length standard deviation \( (L_{SD}) \) and adding that to the mean grain length. This gives an increment of growth based on the grain length distribution.

### 6.3.2.4: Stepping in the width (ST) direction:

\[
LT_{pos}(i) = LT_{pos}(i-1) \\
\]

\[
ST_{pos}(i) = ST_{pos}(i-1) + \left[ gnoise(1) \leq P_{TURN} \times sign(gnoise(1) + 2 \times (P_{LEFT} - 0.5)) \right] \\ 
... \times \left[ W_M + gnoise(W_{SD}) \right] \\
\]

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The second step only involves movement in the ST direction, so the LT position is fixed (given by Equation \( LT_{pos}(i) = LT_{pos}(i - 1) \) (14). Equation

\[
ST_{pos}(i) = ST_{pos}(i - 1) + \left[ \text{enoise}(i) \leq P_{\text{TURN}} \times \text{sign(enoise}(i) + 2 \times (P_{\text{LEFT}} - 0.5)) \right] \\
\cdots \times (W_M + \text{gnoise}(W_{SD}))
\]

is more complex than the other equations described here as it incorporates the probability of turning, \( P_{\text{TURN}} \), and the direction of this turn, \( P_{\text{LEFT}} \). This equation is broken down into the following terms:

- A uniformly distributed random number was generated (by the enoise function) and was compared to the value of \( P_{\text{TURN}} \). Using Boolean algebra, if the random number was smaller than \( P_{\text{TURN}} \), a value of one was returned (i.e. True) and the equation continues as normal. A value of zero was returned if the random number was greater than \( P_{\text{TURN}} \) (giving a False output), and the result of the step increment was zero.

- Another uniformly distributed random number was generated and compared with \( P_{\text{LEFT}} \). As \( P_{\text{LEFT}} \) had a range from zero to one, an equal probability of turning either way is 0.5. Therefore to balance the effect of \( P_{\text{LEFT}} \), the equal probability returned a value of zero (by subtracting 0.5 from \( P_{\text{LEFT}} \)).

- The multiplier of two allowed a left turn probability of one (thus will always turn left) then \( [P_{\text{LEFT}} - 0.5] \) to be positive one – when combined with the random number generated (between negative and positive one), the result was always positive. This resulted in the corrosion path always moving upwards when it does turn, thus turning left (when viewing the turn from the point of view of the tip of the fissure, as it is growing from left to right). The opposite is true if \( P_{\text{LEFT}} \) is zero (the multiplied result is negative one).

- As with the previous step (in the LT direction), a random variable is taken from a Gaussian distribution based on the grain width (ST direction) standard deviation and added to the grain width mean to determine the step increment.

- The results of \( P_{\text{TURN}} \) (zero or one) is combined with the result of the \( P_{\text{LEFT}} \) section (the sign of a positive or negative random number, so basically positive or negative one) and multiplied by the step increment to determine firstly if there would be a change in the ST position, and secondly if that change was positive (indicating a left turn) or negative.
6.3.2.5: Combining the two steps

These two sets of equations (equations \( LT_{pos}(i) = LT_{pos}(i-1) + [L_M + gnoise(L_{SD})] \) (12) to \( ST_{pos}(i) = ST_{pos}(i-1) + \left[\text{noise}(1) \leq \mathcal{F}_{\text{TURN}} \times \text{sign(noise}(1) + 2 \times (P_{LEFT} - 0.5)) \right] \times (W_M + gnoise(W_{SD})) \) (15)) are set up to be analysed one after another in a loop until an end point is reached, in this case the end point is when the LT position of the last step was greater than the corrosion length specified. The loop was made using a FOR command, where the FOR loop counter counts from zero to a variable “\( C_{LC} \)”, where:

\[
C_{LC} = 2 \times \left( \frac{L_{CORR}}{L_M} \right)
\]  

(16)

To separate the two steps, there is an IF statement within the FOR loop that tests whether the counter is an even or odd number. If the counter is even, the step in the LT direction was completed and when the counter is odd the ST step is completed. This is why the equation for \( C_{LC} \) is multiplied by two.

The FOR loop is set out as follows:

\[
\begin{align*}
\text{FOR} & (n = 0, n < C_{LC}, n + 1) \\
\text{IF} & (n = \text{even}) \\
& \text{LT Steps} \\
\text{ELSE} \\
& \text{ST Steps} \\
\text{ENDIF} \\
\text{ENDFOR}
\end{align*}
\]  

(17)
For each step, the position in both the LT and ST direction is recorded by treating $LT_{pos}$ and $ST_{pos}$ as a single column matrix, with each row corresponding to each successive counter value. Thus Equation $LT_{pos}(i) = LT_{pos}(i - 1)$ (14) would become:

$$LT_{pos}[i] = LT_{pos}[i - 1]$$  \hfill (18)

### 6.3.2.6: Grain Size Distribution Selection

The grain size mean and standard deviations are used to create normal distributions of both the grain length and grain width. The gnoise function, which is a Gaussian random number generator within Igor Pro, is then used to select a step size for the length and width steps respectively. Figure 83 shows the grain length and width distributions compared to the predicted distributions based on the mean and standard deviation alone. A Gaussian distribution shows good correlation for both the grain length and width with an $r$-squared value of 0.98 and 0.99 respectively when compared to a perfect fit where the predicted value is equal to the actual value. A T-Test was also conducted and showed both sets of data fit well with a normal distribution.

![Figure 83: Grain length (a) and width (b) distributions compared with their respective normal distributions based on mean and standard deviation](image)

Given distribution used does have the possibility of the value being negative (in extreme circumstances), an IF statement was set up to put a limit on the low values. The IF statement for Equation $LT_{pos}(i) = LT_{pos}(i - 1) + [L_M + gnoise(L_{SD})]$ (12) was set up as follows:
Let \( d = L_M + gnoise(L_{SD}) \)

\[
IF[d] \leq 40 \\
\quad [d] = 40 \\
ELSE \\
\quad [d] = [L_M + gnoise(L_{SD})] \\
ENDIF
\]

This results in the minimum value for the step increment in the LT direction is 40 μm by forcing the step increment to that value if the resulting step size is less than 40 μm was chosen as it is just below the minimum grain length found during analysis of the corrosion specimens.

### 6.3.2.7: Analysis of Multiple Corrosion Paths

The FOR loop can be run multiple times to create a number of corrosion paths using the one Function. This allows for the creation of a corrosion path distribution and gives the ability to analyse a number of corrosion paths with one run of the script. This is incorporated using another FOR loop, with indexing variable \( m \), outside the path generation FOR loop (indexing variable \( n \)) as shown below.

\[
FOR(m = 0, m < N_I, m + 1) \\
\quad FOR(n = 0, n < C_{LC}, n + 1) \\
\quad \quad IF(n = even) \\
\quad \quad \quad LT \text{ Steps} \\
\quad \quad ELSE \\
\quad \quad \quad ST \text{ Steps} \\
\quad \quad ENDIF \\
\quad ENDFOR \\
ENDFOR
\]

Where \( m \) is the counter variable and \( N_I \) is the number of iterations to be run. To ensure each corrosion path is independent, before the path generation FOR loop both \( LT_{pos} \) and \( ST_{pos} \) are
set to zero. This also resulted in each random number being generated independently with each run.

Each corrosion path is recorded into a table (with $N$ columns and $C_{LC} / 2$ rows). This takes each generated corrosion path and places in the corresponding column (based on the value of $m$). The end result is two tables full of corrosion paths (separated into two tables, one containing $LT_{pos}$ and the other $ST_{pos}$) that can then be analysed further.

### 6.3.3: Maximum vertical deviation of IGC Paths

The maximum vertical deviation is the change in vertical position of the end point in relation to the origin, in other words how far the corrosion path has moved upwards or downwards in the ST direction. This was chosen as a damage statistic due to the possibility of a “shielding” effect that IGC may have on the stress field around the hole – if the IGC path travels in an overall downwards direction as it grows, it is possible for it to shield the lower side of the IGC and cause an increase in stress on the upper side (as shown by the results of an FE analysis shown in Figure 84 where higher stresses are shown in red and lower in blue).

![Figure 84: Extreme example of shielding effect of IGC using an unrealistic path (highlighted in white) with the maximum stress location shown by the white arrow](image)

The maximum vertical deviation is determined by querying the values of each column in the $ST_{pos}$ table in the final row. These values are then concatenated into their own table where each row corresponds to each column in the ST table (row 1 corresponds to column/path 1, row 50 corresponds to column/path 50 and so on).
From there, an IF statement was used to determine the largest absolute value of $ST_{pos}$ and that result (and the path number) is printed in the command window. This result was also used to create a table containing the path with the largest vertical deviation.

6.3.4: *Creation of an Automated Script for Stress Analysis of IGC Path*

This section will detail the steps taken to create the automated script, displayed in full in Appendix 2 which will produce the input file required for ABAQUS to analyse the IGC path.

6.3.4.1: *Extracting Base Script from ABAQUS*

The first step in creating the automated script was to extract an example Python script from ABAQUS to base it on. This was completed by manually creating a model within ABAQUS with a hand-generated IGC fissure; the shape or thickness of the fake IGC was of no importance as this model was only to get the layout requirements of the Python script.

The Python input script is read by ABAQUS in the order it is written. This means the script needs to be written with the geometry first, followed by material properties, meshing, loading and boundary conditions and so on. The input script was contained within the .rpy file, which is a transcript of the various commands used to create the model. As such, it was already in the order required; all that needed to be done was to copy the bulk of the script into Igor.

The sections of the script copied contained the model information that does not change such as the baseline geometry (of the plate and hole), material properties, mesh size and loading and boundary conditions.

6.3.4.2: *Exporting a Text File from Igor*
Exporting a text file from Igor is carried out using the fprintf command. This allows text to be copied into an already-opened file (using the Open command, which allows a file to be saved with a specified file name and extension) exactly as it appears within a set of quotation marks. An example of the fprintf command is given below – in this case, the command prints the lines required to specify the material properties.

```plaintext
fprintf refNum,"mdb.models['Model-1'].Material(name='Aluminium')\n
mdb.models['Model-1'].materials['Aluminium'].Elastic(table=((210000.0, 0.3), ))\n"
```

The fprintf command will carry through tab and space characters (which the Python script is very sensitive to) through to the text file by using the standard keys on a keyboard, however return carriages are not. Standard characters for a return carriage did not work, such as \r. It was found that the UNIX standard Newline command had to be used which contains a carriage return command followed by line feed (\r\n). Therefore, the above command produces the following lines in the text file.

```plaintext
mdb.models['Model-1'].Material(name='Aluminium')

mdb.models['Model-1'].materials['Aluminium'].Elastic(table=((210000.0, 0.3), ))
```

6.3.4.3: Finite Element Model Setup

The finite element model was based on a simple plate-with-hole, modelled as a quarter-body due to symmetry. The dimensions of the plate were 40 mm x 40 mm (so the overall dimensions without symmetry would be 80 mm x 80 mm) and it was 2.023 mm thick (to replicate the AP-3C wing skin material). Symmetry boundary conditions are applied in the X and Y directions, shown below in Figure 86. Z symmetry was not considered as the IGC path is not symmetric about that plane. A 6.35 mm (1/4 inch) diameter through-drilled hole was placed at the corner of the model to represent a typical fastener hole found on the AP-3C. The satellite holes were not included as the fatigue initiation analysis was comparative between the corroded and un-corroded models. It is assumed that the effect of the satellite holes on the
un-corroded and corroded samples was the same as the satellite holes are not corroded, and thus will remain unchanged. Removing the satellite holes simplifies the model greatly. In later versions of the model, these values (plate size and main hole diameter) can be changed to model other possible fastener holes. The base FE model is shown in Figure 85.

![Base FE model showing orientation of the hole with respect to the length and width](image)

*Figure 85: Base FE model showing orientation of the hole with respect to the length and width*

The model used standard material properties for 7075-T651 aluminium alloy with a Young’s Modulus of 210 GPa and a Poisson’s Ratio of 0.3 [120]. The mesh was set to a global size of approximately 100 μm due to the relative coarseness of the model details and to give an acceptable trade-off between accuracy and computation time. The global size was set for the sections away from the IGC path – when that was input, the mesh size was set to the geometric nodes of the IGC path, which in most cases result in a mesh size smaller than 100 μm. This means a global size closer to the minimum possible step size (of 40 μm) did not result in an increase in accuracy. The model used 10-node quadratic tetrahedron elements due to the complex shapes of the IGC path (hexagonal elements would not mesh at all).

A tensile load of 1 MPa was applied to the model to allow for the easy calculation of stress concentration factors. As the specimen was straight-edged (with no dog bone waisting), the applied stress is the same as the far-field stress. $K_t$ was calculated by dividing the peak stress in the model by the applied stress. By applying a 1 MPa stress, the stress concentration factor is numerically equal to the peak stress.
Figure 86: FE model showing applied load and boundary conditions. Y-symmetry was achieved by constraining the y-displacement and x and z rotational degrees of freedom (DOF) while X-symmetry was achieved by constraining the x-displacement and y and z rotational DOFs.

6.3.4.4: Incorporating IGC Path into FE Model

The IGC path was incorporated into the FE model by taking the co-ordinates of each individual point in the path, applying a thickness to it and cutting it into the base model. The co-ordinates were taken from the concatenated table of paths or from the “damage statistics” path tables, such as the table containing the path with maximum vertical deviation.

The thickness was applied to replicate realistic IGC – a value of 3 μm was used based on measurements of IGC found in corroded specimens. The thickness of the actual IGC path varied from approximately 4.5 μm near the initiating pit to 1.5 μm towards the end of the IGC. This thickness was applied using a number of equations applied to two new tables, in this case based on the maximum vertical deviation path.

A new table is created which has the FE model co-ordinates of the original maximum deviation path. The $ST_{pos}$ values are the same however the $LT_{pos}$ is taken from the edge of the
hole in the FE model, with the original value transposed based on the hole diameter. The
equation used is given below, where $D$ (diameter of the hole) is in μm:

$$LT_{posMDO} = LT_{pos} + D$$

(21)

The second of the new tables, $MaxDev$, is the new path to incorporate the IGC path thickness.
The vertical thickness was simple to apply using the equation below, where 3 μm were added
to the $ST_{pos}$ value.

$$ST_{posMD} = ST_{pos} + 3$$

(22)

The horizontal thickness was more complicated to apply as the direction of transposing the
new point takes depended on which direction the path turns, as shown below in Figure 87.
Figure 87: Diagram of IGC path (shown with the solid blue lines, growing along the arrows) turning and the respective locations of the new path co-ordinate which is always vertically above the original point (shown in green) to account for thickness (shown between the blue solid and dashed lines). The black arrow indicates the relative change in position of the new point (green) from the original (black corner point).

This dependence on the path turn direction was accounted for by examining the vertical position of the point at the turn, as well as the point before and point after. These values are put into the following equation, which is further demonstrated in Table 18.

\[
LT_{posMD} = LT_{posMDO} - \left[ (ST_{pos}(i) - ST_{pos}(i-1)) + (ST_{pos}(i+1) - ST_{pos}(i)) \right] \\
(23)
\]

Table 18: Examination of individual terms for \(LT_{posMD}\) equation showing results for differing turn types

<table>
<thead>
<tr>
<th>Turn</th>
<th>Required Value</th>
<th>(1): (ST_{pos}(i) - ST_{pos}(i - 1))</th>
<th>(2): (ST_{pos}(i + 1) - ST_{pos}(i))</th>
<th>([-((1) + (2))]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>Negative</td>
<td>Zero</td>
<td>Positive</td>
<td>Negative</td>
</tr>
<tr>
<td>Type 2</td>
<td>Positive</td>
<td>Zero</td>
<td>Negative</td>
<td>Positive</td>
</tr>
<tr>
<td>Type 3</td>
<td>Positive</td>
<td>Negative</td>
<td>Zero</td>
<td>Positive</td>
</tr>
<tr>
<td>Type 4</td>
<td>Negative</td>
<td>Positive</td>
<td>Zero</td>
<td>Negative</td>
</tr>
<tr>
<td>Straight</td>
<td>Zero</td>
<td>Zero</td>
<td>Zero</td>
<td>Zero</td>
</tr>
</tbody>
</table>

These four equations that create two paths (separated by 3 μm) were then placed in the Igor code using the fprintf function in the format required for the Python script. To create the IGC path, a Profile was created based on these two paths with each point joined to the preceding one using the Line function, which is the function within ABAQUS for drawing lines. This function follows the format of a line drawn from Point 1 to Point 2 in a particular profile of Model-1. The first line in creating the IGC path is shown below.

```plaintext
Fprintf refNum,"mdb.models['Model-1'].sketches['__profile__'].Line(point1=(%g, %g), point2=(%g, %g))
LT_{posMDO}(0), ST_{posMDO}(0), LT_{posMDO}(1), ST_{posMDO}(1)
```

- 150 -
One added feature of the fprintf function is the ability to incorporate variables using the \%g symbol shown above. The assigned variables were placed in order at the end of the command line, meaning the first variable in the above code replaces the first \%g symbol and so on. By doing this, the actual values for each point could be taken from the path tables. In the case of the above command, the line was drawn from the initial point of the original maximum deviation path to the first point after the initial one (Igor begins tables with row zero, not one).

This command had to be repeated for every line in the IGC path – no command existed to specify a number of points a profile must travel through. To reduce the complexity of having a large number of separate commands for this, two FOR loops were created to step the profile from the origin to the end point along the original path, then to step the profile back from the end point to the origin along the offset path to give the IGC path thickness. These FOR loops add a line of code describing each successive line for the IGC profile. The first FOR loop is shown below which counts from the origin to the end of the path.

\[
\text{FOR}(t = 0, t < C_{LC} \cdot t + 1) \\
\text{fprintf(\text{refNum}, "\text{...Line}(\text{point1} = (\%g, \%g), \text{point2} = (\%g, \%g))\" ...} \\
\text{...LT}_{posMDO}(t - 1), \text{ST}_{posMDO}(t - 1), \text{LT}_{posMDO}(t), \text{ST}_{posMDO}(t) \\
\text{ENDFOR}
\]

The second FOR loop which counts from the end point back to the origin is shown below. Hence the change in order for the counting command after FOR. Between the first and second FOR loop was a command that draws a line between the end point of the original path and the end point of the offset path to ensure a connected profile.

\[
\text{FOR}(u = C_{LC} \cdot u > 0, u - 1) \\
\text{fprintf(\text{refNum}, "\text{...Line}(\text{point1} = (\%g, \%g), \text{point2} = (\%g, \%g))\" ...} \\
\text{...LT}_{posMDO}(t - 1), \text{ST}_{posMDO}(t - 1), \text{LT}_{posMDO}(t), \text{ST}_{posMDO}(t) \\
\text{ENDFOR}
\]
The path, with its realistic thickness of 3 µm, was then cut into the FE model geometry using the Sweep method, centred about the centre of the hole and following the arc of the hole. This means that at any angle around the fastener hole, the path will be exactly the same. The Sweep cut method was used to provide a simple, but quick, method of analysing the stress field around IGC, particularly focusing on the area where fatigue was likely to initiate from.

Another method for incorporating an IGC path into an FE model is through a Voronoi tessellation [121]. However, the level of detail achieved by using a Voronoi tessellation analysis to create a three-dimensional path [122] requires significantly more computing power and/or time – this Brick Wall model can be run on a basic laptop, meaning analyses could be conducted in the field. The added detail of a Voronoi analysis is simply not required, particularly as a fastener hole is involved; the stress fall-off is quick enough that any feature likely to cause structural integrity issues will be close to the bore of the hole and in the area of highest stress, rendering the added detail of the Voronoi analysis for the whole path unimportant.

6.3.5: Inclusion of Realistic IGC Features in FE Analysis

Intergranular corrosion rarely, if ever, grows on its own. The typical growth of IGC in the AP-3C, as discussed in Section 1.2.2, involves a pit forming down the bore of the hole, with IGC forming from the tip of the pit. This was observed in a number of fatigue specimens that contained IGC growing from the tip of a pit on the fracture surface, an example of which is shown in Figure 88. There were a few cases where the IGC present on the fracture surface did not have an associated pit, however the a visual inspection of the bore of the hole showed a pit in line with the IGC located at another point around the hole. These cases generally resulted in IGC on the fracture surface however no crack initiation was associated with that particular IGC fissure.
One feature of this form of IGC is the presence of corroded inclusions along the IGC path. As the corrosion grows along grain boundaries, it reaches inclusions that have formed during the heat treatment process. As these inclusions have a different electrochemical potential to the precipitates along grain boundaries (which corroded to produce IGC in the first place), some of these inclusions will be preferentially corroded before the IGC continues (i.e. once the inclusion has been corroded completely). This produces a void in the material near the IGC path, as shown in Figure 89.
Figure 89: Examples of corroded inclusions found on fracture surfaces

6.3.5.1: Incorporating Surface Pits into IGC Path Script

Surface pits were represented as a void at the bore of the hole, located at the start of the IGC path along the bore of the hole. Initially, three different shapes were trialled to determine which was the most representative. Two types of elliptical arcs were tested, one with an axis...
of rotation about the edge of IGC (so the LT direction), the other with its rotation axis about the ST direction. The third shape was an extended hemispherical shape with an axis of rotation about the T direction.

The resulting stress concentration of each was manually tested for the same depth and width of pit. The least stress concentration came from the elliptical shape with an axis about the ST axis while the highest stress concentration was from the extended hemispherical shape. Examples of these two pit shapes are shown below in Figure 90.

![Figure 90: Example of (a) elliptical pit shape and (b) the extended hemisphere shape](image)

The extended hemisphere also proved to be the easiest to incorporate into the Igor script. Every geometrical feature in ABAQUS has a geometry “number” assigned to it which is used for any alterations made by the Python script. This means that to draw a pit shaped as an ellipse, the ellipse shape is drawn first followed by a vertical line at the bore of the hole, to split the ellipse in two parts. These two parts are then given their own geometry number that any subsequent action uses, such as trimming the ellipse to remove the excess.

Geometry numbers are also assigned to every line in the IGC path, which has a random number of lines as the number of turns and jumps changes each iteration. As the geometry numbers for the pit shape are assigned after the IGC path, the exact number for the ellipse changes, meaning determining the actual value within the script (before the model is made)
was very difficult. For this reason, the extended hemispherical pit shape was used as it could be drawn with lines and arcs, which are all specified by points rather than geometry numbers.

An issue was found when creating the pit shape as it needed to be pinned to a “face” on the model – this face was chosen based on its geometry number. As with the previous pit shape issue, this number changes with each successive IGC path. The solution to this problem was to change the face the IGC path was drawn – instead of drawing it on the TS plane and cutting it through the material, it was drawn on the LS plane and cut through to the TS plane after the pit shape was made.

The pit shape was drawn by making an arc shape to form the tip of the pit at the required depth and width (the centre, start and end points are all specified for an arc). From there, straight lines were drawn to complete the shape of the pit, with a construction line set in the LT direction to form the axis of rotation, giving the pit shape shown in Figure 90 (b).

6.3.5.2: Incorporating Corroded Inclusion into IGC Path Script

The next step in developing the model was to include a corroded inclusion along the IGC path. This corroded inclusion was represented as a spherical void at a grain boundary junction. The location could either be specified or placed randomly through the use of an IF statement. Grain boundary junctions were chosen as were the easiest points to find a coordinate position along the IGC path. Another IF statement was used to determine the size of the void.

6.3.5.3: Combining both Surface Pits and Corroded Inclusions in IGC Path Script

An attempt was made to combine both the surface pits and the corroded inclusions into the one command in the script, whereas previously these analyses were completed separately. It was too difficult to make the pit shape then put the inclusion in (or vice versa) to make it worthwhile as specifying the location of either requires a “face” to be selected by a geometry
number. As with the previous issues found using geometry numbers, each successive IGC path creates a new set of geometry numbers, even with the pit and inclusion shapes drawn first.

The obvious solution was to draw both the pit and inclusion shapes in the same command as only one “face” geometry number would need to be selected. This resulted in a problem in ABAQUS with it not being able to cut two separate closed shapes (as the pit and inclusion are separate) into the model at once. As such, an analysis was conducted comparing a number of pits and inclusions drawn manually in ABAQUS to determine if they had any effect on each other by analysing them separately and together.

It was found that the results of each pit and inclusion run individually matched the results of when they were analysed together, as shown in Figure 91. Therefore it was possible to determine the results individually and still be able to compare them as if they were analysed together, the only downside being the extra computation time required. In both cases, mesh control was used to specify a finer mesh around arcs. As quadratic elements were used, a coarser bulk mesh could be used, as long as the mesh accurately described the underlying shape (too coarse around arcs, especially the inclusions, resulted in circles described as octagons or similar).

Figure 91: Finite element model run with (a) both a pit and inclusion together (inclusion is further along the IGC path, off the screen), and (b) separately with just a pit showing no difference in the stress concentration of the pit
6.4: Results

Presented here are the results of the development of a finite element model described above. These results are split into three sections for the three stages of model development – firstly, the result of the brick wall model are presented, followed by the stress analysis of IGC alone using the paths predicted by the brick wall model. The final section will present the results of incorporating surface pits and corroded inclusions to the model.

6.4.1: Brick Wall Model

6.4.1.1: Calculation of \( P_{\text{TURN}} \)

\( P_{\text{TURN}} \) was calculated using the corrosion protocol test specimens described in Chapter 4. These polished specimens were etched with Keller’s Reagent to reveal the grain structure and the IGC path was followed from the bore of the hole to the end using an optical microscope. The value for \( P_{\text{TURN}} \) was determined by counting the total number of junctions the IGC path met and the number of junctions the IGC path turned at for various lengths of IGC. These totals are shown in Figure 92, where each set of data points represents the IGC fissure found on a number of individual corrosion specimens.
Figure 92: Total number of junctions met versus number of turns

Figure 92 shows that $P_{\text{TUR}_N}$ was not dependent on path length as the number of turns at junctions increased at the same rate as the total junctions met. Due to this, a constant value could be used to relate $P_{\text{TUR}_N}$ to the corrosion length, rather than a relationship based on the corrosion path length. A turn probability of 0.253 was used to represent IGC in the AP-3C wing skin material.

6.4.1.2: Single Path Analysis

The first step in producing an IGC stress analysis model was to use the IGC path model (based on the Brick Wall models described by [106-108]) to create IGC paths. Shown in Figure 93 are four different IGC paths taken from separate runs of the IGC path model script. These paths show the variation in grain sizes calculated for each step and how that relates to the location of each step along the paths.
6.4.1.3: Multiple IGC Path Distribution

The next step in expanding the IGC model was to incorporate a number of IGC path analyses into one run of the model. As described previously, the user-defined variable $N_I$ is used to describe the number of corrosion paths to be analysed within one model run. Figure 94 shows the distribution of 10, 100, 1,000 and 10,000 IGC paths, showing the increase and eventual asymptote of the maximum vertical deviation.
6.4.1.4: Damage Statistics within Multiple IGC Path Analysis

The IGC path model has the ability to output the path co-ordinates for any path selected, as well as find the paths with the highest damage statistics, namely the path with the largest maximum vertical deviation, shown on one of the output graphs, Figure 95.
Maximum deviation was chosen to test the hypothesis of stress shielding causing an increase in stress on one side of the IGC fissure, and thus causing a bias to one side for fatigue crack initiation. This hypothesis of stress shielding is shown in Figure 84 where an extreme representation of IGC was analysed, highlighting the differences in the stress field above and below the IGC fissure.

As shown in Figure 94, the maximum vertical deviation asymptotes shortly after 1,000 paths, it was decided that the possibility of a larger vertical deviation with 10,000 paths was not required. With 1,000 paths to analyse, the model can easily run on a standard desktop or laptop computer in just over one minute, whereas it can take up to twenty minutes to run 10,000 paths.
6.4.2: Stress Analysis of IGC Path

Following on from the generation of IGC paths, they were placed into an FE model and analysed to determine the resulting stress field. This was to determine if there was any change to the peak stress or if any local stress concentrations developed due to features of the IGC path.

In all the following analyses, the location and magnitude of the peak stress was measured from the FE model output and converted to a stress concentration factor \( K_t \) by dividing it by the far-field stress. To allow for easy calculation of \( K_t \), the applied load was 1 MPa meaning the peak stress was already normalized against the far-field stress.

6.4.2.1: Basic Stress Analysis

Shown in Figure 96 is the completed FE model, prior to submission to the ABAQUS solver. The IGC model creates the path co-ordinates, gives it thickness and places it in the plate-with-hole model shown below using the Arc method discussed previously. The IGC model automatically applies the mesh, loading and boundary conditions shown below. Figure 97 shows a close up of the IGC path to highlight the thickness it is given.
Figure 96: Example of the completed FE model with IGC path, loads and boundary conditions. Mesh has been omitted to simplify image (as mesh is very dense)

Figure 97: Close up of the IGC path cut into the FE model, showing the path's thickness

After the model is analysed in ABAQUS CAE, the results are in the form of a stress plot, as shown in Figure 98. It should be noted that in all cases that involve IGC on its own, the location of maximum stress is at the bore of the hole, at the corner with the start of the IGC path. This is due to the effect shown in Figure 84, where the downward turning of that (unrealistic) example of IGC causes the stress to increase on the upper edge of the IGC, with the highest stress being located at that edge.
6.4.2.2: Effect of IGC on Stress Concentration

A series of FE analyses were conducted using various IGC path lengths and resulting vertical deviations, from extreme values to less severe as shown in Figure 99, to determine the resulting stress concentration at the bore of the hole. This test matrix was determined by selecting a number of useful IGC lengths, from very short to near what was found on the AP-3C. These lengths were chosen as an initial study into the effect of the IGC fissure itself – if a significant effect was found, longer lengths would have been analysed. These path lengths were combined with the average $P_{\text{TURN}}$ values as well as reduced $P_{\text{TURN}}$ to obtain a random spread of path deviations for each length. These stress concentrations were plotted against the vertical deviation and corrosion length of each respective corrosion path. The reason for doing this is to determine what part of the IGC that is present is likely to cause early crack initiation.
Firstly, the stress concentration was plotted against the corrosion length. As can be seen in Figure 100, there is little correlation between corrosion length and the resulting stress concentration. However, as can be seen the stress concentration is higher than the standard plate-with-hole solution of a $K_t$ of 3.0 found with an un-corroded case.

*Figure 99: Length and Deviation values tested in stress analysis*
Following on from corrosion length, the relationship between vertical deviation and stress concentration was examined. There is a clearer relationship here compared with the corrosion length, as seen in Figure 101 where the stress concentration increases as the vertical deviation does. However the actual relationship is not very strong here as at any vertical deviation there is a range of possible stress concentrations for the different paths.
6.4.2.3: Relationship between Stress Concentration and Corrosion Angle

Due to the poor effect vertical deviation alone had on stress concentration of IGC, other possibilities were investigated, particularly when comparing the stress concentration versus the vertical deviation for each particular IGC length, which generally resulted in an increase in $K_t$ with increasing vertical deviation. This relationship did not always hold true however, so other options were required to be investigated. The two investigated closely were what has been coined the “global angle” and the “local angle”. The global angle refers to an angle made between a horizontal line drawn from the origin and a line drawn from the origin of the IGC path to the very end. The local angle uses the same horizontal line; however the angle is between that line and one drawn from the origin of the IGC path to the end of the first vertical step. These two angles are shown in Figure 102.

![Diagram of Global and Local angle with respect to an example IGC path](image)

*Figure 102: Diagram of Global and Local angle with respect to an example IGC path*

The global angle resulted in a stronger relationship, shown in Figure 103, than previous factors as this angle takes into account both corrosion length and vertical deviation, thus no-dimensionalising the relationship. Corrosion length and vertical deviation individually could not produce a strong relationship as there were some long paths with lower deviations and some shorter paths with high deviations. By combining both factors, these anomalous results
are brought more in line with the standard results (where longer paths have larger deviations) to produce a better relationship.

![Graph showing the effect of global angle on stress concentration factor.](image)

**Figure 103: Effect of Global angle on stress concentration factor**

As can be seen in Figure 103, a relationship is beginning to form between the global angle and the resulting stress concentration which supports the hypothesis of an increase in stress due to the IGC path turning – as the angle increases, so too does the stress concentration. However, there were still some results that could not be accounted for by only investigating the global angle.

It was found that some IGC paths had a lower overall angle but still quite a high stress concentration, as seen in the top left corner of Figure 103. These paths were investigated closer and it was found that the overall number of vertical steps these paths had was higher than the others, and in particular there was a number of vertical steps early on in the path close to the bore of the hole. Due to this, the local angle was investigated, which is the angle from horizontal of a line drawn from the origin of the path to the end of the first vertical step,
as shown in Figure 102. The resulting relationship between the local angle and the stress concentration is shown in Figure 104.

![Graph showing the relationship between local angle and stress concentration](image)

*Figure 104: Effect of Local angle on stress concentration factor*

The relationship between local angle and stress concentration still supports the hypothesis of stress shielding from the IGC path turning; however there is still a noticeable scatter in the results. To determine a stronger relationship, combinations of features were investigated rather than individual features. The best of these turned out to be the simple addition of the global angle and the local angle, where this “Total Angle” had a near-linear relationship with stress concentration, as shown in Figure 105. No physical meaning for Total Angle was found apart from it provided good correlations to base further work on.
Figure 105: Effect of combined Global and Local angles on stress concentration factor. A linear line-of-best-fit is shown with an $R^2$ value of 0.8593

This means that the effect on the stress at the bore of the hole due to IGC can be reduced to a single, linear equation, given below.

$$K_f = [0.0137(A_x + A_y) + 3]$$

(24)

6.4.3: Stress Analysis of Surface Pits and Corroded Inclusions

Following on from the stress analysis of IGC alone, the model was adapted to incorporate the realistic features normally associated with IGC. These features are surface pits down the bore of the hole and inclusions that are corroded as IGC grows through the material. This section presents the results of the stress analyses conducted on various sized surface pits and corroded inclusions at different locations along the IGC path.
6.4.3.1: The Effect of Surface Pits on Stress Concentration

Surface pits were represented in the FE model using an extended hemispherical shape cut into the model using the Arc cut method, meaning the opening height and width are the equal. While this is not completely realistic (as [110] showed the pit opening width is larger than the height), it is the most realistic pit shape possible while still retaining the automated FE model creation.

Figure 106 shows the von Mises stress field surrounding a pit used in this model, which clearly shows the extended hemispherical shape used. This figure is typical of the different sized pits analysed, with the pit causing a significant rise in local stress. This increase in stress is present all around the pit, with the highest stressed location along the flat edge of it.

A number of different sized pits were analysed, from 50 μm deep to 350, to determine their stress concentration, as shown in Figure 107. The aspect ratio of these pits was all kept constant so that smaller pits had smaller opening widths, consistent with the work presented in Chapter 4. As the pit size increased, so too did its stress concentration, as consistent with
other work [123]. The stress concentrations given below are of the pit at the bore of a hole, and as such include the underlying stress concentration from that hole, hence why the stress concentration begins at approximately 5. In all cases, the IGC path that was analysed with the pit was altered in the ABAQUS pre-processor so that it had zero vertical deviation (so a flat path) to remove any effect IGC has on the pit stress concentration.

Figure 107: Stress concentration of different sized pits at the bore of the fastener hole

6.4.3.2: The Effect of Corroded Inclusions on Stress Concentration

Following on from the pit analysis, a number of different corroded inclusion sizes and positions were tested. This formed the bulk of modelling work due to the amount of variables tested, as not only were inclusion positioned at grain length intervals from approximately 100 μm to 1,500 μm, so too were inclusion sizes from 5 μm to 55 μm. As with the surface pit analysis, the IGC path was kept flat to remove its effect on the resulting stress concentration.

The full test matrix is shown below in Table 19. The inclusion location was pinned to a grain boundary junction as this is the location where these corroded inclusions were most seen. As
such the interval between each was one average grain size. The inclusion size was based on that found in Chapter 3. The interval was chosen as a round number that provided an even spacing of sizes between the minimum and maximum.

Table 19: FE analysis test matrix of corroded inclusion position and size

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range (μm)</th>
<th>Interval (μm)</th>
<th>Total Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position (depth from bore of hole)</td>
<td>100-1,500</td>
<td>76</td>
<td>18</td>
</tr>
<tr>
<td>Size (diameter of inclusion)</td>
<td>5-55</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>Total number of FE analyses run</td>
<td></td>
<td></td>
<td>108</td>
</tr>
</tbody>
</table>

Figure 108 shows an example of the stress field surrounding the spherical void representation of a corroded inclusion used in this work. As can be seen, there is an increase in the stress around this inclusion, which is typical of any size inclusion at any position. There is a slight offset to the stress field, with a higher stress present on the side closer to the bore of the hole which is to be expected due to the underlying stress field from the hole.

Figure 108: Stress field surrounding a corroded inclusion located at approximately 800µm from the bore of the hole

The results from the stress analysis of the corroded inclusions are displayed as a contour plot of inclusion depth (position) and inclusion size (diameter) versus the resulting stress
concentration, Figure 109. Each line in the contour plot represents a line of constant stress concentration.

Figure 109: Contour plot of stress concentration of corroded inclusions at various depths along the IGC path and at various sizes

This plot shows two features of corroded inclusions; firstly, as the inclusions grow in size (for the same position), their stress concentration reduces. This is to be expected as the radius of curvature reduces as the inclusion grows in size. Secondly, and perhaps more interesting to note, is that as the inclusion is positioned closer to the bore of the hole, its stress concentration is higher for a given inclusion size.

This is a result of the underlying stress caused by the hole itself, which increases as the distance from the hole reduces. The inclusion itself has its own stress concentration (which would be present if the inclusion was in an infinite plate); this stress concentration is superimposed onto the stress concentration of the hole, hence why the overall stress concentration increases as the inclusion is closer to the hole.
This effect is also seen in surface pits, where the underlying stress also has a slight limiting effect on the extent that stress increases as the pit depth increases. However, the difference between a small pit and a large pit is only 300 μm – the difference between a close corroded inclusion and a far one is in excess of 1,000 μm, hence the larger scale of stress concentrations found.

6.4.4: The Effect of IGC Path on Pit and Corroded Inclusion Stress Concentration

Previously, the stress analysis of pits and corroded inclusions used a straight, flat IGC path to remove the shielding effect IGC can have. A small analysis was conducted to determine what effect the vertical deviation of an IGC path has on these features, particularly to determine if the effect can be separated from the previously-found relationship between pit depth and stress concentration, and inclusion position and size and stress concentration.

This analysis was conducted by running the script as normal, and then the same model was re-run with the IGC path altered to be flat. IGC has the same effect on pits and corroded inclusions as it does on the bare hole; the change can be related to Equation 17 with a higher starting stress concentration. This is highlighted below in Table 20 for the various sized pits and in Table 21 for various positions of corroded inclusions. The tables show the original $K_t$ with a flat IGC path, the changed $K_t$ for the original, deviated IGC path and the expected $K_t$, which is the calculated stress concentration based on the Total Angle of the IGC path and Equation (24).

Table 20: Change in stress concentration at pits due to IGC path vertical deviation
<table>
<thead>
<tr>
<th>Pit Depth (μm)</th>
<th>Total Angle (deg.)</th>
<th>Original $K_t$</th>
<th>Changed $K_t$</th>
<th>Expected $K_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
<td>2.5</td>
<td>5.33</td>
<td>5.37</td>
<td>5.37</td>
</tr>
<tr>
<td>85</td>
<td>4.3</td>
<td>5.71</td>
<td>5.77</td>
<td>5.78</td>
</tr>
<tr>
<td>110</td>
<td>6.1</td>
<td>5.91</td>
<td>6.00</td>
<td>5.99</td>
</tr>
<tr>
<td>150</td>
<td>5.2</td>
<td>6.10</td>
<td>6.17</td>
<td>6.17</td>
</tr>
<tr>
<td>190</td>
<td>4.9</td>
<td>6.35</td>
<td>6.44</td>
<td>6.42</td>
</tr>
<tr>
<td>230</td>
<td>2.8</td>
<td>6.49</td>
<td>6.52</td>
<td>6.53</td>
</tr>
<tr>
<td>280</td>
<td>3.1</td>
<td>6.68</td>
<td>6.73</td>
<td>6.73</td>
</tr>
<tr>
<td>320</td>
<td>4.7</td>
<td>6.72</td>
<td>6.76</td>
<td>6.78</td>
</tr>
</tbody>
</table>

Table 21: Change in stress concentration at corroded inclusions due to IGC path vertical deviation

<table>
<thead>
<tr>
<th>Inc. Depth (μm)</th>
<th>Total Angle (deg.)</th>
<th>Original $K_t$</th>
<th>Changed $K_t$</th>
<th>Expected $K_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>230</td>
<td>5.4</td>
<td>5.38</td>
<td>5.41</td>
<td>5.45</td>
</tr>
<tr>
<td>410</td>
<td>2.6</td>
<td>4.76</td>
<td>4.77</td>
<td>4.80</td>
</tr>
<tr>
<td>570</td>
<td>7.2</td>
<td>4.34</td>
<td>4.39</td>
<td>4.43</td>
</tr>
<tr>
<td>620</td>
<td>6.2</td>
<td>4.21</td>
<td>4.24</td>
<td>4.29</td>
</tr>
<tr>
<td>730</td>
<td>3.8</td>
<td>4.01</td>
<td>4.05</td>
<td>4.07</td>
</tr>
<tr>
<td>890</td>
<td>4.5</td>
<td>3.72</td>
<td>3.76</td>
<td>3.79</td>
</tr>
<tr>
<td>1030</td>
<td>6.5</td>
<td>3.48</td>
<td>3.52</td>
<td>3.56</td>
</tr>
<tr>
<td>1260</td>
<td>2.1</td>
<td>3.11</td>
<td>3.13</td>
<td>3.14</td>
</tr>
</tbody>
</table>

These tables show that the issue of stress concentration due to the IGC path and the IGC-related feature can be de-coupled and treated separately. The pit $K_t$ had good correlation to the expected result, as did the corroded inclusions at shorter depths. As the inclusion was positioned further along the IGC path, the change in $K_t$ was less than expected. This is likely due to the reduction in the shielding effect further out along the IGC path.

The IGC path vertical deviation can change the location of maximum stress. Where previously, the maximum stress was even on the top and bottom side of pits and corroded inclusions, this location will change slightly due to any deviation in the IGC path. Because of the stress shielding effect, if the IGC path were to deviate downwards from the vertical origin, the maximum stress will always be located on the top side of any feature (so the opposite side to the direction the path deviates). This is highlighted in an example of a corroded inclusion located 800μm from the bore of the hole, Figure 110.
Figure 110: Effect of (a) straight versus (b) vertically deviated IGC path on stress field surrounding a corroded inclusion

6.5: Discussion

6.5.1: Verification, Comparison and Accuracy of IGC Path Prediction Model

The initial IGC path prediction model was validated using three methods – initially, a first-order validation was made through a direct comparison between the predicted paths and the corrosion paths in actual AP-3C wing skin material. A more in-depth validation was made by comparing the predicted results to those from the previous Brick Wall model this model is based on [106-108]. Finally a comparison has been made between the predicted maximum deviation calculated and the maximum deviation found in the actual corrosion paths.

6.5.1.1: Comparison of Path Prediction Model Results to Actual Corrosion Paths

As can be seen in Figure 111, there is a correlation between one of the predicted corrosion paths and an example of actual corrosion in the studied material. This trend continued for the other corrosion examples shown in Chapter 4 – a matching corrosion path could be calculated using the model. This means that it is possible to use a mathematical model to predict where IGC is likely to grow.
This form of validation is not as robust enough to base a model on – simply comparing the predicted path with actual paths is not enough to ensure this model can accurately predict the fatigue effects of IGC. As such, other forms of validation were used.

6.5.1.2: Comparison of Path Prediction Model Results to Other Brick Wall Models

Secondary validation of the model was conducted using the results found by Zhang et al. [108]. They combined a brick-wall style model (using different equations to achieve their resulting crack path) with foil-penetration tests to determine appropriate values for their model (\(P_{\text{TURN}}\), \(P_{\text{LEFT}}\) and their own addition of the probability the path will split in two at a junction) based on the microstructure they used, of 7178-T6 aluminium alloy wing skin. They found a ratio of 1:4.01 for the shortest path length of corrosion growth in the L direction compared to the ST direction. Meaning that for a 1 mm thick foil, the shortest path length in the L direction was 1 mm, whereas in the ST direction the path length was 4.01 mm.
Swapping the grain sizes in this model effectively swaps the corrosion propagation direction from the L direction to the ST direction and gives a ratio for AP-3C wing skin material of 1:3.47. Again, this means that for the model presented here, the shortest path length for a 1 mm thick foil is 1 mm whereas for the ST direction it is 3.47 mm.

The difference in results can be attributed to the larger grains in the 7181-T6 alloy compared to 7075-T651; the ratio of L to ST grain size is 13.1:1 compared to 9.8:1, resulting in a longer distance travelled around each grain when travelling in the ST direction (so a longer distance in the L direction), as shown in Figure 112. With this grain size difference in mind, it is believed this verification method is effective and therefore this model can predict accurate IGC paths as it can be compared to real-life foil penetration tests.

![Diagram of the different grain structure resulting in a different minimum corrosion length](image)

**Figure 112: Diagram of the different grain structure resulting in a different minimum corrosion length**

### 6.5.1.3: Comparison of Maximum Deviation of Predicted and Actual Corrosion Paths

As a third and final validation method, the maximum deviation values of the predicted and actual corrosion paths were compared to determine if the path prediction model can account
for the variety of path deviations without over-estimating the maximum possible vertical deviation of the actual IGC paths.

Figure 113 shows an image of the most-deviated IGC fissure found in the corrosion protocol test specimens. The image was taken looking at the LT-ST plane following grinding and polishing to a sub-micron finish. The IGC fissure in this case was 2,530 μm deep and had a vertical deviation of 94 μm, giving a deviation rate of 0.037 μm per μm of IGC path length. This supports the maximum deviation rate of 0.040 μm per μm of IGC path length found using the path prediction model.

![Image of IGC fissure](image)

*Figure 113: Highest vertical deviation seen in actual IGC test specimens*

### 6.5.2: Significance of Stress Analysis of IGC Path

By completing the stress analysis of the IGC path by itself (without the other features), it is possible to determine the theoretical maximum stress concentration increase that IGC can cause. This is beneficial as it can rule out the IGC path itself as a cause of early fatigue crack initiation if the stress concentration change is small enough.

As stated previously, the theoretical maximum vertical deviation rate from the path prediction model is 0.040 μm per μm of IGC path length, giving a maximum global angle of 2.7°. The maximum local angle was determined by assuming the IGC path will turn at the first grain boundary junction it meets, giving an 8 μm rise over a 75 μm length, resulting in a maximum local angle of 5.8°. This combination of angles gives a maximum overall angle of 8.5°, resulting in a maximum likely stress concentration of 3.11, an increase of 3.67%.
What this means is there is little change to the stress concentration at the bore of the hole from IGC alone. This is supported by both the FE results of IGC-related features and the fatigue results discussed in Chapter 5. The FE results showed no possible initiation from IGC alone – the \( K_t \) of the pit or inclusion was always significantly higher than that of the IGC path. The fatigue results showed some instances where there was a secondary IGC fissure that did not have a pit on the fatigue surface, but fatigue always initiated from the one with the pit, regardless of the length of either IGC fissures.

6.5.3: FE Model Mesh Sensitivity Analysis

At each step of the IGC model development, a mesh sensitivity analysis was conducted to determine the appropriate mesh size for analysis. For the case of IGC-alone, it was found that the mesh size was not of high importance due to the relatively simple geometries used for the IGC path (consisting of straight lines). The selected global mesh size (average length, width and depth of all the meshed elements) of 100 μm gave the same result as local refinement down to 25 μm of the IGC path area (while keeping the global mesh size at 100 μm). This significantly reduced the complexity of the IGC model as only a global mesh size needed to be specified, without having to determine geometry numbers for local mesh refinement. Only needing to have a single, global mesh size also reduced computation time as a smaller global mesh size was not required.

In the second stage of the IGC model it was found that, once pits and corroded inclusions were added in, the mesh size was bound by the size of the feature to be meshed. As quadratic elements were used, a small mesh size wasn’t as critical as with a linear mesh. The only requirement for the mesh was that it represents the size and shape of each feature accurately; elements needed to be small enough to account for the curvature of the pits and inclusions. Shown in Figure 114 is an example of an inclusion where the elements are a) too large, and thus the actual shape of the inclusion is mis-represented, and b) where the elements are smaller and thus show the curvature of the inclusions. It should be noted that the IGC path shown in Figure 114 (a) is vertically deviated as it was found early on during initial testing of
the FE model that fine elements are required around the inclusions, before it was decided to keep the IGC path horizontal.

![Image of meshed inclusion with large and small elements](image)

*Figure 114: Example of meshed inclusion with a) large elements and b) smaller elements*

ABAQUS has a mesh function known as Curvature Control, which automatically refines the mesh size based on the rate of curvature around arcs; the smaller the arc, the smaller the curvature rate and thus the smaller the elements. This feature was employed as it allows automatic refinement within ABAQUS during the meshing process. The amount of refinement is based on the parameters specified in the Curvature Control function with a maximum deviation factor of 0.05 and a minimum size factor of 0.01 (these are the control numbers used within ABAQUS and don’t have physical meaning outside of this program).

### 6.6: The Combined Effect of Surface Pits and Corroded Inclusions on Fatigue Initiation – the Notion of a “Critical Inclusion Distance”

As shown previously, the IGC path itself will not alter the stress concentration at the bore of the hole by a significant amount – the maximum predicted change in $K_t$ is from 3.0 to 3.11. However, pits down the bore of the hole and corroded inclusions along the IGC fissure do result in a significant increase in $K_t$.

When just a pit and IGC are present, the pit will always have the highest $K_t$ as it is always located at the bore of the hole, and thus crack initiation will always be related to it. The exact
location of crack initiation depends on local features of the pit and thus can occur at the end of the pit, along its edge or at the corner with the bore of the hole. In the case of the FE model, this can occur due to the shape of the pit used – the extended hemisphere shape allows for edge-of-pit initiations, whereas other (such as elliptical) pit shapes may not allow this. However, given edge-of-pit initiations were seen in fatigue tests, this is not just related to the pit shape chosen.

When just a corroded inclusion and IGC are present, the crack initiation is more complex as the inclusion is not located at the bore of the hole, or even at a fixed location. As shown in Figure 109, the stress concentration of the corroded inclusion reduces as the distance from the bore of the hole increases. At larger distances, this $K_t$ decreases to a value below the natural $K_t$ of the hole. This means beyond a certain distance from the hole a corroded inclusion will no longer be the fatigue crack initiating feature – as the stress concentration is higher at the bore of the hole, a crack will be more likely to initiate from there than the inclusion. It was found that this distance is approximately 1.3 mm from the bore of the hole.

This is the first instance of there being a “competition” between features to be the initiating feature, where the feature with the highest stress concentration is most likely the initiating feature. In the case of the corrosion pit, there is a competition between it and the rest of the bore of the hole, but as the pit’s location is fixed in the highest-stressed area of the specimen, it will always win. In the case of the corroded inclusion, it too competes with the bore of the hole. However, as the location of the inclusion changes, it is not always the winner in this competition – beyond the 1.3 mm distance found previously, the winner in this competition is the bore of the hole.

This competition continues when all three features are present together – an IGC fissure, a pit and a corroded inclusion. In this case, the corroded inclusion is still in competition with the bore of the hole; however it is also in competition with the pit. As the pit will always have a significantly higher $K_t$ than the bore of the hole, the competition between the inclusion and bore of the hole is irrelevant (as is the competition between the pit and the bore of the hole).
Now a competition only exists between the pit and corroded inclusion where the feature with the higher stress concentration will be the likely location of fatigue initiation. As the $K_t$ of the pit is significantly higher than the bore of the hole, the corroded inclusion now has to be located closer to increase its $K_t$ to above that of the pit (to allow it to be the initiating feature). As the $K_t$ of the pit increases with increasing pit depths (as shown in Figure 107), the resulting distance at which an inclusion becomes critical reduces (as the inclusion needs to be closer to compete with the higher pit $K_t$). This distance at which the inclusion becomes critical has been coined the “Critical Inclusion Distance”, or CID.

This is shown in Figure 115 where the CID values for a number of different pits are overlaid on the contour plot given in Figure 109. Figure 115 shows that as the pit depth increases, the CID value decreases as the inclusion $K_t$ has to increase to compete with the higher pit $K_t$.

*Figure 115: Inclusion stress concentration contour plot with various pit size CID values overlaid*

Figure 116 shows these CID values for various pit sizes. This graph again shows that as the pit depth increases, the CID value decreases.
Figure 116: Critical Inclusion Distance for various pit sizes

To explain the CID value more clearly, Figure 117 highlights a case where a pit is 150 μm deep. This results in a CID value of 350 μm. If a corroded inclusion is located further from the bore of the hole than 350 μm, the 150 μm deep pit will have a higher $K_t$ and thus fatigue is most likely to initiate from there. If a corroded inclusion is located closer than 350 μm, it will have a higher $K_t$ and thus fatigue will most likely initiate from the inclusion rather than the pit.
The fatigue test results from Chapter 5 (shown in Table A 1.1) were incorporated into the graph of CID values, Figure 118, to validate the values of CID for different sized pits determined from the IGC model. These fatigue results are split into surface pit-related initiations (tip, edge or corner of pit) and initiations from corroded inclusions. The straight line indicates the location of the tip of the pit.

The results show that pit-related initiations fall below the 1:1 line of the tip-of-pit location, as expected. Pit-related initiations can occur at distances further than the CID as it is possible for a pit to grow deeper than the possible CID values (however this was not the case in the results presented here).

The results do show that the inclusion-related initiations fell below, or close to, their respective CID values, showing good correlation between the IGC model results and fatigue tests. The discrepancy with some fatigue test results falling above the CID value could be due
to a number of reasons. Firstly, there will be some error in measuring initiation and pit depths from the fatigue surfaces that could contribute.

Secondly, and probably more influential, is the representative shape of both the pits and inclusions used. Both of these features are not smooth in real life, unlike their FE representations. The both exhibit rough, convoluted shape, as shown in Figure 69 for pits and Figure 71 for corroded inclusions; if the IGC model was adapted to account for this rough shape, the resulting $K_t$ values are likely to be higher and thus the CID value could change.

![Legend](image)

**Figure 118**: Comparison of Critical Inclusion Distance to fatigue test results. It should be noted that some points on this graph are doubled and thus only 23 data points are visible.
6.7: Conclusion

This Chapter details the development of an IGC model that can predict the stress concentration changes due to the presence of IGC around a fastener hole. The model was developed to attempt to explain the underlying mechanism behind the early fatigue crack initiation due to the presence of IGC around AP-3C Orion Dome Nut Hole fasteners. The model creates a Python script that can be submitted for analysis to ABAQUS Standard for finite element analysis.

The script begins by predicting an IGC path through a field of grains (based on the material’s microstructure). An FE model is then generated with a representative IGC fissure placed around the hole that is then automatically meshed followed by the application of boundary conditions and loads. This model is constructed entirely through the use of the Python script – following a quick data check (to ensure loads and boundary conditions are applied in the correct location), the model can be analysed without any further pre-processing. The model requires the following inputs prior to the generation of the Python script:

- Grain size distribution (mean and standard deviation in the LT and ST direction)
- Inclusion size distribution (mean and standard deviation of the inclusion diameter)
- IGC behaviour (required length of IGC and turn probability)
- Pit size distribution (mean and standard deviation of the pit depth)
- Specimen dimensions (diameter of hole and thickness of plate)

A sensitivity analysis showed that the most critical input is the pit size distribution, as it was found the pitting had the largest effect on stress concentration. Secondary to that was the inclusion size distribution, as this had an effect on corroded inclusion size. Finally, the grain size distribution and IGC behaviour had an equal effect on stress concentration as this only changed the shape of the IGC, which did not contribute much to determining $K_I$. 

- 189 -
The FE analysis using the IGC model found there is little effect from the IGC fissure alone on possible early crack initiation due to the small change in stress concentration that it causes. However, the inclusion of IGC related features (such as surface pits and corroded inclusions) did result in an increase to the local stress concentration which would most likely account for the early fatigue crack initiation found in the fatigue test results.

When these features are present with the IGC path, there is a competition between each as to which is most likely to be the fatigue crack initiating feature, based on the stress concentrations found from the FE analysis; the feature with the higher $K_t$ is more likely to be the location of crack initiation. This competition brings about the notion of a “Critical Inclusion Distance” (CID), where for a certain pit size (and thus pit $K_t$), a corroded inclusion has to be located within a certain distance from the bore of the hole to have a high enough $K_t$ to be the initiating defect (as $K_t$ increases with decreasing distance for an inclusion).

The fatigue results found in Chapter 5 match well with the predictions for CID values at different pit sizes as crack initiations from corroded inclusions occurred within, or close to, the CID found for their respective pit sizes, as shown in Figure 118.
CHAPTER 7: REAL WORLD APPLICATION OF IGC MODEL: LIFEING TOOL FOR WORLD-WIDE FLEET OPERATORS

7.1: Introduction

The results work presented so far are useful in that they detail the underlying mechanics of early fatigue crack initiation due to IGC. A model was also developed that could determine the most likely fatigue initiation location for a given combination of IGC, surface pit and corroded inclusion. However, the real world application of this model is limited due to the computer power and specialised analysis programs required, meaning a desktop computer running ABAQUS is needed to analyse a single case in the space of a number of hours. This tool is designed to analyse this case in a matter of minutes on any laptop computer running Microsoft Office.

For that reason, the results of that model were extracted in a form that could be used to develop a tool that can be used in the field by maintenance engineers for the AP-3C Orion. The benefit of such a model is the ability to make maintenance decisions in the field other than the complete removal of any IGC found.

7.1.1: Requirements of a Lifeing Model

As the aim of this chapter is to produce a model that can be used in the field by the AP-3C maintenance engineers, it has a number of requirements to fulfil. These requirements are:

- It must be based on or within software that is readily available on all computers
- It must have a low computing power requirement
- Ideally it will be probabilistic to account for any possible variations (such as pit size and inclusion depth) and to move towards the “predict and manage” approach rather than “find and grind”

- It should be simple and easy to understand so no detailed instructions are required

Any model created should address these requirement, but most importantly it must tie in with the current lifeing methodology for the AP-3C. As the work presented here focused on the effect IGC has on crack initiation, the model developed here will aim to tie in with the first stage of AP-3C lifeing for the time for a crack to grow to 1.27 mm (0.05 inch) [19].

7.2: The Process of Creating a Probabilistic Model

The process of creating this model is shown in Figure 119. Firstly, populations of pit sizes and inclusion depths for the specified IGC length were created. From this population, a number of combinations of a pit size and inclusion depth were analysed to determine the initiation depth, based on the $K_I$ of each feature using equations curve-fit to the FE results from Sections 6.4.3.1: and 6.4.3.2: . These $K_I$ values were compared against each other and the higher one had its initiation depth recorded. The initiation depth was then compared to the fatigue test results which allows a knock-down factor to be determined for that particular combination. This knock-down factor can then be applied to the current lifeing methodology which uses FAMS to determine the number of cycles required for a 1.27 mm (0.05 inch) fatigue crack to grow.
Figure 119: Flowchart of model for predicting knock-down factor for IGC on the AP-3C Orion

This entire model was created within Microsoft Excel using its in-built functions; no extra macros were needed. The user interface is shown below, where the following variables are input:

- Grain size distribution (as grain length and width means and standard deviations)
- Inclusion size distribution (as a mean and standard deviation)
- Probability of the IGC path turning
- Corrosion length
- Pit size distribution (as a mean and standard deviation)

Due to the limits of the AP-3C NDI procedure for finding IGC (ultrasound of the DNH), the corrosion length does not need to be set exactly. The tool takes into account a slight variability from the IGC length measured, as the resolution is not as high as metallographic sectioning and the detection limit for ultrasound is approximately 2 mm. Also, as found in Chapter 6, the IGC length only has a small effect on fatigue initiation.
Most of these variables are set within the model and are not likely to be required to change. The only variable likely to change is the corrosion length, which can be set to the length found during inspection. The outputs of the model include:

- Mean, minimum and maximum initiation depth that can be expected
- The mean and maximum knock-down factor that can be expected
- As well as cumulative distribution graphs for both the initiation depth and knock-down factor with the mean value highlighted

Shown in Figure 120 is the user interface for this model, showing the model inputs in the top left (the white cells), the model outputs in the bottom left (yellow cells) and the cumulative distribution of initiation depth and knock down factor on the right.

**Figure 120: User interface of predictive model within Microsoft Excel**
7.2.1: Pit Size and Inclusion Size Distributions

Both the pit size and inclusion depth distributions were found from the work described in Chapter 4 as well as other sources investigating corrosion on the AP-3C Orion [24, 25]. Figure 121 shows the pit depth distribution used for this model, the data from which was fitted to a normal distribution for ease of use within Excel. A comparison between the actual data and the data predicted from the normal distribution is shown in Figure 122.

![Cumulative Count vs Pit Depth](image)

*Figure 121: Pit depth distribution used in the predictive model*
Figure 122: Comparison of the actual pit depth distribution and the normal distribution fitted to these results

The inclusion size distribution was based entirely from the second corrosion protocol results (using nitrates and sulphates). A normal distribution was also fitted to the inclusion size results for ease of use within Excel. This distribution is shown below in Figure 123 with a comparison between the actual distribution and a normal distribution is shown in Figure 124. These distributions had an $R^2$ value of 0.85 and 0.92 for the LT and ST length respectively when fitted to a normal distribution. An inclusion depth distribution was not determined as the inclusions were placed randomly along the IGC fissure.
7.2.2: Stress Concentration Equations from FE Model

As stated previously, equations were created to determine the stress concentration for different sized pits and inclusions at different sizes and depths. These equations were based on the FE analysis from Chapter 6.

7.2.2.1: Inclusion Stress Concentration

The inclusion stress concentration was fitted to an exponential curve with the following base equation, where $D_i$ is the inclusion depth. The FE results taken were the maximum stress concentration found at each depth, corresponding to the smallest corroded inclusion size found.
This resulted in the following equation relating stress concentration to the distance of the inclusion from the bore of the hole (d). The parameters for this data set are below with the curve shown against the data in Figure 125:

- \(y_0 = 2.4253\)
- \(A = 2.5549\)
- \(x_0 = 1100\)
- \(\tau = 761.03\)

\[
K_i = y_0 + A \left( -\frac{(D_i + x_0)}{\tau} \right)
\]  

\( (25) \)

\[
K_i = 2.4253 + 2.5549 \left( -\frac{(D_i + 1100)}{761.03} \right)
\]  

\( (26) \)

*Figure 125: Curve fit of Equation 25 to relate stress concentration to inclusion depth*
The FE results only start from 250 µm as any size below this is likely to be within the size of the pit present. The equation shown above in Figure 125 only starts from that point in that figure – in the actual analysis, inclusions closer than 250 µm are still analysed.

Due to the effect of changing inclusion size, a correction factor was applied to the stress concentration equation. This reduction in stress due to the increase in size was approximately linear, giving the following equation (where $S_i$ is the inclusion diameter in µm).

$$K_i = 2.4253 + 2.5549 \left(\frac{S_i}{76103}\right) - 0.008333(S_i)$$  \hspace{1cm} (27)

### 7.2.2.2: Pit Stress Concentration

The pit stress concentration results at each pit depth analysed were fitted to a natural logarithm function with the following base equation, where $D_p$ is the pit depth:

$$K_i = A \times \log_b(D_p) + B$$  \hspace{1cm} (28)

This resulted in the following coefficients to fit the curve shown in Figure 126.

- $A = 0.8052$
- $B = 3.0937$
As discussed in Chapter 6, the resulting change to the stress concentration caused by the IGC path deviation has an effect on the pit $K_t$. This is added to the pit stress concentration based on the equation below, determined from the data presented in Figure 105. The final pit $K_t$ equation used in this model is given below, where $A_g$ and $A_l$ are the global and local angles of the IGC path respectively:

$$K_t = 0.8052 \times \log(D_p) + 2.0937 + 0.0129(A_g + A_l)$$ (29)

7.2.2.3: Local and Global Angle Determination

The local and global angles of the IGC fissure are needed to determine the pit stress concentration. These are determined for each individual case. Firstly, the grain length and width values for a particular case are determined, based on a normal distribution using their respective means and standard deviations. A normal distribution is used as it fits the data well and is simple to implement in Excel.
To determine the local angle, a unique value for $P_{\text{TURN}}$ is used in each case by selecting a random value between $P_{\text{TURN}}/2$ and $P_{\text{TURN}}$. Half of $P_{\text{TURN}}$ was used to limit the chance of the first turn being well past the end of the IGC fissure while still giving a representative distribution of paths from nearly straight to maximally deviated. The individual value of $P_{\text{TURN}}$ is then used to determine a local angle coefficient which determines the number of junctions passed before the first turn, where:

$$L_c = \frac{1}{P_{\text{turn}}}$$

(30)

The local angle is then calculated:

$$A_i = \tan^{-1}\left(\frac{G_w}{G_i \times L_c}\right)$$

(31)

And the global angle is calculated using the following equation:

$$A_G = \tan^{-1}\left(\frac{C_L}{G_L} \times P_{\text{turn}} \times G_W}{C_L}\right)$$

(32)

$\frac{C_L}{G_L}$ is the number of grain boundary junctions met. By multiplying this by $P_{\text{TURN}}$, the number of grain boundary junctions turned at is determined. This value is multiplied by the grain width to find the vertical deviation.
7.2.3: Determination of Initiating Feature Depth

The various values and working for IGC angle, pit depth, inclusion size and position and their resulting stress concentrations are set up in columns in Excel with each row containing its own individual case of an IGC path, a pit of a certain depth and an inclusion at a certain position of a certain size.

As fatigue crack initiation related to a pit did not always occur at its tip, variability was incorporated to allow fatigue to initiate along the edge of the pit. This variability was introduced by allowing the initiation depth of the pit to occur randomly between the tip and half its depth, where most pit-related initiations occurred in the fatigue tests. The IF statement is set up as follows, where $D_{\text{crit}}$ is the critical depth, or the depth of initiation. $D_{\text{inc}}$ is the position of the inclusion and $D_{\text{pit}}$ is the initiation depth associated with the pit, which is not necessarily the depth of the pit (due to the variability in initiation depth along the pit edge introduced)

$$\begin{align*}
\text{IF} & \quad K_{t-pit} \leq K_{t-inc} \\
& \quad D_{\text{crit}} = D_{\text{inc}} \\
\text{ELSE} & \\
& \quad D_{\text{crit}} = D_{\text{pit}}
\end{align*}$$

7.2.4: Calculation of Knock-down Factor Based on Initiation Feature Depth

Once the critical depth is determined, a knock-down factor is calculated for each case based on the fatigue results. This can then be applied to the result given by the FAMS used by the RAAF/DSTO.
7.3: Results

Shown in Figure 127 are the results of this predictive model overlaid on the graph of Critical Inclusion Distance shown in Figure 118. This shows that the predictive model is in agreement with the fatigue test results, with a range of initiations from corroded inclusions falling below the values for critical inclusion distance and a range of initiations from pits falling around the fatigue results.

In addition, the modelled initiations at corroded inclusions fell around the fatigue test results. While there was not quite the spread of initiations found, with the two deepest initiation depths not being modelled, those two fatigue results were rather unique. The modelled pit initiations still fell below the 1:1 ratio that shows the tip of the pit, indicating that the model accounts for the tip of the pit.

Figure 127: Results of the predictive model overlaid on the critical inclusion distance graph
7.4: Limitations

This model has three main limitations. The first one stems from the fatigue test results; the knock-down factor is based on the number of cycles to a crack of approximately 1 mm due to the limited resolution for detecting a small crack in fatigue specimens. The AP-3C lifeing methodology is based on the number of cycles to a 1.27 mm crack [19], which leads to a discrepancy in the physical results of this model. 1.27 mm could not be used due to the limited number of data points available to generate a crack growth curve for extrapolation, as discussed in Chapter 4 discussion.

The second limitation is that this model is not verified and validated. Significant amounts of testing would be required to get this model to a stage where it could be field tested to ensure the values predicted are replicated in actual fatigue test specimens. This further testing, however, would improve the first limitation as further investigation could be completed to re-calculate knock-down factors for number of cycles to a 1.27 mm fatigue crack.

Currently, the actual component size inputs is limited to that of the AP-3C Orion, however further adaptations of the lifeing tool will allow for the variation of material thickness, hole size and possibly the inclusion of a countersunk section.

7.5: Other Uses for Lifeing Tool

It is possible for this tool to be adapted to other forms of corrosion, including pitting and exfoliation. Pitting corrosion can be analysed by simply putting the IGC path to zero, resulting in no IGC and no corroded inclusions. This would then need to be validated against other pitting data. Exfoliation is slightly harder to adapt for, however it would only require the addition of a secondary analysis of exfoliated region size based on the grain size distribution (as that would control how far into the material in each direction the exfoliated region would likely progress), then an analysis of how that exfoliated region would affect the local stress field (using a similar method to [9] and [12]).
CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS

8.1: Conclusions

The issue of fatigue crack initiation due to the presence of intergranular corrosion in the AP-3C Orion was investigated through a series of fatigue tests followed by the development of an IGC model. The aim of this work was to develop an understanding of the underlying mechanics of fatigue crack initiation due to IGC in the wing skins and to transfer this understanding into a method of predicting its effects for the world-wide fleet operators.

The process of investigating the mechanics of fatigue crack initiation from IGC lead to the development of two accelerated protocols for producing IGC in a laboratory environment. The first protocol used hydrogen peroxide to increase the content of oxygen in the fissure, whereas the second protocol used the corrosion inhibiting features of sodium nitrides and sulphates to promote IGC formation rather than pitting. Both protocols were able to produce IGC representative of that found naturally on the AP-3C Orion up to 1.8 mm in length using peroxide and 4.2 mm for the nitride method.

Fatigue testing of both corroded and uncorroded DNH fatigue specimens found that there is a fatigue life reduction caused by the presence of IGC. A good linear correlation was found between the knock-down factors of the number of cycles to fatigue crack initiation (where crack initiation is a fatigue crack of approximately 1 mm) and the deepest initiating defect found in each sample. This knock-down factor was determined by comparing the number of cycles to crack initiation of each individual specimen compared to the average fatigue life of the uncorroded specimens at their respective stress level.

To understand what is causing this knock-down of life, an IGC model was developed that can predict the path of an IGC fissure through the wing skin material, place that path and other IGC features (pits and corroded inclusions) into an FE model and analyse the resulting stress field. The FE analysis using the IGC model found there is little effect from the IGC fissure
alone on possible early crack initiation due to the small change in stress concentration that it causes. However, the inclusion of IGC related features (such as surface pits and corroded inclusions) did result in an increase to the local stress concentration which would most likely account for the early fatigue crack initiation found in the fatigue test results.

When these features are present with the IGC path, there is a competition between each as to which is most likely to be the fatigue crack initiating feature, based on the stress concentrations found from the FE analysis; the feature with the higher $K_t$ is more likely to be the location of crack initiation. This competition brings about the notion of a “Critical Inclusion Distance” (CID), where for a certain pit size (and thus pit $K_t$), a corroded inclusion has to be located within a certain distance from the bore of the hole to have a high enough $K_t$ to be the initiating defect (as $K_t$ increases with decreasing distance for an inclusion). The fatigue results match well with the predictions for CID values at different pit sizes as crack initiations from corroded inclusions occurred within, or close to, the CID found for their respective pit sizes.

The results of the FE analysis were combined with the CID values to develop a tool that can be used to predict the knock-down factor of the number of cycles to crack initiation of a population of likely pit sizes and corroded inclusion locations (the population of which was based on the physical corrosion found using the Nitrate method). The results of this model correlated well with the physical fatigue tests results, however further verification and validation is required to ensure this tool can be used by the fleet operators effectively.

8.2: Recommendations for Future Work

There are four recommendations for future work on this topic. Firstly, it is recommended that the fatigue tests are conducted again with a higher rate of data acquisition, particularly the crack camera images. It is recommended that images are taken every 500 cycles rather than the 2,000 cycles as used. This is recommended to allow these images to be extrapolated to make “crack initiation” be the number of cycles to a 1.27 mm (0.05 inch) fatigue crack rather than the current length of “approximately 1 mm). This will bring the fatigue results and lifeing tool more in line with the AP-3C lifeing methodology [23].
Further validation of the IGC lifeing tool is required before it can be suggested as a possible addition to the lifeing methodologies used by the fleet operators. Currently, it has only been validated against the 27 fatigue specimens tested – the certification process will require many hundreds of corroded specimens, as was the case with RRA certification [53]. It is recommended that the lifeing tool be validated against other fatigue test specimens prior to being presented to the fleet operators world-wide.

One of the possible sources of inaccuracy identified for the FE model in Section 6.5.1: was the basic shape used to represent both the pits and corroded inclusions in ABAQUS. It is recommended that more representative shapes be investigated to determine if that will increase the accuracy of the results found, or whether the increase in modelling effort and analysis time simply doesn’t provide a useful improvement on the current results. It is also suggested that the effect of hole diameter, plate thickness, inclusion and pit geometry and micro topography be investigated to determine if there are any other causes of inaccuracy.

Finally it is recommended that the corrosion protocol be modified further to attempt to speed up the process further. One possibly method is to use flowing solution through the main holes, meaning many fatigue specimens can be corroded at once by stacking them on top of each other. A further benefit of this is the solution concentration can be controlled more accurately to promote each stage of corrosion growth (pitting and IGC fissure). This could result in the ability to produce only IGC without the pits to physically test the hypothesis presented in Section 6.4.2.2: that the IGC path alone does not cause a significant change to fatigue crack initiation.
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## APPENDIX 1: FULL FATIGUE RESULTS

### Appendix 1 (a): Fatigue Testing Results

*Table A 1.1: Fatigue test results including initiating feature size, initiation type and IGC and pit depth*

<table>
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<tr>
<th>Coupon</th>
<th>Peak Stress (MPa)</th>
<th>Cycles to Failure</th>
<th>Initiation Depth (μm)</th>
<th>Initiation Type</th>
<th>IGC Depth (μm)</th>
<th>Pit depth (μm)</th>
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5 A “-” in the IGC or pit depth column indicates a specimen where no IGC or pit was found.

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Table A 1.2 shows the following data:

A: Peak stress (MPa)
B: Cycles to failure
C: Initiation Depth
D: Knock-down factor for cycles to failure
E: Cycles to first ligament failure
F: Knock-down factor for cycles to first ligament failure
G: Cycles to first visible crack
H: Knock-down factor for cycles to first visible crack

<table>
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<th></th>
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<th>C</th>
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Appendix 1 (b): Knock-down factor results
Table A 1.2: Knock-down factor results of each fatigue specimen

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<th>E</th>
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APPENDIX 2: FULL IGOR PRO CODE FOR

BRICK WALL MODEL

Function BrickWall4(GrainLength2, GrainWidth2, PTurn2, PLeft2, CorrosionLength2, Iterations2, InclusionPos2, InclusionLength2, InclusionWidth2)
Variable GrainLength2, GrainWidth2, PTurn2, PLeft2, CorrosionLength2, Iterations2, InclusionPos2, InclusionLength2, InclusionWidth2
//Make/D/O StepLength2, StepWidth2, Step2, SumStep2, CumLength2, CumWidth2, cunsumstep2, Travel2, Sumstep2
wave StepLength2, StepWidth2, Step2, SumStep2, CumLength2, CumWidth2, cunsumstep2, Travel2, Sumstep2, CumLength4, CumWidth4, CumWidth4
Variable i, n, OverallLength2
StepLength2 = 0
StepWidth2 = 0
CumWidth2 = nan
CumLength2 = nan
CumWidth4 = nan
CumLength4 = nan
OverallLength2 = (CorrosionLength2/GrainLength2)*2

Redimension/N=(OverallLength2, -1) Cumstep2, cunsumstep2, CumLength2, CumWidth2, CumLength4, CumWidth4, DelayUpdate
Redimension/N=(OverallLength2, maxdeviation2, maxsteps2, randompath2, DelayUpdate
Redimension/N=(OverallLength2, Step2, StepWidth2, StepLength2, Travel2, SumStep2
Redimension/N=0 CumLength2, CumWidth2, cunsumstep2, CumLength4, CumWidth4
n = 0

For(i=0;i<Iterations2;i+=1)
StepLength2 = 0
StepWidth2 = 0
For(n=0;n<(OverallLength2);n+=1)
If (mod(n, 2)<0.1)
StepLength2[n][p] = StepLength2[p-1]+poissonNoise(GrainLength2)
StepWidth2[n][p] = StepWidth2[p-1]
Else
StepLength2[n][p] = StepLength2[p-1]+(((abs(enoise(1))<=0.2)*poissonNoise(GrainWidth2)))
StepWidth2[n][p] = StepWidth2[p-1]+(((abs(enoise(1))<=PTurn2)*sign(enoise(1)-2*(PLeft2-0.5)))*poissonNoise(GrainWidth2))
Step2 = abs(StepWidth2-StepWidth2[p-1])
EndIf
EndFor

concatenate {steplength2}, cumlength2
concatenate {stepwidth2}, cumwidth2
concatenate {steplength2,nanwave}, cumlength4
concatenate {stepwidth2,nanwave}, cumwidth4
SumStep2 = sumStep2
Travel2 = StepWidth2[OverallLength2]

//AppendToTable SumStep2
cumstep2, cunsumstep2
cumstep2, cumstep2

EndFor

//Multiple corrosion paths

//FindMaxSumStep
wave cunsumstep2, cunsumstep2
variable temp = dimsize(cumwidth2,0)
variable maxstep2
wavestats/Q cunsumstep2
print "Max Number of Steps:"
wavemax(cumsumstep2)
print "Max Steps Path ":v_maxcolloc
maxstep2 = v_maxcolloc
make/O/N=(temp) maxsteps2=nan
maxsteps2 = cumwidth2[p][maxstep2]

//end FindMaxSumStep

//FindMaxDeviation
wave cumwidth2, cumstep2
variable temp2 = dimsize(cumwidth2,0)
variable maxdev2
wavestats/Q cumstep2
If ((abs(cumwidth2[(OverallLength2)][v_maxcolloc]))>(abs(cumwidth2[(OverallLength2)][v_mincolloc])))
    maxdev2 = v_maxcolloc
else
    maxdev2 = v_mincolloc
endif
print "Max Deviation:\n.cumwidth2[(OverallLength2)][maxdev2]
print "Max Deviation Path ":maxdev2
print "________________________"
make/O/N=(temp2) maxdeviation2=nan
maxdeviation2 = cumwidth2[p][maxdev2]

//end FindMaxDeviation

//Random Path
wave cumwidth2
variable temp3 = dimsize(cumwidth2,0)
variable randomnumber2
randomnumber2 = (abs(enoise(1)))*Iterations2
print "Random Path Deviation:\n.cumwidth2[OverallLength2][randomnumber2]
print "Random Path Steps:\n.cumsumstep2[p][randomnumber2]
print "________________________"
make/O/N=(temp3) randompath2=nan
randompath2 = cumwidth2[p][randomnumber2]

//end RandomPath

// Max Deviation Corrosion data points
Variable d
Wave MaxDevX, MaxDevY, MaxDevOrigX, MaxDevOrigY
Redimension/N=(OverallLength2) MaxDevY,MaxDevX,MaxDevOrigX,MaxDevOrigY;DelayUpdate
For(d=0;d<(OverallLength2);d+=1)
    MaxDevX = CumWidth2[p][maxdev2]+3
    MaxDevY = -8412.5+CumLength2[p][maxdev2] - (((CumWidth2[p][maxdev2]+CumWidth2[p][maxdev2]-1)[maxdev2])+(CumWidth2[p+1][maxdev2]-CumWidth2[p][maxdev2]))
    MaxDevOrigX = CumWidth2[p][maxdev2]
    MaxDevOrigY = -8412.5+CumLength2[p][maxdev2]
EndFor

//Writing Abaqus Python Script
Close/A
String MaxDeviation = ""

- 220 -
//Corrosion plane selection

fprintf refNum,"mdb.models["Model-1"].ConstrainedSketch(gridSpacing=1418.1, name=\"_sweep__\", sheetSize=56724.24, transform=\n mdb.models["Model-1"].parts[\"Part-1\"].MakeSketchTransform(\n"

fprintf refNum," sketchPlane=mdb.models[\"Model-1\"].parts[\"Part-1\"].faces[6], \n sheetOrientation=RIGHT, \n sketchUpEdge=mdb.models[\"Model-1\"].parts[\"Part-1\"].edges[6], \n"

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// Assembly and Instances
fprintf(refNum,"%n# -- Assembly
%n"mdb.models['Model-1'].rootAssembly.DatumCsysByDefault(CARTESIAN)
%n# -
%nInstances
%n# =%n mdb.models['Model-1'].rootAssembly.Instance(dependent=ON, name='Part-1-1',
%n part=mdb.models['Model-1'].parts['Part-1'])
%n"

// Analysis Step
fprintf(refNum,"%n# -- New analysis step
%nmdb.models['Model-1'].StaticStep(name='Step-1', previous='Initial')%n"

// Boundary Conditions

fprintf(refNum,"%n# -- y symmetry boundary conditions
%nmdb.models['Model-1'].YsymmBC(createStepName='Step-1',
%nname='BC-1', region=%n Region(faces=mdb.models['Model-1'].rootAssembly.instances['Part-1-1'].faces.getSequenceFromMask(
%nmask=('[# # #000000 ]', ), )))
%n"

// Applied load (pressure)
fprintf(refNum,"%n# -- Uniform pressure
%nmdb.models['Model-1'].Pressure(amplitude=UNSET, createStepName='Step-1',
%ndistributionType=UNIFORM, field='', magnitude=100.0, name='Load-1',
%nnregion=%n Region(faces=mdb.models['Model-1'].rootAssembly.instances['Part-1-1'].faces.getSequenceFromMask(
%nmask=('[# # #000000 ]', ), ))
%n"

// Field Output Requests

fprintf(refNum,"%n# -- Field output requests
%nmdb.models['Model-1'].fieldOutputRequests['F-Output-1'].setValues(rebar=EXCLUDE, region=MODEL, sectionPoints=DEFAULT)
%n"

// Job Information

fprintf(refNum,"%n# -- Job input
%nmdb.Job(aTime=None, contactPrint=OFF, description='',
%nechoPrint=OFF, explicitPrecision=SINGLE, getMemoryFromAnalysis=True, historyPrint=OFF,
%nmemory=90, memoryUnits=PERCENTAGE, models=Model-1, multiprocPrint=OFF,
%nmultiprocessingMode=DEFAULT, 
%nname='WithCorrosion', nodalOutputPrecision=0, numCpus=1, queue=None, scratch=
%, type=ANALYSIS, userSubroutines='', waitHours=0, waitMinutes=0)
%nfprint(refNum,"%nfrom part import *
%nfprint(refNum,"%nfrom material import *
%nfprint(refNum,"%nfrom section import *
%nfprint(refNum,"%nfrom assembly import *
%nfprint(refNum,"%nfrom step import *
%nfprint(refNum,"%nfrom interaction import *
%nfprint(refNum,"%nfrom load import *
%nfprint(refNum,"%nfrom mesh import *
%nfprint(refNum,"%nfrom job import *
%nfprint(refNum,"%nfrom sketch import *
%nfprint(refNum,"%nfrom visualization import *
%nfprint(refNum,"%nfrom connectorBehavior import *
%nfprint(refNum,"%n"

// Submit job

fprintf(refNum,"%n# -- Submit job
%nmdb.jobs['WithCorrosion'].submit(consistencyChecking=OFF)
%n"

Close/A

// Add in inclusion

// Writing Abaqus Python Script

Close/A

String Inclusion = ""
Variable refNum3
Open/N=Home refNum3 as "Inclusion.py"

// Python input

fprintf(refNum3,'# -*- coding: mbcs -*-
%nfprint(refNum3,"%nfrom part import *
%nfprint(refNum3,"%nfrom material import *
%nfprint(refNum3,"%nfrom section import *
%nfprint(refNum3,"%nfrom assembly import *
%nfprint(refNum3,"%nfrom step import *
%nfprint(refNum3,"%nfrom interaction import *
%nfprint(refNum3,"%nfrom load import *
%nfprint(refNum3,"%nfrom mesh import *
%nfprint(refNum3,"%nfrom job import *
%nfprint(refNum3,"%nfrom sketch import *
%nfprint(refNum3,"%nfrom visualization import *
%nfprint(refNum3,"%nfrom connectorBehavior import *
%nfprint(refNum3,"n"

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// Sketch info
fprintf refNum3, "\n\n# Sketch info
mdb.models['Model-1'].ConstrainedSketch(name='__profile__', sheetSize=40000.0, gridSpacing=1.0, objects=[ mdb.models['Model-1'].sketches['__profile__'], mdb.models['Model-1'].sketches['__profile__'].Rectangle(point1=(0.0, 0.0), point2=(20000.0, 20000.0)), mdb.models['Model-1'].sketches['__profile__'].CircleByCenterPerimeter(center=(0.0, 0.0), radius=1.0)], content=[])

// Material data
mdb.models['Model-1'].Material(name='Aluminium', Elastic(table=((210000.0, 0.3), )))

// Section Info and Assignment
mdb.models['Model-1'].Material(name='Aluminium', thickness=None)

// Corrosion plane selection
// Add in corrosion - Selecting plane
mdb.models['Model-1'].ConstrainedSketch(name='__edit__', objectToCopy=mdb.models['Model-1'].parts['Part-1'].features['Solid extrude-1'].sketch, gridSpacing=1005.49, constraints=['__profile__'], features=[mdb.models['Model-1'].sketches['__edit__'].Line(point1=(8680.0), point2=(8680.0))], thickness=None, offset=0.0, offsetField='', offsetType=MIDDLE_SURFACE, region=mdb.models['Model-1'].parts['Part-1'].faces[2], sketchPlane=mdb.models['Model-1'].parts['Part-1'].faces[2], sketchOrientation=RIGHT, sketchPlaneSide=SIDE1, sketchUpEdge=mdb.models['Model-1'].parts['Part-1'].edges[5], sketchOrientation=RIGHT)

// Corrosion Path
for(q=0; q<OverallLength2; q+=1)
  mdb.models['Model-1'].sketches['__profile__'].Line(point1=(q, 0.0), point2=(q, 1.0))
  MaxDevX(q)[p], MaxDevY(q)[p], MaxDevX(q+1)[p]
endfor

for(ru=OverallLength2; ru>0; ru-=1)
  mdb.models['Model-1'].sketches['__profile__'].Line(point1=(ru, 0.0), point2=(ru, 1.0))
  MaxDevX(ru)[p], MaxDevY(ru)[p], MaxDevOrigY[rui-1][p], MaxDevOrigX[rui-1][p]
endfor
fprintf refNum3,"\n# -- New analysis step --\nmdb.models['Model-1'].StaticStep(name='Step-1', previous='Initial')\n"

//Boundary Conditions
fprintf refNum3,"\n# -- y symmetry boundary conditions --\nymdb.models['Model-1'].YsymmBC(createStepName='Step-1', name='BC-1', region=\n Region(faces= mdb.models['Model-1'].rootAssembly.instances['Part-1-1'].faces.getSequenceFromMask(\nmask=[('#0 #200000 ', '), ]))\n"

//Applied load (pressure)
fprintf refNum3,"\n# -- Uniform pressure --\nymdb.models['Model-1'].Pressure(amplitude=UNSET, createStepName='Step-1', distributionType=UNIFORM, field=\n name='Load-1', region=\n Region(side1Faces= mdb.models['Model-1'].rootAssembly.instances['Part-1-1'].faces.getSequenceFromMask(\nmask=[('#0 #400000 ', '), ]))\nymdb.models['Model-1'].loads['Load-1'].setValues(magnitude=100.0))\n"

//Field Output Requests
fprintf refNum3,"\n# -- Field output requests --\nymdb.models['Model-1'].fieldOutputRequests['F-Output-1'].setValues(rebar=EXCLUDE,\n region=MODEL, sectionPoints=DEFAULT)\n"

//Job Information
fprintf refNum3,"\n# -- Job input --\nymdb.Job(atTime=None, contactPrint=OFF, description='', echoPrint=OFF, explicitPrecision=SINGLE, getMemoryFromAnalysis=True, historyPrint=OFF, memory=90, memoryUnits=PERCENTAGE,\n model='Model-1', modelPrint=OFF, multiprocessingMode=DEFAULT,\n name='WithCorrosion', nodalOutputPrecision=SINGLE, numCpus=1, queue=None, scratch=\n, type=ANALYSIS, userSubroutines=\n, waitHours=0, waitMinutes=0)\nymdb.jobs['WithCorrosion'].submit(consistencyChecking=OFF)\n"

Close/A

End //Function BrickWall4


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