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A Review of Australian Investigations on Aeronautical Fatigue and Structural Integrity During the Period April 2017 to March 2019

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ABSTRACT

This document has been prepared for presentation to the 36th Conference of the International Committee on Aeronautical Fatigue and Structural Integrity (ICAF) scheduled to be held in Krakow, Poland, 3-4 June 2019. The report contains summaries of the research and associated activities in the field of aircraft fatigue and structural integrity at research laboratories, universities and aerospace companies in Australia during the period April 2017 to March 2019.

A report of the same name will be published by Defence Science and Technology and available for public release.

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1. Introduction

This document presents a review of Australian research in aeronautical fatigue and structural integrity in the period April 2017 to March 2019, and consists of inputs from the organisations listed below. The editors acknowledge these contributions with appreciation. Each contribution includes relevant references for further information and enquiries should be addressed to the person identified against the item of interest.

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2. Research activities

2.1 Early Fatigue Crack Detection using High-Order Harmonic Generation Phenomenon Associated with Propagation of Guided Waves (Ching Tai Ng, Yang Yi and Andrei Kotousov [The University of Adelaide]).

Guided waves are mechanical stress waves that propagate along the structure while guided by its boundaries. These waves propagate at considerable speed, up to a few thousand m/s without significant attenuation. The amplitudes of guided waves are typically very small of order nano-meters, and the propagation of these waves has no influence on the normal operation or the stress state. Aerospace structures often comprise plate- and shell-like load-bearing components, which permit propagation of Rayleigh and Lamb waves. Therefore, the properties of these waves have been extensively investigated over the past two decades with regard to the potential applications in damage detection techniques and integration of these techniques into Structural Health Monitoring systems of aerospace components made of metallic and composite materials.

The current guided wave damage detection techniques largely rely on the reference data obtained from the undamaged structure. But the damage-free reference data can be significantly affected by temperature variations, material degradation other environmental factors and operational conditions. All these conditions and factors significantly reduce the efficiency and reliability of the damage detection techniques based on guided wavers, leading to false alarms or masking the critical damage. Therefore, there is a great practical interest in the development of reference-free damage detection techniques for metallic and composite components, which are not affected by changing environmental factors and operational conditions [1].

The reference-free damage techniques can be based on various nonlinear features and utilise different non-linear phenomena of Lamb and Rayleigh waves, such as the generation of the high-order harmonics. The present paper presents a brief overview of recent studies on fatigue crack detection using the high-order harmonic generation phenomena associated with the propagation of the fundamental symmetric mode (S_0) of Lamb waves. The details of these studies can be found in the published papers provided in the reference section. Some selected results from these studies are briefly discussed below [2-4].

Figure 1a, for example, shows the spectra of the experimentally measured signal for the incident S_0 of Lamb waves. The experimental results indicate that there is a relatively large (with respect to the detection by common PZT sensors) magnitude of the second-order harmonic induced by the interaction of the incident wave signal with a fatigue crack. Figure 1b shows a comparison of 3D finite element (FE) simulations with the experimental data. The comparison demonstrates a good agreement; and it confirms, in particular, that the experimental guided wave studies can be ultimately replicated with high-fidelity numerical simulations.

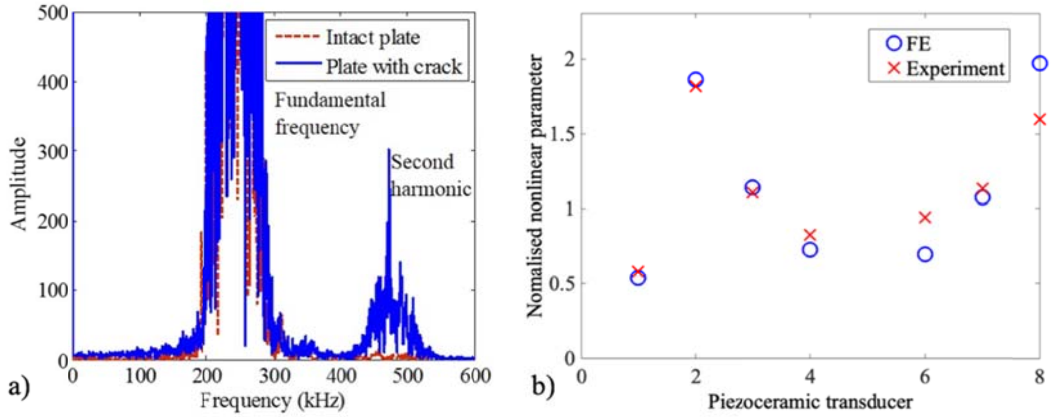

Figure 1. a) Experimentally measured signal for incident S_0 guided wave, b) comparison of 3D FE simulations and experimental results [2].

Figure 2 presents the normalised relative second-order nonlinear parameters as a ratio of the fatigue crack length to the incident wave wavelength of PZTs installed at different locations. There is a clear tendency of this parameter with an increase of the crack length for all PZT locations. The outcomes of the studies can help to identify the optimum location and excitation frequency range for the detection of fatigue cracks with this reference-free guided wave technique.

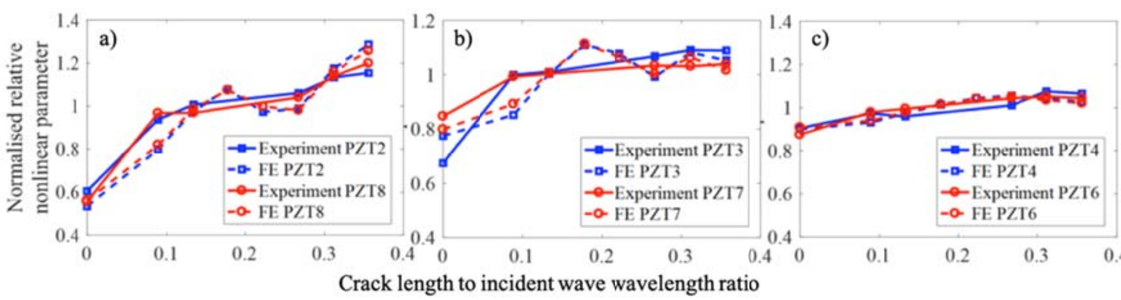

Figure 2. Normalised relative second-order nonlinear parameter as a ratio of the fatigue crack length to the incident wave wavelength of PZTs installed at different locations [3]

In summary, we have recently investigated the effect of the crack length, incident wave propagation direction on the second-order harmonic generation at different wave propagation directions, and elucidated the influence of the stress state on the amplitude of the second-order harmonic associated with propagation of the fundamental modes of Lamb waves [2, 3]. We also investigated the possibility of the detection of debonding in a metallic plate, which was strengthened by fibre-reinforced plastic [4]. The situation is relevant to the composite patch repair technique of aircraft skin. In particular, it was demonstrated that the presence of the debonding between the metallic plate and composite patch leads to the generation of the second-order harmonic, and its amplitude increases with the delamination area.

References

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2.2 Review of Three-Dimentional Effects Assotiated with Fracture and Fatigue Phenomena (Andrei Kotousov and Aditya Khanna [The University of Adelaide])

Fracture and fatigue analysis of plate and shell structural components often relies on plane stress or plane strain simplifications. These common simplifications may occasionally lead to peculiar results due, in part, to the fact that it is an approximate analysis even when the plane stress or plane strain equations are solved exactly [1].

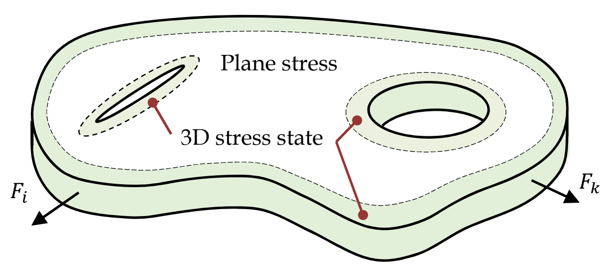

Figure 1. Representation of the exact solution to plane problems of elasticity as a sum of an interior plane stress solution and 3D stress state near boundaries [1].

In linear-elastic problems, it is now commonly accepted that the actual three-dimensional (3D) stress and deformation fields can be resolved as a sum of an interior (2D) plane stress solution and 3D layer solution as illustrated in Figure 1 [1 -10]. The 3D layer solution decays exponentially with the distance from the nearest boundary, and it is normally negligible at the distances comparable with the plate thickness. However, fracture or a fatigue crack are typically initiated from a stress concentrator representing a sharp change in the geometry of the plate boundary, and, therefore, these processes may also be significantly affected by the 3D stress states and 3D effects. The latter was the main motivation and primary subject of several recent efforts of researchers from the University of Adelaide, South Australia and their colleagues [1-11].

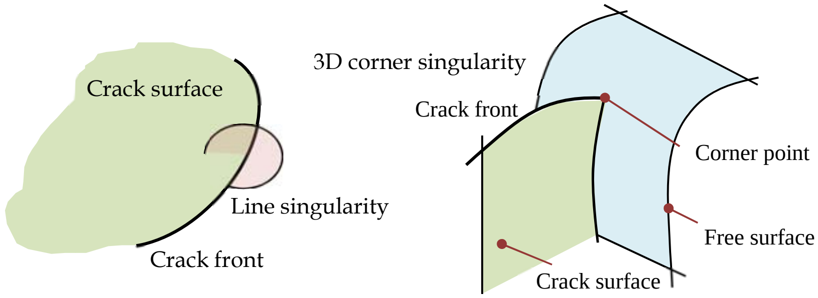

Figure 2. Stress singularities associated with the front of 3D crack [1].

Several 3D effects have been investigated over the past few years with the asymptotic analysis of high-order plate theory solutions and utilising the high-fidelity 3D FE simulations and experimental techniques. These include:

(a) The effect of the 3D corner singularity on the stress state near the crack tip and on the front shape of fatigue cracks, see Figure 2 [7-9];

(b) 3D effects near sharp corners with arbitrary opening angle [2] ;

(c) The generation of the coupled fracture modes (Figure 3) and investigation of scale effects associated with the mismatch in the singular behaviour between the primary and coupled fracture modes [1, 10];

(d) The evolution of a part-elliptical crack front shapes in round bars and other structures subjected to fatigue loading [3].

A new analytical method for the analysis of 3D fracture problems and 3D stress analysis of plate components has been recently developed [6]. The governing equation of this method represents the modified Helmholtz equation. The decaying solution of this equation describes the boundary layer of the characteristic length of an order of the half-plate thickness. This method was applied to analyse elastic and non-elastic 3D fracture problems in plates. Based on this method, a Dugdale-type model has been developed for an edge crack in a large plate of finite thickness, which represents a 3D generalisation of the popular non-linear fracture model [4]. It takes explicitly into account the effect of the plate thickness on the development of plastic deformations and crack tip opening displacement. Earlier a similar model was utilised to model fatigue crack propagation under constant amplitude fatigue loading as well as retardation effects associated with overload.

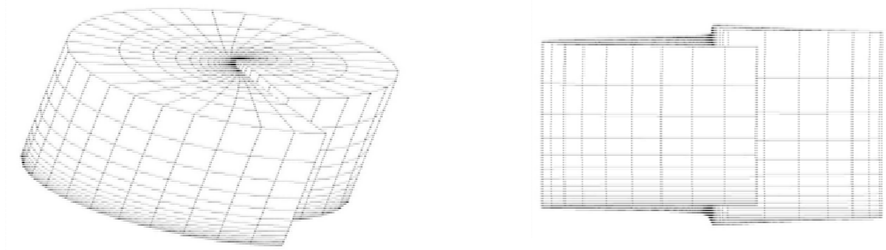

Figure 3. Generation of the coupled fracture mode due to Poisson's effect for a through-the-thickness crack loaded in Mode II [1, 10].

The ultimate objective of these long-term research activities is to develop a 3D Fracture Mechanics framework, which would help to address the drawbacks and inconsistencies associated with the prevalent 2D results in fracture analysis which are based on the plane stress or plane strain simplifications [1, 10, 12].

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2.3 X-ray Computed Tomography of fatigue cracks in aluminium alloy (Bruce R. Crawford, Timothy J. Harrison, and Chris Wood [DST], Lucinda Le Bas [Monash University])

This experiment was a feasibility study to determine the sensitivity of X-ray Computed Tomography (CT) to detect fatigue cracks in aluminium alloy and thereby assess the feasibility of monitoring fatigue crack growth at the Imaging and Medical Beam Line (IMBL) facility at the Australian synchrotron. Ultimately, fatigue crack studies with an in-situ loading apparatus may be performed in the beamline, where the intense flux of the synchrotron may make real time monitoring of fatigue crack growth possible.

Six specimens of the aluminium alloy 7050-T7451 in an initial corroded state were subject to fatigue loading to failure and then were examined in the synchrotron. Three of these specimens (the low-k_t specimens) were flat plates that did not concentrate stress while the other three (the high-k_t specimens) had a central hole which concentrated stresses thereby localising fatigue crack growth to the region of highest stress. The figure below compares the co-location between corrosion damage and fatigue in both geometries. In the low-k_t specimens numerous cracks have initiated on the surface of the material examined. In contrast, in the high-k_t specimens fatigue cracks only initiated in narrow region around the specimen's maximum stress region. The observed difference in localisation of micro-cracking sites exceeded the predicted difference from finite element modelling.

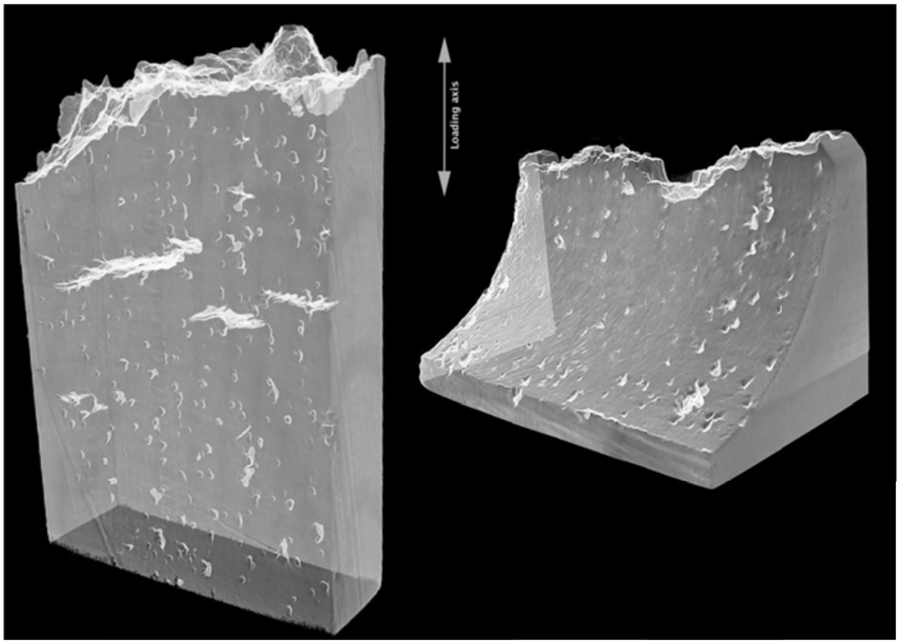

Figure 1. X-Ray synchrotron CT reconstructions of corroded low-k_t (left) and high-k_t (right) fatigue specimens of aluminium alloy 7050-T7451. Each specimen is approximately 5 mm wide.

2.4 A Defect Analysis Tool to Map Regions of Critically in AM Components (D. Agius, C. Wallbrink [DST], M. Qian [RMIT])

The emergence of additive manufacturing (AM) has introduced the capability to build new and innovative components not previously feasible by other manufacturing means. However, there are still significant issues to overcome, including the control and management of the various defects that can result via this new manufacturing technique. Material qualification and part certification are driving a real need to understand the influence of these defects on the mechanical behaviour of AM materials and components. This is particularly important in assessing the fatigue critical regions surrounding individual defects and clusters of defects. In many engineering applications, fatigue life assessment methods have been used to assess the influence of material discontinuities on the life of components. To transition to the next phase of AM design, it is vitally important to evolve these traditional fatigue life assessment methods for use on AM components. The present work explores the use of traditional fatigue life assessment methods to map the fatigue critical areas in AM components based on the assessment of flaws anywhere in the material. The work has resulted in the development of a defect analysis tool. This tool introduces material anisotropy produced in the AM process and can be used in both uniaxial and multiaxial loading conditions. Further, the tool has been developed to process large constant and variable amplitude loading sequences. The capability of this tool is demonstrated by mapping the fatigue critical regions in the vicinity of defects in AM Ti-6Al-4V.

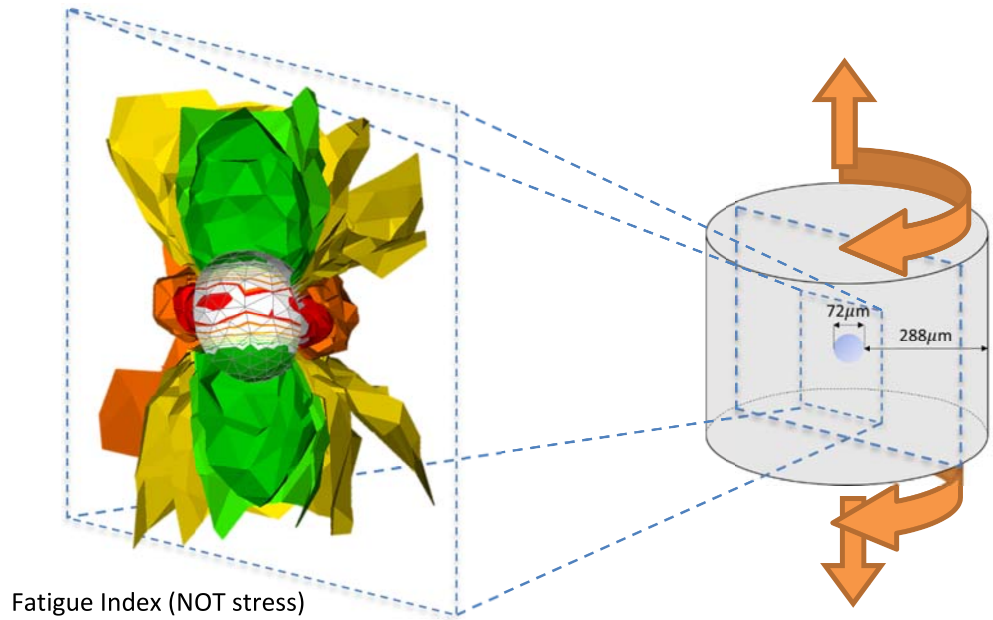

Figure 1. Assessment of fatigue sensitivity around a spherical defect subjected to non-proportional multiaxial loading. Red colours indicate regions of shorter life prediction

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2.5 Effect of Build Condition and Direction on Fatigue Crack Growth Rates of Selective Laser Melted Ti-6Al-4V Specimens (Q. Liu, C. Wallbrink and W. Hu [DST])

Additive manufacturing technologies, such as selective laser melting (SLM), provide game-changing potential to future manufacturing industries. However, it currently faces the challenge of producing components with consistent physical and mechanical properties. To date there is limited data available in the literature characterising the crack growth rate in Ti-6Al-4V material manufactured through SLM powder bed additive manufacture. A wide variety of microstructures are possible as a result of the process parameters used in the manufacturing process. Additionally, it is also well known that these materials also display anisotropic behaviours. Thus there still exist significant unknowns relating to the fatigue crack growth performance of SLM Ti-6Al-4V for a variety of process parameters and building orientation. This research reports the results of an experimental study on the fatigue properties of additively manufactured Ti-6Al-4V compact tension specimens comparing two distinctly different build parameter combinations. Crack growth tests were conducted under constant amplitude fatigue load. Preliminary results showed that both the building orientation and process parameters have significant effects on fatigue crack growth rates.

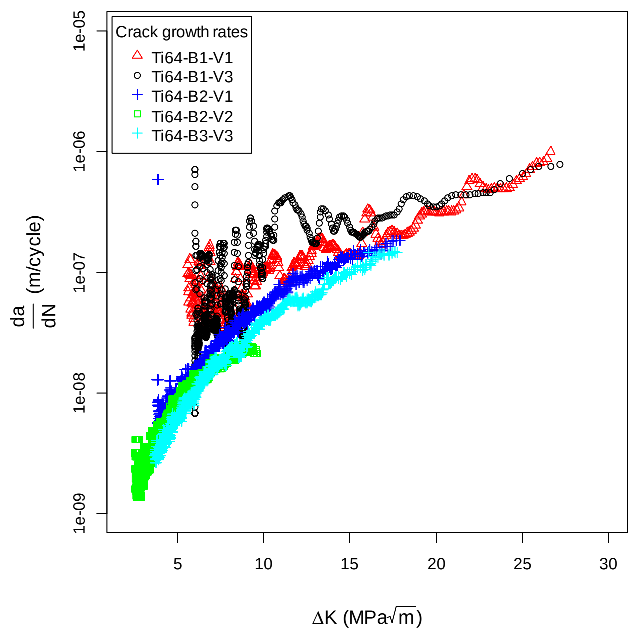

Figure 1. Crack growth rates for the vertically and horizontally built CT specimens of AM *Ti-6Al-4V containing numerous lack-of-fusion defects.*

References

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2.6 The application of piezoelectric strain gauges to enhance fatigue crack closure measurement (C. Wallbrink and D. Agius [DST])

The Defence Science and Technology (DST) Group is responsible to support the Australian Defence Force via research and advice relating to aspects of aircraft structural integrity. One important aim has been to safely manage and improve our understanding of the fatigue life of structures, components and materials that make up an airframe. To quantify and predict fatigue behaviour numerous techniques have been developed (such as the crack closure concept) to predict the influence of load history on the fatigue life of aerospace components. To date, limited experiments have been conducted to assess crack closure in variable amplitude load sequences, in particular aircraft sequences due to limitations in measurement techniques. Crack closure produces a very small non-linear strain response dependant on location (~1-2με) requiring a measurement device with high sensitivity and accuracy. Piezoelectric strain gauges offer new potential by providing superior signal to noise measurements. These sensors provide the potential to monitor crack closure in variable amplitude load spectrums to an unprecedented level of fidelity. In this work a remote piezoelectric strain gauge was used to measure the non-linear strain response in a compact tension specimen.

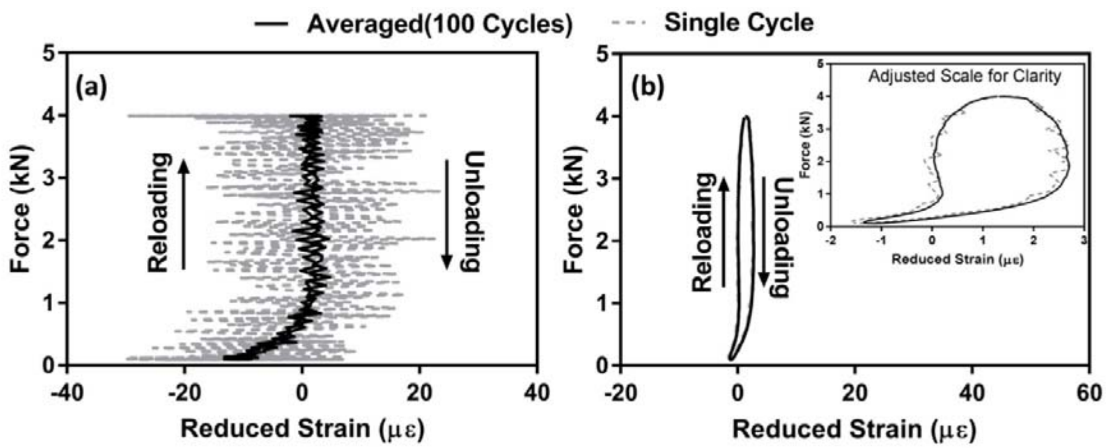

Figure 1. Reduced strain measurements at block 282 where the dashed line is a single cycle and the solid line is averaged over 100 cycles for a) resistive strain gauge and b) piezoelectric strain gauge

The applied force vs reduced strain is plotted in Fig 1 for both piezoelectric and resistive strain gauges. The reduced strain is the total strain with the linear portion subtracted to reveal any nonlinear response. At a crack length of 4 mm in size, crack closure was observable on the largest load cycle in the sequence with an opening load of ~0.25 of the maximum load. It is clear in Fig 1 that the signal to noise ratio for the piezoelectric strain gauge is far superior to that of the resistive strain gauges. The piezoelectric strain gauge displayed a measurement error of approximately 0.5 με where the resistive strain gauge displayed a measurement error of approximately 45 με. The results indicate that crack closure is observable on a cycle-by-cycle basis in a variable amplitude load sequence. Notably individual cycles produced by the piezoelectric strain gauge are consistent with the averaged loops, unlike the resistive strain gauge results where crack closure is only observable after averaging across 100 cycles. This work has found that piezoelectric strain gauges are a viable measurement tool for higher order strain based effects such as crack closure.

References

[1] C. Wallbrink and D. Agius, The application of piezoelectric strain gauges to enhance fatigue crack closure measurement, in *SIF. 2018*.

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2.7 Computational model development for Additive Manufacturing based laser cladding structural repairs of high strength metallic aerospace components (K. Walker, DST, T. Cooper, QinetiQ Australia, O. Muransky and P. Bendeich ANSTO Australia)

Laser cladding is an Additive Manufacturing technology which is emerging as a suitable means to repair high strength metallic aerospace components and structures. The technology has now been applied for a range of cases involving geometry restoration. Further work is now underway to extend the application to cases of fracture critical parts where the repair material is verified to carry loads and restore structural integrity. Computational modelling techniques have been developed for high strength martensitic steels including AerMet®100 which is often used for landing gear components. **Error! Reference source not found.** shows recent results for crack growth modelling involving crack growth through the clad and Heat Affected Zone (HAZ) and into the substrate material. The modelling [1] also accounted for the significant (and beneficial compressive) stress associated with the process. The modelling was conducted using FASTRAN and also the USAF sponsored BAMF code which is a plug-in with AFGROW and also interfaces with the StressCheck® p-version Finite Element Analysis code.

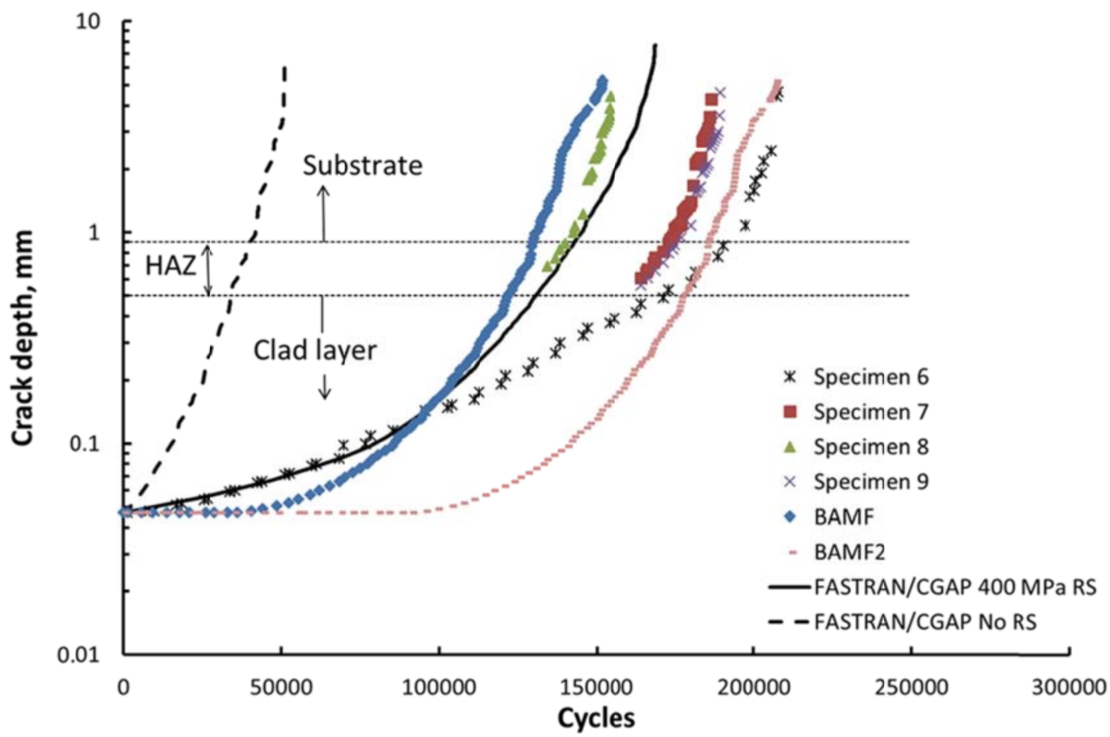

Figure 2. Modelling results for crack propagation through compressive residual stress field in case of laser cladding repair of AerMet®100 steel

The work has progressed to also develop modelling of the residual stress field [2]. The residual stress field modelling is extremely complex. It involves accounting for constrained thermal expansion and plasticity, and also non-linear Solid State Phase Transformation (SSPT) effect which occur for martensitic steels such as AerMet®100, 300M and AISI4340. Early attempts to model the process without including the SSPT resulted in significant error, including predicting tension at the surface instead of compression. Preliminary results with 4340 steel including the SSPT effect are encouraging, as shown in **Error! Reference source not found.**. Further work is ongoing to include important details in the modelling including material addition and overlapping tracks with subsequent re-heat effects.

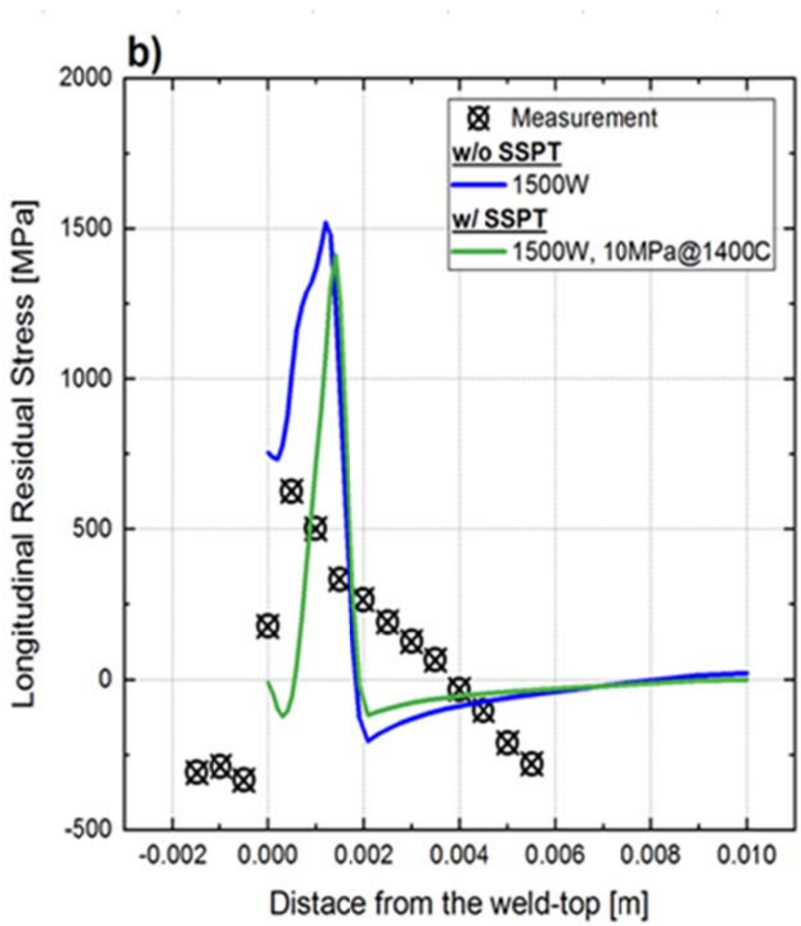

Figure 3. Residual stress profile comparisons, with and without SSPT

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2.8 Analytical modelling of fatigue crack behavior under representative spectrum loading in the F/A-18 A/B Y508 wing root shear tie (K. Walker, R. Evans, X. Yu, L. Molent, B. Main DST, M. Hill and J. Hodges Hill Engineering USA)

The Defence Science and Technology Group (DST) has been investigating and enhancing metal fatigue predictive tools for many years. Recently a local blind-prediction challenge was conducted by DST for a series of coupons manufactured from Aluminium Alloy 7050-T7451 plate simulating a combat aircraft wing root shear restraint (or shear tie post) subject to a combined aerodynamic buffet and manoeuvre load spectrum. Analysts were provided with details including the geometry, material and loading, and were asked to predict the total fatigue life. Results from a detailed three dimensional finite element model of a cracked or uncracked test coupon were also available to the analysts. The results from that exercise are detailed at [1].

Following the blind prediction phase, further analysis was undertaken using a USAF sponsored code known as the "Broad Application for Modelling Failure", BAMF. BAMF is a plug-in for the crack growth analysis code AFGROW. BAMF interfaces with the StressCheck p-version Finite Element Analysis code. The BAMF approach is as follows. The initial crack shape has to be assumed. In this case a semi-circular surface flaw of 0.02 mm deep was applied, as shown in **Error! Reference source not found.** which also shows a typical crack surface from the experiments. StressCheck is used to calculate the stress intensity solution at 20 points around the crack front. AFGROW is then used to grow the crack for a given size increment, typically 3%. The new crack shape is then passed back to StressCheck for a SIF update and then crack growth is again calculated by AFGROW. The process then continues and the crack shape is free to adapt according to the loading and material conditions.

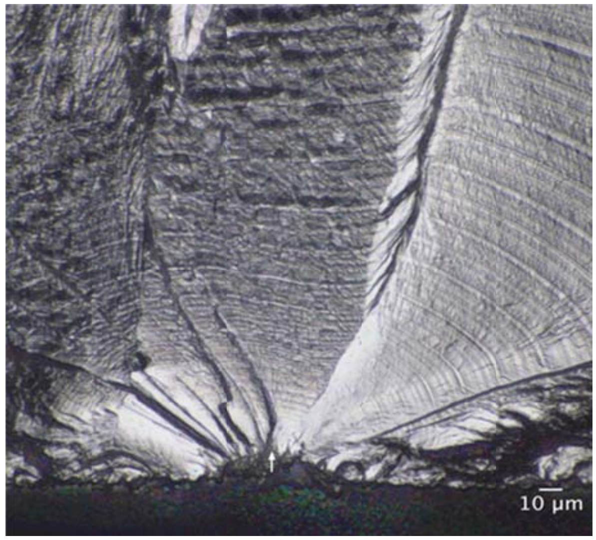

Figure 1. Crack surface

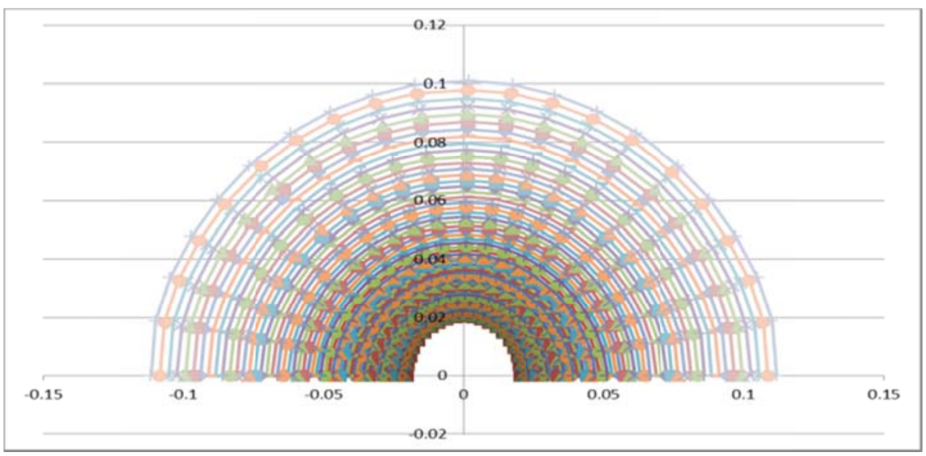

Figure 2. BAMF Model

The analyst can include the effect of a known residual stress condition such as shot peening. This can cause the crack to adopt an unusual shape, see **Error! Reference source not found.** for example for the case with shot peening. The results in terms of crack size against simulated flight hours for with and without shot peening cases is shown in **Error! Reference source not found.**. Further details are available at [2].

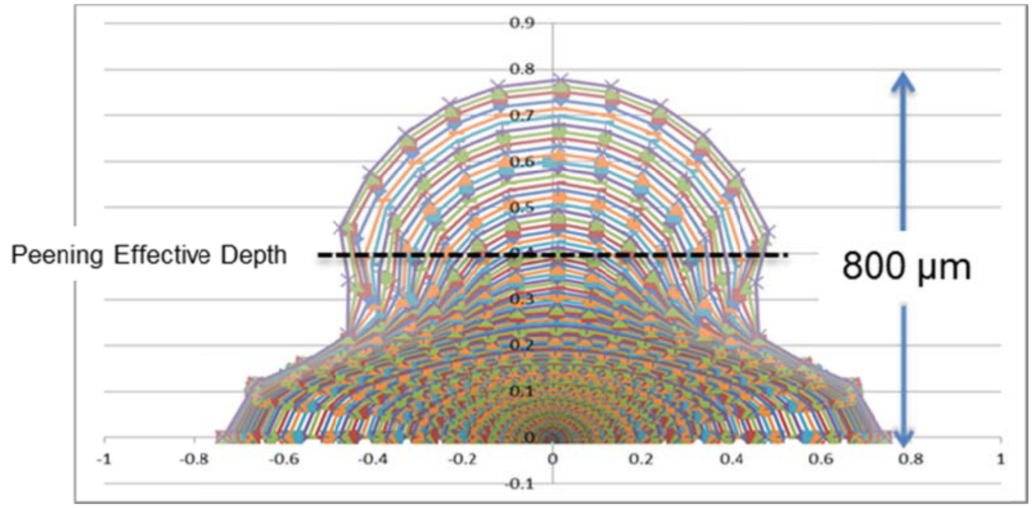

Figure 3. BAMF model after growth through the shot peen RS field

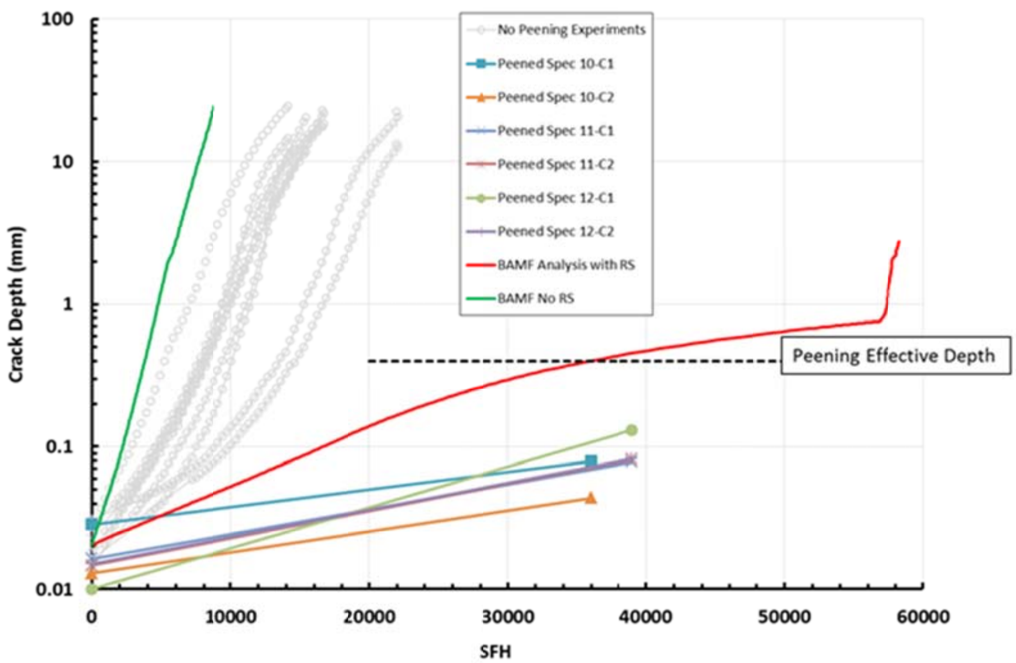

Figure 4. Crack growth predictions vs experiment for with and without shot peening

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2.9 Lessons from a fatigue prediction challenge for an aircraft wing root shear tie post (Ben Main, Rebecca Evans, Kevin Walker, Xiaobo Yu and Loris Molent [DST])

Like many aircraft operators and maintainers, the Royal Australia Air Force requires the most robust of metal fatigue analysis tools for both informed acquisition and cost effective sustainment of aircraft. The Defence Science and Technology (DST) has been investigating and enhancing metal fatigue predictive tools for many years. This work included a local blind-prediction challenge for a series of coupons manufactured from Aluminium Alloy 7050-T7451 plate simulating a combat aircraft wing root shear restraint (or shear tie post) subject to a combined aerodynamic buffet and manoeuvre load spectrum. Analysts were provided with details including the geometry, material and loading, and were asked to predict the total fatigue life. Results from a detailed three dimensional finite element model of a cracked or uncracked test coupon and strain survey results were also available to the analysts.

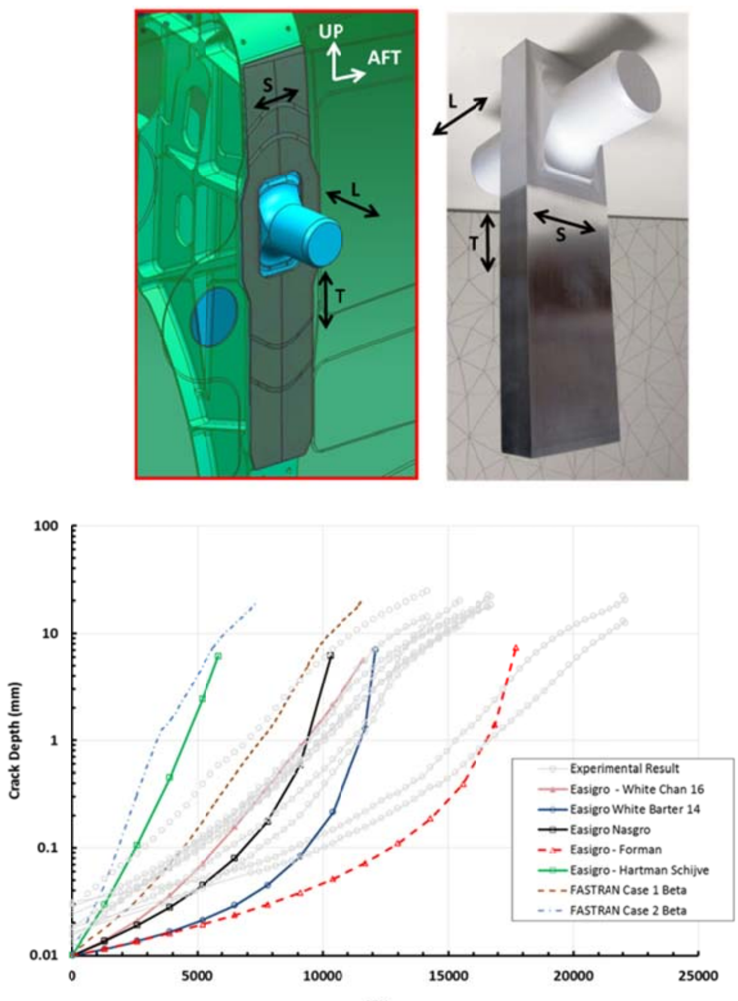

Figure 1. The shear tie post (top), an integral part of a centre fuselage former on a combat aircraft, represented by a symmetric coupon (top right) Note: transverse, long and short relate to plate

rolling direction. Blind crack growth predictions compared to coupon quantitative fractography is shown (at bottom).

The results from two separate, independent blind predictions are presented and assessed along with further non-blind analyses to evaluate the current capabilities. The exercise found that accurate and reliable predictions are possible in a case like this, but the results are dependent on the availability of high-fidelity short crack rate data and a suitable stress intensity Beta solution. The work will provide confidence in existing fatigue life modelling capabilities leading to improvements in safety, availability and cost reduction.

Reference

[1] Main, B., Evans, R., Walker, K., Yu, X. and Molent, L. (2019) *Lessons from a Fatigue Prediction Challenge for an Aircraft Wing Root Shear Tie Post*, International Journal of Fatigue, Vol. 123 pp 53-65.

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2.10 Graphene – Applications within the Aerospace Domain and its potential to provide Corrosion protection to Metallic Materials (Stephen Russo, Rafal Rutkowski, Andrew Foreman [QinetiQ])

Since its isolation in 2004, graphene has captured the attention of academia and industry alike. This two-dimensional material has demonstrated unparalleled mechanical, electrical and thermal properties and has the potential to revolutionise the aerospace sector. In particular, impermeability to gases and salts renders graphene an excellent candidate as a coating to provide corrosion resistance.

The exploitation of graphene for aerospace applications is in its infancy and as the understanding of graphene matures its applicability will continue to expand. QinetiQ has been at the forefront in exploiting graphene through a number of collaborative programs. One such program has involved its use as a protective coating within the aerospace industry.

Currently, in order to provide superior corrosion resistance characteristics, aerospace coating systems have relied on the use of chromates. Hexavalent chromium or chromate is currently the most effective way to inhibit corrosion of high strength aluminium alloys. However, these compounds typically have large environmental and process footprints and lead to the generation of large volumes of toxic liquid waste. They are widely accepted as hazardous to human health and their use throughout most industries has been reduced. Alternatives to the use of chromates have been explored for a number of years without much success. Conventional corrosion-inhibitor pigments (such as chromates) typically act by chemically inhibiting cathodic electron transfer to oxygen. However, various studies have claimed that the benefits of graphene and graphene-composites for corrosion protection arise principally from reduced permeation to oxygen and water. Graphene provides a new and novel approach for corrosion protection.

A review of the literature demonstrated the benefits graphene has in affording corrosion protection to a number of metallic materials, including high strength aluminium alloys used for aerospace applications. A variety of methods have been used to deposit graphene or graphene rich coatings on metallic surfaces. These methods have involved both 'direct' and 'indirect' applications of graphene. Direct methods in the form of Chemical Vapour Deposition (CVD) are not applicable to aluminium alloys, but have been successful in reducing corrosion of over an order of magnitude on other metals including nickel, copper and iron alloys. Corrosion testing of graphene coatings on aluminium alloys has focused on the use of Graphene Oxide (GO), sol gels and its incorporation in epoxy resins.

Numerous studies on the electrochemical behaviour of these coatings have shown improved corrosion performance Most recently, Hybrid coatings based on CVD, comprising two single layers of CVD graphene sandwiched by three layers of polyvinyl butyral, (P) provide complete corrosion protection of a commercial aluminium alloy (AA) up to 120 days of exposure to simulated seawater (Figure 1).

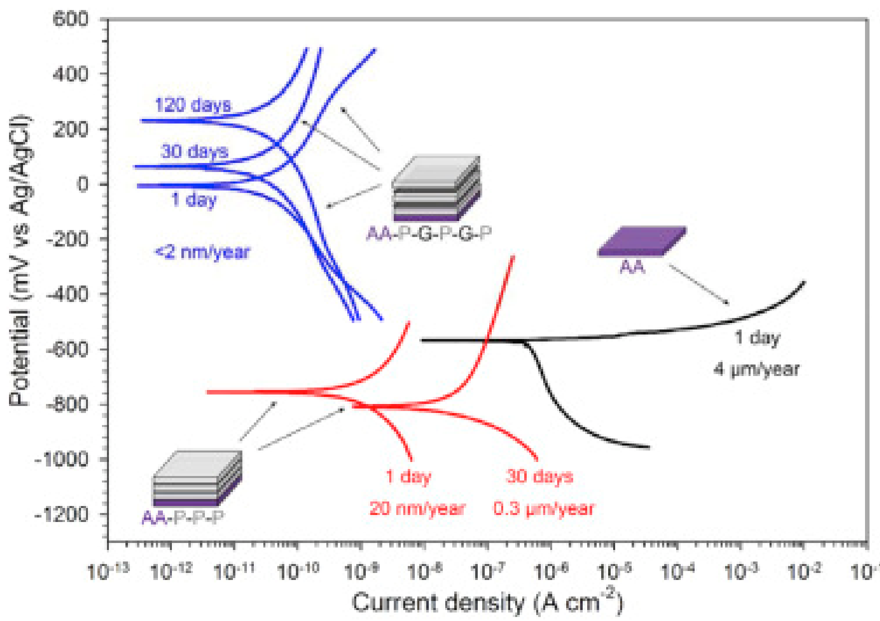
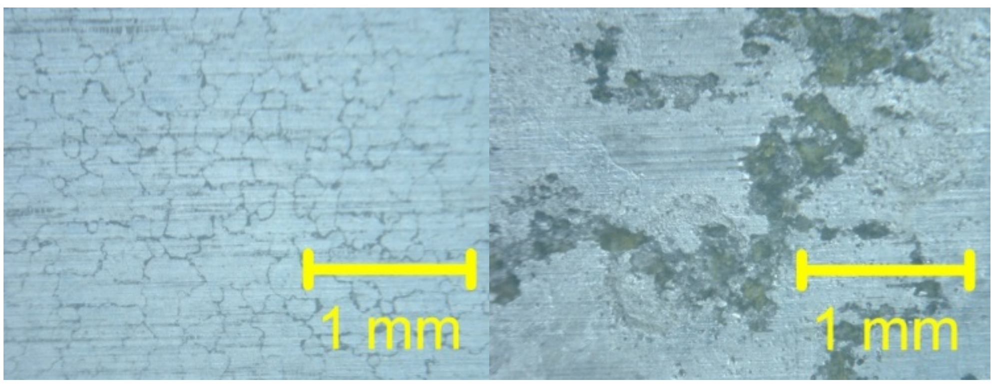


Figure 1. Potentiodynamic scans for various exposure times in NaCl solution

A collaborative corrosion program, exploratory in nature, with DST and industry was conducted on bare 2024-T3 aluminium alloy material deposited with a variety of graphene coatings. The coatings were provided by a number of suppliers including industry (using a proprietary graphene based dip coating process), QinetiQ (UK) and The University of Surrey. Those from QinetiQ were coated in a layer of reduced Graphene Oxide flakes encapsulated in a conducting polymer matrix whilst those from the University of Surrey coatings were coated using a CVD process graphene. A standard chromate conversion coating (IAW MIL-DTL-5541F Type 1 Class 1A) was also used for comparative purposes. Corrosion testing was undertaken in a cyclic salt spray chamber to simulate a corrosive environment IAW ASTM B-117. The testing profile used for the chamber was developed by DST and has been shown to best replicate typical environmental conditions experienced by ADF aircraft. The cycle had a 24 frequency where the salt concentration, temperature and relative humidity were varied. The duration of the testing was up to 58 days.

The onset of pitting corrosion was evident on the bare 2024-T3 coupons after only 24 hours exposure with no evidence of corrosion attack on the other coupons. However, after 7 days exposure, corrosion initiation had commenced on the coupons coated with graphene. Comparison of the surface morphology both prior to and post corrosion testing is shown in Figure.2. It was found that prior to corrosion testing the graphene coating exhibited segregation of metallics at the grain boundaries and may have led to preferential corrosion attack at these sites. Wettability of graphene in these areas appeared to be incomplete. Further visual inspection of the coupons revealed there were distinct areas on the surface that had significant GO coverage and these areas were found to have minimal corrosion damage. It appears that a defect free graphene coating may provide corrosion protection in this environment. There was also anecdotal evidence that while the graphene coatings performed poorly with respect to their maximum pit depth, the mean pit depths showed improvements.



(a) (b)

Figure. 2. Micrograph of the graphene coating (a) prior and (b) post corrosion testing

It was concluded that the 'dip process' may not be the most appropriate method for use on aluminium alloys to protect against corrosion. Observed limitations with this process have provided direction for examination of other coating processes that may provide better corrosion protection performance. This exploratory corrosion pilot study has also driven the development of a roadmap to better understand its corrosion protection properties of graphene.

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2.11 Laser Deposition as a Viable Additive Manufacturing Repair Process, with Application to High Value Aircraft Steel Components (Tim Cooper [QinetiQ] and Dr. Kevin Walker [DST])

Typically, aircraft structural systems in high strength steel materials such as landing gear assemblies contain complex, high value parts that have very small allowable damage limits. This can result in high value components being scrapped when the majority of the part is still serviceable. Laser Deposition (LD) Additive Manufacturing Methods offer a promising solution to cost-effective repair of such damaged components with full restoration of strength with a definable life for the repair.

Previous work [References 1, 2, 3, 4] has shown that Laser Deposition of high strength Steels and Titanium alloys is a viable method for geometry restoration of damaged aerospace structural parts. The LD process does induce residual stress within the deposited and adjacent existing material by the nature of the transient thermal processes involved. Understanding the nature (compressive or tensile) and magnitude of the induced residual stresses is a key element of determining a remaining service life for a repaired component. To enable this understanding, work has been conducted to develop and refine thermo-mechanical finite element modelling (FEM) techniques to model the LD additive manufacturing process, and correlate these models against new material test data obtained from instrumented test samples undergoing the LD process. For steels that are subject to martensitic phase change, including the phase transformation effects in the Finite Element Model in addition to a valid representation of the thermal environment and material elastic/plastic properties is vital to ensure capture of an accurate residual stress state.

Testing and associated FEM of 300M and 316 Steels undergoing the LD process has been conducted and comparison of the predicted and measured residual stress states for the two materials types is underway, noting that 300M undergoes Martensitic phase transformation, and 316 does not. The Contour and Neutron Diffraction methods of residual stress measurement were used, and the development of the FEM's in ABAQUS software to simulate the tests is underway, to be followed by comparison and correlation of the FEM results. The next stage of development is to choose a representative candidate component for repair and conduct a realistic simulation of the repair, to yield repaired component residual stress profiles that can be used in the prediction of a repaired component life. Following this, a batch of similarly repaired components would be tested under representative loading to determine actual life.

This repair methodology offers significant future potential to platform operators by reducing costs and lead times where these factors are critical for steel structural items in air, land and sea platforms once the predictive capability of the modelling and life prediction has been matured and verified to support repair process certification.

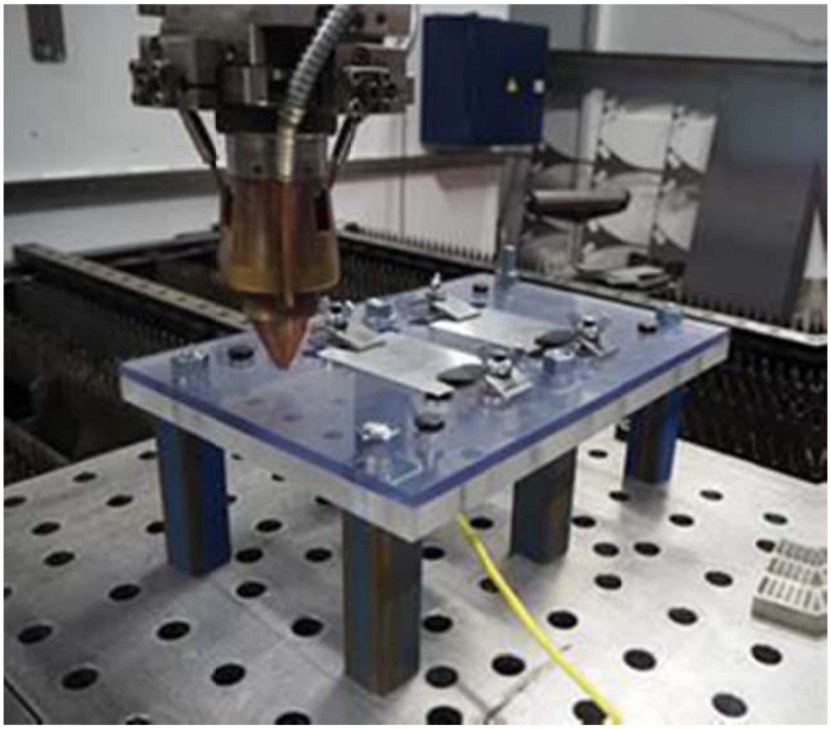

Figure 1. Test Samples Mounted in the RMIT Trumpf Laser

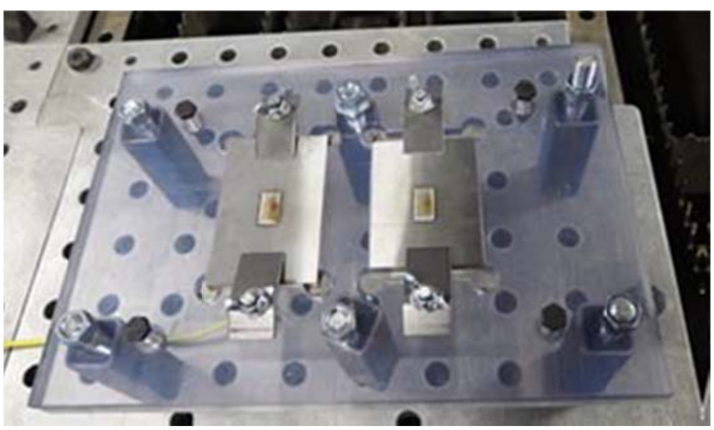

Figure 2. Test Sample Detail

Figure 3. Deposition Area Detail

References:

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2.12 Analysis of Crack Growth Both in AM Replacement Parts and In Laser Additive Repairs (Neil Matthews [RUAG] and Rhys Jones [Monash University])

Both AM replacement parts and Laser Additive Deposition (LAD) are now being considered for sustaining military aircraft fleets. However, the US certification standard MIL-STD-1530 highlights the need to assess the damage tolerance. To this end this work focuses on how to accurately compute the growth of cracks in AM materials, as well as in laser clad Aermet100 steel. In this context it is shown that the Hartman-Schijve variant of the NASGRO crack growth equation accurately computes crack growth both in AM parts, and also in LAD repairs to AerMet100 under variable amplitude loads. In both cases it is shown that it is necessary to account for the scatter seen in crack growth.

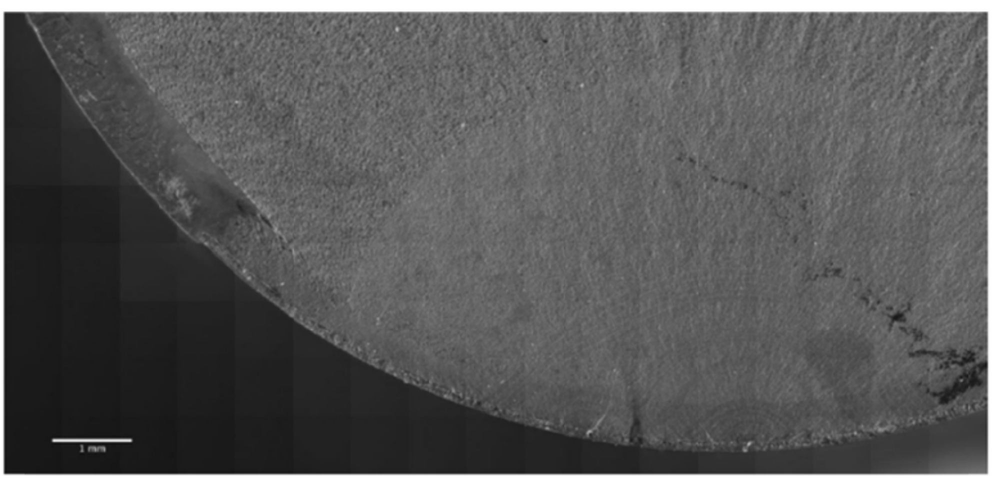

Figure 1. The LAD repaired specimen from [2]

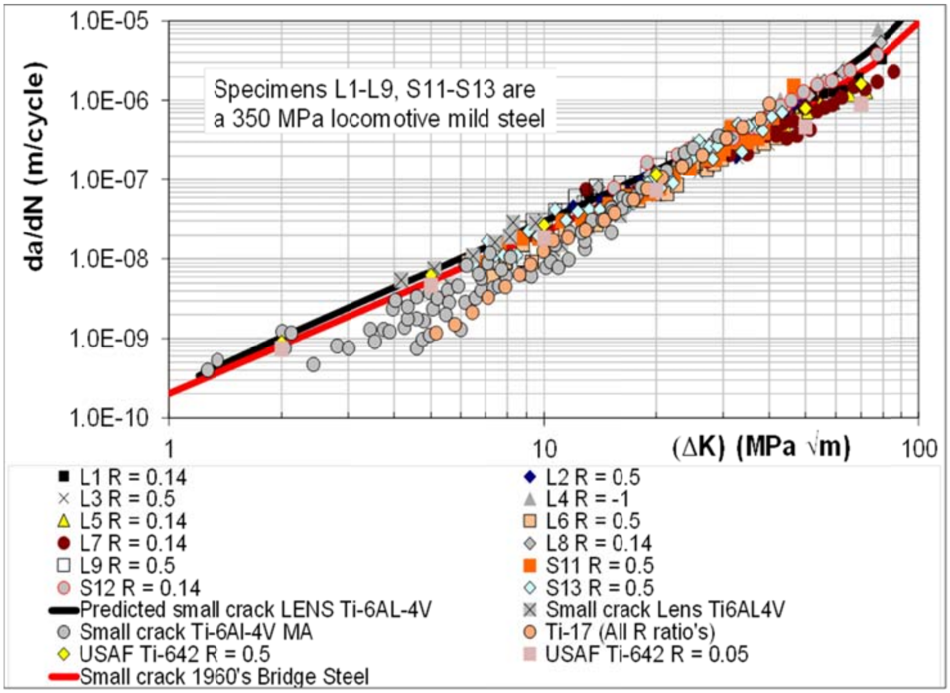

Figure 2. Comparison of crack growth rate data for some Conventionally Manufactured Materials as well as various AM repaired specimens using LAD and Cold Spray (SPD)

At first glance the experimental data suggests that the fatigue behaviour of post-heat treated LAD repaired specimens would appear to be superior to that of the baseline AerMet100 steel. However, it is shown that the variability in the crack growth rates is such that this "apparent" superior performance should not be taken into account when assessing the fatigue performance of post-heat treated LAD repairs.

This work was initially presented at the Australian International Aerospace Conference (AIAC), February 2019

References:

[1] Iliopoulos AP., R. Jones R., Michopoulos JG., Phan N., Singh Raman RK., Crack growth in a range of additively manufactured aerospace structural materials, Special Issue, Civil and Military Airworthiness: Recent Developments and Challenges, Aerospace, doi:10.3390/aerospace5040118

[2] Walker KF., Lourenço JM., Sun S., Brandt M., Wang CH., Quantitative fractography and modelling of fatigue crack propagation in high strength AerMet100 steel repaired with a laser cladding process, International Journal of Fatigue, 94 (2017), pp. 288–301.

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2.13 Developing Experimental Techniques for Detecting Composite Failure Modes and Fatigue Crack Growth in an Aircraft Panel (Michael Forsey, Matt Pelosi, Kai Maxfield, Matt McCoy, Robert Ogden and Wyman Zhuang [DST])

Modern aircraft structural integrity is underpinned by understanding the formation and growth of damage in primary structure, and the ability to predict and monitor potential failures. With modern aircraft utilising advanced metallic alloys and composites in primary structural applications, maintaining aircraft structural integrity to ensure safe operation of the fleet is critically dependent on understanding composite failure mechanisms and fatigue crack growth in both composite and metallic aircraft structures. In order to model this behaviour, obtaining detailed and representative experimental data is vital, and this often involves the use of innovative techniques to gain further understanding of complex structural responses.

This work examined two evolving experimental techniques for structural integrity investigations; an ultra-high-speed camera was used to monitor a composite failure process and modes in-situ, at rates up to two million frames per second. The specialised imaging obtained in this study clearly captured the sequence of composite failure events and revealed the unique failure pattern and modes in a typical aircraft composite material (Figure 1). A second study developed an innovative experimental technique using three-dimensional Digital Image Correlation (DIC). Strain fields near the tips of fatigue cracks in a stiffened aircraft metallic wing panel have been studied in-situ using this technique, with the evolution of the strain field ahead of a crack tip monitored during fatigue spectrum loading and crack growth.

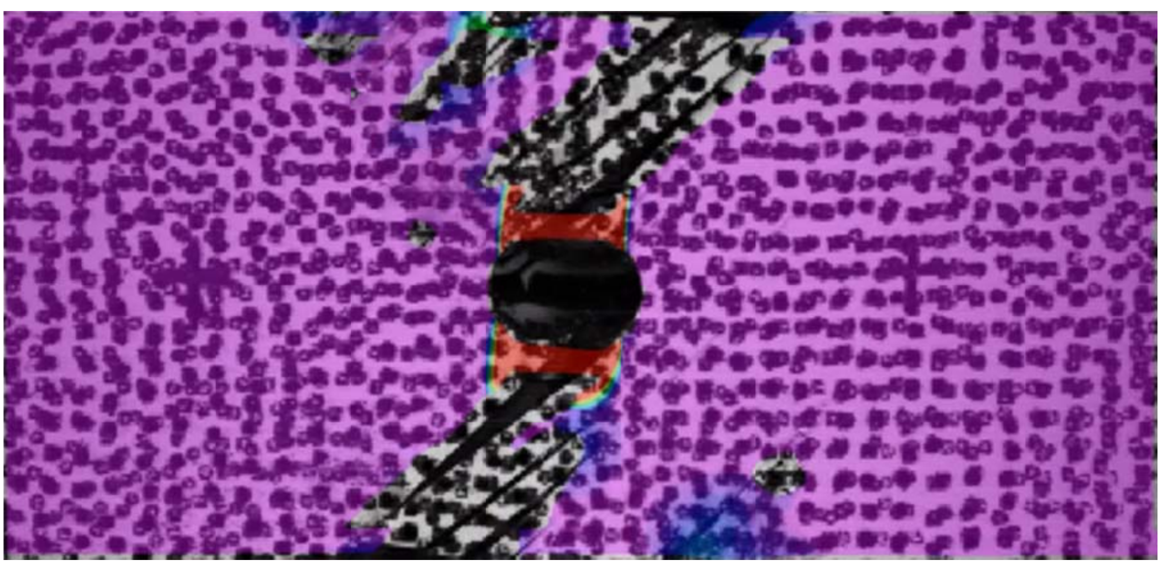

Figure 1. The failure mode of a typical aircraft composite material captured by an ultra-high speed camera at 1million FPS overlayed with surface strain data represented by different colours.

The experimental techniques developed in this study can provide innovative solutions and improved science and technology support to the current and future Australian Defence Force aircraft structural integrity needs.

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2.14 An Empirical Model to Predict the Effect of Thermal Exposure on the Tensile Mechanical Properties of 7000 Aluminium Alloys (Suzanna Turk, Tim Harrison, Christine Trasteli and Alex Shekhter [DST])

Improvements in the performance of next generation military aircraft have resulted in a more demanding operating environment for the airframe when compared to legacy aircraft. When considering components manufactured from high strength age-hardenable aluminium alloys, higher operating temperatures or accidental exposure to high temperatures can degrade mechanical properties.

DST designed an experimental program to assess this risk by measuring static properties for various exposure conditions between 93°C to 218°C for 1 hour, 10 hours and 100 hours. The experimental results were used to develop an empirical model to accurately predict retained baseline yield strength following thermal exposure for AA7050 and AA7085 aluminium alloys. The empirical model, based on a sigmoidal function, was successfully validated using DST historic data and independent published data. It was able to predict the retained baseline yield strength for temperature ranges of 93°C to 350°C, over exposure times ranging from 10 minutes to 10,000 hours for AA7050, and exposure times ranging from 10 minutes to 100 hours for AA7085. The average percentage error for this model was 2.9%, with a maximum error of 12.9%.

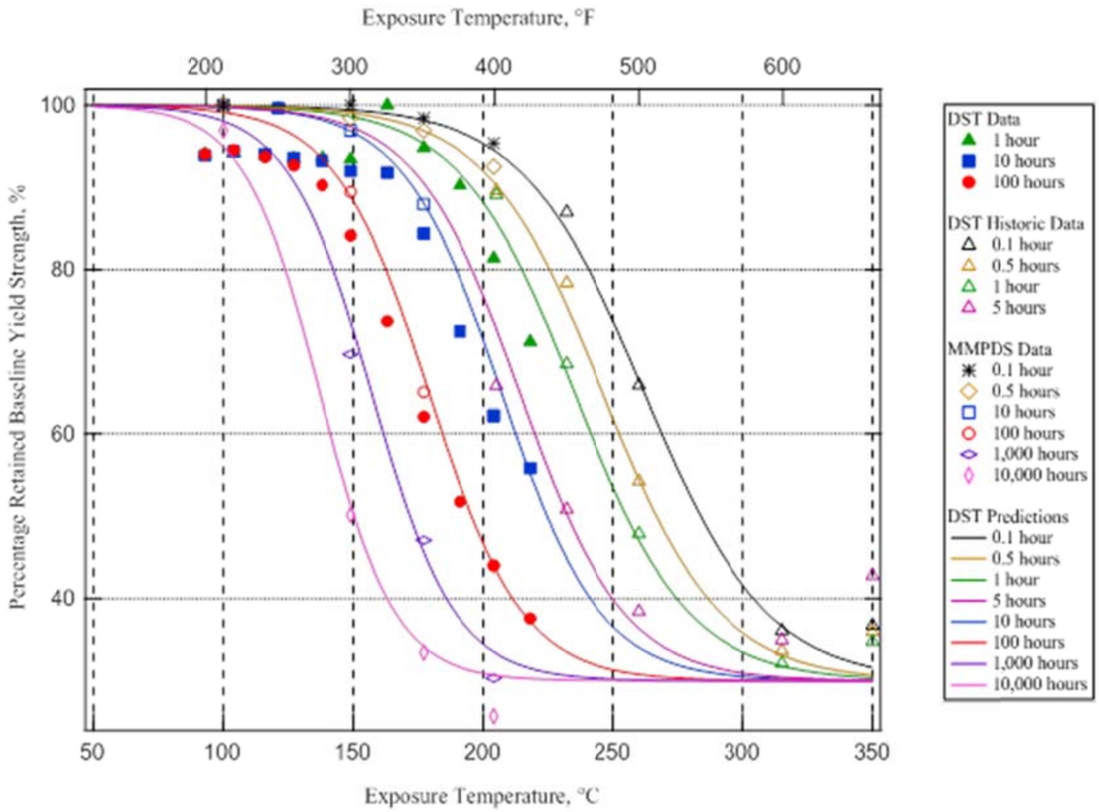

Figure 1. DST Group retained strength model predications for AA7050 tested against independent data

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2.15 Cyclic Elastoplastic Performance of Aluminum 7075-T6, as-built SLM and wrought Ti-6Al-4V under symmetric and asymmetric strain-controlled cyclic loading (D. Agius, C. Wallbrink, K. Kourousis[DST])

Recent studies [1-3] have demonstrated the potential improvements that can be achieved in strain-life fatigue predictions through the application of phenomenological constitutive models which are capable of accounting for transient cyclic effects. These models belong to a branch of modelling approach which uses nonlinear kinematic hardening to predict the macroscopic stress and strain, with the most widely employed models being those based on the original Armstrong- Frederick (AF) model. The AF-based models are favoured for strain- life applications due to their numerical implementation simplicity and computational efficiency, which is particularly important when performing fatigue life predictions requiring the input and analysis of inservice aircraft spectra. When applying constitutive models to strain-life predictions it was shown by Agius et al. [2] that the hysteresis loop development is very important in the accurate prediction of fatigue life. In particular, the combination of the applied isotropic hardening and kinematic hardening coefficients has been shown to have a considerable influence on the hysteresis loop predictions and simulation accuracy of both strain ratcheting and mean stress relaxation. Therefore, accurate simulation of not only the mean stress relaxation but also of the hysteresis loop development is of outmost importance in strain-life fatigue analysis methods.

In this work experiments were conducted to investigate the cyclic elastoplastic performance of aluminium 7075-T6, as-built SLM and wrought Ti-6Al-4V loaded in symmetric strain control and asymmetric stress and strain control. A Multicomponent Armstrong and Frederick (AF) model with Multiplier (MAFM) was used to fit the data. Example results for specimens manufactured using a powder bed selective laser melting process are presented in Figure 1. The results compare test and model and show good correlation and demonstrate the models ability to capture evolutionally changes in elastic plastic response due to repeated cyclic loading.

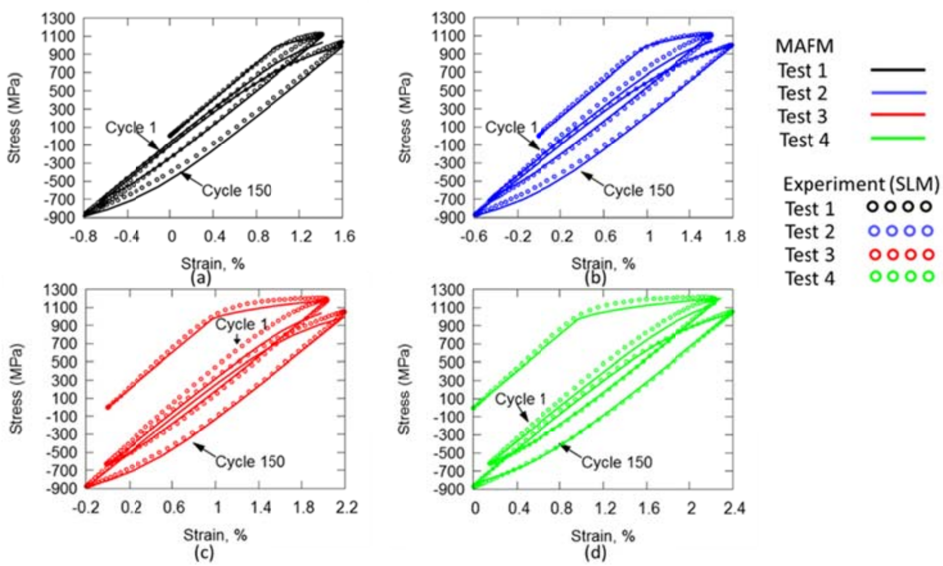

Figure 1; Experimental and computed SLM Ti-6Al-4V first and 150th cycle hysteresis loops for asymmetric strain controlled loading on vertically built specimens (a) {1.6%,-0.8%} (b) {1.8%,-0.6%} (c) {2.2%,-0.2%} and (d) {2.4%,0.0%}

This work compliments initiatives in DST to support the Australian Defence Force via the development of new capability to sustainment activities. As technologies such as advance additive manufacturing techniques mature analytical methods must also evolve not just to keep pace but enhance the benefits these new technologies can provide.

References

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[4] Agius, D., Kourousis, K. I., Wallbrink, C., 2018, 'Elastoplastic Response of As-built SLM and Wrought Ti-6Al-4V under Symmetric and Asymmetric Strain-controlled Cyclic Loading', Rapid Prototyping Journal, Vol 24. Issue 9. pp.1409-1420
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3. Full Scale Test Activities

3.1 Progress on the Pathway to a Virtual Fatigue Test; Ben Dixon, Madeleine Burchill, Ben Main [DST]

At ICAF 2017, Albert Wong (DST) proposed a pathway to a virtual fatigue test [1], to address the costly problem of being able to reliably and accurately predict structural fatigue at the airframe level. The aim of the *TITANS* (Trans-global Integrated Tests and Analyses Network for Structures) program was to strive towards a virtual fatigue test, by driving progressive improvements in aircraft fatigue modelling and experimentation through an international collaborative effort.

Clearly, a virtual fatigue test is too complex, too large and too important for any single team or even country to solve alone and therefore a coordinated and collaborative effort on an international scale is required. The notion of a virtual fatigue test[1] to replace (or enhance outcomes from) a real test is an emerging theme within the aerospace industry, but despite decades of research in fatigue, abundant analytical models and exponentially increasing computational capabilities within this period, full scale fatigue tests continue to produce surprises and unplanned failures.

Importantly, many of the elements that are necessary to progress towards a virtual fatigue test already exist, principally the very large and diverse fatigue test programs that are currently being undertaken (or recently completed). If, as proposed in the TITANS program, fatigue test data and associated outputs from teardown programs are made more generally available to the international community, more rapid scientific progress can be made;. The TITANS program proposed that this be done via the critical review of blind predictions of a series of real fatigue experiments.

The goal of reducing the cost and length of the full scale tests (both static and fatigue) currently necessary to achieve type certification or life assessment was also held by others in the ICAF community, for example AIRBUS, and a community of interest was formed. Furthermore, DST recognised that the capability to undertake a virtual fatigue test would result in far-reaching beneficial consequences to the sustainment of fleets, including: enhancing individual aircraft tracking capabilities, increased confidence in fatigue life predictions and the rapid validation of repair/modifications to airframes.

To better capture this broader context, DST has renamed TITANS, to ASSIST (Advancing Structural Simulation to drive Innovative Sustainment Technologies). ASSIST remains true to the original TITANS blueprint for a collaborative program, which has been initiated with the following framework:

- ASSIST community members perform blind fatigue life predictions for airframe prediction challenges, which are based on realistic aircraft loads and structures.
- The merits of each prediction methodology will be discussed within the community based on the demonstrated predictive ability versus actual test results.
- Publication of the collaborative forensic review of the results and the current shortcomings of each methodology.

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[1] highly complementary digital twin/digital thread principles [2, 3, 4]

- Development of a growing database of predictions for realistic aircraft loads and structures that can be used to establish error bands defining the expected accuracy and consistency for each methodology.

The ASSIST program is designed to facilitate a multi-nation multidisciplinary collaborative effort and at its heart is the collaborative online space that has been established at the Australian Government GOVTEAMS portal: https://www.govteams.gov.au. It is being used by DST to share the essential data associated with each airframe challenge, provide a collaborative space for discussions, and post results and evaluations. The site provides an opportunity to have both open and closed communities. Collaborative efforts are encouraged at any level and any arrangement, both within this portal or elsewhere – with the aim of publishing the key findings to drive the technology advances in the industry as a whole. To join the ASSIST community on the GOVTEAMS portal, interested parties are encouraged to seek membership by contacting ASSIST2019@dst.defence.gov.au.

One challenge, shown in Figure 1 below, has been completed and lessons learnt from a critical and joint review of individual blind predictions have been published [5,6]. Key findings from this challenge include:

- Variability in handbook stress intensity/beta solutions for this not uncommon geometry,
- crack path & morphology assumptions were often influenced by computational time/complexity limitations, and
- a need for high quality small crack growth data to predict crack growth from 10 microns.

DST has posted two further challenges, listed in Table 1, onto the GOVTEAMS portal. The ICAF community are invited to submit predictions, post challenges and join the discussion; to drive improvements in aircraft fatigue modelling and experimentation methodologies.

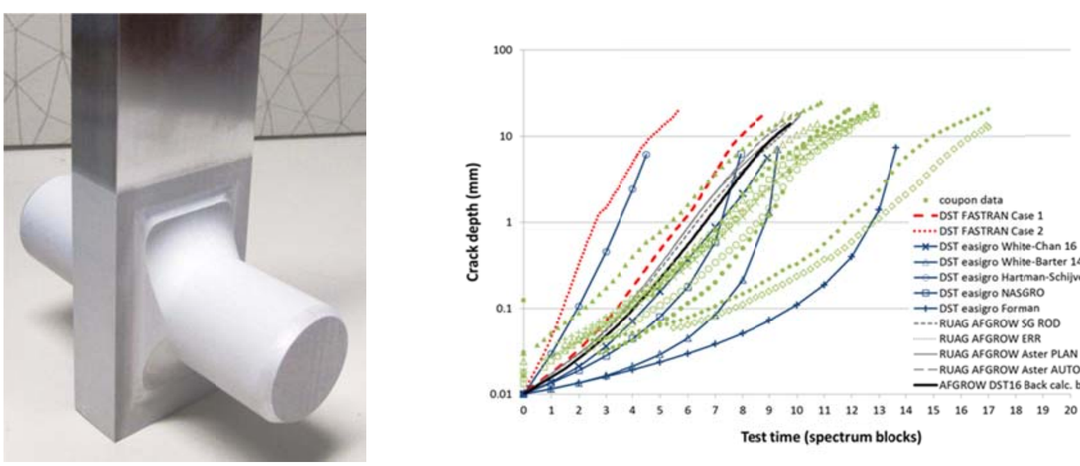

Figure 1. Fatigue test specimen and combined results [2] from first challenge – combat aircraft wing root shear tie (full details can be found on www.govteams.gov.au)

Table 1. Summary of the three ASSIST airframe structure challenges initiated to date.

Challenge name & details	**Estimated dates**		
	data posted on portal	**predictions due & results released**	**draft report for review**
Challenge #2 – helicopter truncated spectra (Helo) Material - AA7050-T7451 Spectrum – high frequency flight loads Test component - hourglass coupons	30 Mar 2019	01 Aug 2019	01 Dec 2019
Challenge #3 – military transport aircraft (MTA) Material - AA7075-T7351 Spectrum - military transport aircraft Test component – wide flat panels, pre-cracked holes	30 Mar 2019	01 Aug 2019	01 Dec 2019

References

[1] A.K. Wong, Blueprint TITANS: A Roadmap towards the Virtual Fatigue Test through a Collaborative International Effort, 29th ICAF Symposium – Nagoya, 7–9 June 2017

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3.2 C-130J Wing Fatigue Test – Deterministic Interpretation of Failure of the Butt Line 61 Wing to Fuselage Interface. (Kai Maxfield, Matthew McCoy*, Robert Ogden, Vuitung Mau* and Anthony Zammit* [DST/* QinetiQ])

On the 25th November 2015 the C-130J Hercules Wing Fatigue Test Program, conducted in collaboration between the Royal Australian Air Force (RAAF) and the Royal Air Force (RAF) reached a final successful conclusion, demonstrating structural durability and residual strength after application of two nominal lifetimes of test loading. Following this successful period of testing, a period of severe constant amplitude loading was applied to accelerate the growth of fatigue damage and identify life limiting structure. This aim was achieved a short time later following catastrophic structural failure of the port side wing.

In addition to providing critical science and technology support throughout this structural test program (with the test contracted to Marshall Aerospace and Defence Group in Cambridge, United Kingdom) the Defence Science and Technology (DST) Group was also fundamentally responsible for developing the complex tools and processes necessary to translate fatigue test findings into RAAF instructions for continuing airworthiness. These deterministic tools and processes [1] have been transitioned for use by Australian industry; however DST retained responsibility for interpretation of the life limiting structural region. This interpretation was completed by DST in early 2019 with the life limiting structure identified as the Butt Line (BL) 61 wing-to-fuselage interface (See Figure 1). Catastrophic structural failure occurred at this location as a result of multi-site cracking in the wing lower surface panels, with adjacent damage also present in the rear lower spar cap and selected lower surface stringers. DST interpretation of damage within this critical region subsequently provided a robust basis for development of ongoing instructions for continuing airworthiness with the analysis demonstrating an achievable expansion of current critical location inspection limits.

Further work is continuing at DST to apply probabilistic risk analysis methods aimed at establishing a Structural Life of Type for this platform under RAAF configuration, role and environmental conditions.

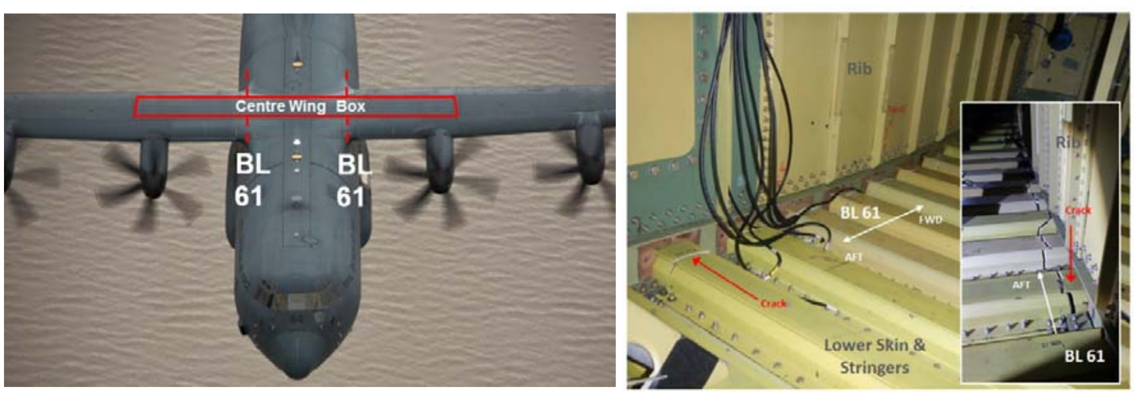

Figure 1. Life Limiting BL 61 region of the C-130J Hercules

Reference

[1] Maxfield, K., Ogden R. and McCoy M (2017) *Australian Test Interpretation Guide (Phase I) for the C-130J Wing Fatigue Test*, DST-Group-TR-3350, Defence Science and Technology, Melbourne.

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3.3 Forensic Analysis of Damage found during the Teardown of a Military Transport Aircraft Fatigue Test Article (Douglas Williams, Vui Tung Mau*, Anthony Zammit*, Robert Ogden, Kai Maxfield and Matt McCoy* [DST/ * QinetiQ]

Teardown and forensic examination of the test structure from the Royal Air Force and Royal Australian Air Force (RAAF) full scale C-130J wing fatigue test has recently been completed by DST in collaboration with Airbus Group Australia Pacific and QinetiQ Australia.

The teardown phase of the program, an activity recommended by [1], recorded in excess of fourteen hundred discrete damage findings. The most significant of these were selected for forensic analyses to provide valuable crack growth data for test interpretation activities. Figure 1 presents a span-wise distribution of some of the damage found during teardown in the centre wing structure.

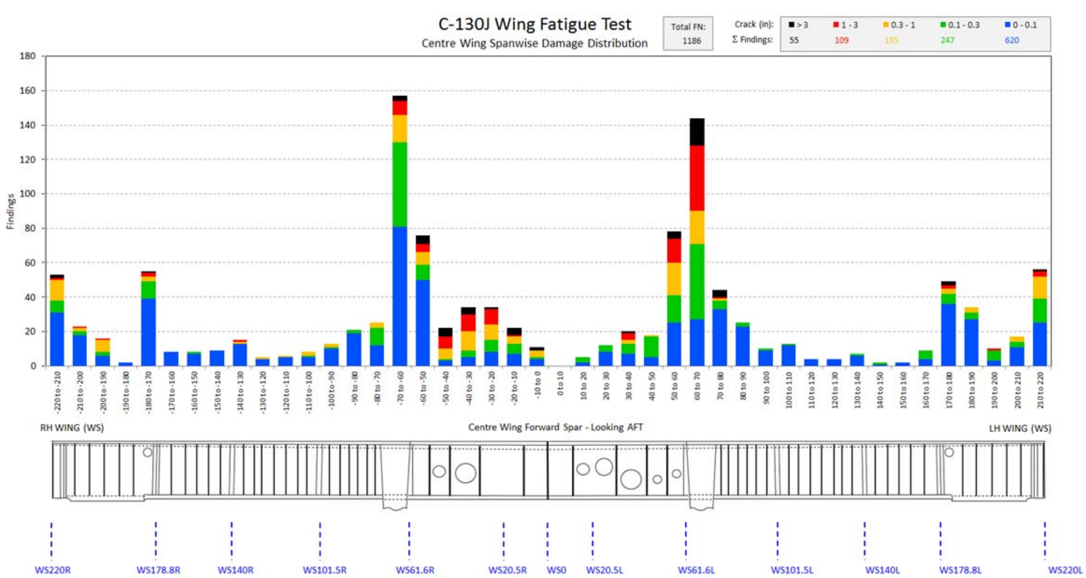

Figure 1. C-130J Wing Fatigue Test teardown centre wing span-wise damage distribution map

Quantitative Fractography (QF), material testing and load application assessments of the significant damage items was conducted at DST. A sample of QF analysis for the centre wing rear lower wing panel (BL 61 region) is shown in Figure 2.

In general the detailed forensic examination conducted in support of this test program provided detailed information on; the benefits of load spectrum effects in QF analysis, fatigue damage progression, the efficacy of damage insertion techniques used during the testing phase, and the impact of surface treatments such as shot peening on discrete locations of damage.

The outcomes of the forensic analyses form a significant and fundamental input into the RAAF program of test interpretation [2] and underpin the program of ongoing airworthiness management and sustainment for the RAAF C-130J-30 fleet. Figure 3 presents a sample of such cracking in the BL 61 region. The QF data and crack growth curves generated by this activity, underpin the test interpretation work at every location on the aircraft. The lessons learnt from this program are being passed on to future life assessment programs and associated research.

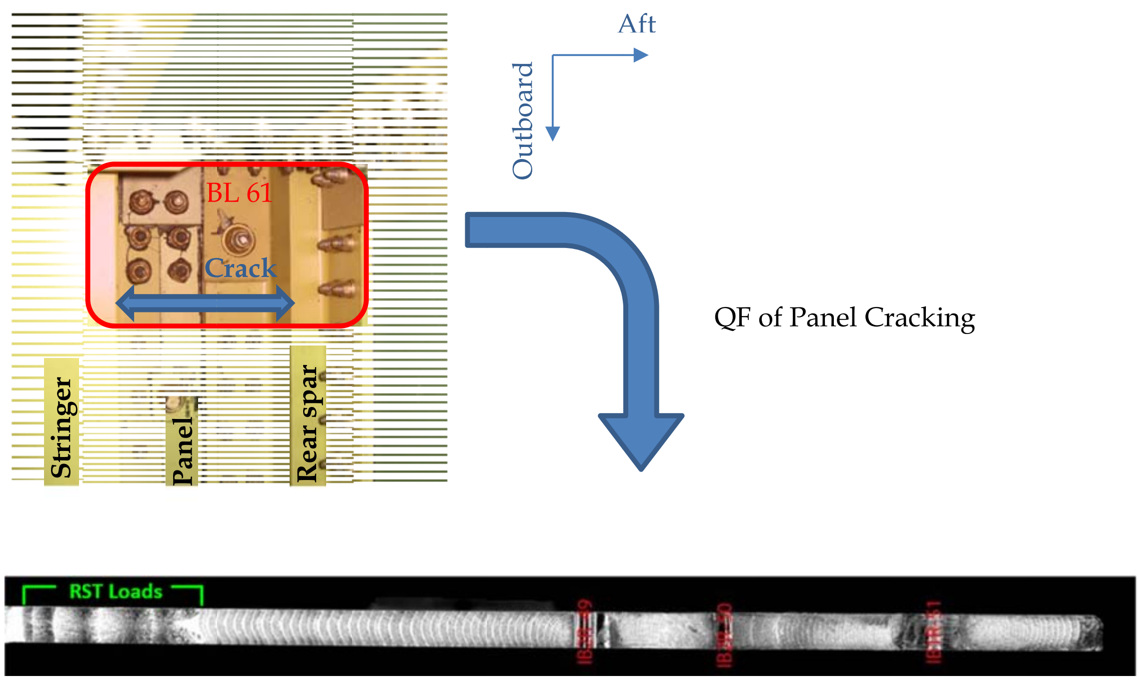

Figure 2. Example teardown location and fracture surface picture ready for QF in the BL 61 region (centre wing to fuselage attachment point at the rear spar cap)

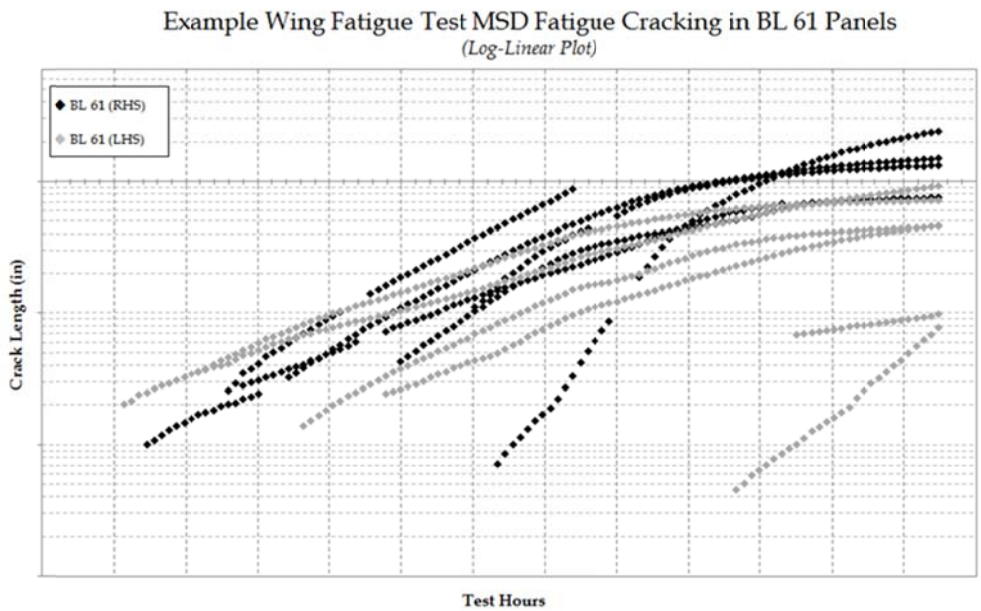

Figure 3. Indicative log-linear crack growth curves determined from QF that underpin Test Interpretation activities

References

[1] US DoD (1998) Department of Defense Joint Specification Guide, Aircraft Structures, JSSG-2006, US DoD.

[2] Maxfield, K., McCoy, M. & Ogden, R. (2017) Australian Test Interpretation Guide (Phase I) for the C-130J Wing Fatigue Test, DST-Group-TR-3350, DST Group.

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3.4 C-130J-30 Wing Fatigue Test - Test Interpretation and Implementation (Ross Stewart and Mathew Richmond [QinetiQ])

A combined RAAF - RAF C-130J-30 Wing Fatigue Test (WFT) concluded testing in 2015. Test Interpretation (TI) is being undertaken by DST and QinetiQ, with DST investigating the more complex locations with multi-site or multi element damage. Implementation of TI outcomes starts from the Damage Tolerance Assessment (DTA) derived intervals through to the development of a EASA Part 21 design containing Instructions for Continuing Airworthiness (ICA) whilst at the same time remaining cognisant of the impact on the current maintenance program and the life objectives of the fleet.

The Type Certification Basis (TCB) for C-130J TI is based on JSSG 2006, supplemented by EN-SB-08-001 and EN-SB-08-002, as detailed in reference A.

Implementation for the C-130J TI consisted of the following activities:

- **Verification and Validation of the TI process.** To ensure TI outcomes are compliant with the TCB, QinetiQ undertook V&V of the tools, data and TI process, covering all aspects from test loading through to DST developed analysis tools.

- **Part 21 Design.** This includes all TI requirements along with the implementation aspects listed below. For DST TI work, the outcomes are included within the QinetiQ design.

- **Holistic Implementation.** Rather than complete individual designs for each location, a holistic approach is undertaken covering all locations on the same structural element. This ensures that all findings are covered and allows for the alignment of inspections with similar access requirements.

- **Configuration.** Comparison is made to ensure intervals are not impacted by differences between the fleet configuration and the DTA configuration.

- **NDI.** The suitability of the extant procedures was assessed to ensure they cover the required structure, if there is any obscured structure, and the access requirements. All these may necessitate revising the DTA using less conservative assumptions.

- **Implementation urgency.** The WFT derived intervals are promulgated in Equivalent Flight Hours with usage tracked by the C-130J Individual Aircraft Tracking Program - APaCHE. However, there is the possibility that the new intervals may be overflown before the inspections can be undertaken. In these cases QinetiQ, provides a strategy that allows the next inspection to occur at a more suitable time, whilst remaining compliant with the TCB. This may require re-assessment of the assumptions underpinning the DTA.

- **Modifications.** An interval that cannot be extended to a suitable frequency may dictate the need for a modification to provide inspection relief. In a similar manner a location where in service cracking is deemed likely, a modification may be recommended to assist with aircraft availability.

Thus far, TI and implementation has been able to provide maintenance/availability relief by alignment of inspections with the deeper maintenance cycle for the RAAF C-130J fleet.

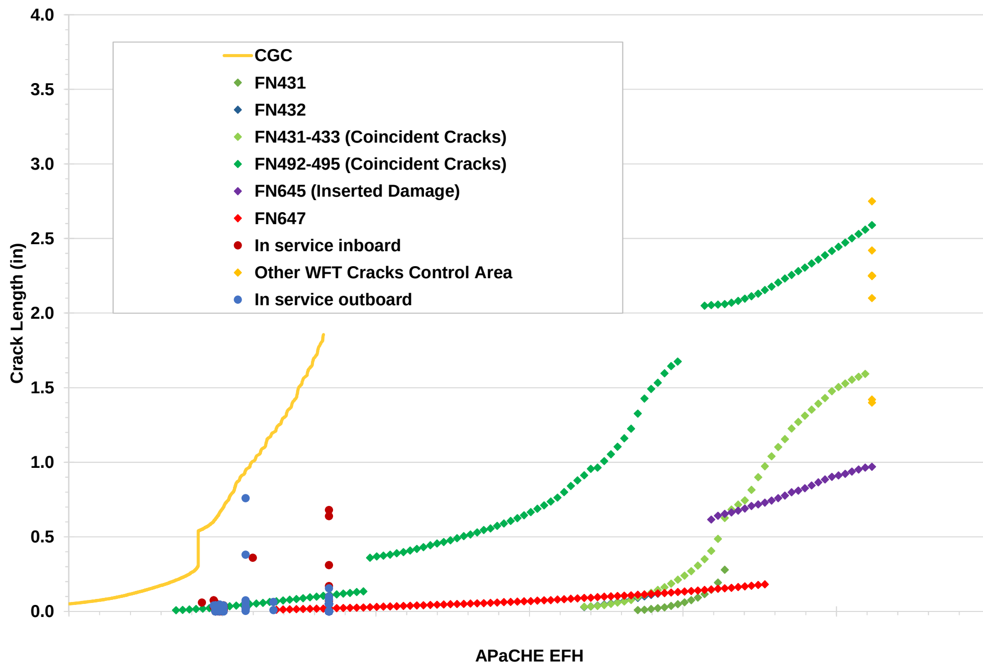

Figure 1. Crack growth modelling verses test cracking and fleet observations

Reference

[1] DGTA-ADF, C-130J Full Scale Fatigue Test Programme – RAAF Durability and Damage Tolerance Requirements for Full Scale Fatigue Test Interpretation and Subsequent Fleet Management, U320975, Version 1.00, 31 January 2013.

Acknowledgements

[1] Mr. Rob Ogden, Mr Kai Maxfield DST Group, FLTLT Danishyar Sekandar DAVENG DASA.

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3.5 Evaluation of a PC-9/A Wing Main Spar with Misdrills using Enhanced Teardown at Resonance (Ben Main, Keith Muller*, Michael Konak, Michael Jones, Sudeep Sudhakar^ and Simon Barter [DST/*RMIT/^DASA])

Widespread production miss-drills in Royal Australian Air Force (RAAF) PC-9/A wing main spar lower caps were a potential threat to airworthiness and fleet availability late in the service life of the aircraft. A rapid, novel, enhanced teardown of a retired RAAF PC-9/A wing spar with production miss-drills was successfully completed to assess this risk. Dynamic block loading was applied to the main spar lower cap of a wing with multiple miss-drill indications identified in-service using x-ray inspection. Using an enhanced teardown experimental method of cycling the wing at resonance, fatigue failure occurred within the test section from a main spar miss-drill in less than fifty cumulative hours of cycling. A damage tolerance prediction, testing results, teardown inspection and forensic assessment of the spar lower cap was combined to deliver timely and valuable risk mitigation advice for PC-9/A fleet structural integrity managers. Greater confidence in existing fleet management was fostered in a very short timeframe and the opportunity presented by a retired wing with miss-drills was fully leveraged. In addition, an innovative structural experimentation method for aircraft sustainment was developed based on techniques and equipment from earlier tests.

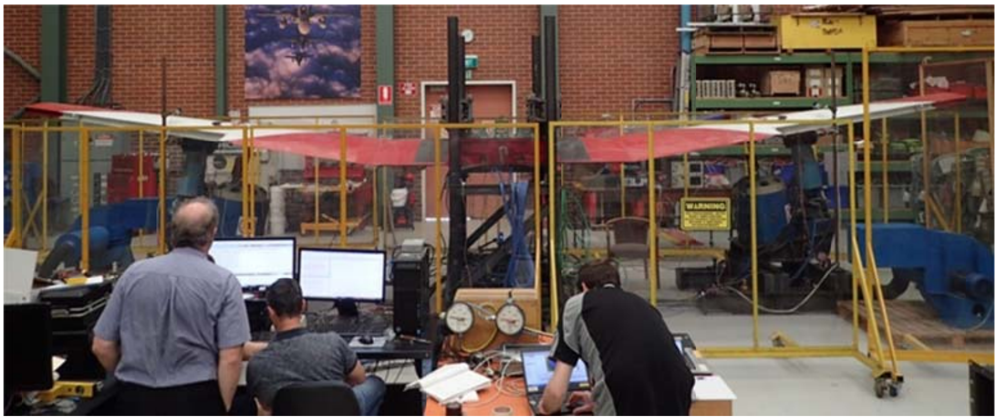

Figure 1. The PC-9/A wing enhanced teardown test rig at DST Fishermans Bend, Melbourne

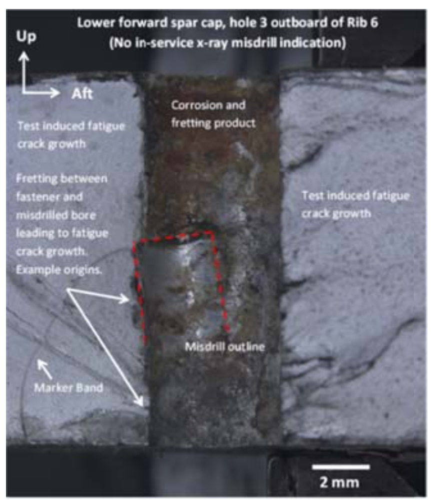

Figure 2. Fractography of the main spar cap primary failure location which contained a miss-drill not identified in-service.

Reference

[1] Main, B., Muller, K., Konak, M., Jones, M., Sudhakar, S. and Barter, S. (2019) *Evaluation of a PC-9/A Wing Main Spar with Misdrills using Enhanced Teardown at Resonance* In: Proceedings of the 29th International Conference on Aeronautical Fatigue and Structural Integrity (ICAF) Krakow, Poland [in publication]

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4. In-Service Structural Integrity Management

4.1 Hypotrochoid-based design of optimal rework shapes for repair of fatigue damaged aircraft structures (Xiaobo Yu and Manfred Heller [DST])

Fatigue cracking is one of the main concerns that affect the structural integrity of metallic aircraft components. To effectively repair and extend the life of fatigue damaged aircraft components, the Defence Science and Technology (DST in Australia has developed an innovative repair technology known as rework shape optimisation **Error! Reference source not found.**. With this repair technology, the fatigue damaged region is three-dimensionally modified into a new shape that is optimised for stress reduction. The repair only involves localised material removal, and can be applied precisely, either in-situ or at a repair depot.

Prior to 2017, the optimal rework shapes developed by DST for service applications were mainly by a freeform-based approach, where a series of control points were used to define a 2D master curve, which is then used to construct the rework profile via extrusion. With this approach, the rework shape was optimised by gradual repositioning of the control points using a DST in-house optimisation code interfaced with standard finite element analysis (FEA). As demonstrated previously, the freeform-based approach is capable to produce an optimal shape that leads to the most stress reduction. Nevertheless, it requires high-level FEA and programming skills to establish application-specific links between the in-house code and the standard FEA to automate the iterative process.

Recently, a new approach, namely the hypotrochoid-based approach, has been developed in DST for the design of optimal rework shape **Error! Reference source not found.**. The mathematical formula that defines hypotrochoid shape is given in Ref **Error! Reference source not found.**, and here re-presented as Eq (1).

$$\begin{cases} x = R[(1+m)\cos\theta - n\cos 3\theta] \\ y = R[(1-m)\sin\theta + n\sin 3\theta] \end{cases} \tag{1}$$

When compared to the freeform-based optimisation, the hypotrochoid-based approach has a range of benefits, including: no requirement for dedicated optimisation software or customised coding, readily executable by a typical finite element analyst, and nearly as good optimal designs achievable with very few numbers of FEA iterations. The effectiveness of the hypotrochoid-based approach is elaborated through two recent applications. One relates to the optimal design of rework shapes to recover an F/A-18 inner wing with fatigue damage at the aft spar shear tie location **Error! Reference source not found.**. The geometry and peak stress of the optimal repair are illustrated in Figure 1 (a), in comparison to the as-received profiles. With the sufficient stress reduction, the optimal design was implemented as shown in Figure 1(b) and the recovered wing was returned to service, managed on an unaltered fleet safety-by-inspection program interval.

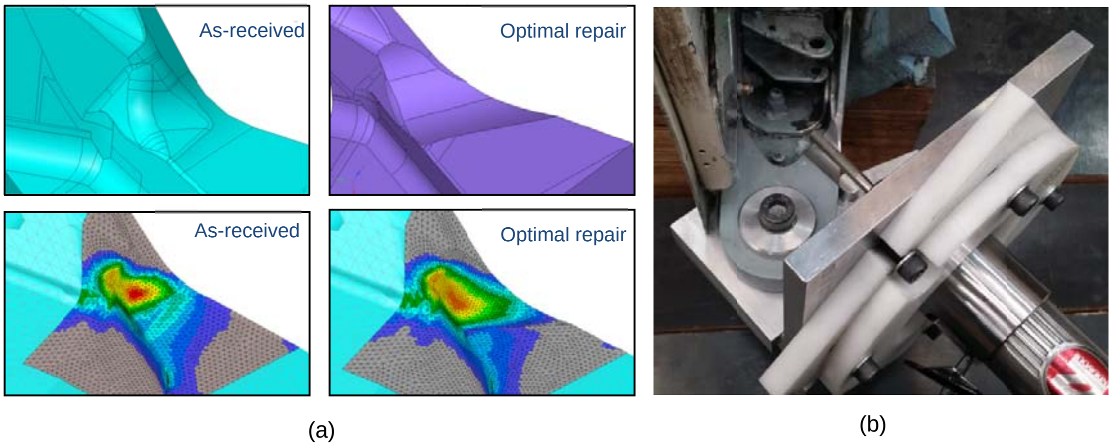

Figure 1. Application of the hypotrochoid-based optimal rework shape design for the recovery of an F/A-18 A/B inner wing shear tie. (a) comparison of geometry and stress at the aft spar shear tie location before and after optimal rework; and (b) In-situ machining, implementing the optimal rework design.

The other recent application relates to the optimal design of a run-out shape for pre-emptive modification of fuselage beam replacements on C-130J aircraft **Error! Reference source not found.**. Figure 2 illustrates the location of the bow beams and compares the shape and stress between the baseline and optimal profiles.Both applications showed that the hypotrochoid-based optimal design approach is readily transferrable for broader applications.

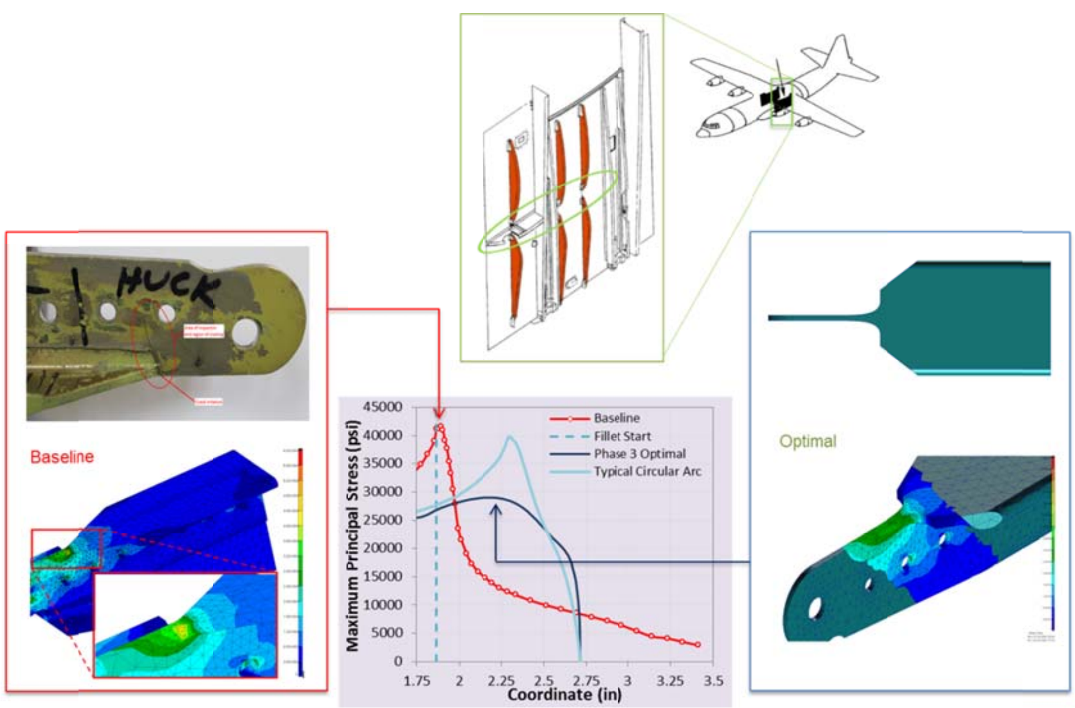

Figure 2. Application of the hypotrochoid-based approach for the design of optimal rework shape of C-130J bow beam runout.

References

[1] Heller, M., Burchill, M., Wescott, R., Waldman, W., Kaye, R., Evans, R. and McDonald, M. (2009) Airframe life extension by optimised shape reworking – Overview of DSTO developments, In: *Bridging the Gap between theory and Operational Practice, Proceedings of the 25th ICAF Symposium, 279-299, Bos, M. (Ed.)*, Springer Science+Business Media B.V., Dordrecht.

[2] Yu, X. and Heller, M. (2019), Hypotrochoid-based optimal design of rework shapes for repair of fatigue damaged aircraft structures, invited talk, *13th International Conference on the Mechanical Behaviour of Materials (ICM13), 11-14 June 2019,* Melbourne, Australia.

[3] Pickthall, P., Wescott, R., Heller, M. (2019), *Robust Optimal Hypotrochoid-Based Holes in a Large Biaxially-loaded Plate*, AV16006671, DST-XX-XXXX, Defence Science and Technology, Melbourne.

[4] Yu, X., Hiller, G., Tata, D., and Heller, M. (2019), *Optimal Shape Rework Design for Repair of an F/A-18A/B Inner Wing Aft Spar Shear Tie Location (Wing A120521 LH)* , AV14811529, DST-TR-XXXX, Defence Science and Technology, Melbourne.

[5] Tata, D., Williams, D. and Heller, M. (2019) Hypotrochoid-based Shape Optimisation of the C-130J Bow Beam Runouts, DST-Report, AV15486661, DST-TR-XXXX, Defence Science and Technology, Melbourne.

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4.2 Recovery of a cracked F/A-18A/B inner wing using acetate replica inspection and shape optimisation. (Ben Main, Xiaobo Yu, David Russell, Brett Lemke*, Grant Hiller*, David Tata* and Simon Barter [DST / *QinetiQ])

Repeated fatigue cracking was observed in the Royal Australian Air Force fleet during Safety-by-Inspection (SBI) program inspections of the inner wing aft spar upper flange shear tie radius of a Hornet wing. Previous hand blends and conventional non-destructive testing had either missed the crack tip, or fatigue cracking had reoccurred in-service. To repair the wing again by blending away further material, confirmation of full crack removal was required along with a blend profile which would not exacerbate the peak stress in the radius location. A repair scheme was developed with these objectives by Defence Science and Technology (DST) and QinetiQ Pty Ltd using acetate replica inspection and numerical shape optimisation modelling techniques.

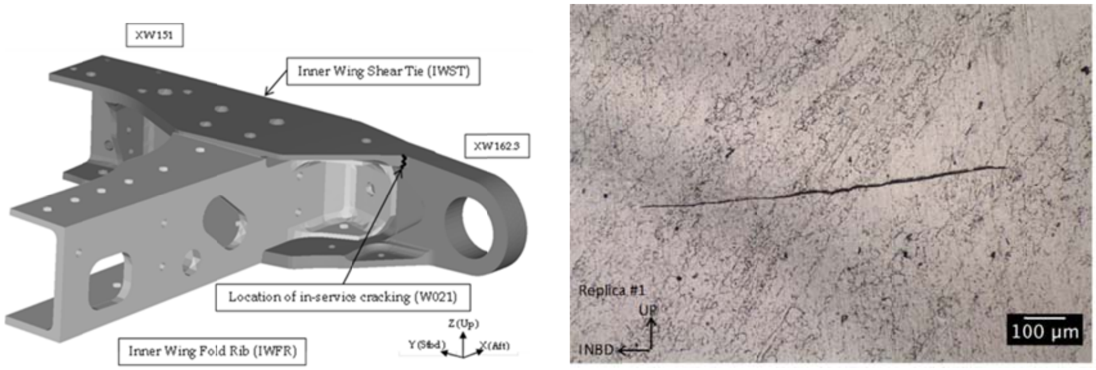

Figure 1. The inner wing aft spar upper flange shear tie radius location (left), and a replica inspection of the 're-cracked' condition of the location prior to shape optimised blend repair (right).

The optimised repair procedure was successfully incorporated and full removal of fatigue cracking confirmed by acetate replica inspection. Post repair finite element analysis concluded peak stress in the as-repaired configuration was within 2% of the blueprint configuration.

F/A-18 A/B inner wing was returned to the Royal Australian Air Force as a serviceable asset under engineering disposition to continue management on an unaltered fleet safety-by-inspection program interval.

References

[1] X. Yu, G. Hiller, D. Tata, M. Heller (2019), *Optimal Shape Rework Design for Repair of an F/A-18A/B Inner Wing Aft Spar Shear Tie Location (Wing A120521 LH*) , AV14811529, DST-Group-TR-XXXX, Defence Science and Technology, Melbourne.

[2] Main, B., Hiller, G., Russell, D., Lemke, B. and Barter, S. (2017) *Update: A12-0521 LH W021 Blend Repair*, Presentation to Classic Hornet ASI Working Group, Newcastle.

[3] Lemke, B. and Cooper, T. (2018) *Inspection of W021 Shear Tie Re-Profiling*, 4-52-15-36-2987.QES1503, QinetiQ Australia Pty Ltd, Melbourne.

[4] Tata, D., Trezise, S. and Jackson, K. (2019) *Analysis of F/A-18A/B Inner Wing A120521 W021 Optimised Blend Repair*, ER-F18-QQ00157, QinetiQ Australia Pty Ltd, Melbourne.

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4.3 Fractographic investigation of maintenance induced damage and fatigue cracking in F/A-18A/B Outer Wing A13-0361 Outboard Leading Edge Flap (OLEF) Hinge Lugs (Ben Main, Michael Jones, David Russell and Simon Barter [DST])

Widespread maintenance induced damage (MID) leading to fatigue crack growth has been found in the Royal Australian Air Force F/A-18A/B fleet in Outboard Leading Edge Flap

(OLEF) lug radii. The uniformity and extent of MID suggests a cutting tool may have been used to trim the skin or sealant at the front spar to skin joint and that the lug roots were damaged as a consequence. Thus far, root cause of the MID has not been confirmed.

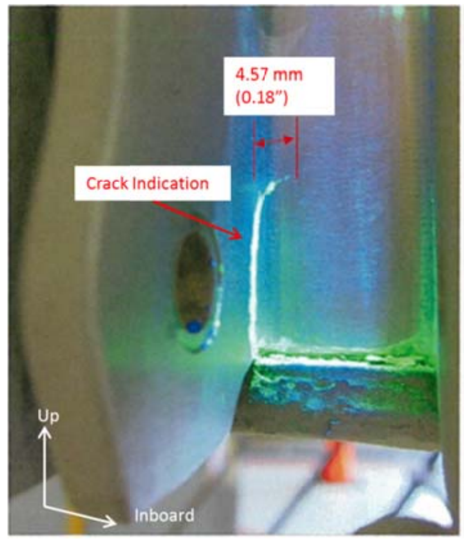

Figure 1. The outer wing of the F/A-18A/B Hornet with the location of the OLEF Hinge Lugs marked (left) and (right) liquid penetrant indications of fatigue crack growth from an in-service outer wing exhibiting MID.

DST was provided a retired RAAF Outer Wing exhibiting such damage and cracking that was deemed beyond economic repair. After breaking open all the OLEF lug radii, forensic examination was undertaken using optical and electron optical microscopy. These examinations assessed the size, number, extent and origin of fatigue cracks along with a qualitative evaluation of their crack growth characteristics. These findings were compared to relevant full-scale fatigue test results which formed the basis of in-service management assumptions.

The comparison of fleet findings against the original fatigue life analysis will enable the current fleet management actions to be updated to assure aircraft safety and component repair management.

Reference

[1] Main, B., Jones, M., Russell, D. and Barter, S. (2019) *Fractographic Investigation of Maintenance Induced Damage and Fatigue Cracking in F/A-18A/B Outer Wing A13-0361 Outboard Leading Edge Flap (OLEF) Hinge Lugs*, DST-Group-TN-XXXX, Defence Science and Technology, Melbourne.

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4.4 DST approach to harvesting free energy inside a Rotorcraft Gearbox - Powering next generation of long-duration HUMS experiments with Wireless Acceleration Transducer (Riyazal Hussein, Scott D. Moss, George Jung and Henry J. Kissick [DST])

Health and Usage Monitoring Systems (HUMS), and/or Condition-Based Maintenance are useful if they can detect abnormalities via algorithms. Recently reported Class-A helicopter [1, 2] mishaps have been attributed to faulty planetary bearings/gears in the main transmission gearbox. Potentially, these faults - which lead to catastrophic failure - could have been detected by HUMS however, it failed to detect as currently, these algorithms to detect this types of faults doesn't exist.

A commercial-of-the-shelf (COTS) Ridgetop's RotorSense ™ wireless sensor [3] was acquired to conduct next generation of long–duration HUMS experiments on this type of fault where crack is propagated along the valley/tooth of planet gear of Kiowa Bell 206B Gearbox. The sensor is attached to the planet carrier just above propagated crack gear; wirelessly transmitting data to a gateway outside the gearbox and finally accessed on a computer via network by data analysis research scientist. The experiments require a 158 mW of continuous power (3.5 volts @ ≈ 45 mA) [4] over many months, which is beyond the capacity of the manufacturer supplied primary cell. Hence, DST has developed an approach for harvesting energy inside the Bell 206 gearbox. This approach uses a wire pancake-coil electromagnetic transducer also attached to the planet carrier inside a gearbox that is rotating at 5.8 Hz, and a series of stationary permanent magnets attached to the inside of the casing and adjacent to the circular transducer arrangement. When operating at ~350 revolutions-per-minute (rpm), the prototype harvester device examined in this work produces an average electrical power of 280 mW. The modelling and experimental approach of this harvester is detailed in reference [5].

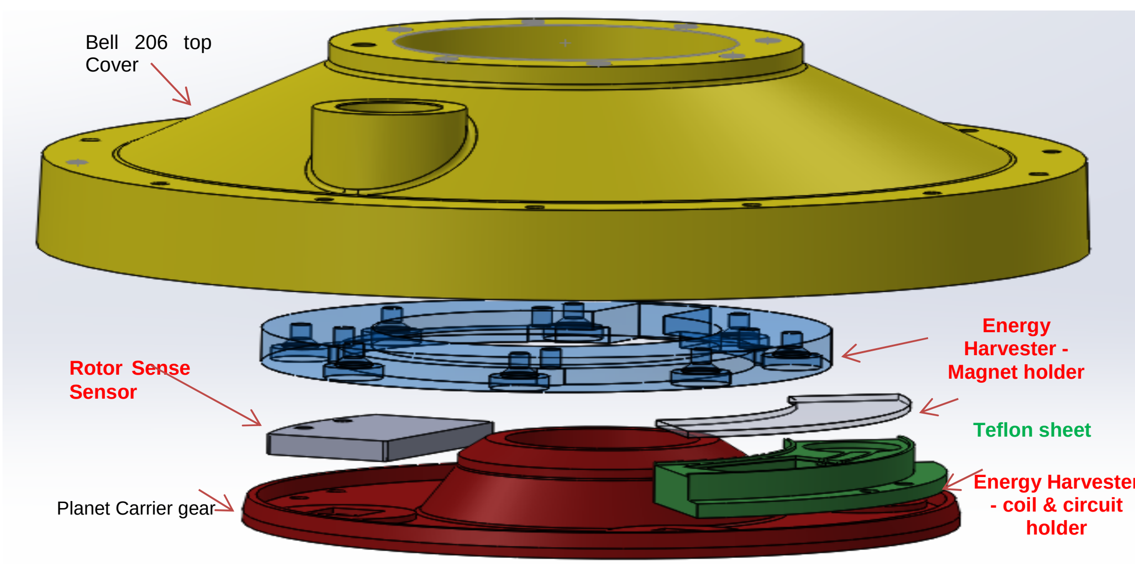

Figure 1. Exploded view in Solid Works for the components of energy harvester to be 3D printed

As shown in Figure 1, Ridgetop's Rotor Sense ™ sensor system is a COTS wireless rotational and acceleration sensor (3-axis) designed to extract high-resolution vibration signatures caused by gear faults. The energy harvester itself consists of two parts: (i) a magnet holder, and (ii) a coil and circuit holder, both were designed using computer aided design (Solidworks) and were three-dimensionally (3D) printed using polycarbonate. The magnet holder is attached to the inner casing of the Bell 206 gearbox top cover using four out of its eight studs, and contains up to eight equally spaced Samarium-Cobalt rare earth magnets along its circumference.

The rotating coil is positioned such that there is a gap of 2 mm to the lower face of the magnets, and underneath is a protective Teflon cover. As the transducer sweeps past the magnets during rotation, the permanent magnets induces an electro-motive force via Faraday's Law of Induction [6].

$$V_{e.m.f.} = -\mathrm{N}l\,\frac{\Delta\Phi_B}{\Delta t} \tag{1}$$

where $V_{\mathrm{e.m.f.}}$ is the electro-motive force (voltage), $-N$ is the number of turns contained in a wire coil, l is effective length of the coil, $\Delta\Phi_B$ is the change of flux density going through the coil and Δt is change in time. At 350 rpm, eight magnets produced a discrete voltage impulse of 30 V amplitude which is not suitable for powering electronics directly. A power-conditioning circuit converts the high voltage pulses into a steady, regulated DC voltage source of 3.49 Volts with a "critical" measured load resistance of 43 Ω. Hence, maximum power of the energy harvester is P=V^2/R = 283 mW that is used to power the wireless sensor.

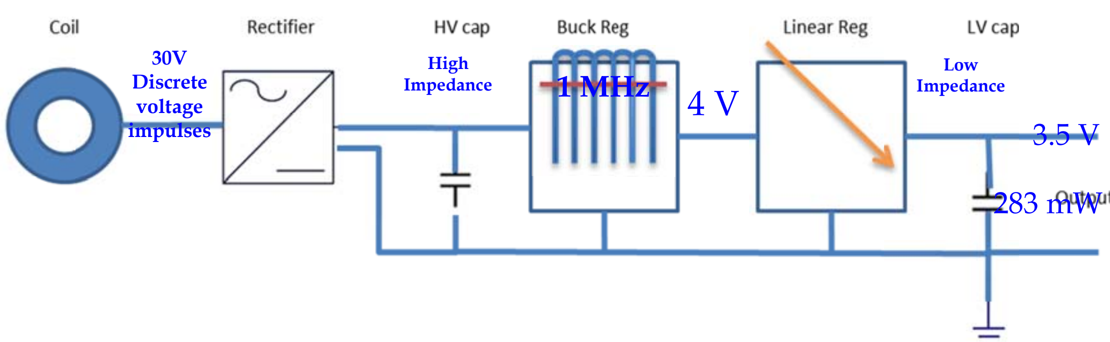

Figure 2. Energy harvester functional block diagram

The coil and circuit holder (Figure 1) hosts an electromagnetic coil transducer that is accompanied by a DST designed and built power-conditioning circuit to regulate the harvested electrical power. Detailing to operation of the power-conditioner, the voltage pulses are first rectified (diode bridge) which then charge a small high voltage storage capacitor. A buck regulator converts the high voltage to approximately 4 V with high efficiency. This is followed by a low dropout linear regulator for filtering and final regulation to a sufficiently clean, constant output of approximately 3.5 V (Figure 2). The power-conditioning circuit also features overvoltage protection at both the input and output stage to protect itself and the attached sensor. Any excess power produced during operation is safely dissipated. The harvesting system generates ≈ 50% more power than is needed to meet Ridgetop's sensor operating requirement.

References

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[3] Ridgetop's Rotor Sense ™ sensor system, User guide, July 2018

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[6] J. C. Maxwell, A treatise on electricity and magnetism vol. II, Clarendon Press, Oxford,1904

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4.5 Developments in Risk-Based Fatigue Failure Prediction for Application to Military Aircraft (Ribe Torregosa and Weiping Hu [DST])

Fatigue life prediction is a major issue in the field of engineering especially in aerospace structures which requires accurate prediction due to underlying costs involved. Although prediction of crack behavior over the years has improved and modelling has become more sophisticated, the accuracy of deterministic prediction cannot be accepted without question. Some airframe cracking scenarios are highly complex, requiring sophisticated methods to appropriately manage potential risks including variability of influencing parameters. This parameter variability and its influence on fatigue is addressed in the MIL-STD 1530D [1], which mandates the application of probabilistic risk analysis (PRA) in structural integrity assessment. Conducting a probabilistic risk analysis (PRA) of fatigue failure requires the following data: i) the equivalent initial damage size (EIDS) distribution, ii) the master crack growth curve, iii) the maximum stress distribution per flight and iv) the residual strength corresponding to a given crack size. Of the four parameters, the EIDS distribution and the master crack growth curve have been found to be influential. It should be noted that the EIDS is dependent on the master crack growth curve since EIDS is derived by analytically determining the initial damage size distribution that characterizes the damage size distribution observed during test or in service using the master crack growth curve [1]. Risk-based fatigue failure research at the Defence Science and Technology (DST) has focused on three areas: i) methods to improve the accuracy and robustness in estimation of the EIDS distribution, ii) the effect of the variability of the master crack growth curve, and iii) development of tools for the risk-based aircraft structural integrity. The risk-based methods and approaches developed by DST have also been partially validated via experimental data obtained by DST and other sources. By 2020, the DST developed risk-based methodology should be used to augment the structural safety management procedures for the ADF aircraft fleet.

Development of FracRisk – a risk-based fatigue failure assessment tool

As part of DST's risk-based structural integrity assessment of C-130 aircraft, a new analysis tool called FracRisk has been developed. The development started with a Defence requirement to replicate the C-130H PRA [2] on center wing lower surface panel location. With the RAAF planning to use FracRisk analysis on other platforms, the Defence Aviation Safety Authority (DASA) contracted QinetiQ Engineering to conduct a preliminary evaluation and validation by comparing FracRisk and the United States Air Force (USAF) developed analysis tool PROF [3]. Comparison of the analysis results between FracRisk and PROF for the analysis of C-130J CW-3A location are shown in Fig. 1 and Fig. 2.

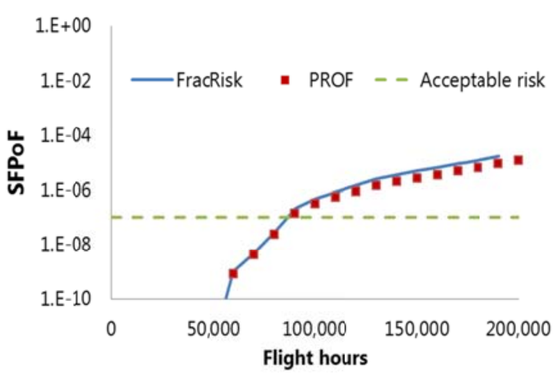

Figure 1. Comparison of FracRisk and PROF results using tabulated stress exceedance data for C-130J CW-3A location

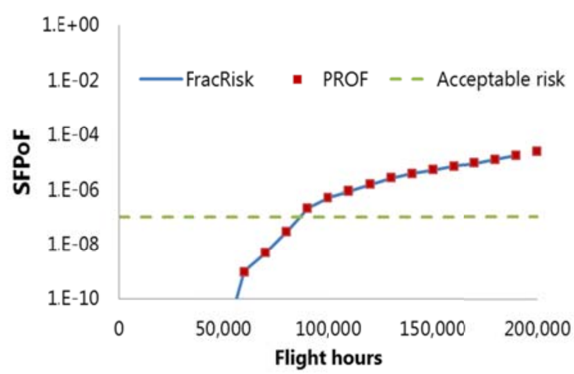

Figure 2. Comparison of FracRisk and PROF results using Gumbel peak stress distribution for C-130J CW-3A location

In the analysis the input data between FracRisk and PROF were identical, including the EIDS which was modeled as a beta distribution. The FracRisk analysis results are almost indistinguishable with PROF results especially in the region where the SFPoF is $1x10^{-7}$ or less. This result shows a verification of FracRisk against PROF. Compared to PROF, FracRisk has more flexible input data format such as the capability to use the residual strength curve as the input parameter instead of using stress intensity factors. Robustness of the graphical user interface was also evaluated by QinetiQ after which a few improvements were proposed. Following the recommendations from QinetiQ, FracRisk user interface was modified to incorporate the suggested improvements. An example of the user interface is presented in **Error! Reference source not found.**.

Summary

With the increasing demand for risk-based approaches to structural integrity assessment of military aircraft, DST has been actively supporting the RAAF by conducting research to improve the methods associated with fatigue failure prediction of structures. Investigations examining the application of different distribution models for the EIDS distribution resulted in a new proposed model using bounded distributions such as beta distribution. The use of a bounded distribution addresses one of the critical issues in risk analysis, in which commonly used distribution model are unbounded to the right which allows the possibility of an EIDS greater than the size of the component itself. Even the smallest possibility of unrealistically large initial crack size has the potential to increase the calculated single flight probability of failure risk by several orders of magnitude. Thus, the need for unbounded crack size probability distribution model which does not allow infinitely large initial crack size.

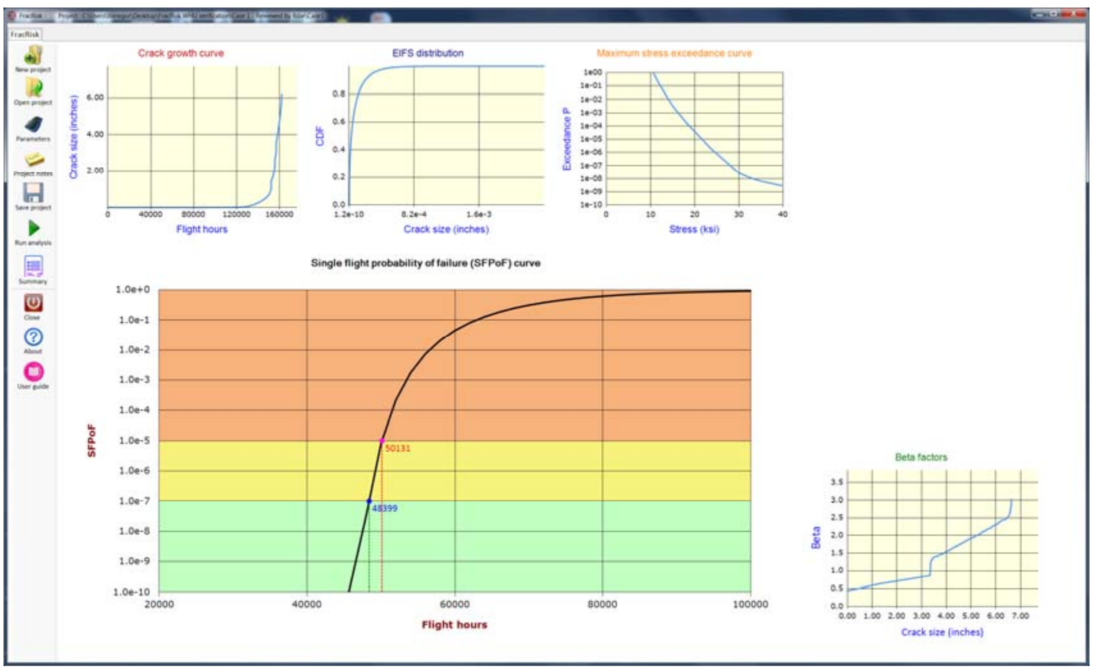

Figure. 3 FracRisk graphical user interface

DST investigated the validity of a DST developed risk assessment methodology in conjunction with the MIL-STD1530D guidelines. Preliminary investigations based on DST coupon tests showed that the probabilistic approach predicted failure results in the expected range. In the future, analysis of multi-site fatigue damage (MSD) considering multiple and interacting cracks will be added to capabilities of FracRisk.

References

[1] Defence, U.S.D.o., *MIL-STD-1530D Standard Practice - Aircraft Structural Integrity Program (ASIP)*. 2016: USA.

[2] Torregosa, R. and W. Hu, *C-130H Centre Wing Lower Surface Panel Number 3 Probabilistic Risk Analysis*, Defence Science and Technology Organisation, DSTO-RR-0371, 2011.

[3] QinetiQ Pty Ltd., *Independent Evaluation and Validation of FracRisk* , ER-C130-QQ000136, 2018.

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4.6 Damage Tolerance Analysis of the PC-9/A Wing Main Spar with Miss-drill Damage (Kevin Jackson, Mark Spiteri, David Tata, Jason Wittkopp, Mathew Richmond [QinetiQ])

In March 2003 miss-drill damage was detected in a fastener hole of the lower spar cap of a PC-9/A wing. This led to fleet wide radiographic inspections to determine the presence of gross manufacturing defects in the wing lower spar caps. In addition, a lifing tool was developed and significant detected miss-drill defects were repaired.

In 2016, QinetiQ was tasked by the Defence Aviation Safety Authority (DGTA) to revisit the Through Life Management Strategy (TLMS) for the PC-9 wing main spar in the presence of miss-drill damage. Aspects of the task included: 1) Crack growth analysis of a blueprint main spar and correlation to Full Scale Fatigue Test results; 2) Crack growth analysis to determine the effect of miss-drill damage on fatigue cracking rates; and 3) Validation of the fleet wide X-ray inspection technique to establish a detectable miss-drill size. The analysis was performed using AFGROW and StressCheck software packages. Using the results from this work, a TLMS for the spar with miss-drill damage was developed consistent with relevant airworthiness regulations.

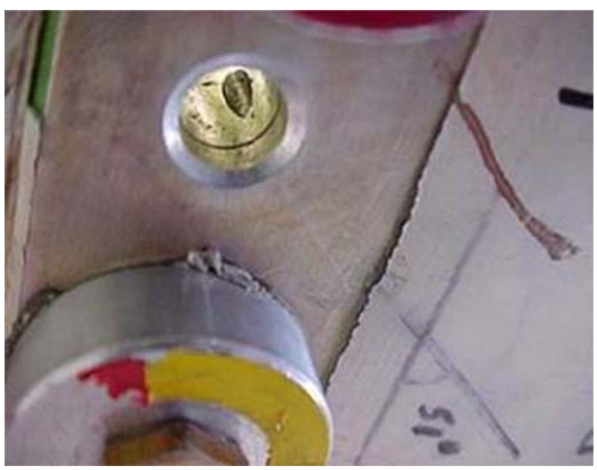

Figure 1. Miss-Drill Damage at Spar Cap Hole

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5. Fatigue Investigations of In-Service Aircraft

5.1 Update: Final report on the in-flight loss of a Propeller from a Saab 340B Commuter Aircraft [ATSB]

On 17 March 2017 a Regional Express Saab 340B aircraft registered VH-NRX was forced to make an emergency landing after the right propeller departed mid-air Figure 1. The propeller was found a few days later in bushland in Sydney's south-west, Figure 2. In its preliminary report, the Australian Transportation Safety Board (ATSB) stated that a fatigue crack had formed in the propeller mounting flange, where the propeller attaches to the gearbox, and transitioned into the shaft section. The crack originated at the bore of a dowel pin near the forward face of the propeller hub flange, see Figure 4. The dowel pin bore was corroded in parts and corrosion pitting was found near the fracture. Further work is ongoing to ascertain whether the corrosion or other factors contributed to the fracture initiation.

Figure 1. View of the aircraft after landing

Figure 2. Propeller as found

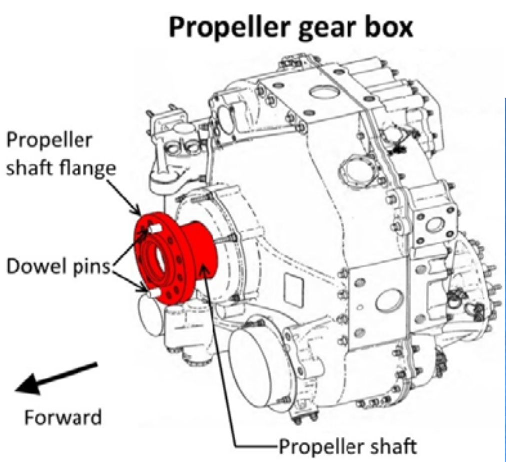


Figure 3. Gear box schematic

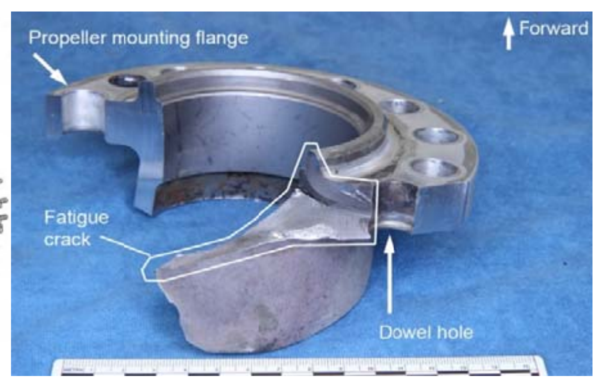


Figure 4. Section of propeller shaft

According to the ATSB this is the first known critical failure of this type, initiating within the propeller hub flange of the GE Aviation CT7-9B engine. The same propeller gearbox is fitted to multiple variants of the CT7 engine and SAAB 340 and EADS CASA CN-235 aircraft

There is currently no maintenance requirements specified in existing maintenance manuals for routine inspection of dowel pin bores. Inspection for surface defects only occurs when the gearbox is disassembled for overhaul. Both the operator and the engine manufacturer have already taken proactive safety action in response to the ATSB's safety advisory notice.

Figure 5. Image shows the beachmarks on the fracture surface, which was indicative of a fatigue failure mechanism. Source: ATSB

The draft report referenced in the 2017 Australian national review has now been updated to final report status dated 10 October 2018. Fatigue cracking initiating from an area of significant corrosion was confirmed. The summary of findings summary from the reference ATSB report is below.

What the ATSB found

An inspection of the aircraft by the ATSB at Sydney Airport identified that the propeller gearbox (PGB) propeller shaft had fractured, leading to the separation of the propeller. Subsequent laboratory analysis of the propeller shaft revealed that the failure occurred as a result of a fatigue crack that had initiated from the PGB propeller shaft flange dowel pin hole.

The ATSB found that the manufacturer's maintenance documentation did not include specific inspection procedures to detect fatigue cracking of the propeller shaft. In addition, the operator's inspection worksheets did not provide for the recording of inspection findings as defined within documented procedures. Consequently, this may not have provided for the best opportunity to ensure potential defects were identified, recorded and monitored.

What's been done as a result

Following the occurrence, the engine manufacturer (General Electric) released a number of service bulletins (SB 72-0530 and SB 72-0531) requiring immediate inspection of the PGB propeller shaft. Changes were also made to the engine maintenance manuals to include more ongoing detailed inspections of this area. Additionally, the United States Federal Aviation Administration, issued airworthiness directive AD 2018-03-13, on 14 February 2018, which required initial and repetitive visual inspection and fluorescent-penetrant inspection (FPI) of the main propeller shaft for affected engines.

Safety message

This occurrence highlighted how non-life-limited components such as a propeller shaft may still develop defects and fail in-flight. Appropriate training, the use of checklists and effective crew interaction, provide the best opportunity for a positive outcome in the event of such a failure affecting flight safety. Additionally, operators are reminded of the importance of having work sheets that accurately reflect the requirements and intentions of associated maintenance documentation.

Reference

[1] Australian Transport Safety Bureau report AO-2017-032

5.2 RAAF Aileron Shroud Cracking; (N. Athiniotis [DST])

During servicing of a RAAF fighter/trainer type aircraft both aileron shrouds (LH and RH) were discovered cracked in approximately the same location. The DST investigation revealed that cracks in both the left and right hand aileron shrouds formed via the initiation and propagation of fatigue cracking. The cracks initiated from discontinuities below the Ion Vapour Deposited (IVD) aluminium surface layer. The discontinuities at the crack origins were consistent with etch pits that can form during the acid pickling stage of IVD coating.

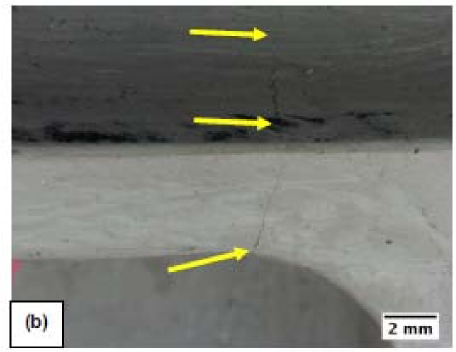
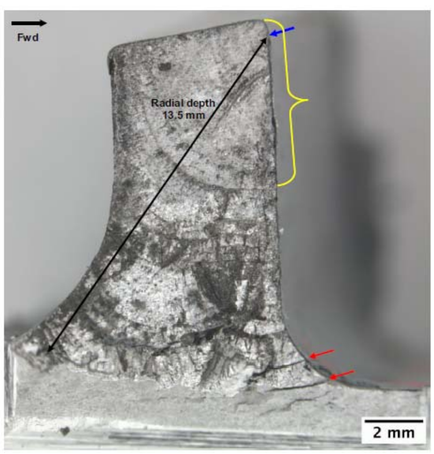


Figure 1: *Location of cracking*



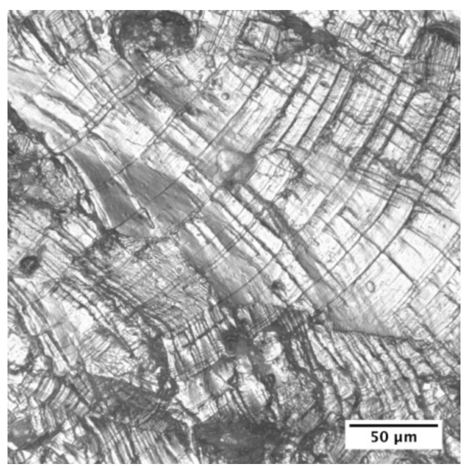


Figure 2. Fatigue cracking direction and visible progression marks

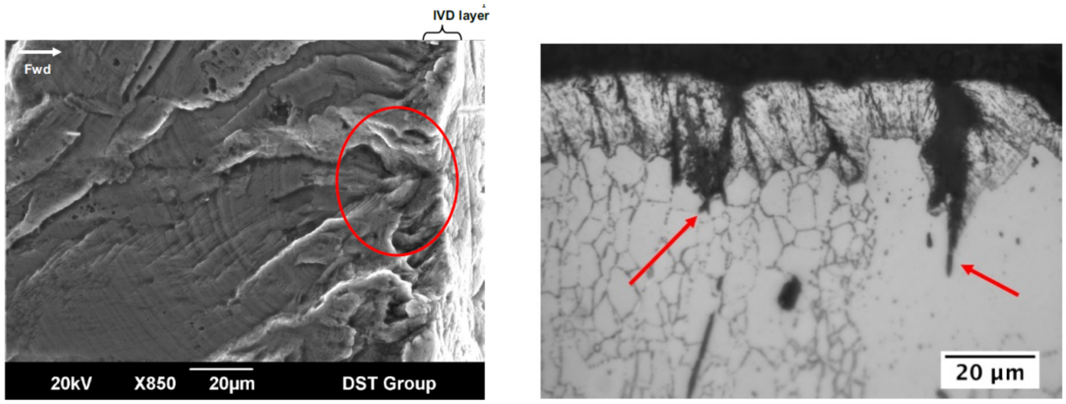


Figure 3. Crack origin below IVD and other etch pits below the IVD layer that could potentially act as crack initiation sites

As the cracks initiated from pre-existing surface defects, it is likely that cracking began when the components first entered service or very shortly thereafter. The fatigue cracks progressed via loads arising during normal operation, and it is likely that other aileron shrouds in the fleet will also suffer fatigue cracking in this location. It is likely that this is issue will have resulted from manufacturing shortfalls.

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5.3 Trailing Edge Flap Transfer Tube Assembly Failures

First-in-RAAF service failure of two Trailing Edge Flap (TEF) Servo Cylinder Transfer Tube Assemblies was discovered during inspections on a fighter/trainer type aircraft. Cracking was due to fatigue under combined bending and compressive loads that arose during normal operation. The cracks were located at the forward radius of the central tubular section and crack initiation was from the external surface of the Tube. Results from the fatigue crack growth analysis as well as examination of the fracture surface indicated it was likely that fatigue cracks began propagating early in the life of the Tube. Component age and usage are suspected factors.

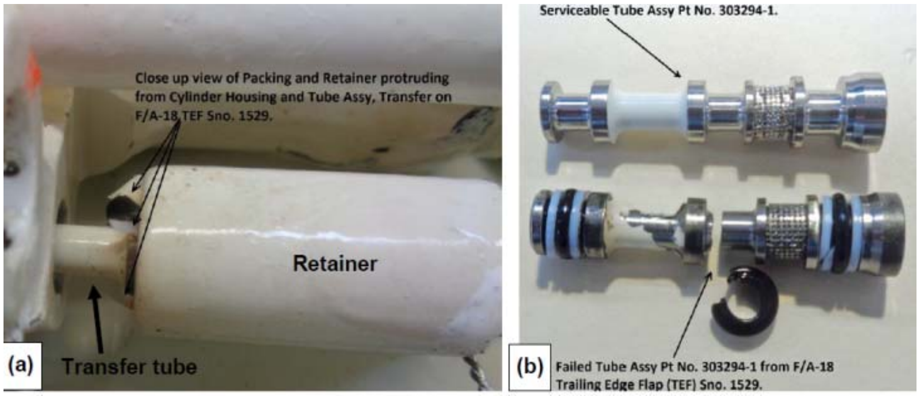

Figure 1. Location of cracking

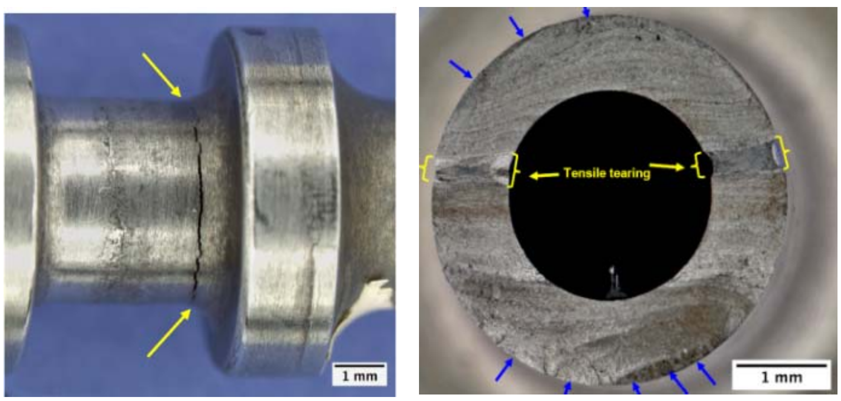

Figure 2. Crack location and fracture surface. Numerous crack origins, with multiple small fatigue cracks having merged to form single crack fronts

5.4 Fuel Tank Vent Stringer Crack

In a transport aircraft, un-commanded fuel transfer from the #1 main tank into the centre tank was observed during an extended period the aircraft was on the ground. Investigation of the left hand wing fuel vent stringer revealed a cracked tab at wing rib number 6. The subject stringer is fabricated from AA7055 aluminium alloy heat treated to a T77511 temper. The through-crack located adjacent to the attachment tab on the left hand wing fuel vent stringer was caused by stress-corrosion. The gap in between the attachment tab on the vent stringer and the wing rib resulted due to insufficient shimming during the manufacturing of the aircraft, exacerbating the stress experienced at the attachment tab location, and contributing to the initiation and propagation of the stress corrosion crack.

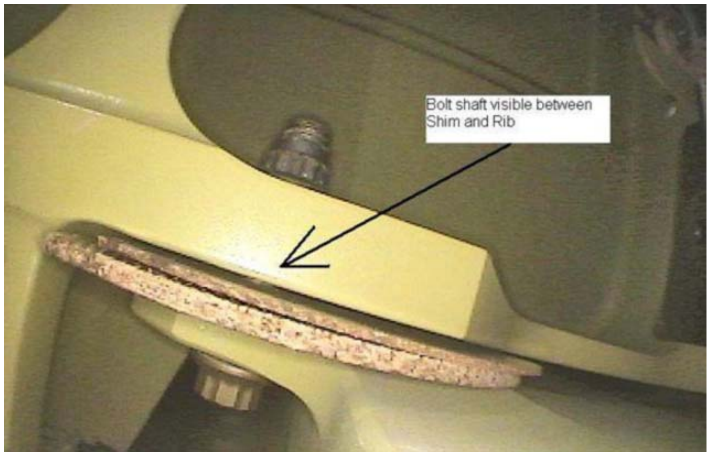

Figure 1. Bolt shaft can be seen through the gap between the shim and rib

Figure 2. Location of cracking along tab

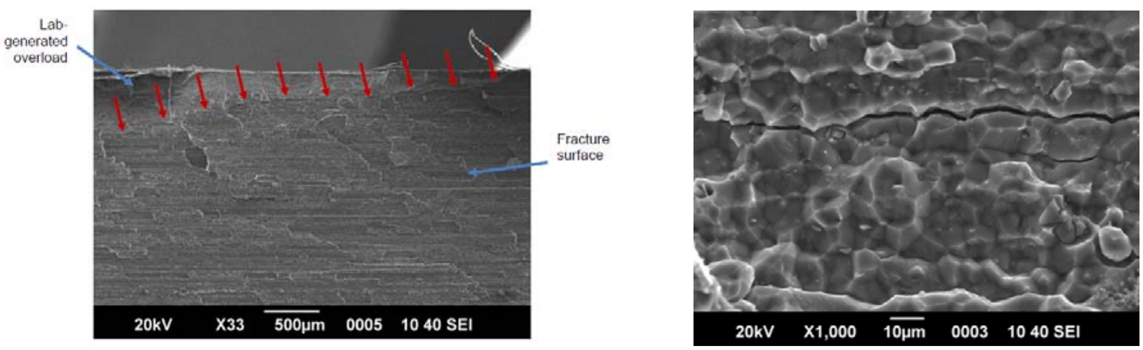

Figure 3. The intergranular nature of the fracture surface