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A Review of Australian Aeronautical Fatigue and Structural Integrity Investigations During May 2021 to April 2023

Defence Science and Technology Group

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EXECUTIVE SUMMARY

This document has been prepared to support the aims and objectives of the International Committee on Aeronautical Fatigue and Structural Integrity (ICAF). This report contains summaries of the research, engineering and technology activities in the field of aeronautical fatigue and structural integrity that have occurred at Australian research laboratories, universities and within industry during May 2021 to April 2023. The Australian national review was presented during the 38th ICAF Conference and 31st ICAF Symposium at Delft, the Netherlands 26–29 June 2023 and published on the Committee's website www.icaf.aero.

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CONTENTS

GLOSSARY

AA	Aluminium alloy
ADF	Australian Defence Force
AM	Additive manufacturing
AR	Augmented reality
ASE	Aero-servo elasticity
ASI	Aircraft structural integrity
ASIP	Aircraft structural integrity program
BVID	Barely visible impact damage
CAI	Compression after impact
CASG	Capability Acquisition and Sustainment Group
CFRCAS	Continuous fibre reinforced composite auxetic structures
CFRP	Carbon fibre reinforced polymers
CIC	Corrosion inhibiting compounds
CP-FFT	Fourier transforms formulation of classical crystal plasticity
DaDT	Durability and Damage Tolerance
da/dN	Fatigue crack growth rate
DASA	Defence Aviation Safety Authority
DASR	Defence Aviation Safety Regulation
DIC	Digital image correlation
DPPT	Dynamic pulse phased thermography
DSTG	Defence Science and Technology Group
EIFS	Equivalent initial flaw size
FCG	Fatigue crack growth
FDM	Fused deposition modelling
FE	Finite element (analysis)
FOS	Fibre-optic strain (sensor)
FSFT	Full-scale fatigue test

FSG	Foil strain gauge
HAFT-TD	Helicopter Advanced Fatigue Test – Test Demonstrator
HIP	Hot isostatic press
ICAF	International Committee on Aeronautical Fatigue and Structural Integrity
LDED	Laser directed energy deposition
LEFM	Linear elastic fracture mechanics
LST	Line scan thermography
LUT	Laser ultrasound testing
MSET	Modified single-edge tension (specimen)
NDI	Non-destructive inspection
QF	Quantitative-fractography
RVE	Representative volume elements
SCFRP	Steel and carbon fibre reinforced polymers
SERVE	Statistically equivalent (microstructure) representative volume elements
SLM	Selective laser melting
SMA	Shape memory alloy
SMI	Structural mode interaction
SRSPO	Surveillance Reconnaissance Systems Project Office
STRETCH	Swiss Titanium Experiments on the Classic Hornet
TSA	Thermo-elastic stress analysis
TTCS	Time to crack size
UHS	Ultra-high speed
WAAM	Wire arc additively manufactured
3D	Three-dimensions
ΔK	Cyclic stress intensity factor

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1. INTRODUCTION

This report presents a review of Australian research, engineering and technology activities in the field of aeronautical fatigue and structural integrity from May 2021 to April 2023. The review includes inputs from the government, industry and academic institutions below. The editor acknowledges each of these contributions with appreciation and encourages readers to approach the listed author(s) directly with any enquiries; contact details are provided at the end of each section.

Contributions are arranged into chapters by broad field of structural integrity activity. The organisations contributing to this review include:

- Airbus Asia Pacific, https://australia-pacific.airbus.com
- Advanced Composite Structures – Australia (ACS-A), www.acs-aus.com
- BAE Systems Australia, www.baesystems.com/en-aus
- Boeing Aerostructures Australia, www.boeing.com.au
- Deakin University, www.deakin.edu.au
- Defence Science and Technology Group (DSTG), www.dst.defence.gov.au
- Flinders University, www.flinders.edu.au
- Monash University, www.monash.edu
- QinetiQ Australia, www.qinetiq.com/en-au
- Swinburne University of Technology, www.swinburne.edu.au
- The University of Adelaide, www.adelaide.edu.au
- 1Millikelvin Pty Ltd, www.1millikelvin.com

2. FATIGUE CRACK GROWTH

2.1. Advantages of using MSET specimens to evaluate the da/dN vs. ΔK curves associated with small/short cracks: an experimental analysis – S. Kundu, D. Peng, R. K. Singh Raman, A. Alankar and R. Jones [Monash/Swinburne Universities]

The recent paper [1] revealed shown that modified single edge tension (MSET) specimens (Figure 1) are particularly useful when measuring the long crack da/dN versus ΔK curves associated with additive manufacturing (AM) materials. This work reveals that MSET specimens can also be particularly useful when measuring the da/dN versus ΔK curves associated with small/short cracks in conventionally built materials. In this context it is shown that for small/short cracks in MSET specimens, crack growth is approximately exponential.

Furthermore, this study reveals that for conventionally manufactured AA7075-T6 specimens the small/short crack growth history can (also) be accurately computed using the Hartman-Schijve crack growth equation with the fatigue threshold term set to a small value.

Figure 1. Specimen in the test facility.

References

1. Jones R., Peng D., 'A Building Block Approach to Sustainment and Durability Assessment: Experiment and Analysis', Reference Module in *Materials Science and Materials Engineering*, Elsevier Reference Collection, September 2022. ISBN: 978128035818; http://doi.org/10.1016/B978-0-12-822944-6.00036-0

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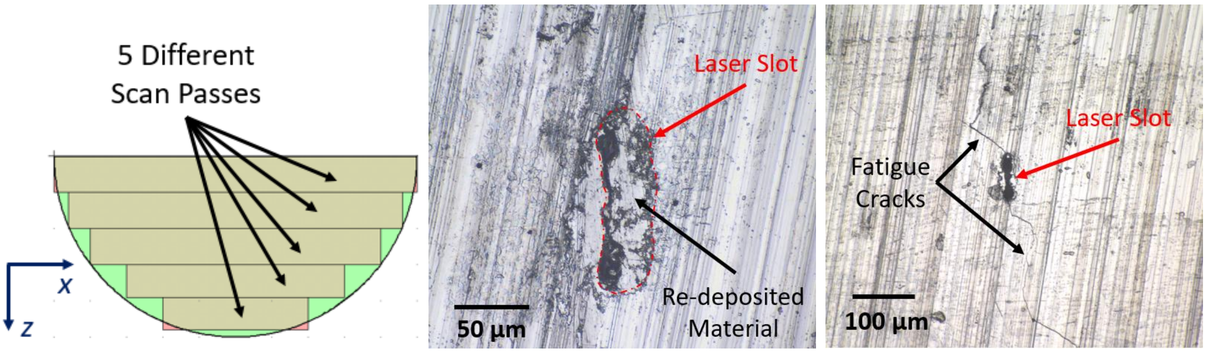
2.2. Nucleating small fatigue cracks reliably and repeatably – M. Jones, H. Shen, B. Main, S. Barter and R. Das [RMIT University/DSTG]

High fidelity small crack growth rate data is essential to accurately predict the growth of small fatigue cracks. These data are best obtained from direct measurements of fatigue cracks grown from small initiating discontinuities. Therefore, it can be beneficial to have a reliable and repeatable experimental method for nucleating small fatigue cracks. It is also essential to sample a large area of material to find the preferential material features, conditions or grain structure required to grow the most severe fatigue cracks (lead fatigue cracks).

DSTG, in partnership with the Micro Nano Research Facility at RMIT University, have utilised a laser-etching method, using a DCT DL561 UV laser, to apply an array of very small laser-etched slots to the surface of test coupons to initiate fatigue cracks (Figure 2). This work analyses the reliability and repeatability of these laser-etched discontinuities in a range of aerospace aluminium alloys, including 7075-T7351, 2024-T351 and 7085-T7452. Measurements of crack growth rates from a number of cracks nucleating on the same specimen allowed conclusions to be drawn on the reliability of the laser etching method, whilst an analysis of the size and shape of the laser-etched discontinuities determined the repeatability. The results demonstrated the laser-etching method exhibited excellent control in governing the size and shape of discontinuities and has been successfully applied to generate small fatigue crack growth rate data in a number of materials. Having a reliable and repeatable method for nucleating fatigue cracks can increase the likelihood of nucleating lead fatigue cracks and can significantly reduce the variability of fatigue test results attributed to large variations in naturally occurring fatigue crack nucleating discontinuities.



(a) (b) (c)

Figure 2. (a) the five different scan passes used to create laser slot semi-circular profile, (b) an example photograph of the re-deposited material blocking view of the laser slot

opening, and (c) examples of fatigue cracks growing from a laser slot where loading was applied left-to-right in the image.

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2.3. Fatigue life behaviour with CIC application depends on joint configuration: experimental and FE study – J. Codrington, L. Button, R. Ferber and T. Simcock [University of Adelaide]

Corrosion inhibiting compounds (CICs) are often utilised in maintenance programs for civil and military aircraft. Application of CICs has proven to be a successful preventative measure in reducing the rate of corrosion growth, however, the physical presence of the CIC within a lap joint can alter the mechanical behaviour. Any changes to fatigue life must be understood as they can impact the continued airworthiness of an aircraft if not accounted for in the life management program. Separate understanding of both fatigue initiation and crack growth is also pivotal as the relevance of each depends on the certification basis being used.

A program of research has been undertaken to investigate the mechanisms of how CICs affect the fatigue life of lap joints; and to develop a predictive capability to assess joint designs beyond those tested in the lab.

Six different lap joint designs have been utilised including standard single-shear lap joints, 1.5 single-shear joints, butt joints, double-shear lap joints (with crack starter notch), and stiffened 1.5 lap joints (with crack starter notch). Both rivet and Hi-Lok fastener types have been considered, as well as the inclusion of faying surface sealant. The sheet material for all designs was 7075-T6 Alclad aluminium with the primary thickness of 0.063". All designs have been tested with and without CIC application. Constant amplitude fatigue cyclic testing was undertaken for the various specimen designs with the maximum applied loading for all samples being approximately a third of the net section yield limit. Thermoelastic stress analysis (TSA) was used during testing for tracking of crack growth and for validation of the finite element (FE) models. Non-linear FE modelling of the fatigue initiation and crack growth stages was conducted to support the experimental observations. The modelling also provides a means to predict behaviour for any lap joint configuration beyond those tested in the lab.

Results from the total life testing (Figure 3) show that there are two key driving forces for crack initiation, which are the local internal stress concentration and fretting from frictional work. How each of these driving forces change with CIC application depends on the joint configuration, which in turn determines the overall effect on the fatigue initiation life. The crack growth stage (Figure 4) is controlled by the load flow through the joint and the resultant crack tip stress intensity factor. Key factors that affect fatigue initiation and crack growth behaviour are the fastener clamping force, interference fit (or hole fill pressure), secondary bending, applied load level, and the presence of sealant (and the sealant coverage). The FE modelling showed a good match to the experimental observations for the initiation and crack growth behaviour for all joint designs.

Overall, this research program has provided an understanding of how CICs affect fatigue life, as well as the ability to predict crack initiation and growth for various joint configurations. Future work will see investigation of specific in-service configurations, such that the findings can be directly transferred for use with structural life management of operational aircraft.

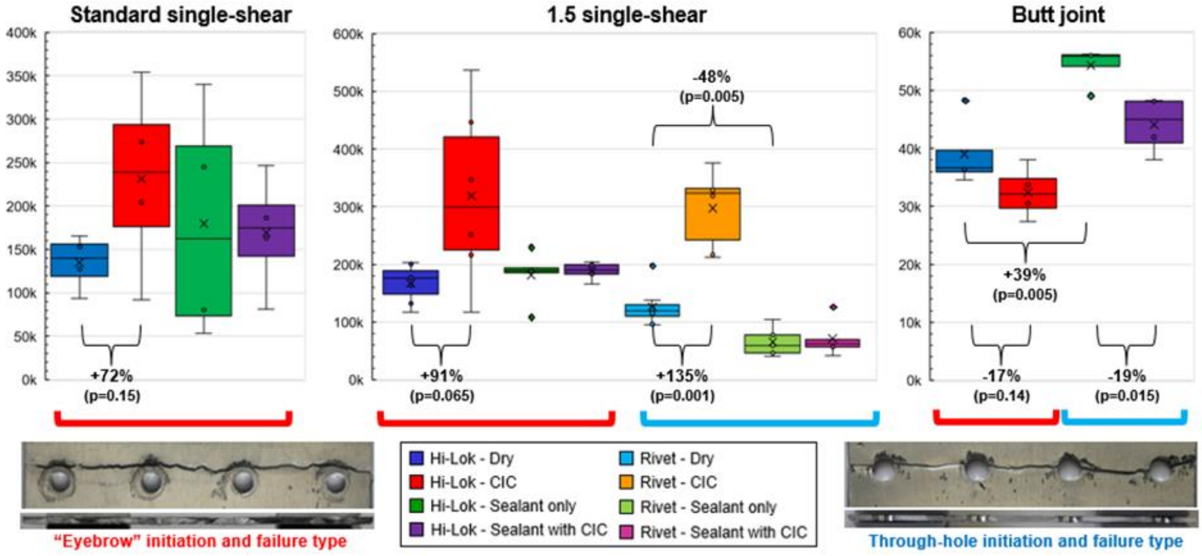

Figure 3. Box plots for total life fatigue test results for various specimen designs.

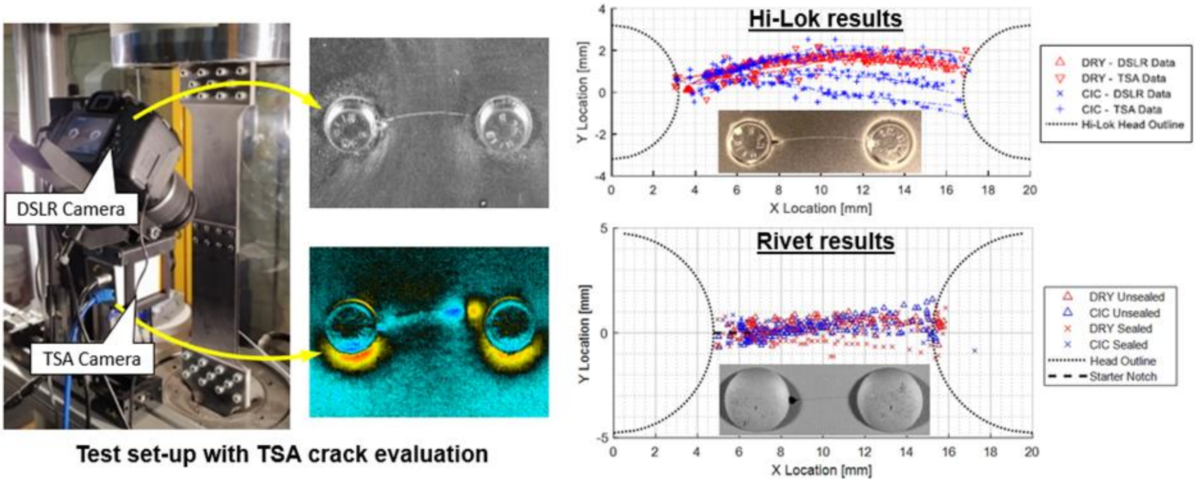

Figure 4. Crack path results for Hi-Lok (double-lap) and rivet (stiffened 1.5) designs.

Acknowledgment

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2.4. The outcomes of research into small fatigue crack nucleation and growth in AA7085-T7452 – B. Main, B. Dixon, M. Jones and S. Barter [DSTG/RMIT University]

Aluminium alloy (AA) 7085-T7452 is a recent addition to the 7XXX series of aluminium (Al), zinc (Zn), magnesium (Mg) and copper (Cu) high strength aerospace alloys which has applications in primary airframe structure of the Airbus A380 and Lockheed Martin F-35 (Figure 5). AA7085-T7452 was developed for large unitized, lightweight airframe structures since its low quench sensitivity and good through-thickness fracture toughness enables forgings of up to 12 inches (305mm) thick. DSTG, working with RMIT University, have completed several studies concerning small fatigue crack nucleation and growth in this material using specimens with representative production surface finishes and loaded with service representative spectra [1,3].

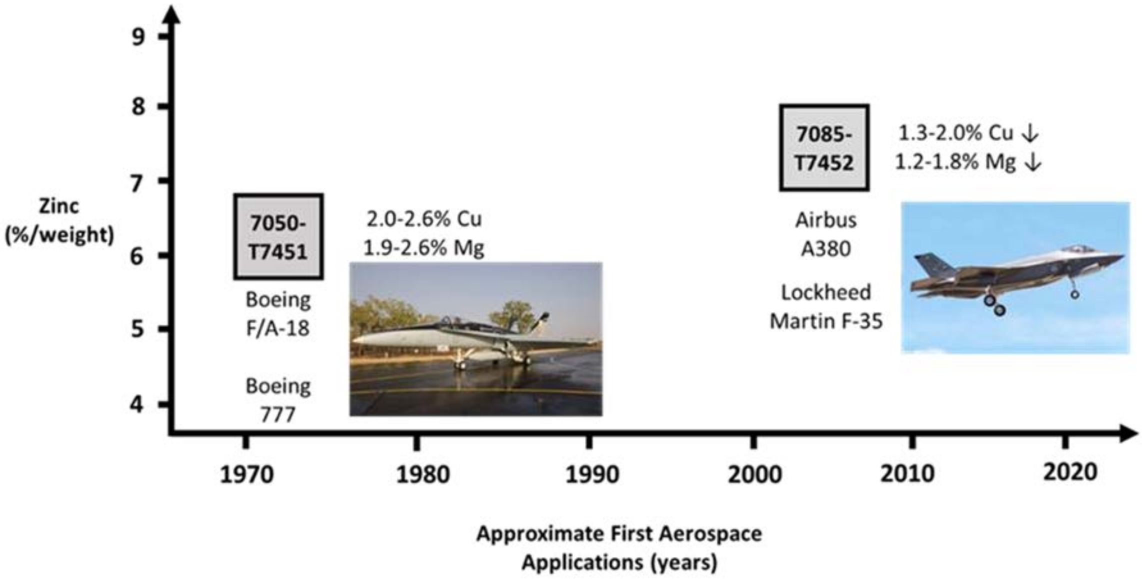

Figure 5. Chemical composition and approximate timeframe of significant aircraft structural applications of AA7050 vs AA7085.

This work has made a number of observations concerning fatigue crack nucleation and small fatigue crack growth rates (FCGR) in AA7085-T7X in contrast with other 7XXX-T7X alloys. Two influences on the fatigue durability of this alloy were investigated. Firstly, the 'fatigue crack like effectiveness' of surface etch pitting arising from the commonly used Type 1C anodising process was assessed by deriving equivalent initial discontinuity size (EIDS) values via a fractography-based method. This work showed etch pitting associated with Type 1C anodising surface treatments is less effective in nucleating fatigue cracks in AA7085-T7X compared to AA7050-T7X. Secondly, FCGRs for physically small or near-threshold fatigue cracks were quantified for AA7085 using fractography-based measurements and these were compared with equivalent measurements for AA7050 and AA7075 in the T7X condition. Here, small crack and near-threshold FCGRs in AA7085 were largely consistent with those for AA7050 and AA7075 T7X materials. These results highlight the authors' current progress toward their goal of understanding the fatigue properties of AA7085-T7452 well enough to allow accurate fatigue life predictions for structural certification and sustainment of AA7085-T7452 airframe components.

References

1. B. Main, M. Jones, B. Dixon and S. Barter, 'On small fatigue crack growth rates in AA7085-T7452', *International Journal of Fatigue*, vol. 156, 2022. https://doi.org/10.1016/j.ijfatigue.2021.106704

2. B. Main, B. Dixon, M. Jones and S. Barter, 'Microstructure and surface finish influences on AA7085-T7452 small fatigue crack growth rates', *Engineering Failure Analysis*, vol. 141, July 2022. https://doi.org/10.1016/j.engfailanal.2022.106628

3. B. Dixon, B. Main, S. Turk, S. Barter and J. Niclis, 'Fatigue crack growth behaviour in Type 1C anodised AA7085-T7452 under variable amplitude loading', DSTG-TR-3991, Defence Science and Technology Group, 2022.

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2.5. Improved capability to model long cracks in high-strength aerospace alloys – K. Walker, A. Grice and J. C. Newman Jr. [QinetiQ Australia]

Aircraft persistently present cracks, so ensuring the structural integrity of the Defence Aircraft fleets is crucial. Accurate and reliable modelling is essential, particularly for fatigue cracking in high-strength metallic alloy structures. The best available modelling tools tend to be conservative and can be used safely because additional safety factors are also applied. The result is that aircraft fleets are sometimes retired prematurely, and/or excessive inspection and component retirement times are imposed. These factors limit operational capability and effectiveness and set a heavier cost burden than otherwise may be possible.

A recent fatigue crack growth prediction assessment activity [1] showed that a range of commonly used methods and tools produce faster rates and shorter lives than experiments by a factor of approximately two. That is acceptable from a safety perspective, but it means that potentially useable 'life' is being ignored. The results of comparing the analysis and experiment for a typical transport aircraft wing skin case under representative spectrum loading are shown in Figure 6.

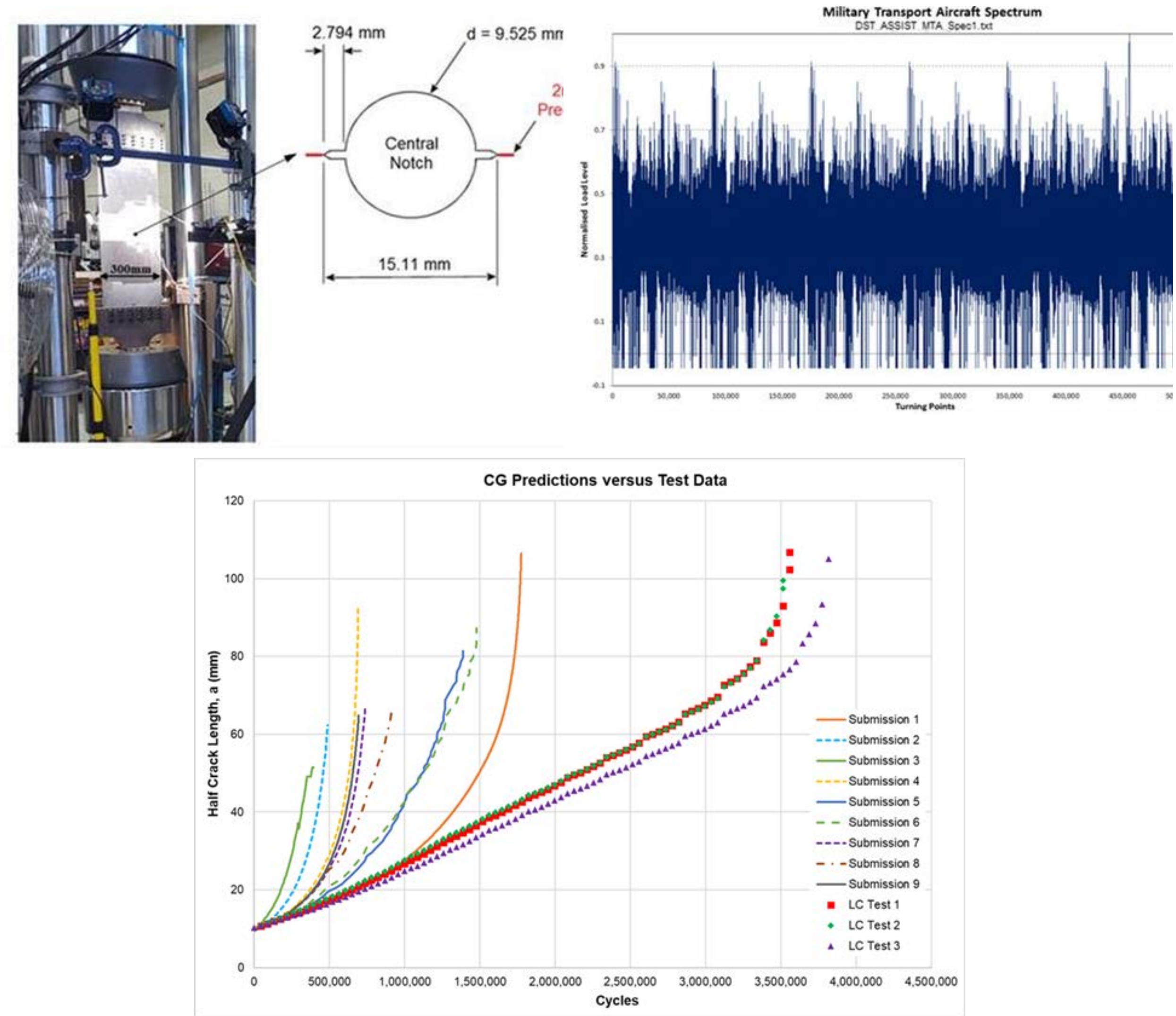

Figure 6. Transport aircraft crack growth comparison.

A research program is being conducted at QientiQ to address this issue. The research is being conducted in collaboration with Professor Jim Newman at Mississippi State University and Fatigue and Fracture Associates in the USA. The research includes testing Middle Tension (M(T)) specimens under constraint-loss, spike overload/underload and spectrum loading conditions. The specimens manufactured from 7075-T6 and 2024-T3 are being tested at Mississippi State University, and specimens from 7075-T7351 are to be tested in Australia at the DSTG Laboratory in Melbourne. The results for the 7075-T6 and 2024-T3 are available at [2] and suggest that the analysis can be greatly improved if the constraint-loss regime is well understood and characterised.

A comparison between the test and examinations for spike overloads in 2024-T3 is shown in Figure 7, and a comparison of the crack opening load for 7075-T6 is shown in Figure 8.

The research will produce an improved method and data to assess spectrum loading for long cracks in transport type-aircraft structures. This will lead to significant benefits regarding aircraft availability and reduced life cycle costs.

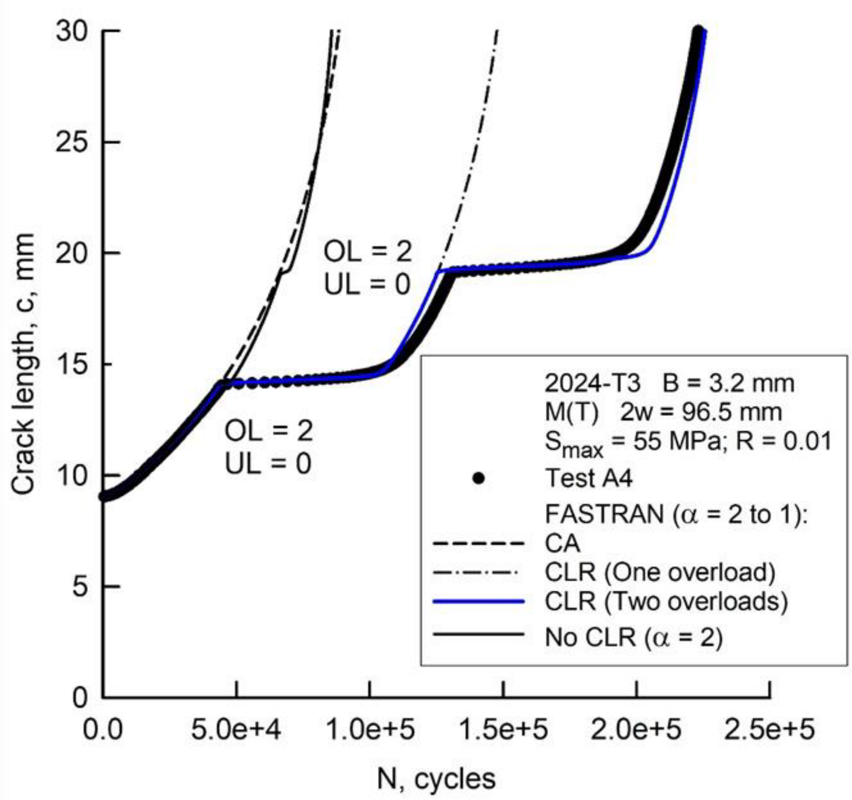

Figure 7. Spike overload results for 2024-T3.

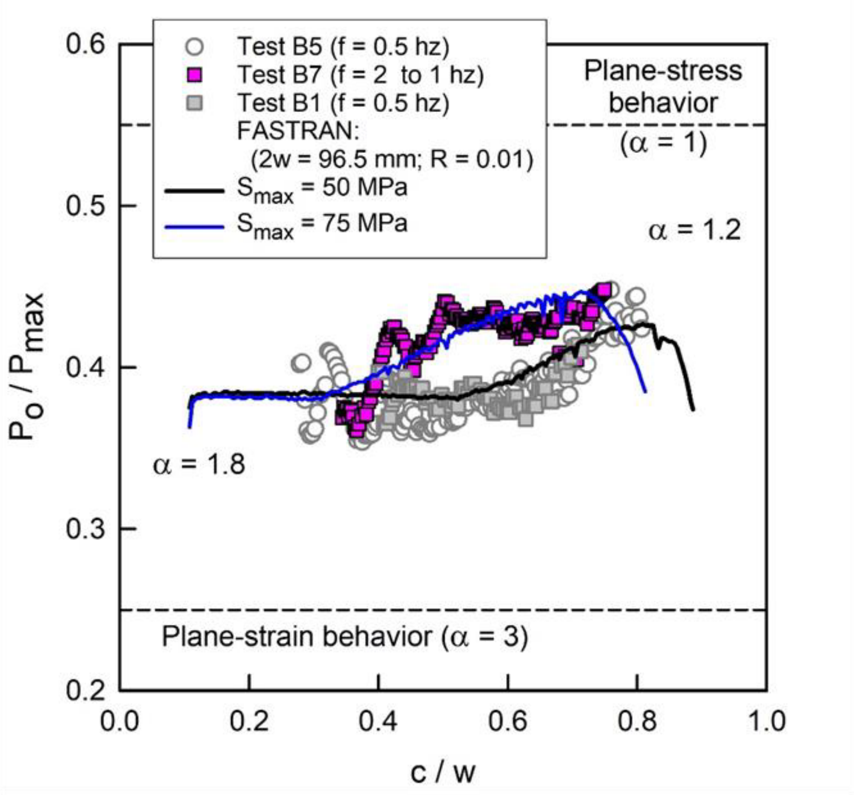

Figure 8. Crack opening rise measured over the constraint-loss region for 7075-T6.

References:

1. Walker, K.F., McCoy, M., Ogden, R., and Maxfield, K., Crack growth prediction challenge in wide 7075 T7351 panels, in ASIP Conference. 2020: On-Line.

2. Newman , J.C., Jr. and Walker, K.F., Fatigue-Crack-Growth under Single-Spike Overloads/Underloads and Aircraft Spectra during Constraint-Loss Behaviour, in Aircraft Structural Integrity Program Conference. 2022: Phoenix AZ USA.

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3. COMPOSITES

3.1. Reviewing the experimental setup of ultra-high-Speed and low-speed 3D digital image correlation for composite CAI testing – C. Dunne, P. Frezza, L. J. Burgess-Orton, L. T. Robertson and C. G. Wright [RMIT University/Advanced Composite Structures – Australia/DSTG]

The use of composite materials in aircraft systems is increasing and to aid the development of FE modelling of post-impact damage, there exists a requirement to increase the strain data output of compressive specimen testing. In order to capture more full-field strain data, three pairs of cameras have been employed to carry out digital image correlation (DIC) of the front and rear faces of a composite test specimen as it is subjected to compression after impact (CAI) destructive testing. 3D DIC is captured from two pairs of cameras, with one pair pointed at the front and one pair pointed at the rear of the specimen respectively. They are able to capture full-field strain of the specimen in high spatial resolution over the lifetime of the test.

A third pair of ultra-high-speed (UHS) cameras, focussed on the impact damage site, were also used to capture the failure event. The key technical considerations and challenges encountered while developing the test setup are presented in this paper.

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3.2. Multi-functional shape memory alloy tufted composite joints technology – T. Cooper, A. Ravindran, R. Ladani, A. N. Rider and A. P. Mouritz [QinetiQ Australia/RMIT University/DSTG]

The design of co-cured tough and multi-functional fibre reinforced composite joints, particularly for aerospace applications, is essential to the development of high strength, lightweight structures. In the present work, the multi-functional shape memory alloy (SMA) tufted composite joints (MuST) modelling framework project has developed an innovative, composite joining and monitoring technology, with increased structural performance, durability, health monitoring and self-repair potential. This project runs in conjunction with research partners in Australia and the UK. The UK project built and tested the representative capability to create three-dimension reinforced composites using SMA tufts to infer enhanced damage tolerance, damage detection capability and self-repair behaviour of carbon fibre reinforced laminates. The sister Australian project developed detailed and successful finite element models of the tested laminate and joint configurations, to enable performance characterisation and prediction for future laminate and joint designs.

This research presents the outcomes of the Australian project, concentrating on the performance benefits gained from the SMA tufting technology, and the allied analytical models and their effectiveness in both matching test results and in predicting fracture toughness properties of SMA reinforced composites, T-joints subjected to pull-off loading and a T-stiffened panel subjected to uniaxial compression. Experimental and numerical simulation results revealed that the incorporation of a low density of SMA tufts (0.21 vol.% with a diameter of 0.13 mm) can enhance interlaminar fracture toughness properties and the pull-off ultimate strength properties by ~500% and 110%, respectively. This SMA tufting technology can be used also as a damage detection platform in identifying crack or delamination formation within the composite; where analytical models have been developed. In addition, thermally activating the SMA tuft through Joule heating can invoke a crack closure response to improve the damage tolerance. Therefore, the present work demonstrates the performance benefits of this new tufting technology, and the ability to predict damage within composite structures used for a broad range of applications.

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3.3. Robotic fibre placement of hybrid steel and carbon fibre for multifunction aerospace structure – M. M. A. Ammar and B. Shirinzadeh [Monash University]

Automated fibre placement is a fully controlled process that is introduced to fabricate high-quality composite structures. The current study uses robotic manufacturing to produce new multifunction hybrid composites for aerospace structures. An industrial robotic arm (Yaskawa Motoman SK120) is used to perform the placement of the prepreg tows of stainless steel and carbon fibre reinforced polymers (SCFRP). A fibre placement head is adjusted to provide a suitable environment to melt then consolidate the prepreg tows into layers and form the composite laminates. A creel cabinet system is used to source the tows from the spools of the two fibres. A series of rollers are installed to bring the tows to the placement head. A cooling chamber is also attached to provide a quick precooling process to avoid bonding the prepreg tows into the roller system. A hot gas torch sourced with nitrogen gas, is used to provide instantaneous heating to increase the tackiness of the resin/epoxy and ensure a suitable bonding between the layers. The compaction roller is the last stage of the placement process as it applies pressure on the top of the placed layers using a pneumatic system to consolidate the laid-up material. A sensory feedback control system with a real-time process is utilised to monitor and control the placement process conditions. A path generation method is proposed to maintain the direction and the magnitude of the applied force to ensure an even and constant compaction force during the entire process regardless of the direction and topography of the mould surface. The proposed system was able to produce different hybrid laminates of SCFRP with different volume ratios of both fibres. The produced laminates could be used for the aircraft structures as well as the possibility of compensation for the installations of the aeroplane's electrical systems.

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4. NON-DESTRUCTIVE INSPECTION (NDI)

4.1. Development of benchmark composite panels for ARH and MRH rotary wing platforms Non-Destructive-Inspection – P. Blanloeuil, E. Yeo, J. Wang and P. Chang [Airbus Australia Pacific/DSTG]

Non-destructive inspection (NDI) is an essential capability to manage service life of safety critical assets such as aircraft. The airframe of advanced military rotary wings platforms such as ARH Tiger and MRH90 Taipan helicopters is made of complex composites structures. Detecting small damage such as barely visible impact damage (BVID), delaminations and cracks remains challenging in the field for maintenance organisations, due to the inherent complexity of the structures and the difficulty to distinguish damage from features.

In this work, NDI benchmark composite panels have been designed to include various representative production features present in aircraft structures. These include a skin/honeycomb sandwich structure transitioning to a monolithic laminate skin, copper mesh and copper strip, an aramid top ply on carbon/epoxy laminate, ply drop, bonded joint, microballoon core filler and bonded components.

Four panels were manufactured and several NDI methods, including ultrasonics A-scan and C-scan phased array, and lock-in thermography, have been tested on these panels with a twofold objective: 1) provide a training base to inform NDI technicians of the response from a known feature, 2) compare the performances and limitations of NDI methods on the same panels.

The outcomes of this work are expected to improve damage detection accuracy and confidence, provide better through-life support to Australian Defence Force (ADF) fleets and a guide for future NDI capability development.

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4.2. Non-destructive testing of CFRP laminates – laser ultrasonic testing – D. K. Elangovan, R. A. R. Rashid, P. Stoddart, A. Di Pietro and S. Palanisamy [Swinburne University]

The advent of advanced composites is changing the material world. The increase in the use of composite materials for aviation has been attributed to their high strength-to-weight ratio and improved mechanical properties. Carbon fibre reinforced polymers (CFRPs) have high specific strength and adaptable (mid to high) specific modulus. It is the most common composite material in the newest generation of aircraft. Materials anomalies are inherent in composites. The defects can be caused either during manufacturing or in-service phases. Since composites are often non-homogeneous and anisotropic, detection and assessment to preserve structural integrity are particularly difficult. Defects and damage can appear in many locations at different scales, making it difficult to keep track of all the damage sites and resulting in sophisticated damage mechanisms. Hence, accurate NDI of composites is critical for lowering safety concerns and maintenance costs. The NDI technique should ideally exhibit lower operating costs and a higher inspection rate. This paper will discuss the potential NDI methods for identifying defects in CRFP laminates. Delamination is the most prevalent problem in this class of structure. The potential application of laser ultrasound testing (LUT) as a non-destructive testing method for CFRP samples with intentionally created defects has been evaluated.

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4.3. The effects of positional instability on a machine learning based detection method for sub-surface defects in composite materials – P. Muir, M. Richards, J. Gray, C. Rosalie and N. Rajic [DSTG]

Line scan thermography (LST) is an NDI method capable of rapidly detecting barely visible impact damage (BVID) in CFRP components. LST is a method in which a line heat-source is swept over an object and an infrared imager used to observe the surface temperature in the wake of the source. Sub-surface defects are identified by the thermal contrast relative to undamaged sections of the specimen where regions of damage such as delamination impede through-thickness heat flow. Using an image processing technique called dynamic pulse phased thermography (DPPT), this thermal contrast is enhanced by observing the specimen's surface temperature in the phase domain, where regions containing abnormal heat flow result in a dipole-like signature, as shown in

Figure 9. Two robotic implementations of LST have been developed, one using a fixed Cartesian robot and the other a ground-based robot, both equipped with the same infrared source and detector apparatus. The detection performance of both implementations has been encouraging. BVID in 16 ply carbon fibre composite panels produced by controlled impact at energy levels from 5-30J has been shown to be detectible at scan speeds of between 50 and 100 mm/sec. A complementary machine learning capability has been developed for automated BVID signature detection in quasi-real time.

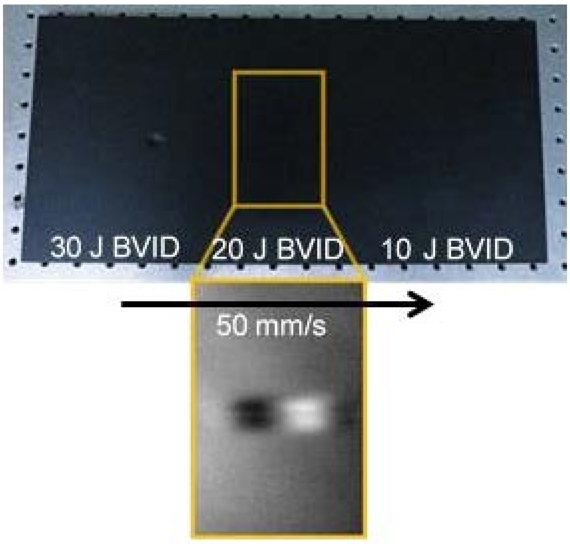

Figure 9. CFRP panel containing BVID specimens. DPPT result shown for a 20 J BVID scanned at 50 mm/s with the Cartesian robot.

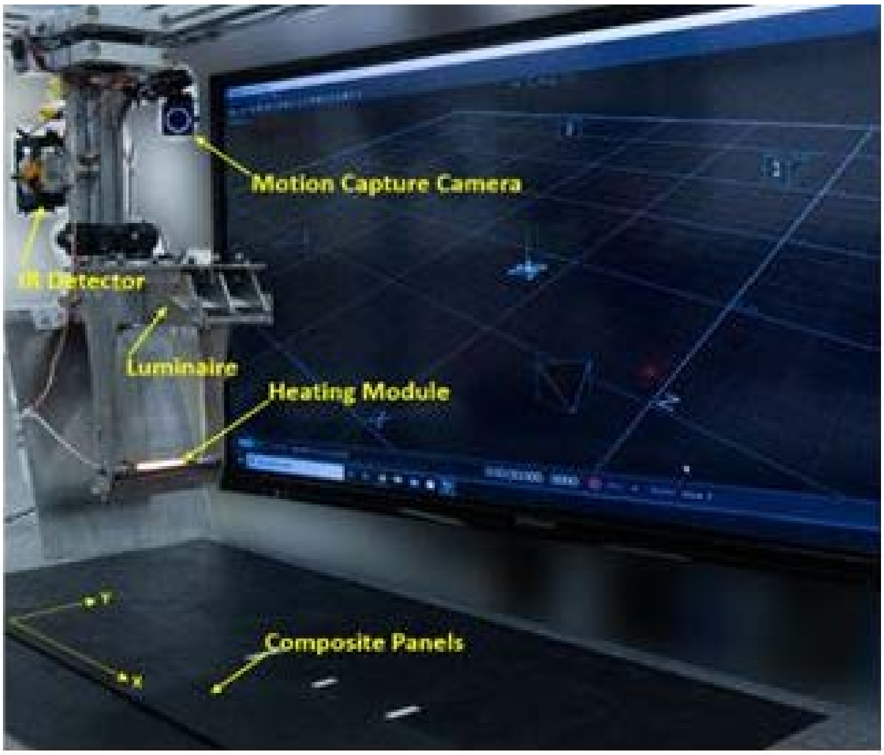

Figure 10. Cartesian robot conducting LST on a CFRP panel.

This capability demonstrates strong potential for rapid low-cost inspection of large composite aircraft components. Further work is underway to develop an aerial drone implementation of this capability.

Acknowledgments

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5. ADDITIVE MANUFACTURING (AM)

5.1. A comparison of length scale dependent classical crystal plasticity models for modelling the deformation of additively manufactured Ti-6Al-4V – C. Dionyssopoulos, C. Wallbrink, D. Agius, D. Qiu, M. Easton, S. Barter and R. Das [RMIT University/DSTG]

The use of AM to produce metal parts for aerospace applications has gained increasing popularity in recent years, however, the range of usable metal alloys for AM processes is limited compared to traditional manufacturing methods. The optimisation of existing alloys or design of new alloys to address this challenge can be accelerated through understanding of microstructure-property relationships using crystal plasticity models. Classical crystal plasticity models lack an inherent material length scale and consequently produce less representative predictions of meso-scale and macro-scale deformation responses. In this study, two methods of incorporating length scale dependence into a fast Fourier transforms formulation of classical crystal plasticity (CP-FFT) are investigated. Both methods introduce a modification to slip system hardening using a micro-Hall-Petch term. In the first method, the micro-Hall-Petch term is calculated from statistically derived equivalent spherical diameters representing grain sizes. The second method is based on the influence of dislocation pileups at grain boundaries, where an algorithm is used to determine the micro-Hall-Petch term according to the slip distance in neighbouring grains and misorientation of the slip systems between interacting grains. The methods were used to predict the tensile response of a Ti-6Al-4V alloy manufactured using selective laser melting (SLM) using realistic microstructural representative volume elements (RVEs) and statistically equivalent microstructural representative volume elements (SERVEs). The accuracy of the stress-strain response predicted by the length scale models was assessed using experimental tensile data and the local plasticity developed in each model was compared. The results demonstrate the improved ability of the dislocation-pileup-based length scale model to capture micro-scale plastic localization phenomena compared to the equivalent spherical diameter method. The evaluation of the crystal plasticity modelling approaches highlights their potential in furthering the understanding of microstructure-property relationship of new materials designed for AM.

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5.2. Durability assessment of WAAM 18Ni 250 Maraging steel specimens with large near surface internal porosity – D. Peng, A. Ang, S. Pinches, V. Champagne, A. Birt, A. Michelson, R. K. Singh Raman and R. Jones [Swinburne University/Monash University]

USAF MIL-STD 1530D states that the design and certification approval requires analytical tools that are capable of modelling crack growth, and that the role of testing is to validate or correct the durability and damage tolerance analyses (DaDT). Mil-STD-1530D also stresses that the DaDT analyses should be based on LEFM and should be performed in a fashion that is consistent with the mandated building block approach delineated in the USAF MIL-STD-1530D, US Joint Services Structural Guidelines JSSG2006, USAF Structures Bulletin EZ-19-01. This requirement is also a feature of NASA Handbook NASA-HDBK-5010. This paper presents examples of how to perform such an analysis in a fashion that is consistent with the 'building block approach' mandated in JSSG2006 and MIL-STD-1530D. The specific examples presented are related to a series of durability tests performed on several wire and arc additively manufactured (WAAM) 18Ni 250 Maraging steel specimens.

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5.3. 3D printed continuous fibre composites: fabricating and evaluating topology optimised component – M. Joosten, A. B. Harman, A. N. Rider and M. Flores [Deakin University/DSTG]

Three-dimensional (3D) printing is a manufacturing method that can be used to produce structures that are difficult to manufacture using traditional manufacturing methods such as subtractive machining. A common 3D printing processes is fused deposition modelling (FDM) that produces a component by depositing material using a fine diameter nozzle. The material is built up in layers to produce a 3D component. 3D FDM printing can be used to accelerate the design process via rapid prototyping or manufacture complex geometries produced using topology optimisation. There are some obvious limitations when using this manufacturing process to produce structural components. The materials that are compatible with FDM are typically thermoplastic polymers and these materials have a very low strength when compared to typical engineering materials such as aluminium or steel. A solution to this issue is to incorporate long continuous fibre reinforcement into the base material. 3D printed continuous fibre composites are on average 15 times stiffer and 10 times stronger than thermoplastic filaments used in most FDM 3D printers.

To examine the capabilities of 3D printed continuous fibre composites, a topology optimised truss-like structure was selected (shown in Figure 11) as a candidate to 'stress test' the capabilities of a customised 3D printer developed at Deakin University. A new CAD interface was developed to generate tow trajectories that were subsequently converted to gcode commands to communicate the design to the 3D printer. A fabricated component is shown on the right-hand side of the Figure 11 and it should be noted that the component required no post-processing operations. Whilst the present study represents progress towards complex 3D printed composite structures further research is required to understand the performance of these components due to the effect of stress concentrations arising from the fabricated geometry and defects introduced during the manufacturing process.

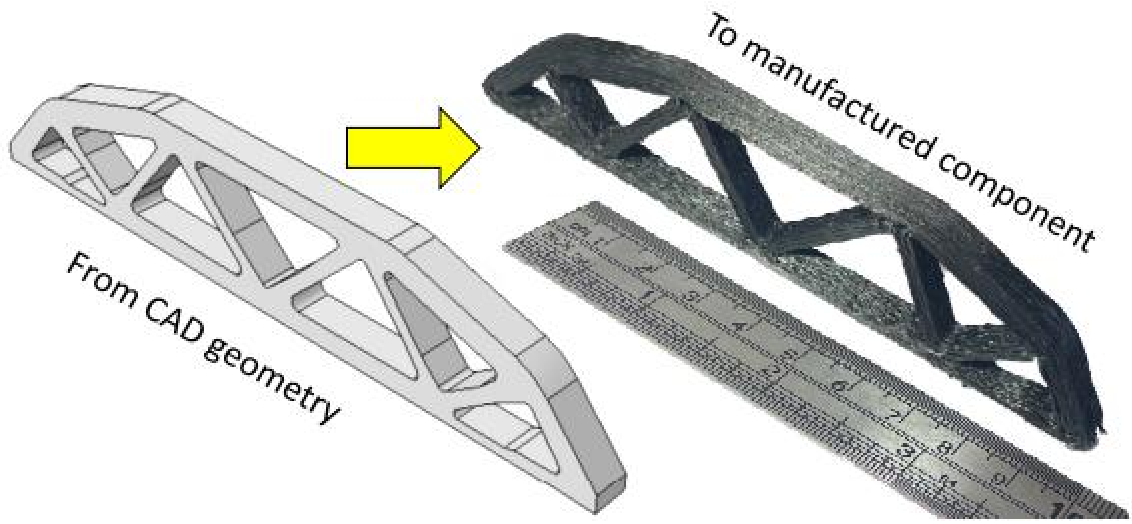

Figure 11. 3D printed continuous fibre composites: Technology demonstrator. (left) Candidate geometry: a topology optimised truss structure; (right) a carbon-fibre reinforced 3D printed continuous fibre component.

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5.4. Additively manufactured pearlitic titanium-copper alloys: the effect of copper concentration on the microstructure and hardness – M. Popovski, D. Qiu, M. Easton, S. Barter, Q. Liu and R. Das [RMIT University/DSTG]

Additive manufacturing (AM) is revolutionising the design philosophies of the past, allowing prototypes and small-scale products to be manufactured faster and cheaper. It allows for complex and optimised designs which simplify the assembly process, save weight, and reduce the buy-to-fly ratio. Traditional and AM Ti-6Al-4V is widely used in the aerospace field for its high strength-to-weight ratio, corrosion resistance and composite compatibility. However, as-built AM Ti-6Al-4V components usually feature columnar grains resulting in anisotropic properties, which could compromise performance.

Hot isostatic pressing (HIP) and in-situ high-intensity ultrasound treatment have been used to mitigate columnar grains in AM Ti-6Al-4V alloys. However, these processes significantly increase the time and cost of manufacturing as well as restrict the geometries that can be made. In contrast, simply adding copper to pure titanium proves to be a very promising approach as fully equiaxed and fine grains (~10 μm) with ultrafine pearlite can be achieved throughout as-fabricated samples manufactured by laser directed energy deposition (L-DED). This approach produced mechanical properties similar to heat-treated Ti-6Al-4V typically used in airframe components.

To probe the effects that copper concentration has on the grain size and pearlitic microstructure, a series of Ti-xCu alloys about the 7.1 wt% eutectoid composition (x = 6, 7 and 8.5 wt.%). The grain size and microstructure percentage of pearlite were analysed. The microstructures of the hypo-eutectoid, eutectoid, and hyper-eutectoid compositions are primarily alpha laths and martensite, alpha laths and eutectic pearlite, and globular and eutectic pearlite respectively. Build anomalies were also observed, such as the hardness increasing from the bottom to the top of the printed samples with a sharp increase at the heat-affected zone (Figure 12) where the microstructure is dominated by lamellar pearlite (Figure 13). Understanding this microstructure-properties relationship aids in future alloy development.

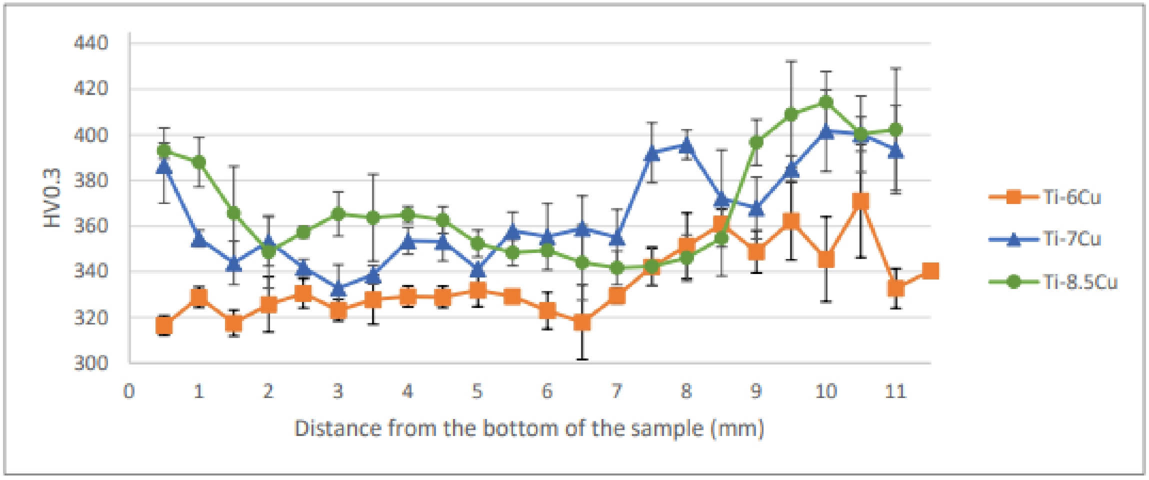

Figure 12. Graph showing the hardness versus the distance away from the substrate in Ti-6Cu (hypo-eutectoid alloy), Ti-7Cu (eutectoid alloy) and Ti-8.5Cu (hyper-eutectoid alloy).

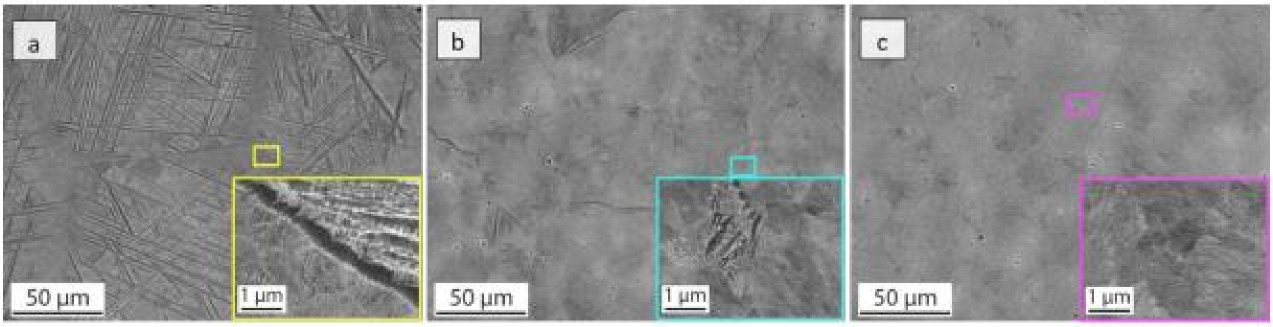

Figure 13. SEM images of typical microstructure in the HAZ with enlarged areas of the respective boxed for; a) Ti-6Cu, b) Ti-7-Cu, c) Ti-8.5Cu.

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5.5. Mechanical behaviour of 3D printed continuous fibre reinforced composite auxetic structures – V. Diwakar, K. M. Tse, A. Di Pietro and D. Ruan [Swinburne University]

In modern aircraft, fibre-reinforced composite structures are often used in aircraft surfaces such as flaps, elevators, and rudders. The advent of additive manufacturing techniques facilitates the fabrication of structures with intricate geometries, including the possibility for previously unmanufacturable Auxetic structures. Auxetic structures are a type of lightweight cellular structure with a negative Poisson's ratio, i.e. the structure expands laterally during axial stretching and contract when axially compressed. Some of the key features of auxetic structures are high shear stiffness, high energy absorption, high fracture toughness and enhanced indentation resistance. Auxetic structures have been used as smart bandages in medical and as padding in sports and safety equipment. However, the mechanical responses of 3D printed continuous fibre reinforced composite auxetic structures have seldomly been investigated for application in aircraft structures and components. Therefore, in this study, continuous fibre reinforced composite auxetic structures (CFRCASs) will be additively manufactured by filament deposition modelling technology. The topologies of auxetic structures will be identified and designed based on the uniform fibre continuity. The printed auxetic structures will be mechanically tested under quasi-static and dynamic loading conditions. The deformation history will be recorded by a digital camera and a high-speed camera, respectively. Force and displacement will be recorded by the load cell and sensor of the universal mechanical testing machine. The effects of printing parameters (such as fibre volume fraction, orientation and stacking sequence), structure topology, and the number and dimensions of unit cells on the deformation mode, load carry capacity and energy absorption of structures will be examined. The results show that when fibre volume increases, the structure's mechanical strength increases. Finally, the mechanical performance of 3D printed CFRCAS will be compared with several widely used cellular structures to explore their potential to be employed as lightweight aerostructures with load carrying and energy absorption capacities.

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6. FLIGHT LOADS AND DYNAMICS

6.1. A novel method to minimise adverse thermal effects in flight test loads measurement – M. J. Kelson, D. O. Franke and K. E. Niessen [DSTG]

A well-established method of measuring the operational forces (loads) on an aircraft is through the installation and load calibration of strain gauges fixed to the aircraft structure. A key assumption which underpins this method is the ability for a full-bridge strain gauge installation to be fully temperature compensated to remove the effect of any thermally induced strain. This work investigates a scenario where this assumption broke down and proposes a novel solution to overcome the issue.

Following extensive instrumentation, a C-27J aircraft underwent load calibration in preparation for a flight loads test program. During the conduct of flight test activities, drifting of the predicted wing loads was observed whilst the aircraft was stationary on the ground. It was hypothesised that the observed load drift was caused by intense solar radiation on the upper wing surface inducing thermal gradients through the structure. A short series of dedicated ground tests, varying the aircraft's exposure to solar radiation, were carried out and found to support the hypothesis.

To overcome this phenomenon, a new load equation generation process was developed and implemented. The new process combines the traditional linear regression techniques with secondary selection methods based on data collected during dedicated ground tests. The methods are combined and local minima can be selected, ensuring sufficient strain gauges are included to ensure a highly accurate model while also avoiding gauges that are especially susceptible to solar radiation induced drift.

Load equations produced with the new method resulted in slightly higher standard errors, however the effects of the thermal drift were significantly reduced. This resulted in load models which had much better overall accuracy in the operational flight test environment.

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6.2. Analysis framework for the attenuation of structural mode interaction – R. Carrese, N. Olshina, D. Dyer, R. Smart, M. D. Reece and F. Valentinis [Boeing Aerostructures Australia/BAE Systems Australia]

Structural mode interaction (SMI) can be a serious problem in flight vehicles with high-gain feedback control and low-frequency elastic modes. The conventional solution is to use notch filters in the control paths designed to attenuate the interaction, however, this can cause difficulties in achieving specified stability margins over the flight envelope. In this paper, an innovative design and analysis framework for predicting and attenuating SMI is described.

The observed coupling between all-movable surfaces and apparent actuator authority at high frequency, has led to the development of a closed-loop Aero-servo elastic (ASE) framework. Following the digital twin paradigm, the ASE framework is modular, which allows block interchange which increases the fidelity of the analysis with progressing maturity of the design cycle. The framework is designed with the functionality to inject sources of mechanical nonlinearities and asynchronous data rates, which may cause the system to depart from linearized behaviour. Moreover, the need to ensure minimum phase loss in closed-loop operation has led to the development of a novel filter design methodology, which designs filters to satisfy the dual objectives of providing required SMI attenuation whilst minimising low frequency phase loss.

Successful demonstration of the concept in a representative ground-test evaluation provides the opportunity to reduce the design constraints and envelope restrictions due to SMI in UASs with high gain control systems.

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7. FULL-SCALE FATIGUE TEST (FSFT)

7.1. Swiss Titanium Research Experiments on the Classic Hornet (STRETCH) – B. Main, I. Field, K. Muller, R. F. do Rosario, M. Figliolino and S. Barter [DSTG\RMIT University]

The Swiss Titanium Research Experiments on the Classic Hornet (STRETCH) is a collaboration between Swiss and Australian Governments, with support of RMIT University and RUAG Switzerland, to experimentally evaluate small fatigue crack growth in titanium combat aircraft structures, to improve related analytical tools and finally to support, with its results, the Swiss F/A-18 life extension program. The centrepiece of the collaboration is the full-scale fatigue test (FSFT) of a Swiss F/A-18 C/D centre barrel (Figure 14). Research undertaken includes coupon level small fatigue crack growth (FCG) studies, damage induction studies, and full-scale DaDT testing.

The coupon level small FCG tests focused on spectrum truncation and marker band studies for recrystallization annealed Ti-6Al-4V. These studies included a marker band development set of tests and the application of the best result in conjunction with quantitative fractography (QF) to provide the groundwork for the FSFT spectrum design. A novel method of damage induction has also been investigated that utilises plasma arc spot melting to impart precise and localised damage to the Ti-6Al-4V bulkheads of the test article. This damage induction method is shown to impart controllable crack-like damage down to depths less than 0.01 inches (0.254 mm). Finally, DaDT testing of the F/A-18 C/D centre barrel has demonstrated the full-scale application of the derived spectrum and damage induction methods.

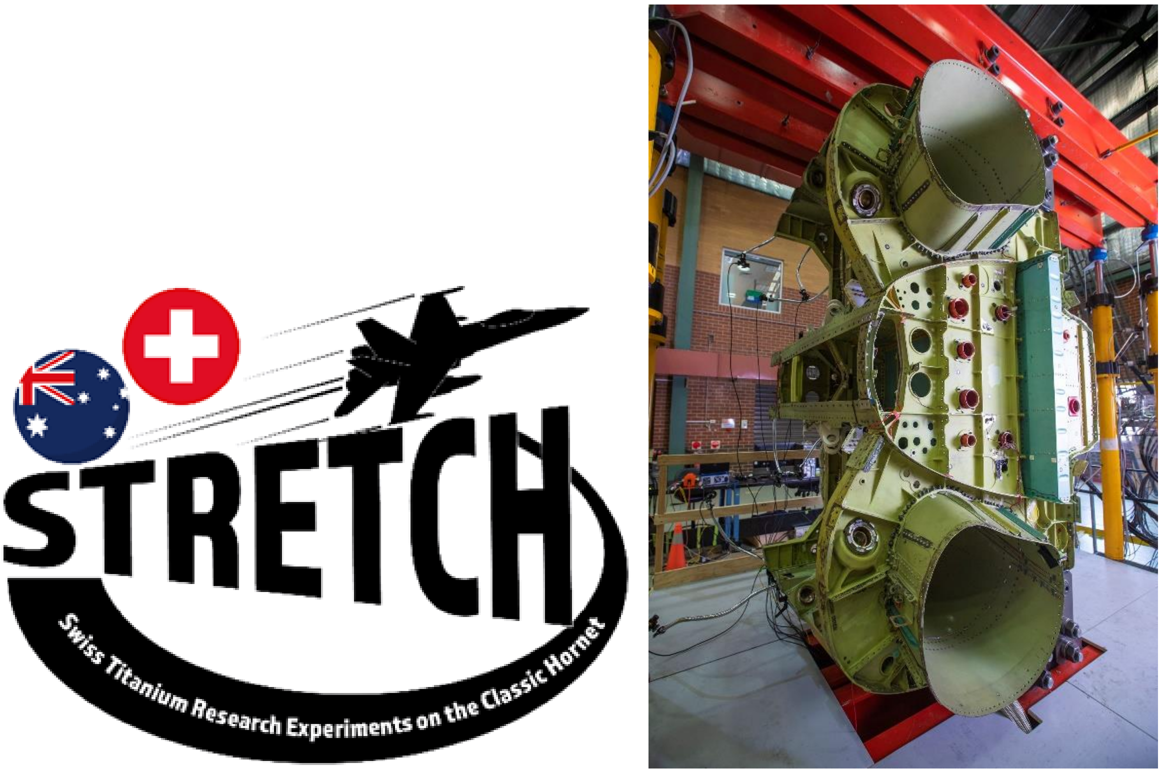

Figure 14. STRETCH Project logo (left) and centre barrel test rig (right).

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7.2. Assembly and systems integration of a full-scale helicopter fatigue test demonstrator – G. Swanton, L. Robertson, A. Manning, J. Carroll and E. Knott [DSTG/RMIT University]

Airframe structural fatigue testing of fixed wing aircraft is an established practice amongst aircraft manufacturers and operators. Airframes are subjected to representative flight loads to correlate fatigue design tools and demonstrate the safe and economic life of the structure. Helicopter airframes experience complex loads with differing sources to fixed-wing airframes, which are often high frequency and vibratory in nature. This creates unique challenges that have yet to be overcome using conventional, fixed-wing testing methods. The Helicopter Advanced Fatigue Test – Technical Demonstrator (HAFT-TD) program seeks to address this capability gap by using a novel closed-loop servo-hydraulic control system coupled with significant spectrum truncation techniques to increase testing rates by an order of magnitude over what is currently achievable with fixed-wing tests.

The HAFT-TD program has entered its final phase, which involves applying representative manoeuvre loads to a retired Seahawk helicopter airframe. A model-in-the-loop control system add-on was developed on a scaled-down concept demonstrator in an earlier phase of the program, which is being employed here to control 17 servo-hydraulic actuators to impart forces and moments to simulate flight loads on the airframe. These loads are introduced via the main rotor shaft, dummy tail rotor, and stabilator hinge, while inertial loads are reacted at several locations on the airframe.

Extensive checks are being conducted to verify essential test rig systems (Figure 15) prior to the application of simulated flight loads to the airframe, primarily to ensure the safety of the test article and personnel. This process includes installation of the hydraulic system, configuration of both hydraulic and control systems, and careful adherence to sign conventions, as well as the development of shutdown and safety procedures and systems to ensure safety when the test enters an unpowered state.

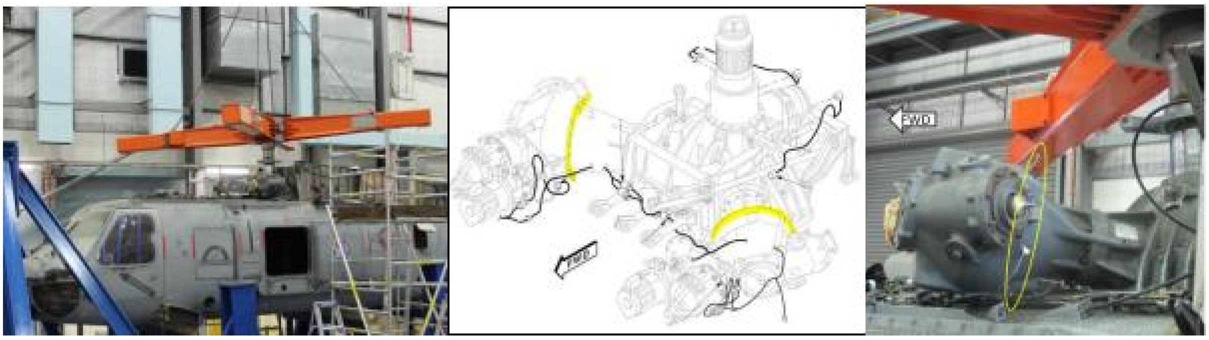

Figure 15. (left) Main rotor cruciform installation on test article, (centre) schematic of main rotor gearbox and two transmission input modules with rotor torque reaction locations highlighted, and (right) view of transmission input module with circled area depicting where torque reaction fitting will be installed.

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7.3. Model Assisted Control for High Speed Testing of Full-Scale Aircraft Structures – Q. Nguyen, A. Nelson, S. Gao, R. Yang, S. You, C. Zhang, J. Zhang, A. Manning and G. Woelffer [DSTG/Swinburne University/MTS Systems]

DSTG, working in partnership with MTS Systems (USA) and Swinburne University have undertaken a project to advance the control methods for full scale structural testing, specifically to improve testing speed and accuracy. This project has developed and demonstrated a 'model-in-the-loop' control capability to reduce cross-coupling interaction between actuators during full-scale testing. This capability was successfully implemented by MTS engineers within AeroPro control system software as the model assisted compensator (MAC) module.

To develop the MAC, an independent 'target' computer was used to run a reduced order mass and stiffness model of a test article (i.e. the model-in-the-loop) and to predict its structural response to the interaction of the actuators. The 6-Degree of Freedom Dynamic Demonstrator (6DDD) test article and rig was developed and built specifically for the development and demonstration of this model-in-the-loop software (Figure 16). The model-in-the-loop calculated a compensation signal to improve control accuracy and stability of the 6DDD test, all within each clock update of the control computer. Real-time transfer of information between the two computers was enabled via SCRAMNet shared memory, which allowed the controller to execute regular test functions including safety limits, proportional-integral-derivative (PID) controller, function generation and so on, whilst the target computer predicted the next step.

This work is a key input into the HAFT-TD, where traditional control methods for full scale testing cannot achieve testing speeds sufficient to conduct a helicopter full-scale structural fatigue test.

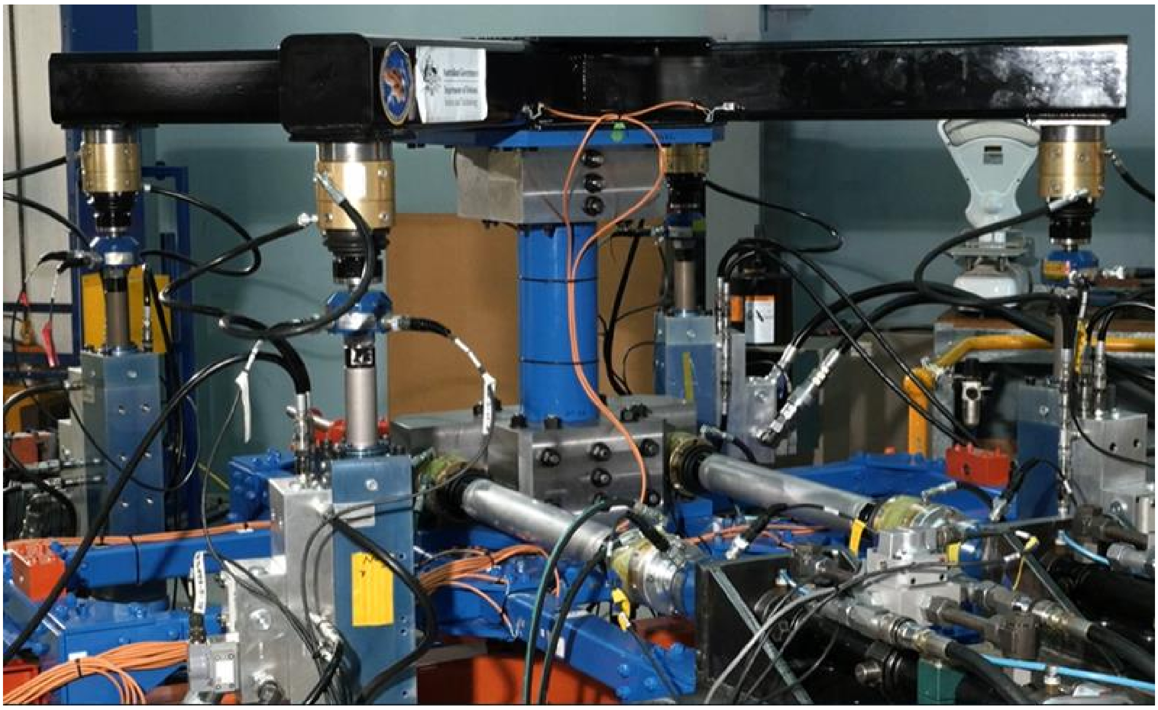

Figure 16. 6DDD test configuration showing the (black) cruciform beam arrangement on top, (blue) truss structure below and connecting (blue) shaft. The four vertical and two horizontal actuators can also been seen.

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8. STRESS IMAGING/SENSING

8.1. Application of thermal crack tracking for evaluation of fatigue crack growth rates within fastened aircraft structures – L. Button, J. Codrington, T. Simcock, C. Brooks and N. Rajic [University of Adelaide/DSTG]

The use of TSA for crack tip location and characterisation is a novel technology seeing increased adaptation in both academia and industry. It is showing great potential for use within the fatigue and damage tolerance assessment of safety critical aerospace structures.

An investigation has been conducted into the determination of crack tip locations within complex stress fields, namely within bolted aircraft joints, throughout the course of a fatigue crack growth test. The complex stress field associated with a fastened lap-joint invalidates simple shape-factor/stress-intensity factor solutions, and the location of the crack prohibits the use of a crack mouth gauge for direct crack tip evaluation. The effectiveness of the TSA method is demonstrated here as a solution to these limitations.

Samples were designed to represent a two row aircraft joint with minimal secondary bending such that through thickness cracks were dominant. This was achieved with a double-lap configuration which also utilised an extra thick centre sheet to ensure cracks form in the outer (visible) sheets. Samples were manufactured from 7075 T6 alclad aluminium and secured using interference-fit Hi-Lok fasteners.

Testing was conducted under constant amplitude cyclic loading, ($R=0.1$), until the crack reached the adjacent fastener, or the sample catastrophically failed. The samples were divided into two treatment groups: a dry (untreated) group and a group with corrosion treatments applied (CorrosionX).

Data was collected at 5000 cycle intervals. The collection consisted of an approximately 500 cycle acquisition period. Including load and displacement data from the test machine, strain gauge readings (all acquired at 500 Hz), and the TSA data acquired by the thermal camera and the MiTE software. A digital camera (DSLR) was also included to act as a baseline measurement for verification of crack tip locations determined using the TSA method.

Crack tip locations were identified from the captured images of the thermal response fields. The crack tip finding algorithm used the location of the maximum spatial gradient of the thermal (quadrature) field in the direction of crack growth (Figure 17).

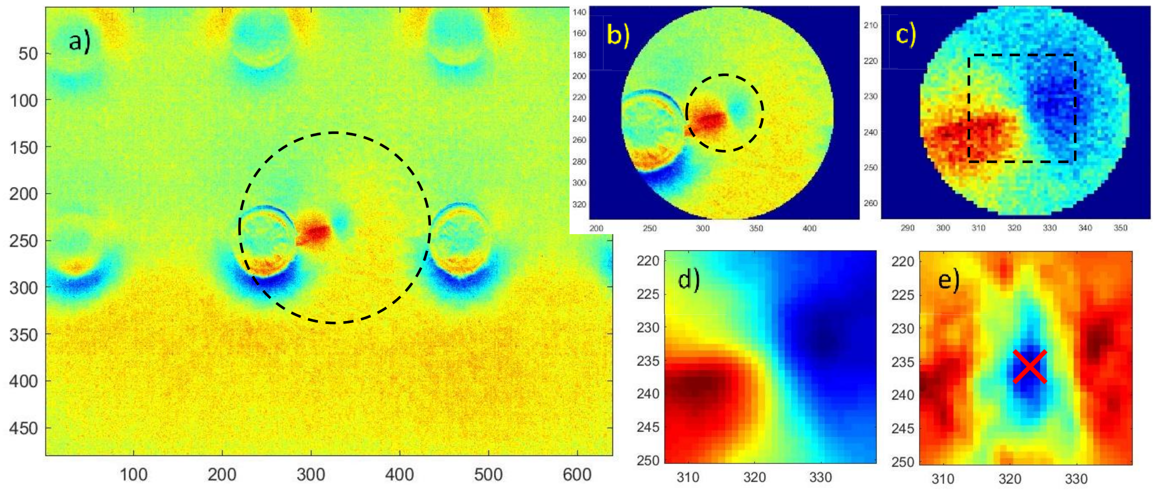

Figure 17. a) Full quadrature response, b–d) Progressive masking, e) Spatial derivative and associated maximum (crack tip).

From the crack path data, the dry (untreated) samples show tightly grouped path data between samples, whereas the CIC treated samples show significantly greater variation in the path data (Figure 18). This is attributed to the variable nature of the CIC treatment.

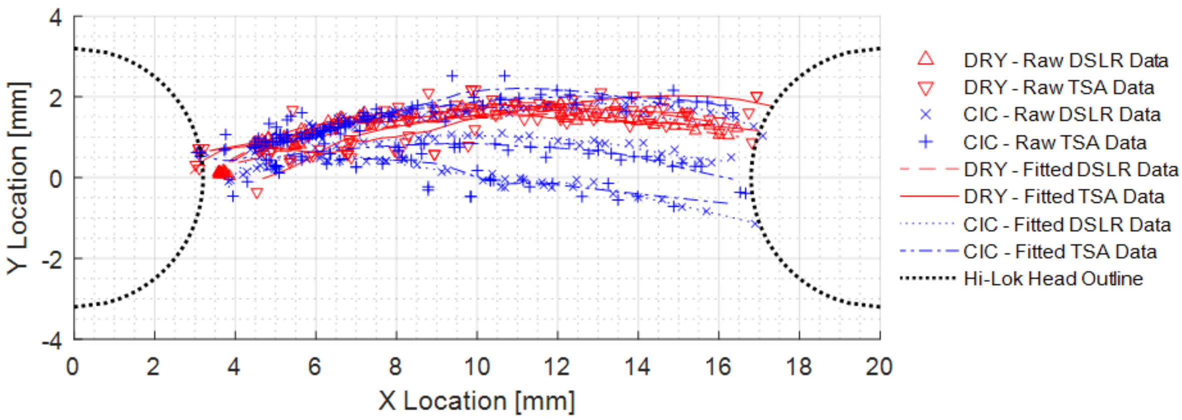

Figure 18. Crack path as measured by the TSA and DSLR systems. Raw data and Savitsky-Golay fit shown.

Resultant crack growth rates were further verified using quantitative fractography. For the clear regions of consistent striations that were found oriented in the direction of global crack growth, the crack growth rate(s) align very well with the data obtained by both TSA and DSLR.

Similar investigation is currently underway for samples fastened with rivets, to provide a low interference fit, low clamping force test case for the method. This will complement the high interference fit, high clamping force of the Hi-Lok fastened samples presented here.

The crack tip location results obtained from this study are now being employed in a method for direct evaluation of stress intensity factor from TSA data, such that the severity of a crack can be characterised within an arbitrarily complex stress field.

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8.2. A stress-imaging capability for the digital enterprise – N. Rajic, C. Brooks, S. van der Velden, P. Muir, K. Khauv, A. Mukhaimar, R. Tennakoon, F. Zambetta, P. Marzocca and R. Hoseinnezhad [DSTG/1MILLIKELVIN Pty Ltd/RMIT University]

A confluence of traditional digital design and development methods with recent Industry 4.0 digital innovations and new material and manufacturing technologies is radically reshaping the way aerospace platforms are designed, built, tested, operated and sustained. For the latter two, the centrepiece of this emerging practice is the digital twin, a virtual representation of a physical structure, system or capability that, supported by a digital thread, mirrors the characteristics, behaviours and performance of a physical counterpart. In the context of a structural digital twin (SDT), a realisation of this concept presupposes the availability of material state sensing capabilities that are able to supply the empirical data necessary to support an SDT, initially for its validation, and then its ongoing assurance. Electrical resistance strain gauge sensor technology provides the backbone of present structural model validation practice. However, its capacity to fulfil the validation and assurance requirements of an SDT is limited.

A new stress imaging capability has been developed, consisting of a novel sensing hardware architecture and a complementary image processing and visualisation framework that transforms pervasive 2D stress-imagery into a composite 3D stress map able to be projected into an augmented reality (AR) environment for digital exploitation. This capability was demonstrated on an F/A-18 centre-barrel undergoing full scale structural fatigue testing. Figure 19a shows a view of an AR/VR compatible 3D digital object comprising a CAD model of the F/A-18 centre-barrel structure pictured in Figure 19b, obtained using laser scanning, superimposed with pervasive experimental stress imagery obtained using an array of stress-imaging cameras under low-intensity constant-amplitude loading.

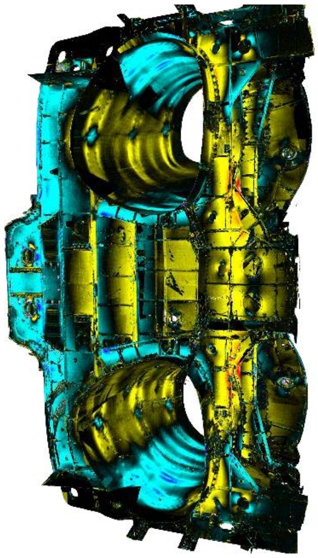
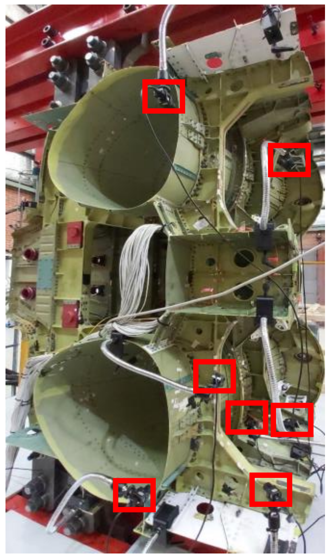
a)  b) 

Figure 19. a) 3D stress-superimposed digital representation of the F/A-18 centre-barrel full-scale structural fatigue test article pictured in b), where red boxes highlight camera positions corresponding to one of the imaging array configurations.

Acknowledgments

The authors acknowledge Daniel Bitton for technical contributions and the following members of the STRETCH (Swiss Titanium Research Experiments on the Classic Hornet) team for their support in the CB demonstration: Ben Main, Keith Muller, and Isaac Field from DSTG, Mirco Figliolino from Armasuisse and Ricardo Filipe Do Rosario from RUAG.

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8.3. Comparative Strain Survey of an Aircraft Structure Using Distributed Fibre Optic Strain Sensing Technology – G. Natividad, S. Turk, K. Tsoi and D. Bitton [DSTG]

Distributed fibre optic sensors (FOSs) have a high tensile fatigue failure strain and can deliver high-density strain measurements with significant reductions in weight and the complexity of installation when compared to conventional electrical resistance foil strain gauges (FSGs). These attributes make FOSs highly suitable for application in structural testing and structural health monitoring. However, prior to implementation on operational aerospace platforms, further full-scale demonstration on geometrically complex aircraft structures is required to develop confidence in the method.

The present work demonstrates a FOS-based high-density strain measurement capability on an F/A-18 centre-barrel assembly subjected to a full-scale fatigue test under representative flight loading. Multiple adhesive packaging techniques for FOS installation were experimentally validated and assessed for robustness and strain transfer effectiveness. Performance factors including sensor durability and measurement accuracy were also quantified and compared to FSGs.

FOSs were bonded to known fracture critical structural members, as well as other areas important to the structural integrity of the fatigue test article. FOSs were installed adjacent and parallel to 13 EA-series self-compensating FSGs [1] to enable direct comparison of strain readings at multiple locations throughout the structure. Figure 20a shows strain comparisons between readings from a FSG and corresponding FOS values, recorded continuously during a strain survey load application sequence. The FSG and FOS strain values are in close agreement at all applied loads, as shown by the overlapping line graphs. Figure 20b shows the comparative strain response during a 15-second interval at peak strain. The difference between FOS and FSG measured strains was approximately 45 με at a peak strain of 1,650 με, Figure 20b. As the FOS and FSG sensors are not coincident, a small difference in measured strain values is not unexpected. The noise level for this FOS system (comprising sensor and interrogator) is approximately 5 με which is 0.3% of the strain at this load level. Close agreement between FOS and FSG measured values was observed at all 13 locations.

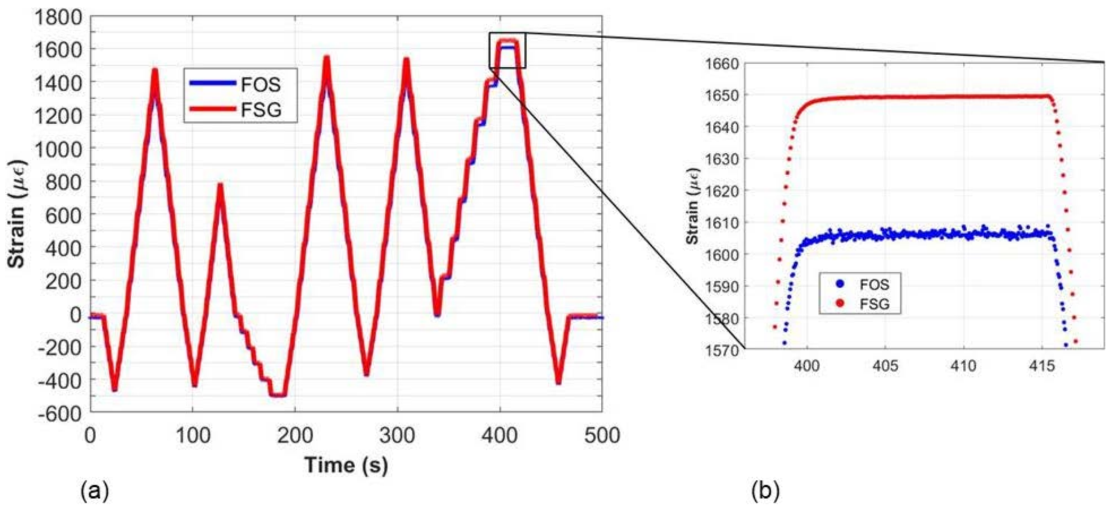

Figure 20. Fibre optic sensor (FOS) and foil strain gauge (FSG) strain response during (a) the strain survey load sequence and (b) a 15-second interval at peak strain.

Four FOS bonding strategies were also experimentally validated under the same representative flight loading [2]. Sensors were surface mounted using three aerospace grade adhesives and an adhesive mesh tape. The strain measurements obtained were comparable, with key strain distribution features consistent, Figure 21. The FOS measurements were also compared at multiple locations to single point strain measurements from four FSGs, with good correlation demonstrated. The high-density distributed FOS strain measurements provided information about the magnitude and location of peak strain and high strain gradients that is unavailable from FSGs. Additionally, the comparative strains were consistent in multiple strain surveys thus demonstrating a good level of repeatability and reliability of the FOS technology.

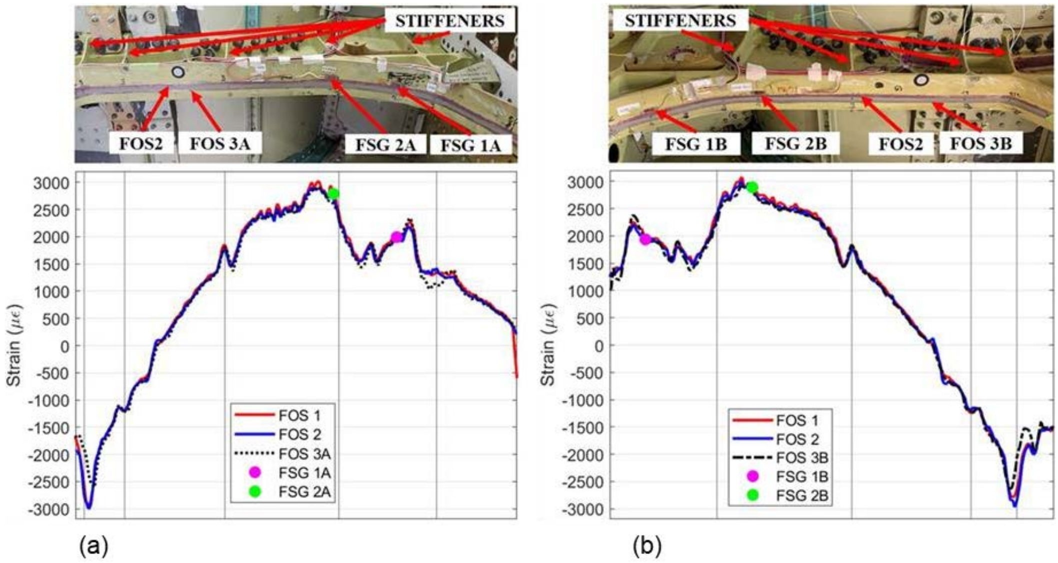

Figure 21. Strain profiles corresponding to the (a) left and (b) right flanges obtained from three FOS installations showing stiffener-flange intersections (represented by vertical lines) and average measured FSG strain values across three strain surveys.

All adhesive packaging strategies performed comparably and are mechanically robust, withstanding for the moment two lifetimes of simulated flying hours (12,000 FH of a combat aircraft) and strains up to 4,000 μƐ and are still working. The results presented here demonstrate some key advantages of distributed FOSs for airframe strain monitoring applications, including reliable and repeatable high-density strain measurements and a relatively small sensor footprint.

References

1. Natividad, G., Turk, S., Tsoi, K. and Bitton, D., “Comparative Strain Survey of an Aerospace Structure Using Distributed Fibre Optic Strain Sensing Technology”. Asia Pacific Workshop on Structural Health Monitoring, Cairns Australia, 2022.
2. Natividad, G., Turk, S., Tsoi, K. and Bitton, D., “Distributed Fibre Optic Sensing and Adhesion Strategies for Strain Evaluation of an Aircraft Structure”. Australian International Aerospace Congress, Melbourne Australia, 2023.

Acknowledgments

The authors acknowledge Daniel Bitton for technical contributions and the following members of the STRETCH (Swiss Titanium Research Experiments on the Classic Hornet) team for their support in the CB demonstration: Ben Main, Keith Muller, and Isaac Field from DSTG, Mirco Figliolino from Armasuisse and Ricardo Filipe Do Rosario from RUAG.

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9. PROBABILISTIC MODELLING AND RISK ANALYSIS

9.1. Effect of using a bounded initial crack size distribution in probabilistic risk analysis of fatigue failures of military aircraft – R. F. Torregosa, W. Hu and H. Stone [DSTG/Airbus Australia Pacific]

In spite of the advancement in materials and mechanical sciences, the accurate prediction of fatigue life of a given aircraft structural component under service load is still a significant challenge. This is because fatigue is inherently a stochastic process. Every parameter that influences the fatigue life of metallic structures has its uncertainty, thus there is a need for a risk based-approach to ensure safety of flight. In probabilistic fatigue life predictions, a key assumption is the choice of a probability distribution to represent the variation of equivalent initial flaw sizes (or the size of the initial crack) at structurally significant locations. The most commonly used probability distribution model is the Lognormal Distribution which is unbounded on the right tail. This paper examines the impact of changes in the maximum equivalent initial flaw size (EIFS) that influence the right tail for a chosen distribution by using a bounded distribution model. The choice of a bounded distribution prevents a scenario where an unrealistically large EIFS is selected and permits an evaluation of the sensitivity of the analysis to the right tail. The bounded crack size distribution is obtained by applying the Time to Crack Size (TTCS) method, in which all the crack data are first regressed to a. Crack size data were obtained from the C-130J Hercules database and used to develop the EIFS distribution. A new tool was developed for generating the EIFS distribution using the TTCS method. The sensitivity of the probabilistic risk analysis was evaluated by selecting different baseline crack sizes in the TTCS method. Using an in-house risk analysis tool, the single flight probability of failure was found to be sensitive to the upper bound of the crack size distribution. This highlights the importance of utilising realistic estimates of the baseline value that affect the right tail of the EIFS probability distribution. Furthermore, it was observed that at higher flight hours where the risk of failure is very high, the influence of the left region of the probability density becomes higher. In conclusion, care is required in selecting the upper bound of the probability distribution of crack size to obtain robust predictions of the probability of failure.

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10. AIRWORTHINESS

10.1. Ageing aircraft regulations in the Australian Defence Force (ADF) – M. Richmond [QinetiQ Australia]

Under contract to the Defence Aviation Safety Authority (DASA) the current regulations and practices to address airworthiness concerns with respect to ageing aircraft structure within the ADF were examined. These were compared to the regulations and structural integrity actions of civil and military airworthiness authorities in order to determine best practice to apply to aviation safety in the ADF.

Ageing of the aircraft structure is an inevitable outcome for any aircraft, both in civil and military service. The configuration, roles and operational environments impact the rate of structural degradation caused by ageing at both a type and individual aircraft level. Compared to civil operations of large transport aircraft, military aircraft operation was considered to place greater demand on the aircraft structure (seeking to make use of maximum structural capability) and have a greater variability in both number and nature of operational roles.

Similar to large civil aircraft, initial military certification includes airworthiness requirements that seek to establish and verify a structural airworthiness service limit. Once in service, managing structural ageing requires airworthiness systems to confirm how aircraft are used relative to design intent and determine the rate of structural degradation. Thus, a fundamental objective is to implement processes to monitor ageing, so that appropriate airworthiness action can be determined.

Ignoring structural ageing means ignoring the increasing risk of catastrophic structural failure. An example given (from UK Defence Safety Authority Manual of Air System Integrity Management) was the in-flight failure of the centre wing section of an ex-military C-130A Hercules aircraft during low level firefighting operations in 2002, shown in Figure 22. This resulted in the loss of all three crew members. The effect of prior military use and current civil use were not adequately considered, leading to undetected widespread cracking which could no longer support flight loads.

Figure 22. In-flight failure of the centre wing section of an ex-military C-130A Hercules aircraft during low level firefighting operations in 2002.

Controls introduced by civil airworthiness authorities in response to structural ageing related incidents were examined. Consideration was given to the applicability of such controls within the ADF military aviation environment, including the need for any revision or addition to the Defence Aviation Safety Regulations (DASR).

A number of recommendations were made in the QinetiQ report QPL-TR-1079 which is presently being reviewed by DASA. Any changes to the DASR to address ageing aircraft will undergo consultation prior to implementation.

Reference

1. QPL-TR-1079 Ageing Aircraft Structural Requirements Review

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