UNCLASSIFIED

Review of aeronautical fatigue and structural integrity investigations in the UK during the period April 2011 - April 2013

Reed, S. C.

DSTL/TR71962 Ver 2
29 March 2013

Dstl

Physical Sciences
Porton Down
Salisbury
Wilts
SP4 0JQ

UNCLASSIFIED

Release Conditions

This document is cleared for public release.

Authorisation			
Role	**Name**	**Signature**	**Date**
Reviewer	Mr Mark Saunders		29 Mar 13
Compiler	Dr Steve Reed		29 Mar 13

Executive summary

This review is a summary of the aeronautical fatigue and structural integrity investigations carried out in the United Kingdom during the period April 2011 to April 2013. The review has been compiled for presentation at the 33rd Conference of the International Committee on Aeronautical Fatigue (ICAF), to be held in Jerusalem, Israel in June 2013

The contributions generously provided by colleagues from within the aerospace industry and universities are gratefully acknowledged. The names of contributors and their affiliation are shown below the title of each item.

Table of contents

1 Introduction

This review is a summary of the aeronautical fatigue and structural integrity investigations carried out in the United Kingdom during the period April 2011 to April 2013. The review has been compiled for presentation at the 33rd Conference of the International Committee on Aeronautical Fatigue (ICAF), to be held in Jerusalem, Israel in June 2013

The contributions generously provided by colleagues from within the aerospace industry and universities are gratefully acknowledged. The names of contributors and their affiliation are shown below the title of each item.

The format of the paper is similar to that of recent UK ICAF reviews; the topics covered include:

- Developments in fatigue design tools
- Fatigue of metallic and non-metallic structural features
- Damage tolerance
- Structural ageing aircraft programmes
- Fatigue testing
- Developments in fatigue, usage and structural health monitoring

References are annotated at the end of each contribution and are self-contained within the contribution. Figure and table numbers are also self-contained within the contribution.

2 Development in fatigue design tools

2.1 Hawk Updated Analysis Techniques for Rework/Modification Action

Graham Duck, BAE Systems Brough

The strain life analysis approach is utilised on the Hawk project in order to calculate the safe life to crack initiation for key and critical structural locations. When a design change, repair, or modification is embodied at a location, the standard practice is to account for the two damage rates in a 'double damage' calculation. When the modification involves oversizing (opening a fastener hole from one size to another), a proportion of accumulated damage is removed during the modification process. The amount of damage removed is derived from the elastic stress distribution away from the original hole wall (e.g. Reference [1]).

The standard analytical approach for damage accumulation described above has been further enhanced to cater for cases where a repair is embodied to a location that has some degree of cracking present. In such cases where NDT has demonstrated a small crack present at a hole, oversizing of the hole has been conducted to remove the very small crack defect. However, the retained damage fraction (to crack initiation) in this particular case does not use the standard elastic stress distribution as before, but instead accounts for the more aggressive damage consumption that takes over during the crack growth phase.

Reference:

[1]. Timoshenko, S. P. (1945). Strength of Materials – Part II, Page 316.

2.2 Developments in fatigue analysis

A Halfpenny and R Plaskitt, HBM-nCode

Over the last couple of years HBM-nCode has released a number of significant fatigue capabilities to its software product range. nCode DesignLife and nCode GlyphWorks, which are used for finite element-based fatigue and test-based fatigue analysis respectively, benefit from the following new capabilities:

- Thermo-Mechanical Fatigue (TMF) – used for fatigue and combined creep/fatigue analysis of components at high-temperatures or in variable temperature environments

- Multi-axial Strain Life – used for fatigue analysis of non-proportional loading based on a multi-axial strain life damage model

- Fatigue of Short Fibre Composites – used for analysis of short fibre composites, such as polymers, as well as laminar composites where failure modes due to inter-laminar stress can be ignored

- Fatigue of Adhesive Bonded Joints – used for analysis of adhesive joints in metallic structures

Durability of composites continues to be an important focus for R&D efforts, including continuous fibre laminates.

Away from fatigue analysis, their data management software, nCode Automation, has expanded considerably and is being used for some noteworthy aerospace and fatigue applications:

Lockheed Martin

nCode Automation is used to monitor, collect, analyse and manage test data for the F-35 Joint Strike Fighter programme. Full-scale test articles are instrumented for both “static” testing, to investigate the effect of critical loading, and “durability” testing, to simulate the effect of fatigue over several lifetime scenarios.

Test articles include those from the CTOL variant which are tested at BAE Systems Structural and Dynamic Test facility at Brough, East Yorkshire.

US Forestry Service

nCode Automation is used as part of a Structural Health Monitoring (SHM) system to determine the operational loads on a fleet of fire fighting aircraft. This is particularly challenging because these aging aircraft are now used in a role that is far more severe than their original design brief.

Condition Based Maintenance (CBM) of Ground Vehicles

nCode Automation is used as part of a Condition Based Maintenance (CBM) system for military ground vehicles. CBM is based on real-time assessments of equipment conditions obtained from embedded or external sensors and measurement equipment.

nCode Automation is used to convert the raw sensor data into information identifying potential efficiencies in the maintenance processes to increase readiness, improve life cycle fleet management and improve operational knowledge for future vehicle design and evaluation.

Further information on these can be found in the public domain at www.ncode.com.

Material Testing

nCode Material Testing focuses on the delivery of fully characterized design curves for use directly in fatigue analysis. Test data are analysed and interpreted by our in-house experts to derive design curves to the customer's required Certainty of Survival and specified Confidence Interval. Services include:

- Full Material Characterization – to determine strain-life, stress-life, thermo-mechanical fatigue and basic mechanical properties of metals, composites and jointed components. In the last couple of years, HBM-nCode has been heavily involved in qualifying surface coatings for replacement of hexavalent chromium on aircraft parts

- Material Assurance Service - to determine whether supplied specimens correlate with a supplied design curve. The service is used to determine whether a company's existing design curve offers a suitable and safe representation of their current material. Using fewer specimens than the full material characterisation service, the materials assurance service offers a rapid and efficient means of comparing the fatigue performance of different materials and different suppliers

2.3 BEASY National Review Report 2013

Dr Sharon Mellings, C M Beasy Ltd

Research and development programs have been progressed in a number of specific areas of capability as explained below:

2.3.1 Crack growth in a residual stress field

BEASY solves for a linear elastic analysis, but it is nevertheless possible to consider the effects of residual stresses acting on the crack faces. These residual stress loads can arise from a number of different sources such as: overloads due to damage; surface treatment processes; and manufacturing stresses.

When residual stresses apply to a model they may, for the case of compressive stresses, prevent the crack opening for all or part of the loading, thus reducing the SIF range. Alternatively the stresses may be tensile and cause higher applied loads. In this case the maximum SIF is raised (which could potentially, and unexpectedly, result in a part failure), and has the effect of reducing the computed load ratio (ratio between minimum and maximum loads). In many cases this will result in a change in the fatigue growth equation that is appropriate to be used.

During a crack growth evaluation, the size and direction of the residual stress load can vary along the crack surface, and will (in most cases) change as the crack grows through the residual stress field. BEASY enables this effect to be automatically computed by interrogating result files to identify the local stress field, and then applying this stress to the crack faces.

In a case study, the effect of a residual stress on the grown crack shape was studied, comparing behaviour with and without residual stress loading. Figure1 shows the geometry of the panel. A crack was grown from the centre of the hole.

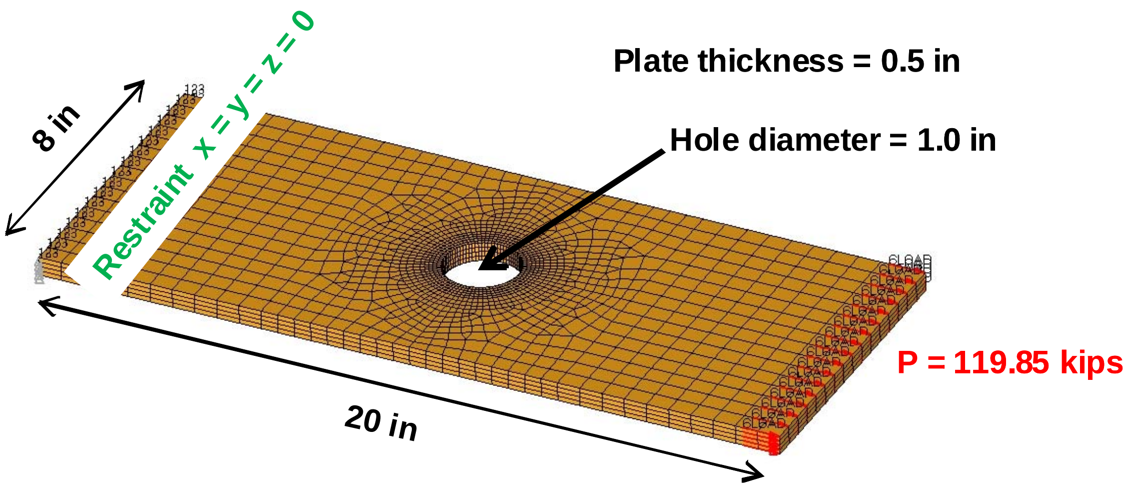

Figure1: Plate with a hole: Model geometry

Figure 12 and Figure 23 below show the resultant crack growth changes without and with residual stress loading. The residual stress causes the crack to grow more slowly along the inner surface of the hole, so that when the crack transitions to a through crack the crack shapes have changed slightly. This residual stress also increased the number of cycles required to grow the crack to a through crack by around 70%.

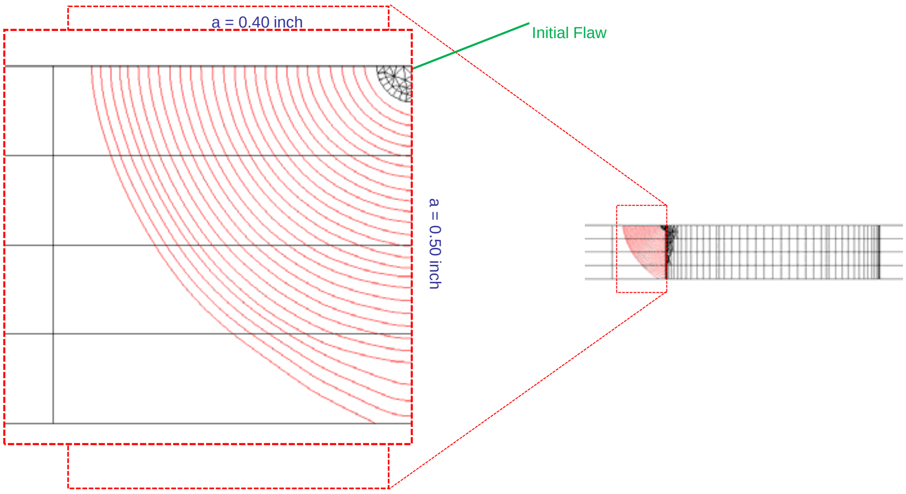

Figure 1 Crack growth without residual stresses

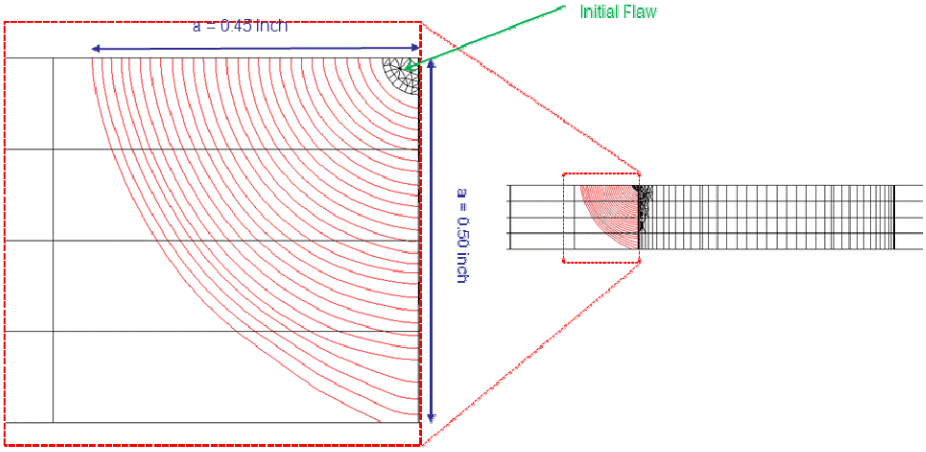

Figure 2 Crack growth with residual stresses

BEASY has shown also the ability to determine changes in crack shape as the crack front moves through regions with varying levels of residual stress.

2.3.2 Parametric pipe analysis

Development has been undertaken to enable analysis of cracks within pipelines. Pipes can be modelled parametrically (using only simple input parameters) with a crack modelled in the pipe wall. The tool then automatically creates a cracked meshed model, without any user modelling required, which can then be solved to give accurate stress intensity factors, automatically allowing for wall thickness effects to be taken into account.

SIF's can be plotted, or alternatively the SIF values can be used to automatically grow the crack; determining the fatigue life and the change of shape of the crack as it grows.

2.3.3 Stiffened Panels

Further work (using two dimensional BEASY models) has been undertaken enhancing the analysis capability to encompass layered, and stiffened, panel structures. The methodology implemented allows panels to be investigated using simplified planar models, with in-plane load transfer between different structural members. Specifically, crack growth in panels with discrete riveted connections can be studied.

This type of analysis is targeted at aircraft panels, enabling the study of crack growth in airframe skins connected with rivets, and with connections to ribs and stringers. Figure 34 shows an example of this type of model where a number of layers of panel, connected together by rivets, are analysed. Crack growth can then be performed in any of the panels, allowing the load redistribution to be computed as the crack grows.

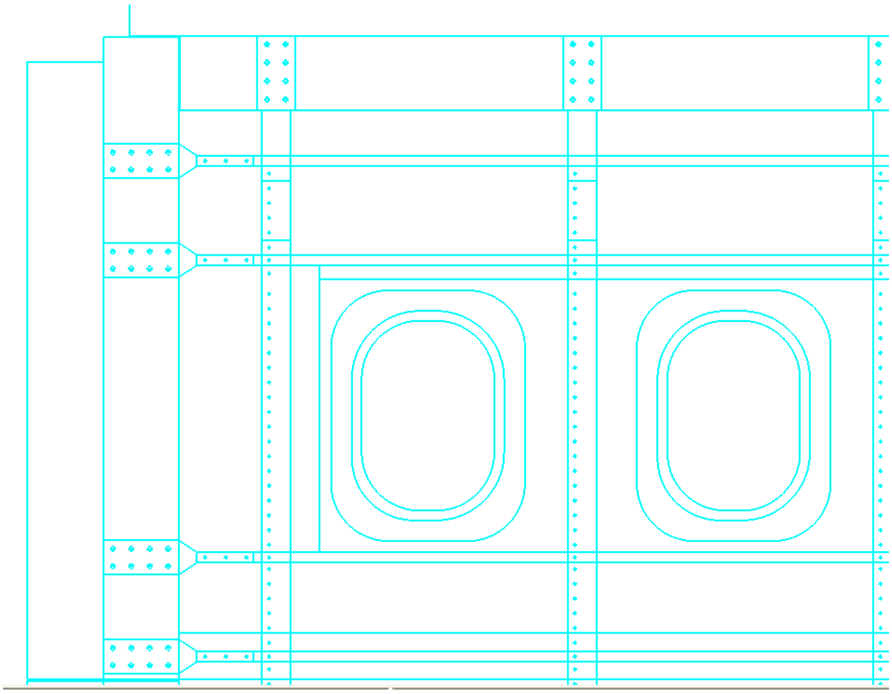

Figure 3 Example of stiffened panel structure (courtesy of R.Citarella, University of Salerno)

2.3.4 Partial crack growth

One of the benefits of the BEASY automatic crack growth process is the ability to track changes in the crack shape as a crack develops through a structure. However, solution becomes complex in the situation where part of the crack fails to grow, or grows very slowly. In these cases the crack growth could be performed but required manual intervention to create new crack shapes at each step, rather than leaving the crack growth process running automatically.

A development programme is well advanced to enable partial crack growth to run automatically. This feature is especially important when considering residual stress analysis as this may prevent the crack growing at the surface of the body, but allowing sub-surface crack growth. In this case the crack growth “arresting” at the surface can now automatically be predicted, enabling enhanced computation of the fatigue life.

The plot below shows the computed crack fronts during the crack growth of an initial corner crack. In this model a non-uniform loading has been defined, initially preventing crack growth at the lower edge.

After a few steps, as the crack grows, the stresses in the part redistribute and the stress intensity factors at the lower edge rise above the threshold SIF level and the crack slowly starts to grow at this edge. The crack front shape change is fully captured during the analysis which required no manual user intervention.

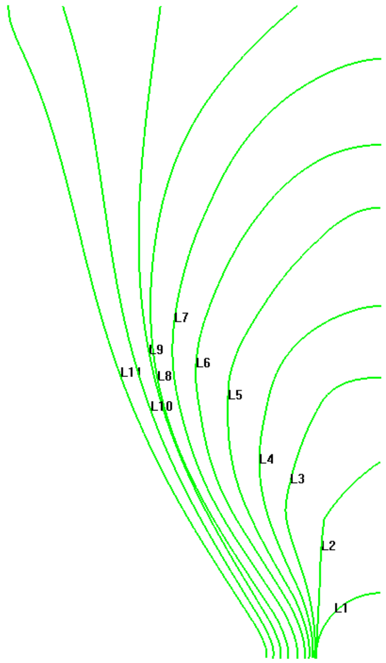

Figure 4 Crack front lines during growth – simple corner crack in a box

A second application related to assessment of a crack in a gear tooth (shown in Figure 56 and Figure 67). Due the loading applied, this crack grows faster at the ends of the crack, along the surface of the part, but more slowly in the middle of the crack, through the depth of the gear tooth.

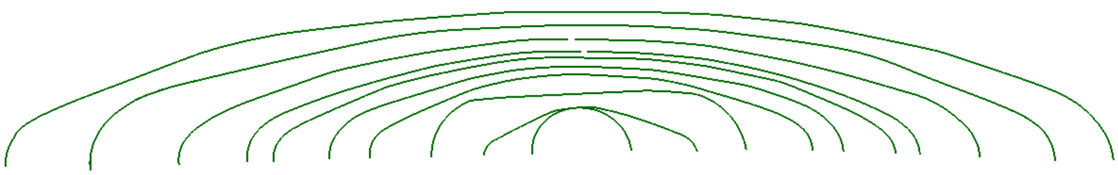

Figure 5 Crack front lines during growth edge crack in a gear tooth

In the initial analysis step, no crack growth was predicted in the middle of the crack front, but growth has been predicted at the ends of the crack front.

After the first step, the load redistribution around the crack results in the stress intensity factors rising above the threshold SIF level, enabling growth in the middle of the crack.

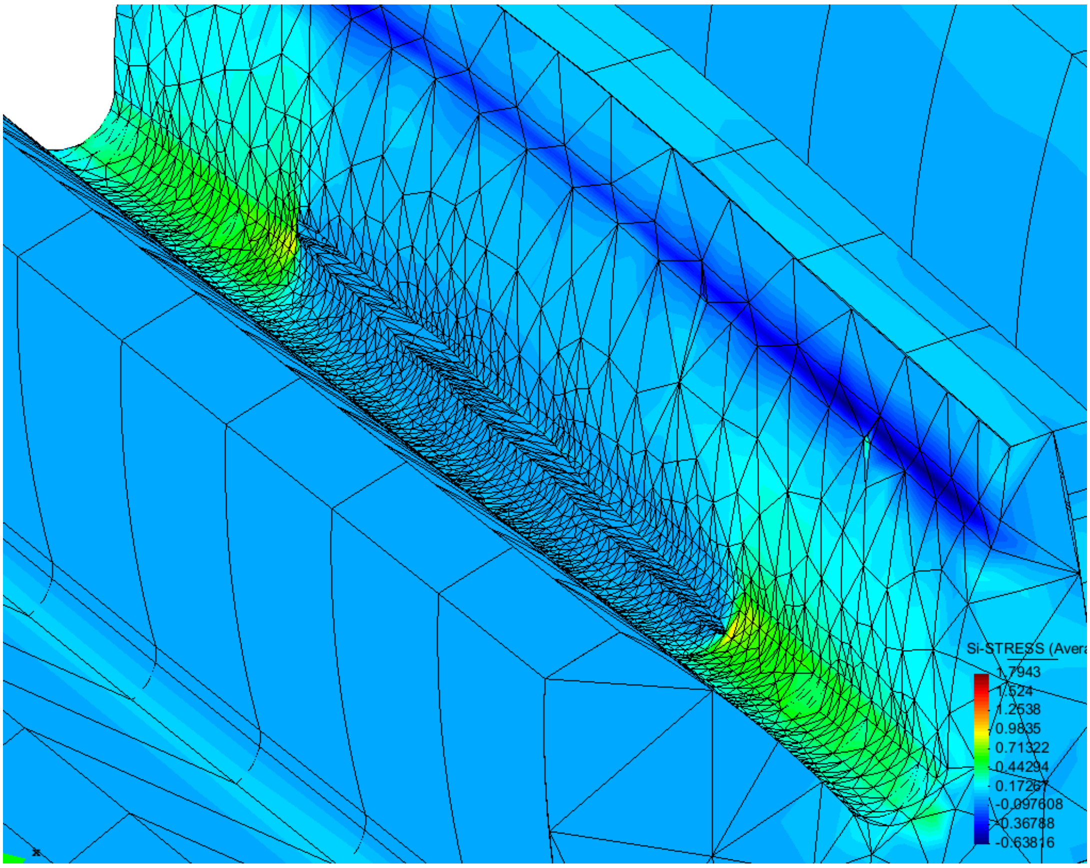

Figure 6 Deformed plot of the crack after a number of crack growth steps

2.3.5 Modelling of aircraft corrosion

Building on the research work carried out in the SICOM programme, BEASY has now introduced a modelling tool to predict galvanic corrosion for multi-material structures exposed to thin aqueous layer of electrolytes such as those typically found in aircraft environments. The tool provided good agreement between the model predictions and an experimental test consisting or two coplanar plates (aluminium 2024 and CFRP). Both the trends and results obtained from the model in terms of the galvanic coupling current flowing between electrodes, and also total current values were validated as being in good agreement with experimental data.

Further work is underway focused on the effects of electrolyte concentration and layer thickness.

Analysis of two cases has been undertaken, firstly to understand the behaviour of a partially coated CFRP plate as part of a rib-stringer assembly incorporating AA2024; and secondly of a landing gear with cadmium plated parts in contact with coated steel.

The development provides the capability to assess the distribution of corrosion rate on the modelled structure expressed in millimetres per year (mpy) according to the colour scale. In this evaluation, it demonstrated how most of the corrosion takes place near the edge in contact with the CFRP (i.e. the region of rib further away from the CFRP does not experience significant corrosion). It was also shown that the maximum value of corrosion rate occurs at the edge between the two materials, how the rate varied between three different cases assessed, and hence how extending the coating just a few tens of centimetres away from the edge in common to both materials can impact the corrosion rate on the structure.

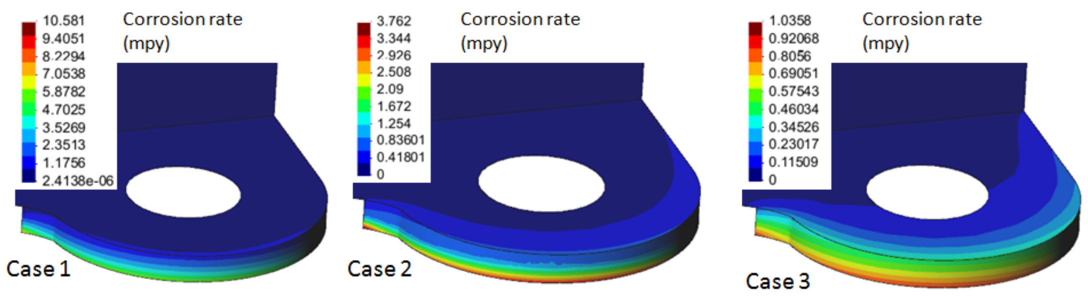

Figure 7 Illustration of corrosion rate (different coating extent on stringer)

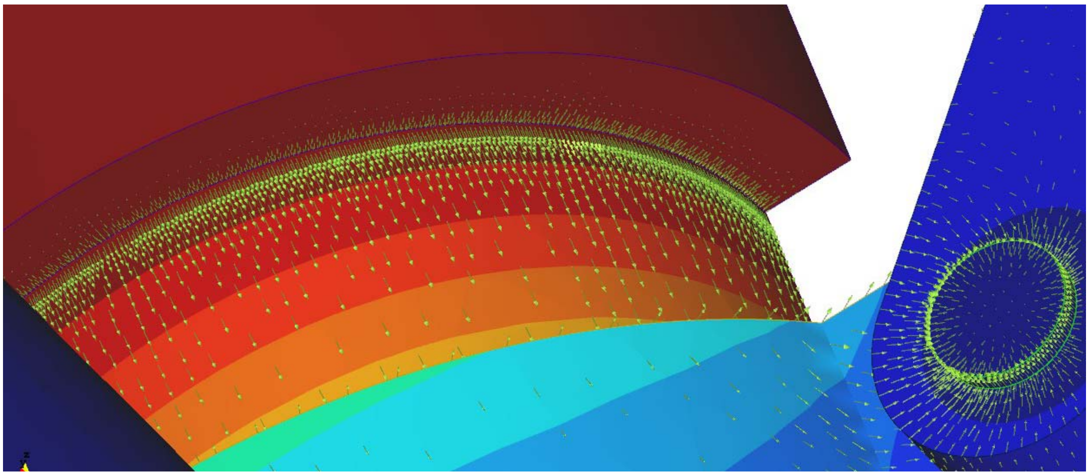

Figure 8 Illustration of tangential current flow and potential gradient through the thin film electrolyte (highest galvanic stress)

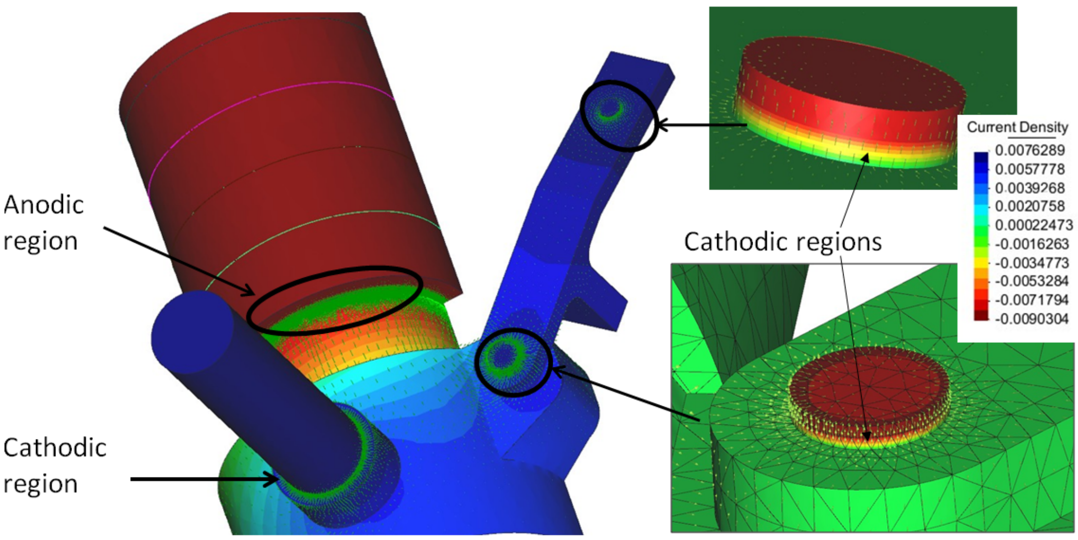

Figure 9 Illustration of the distribution of current density

3 Fatigue of metallic and non-metallic structural features

3.1 Fatigue failure of a gear in a helicopter main gearbox

S. J. Harris. QinetiQ Ltd

An investigation into the failure of a helicopter main gearbox concluded that the first component to fail had been a second stage planet gear in the epicyclic module of the main rotor drivetrain.

The gear was approximately 57mm wide and 138mm outside diameter. It was self-aligning and the bearing was not a separate component - the inner surface of the gear was hardened (by carburising), ground and honed to form the outer race of a spherical bearing (Figure 1). The rolling elements consisted of two rows of tapered barrel-shaped rollers. These rollers have a non-uniform contact pressure along their length. In this case, the maximum contact pressures on the gear occurred along two loci approximately 14mm from the outside surfaces of the gear and so the pressures either side reduced towards the centre and towards the edges of the gear.

Figure 1: Intact but damaged gear showing spherical bearing surface inside

A small flake of the same steel used for the gear had been recovered from the epicyclic module magnetic chip detector approximately 36 flying hours before the failure of the gear. It was not possible to confirm exactly where the flake had come from because the gear had broken up; not all of the fragments had been recovered and there was some mechanical damage to the remains. The presence of honing marks suggested that this flake of steel came from a bearing surface. Measurement of the angles between the honing marks indicated that it came from a location approximately 14mm from the edge of a gear, i.e. along a track of maximum rolling contact pressure.

Evidence of fatigue cracking was found in several different orientations on a recovered part of the failed gear (Figure 2). An unusual concave fatigue fracture surface was noted, centred approximately 14mm from one edge of the gear; it originated near the bearing surface and had grown towards the gear teeth. Flatter fracture surfaces were noted closer to the gear teeth.

Figure 2: Fatigue fracture surfaces on a fragment of the failed gear

Further examination using X-ray tomography revealed the presence of other sub-surface cracks (Figure 3) later confirmed by cross-sections through the failed part. One crack followed the curvature of the bearing surface before branching to form a similarly-curved crack behind the concave part of the fracture surface.

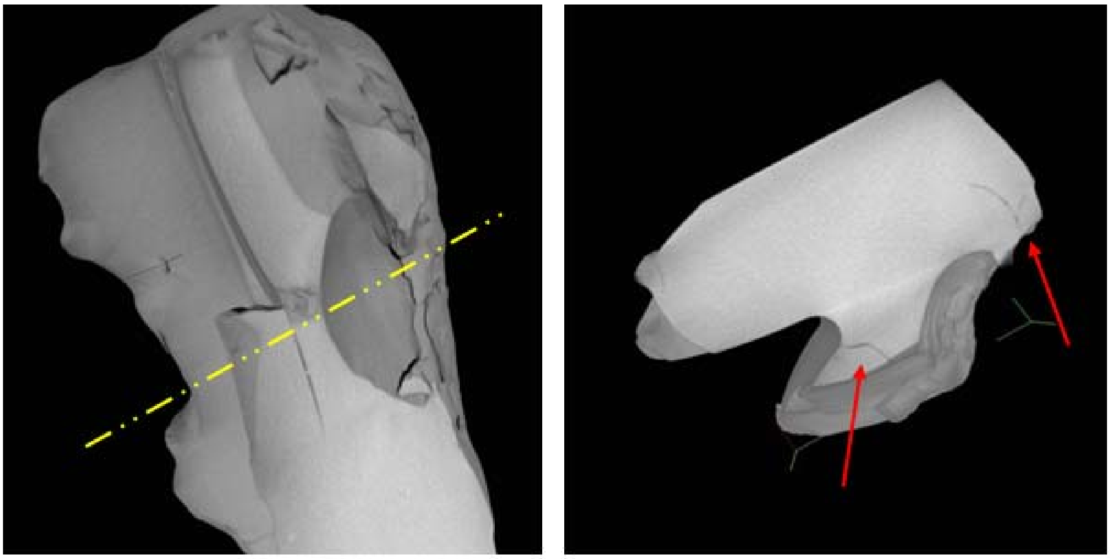

Figure 3: X-ray tomography images showing a cross-section of the gear fragment viewed in the direction of the yellow arrow. Sub-surface cracks are indicated by the red arrows

The stress fields in the gear are very complex, resulting from a combination of loading actions and residual stresses in the material. Crack propagation was influenced in different ways in different locations within the gear:

- The path of the crack close to the bearing surface was influenced by the residual stresses induced by the presence of the carburised layer.
- The curved cracks were influenced by the 3-dimensional stress field from the Herzian stresses caused by the rolling elements and were centred on the line of maximum rolling contact pressure.
- The flatter parts of the fracture were influenced by the general loads on the gear and the alternating bending loads on the gear teeth.

Crack initiation is thought to have occurred following the spalling of a flake of metal from the bearing surface somewhere along a line of maximum rolling contact pressure. Although spalling was not expected to cause cracks to propagate through the carburised layer, stress analysis by the manufacturer has indicated that sliding of the rollers over a spalled surface could have this consequence.

Reference:

[1]. QINETIQ/13/00774

4 Damage tolerance

4.1 Bonded crack retarders for aerospace

M. E. Fitzpatrick, A. K. Syed, Materials Engineering, The Open University, Walton Hall, Milton Keynes MK7 6AA

Bonded crack retarder technology has proven to be efficient in improving the damage tolerance of aircraft structures that do not contain natural crack stoppers. The mechanism is to adhesively bond strap of a reinforcing material in critical locations of a structure, and the local stiffening that they provide acts to retard fatigue crack growth and thereby improve the overall fatigue life.

Previous work [1-4] at the Open University has investigated the use of different reinforcing materials on the residual stresses generated following elevated temperature curing of the adhesive. The residual stress generated in the substrate is related to the difference in coefficient of thermal expansion between the strap and the substrate. Titanium and CFRP lead to high residual stresses, aluminium and GLARE (a glass fibre / aluminium sandwich) are much lower. GLARE has been selected as the optimum strap material for the next stage of research. The stability of GLARE straps when incorporated into structural applications is now under investigation. The additional thermal residual stresses introducing during the bonding are further concern, these increase the stress concentration factor at the crack tip resulting in the premature failure of the structure.

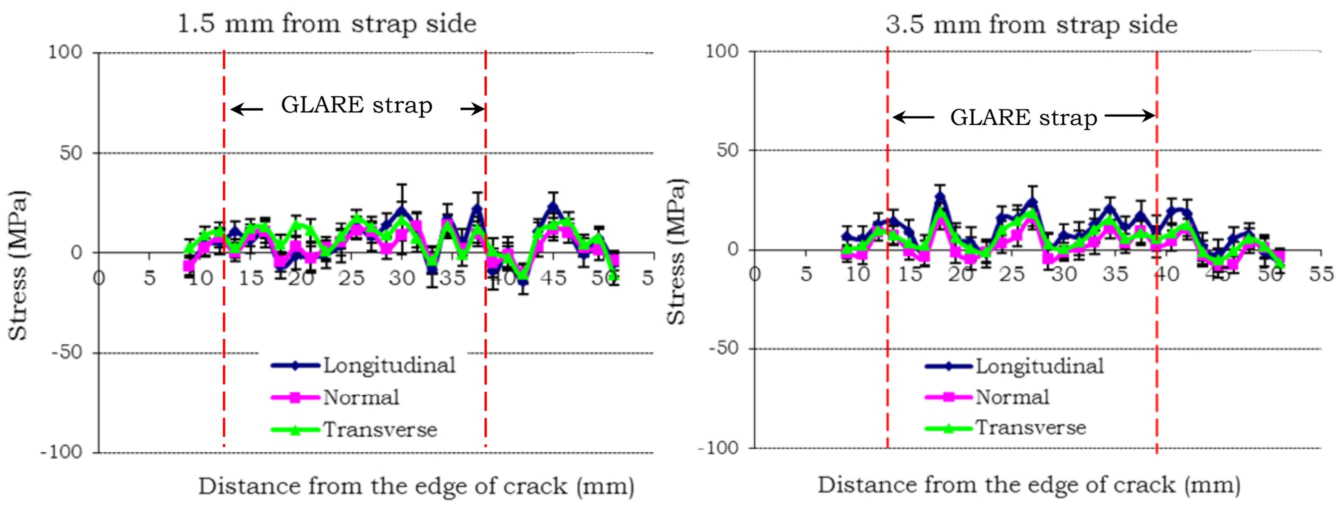

Figure 1: Residual stress measurements in M(T) specimens due to GLARE strap bonding

Recently residual stress measurements and constant amplitude fatigue tests on middle crack tension M(T) specimens bonded with GLARE strap were performed. Residual stress measurements were carried at 1.5 mm and 3.5 mm below the strap in the substrate by using neutron diffraction. Figure 1 shows the residual stress measurements in the substrate at different locations through the thickness. Thermal residual stresses generated due to the strap bonding are low (< 30 MPa) and there is no variation in the stresses in through thickness.

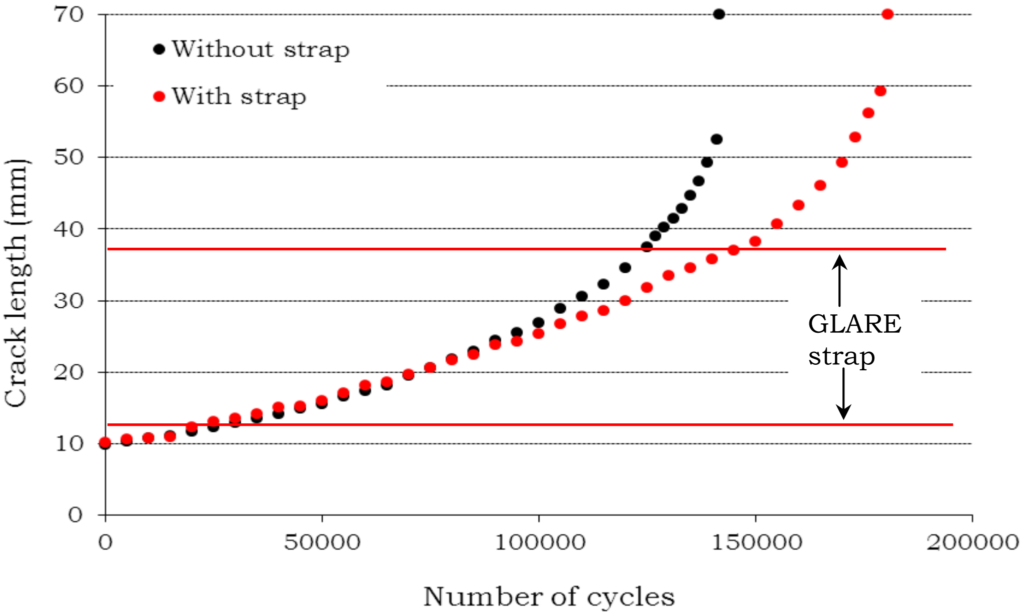

Figure2: Fatigue life of M(T) specimen with and without GLARE strap

Figure 2 shows the results of fatigue tests on M(T) specimens with and without a GLARE strap. It can be clearly seen that there is a considerable increase in fatigue life for the sample with the GLARE strap. The crack growth is slowed down by the presence of the strap.

References:

[1]. C.D.M. Liljedahl, M.E. Fitzpatrick, L. Edwards, Composite Structures 86 (2008) 344–355.

[2]. Liljedahl CDM, Fitzpatrick ME, Edwards L. Distortion and residual stresses in structures reinforced with titanium straps for improved damage tolerance. Mater. Sci. Engng 2008; 486:104.

[3]. Liljedahl CDM, Fitzpatrick ME, Edwards L. Evolution of residual stresses with fatigue crack growth in integral structures with crack retarders. Mater. Sci. Engng 2009; A523:152.

[4]. C. D. M. Liljedahl, M. E. Fitzpatrick, O. Zanellato, L. Edwards, ‘Effect of temperature on the residual stresses in an integral structure with a crack retarding patch’, Strain: 2011:47:s2:293-298.

4.2 Laser peening of aerospace aluminium alloys

M. E. Fitzpatrick, M. B. Toparli, Materials Engineering, The Open University, Walton Hall, Milton Keynes MK7 6AA

The Open University is working on residual stress characterization and optimization for aluminium alloys after laser shock peening (LSP), one of the newest surface treatment techniques. The possibility of application of laser peening to 2.0-mm-thick Al2024-T351 plates that are used in fuselage skins in aerospace construction was explored in terms of the residual stress distribution. The residual stresses were measured by different techniques including surface X-ray diffraction (with layer removal), incremental hole drilling, the contour method, synchrotron X-ray diffraction and neutron diffraction techniques.

The extensive experimental programme includes characterization of residual stresses of thin Al2024-T351 plates treated with three different laser systems and different sets of process parameters. Initial studies showed that it is very challenging to obtain desired stress profiles after laser peening for thin samples. Tensile surface stresses and non-equibiaxial stress state were the most important difficulties. However, due to our optimization work, it can be concluded that beneficial compressive residual stress can be introduced into thin aluminium alloys as long as the process parameters are selected accordingly (Figure 1). It was also found that the process parameters for thick and thin samples are different than each other.

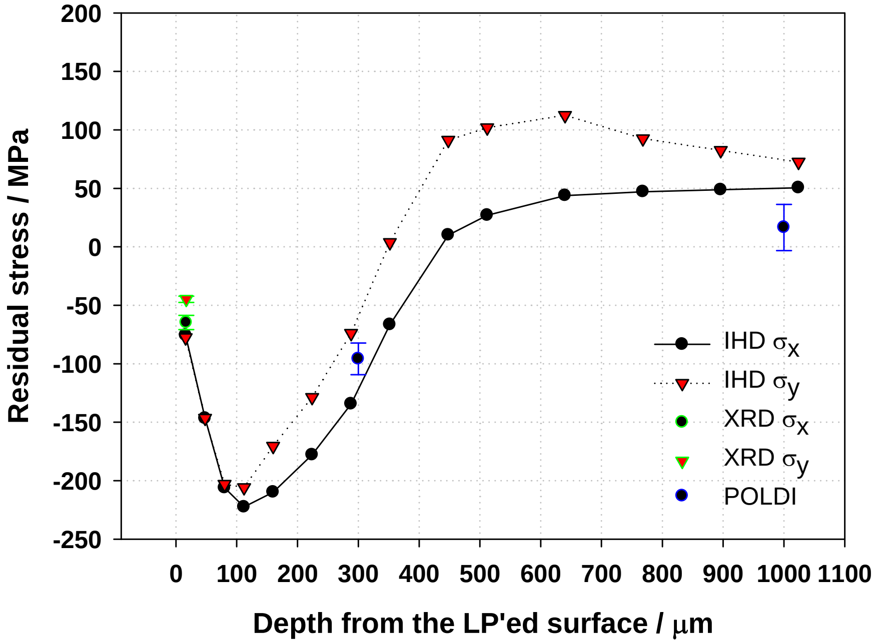

Figure 10: In-depth residual stress profiles obtained from 2.0 mm thick Al2024-T351 plate. The residual stresses were measured in two directions, i.e. parallel and transverse to peening direction, x and y-directions, respectively. Incremental hole drilling (IHD), surface X-ray diffraction (XRD) and neutron diffraction carried out at POLDI, PSI, Switzerland (POLDI) were used to obtain stress fields. As can be seen, compressive residual stresses up to 0.4 mm from peened surface can be obtained by laser peening, as long as process parameters are selected appropriately.

5 Structural ageing aircraft programmes

5.1 Ageing aircraft audit programme for UK military registered aircraft

Martin Hepworth, Aviation Support Consultants Ltd, martin.hepworth@virgin.net

Introduction

The UK Ministry of Defence (MOD) has been carrying out Ageing Aircraft Audits (AAA) for over 15 years, initially these audits focused only on the ageing of aircraft structure. Following the high profile loss of two commercial airliners and perhaps more poignantly the loss of Nimrod XV230 over Afghanistan in 2006 AAAs were extended to encompass sub-audits for Systems and Propulsion Systems. The policy for AAAs, requires that an AAA be carried out 15 years after the declared In Service Date (ISD) for the type and thereafter at 10-yearly intervals. The Policy is intended provide assurance to a Project Team Leader that the integrity, and hence the airworthiness, availability and cost of a fleet of ageing aircraft is being managed in accordance with the appropriate airworthiness regulations. .

The Aim of an Ageing Aircraft Audit is to:

- Consider individually and collectively the Structural Integrity, Systems Integrity and Propulsion Integrity activities, often carried out in isolation, in order to assess the effectiveness of the fleet's airworthiness management.
- Undertake an independent review of the continued applicability of procedures, management processes, technical information and documentation that are in place to ensure airworthiness, integrity and functionality.
- Undertake a detailed, independent physical examination of the condition of representative aircraft from the fleet.
- Identify patterns or trends that suggest future airworthiness and integrity problems.
- Identify significant airworthiness and integrity risks to the aircraft.

All AAAs employ a common approach to carrying out the task and address two separate areas of aircraft support, each concerned with validating, sustaining and, exploiting the Integrity of Structures, Systems and Propulsion Systems, these areas are as follows:

- In-Service Project Team activities; e.g. intended and applied maintenance philosophy, adherence to limitations, defect reporting and analysis, management of the integrity recovery and enhancement.
- A review of Design Organisation (DO) based static and fatigue clearances for Structure and the initial Systems certification and qualification evidence compared with In-Service limitations and current usage.

The requirement to address in-service activities is fulfilled by a combination of fact finding visits, technical reviews and analysis of DO records relating to the aircraft. The fact finding visits included discussions with maintenance staff on the problems encountered during inspection and repair and these proved particularly valuable in identifying potential ageing problems.

The Ageing Aircraft Audit Programme Status

The Chart at Figure 1 shows the current status of the AAA programme. Because of the changes in requirement since AAAs were commenced 13% of the Fleet have undergone a structural audit but have the Systems and Propulsion System Audit outstanding. The 19% shown as Not Applicable are for the most part Military Registered Civil Owned Aircraft (MRCOA) that provide long term service to the MOD these aircraft are maintained to civil regulations with oversight provided by the UK CAA.

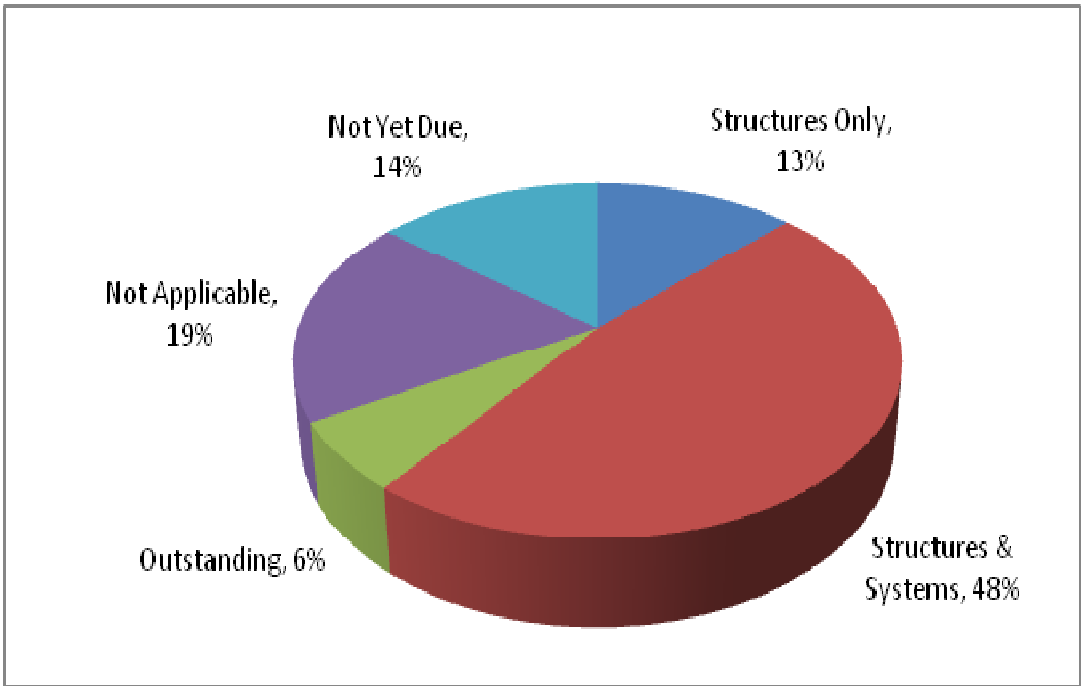

Figure 1: UK MOD Ageing Aircraft Audit Status January 2013

Notable AAAs recently Carried Out

Completed in June 2012 the Tornado AAA was by far the largest carried out to date both in terms of the complexity of the aircraft and the size and composition of the fleet. The Audit included General Condition Surveys on a significant percentage of the fleet and, whilst not part of the Audit, a Zonal Hazard Assessment programme was carried out concurrently.

The other Audit involved the BAES 146 and HS125 aircraft part of the RAF's communication fleet. These aircraft use the civilian Maintenance Programme and for the 146 in particular the Audit was able to draw on the work associated with ageing carried out by the Type Certificate Holder, including the Continuing Structural Integrity Programme Carried out to EASA AMC 20-20. Similarly when addressing the Systems element of the material provided by AMC20-21, 22 and 23 was used to assess the adequacy of the systems put in place by the PT to address the management of Electrical Wiring Interconnect Systems (EWIS). When assessing the design and qualification of the Systems the evidence provided by JAR/EASA CS25.1309 Systems Safety Assessment could also be used.

Emerging AAA policy

The recommendations of the Review into the loss of Nimrod XV230 led to major changes within the MODs aviation regulatory structure which may in turn lead to changes to AAA regulations. Most significant were the formation of the Military Aviation Authority and the publication of a new set of Regulatory Articles, these subsumed the content of several diverse regulatory publications. Other developments emanating from the Review include routine Auditing of the PTs, the creation of Continuing Airworthiness Management Organisations (CAMO) and the instigation of Airworthiness Review Certificates (ARC). These new measures should ensure that PT processes and procedures and more tightly controlled and scrutinised meaning that the format of future AAAs could be changed to focus on more on ageing and less on the PT's procedures. The MAA have established an Ageing Aircraft Programmes Working Group (AAPWG) to develop an Ageing Aircraft Programme that will identify the onset of ageing within a fleet and to implement remedial action.

5.2 Understanding the corrosion threat to military ageing aircraft

Dennis Taylor, Dennis Taylor Associates Ltd

With many military aircraft platforms being required to operate past their original out of service date (OSD) there is an increasing concern that structures and systems may be experiencing an increased airworthiness risk from corrosion. This work has been commissioned to capture the full extent of corrosion issues in the long-term UK Ministry of Defence (MOD) air fleets. The information gained during this work will be used to focus the MOD's Research and Development (R&D) Corrosion Programme onto key remedial action requirements.

As well as the physical corrosion issues being identified, the UK MOD Military Aviation Authority (MAA) regulations are also being assessed as to their suitability and application for ensuring that Platform Project Teams (PTs) may deliver a safe and cost effective management solution to this problem.

The platforms have been divided up into three generic types, namely;

- Rotary wing,
- Fast jets and training aircraft
- Heavy and communications aircraft

To date the work has concentrated on the rotary wing aircraft and the fast jets and training types. Within the rotary wing group, no one common concern has been identified apart from the problems with getting blade erosion tape to adhere in hot and sandy climates.

Only two fast jet types have been reviewed so far; however, in both cases a common problem has been corrosion to landing gear and degradation of carbon brake units, possible as a result of contamination from runway de-icer fluids.

There are at least 23 Regulatory Articles (RAs) that have some impact on the way in which corrosion and its effects are managed. These RAs are also being reviewed, as has the manner in which the various PTs apply them and manage their fleets to meet the regulatory requirements.

When all of the platforms have been reviewed a database will be produced so that common issues may be easily identified. It will also be possible to review where best practice is available so that it can be applied to other platforms with similar issues.

The results from the review will be passed to the MAA so that they may consider if any changes are required with the Regulations.

One final area to be addressed is the way in which training is delivered throughout the three services on the subject. It is important that the basic training and knowledge required to identify, repair and ensure that surface protection is maintained is fundamental to combating corrosion in all its forms on airframes and systems in the future.

5.3 Monitoring of surface coatings on aircraft

J. N. Patel, QinetiQ Ltd

The surface finish of an aircraft protects the structure from environmental damage; corrosion can lead to other forms of damage such as fatigue. The chromate content of the primer reduces over time and eventually becomes ineffective at preventing corrosion.

The exterior coating system on UK military aircraft is removed and re-finished at intervals which are usually based around the scheduled engineering maintenance requirements for specific aircraft. If the condition of the surface finish is satisfactory, then there may be no need to re-finish the aircraft at these specified periods and hence there may be potential cost savings.

Non-destructive techniques were required to assess the durability of a coating and to determine the chromate content of primer films. These non-destructive techniques were required to provide good correlation with destructive test methods and for ‘field use’ the equipment would need to be portable.

Research was undertaken to evaluate the durability and performance of a coating system under artificial weathering conditions in the laboratory by adopting non-destructive and destructive test methods. The work evaluated the performance of an aged and un-aged coating system in the laboratory. The colour and gloss determinations, i.e. non-destructive test methods, were correlated with the results from destructive test methods, including flexibility and fluid resistance tests.

On exposure to the accelerated weathering, the gloss level of the top-coat reduces as weathering progresses. The flexibility of the coating was also found to reduce. The colour of the coating remained relatively unchanged throughout the exposure period. Resistance to tri-n-butyl phosphate (synthetic hydraulic fluid) was found to have improved with ageing; resistance to water remained unaffected by the ageing processes. The study indicated that there is a correlation between gloss changes and the flexibility of the coating.

The feasibility of using an X-ray fluorescence (XRF) technique for determining the chromate content of primer paint films was also investigated. The results were checked by Energy Dispersive X-ray (EDX) analysis in a Scanning Electron Microscope (SEM) and the early indications are that XRF has the potential for determining the chromate content of primers.

Reference:

[1]. QINETIQ/13/00778

5.4 The effect of REACH legislation on surface coatings

J. N. Patel, QinetiQ Ltd

The European legislation (Regulation (EC) No 1907/2006 dated 18 December 2006) for controlling the manufacture and use of chemicals is known as REACH (Registration, Evaluation, Authorisation and restriction of Chemicals) and became embodied into UK law on 1st June 2007.

REACH affects the availability and use of certain chemicals, some of which are present in the materials used for maintaining aircraft. Aircraft maintenance is vital to ensure its safe operation and is performed at regular intervals to meet this important criterion. One method for preserving and protecting the airframe and systems is by the use of surface coatings.

REACH is being implemented in stages and is due for completion on 1st June 2018. When REACH is fully enforced, the legislation will require the registration of chemical substances that are either manufactured or imported in quantities greater than 1 tonne/year. The deadline for <u>registering</u> chemicals manufactured or imported in quantities greater than:

- 1000 tonnes/year was December 2010
- 100 tonnes/year is by June 2013
- 1 tonne/year is by June 2018

In addition to the registration of chemicals, REACH also addresses ‘substances of very high concern’ or SVHCs. These SVHCs are classed as hazardous (e.g. carcinogens and bio-accumulatives) and are controlled by regulating their use if more than 1 tonne/year is used or if the substance is present in a paint or other compound with a concentration of more than 0.1% by weight.

A registered substance will be <u>evaluated</u> for its risks to human health or the environment.

Substances identified as SVHC will require <u>authorisation</u> before they can be used or sold. To date, the list of SVHCs (known as Annex XIV (Article 59(10))) comprises 138 chemicals. If an authorisation is not granted, then the use of that SVHC will be prohibited beyond a date (called the sunset date) specified by the Commission.

A substance which poses an unacceptable risk to health or the environment will be <u>restricted</u> in the way it is used. The main consequences from the REACH legislation are:

- Substances may become more expensive to procure due to the cost of registration and associated procedures
- Substances, if classified as hazardous, may not be readily available
- Substances will not be available if not registered or authorised

A systematic assessment that the impact of REACH could have on the supply of products listed is required. It is noteworthy that any potential alternative substances may have to be tested and validated by the appropriate aircraft design organisations before they are adopted for use.

A preliminary check of the current list of 138 SVHCs suggests the following chemicals used for surface finishing activities will need to undergo the authorisation process: Potassium dichromate, Sodium dichromate, Chromium trioxide, Pentazinc chromate octahydroxide, and Strontium chromate.

Reference:

[1]. QINETIQ/13/00784

6 Fatigue testing

6.1 Hawk tailplane full scale fatigue test

William Lennox, Graham Duck and Bob Young, BAE Systems Brough

The Hawk Tailplane and Rear Fuselage Manoeuvre and Buffet Test achieved 30,000 test hours on 3rd December 2009. At this stage sufficient test based clearance evidence was available to meet all existing customer contracted fatigue requirements. However, the decision was taken to postpone the scheduled Residual Strength Testing and Teardown activities in favour of accumulating increased test damage and hence increased test based qualification evidence. A contract was signed with the RAF in March 2010 to run the test for a further 10,000 test hours (an initial 3,000 test hours of the same test spectrum and a further 7,000 test hours of an agreed enhanced spectrum) taking the test article to 40,000 test hours.

The current status (February 2013) is that the test article has achieved a total of 36,000 test hours. Following a Major Inspection conducted at 36,000 test hours the test article will be re-commissioned and continue further test running using the enhanced manoeuvre and buffet spectrum. As testing progresses, the test article continues to provide evidence of structural capabilities at a variety of locations thus supporting the development of inspection techniques, modification solutions and potential future enhancements of the Hawk product. The test (Figure 1) continues to retain an overall sound residual capability and hence the test will continue to run towards the target of 40,000 test hours.

Figure 1: Hawk tailplane full scale fatigue test

6.2 Lead-in fighter full scale fatigue test

Richard Aaron and Bob Young, BAE Systems Brough

As part of the contract for the supply of Lead-In Fighter (LIF) Hawk aircraft to the Commonwealth of Australia (CoA) a Full Scale Fatigue Test (FSFT) is being carried out on the LIF Hawk airframe. The FSFT is the responsibility of BAE Systems and is being carried out on BAE Systems behalf by the Defence Science & Technology Organisation (DSTO) at Fisherman's Bend, Melbourne. The test requirement is 50,000 test hours. The test rig design, as well as derivation of the loading spectrum, was carried out by BAE Systems, Brough. The spectrum and loading are derived from RAAF in-service data, taking due account of potential future increases in usage, as well as a requirement for the LIF Hawk FSFT to provide clearance for other Hawk fleets.

The current status (February 2013) is that the test article has achieved a total of 24,872 test hours and is continuing to run. As testing progresses, the test article continues to provide evidence of structural capabilities at a variety of locations thus supporting the development of inspection techniques, modification solutions and potential future enhancements of the Hawk product. The test (Figure 1) continues to retain an overall sound residual capability and hence the test will continue to run towards the target of 50,000 test hours.

Figure 1: LIF full scale fatigue test

6.3 Joint RAF and RAAF C-130J Full Scale Wing Fatigue Test Loads Development and Test Running

Stephen Dosman, Marshall Aerospace and Defence Group, Cambridge, UK

Introduction

The C-130J Wing Fatigue Test (WFT) being carried out by Marshall Aerospace and Defence Group (Marshall) on behalf of the Royal Air Force (RAF) and Royal Australian Air Force (RAAF) represents a complex multi-year programme as part of the efforts to establish the Life of Type (LoT) for the airframe.

The goal of the test is to achieve a minimum of 62,500 Test Hours (TH) of equivalent usage (With possible extension to 100,000 TH), to provide crack initiation and crack growth rate data for test interpretation, and to underwrite the LoT for the C-130J Wings for the RAF and RAAF.

Testing began in earnest in early 2009. As of February 2013 the test was completing planned maintenance following the reaching of the 37,500 TH milestone.

Test Background

The test article was constructed as a standard C-130J wing by Lockheed Martin (LM), but was removed from the line prior to the introduction of secondary structure such as leading and trailing edges, fuel systems, etc. It comprises complete outer and centre wings less leading/trailing edges and flaps with the addition of engine powermounts/quick engine change (QEC) units and additional partial fuselage sidewalls.

The test rig applies loads via hydraulic actuators to the wing, engines and sidewalls and utilises an airbag to apply cabin differential to the lower wing skin between BL+/-61.

Figure 1: Wing Fatigue Test Article and Rig Structure

The control system was developed by FCS Kelsey (Now Moog) as a turnkey solution and is operated as a conventional proportional-integral-derivative (PID) feedback loop based control system.

An extensive strain gauge and data acquisition system is used on the WFT. Over 500 strain gauges have been installed on the test article.

Loads Development

Many conventional full scale wing fatigue test programmes have been developed around building up a theoretical spectrum based on a combination of flight test, fleet experience, and theoretical models; however early on in the WFT loads development phase the decision was made to capitalise on the RAF C-130J Operational Loads Monitoring (OLM) programme that was collecting whole-aircraft, high-sample rate loads from two long-body aircraft for operational flights over several years.

A relatively limited pool of high fidelity / high sample rate loads data meant that the repeating spectrum blocks would be based on a relatively short number of flights, but that significant effort would be required to reduce the number of load-lines applied in individual flights down to a manageable number while retaining sufficient crack growth and initiation fidelity.

Flight Selection:

The final test block structure adopted for the test was a 250 flight ‘normal’ block and another more severe 250 flight ‘modified’ block. A sequence of 5 normal blocks plus 1 modified block would be combined together into a single longer repeating 1500 flight /~3000 flight hour sequence, called here ‘superblock’.

The flight profile selection process was based around matching an agreed target utilisation as well as parametric data. Individual targets were first developed independently for the two air forces based on both service experience and predicted usage data.

Truncation:

Given the extreme length of the OLM data set a robust and verifiable means to truncate the load spectrum was needed. This was achieved by using a non-standard loads gating process that removed cycles based on damage (at a number of locations across the wing) rather than stress range, and by the use of extensive coupon testing for verification. The final truncated loads set resulted in blocks with approximately 200-300 load lines per flight hour.

To summarise the truncation process:

[1]. Take Analysis Point (AP) stresses and filter and gate the raw data set to generate a Baseline spectrum

[2]. Identify target relative retained damage for all APs

[3]. Cycle count and assess damage for all APs

[4]. Attribute damage to individual load lines (½ damage on peak and ½ on valley) for each AP

[5]. Rank load lines based on damage at each AP

[6]. Identify a pool of load lines for each AP that represents the target relative damage target

[7]. Take the union of all load lines in each AP's pool, reform into a sequence, and assess overall retained damage for the total set

[8]. Start process again at step 2 with updated target relative retained damage for all APs

Once this process has been carried out for a number of different target relative retained damages, then overall damage versus total retained load lines can be plotted, and a desired damage retention vs load lines chosen. The pool of load lines that is associated with the retained damage across all the APs then represents the final truncated load set. This pooling is called 'Venn combination' here, and it allows different levels of fidelity to be achieved in different locations on the wing. The final result following coupon testing and further analytical work was a spectrum that was reduced approximately 1000-fold against the raw data set (see Figure 2).

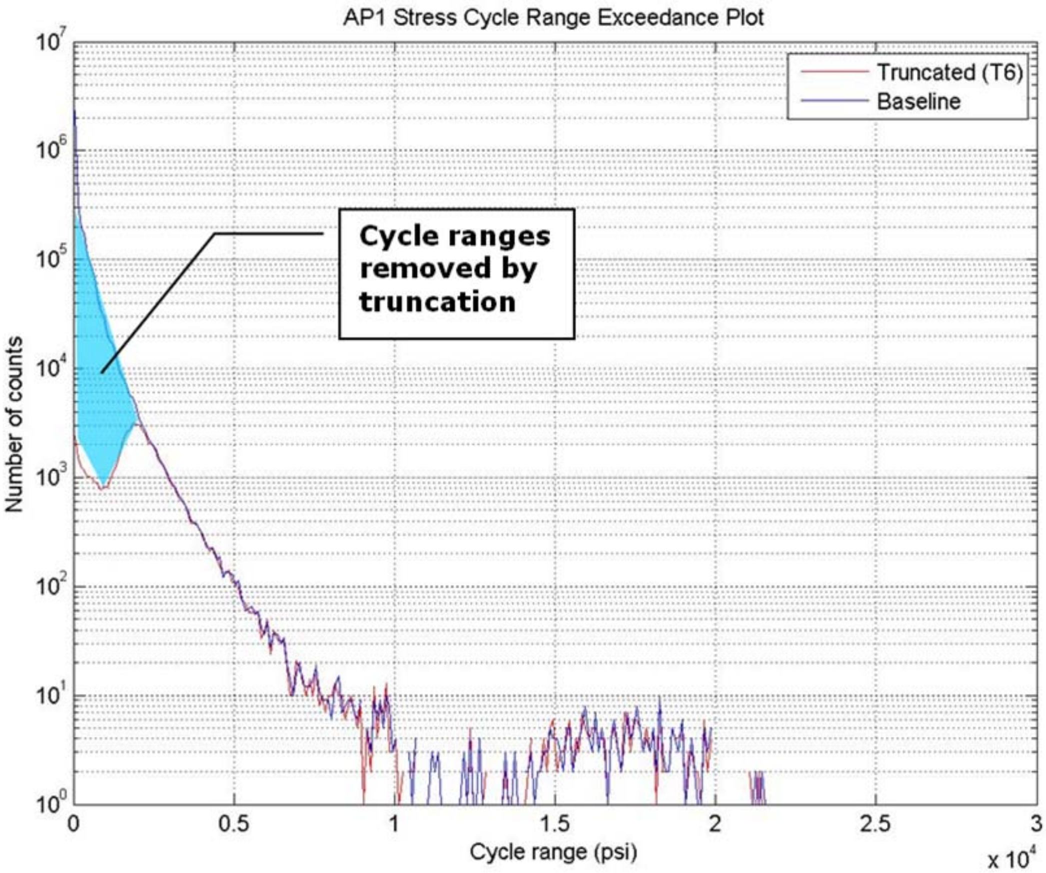

Figure 2: Impact of truncation on an Analysis Point's (AP) retained cycles

<u>Test Running</u>

At the end of the 37,500 TH Major Maintenance there stands 233 Damage Items; however many of these are associated with non-test critical findings such as build deviations, QEC damage (which is not test structure), and secondary structure damage. There are, however, a number of more significant findings which are of particular interest including wing tang at rainbow fitting cracking, wing plank at fuselage drag angle cracking, and wing plank at engine drag angle cracking.

Summary

The C-130J Wing Fatigue Test is a challenging multi-year programme, which provided many opportunities for innovation and process improvement. Of these opportunities the loads development process presented a particularly complex challenge due to the loads being directly taken from OLM aircraft. The large size of the data set and the customer requirement for high crack growth fidelity lead to the use of damage, rather than stress-range, based truncation and by ranking load lines for inclusion with a combitorial approach. This meant that damage fidelity could be targeted efficiently across the wing resulting in a 1000-fold reduction in the length of the spectrum while retaining acceptable crack growth and initiation fidelity.

Initial crack findings have generally followed expectations.

7 Developments in fatigue, usage and structural health monitoring

7.1 Demonstration of structural health monitoring on the Gazelle helicopter

Dr. R Dalton, QinetiQ Ltd

The primary objective of the Monitoring of Aircraft Component Health (MACH) Guided Wave project was to develop and demonstrate an SHM system to monitor the rib on the horizontal stabiliser, of QinetiQ's Gazelle helicopter (shown in Figure 1), for an extended period of operational service. The system, which is based on the transmission and reception of ultrasonic guided wave signals through the structure, comprises an array of installed sensors, which are connected to the Hand Held Transceiver (HHT) unit during ground maintenance. The purpose of the project is to demonstrate the capabilities of the system by detecting cracks in the structure of an aircraft in service and builds on an earlier SHM system development demonstrated on a HAWK. The collaborative Partner working with QinetiQ in the MACH Guided Wave project is Blazepoint Ltd, who is one of the current market leaders in ruggedised electronic equipment. Blazepoint are responsible for the design and fabrication of the HHT, whilst QinetiQ are responsible for the sensor design, defect detection software module and system operation.

Figure1: QinetiQ Gazelle helicopter on Empire Test Pilot School operations at QinetiQ Boscombe Down.

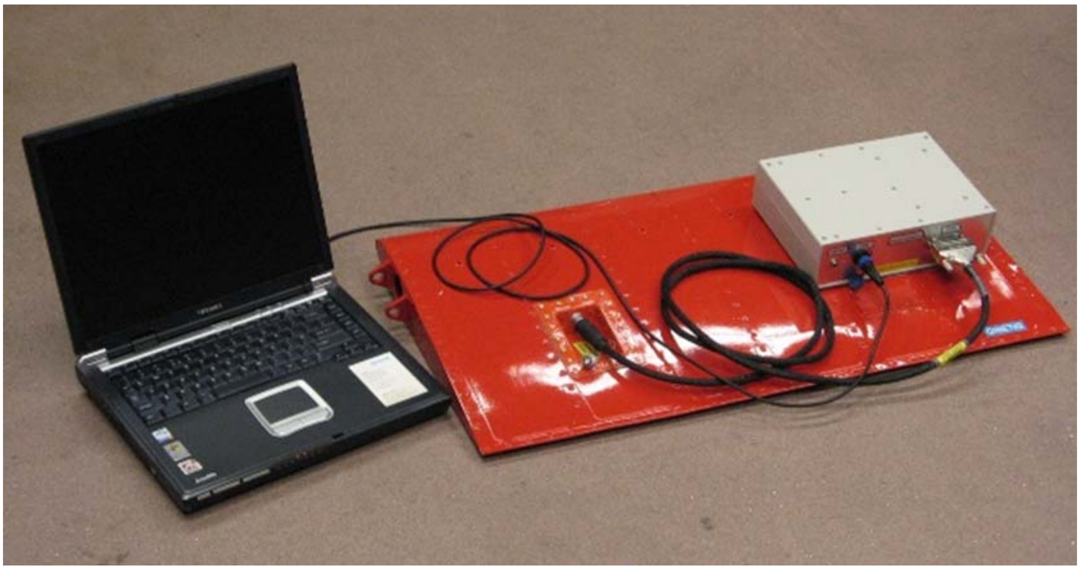

Figure2: QinetiQ Prototype Gazelle SHM System showing the prototype Hand-Held Transceiver

The HHT is an electronic hardware component of the Gazelle SHM System. It is responsible for the control of the transmission and reception of signals by the array of aircraft-mounted sensors and also the processing, storage and display of results. The entire system was conceived to be the HHT connected to a plug on the aircraft stabiliser skin by a bespoke cable and connected internally to the permanently installed sensor array. To reduce development costs the HHT of the prototype system, shown in figure 2, comprised a separate battery-powered transceiver and laptop components. The system is only active when the aircraft is stationary and powered down; no connection to aircraft power systems is required. During a test operation, the battery-powered HHT first acquires a set of signals from an array of eight ultrasonic sensors permanently-mounted on one of the ribs in the stabiliser. These signals are subsequently analysed by the unit and the results displayed to the operator on a laptop PC. The signals are also stored in a file on the PC for recording and further analysis if required.

The term sensor refers to a single interdigital transducer, of which there are a total of eight in the Gazelle system, and are referenced by number (1-8) as shown in figure 3. Ultrasonic signals are transmitted through the aircraft structure by a transmitting sensor before being received by an identical receiving sensor. The transmitter and receiver may be separate sensors (pitch-catch operation), or alternatively, may be the same sensor (pulse-echo operation). Thus, two numbers are always used to identify the active sensor pair (these being identical for pulse-echo operations).

Figure3: Encapsulated sensor elements with their numbering convention on the Gazelle rib

A typical signal from an opposing pair is shown in Figure 4 below.

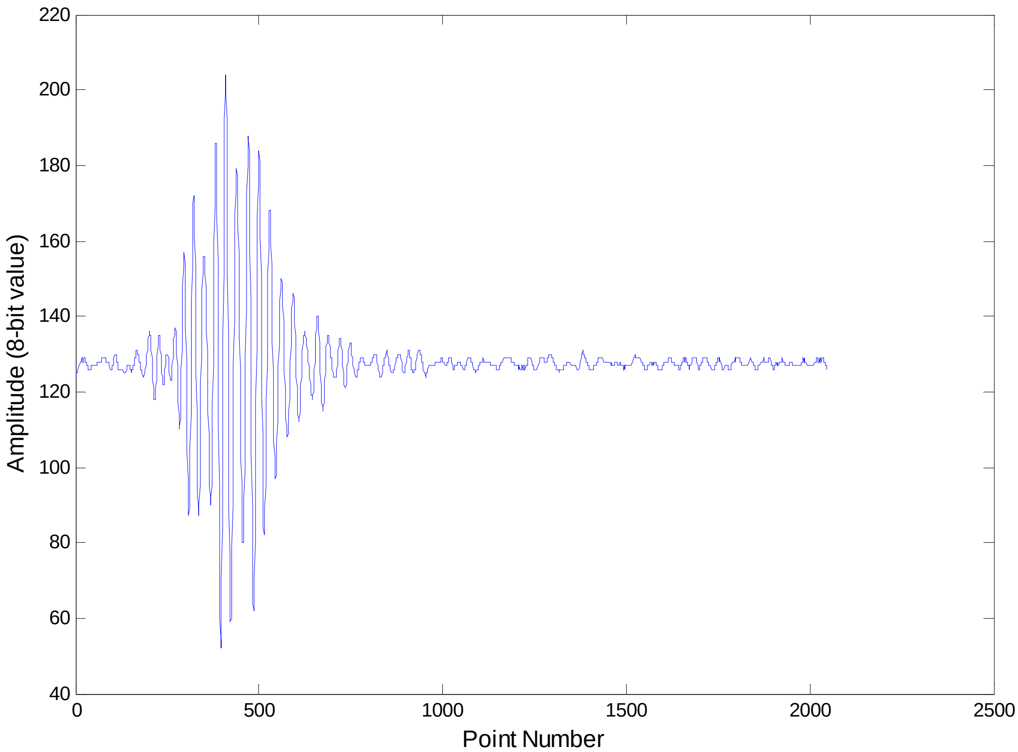

Figure 4: A typical signal from an opposing sensor pair (sensor 4 to sensor 1)

Sensitivity to the expected crack types was tested in the laboratory using simulated cracks of increasing length made with a 0.01 mm wide saw cut. Figure 5 shows the maximum change in the signal amplitude with increases in the length of a simulated crack emanating from the spar tube mid-way between sensors 5 and 6. It is seen that the amplitude of the signal transmission between sensors 1 and 4 (1-4) changes significantly whilst the remaining sensor pair signals show little change.

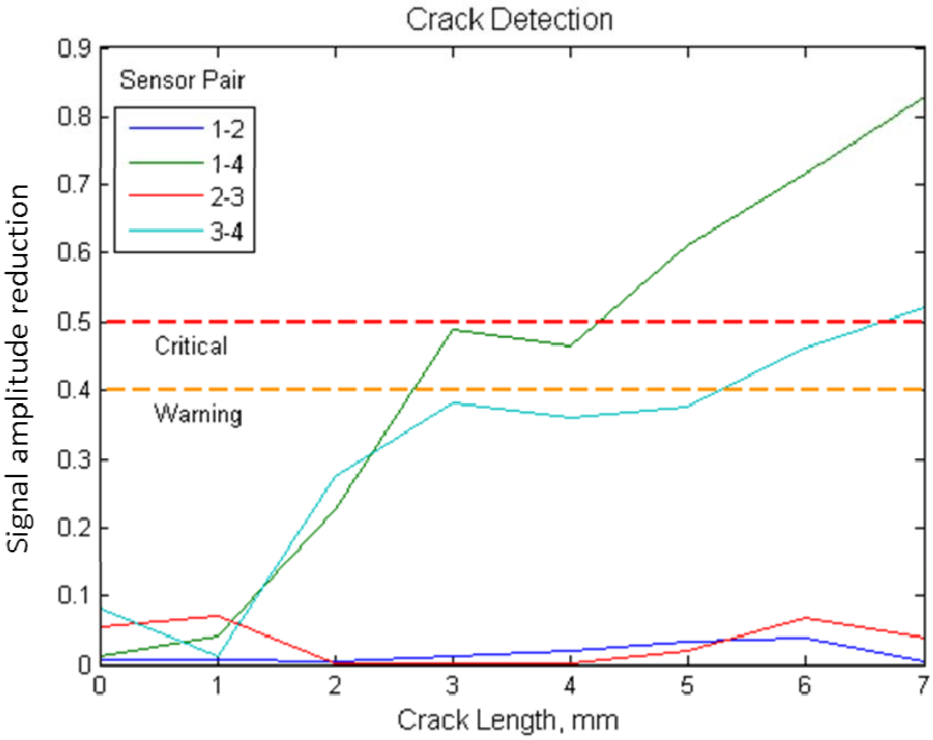

Figure 5: Graph of reduction in the transmission signal amplitude between various sensor pairs with the increasing length of a simulated crack from the spar tube aperture towards the rivet adjacent to sensor 4 (see Figure 3).

To date the system has been in operation on Gazelle ZX939 since May 2012 and has flown for 174 hrs. Data is acquired on a weekly basis by aircraft technicians at Boscombe Down as depicted in Figure 6.

Figure 6. Routine structural health monitoring of the Gazelle stabiliser is now being carried out by aircraft technicians at Boscombe Down.

Cracks, in the rib, are expected to appear in less than 300 flying hours and the system has completed 175 flying hours to date; no cracks have yet been detected by the system and this result has recently been validated by endoscopic inspection of the stabiliser.

Reference:

[1]. QINETIQ/MS/AD/PUB1300962

7.2 Coating Degradation and Corrosion Sensing

Steve Morris, Business Development Manager, BAE Systems Advanced Technology Centre steve.b.morris@baesystems.com

Corrosion in aerospace platforms and vehicles in general is an enormously costly problem, both in terms of part replacement and preventative inspection and maintenance. Accurate, dependable corrosion sensors can allay both these aspects and produce significant running cost benefits.

BAE Systems corrosion sensors use strips of alloy that mimic the corrosion in structural alloys they are monitoring. The sensor measures the electrical resistance of the alloy strips, which is dependant on how much corrosion has taken place, and in turn is a measure of degradation of the protection provided by the paint scheme.

BAE Systems offers different sensor types to monitor three different aspects of degradation and corrosion:

[1]. Corrosion Sensors (CSR)

[2]. Coating degradation (CDR)

[3]. Environmental (including ToW (Time of Wetness) and Commercial-off-the-Shelf (COTS) sensors for variables such as temperature and humidity

<u>Corrosion sensors - resistive (CSR)</u>

In CSR sensor types (Figure 1) the sensor alloy strips line up with deliberately defined gaps in the sensor’s paint coating, and as such are intentional defects for the monitoring of corrosion progress in simulated flawed paint schemes. In this sensor type, artificially large defects act as early warnings before any actual corrosion should have taken place on the platform. However the narrowest strip is designed to equate to real platform defects such as cracks around fasteners.

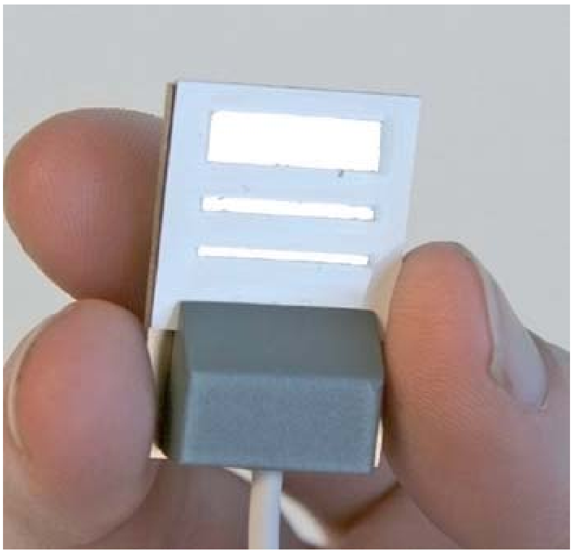

Figure 1: Corrosion sensor - resistive

Type CSR 2V2 has a group of 3 strips, designed to offer a ‘traffic light’ early warning system, as in a corrosive atmosphere the strips will suffer corrosion and ‘burn out’ in sequence, giving a stepped resistance output. This type is read out directly, using constant current interrogation

Type CSR 2V3 has the same corrodible strips as CSR 2V2, but the group is placed in one arm of an on-chip Wheatstone bridge, so that it can be read out as a millivolt change emulating a strain gauge. The Wheatstone additionally offers a good degree of temperature compensation.

All the sensors described above are wired with PTFE cabling and packaged with PR2001 sealant, ready to be fixed to a platform substrate with further sealant.

Type CSR 2V4 is as CSR 2V3, but with modified packaging which offers rugged handling tolerance and reduced need for additional sealing detail when fixing to a platform.

All the above sensors are designed to mimic actual platform alloys and coating systems and as such exhibit realistic cumulative degradation/corrosion status, and do not rely on constant powering or monitoring.

Coating degradation sensors (CDS)

In CDS sensor types (Figure 2) the fundamental ageing of the structure’s protective coating scheme (normally paint) is measured, assuming no flaws, thus the sensors are all-over painted and do not feature any deliberate defects. Whilst coating degradation is the main aim, this is measured indirectly through corrosion of the sensor’s elements beneath the paint and so the sensor also provides information about corrosion once the coating has degraded. The CDS sensor is specifically designed to measure a variety of degradation mechanisms e.g. weather, pin-hole, impact, UV and physical erosion of the coating protection system.

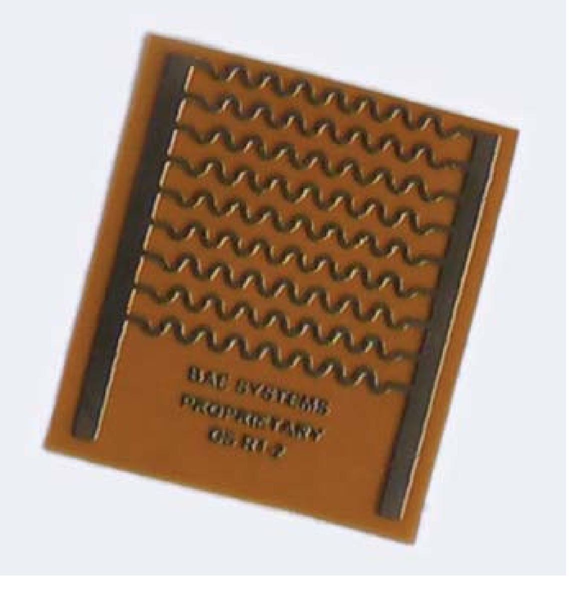

Figure 2: Coating degradation sensor

Type CDS 1VA consists of a serpentine element which will fail in a very marked way when any part of the serpentine is corroded as a result of coating degradation. The element's track width is chosen to suit the application, related to critical spot failure size in the specific coating. This device allows the primer and paint top coat degradation to be independently monitored.

Metal Loss Sensors (MLR) In this sensor type, activity beyond paint degradation is measured resistively for situations where a platform can tolerate significant metal loss e.g in marine applications, the point at which a few hundred microns has been lost can be sensed.

Time of wetness sensor (TOW)

The ToW sensor (Figure 3) is used as an environmental sensor to record periods when the monitored surface experiences wetting. As such these sensors are used in environmental data gathering systems and corrosion prediction systems.

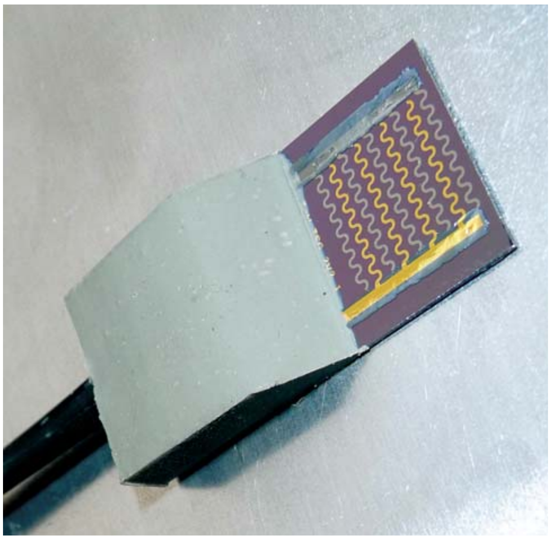

Figure 3: Time of wetness sensor

Two variants of ToW sensors are available, depending upon the severity of the environment:

Type TSG 2V2 is a galvanic sensor consisting of interdigitated gold and tungsten electrodes. This is sensed potentiometrically (Voltage) and is the most sensitive, but electrochemically consumed through life.

Type TSNG 1A is a non-galvanic sensor, which is suited for more severe environments, but requires a constant current to evaluate wetness.

The wetness can be interpreted digitally (wet/not wet) or in an analogue manner (indication of how much of the surface is wet, correlating to humidity in the range 70-100%).

Supplementary commercial-off-the-shelf (COTS) sensors

Systems are often formulated with the addition of COTS sensors for environmental monitoring, and we have chosen examples of Temperature, Humidity and atmospheric pressure/altitude sensors.

Qualification

Type CSR 2 and TSG sensors have achieved interim qualification through customers for flight on JSF, Hawk and Dassault Falcon 50 aircraft.

Applications

The principal application of the corrosion sensor system is in platform locations (Figure 4) that are difficult and time-consuming to inspect manually. A particularly suitable application is nominally-sealed internal bays in aircraft, where unsealing introduces a risk of faulty re-sealing. The corrosion sensor acts as an early warning device for corrosion in such areas which, once confidence is gained with the application, reduces the need and cost of regular manual inspections. In this mode the sensors can be used as stand-alone monitors of cumulative paint degradation/corrosion, and do not need constant reading.

Figure 4: Application example

Corrosion and time-of-wetness sensors can also be used as part of a corrosion prediction system, where supplementary inputs are used, such as temperature, humidity and time-of-wetness.

7.3 Fixed-wing structural usage monitoring

Dr Steve Reed, Dstl

Dstl has developed a low-cost structural usage monitoring system, based upon commercially-available, Micro Electro Mechanical System (MEMS) technology. The Modular Signal Recorder (MSR) is self contained and places a very low burden on front-line maintenance crews.

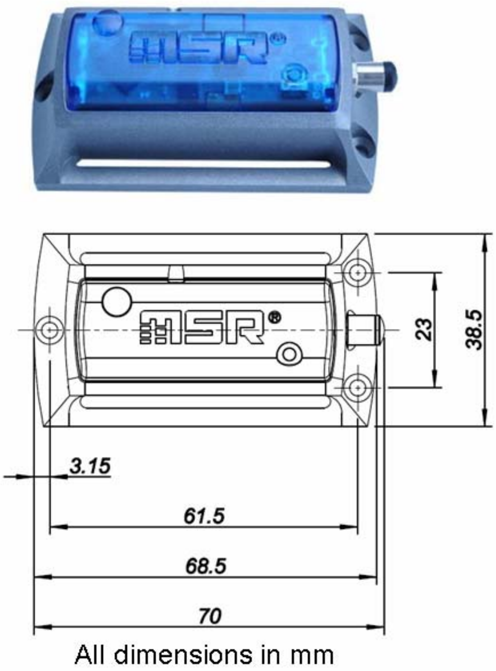

Figure 1: Modular Signal Recorder

In addition, Dstl has developed a universal Aircraft Data Analysis and Monitoring system (ADAM) for analysing flight data from a range of acquisition systems (including the MSR), using a common-core-code approach.

This technology has now been exploited with a fleet-wide fit for Islander and Defender aircraft (Figure 2), from which over 3000 flying hours of data have been captured.

Figure 2: Islander (top) and Defender (bottom) aircraft

The aim is to allow comparison between the current fleet usage with the fatigue test spectrum and historical usage data. The system has also been used to support usage data capture for the Lancaster, Swordfish, Beaver and Hunter aircraft (Figure 4, typical data Figure 5) as well as road transport monitoring of a Puma fuselage (Figure 6) during transit into the Life Extension Programme.

Figure 4: Lancaster, Swordfish, Beaver and Hunter aircraft

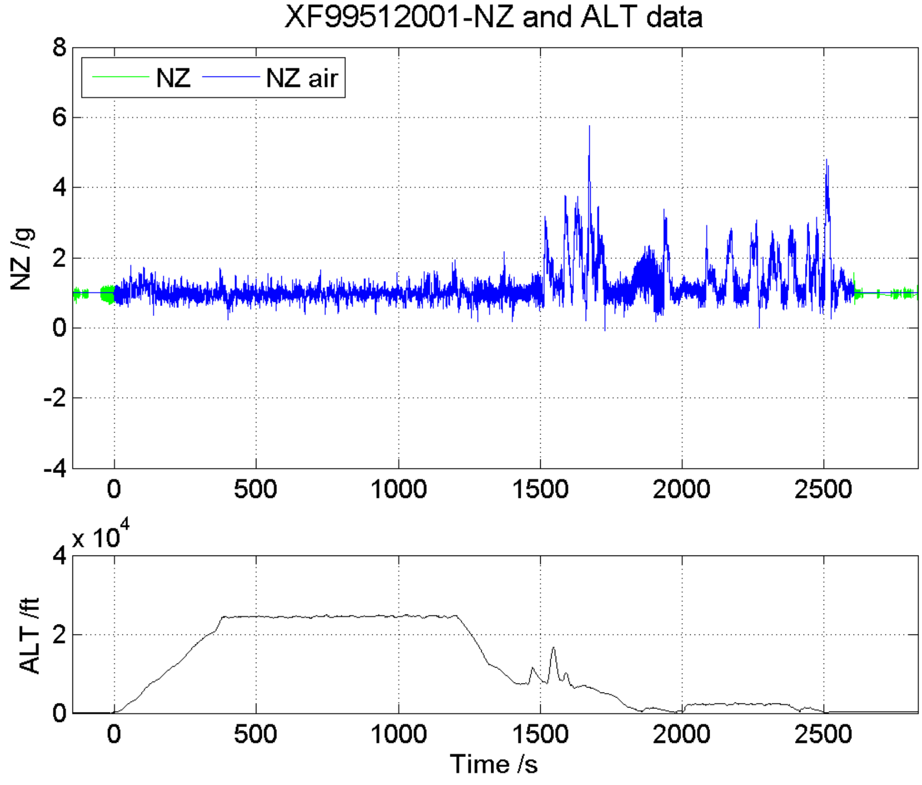

Figure 5: Example Hunter structural usage data

Figure 6: MSR located on Puma fuselage for road transport

Additional programmes are underway or are planned to roll out this capability to the Shadow R1 fleet, the remainder of the Battle of Britain Memorial Flight and to identify accelerations seen by the C130J Modular Maritime Platform.

Initial distribution

1.	ICAF2013	
2.	Contributors	
3.	Dstl KIS	Athena

Report documentation page

v3.0

1a.	Report number:	DSTL/TR71962	1b.	Version number:	Ver 2
2.	Date of publication:	29/03/2013	3.	Number of pages:	ii + 42
4a.	Report UK protective marking:	UNCLASSIFIED			
4b.	Report national caveats:				
4c.	Report descriptor:				
5a.	Title: Review of aeronautical fatigue and structural integrity investigations in the UK during the period April 2011 - April 2013				
5b.	Title UK protective marking:	UNLIMITED			
5c.	Title national caveats:				
5d.	Title descriptor:				
6a.	Alternate title:				
6b.	Alternate title UK protective marking:				
6c.	Alternate title national caveats:				
6d.	Alternate title descriptor:				
7.	Authors: Reed, S.C.				
8.	Name and address of publisher: Dstl Physical Sciences Porton Down Salisbury Wilts SP4 0JQ		9.	Name and address of sponsor: - -	
10.	Sponsor contract:	-			
11.	Dstl project number:	-			
12.	Work package number:				
13.	Other report numbers:				
14a.	Contract start date:		14b.	Contract end date:	
15a.	IPR:				
15b.	Patents:	NO			
15c.	Application number:				

16a.	**Abstract:** This report provides a review of the aeronautical fatigue and structural integrity investigations carried out in the UK during the period April 2011 to April 2013.		
16b.	**Abstract UK protective marking:**	UNLIMITED	
16c.	**Abstract national caveats:**		
16d.	**Abstract descriptor:**		
17.	**Keywords:** Aeronautical fatigue, structural integrity, ICAF		
18.	**Report announcement and availability**		
	Announce to?	Available to?	
18a.	☒	☒	UK MOD has unlimited distribution rights
18b.	☐	☐	UK MOD has no rights of distribution
18c.	☐	☐	Can be distributed to UK MOD and its agencies
18d.	☐	☐	Can be distributed to all UK government departments
18e.	☐	☐	Can be distributed to all UK defence contractors
18f.	☐	☐	Can be distributed to all foreign government departments
18g.	**Additional announcement:**		
18h.	**Additional availability:**		
18i.	**Release authority role:**		

THIS PAGE INTENTIONALLY LEFT BLANK